p-Adic Monodromy of the Universal Deformation of a HW-Cyclic Barsotti-Tate Group

Yichao Tian

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Abstract. Let k be an algebraically closed field of characteristic $p > 0$, and G be a Barsotti-Tate over k. We denote by $\mathbf{S}$ the "algebraic" local moduli in characteristic p of G, by $\mathbf{G}$ the universal deformation of G over $\mathbf{S}$, and by $\mathbf{U} \subset \mathbf{S}$ the ordinary locus of $\mathbf{G}$. The étale part of $\mathbf{G}$ over $\mathbf{U}$ gives rise to a monodromy representation $\rho_{\mathbf{G}}$ of the fundamental group of $\mathbf{U}$ on the Tate module of $\mathbf{G}$. Motivated by a famous theorem of Igusa, we prove in this article that $\rho_{\mathbf{G}}$ is surjective if G is connected and HW-cyclic. This latter condition is equivalent to saying that Oort's a-number of G equals 1, and it is satisfied by all connected one-dimensional Barsotti-Tate groups over k.

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1. Introduction

1.1. A classical theorem of Igusa says that the monodromy representation associated with a versal family of ordinary elliptic curves in characteristic $p > 0$ is surjective [Igu, Ka2]. This important result has deep consequences in the theory of p-adic modular forms, and inpsired various generalizations. Faltings and Chai [Ch2, FC] extended it to the universal family over the moduli space of higher dimensional principally polarized ordinary abelian varieties in characteristic p, and Ekedahl [Eke] generalized it to the jacobian of the universal n-pointed curve in characteristic p, equipped with a symplectic level structure. Recently, Chai and Oort [CO] proved the maximality of the p-adic monodromy over each "central leaf" in the moduli space of abelian varieties which is not contained in the supersingular locus. We refer to Deligne-Ribet [DR] and Hida [Hid] for other generalizations to some moduli spaces of PEL-type and their arithmetic applications. Though it has been formulated in a global setting, the proof of Igusa's theorem is purely local, and it has got also local generalizations. Gross [Gro] generalized it to one-dimensional formal $\mathscr{O}$-modules over a complete discrete valuation ring of characteristic p, where $\mathscr{O}$ is the integral closure of $\mathbb{Z}_p$ in a finite extension of $\mathbb{Q}_p$. We refer to Chai [Ch2] and Achter-Norman [AN] for more results on local monodromy of Barsotti-Tate groups. Motivated by these results, it has been longly expected/conjectured that the monodromy of a *versal* family of ordinary Barsotti-Tate groups in characteristic $p > 0$ is maximal. The aim of this paper is to prove the surjectivity of the monodromy representation associated with the universal deformation in characteristic p of a certain class of Barsotti-Tate groups.

1.2. To describe our main result, we introduce first the notion of HW-cyclic Barsotti-Tate groups. Let k be an algebraically closed field of characteristic $p > 0$, and G be a Barsotti-Tate group over k. We denote by $G^\vee$ the Serre dual of G, and by $\mathrm{Lie}(G^\vee)$ its Lie algebra. The Frobenius homomorphism of G (or dually the Verschiebung of $G^\vee$) induces a semi-linear endomorphism φ_G on $\mathrm{Lie}(G^\vee)$, called the Hasse-Witt map of G (2.6.1). We say that G is *HW-cyclic*, if $c = \dim(G^\vee) \geq 1$ and there is a $v \in \mathrm{Lie}(G^\vee)$ such that $v, \varphi_G(v), \cdots, \varphi_G^{c-1}(v)$ form a basis of $\mathrm{Lie}(G^\vee)$ over k (4.1). We prove in 4.7 that G is HW-cyclic and non-ordinary if and only if the a-number of G, defined previously by Oort, equals 1. Basic examples of HW-cyclic Barsotti-Tate groups are given as follows. Let r, s be relatively prime integers such that $0 \leq s \leq r$ and $r \neq 0$, $\lambda = s/r$, G^λ be the Barsotti-Tate group over k whose (contravariant) Dieudonné module is generated by an element e over the non-commutative Dieudonné ring with the relation $(F^{r-s} - V^s) \cdot e = 0$ (4.10). It is easy to see that G^λ is HW-cyclic for any $0 < \lambda < 1$. Any connected Barsotti-Tate group over k of dimension 1 and height h is isomorphic to $G^{1/h}$ [Dem, Chap.IV §8].

Let G be a Barsotti-Tate group of dimension d and height $c+d$ over k; assume $c \geq 1$. We denote by $\mathbf{S}$ the "algebraic" local moduli of G in characteristic p, and by $\mathbf{G}$ be the universal deformation of G over $\mathbf{S}$ (cf. 3.8). The scheme $\mathbf{S}$ is affine of ring $R \simeq k[[(t_{i,j})_{1\leq i\leq c, 1\leq j\leq d}]]$, and the Barsotti-Tate group $\mathbf{G}$ is obtained by algebraizing the formal universal deformation of G over $\mathrm{Spf}(R)$ (3.7). Let $\mathbf{U}$ be the ordinary locus of $\mathbf{G}$ (*i.e.* the open subscheme of $\mathbf{S}$ parametrizing the ordinary fibers of $\mathbf{G}$), and $\overline{\eta}$ a geometric point over the generic point of $\mathbf{U}$. For any integer $n \geq 1$, we denote by $\mathbf{G}(n)$ the kernel of the multiplication by p^n on $\mathbf{G}$, and by

$$\mathrm{T}_p(\mathbf{G}, \overline{\eta}) = \varprojlim_n \mathbf{G}(n)(\overline{\eta})$$

the Tate module of $\mathbf{G}$ at $\overline{\eta}$. This is a free $\mathbb{Z}_p$-module of rank c. We consider the monodromy representation attached to the étale part of $\mathbf{G}$ over $\mathbf{U}$

$$\rho_{\mathbf{G}} : \pi_1(\mathbf{U}, \overline{\eta}) \to \mathrm{Aut}_{\mathbb{Z}_p}(\mathrm{T}_p(\mathbf{G}, \overline{\eta})) \simeq \mathrm{GL}_c(\mathbb{Z}_p). \tag{1.2.1}$$

The aim of this paper is to prove the following :

Theorem 1.3. *If G is connected and HW-cyclic, then the monodromy representation $\rho_{\mathbf{G}}$ is surjective.*

Igusa's theorem mentioned above corresponds to Theorem 1.3 for $G = G^{1/2}$ (cf. 5.7). My interest in the p-adic monodromy problem started with the second part of my PhD thesis [Ti1], where I guessed 1.3 for $G = G^{\lambda}$ with $0 < \lambda < 1$ and proved it for $G^{1/3}$. After I posted the manuscript on ArXiv [Ti2], Strauch proved the one-dimensional case of 1.3 by using Drinfeld's level structures [Str, Theorem 2.1]. Later on, Lau [Lau] proved 1.3 without the assumption that G is HW-cyclic. By using the Newton stratification of the universal deformation space of G due to Oort, Lau reduced the higher dimensional case to the one-dimensional case treated by Strauch. In fact, Strauch and Lau considered more generally the monodromy representation over each p-rank stratum of the universal deformation space. In this paper, we provide first a different proof of the one-dimensional case of 1.3. Our approach is purely characteristic p, while Strauch used Drinfeld's level structure in characteristic 0. Then by following Lau's strategy, we give a new (and easier) argument to reduce the general case of 1.3 to the one-dimensional case for HW-cyclic groups. The essential part of our argument is a versality criterion by Hasse-Witt maps of deformations of a connected one-dimensional Barsotti-Tate group (Prop. 4.11). This criterion can be considered as a generalization of another theorem of Igusa which claims that the Hasse invariant of a versal family of elliptic curves in characteristic p has simple zeros. Compared with Strauch's approach, our characteristic p approach has the advantage of giving also results on the monodromy of Barsotti-Tate groups over a discrete valuation ring of characteristic p.

1.4. Let $A = k[[\pi]]$ be the ring of formal power series over k in the variable π, K its fraction field, and $\mathtt{v}$ the valuation on K normalized by $\mathtt{v}(\pi) = 1$. We fix an algebraic closure $\overline{K}$ of K, and let K^{sep} be the separable closure of K contained in $\overline{K}$, I be the Galois group of K^{sep} over K, $I_p \subset I$ be the wild inertia subgroup, and $I_t = I/I_p$ the tame inertia group. For every integer $n \geq 1$, there is a canonical surjective character $\theta_{p^n-1} : I_t \to \mathbb{F}_{p^n}^{\times}$ (5.2), where $\mathbb{F}_{p^n}$ is the finite subfield of k with p^n elements.
We put $S = \mathrm{Spec}(A)$. Let G be a Barsotti-Tate group over S, $G^{\vee}$ be its Serre dual, $\mathrm{Lie}(G^{\vee})$ the Lie algebra of $G^{\vee}$, and φ_G the Hasse-Witt map of G, *i.e.* the semi-linear endomorphism of $\mathrm{Lie}(G^{\vee})$ induced by the Frobenius of G. We define $h(G)$ to be the valuation of the determinant of a matrix of φ_G, and call it the *Hasse invariant* of G (5.4). We see easily that $h(G) = 0$ if and only if G is ordinary over S, and $h(G) < \infty$ if and only if G is generically ordinary. If G is connected of height 2 and dimension 1, then $h(G) = 1$ is equivalent to that G is versal (5.7).

Proposition 1.5. *Let $S = \mathrm{Spec}(A)$ be as above, G be a connected HW-cyclic Barsotti-Tate group with Hasse invariant $h(G) = 1$, and $G(1)$ the kernel of the multiplication by p on G. Then the action of I on $G(1)(\overline{K})$ is tame; moverover,*

$G(1)(\overline{K})$ is an $\mathbb{F}_{p^c}$-vector space of dimension 1 on which the induced action of I_t is given by the surjective character $\theta_{p^c-1} : I_t \to \mathbb{F}_{p^c}^{\times}$.

This proposition is an analog in characteristic p of Serre's result [Se3, Prop. 9] on the tameness of the monodromy associated with one-dimensional formal groups over a trait of mixed characteristic. We refer to 5.8 for the proof of this proposition and more results on the p-adic monodromy of HW-cyclic Barsotti-Tate groups over a trait in characteristic p.

