On differential modules associated to de Rham representations in the imperfect residue field case

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Let $K$ be a complete discrete valuation field of mixed characteristic $(0, p)$ with possibly imperfect residue fields, and let $G_K$ the absolute Galois group of $K$. In the first part of this paper, we prove that Scholl’s generalization of fields of norms over $K$ is compatible with Abbes–Saito’s ramification theory. In the second part, we construct a functor $\mathcal{N}_{dR}$ that associates a de Rham representation $V$ to a $(\varphi, \nabla)$-module in the sense of Kedlaya. Finally, we prove a compatibility between Kedlaya’s differential Swan conductor of $\mathcal{N}_{dR}(V)$ and the Swan conductor of $V$, which generalizes Marmora’s formula.

Introduction

Hodge theory relates the singular cohomology of complex projective manifolds $X$ to the spaces of harmonic forms on $X$. Its $p$-adic analogue, $p$-adic Hodge theory, enables us to compare the $p$-adic étale cohomology $H^m_{\text{ét}}(X_{\overline{\mathbb{Q}_p}}, \mathbb{Q}_p)$ of proper smooth varieties $X$ over the $p$-adic field $\mathbb{Q}_p$ with the de Rham cohomology of $X$. Precisely speaking, the natural action of the absolute Galois group $G_{\overline{\mathbb{Q}_p}}$ of $\mathbb{Q}_p$ on the $p$-adic étale cohomology can be recovered after tensoring both cohomologies with $\mathbb{B}_{dR}$, which is the ring of $p$-adic periods introduced by Jean-Marc Fontaine. If $X$ has

MSC2010: 11S15.
Keywords: $p$-adic Hodge theory, ramification theory.
semistable reduction, then one can obtain a more precise comparison theorem between the $p$-adic étale cohomology of $X$ and the log-cristalline cohomology of the special fiber of $X$. Thus, we have a satisfactory $p$-adic étale cohomology theory on proper smooth varieties over $\mathbb{Q}_p$.

A $p$-adic representation $V$ of $G_{\mathbb{Q}_p}$ is a finite dimensional $\mathbb{Q}_p$-vector space with a continuous linear $G_{\mathbb{Q}_p}$-action. Fontaine [1994] defined the notions of de Rham, crystalline, and semistable representations, which form important subcategories of the category of $p$-adic representations of $G_{\mathbb{Q}_p}$. Then, he associated linear algebraic objects such as filtered vector spaces with extra structures to objects in each category. Fontaine’s classification is compatible with geometry in the following sense: for a proper smooth variety $X$ over $\mathbb{Q}_p$, the $p$-adic representation $H^m_{\text{ét}}(X_{\mathbb{Q}_p}, \mathbb{Q}_p)$ of $G_{\mathbb{Q}_p}$ is only de Rham in general. However, if $X$ has a semistable reduction (resp. good reduction), then $H^m_{\text{ét}}(X_{\mathbb{Q}_p}, \mathbb{Q}_p)$ is semistable (resp. crystalline).

There also exists a more analytic description of general $p$-adic representations. Let $\mathbb{B}_{\mathbb{Q}_p}$ be the fraction field of the $p$-adic completion of $\mathbb{Z}_p[[t]][1/t]$. We define the action of $\Gamma_{\mathbb{Q}_p} := G_{\mathbb{Q}_p}(\mu_{p^\infty})/\mathbb{Q}_p$ on $\mathbb{B}_{\mathbb{Q}_p}$ by $\gamma(t) = (1 + t)\gamma(t) - 1$, where $\chi : \Gamma_{\mathbb{Q}_p} \rightarrow \mathbb{Z}_p^\times$ is the cyclotomic character. We also define a Frobenius lift $\varphi$ on $\mathbb{B}_{\mathbb{Q}_p}$ by $\varphi(t) = (1 + t)^p - 1$. An étale $(\varphi, \Gamma_{\mathbb{Q}_p})$-module over $\mathbb{B}_{\mathbb{Q}_p}$ is a finite dimensional $\mathbb{B}_{\mathbb{Q}_p}$-vector space $M$ endowed with compatible actions of $\varphi$ and $\Gamma_{\mathbb{Q}_p}$ such that the Frobenius slopes of $M$ are all zero. Using Fontaine–Wintenberger’s isomorphism

$$G_{\mathbb{Q}_p}(\mu_{p^\infty}) \cong G_{\mathbb{F}_p((t))},$$

of Galois groups, Fontaine [1990] proved an equivalence between the category of $p$-adic representations and the category of étale $(\varphi, \Gamma_{\mathbb{Q}_p})$-modules over $\mathbb{B}_{\mathbb{Q}_p}$. We consider the overconvergent subring

$$\mathbb{B}^+_\mathbb{Q}_p := \left\{ \sum_{n \in \mathbb{Z}} a_n t^n \in \mathbb{B}_{\mathbb{Q}_p} ; \ a_n \in \mathbb{Q}_p, \ |a_n| \rho^n \rightarrow 0 \text{ for some } \rho \in (0, 1] \text{ and } n \rightarrow -\infty \right\}$$

of $\mathbb{B}_{\mathbb{Q}_p}$. Frédéric Cherbonnier and Pierre Colmez [1998] proved that the category of étale $(\varphi, \Gamma_{\mathbb{Q}_p})$-modules over $\mathbb{B}_{\mathbb{Q}_p}$ is equivalent to the category of étale $(\varphi, \Gamma_{\mathbb{Q}_p})$-modules over $\mathbb{B}^+_\mathbb{Q}_p$. As a consequence of Cherbonnier–Colmez’ theorem, $p$-adic analysis over the Robba ring

$$\mathcal{R}_{\mathbb{Q}_p} := \bigcup_{\rho' \in (0, 1)} \left\{ \sum_{n \in \mathbb{Z}} a_n t^n ; \ a_n \in \mathbb{Q}_p, \ |a_n| \rho^n \rightarrow 0 \text{ for all } \rho \in (\rho', 1] \text{ and } n \rightarrow \pm \infty \right\}$$

comes into play. Actually, via the above equivalences, Laurent Berger [2002] associated a $p$-adic differential equation $\mathbb{N}_{\text{dR}}(V)$ over $\mathcal{R}_{\mathbb{Q}_p}$ to a de Rham representation $V$. By using this functor $\mathbb{N}_{\text{dR}}$ and the quasi-unipotence of $p$-adic differential equations due to Yves André, Zoghman Mebkhout and Kiran Kedlaya, Berger proved Fontaine’s $p$-adic local monodromy conjecture, which is a $p$-adic analogue of Grothendieck’s $l$-adic monodromy theorem. We note that in the above theory,
Recently, based on earlier work of Gerd Faltings and Osamu Hyodo, Fabrizio Andreatta and Olivier Brinon [2008] started to generalize Fontaine’s theory in the valuation ring of characteristic $p$ via Bloch–Kato’s dual exponential map $\exp$ varying $n$ valuation field, but it has a nonperfect residue field $\mathbb{A}$ isomorphism of Galois groups $\text{FÉt}$. Similar limit procedure gives an equivalence of categories $\text{FÉt}$ $\text{FÉt}$. In this paper, we work in the most basic case of Andreatta–Brinon’s setup. That is, our ground ring $K$ is still a complete valuation field, but it has a nonperfect residue field $k_K$ such that $p^d = [k_K : k_F^p] < \infty$. Such a complete discrete valuation field arises as the completion of a ground ring along the special fiber in Andreatta–Brinon’s setup.

Even in our situation, a generalization of Fontaine’s theory could be useful as in the proof of Kato’s divisibility result [2004] in the Iwasawa main conjecture for $\text{GL}_2$. Using compatible systems of $K_2$ of affine modular curves $Y(p^n N)$ for varying $n$, Kato defines ($p$-adic) Euler systems in Galois cohomology groups over $\mathbb{Q}_p$ whose coefficients are related to cusp forms. A key ingredient in this paper is that Kato’s Euler systems are related with some products of Eisenstein series via Bloch–Kato’s dual exponential map $\exp^*$. In the proof of this fact, $p$-adic Hodge theory for “the field of $q$-expansions” $\mathcal{K}$ plays an important role, where $\mathcal{K}$ is the fraction field of the $p$-adic completion of $\mathbb{Z}_p[\zeta_p^n][[q^{1/N}][q^{-1}]]$. Roughly speaking, Tate’s universal elliptic curve together with its torsion points induces a morphism $\text{Spec}(\mathcal{K}(\zeta_p^n, q^{p^n})) \to Y(p^n N)$. Using a generalization of Fontaine’s ring $\mathbb{B}_\text{dR}$ over $\mathcal{K}$, Kato defines a dual exponential map for Galois cohomology groups over $\mathcal{K}(\zeta_p^n, q^{p^n})$, and proves its compatibility with $\exp^*$. Then, the image of Kato’s Euler system under $\exp^*$ is calculated by using Kato’s generalized explicit reciprocity law for $p$-divisible groups over $\mathcal{K}(\zeta_p^n, q^{p^n})$.

To explain our results, we recall Anthony Scholl’s theory [2006] of field of norms, which is a generalization of Fontaine–Wintenberger’s theorem when $k_K$ is nonperfect. In the rest of the introduction we restrict ourselves for simplicity to the “Kummer tower case”: we choose a lift $\{t_j\}_{1 \leq j \leq d}$ of a $p$-basis of $k_K$ and define a tower $\mathcal{K} := \{K_n\}_{n>0}$ of fields by $K_n := K(\mu_{p^n}, t_1^{p^n}, \ldots, t_d^{p^n})$ for $n > 0$, and set $K_{\infty} := \bigcup_n K_n$. Then, the Frobenius on $\mathcal{O}_{K_{n+1}}/p\mathcal{O}_{K_{n+1}}$ factors through $\mathcal{O}_{K_n}/p\mathcal{O}_{K_n} \to \mathcal{O}_{K_{n+1}}/p\mathcal{O}_{K_{n+1}}$, and the limit $X_{\mathcal{K}}^+ := \lim_{d \to \infty} \mathcal{O}_{K_d}/p\mathcal{O}_{K_d}$ is a complete valuation ring of characteristic $p$. Here, we denote the integer ring of a valuation field $F$ by $\mathcal{O}_F$. Let $X_{\mathcal{K}}$ be the fraction field of $X_{\mathcal{K}}$. Then, Scholl proved that a similar limit procedure gives an equivalence of categories $\text{FÉt}_{K_{\mathcal{K}}} \cong \text{FÉt}_{X_{\mathcal{K}}}$, where $\text{FÉt}_A$ denotes the category of finite étale algebras over $A$. In particular, we obtain an isomorphism of Galois groups

$$\tau : G_{K_{\infty}} \cong G_{X_{\mathcal{K}}}.$$
The Galois group of a complete valuation field \( F \) is canonically endowed with nonlog and log ramification filtrations in the sense of [Abbes and Saito 2002]. By using the ramification filtrations, one can define Artin and Swan conductors of Galois representations, which are important arithmetic invariants. It is natural to ask that Scholl’s isomorphism \( \tau \) is compatible with ramification theory. The first goal of this paper is to answer this question in the following form:

**Theorem 0.0.1** (Theorem 3.5.3). Let \( V \) be a \( p \)-adic representation of \( G_K \), where the \( G_K \)-action of \( V \) factors through a finite quotient. Then, the Artin and Swan conductors of \( V|_{K_n} \) are stationary and their limits coincide with the Artin and Swan conductors of \( \tau^*(V|_{K_\infty}) \).

We briefly mention the idea of the proof in the Artin case. Note that in the perfect residue field case, the result follows from the fact that the upper numbering ramification filtration is a renumbering of the lower numbering one, and this latter filtration is compatible with the field of norms construction; see [Marmora 2004, Lemme 5.4]. However, in the imperfect residue field case, since Abbes–Saito’s ramification filtration is not a renumbering of the lower numbering one, we proceed as follows. Let \( L/K \) be a finite Galois extension. Let \( X_L \) be an extension of \( X_R \) corresponding to the tower \( \mathfrak{L} = \{L_n := L K_n\}_{n>0} \) under Scholl’s equivalence. Then, it suffices to prove that the nonlog ramification filtrations of \( G_{L_n/K_n} \) and \( G_{X_L/X_R} \) coincide with each other. Abbes–Saito’s nonlog ramification filtration of a finite extension \( E/F \) of complete discrete valuation fields is described by a certain family of rigid analytic spaces \( a_{E/F} \) for \( a \in \mathbb{Q}_{\geq 0} \) attached to \( E/F \). In terms of Abbes–Saito’s setup, we only have to prove that the number of connected components of \( a_{X_L/X_R} \) and \( a_{L_n/K_n} \) are the same for sufficiently large \( n \). An optimized proof of this assertion is as follows: we construct a characteristic 0 lift \( R \) of \( X^+ \), which is realized as the ring of functions on the open unit ball over a complete valuation ring. We can find a prime ideal \( p_n \) of \( R \) such that \( R/p_n \) is isomorphic to \( \mathcal{O}_{K_n} \). Then, we construct a lift \( A_{X_L/X_R} \) over \( \text{Spec}(R) \) of \( a_{X_L/X_R} \), whose generic fiber at \( p_n \) is isomorphic to \( a_{L_n/K_n} \). We may also regard \( A_{X_L/X_R} \) as a family of rigid spaces parametrized by \( \text{Spec}(R) \). What we actually prove is that in such a family of rigid spaces over \( \text{Spec}(R) \), the number of the connected components of the fiber varies “continuously”. This is done by Gröbner basis arguments over complete regular local rings, extending the method of Liang Xiao [2010]. The continuity result implies our assertion since the point \( p_n \in \text{Spec}(R) \) “converges” to the point \((p) \in \text{Spec}(R) \).

Note that Shin Hattori reproved [2014] the above ramification compatibility of Scholl’s isomorphism \( \tau \) by using Peter Scholze’s perfectoid spaces [2012], which form a geometric interpretation of the Fontaine–Wintenberger theorem. We briefly explain Hattori’s proof. Let \( \mathbb{C}_p \) (resp. \( \mathbb{C}_p^0 \)) be the completion of the algebraic closure
of $K_{\infty}$ (resp. $X_{\mathcal{R}}$). Scholze proved the tilting equivalence between certain adic spaces (resp. perfectoid spaces) over $\mathbb{C}_p$ and $\mathbb{C}_p^\flat$. Let $C$ be a perfectoid field and $Y$ a subvariety of $\mathbb{A}^n_C$. A perfection of $Y$ is the perfectoid space defined as the pullback of $Y$ under the canonical projection $\lim_{\leftarrow} T_i \to T_i^p \mathbb{A}^n_C \to \mathbb{A}^n_C$, where $T_1, \ldots, T_n$ denotes a coordinate of $\mathbb{A}^n_C$. Hattori proved that the tilting of the perfections of $(\phi^n_{L_\mathcal{R}/K_{\mathcal{R}}})_{\mathbb{C}_p}$ and $(\phi^n_{\mathcal{R}_\mathcal{R}/\mathcal{R}_\mathcal{R}})_{\mathbb{C}_p}$ are isomorphic under the tilting equivalence. Since the underlying topological spaces are homeomorphic under taking perfections and the tilting equivalence, he obtained the ramification compatibility.

The second goal of this paper is to generalize Berger’s functor $N_{\text{dR}}$ and prove a ramification compatibility of $N_{\text{dR}}$ which extends Theorem 0.0.1. Precisely, we construct a functor from the category of de Rham representations to the category of $(\phi, \nabla)$-modules over the Robba ring. Our target objects $(\phi, \nabla)$-modules are defined by Kedlaya [2007] as generalizations of $p$-adic differential equations. Kedlaya also defined the differential Swan conductor $\text{Swan}^\nabla(M)$ for a $(\phi, \nabla)$-module $M$, which is a generalization of the irregularity of $p$-adic differential equations. Then, we prove the following de Rham version of Theorem 0.0.1:

**Theorem 0.0.2** (Theorem 4.7.1). Let $V$ be a de Rham representation of $G_K$. Then we have

$$\text{Swan}^\nabla(N_{\text{dR}}(V)) = \lim_{n \to \infty} \text{Swan}(V|_{K_n}),$$

where $\text{Swan}$ on the right-hand side means Abbes–Saito’s Swan conductor. Moreover, the sequence $\{\text{Swan}(V|_{K_n})\}_{n>0}$ is eventually stationary.

Both Theorems 0.0.1 and 0.0.2 are due to Adriano Marmora [2004] when the residue field is perfect. Even when the residue field is perfect, our proof of Theorem 0.0.2 is slightly different from Marmora’s proof since we use a dévissage argument to reduce to the pure slope case. As is addressed in [Kedlaya 2007, §3.7], it seems to be possible to define a ramification invariant of $N_{\text{dR}}(V)$ in terms of $(\phi, \Gamma_K)$-modules so that one can compute $\text{Swan}(V)$ instead of $\text{Swan}(V|_{K_n})$. It is also important to extend the construction of $N_{\text{dR}}$ to the general relative case: one may expect that a relative version of slope theory, described in [Kedlaya 2013] for example, will be an important tool.

**Structure of the paper**

In Section 1, we gather various basic results used in this paper. These contain some $p$-adic Hodge theory, Abbes–Saito’s ramification theory, Kedlaya’s theory of overconvergent rings, and Scholl’s fields of norms. In Section 2, we prove some ring theoretic properties of overconvergent rings by using Kedlaya’s slope theory. In Section 3, we develop a Gröbner basis argument over complete regular local rings and overconvergent rings. We apply the Gröbner basis argument to study families.
of rigid spaces, and use it to prove Theorem 0.0.1. In Section 4, we generalize Berger’s gluing argument to construct a differential module $\mathbb{N}_{\text{dR}}(V)$ for de Rham representations $V$. We also study the graded pieces of $\mathbb{N}_{\text{dR}}(V)$ with respect to Kedlaya’s slope filtration to reduce Theorem 0.0.2 to Theorem 0.0.1 by dévissage.

**Convention**

Throughout this paper, let $p$ be a prime number. All rings are assumed to be commutative unless otherwise stated. For a ring $R$, denote by $\pi^\text{Zar}_0(R)$ the set of connected components of $\text{Spec}(R)$ with respect to the Zariski topology. For a field $E$, fix an algebraic closure, denoted by $E^\text{alg}$ or $\overline{E}$, and a separable closure $E^\text{sep}$. Let $G_{F/E}$ be the Galois group of a finite extension $F/E$, and let $G_E$ be the absolute Galois group of $E$. For a field $k$ of characteristic $p$, let $k^\text{pf} := k^{p^{-\infty}}$ be the perfect closure in a fixed algebraic closure of $k$.

For a complete valuation field $K$, we let $\mathcal{O}_K$ be its integer ring, $\pi_K$ a uniformizer, and $k_K$ the residue field. Let $v_K : K \to \mathbb{Z} \cup \{\infty\}$ be the discrete valuation satisfying $v_K(\pi_K) = 1$. We let $K^\text{ur}$ be the $p$-adic completion of the maximal unramified extension of $K$ and denote by $I_K$ the inertia subgroup of $G_K$. We assume that $K$ is of mixed characteristic $(0, p)$ and that $[k_K : k_K^p] = p^d < \infty$ in the rest of this paragraph. Let $e_K$ be the absolute ramification index. Let $\mathbb{C}_p$ be the $p$-adic completion of $K^\text{alg}$ and let $v_p$ be the $p$-adic valuation of $\mathbb{C}_p$, normalized by $v_p(p) = 1$. We fix a system of $p$-power roots of unity $\{\zeta_{pn}\}_{n \geq 0}$ in $K^\text{alg}$, i.e., $\zeta_p$ is a primitive $p$-th root of unity and $\zeta_{pn+1}^{p^n} = \zeta_{pn}$ for all $n \in \mathbb{N}_{>0}$. Let $\chi : G_K \to \mathbb{Z}_p^\times$ be the cyclotomic character defined by $g(\zeta_{pn}) = \zeta_{pn}^{\chi(g)}$ for all $n > 0$. We denote the fraction field of a Cohen ring of $k_K$ by $K_0$. Denote a lift of a $p$-basis of $k_K$ in $\mathcal{O}_K$ by $(t_j)_{1 \leq j \leq d}$. For a given $(t_j)_{1 \leq j \leq d}$, we can choose an embedding $K_0 \hookrightarrow K$ such that $(t_j)_{1 \leq j \leq d} \subseteq \mathcal{O}_K$, see [Ohkubo 2013, §1.1]. Unless otherwise stated, we always choose $(t_j)_{1 \leq j \leq d}$ and an embedding $K_0 \hookrightarrow K$ in this way, and we fix sequences of $p$-power roots $(t_j^{p^{-n}})_{n \geq 0, 1 \leq j \leq d}$ of $(t_j)_{1 \leq j \leq d}$ in $K^\text{alg}$, i.e., we have $(t_j^{p^{-n-1}})^p = t_j^{p^{-n}}$ for all $n > 0$. For such a sequence, we define $K_{\text{pf}}$ as the $p$-adic completion of $\bigcup_n K(t_j^{p^{-n}})_{1 \leq j \leq d})$. This is a complete discrete valuation field with perfect residue field $k_{\text{pf}}^p$, and we regard $C_p$ as the $p$-adic completion of the algebraic closure of $K_{\text{pf}}$.

For a ring $R$, let $W(R)$ be the Witt ring with coefficients in $R$. If $R$ is of characteristic $p$, then we denote the absolute Frobenius on $R$ by $\varphi$ and also denote the ring homomorphism $W(\varphi) : W(R) \to W(R)$ by $\varphi$. Let $[x] \in W(R)$ be the Teichmüller lift of $x \in R$.

For an integer $h > 0$, define $\mathbb{Q}_{p^h} := W(\mathbb{F}_{p^h})[1/p]$. Let $K$ be a complete discrete valuation field, and $F/\mathbb{Q}_p$ a finite extension. A finite dimensional $F$-vector space $V$ with continuous semilinear $G_K$-action is called an $F$-representation of $G_K$. If moreover $F = \mathbb{Q}_p$, then we call $V$ a $p$-adic representation of $G_K$. We denote the category of $F$-representations of $G_K$ by $\text{Rep}_F(G_K)$. We say that $V$ is finite (resp.
of finite geometric monodromy) if \( G_K \) (resp. \( I_K \)) acts on \( V \) via a finite quotient. We
denote the category of finite (resp. finite geometric monodromy) \( F \)-representations
of \( G_K \) by \( \text{Rep}_F^f(G_K) \) (resp. \( \text{Rep}_F^{f,r}(G_K) \)).

For homomorphisms \( f, g : M \to N \) of abelian groups, we denote by \( M^{f=g} \) the
kernel of the map \( f - g \). For \( x \in \mathbb{R} \), let \( [x] := \inf \{ n \in \mathbb{Z} ; n \geq x \} \) be the least integer
greater than or equal to \( x \). We let \( \mathbb{N} = \mathbb{Z}_{\geq 0} \) be the set of all natural numbers.

1. Preliminaries

In this section, we fix notation and recall basic results needed in this paper.

1.1. Fréchet spaces. We will define some basic terminology of topological vector
spaces. Although we will use both valuations and norms to consider topologies,
we will define our terminology in terms of valuations for simplicity. See [Kedlaya

Notation 1.1.1. Let \( M \) be an abelian group. A valuation \( v \) of \( M \) is a map \( v : M \to \mathbb{R} \cup \{\infty\} \) such that \( v(x - y) \geq \inf \{v(x), v(y)\} \) for all \( x, y \in R \) and \( v(x) = \infty \)
if and only if \( x = 0 \). Moreover, when \( M = R \) is a ring, \( v \) is multiplicative if
\( v(xy) = v(x) + v(y) \) for all \( x, y \in R \). A ring equipped with a multiplicative valuation
is called a valuation ring. If \( (R, v) \) is a valuation ring and \( (M, v_M) \) is an \( R \)-module
with valuation \( v_M \), then we say that \( v_M \) is an \( R \)-valuation if \( v_M(\lambda x) = v(\lambda) + v_M(x) \)
holds for all \( \lambda \in R \) and \( x \in M \).

Let \( (R, v) \) be a valuation ring and \( M \) a finite free \( R \)-module. For an \( R \)-basis
\( e_1, \ldots, e_n \) of \( M \), we define the \( R \)-valuation \( v_M \) on \( M \) (compatible with \( v \)) associated
to \( e_1, \ldots, e_n \) by \( v_M(\sum_{1 \leq i \leq n} a_i e_i) = \inf_i v(a_i) \) for \( a_i \in R \) ([Kedlaya
2010, Definition 1.3.2]). The topology defined by \( v_M \) is independent of the choice of a basis of \( M \)
([Kedlaya 2010, Definition 1.3.3]). Hence, we do not refer to a basis to consider
\( v_M \) and we just denote \( v_M \) by \( v \) unless otherwise stated.

For any valuation \( v \) on \( M \), we define the associated nonarchimedean norm
\( |\cdot| : M \to \mathbb{R} \) by \( |x| := a^{-v(x)} \) for a fixed \( a \in \mathbb{R}_{>1} \) (nonarchimedean means that
it satisfies the strong triangle inequality). Conversely, for any nonarchimedean
norm \( |\cdot|, v(\cdot) = -\log_a |\cdot| \) is a valuation. We will apply various definitions made
for norms to valuations, and vice versa in this manner.

Notation 1.1.2. Let \( (K, v) \) be a complete valuation field. Let \( \{w_r\}_{r \in I} \) be a family
of \( K \)-valuations of a \( K \)-vector space \( V \). Consider the topology \( T \) of \( V \) whose
neighborhoods at 0 are generated by \( \{x \in V; w_r(x) \geq n\} \) for all \( r \in I \) and \( n \in \mathbb{N} \).
We call \( T \) the topology of \( V \) defined by \( \{w_r\}_{r \in I} \) and denote the topological space
\( V \) with this topology by \( (V, \{w_r\}_{r \in I}) \), or simply by \( V \). If \( T \) is equivalent to the
topology defined by \( \{w_r\}_{r \in I_0} \) for some countable subset \( I_0 \subseteq I \), we call \( T \) the
\( K \)-Fréchet topology defined by \( \{w_r\}_{r \in I} \). For a \( K \)-vector space, it is well-known that
a $K$-Fréchet topology is metrizable (and vice versa). Moreover, when $V$ is complete, we call $V$ a $K$-Fréchet space. Note that $V$ is just a $K$-Banach space when $\#I_0 = 1$. Also, note that a topological $K$-vector space $V$ is a $K$-Fréchet space if and only if $V$ is isomorphic to an inverse limit of $K$-Banach spaces whose transition maps consist of bounded $K$-linear maps. More precisely, let $V$ be a $K$-Fréchet space with valuations $w_0 \geq w_1 \geq \ldots$, and $V_n$ the completion of $V$ with respect to $w_n$. Then the canonical map $V \to \lim_{\rightarrow \infty} V_n$ is an isomorphism of $K$-Fréchet spaces. Also, note that if $V$ and $W$ are $K$-Fréchet spaces, then $\text{Hom}_K(V, W)$ is again a $K$-Fréchet space with respect to the operator norm.

Let $(R, \{w_r\}_{r \in I})$ be a $K$-Fréchet space for a ring $R$. If $\{w_r\}_{r \in I}$ are multiplicative, then we call $R$ a $K$-Fréchet algebra. For a finite free $R$-module $M$, we choose a basis of $M$ and let $\{w_{r, M}\}_{r \in I}$ be the $R$-valuations compatible with $\{w_r\}_{r \in I}$. Obviously, $(M, \{w_{r, M}\}_{r \in I})$ is a $K$-Fréchet space. Unless otherwise stated, we always endow a finite free $R$-module with such a family of valuations.

In the rest of the paper, we omit the prefix “$K$” unless otherwise stated.

Recall that the category of Fréchet spaces is closed under quotients, completed tensor products and direct sums and that the open mapping theorem holds.

1.2. Continuous derivations over $K$. In this subsection, we recall the continuous Kähler differentials ([Hyodo 1986, §4]). Let $K$ be a complete discrete valuation field of mixed characteristic $(0, p)$ such that $[k_K : k_p^0] = p^d < \infty$.

Definition 1.2.1. Let $\Omega^1_{O_K}$ be the $p$-adic Hausdorff completion of $\Omega^1_{O_K/\mathbb{Z}}$ and put $\widehat{\Omega}^1_K := \Omega^1_{O_K}[1/p]$. Let $d : K \to \widehat{\Omega}^1_K$ be the canonical derivation.

Recall that $\widehat{\Omega}^1_K$ is a finite $K$-vector space with basis $\{dt_j\}_{1 \leq j \leq d}$. Moreover, if $K$ is absolutely unramified, then $\widehat{\Omega}^1_{O_K}$ is a finite free $O_K$-module with basis $\{dt_j\}_{1 \leq j \leq d}$. Also, $\widehat{\Omega}^1_{O_K}$ is compatible with base change, i.e., $L \otimes_K \widehat{\Omega}^1_K \cong \widehat{\Omega}^1_L$ for any finite extension $L/K$.

Notation 1.2.2. Let $R$ be a topological ring and $M$ a topological $R$-module. We let $\text{Der}_{\text{cont}}(R, M)$ be the $R$-module of continuous derivations $d : R \to M$.

One can prove the next lemma by dévissage and the universality of the usual Kähler differentials.

Lemma 1.2.3. For an inductive limit $M$ of $K$-Fréchet spaces, we have the canonical isomorphism

$$d^* : \text{Hom}_K(\widehat{\Omega}^1_K, M) \cong \text{Der}_{\text{cont}}(K, M).$$

Definition 1.2.4. Let $\{\delta_j\}_{1 \leq j \leq d} \subset \text{Der}_{\text{cont}}(K_0, K_0) \cong \text{Hom}_{K_0}(\Omega^1_{K_0/\mathbb{Z}}, K_0)$ be the dual basis of $\{dt_j\}_{1 \leq j \leq d}$. We call $\{\delta_j\}$ the derivations associated to $\{t_j\}$. We also denote by $\partial_j$ the canonical extension of $\delta_j$ to $\partial_j : K_{\text{alg}} \to K_{\text{alg}}$. Since $\partial_j(t_i) = \delta_{ij}$, we may denote $\partial_j$ by $\partial/\partial t_j$. 

1.3. Some Galois extensions. In this subsection, we will fix some notation of a certain Kummer extension which will be studied later. See [Hyodo 1986, §1] for details. In this subsection, let \( \tilde{K} \) be an absolutely unramified complete discrete valuation field of mixed characteristic \((0, p)\) with \([k_{\tilde{K}} : k_{\tilde{K}}^p] = p^d < \infty\). We put

\[
\tilde{K}_n := \tilde{K}(\xi_{p^n}, t_1^{p^{-n}}, \ldots, t_i^{p^{-n}}) \quad \text{for} \quad n > 0, \quad \tilde{K}_\infty := \bigcup_{n > 0} \tilde{K}_n, \quad \tilde{K}_{\text{arith}} := \bigcup_{n > 0} \tilde{K}(\xi_{p^n}),
\]

\[
\Gamma_{\text{arith}}^\tilde{K} := G_{\tilde{K}_\infty/\tilde{K}_{\text{arith}}}, \quad \Gamma_{\text{geom}}^\tilde{K} := G_{\tilde{K}_{\text{arith}}/\tilde{K}}, \quad \Gamma_{\text{geom}}^\tilde{K} := G_{\tilde{K}_{\text{arith}}/\tilde{K}_{\infty}}.
\]

Then, we have isomorphisms

\[
\Gamma_{\text{arith}}^\tilde{K} \cong \mathbb{Z}_p^\times, \quad \Gamma_{\text{geom}}^\tilde{K} \cong \mathbb{Z}_p^d,
\]

which are compatible with the action of \( \Gamma_{\text{arith}}^\tilde{K} \) on \( \Gamma_{\text{geom}}^\tilde{K} \). The isomorphisms are defined as follows: an element \( a \in \mathbb{Z}_p^\times \) corresponds to \( \gamma_a \in \Gamma_{\text{arith}}^\tilde{K} \) such that \( \gamma_a(\xi_{p^n}) = \xi_{p^n}^a \) for all \( n \). An element \( b = (b_j) \in \mathbb{Z}_p^d \) corresponds to \( \gamma_b \in \Gamma_{\text{geom}}^\tilde{K} \) for \( 1 \leq j \leq d \) such that \( \gamma_b(\xi_{p^n}) = \xi_{p^n}^b \) for all \( n \in \mathbb{N} \) and \( \gamma_b(t_j^{p^{-n}}) = \xi_{p^n}^{b_j} t_j^{p^{-n}} \). By regarding \( \Gamma_{\text{arith}}^\tilde{K} \) as a subgroup \( G_{\tilde{K}_\infty/\bigcup_{n} \tilde{K}(t_1^{p^{-n}}, \ldots, t_i^{p^{-n}})} \) of \( \Gamma_{\tilde{K}} \), we obtain isomorphisms

\[
\eta = (\eta_0, \ldots, \eta_d) : \Gamma_{\tilde{K}} \cong \Gamma_{\text{arith}}^\tilde{K} \times \Gamma_{\text{geom}}^\tilde{K} \cong \mathbb{Z}_p^\times \times \mathbb{Z}_p^d.
\]

Since we have a canonical isomorphism

\[
\mathbb{Z}_p^\times \times \mathbb{Z}_p^d \cong \mathbb{Z}_p^\times \begin{pmatrix} \mathbb{Z}_p & \mathbb{Z}_p & \cdots & \mathbb{Z}_p \\ 1 & \cdots & \cdots & 1 \end{pmatrix} \leq \text{GL}_{d+1}(\mathbb{Z}_p),
\]

the group \( \Gamma_{\tilde{K}} \) can be regarded as a classical \( p \)-adic Lie group with Lie algebra

\[
g := \text{Lie}(\Gamma_{\tilde{K}}) \cong \mathbb{Q}_p \times \mathbb{Q}_p^d = \begin{pmatrix} \mathbb{Q}_p & \cdots & \mathbb{Q}_p \\ 0 & \cdots & \cdots \end{pmatrix} \subset \mathfrak{gl}_{d+1}(\mathbb{Q}_p).
\]

For an integer \( n > 0 \) and a finite extension \( L/\tilde{K} \), we put

\[
L_n := \tilde{K}_n L, \quad L_\infty := \tilde{K}_\infty L, \quad \Gamma_L := G_{L_\infty/L}, \quad H_L := G_{\tilde{K}_{\text{arith}}/L_\infty}.
\]

Then, \( \Gamma_L \) is an open subgroup of \( \Gamma_{\tilde{K}} \). Hence, there exists an open normal subgroup of \( \Gamma_L \) which is isomorphic to an open subgroup of \((1 + 2p\mathbb{Z}_p) \times \mathbb{Z}_p^d \) by the map \( \eta \). Also, we may identify the \( p \)-adic Lie algebra of \( \Gamma_L \) with \( g \). Finally, we define
closed subgroups of $\Gamma_L$

$$\Gamma_{L,0} := \{ \gamma \in \Gamma_L; \; \eta_j(\gamma) = 0 \text{ for all } 1 \leq j \leq d \},$$
$$\Gamma_{L,j} := \{ \gamma \in \Gamma_L; \; \eta_0(\gamma) = 1, \; \eta_j(\gamma) = 0 \text{ for all } 1 \leq i \leq d, \; i \neq j \} \text{ for } 1 \leq j \leq d.$$

1.4. Basic construction of Fontaine’s rings. In this subsection, we recall the definition of rings of $p$-adic periods due to Fontaine, see [Ohkubo 2013, §3] for details.

Let $K$ be a complete discrete valuation field of mixed characteristic $(0, p)$ with $[k_K : k'_K] = p^d < \infty$. Let $\tilde{E}^+ := \lim_n \mathcal{O}_{C_p}/p\mathcal{O}_{C_p}$, where the transition maps are given by the Frobenius. This is a complete valuation ring of characteristic $p$ whose (algebraically closed) fractional field is denoted by $\tilde{E}$. We have a canonical identification

$$\tilde{E} \cong \{ (x^{(n)})_{n \in \mathbb{N}} \in C_p^n ; (x^{(n+1)})^p = x^{(n)} \text{ for all } n \in \mathbb{N} \}.$$ 

For $x \in C_p$, we denote by $\tilde{x} \in \tilde{E}$ an element $\tilde{x} = (x^{(n)})$ such that $x^{(0)} = x$. In particular, we put $\varepsilon := (1, \xi_p, \xi_p^2, \ldots)$, $\tilde{t}_j := (t_j, t_j^{1/p}, \ldots) \in \tilde{E}^+$. We define the valuation $v_\tilde{E}$ by $v_\tilde{E}((x^{(n)})) = v_p(x^{(0)})$. We put

$$\tilde{A}^+ := W(\tilde{E}^+) \subset \tilde{A} := W(\tilde{E}),$$
$$\tilde{B}^+ := \tilde{A}^+[1/p] \subset \tilde{B} := \tilde{A}[1/p],$$
$$\pi := [\varepsilon] - 1, \quad q := \pi/\varphi^{-1}(\pi) = \sum_{0 \leq i < p} [\varepsilon^{1/p}]^i \in \tilde{A}^+$$

and we define a surjective ring homomorphism

$$\theta : \tilde{B}^+ \to C_p$$
$$\sum_{n \gg -\infty} p^n x_n \mapsto p^n x^{(0)},$$

which maps $\tilde{A}^+$ to $\mathcal{O}_{C_p}$. Note that $q$ is a generator of the kernel of $\theta|_{\tilde{A}^+}$.

Let $K$ be a closed subfield of $C_p$ whose value group $v_p(K^\times)$ is discrete. We will define rings

$$\tilde{A}_{inf,C_p/K}, \quad \tilde{B}_{dR,C_p/K}^+, \quad \tilde{B}_{dR,C_p/K}.$$ 

Let $\tilde{A}_{inf,C_p/K}$ be the universal $p$-adically formal pro-infinitesimal $O_K$-thickening of $\mathcal{O}_{C_p}$. More precisely, if $\theta_{C_p/K} : \mathcal{O}_K \otimes_{\mathbb{Z}} \tilde{A}^+ \to \mathcal{O}_{C_p}$ denotes the linear extension of $\theta$, then $\tilde{A}_{inf,C_p/K}$ is the $(p, \ker\theta_{C_p/K})$-adic Hausdorff completion of $\mathcal{O}_K \otimes_{\mathbb{Z}} \tilde{A}^+$. The map $\theta_{C_p/K}$ extends to $\tilde{A}_{inf,C_p/K} : \tilde{A}_{inf,C_p/K} \to \mathcal{O}_{C_p}$. Note that $\tilde{A}_{inf,C_p/K}$ is canonically identified with $\tilde{A}^+$. Let $\tilde{B}_{dR,C_p/K}^+$ be the ker $\theta_{C_p/K}$-adic Hausdorff completion of $\tilde{A}_{inf,C_p/K}[1/p]$ and $\theta_{C_p/K} : \tilde{B}_{dR,C_p/K} \to C_p$ the canonical map induced by $\theta_{C_p/K}$. 
Let
\[ u_j := t_j - [t_j] \in A_{\text{inf}, C_p/K_0}, \]
\[ t := \log([\varepsilon]) := \sum_{n \geq 1} (-1)^{n-1} \frac{[\varepsilon] - 1^n}{n} \in B^{+}_{dR, C_p/Q_p} \subset B^{+}_{dR, C_p/K}. \]

Finally, we define \( B^{+}_{dR, C_p/K} := B^{+}_{dR, C_p/K}[1/t] \). These constructions are functorial with respect to \( C \) and \( \mathcal{K} \). In particular:
\[ A_{\text{inf}, C_p/Q_p} \subset A_{\text{inf}, C_p/K}, \quad B^{+}_{dR, C_p/Q_p} \subset B^{+}_{dR, C_p/K}, \quad B_{dR, C_p/Q_p} \subset B_{dR, C_p/K}. \]

Therefore, any continuous \( \mathcal{K} \)-algebra automorphism of \( C_p \) acts on these rings. We also have the following explicit descriptions:
\[ A_{\text{inf}, C_p/K_0} \cong \hat{A}^+[u_1, \ldots, u_d], \quad B^{+}_{dR, C_p/K} \cong B^{+}_{dR, C_p/Q_p} \otimes K [u_1, \ldots, u_d] \]

and \( B^{+}_{dR, C_p/K} \) is a complete discrete valuation field with uniformizer \( t \) and residue field \( C_p \). Also, \( B^{+}_{dR, C_p/K} \) and \( B^{+}_{dR, C_p/K} \) are invariant after replacing \( K \) by a finite extension. In particular, these rings are endowed with canonical \( K^{alg} \)-algebra structures.

For \( V \in \text{Rep}_{Q_p}(G_K) \), we define \( D_{dR}(V) := (B^{+}_{dR, C_p/K} \otimes_{Q_p} V)^{G_K} \), which is a finite dimensional \( K \)-vector space with \( \dim_K D_{dR}(V) \leq \dim_{Q_p} V \). When the dimensions are equal, we call \( V \in \text{de Rham} \) and denote the category of de Rham representations of \( G_K \) by \( \text{Rep}_{dR}(G_K) \).

We endow \( \lim_{\longleftarrow k} A_{\text{inf}, C_p/K}[1/p]/(\ker \theta_{C_p/K})^k \) with the inverse limit topology, equipping \( A_{\text{inf}, C_p/K}[1/p]/(\ker \theta_{C_p/K})^k \) with the \( K \)-Banach space structure whose unit disc is the image of \( A_{\text{inf}, C_p/K} \). The identification of \( B^{+}_{dR, C_p/K} \) and \( \lim_{\longleftarrow k} A_{\text{inf}, C_p/K}[1/p]/(\ker \theta_{C_p/K})^k \) gives \( B^{+}_{dR, C_p/K} \) its canonical topology and it is a \( K \)-Fréchet algebra.

The ring \( B^{+}_{dR, C_p/K} \) is endowed with a continuous \( B^{+}_{dR, C_p/Q_p} \)-linear connection
\[ \nabla^{\text{geom}} : B^{+}_{dR, C_p/K} \to B^{+}_{dR, C_p/K} \otimes K \hat{\Omega}^1_{K}/, \]

which is induced by the canonical derivation \( d : \mathcal{K} \to \hat{\Omega}^1_{K} \). More precisely, if we denote by \( \{ \partial_j \}_{1 \leq j \leq d} \) the derivations of \( B^{+}_{dR, C_p/K} \) given by \( \nabla^{\text{geom}}(x) = \sum_j \partial_j(x) \otimes dt_j \), then \( \partial_j \) is the unique \( B^{+}_{dR, C_p/Q_p} \)-linear extension of \( \partial/\partial t_j : K \to K \). Thus, we can regard the above connection as a connection associated to a “coordinate” \( t_1, \ldots, t_d \) of \( K \), hence we put the superscript “geom”. We denote the kernel of \( \nabla^{\text{geom}} \) by \( B^{+}_{dR, C_p/K} \), which coincides with the image of \( B^{+}_{dR, C_p/Q_p} \). Therefore, we may identify \( B^{+}_{dR, C_p/K} \) with \( B^{+}_{dR, C_p/Q_p} \).

We also define a subring \( B^{+}_{\text{rig}, C_p/Q_p} \) of \( B^{+}_{dR, C_p/Q_p} \) as follows: let \( A_{\text{cris}, C_p/Q_p} \) be the universal \( p \)-adically formal \( Z_p \)-thickening of \( \mathcal{O}_{C_p} \), i.e., the \( p \)-adic Hausdorff completion of the PD-envelope of \( \hat{A}^+ \) with respect to the ideal \( \ker \theta_{C_p/Q_p} \), compatible with
the canonical PD-structure on the ideal \((p)\). Since the construction is functorial, the Frobenius \(\varphi : \mathbb{A}^n \to \mathbb{A}^n\) acts on both \(\mathbb{A}_{\text{cris}}/\mathbb{Q}_p\) and \(\mathbb{B}_{\text{cris}}^{+}/\mathbb{Q}_p = \mathbb{A}_{\text{cris}}/\mathbb{Q}_p[1/p]\).

We define \(\mathbb{B}_{\text{rig}}^{+}\) (which is an affinoid subdomain of the log structure. Let \(P\) be the nonlog ramification break. If \(L\) define a filtration that is stable under \(\varphi\). By construction, \(\mathbb{B}_{\text{rig}}^{+}/\mathbb{Q}_p\) is a subring of \(\mathbb{B}_{\text{dR}}^{+}/\mathbb{Q}_p \cong \mathbb{B}_{\text{dR}}^{+}/\mathbb{Q}_p/K\).

Finally, for simplicity, we denote

\[
\begin{align*}
\mathbb{B}_{\text{dR}}^{+} & := \mathbb{B}_{\text{dR}}^{+}/\mathbb{Q}_p/K, \\
\mathbb{B}^{\text{rig}}^{+} & := \mathbb{B}_{\text{rig}}^{+}/\mathbb{Q}_p/K, \\
\mathbb{B}_{\text{dR}}^{+} & := \mathbb{B}_{\text{dR}}^{+}/\mathbb{Q}_p/K, \\
\mathbb{B}^{\text{rig}}^{+} & := \mathbb{B}_{\text{rig}}^{+}/\mathbb{Q}_p
\end{align*}
\]

when no confusion arises.

1.5. Ramification theory of Abbes–Saito. In this subsection, we review Abbes–Saito’s ramification theory, see [Abbes and Saito 2002, 2003] for details.

Let \(K\) be a complete discrete valuation field with residue field of characteristic \(p\). Let \(L/K\) be a finite separable extension. Let \(Z = \{z_0, \ldots, z_n\}\) be a set of generators of \(\mathcal{O}_L\) as an \(\mathcal{O}_K\)-algebra. View \(\mathcal{O}_K(Z_0, \ldots, Z_n)\) as a Tate algebra, and let \(Z_i \mapsto z_i\) be the corresponding surjective \(\mathcal{O}_K\)-algebra homomorphism from \(\mathcal{O}_K(Z_0, \ldots, Z_n)\) to \(\mathcal{O}_L\) with kernel \(I_Z\). For \(a \in \mathbb{Q}_{>0}\), we define the nonlog Abbes–Saito space by

\[
as_{L/K,Z}^{a} := D^{a+1}(\pi_K^{-a}f; f \in I_Z) = \{x \in D^{a+1}; |f(x)| \leq |\pi_K|^a \forall f \in I_Z\},
\]

which is an affinoid subdomain of the \((n+1)\)-dimensional polydisc \(D^{n+1}\). Let \(\pi_0^{\text{geom}}(as_{L/K,Z}^{a})\) be the geometric connected components of \(as_{L/K,Z}^{a}\), i.e., the connected components of \(as_{L/K,Z}^{a} \times_K K^{\text{alg}}\) with respect to the Zariski topology. We define a \(G_K\)-set \(\mathcal{F}_{a}(L) := \pi_0^{\text{geom}}(as_{L/K,Z}^{a})\) and let

\[
b(L/K) := \inf\{a \in \mathbb{R}; \#\mathcal{F}_{a}(L) = [L : K]\} \in \mathbb{Q}.
\]

be the nonlog ramification break. If \(L/K\) is Galois, then \(\mathcal{F}_{a}(L)\) can be identified with a quotient of \(G_{L/K}\). Moreover, the system \(\{\mathcal{F}_{a}(L)\}_a\) of \(G_K\)-sets defines a filtration \(\{G_{L/K}^{a}\}_{a \in \mathbb{Q}_{>0}}\) of \(G_{L/K}\) such that \(\mathcal{F}_{a}(L) \cong G_{L/K}/G_{L/K}^{a}\) as \(G_K\)-sets.

There exists a log variation of this construction by considering the following log structure. Let \(P \subset Z\) be a subset containing a uniformizer, and take a lift \(g_j \in \mathcal{O}_K(Z_0, \ldots, Z_n)\) of \(z_j^{e_k}/\pi_K\) for each \(z_j \in P\). For each pair \((z_i, z_j) \in P \times P\), we take a lift \(h_{i,j} \in \mathcal{O}_K(Z_0, \ldots, Z_n)\) of \(z_j^{v_L(z_i)}/z_i^{v_L(z_j)}\). For \(a \in \mathbb{Q}_{>0}\), we define the log Abbes–Saito space by

\[
as_{L/K,Z,P}^{a} := D^{a+1} \left( \begin{array}{c}
|\pi_K|^{-a}f \\
|\pi_K|^{-a-v_L(z_i)}(X_i^{e_L/K} - \pi_K g_i) \\
|\pi_K|^{-a-v_L(z_i)+v_L(z_j)}/e_{L/K}(X_j^{v_L(z_i)} - X_j^{v_L(z_j)}h_{i,j})
\end{array} \right)
\]
as an affinoid subdomain of $D^{n+1}$. Here, $f$ ranges over $I_Z$ and the indices $z_i$ and $(z_i, z_j)$ range over $P$ and $P \times P$ respectively. As before, we define the $G_K$-set $F_0^a_\text{log}(L) := \pi_0^\text{geom}(as_{L/K,Z,P}^a)$ and define the log ramification break by

$$b_{\log}(L/K) := \inf\{a \in \mathbb{R}; \#F_0^a_\text{log}(L) = [L : K]\} \in \mathbb{Q}.$$  

A similar procedure as before defines the log ramification filtration $\{G_{L/K,\text{log}}^a\}_{a \in \mathbb{Q} \geq 0}$ of $G_{L/K}$. 

In this paper, we consider only the following simple Abbes–Saito spaces. With the notation as above, let $p_0, \ldots, p_m$ be a system of generators of the kernel of the surjection $O_K\langle X_0, \ldots, X_n \rangle \to O_L$. Assume that $z_0$ is a uniformizer of $L$ and $p_0 = X_0^{e_{L/K}} - \pi g_0$ for some $g_0 \in O_K\langle X_0, \ldots, X_n \rangle$. In this case, we have a simple log structure: we put $P := \{z_0\}$ and we choose $g_0$ as a lift of $z_0^{e_{L/K}} / \pi K$. We also choose 1 as $h_1, 1$. Hence, Abbes–Saito spaces are given by

$$as_{L,K,Z}^a = D^{n+1}(|\pi K|^{-a} p_j \text{ for } 0 \leq j \leq m),$$

$$as_{L,K,Z,P}^a = D^{n+1}(|\pi K|^{-a-1} p_0, |\pi K|^{-a} p_j \text{ for } 1 \leq j \leq m).$$

Let $F/\mathbb{Q}_p$ be a finite extension and $V$ an $F$-representation of $G_K$ with finite local monodromy. We define Abbes–Saito’s Artin and Swan conductors by

$$\text{Art}^{\text{AS}}(V) := \sum_{a \in \mathbb{Q} \geq 0} a \cdot \dim_F(V \cap_{b > a} G_K^b / V G_K^a),$$

$$\text{Swan}^{\text{AS}}(V) := \sum_{a \in \mathbb{Q} \geq 0} a \cdot \dim_F(V \cap_{b > a} G_{K,\text{log}}^b / V G_{K,\text{log}}^a).$$

Note that the above construction does not depend on other choices, like $Z$ and $P$. Also, note that both the Artin and Swan conductors are additive and compatible with unramified base change. When $k_K$ is perfect, the log (resp. nonlog) ramification filtration is compatible with the usual upper numbering filtration (resp. shift by one). Moreover, our Artin and Swan conductors coincide with the classical Artin and Swan conductors when $k_K$ is perfect.

**Theorem 1.5.1** (Hasse–Arf theorem, [Xiao 2012, Theorem 4.5.14]). Assume that $K$ is of mixed characteristic. Let $F/\mathbb{Q}_p$ be a finite extension and $V \in \text{Rep}_{\mathbb{Q}_p}^{\text{f.g.}}(G_K)$. Then, we have $\text{Art}(V) \in \mathbb{Z}$ if $K$ is not absolutely unramified; we have $\text{Swan}^{\text{AS}}(V) \in \mathbb{Z}$ if $p \neq 2$, and $\text{Swan}^{\text{AS}}(V) \in 2^{-1}\mathbb{Z}$ if $p = 2$.

Xiao gives more precise results in the equal characteristic case, as we will see in Theorem 1.7.10.
1.6. Overconvergent rings. In this subsection, we will recall basic definitions of overconvergent rings associated to complete valuation fields of characteristic $p$, following [Kedlaya 2004, §2–3] and [Kedlaya 2005, §2].

Construction 1.6.1 (Kedlaya 2005, §2.1–2.2). Let $(E, v)$ be a complete valuation field of characteristic $p$. Assume that either $E$ is perfect or that $v$ is a discrete valuation. We will construct an overconvergent ring associated to $E$. We first consider the case where $E$ is perfect. Note that any element of $W(E)[1/p]$ is uniquely expressed as $\sum_{k \gg -\infty} p^k [x_k]$ with $x_k \in E$. For $n \in \mathbb{Z}$, we define a “partial valuation” on $W(E)[1/p]$ by

$$v^{\leq n} \left( \sum_{k \gg -\infty} p^k [x_k] \right) := \inf_{k \leq n} v(x_k).$$

For $r \in \mathbb{R}_{\geq 0}$, we define

$$w_r(x) := \inf_{n} \{ rv^{\leq n}(x) + n \},$$

$$W(E)_r := \{ x \in W(E); w_r(x) < \infty \}.$$  

Then, $W(E)_r[1/p]$ is a subring of $W(E)[1/p]$ and $w_r$ is a multiplicative valuation of $W(E)_r[1/p]$. Moreover, we have $W(E)_r \subset W(E)_{r'}$ for $r' \leq r$. We put $W_{\text{con}}(E) := \lim_{r \to 0} W(E)_r$.

Next, we consider the general case, i.e., we do not need to assume that $E$ is perfect in the following. Let $\Gamma$ be a Cohen ring of $E$ with a Frobenius lift $\varphi$. Then, we can obtain a Frobenius-compatible embedding $\Gamma \hookrightarrow W(E)_{pf} \hookrightarrow \hat{E}_{\text{alg}}$, where $\hat{E}_{\text{alg}}$ is the completion of $E_{\text{alg}}$. By using this embedding, we can define $v^{\leq n}$ and $w_r$ on $\Gamma$. Moreover, we define $\Gamma_r := \Gamma \cap W(\hat{E})_{\text{alg}}$ and $\Gamma_{\text{con}} := \lim_{r \to 0} \Gamma_r = \Gamma \cap W_{\text{con}}(\hat{E})_{\text{alg}}$. We say that $\Gamma$ has enough $r$-units if the canonical map $\Gamma_r \to E$ is surjective. We say that $\Gamma$ has enough units if $\Gamma$ has enough $r$-units for some $r > 0$. Note that if $E$ is perfect, then $\Gamma$ has enough $r$-units for any $r$. In general, by [Kedlaya 2004, Proposition 3.11], $\Gamma$ has enough $r$-units for all sufficiently small $r$. In the following, we fix $r_0$ such that $\Gamma$ has enough $r$-units for all $r \leq r_0$. Note that $\Gamma_r$ is a PID for $r < r_0$, and $\Gamma_{\text{con}}$ is a Henselian local ring with maximal ideal $(p)$, residue field $E$ and fraction field $\Gamma_{\text{con}}[1/p]$ [Kedlaya 2005, Lemma 2.1.12]. We endow $\Gamma_r[1/p]$ with the Fréchet topology defined by the family of valuations $\{ w_s \}_{0 < s \leq r}$. Let $\Gamma_{\text{an}, r}$ be the completion of $\Gamma_r[1/p]$ with respect to the Fréchet topology and $\Gamma_{\text{an}, \text{con}} := \lim_{r \to 0} \Gamma_{\text{an}, r}$. We extend $v^{\leq n}$ and $w_r$ to $v^{\leq n}$, $w_r : \Gamma_{\text{an}, r} \to \mathbb{R}$ and we endow $\Gamma_{\text{an}, r}$ (resp. $\Gamma_{\text{an}, \text{con}}$) with the Fréchet topology defined by $\{ w_s \}_{0 < s \leq r}$ (resp. the inductive limit topology of Fréchet topologies). Note that $\varphi(\Gamma_r) \subset \Gamma_r/p$; hence, $\varphi$ extends to a map $\varphi : \Gamma_{\text{an}, r} \to \Gamma_{\text{an}, r}/p$. In particular, $\Gamma_{\text{con}}$ and $\Gamma_{\text{an}, \text{con}}$ are canonically endowed with endomorphisms $\varphi$. Also, note that $\Gamma_{\text{an}, r}$ for all $r < r_0$ and hence, $\Gamma_{\text{an}, \text{con}}$ are Bézout integral domains [Kedlaya 2005, Theorem 2.9.6].
In the rest of this subsection, we will see explicit descriptions of \( \Gamma_{\text{con}} \), together with its finite étale extensions, by using rings of overconvergent power series ring.

**Notation 1.6.2.** Let \( \mathcal{O} \) be a complete discrete valuation ring of mixed characteristic \((0, p)\). Let \( \mathcal{O}([S]) \) be the \( p \)-adic Hausdorff completion of \( \mathcal{O}((S)) := \mathcal{O}[[S]][S^{-1}] \). For \( r \in \mathbb{Q}_{>0} \), we define the ring of overconvergent power series over \( \mathcal{O} \) as

\[
\mathcal{O}((S))^\dagger_r := \{ f \in \mathcal{O}([S]) : f \text{ converges on } 0 < v_p(S) \leq r \}. 
\]

Recall that \((\mathcal{O}((S))^\dagger, (\pi_\mathcal{O}))\) is a Henselian discrete valuation ring [Matsuda 1995, Proposition 2.2]. We also define the Robba ring \( \mathcal{R} \) associated to \( \mathcal{O}((S))^\dagger \) by

\[
\mathcal{R} := \left\{ f = \sum_{n \in \mathbb{Z}} a_n S^n : a_n \in \text{Frac}(\mathcal{O}), f \text{ converges on } 0 < v_p(S) \leq r \text{ for some } r > 0 \right\}.
\]

**Construction 1.6.3.** We construct a realization of a finite étale extension of \( \mathcal{O}((S))^\dagger \) as an overconvergent power series ring. Let \( \Gamma \) be a Cohen ring of a complete discrete valuation field \( E \) of characteristic \( p \). By fixing an isomorphism \( f : \Gamma \cong \mathcal{O}([S]) \), where \( \mathcal{O} \) is a Cohen ring of \( k_E \), we identify \( \Gamma \) and \( E \) with \( \mathcal{O}((S)) \) and \( k_E((S)) \). Let \( \Gamma' / \Gamma \) be a finite étale extension, with \( \Gamma' \) connected and \( F/E \) the corresponding residue field extension. Then, \( \Gamma' \) is again a Cohen ring of \( F \). We identify \( F \) with \( k_F((T)) \) and fix a Cohen ring \( O' \) of \( k_F \). We claim that there exists an isomorphism \( f' : \Gamma' \cong O'([T]) \) such that \( f' \) modulo \( p \) is the identity, \( f'(\mathcal{O}([S])) \subset O'[[T]] \) and \( f' : \mathcal{O}[[S]] \to O'[[T]] \) is finite flat. We can write \( S = T^{ef/E} \bar{u} \) in \( O_F \) with some \( \bar{u} \in O_E^\times \). We fix a lift \( u \in O'[[T]]^\times \) of \( \bar{u} \) with respect to the projection \( O'[[T]] \to O_F \) and let \( s' : \mathbb{Z}[S_0] \to O'[[T]] ; S_0 \mapsto T^{ef/E} u \) be a ring homomorphism. Let \( s : \mathbb{Z}[S_0] \to \mathcal{O}([S]) \) be the ring homomorphism sending \( S_0 \) to \( S \). By the formal smoothness of \( s \) (see [Ohkubo 2013, §1A]), there exists a local ring homomorphism \( \beta : \mathcal{O}[[S]] \to O'[[T]] \):

\[
\begin{array}{ccc}
\mathcal{O}[[S]] & \xrightarrow{s} & \mathbb{Z}[S_0] \\
& \xrightarrow{\beta} & \ \ \\
& \xleftarrow{s'} & \ O'[[T]] \\
\end{array}
\]

By the local criteria of flatness and Nakayama’s lemma, \( \beta \) is finite flat. By the definition of \( s \) and \( s' \), \( \beta \) induces a map \( \beta : \mathcal{O}((S)) \to O'((T)) \), and hence a map \( \hat{\beta} : \mathcal{O}([S]) \to O'([T]) \). Since \( \hat{\beta} \) is finite étale with residue field extension \( F/E \), there exists a canonical isomorphism \( f' : \Gamma' \cong O'([T]) \), which satisfies the desired properties by the construction of \( \beta \).

The relation \( S = T^{ef/E} u \) for \( u \in O'[[T]]^\times \) gives \( f'(\mathcal{O}((S))^\dagger_r) \subset O'((T))^\dagger_{r/ef/E} \). In the limit \( r \to \infty \), we obtain a flat morphism \( f' : \mathcal{O}((S))^\dagger \to O'((T))^\dagger \). Finally, we prove the finiteness of \( f' : \mathcal{O}((S))^\dagger \to O'((T))^\dagger \). We fix a basis \( \omega_1, \ldots, \omega_k \) of \( O'[[T]] \) as an \( \mathcal{O}([S]) \)-module. Then, we only have to prove that \( x \in \mathcal{O}((T^{ef/E}))^{\dagger_r} \)
can be written as $\sum_i \omega_i \sum_n a_{i,n} S^n$ with $\sum_n a_{i,n} S^n \in \mathcal{O}((S))^{\dagger, re_{F/E}}$. By the relation $Su^{-1} = T^*_{re_{F/E}}$ again, any element $x \in \mathcal{O}'((T^*_{re_{F/E}}))^{\dagger,r}$ can be written as $\sum_{n \in \mathbb{Z}} a_n S^n$ with $a_n \in \mathcal{O}'[[T]]$ such that $|a_n||p|^{re_{F/E} n} \to 0$ for $n \to -\infty$, where $|\cdot|$ is a norm of $\mathcal{O}'[[T]]$ associated to the $p$-adic valuation. We write $a_n = \sum_i a_{n,i} \omega_i$. Then, we have $|a_n| = \sup_i |a_{n,i}|$, where $|\cdot|$ on the RHS is a norm of $\mathcal{O}[[S]]$ associated to the $p$-adic valuation. Hence, $\sum_n a_{n,i} S^n$ belongs to $\mathcal{O}((S))^{\dagger, re_{F/E}}$, which implies the assertion.

**Lemma 1.6.4** [Kedlaya 2005, Lemma 2.3.5, Corollary 2.3.7]. Let $\Gamma$ be a Cohen ring of a complete discrete valuation field $E$ of characteristic $p$ and $\varphi : \Gamma \to \Gamma$ a Frobenius lift. By fixing an isomorphism $f : \Gamma \cong \mathcal{O}[[S]]$, we identify $\Gamma$ and $E$ with $\mathcal{O}([S])$ and $k_E((S))$. Assume that $\varphi(S) \in \mathcal{O}((S))^{\dagger}$. Then, we have

$$\Gamma_r = \mathcal{O}((S))^{\dagger,r}, \quad \Gamma_{\text{con}} = \mathcal{O}((S))^{\dagger}$$

for all sufficiently small $r > 0$.

Moreover, let $F/E$ be a finite separable extension, $\Gamma' / \Gamma$ the corresponding finite étale extension and $\varphi : \Gamma' \to \Gamma'$ the corresponding Frobenius lift extending $\varphi$. We fix an isomorphism $f' : \Gamma' \cong \mathcal{O}'([T])$ as in Construction 1.6.3. Then, $f'$ induces isomorphisms

$$\Gamma'_r \cong \mathcal{O}'((T))^{\dagger,r/e_{F/E}}, \quad \Gamma'_{\text{con}} \cong \mathcal{O}'((T))^{\dagger}$$

for all sufficiently small $r > 0$.

**Proof.** Let $\varphi$ be the Frobenius lift of $\mathcal{O}'([T])$ obtained by identifying $\mathcal{O}'([T])$ with $\Gamma'$. We only have to check that the assumption $\varphi(T) \in \mathcal{O}'((T))^{\dagger}$ in [Kedlaya 2005, Convention 2.3.1] is satisfied. This follows from the fact that $\mathcal{O}'((T))^{\dagger}$ is integrally closed in $\mathcal{O}'([T])$, which in turn is a consequence of Raynaud’s criteria of integral closedness for Henselian pairs [Raynaud 1970, Théorème 3(b), Chapitre XI]. □

Finally, we define (pure) $\varphi$-modules over overconvergent rings.

**Definition 1.6.5** [Kedlaya 2005, Definition 4.6.1]. Let $R$ be $\Gamma[1/p]$, $\Gamma_{\text{con}}[1/p]$, or $\Gamma_{\text{an, con}}$ (Construction 1.6.1) and let $\sigma := \varphi^h$ for some $h \in \mathbb{N}_{>0}$. A $\sigma$-module over $R$ is a finite free $R$-module $M$ endowed with a semilinear $\sigma$-action such that $1 \otimes \sigma : M \otimes_{R, \sigma} R \to M$ is an isomorphism. Assume that $E$ is algebraically closed. Then, any $\sigma$-module over $\Gamma[1/p]$ or $\Gamma_{\text{an, con}}$ admits a Dieudonné–Manin decomposition [Kedlaya 2005, Theorem 4.5.7] and we define the slope multiset of $M$ as the multiset of the $p$-adic valuations of the “eigenvalues”. For a $\sigma$-module $M$ over $\Gamma_{\text{con}}[1/p]$, we define the slope multiset of $M$ as the slope multiset of $\Gamma \otimes \Gamma_{\text{con}}[1/p] M$, which coincides with that of $\Gamma_{\text{an, con}} \otimes \Gamma_{\text{con}}[1/p] M$. For a general $E$, we define the slope multiset after the base change $\Gamma \to W(\bar{E}_{\text{alg}})$. A $\sigma$-module over $R$ is pure of slope $s$ if the slope multiset consists of only $s$. If $M$ is a $\sigma$-module that is pure of slope 0, then we call $M$ étale.
Let ϕ be a Frobenius lift of \( \Gamma := \mathcal{O}(\{S\}) \) with \( \varphi(S) \subset \mathcal{O}((S))^\dagger \). By Lemma 1.6.4, we can view \( \mathcal{O}((S))^\dagger[1/p] \) and \( \mathcal{R} \) in Notation 1.6.2 as \( \Gamma_{\text{con}}[1/p] \) and \( \Gamma_{\text{an,con}} \), and we can give similar definitions for \( R = \mathcal{O}((S))^\dagger[1/p] \) and \( \mathcal{R} \).

When \( R \) is one of the above rings, we denote the category of \( \sigma \)-modules (resp. étale \( \sigma \)-modules, \( \sigma \)-modules of pure slope \( s \)) over \( R \) by \( \text{Mod}_R(\sigma) \) (resp. \( \text{Mod}_R^{\text{et}}(\sigma) \), \( \text{Mod}_R^\dagger(\sigma) \)).

1.7. Differential Swan conductor. The aim of this subsection is to recall the definition of the differential Swan conductor. The following coordinate free definition of the continuous Kähler differentials for overconvergent rings will be useful.

**Definition 1.7.1.** Let \( \Gamma \) be an absolutely unramified complete discrete valuation ring of mixed characteristic \((0, p)\). For a subring \( R \) of \( \Gamma \), we define \( \Omega_R^1 \) as the \( R \)-submodule of \( \hat{\Omega}_\Gamma^1 \) generated by the image of \( R \) under \( d : \Gamma \to \hat{\Omega}_\Gamma^1 \).

**Lemma 1.7.2.** Let \( \Gamma := \mathcal{O}(\{S\}) \) and \( \Gamma^\dagger := \mathcal{O}((S))^\dagger \), where \( \mathcal{O} \) is a Cohen ring of a field \( k \) of characteristic \( p \). Assume that \( [k : k^p] = p^d < \infty \). Then, \( \Omega_{\Gamma^\dagger}^1 \) is the unique \( \Gamma^\dagger \)-submodule \( \mathcal{M} \) of \( \hat{\Omega}_\Gamma^1 \) such that

- (i) \( \mathcal{M} \) is of finite type over \( \Gamma^\dagger \).
- (ii) The image of \( \Gamma^\dagger \) under \( d : \Gamma \to \hat{\Omega}_\Gamma^1 \) is contained in \( \mathcal{M} \).
- (iii) The canonical map \( \Gamma \otimes_{\Gamma^\dagger} \mathcal{M} \to \hat{\Omega}_\Gamma^1 \) is an isomorphism.

Also, if \( \varphi : \Gamma \to \Gamma \) is a Frobenius lift \( \varphi(\Gamma^\dagger) \subset \Gamma^\dagger \), \( \Omega_{\Gamma^\dagger}^1 \) is stable under \( \varphi : \hat{\Omega}_\Gamma^1 \to \hat{\Omega}_\Gamma^1 \).

We omit the proof since it is elementary. Note that if \( \{t_j\} \subset \mathcal{O} \) is a lift of a \( p \)-basis of \( k \), then \( \Omega_{\Gamma^\dagger}^1 \) is a free of rank \( d + 1 \) with basis \( dS, dt_1, \ldots, dt_d \).

**Corollary 1.7.3.** With the notation as in Lemma 1.6.4, the canonical isomorphism \( \Gamma' \otimes_{\Gamma} \hat{\Omega}_\Gamma^1 \cong \widehat{\Omega}_{\Gamma'}^1 \) descends to a canonical isomorphism \( \Gamma'_\text{con} \otimes_{\Gamma^\dagger\text{con}} \Omega_{\Gamma^\dagger\text{con}}^1 \cong \Omega_{\Gamma^\dagger\text{con}}^1 \).

**Notation 1.7.4.** In the rest of this section, let the notation be as in Lemma 1.7.2. We fix a Frobenius lift \( \varphi : \Gamma \to \Gamma \) satisfying \( \varphi(\Gamma^\dagger) \subset \Gamma^\dagger \). Let \( \mathcal{R} \) be the Robba ring associated to \( \Gamma^\dagger \) and assume that \( \varphi(\mathcal{R}) \subset \mathcal{R} \). We put \( \Omega_{\mathcal{R}}^1 := \mathcal{R} \otimes_{\Gamma^\dagger} \Omega_{\Gamma^\dagger}^1 \). Note that the canonical derivation \( d : \Gamma^\dagger \to \Omega_{\Gamma^\dagger}^1 \) extends to \( d : \mathcal{R} \to \Omega_{\mathcal{R}}^1 \).

**Definition 1.7.5.** A \( \nabla \)-module \( M \) over \( \mathcal{R} \) is a finite free module over \( \mathcal{R} \) together with a connection \( \nabla = \nabla_M : M \to M \otimes_{\mathcal{R}} \Omega_{\mathcal{R}}^1 \) such that the composition of \( \nabla_M \) with the map \( M \otimes_{\mathcal{R}} \Omega_{\mathcal{R}}^1 \to M \otimes_{\mathcal{R}} \Omega_{\mathcal{R}}^1 \) induced by \( \nabla \) is the zero map. For \( h \in \mathbb{N}_{>0} \), a \((\varphi^h, \nabla)\)-module \( M \) over \( \mathcal{R} \) is a \( \varphi^h \)-module over \( \mathcal{R} \) endowed with a \( \nabla \)-module structure commuting with the action of \( \varphi^h \). We call a \((\varphi^h, \nabla)\)-module pure (resp. étale) if the underlying \( \varphi^h \)-module is pure (resp. étale). Similarly, we define étale or pure \((\varphi^h, \nabla)\)-modules over \( \Gamma^\dagger \) and \( \Gamma \). Denote by \( \text{Mod}_R(\varphi^h, \nabla) \) the category of pure \((\varphi^h, \nabla)\)-modules over \( R \), where \( R \) is either \( \Gamma \), \( \Gamma^\dagger[1/p] \) or \( \mathcal{R} \).
Theorem 1.7.6 [Kedlaya 2007, Theorem 3.4.6]. For a \((\varphi, \nabla)\)-module \(M\) over \(R\), there exists a canonical slope filtration
\[
0 = \Fil^0(M) \subset \cdots \subset \Fil^l(M) = M,
\]
whose graded pieces are \((\varphi, \nabla)\)-modules of pure slope \(s_1 < \cdots < s_l\).

Construction 1.7.7 [Kedlaya 2007, Definition 3.3.4]. Let \(F/\mathbb{Q}_p\) be a finite unramified extension and \(V \in \Rep_{f.g.} F(G_E)\). Let \(\Gamma_{1,\text{ur}}^\dagger := \lim \Omega_{\Gamma_1^\dagger}^{1,\text{ur}}\), where the limit runs all the finite étale extensions \(\Gamma_{1,\text{ur}}^\dagger / \Gamma_{\dagger}^\dagger\) connected. We consider the connection
\[
\nabla : \Gamma_{1,\text{ur}}^\dagger \otimes \mathcal{O}_F V \to \Omega_{\Gamma_1^\dagger}^{1,\text{ur}} \otimes \mathcal{O}_F V
\]
\[
\lambda \otimes y \mapsto d\lambda \otimes y.
\]
Since \(\Omega_{\Gamma_1^\dagger}^{1,\text{ur}} \cong \Gamma_{1,\text{ur}}^\dagger \otimes \Omega_{\Gamma_1^\dagger}^{1}\) as \(G_E\)-modules by Corollary 1.7.3, we obtain a connection
\[
\nabla : D^\dagger(V) \to \Omega_{\Gamma_1^\dagger}^{1} \otimes \Gamma_{1,\text{ur}}^\dagger D^\dagger(V),
\]
where \(D^\dagger(V) := (\Gamma_{1,\text{ur}}^\dagger \otimes \mathcal{O}_F V)^{G_E}\) is a finite dimensional \(\Gamma_{1,\text{ur}}^\dagger[1/p]\)-module of rank \(\text{dim}_F V\), by taking \(G_E\)-invariants of \((*)\). Thus, we obtain a rank preserving functor
\[
D^\dagger : \Rep_{f.g.}^{f.g.}(G_E) \to \text{Mod}_{\Gamma_{1,\text{ur}}^\dagger[1/p]}(\nabla).
\]
By extending scalars, we also obtain a rank preserving functor
\[
D^\dagger_{\text{rig}} : \Rep_{f.g.}^{f.g.}(G_E) \to \text{Mod}_R(\nabla).
\]
Note that if \(V\) is endowed with a semilinear action of \(\varphi^h\) for \(h \in \mathbb{N}\), then \(D^\dagger(V)\) and \(D^\dagger_{\text{rig}}(V)\) are also endowed with semilinear \(\varphi^h\)-actions.

Definition 1.7.8. For a \(\nabla\)-module \(M\) over \(R\), let \(\text{Swan}^\nabla(M)\) be the differential Swan conductor of \(M\) as in [Kedlaya 2007, Definition 2.8.1].

Recall that the differential Swan conductor is defined in terms of the behavior of the logarithmic radius of convergence [Xiao 2010, Definition 2.3.20], which depends only on the Jordan–Hölder factors of a given \(\nabla\)-module by definition. In particular, we have:

Lemma 1.7.9 (The additivity of the differential Swan conductor). Let \(0 \to M' \to M \to M'' \to 0\) be an exact sequence of \(\nabla\)-modules over \(R\). Then, we have \(\text{Swan}^\nabla(M) = \text{Swan}^\nabla(M') + \text{Swan}^\nabla(M'')\).

The following is Xiao’s Hasse–Arf Theorem in the characteristic \(p\) case.

Theorem 1.7.10 [Xiao 2010, Theorem 4.4.1, Corollary 4.4.3]. Let \(V\) be an \(F\)-representation of \(G_E\) of finite local monodromy. Then, we have
\[
\text{Swan}^{\text{AS}}(V) = \text{Swan}^\nabla(D^\dagger_{\text{rig}}(V)).
\]
Moreover, these invariants are nonnegative integers.
1.8. Scholl’s fields of norms. In this subsection, we recall some results of [Scholl 2006, §1.3], which are a generalization of Fontaine–Wintenberger’s fields of norms. Throughout this subsection, let $K$ be a complete discrete valuation field of mixed characteristic $(0, p)$ with $[k_K : k_K^p] = p^d < \infty$.

Definition 1.8.1. Let $K_1 \subset K_2 \subset \ldots$ be finite extensions of $K$ and put $K_\infty = \bigcup K_n$. We say that a tower $\mathfrak{r} := \{K_n\}_{n \geq 0}$ is strictly deeply ramified if there exists $n_0 > 0$ and an element $\xi \in \mathcal{O}_{K_{n_0}}$ such that $0 < v_p(\xi) \leq 1$, and such that the following condition holds: for every $n \geq n_0$, the extension $K_{n+1}/K_n$ has degree $p^{d+1}$, and there exists a surjection $\Omega^1_{\mathcal{O}_{K_{n+1}}/\mathcal{O}_{K_n}} \rightarrow (\mathcal{O}_{K_{n+1}}/\xi \mathcal{O}_{K_{n+1}})^{d+1}$ of $\mathcal{O}_{K_{n+1}}$-modules.