1.6. This paper is organized as follows. In Section 2, we review some well known facts on ordinary Barsotti-Tate groups. Section 3 contains some preliminaries on the Dieudonné theory and the deformation theory of Barsotti-Tate groups. In Section 4, after establishing some basic properties of HW-cyclic groups, we give the fundamental relation between the versality of a Barsotti-Tate group and the coefficients of its Hasse-Witt matrix (Prop. 4.11). Section 5 is devoted to the study of the monodromy of a HW-cyclic Barsotti-Tate group over a complete trait of characteristic p. Section 6 is totally elementary, and contains a criterion (6.3) for the surjectivity of a homomorphism from a profinite group to $\mathrm{GL}_n(\mathbb{Z}_p)$. Section 7 is the heart of this work, and it contains a proof of Theorem 1.3 in the one-dimensional case. Finally in Section 8, we follow Lau's strategy and complete the proof of 1.3 by reducing the general case to the one-dimensional case treated in Section 7.
The proof in Section 7 of 1.3 in the one-dimensional case is based on an induction on the height $n+1 \geq 2$ of G. The case $n = 1$ is just the classical Igusa's theorem (5.7). For $n \geq 2$, by lemmas 6.3 and 6.5, it suffices to prove the following two statements: (a) the image of reduction modulo p of $\rho_{\mathbf{G}}$ contains a non-split Cartan subgroup; (b) under a suitable basis, the image of $\rho_{\mathbf{G}}$ contains all matrix of the form $\begin{pmatrix} B & b \\ 0 & 1 \end{pmatrix}$ with $B \in \mathrm{GL}_{n-1}(\mathbb{Z}_p)$ and $b \in \mathrm{M}_{(n-1)\times 1}(\mathbb{Z}_p)$. The first statement follows easily from 1.5 by considering a certain base change of $\mathbf{G}$ to a complete discrete valuation ring. To prove (b), we consider the formal completion $\mathrm{Spec}(R')$ of the localization of the local moduli $\mathbf{S} = \mathrm{Spec}(R)$ of G at the generic point of the locus where the universal deformation $\mathbf{G}$ has p-rank ≤ 1 (7.4). The ring R' is a complete regular ring of dimension $n-1$, and the Barsotti-Tate group $\mathscr{G}' = \mathbf{G} \otimes_R R'$ has a connected part of height n and an étale part of height 1. Let K_0 be the residue field of R', and $\overline{K}_0$ an algebraic closure of K_0. In order to apply the induction hypothesis, we consider the set of k-algebra homomorphisms $\sigma : R' \to \widetilde{R'} = \overline{K}_0[[t_1, \cdots, t_{n-1}]]$ lifting the natural inclusion $K_0 \to \overline{K}_0$. The key point is that, the natural map $\sigma \mapsto \mathscr{G}_{\widetilde{R'},\sigma} = \mathscr{G}' \otimes_{R',\sigma} \widetilde{R'}$ gives a bijection between the set of such σ's and the set of deformations of $\mathscr{G}_{\overline{K}_0} = \mathscr{G}' \otimes_{R'} \overline{K}_0$ to $\widetilde{R'}$; moreover, we can compute explicitly the Hasse-Witt map of the connected component $\mathscr{G}^{\circ}_{\widetilde{R'},\sigma}$ of $\mathscr{G}_{\widetilde{R'},\sigma}$ (Lemma 7.8). From the versality criterion for one-dimensional Barsotti-Tate groups in terms of the Hasse-Witt map established in Section 4 (Prop. 4.11), it follows immediately that there exists a σ such that the Barsotti-Tate group $\mathscr{G}^{\circ}_{\widetilde{R'},\sigma}$, which

is connected and one-dimensional of height n, is the universal deformation of its closed fiber. We fix such a σ. Then the set of all σ' with $\mathscr{G}^{\circ}_{\widetilde{R'},\sigma'} \simeq \mathscr{G}^{\circ}_{\widetilde{R'},\sigma}$ as deformations of their common closed fiber is actually a group isomorphic to $\mathrm{Ext}^1_{\widetilde{R'}}(\mathbb{Q}_p/\mathbb{Z}_p, \mathscr{G}^{\circ}_{\widetilde{R'},\sigma})$ (Prop. 3.10). Let σ_1 be the element corresponding to neutral element in $\mathrm{Ext}^1_{\widetilde{R'}}(\mathbb{Q}_p/\mathbb{Z}_p, \mathscr{G}^{\circ}_{\widetilde{R'},\sigma})$. Applying the induction hypothesis to $\mathscr{G}^{\circ}_{\widetilde{R'},\sigma_1}$, we see that the monodromy group of $\mathscr{G}_{\widetilde{R'},\sigma_1}$, hence that of $\mathbf{G}$, contains the subgroup $\begin{pmatrix}\mathrm{GL}_{n-1}(\mathbb{Z}_p) & 0\\ 0 & 1\end{pmatrix}$ under a suitable basis of the Tate module (7.5.3). In order to conclude the proof, we need another σ_2 such that $\mathscr{G}_{\widetilde{R'},\sigma_2}$ has the same connected component as $\mathscr{G}_{\widetilde{R'},\sigma_1}$, and that the induced extension between the Tate module of the étale part of $\mathscr{G}_{\widetilde{R'},\sigma_2}$ and that of $\mathscr{G}^{\circ}_{R',\sigma_2}$ is non-trivial after reduction modulo p (see 7.5 and 7.5.4). To verify the existence of such a σ_2, we reduce the problem to a similar situation over a complete trait of characteristic p (see 7.9), and we use a criterion of non-triviality of extensions by Hasse-Witt maps (5.12).

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1.8. Notations. Let S be a scheme of characteristic $p > 0$. A *BT-group* over S stands for a Barsotti-Tate group over S. Let G be a commutative finite group scheme (*resp.* a BT-group) over S. We denote by $G^{\vee}$ its Cartier dual (*resp.* its Serre dual), by ω_G the sheaf of invariant differentials of G over S, and by $\mathrm{Lie}(G)$ the sheaf of Lie algebras of G. If $S = \mathrm{Spec}(A)$ is affine and there is no risk of confusions, we also use ω_G and $\mathrm{Lie}(G)$ to denote the corresponding A-modules of global sections. We put $G^{(p)}$ the pull-back of G by the absolute Frobenius of S, $F_G\colon G \to G^{(p)}$ the Frobenius homomorphism and $V_G\colon G^{(p)} \to G$ the Verschiebung homomorphism. If G is a BT-group and n an integer ≥ 1, we denote by $G(n)$ the kernel of the multiplication by p^n on G; we have $G^{\vee}(n) = (G^{\vee})(n)$ by definition. For an $\mathscr{O}_S$-module M, we denote by $M^{(p)} = \mathscr{O}_S \otimes_{F_S} M$ the scalar extension of M by the absolute Frobenius of $\mathscr{O}_S$. If $\varphi : M \to N$ be a semi-linear homomorphism of $\mathscr{O}_S$-modules, we denote by $\widetilde{\varphi} : M^{(p)} \to N$ the linearization of φ, *i.e.* we have $\widetilde{\varphi}(\lambda \otimes x) = \lambda \cdot \varphi(x)$, where λ (*resp.* x) is a local section of $\mathscr{O}_S$ (*resp.* of M).
Starting from Section 5, k will denote an algebraically closed field of characteristic $p > 0$.

2. Review of ordinary Barsotti-Tate groups

In this section, S denotes a scheme of characteristic $p > 0$.

2.1. Let G be a commutative group scheme, locally free of finite type over S. We have a canonical isomorphism of coherent $\mathscr{O}_S$-modules [Ill, 2.1]

$$\mathrm{Lie}(G^\vee) \simeq \mathscr{H}om_{S_{\mathrm{fppf}}}(G, \mathbb{G}_a), \tag{2.1.1}$$

where $\mathscr{H}om_{S_{\mathrm{fppf}}}$ is the sheaf of homomorphisms in the category of abelian fppf-sheaves over S, and $\mathbb{G}_a$ is the additive group scheme. Since $\mathbb{G}_a^{(p)} \simeq \mathbb{G}_a$, the Frobenius homomorphism of $\mathbb{G}_a$ induces an endomorphism

$$\varphi_G : \mathrm{Lie}(G^\vee) \to \mathrm{Lie}(G^\vee), \tag{2.1.2}$$

semi-linear with respect to the absolute Frobenius map $F_S : \mathscr{O}_S \to \mathscr{O}_S$; we call it the *Hasse-Witt* map of G. By the functoriality of Frobenius, φ_G is also the canonical map induced by the Frobenius of G, or dually by the Verschiebung of $G^\vee$.

2.2. By a *commutative p-Lie algebra* over S, we mean a pair (L, φ), where L is an $\mathscr{O}_S$-module locally free of finite type, and $\varphi : L \to L$ is a semi-linear endomorphism with respect to the absolute Frobenius $F_S : \mathscr{O}_S \to \mathscr{O}_S$. When there is no risk of confusions, we omit φ from the notation. We denote by p-$\mathfrak{L}\mathrm{ie}_S$ the category of commutative p-Lie algebras over S.
Let (L, φ) be an object of p-$\mathfrak{L}\mathrm{ie}_S$. We denote by

$$\mathscr{U}(L) = \mathrm{Sym}(L) = \oplus_{n\geq 0} \mathrm{Sym}^n(L),$$

the symmetric algebra of L over $\mathscr{O}_S$. Let $\mathscr{I}_p(L)$ be the ideal sheaf of $\mathscr{U}(L)$ defined, for an open subset $V \subset S$, by

$$\Gamma(V, \mathscr{I}_p(L)) = \{x^{\otimes p} - \varphi(x)\ ;\ x \in \Gamma(V, \mathscr{U}(L))\},$$

where $x^{\otimes p} = x \otimes x \otimes \cdots \otimes x \in \Gamma(V, \mathrm{Sym}^p(L))$. We put $\mathscr{U}_p(L) = \mathscr{U}(L)/\mathscr{I}_p(L)$, and call it the *$p$-enveloping algebra of* (L, φ). We endow $\mathscr{U}_p(L)$ with the structure of a Hopf-algebra with the comultiplication given by $\Delta(x) = 1 \otimes x + x \otimes 1$ and the coinverse given by $i(x) = -x$.
Let G be a commutative group scheme, locally free of finite type over S. We say that G is *of coheight one* if the Verschiebung $V_G : G^{(p)} \to G$ is the zero homomorphism. We denote by $\mathfrak{G}\mathrm{V}_S$ the category of such objects. For an object G of $\mathfrak{G}\mathrm{V}_S$, the Frobenius $F_{G^\vee}$ of $G^\vee$ is zero, so the Lie algebra $\mathrm{Lie}(G^\vee)$ is locally free of finite type over $\mathscr{O}_S$ ([DG] $\mathrm{VII_A}$ Théo. 7.4(iii)). The Hasse-Witt map of G (2.1.2) endows $\mathrm{Lie}(G^\vee)$ with a commutative p-Lie algebra structure over S.