Let $\mathfrak{r} = \{K_n\}_{n \geq 0}$ be a strictly deeply ramified tower. For $n \geq n_0$, we have $e_{K_{n+1}/K_n} = p$ and $k_{K_{n+1}} = k_{K_n}^{1/p}$, and the Frobenius $\mathcal{O}_{K_{n+1}}/\xi \mathcal{O}_{K_{n+1}} \rightarrow \mathcal{O}_{K_{n+1}}/\xi \mathcal{O}_{K_{n+1}}$ induces a surjection $f_n: \mathcal{O}_{K_{n+1}}/\xi \mathcal{O}_{K_{n+1}} \rightarrow \mathcal{O}_{K_n}/\xi \mathcal{O}_{K_n}$. We also choose a uniformizer $\pi_{K_n}$ of $K_n$ with $\pi_{K_{n+1}}^p \equiv \pi_{K_n} \mod \xi \mathcal{O}_{K_n}$. Then, we define $X^+ := X^+(\mathfrak{r}, \xi, n_0) := \lim_{\leftarrow n \geq n_0} \mathcal{O}_{K_n}/\xi \mathcal{O}_{K_n}$, with transition maps $\{f_n\}$. Let $p_n: X^+ \rightarrow \mathcal{O}_{K_n}/\xi \mathcal{O}_{K_n}$ be the $n$-th projection for $n \geq n_0$. We put $\Pi := (\pi_{K_n} \mod \xi \mathcal{O}_{K_n}) \in X^+$. Let $k_{\mathfrak{r}} := \lim_{\leftarrow n \geq n_0} k_{K_n}$, where the transition maps are induced by $f_n$’s. Since $k_{K_{n+1}} = k_{K_n}^{1/p}$, the projections $p_n: k_{\mathfrak{r}} \rightarrow k_{K_n}$ are isomorphisms for all $n \geq n_0$. Moreover, $X^+$ is a complete discrete valuation ring of characteristic $p$, with uniformizer $\Pi$ and residue field $k_{\mathfrak{r}}$. The construction does not depend on $\xi$ or $n_0$, and $X^+$ is invariant after changing $\{K_n\}$ by $\{K_{n+m}\}$ for some $m$. Hence, we may denote $X^+(\mathfrak{r}, \xi, n_0)$ by $X^+_{\mathfrak{r}}$ and denote the fractional field of $X^+_{\mathfrak{r}}$ by $X_{\mathfrak{r}}$. Note that if $K_n/K$ is Galois for all $n$, then $X^+_{\mathfrak{r}}$ and $X_{\mathfrak{r}}$ are canonically endowed with $G_{K_\infty/K}$-actions by construction.

Example 1.8.2 (Kummer tower case). Let $K = \overline{K}$ and $\{L_n\}$ be as in Section 1.3. Then, $\{L_n\}$ is strictly deeply ramified [Ohkubo 2010, Example 6.2].

Let $L_\infty/K_\infty$ be a finite extension. We choose a finite extension $L/K$ such that $L_\infty = L K_\infty$. Then, the tower $\Sigma := \{L_n := L K_n\}$ depends only on $L_\infty$ up to shifting, and is also strictly deeply ramified with respect to any $\xi' \in K_{n_0}$ with $0 < v_p(\xi') < v_p(\xi')$ ([Scholl 2006, Theorem 1.3.3]). Note that if $L_n/K$ is Galois for all $n$, then $X^+_{\mathfrak{r}}$ and $X_{\mathfrak{r}}$ are canonically endowed with $G_{L_\infty/K}$-actions by construction.

Theorem 1.8.3 [Scholl 2006, Theorem 1.3.4]. Let the notation be as above. Denote the category of finite étale algebras over $K_{\infty}$ (resp. $X_{\mathfrak{r}}$) by $\mathbb{FÉt}_{K_{\infty}}$ (resp. $\mathbb{FÉt}_{X_{\mathfrak{r}}}$). Then, the functor

$$X_*: \mathbb{FÉt}_{K_{\infty}} \rightarrow \mathbb{FÉt}_{X_{\mathfrak{r}}}$$

$$L_\infty \mapsto X_{\Sigma}$$

is an equivalence of Galois categories. In particular, the corresponding fundamental groups are isomorphic, i.e., $G_{K_\infty} \cong G_{X_{\mathfrak{r}}}$. Moreover, the sequences $\{[L_n : K_n]\}_n$, $\{e_{L_n/K_n}\}_n$ and $\{[k_{L_n} : k_{K_n}]\}_n$ are stationary for sufficiently large $n$. Their limits are equal to $[X_{\Sigma} : X_{\mathfrak{r}}]$, $e_{X_{\Sigma}/X_{\mathfrak{r}}}$ and $[k_{X_{\Sigma}} : k_{X_{\mathfrak{r}}}]$. 
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1.9. \((\varphi, \Gamma_K)\)-modules. Throughout this subsection, let \(K\) be a complete discrete valuation field of mixed characteristic \((0, p)\). In this subsection, we will recall the theory of \((\varphi, \Gamma_K)\)-modules in the Kummer tower case [Andreatta 2006]. To avoid complications, especially when verifying the assumption [Scholl 2006, (2.1.2)], we will assume the following to work under the settings of [Andreatta 2006; Andreatta and Brinon 2008; 2010].

**Assumption 1.9.1** [Andreatta 2006, §1]. Let \(V\) be a complete discrete valuation field of mixed characteristic \((0, p)\) with perfect residue field. Let \(R_0\) be the \(p\)-adic Hausdorff completion of \(V[T_1, \ldots, T_d][1/T_1 \ldots T_d]\) and \(\tilde{R}\) a ring obtained from \(R_0\) by iterating finitely many times the following operations:

- (ét) The \(p\)-adic Hausdorff completion of an étale extension.
- (loc) The \(p\)-adic Hausdorff completion of the localization with respect to a multiplicative system.
- (comp) The Hausdorff completion with respect to an ideal containing \(p\).

We assume that there exists a finite flat morphism \(\tilde{R} \to O_K\), which sends \(T_j\) to \(t_j\).

Note that \(\tilde{R}\) is an absolutely unramified complete discrete valuation ring. Denote \(\tilde{R}\) by \(O_{\tilde{K}}\) and \(\text{Frac}(\tilde{R})\) by \(\tilde{K}\). Let \(L/\tilde{K}\) be a finite extension. In the rest of this subsection, we will use the notation from Sections 1.3 and 1.4. We also apply the results of Section 1.8 to the Kummer tower \(\{L_n\}_{n > 0}\).

**Notation 1.9.2** [Andreatta and Brinon 2008, §4.1]. We will denote

\[ E^+_L := X^+_L, \quad E_L := X_L. \]

For any nonzero \(\xi \in pO_{L_\infty}\), we put

\[ \tilde{E}^+_L := \lim_{x \to x^p} O_{L_\infty}/\xi O_{L_\infty}, \quad \tilde{E}_L := \text{Frac}(\tilde{E}^+_L), \]

where both rings are independent of the choice of \(\xi\). We also put

\[ \tilde{A}^+_L := W(\tilde{E}^+_L), \quad \tilde{A}_L := W(\tilde{E}_L), \quad \tilde{B}_L := \tilde{A}_L[1/p]. \]

By definition, we have \(E^+_L \subset \tilde{E}^+_L\) and \(E_L \subset \tilde{E}_L\), and \(\tilde{E}_L\) can be viewed as a closed subring of \(\tilde{E}\). In particular, the rings \(\tilde{A}^+_L, \tilde{A}_L\) and \(\tilde{B}_L\) can be viewed as subrings of \(\tilde{A}^+_L, \tilde{A}_L\) and \(\tilde{B}_L\). Note that the completion of an algebraic closure of \(E_L\) coincides with \(\tilde{E}\). Moreover, \(\tilde{E}\) is perfect and \((\tilde{E}_L, \nu_{\tilde{E}})\) is a perfect complete valuation field, whose integer ring is \(\tilde{E}^+_L\). By using the \(G_{\tilde{K}}\)-actions on \(\tilde{E}\) and \(\tilde{A}\), we can write

\[ \tilde{E}^+_L = (\tilde{E}^+_L)^{H_L}, \quad \tilde{E}_L = \tilde{E}_L^{H_L}, \quad \tilde{A}_L = \tilde{A}_L^{H_L}, \quad \tilde{B}_L = \tilde{B}_L^{H_L}, \]

see [Andreatta and Brinon 2008, Lemma 4.1].
**Lemma 1.9.3** (a special case of [Andreatta and Brinon 2008, Proposition 4.42]). We put $\mathbb{A}_{W(k)}^+: = W(k)[[\pi]] \subset \mathbb{A}_p^+$, where $\pi = [\varepsilon] - 1 \in \mathbb{A}_p^+$. Let $L/\tilde{K}$ be a finite extension. The weak topology of $\mathbb{A}_L \simeq \mathbb{E}_L^n$ is the product topology $\mathbb{E}_L^n$, where $\mathbb{E}_L$ is endowed with the valuation topology. Then, there exists a unique subring $\mathbb{A}_L$ of $\mathbb{A}_L$ such that:

(i) $\mathbb{A}_L$ is complete for the weak topology.

(ii) $p\mathbb{A}_L \cap \mathbb{A}_L = p\mathbb{A}_L$.

(iii) One has a commutative diagram

\[
\begin{array}{ccc}
\mathbb{A}_L & \longrightarrow & \mathbb{E}_L \\
\downarrow & & \downarrow \\
\tilde{\mathbb{A}}_L & \longrightarrow & \tilde{\mathbb{E}}_L \\
\end{array}
\]

(iv) $[\varepsilon], [\tilde{t}_j] \in \mathbb{A}_L$ for all $j$.

(v) There exists an $\mathbb{A}_{W(k)}^+$-subalgebra $\mathbb{A}_L^+$ of $\mathbb{A}_L$ and $r_L \in \mathbb{Q}_{>0}$ such that:

(a) There exists $a \in \mathbb{N}$ such that $p/\pi^a \in \mathbb{A}_L^+$ and $\mathbb{A}_L^+/(p/\pi^a) \cong \mathbb{E}_L^n$.

(b) If $\alpha, \beta \in \mathbb{N}_{>0}$ are such that $\alpha/\beta < pr_L/(p - 1)$, then $\mathbb{A}_L^+ \subset \mathbb{A}_L^+[p^a/\pi^\beta]$; here, $\mathbb{A}_L^+[p^a/\pi^\beta]$ denotes the $p$-adic Hausdorff completion of $\mathbb{A}_L^+[p^a/\pi^\beta]$.

(c) $\mathbb{A}_L^+$ is complete for the weak topology.

Moreover, by the uniqueness, $\mathbb{A}_L$ is stable under the actions of $\varphi$ and $G_{L,\infty/K}$ if $L/\tilde{K}$ is Galois.

**Definition 1.9.4.** Let $\mathbb{A}$ be the $p$-adic Hausdorff completion of $\bigcup_{L/\tilde{K}} \mathbb{A}_L$, which is a subring of $\mathbb{A}$ that is stable under the actions of both $G_{\tilde{K}}$ and $\varphi$. We also put $\mathbb{B}_L := \mathbb{A}_L[1/p]$ and $\mathbb{B} := \mathbb{A}[1/p]$.

**Remark 1.9.5.** (i) As remarked in [Andreatta and Brinon 2008, §4.3], $\mathbb{A}_L$ is the unique finite étale $\mathbb{A}_{\tilde{K}}$-algebra corresponding to $\mathbb{E}_L/\mathbb{E}_{\tilde{K}}$; in particular, $\mathbb{A}_L$ is a Cohen ring of $\mathbb{E}_L$.

(ii) The action of $\Gamma_{\tilde{K}}$ on $\mathbb{A}_{\tilde{K}}$ is determined by the action of $\Gamma_{\tilde{K}}$ on $\pi, [\tilde{t}_1], \ldots, [\tilde{t}_d]$, since $\varepsilon - 1, \tilde{t}_1, \ldots, \tilde{t}_d$ form a $p$-basis of $\mathbb{E}_{\tilde{K}}$. Explicit descriptions are given by:

$\gamma_a(\pi) = (1 + \pi)^a - 1, \quad \gamma_a([\tilde{t}_j]) = [\tilde{t}_j]$ for $a \in \mathbb{Z}_p^\times$,

$\gamma_b(\pi) = \pi, \quad \gamma_b([\tilde{t}_j]) = (1 + \pi)^b[\tilde{t}_j]$ for $b = (b_j) \in \mathbb{Z}_p^d$.

**Definition 1.9.6.** For $h \in \mathbb{N}_{>0}$, an étale $(\varphi^h, \Gamma_L)$-module $M$ over $\mathbb{B}_L$ is an étale $\varphi^h$-module over $\mathbb{B}_L$ endowed with a semilinear continuous $G_{\tilde{K}}$-action that commutes with the action of $\varphi^h$. Denote by $\text{Mod}_{\mathbb{B}_L}^{\text{ét}}(\varphi^h, \Gamma_L)$ the category of étale $(\varphi^h, \Gamma_L)$-modules over $\mathbb{B}_L$. 
For $V \in \text{Rep}_{Q,\rho}(G_L)$, let $\mathbb{D}(V) := (\mathbb{B} \otimes_{Q,\rho} V)^{H_L}$. For $M \in \text{Mod}^e_{\mathbb{B}L}(\phi^h, \Gamma_L)$, let $\mathbb{V}(M) := (\mathbb{B} \otimes_{\mathbb{B}K} M)^{\phi^h = 1}$.

**Theorem 1.9.7** ([Andreatta 2006, Theorem 7.11] or [Andreatta and Brinon 2008, Théorème 4.34]). Let $h \in \mathbb{N}_{>0}$. Then, the functor $\mathbb{D}$ gives a rank preserving equivalence of categories

$$\mathbb{D} : \text{Rep}_{Q,\rho}(G_L) \to \text{Mod}^e_{\mathbb{B}L}(\phi^h, \Gamma_L)$$

with quasi-inverse $\mathbb{V}$.

**1.10. Overconvergence of $p$-adic representations.** In this subsection, we will recall the overconvergence of $p$-adic representations in [Andreatta and Brinon 2008]. We still keep the notations of Section 1.9 and Assumption 1.9.1.

**Definition 1.10.1.** We apply Construction 1.6.1 to $(\mathcal{E}, v_\mathcal{E})$ with $\Gamma = \tilde{\mathbb{A}}$ and write

$$\tilde{\mathbb{A}}^{+,r} := \Gamma_r, \quad \tilde{\mathbb{A}}^+ := \Gamma_{\text{con}}, \quad \tilde{\mathbb{B}}^{+,r} := \Gamma_r[1/p], \quad \tilde{\mathbb{B}}^+ := \Gamma_{\text{con}}[1/p],$$

$$\tilde{\mathbb{B}}^{\text{rig},r} := \Gamma_{\text{an},r}, \quad \tilde{\mathbb{B}}^\text{rig} := \Gamma_{\text{an,con}}.$$

We define $v_{\mathcal{E}}^{\mathbb{E}}$ and $w_r$ the same way. For a finite extension $L/\tilde{K}$, we apply a similar construction to the following $(E, v_\mathcal{E})$ with $\Gamma$ and we denote:

<table>
<thead>
<tr>
<th>$\Gamma$</th>
<th>$E$</th>
<th>$\Gamma_r$</th>
<th>$\Gamma_{\text{con}}$</th>
<th>$\Gamma_{\text{con}}[1/p]$</th>
<th>$\Gamma_{\text{an},r}$</th>
<th>$\Gamma_{\text{an,con}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathbb{A}$</td>
<td>$\mathbb{A}$</td>
<td>$\mathbb{A}^{+,r}$</td>
<td>$\mathbb{A}^+$</td>
<td>$\mathbb{B}^{+,r}$</td>
<td>$\mathbb{B}^+$</td>
<td>$\mathbb{B}^{\text{rig},r}$</td>
</tr>
<tr>
<td>$\tilde{\mathbb{A}}$</td>
<td>$\tilde{\mathbb{A}}_L$</td>
<td>$\tilde{\mathbb{A}}^{+,r}_L$</td>
<td>$\tilde{\mathbb{A}}^+_L$</td>
<td>$\tilde{\mathbb{B}}^{+,r}_L$</td>
<td>$\tilde{\mathbb{B}}^+_L$</td>
<td>$\tilde{\mathbb{B}}^{\text{rig},r}_L$</td>
</tr>
<tr>
<td>$\mathbb{A}_L$</td>
<td>$\mathbb{E}_L$</td>
<td>$\mathbb{A}^{+,r}_L$</td>
<td>$\mathbb{A}^+_L$</td>
<td>$\mathbb{B}^{+,r}_L$</td>
<td>$\mathbb{B}^+_L$</td>
<td>$\mathbb{B}^{\text{rig},r}_L$</td>
</tr>
</tbody>
</table>

By construction, we have $\tilde{\mathbb{B}}^+ = \bigcup_r \tilde{\mathbb{B}}^{+,r}, \mathbb{B}^+ = \bigcup_r \mathbb{B}^{+,r}, \tilde{\mathbb{B}}^{+,r}_K = \tilde{\mathbb{B}}_K \cap \tilde{\mathbb{B}}^{+,r}, \mathbb{B}^{+,r}_K = \bigcup_r \mathbb{B}_K^{+,r}$. We endow $\tilde{\mathbb{B}}^{+,r}, \tilde{\mathbb{B}}^{\text{rig},r}, \ldots$, etc. with the Fréchet topologies defined by $\{w_s\}_{0<s<r}$.

We can describe $\mathbb{A}_L^+$ by the ring of overconvergent power series.

**Lemma 1.10.2** (cf. [Berger 2002, Proposition 1.4]). Let $\mathcal{O}$ be a Cohen ring of $k_{\mathcal{E}}$. Then, there exists an isomorphism $\mathbb{A}_\mathcal{E} \cong \mathcal{O}[[\pi]]$, which induces an isomorphism $\mathbb{A}_\mathcal{E}^{+,r} \cong \mathcal{O}((\pi))^r$ for all sufficiently small $r > 0$. Similarly, there exists an isomorphism $\mathbb{A}_L \cong \mathcal{O}'[[\pi']]$, which induces an isomorphism $\mathbb{A}_L^{+,r} \cong \mathcal{O}'((\pi'))^r_{/\mathcal{E}}$, where $\mathcal{O}'$ is a Cohen ring of $k_{\mathcal{E}}$.

**Proof.** Fix any isomorphism $\mathbb{A}_\mathcal{E} \cong \mathcal{O}[[\pi]]$ (Remark 1.9.5(i)). Since $\phi(\pi) = [\pi]^p - 1 = (1 + \pi)^p - 1 \in \mathcal{O}[[\pi]]$, the assertion follows from Lemma 1.6.4. □
Notation 1.10.3. The isomorphism in Lemma 1.10.2 enables us to apply the results of Section 1.7. In particular, for any finite extension $L/\bar{K}$, we have a canonical continuous derivation

$$d : \mathcal{B}_{\text{rig.}L} \to \Omega^1_{\mathcal{B}_{\text{rig.}L},}$$

with $\Omega^1_{\mathcal{B}_{\text{rig.}L}} := \mathcal{B}_{\text{rig.}L} \otimes_{\mathcal{A}_{\text{rig.}L}} \Omega^1_{\mathcal{A}_{\text{rig.}L}}$, a free $\mathcal{B}_{\text{rig.}L}$-module with basis $d\pi, d[\tilde{t}_1], \ldots, d[\tilde{t}_d]$. Hence, we have a notion of $(\varphi, \nabla)$-modules over $\mathcal{B}_{\text{rig.}L}$ and the associated differential Swan conductors.

Definition 1.10.4. Let $h \in \mathbb{N}_{>0}$. An étale $(\varphi^h, \Gamma_L)$-module $M$ over $\mathcal{B}_L^\dagger$ is an étale $\varphi^h$-module over $\mathcal{B}_L^\dagger$ endowed with a continuous semilinear $G_K$-action that commutes with the $\varphi^h$-action. Denote by $\text{Mod}^{\text{et}}_{\mathcal{B}_L^\dagger}((\varphi^h, \Gamma_L))$ the category of étale $(\varphi^h, \Gamma_L)$-modules over $\mathcal{B}_L^\dagger$.

For $V \in \text{Rep}_{\mathbb{Q}_{\varphi^h}}(G_L)$, let

$$\mathbb{D}^{\dagger,r}(V) := (\mathbb{B}_L^{\dagger,r} \otimes_{\mathbb{Q}_{\varphi^h}} V)^{H_L}, \quad \mathbb{D}^{\dagger}(V) = \bigcup_r \mathbb{D}^{\dagger,r}(V),$$

$$\mathbb{D}^{\dagger,\text{rig}}_L(V) := \mathbb{B}_L^{\dagger,r} \otimes_{\mathbb{B}_L^{\dagger,r}} \mathbb{D}^{\dagger,r}(V), \quad \mathbb{D}^{\dagger}_L(V) = \bigcup_r \mathbb{D}^{\dagger,\text{rig}}_L(V).$$

For $M \in \text{Mod}^{\text{et}}_{\mathcal{B}_L^\dagger}((\varphi^h, \Gamma_L))$, let $\mathbb{V}(M) := (\mathbb{B}_L^\dagger \otimes_{\mathbb{B}_L^\dagger} M)^{\varphi^h=1}$.

Theorem 1.10.5 [Andreatta and Brinon 2008, Theorem 4.35]. Let $h \in \mathbb{N}_{>0}$. The functor $\mathbb{D}^\dagger$ gives a rank preserving equivalence of categories

$$\mathbb{D}^\dagger : \text{Rep}_{\mathbb{Q}_{\varphi^h}}(G_L) \to \text{Mod}^{\text{et}}_{\mathcal{B}_L^\dagger}((\varphi^h, \Gamma_L))$$

with quasi-inverse $\mathbb{V}$. Moreover, $\mathbb{D}^\dagger$ and $\mathbb{V}$ are compatible with $\mathbb{D}$ and $\mathbb{V}$ in Theorem 1.9.7. Furthermore, $\mathbb{D}^{\dagger,r}(V)$ is free of rank $\text{dim}_{\mathbb{Q}_{\varphi^h}} V$ over $\mathbb{B}_K^{\dagger,r}$ for all sufficiently small $r$, and we have a canonical isomorphism $\mathbb{B}_K^{\dagger,r} \otimes_{\mathbb{B}_K^{\dagger,r}} \mathbb{D}^{\dagger,r}(V) \cong \mathbb{D}^{\dagger}(V)$.

The functor $\mathbb{D}^{\dagger,\text{rig}}_L$ will be studied in Section 4.5.

2. Adequateness of overconvergent rings

In this section, we will prove the “adequateness”, which ensures that the elementary divisor theorem holds, for overconvergent rings defined in Section 1.6. The adequateness of overconvergent rings seems to be well-known to the experts: at least when the overconvergent ring is isomorphic the Robba ring, the adequateness follows from Lazard’s results [1962] as in [Berger 2002, Proposition 4.12(5)]. Since the author could not find an appropriate reference, we give a proof.

Definition 2.0.1 [Helmer 1943, §2]. An integral domain $R$ is adequate if the following hold:

(i) $R$ is a Bézout ring, that is, any finitely generated ideal of $R$ is principal.
(ii) For any $a, b \in R$ with $a \neq 0$, there exists a decomposition $a = a_1a_2$ such that $(a_1, b) = R$ and $(a_3, b) \neq R$ for any nonunit factor $a_3$ of $a_2$.

Recall that if $R$ is an adequate integral domain, then the elementary divisor theorem holds for free $R$-modules, see [Helmer 1943, Theorem 3]. Precisely speaking, let $N \subset M$ be finite free $R$-modules of ranks $n$ and $m$ respectively. Then, there exists a basis of $e_1, \ldots, e_m$ (resp. $f_1, \ldots, f_n$) of $M$ (resp. $N$) and nonzero elements $\lambda_1 | \cdots | \lambda_n \in R$ such that $f_i = \lambda_je_i$ for $1 \leq i \leq n$.

In the rest of this section, let the notation be as in Construction 1.6.1. We fix $r_0 > 0$ such that $\Gamma$ has enough $r_0$-units and let $r \in (0, r_0)$ unless otherwise stated. Recall that $\Gamma_{an,r}$ is a Bézout integral domain.

**Definition 2.0.2.** We recall basic terminologies, see also [Kedlaya 2004, §3.5]. For $x \in \Gamma_{an,r}$ nonzero, we define the Newton polygon of $x$ as the lower convex hull of the set of points $(v \leq n(x), n)$, minus any segments of slope less than $-r$ on the left end and/or any segments of nonnegative slope on the right end of the polygon. We define the slopes of $x$ as the negatives of the slopes of the Newton polygon of $x$. We also define the multiplicity of a slope $s \in (0, r]$ of $x$ as the positive difference in $y$-coordinates between the endpoints of the segment of the Newton polygon of slope $-s$, or 0 if there is no such segment. If $x$ has only one slope $s$, we say that $x$ is pure of slope $s$.

A slope factorization of a nonzero element $x$ of $\Gamma_{an,r}$ is a Fréchet-convergent product $x = \prod_{1 \leq i \leq n} x_i$ for $n$ either a positive integer or $\infty$, where each $x_i$ is pure of slope $s_i$ with $s_1 > s_2 > \ldots$ (cf. an explanation before [Kedlaya 2004, Lemma 3.26]).

Recall that the multiplicity is compatible with multiplication, i.e., the multiplicity of a slope $s$ of $xy$ is the sum of its multiplicities as a slope of $x$ and of $y$ [Kedlaya 2004, Corollary 3.22]. Also, recall that $x \in \Gamma_{an,r}$ is a unit if and only if $x$ has no slopes [Kedlaya 2005, Corollary 2.5.12].

**Lemma 2.0.3** [Kedlaya 2004, Lemma 3.26]. Every nonzero element of $\Gamma_{an,r}$ has a slope factorization.

For simplicity, we denote $\Gamma_{an,r}$ by $R$ in the rest of this subsection. The lemma below is an immediate consequence of $R$ being Bézout and the additivity of the multiplicity of a slope.

**Lemma 2.0.4.** (i) Let $x, y \in R$ such that $x$ is pure of slope $s$ and let $z$ be a generator of $(x, y)$. Then, $z$ is also pure of slope $s$, with multiplicity less than or equal to the multiplicity of slope $s$ of $x$. In particular, if the multiplicity of the slope $s$ of $y$ is equal to zero, then $z$ is a unit and we have $(x, y) = R$.

(ii) Let $x, y \in R$ such that $x$ is pure of slope $s$. Then, the decreasing sequence of the ideals $\{(x, y^n)\}_{n \in \mathbb{N}}$ is eventually stationary.
Lemma 2.0.5 (the uniqueness of slope factorizations). Let \( x \in R \) be a nonzero element. Let \( x = \prod_{i} x_i = \prod_{i} x_i' \) be slope factorizations whose slopes are \( s_1 > s_2 > \ldots \) and \( s_1' > s_2' > \ldots \). Let \( m_i \) and \( m_i' \) be the multiplicities of \( s_i \) and \( s_i' \) for \( x_i \) and \( x_i' \). Then, we have \( s_i = s_i' \) and \( x_i = x_i' u_i \) for some \( u_i \in R^\times \). In particular, we have \( m_i = m_i' \).

Proof. We can easily reduce to the case \( i = 1 \). Since the multiplicity of the slope \( s_1 \) of \( \prod_{i>1} x_i' \) is equal to zero, we have \( (x_1, \prod_{i>1} x_i') = R \) by Lemma 2.0.4(i). Hence, we have \( (x_1, x) = (x_1, x_1 \prod_{i>1} x_i) = (x_1) \). By assumption, we have \( s_1 \neq s_1' \) except for at most one \( j \). Just as before, we have

\[
(x_1, x) = (x_1, x_j \prod_{i \neq j} x_i') = (x_1, x_j') = (x_1 \prod_{i \neq j} x_i, x_j') = (x_1', \prod_{i \neq j} x_i', x_j') = (x_j'),
\]
i.e., \( (x_1) = (x_j') \). Hence, there exists \( u \in R^\times \) such that \( x_1 = x_j' u \). By the same argument, \( x_i' = x_l u' \) for some \( l \) and \( u' \in R^\times \). Since \( \{s_i\} \) and \( \{s_i'\} \) are strictly decreasing, we must have \( j = l = 1 \), which implies the assertion.

Lemma 2.0.6. The integral domain \( \Gamma_{an,r} \) is adequate. In particular, the elementary divisor theorem holds over \( \Gamma_{an,r} \).

Proof. We only have to prove that condition (ii) in Definition 2.0.1 is satisfied. Let \( a, b \in R \) with \( a \neq 0 \). If \( b = 0 \), then it suffices to put \( a_1 = 1, a_2 = a \). If \( b \) is a unit, then it suffices to put \( a_1 = a, a_2 = 1 \). Therefore, we may assume that \( b \) is neither a unit nor zero. Let \( b = \prod_{i>0} b_i \) be a slope factorization with slopes \( s_1 > s_2 > \ldots \). By Lemma 2.0.4(ii), there exists \( z_i \in R \) such that \( (a, b^n_i) = (z_i) \) for all sufficiently large \( n \). By [Kedlaya 2004, Proposition 3.13], we may assume that \( z_i \) admits a semi-unit decomposition, meaning that \( z_i \) is equal to a convergent sum of the form \( 1 + \sum_{j < 0} u_{i,j} b^j \), where \( u_{i,j} \in R^\times \cup \{0\} \). As in the proof of [Kedlaya 2004, Lemma 3.26], we can prove that \( \{z_1 \ldots z_i\}_{i>0} \) converges. Next, we claim that there exists \( u_i \in R \) such that \( a = z_1 \ldots z_i u_i \). We proceed by induction on \( i \). By definition, we have \( a = z_1 u_1 \) for some \( u_1 \). Assume that we have defined \( u_i \). Since the multiplicity of the slope \( s_{i+1} \) of \( z_j \) is equal to zero for \( 1 \leq j \leq i \), we have \( (z_j, z_{i+1}) = R \) for \( 1 \leq j \leq i \). Hence, we have \( (z_{i+1}) = (a, z_{i+1}) = (z_1 \ldots z_i u_i, z_{i+1}) = (u_i, z_{i+1}) \), which implies \( z_{i+1} \mid u_i \). Therefore, \( u_{i+1} := u_i / z_{i+1} \) satisfies the condition. By this proof, we can choose \( u_i = u_1 / (z_1 \ldots z_i) \). We put \( a_1 := \lim_{i \to \infty} u_i = u_1 / \prod_{i \geq 1} z_i \) and \( a_2 := \prod_{i>0} z_i \), which is a slope factorization of \( a_2 \). We prove that the factorization \( a = a_1 a_2 \) satisfies the condition. We first prove \( (a_1, b_i) = R \) for all \( i \). Fix \( i \in \mathbb{N}_{>0} \). Then, for all sufficiently large \( n \in \mathbb{N} \), we have

\[
(z_i) = (a, b_i^n) = (a_1 a_2, b_i^{n+1}) \subset (a_1, b_i)(a_2, b_i^n) \subset (a_1, b_i)(z_i, b_i^n) = (a_1, b_i)(z_i).
\]
Since \( z_i \neq 0 \), we have \( R \subset (a_1, b_i) \), which implies the assertion. Finally, we prove \( (a_3, b) \neq R \) for any nonunit \( a_3 \in R \) dividing \( a_2 \). By replacing \( a_3 \) by any factor of a slope factorization of \( a_3 \), we may assume that \( a_3 \) is pure. By the uniqueness of slope factorizations, \( a_3 \) divides \( z_i \) for some \( i \). Since \( z_i \mid b^n_i \) for sufficiently large \( n \), we also have \( a_3 \mid b^n_i \). Hence, we have \( (a_3, b_i) \neq R \), and in particular, \( (a_3, b) \neq R \). \( \square \)

3. Variations of Gröbner basis argument

In this section, we will systematically develop a basic theory of Gröbner bases over various rings. Our theory generalizes the basic theory of Gröbner bases over fields ([Cox et al. 1997], particularly, §2). As a first application, we will prove the continuity of connected components of flat families of rigid analytic spaces over annuli (Proposition 3.4.5(iii)). As a second application, we prove the ramification compatibility of Scholl’s fields of norms (Theorem 3.5.3).

The idea to use a Gröbner basis argument to study Abbes–Saito’s rigid spaces of positive characteristic is in [Xiao 2010, §1]. Some results of this section, particularly Sections 3.2 and 3.3, are already proved there, however we do not use Xiao’s results. We will work under a slightly stronger assumption and deduce stronger results, with much clearer and simpler proofs, than Xiao’s. Note that this section is independent from the other parts of this paper, except Sections 1.5 and 1.8.

**Notation 3.0.1.** Throughout this section, we will use multi-index notation. We write \( n = (n_1, \ldots, n_l) \in \mathbb{N}^l \), \( |n| := n_1 + \cdots + n_l \) and \( X^n = X_1^{n_1} \cdots X_l^{n_l} \) for variables \( X = (X_1, \ldots, X_l) \). We also denote by \( X^n \) the set of monic monomials \( \{X^n | n \in \mathbb{N}^l\} \).

In this section, when we consider a topology on a ring, we will use a norm \( |\cdot| \) rather than a valuation.

3.1. Convergent power series. In this subsection, we consider rings of strictly convergent power series over the ring of rigid analytic functions over annuli, which play an analogous role to Tate algebra in the classical situation. We also gather basic definitions and facts on these rings for the rest of this section.

**Definition 3.1.1.** Let \( R \) be a ring. For \( f = \sum_n a_n X^n \in R[[X]] \) with \( a_n \in R \), we call each \( a_n X^n \) a term of \( f \). If \( f = a_n X^n \) with \( a_n \in R \), then we call \( f \) a monomial. If \( a_n = 1 \), then \( f \) is called monic.

**Definition 3.1.2** [Bosch et al. 1984, Section 1.4.1, Definition 1]. Let \( (R, |\cdot|) \) be a normed ring. We define a Gauss norm on \( R[X] \) by \( |\sum_n a_n X^n| := \sup_n |a_n| \). A formal power series \( \sum_n a_n X^n \in R[[X]] \) is strictly convergent if \( |a_n| \to 0 \) as \( |n| \to \infty \). We denote the ring of strictly convergent power series over \( R \) by \( R \langle X \rangle \). The above norm \( |\cdot| \) can be uniquely extended to \( |\cdot| : R\langle X \rangle \to \mathbb{R}_{\geq 0} \). Note that if \( R \) is complete with respect to \( |\cdot| \), then \( R\langle X \rangle \) is also complete with respect to \( |\cdot| \), see [Bosch et al. 1984, Section 1.4.1, Proposition 3].
We recall basic facts on rings of strictly convergent power series. Let $R$ be a complete normed ring, whose topology is equivalent to the $a$-adic topology for an ideal $a$. Then, $R\langle X \rangle$ is canonically identified with the $a$-adic Hausdorff completion of $R[X]$. We further assume that $R$ is Noetherian. Then, $R\langle X \rangle$ is $R$-flat. Moreover, for any ideal $b$ of $R$, we have a canonical isomorphism

$$R\langle X \rangle \otimes_R (R/b) \cong (R/b)\langle X \rangle,$$

where the RHS means the $a$-adic Hausdorff completion of $(R/b)[X]$.

For a complete discrete valuation ring $O$ with $F = \text{Frac}(O)$, we denote by $O\langle X \rangle$ (resp. $F\langle X \rangle$) the rings of convergent power series over $O$ (resp. $F$).

**Lemma 3.1.3.** Assume that $R$ is a complete normed Noetherian ring, whose topology is equivalent to the $a$-adic topology for some ideal $a$ of $R$. Let $I \subset R\langle X \rangle$ be an ideal such that $R\langle X \rangle/I$ is $R$-flat. Then, $I$ is also $R$-flat. Moreover, for any ideal $J \subset R$, we have a canonical isomorphism

$$R\langle X \rangle \otimes_R (R/J) \cong (R/J)\langle X \rangle,$$

which is multiplicative by $|\cdot|$. We omit the proof since it is an easy exercise in flatness.

**Notation 3.1.4.** In the rest of this subsection, we fix the notation as follows. Let $O$ be a Cohen ring of a field $k$ of characteristic $p$ and fix a norm $|\cdot|$ on $O$ corresponding to the $p$-adic valuation. We put $R^+ := \text{O}\llbracket S \rrbracket \subset R := \text{O}(S)$ and for $r \in \mathbb{Q}_{>0}$, we define a norm

$$|\cdot|_r : R \rightarrow \mathbb{R}_{\geq 0}$$

$$\sum_{n \gg -\infty} a_n S^n \mapsto \sup_n |a_n||p|^n,$$

which is multiplicative by [Kedlaya 2010, Proposition 2.1.2]. Recall the definition

$$R^+, r = \left\{ \sum_{n \in \mathbb{Z}} a_n S^n \in \text{O}\llbracket S \rrbracket; \ |a_n S^n|_r \rightarrow 0 \text{ as } n \rightarrow -\infty \right\}$$

from Notation 1.6.2. Note that we may canonically identify $R^+, r / p R^+, r$ with $k((S))$. We can extend $|\cdot|_r$ to $|\cdot|_{r'} : R^+, r \rightarrow \mathbb{R}_{\geq 0}$ by $|\sum_n a_n S^n|_r := \sup_n |a_n S^n|_r$. We define subrings of $R^+, r$ by

$$R^+, r_0 = \left\{ f \in R^+, r; \ |f|_r \leq 1 \right\},$$

$$R^+, r_0 := R^+, r \cap R = \left\{ f \in R; \ |f|_r \leq 1 \right\}.$$

Note that for $a, b \in \mathbb{N}$ with $b > 0$, $|p^a/S^b|_r \leq 1$ if and only if $a/b \geq r$. Also, note that $R^+, r = R^+, r_0[S^{-1}]$ since $|S|_r < 1$. We may regard $R^+, r$ as the ring of rigid
Lemma 3.1.5.  
(i) The $R^+_0$-algebra $R^+_0$ is finitely generated.

(ii) The topologies of $R^+_0$ defined by $| \cdot |_r$ and by the ideal $(p, S)$ are equivalent.

(iii) The rings $R^+_0$ and $R^+_r$ are complete with respect to $| \cdot |_r$, and $R^+_0$ is dense
in $R^+_r$.

(iv) The rings $R^+_0$, $R^+_r$, and $R^+_r$ are Noetherian integral domains.

Proof. Let $a$, $b \in \mathbb{N}_{>0}$ denote relatively prime integers such that $r = a/b$.

(i) It is straightforward to check that $R^+_0$ is generated as an $R^+_0$-algebra by
$p^{|rb^j|}/S^{b^j}$ for $b^j \in \{0, \ldots, b\}$.

(ii) For $n \in \mathbb{N}$, we have
$$\sup \{|x|_r; \ x \in (p, S)^n R^+_0 \} \leq \inf \{|p|, |S|_r\}^n$$
and the RHS converges to 0 as $n \to \infty$. Hence, the $(p, S)$-adic topology of
$R^+_0$ is finer than the topology defined by $| \cdot |_r$. To prove that the topology of
$R^+_0$ defined by $| \cdot |_r$ is finer than the $(p, S)$-adic topology, it suffices to prove that
$$\{ x \in R^+_0; |x|_r \leq |(pS)^n|_r \} \subset (p, S)^n R^+_0$$
for all $n \in \mathbb{N}$. Let $x = \sum_{m \in \mathbb{Z}} a_m S^m \in \text{LHS}$ with $a_m \in \mathcal{O}$. Then, we have
$|a_m S^{m-n}|_r \leq |p^n| \leq 1$. Hence, $x = S^n \sum_{m \in \mathbb{Z}} a_m S^{m-n} \in S^n \cdot R^+_0$, which
implies the assertion.