Proposition 2.3 ([DG] $\mathrm{VII_A}$, Théo. 7.2 et 7.4). *The functor $\mathfrak{G}\mathrm{V}_S \to p$-$\mathfrak{L}\mathrm{ie}_S$ defined by $G \mapsto \mathrm{Lie}(G^\vee)$ is an anti-equivalence of categories; a quasi-inverse is given by $(L, \varphi) \mapsto \mathrm{Spec}(\mathscr{U}_p(L))$.*

2.4. Assume $S = \mathrm{Spec}(A)$ affine. Let (L, φ) be an object of p-$\mathfrak{L}\mathrm{ie}_S$ such that L is free of rank n over $\mathscr{O}_S$, $(e_1, \cdots, e_n)$ be a basis of L over $\mathscr{O}_S$, $(h_{ij})_{1\leq i,j\leq n}$ be the matrix of φ under the basis $(e_1, \cdots, e_n)$, *i.e.* $\varphi(e_j) = \sum_{i=1}^n h_{ij} e_i$ for

$1 \leq j \leq n$. Then the group scheme attached to (L, φ) is explicitly given by

$$\mathrm{Spec}(\mathscr{U}_p(L)) = \mathrm{Spec}\left(A[X_1, \cdots, X_n]/(X_j^p - \sum_{i=1}^{n} h_{ij}X_i)_{1\leq j\leq n}\right),$$

with the comultiplication $\Delta(X_j) = 1 \otimes X_j + X_j \otimes 1$. By the Jacobian criterion of étaleness [EGA, IV_0 22.6.7], the finite group scheme $\mathrm{Spec}(\mathscr{U}_p(L))$ is étale over S if and only if the matrix $(h_{ij})_{1\leq i,j\leq n}$ is invertible. This condition is equivalent to that the linearization of φ is an isomorphism.

Corollary 2.5. *An object G of $\mathfrak{G}\mathrm{V}_S$ is étale over S, if and only if the linearization of its Hasse-Witt map* (2.1.2) *is an isomorphism.*

Proof. The problem being local over S, we may assume S affine and $L = \mathrm{Lie}(G^\vee)$ free over $\mathscr{O}_S$. By Theorem 2.3, G is isomorphic to $\mathrm{Spec}(\mathscr{U}_p(L))$, and we conclude by the last remark of 2.4. □

2.6. Let G be a BT-group over S of height $c+d$ and dimension d. The Lie algebra $\mathrm{Lie}(G^\vee)$ is an $\mathscr{O}_S$-module locally free of rank c, and canonically identified with $\mathrm{Lie}(G^\vee(1))$([BBM] 3.3.2). We define the *Hasse-Witt map* of G

$$\varphi_G : \mathrm{Lie}(G^\vee) \to \mathrm{Lie}(G^\vee) \tag{2.6.1}$$

to be that of $G(1)$ (2.1.2).

2.7. Let k be a field of characteristic $p > 0$, G be a BT-group over k. Recall that we have a canonical exact sequence of BT-groups over k

$$0 \to G^\circ \to G \to G^{\text{ét}} \to 0 \tag{2.7.1}$$

with G° connected and $G^{\text{ét}}$ étale ([Dem] Chap.II, §7). This induces an exact sequence of Lie algebras

$$0 \to \mathrm{Lie}(G^{\text{ét}\vee}) \to \mathrm{Lie}(G^\vee) \to \mathrm{Lie}(G^{\circ\vee}) \to 0, \tag{2.7.2}$$

compatible with Hasse-Witt maps.

Proposition 2.8. *Let k be a field of characteristic $p > 0$, G be a BT-group over k. Then $\mathrm{Lie}(G^{\text{ét}\vee})$ is the unique maximal k-subspace V of $\mathrm{Lie}(G^\vee)$ with the following properties:*
(a) *V is stable under φ_G;*
(b) *the restriction of φ_G to V is injective.*

Proof. It is clear that $\mathrm{Lie}(G^{\text{ét}\vee})$ satisfies property (a). We note that the Verschiebung of $G^{\text{ét}}(1)$ vanishes; so $G^{\text{ét}}(1)$ is in the category $\mathfrak{G}\mathrm{V}_{\mathrm{Spec}(k)}$. Since k is a field, 2.5 implies that the restriction of φ_G to $\mathrm{Lie}(G^{\text{ét}\vee})$, which coincides with $\varphi_{G^{\text{ét}}}$, is injective. This proves that $\mathrm{Lie}(G^{\text{ét}\vee})$ verifies (b). Conversely, let V be an arbitrary k-subspace of $\mathrm{Lie}(G^\vee)$ with properties (a) and (b). We have to show that $V \subset \mathrm{Lie}(G^{\text{ét}\vee})$. Let σ be the Frobenius endomorphism of k. If M is a k-vector space, for each integer $n \geq 1$, we put $M^{(p^n)} = k \otimes_{\sigma^n} M$, *i.e.* we have $1 \otimes ax = \sigma^n(a) \otimes x$ in $k \otimes_{\sigma^n} M$ for $a \in k, x \in M$. Since $\varphi_G|_V : V \to V$ is injective by assumption, the linearization $\widetilde{\varphi_G^n}|_{V^{(p^n)}} : V^{(p^n)} \to V$ of $\varphi_G^n|_V$

is injective (hence bijective) for any $n \geq 1$. We have $V = \widetilde{\varphi^n_G}(V^{(p^n)})$. Since G° is connected, there is an integer $n \geq 1$ such that the n-th iterated Frobenius $F^n_{G^\circ(1)} : G^\circ(1) \to G^\circ(1)^{(p^n)}$ vanishes. Hence by definition, the linearized n-iterated Hasse-Witt map $\widetilde{\varphi^n_{G^\circ}} : \mathrm{Lie}(G^{\circ\vee})^{(p^n)} \to \mathrm{Lie}(G^{\circ\vee})$ is zero. By the compatibility of Hasse-Witt maps, we have $\widetilde{\varphi^n_G}(\mathrm{Lie}(G^\vee)^{(p^n)}) \subset \mathrm{Lie}(G^{\text{ét}\vee})$; in particular, we have $V = \widetilde{\varphi^n_G}(V^{(p^n)}) \subset \mathrm{Lie}(G^{\text{ét}\vee})$. This completes the proof. □

Corollary 2.9. *Let k be a field of characteristic $p > 0$, G be a BT-group over k. Then G is connected if and only if φ_G is nilpotent.*

Proof. In the proof of the proposition, we have seen that the Hasse-Witt map of the connected part of G is nilpotent. So the "only if" part is verified. Conversely, if φ_G is nilpotent, $\mathrm{Lie}(G^{\text{ét}\vee})$ is zero by the proposition. Therefore G is connected. □

Definition 2.10. Let S be a scheme of characteristic $p > 0$, G be a BT-group over S. We say that G is *ordinary* if there exists an exact sequence of BT-groups over S

$$0 \to G^{\text{mult}} \to G \to G^{\text{ét}} \to 0, \tag{2.10.1}$$

such that G^{mult} is multiplicative and $G^{\text{ét}}$ is étale.

We note that when it exists, the exact sequence (2.10.1) is unique up to a unique isomorphism, because there is no non-trivial homomorphisms between a multiplicative BT-group and an étale one in characteristic $p > 0$. The property of being ordinary is clearly stable under arbitrary base change and Serre duality. If S is the spectrum of a field of characteristic $p > 0$, G is ordinary if and only if its connected part G° is of multiplicative type.

Proposition 2.11. *Let G be a BT-group over S. The following conditions are equivalent:*
(a) *G is ordinary over S.*
(b) *For every $x \in S$, the fiber $G_x = G \otimes_S \kappa(x)$ is ordinary over $\kappa(x)$.*
(c) *The finite group scheme* $\mathrm{Ker}\, V_G$ *is étale over S.*
(c') *The finite group scheme* $\mathrm{Ker}\, F_G$ *is of multiplicative type over S.*
(d) *The linearization of the Hasse-Witt map φ_G is an isomorphism.*

First, we prove the following lemmas.

Lemma 2.12. *Let T be a scheme, H be a commutative group scheme locally free of finite type over T. Then H is étale (*resp. *of multiplicative type) over T if and only if, for every $x \in T$, the fiber $H \otimes_T \kappa(x)$ is étale (*resp. *of multiplicative type) over $\kappa(x)$.*

Proof. We will consider only the étale case; the multiplicative case follows by duality. Since H is T-flat, it is étale over T if and only if it is unramified over T. By [EGA, IV 17.4.2], this condition is equivalent to that $H \otimes_T \kappa(x)$ is unramified over $\kappa(x)$ for every point $x \in T$. Hence the conclusion follows. □

Lemma 2.13. *Let G be a BT-group over S. Then* $\operatorname{Ker} V_G$ *is an object of the category* $\mathfrak{G}\mathrm{V}_S$, i.e. *it is locally free of finite type over S, and its Verschiebung is zero. Moreover, we have a canonical isomorphism* $(\operatorname{Ker} V_G)^\vee \simeq \operatorname{Ker} F_{G^\vee}$, *which induces an isomorphism of Lie algebras* $\operatorname{Lie}\big((\operatorname{Ker} V_G)^\vee\big) \simeq \operatorname{Lie}(\operatorname{Ker} F_{G^\vee}) = \operatorname{Lie}(G^\vee)$, *and the Hasse-Witt map* (2.1.2) *of* $\operatorname{Ker} V_G$ *is identified with* φ_G (2.6.1).

Proof. The group scheme $\operatorname{Ker} V_G$ is locally free of finite type over S ([Ill] 1.3(b)), and we have a commutative diagram

$$\begin{tikzcd}
(\operatorname{Ker} V_G)^{(p)} \arrow[r, "V_{\operatorname{Ker} V_G}"] \arrow[d, hook] & \operatorname{Ker} V_G \arrow[d, hook] \\
(G^{(p)})^{(p)} \arrow[r, "V_{G^{(p)}}"] & G^{(p)}
\end{tikzcd}$$

By the functoriality of Verschiebung, we have $V_{G^{(p)}} = (V_G)^{(p)}$ and $\operatorname{Ker} V_{G^{(p)}} = (\operatorname{Ker} V_G)^{(p)}$. Hence the composition of the left vertical arrow with $V_{G^{(p)}}$ vanishes, and the Verschiebung of $\operatorname{Ker} V_G$ is zero.