(iii) If $f = \sum_{n \in \mathbb{Z}} a_n S^n \in R^+_0$, then $\{ \sum_{n \in \mathbb{Z}} a_n S^n \}_{m \in \mathbb{N}} \subset R^+_0$
converges to $f$, which implies the last assertion. Since $R^+_0$ is an open subring
of $R^+_r$, we only have to prove completeness of $R^+_0$. Let $\{ f_m \}_{m \in \mathbb{N}} \subset R^+_0$
be a sequence such that $|f_m|_r \to 0$ as $m \to \infty$. We only have to prove that
the limit $\sum_m f_m$ exists in $R^+_0$ with respect to $| \cdot |_r$. Write $f_m = \sum_{n \in \mathbb{Z}} a_n^{(m)} S^n$
with $a_n^{(m)} \in \mathcal{O}$. For $n \in \mathbb{Z}$, we have
$$|a_n^{(m)}| \leq \frac{|f_m|_r}{|S^n|_r} = |p|^{-nr} |f_m|_r,$$
hence, $|a_n^{(m)}| \to 0$ as $m \to \infty$. Moreover, $a_n := \sum_{m \in \mathbb{N}} a_n^{(m)} \in \mathcal{O}$ converges
to 0 as $n \to -\infty$. Hence, the formal Laurent series $f := \sum_{n \in \mathbb{Z}} a_n S^n$ belongs
to $\mathcal{O}(\{S\})$. Since
$$|a_n S^n|_r \leq \sup_{m \in \mathbb{N}} |a_n^{(m)} S^n|_r \leq \sup_{m \in \mathbb{N}} |f_m|_r \leq 1,$$
we have \( f \in R_0^{†,r} \). For \( m \in \mathbb{N} \), we have
\[
|f - (f_0 + \cdots + f_m)|_r \leq \sup_n |a_n S^n - (a_n^{(0)} + \cdots + a_n^{(m)}) S^n|_r \\
\leq \sup_{n,l>m} |a_n^{(l)} S^n|_r = \sup_{l>m} \sup_n |a_n^{(l)} S^n|_r \leq \sup_l |f_l|_r
\]
and the last term converges to 0 as \( m \to \infty \), which implies \( f = \sum_m f_m \).

(iv) This follows from (i), (ii) and (iii). \( \square \)

**Definition 3.1.6.** Let \( R^+ (X) \) be the \((p, S)\)-adic Hausdorff completion of \( R^+[X] \). We also define \( R_0^{†,r} (X) \) and \( R^{†,r} (X) \) as the rings of strictly convergent power series over \( R_0^{†,r} \) and \( R^{†,r} \) with respect to \( |\cdot|_r \). We endow \( R_0^{†,r} (X) \) and \( R^{†,r} (X) \) with the topology defined by the norm \( |\cdot|_r \). By Lemma 3.1.5(iii), \( R_0^{†,r} (X) \) and \( R^{†,r} (X) \) are complete. By Lemma 3.1.5(ii), \( R_0^{†,r} (X) \) can be regarded as the \((p, S)\)-adic Hausdorff completion of \( R_0^{†,r}[X] \), hence, \( R_0^{†,r} (X) \) and \( R^{†,r} (X) = R_0^{†,r} (X)[S^{-1}] \) are Noetherian integral domains by Lemma 3.1.5(iv). Also, we may view \( R^+ (X) \) as a subring of \( R_0^{†,r} (X) \).

The following lemma seems to be used implicitly in [Xiao 2010, §1].

**Lemma 3.1.7.** The canonical map \( R^+ (X) \to R_0^{†,r} (X) \) is flat.

**Proof (due to Liang Xiao).** We may regard \( R_0^{†,r} (X) \) as the \((p, S)\)-adic Hausdorff completion of \( R^+ (X) \otimes_R R_0^{†,r} \). Since \( \mathcal{R}_0^{†,r} \) is dense in \( R_0^{†,r} \) by Lemma 3.1.5(iii), \( R_0^{†,r} (X) \) can be viewed as the \((p, S)\)-adic Hausdorff completion of \( R^+ (X) \otimes_R \mathcal{R}_0^{†,r} \), which is Noetherian by Lemma 3.1.5(i). Hence, the canonical map
\[
\alpha : R^+ (X) \otimes_R R_0^{†,r} \to R_0^{†,r} (X)
\]
is flat. Since \( \mathcal{R}_0^{†,r}[S^{-1}] = R \) and \( R_0^{†,r} (X)[S^{-1}] = R^{†,r} (X) \), the canonical map \( \alpha[S^{-1}] \) is also flat, which implies the assertion. \( \square \)

Next, we consider prime ideals corresponding to good “points” of the open unit disc \( R^+ = \mathcal{O}[S] \).

**Definition 3.1.8.** An Eisenstein polynomial in \( R^+ \) is a polynomial in \( \mathcal{O}[S] \) of the form \( P(S) = S^e + a_{e-1}S^{e-1} + \cdots + a_0 \) with \( a_i \in \mathcal{O} \) such that \( p \mid a_i \) for all \( i \) and \( p^2 \not\mid a_0 \). We call \( p \in \text{Spec}(R^+) \) an Eisenstein prime ideal if \( p \) is generated by an Eisenstein polynomial \( P(S) \). Then, we put \( \text{deg} (p) := e \) if \( e \neq 0 \) and \( \text{deg} (p) := \infty \) if \( e = 0 \). Note that we may regard \( \kappa (p) := R/pR \) as a complete discrete valuation field with integer ring \( R^+ / pR^+ \). We denote by \( \pi_p \in \mathcal{O}_{\kappa (p)} \), the image of \( S \), which is a uniformizer of \( \mathcal{O}_{\kappa (p)} \). Note that \( \text{deg} (p) < \infty \) if and only if the characteristic of \( R/p \) is zero. For simplicity, we write \( \kappa (p) \) and \( S \) instead of \( \kappa ((p)) \) and \( \pi_{\kappa ((p))} \).
Lemma 3.1.9. Let $p$ and $q$ be Eisenstein prime ideals of $R^+$. If
\[ \inf (v_{k(p)}(x \mod p), v_{k(q)}(x \mod q)) < \inf (\deg p, \deg q), \]
for $x \in R^+$, then we have $v_{k(p)}(x \mod p) = v_{k(q)}(x \mod q)$.

Proof. Let $x \in R^+$ and $i \in \mathbb{N}$ such that $0 \leq i < \deg p$. Then, we have the following equivalences:
\[
\begin{align*}
v_{k(p)}(x \mod p) = i & \iff x \in (p, S^i) \setminus (p, S^{i+1}) \\
& \iff x \in (p, S^i) \setminus (p, S^{i+1}) \iff v_{k(p)}(x \mod p) = i,
\end{align*}
\]
where the second equivalence follows from the fact $(p, S^i) = (p, S^i)$, and the other equivalences follow from the definitions. By replacing $q$ by $p$, we obtain similar equivalences. As a result, $v_{k(p)}(x \mod p) = i \iff v_{k(q)}(x \mod q) = i$ for $x \in R^+$ and $i < \inf (\deg(p), \deg(q))$, which implies the assertion. \qed

The ring $R^{\dagger, r}(X)$ can be considered as a family of Tate algebras:

Lemma 3.1.10. Let $p$ be an Eisenstein prime ideal of $R^+$ with $e = \deg(p)$. Let $r \in \mathbb{Q}_{>0}$ satisfy $1/e \leq r$. Then, there exists a canonical isomorphism
\[
R^{\dagger, r}(X)/pR^{\dagger, r}(X) \simeq \kappa(p)(X).
\]
In particular, $pR^{\dagger, r} \neq R^{\dagger, r}$.

Proof. We will briefly recall a result in [Lazard 1962]. Let $F$ be a complete discrete valuation field of mixed characteristic $(0, p)$. Recall that $L_F[0, r]$ is the ring of Laurent series with variable $S$ and coefficients in $F$, which converge in the annulus $|p|^r \leq |S| < 1$, see [Lazard 1962, §1.3]. For $r' \in \mathbb{Q}_{>0}$, a polynomial $P \in F[S]$ is said to be $r'$-extremal if all zeroes $x$ of $P$ in $F^{\alg}$ satisfy $v(x) = r'$, see [Lazard 1962, §2.7]. Let $r' \leq r$ be a positive rational number and $P \in F[S]$ an $r'$-extremal polynomial. Then, for $f \in L_F[0, r]$, there exist a unique $g \in L_F[0, r]$ and a unique polynomial $Q \in F[S]$ of degree less than $\deg P$ such that $f = Pg + Q$, which is a special case of [Lazard 1962, Lemme 2]. Note that if $f \in F[S]$ with $\deg(f) < \deg(P)$, then we have $g = 0$ and $Q = f$ by the uniqueness. In particular, the canonical map $\delta : F[S]/P \cdot F[S] \rightarrow L_F[0, r]/P \cdot L_F[0, r]$ is an isomorphism.

We prove the assertion. We can easily reduce to the case $X = \phi$. That is, we only have to prove that the canonical map
\[
R^{\dagger, r}/pR^{\dagger, r} \rightarrow \kappa(p)
\]
is an isomorphism. The assertion is trivial when $p = (p)$. Hence, we may assume $p \neq (p)$. Since $p$ is invertible in $\kappa(p)$, $p$ is also invertible in $R^{\dagger, r}/pR^{\dagger, r}$. Hence, we have $R^{\dagger, r}/pR^{\dagger, r} = R^{\dagger, r}[1/p]/pR^{\dagger, r}[1/p]$. Note that $R^{\dagger, r}[1/p]$ coincides, by definition, with $L_F[0, r]$ with $F := \text{Frac}(\mathcal{O})$. Let $P \in \mathcal{O}[S]$ be an Eisenstein
polynomial which generates \( p \). Then, \( P \) is 1/e-extremal by a property of Eisenstein polynomials. Hence, the assertion follows from the isomorphisms

\[
L_F[0, r]/pL_F[0, r] \cong F[S]/P \cdot F[S] \\
\cong (\mathcal{O}[S]/P \cdot \mathcal{O}[S])[1/p] \cong (R^+/p)[1/p] = \kappa(p).
\]

Here, the first isomorphism is Lazard’s \( \delta \), with \( r' = 1/e \).

3.2. Gröbner basis argument over complete regular local rings. In this subsection, we will develop a basic theory of Gröbner bases over complete regular local rings \( R \), which generalizing that over fields. This is done in [Xiao 2010, §1.1], when \( R \) is a 1-dimensional complete regular local ring of characteristic \( p \). We assume knowledge of the classical theory of Gröbner bases over fields; our basic reference is [Cox et al. 1997].

Recall that the classical theory of Gröbner bases on \( F[X] \) for a field \( F \) can be regarded as a multi-variable version of the Euclidean division algorithm of the 1-variable polynomial ring \( F[X] \). To obtain an appropriate division algorithm in \( F[X] \), we need to fix a “monomial order” on \( F[X] \) in order to define a leading term, which is the analogue of the naïve degree function in the 1-variable case. Hence, we should first define a notion of leading terms over the ring of convergent power series.

**Definition 3.2.1.** A monomial order \( \succeq \) on a commutative monoid \( (M, +) \) is an well-order such that if \( \alpha \succeq \beta \), then \( \alpha + \gamma \succeq \beta + \gamma \). When \( \alpha \succeq \beta \) and \( \alpha \neq \beta \), we write \( \alpha > \beta \).

In the following, we restrict to the case where \( M \) is isomorphic to \( \mathbb{N}^d \). Moreover, the reader may assume that \( > \) is a lexicographic order; the lexicographic order \( \succeq_{\text{lex}} \) on \( \mathbb{N}^d \) is defined by \( (a_1, \ldots, a_i) >_{\text{lex}} (a'_1, \ldots, a'_i) \) if \( a_1 = a'_1, \ldots, a_i = a'_i, a_{i+1} > a'_{i+1} \). A lexicographic order is a monomial order, see [Cox et al. 1997, §2.2, Proposition 4].

For convenience, we define a monoid \( M \cup \{\infty\} \) by \( \alpha + \infty = \infty \) for any \( \alpha \in M \cup \{\infty\} \). We extend any monomial order \( \succeq \) on \( M \) to \( M \cup \{\infty\} \) by \( \infty > \alpha \) for any \( \alpha \in M \).

**Construction 3.2.2.** Let \( R \) be a complete regular local ring of Krull dimension \( d \) with fixed regular system of parameters \( \{s_1, \ldots, s_d\} \). We put \( R_i := R/(s_1, \ldots, s_i)R \), which is also a regular local ring. We denote the image of \( s_{i+1}, \ldots, s_d \) in \( R_i \) by \( s_{i+1}, \ldots, s_d \) again and we regard these as a fixed regular system of parameters. Let \( v_{s_i} : R_i \to \mathbb{N} \cup \{\infty\} \) be the multiplicative valuation associated to the divisor \( s_i = 0 \). For a nonzero \( f \in R \) and \( 0 \leq i \leq d \), we define a nonzero \( f^{(i)} \in R_i \) inductively as follows.

We put \( f^{(0)} := f \), and define \( f^{(i+1)} \) as the image of \( f^{(i)}/s_i^{v_{s_i}(f^{(i)})} \) in \( R_{i+1} \), which is nonzero by definition. We put \( v_R(f) := (v_{s_1}(f^{(0)}), v_{s_2}(f^{(1)}), \ldots, v_{s_d}(f^{(d-1)})) \in \mathbb{N}^d \) and \( v_R(0) := \infty \). Thus, we obtain a map \( v_R : R \to \mathbb{N}^d \cup \{\infty\} \). We also apply this
construction to each \( R_i \). Note that we have a formula
\[
\overline{v}_R(f) = (v_{s_1}(f), \overline{v}_{R_1}(f^{(1)})),
\]
(1)
Also, note that \( \overline{v}_R \) is multiplicative, i.e., \( \overline{v}_R(fg) = \overline{v}_R(f) + \overline{v}_R(g) \), which follows by induction on \( d \) and by using the formula.

Let \( R\langle X \rangle \) be the \( m_R \)-adic Hausdorff completion of \( R[X] \). We fix a monomial order \( \succeq \) on \( X^N \cong \mathbb{N}^d \). For any nonzero \( f = \sum_n a_n X^n \in R\langle X \rangle \) with \( a_n \in R \), we define \( v_R(f) := \inf_{\succeq_{\text{lex}}} v_R(a_n) \), where \( \succeq_{\text{lex}} \) is the lexicographic order on \( \mathbb{N}^d \), and \( \deg_E(f) := \inf_{\succeq} \{ n \in \mathbb{N}^d ; \ v_R(a_n) = v_R(f) \} \). We put \( \deg_E(0) := \infty \). Note that when \( f \neq 0 \), we have a formula
\[
\deg_E(f) = \deg_R(f^{(0)}) = \deg_R(f^{(1)}) = \ldots = \deg_R(f^{(d)}),
\]
(2)
which follows from (1). Also, note that \( \deg_E \) is multiplicative. Indeed, formula (2) allows us to reduce to the case where \( R \) is a field; here \( \deg_E \) is multiplicative by [Cox et al. 1997, Chapter 2, Lemma 8]. Thus, we obtain a multiplicative map
\[
\overline{v}_R \times \deg_E : R\langle X \rangle \to (\mathbb{N}^d \times \mathbb{N}^d) \cup \{ \infty \},
\]
where \( \infty \) in the RHS denotes \( (\infty, \infty) \). We endow \( \mathbb{N}^d \times \mathbb{N}^d \) with a total order \( \succeq \) by
\[
(a, n) \succeq (a', n') \text{ if } a \leq a' \text{ or } a = a' \text{ and } n \geq n'
\]
and extend it to \( (\mathbb{N}^d \times \mathbb{N}^d) \cup \{ \infty \} \) as in Definition 3.2.1. Note that this order is an extension of the fixed order on \( \mathbb{N}^d = \{ 0 \} \times \ldots \times \{ 0 \} \times \mathbb{N}^d \). As in the classical notation, we also define
\[
LT_R(f) := \overline{v}_R(f) X^{\deg_E(f)} \quad \text{for } f \neq 0, \quad LT_R(0) := 0,
\]
where \( s = (s_1, \ldots, s_d) \). Note that \( LT_R \) is also multiplicative by the multiplicativities of \( \overline{v}_R \) and \( \deg_E \). We also have the formula
\[
LT_R(f) \equiv \overline{LT}_{R_i}(f \mod (s_1, \ldots, s_i)) \mod (s_1, \ldots, s_i), \quad \forall f \in R\langle X \rangle.
\]
(3)
Indeed, if \( s_i \mid f^{(i-1)} \) for some \( i \), then both sides are zero. If \( s_i \nmid f^{(i-1)} \) for all \( i \), then the formula follows from (1) and (2). The map \( LT_R \) takes values in the subset \( s^{\mathbb{N}} \mathbb{N} \cup \{ 0 \} \) of \( R\langle X \rangle \). We identify \( s^{\mathbb{N}} \mathbb{N} \cup \{ 0 \} \) with \( (\mathbb{N}^d \times \mathbb{N}^d) \cup \{ \infty \} \) as a monoid and consider the total order \( \succeq \) on \( s^{\mathbb{N}} \mathbb{N} \cup \{ 0 \} \).

When \( R \) is a field, the above definition coincides with the classical definition as in [Cox et al. 1997, §2].

**Remark 3.2.3.** \( LT \) stands for “leading term” with respect to a given monomial order in the classical case \( d = 0 \). To define an appropriate \( LT \) in the case \( d > 0 \), we should consider a suitable order on the coefficient ring \( R \), which is defined by using an ordered regular system of parameters as above. Our definition is compatible with
dévissage, namely, compatible with parameter-reducing maps $R \rightarrow R_1 \rightarrow \cdots \rightarrow R_d$. This property enables us to reduce everything about Gröbner bases to the classical case by assuming a certain “flatness” as we will see below.

In the rest of this subsection, let the notation be as in Construction 3.2.2. In particular, we fix a monomial order $\succeq$ on $\mathbb{X}^{|n|}$.

**Definition 3.2.4.** For an ideal of $R\langle X \rangle$, we denote by $LT_R(I)$ the ideal of $R\langle X \rangle$ generated by $\{LT_R(f); f \in I\}$. Assume that $R\langle X \rangle/I$ is $R$-flat. We say that $f_1, \ldots, f_s \in I$ form a Gröbner basis if $(LT_R(f_1), \ldots, LT_R(f_s)) = LT_R(I)$. Note that a Gröbner basis always exists since $R\langle X \rangle$ is Noetherian.

Note that for monomials $f, f_1, \ldots, f_s \in R\langle X \rangle$, we have $f \in (f_1, \ldots, f_s)$ if and only if $f$ is divisible by some $f_i$. Indeed, any term of $g \in (f_1, \ldots, f_s)$ is divisible by some $f_i$, which implies the necessity.

**Notation 3.2.5.** Let $I$ be an ideal of $R\langle X \rangle$ such that $R\langle X \rangle/I$ is $R$-flat. We write $I_i := I/(s_1, \ldots, s_i)I$. We may identify $R\langle X \rangle \otimes_R R_i$ and $I \otimes_R R_i$ with $R_i\langle X \rangle$ and $I_i$, respectively. Note that $R_i\langle X \rangle/I_i$ is $R_i$-flat.

**Lemma 3.2.6.** Let $I$ be an ideal of $R\langle X \rangle$ such that $R\langle X \rangle/I$ is $R$-flat. The following are equivalent for $f_1, \ldots, f_s \in I$:

(i) $f_1, \ldots, f_s$ form a Gröbner basis of $I$.

(ii) The images of $f_1, \ldots, f_s$ form a Gröbner basis of $I_i \subset R_i\langle X \rangle$ for some $i$.

Moreover, when $f_1, \ldots, f_s$ is a Gröbner basis of $I$, $f_1, \ldots, f_s$ generate $I$.

**Proof.** We prove the first assertion by induction on $d = \dim R$. When $d = 0$, there is nothing to prove. Assume the assertion is true for dimension $< d$. By the induction hypothesis, we only have to prove the equivalence between (i) and (ii) with $i = 1$.

We first prove (i) $\Rightarrow$ (ii). Let $\bar{f} \in I_1$ be a nonzero element and $f \in I$ a lift of $\bar{f}$. By assumption, we have $LT_R(f_j) \mid LT_R(f)$ for some $j$. Then, $LT_{R_1}(f_j \mod s_1)$ divides $LT_{R_1}(\bar{f})$ by formula (3).

We prove (ii) $\Rightarrow$ (i). Let $f \in I$ be a nonzero element. By Lemma 3.1.3, we have $f^{(1)} = f/s_1v_{s_1}(f) \in I$. By assumption, we have $LT_{R_1}(f_j \mod s_1) \mid LT_{R_1}(f^{(1)} \mod s_1)$ for some $j$. Since $LT_{R_1}(f^{(1)} \mod s_1) \neq 0$, $s_1$ does not divides $f_j$, i.e., $v_{s_1}(f_j) = 0$. By formulas (1) and (2), $LT_{R_1}(f_j)$ divides $LT_{R_1}(f^{(1)})$, and hence divides $LT_R(f)$, which implies the assertion.

We prove the last assertion. By Nakayama’s lemma and (ii) with $i = d$, the assertion is reduced to the case where $R$ is a field. In this case, the assertion follows from [Cox et al. 1997, §2.5, Corollary 6].

**Remark 3.2.7.** By Lemma 3.2.6, $f_1, \ldots, f_s$ is a Gröbner basis of $I$ if and only if $f_1 \mod m_R, \ldots, f_s \mod m_R$ is a Gröbner basis of $I/m_R I$. In particular, the definition of Gröbner basis does not depend on the choice of a regular system of parameters $\{s_1, \ldots, s_d\}$. 

We can generalize the classical division algorithm, which is a basic tool in many Gröbner basis arguments.

**Proposition 3.2.8** (division algorithm). Let \( I \) be an ideal of \( R(\mathbf{X}) \) such that \( R(\mathbf{X})/I \) is \( R \)-flat. Let \( f_1, \ldots, f_s \in I \) be a Gröbner basis of \( I \). Then, for any nonzero \( f \in R(\mathbf{X}) \), there exist \( a_i, r \in R(\mathbf{X}) \) for all \( i \) such that

\[
f = \sum_{1 \leq i \leq s} a_i f_i + r,
\]

with \( \text{LT}_R(f) \geq \text{LT}_R(a_i f_i) \) if \( a_i f_i \neq 0 \), and any nonzero term of \( r \) is not divisible by any \( \sum v_{\deg R(f_i)} \). Moreover, such \( r \) is uniquely determined (but the \( a_i \)'s are not), and \( f \in I \) if and only if \( r = 0 \).

**Proof.** When \( d = 0 \), i.e., \( R \) is a field, the assertion is well known (see [Cox et al. 1997, §2.6, Proposition 1] for example). We prove the first assertion by induction on \( d = \dim R \). Assume that the assertion is true for dimension \( < d \). We may assume \( s_1 \nmid f_i \) for all \( i \). Indeed, by Lemma 3.2.6, the set \( \{f_i; s_1 \nmid f_i\} \) forms a Gröbner basis of \( I \). Moreover, any \( \text{LT}_R(f_i) \) is divisible by some \( \text{LT}_R(f_i) \) with \( s_1 \mid f_i \). Therefore, if we can write \( f = \sum_{i:s_i \mid f_i} a_i f_i + r \) with respect to \( \{f_i; s_1 \nmid f_i\} \), then we can write \( f \) in the same way with respect to \( f_1, \ldots, f_s \). First, we construct \( g_n \in R(\mathbf{X}) \) by induction on \( n \in \mathbb{N} \). For \( h \in R(\mathbf{X}) \), let \( h \) be its image in \( R_1(\mathbf{X}) \). Put \( g_0 := f \). Assume that \( g_n \) has been defined. Put \( g'_n := g_n/s_1^{v_{s_1}(g_n)} \). By applying the induction hypothesis to \( I_1 = (f_1, \ldots, f_s) \), we have \( \tilde{a}_{i,n}, \tilde{r}_n \in R_1(\mathbf{X}) \) with

\[
\tilde{g}_n = \sum_i \tilde{a}_{i,n} \tilde{f}_i + \tilde{r}_n,
\]

such that no nonzero terms of \( \tilde{r}_n \) are divisible by any \( \sum v_{\deg R(f_i)} \), and such that \( \text{LT}_{R_1}(\tilde{g}_n) \geq \text{LT}_{R_1}(a_i \tilde{f}_i) \) if \( a_i \tilde{f}_i \neq 0 \). We choose lifts \( a_{i,n} \) and \( r_n \) in \( R(\mathbf{X}) \) of \( \tilde{a}_{i,n} \) and \( \tilde{r}_n \), respectively, such that no nonzero terms of \( a_{i,n} \) and \( r_n \) are divisible by \( s_1 \). Then, we put \( g_{n+1} := g_n - s_1^{v_{s_1}(g_n)} (\sum_i a_{i,n} f_i + r_n) \). By construction, we have \( v_{s_1}(g_{n+1}) > v_{s_1}(g_n) \), hence, \( \{g_n\} \) converges \( s_1 \)-adically to zero. Moreover, \( a_i := \sum_n s_1^{v_{s_1}(g_n)} a_{i,n} \) and \( r := \sum_n s_1^{v_{s_1}(g_n)} r_n \) converge \( s_1 \)-adically and we have \( f = \sum_i a_i f_i + r \). We will check that \( a_i \) and \( r \) satisfy the condition. Since \( s_1 \nmid f_i \) and since no nonzero term of \( r_n \) is divisible by \( s_1 \), no nonzero term of \( r \) is divisible by \( \sum v_{\deg R(f_i)} \) for all \( i \). We have \( v_{s_1}(f_i) = 0 \) by assumption and \( v_{s_1}(a_i) \geq v_{s_1}(f) \) by definition. If \( v_{s_1}(a_i) > v_{s_1}(f) \), then we have \( v_{s_1}(f_i) \leq v_{s_1}(a_i f_i) \), hence, \( \text{LT}_R(f) \geq \text{LT}_R(a_i f_i) \). If \( v_{s_1}(a_i) = v_{s_1}(f) \), then we have \( a_i^{(0)} \equiv a_i \mod s_1 \), hence, \( v_{s_1}(f) \leq v_{s_1}(a_i f_i) \) by formulas (1), (2) and the choice of \( \tilde{a}_{i,0} \). In particular, \( \text{LT}_R(f) \geq \text{LT}_R(a_i f_i) \). Thus, we obtain the first assertion.

We prove the rest of the assertion. We first prove the uniqueness of \( r \). Let \( f = \sum a_i f_i + r = \sum a'_i f_i + r' \) be expressions satisfying the conditions. Then, we
have $r - r' \in I$, hence, $\text{LT}_R(r - r) \in \text{LT}_R(I)$. Therefore, $r - r'$ is divisible by $\text{LT}_R(f_i)$ for some $i$. Since no nonzero term of $r - r'$ is divisible by any $\text{LT}_R(f_i)$, we must have $r = r'$. We prove the equivalence $r = 0 \Leftrightarrow f \in I$. We only have to prove the necessity. Since $r \in I$, we have $\text{LT}_R(r) \in \text{LT}_R(I)$. Hence, $\text{LT}_R(r)$ is divisible by $\text{LT}_R(f_i)$ for some $i$. Since all nonzero terms of $r$ are divisible by $X^{\deg(f_i)}$, we must have $r = 0$.

**Definition 3.2.9.** We call the above expression $f = \sum a_i f_i + r$ a standard expression (of $f$) and call $r$ the remainder of $f$ (with respect to $f_1, \ldots, f_s$). Note that standard expressions are additive and compatible with scalar multiplications, that is, if $f = \sum_i a_i f_i + r$ and $g = \sum_i a_i' f_i + r'$ are standard expressions, then $f + g = \sum_i (a_i + a_i') f_i + r + r'$ is also a standard expression of $f + g$, and $\lambda f = \sum_i \lambda a_i f_i + \lambda r$ is a standard expression of $\lambda f$ for $\lambda \in R$ by formulas (1) and (2). The remainder of $f$ depends only on the class $f \mod I$ by Proposition 3.2.8 and the above additive property. Therefore, we may call $r$ the remainder of $f \mod I$.

As in the classical case, we have the following.

**Lemma 3.2.10.** Let $I$ be an ideal of $R\langle X \rangle$ such that $R\langle X \rangle/I$ is $R$-flat. Let $f_1, \ldots, f_s \in I$ be a Gröbner basis of $I$. Let $f \in R\langle X \rangle$ be a nonzero element. For $r \in R\langle X \rangle$, the following are equivalent:

(i) $r$ is the remainder of $f$.

(ii) $f - r \in I$ and no nonzero term of $r$ is divisible by $X^{\deg(f_i)}$ for all $i$.

**Proof.** Since the assertion (i) $\Rightarrow$ (ii) is trivial, we prove the converse. By applying the division algorithm to $f - r$, we have $f - r = \sum a_i f_i$ such that $\text{LT}_R(f) \geq \text{LT}_R(a_i f_i)$ if $a_i f_i \neq 0$. This means exactly that $r$ is the remainder of $f$. 

**Corollary 3.2.11.** Let the notation be as in Lemma 3.2.10. We regard $f_1 \mod s_1, \ldots, f_s \mod s_1$ as a Gröbner basis of $I_1$. For $f \in R\langle X \rangle$ with $s_1 \nmid f$, denote by $r$ and $r'$ the remainders of $f$ and $f \mod s_1$, respectively. Then, we have $r \mod s_1 \equiv r'$.

Finally, we give a concrete example of a Gröbner basis, which will appear in Section 3.5.

**Proposition 3.2.12.** Let $I = (f_1, \ldots, f_s) \subset R\langle X \rangle$ be an ideal. Assume that there exists relatively prime monic monomials $T_1, \ldots, T_s$ and units $u_1, \ldots, u_s \in R^\times$ such that $\text{LT}_R(f_i) = u_i T_i$ for $1 \leq i \leq s$. Then, we have the following:

(i) $R\langle X \rangle/I$ is $R$-flat.

(ii) $f_1, \ldots, f_s$ is a Gröbner basis of $I$.

(iii) $f_1, \ldots, f_s$ is a regular sequence in $R\langle X \rangle$.  Differential modules associated to de Rham representations
Proof. We may assume that \( \text{LT}_R(f_1), \ldots, \text{LT}_R(f_s) \) are relatively prime monic monomials by replacing \( f_i \) by \( f_i/u_i \). We first note that in the case of \( d = 0 \), the assertion is basic, since condition (i) is automatically satisfied. Condition (ii) directly follows from [Cox et al. 1997, §2.9, Theorem 3 and Proposition 4]. Condition (iii) follows from [Eisenbud 1995, Proposition 15.15] with \( F = S = R[X] \) and \( M = 0 \), \( h_j = f_j \), where \( F, S \) and \( M, h_j \)'s are as in the reference. We prove the assertion by induction on \( s \). In the case of \( s = 1 \), we have only to prove condition (i). We proceed by induction on \( d \). By the local criteria of flatness and the induction hypothesis, we only have to prove that the multiplication by \( s_1 \) on \( R(X)/I \) is injective. Let \( f \in R(X) \) such that \( s_1f \in I \). Write \( s_1f = f_1h \) for some \( h \in R(X) \). By taking \( u_{s_1} \), we have \( s_1 \mid h \) since \( s_1 \nmid f_1 \). This implies \( f_1 \mid f \), i.e., \( f \in I \). This finishes the case \( s = 1 \). We assume that the assertion is true when the cardinality of \( f_i \)'s is \( < s \). We proceed by induction on \( d \). The case \( d = 0 \) can be done as above. Assume that the assertion is true for dimension \( < d \). For \( h \in R(X) \), denote by \( \overline{h} \) its image in \( R_1(X) \). By assumption, \( s_1 \nmid f_i \) for all \( i \), hence, we can apply the induction hypothesis to \( \overline{f_1}, \ldots, \overline{f_s} \in I_1 := (\overline{f_1}, \ldots, \overline{f_s}) \subset R_1(X) \) by formula (3). Hence, \( R_1(X)/I_1 \) is \( R_1 \)-flat, \( \overline{f_1}, \ldots, \overline{f_s} \) are a Gröbner basis of \( I_1 \), and \( \overline{f}_1, \ldots, \overline{f}_s \) is a regular sequence in \( R_1(X) \). Condition (ii) follows from Lemma 3.2.6. Next, we check condition (i). By the local criteria of flatness, we only have to prove that multiplication by \( s_1 \) on \( R(X)/I \) is injective. It suffices to prove \( I \cap s_1 \cdot R(X) \subset s_1I \). Denote by \( C_\bullet \) and \( \overline{C}_\bullet \) Koszul complexes for \( \{f_1, \ldots, f_s\} \) and \( \{\overline{f}_1, \ldots, \overline{f}_s\} \) [Matsumura 1980, 18.D]. Then, we have \( \overline{C}_i = C_i/s_1C_i \) for \( i \geq 1 \) by definition, and \( \overline{C}_\bullet \) is exact since \( \overline{f}_1, \ldots, \overline{f}_s \) is a regular sequence. We also have a morphism of complexes \( C_\bullet \rightarrow \overline{C}_\bullet \), whose first few terms are

\[
\begin{array}{ccccccc}
\vdots & \rightarrow & C_2 & \xrightarrow{d_2} & C_1 & \xrightarrow{d_1} & I & \rightarrow & 0 \\
\downarrow & & \downarrow & & \downarrow & & \downarrow & & \\
\vdots & \rightarrow & \overline{C}_2 & \xrightarrow{\overline{d}_2} & \overline{C}_1 & \xrightarrow{\overline{d}_1} & \overline{I} & \rightarrow & 0
\end{array}
\]

Let \( f \in I \cap s_1 \cdot R(X) \). Then, there exists \( a \in C_1 \) such that \( d_1(a) = f \). Since \( \overline{d}_1(\overline{a}) \equiv 0 \) mod \( s_1 \), there exists \( \overline{b} \in C_2 \) with \( \overline{d}_2(\overline{b}) = \overline{a} \). Let \( b \in C_2 \) be a lift of \( \overline{b} \). Then, there exists \( a' \in C_1 \) such that \( a - d_2(b) = s_1a' \). Therefore, we have \( f = d_1(a - d_2(b)) = s_1d_1(a') \in s_1I \). Thus, condition (i) is proved. Finally, we check condition (iii). We only have to prove that if \( f, f_1, \ldots, f_{i-1} \) for some \( f \in R(X) \) and \( 1 \leq i \leq s \), then we have \( f \in (f_1, \ldots, f_{i-1}) \). Note that \( f_1, \ldots, f_{i-1} \) is a Gröbner basis of \( (f_1, \ldots, f_{i-1}) \) by the induction hypothesis. Let \( f = \sum_{1 \leq j < i} a_j f_j + r \) be a standard expression of \( f \) with respect to \( f_1, \ldots, f_{i-1} \). It suffices to prove that \( r = 0 \). We suppose the contrary and deduce a contradiction. No nonzero term of \( r \) is divisible by \( \text{LT}_R(f_j) \) for any \( 1 \leq j < i \); in particular, we have \( \text{LT}_R(f_j) \nmid \text{LT}_R(r) \). By assumption, \( f_i f = f_i\left(\sum_{1 \leq j < i} a_j f_j \right) + f_i r \in (f_1, \ldots, f_{i-1}) \). We therefore have
\( f_i r \in (f_1, \ldots, f_{i-1}) \). In particular, there exists \( 1 \leq j < i \) with \( \text{LT}_R(f_j) | \text{LT}_R(f_i r) \). Since \( \text{LT}_R(f_i) \) and \( \text{LT}_R(f_j) \) are relatively prime, we have \( \text{LT}_R(f_j) | \text{LT}_R(r) \), which is a contradiction. Thus, we obtain assertion (iii).

A remarkable feature of the remainder is the compatibility with quotient norms:

**Lemma 3.2.13.** Let \( I \) be an ideal of \( R(X) \) such that \( R(X)/I \) is \( R \)-flat. Let \( f_1, \ldots, f_s \in I \) be a Gröbner basis of \( I \). Let \( |\cdot|: R \to \mathbb{R}_{\geq 0} \) be any nonarchimedean norm satisfying \( |R| \leq 1 \) and \( |m_R| < 1 \). We extend \( |\cdot| \) to a norm on \( R(X) \) by \( |\sum_n a_n X^n| := \sup_n |a_n| < \infty \). If we denote by \( |\cdot|_{qt}: R(X)/I \to \mathbb{R}_{\geq 0} \) the quotient norm of \( |\cdot| \), then the remainder \( r \) of \( f \in R(X) \) achieves the quotient norm of \( f \mod I \), i.e.,

\[
|r| = |f \mod I|_{qt}.
\]

**Proof.** Let \( f = \sum \lambda_n X^n \) with \( \lambda_n \in R \). Let \( X^n = \sum a_{n,i} f_i + r_n \) be a standard expression of \( X^n \). Let \( a_i := \sum_n \lambda_n a_{n,i} \) and \( r := \sum_n \lambda_n r_n \), which converge since \( \lambda_n \to 0 \) as \( |n| \to \infty \). Then, \( f = \sum a_i f_i + r \) is a standard expression of \( f \) by Lemma 3.2.10. We have \( |a_i f_i| \leq |a_i| \leq \sup_n |\lambda_n a_{n,i}| \leq \sup_n |\lambda_n| = |f| \). Hence, we have \( |r| \leq |f| \). Since the remainder depends only on the class \( f \mod I \), we have

\[
|f \mod I|_{qt} = \inf_{g \in I} |f + g| \geq |r| \geq |f \mod I|_{qt},
\]

which implies the assertion. \( \square \)

### 3.3. Gröbner basis argument over annuli

In this subsection, we will give an analogue of a Gröbner basis argument over rings of overconvergent power series. We use the notations of Section 3.1 and 3.2 and further use the following notation.

**Notation 3.3.1.** Let \( O, R^+ \), and \( R \) be as in Notation 3.1.4. Fix \( \{p, S\} \) as a regular system of parameters of \( R^+ \). Let \( I \subset R^+(X) \) be an ideal such that \( R^+(X)/I \) is \( R^+ \)-flat. For \( r \in \mathbb{Q}_{\geq 0} \), we give \( R^{+,r}(X) \) the topology defined by the norm \( |\cdot|_r \), and write

\[
A := R^+(X)/I, \quad I^{+,r} := I \otimes_{R(X)} R^{+,r}(X), \quad A^{+,r} := A \otimes_{R(X)} R^{+,r}(X).
\]

(When \( I = 0 \), \( R^{+,r}(X) \) is denoted by \( R(X)^{+,r} \) in this notation. However, we use this notation for simplicity.) Since \( R^+(X) \to R^{+,r}(X) \) is flat (Lemma 3.1.7), we may identify \( I^{+,r} \) and \( A^{+,r} \) with \( I \cdot R^{+,r}(X) \) and \( R^{+,r}(X)/I^{+,r} \). Since \( R^+ \) is an integral domain, \( A \) and hence, \( A^{+,r} \) are \( R^+ \)-torsion free by flatness.

Let \( |\cdot|_{r,qt} : A^{+,r} \to \mathbb{R}_{\geq 0} \) be the quotient norm of \( |\cdot|_r \). Note that \( A^{+,r} \) is complete with respect to \( |\cdot|_{r,qt} \) by [Bosch et al. 1984, Section 1.1.7, Proposition 3].