By Cartier duality, we have $(\operatorname{Ker} V_G)^\vee = \operatorname{Coker}(F_{G^\vee(1)})$. Moreover, the exact sequence

$$\cdots \to G^\vee(1) \xrightarrow{F_{G^\vee(1)}} \big(G^\vee(1)\big)^{(p)} \xrightarrow{V_{G^\vee(1)}} G^\vee(1) \to \cdots,$$

induces a canonical isomorphism

$$\operatorname{Coker}(F_{G^\vee(1)}) \xrightarrow{\sim} \operatorname{Im}(V_{G^\vee(1)}) = \operatorname{Ker} F_{G^\vee(1)} = \operatorname{Ker} F_{G^\vee}. \tag{2.13.1}$$

Hence, we deduce that

$$(\operatorname{Ker} V_G)^\vee \simeq \operatorname{Coker}(F_{G^\vee(1)}) \xrightarrow{\sim} \operatorname{Ker} F_{G^\vee} \hookrightarrow G^\vee(1). \tag{2.13.2}$$

Since the natural injection $\operatorname{Ker} F_{G^\vee} \to G^\vee(1)$ induces an isomorphism of Lie algebras, we get

$$\operatorname{Lie}\big((\operatorname{Ker} V_G)^\vee\big) \simeq \operatorname{Lie}(\operatorname{Ker} F_{G^\vee}) = \operatorname{Lie}(G^\vee(1)) = \operatorname{Lie}(G^\vee). \tag{2.13.3}$$

It remains to prove the compatibility of the Hasse-Witt maps with (2.13.3). We note that the dual of the morphism (2.13.2) is the canonical map $F : G(1) \to \operatorname{Ker} V_G = \operatorname{Im}(F_{G(1)})$ induced by $F_{G(1)}$. Hence by (2.1.1), the isomorphism (2.13.3) is identified with the functorial map

$$\mathscr{H}om_{S_{\mathrm{fppf}}}(\operatorname{Ker} V_G, \mathbb{G}_a) \to \mathscr{H}om_{S_{\mathrm{fppf}}}(G(1), \mathbb{G}_a)$$

induced by F, and its compatibility with the Hasse-Witt maps follows easily from the definition (2.1.2). $\square$

Proof of 2.11. (a)$\Rightarrow$(b). Indeed, the ordinarity of G is stable by base change.
(b)$\Rightarrow$(c). By Lemma 2.12, it suffices to verify that for every point $x \in S$, the fiber $(\operatorname{Ker} V_G) \otimes_S \kappa(x) \simeq \operatorname{Ker} V_{G_x}$ is étale over $\kappa(x)$. Since G_x is assumed to be ordinary, its connected part $(G_x)^\circ$ is multiplicative. Hence, the Verschiebung of

$(G_x)^\circ$ is an isomorphism, and $\operatorname{Ker} V_{G_x}$ is canonically isomorphic to $\operatorname{Ker} V_{G_x^{\text{ét}}} \subset (G_x^{\text{ét}})^{(p)} \simeq (G_x^{(p)})^{\text{ét}}$, so our assertion follows.
$(c) \Leftrightarrow (d)$. It follows immediately from Lemma 2.13 and Corollary 2.5.
(c)⇔(c'). By 2.12, we may assume that S is the spectrum of a field. So the category of commutative finite group schemes over S is abelian. We will just prove (c)⇒(c'); the converse can be proved by duality. We have a fundamental short exact sequence of finite group schemes

$$0 \to \operatorname{Ker} F_G \to G(1) \xrightarrow{F} \operatorname{Ker} V_G \to 0, \tag{2.13.4}$$

where F is induced by $F_{G(1)}$, That induces a commutative diagram

$$\begin{tikzcd}
0 \arrow[r] & \big(\operatorname{Ker} F_G\big)^{(p)} \arrow[r] \arrow[d, "V'"] & \big(G(1)\big)^{(p)} \arrow[r, "F^{(p)}"] \arrow[d, "V_{G(1)}"] & \big(\operatorname{Ker} V_G\big)^{(p)} \arrow[r] \arrow[d, "V''"] & 0 \\
0 \arrow[r] & \operatorname{Ker} F_G \arrow[r] & G(1) \arrow[r, "F"] & \operatorname{Ker} V_G \arrow[r] & 0
\end{tikzcd}$$

where vertical arrows are the Verschiebung homomorphisms. We have seen that $V'' = 0$ (2.13). Therefore, by the snake lemma, we have a long exact sequence

(2.13.5)
$$\begin{aligned} 0 \to \operatorname{Ker} V' \to \operatorname{Ker} V_{G(1)} \xrightarrow{\alpha} \big(\operatorname{Ker} V_G\big)^{(p)} \to \\ \to \operatorname{Coker} V' \to \operatorname{Coker} V_{G(1)} \xrightarrow{\beta} \operatorname{Ker} V_G \to 0, \end{aligned}$$

where the map α is the Frobenius of $\operatorname{Ker} V_G$ and β is the composed isomorphism

$$\operatorname{Coker}(V_{G(1)}) \simeq G(1)/\operatorname{Ker} F_{G(1)} \xrightarrow{\sim} \operatorname{Im}(F_{G(1)}) \simeq \operatorname{Ker} V_G.$$

Then condition (c) is equivalent to that α is an isomorphism; it implies that $\operatorname{Ker} V' = \operatorname{Coker} V' = 0$, *i.e.* the Verschiebung of $\operatorname{Ker} F_G$ is an isomorphism, and hence (c').
(c)⇒(a). For every integer $n > 0$, we denote by F_G^n the composed homomorphism

$$G \xrightarrow{F_G} G^{(p)} \xrightarrow{F_{G^{(p)}}} \cdots \xrightarrow{F_{G^{(p^{n-1})}}} G^{(p^n)},$$

and by V_G^n the composed homomorphism

$$G^{(p^n)} \xrightarrow{V_{G^{(p^{n-1})}}} G^{(p^{n-1})} \xrightarrow{V_{G^{(p^{n-2})}}} \cdots \xrightarrow{V_G} G;$$

F_G^n and V_G^n are isogenies of BT-groups. From the relation $V_G^n \circ F_G^n = p^n$, we deduce an exact sequence

$$0 \to \operatorname{Ker} F_G^n \to G(n) \xrightarrow{F^n} \operatorname{Ker} V_G^n \to 0, \tag{2.13.6}$$

where F^n is induced by F^n_G. For $1 \leq j < n$, we have a commutative diagram

$$\begin{tikzcd} G^{(p^n)} \arrow[rr, "V^{n-j}_{G^{(p^j)}}"] \arrow[dr, "V^n_G"'] & & G^{(p^j)} \arrow[dl, "V^j_G"] \\ & G. & \end{tikzcd} \tag{2.13.7}$$

One notices that $\operatorname{Ker} V^{n-j}_{G^{(p^j)}} = (\operatorname{Ker} V^{n-j}_G)^{(p^j)}$ by the functoriality of Verschiebung . Since all maps in (2.13.7) are isogenies, we have an exact sequence

$$0 \to (\operatorname{Ker} V^{n-j}_G)^{(p^j)} \xrightarrow{i'_{n-j,n}} \operatorname{Ker} V^n_G \xrightarrow{p_{n,j}} \operatorname{Ker} V^j_G \to 0. \tag{2.13.8}$$

Therefore, condition (c) implies by induction that $\operatorname{Ker} V^n_G$ is an étale group scheme over S. Hence the j-th iteration of the Frobenius $\operatorname{Ker} V^{n-j}_G \to (\operatorname{Ker} V^{n-j}_G)^{(p^j)}$ is an isomorphism, and $\operatorname{Ker} V^{n-j}_G$ is identified with a closed subgroup scheme of $\operatorname{Ker} V^n_G$ by the composed map

$$i_{n-j,n} : \operatorname{Ker} V^{n-j}_G \xrightarrow{\sim} (\operatorname{Ker} V^{n-j}_G)^{(p^j)} \xrightarrow{i'_{n-j,n}} \operatorname{Ker} V^n_G.$$

We claim that the kernel of the multiplication by p^{n-j} on $\operatorname{Ker} V^n_G$ is $\operatorname{Ker} V^{n-j}_G$. Indeed, from the relation $p^{n-j} \cdot \mathrm{Id}_{G^{(p^n)}} = F^{n-j}_{G^{(p^j)}} \circ V^{n-j}_{G^{(p^j)}}$, we deduce a commutative diagram (without dotted arrows)

$$\begin{tikzcd} \operatorname{Ker} V^n_G \arrow[rr] \arrow[dd, "p^{n-j}"'] \arrow[dr, dashed, "p_{n,j}"] & & G^{(p^n)} \arrow[dd, "p^{n-j}"' near start] \arrow[dr, "V^{n-j}_{G^{(p^j)}}"] & \\ & \operatorname{Ker} V^j_G \arrow[rr, dashed] \arrow[dl, dashed, "i_{j,n}"] & & G^{(p^j)} \arrow[dl, "F^{n-j}_{G^{(p^j)}}"] \\ \operatorname{Ker} V^n_G \arrow[rr] & & G^{(p^n)}. & \end{tikzcd} \tag{2.13.9}$$

It follows from (2.13.8) that the subgroup $\operatorname{Ker} V^n_G$ of $G^{(p^n)}$ is sent by $V^{n-j}_{G^{(p^j)}}$ onto $\operatorname{Ker} V^j_G$. Therefore diagram (2.13.9) remains commutative when completed by the dotted arrows, hence our claim. It follows from the claim that $(\operatorname{Ker} V^n_G)_{n\geq 1}$ constitutes an étale BT-group over S, denoted by $G^{\text{ét}}$. By duality, we have an exact sequence

$$0 \to \operatorname{Ker} F^j_G \to \operatorname{Ker} F^n_G \to (\operatorname{Ker} F^{n-j}_G)^{(p^j)} \to 0. \tag{2.13.10}$$

Condition (c') implies by induction that $\operatorname{Ker} F^n_G$ is of multiplicative type. Hence the j-th iteration of Verschiebung $(\operatorname{Ker} F^{n-j}_G)^{(p^j)} \to \operatorname{Ker} F^{n-j}_G$ is an isomorphism. We deduce from (2.13.10) that $(\operatorname{Ker} F^n_G)_{n\geq 1}$ form a multiplicative BT-group over S that we denote by G^{mult}. Then the exact sequences (2.13.6) give a decomposition of G of the form (2.10.1). $\square$

COROLLARY 2.14. *Let G be a BT-group over S, and S^{ord} be the locus in S of the points $x \in S$ such that $G_x = G \otimes_S \kappa(x)$ is ordinary over $\kappa(x)$. Then S^{ord} is open in S, and the canonical inclusion $S^{\mathrm{ord}} \to S$ is affine.*

The open subscheme S^{ord} of S is called the *ordinary locus* of G.

3. PRELIMINARIES ON DIEUDONNÉ THEORY AND DEFORMATION THEORY

3.1. We will use freely the conventions of 1.8. Let S be a scheme of characteristic $p > 0$, G be a Barsotti-Tate group over S, and $\mathbf{M}(G) = \mathbb{D}(G)_{(S,S)}$ be the coherent $\mathscr{O}_S$-module obtained by evaluating the (contravariant) Dieudonné crystal of G at the trivial divided power immersion $S \hookrightarrow S$ [BBM, 3.3.6]. Recall that $\mathbf{M}(G)$ is an $\mathscr{O}_S$-module locally free of finite type satisfying the following properties:
(i) Let $F_M : \mathbf{M}(G)^{(p)} \to \mathbf{M}(G)$ and $V_M : \mathbf{M}(G) \to \mathbf{M}(G)^{(p)}$ be the $\mathscr{O}_S$-linear maps induced respectively by the Frobenius and the Verschiebung of G. We have the following exact sequence:

$$\cdots \to \mathbf{M}(G)^{(p)} \xrightarrow{F_M} \mathbf{M}(G) \xrightarrow{V_M} \mathbf{M}(G)^{(p)} \to \cdots .$$

(ii) There is a connection $\nabla : \mathbf{M}(G) \to \mathbf{M}(G) \otimes_{\mathscr{O}_S} \Omega^1_{S/\mathbb{F}_p}$ for which F_M and V_M are horizontal morphisms.
(iii) We have two canonical filtrations on $\mathbf{M}(G)$ by $\mathscr{O}_S$-modules locally free of finite type:

$$0 \to \omega_G \to \mathbf{M}(G) \to \mathrm{Lie}(G^\vee) \to 0, \tag{3.1.1}$$

called the *Hodge filtration* on $\mathbf{M}(G)$ [BBM, 3.3.5], and the *conjugate filtration* on $\mathbf{M}(G)$

$$0 \to \mathrm{Lie}(G^\vee)^{(p)} \xrightarrow{\phi_G} \mathbf{M}(G) \to \omega_G^{(p)} \to 0, \tag{3.1.2}$$

which is obtained by applying the Dieudonné functor to the exact sequence of finite group schemes $0 \to \mathrm{Ker}\, F_G \to G(1) \to \mathrm{Ker}\, V_G \to 0$ [BBM, 4.3.1, 4.3.6, 4.3.11]. Moreover, we have the following commutative diagram (cf. [Ka1, 2.3.2

and 2.3.4])
(3.1.3)

$$\begin{tikzcd}
 & 0 \arrow[d] & 0 \arrow[d] & 0 \arrow[d] & \\
 & \omega_G^{(p)} \arrow[d] & \omega_G \arrow[r, "\psi_G"] \arrow[d] & \omega_G^{(p)} \arrow[d] & \\
 {} \arrow[r] & \mathbf{M}(G)^{(p)} \arrow[r, "F_M"] \arrow[d] & \mathbf{M}(G) \arrow[r, "V_M"] \arrow[d] \arrow[ur] & \mathbf{M}(G)^{(p)} \arrow[r] \arrow[d] & {} , \\
 & \mathrm{Lie}(G^\vee)^{(p)} \arrow[r, "\widetilde{\varphi_G}"] \arrow[d] \arrow[ur, hook, "\phi_G"] & \mathrm{Lie}(G^\vee) \arrow[d] & \mathrm{Lie}(G^\vee)^{(p)} \arrow[d] & \\
 & 0 & 0 & 0 &
\end{tikzcd}$$

where the columns are the Hodge filtrations and the anti-diagonal is the conjugate filtration. By functoriality, we see easily that $\widetilde{\varphi_G}$ above is nothing but the linearization of the Hasse-Witt map φ_G (2.6.1), and the morphism $\psi_G^* : \mathrm{Lie}(G)^{(p)} \to \mathrm{Lie}(G)$, which is obtained by applying the functor $\mathscr{H}om_{\mathscr{O}_S}(\_, \mathscr{O}_S)$ to ψ_G, is identified with the linearization $\widetilde{\varphi_{G^\vee}}$ of $\varphi_{G^\vee}$.
The formation of these structures on $\mathbf{M}(G)$ commutes with arbitrary base changes of S. In the sequel, we will use $(\mathbf{M}(G), F_M, \nabla)$ to emphasize these structures on $\mathbf{M}(G)$.

3.2. In the reminder of this section, k will denote an algebraically closed field of characteristic $p > 0$. Let S be a scheme formally smooth over k such that $\Omega^1_{S/\mathbb{F}_p} = \Omega^1_{S/k}$ is an $\mathscr{O}_S$-module locally free of finite type, *e.g.* $S = \mathrm{Spec}(A)$ with A a formally smooth k-algebra with a finite p-basis over k. Let G be a BT-group over S. We put KS to be the composed morphism

$$(3.2.1) \qquad \mathrm{KS} : \omega_G \to \mathbf{M}(G) \xrightarrow{\nabla} \mathbf{M}(G) \otimes_{\mathscr{O}_S} \Omega^1_{S/k} \xrightarrow{pr} \mathrm{Lie}(G^\vee) \otimes_{\mathscr{O}_S} \Omega^1_{S/k}$$

which is $\mathscr{O}_S$-linear. We put $\mathscr{T}_{S/k} = \mathscr{H}om_{\mathscr{O}_S}(\Omega^1_{S/k}, \mathscr{O}_S)$, and define the *Kodaira-Spencer map* of G

$$(3.2.2) \qquad \mathrm{Kod} : \mathscr{T}_{S/k} \to \mathscr{H}om_{\mathscr{O}_S}(\omega_G, \mathrm{Lie}(G^\vee))$$

to be the morphism induced by KS. We say that G is *versal* if Kod is surjective.

3.3. Let r be an integer ≥ 1, $R = k[[t_1, \cdots, t_r]]$, $\mathfrak{m}$ be the maximal ideal of R. We put $\mathscr{S} = \mathrm{Spf}(R)$, $S = \mathrm{Spec}(R)$, and for each integer $n \geq 0$, $S_n = \mathrm{Spec}(R/\mathfrak{m}^{n+1})$. By a BT-group $\mathscr{G}$ over the formal scheme $\mathscr{S}$, we mean a sequence of BT-groups $(G_n)_{n\geq 0}$ over $(S_n)_{n\geq 0}$ equipped with isomorphisms $G_{n+1} \times_{S_{n+1}} S_n \simeq G_n$.

According to [deJ, 2.4.4], *the functor* $G \mapsto (G \times_S S_n)_{n \geq 0}$ *induces an equivalence of categories between the category of BT-groups over* S *and the category of BT-groups over* $\mathscr{S}$. For a BT-group $\mathscr{G}$ over $\mathscr{S}$, the corresponding BT-group G over S is called the *algebraization* of $\mathscr{G}$. We say that $\mathscr{G}$ is *versal* over $\mathscr{S}$, if its algebraization G is versal over S. Since S is local, by Nakayama's Lemma, $\mathscr{G}$ or G is versal if and only if the reduction of Kod modulo the maximal ideal

$$\mathrm{Kod}_0 : \mathscr{T}_{S/k} \otimes_{\mathscr{O}_S} k \longrightarrow \mathrm{Hom}_k(\omega_{G_0}, \mathrm{Lie}(G_0^\vee)) \tag{3.3.1}$$

is surjective.

3.4. We recall briefly the deformation theory of a BT-group. Let $\mathfrak{AL}_k$ be the category of local artinian k-algebras with residue field k. We notice that all morphisms of $\mathfrak{AL}_k$ are local. A morphism $A' \to A$ in $\mathfrak{AL}_k$ is called a *small extension*, if it is surjective and its kernel I satisfies $I \cdot \mathfrak{m}_{A'} = 0$, where $\mathfrak{m}_{A'}$ is the maximal ideal of A'.
Let G_0 be a BT-group over k, and A an object of $\mathfrak{AL}_k$. A deformation of G_0 over A is a pair (G, ϕ), where G is a BT-group over $\mathrm{Spec}(A)$ and ϕ is an isomorphism $\phi : G \otimes_A k \xrightarrow{\sim} G_0$. When there is no risk of confusions, we will denote a deformation (G, ϕ) simply by G. Two deformations (G, ϕ) and (G', ϕ') over A are isomorphic if there exists an isomorphism of BT-groups $\psi : G \xrightarrow{\sim} G'$ over A such that $\phi = \phi' \circ (\psi \otimes_A k)$. Let's denote by $\mathcal{D}$ the functor which associates with each object A of $\mathfrak{AL}_k$ the set of isomorphsm classes of deformations of G_0 over A. If $f : A \to B$ is a morphism of $\mathfrak{AL}_k$, then the map $\mathcal{D}(f) : \mathcal{D}(A) \to \mathcal{D}(B)$ is given by extension of scalars. We call $\mathcal{D}$ the *deformation functor* of G_0 over $\mathfrak{AL}_k$.

Proposition 3.5 ([Ill], 4.8). *Let* G_0 *be a BT-group over* k *of dimension* d *and height* $c + d$, $\mathcal{D}$ *be the deformation functor of* G_0 *over* $\mathfrak{AL}_k$.
(i) *Let* $A' \to A$ *be a small extension in* $\mathfrak{AL}_k$ *with ideal* I, $x = (G, \phi)$ *be an element in* $\mathcal{D}(A)$, $\mathcal{D}_x(A')$ *be the subset of* $\mathcal{D}(A')$ *with image* x *in* $\mathcal{D}(A)$. *Then the set* $\mathcal{D}_x(A')$ *is a nonempty homogenous space under the group* $\mathrm{Hom}_k(\omega_{G_0}, \mathrm{Lie}(G_0^\vee)) \otimes_k I$.
(ii) *The functor* $\mathcal{D}$ *is pro-representable by a formally smooth formal scheme* $\mathscr{S}$ *over* k *of relative dimension* cd, i.e. $\mathscr{S} = \mathrm{Spf}(R)$ *with* $R \simeq k[[(t_{ij})_{1 \leq i \leq c, 1 \leq j \leq d}]]$, *and there exists a unique deformation* $(\mathscr{G}, \psi)$ *of* G_0 *over* $\mathscr{S}$ *such that, for any object* A *of* $\mathfrak{AL}_k$ *and any deformation* (G, ϕ) *of* G_0 *over* A, *there is a unique homomorphism of local* k*-algebras* $\varphi : R \to A$ *with* $(G, \phi) = \mathcal{D}(\varphi)(\mathscr{G}, \psi)$.
(iii) *Let* $\mathscr{T}_{\mathscr{S}/k}(0) = \mathscr{T}_{\mathscr{S}/k} \otimes_{\mathscr{O}_{\mathscr{S}}} k$ *be the tangent space of* $\mathscr{S}$ *at its unique closed point,*

$$\mathrm{Kod}_0 : \mathscr{T}_{\mathscr{S}/k}(0) \longrightarrow \mathrm{Hom}_k(\omega_{G_0}, \mathrm{Lie}(G_0^\vee))$$

be the Kodaira-Spencer map of $\mathscr{G}$ *evaluated at the closed point of* $\mathscr{S}$. *Then* Kod_0 *is bijective, and it can be described as follows. For an element* $f \in \mathscr{T}_{\mathscr{S}/k}(0)$, i.e. *a homomorphism of local* k*-algebras* $f : R \to k[\epsilon]/\epsilon^2$, $\mathrm{Kod}_0(f)$ *is the difference of deformations*

$$[\mathscr{G} \otimes_R (k[\epsilon]/\epsilon^2)] - [G_0 \otimes_k (k[\epsilon]/\epsilon^2)],$$

which is a well-defined element in $\mathrm{Hom}_k(\omega_{G_0}, \mathrm{Lie}(G_0^\vee))$ *by* (i).