**Lemma 3.3.2** (cf. [Xiao 2010, Lemma 1.1.22]). Let \( f_1, \ldots, f_s \in I \) be a Gröbner basis of \( I \). For \( f \in R^{+,r}(X) \), there exists a unique \( \tau \in R^{+,r}(X) \) such that \( f - \tau \in I^{+,r} \) and no nonzero term of \( \tau \) is divisible by \( X^{\deg_k(f)} \). Moreover, we have \( |\tau|_r = |f|_{r,qt} \) for \( r' \in \mathbb{Q} \cap (0, r] \), and \( \tau = 0 \) if and only if \( f \in I^{+,r} \). We call \( \tau \) the remainder of \( f \) (with respect to \( f_1, \ldots, f_s \)).
Proof. We first construct $r$. Let $f = \sum \lambda_n X^n \in R^{t,r}(X)$ with $\lambda_n \in R^{t,r}$. Let

$$X^n = \sum_i a_{i,n} f_i + r_n$$

be the standard expression of $X^n$ in $R^+(X)$ with respect to $f_1, \ldots, f_s$. Since $\lambda_n \to 0$ as $|n| \to \infty$, the series

$$a_i := \sum_n \lambda_n a_{n,i}, \quad r := \sum_n \lambda_n r_n$$

converge in $R^{t,r}(X)$ with respect to the topology defined by $| \cdot |_r$. Then, we have

$$|r|_r \leq \sup_n |\lambda_n r_n|_r \leq \sup_n |\lambda_n|_r = |f|_r. \quad (4)$$

Obviously, no nonzero term of $r$ is divisible by any $X^{\deg_k(f_i)}$ and we have $f - r = \sum_i a_i f_i \in I^{t,r}$.

We prove the uniqueness of $r$. We suppose the contrary and deduce a contradiction. Let $r' \in R^{t,r}(X)$ be an element such that $f - r' \in I^{t,r}$ and such that no nonzero term of $r'$ is divisible by any $X^{\deg_k(f_i)}$. We choose $m \in \mathbb{N}$ such that $\delta := S^m(r - r')$ belongs to $I_0^{t,r} := I \otimes_{R^+(X)} R_0^{t,r}(X)$. If we write $\delta = p^n \delta'$ such that $\delta' \in R_0^{t,r}(X)$ is not divisible by $p$ in $R_0^{t,r}(X)$, then we have $\delta' \in I_0^{t,r}$ by Lemma 3.1.3. We may identify $I_0^{t,r} / pI_0^{t,r}$ with $I/pI$ by Lemma 3.1.10. We write $\tilde{\delta}' := \delta' \mod pI_0^{t,r} \in I/pI$. We also write $R_1^{t,r} := R^+/pR^+$, which is a complete discrete valuation ring with uniformizer $S$. Then, no nonzero term of $\tilde{\delta}'$ is divisible by $X^{\deg_k(f_i \mod p)}$. Hence, $\tilde{\delta}'$ is the remainder of 0 with respect to $f_1 \mod p, \ldots, f_s \mod p$ in $R_1(X)$. By Lemma 3.2.10, $\tilde{\delta}' = 0$, i.e., $\delta' \in \mod pI_0^{t,r}$, contradicting $p \not| \delta'$.

We prove $f = I^{t,r} \iff r = 0$. If $f \in I^{t,r}$, then 0 satisfies the required property for the remainder, and hence $r = 0$ by uniqueness. If $r = 0$, then $f \in I^{t,r}$ by definition.

We prove $|r|_r = |f \mod I^{t,r}|_{r',\text{qt}}$. Let $\alpha \in I^{t,r}$. Since $r$ satisfies the required condition for the remainder of $f + \alpha$, the remainder of $f + \alpha$ is equal to $r$ by uniqueness. In particular, the remainder depends only on the of class $f \mod I^{t,r}$. Hence, the assertion follows from

$$|f \mod I^{t,r}|_{r',\text{qt}} = \inf_{\alpha \in I^{t,r}} |r + \alpha|_r \geq |r|_r \geq |f \mod I^{t,r}|_{r',\text{qt}},$$

where the first equality follows from (4) and the second inequality follows by definition. \hfill \Box

The following is an immediate consequence of the above lemma.

Lemma 3.3.3. Let $f_1, \ldots, f_s$ be a Gröbner basis of $I$. Let $f, g \in R^{t,r}(X)$ and let $r, r'$ be their remainders with respect to $f_1, \ldots, f_s$. Then, we have the following:

(i) The remainder of $f + g$ is equal to $r + r'$. 
(ii) The remainder \( r \) depends only on \( f \mod I^{1,r} \). One may call the remainder of \( f \) the remainder of \( f \mod I^{1,r} \).

(iii) For \( \lambda \in R^{1,r} \), the remainder of \( \lambda f \) is equal to \( \lambda r \). Moreover, if \( f \mod I^{1,r} \) is divisible by \( \lambda \in R^{1,r} \), then \( r \) is also divisible by \( \lambda \).

**Corollary 3.3.4.** Let \( \alpha \in \mathbb{N} \) be a principal ideal. Then, we have \( \bigcap_{n \in \mathbb{N}} \alpha^n \cdot A^{1,r} = 0 \).

**Proof.** Fix a Gröbner basis \( f_1, \ldots, f_s \) of \( I \). Let \( f \in \bigcap_{n \in \mathbb{N}} \alpha^n \cdot A^{1,r} \) and let \( r \) be the remainder of \( f \) with respect to \( f_1, \ldots, f_s \). By Lemma 3.3.3(iii) and the assumption, we have \( r \in \bigcap_{n \in \mathbb{N}} \alpha^n = 0 \).

**Remark 3.3.5.** Using [Kedlaya 2005, Proposition 2.6.5], one can prove that \( R^{1,r} \) is a principal ideal domain. We do not use this fact in this paper.

### 3.4. Continuity of connected components for families of affinoids

In this subsection, we will apply the previous results to prove a continuity of connected components of fibers of families of affinoids.

**Lemma 3.4.1.** Let \( f : R \rightarrow S \) be a morphism of Noetherian rings and let \( \text{Idem}(T) \) denote the set of idempotents of a ring \( T \). If the canonical map \( f^* : \text{Idem}(R) \rightarrow \text{Idem}(S) \) is surjective and \( f^{-1} \cdot \{0\} = \{0\} \), then \( f^* : \pi^\text{Zar}_0(S) \rightarrow \pi^\text{Zar}_0(R) \) is bijective.

**Proof.** We first recall a basic fact on commutative algebras. For a ring \( A \), finite partitions of \( \text{Spec}(A) \) into nonempty open subspaces as a topological space correspond to finite sets of nonzero idempotents \( e_1, \ldots, e_n \) of \( A \) such that \( \sum_i e_i = 1 \) and \( e_i e_j = 0 \) for all \( i \neq j \). Precisely, \( e_1, \ldots, e_n \) correspond to \( \text{Spec}(Ae_1) \sqcup \cdots \sqcup \text{Spec}(Ae_n) \) (for details, see [Bourbaki 1998, Proposition 15, II, §4, no 3]).

Decompose \( \text{Spec}(R) \) into connected components and choose the corresponding idempotents \( e_1, \ldots, e_n \) as above. Since the nonzero idempotents \( f(e_1), \ldots, f(e_n) \) satisfy \( \sum_{1 \leq i \leq n} f(e_i) = 1 \) and \( f(e_i) f(e_j) = 0 \) for \( i \neq j \), we obtain a finite partition \( \text{Spec}(S) = \text{Spec}(Sf(e_1)) \sqcup \cdots \sqcup \text{Spec}(Sf(e_n)) \). Hence, we only have to prove that \( \text{Spec}(Sf(e_i)) \) is connected for all \( 1 \leq i \leq n \). Let \( e' \in \text{Idem}(Sf(e_i)) \). By regarding \( e' \) as an element of \( \text{Idem}(S) \), we obtain an \( x \in \text{Spec}(R) \) such that \( e' = f(x) \). Since \( xe_i \in \text{Idem}(Re_i) \) and \( \text{Spec}(Re_i) \) is connected by definition, we either have \( xe_i = 0 \) or \( xe_i = e_i \). Since we have \( e' = e'f(e_i) = f(x)f(e_i) = f(xe_i) \), we either have \( e' = 0 \) or \( e' = f(e_i) \). Hence, \( Sf(e_i) \) has only trivial idempotents, which implies the assertion. \( \square \)

**Notation 3.4.2.** In the remainder of this subsection, we let the notation be as in Notation 3.3.1 and Definition 3.1.8, unless otherwise stated. For an Eisenstein prime ideal \( \mathfrak{p} \) of \( R^+ \), we fix a norm \( | \cdot |_p \) of the complete discrete valuation field \( \kappa(\mathfrak{p}) \) and write

\[
A_{\kappa(\mathfrak{p})} := (A/\mathfrak{p}A)[S^{-1}].
\]
We identify \( R^+(X)/p R^+(X) \) with \( \mathcal{O}_{\kappa(p)}(X) \), and denote the Gauss norm on \( \kappa(p)(X) \) by \( | \cdot |_p \). We also denote the quotient (resp. spectral) norm of \( | \cdot |_p \) on \( A/pA \) and \( A_{\kappa(p)} \) by \( | \cdot |_{p,qt} \) (resp. \( | \cdot |_{p,sp} \)). For simplicity, we also write \( | f \mod I/pI|_{p,qt} \) (resp. \( | f \mod I/pI|_{p,sp} \)) for \( f \in \kappa(p)(X) \).

For \( f = \sum_n a_n X^n \in \mathcal{O}_{\kappa(p)}(X) \) with nonzero \( a_n \in \mathcal{O}_{\kappa(p)} \), let \( \tilde{a}_n \in R^+ \) be a lift of \( a_n \). Then, \( f := \sum_n \tilde{a}_n X^n \in R^+(X) \) is called a minimal lift of \( f \).

We may apply Construction 3.2.2 to \( R = \mathcal{O}_{\kappa(p)}(X) \) and \( s_1 = \pi_p \) with the same monomial order \( \geq \) for \( \mathcal{O}[[S]] \). Let \( f_1, \ldots, f_s \) be a Gröbner basis of \( I \). Then, the images of \( f_i \)'s in \( R^+/mR+[X] \) form a Gröbner basis by Lemma 3.2.6. Hence, the images of \( f_i \)'s in \( \mathcal{O}_{\kappa(p)}(X) \) form a Gröbner basis of \( I/pI \) by Lemma 3.2.6 again. In particular, if \( \bar{r} \) is the remainder of \( f \in R^+(X) \) with respect to \( f_1, \ldots, f_s \), then the image of \( \bar{r} \) in \( \mathcal{O}_{\kappa(p)}(X) \) is the remainder of \( f \mod p \) with respect to \( f_1 \mod p, \ldots, f_s \mod p \).

By using our Gröbner basis argument, Lemma 3.1.9 can be converted into the following form:

**Lemma 3.4.3.** Let \( c \in \mathbb{N} \) and let \( p, q \) be Eisenstein prime ideals of \( R^+ \) such that \( c < \inf (\deg p, \deg q) \). Assume that for \( n \in \mathbb{N} \), we have

\[
|f^n|_{p,qt} \geq |\pi_p|^c |f|^{n}_{p,qt}, \quad \forall f \in A_{\kappa(p)}.
\]

Then, we have

\[
|f^n|_{q,qt} \geq |\pi_q|^c |f|^{n}_{q,qt}, \quad \forall f \in A_{\kappa(q)}.
\]

**Proof.** We fix a Gröbner basis \( f_1, \ldots, f_s \) of \( I \). We may regard the \( f_i \mod p \)'s (resp. \( f_i \mod q \)'s) as a Gröbner basis of \( I/pI \) (resp. \( I/qI \)). To prove the assertion, we must assume that \( f \in A/qA \). Let \( \bar{r} \in \mathcal{O}_{\kappa(q)}(X) \) be the remainder of \( f \). We have \( |f|_{q,qt} = |\bar{r}|_q = |\pi_q|^m \) for some \( m \in \mathbb{N} \). To prove the assertion, we may assume \( |f|_{q,qt} = |\bar{r}|_q = 1 \) by replacing \( f, \bar{r} \) by \( f/\pi_q^m, \bar{r}/\pi_q^m \).

Let \( \tilde{r} \in R^+(X) \) be a minimal lift of \( \bar{r} \) and let \( \tilde{f} \in A \) denote the image of \( \tilde{r} \). Denote by \( \tau_n \in R^+(\hat{X}) \) the remainder of \( \tilde{f}^n \). Then, we have

\[
|\tau_n \mod p| = |\tilde{f}^n \mod p|_{p,qt} \geq |\pi_p|^c |\tilde{f} \mod p|^{n}_{p,qt}
\]

by Lemma 3.2.13 and by assumption. Since \( |\tau|_q = 1 \), the coefficient of some \( X^n \) in \( \tau \) belongs to \( \mathcal{O}_{\kappa(p)} \). Therefore, the coefficient of \( X^n \) in \( \tilde{r} \), hence, in \( \bar{r} \mod p \) is a unit. Therefore, we have

\[
|\tilde{f} \mod p|_{p,qt} = |\tilde{r} \mod p| = 1,
\]

hence, \( |\tau_n \mod p| \geq |\pi_p|^c \). By applying Lemma 3.1.9 to the coefficient \( \lambda \) of \( \tau_n \) that satisfies \( |\lambda \mod p| \geq |\pi_p|^c \), we obtain \( |\tau_n \mod q| \geq |\pi_q|^c \). Since \( \tau_n \mod q \) is the remainder of \( f^n \), we have \( |f^n|_{q,qt} = |\tau_n \mod q| \geq |\pi_q|^c \) by Lemma 3.2.13, which implies the assertion. \( \square \)
The following lemma can be considered as an analogue of Hensel’s lemma.

**Lemma 3.4.4** (cf. [Xiao 2010, Theorem 1.2.11]). Assume that there exists $c \in \mathbb{R}_{\geq 0}$ such that

$$| \cdot |_{p, sp} \geq |\pi_p|^c \cdot |\cdot|_{p, qt} \text{ on } A_{\kappa(p)}.$$

Then, for all $r \in \mathbb{Q}_{>0} \cap \{1/ \deg p, 1/2c\}$, there exists a canonical bijection

$$\pi_0^{zar}(A_{\kappa(p)}) \rightarrow \pi_0^{zar}(A^{\downarrow r}).$$

**Proof.** Replacing $c$ by $\lfloor c \rfloor$, we may assume $c \in \mathbb{N}$. Denote by $\alpha$ the canonical map $\text{Idem}(A^{\downarrow r}) \rightarrow \text{Idem}(A_{\kappa(p)})$. By Lemma 3.4.1, we only have to prove that we have $\alpha^{-1}(\{0\}) = \{0\}$ and that $\alpha$ is surjective. Let $e \in \text{Idem}(A^{\downarrow r})$ satisfy $\alpha(e) = 0$. Then, we have $e \in p \cdot A^{\downarrow r}$. Since $e = e^n$, we have $e \in \bigcap_{n \in \mathbb{N}} p^n \cdot A^{\downarrow r} = 0$ by Corollary 3.3.4, which implies the first assertion. We will prove the surjectivity of $\alpha$. Let $e \in \text{Idem}(A_{\kappa(p)})$. Since $|e|_{p, sp} = 1 \geq |\pi_p|^c |e|_{p, qt}$ by assumption, we have $e \in \pi_p^{-c} A/pA$. Hence, we can choose $e' \in A$ such that $e \equiv S^{-c} e' \mod p$. Put $h_0 := S^{-2c} (e^2 - S^c e') \in A[S^{-1}]$. Since

$$e^2 - S^c e' \equiv (S^c e)^2 - S^c \cdot S^c e \equiv S^{2c} (e^2 - e) \equiv 0 \mod p,$$

we have $h_0 \in pS^{-2c} \cdot A$. Since $p \subset (p, S^c) R^{\downarrow}$, we obtain

$$|h_0|_{r, qt} \leq \sup(|S^c|, |p|)|S|^{-2c} = |p^{1-2cr}| < 1.$$

We define sequences $\{f_n\}$ and $\{h_n\}$ in $A[S^{-1}]$ inductively as follows. Put $f_0 := S^{-c} e'$ and let $h_0$ be as above. For $n \geq 0$, we put

$$f_{n+1} := f_n + h_n - 2h_n f_n, \quad h_{n+1} := f_{n+1}^2 - f_{n+1} \in A[S^{-1}].$$

Note that for $n \in \mathbb{N}$, we have

$$f_{n+1} = -f_n^2 (2f_n - 3), \quad f_{n+1} - 1 = -(f_n - 1)^2 (2f_n + 1),$$

hence, $h_{n+1} = f_n^2 (f_n - 1)^2 (4f_n^2 - 4h_n - 3) = h_n^2 (4h_n - 3)$. Then, we have

$$|h_{n+1}|_{r, qt} \leq |h_n|_{r, qt}^2 \sup(|h_n|_{r, qt}, 1).$$

Therefore, by induction on $n$, we have $|h_n| < 1$, hence, $|h_{n+1}| \leq |h_n|^3$. In particular, we have $|h_n| \rightarrow 0$ for $n \rightarrow \infty$. We also have

$$\sup(|f_{n+1}|_{r, qt}, 1) \leq \sup(|f_n|_{r, qt}, |h_n|_{r, qt}, |h_n|_{r, qt}|f_n|_{r, qt}, 1) = \sup(|f_n|_{r, qt}, 1),$$

hence, $\sup(|f_n|_{r, qt}, 1) \leq \sup(|f_0|_{r, qt}, 1)$. Therefore, we have

$$|f_{n+1} - f_n|_{r, qt} = |h_n (1 - 2f_n)|_{r, qt} \leq |h_n|_{r, qt} \sup(|f_n|_{r, qt}, 1) \leq |h_n|_{r, qt} \sup(|f_0|_{r, qt}, 1).$$

In particular, $\{f_n\}$ is a Cauchy sequence in $A^{\downarrow r}$ with respect to $| \cdot |_{r, qt}$. The element $f := \lim_{n \rightarrow \infty} f_n$ satisfies $f^2 - f = \lim_{n \rightarrow \infty} h_n = 0$ and is an idempotent of $A^{\downarrow r}$. Since we have $h_n \in p \cdot A^{\downarrow r}$ by induction on $n$, $f \equiv f_0 \equiv e \mod p$, i.e., $\alpha(f) = e$. □
**Proposition 3.4.5** (Continuity of connected components). Let $A_{\kappa(p)}$ be reduced.

(i) There exists $c \in \mathbb{R}_{\geq 0}$ such that

$$|\cdot|_{(p), \text{sp}} \geq |S|_{(p)}^{c(n)} \cdot |\cdot|_{(p), \text{qt}}$$

on $A_{\kappa(p)}$. We fix such $c$ in the following.

(ii) Let $n \in \mathbb{N}_{\geq 2}$ and $p$ an Eisenstein prime ideal of $R^+$ with $\deg p > nc$. Then:

$$|\cdot|_{p, \text{sp}} \geq |\pi_p|_p^{nc} |\cdot|_{p, \text{qt}}$$
on $A_{\kappa(p)}$.

(iii) Let $p$ be an Eisenstein prime ideal of $R^+$ such that $\deg p > 3c$. Then, for $r \in \mathbb{Q}_{>0} \cap [1/\deg p, \frac{1}{3}c)$, there exists a canonical bijection

$$\pi_0^\text{Zar}(A_{\kappa(p)}) \to \pi_0^\text{Zar}(A^{\top, r}).$$

In particular, we have

$$\#\pi_0(A_{\kappa(p)}) = \#\pi_0(A_{\kappa(p)}) = \#\pi_0^\text{Zar}(A^{\top, r}).$$

**Proof.**

(i) By assumption, $|\cdot|_{(p), \text{sp}}$ is equivalent to $|\cdot|_{(p), \text{qt}}$ on $A_{\kappa(p)}$. Hence, there exists $\lambda \in \mathbb{R}_{>0}$ such that $|\cdot|_p \geq \lambda |\cdot|_{\text{qt}}$. From $|1|_p = |1|_{\text{qt}} = 1$, we deduce $\lambda \leq 1$. Hence, $c = \log_{|S|} \lambda \geq 0$ satisfies the condition.

(ii) By (i), we have

$$|f^n|_{(p), \text{qt}} \geq |f^n|_{(p), \text{sp}} = |f^n|_{(p), \text{sp}}^{n c} \geq |S|_{(p)}^{nc} |f^n|_{(p), \text{qt}} \cdot \quad \forall f \in A_{\kappa(p)}.$$

From Lemma 3.4.3, we obtain

$$|f^n|_{p, \text{qt}} \geq |\pi_p|_p^{nc} |f^n|_{p, \text{qt}} \cdot \quad \forall f \in A_{\kappa(p)}.$$

By using this inequality iteratively, we obtain

$$|f^{n'}|_{p, \text{qt}} \geq |\pi_p|_p^{nc+n'^2c+\ldots+nc} |f^{n'}|_{p, \text{qt}} = |\pi_p|_p^{nc \cdot \frac{n'^{-1}}{n^{-1}}} |f^{n'}|_{p, \text{qt}} \cdot \quad \forall f \in A_{\kappa(p)}.$$

Hence, for all $f \in A_{\kappa(p)}$, we have $|f|_{p, \text{sp}} = \inf_{i \in \mathbb{N}} |f^{n'}|_{p, \text{qt}}^{1/n'} \geq |\pi_p|_p^{nc/(n-1)} |f|_{p, \text{qt}}$.

(iii) When $p = (p)$, the assertion follows from (i) and Lemma 3.4.4. We consider the case $p \neq (p)$. By applying Lemma 3.4.4 to the inequality in (ii) with $n = 3$, we obtain the assertion for $r \in \mathbb{Q} \cap [1/\deg p, \frac{1}{3}c)$. For general $r \in \mathbb{Q} \cap [1/\deg p, \frac{1}{3}c)$, the assertion is reduced to the previous case by taking $\pi_0^\text{Zar}$ of the commutative diagram

$$
\begin{array}{ccc}
A_{\kappa(p)} & \xrightarrow{\text{can.}} & A^{\top, r} & \xrightarrow{\text{can.}} & A_{\kappa(p)} \\
\downarrow \text{id} & & \downarrow \text{can.} & & \downarrow \text{id} \\
A_{\kappa(p)} & \xrightarrow{\text{can.}} & A^{\top, \frac{1}{\deg p}} & \xrightarrow{\text{can.}} & A_{\kappa(p)}
\end{array}
$$

□
Differential modules associated to de Rham representations 1923

**Remark 3.4.6.** In Theorem 1.2.11 of [Xiao 2010], Xiao proves $\#\pi_0(A_{\kappa(p)}) = \#\pi_0^{\text{zar}}(A_{\kappa(p)})$ under the slightly mild Hypothesis 1.1.10 on $A$ by a similar idea. To generalize Xiao’s result for Eisenstein prime ideals, it seems needed to assume that $A$ is flat over $R$.

To obtain a geometric version of this proposition, we need the following lifting lemma.

**Lemma 3.4.7.** Let $\mathfrak{p}$ be an Eisenstein prime ideal of $R^+$ and $L/\kappa(\mathfrak{p})$ a finite extension. Let $\mathcal{O}'$ be a Cohen ring of $k_L$ and put $R' := \mathcal{O}'[[T]]$. Then, there exists a finite flat morphism $\alpha : R^+ \to R'$ and an isomorphism $R'/\mathfrak{p}R' \cong \mathcal{O}_L$ of $R^+/\mathfrak{p}$-algebras. Moreover, for any Eisenstein prime $\mathfrak{q}$ of $R^+$, $\mathfrak{q}R'$ is again an Eisenstein prime ideal with degree $e_{\mathfrak{q},L}/\kappa(\mathfrak{p})$.

**Proof.** We can define $\alpha$ similar to the definition of the homomorphism $\beta$ in Construction 1.6.3: we fix an $\mathcal{O}'$-algebra structure on $\mathcal{O}_L$, and let $f : R' \to \mathcal{O}_L$ be the local $\mathcal{O}'$-algebra homomorphism, which maps $T$ to a uniformizer $\pi_L$ of $L$. Write $\pi_\mathfrak{p} = \pi_L^{e_{\mathfrak{q},L}/\kappa(\mathfrak{p})} \bar{u}$ with $u \in \mathcal{O}_L^\times$. Since $f$ is surjective by Nakayama’s lemma, we can choose a lift $u \in (R')^\times$ of $\bar{u}$. Since $R^+$ is $p$-adically formally smooth over $\mathbb{Z}[S]$, we can define a morphism $\alpha : R^+ \to R'$, which maps $S$ to $T^{e_{\mathfrak{q},L}/\kappa(\mathfrak{p})}u$, by the lifting property.

We claim that $\mathfrak{p}R'$ is an Eisenstein prime. Let $P$ be an Eisenstein polynomial of $\mathcal{O}[S]$ that generates $\mathfrak{p}$. We have $P \equiv T^{\deg(p)e_{\mathfrak{q},L}/\kappa(\mathfrak{p})}u \mod \mathfrak{p}R'$ for some unit $u \in R'$. By the Weierstrass preparation theorem, there exists a distinguished polynomial $Q(T)$ of degree $\deg(p)e_{\mathfrak{q},L}/\kappa(\mathfrak{p})$ and a unit $U(T) \in R'$ such that $P = Q(T)U(T)$. By evaluating at $T = 0$, we see that $Q(0)$ is equal to $p$ times a unit of $\mathcal{O}'$, which implies the claim. In particular, $R'/\mathfrak{p}R'$ is a discrete valuation ring. Hence, the canonical surjection $R'/\mathfrak{p}R' \to \mathcal{O}_L$ induced by $f$ is an isomorphism. By Nakayama’s lemma and the local criteria of flatness, $\alpha$ is finite flat. The second assertion also follows from the Weierstrass preparation theorem. \qed

The following is our main result of this subsection:

**Proposition 3.4.8** (continuity of geometric connected components). Assume that $A_{\kappa(p)}$ is geometrically reduced.

(i) If all connected components of $A_{\kappa(p)}$ are geometrically connected, then all connected components of $A_{\kappa(p)}$ are also geometrically connected for all Eisenstein prime ideals $\mathfrak{p}$ of $R^+$ with $\deg \mathfrak{p} \gg 0$.

(ii) For all Eisenstein prime ideals $\mathfrak{p}$ of $R^+$ with $\deg \mathfrak{p} \gg 0$, we have $\#\pi_{0}^{\text{geom}}(A_{\kappa(p)}) = \#\pi_{0}^{\text{geom}}(A_{\kappa(p)})$. 

Proof.

(i) By assumption, there exists \( c \in \mathbb{R}_{\geq 0} \) such that \( \cdot |_{(p), sp} \geq |S|_{(p), qt}^{c} \) on \( A_{k(p)} \otimes_{k(p)} k(p)^{alg} \). We prove that all Eisenstein prime ideals \( p \) of \( R^{+} \) with \( \deg(p) > 3c \) satisfy the condition. Let \( L/k(p) \) be a finite extension. Let \( R' \) be as in Lemma 3.4.7. Since \( R' \) is finite flat over \( R^{+} \), we have \( R^{+}(\mathcal{X}) \otimes_{R^{+}} R' \cong R'(\mathcal{X}) \) and \( I' := I \otimes_{R^{+}} R' \cong I \cdot R'(\mathcal{X}) \). Hence, we can apply Proposition 3.4.5 to \( R^{+} = R' \), \( I = I' \) and \( A = A' := A \otimes_{R^{+}} R' \cong R'(\mathcal{X})/I' \). Note that \( c \in L/k(p) \) can be taken as \( c \) in Proposition 3.4.5(i). Therefore, Proposition 3.4.5(iii) yields

\[
\#_{0}^{\Zar}(A_{k(p)} \otimes_{k(p)} L) = \#_{0}^{\Zar}(A'_{k(p')}) = \pi_{0}^{\Zar}(A'_{k(p)}) \\
= \#_{0}^{\Zar}(A_{k(p)}) = \#_{0}^{\Zar}(A_{k(p)}),
\]

where the third equality follows from the assumption. Therefore, we have \( \#_{0}^{\geom}(A_{k(p)}) = \#_{0}(A_{k(p)}) \), which implies the assertion.

(ii) Let \( L/k(p) \) be a finite extension such that all connected components of \( A_{k(p)} \otimes_{k(p)} L \) are geometrically connected. Let \( R' \) be a lifting of \( \mathcal{O}_{L} \) as in Lemma 3.4.7 and \( A' \) as in the proof of (i). Part (i) and Proposition 3.4.5(iii) give the assertion. \( \square \)

3.5. Application: Ramification compatibility of fields of norms. In this subsection, we prove Theorem 3.5.3, which is the ramification compatibility of Scholl’s equivalence in Theorem 1.8.3, as an application of our Gröbner basis argument.

We first construct a characteristic zero lift of the Abbes–Saito space in characteristic \( p \).

Lemma 3.5.1. Let \( F/E \) be a finite extension of complete discrete valuation fields of characteristic \( p \). Assume that the residue field extension \( k_{F}/k_{E} \) is either trivial or purely inseparable. For \( m \in \mathbb{N} \), we put \( X := (X_{0}, \ldots, X_{m}) \) and \( Y := (Y_{0}, \ldots, Y_{m}) \).

(i) [Xiao 2010, Notation 3.3.8] For some \( m \in \mathbb{N} \), there exist a set of generators \( \{z_{0}, \ldots, z_{m}\} \) of \( \mathcal{O}_{F} \) as an \( \mathcal{O}_{E} \)-algebra, with \( z_{0} \) a uniformizer of \( F \), and a set of generators \( \{p_{0}, \ldots, p_{m}\} \) of the kernel of the \( \mathcal{O}_{E} \)-algebra homomorphism \( \mathcal{O}_{E}(X) \to \mathcal{O}_{F} \) defined by \( X_{j} \mapsto z_{j} \) such that

\[
p_{0} = X_{0}^{e_{F/E}} + \pi_{E} \eta_{0},
\]

\[
p_{j} = X_{j}^{f_{j}} - \varepsilon_{j} + X_{0} \delta_{j} + \pi_{E} \eta_{j} \quad \text{for } 1 \leq j \leq m,
\]

where \( \delta_{j}, \eta_{j} \in \mathcal{O}_{E}(X), \varepsilon_{j} \in \mathcal{O}_{E}(X_{0}, \ldots, X_{j-1}) \) and \( f_{j} \in \mathbb{N} \).

(ii) Let \( \succeq \) be the lexicographic order on \( \mathcal{O}_{E}(X) \) defined by \( X_{m} > \cdots > X_{0} \). We view \( \pi_{E} \) as a regular system of parameters of \( \mathcal{O}_{E} \) and apply Construction 3.2.2. Then, we have \( \LT_{\mathcal{O}_{E}}(p_{0}^{n}) = X_{0}^{ne_{F/E}} \) for all \( n \in \mathbb{N} \). Let \( l, n \in \mathbb{N}_{>0} \) satisfy...
\[
p^l n \geq e_{F/E}.
\]
Then, for \(1 \leq j \leq m\), there exists \(\theta_{j,l,n} \in \mathcal{O}_E \langle X \rangle\) such that 
\[
\mathrm{LT}_{\mathcal{O}_E}(p_j^{p^n} - p_0^{[p^n/e_{F/E}]} \theta_{j,l,n}) = u X_j^{f_j p^n} \text{ for some unit } u \in 1 + \pi_E \mathcal{O}_E.
\]

(iii) (cf. [Xiao 2010, Example 1.3.4.]). Fix an isomorphism \(E \cong k_E((S))\). Let \(\mathcal{O}\) be a Cohen ring of \(k_E\) and let \(R := \mathcal{O}[[S]]\) with canonical projection \(R \to \mathcal{O}_E\). Fix a lift \(P_j \in R \langle X \rangle\) of \(p_j\) for all \(j\). Let \(\alpha \in \mathbb{N}^{m+1}, \beta \in \mathbb{N}^{m+1}\). Assume that \([\beta_j/e_{F/E}] \geq \beta_0\) for all \(1 \leq j \leq m\), and assume that there exists \(l \in \mathbb{N}_0\) such that \(p^l \mid \beta_j\) for all \(1 \leq j \leq m\). Then, the \(R\)-algebra
\[
A_{\alpha, \beta} := R \langle X, Y \rangle/(S_0^\alpha Y_j - P_j^\beta, \ 0 \leq j \leq m).
\]
is \(R\)-flat. Moreover, the fiber of \(A_{\alpha, \beta}\) at any Eisenstein prime \(p\) of \(R\) is an affinoid variety, which gives rise to the following affinoid subdomain of \(D^{m+1}_{k(p)}\):
\[
D^{m+1}((\pi_p)^{\langle -\alpha_j / \beta_j \rangle} (P_j \mod p), \ 0 \leq j \leq m).
\]

Proof.

(i) See [Xiao 2010, Construction 3.3.5] for details.

(ii) Since the coefficient of \(X_0^{ne_{F/E}}\) in \(p_0^{p^n}\) is equal to 1, the first assertion follows from 
\[
p_0^{p^n} \equiv X_0^{ne_{F/E}} \mod \pi_E.
\]
For the second, we put \(\theta_{j,l,n} := X_0^{p^n-e_{F/E}[p^n/e_{F/E}]} \delta_j^{p^n} \mod \pi_E\). Since 
\[
p_j^{p^n} \equiv X_j^{p^nf_j} - \varepsilon_j^{p^n} + X_j^{p^n \delta_j^{p^n}} \equiv X_j^{p^nf_j} - \varepsilon_j^{p^n} + p_0^{[p^n/e_{F/E}]} \theta_{j,l,n} \mod \pi_E,
\]
we have \(\mathrm{LT}_{k_E}(p_j^{p^n} - p_0^{[p^n/e_{F/E}]} \theta_{j,l,n} \mod \pi_E) = \mathrm{LT}_{k_E}(X_j^{p^nf_j} - \varepsilon_j^{p^n} \mod \pi_E) = X_j^{f_j p^n},\) which implies the assertion.

(iii) The last assertion is trivial. We prove the first assertion. Let \(\succeq\) be the lexicographic order on \(\mathcal{O}_E \langle X, Y \rangle\) defined by \(X_m \succ \cdots \succ X_0 \succ Y_m \succ \cdots \succ Y_0\). We view \(\{p, S\}\) as a regular system of parameters of \(R\) and apply Construction 3.2.2. For \(1 \leq j \leq m\), we choose a lift of \(\theta_{j,l,\beta_j/p}\) and denote it by \(\Theta_j\) for simplicity. Then, the ideal \((S_0^\alpha Y_j - P_j^{\beta_j}, \ 0 \leq j \leq m)\) is generated by \(Q_0 := S_0^\alpha Y_0 - P_0^{\beta_0}\) and 
\[
Q_j := S_0^\alpha Y_j - P_j^{\beta_j} - (S_0^\alpha Y_0 - P_0^{\beta_0}) P_0^{[\beta_j/e_{F/E}]} P_0^{\langle \beta_j / e_{F/E} \rangle - \beta_0} \Theta_j
\]
for \(1 \leq j \leq m\). It follows from Proposition 3.2.12 that we only have to prove that \(\mathrm{LT}_{R/m_R}(-Q_j \mod m_R)\) are relatively prime monic monomials. We have \(\mathrm{LT}_{R/m_R}(Q_0 \mod m_R) = -\mathrm{LT}_{R/m_R}(P_0^{\beta_0}) = -X_0^{e_{F/E} \beta_0}\). Since 
\[
Q_j = -p_j^{\beta_j} + p_0^{[\beta_j/e_{F/E}]} \theta_{j,l,\beta_j/p} \mod m_R,
\]
we have \(\mathrm{LT}_{R/m_R}(Q_j \mod m_R) = -X_j^{f_j \beta_j}\) by (ii), which yields the assertion. \(\square\)
In the rest of this subsection, let the notation be as in Definition 1.8.1.

**Lemma 3.5.2.** Fix an isomorphism $X_{\mathcal{R}} \cong k_{\mathcal{R}}((\Pi))$, let $\mathcal{O}$ be a Cohen ring of $k_{\mathcal{R}}$ and put $R := \mathcal{O}[\![\Pi]\!]$.

(i) There exists a surjective local ring homomorphism $\phi_n : R \to \mathcal{O}_{K_n}$ for all sufficiently large $n$ such that diagram

\[
\begin{array}{ccc}
R & \xrightarrow{\text{can.}} & X^+_{\mathcal{R}} \\
\downarrow \phi_n & & \downarrow \text{pr}_n \\
\mathcal{O}_{K_n} & \xrightarrow{\text{can.}} & \mathcal{O}_{K_n}/\xi \mathcal{O}_{K_n}
\end{array}
\]

commutes, and $\ker (\phi_n)$ is an Eisenstein prime ideal of $R$. We fix $\phi_n$ in the following and put $p_n := \ker (\phi_n)$.

(ii) Let $r \in \mathbb{Q}_{>0}$ and let $L_{\infty}/K_{\infty}$ be a finite extension and $\Sigma = \{L_n\}_{n>0}$ a corresponding strictly deeply ramified tower. Assume that the residue field extension of $X_{\Sigma}/X_{\mathcal{R}}$ is either trivial or purely inseparable. Then, there exists a flat $R$-algebra $A_{\log}^r$ (resp. $A_{\log}^r_{\text{can.}}$) of the form $R(\langle X \rangle)/I$ for an ideal $I \subset R(\langle X \rangle)$, whose fibers at $(p)$ and $p_n$ are isomorphic to the Abbes–Saito spaces $as^r_{X_{\Sigma}/X_{\mathcal{R}}, \cdot}$ and $as^r_{L_n/K_n, \cdot}$ (resp. $as^r_{X_{\Sigma}/X_{\mathcal{R}}, \cdot}$ and $as^r_{L_n/K_n, \cdot}$) for all sufficiently large $n$.

(iii) With the notation and assumption of (ii), we have for all sufficiently large $n$:

$$\#F^r(X_{\Sigma}) = \#F^r(L_n), \quad \#F^r_{\log}(X_{\Sigma}) = \#F^r_{\log}(L_n).$$

**Proof:** Put $E := X_{\mathcal{R}}$ and $F := X_{\Sigma}$.

(i) For all sufficiently large $n$, the projection $\text{pr}_n : \mathcal{O}_E \to \mathcal{O}_{K_n}/\xi \mathcal{O}_{K_n}$ induces an isomorphism $\Phi_n : k_{\mathcal{R}} \to k_{K_n}$ of the residue fields. Hence, we can choose an embedding $\mathcal{O} \to \mathcal{O}_{K_n}$ that lifts $\Phi_n$. Let $\pi_{K_n}$ be a uniformizer of $\mathcal{O}_{K_n}$, which is a lift of $\text{pr}_n (\Pi) \in \mathcal{O}_{K_n}/\xi \mathcal{O}_{K_n}$. Since the $\mathcal{O}$-algebra homomorphism $\mathcal{O}[\![\Pi]\!] \to R; \; \Pi \mapsto \Pi$ is formally étale, we have a map $\phi_n$ sending $\Pi$ to $\pi_{K_n}$. Since $\mathcal{O}_{K_n}/\mathcal{O}$ is totally ramified, the kernel of $\phi_n$ is generated by an Eisenstein polynomial.

(ii) Fix $\xi' \in \mathcal{O}_{K_n}$ such that $0 < v_p(\xi') < v_p(\xi)$ and such that $\{L_n\}_{n>0}$ is strictly deeply ramified with respect to $\xi'$. We denote the composite $\circ \text{pr}_n : \mathcal{O}_E \to \mathcal{O}_{K_n}/\xi \mathcal{O}_{K_n} \to \mathcal{O}_{K_n}/\xi' \mathcal{O}_{K_n}$ by $pr_n$ again, and fix an expression $r = a/b$ with $a, b \in \mathbb{N}$ and $b > 0$. Also, fix $l \in \mathbb{N}$ with $p^l \geq e_{F/E}$. Define $\alpha, \alpha_{\log}, \beta, \beta_{\log} \in \mathbb{N}^l$ via $\alpha_0 := a, \alpha_{\log, 0} := a + b, \beta_0 := \beta_{\log, 0} := b, \alpha_j = \alpha_{\log, j} = ap^j, \beta_j = \beta_{\log, j} := bp^j$ for $1 \leq j \leq m$. Then, we can apply Lemma 3.5.1 to the finite extension $F/E$. In the following, we use the notation as of that lemma. We will prove that $A_{\alpha, \beta}$ (resp. $A_{\alpha_{\log}, \beta_{\log}}$) satisfies the desired condition. We first consider the nonlog case. By Lemma 3.5.1(iii), the fiber of $A_{\alpha, \beta}$ at $(p)$ is isomorphic to
as $F_E \otimes Z$, where $Z = \{z_0, \ldots, z_m\}$. Recall that we have a canonical surjection $pr_n : \mathcal{O}_F \to \mathcal{O}_{L_n}/\xi' \mathcal{O}_{L_n}$ for all sufficiently large $n$. We choose a lift $z_j^{(n)} \in \mathcal{O}_{L_n}$ of $pr_n(z_j) \in \mathcal{O}_{L_n}/\xi' \mathcal{O}_{L_n}$. Then, the $z_j^{(n)}$'s are generators of $\mathcal{O}_{L_n}$ as an $\mathcal{O}_{K_n}$-algebra by Nakayama’s lemma and, by lemma Lemma 3.5.1(i), $z_j^{(0)}$ is a uniformizer of $\mathcal{O}_{L_n}$. We consider the surjection $\varphi_n : \mathcal{O}_{K_n}(X) \to \mathcal{O}_{L_n}; \, X_j \mapsto z_j^{(n)}$ and choose a lift $p_j^{(n)} \in \ker(\varphi_n)$ of $pr_n(p_j) \in \mathcal{O}_{K_n}/\xi' \mathcal{O}_{K_n}[X]$:

$$\begin{array}{ccc}
\mathcal{O}_{E}(X) & \xrightarrow{X_j \mapsto z_j} & \mathcal{O}_F \\
pr_n \downarrow & & \downarrow pr_n \\
\mathcal{O}_{K_n}/\xi' \mathcal{O}_{K_n}[X] & \xrightarrow{X_j \mapsto pr_n(z_j)} & \mathcal{O}_{L_n}/\xi' \mathcal{O}_{L_n} \\
\text{can.} \downarrow & & \downarrow \text{can.} \\
\mathcal{O}_{K_n}(X) & \xrightarrow{\varphi_n; X_j \mapsto z_j^{(n)}} & \mathcal{O}_{L_n}.
\end{array}$$

By Nakayama’s lemma, the $p_j^{(n)}$’s are generators of $\ker(\varphi_n)$. We may assume $v_{K_n}(\xi') \geq r$ by choosing $n$ sufficiently large. Since $\varphi_n(p_j^{(n)}) = p_j^{(n)} \mod (\xi')$, we have $|\varphi_n(p_j^{(n)}(x))| \leq |\pi_{K_n}|^r$ if and only if $|p_j^{(n)}(x)| \leq |\pi_{K_n}|^r$ for any $x \in \mathcal{O}_n^{n+1}$. This implies that the fiber of $AS^r$ at $p_n$ is isomorphic to $as_{L_n/K_n}^{r'}$, where $Z^{(n)} = \{z_0^{(n)}, \ldots, z_m^{(n)}\}$, which implies the assertion. In the log case, a similar proof works if we choose $n$ sufficiently large such that $v_{K_n}(\xi') \geq r + 1$.

(iii) This follows from applying Proposition 3.4.8 to $AS^r$ and $AS_{\log}^{r'}$.

The following is the main theorem in this subsection. See [Hattori 2014, §6] for an alternative proof.

**Theorem 3.5.3.** Let $L_\infty/K_\infty$ be a finite separable extension and $\Sigma = \{L_n\}_{n>0}$ a corresponding strictly deeply ramified tower. Then, the sequence $\{b(L_n/K_n)\}_{n>0}$ (resp. $\{b_{\log}(L_n/K_n)\}_{n>0}$) converges to $b(X_\Sigma/X_{\bar{\Sigma}})$ (resp. $b_{\log}(X_\Sigma/X_{\bar{\Sigma}})$).

**Proof.** Since the nonlog and log ramification filtrations are invariant under base change, so are the nonlog and log ramification breaks. Hence, we may assume that the residue field extension of $X_\Sigma/X_{\bar{\Sigma}}$ is either trivial or purely inseparable by replacing $K_\infty$ and $L_\infty$ by their maximal unramified extensions. We first prove the nonlog case. Recall that we have $[X_\Sigma : X_{\bar{\Sigma}}] = [L_n : K_n]$ for all sufficiently large $n$ by Theorem 1.8.3. For $r \in \mathbb{Q}_{>0}$ with $b(X_\Sigma/X_{\bar{\Sigma}}) < r$, we have $\#F^r(L_n) = \#F^r(X_\Sigma) = [L_n : K_n]$ for all sufficiently large $n$ by Lemma 3.5.2. Hence, we have $\limsup_n b(L_n/K_n) \leq b(X_\Sigma/X_{\bar{\Sigma}})$. For $r \in \mathbb{Q}_{>0}$ with $b(X_\Sigma/X_{\bar{\Sigma}}) > r$, we have $\#F^r(L_n) = \#F^r(X_\Sigma) < [L_n : K_n]$ for all sufficiently large $n$ by Lemma 3.5.2 and the definition of $F^r$. Hence, we have $\liminf_n b(L_n/K_n) \geq b(X_\Sigma/X_{\bar{\Sigma}})$. Therefore, we
have \( b(X_{\mathbb{C}} / X_{\mathbb{R}}) \leq \lim \inf_n b(L_n / K_n) \leq \lim \sup_n b(L_n / K_n) \leq b(X_{\mathbb{C}} / X_{\mathbb{R}}) \), which implies the assertion. In the log case, the same argument with \( b \) and \( F^r \) replaced by \( b_{\log} \) and \( F^r_{\log} \) works.

The following representation version of Theorem 3.5.3 will be used in the proof of Theorem 4.7.1.

**Lemma 3.5.4.** Let \( F / \mathbb{Q}_p \) be a finite extension and let \( V \in \text{Rep}_F^n(G_{K_\infty}) \) a finite \( F \)-representation for some \( n \). We identify \( G_{X_{\mathbb{R}}} \) with \( G_{K_\infty} \) via the equivalence in Theorem 1.8.3.

(i) For \( m \geq n \), let \( L_m \) (resp. \( L_\infty \), \( X' \)) be the finite Galois extension corresponding to the kernel of the action of \( G_{K_m} \) (resp. \( G_{K_\infty} \), \( G_{X_{\mathbb{R}}} \)) on \( V \). Then, \( L_\infty \) corresponds to \( X' \) under the equivalence in Theorem 1.8.3 and \( \{ L_m \}_{m \geq n} \) is a strictly deeply ramified tower corresponding to \( L_\infty \).

(ii) The sequences \( \{ \text{Art}^{AS}(V|_{K_m}) \}_{m \geq n} \) and \( \{ \text{Swan}^{AS}(V|_{K_m}) \}_{m \geq n} \) are eventually stationary and their limits are equal to \( \text{Art}^{AS}(V|_{X_{\mathbb{R}}}) \) and \( \text{Swan}^{AS}(V|_{X_{\mathbb{R}}}) \).

**Proof.**

(i) The first assertion is trivial. We prove the second assertion. Since \( G_{L_n} \cap G_{K_m} = G_{L_m} \) for all \( m \geq n \), we have \( L_m = L_n K_m \). Therefore, \( \{ L_m \} \) is a strictly deeply ramified tower corresponding to \( L'_\infty := \bigcup_m L_m \). Hence, we only have to prove that \( L_\infty = L'_\infty \). Let \( \rho : G_{K_n} \to \text{GL}(V) \) be a matrix presentation of \( V \). By the commutative diagram

\[
\begin{array}{ccc}
1 & \longrightarrow & G_{L_\infty} \\
& \text{inc.} & \downarrow \text{can.} \\
G_{L_m} & \longrightarrow & G_{K_m} \\
& \text{inc.} & \downarrow \text{id} \\
1 & \longrightarrow & \rho|_{G_{K_m}} \longrightarrow \text{GL}(V),
\end{array}
\]

where the horizontal sequences are exact, we obtain a canonical injection \( G_{L_\infty} \hookrightarrow G_{L_m} \). Therefore, we have \( L_m \subset L_\infty \), hence, \( L'_\infty \subset L_\infty \). To prove the converse, we only have to prove \( [ L_\infty : K_\infty ] \leq [ L'_\infty : K_\infty ] \). Since \( (K_\infty \cap L_n)/K_n \) is finite, we have \( K_\infty \cap L_n = K_m \cap L_n \) for sufficiently large \( m \). In particular,

\[
[L'_\infty : K_\infty] = [L_n K_\infty : K_\infty] = [L_n : K_\infty \cap L_n] = [L_n : K_m \cap L_n] = [L_n K_m : K_m] = [L_m : K_m].
\]

Then, the assertion follows from

\[
[L_\infty : K_\infty] = \# \rho(G_{K_\infty}) \leq \# \rho(G_{K_m}) = [L_m : K_m].
\]

(ii) By Maschke’s theorem, there exists an irreducible decomposition \( V|_{X_{\mathbb{R}}} = \bigoplus_\lambda V^\lambda \) with \( V^\lambda \in \text{Rep}_F^n(G_{X_{\mathbb{R}}}) \). We choose \( m_0 \in \mathbb{N} \) such that the canonical
map \( G_{L_\infty/K_\infty} \to G_{L_m/K_m} \) is an isomorphism for all \( m \geq m_0 \). Then, \( V^\lambda \) is \( G_{K_m} \)-stable for all \( m \geq m_0 \). Moreover, \( V^\lambda|_{K_m} \in \text{Rep}_F^f(G_{K_m}) \) is irreducible. For \( m \geq m_0 \), let \( L_m^\lambda/K_m \) be the finite Galois extension corresponding to the kernel of the action of \( G_{K_m} \) on \( V^\lambda \). By (i), \( L_m^\lambda = \{ L_m^\lambda \}_{m \geq m_0} \) is a strictly deeply ramified tower and \( X_{\Omega^\lambda} \) corresponds to the kernel of the action of \( G_{X_{\lambda}} \) on \( V^\lambda \).

By the irreducibility of the action of \( G_{K_m} \) (resp. \( G_{X_{\lambda}} \)) on \( V^\lambda \), we have

\[
\text{Art}^{AS}(V^\lambda|_{K_m}) = b(L_m^\lambda/K_m) \dim_F(V),
\]

for \( m \geq m_0 \). We apply Theorem 3.5.3 to each \( L_m \), to get \( \lim_{m \to \infty} \text{Art}(V|_{K_m}) = \text{Art}(V|_{X_{\lambda}}) \). Note that \( K_m \) is not absolutely unramified for sufficiently large \( m \). Indeed, the definition of strictly deeply ramified implies that \( K_{m+1}/K_m \) is not unramified. By Theorem 1.5.1, the convergence of \( \{ \text{Art}(V|_{K_m}) \} \) implies that \( \{ \text{Art}(V|_{K_m}) \} \) is eventually stationary, which implies the assertion for the Artin conductor. The assertion for the Swan conductor follows from the same argument by replacing Art and \( b \) by Swan and \( b_{\log} \). \( \square \)

**Remark 3.5.5** (a Hasse–Arf property). Let the notation be as in Lemma 3.5.4 and let \( p = 2 \). By Theorem 1.7.10 and Lemma 3.5.4(ii), \( \text{Swan}(V|_{K_m}) \) is an integer for all sufficiently large \( m \) (cf. Theorem 1.5.1).

### 4. Differential modules associated to de Rham representations

In this section, we first construct \( \mathbb{N}_{\text{dR}}(V) \) as a \((\varphi, \Gamma_K)\)-module for de Rham representations \( V \in \text{Rep}_{\mathbb{Q}_p}(G_K) \), see Section 4.2. Then, we prove that \( \mathbb{N}_{\text{dR}}(V) \) can be endowed with a \((\varphi, \nabla)\)-module structure (Section 4.4). Then, we define Swan conductors of de Rham representations (Section 4.6) and we prove that the differential Swan conductor of \( \mathbb{N}_{\text{dR}}(V) \) and Swan conductor of \( V \) are compatible (Section 4.7).

Throughout this section, let \( K \) be a complete discrete valuation field of mixed characteristic \((0, p)\). Except for Section 4.6, we assume that \( K \) satisfies Assumption 1.9.1, and we use the notation of Section 1.3.

#### 4.1. Calculation of horizontal sections.

For perfect \( k_K \), \( \mathbb{N}_{\text{dR}}(V) \) is constructed by gluing a certain family of vector bundles over \( K_n[[t]] \) for \( n \gg 0 \), see [Berger 2008b, Section II.1]. When \( k_K \) is not perfect, \( K_n[[t]] \) should be replaced by the ring of horizontal sections of \( K_n[[u, t_1, \ldots, t_d]] \) with respect to the connection \( \nabla^{\text{geom}} \), which will be studied in this subsection.

**Definition 4.1.1.** (i) We have a canonical \( K_n \)-algebra injection

\[
K_n[[t, u_1, \ldots, u_d]] \to \mathbb{B}_{\text{dR}}^+.
\]
since $\mathbb{B}_d^{+\text{dr}}$ is a complete local $K^{\text{alg}}$-algebra. The topology of $K_n[[t, u_1, \ldots, u_d]]$ as a subring of $\mathbb{B}_d^{+\text{dr}}$ (endowed with the canonical topology) is called the canonical topology. Note that $K_n[[t, u_1, \ldots, u_d]]$ is stable under the $G_K$-action, and that the $G_K$-action factors through $\Gamma_K$.

(ii) Let $F$ be a complete valuation field. The Fréchet topology on

$$F[[X_1, \ldots, X_n]] \cong \lim_{\leftarrow m} F[X_1, \ldots, X_n]/(X_1, \ldots, X_n)^m$$

is the inverse limit topology, where $F[X_1, \ldots, X_n]/(X_1, \ldots, X_n)^m$ is endowed with a (unique) topological $F$-vector space structure. Note that $F[[X_1, \ldots, X_n]]$ is a Fréchet space, and that the $(X_1, \ldots, X_n)$-adic topology of $F[[X_1, \ldots, X_n]]$ is finer than the Fréchet topology.

**Lemma 4.1.2.** The canonical topology of $K_n[[t, u_1, \ldots, u_d]]$ and the Fréchet topology are equivalent. In particular, $K_n[[t, u_1, \ldots, u_d]]$ is a closed subring of $\mathbb{B}_d^{+\text{dr}}$.

**Proof.** Put $V_m := K_n[[t, u_1, \ldots, u_d]]/(t, u_1, \ldots, u_d)^m$ and identify $K_n[[t, u_1, \ldots, u_d]]$ with $\lim_{\leftarrow m} V_m$. If we endow $V_m$ with a (unique) topological $K_n$-vector space structure, then the resulting inverse limit topology is the Fréchet topology. We have a canonical injection $V_m \to \mathbb{B}_d^{+\text{dr}}/(t, u_1, \ldots, u_d)^m$. If we endow $V_m$ with the subspace topology as a subset of $\mathbb{B}_d^{+\text{dr}}/(t, u_1, \ldots, u_d)^m$, which is endowed with the canonical topology, then the resulting inverse limit topology is the canonical topology. Since $\mathbb{B}_d^{+\text{dr}}/(t, u_1, \ldots, u_d)^m$ is $K_n$-Banach space by definition, $V_m$ endowed with this topology is a topological $K_n$-vector space. This implies the assertion. \hfill \square

**Notation 4.1.3.** The subring $K_n[[t, u_1, \ldots, u_d]]^\text{geom} = 0 = \mathbb{B}_d^{+\text{dr}} \cap K_n[[t, u_1, \ldots, u_d]]$ of $\mathbb{B}_d^{+\text{dr}}$ is denoted by $K_n[[t, u_1, \ldots, u_d]]^\text{geom}$ for $n \in \mathbb{N}$. We call the subspace topology of $K_n[[t, u_1, \ldots, u_d]]^\text{geom}$ as a subring of $\mathbb{B}_d^{+\text{dr}}$ (endowed with the canonical topology) the canonical topology. Note that $K_n[[t, u_1, \ldots, u_d]]^\text{geom}$ is a closed subring of $\mathbb{B}_d^{+\text{dr}}$ since the connection $\nabla^\text{geom} : \mathbb{B}_d^{+\text{dr}} \to \mathbb{B}_d^{+\text{dr}} \otimes_K \hat{G}_K^1$ is continuous and $\mathbb{B}_d^{+\text{dr}}$ is closed in $\mathbb{B}_d^{+\text{dr}}$.

**Lemma 4.1.4.** The ring $K_n[[t, u_1, \ldots, u_d]]^\text{geom}$ is a complete discrete valuation ring with residue field $K_n$ and uniformizer $t$.

**Proof.** We define a map

$$f : K_n[t, u_1, \ldots, u_d] \to K_n[[t, u_1, \ldots, u_d]]$$

$$x \mapsto \sum_{(n_1, \ldots, n_d) \in \mathbb{N}^d} \frac{(-1)^{n_1 + \cdots + n_d}}{n_1! \cdots n_d!} u_1^{n_1} \cdots u_d^{n_d} \partial_1^{n_1} \circ \cdots \circ \partial_d^{n_d}(x).$$

It is easy to check that this is an abstract ring homomorphism such that $\text{Im}(f) \subset K_n[[t, u_1, \ldots, u_d]]^\text{geom}$, $f(t^j) = tf(x)$ for all $x \in K_n[t, u_1, \ldots, u_d]$ and $f(u_j) = 0$ for
all $j$. In particular, $f$ is $(t, u_1, \ldots, u_d)$-adically continuous. Passing to the completion, we obtain a ring homomorphism $f : K_n[[t, u_1, \ldots, u_d]] \to K_n[[t, u_1, \ldots, u_d]]^\vee$. Since $f$ is identity on $K_n[[t, u_1, \ldots, u_d]]^\vee$, $f$ is surjective and $f$ induces a surjection

$$\tilde{f} : K_n[[t]] \cong K_n[[t, u_1, \ldots, u_d]]/(u_1, \ldots, u_d) \to K_n[[t, u_1, \ldots, u_d]]^\vee,$$

where the first isomorphism is induced by the inclusion $K_n[[t]] \subset K_n[[t, u_1, \ldots, u_d]]$. Since $\tilde{f}(t) = t$ is nonzero, $\tilde{f}$ is an isomorphism, which implies the assertion. □

**Lemma 4.1.5.** The $t$-adic topology on $K_n[[t, u_1, \ldots, u_d]]^\vee$ is finer than the canonical topology.

**Proof.** Denote $K_n[[t, u_1, \ldots, u_d]]^\vee$ by $R$ and identify $R$ with $\lim_{\to} R/t^m R$. If we endow $R/t^m R$ with the discrete topology, then the resulting inverse limit topology is the $t$-adic topology. By Lemma 4.1.4 and dévissage, the canonical map $R/t^m R \to K_n[[t, u_1, \ldots, u_d]]/(t, u_1, \ldots, u_d)^m$ is injective. If we endow $R/t^m R$ with the subspace topology as a subset of $K_n[[t, u_1, \ldots, u_d]]/(t, u_1, \ldots, u_d)^m$, endowed with a (unique) topological $K_n$-vector space structure, then the resulting inverse limit topology is the canonical topology. Since the discrete topology is the finest topology, we obtain the assertion. □

The map $f$ defined in the proof of Lemma 4.1.4 is continuous when $K = \hat{K}$:

**Lemma 4.1.6.** Let $\varphi : O_{\hat{K}} \to O_{\hat{K}}$ be the unique Frobenius lift, characterized by $\varphi(t_j) = t_j^p$ for all $1 \leq j \leq d$. Then, the map $f : \hat{K}_n[[t, u_1, \ldots, u_d]] \to \hat{K}_n[[t, u_1, \ldots, u_d]]^\vee$ defined in the proof of Lemma 4.1.4 is continuous with respect to the Fréchet topologies.

**Proof.** By the definition of $f$, we only have to prove the following claim: for all $m \in \mathbb{N}$ and $1 \leq j \leq d$, we have

$$\varphi^m_j(O_{\hat{K}}) \subset m! O_{\hat{K}}.$$

We first note since $d : O_{\hat{K}} \to \hat{O}_{\hat{K}}$ and $\varphi : \hat{O}_{\hat{K}} \to \hat{O}_{\hat{K}}$ commute, we have

$$\partial_j \circ \varphi^i = p^i t_j^{p-1} \varphi^i \circ \partial_j \quad (5)$$

for all $i \in \mathbb{N}$ and $1 \leq j \leq d$. We prove the claim. Fix $m$ and choose $i \in \mathbb{N}$ such that $v_p(m!) \leq i$. Since $k_{\hat{K}} = k_{\bar{K}}^{p^i} [t_1, \ldots, t_d]$, we have $O_{\hat{K}} = \varphi^i(O_{\hat{K}})[t_1, \ldots, t_d]$ by Nakayama’s lemma. By Leibniz’s rule, we have

$$\partial_j^m(\varphi^i(\lambda)t_1^{a_1} \cdots t_d^{a_d}) = \sum_{0 \leq m_0 \leq m} \binom{m}{m_0} \partial_j^{m_0}(\varphi^i(\lambda))t_1^{a_1} \cdots \partial_j^{m-m_0}(t_j^{a_j}) \cdots t_d^{a_d} \quad (6)$$

for $\lambda \in O_{\hat{K}}$ and $a_1, \ldots, a_d \in \mathbb{N}$. We have $\partial_j^{m_0}(\varphi^i(\lambda)) \in p^i O_{\hat{K}} \subset m! O_{\hat{K}}$, unless $m_0 = 0$, by (5), and $\partial_j^m(t_j) \in m! O_{\hat{K}}$. Hence, the RHS of (6) belongs to $m! O_{\hat{K}}$, which implies the claim. □
4.2. Construction of $\mathbb{N}_{dR}$. In this subsection, we construct $\mathbb{N}_{dR}(V)$ as a $(\varphi, \Gamma_K)$-module for de Rham representations $V$. The idea is similar to [Berger 2008b, §III], i.e., gluing a compatible family of vector bundles over $K_n[[t, u_1, \ldots, u_d]]^\vee$ to obtain vector bundles over $B_{\text{rig}}^{\dagger,r}$.

**Notation 4.2.1.** For $n \in \mathbb{N}$, put $r(n) := 1/p^{n-1}(p-1)$. For $r \in \mathbb{Q}_{>0}$, let $n(r) \in \mathbb{N}$ be the smallest integer $n$ with $r \geq r(n)$.

For each $K$, we fix $t_0$ such that $A_K$ has enough $r_0$-units (Construction 1.6.1) and $A_K^{\dagger,r} \simeq O'((\pi')^{\dagger,r}/E_{K'/K})$ for all $r \in \mathbb{Q}_{>0} \cap (0, t_0)$ (Lemma 1.10.2), where $O'$ is a Cohen ring of $k_{E_{K'}}$. In the rest of this section, let $r \in \mathbb{Q}_{>0}$, and when we consider $A_K^{\dagger,r}$, $B_K^{\dagger,r}$ and $B_{\text{rig},K}^{\dagger,r}$, we tacitly assume $r \in \mathbb{Q}_{>0} \cap (0, t_0)$ unless otherwise stated. Moreover, for $V \in \text{Rep}_{\mathcal{D}}(G_K)$, we further choose $t_0$ sufficiently small (dependent on $V$ though) such that $B^{\dagger,r}(V)$ admits a $B_K^{\dagger,r}$-basis for all $r \in (0, t_0)$. Note that $A_K^{\dagger,r}$, $B_K^{\dagger,r}$ are PID’s and that $B_{\text{rig},K}^{\dagger,r}$ is a Bézout integral domain.

**Definition 4.2.2.** Let $r > 0$ and $n \in \mathbb{N}$ with $n \geq n(r)$. For $x = \sum_{k \gg -\infty} p^k[x_k] \in \tilde{B}_{\text{rig}}^{\dagger,r}$, the sequence $\{\sum_{k \leq N} p^k[x_k^{p^{-n}}]\}_{N \in \mathbb{Z}}$ converges in $B_{dR}^{\dagger,r}$. Moreover, if we put

$$\iota_n : \tilde{B}_{\text{rig}}^{\dagger,r} \to B_{dR}^{\dagger,r},$$

$$x \mapsto \sum_{k \gg -\infty} p^k[x_k^{p^{-n}}],$$

then $\iota_n$ is a continuous ring homomorphism (see the proof of [Andreatta and Brinon 2010, Lemme 7.2] for details). Since $B_{dR}^{\dagger,r}$ is Fréchet complete, $\iota_n$ extends to a continuous ring homomorphism

$$\iota_n : \tilde{B}_{\text{rig},K}^{\dagger,r} \to B_{dR}^{\dagger,r}.$$ We also denote by $\iota_n$ the restriction of $\iota_n$ to $\tilde{B}_{\text{rig},K}^{\dagger,r}$ or $B_{\text{rig},K}^{\dagger,r}$. Unless otherwise stated, we also denote by $\iota_n$ the composite of $\iota_n$ and the inclusion $B_{dR}^{\dagger,r} \subset B_{dR}^{\dagger,r}$.

**Lemma 4.2.3.** For $x \in B_{\text{rig},K}^{\dagger,r}$, we have

$$x \in (B_{\text{rig},K}^{\dagger,r})^\times \iff x \in (B_{\text{rig},K}^{\dagger,r})^\times \iff x \text{ has no slopes} \iff x \in (B_{K}^{\dagger,r})^\times \iff x \in (\tilde{B}_{\text{rig},K}^{\dagger,r})^\times.$$  

**Proof.** Note that the slopes of $x$ as an element of $B_{\text{rig},K}^{\dagger,r}$ or $\tilde{B}_{\text{rig},K}^{\dagger,r}$ are the same by definition (see Section 2). Therefore, the assertion follows from [Kedlaya 2005, Corollary 2.5.12].

**Lemma 4.2.4.** For $B = B_{K}^{\dagger,r}$, $B_{\text{rig},K}^{\dagger,r}$, $\tilde{B}_{K}^{\dagger,r}$, $\tilde{B}_{\text{rig},K}^{\dagger,r}$, we have

$$\ker (\theta \circ \iota_n : B \to \mathbb{C}_p) = \varphi^{n-1}(q)B$$

for $n \geq n(r)$. 

Proof. Note that since $\widehat{E}_K$ and $\widehat{E}_K^{\mathrm{rig}}$ are isomorphic, the associated analytic rings $\widehat{B}^{\dagger,r}_{\mathrm{rig},K}$ and $\widehat{B}^{\dagger,r}_{\mathrm{rig},K}$ are isomorphic. Hence, in the case of $B = \widehat{B}^{\dagger,r}_{\mathrm{rig},K}$, the claim follows from [Berger 2008b, Proposition 4.8]. By regarding $C_p$ as the completion of an algebraic closure of $K^{\mathrm{pf}}$ and applying [Berger 2008b, Remarque 2.14], we have $\ker(\theta \circ t_n : B^{\dagger,r}_{\mathrm{rig},K} \to C_p) = \varphi^{-1}(q) \widehat{B}^{\dagger,r}_{\mathrm{rig},K}$. Since $(\widehat{B}^{\dagger,r})_{\mathrm{rig},K} = \widehat{B}^{\dagger,r}_{\mathrm{rig},K}$ and $\varphi^{-1}(q) \in \widehat{B}^{\dagger,r}_{\mathrm{rig},K}$, we obtain the assertion for $B = \widehat{B}^{\dagger,r}_{\mathrm{rig},K}$. We will prove the assertion for $B = \widehat{B}^{\dagger,r}_{\mathrm{rig},K}$. Let $x \in \ker(\theta \circ t_n : \widehat{B}^{\dagger,r}_{\mathrm{rig},K} \to C_p)$. Since $\widehat{B}^{\dagger,r}_{\mathrm{rig},K}$ is a Bézout integral domain, we have $(x, \varphi^{-1}(q)) = (y)$ for some $y \in \widehat{B}^{\dagger,r}_{\mathrm{rig},K}$. Let $y' \in \widehat{B}^{\dagger,r}_{\mathrm{rig},K}$ such that $\varphi^{-1}(q) = yy'$. Since $y \in \ker(\theta \circ t_n : \widehat{B}^{\dagger,r}_{\mathrm{rig},K} \to C_p) = \varphi^{-1}(q) \widehat{B}^{\dagger,r}_{\mathrm{rig},K}$, we have $y = \varphi^{-1}(q)y''$ for some $y'' \in \widehat{B}^{\dagger,r}_{\mathrm{rig},K}$, hence, $y'y'' = 1$. By Lemma 4.2.3, $y'$ is a unit in $\widehat{B}^{\dagger,r}_{\mathrm{rig},K}$. Hence, we have $x \in \varphi^{-1}(q) \widehat{B}^{\dagger,r}_{\mathrm{rig},K}$ for any $x \in \ker(\theta \circ t_n : \widehat{B}^{\dagger,r}_{\mathrm{rig},K} \to C_p)$, which implies the assertion. For $B = \widehat{B}^{\dagger,r}_{\mathrm{rig},K}$, a similar proof works since $\widehat{B}^{\dagger,r}_{\mathrm{rig},K}$ is a PID, hence, a Bézout integral domain.

**Lemma 4.2.5.** The image of $B^{\dagger,r}_{\mathrm{rig},K}$ under $t_n$ is contained in $K_n[t, u_1, \ldots, u_d]$ for $n \geq n(r)$. In particular, $t_n$ induces a morphism $t_n : B^{\dagger,r}_{\mathrm{rig},K} \to K_n[t, u_1, \ldots, u_d]$ for $n \geq n(r)$.

**Proof.** Since $B^{\dagger,r}_{\mathrm{rig},K} \subset B^{\dagger,r(n)}_{\mathrm{rig},K}$, we may assume $r = r(n)$. By [Andreatta and Brinon 2010, Remarque 8.5], there exists a subring $A_{K_{(1,(p-1)p^{n-1})}}$ of $B^{(1,(p-1)p^{n-1})}$. The inclusion $t_n(B^{\dagger,r}_{K}) \subset K_n[t, u_1, \ldots, u_d]$ is proved in Proposition 8.6 of the same paper. Since $K_n[t, u_1, \ldots, u_d]$ is closed in $B_{\mathrm{dR}}$, we obtain the assertion.

**Lemma 4.2.6.** For $h \in \mathbb{N}$ and $n \geq n(r)$, the morphism

$$\text{pr}_h \circ t_n : B^{\dagger,r}_{\mathrm{rig},K} \to K_n[t, u_1, \ldots, u_d]^{\nabla}/t^hK_n[t, u_1, \ldots, u_d]^{\nabla}$$

is surjective.

**Proof.** Since $t \in B^{\dagger,r}_{\mathrm{rig},K}$, we may assume $h = 1$ by Lemma 4.1.4. Put $\theta_n := \theta \circ t_n$. Let $A^{+_\mathbb{K}} \subset A^{+}_{\mathbb{K}}$ be as in [Andreatta and Brinon 2008, Proposition 4.42]. By the proof of [Andreatta and Brinon 2010, Lemme 8.2], $\theta_n : A^{+_\mathbb{K}} \to \mathcal{O}_{K_n}$ is surjective after taking the reduction modulo some power of $p$. Since $A^{+_\mathbb{K}}$ is Noetherian and $(p/p^a, p)$-adically Hausdorff complete, $A^{+}_{\mathbb{K}}$ is $p$-adically Hausdorff complete, which implies the surjectivity of $\theta_n : A^{+_\mathbb{K}} \to \mathcal{O}_{K_n}$ by Nakayama’s lemma.

**Lemma 4.2.7.** The image of $B^{\dagger,r}_{\mathrm{rig},K}$ under $t_n$ is dense in $K_n[t, u_1, \ldots, u_d]^{\nabla}$ with respect to the canonical topology for $n \geq n(r)$.

**Proof.** By Lemma 4.1.5, the assertion follows from Lemma 4.2.6.
Lemma 4.2.8 ([Kedlaya 2005, Corollary 2.8.5, Definition 2.9.5], see also [Berger 2008a, Proposition 1.1.1]). For $B = \widehat{B}_\text{rig}^+, \widehat{B}_\text{rig,K}^+, B_\text{rig,K}^+$ and a $B$-submodule $M$ of a finite free $B$-module, the following are equivalent:

(i) $M$ is finite free.
(ii) $M$ is closed.
(iii) $M$ is finitely generated.

Lemma 4.2.9. Let $B$ be either $\widehat{B}_\text{rig}^+$ or $B_\text{rig,K}^+$. If $I$ is a principal ideal of $B$ which divides $(r^h)$ for some $h \in \mathbb{N}$, then $I$ is generated by an element of the form $\prod_{n \geq n(r)} (\varphi^{n-1}(q)/p)^{j_n}$ with $j_n \leq h$.

Proof. Note that we have a slope factorization $t = \pi \prod_{n \geq n(r)} (\varphi^{n-1}(q)/p)$ in $\mathbb{B}_{\text{rig},Q_p}$ (see the proof of [Berger 2008b, Proposition 1.2.2]). For $n < n(r)$, $\varphi^{n-1}(q)/p$ is a unit in $\mathbb{B}_{\text{rig},Q_p}$ and for $n \geq n(r)$, $\varphi^{n-1}(q)/p$ generates a prime ideal of $B$ by Lemma 4.2.4. Hence, the assertion follows from the uniqueness of slope factorizations, see Lemma 2.0.5.

Lemma 4.2.10 (The existence of a partition of unity). Let $n \in \mathbb{N}$ and $r > 0$ satisfy $n \geq n(r)$. For $w \in \mathbb{N}_{>0}$, there exists $t_{n,w} \in \mathbb{B}_{\text{rig,K}}^+$ such that $t_{n}(t_{n,w}) = 1$ mod $t^w K_n \llbracket t, u_1, \ldots, u_d \rrbracket^\nabla$ and $t_{m}(t_{n,w}) \in t^w K_m \llbracket t, u_1, \ldots, u_d \rrbracket^\nabla$ if $m \neq n$ and $m \geq n(r)$.

Proof. Since $\mathbb{B}_{\text{rig,K}}^+ \subset \mathbb{B}_{\text{rig,K}}^+$ and $Q_p(\xi_p^m) \llbracket t \rrbracket \subset K_m \llbracket t, u_1, \ldots, u_d \rrbracket^\nabla$, we may assume $K = Q_p$. The assertion then follows from [Berger 2008b, Lemma 2.1.1].

Lemma 4.2.11. Let $B$ be either $\widehat{B}_{\text{rig}}^+$ or $B_{\text{rig,K}}^+$. For $n \geq n(r)$, write $t_n : B := \widehat{B}_{\text{rig}}^+ \to B_n := dR^+$ in the first case and $t_n : B := \mathbb{B}_{\text{rig,K}}^+ \to B_n := K_n \llbracket t, u_1, \ldots, u_d \rrbracket^\nabla$ in the second case. Let $D$ be a $\varphi$-module over $B$ of rank $d'$ and $D^{(1)}$ and $D^{(2)}$ two $B$-submodules of rank $d'$ stable by $\varphi$ on $D[1/t] = B[1/t] \otimes_B D$ such that

(i) $D^{(1)}[1/t] = D^{(2)}[1/t] = D[1/t]$;
(ii) $B_n \otimes_{t_n,B} D^{(1)} = B_n \otimes_{t_n,B} D^{(2)}$ for all $n \geq n(r)$.

Then, we have $D^{(1)} = D^{(2)}$.

Proof. Since $D^{(1)} + D^{(2)}$ is finite free by Lemma 4.2.8 and satisfies the same condition as $D^{(2)}$, we may assume that $D^{(1)} \subset D^{(2)}$ by replacing $D^{(2)}$ by $D^{(1)} + D^{(2)}$. Then, the proof of [Berger 2008b, Proposition I.3.4] works by using the ingredients Lemma 2.0.6 and Lemma 4.2.9 instead of [Berger 2008b, Proposition I.2.2].

Proposition 4.2.12 (cf. [Berger 2008b, Théorème II.1.2]). Let $V \in \text{Rep}_{dR}(G_K)$ be a de Rham representation with negative Hodge–Tate weights. Let $B$ be either $\widehat{B}_{\text{rig}}^+$ or $B_{\text{rig,K}}^+$ and $B_n$ and $t_n : B \to B_n$ be as in Lemma 4.2.11. In the first case, let $D_n := (\mathbb{B}_{dR} \otimes_K \mathbb{D}_{dR}(V))^{\nabla = 0}$, and let $D_n := (K_n \llbracket t, u_1, \ldots, u_d \rrbracket \otimes_K \mathbb{D}_{dR}(V))^{\nabla = 0}$ in
the second case. Put $D := \mathbb{B}_{\text{rig}}^{t,r} \otimes_{\mathbb{Q}_p} V$ in the first case and $D := D_{\text{rig}}^{-1+r}(V)$ in the second case. Then, the following holds.

(i) There exists $h \in \mathbb{N}$ such that

$$t^n B_n \otimes_{t_n,B} D \subset D_n \subset B_n \otimes_{t_n,B} D$$

for all $n \geq n(r)$.

(ii) Let $\iota_n : D \to B_n \otimes_{t_n,B} D$ be given by $x \mapsto 1 \otimes x$ and put

$$\mathcal{N} := \{ x \in D; \; \iota_n(x) \in D_n \; \text{for all} \; n \geq n(r) \}. $$

Then, $\mathcal{N}$ is a finite free $B$-submodule of $D$, whose rank is equal to $\dim_{\mathbb{Q}_p} V$. Moreover, there exists a canonical isomorphism

$$B_n \otimes_{t_n,B} \mathcal{N} \to D_n$$

for all $n \geq n(r)$.