Remark 3.6. Let $(e_j)_{1\leq j\leq d}$ be a basis of ω_{G_0}, $(f_i)_{1\leq i\leq c}$ be a basis of $\mathrm{Lie}(G_0^\vee)$. In view of 3.5(iii), we can choose a system of parameters $(t_{ij})_{1\leq i\leq c, 1\leq j\leq d}$ of $\mathscr{S}$ such that

$$\mathrm{Kod}_0(\frac{\partial}{\partial t_{ij}}) = e_j^* \otimes f_i,$$

where $(e_j^*)_{1\leq j\leq d}$ is the dual basis of $(e_j)_{1\leq j\leq d}$. Moreover, if $\mathfrak{m}$ is the maximal ideal of R, the parameters t_{ij} are determined uniquely modulo $\mathfrak{m}^2$.

Corollary 3.7 (Algebraization of the universal deformation). *The assumptions being those of* (3.5), *we put moreover* $\mathbf{S} = \mathrm{Spec}(R)$ *and* $\mathbf{G}$ *the algebraization of the universal formal deformation* $\mathscr{G}$. *Then the BT-group* $\mathbf{G}$ *is versal over* $\mathbf{S}$, *and satisfies the following universal property: Let A be a noetherian complete local k-algebra with residue field k, G be a BT-group over A endowed with an isomorphism $G\otimes_A k \simeq G_0$. Then there exists a unique continuous homomorphism of local k-algebras $\varphi: R\to A$ such that $G\simeq \mathbf{G}\otimes_R A$.*

Proof. By the last remark of 3.3, $\mathbf{G}$ is clearly versal. It remains to prove that it satisfies the universal property in the corollary. Let G be a deformation of G_0 over a noetherian complete local k-algebra A with residue field k. We denote by $\mathfrak{m}_A$ the maximal ideal of A, and put $A_n = A/\mathfrak{m}_A^{n+1}$ for each integer $n\geq 0$. Then by 3.5(b), there exists a unique local homomorphism $\varphi_n : R\to A_n$ such that $G\otimes A_n \simeq \mathbf{G}\otimes_R A_n$. The φ_n's form a projective system $(\varphi_n)_{n\geq 0}$, whose projective limit $\varphi: R\to A$ answers the question. □

Definition 3.8. The notations are those of (3.7). We call $\mathbf{S}$ the *local moduli in characteristic* p of G_0, and $\mathbf{G}$ the *universal deformation of* G_0 *in characteristic* p.

If there is no confusions, we will omit "in characteristic p" for short.

3.9. Let G be a BT-group over k, G° be its connected part, and $G^{\text{ét}}$ be its étale part. Let r be the height of $G^{\text{ét}}$. Then we have $G^{\text{ét}} \simeq (\mathbb{Q}_p/\mathbb{Z}_p)^r$, since k is algebraically closed. Let $\mathcal{D}_G$ (*resp.* $\mathcal{D}_{G^\circ}$) be the deformation functor of G (*resp.* G°) over $\mathfrak{AL}_k$. If A is an object in $\mathfrak{AL}_k$ and $\mathscr{G}$ is a deformation of G (*resp.* G°) over A, we denote by $[\mathscr{G}]$ its isomorphism class in $\mathcal{D}_G(A)$ (*resp.* in $\mathcal{D}_{G^\circ(A)}$).

Proposition 3.10. *The assumptions are as above, let $\Theta: \mathcal{D}_G\to\mathcal{D}_{G^\circ}$ be the morphism of functors that maps a deformation of G to its connected component.*
(i) *The morphism Θ is formally smooth of relative dimension r.*
(ii) *Let A be an object of $\mathfrak{AL}_k$, and $\mathscr{G}^\circ$ be a deformation of G° over A. Then the subset $\Theta_A^{-1}([\mathscr{G}^\circ])$ of $\mathcal{D}_G(A)$ is canonically identified with $\mathrm{Ext}^1_A(\mathbb{Q}_p/\mathbb{Z}_p,\mathscr{G}^\circ)^r$, where Ext^1_A means the group of extensions in the category of abelian* fppf*-sheaves on* $\mathrm{Spec}(A)$.

Proof. (i) Since $\mathcal{D}_G$ and $\mathcal{D}_{G^\circ}$ are both pro-representable by a noetherian local complete k-algebra and formally smooth over k (3.5), by a formal completion version of [EGA, IV 17.11.1(d)], we only need to check that the tangent map

$$\Theta_{k[\epsilon]/\epsilon^2} : \mathcal{D}_G(k[\epsilon]/\epsilon^2)\to\mathcal{D}_{G^\circ}(k[\epsilon]/\epsilon^2)$$

is surjective with kernel of dimension r over k. By 3.5(iii), $\mathcal{D}_G(k[\epsilon]/\epsilon^2)$ (*resp.* $\mathcal{D}_{G^\circ}(k[\epsilon]/\epsilon^2)$) is isomorphic to $\mathrm{Hom}_k(\omega_G, \mathrm{Lie}(G^\vee))$ (*resp.* $\mathrm{Hom}_k(\omega_{G^\circ}, \mathrm{Lie}(G^{\circ\vee}))$) by the Kodaira-Spencer morphism. In view of the canonical isomorphism $\omega_G \simeq \omega_{G^\circ}$, $\Theta_{k[\epsilon]/\epsilon^2}$ corresponds to the map

$$\Theta'_{k[\epsilon]/\epsilon^2} : \mathrm{Hom}_k(\omega_G, \mathrm{Lie}(G^\vee)) \to \mathrm{Hom}_k(\omega_G, \mathrm{Lie}(G^{\circ\vee}))$$

induced by the canonical surjection $\mathrm{Lie}(G^\vee) \to \mathrm{Lie}(G^{\circ\vee})$. It is clear that $\Theta'_{k[\epsilon]/\epsilon^2}$ is surjective of kernel $\mathrm{Hom}_k(\omega_G, \mathrm{Lie}(G^{\text{ét}\vee}))$, which has dimension r over k.
(ii) Since $G^{\text{ét}}$ is isomorphic to $(\mathbb{Q}_p/\mathbb{Z}_p)^r$, every element in $\mathrm{Ext}^1_A(\mathbb{Q}_p/\mathbb{Z}_p, \mathscr{G}^\circ)^r$ defines clearly an element of $\mathcal{D}_G(A)$ with image $[\mathscr{G}^\circ]$ in $\mathcal{D}_{G^\circ}(A)$. Conversely, for any $\mathscr{G} \in \mathcal{D}_G(A)$ with connected component isomorphic to $\mathscr{G}^\circ$, the isomorphism $G^{\text{ét}} \simeq (\mathbb{Q}_p/\mathbb{Z}_p)^r$ lifts uniquely to an isomorphism $\mathscr{G}^{\text{ét}} \simeq (\mathbb{Q}_p/\mathbb{Z}_p)^r$ because A is henselian. The canonical exact sequence $0 \to \mathscr{G}^\circ \to \mathscr{G} \to \mathscr{G}^{\text{ét}} \to 0$ shows that $\mathscr{G}$ comes from an element of $\mathrm{Ext}^1_A(\mathbb{Q}_p/\mathbb{Z}_p, \mathscr{G}^\circ)^r$.

□

4. HW-cyclic Barsotti-Tate Groups

DEFINITION 4.1. Let S be a scheme of characteristic $p > 0$, G be a BT-group over S such that $c = \dim(G^\vee)$ is constant. We say that G is *HW-cyclic*, if $c \geq 1$ and there exists an element $v \in \Gamma(S, \mathrm{Lie}(G^\vee))$ such that

$$v, \varphi_G(v), \cdots, \varphi_G^{c-1}(v)$$

generate $\mathrm{Lie}(G^\vee)$ as an $\mathscr{O}_S$-module, where φ_G is the Hasse-Witt map (2.6.1) of G.

REMARK 4.2. It is clear that a BT-group G over S is HW-cyclic, if and only if $\mathrm{Lie}(G^\vee)$ is free over $\mathscr{O}_S$ and there exists a basis of $\mathrm{Lie}(G^\vee)$ over $\mathscr{O}_S$ under which φ_G is expressed by a matrix of the form

$$\begin{pmatrix} 0 & 0 & \cdots & 0 & -a_1 \\ 1 & 0 & \cdots & 0 & -a_2 \\ 0 & 1 & \cdots & 0 & -a_3 \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & \cdots & 1 & -a_c \end{pmatrix}, \tag{4.2.1}$$

where $a_i \in \Gamma(S, \mathscr{O}_S)$ for $1 \leq i \leq c$.