**Proof.**

(i) Since the inclusion $B_n \subset \mathbb{B}_{\text{dr}}^+$ is faithfully flat by Lemma 4.1.4, we only have to prove the assertion after tensoring $\mathbb{B}_{\text{dr}}^+$ over $B_n$. We have the following isomorphisms:

$$\mathbb{B}_{\text{dr}}^+ \otimes_{B_n,B} D_n \cong \mathbb{B}_{\text{dr}}^+ \otimes_{B_n,B} D_{\text{rig}}^{t,r} \cong \mathbb{B}_{\text{dr}}^+ \otimes_{B_n,B} \mathbb{B}_{\text{dr}}^+ \otimes_{\mathbb{B}_{\text{dr}}^+} V_{\text{rig}} \otimes_{\mathbb{B}_{\text{dr}}^+} \mathbb{B}_{\text{dr}}^+ \otimes_{\mathbb{B}_{\text{dr}}^+} V_{\text{rig}},$$

where $D_{\text{rig}}^{t,r} := \mathbb{B}_{\text{rig}}^{t,r} \otimes_{\mathbb{Q}_p} V$ in the first case and $D_{\text{rig}}^{-1+r} := D_{\text{rig}}^{-1+r}(V)$ in the second case. Since $\mathbb{B}_{\text{dr}}^+ \otimes_{B_n,B} D_n \subset \mathbb{B}_{\text{dr}}^+ \otimes_{\mathbb{Q}_p} V$ by assumption and $\mathbb{B}_{\text{dr}}^+ \otimes_{B_n,B} D_{n}[1/t] \cong \mathbb{B}_{\text{dr}}^+ \otimes_{\mathbb{Q}_p} V$, there exists $h \in \mathbb{N}$ such that

$$t^h \mathbb{B}_{\text{dr}}^+ \otimes_{\mathbb{B}_{\text{dr}}^+} V \subset \mathbb{B}_{\text{dr}}^+ \otimes_{B_n,B} D_n \subset \mathbb{B}_{\text{dr}}^+ \otimes_{\mathbb{Q}_p} V,$$

which implies the assertion.

(ii) Since $\mathcal{N}$ is a closed $B$-submodule of $D$ containing $t^n D$, $\mathcal{N}$ is free of rank $\dim_{\mathbb{Q}_p} V$ by Lemma 4.2.8. To prove the second assertion, we only have to prove that the canonical map $B_n \otimes_{t_n,B} \mathcal{N} \to D_n/tD_n$ is surjective for all $n \geq n(r)$ since $B_n$ is a $t$-adically complete discrete valuation ring. Fix $n$ and let $x \in D_n$. Note that $\text{pr}_{n+1} \circ \iota_n : B \to B_n/t^{n+1}B_n$ is surjective. Indeed, when $B = \mathbb{B}_{\text{rig}}^{t,r}$, this follows from Lemma 4.2.6. When $B = \mathbb{B}_{\text{rig}}^{t,r}$, it is reduced to the case $h = 0$, and $\text{pr}_1 \circ \iota_n = \theta \circ \iota_n : \mathbb{B}_{\text{rig}}^{t,r} \to \mathbb{C}_p$ is surjective since $\mathbb{B}_{\text{rig}}^t \subset \mathbb{B}_{\text{rig}}^{t,r}$. Hence, there exists $y \in D$ such that $\iota_n(y) - x \in t^{n+1}B_n \otimes_{t_n,B} D \subset tD_n$. We put
$z := t_n, h_1 y \in D$, where $t_n, h_1$ is as in Lemma 4.2.10. By the property of $t_{\bullet, \bullet}$, we have

$$t_n(z) - x = (t_n(t_n, h_1) - 1)t_n(y) + t_n(y) - x \in tD_n$$

and for $m \neq n$,

$$t_m(z) \in t^{h_1} B_n \otimes_{t_n y} B \subset tD_n.$$

These imply $z \in \mathcal{N}$; hence, we obtain the assertion. □

**Definition 4.2.13.** In the context of Proposition 4.2.12, we denote $\mathcal{N}$ by $\tilde{N}_{\text{rig}}^{t, r}(V)$ in the first case and by $\mathcal{N}_{\text{dr}, r}(V)$ in the second case. For a de Rham representation $V$ with arbitrary Hodge–Tate weights, we put $\tilde{N}_{\text{rig}}^{t, r}(V) := \tilde{N}_{\text{rig}}^{t, r}(V(-n))(n)$ and $\mathcal{N}_{\text{dr}, r}(V) := \mathcal{N}_{\text{dr}, r}(V(-n))(n)$ for sufficiently large $n \in \mathbb{N}$. These definitions are independent of the choice of $n$. We also put $\tilde{N}_{\text{rig}}^{t, r}(V) := \bigcup_r \tilde{N}_{\text{rig}}^{t, r}(V)$ and $\mathcal{N}_{\text{dr}, r}(V) := \bigcup_r \mathcal{N}_{\text{dr}, r}(V)$. We note that for $0 < s \leq r$, the canonical map $\mathbb{B}_{\text{rig}, K} \otimes_{\mathbb{B}_{\text{rig}, r}} \mathcal{N}_{\text{dr}, r}(V) \to \mathcal{N}_{\text{dr}, s}(V)$ is an isomorphism by Lemma 4.2.11 and Proposition 4.2.12. So, the canonical morphism $\mathbb{B}_{\text{rig}, K} \otimes_{\mathbb{B}_{\text{rig}, r}} \mathcal{N}_{\text{dr}, r}(V) \to \mathcal{N}_{\text{dr}}(V)$ is an isomorphism, and in particular, $\mathcal{N}_{\text{dr}}(V)$ is a finite free $\mathbb{B}_{\text{rig}, K}$-module of rank $\dim_{\mathbb{Q}_p} V$. Since the map $\varphi : \mathbb{D}_{\text{rig}}^{t, r}(V) \to \mathbb{D}_{\text{rig}}^{t, r/p}(V)$ induces a map $\varphi : \mathcal{N}_{\text{dr}, r}(V) \to \mathcal{N}_{\text{dr}, r/p}(V)$ by the formula $t_{n+1} \circ \varphi = t_n$, $\mathcal{N}_{\text{dr}}(V)$ is stable under the $(\varphi, \Gamma_K)$-action of $\mathbb{D}_{\text{rig}}(V)$. Similarly, $\tilde{N}_{\text{rig}}^{t, r}(V)$ is free of rank $\dim_{\mathbb{Q}_p} V$ and is stable under the $(\varphi, \Gamma_K)$-action of $\mathbb{B}_{\text{rig}}^{t, r} \otimes_{\mathbb{Q}_p} V$. Thus, we obtain a $(\varphi, \Gamma_K)$-module $\tilde{N}_{\text{rig}}^{t, r}(V)$ over $\mathbb{B}_{\text{rig}}^{t, r}$ and a $(\varphi, \Gamma_K)$-module $\mathcal{N}_{\text{dr}}(V)$ over $\mathbb{B}_{\text{rig}, K}^{t, r}$.

### 4.3. Differential action of a $p$-adic Lie group

In this subsection, we recall basic facts on the differential action of a certain $p$-adic Lie group. Throughout this subsection, let $G$ be a $p$-adic Lie group, which is isomorphic to an open subgroup of $(1 + 2p\mathbb{Z}_p) \times \mathbb{Z}_p^d$ via a continuous group homomorphism $\eta : G \hookrightarrow \mathbb{Z}_p^\times \times \mathbb{Z}_p^d$. Denote $\eta(\gamma) = (\eta_0(\gamma), \ldots, \eta_d(\gamma)) \in \mathbb{Z}_p^\times \times \mathbb{Z}_p^d$ for $\gamma \in G$. For $1 \leq j \leq d$, let

$$G_0 := \{ \gamma \in G; \eta_j(\gamma) = 0 \text{ for all } j > 0 \},$$

$$G_j := \{ \gamma \in G; \eta_0(\gamma) = 1, \eta_i(\gamma) = 0 \text{ for all positive } i \neq j \}.$$

**Notation 4.3.1.** Let $(R, v)$ be a $\mathbb{Q}_p$-Banach algebra and $M$ a finite free $R$-module endowed with an $R$-valuation $v$. Assume that $G$ acts on $R$ and $M$ such that:

(i) The $G$-action on $R$ is $\mathbb{Q}_p$-linear and the action of $G$ on $M$ is $R$-semilinear.

(ii) We have $v \circ \gamma(x) = v(x)$ for all $x \in R$ and $\gamma \in G$.

(iii) There exists an open subgroup $G_o \leq G$ such that

$$v((\gamma - 1)x) \geq v(x) + v(p)$$

for all $\gamma \in G_o$ and $x \in R$. 
(iv) For any \( x \in M \), there exists an open subgroup \( G_x \leq_o G_o \) such that
\[
v((\gamma - 1)x) \geq v(x) + v(p)
\]
for all \( \gamma \in G_x \).

**Construction 4.3.2.** Let the notation be as in Notation 4.3.1. We extend the construction of the differential operator \( \nabla_V \) in [Berger 2002, §5.1] to this setting. By assumption, there exists an open subgroup \( G_M \leq_o G_o \) such that
\[
v((\gamma - 1)x) \geq v(x) + v(p)
\]
for all \( x \in M \) and \( \gamma \in G_M \). Hence, we can apply Berger’s argument to the 1-parameter subgroup \( \gamma Z_p \) for \( \gamma \in G_M \). Thus, we can define a continuous \( \mathbb{Q}_p \)-linear map
\[
\log(\gamma) : M \to M
\]
\[
x \mapsto \log(\gamma)(x) := \sum_{n \geq 1} (-1)^{n-1} \frac{(\gamma - 1)^n}{n} x
\]
for \( \gamma \in G_M \). Moreover, the operators
\[
\nabla_0(x) := \frac{\log(\gamma)(x)}{\log(\eta_0(\gamma))}
\]
for \( \gamma \in G_M \cap G_0 \),
\[
\nabla_j(x) := \frac{\log(\gamma)(x)}{\eta_j(\gamma)}
\]
for \( \gamma \in G_M \cap G_j \)
for \( 1 \leq j \leq d \) are independent of the choice of \( \gamma \).

Assume that \( N \) satisfies the conditions of Notation 4.3.1. Then, \( M \otimes_R N \) satisfies the conditions of Notation 4.3.1, and we have
\[
\log(\gamma \otimes \gamma') = \log(\gamma) \otimes \text{id}_N + \text{id}_M \otimes \log(\gamma) \quad \text{for } \gamma \in G_M \cap G_N
\]
in \( \text{End}_{\mathbb{Q}_p}(M \otimes_R N) \). With \( (M, N) = (R, R) \) or \( (M, R) \), \( \nabla : R \to R \) is a continuous derivation and \( \nabla_j : M \to M \) is a continuous derivation, compatible with \( \nabla_j : R \to R \), that is, \( \nabla_j(\lambda x) = \nabla_j(\lambda)x + \lambda \nabla_j(x) \) for \( \lambda \in R \) and \( x \in M \).

**Lemma 4.3.3.** Let the notation be as in Construction 4.3.2. In \( \text{End}_{\mathbb{Q}_p}(M) \), we have
\[
[\nabla_i, \nabla_j] = -[\nabla_j, \nabla_i] = \begin{cases} 
\nabla_j & \text{if } i = 0, 1 \leq j \leq d, \\
0 & \text{if } 1 \leq i, j \leq d.
\end{cases}
\]

**Proof.** Since \( G_i \) and \( G_j \) are commutative for \( 1 \leq i, j \leq d \), the assertion in the second case is trivial. We prove the other case. Fix \( x \in M \). We regard \( G \) as a subgroup of \( \text{GL}_{d+1}(\mathbb{Z}_p) \) as in Section 1.3. For sufficiently small \( u_0, u_j \in \mathbb{Z}_p \), put \( \gamma_0 := 1 + u_0 E_{1,0} \in G_0 \cap G_M \), \( \gamma_j := 1 + u_j E_{1,j} \in G_j \cap G_M \), where \( E_{1,j} \) is the
After applying both sides to $x$, the actions of $\nabla$ thus the assumption that for all $0 \leq j \leq d$, which are compatible with $\nabla_j : R \to R$ that satisfy

$$[\nabla_0, \nabla_j] = \nabla_j \quad \text{for } 1 \leq j \leq d, \quad [\nabla_i, \nabla_j] = 0 \quad \text{for } 1 \leq i, j \leq d.$$ 

Thus, the actions of $\nabla_0, \ldots, \nabla_d$ give rise to a differential action of the Lie algebra $\text{Lie}(G) \cong \mathbb{Q}_p \ltimes \mathbb{Q}_p^d$.

4.4. Differential action and differential conductor of $\mathbb{N}_{\text{dR}}$. In Section 4.2, we constructed $\mathbb{N}_{\text{dR}}(V)$ for de Rham representations $V$ as a $(\varphi, \Gamma_K)$-module. The aim of this subsection is to endow $\mathbb{N}_{\text{dR}}(V)$ with the structure of $(\varphi, \nabla)$-module in the sense of Definition 1.7.5 by using the results in Section 4.3. As a consequence, we can define the differential Swan conductor of $\mathbb{N}_{\text{dR}}(V)$ (Definition 4.4.9). Throughout this subsection, let $V$ denote a $p$-adic representation of $G_K$.

**Lemma 4.4.1.** There exists an open normal subgroup $\Gamma_K^r \leq o \Gamma_K$ and $r_K > 0$ such that for all $0 < r \leq r_K$, there exists $c_r > 0$ such that

$$w_r((1 - \gamma)x) \geq w_r(x) + c_r, \quad \forall x \in \mathbb{B}_{K}^{\varphi, r}, \forall \gamma \in \Gamma_K^r.$$ 

**Proof.** We may assume $x \in \mathbb{A}_K^{\varphi, r}$. Recall that the ring $\Lambda_{m, \mathcal{O}_K}^{(i)}$ is a subring of $\mathbb{A}_K^{\varphi, r}$ containing $\mathbb{A}_K^{\varphi, r}$ for $m \in \mathbb{N}$ by [Andreatta and Brinon 2008, page 82]. Hence, we
only have to prove a similar assertion for $\Lambda_{m,\mathcal{O}_K}^{(i)}$. Then, the assertion follows from [Andreatta and Brinon 2008, Proposition 4.22] if we define $\Gamma_K^o$ as the closed subgroup of $\Gamma_K$ topologically generated by $\{y_j^{m_j}; 0 \leq j \leq d\}$ for sufficiently large $m$.

By shrinking $\Gamma_K^o$, if necessary, we may assume that $\Gamma_K^o$ is an open subgroup of $(1 + 2p\mathbb{Z}_p) \times \mathbb{Z}_p$ as in Section 1.3. In the rest of this paper, we assume that $r_0$ in Notation 4.2.1 is sufficiently small such that $r_0 \leq r_K$.

**Lemma 4.4.2.** For $x \in \mathbb{F}^{1,r}$ and $c > 0$, there exists an open subgroup $U_{x,c} \leq_o G_K$ such that

$$w_r((g - 1)x) \geq c \quad \text{for all } g \in U_{x,c}.$$  

**Proof.** We may assume that $x$ is of the form $[\bar{x}]$ with $\bar{x} \in \mathbb{F}$. Indeed, if we write $x = \sum_{k \geq -\infty} p^k [x_k]$ with $x_k \in \mathbb{F}$, then, by definition, there exists $N$ such that $w_r(p^k [x_k]) \geq c$ for all $k \geq N$. We choose $U_{x,c}$ such that $w_r((g - 1)(p^k [x_k])) \geq c$ for all $k \leq N$ and all $g \in U_{x,c}$. Then, $U_{x,c}$ satisfies the condition.

Let $x = [\bar{x}]$ with $\bar{x} \in \mathbb{F}$. Since the action of $G_K$ on $\mathbb{F}$ is continuous, there exists $U_{x,c} \leq_o G_K$ such that $v_\mathbb{F}((g - 1)\bar{x}) \geq p^{|c|}c/r > 0$ for all $g \in U_{x,c}$. We prove that $U_{x,c}$ satisfies the desired condition. We can write

$$(g - 1)[\bar{x}] = [(g - 1)\bar{x}] + \sum_{k \geq 1} p^k [x_k]$$

for some $x_k \in \mathbb{F}$. Since

$$[\bar{x}][(g - 1)\bar{x}] + 1 = (g(\bar{x}), -x_1^p, -x_2^p, \ldots),$$

$x_k^{p^k}/\bar{x}$ can be written as the value of a polynomial, with coefficients in $\mathbb{Z}$ with zero constant term, at $(g - 1)\bar{x}/\bar{x}$. Indeed, let $S_m \in \mathbb{Z}[X_0, \ldots, X_m, Y_0, \ldots, Y_m]$ for $m \in \mathbb{N}$ be a family of polynomials defining the addition on the ring of Witt vectors, see [Bourbaki 2006, n°3, §1, IX]. Then, $S_m$ is homogeneous of degree $p^m$, where deg$(X_i) = deg(Y_i) = p^i$. Since $S_0 = X_0 + Y_0$ and $\sum_{0 \leq i \leq m} p^i S_i = \sum_{0 \leq i \leq m} p^i X_i^{p^m-1} + \sum_{0 \leq i \leq m} p^i Y_i^{p^m-1}$ for $m \geq 1$, the coefficients of both $X_0^{p^m}, Y_0^{p^m} \in S_m$ are equal to zero, which implies the assertion. Hence, for $n \in \mathbb{N}$, we have

$$v_\mathbb{F}^n((g - 1)[\bar{x}]) = \inf_{1 \leq k \leq n} \left\{ v_\mathbb{F}((g - 1)\bar{x}), v_\mathbb{F}(x_k) \right\}$$

$$\geq \inf_{1 \leq k \leq n} \left\{ v_\mathbb{F}((g - 1)\bar{x}), \frac{1}{p^k} v_\mathbb{F}((g - 1)\bar{x}) \right\} = \frac{1}{p^n} v_\mathbb{F}((g - 1)\bar{x}).$$

Note that $v_\mathbb{F}^n((g - 1)[\bar{x}]) = \infty$ for $n \in \mathbb{Z}_{\leq 0}$. Hence, we have $w_r((g - 1)[\bar{x}]) = \inf_{n \in \mathbb{N}} (r v_\mathbb{F}^n((g - 1)[\bar{x}]) + n) \geq \inf (r \cdot \frac{1}{p^{|c|}} v_\mathbb{F}((g - 1)\bar{x}), [c]) \geq c$, which implies the assertion.
Lemma 4.4.3. Let \( \{e_i\} \) be a \( \mathbb{B}^{t,r}_K \)-basis of \( \mathbb{D}^{t,r}(V) \). We endow \( \mathbb{D}^{t,r}(V) \) with valuations \( \{w_s\}_{0<s\leq r} \) that are compatible with the \( \{w_s\}_{0<s\leq r} \) associated to \( \{e_i\} \). Then, the actions of \( \Gamma^o_K \) on \( \mathbb{B}^{t,r}_{\text{rig},K} \) and \( \mathbb{D}^{t,r}(V) \) satisfy the conditions of Notation 4.3.1.

Proof. Conditions (i) and (ii) follow from the definition. Condition (iii) follows from the formula \( \gamma^p - 1 = \sum_{1 \leq i \leq p} \binom{p}{i} (\gamma - 1)^i \) and Lemma 4.4.1. To prove condition (iv), we may assume \( x \in \mathbb{D}^{t,r}(V) \). We choose a lattice \( T \) of \( V \) stable under the \( G_K \)-action. Let \( \{f_i\} \) be a basis of \( T \) and endow \( \mathbb{B}^{t,r}_{\text{rig}} \otimes \mathbb{Q}_p V \) with the valuations \( \{w'_{s}\}_{0<s\leq r} \), compatible with the \( \{w_s\}_{0<s\leq r} \), associated to the \( \mathbb{B}^{t,r}_{\text{rig}} \)-basis \( \{1 \otimes f_i\} \). By the canonical isomorphism \( \mathbb{B}^{t,r}_{\text{rig}} \otimes \mathbb{Q}_p \mathbb{D}^{t,r}(V) \cong \mathbb{B}^{t,r}_{\text{rig}} \otimes \mathbb{Q}_p V \) following from Theorem 1.10.5, we regard \( \{1 \otimes e_i\} \) as a \( \mathbb{B}^{t,r}_{\text{rig}} \)-basis of \( \mathbb{B}^{t,r}_{\text{rig}} \otimes \mathbb{Q}_p V \). Then, \( w_s \) is equivalent to \( w'_s \); therefore, we only have to prove that for any \( x \in \mathbb{B}^{t,r}_{\text{rig}} \otimes \mathbb{Q}_p V \) and \( 0 < s \leq r \), there exists an open subgroup \( G^o_{K,s,x} \leq_o G_K \) such that \( w'_s((g-1)x) \geq w'_s(x) + w'_s(p) \) for all \( g \in G^o_{K,s,x} \). We may assume that \( x \) is of the form \( \lambda \otimes v \) for \( \lambda \in \tilde{\mathbb{B}}^{t,r} \) and \( v \in T \). Since the action of \( G_K \) on \( T \) is continuous, there exists an open subgroup \( U \leq_o G_K \) such that \( U \) acts trivially on \( T/pT \). We apply Lemma 4.4.2 after regarding \( \lambda \in \tilde{\mathbb{B}}^{t,s} \), and get that there exists an open subgroup \( U' \leq_o G_K \) such that \( w_s((g-1)\lambda) \geq w_s(\lambda) + w_s(p) \) for all \( g \in U' \). If we put \( G^o_{K,s,x} := U \cap U' \), then the assertion follows from

\[
(g-1)(\lambda \otimes v) = (g-1)(\lambda \otimes g(v) + \lambda \otimes (g-1)v).
\]

\[\Box\]

Definition 4.4.4. By Lemma 4.4.3, we can apply Construction 4.3.4 to \( \mathcal{G} = \Gamma_K \), \( R = \mathbb{B}^{t,r}_{\text{rig},K} \) and \( M = \mathbb{D}^{t,r}(V) \). Thus, we obtain continuous differentials operators \( \nabla_j \) on \( \mathbb{D}^{t,r}_{\text{rig}}(V) \) for \( 0 \leq j \leq d \). The operator \( \nabla_j \) induces a continuous differential operator on \( \mathbb{D}^1_{\text{rig}}(V) \), which is denoted by \( \nabla_j \) again. Since the actions of \( \Gamma_K \) and \( \varphi \) commute, \( \nabla_j \) commutes with \( \varphi \) by definition.

Until otherwise stated, let \( V = \mathbb{Q}_p \) and regard \( \mathbb{D}^{t,r}_{\text{rig}}(\mathbb{Q}_p) \) as \( \mathbb{B}^{t,r}_{\text{rig},K} \). Then, \( \nabla_j \) can be regarded as a continuous derivation on \( \mathbb{B}^{t,r}_{\text{rig},K} \). In the following, we will describe this derivation explicitly.

Construction 4.4.5. As in [Andreotta and Brinon 2010, Proposition 4.3], the action of \( \Gamma_K \) on \( K_n[t,u_1, \ldots, u_d] \) induces \( K_n \)-linear differentials

\[
\tilde{\nabla}_0 := \frac{\log(\gamma_0)}{\log(\eta_0(\gamma_0))} = t(1+\pi) \frac{\partial}{\partial \pi},
\]

\[
\tilde{\nabla}_j := \frac{\log(\gamma_j)}{\eta_j(\gamma_j)} = -t_i[\tilde{r}_j] \frac{\partial}{\partial u_j}
\]

for all sufficiently small \( \gamma_0 \in \Gamma_{K,0} \) and \( \gamma_j \in \Gamma_{K,j} \). Note that these are continuous with respect to the canonical topology. Since the action of \( \Gamma_K \) commutes with \( \nabla^{\text{geom}} \) by definition, \( \tilde{\nabla}_j \) acts on \( K_n[t,u_1, \ldots, u_d]^{\nabla} \).
We assume $K = \tilde{K}$ until otherwise stated. By the isomorphism $\mathbb{A}_k^{\dagger,r} \cong O((\pi))^{\dagger,r}$, we have derivations
\[
\partial_0 := \frac{\partial}{\partial \pi}, \quad \partial_1 := \frac{\partial}{\partial \tilde{t}_1}, \ldots, \quad \partial_d := \frac{\partial}{\partial \tilde{t}_d},
\]
on $\mathbb{A}_k^{\dagger,r}$ (see Section 1.7), which are continuous with respect to the Fréchet topology defined by $\{w_s\}_{0 < s \leq r}$. By passing to the completion, we obtain continuous derivations $\partial_j : \mathbb{B}_{\text{rig}, K}^{\dagger,r} \to \mathbb{B}_{\text{rig}, K}^{\dagger,r}$ for $0 \leq j \leq d$. The derivation $\partial_j$ also extends to a derivation $\partial_j : \mathbb{B}_{\text{rig}, K}^{\dagger,r} \to \mathbb{B}_{\text{rig}, K}^{\dagger,r}$. By Lemma 4.2.7, we may regard $\mathbb{B}_{\text{rig}, K}^{\dagger,r}$ as a dense subring of $K_n[[t, u_1, \ldots, u_d]]^\vee$ via $\iota_n$. Hence, we can extend any continuous derivation $\partial$ on $\mathbb{B}_{\text{rig}, K}^{\dagger,r}$ to a continuous derivation on $K_n[[t, u_1, \ldots, u_d]]^\vee$, which is denoted by $\iota_n(\partial)$. Note that we have a formula
\[
\iota_n(\partial)(\iota_n(x)) = \iota_n(\partial(x)) \text{ for } x \in \mathbb{B}_{\text{rig}, K}^{\dagger,r}.
\]
\textbf{Lemma 4.4.6.} For $n \geq n(r)$, we have
\[
\iota_n(t(1 + \pi)\partial_0) = \tilde{\nabla}_0, \quad \iota_n(t[\tilde{t}_j]\partial_j) = \tilde{\nabla}_j \text{ for } 1 \leq j \leq d.
\]
\textbf{Proof.} Let $1 \leq j \leq d$ and put $\delta_0 := \iota_n(t(1 + \pi)\partial_0) - \tilde{\nabla}_0$ and $\delta_j := \iota_n(t[\tilde{t}_j]\partial_j) - \tilde{\nabla}_j$. Let $f : K_n[[t, u_1, \ldots, u_d]] \to K_n[[t, u_1, \ldots, u_d]]^\vee$ be the map defined in the proof of Lemma 4.1.4, which is continuous by Lemma 4.1.6. Since $f$ induces a surjection on the residue fields by definition, $f(K_n[t])$ is a dense subring of $K_n[[t, u_1, \ldots, u_d]]^\vee$ by Lemmas 4.1.4 and 4.1.5. Hence, we only have to prove that $\delta_0 \circ f(K_n[t]) = \delta_j \circ f(K_n[t]) = 0$. We view $\delta_0 \circ f|_{K_n}$, $\delta_j \circ f|_{K_n} \in \text{Der}_{\text{cont}}(K_n, K_n[[t, u_1, \ldots, u_d]]^\vee)$, which is isomorphic to $\text{Hom}_{K_n}(\tilde{\Omega}^1_{K_n}, K_n[[t, u_1, \ldots, u_d]]^\vee)$ by Lemma 1.2.3. Since $\tilde{\Omega}^1_{K_n} \cong K_n \otimes_K \tilde{\Omega}^1_K$ has a $K_n$-basis $\{dt_i : 1 \leq i \leq d\}$ and since we have $f(t) = t$ and $f(t_i) = [\tilde{t}_i]$ by definition, we only have to prove $\delta_0(t) = \delta_j(t) = 0$ and $\delta_0([\tilde{t}_i]) = \delta_j([\tilde{t}_i]) = 0$ for all $1 \leq i \leq d$. By using formula (7), we get
\[
\iota_n(t(1 + \pi)\partial_0)(t) = t = \tilde{\nabla}_0(t), \quad \iota_n(t(1 + \pi)\partial_0)[\tilde{t}_j] = 0,
\]
\[
\iota_n(t[\tilde{t}_j]\partial_j)(t) = 0 = \tilde{\nabla}_j(t), \quad \iota_n(t[\tilde{t}_j]\partial_j)[\tilde{t}_i] = \delta_{ij} t[\tilde{t}_j]
\]
for all $1 \leq i \leq d$. Since $(\partial/\partial u_i)[\tilde{t}_j] = -(\partial/\partial u_j)u_i = -\delta_{ij}$ for all $1 \leq i \leq d$, we obtain the assertion.

For the rest of this section, we drop the assumptions $K = \tilde{K}$ and $V = \mathbb{Q}_p$.

\textbf{Corollary 4.4.7.} The derivation
\[
d' : \mathbb{B}_{\text{rig}, K}^{\dagger,r} \to \tilde{\Omega}^1_{\mathbb{B}_{\text{rig}, K}^{\dagger,r}}
\]
\[
x \mapsto \nabla_0(x) \frac{1}{t(1 + \pi)} d\pi + \sum_{1 \leq j \leq d} \nabla_j(x) \frac{1}{t} d[\tilde{t}_j]
\]
coincides with the canonical derivation $d : \mathbb{B}_{\text{rig}, K}^{\dagger,r} \to \tilde{\Omega}^1_{\mathbb{B}_{\text{rig}, K}^{\dagger,r}}$. 

Proof. Since the canonical map $\mathbb{B}_{\text{rig}, \bar{K}}^{\dagger} \to \mathbb{B}_{\text{rig}, K}^{\dagger}$ is finite étale by [Kedlaya 2005, Proposition 2.4.10], we can reduce to the case $K = \bar{K}$. Let the notation be as in Lemma 4.4.6. Obviously, $\nabla_j$ extends to $\tilde{\nabla}_j$ by passing to the completion. Since $t_n$ is injective, we have

$$\nabla_0 = t(1 + \pi)\partial_0, \quad \nabla_j = t[\tilde{\nabla}_j] \partial_j \quad \text{for } 1 \leq j \leq d.$$

as derivations of $\mathbb{B}_{\text{rig}, K}^{\dagger, r}$ by Lemma 4.4.6, which implies the assertion. \hfill \square

**Lemma 4.4.8.** Let $V \in \text{Rep}_{\text{dR}}(G_K)$.

(i) We have $\nabla_j(\mathbb{N}_{\text{dR}}(V)) \subset t\mathbb{N}_{\text{dR}}(V)$ for all $0 \leq j \leq d$. We put $\nabla'_j := 1/t\nabla_j$, which is a continuous differential operator on $\mathbb{N}_{\text{dR}}(V)$.

(ii) For all $0 \leq i, j \leq d$, we have

$$[\nabla'_i, \nabla'_j] = 0$$

(iii) For all $0 \leq i, j \leq d$, we have

$$\nabla'_j \circ \phi = p\phi \circ \nabla'_j$$

**Proof.**

(i) By Tate twist, we may assume that the Hodge–Tate weights of $V$ are sufficiently small. Let the notation be as in Construction 4.4.5 and Proposition 4.2.12 (with $B = \mathbb{B}_{\text{rig}, K}^{\dagger, r}$). By viewing $t\mathbb{N}_{\text{dR}, r}(V)$ and $t\mathbb{D}_{\text{dR}}(V)$ as $\mathbb{N}_{\text{dR}, r}(V(1))$ and $\mathbb{D}_{\text{dR}}(V(1))$, respectively, we only have to prove that $t_n(\nabla_j(x)) \in tD_n$ for all $n \geq n(r)$ and $x \in \mathbb{N}_{\text{dR}, r}(V)$.

For sufficiently small $\gamma_j \in \Gamma_{K, j}$, we have $t_n \circ \log(\gamma_j)(x) = \log(\gamma_j)(t_n(x))$ and $t_n(x) \in D_n \subset B_n \otimes_K \mathbb{D}_{\text{dR}}(V)$. Since $\Gamma_K$ acts trivially on $\mathbb{D}_{\text{dR}}(V)$, $\log(\gamma_j)$ acts on $B_n \otimes_K \mathbb{D}_{\text{dR}}(V)$ as $\log(\gamma_j) \otimes 1$. Since $\log(\gamma_j)(B_n) \subset tB_n$ (see Construction 4.4.5), we have $t_n \circ \log(\gamma_j)(x) \in (B_n \otimes_K \mathbb{D}_{\text{dR}}(V(1)))^\text{tors} = 0 = tD_n$.

(ii) This follows from a straightforward calculation using Lemma 4.3.3, $\nabla_0(t) = t$, and $\nabla_i(t) = \nabla_j(t) = 0$.

(iii) Since $\nabla_j$ commutes with $\phi$, we have $t\nabla'_j \circ \phi = \nabla_j \circ \phi = \phi \circ \nabla_j = \phi(t) \varphi \circ \nabla'_j = pt \varphi \circ \nabla'_j$. By dividing by $t$, we obtain the assertion since $\mathbb{N}_{\text{dR}}(V)$ is torsion free. \hfill \square

**Definition 4.4.9.** Let the notation be as in Lemma 4.4.8. For $V \in \text{Rep}_{\text{dR}}(G_K)$, put

$$\nabla : \mathbb{N}_{\text{dR}}(V) \to \mathbb{N}_{\text{dR}}(V) \otimes_{\mathbb{B}_{\text{rig}, K}^{\dagger}} \Omega_{\mathbb{B}_{\text{rig}, K}^{\dagger}}^1$$

$$x \mapsto \nabla'_0(x) \otimes \frac{1}{1 + \pi} d\pi + \sum_{1 \leq j \leq d} \nabla'_j(x) \otimes d[\tilde{\nabla}_j],$$
which defines a $\nabla$-structure on $\mathbb{N}_{\text{dR}}(V)$ by Corollary 4.4.7. Furthermore, this $\nabla$-structure is compatible with the $\varphi$-structure on $\mathbb{N}_{\text{dR}}(V)$ by Lemma 4.4.8(iii) and $\varphi((1 + \pi)^{-1}d\pi) = p(1 + \pi)^{-1}d\pi$ and $\varphi(d[\tilde{t}_j]) = pd[\tilde{t}_j]$. Thus, $\mathbb{N}_{\text{dR}}(V)$ is endowed with a $(\varphi, \nabla)$-module structure and we obtain the differential Swan conductor $\nabla^V(\mathbb{N}_{\text{dR}}(V))$ of $\mathbb{N}_{\text{dR}}(V)$. The slope filtration of $\mathbb{N}_{\text{dR}}(V)$ as a $(\varphi, \nabla)$-module (Theorem 1.7.6) is $\Gamma_K$-stable by the commutativity of the $\Gamma_K$- and $\varphi$-actions, and the uniqueness of the slope filtration ([Kedlaya 2007, Theorem 6.4.1]).

4.5. Comparison of pure objects. In this subsection, we will study “pure” objects in various categories.

Notation 4.5.1. Let $G$ be a topological group and $R$ a topological ring on which $G$ acts. Let $\phi : R \to R$ be a continuous ring homomorphism that commutes with the action of $G$. A $(\phi, G)$-module over $R$ is a finite free $R$-module with continuous and semilinear action of $G$ and a semilinear endomorphism $\phi$, both of which are commutative. We denote the category of $(\phi, G)$-modules over $R$ by $\text{Mod}_R(\phi, G)$. The morphisms in $\text{Mod}_R(\phi, G)$ consist of $R$-linear maps commuting with $\phi$ and $G$.

Definition 4.5.2 [Berger 2008a, Definition 3.2.1]. Let $h \geq 1$ and $a \in \mathbb{Z}$ be relatively prime. Let $\text{Rep}_{a,h}(G_K)$ be the category with objects $V_{a,h} \in \text{Rep}_{\mathbb{Q},p}\mathbb{A}_{\text{dR}}(G_K)$, endowed with a semilinear Frobenius action $\varphi : V_{a,h} \to V_{a,h}$ that commutes with the $G_K$-action such that $\varphi^h = p^a$. The morphisms of this category are $\mathbb{Q}_{p^h}$-linear maps that commute with $(\varphi, G_K)$-actions. When $h = 1$ and $a = 0$, $\text{Rep}_{a,h}(G_K) = \text{Rep}_{\mathbb{Q},p}(G_K)$.

Let $s := a / h \in \mathbb{Q}$. We denote by $D_{[s]}$ the $\mathbb{Q}_p$-vector space $\bigoplus_{1 \leq i \leq h} \mathbb{Q}_p e_i$ endowed with a trivial $G_K$-action and with $\varphi$-actions via $\varphi(e_i) := e_{i+1}$ if $i \neq h$ and $\varphi(e_h) := p^a e_1$. Then, $\mathbb{Q}_p \otimes_{\mathbb{Q}_p} D_{[s]}$ belongs to $\text{Rep}_{a,h}(G_K)$.

Definition 4.5.3. For $s \in \mathbb{Q}$, we define

\[ \text{Mod}_{\mathbb{B}_{\text{dR}}}^s(\varphi, G_K), \quad \text{Mod}_{\mathbb{B}_{\text{dR}}}^s(\varphi, \Gamma_K), \quad \text{Mod}_{\mathbb{B}_K}^s(\varphi, G_K), \quad \text{Mod}_{\mathbb{B}_K}^s(\varphi, \Gamma_K) \]

to be the full subcategories of $\text{Mod}_{\mathbb{B}_{\text{dR}}}^s(\varphi, G_K), \text{Mod}_{\mathbb{B}_{\text{dR}}}^s(\varphi, \Gamma_K), \text{Mod}_{\mathbb{B}_K}^s(\varphi, G_K)$ and $\text{Mod}_{\mathbb{B}_K}^s(\varphi, \Gamma_K)$, whose objects are pure of slope $s$ as $\varphi$-modules.

Lemma 4.5.4. (i) For any $r > 0$, there exists a canonical injection

\[ \widehat{B}_{\text{rig}}^\nabla + \to \widehat{B}_{\text{rig}}^{\nabla, r}, \]

which is $(\varphi, G_K)$-equivariant. In the following, we regard $\widehat{B}_{\text{rig}}^\nabla$ as a subring of $\widehat{B}_{\text{rig}}^{\nabla, r}$ and we endow $\widehat{B}_{\text{rig}}^\nabla$ with a Fréchet topology induced by the family of valuations $\{w_r\}_{r > 0}$.