LEMMA 4.3. *Let R be a local ring of characteristic $p > 0$, k be its residue field.*
(i) *A BT-group G over R is HW-cyclic if and only if so is $G \otimes k$.*
(ii) *Let $0 \to G' \to G \to G'' \to 0$ be an exact sequence of BT-groups over R. If G is HW-cyclic, then so is G'. In particular, if R is henselian, the connected part of a HW-cyclic BT-group over R is HW-cyclic.*

Proof. (i) The property of being HW-cyclic is clearly stable under arbitrary base changes, so the "only if" part is clear. Assume that $G_0 = G \otimes k$ is HW-cyclic. Let $\overline{v}$ be an element of $\mathrm{Lie}(G_0^\vee) = \mathrm{Lie}(G^\vee) \otimes k$ such that

$(\overline{v}, \varphi_{G_0}(\overline{v}), \cdots, \varphi_{G_0}^{c-1}(\overline{v}))$ is a basis of $\mathrm{Lie}(G_0^\vee)$. Let v be any lift of $\overline{v}$ in $\mathrm{Lie}(G^\vee)$. Then by Nakayama's lemma, $(v, \varphi_G(v), \cdots, \varphi_G^{c-1}(v))$ is a basis of $\mathrm{Lie}(G^\vee)$.
(ii) By statement (i), we may assume $R = k$. The exact sequence of BT-groups induces an exact sequence of Lie algebras

$$0 \to \mathrm{Lie}(G''^\vee) \to \mathrm{Lie}(G^\vee) \to \mathrm{Lie}(G'^\vee) \to 0, \tag{4.3.1}$$

and the Hasse-Witt map $\varphi_{G'}$ is induced by φ_G by functoriality. Assume that G is HW-cyclic and $G^\vee$ has dimension c. Let u be an element of $\mathrm{Lie}(G^\vee)$ such that

$$u, \varphi_G(u), \cdots, \varphi_G^{c-1}(u)$$

form a basis of $\mathrm{Lie}(G^\vee)$ over k. We denote by u' the image of u in $\mathrm{Lie}(G'^\vee)$. Let $r \leq c$ be the maximal integer such that the vectors

$$u', \ \varphi_{G'}(u'), \ \cdots, \ \varphi_{G'}^{r-1}(u')$$

are linearly independent over k. It is easy to see that they form a basis of the k-vector space $\mathrm{Lie}(G'^\vee)$. Hence G' is HW-cyclic. □

LEMMA 4.4. *Let $S = \mathrm{Spec}(R)$ be an affine scheme of characteristic $p > 0$, G be a HW-cyclic BT-group over R with $c = \dim(G^\vee)$ constant, and*

$$\begin{pmatrix} 0 & 0 & \cdots & 0 & -a_1 \\ 1 & 0 & \cdots & 0 & -a_2 \\ 0 & 1 & \cdots & 0 & -a_3 \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & \cdots & 1 & -a_c \end{pmatrix} \in \mathrm{M}_{c\times c}(R),$$

be a matrix of φ_G. Put $a_{c+1} = 1$, and $P(X) = \sum_{i=0}^{c} a_{i+1} X^{p^i} \in R[X]$.
(i) *Let $V_G : G^{(p)} \to G$ be the Verschiebung homomorphism of G. Then $\mathrm{Ker}\, V_G$ is isomorphic to the group scheme $\mathrm{Spec}(R[X]/P(X))$ with comultiplication given by $X \mapsto 1 \otimes X + X \otimes 1$.*
(ii) *Let $x \in S$, and G_x be the fibre of G at x. Put*

$$i_0(x) = \min_{0 \leq i \leq c} \{i; a_{i+1}(x) \neq 0\}, \tag{4.4.1}$$

where $a_i(x)$ denotes the image of a_i in the residue field of x. Then the étale part of G_x has height $c - i_0(x)$, and the connected part of G_x has height $d + i_0(x)$. In particular, G_x is connected if and only if $a_i(x) = 0$ for $1 \leq i \leq c$.

Proof. (i) By 2.3 and 2.13, $\mathrm{Ker}\, V_G$ is isomorphic to the group scheme

$$\mathrm{Spec}\Big(R[X_1, \ldots, X_c]/(X_1^p - X_2, \cdots, X_{c-1}^p - X_c, X_c^p + a_1 X_1 + \cdots + a_c X_c)\Big)$$

with comultiplication $\Delta(X_i) = 1 \otimes X_i + X_i \otimes 1$ for $1 \leq i \leq c$. By sending $(X_1, X_2, \cdots, X_c) \mapsto (X, X^p, \cdots, X^{p^{c-1}})$, we see that the above group scheme is isomorphic to $\mathrm{Spec}(R[X]/P(X))$ with comultiplication $\Delta(X) = 1 \otimes X + X \otimes 1$.

(ii) By base change, we may assume that $S = x = \mathrm{Spec}(k)$ and hence $G = G_x$. Let $G(1)$ be the kernel of the multiplication by p on G. Then we have an exact sequence

$$0 \to \mathrm{Ker}\, F_G \to G(1) \to \mathrm{Ker}\, V_G \to 0.$$

Since $\mathrm{Ker}\, F_G$ is an infinitesimal group scheme over k, we have $G(1)(\overline{k}) = (\mathrm{Ker}\, V_G)(\overline{k})$, where $\overline{k}$ is an algebraic closure of k. By the definition of $i_0(x)$, we have $P(X) = Q(X^{p^{i_0(x)}})$, where $Q(X)$ is an additive sepearable polynomial in $k[X]$ with $\deg(Q) = p^{c-i_0(x)}$. Hence the roots of $P(X)$ in $\overline{k}$ form an $\mathbb{F}_p$-vector space of dimension $c - i_0(x)$. By (i), $(\mathrm{Ker}\, V_G)(\overline{k})$ can be identified with the additive group consisting of the roots of $P(X)$ in $\overline{k}$. Therefore, the étale part of G has height $c - i_0(x)$, and the connected part of G has height $d + i_0(x)$. $\square$

4.5. Let k be a perfect field of characteristic $p > 0$, and $\alpha_p = \mathrm{Spec}(k[X]/X^p)$ be the finite group scheme over k with comultiplication map $\Delta(X) = 1 \otimes X + X \otimes 1$. Let G be a BT-group over k. Following Oort, we call

$$a(G) = \dim_k \mathrm{Hom}_{k_{\mathrm{fppf}}}(\alpha_p, G)$$

the a-number of G, where $\mathrm{Hom}_{k_{\mathrm{fppf}}}$ means the homomorphisms in the category of abelian fppf-sheaves over k. Since the Frobenius of α_p vanishes, any morphism of α_p in G factorize through $\mathrm{Ker}(F_G)$. Therefore we have

$$\begin{aligned}\mathrm{Hom}_{k_{\mathrm{fppf}}}(\alpha_p, G) &= \mathrm{Hom}_{k-gr}(\alpha_p, \mathrm{Ker}(F_G))\\ &= \mathrm{Hom}_{k-gr}(\mathrm{Ker}(F_G)^\vee, \alpha_p)\\ &= \mathrm{Hom}_{p\text{-}\mathfrak{Lie}_k}(\mathrm{Lie}(\alpha_p), \mathrm{Lie}(\mathrm{Ker}(F_G))),\end{aligned}$$

where Hom_{k-gr} denotes the homomorphisms in the category of commutative group schemes over k, and the last equality uses Proposition 2.3. Since we have a canonical isomorphism $\mathrm{Lie}(\mathrm{Ker}(F_G)) \simeq \mathrm{Lie}(G)$ and $\mathrm{Lie}(\alpha_p)$ has dimension one over k with $\varphi_{\alpha_p} = 0$, we get

$$a(G) = \dim_k \{x \in \mathrm{Lie}(G) | \varphi_{G^\vee}(x) = 0\} = \dim_k \mathrm{Ker}(\varphi_{G^\vee}). \tag{4.5.1}$$

Due to the perfectness of k, we have also $a(G) = \dim_k \mathrm{Ker}(\widetilde{\varphi_{G^\vee}})$, where $\widetilde{\varphi_{G^\vee}}$ is the linearization of $\varphi_{G^\vee}$. By Proposition 2.11, we see that $a(G) = 0$ if and only if G is ordinary.

LEMMA 4.6. *Let G be a BT-group over k, and $G^\vee$ its Serre dual. Then we have $a(G) = a(G^\vee)$.*

Proof. Let $\psi_G : \omega_G \to \omega_G^{(p)}$ be the k-linear map induced by the Verschiebung of G. Then ψ_G^*, the morphism obtained by applying the functor $\mathrm{Hom}_k(\_, k)$ to ψ_G, is identified with $\widetilde{\varphi_{G^\vee}}$. By (4.5.1) and the exactitude of the functor $\mathrm{Hom}_k(\_, k)$, we have $a(G) = \dim_k \mathrm{Ker}(\psi_G^*) = \dim_k \mathrm{Coker}(\psi_G)$. Using the additivity of $\dim_k$, we get finally $a(G) = \dim_k \mathrm{Ker}(\psi_G)$. By considering the commutative diagram (3.1.3), we have

$$a(G) = \dim_k\Big(\omega_G \cap \phi_G(\mathrm{Lie}(G^\vee)^{(p)})\Big).$$

On the other hand, it follows also from (3.1.3) that

$$a(G^\vee) = \dim_k \mathrm{Ker}(\widetilde{\varphi_G}) = \dim_k \Big(\phi_G(\mathrm{Lie}(G^\vee)^{(p)}) \cap \omega_G\Big).$$

The lemma now follows immediately. □

Proposition 4.7. *Let k be a perfect field of characteristic $p > 0$, G a BT-group over k. Consider the following conditions:*
(i) *G is HW-cyclic and non-ordinary;*
(ii) *the connected part G° of G is HW-cyclic and not of multiplicative type;*
(iii) *$a(G^\vee) = a(G) = 1$.*
We have (i) $\Rightarrow$ (ii) $\Leftrightarrow$ (iii). *If k is algebraically closed, we have moreover* (ii) $\Rightarrow$ (i).

Remark 4.8. In [Oo1, Lemma 2.2], Oort proved the following assertion, which is a generalization of (iii) $\Rightarrow$ (ii): Let k be an algebraically closed field of characteristic $p > 0$, and G be a connected BT-group with $a(G) = 1$. Then there exists a basis of the Dieudonné module M of G over $W(k)$, such that the action of Frobenius on M is given by a display-matrix of "normal form" in the sense of [Oo1, 2.1].