(ii) For $h \in \mathbb{N}_{>0}$,

\[ (\widehat{B}_{\text{rig}}^\nabla)^{\psi^h} = 1 = (\widehat{B}_{\text{rig}}^{\nabla, r})^{\psi^h} = \mathbb{Q}_{p^h}. \]
Proof. By definition, $\tilde{\mathbb{B}}_{\text{rig}}^{\nabla+}$ and $\tilde{\mathbb{B}}_{\text{rig}}^{\nabla,r}$ depend only on $\mathbb{C}_p$ and not on $K$. By regarding $\mathbb{C}_p$ as the $p$-adic completion of the algebraic closure of $K^{pf}$, we can reduce to the perfect residue field case. Assertion (i) follows from [Berger 2002, Exemple 2.8(2), Definition 2.16]. Assertion (ii) for $\tilde{\mathbb{B}}_{\text{rig}}^{\nabla+}$ is due to Colmez, see [Ohkubo 2013, Lemma 6.2], and (ii) for $\tilde{\mathbb{B}}_{\text{rig}}^{\nabla,r}$ is a consequence of [Berger 2002, Proposition 3.2]. □

Definition 4.5.5. For $s \in \mathbb{Q}$, an object $M \in \text{Mod}_{\tilde{\mathbb{B}}_{\text{rig}}^{\nabla+}}(\varphi, G_K)$ is said to be pure of slope $s$ if $M$ is isomorphic to $(\tilde{\mathbb{B}}_{\text{rig}}^{\nabla+} \otimes_{\mathbb{Q}_p} D[s])^m$ as a $\varphi$-module for some $m \in \mathbb{N}$. Denote by $\text{Mod}^s_{\tilde{\mathbb{B}}_{\text{rig}}^{\nabla+}}(\varphi, G_K)$ the category of $(\varphi, G_K)$-modules over $\tilde{\mathbb{B}}_{\text{rig}}^{\nabla+}$, which are pure of slope $s$.

Lemma 4.5.6. Let the notation be as in Notation 1.6.2 and Definition 1.7.5. For $s \in \mathbb{Q}$, the forgetful functor

$$\text{Mod}^s_{\tilde{\mathbb{R}}}(\varphi, \nabla) \to \text{Mod}^s_{\tilde{\mathbb{R}}}(\varphi).$$

is fully faithful.

Proof. We consider the following commutative diagram

$$\begin{array}{ccc}
\text{Mod}^s_{\Gamma[1/p]}(\varphi, \nabla) & \xrightarrow{\alpha_1} & \text{Mod}^s_{\Gamma[1/p]}(\varphi) \\
\beta_1 \uparrow & & \uparrow \gamma_1 \\
\text{Mod}^s_{\Gamma[1/p]}(\varphi, \nabla) & \xrightarrow{\alpha_2} & \text{Mod}^s_{\Gamma[1/p]}(\varphi) \\
\beta_2 \downarrow & & \downarrow \gamma_2 \\
\text{Mod}^s_{\tilde{\mathbb{R}}}(\varphi, \nabla) & \xrightarrow{\alpha_3} & \text{Mod}^s_{\tilde{\mathbb{R}}}(\varphi)
\end{array}$$

where $\alpha_\bullet$ is a forgetful functor, and $\beta_\bullet$ and $\gamma_\bullet$ are base change functors. We first note that $\gamma_1$ (resp. $\gamma_2$) is fully faithful (resp. an equivalence) by [Kedlaya 2005, Theorem 6.3.3(a)] (resp. [Kedlaya 2005, Theorem 6.3.3(b)]). Let $M, N \in \text{Mod}^s_{\Gamma[1/p]}(\varphi, \nabla)$ and let $\hat{M}, \hat{N}$ be the base changes of $M, N$ via the canonical map $\Gamma[1/p] \to \Gamma[1/p]$. Then, we have

$$\text{Hom}_{\text{Mod}^s_{\Gamma[1/p]}(\varphi, \nabla)}(M, N) = \text{Hom}_{\Gamma[1/p]}(M, N)^{\psi=1, \nabla=0}$$

$$= \text{Hom}_{\Gamma[1/p]}(\hat{M}, \hat{N})^{\psi=1, \nabla=0},$$

where the first equality follows by definition and the second equality follows because $\gamma_1$ is fully faithful. Therefore, $\beta_1$ is fully faithful. For the same reason, since $\gamma_2$ is fully faithful, so is $\beta_2$. Note that $\alpha_1$ is an equivalence in the étale case, i.e., $s = 0$ ([Kedlaya 2007, Proposition 3.2.8]). Let $M, N \in \text{Mod}^s_{\Gamma[1/p]}(\varphi, \nabla)$. Since $\text{Hom}_{\Gamma[1/p]}(M, N) \cong M^\vee \otimes_{\Gamma[1/p]} N$ can be regarded as an étale $(\varphi, \nabla)$-module over
Lemma 4.5.7. Let $s \in \mathbb{Q}$ and let $h \in \mathbb{N}_{\geq 1}$, $a \in \mathbb{Z}$ be relatively prime with $s = a/h$.

(i) There exist equivalences of categories

\begin{align*}
\tilde{\mathbb{D}}_{\text{rig}}^+ & : \text{Rep}_{a,h}(G_K) \to \text{Mod}_{B_{\text{rig}, K}}^\ast (\varphi, G_K); \quad V_{a,h} \mapsto \tilde{\mathbb{D}}_{\text{rig}}^+ \otimes_{\mathbb{Q}_p^h} V_{a,h}, \\
\tilde{\mathbb{D}}_{\text{rig}} & : \text{Rep}_{a,h}(G_K) \to \text{Mod}_{B_{\text{rig}, K}}^\ast (\varphi, \Gamma_K); \quad V_{a,h} \mapsto \tilde{\mathbb{D}}_{\text{rig}} \otimes_{\mathbb{Q}_p^h} V_{a,h}, \\
\tilde{\mathbb{D}}_{\text{rig}}^\dagger & : \text{Rep}_{a,h}(G_K) \to \text{Mod}_{B_{\text{rig}, K}}^\ast (\varphi, G_K); \quad V_{a,h} \mapsto \tilde{\mathbb{D}}_{\text{rig}}^\dagger \otimes_{\mathbb{Q}_p^h} V_{a,h}, \\
\tilde{\mathbb{D}}^\dagger & : \text{Rep}_{a,h}(G_K) \to \text{Mod}_{B_{\text{rig}, K}}^\ast (\varphi, \Gamma_K); \quad V_{a,h} \mapsto (\tilde{\mathbb{D}}_{\text{rig}} \otimes_{\mathbb{Q}_p^h} V_{a,h})^{H_K}.
\end{align*}

More precisely, quasi-inverses of $\tilde{\mathbb{D}}_{\text{rig}}^+$, $\tilde{\mathbb{D}}_{\text{rig}}$ and $\tilde{\mathbb{D}}^\dagger$ are given by $M \mapsto M^{\psi_h} = p^a$.

(ii) We denote by $\alpha_i$ for $1 \leq i \leq 5$ the following canonical morphisms of rings:

\begin{align*}
\mathbb{B}_K^+ & \xrightarrow{\alpha_1} \mathbb{B}_{\text{rig}, K}^+ \\
\mathbb{B}_{\text{rig}}^+ & \xrightarrow{\alpha_2} \mathbb{B}_{\text{rig}}^+ \\
\tilde{\mathbb{B}}_{\text{rig}}^+ & \xrightarrow{\alpha_3} \tilde{\mathbb{B}}_{\text{rig}}^+ \\
\mathbb{B}_{\text{rig}}^+ & \xleftarrow{\alpha_5} \mathbb{B}_{\text{rig}}^+, \\
\end{align*}

where the left square is commutative. Then, the $\alpha_i$’s induce the following base change functors $\alpha^\ast_i$:

\begin{align*}
\text{Mod}_{B_{\text{rig}, K}}^\ast (\varphi, \Gamma_K) & \xrightarrow{\alpha_1^\ast} \text{Mod}_{B_{\text{rig}, K}}^\ast (\varphi, \Gamma_K) \\
\text{Mod}_{B_{\text{rig}, K}}^\ast (\varphi, G_K) & \xrightarrow{\alpha_2^\ast} \text{Mod}_{B_{\text{rig}, K}}^\ast (\varphi, G_K) \\
\text{Mod}_{B_{\text{rig}, K}}^\ast (\varphi, G_K) & \xleftarrow{\alpha_5^\ast} \text{Mod}_{B_{\text{rig}, K}}^\ast (\varphi, G_K),
\end{align*}

where the left square is commutative. Moreover, the functors $\alpha^\ast_i$’s are compatible with the functor defined in (i), i.e., $\alpha_1^\ast \circ \tilde{\mathbb{D}}^\dagger = \tilde{\mathbb{D}}^\dagger_{\text{rig}}$, etc. In particular, the $\alpha^\ast_i$’s are equivalences.
Proof.

(i) We prove the assertion for $\tilde{\mathbb{D}}_{\text{rig}}^{\mathcal{V}^+}$. Let $D := \tilde{\mathbb{D}}_{\text{rig}}^{\mathcal{V}^+}$ and let $\mathcal{V}$ be, as before, the functor in the other direction. Let $V \in \text{Rep}_{a,h}(G_K)$. Then, there exists a functorial morphism $V \to \mathcal{V} \circ D(V)$, which is bijective by Lemma 4.5.4(ii). Hence, we have a natural equivalence $\mathcal{V} \circ D \simeq \text{id}$. For $M \in \text{Mod}^{s}_{\mathbb{B}_{\text{rig}}^{\mathcal{V}^+}}(\varphi, G_K)$, we get a functorial morphism $D \circ \mathcal{V}(M) \to M$ that is bijective by the isomorphism $M \simeq (\tilde{\mathbb{B}}_{\text{rig}}^{\mathcal{V}^+} \otimes_{Q_p} D_{[x]})^m$ of $\varphi$-modules and Lemma 4.5.4(ii). Hence, we have a natural equivalence $D \circ \mathcal{V} \simeq \text{id}$.

The assertions for $\tilde{\mathbb{D}}_{\text{rig}}^{\mathcal{V}^+}$ and $\tilde{\mathbb{D}}^{\mathcal{V}^+}$ follow similarly: instead of using the isomorphism $M \simeq (\tilde{\mathbb{B}}_{\text{rig}}^{\mathcal{V}^+} \otimes_{Q_p} D_{[x]})^m$, we use Kedlaya’s Dieudonné–Manin decomposition theorems over $\mathbb{B}_{\text{rig}}^{\mathcal{V}^+}$ and $\tilde{\mathbb{D}}^{\mathcal{V}^+}$, see Propositions 4.5.3 and 4.5.10 and Definition 4.6.1; Theorem 6.3.3(b) of [Kedlaya 2005], respectively. These assert that any object $M$ in $\text{Mod}^{s}_{\mathbb{B}_{\text{rig}}^{\mathcal{V}^+}}(\varphi)$ or $\text{Mod}^{s}_{\mathbb{B}_{\text{rig}}^{\mathcal{V}^+}}(\varphi)$ is isomorphic to a direct sum of $\tilde{\mathbb{B}}_{\text{rig}}^{\mathcal{V}^+} \otimes_{Q_p} D_{[x]}$ or of $\tilde{\mathbb{D}}^{\mathcal{V}^+} \otimes_{Q_p} D_{[x]}$, respectively.

We next prove the assertion for $\tilde{\mathbb{D}}^{\mathcal{V}^+}$. For $M \in \text{Mod}^{s}_{\mathbb{B}_{\text{rig}}^{\mathcal{V}^+}}(\varphi, \Gamma_K)$, let $\mathcal{V}(M) := (\mathbb{B}^{\mathcal{V}^+} \otimes_{\mathbb{B}_{\text{rig}}^{\mathcal{V}^+}} M)^{p^a} = p^a$. We will check that $\mathcal{V}$ gives a quasi-inverse of $\tilde{\mathbb{D}}^{\mathcal{V}^+}$. Let $V_{a,h} \in \text{Rep}_{a,h}(G_K)$. By forgetting the action of $\varphi$ on $V_{a,h}$ and applying Theorem 1.10.5 to $V = V_{a,h}$, we get a canonical bijection $\mathbb{B}_{\text{rig}}^{\mathcal{V}^+} \otimes_{\mathbb{B}_{\text{rig}}^{\mathcal{V}^+}} (V_{a,h}) \to \mathbb{B}_{\text{rig}}^{\mathcal{V}^+} \otimes_{Q_p} V_{a,h}$. Since this map is $\varphi$-equivariant, we have canonical isomorphisms $\mathcal{V} \circ \mathbb{D}^{\mathcal{V}^+}(V_{a,h}) \simeq (\mathbb{B}_{\text{rig}}^{\mathcal{V}^+} \otimes_{Q_p} V_{a,h}) \simeq \mathcal{V}(V_{a,h})$ by Lemma 4.5.4(ii). Thus, we obtain a natural equivalence $\mathcal{V} \circ \mathbb{D}^{\mathcal{V}^+} \simeq \text{id}$. We prove $\mathbb{D}^{\mathcal{V}^+} \circ \mathcal{V} \simeq \text{id}$. We next prove the assertion for $\tilde{\mathbb{D}}_{\text{rig}}^{\mathcal{V}^+}$. By the base change equivalence

$$\alpha_1^* : \text{Mod}^{s}_{\mathbb{B}_{\text{rig}}^{\mathcal{V}^+}}(\varphi) \to \text{Mod}^{s}_{\mathbb{B}_{\text{rig}}^{\mathcal{V}^+}}(\varphi),$$

see [Kedlaya 2005, Theorem 6.3.3(b)], we also have the base change equivalence $\alpha_2^* : \text{Mod}^{s}_{\mathbb{B}_{\text{rig}}^{\mathcal{V}^+}}(\varphi) \to \text{Mod}^{s}_{\mathbb{B}_{\text{rig}}^{\mathcal{V}^+}}(\varphi, \Gamma_K)$. Hence, the assertion follows from the étale case (Theorem 1.10.5).

(ii) To check that the $\alpha_2^*$'s are well-defined, we have only to prove that pure objects are preserved by base change. For $\alpha_1$ and $\alpha_3$, this follows from [Kedlaya 2005, Theorem 6.3.3(b)]. For $\alpha_2$, $\alpha_4$, this follows from the definitions: $M \in \text{Mod}^{s}_{\mathbb{B}_{\text{rig}}^{\mathcal{V}^+}}(\varphi)$ and $\text{Mod}^{s}_{\mathbb{B}_{\text{rig}}^{\mathcal{V}^+}}(\varphi)$ are pure if $\tilde{\mathbb{B}}_{\text{rig}}^{\mathcal{V}^+} M$ and $\tilde{\mathbb{D}}_{\text{rig}}^{\mathcal{V}^+} M$, respectively, are pure.
We define the slope multiset of $M$ as the multiset of cardinality rank

$\Phi$ of $V$. It admits a Dieudonné–Manin decomposition if there exists an isomorphism $f : M \cong \bigoplus_{i \leq m} \widehat{B}^+_{\text{rig}} \otimes_{\mathbb{Q}_p} D_{[s_i]}$ of $\varphi$-modules over $\widehat{\mathbb{B}}^+_{\text{rig}}$ with $s_1 \leq \cdots \leq s_m \in \mathbb{Q}$. We define the slope multiset of $\eta$ as the multiset of cardinality rank($M$), consisting of the $s_i$, together with its multiplicity $\dim_{\mathbb{Q}_p} D_{[s_i]}$. Let $s'_1 < \cdots < s'_{r'}$ be the distinct elements in the slope multiset of $M$. Then, we define $\text{Fil}^f_0(M) := 0$ and $\text{Fil}^f_i(M) := f^{-1}(\bigoplus_{j ; s_j \leq i} \widehat{B}^+_{\text{rig}} \otimes_{\mathbb{Q}_p} D_{[s_j]})$ for $1 \leq i \leq r'$. Note that the filtration and the slope multiset are independent of the choice of $f$ above.

**Definition 4.6.1** [Colmez 2008b, Remarque 3.3]. A $\varphi$-module $M$ over $\widehat{B}^+_{\text{rig}}$ is a finite free $\widehat{B}^+_{\text{rig}}$-module together with a semilinear $\varphi$-action. A $\varphi$-module $M$ over $\widehat{B}^+_{\text{rig}}$ admits a Dieudonné–Manin decomposition if there exists an isomorphism $f : M \cong \bigoplus_{i \leq m} \widehat{B}^+_{\text{rig}} \otimes_{\mathbb{Q}_p} D_{[s_i]}$ of $\varphi$-modules over $\widehat{\mathbb{B}}^+_{\text{rig}}$ with $s_1 \leq \cdots \leq s_m \in \mathbb{Q}$.

**Definition 4.6.2.** Let $V \in \text{Rep}_{dR}(G_K)$. First, we assume that the Hodge–Tate weights of $V$ are negative. By assumption, we have $\mathbb{D}_{dR}(V) = (\mathbb{B}^+_{dR} \otimes_{\mathbb{Q}_p} V)^{G_K}$. As in [Ohkubo 2013, Proposition 5.3], we define

$$\tilde{\mathbb{N}}^+_{\text{rig}}(V) := \{ x \in \tilde{\mathbb{B}}^+_{\text{rig}} \otimes_{\mathbb{Q}_p} V ; \ t_n(x) \in (\mathbb{B}_{dR}^+ \otimes_K \mathbb{D}_{dR}(V))^{\text{geom}=0} \text{ for all } n \in \mathbb{Z} \},$$

where $t_n : \tilde{\mathbb{B}}^+_{\text{rig}} \otimes_{\mathbb{Q}_p} V \to \mathbb{B}_{dR}^+ \otimes_{\mathbb{Q}_p} V$ is defined by $x \otimes v \mapsto \varphi^{-n}(x) \otimes v$. Since $\tilde{\mathbb{N}}^+_{\text{rig}}(V)$ admits a Dieudonné–Manin decomposition due to Colmez ([Ohkubo 2013, Proposition 6.2]), $\tilde{\mathbb{N}}^+_{\text{rig}}(V)$ is endowed with a canonical slope filtration $\text{Fil}^f(\tilde{\mathbb{N}}^+_{\text{rig}}(V))$ of $\varphi$-modules by Definition 4.6.1. Let $s_1 < \cdots < s_r$ be the distinct elements in the slope multiset of $\tilde{\mathbb{N}}^+_{\text{rig}}(V)$. Write $s_i = a_i/h_i$ with $a_i \in \mathbb{Z}$, $h_i \in \mathbb{N}_{>0}$ relatively prime. By the uniqueness of slope filtrations, $\text{Fil}^f$ is $G_K$-stable and the graded piece $\text{gr}^f(\tilde{\mathbb{N}}^+_{\text{rig}}(V))$ lies in $\text{Mod}_{\mathbb{B}^+_{\text{rig}}(\varphi, G_K)}$. Hence, by Lemma 4.5.7, there exists a unique $\mathcal{V}_i \in \text{Rep}_{dR}(G_K)$, up to isomorphism, such that $\text{gr}^f(\tilde{\mathbb{N}}^+_{\text{rig}}(V)) \cong \tilde{\mathbb{B}}^+_{\text{rig}} \otimes_{\mathbb{Q}_p} \mathcal{V}_i$. It is proved in Step 1 of the proof of the main theorem of [Ohkubo 2013] that the inertia $I_K$ acts on $\mathcal{V}_i$ via a finite quotient, i.e., $\mathcal{V}_i \in \text{Rep}_{\mathbb{Q}_p}(G_K)$ (in the reference, $\text{Fil}^f$ and $\mathcal{V}_i$ are denoted by $M_i$ and $W_i$). Hence, we can define

$$\text{Swan}(V) := \sum_i \text{Swan}^{\text{AS}}(\mathcal{V}_i).$$
In the general Hodge–Tate weights case, we define $\tilde{\mathcal{N}}^+_{\text{rig}}(V) := \tilde{\mathcal{N}}^+_{\text{rig}}(V(-n))(n)$ and $\text{Swan}(V) := \text{Swan}(V(-n))$ for sufficiently large $n$. The definition is independent of the choice of $n$ since the above construction is compatible with Tate twist.

**Remark 4.6.3.** As in [Colmez 2008a], we should consider an appropriate contribution of “monodromy action” to define the Artin conductor. To avoid complication, we do not define Artin conductors for de Rham representations in this paper.

The lemma below easily follows from Hilbert 90.

**Lemma 4.6.4.** Let $V \in \text{Rep}_{dR}(G_K)$.

(i) If $L$ is the $p$-adic completion of an unramified extension of $K$, then we have $\text{Swan}(V|_L) = \text{Swan}(V)$.

(ii) Assume $V \in \text{Rep}_{Q_p}^f(G_K)$. Then, we have $\text{Swan}(V) = \text{Swan}^{AS}(V)$.

Though the following result will not be used in the proof of the main theorem, we remark that when $k_K$ is perfect, our definition is compatible with the classical definition.

**Lemma 4.6.5** (Compatibility of usual Swan conductor in the perfect residue field case). Assume that $k_K$ is perfect. Then, we have $\text{Swan}(V) = \text{Swan}(L_{\text{pst}}(V))$ (see [Colmez 2008a, §0.4] for the definition of $L_{\text{pst}}$).

**Proof.** Let the notation be as in Definition 4.6.2. By Tate twist, we may assume that all Hodge–Tate weights of $V$ are negative. By $\text{Swan}(L_{\text{pst}}(V)) = \text{Swan}(L_{\text{pst}}(V|_{K^ur}))$ and Lemma 4.6.4(i), we may assume that $k_K$ is algebraically closed by replacing $K$ by $K^ur$. Since $B^+_{dR} \otimes_K \mathcal{D}_{dR}(V)$ is a lattice of $B^+_{dR} \otimes_{Q_p} V$, we may identify $\tilde{\mathcal{N}}^+_{\text{rig}}(V)(1/t)$ with $\tilde{\mathcal{N}}^+_{\text{rig}} \otimes_{Q_p} V[1/t]$. By the $p$-adic monodromy theorem, there exists a finite Galois extension $L/K$ such that $D_{\text{st},L}(V) := (B_{st} \otimes_{Q_p} V)^{G_L}$ has dimension $\dim_{Q_p} V$. Moreover, we may assume that $G_L$ acts trivially on each $V_i$. Put $D_i := (B_{st} \otimes_{Q_p} \text{Fil}^i(\tilde{\mathcal{N}}^+_{\text{rig}}(V)))^{G_L}$. This forms an increasing filtration of $D_{\text{st},L}(V)$.

Then, we have canonical morphisms $D_i/D_{i+1} \hookrightarrow (B_{st} \otimes_{Q_p} \text{Fil}^i(\tilde{\mathcal{N}}^+_{\text{rig}}(V)))^{G_L} \cong (B_{st} \otimes_{Q_p} \text{Fil}^i V)^{G_L} \cong W(k_L)[1/p] \otimes_{Q_p} \text{Fil}^i V_i$, where the first injection is an isomorphism by counting dimensions. By the additivity of Swan conductors, we have $\text{Swan}(L_{\text{pst}}(V)) = \text{Swan}(D_{\text{st},L}(V)) = \sum_i \text{Swan}(D_i/D_{i+1}) = \sum_i \text{Swan}(V_i) = \text{Swan}(V)$. 

**4.7. Main theorem.** The aim of this subsection is to prove the following theorem, which generalizes Marmora’s formula in Remark 4.7.2:

**Main Theorem 4.7.1.** Let $V$ be a de Rham representation of $G_K$. Then, the sequence $\{\text{Swan}(V|_{K_n})\}_{n>0}$ is eventually stationary and we have $\text{Swan}^{\text{V}}(N_{dR}(V)) = \lim_{n} \text{Swan}(V|_{K_n})$. 

Remark 4.7.2. When $k_K$ is perfect, we explain that our formula coincides with the following formula from [Marmora 2004, Théorème 1.1]:

$$\text{Irr}(\mathbb{N}_{dR}(V)) = \lim_{n \to \infty} \text{Swan}(\mathbb{D}_{pst}(V|_{K_n})).$$

Here, the LHS means the irregularity of $\mathbb{N}_{dR}(V)$ regarded as a $p$-adic differential equation. By Lemma 4.6.5, the RHS is equal to the RHS in Main Theorem 4.7.1. Therefore, we only have to prove $\text{Irr}(D) = \text{Swan}^\nabla(D)$ for a $(\varphi, \nabla)$-module $D$ over the Robba ring. Since $D$ is étale by dévissage. Let $V$ be the corresponding $p$-adic representation of finite local monodromy. Then, the differential Swan conductor $\text{Swan}^\nabla(D)$ coincides with the usual Swan conductor of $V$ ([Kedlaya 2007, Proposition 3.5.5]). On the other hand, $\text{Irr}(D)$ coincides with the usual Swan conductor of $V$ ([Tsuzuki 1998, Theorem 7.2.2]), which implies the assertion.

We will deduce Theorem 4.7.1 from Lemma 3.5.4(ii) by dévissage. In the following, we use the notation as in Definition 4.6.2.

Lemma 4.7.3. Let $V$ be a de Rham representation of $G_K$ with nonpositive Hodge–Tate weights.

(i) The $(\varphi, G_K)$-modules

$$\tilde{\mathbb{B}}_{\text{rig}}^{\dagger} \otimes_{\mathbb{B}_{\text{rig},k}} \mathbb{N}_{dR}(V), \quad \tilde{\mathbb{B}}_{\text{rig}}^{\dagger} \otimes_{\mathbb{B}_{\text{rig}}^{\nabla+}} \tilde{\mathbb{N}}_{\text{rig}}^{\nabla+}(V)$$

coincide with each other in $\tilde{\mathbb{B}}_{\text{rig}}^{\dagger} \otimes_{\mathbb{Q}_p} V$. Moreover, the two filtrations induced by the slope filtrations of $\mathbb{N}_{dR}(V)$ and $\tilde{\mathbb{N}}_{\text{rig}}^{\nabla+}(V)$ also coincide with each other.

(ii) Let the notation be as in Construction 1.7.7. Then, there exists a canonical isomorphism

$$\text{gr}^j(\mathbb{N}_{dR}(V)) \cong D_{\text{rig}}^{\dagger}(V|_{\mathbb{E}_K})$$

as $(\varphi, \nabla)$-modules over $\mathbb{B}_{\text{rig},k}^{\dagger}$.

Proof. (i) We prove the first assertion. By Lemma 4.2.11 (with $B = \mathbb{B}_{\text{rig}}^{\dagger}$), we only have to prove that $D^{(1)} := \tilde{\mathbb{B}}_{\text{rig}}^{\dagger} \otimes_{\mathbb{B}_{\text{rig},k}} \mathbb{N}_{dR,r}(V)$, $D^{(2)} := \tilde{\mathbb{B}}_{\text{rig}}^{\dagger} \otimes_{\mathbb{B}_{\text{rig}}^{\nabla+}} \tilde{\mathbb{N}}_{\text{rig}}^{\nabla+}(V)$ and $D := \tilde{\mathbb{B}}_{\text{rig}}^{\dagger} \otimes_{\mathbb{Q}_p} V$ satisfy the conditions in the lemma. We have $\mathbb{N}_{dR,r}(V)[1/t] = \mathbb{D}_{\text{rig}}^{\dagger,r}(V)[1/t]$ by definition and

$$\tilde{\mathbb{B}}_{\text{rig}}^{\dagger} \otimes_{\mathbb{B}_{\text{rig},k}} \mathbb{D}_{\text{rig}}^{\dagger,r}(V) \cong \tilde{\mathbb{B}}_{\text{rig}}^{\dagger} \otimes_{\mathbb{B}_{\text{rig}}^{\nabla+}} \mathbb{B}_{\text{rig}}^{\dagger,r} \otimes_{\mathbb{B}_{\text{rig}}^{\nabla+}} \mathbb{D}_{\text{rig}}^{\dagger,r}(V) \cong \tilde{\mathbb{B}}_{\text{rig}}^{\dagger} \otimes_{\mathbb{B}_{\text{rig}}^{\nabla+}} \mathbb{B}_{\text{rig}}^{\dagger,r} \otimes_{\mathbb{Q}_p} V \cong \tilde{\mathbb{B}}_{\text{rig}}^{\dagger} \otimes_{\mathbb{Q}_p} V.$$

As we have $\tilde{\mathbb{N}}_{\text{rig}}^{\nabla+}(V)[1/t] = \tilde{\mathbb{B}}_{\text{rig}}^{\dagger} \otimes_{\mathbb{Q}_p} V$ by definition, we obtain a canonical isomorphism

$$\tilde{\mathbb{B}}_{\text{rig}}^{\dagger} \otimes_{\mathbb{B}_{\text{rig}}^{\nabla+}} \tilde{\mathbb{N}}_{\text{rig}}^{\nabla+}(V)[1/t] \cong \tilde{\mathbb{B}}_{\text{rig}}^{\dagger} \otimes_{\mathbb{Q}_p} V,$$
By Proposition 4.2.12(ii), we have a canonical isomorphism \( \mathbb{B}_{dR}^+ \otimes_{\mathbb{B}_{rig}^{-1}} \mathbb{N}_{dR,r}(V) \cong \mathbb{B}_{dR}^+ \otimes_K \mathbb{D}_{dR}(V) \). On the other hand, we have canonical isomorphisms

\[
\mathbb{B}_{dR}^+ \otimes_{\mathbb{B}_{rig}^{-1}} \mathbb{N}_{dR,r}(V) \cong \mathbb{B}_{dR}^+ \otimes_{\mathbb{B}_{rig}^{-1}} (\mathbb{B}_{dR}^+ \otimes_K \mathbb{D}_{dR}(V)) \overset{\text{geom}}{=} 0 \cong \mathbb{B}_{dR}^+ \otimes_K \mathbb{D}_{dR}(V),
\]

where the first isomorphism follows from [Ohkubo 2013, Proposition 5.3(ii)] and the second isomorphism follows from [Ohkubo 2013, Proposition 5.4]. Since the canonical map \( \mathbb{B}_{dR}^+ \rightarrow \mathbb{B}_{dR}^+ \) is faithfully flat, condition (ii) is verified. The second assertion follows from the uniqueness of the slope filtration [Kedlaya 2005, Theorem 6.4.1].

(ii) By (i), there exists canonical isomorphisms

\[
\mathcal{B}_{\text{rig}}^+ \otimes_{\mathbb{B}_{rig}^{-1}} \mathcal{N}_{dR}(V) \cong \mathcal{B}_{\text{rig}}^+ \otimes_{\mathcal{B}_{\text{rig}}^{-1}} \mathcal{B}_{\text{rig}}^+ \otimes_{\mathbb{B}_{rig}^{-1}} \mathcal{N}_{dR}(V) \cong \mathcal{B}_{\text{rig}}^+ \otimes_{\mathcal{O}_{\rho,h}} \mathcal{V}_i
\]

as \((\varphi, G_K)\)-modules. By Lemma 4.5.7, we obtain a canonical isomorphism between \( \mathcal{B}_{\text{rig}}^+ \otimes_{\mathcal{B}_{\text{rig}}^{-1}} \mathcal{N}_{dR}(V) \) and \( \mathcal{B}_{\text{rig}}^+ \otimes_{\mathcal{O}_{\rho,h}} \mathcal{V}_i \) as \((\varphi, \Gamma_K)\)-modules. Since \( \mathcal{V}_i \) is of finite local monodromy, so is \( \mathcal{V}_i|_{\mathcal{E}_K} \). So, \( \dim_{\mathcal{B}_{\text{rig}}^+} D^+(\mathcal{V}_i|_{\mathcal{E}_K}) = \dim_{\mathcal{O}_{\rho,h}} \mathcal{V}_i \); in particular, the canonical injection \( D^+(\mathcal{V}_i|_{\mathcal{E}_K}) \hookrightarrow (\mathcal{B}_{\text{rig}}^+ \otimes_{\mathcal{O}_{\rho,h}} \mathcal{V}_i)^{H_K} \) is an isomorphism. Therefore, we have canonical isomorphisms \( D^+_{\text{rig}}(\mathcal{V}_i|_{\mathcal{E}_K}) \cong \mathcal{D}^+_{\text{rig}}(\mathcal{V}_i) \cong \mathcal{D}^+_{\text{rig}}(\mathcal{N}_{dR}(V)) \) as (pure) \( \varphi \)-modules over \( \mathcal{B}_{\text{rig}}^+ \); hence, the assertion follows from Lemma 4.5.6.

\[\Box\]

**Remark 4.7.4.** One can prove that there exist canonical isomorphisms

\[
\mathcal{B}_{\text{rig}}^+ \otimes_{\mathcal{B}_{\text{rig}}^{-1}} \mathcal{N}_{dR}(V) \cong \mathcal{B}_{\text{rig}}^+ \otimes_{\mathcal{B}_{\text{rig}}^{-1}} \mathcal{N}_{dR}(V) \cong \mathcal{N}_{dR}^+(V).
\]

**Lemma 4.7.5.** We have

\[
\text{Swan}^\nabla(\mathcal{N}_{dR}(V)) = \sum_{1 \leq i \leq r} \text{Swan}^{\text{AS}}(\mathcal{V}_i|_{\mathcal{E}_K}).
\]

**Proof.** We have

\[
\text{Swan}^\nabla(\mathcal{N}_{dR}(V)) = \sum_{1 \leq i \leq r} \text{Swan}^\nabla(\mathcal{N}_{dR}(V)) \]

\[
= \sum_{1 \leq i \leq r} \text{Swan}^\nabla(D^+_{\text{rig}}(\mathcal{V}_i|_{\mathcal{E}_K})) = \sum_{1 \leq i \leq r} \text{Swan}^{\text{AS}}(\mathcal{V}_i|_{\mathcal{E}_K}),
\]

where the first equality follows from the additivity of the differential Swan conductor (Lemma 1.7.9), the second one follows from Lemma 4.7.3(ii), and the third one follows from Xiao’s comparison theorem (Theorem 1.7.10).

\[\Box\]

**Proof of Main Theorem 4.7.1.** By Lemma 4.7.5 and the definition of the Swan conductor (Definition 4.6.2), we only have to prove \( \text{Swan}^{\text{AS}}(\mathcal{V}_i|_{\mathcal{E}_K}) = \text{Swan}^{\text{AS}}(\mathcal{V}_i|_{\mathcal{E}_K}) \) for all sufficiently large \( n \). This follows from Lemma 3.5.4(ii).

\[\Box\]
Appendix: list of notation

The following is a list of notation in order defined.

1.2: $\hat{\Omega}_{K}^{1}, \partial_j, \partial_j/\partial t_j$.

1.3: $\tilde{K}, K_{\infty}, \Gamma_{\tilde{K}}, H_{\tilde{K}}, \gamma_a, \gamma_b, \eta = (\eta_0, \ldots, \eta_d), g, L_{n}, L_{\infty}, \Gamma_{L}, H_{L}, \Gamma_{L,j}$.

1.4: $\tilde{E}^{(+), \nu_{\bar{E}}}, \tilde{A}_{L}, \tilde{B}^{(+), \nu_{\bar{E}}}, \tilde{\iota}_j, \pi, q, \mathcal{A}_{\inf}, \mathcal{B}_{\text{DR}}^{(+), \nu_{\bar{E}}}, \mathcal{B}_{\text{rig}}^{(+), \nu_{\bar{E}}}, \mathcal{A}_{\text{cris}}$, $\mathcal{B}_{\text{cris}}, \mathcal{B}_{\text{reg}}^{(+), \nu_{\bar{E}}}$.

1.5: $a_{L/K,Z}, \mathcal{F}^{a}(L), b(L/K), a_{L/K,Z,P}, \mathcal{F}_{\text{log}}^{a}(L), b_{\text{log}}(L/K), \text{Art}^{AS} (\cdot), \text{Swan}^{AS} (\cdot)$.

1.6: $v^{\nu_{\bar{E}}}, w_{\nu_{\bar{E}}}, W(E), W_{\text{con}}(E), \Gamma_{E}, \Gamma_{\text{con}}, \Gamma_{\text{an}}, \Gamma_{\text{an, con}}, \mathcal{O}([S]), \mathcal{O}((S))^\dagger, \mathcal{O}((S))^\dagger$, $\mathcal{R}, \mathcal{M}, \mathcal{M}^{\dagger} (\mathcal{S}), \mathcal{M}^{\dagger} (\sigma), \mathcal{M}^{\dagger} (\sigma)$.

1.7: $\Omega^{1}_{R}, \Omega^{1}_{\mathcal{R}}, d : \mathcal{R} \to \Omega^{1}_{\mathcal{R}}, \mathcal{M}^{\dagger} (\mathcal{S})$, $\mathcal{D}, \mathcal{D}^\dagger$, $\text{Swan} (\cdot)$.

1.8: $X^{(+)}_{R} = X^{(+)}(\mathcal{R}, \xi, n_{0})$.

1.9: $\tilde{E}^{(+), \tilde{E}_{L}} \mathcal{A}^{(+), \mathcal{B}_{L}}, \mathcal{A}, \mathcal{B}, \mathcal{B}, \mathcal{M}^{\dagger} (\mathcal{S})$, $\mathcal{D}, \mathcal{V}$.

1.10: $\mathcal{A}^{+}, \mathcal{B}^{+}, \mathcal{B}^{+}, \mathcal{B}^{+}, \mathcal{B}^{+}, \mathcal{B}^{+}, \mathcal{B}^{+}, \mathcal{B}^{+}, \mathcal{B}^{+}, \mathcal{B}^{+}, \mathcal{B}^{+}, \mathcal{B}^{+}, \mathcal{B}^{+}, \mathcal{B}^{+}$.

3.1: $R(X), \mathcal{O}((S))_{0}^{\dagger}, \mathcal{O}((S))_{0}^{\dagger}(X), \mathcal{O}((S))_{0}^{\dagger}(X), \mathcal{O}((S))_{0}^{\dagger}(X)$.

3.2: $\ge, >, \ge_{\text{lex}}, \mathcal{V}_{R}, \mathcal{D}_{\text{logs}}, \mathcal{D}_{\text{logs}}$.

3.3: $\mathcal{N}(\cdot), \mathcal{N}(\cdot), \mathcal{N}(\cdot), \mathcal{N}(\cdot), \mathcal{N}(\cdot), \mathcal{N}(\cdot)$.

3.4: $\mathcal{V}_{1}, \mathcal{V}_{1}, \mathcal{V}_{1}, \mathcal{V}_{1}, \mathcal{V}_{1}$.

4.1: $k, \mathcal{N}(\cdot), \mathcal{N}(\cdot), \mathcal{N}(\cdot), \mathcal{N}(\cdot), \mathcal{N}(\cdot)$.

4.2: $\mathcal{N}_{\mathcal{D}}, \mathcal{N}_{\mathcal{D}}(\cdot), \mathcal{N}_{\mathcal{D}}(\cdot), \mathcal{N}_{\mathcal{D}}(\cdot), \mathcal{N}_{\mathcal{D}}(\cdot)$.

4.3: $\mathcal{V}_{1}, \mathcal{V}_{1}, \mathcal{V}_{1}, \mathcal{V}_{1}, \mathcal{V}_{1}$.

4.4: $\mathcal{V}_{1}, \mathcal{V}_{1}, \mathcal{V}_{1}$.

4.5: $\mathcal{R}_{\nu_{\bar{E}}} (\mathcal{S})^{\dagger}, \mathcal{R}_{\nu_{\bar{E}}} (\mathcal{S})^{\dagger}, \mathcal{R}_{\nu_{\bar{E}}} (\mathcal{S})^{\dagger}$.

4.6: $\mathcal{N}_{\mathcal{D}}^{\dagger}, \mathcal{N}_{\mathcal{D}}^{\dagger}, \mathcal{N}_{\mathcal{D}}^{\dagger}, \mathcal{N}_{\mathcal{D}}^{\dagger}$.


Differential modules associated to de Rham representations


Communicated by Brian Conrad
Received 2015-02-27 Revised 2015-05-28 Accepted 2015-06-25
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