Proof. (i) $\Rightarrow$ (ii) follows from 4.3(ii).
(ii) $\Rightarrow$ (iii). First, we note that $a(G) = a(G^\circ)$, so we may assume G connected. Since G is not of multiplicative type, we have $c = \dim(G^\vee) \geq 1$. By Lemma 4.4(ii), there exists a basis of $\mathrm{Lie}(G^\vee)$ over k under which φ_G is expressed by

$$\begin{pmatrix} 0 & 0 & \cdots & 0 & 0 \\ 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & \cdots & 1 & 0 \end{pmatrix} \in \mathrm{M}_{c\times c}(k).$$

According to (4.5.1), $a(G^\vee)$ equals to $\dim_k \mathrm{Ker}(\varphi_G)$, *i.e.* the k-dimension of the solutions of the equation system in $(x_1, \cdots, x_c)$

$$\begin{pmatrix} 0 & 0 & \cdots & 0 & 0 \\ 1 & 0 & \cdots & 0 & 0 \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & \cdots & 1 & 0 \end{pmatrix} \begin{pmatrix} x_1^p \\ x_2^p \\ \vdots \\ x_c^p \end{pmatrix} = 0$$

The solutions $(x_1, \cdots, x_c)$ form clearly a vector space over k of dimension 1, *i.e.* we have $a(G^\vee) = 1$.
(iii) $\Rightarrow$ (ii). Let $G^{\text{ét}}$ be the étale part of G. Since k is perfect, the exact sequence (2.7.1) splits [Dem, Chap. II §7]; so we have $G \simeq G^\circ \times G^{\text{ét}}$. We put $M = \mathrm{Lie}(G^\vee)$, $M_1 = \mathrm{Lie}(G^{\circ\vee})$ and $M_2 = \mathrm{Lie}(G^{\text{ét}\vee})$ for short. By 2.8 and 2.9, we have a decomposition $M = M_1 \oplus M_2$, such that M_1, M_2 are stable under φ_G, and the action of φ_G is nilpotent on M_1 and bijective on M_2. We note

that $a(G^{\circ\vee}) = a(G^\circ) = a(G) = 1$. By the last remark of 4.5, G° is not of multiplicative type, hence $\dim_k M_1 = \dim(G^{\circ\vee}) \geq 1$. It remains to prove that G° is HW-cyclic. Let n be the minimal integer such that $\varphi_G^n(M_1) = 0$. We have a strictly increasing filtration

$$0 \subsetneq \mathrm{Ker}(\varphi_G) \subsetneq \cdots \subsetneq \mathrm{Ker}(\varphi_G^n) = M_1.$$

If $n = 1$, then M_1 is one-dimensional, hence G° is clearly HW-cyclic. Assume $n \geq 2$. For $2 \leq m \leq n$, φ_G^{m-1} induces an injective map

$$\overline{\varphi_G^{m-1}} : \mathrm{Ker}(\varphi_G^m)/\,\mathrm{Ker}(\varphi_G^{m-1}) \longrightarrow \mathrm{Ker}(\varphi_G).$$

Since $\dim_k \mathrm{Ker}(\varphi_G) = a(G^{\circ\vee}) = 1$, $\overline{\varphi_G^{m-1}}$ is necessarily bijective. So we have $\dim_k \mathrm{Ker}(\varphi_G^m) = m$ for $1 \leq m \leq n$. Let v be an element of M_1 but not in $\mathrm{Ker}(\varphi_G^{n-1})$. Then $v, \varphi_G(v), \cdots, \varphi_G^{n-1}(v)$ are linearly independant, hence they form a basis of M_1 over k. This proves that G° is HW-cyclic.
Assume k algebraically closed. We prove that (ii) $\Rightarrow$ (i). Noting that G is ordinary if and only if G° is of multiplicative type, we only need to check that G is HW-cyclic. We conserve the notations above. Since φ_G is bijective on M_2 and k algebraically closed, there exists a basis $(e_1, \cdots, e_m)$ of M_2 such that $\varphi_G(e_i) = e_i$ for $1 \leq i \leq m$. Let $v \in M_1$ but not in $\mathrm{Ker}(\varphi_G^{n-1})$ as above, and put $u = v + \lambda_1 e_1 + \cdots \lambda_m e_m$, where $\lambda_i (1 \leq i \leq m)$ are some elements in k to be determined later. Then we have

$$\begin{pmatrix} \varphi_G^n(u) \\ \vdots \\ \varphi_G^{n+m-1}(u) \end{pmatrix} = \begin{pmatrix} \lambda_1^{p^n} & \cdots & \lambda_m^{p^n} \\ \vdots & \ddots & \vdots \\ \lambda_1^{p^{n+m-1}} & \cdots & \lambda_m^{p^{n+m-1}} \end{pmatrix} \begin{pmatrix} e_1 \\ \vdots \\ e_m \end{pmatrix}.$$

Let $L(\lambda_1, \cdots, \lambda_m) \in k[\lambda_1, \cdots, \lambda_m]$ be the determinant polynomial of the matrix on the right side. An elementary computation shows that the polynomial $L(\lambda_1, \cdots, \lambda_m)$ is not null. We can choose $\lambda_1, \cdots, \lambda_m \in k$ such that $L(\lambda_1, \cdots, \lambda_m) \neq 0$ because k is algebraically closed. So $\varphi_G^n(u), \cdots, \varphi_G^{n+m-1}(u)$ form a basis of M_2 over k. Since

$$\varphi_G^i(u) \equiv \varphi_G^i(v) \mod M_2 \quad \text{for} \quad 0 \leq i \leq n,$$

by the choice of u, we see that $\{u, \varphi_G(u), \cdots, \varphi_G^{n+m-1}(u)\}$ form a basis of $M = \mathrm{Lie}(G^\vee)$ over k. □

By combining 4.6 and 4.7, we obtain the following

COROLLARY 4.9. *Let k be an algebraically closed field of characteristic $p > 0$. Then a BT-group over k is HW-cyclic if and only if so is its Serre dual.*

4.10. EXAMPLES. Let k be a perfect field, $W(k)$ be the ring of Witt vectors with coefficients in k, and σ be the Frobenius automorphism of $W(k)$. Let s, r be relatively prime integers such that $0 \leq s \leq r$ and $r \neq 0$; put $\lambda = \frac{s}{r}$. We consider the Dieudonné module $M^\lambda \simeq W(k)[F,V]/(F^{r-s} - V^s)$, where $W(k)[F,V]$ is the non-commutative ring with relations $FV = VF = p$, $Fa = \sigma(a)F$ and $V\sigma(a) = aV$ for all $a \in W(k)$. We note that M^λ is free of rank

r over $W(k)$ and $M^\lambda/VM^\lambda \simeq k[F]/F^{r-s}$. By the contravariant Dieudonné theory, M^λ corresponds to a BT-group G^λ over k of height r with $\mathrm{Lie}(G^{\lambda\vee}) = M^\lambda/VM^\lambda$. We see easily that G^λ is HW-cyclic, and we call it the *elementary BT-group of slope* λ. We note that $G^0 \simeq \mathbb{Q}_p/\mathbb{Z}_p$, $G^1 \simeq \mu_{p^\infty}$, and $(G^\lambda)^\vee \simeq G^{1-\lambda}$ for $0 \le \lambda \le 1$.
Assume k algebraically closed. Then by the Dieudonné-Manin's classification of isocrystals [Dem, Chap.IV §4], any BT-group over k is isogenous to a finite product of G^λ's; moreover, any connected one-dimensional BT-group over k of height r is necessarily isomorphic to $G^{1/r}$ [Dem, Chap.IV §8], hence in particular HW-cyclic.

Proposition 4.11. *Let k be an algebraically closed field of characteristic $p > 0$, R be a noetherian complete regular local k-algebra with residue field k, and $S = \mathrm{Spec}(R)$. Let G be a connected HW-cyclic BT-group over R of dimension $d \ge 1$ and height $c + d$,*

$$\mathfrak{h} = \begin{pmatrix} 0 & 0 & \cdots & 0 & -a_1 \\ 1 & 0 & \cdots & 0 & -a_2 \\ 0 & 1 & \cdots & 0 & -a_3 \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & \cdots & 1 & -a_c \end{pmatrix} \in \mathrm{M}_{c\times c}(R)$$

be a matrix of φ_G.
(i) *If G is versal over S, then $\{a_1, \cdots, a_c\}$ is a subset of a regular system of parameters of R.*
(ii) *Assume that $d = 1$. The converse of* (i) *is also true,* i.e. *if $\{a_1, \cdots, a_c\}$ is a subset of a regular system of parameters of R then G is versal over S. Furthermore, G is the universal deformation of its special fiber if and only if $\{a_1, \cdots, a_c\}$ is a system of regular parameters of R.*

Proof. Let $(\mathbf{M}(G), F_M, \nabla)$ be the finite free $\mathscr{O}_S$-module equipped with a semi-linear endomorphism F_M and a connection $\nabla : \mathbf{M}(G) \to \mathbf{M}(G) \otimes_{\mathscr{O}_S} \Omega^1_{S/k}$, obtained by evaluating the Dieudonné crystal of G at the trivial immersion $S \hookrightarrow S$ (cf. 3.1). Recall that we have a commutative diagram

(4.11.1)
$$\begin{tikzcd} \mathbf{M}(G)^{(p)} \arrow[r, "F_M"] \arrow[d, "pr"'] & \mathbf{M}(G) \arrow[d, "pr"] \\ \mathrm{Lie}(G^\vee)^{(p)} \arrow[r, "\widetilde{\varphi_G}"'] \arrow[ur, hook, "\phi_G"] & \mathrm{Lie}(G^\vee), \end{tikzcd}$$

where ϕ_G is universally injective (3.1.3). Let $\{v_1, \cdots, v_c\}$ be a basis of $\mathrm{Lie}(G^\vee)$ over $\mathscr{O}_S$ under which φ_G is expressed by $\mathfrak{h}$, *i.e.* we have $\varphi_G^{i-1}(v_1) = v_i$ for $1 \le i \le c$ and $\varphi_G^c(v_1) = \varphi_G(v_c) = -\sum_{i=1}^c a_i v_i$. Let f_1 be a lift of v_1 to $\Gamma(S, \mathbf{M}(G))$, and put $f_{i+1} = \phi_G(v_i^{(p)})$ for $1 \le i \le c-1$, where $v_i^{(p)} = 1 \otimes v_i \in \Gamma(S, \mathrm{Lie}(G^\vee)^{(p)})$. The image of f_i in $\Gamma(S, \mathrm{Lie}(G^\vee))$ is thus v_i for $1 \le i \le c$ by

(4.11.1). We put

$$e_1 = \phi_G(v_c^{(p)}) + a_1 f_1 + \cdots + a_c f_c \in \Gamma(S, \mathbf{M}(G)). \tag{4.11.2}$$

The image of e_1 in $\Gamma(S, \mathrm{Lie}(G^\vee))$ is $\varphi_G(v_c) + \sum_{i=1}^{c} a_i v_i = 0$; so we have $e_1 \in \Gamma(S, \omega_G)$. By 4.4(ii), we notice that $a_1, \cdots, a_c$ belong to the maximal ideal $\mathfrak{m}_R$ of R, as G is connected. Hence, we have $\overline{e_1} = \overline{\phi_G(v_c^{(p)})}$, where for a R-module M and $x \in M$, we denote by $\overline{x}$ the canonical image of x in $M \otimes k$. Since ϕ_G commutes with base change and is universally injective, we get $\overline{e_1} = \overline{\phi_G(v_c^{(p)})} = \phi_{G\otimes k}(\overline{v_c^{(p)}}) \neq 0$. Therefore, we can choose $e_2, \cdots, e_d \in \Gamma(S, \omega_G)$ such that $(e_1, \cdots, e_d)$ becomes a basis of ω_G over $\mathscr{O}_S$, so $(e_1, \cdots, e_d, f_1, \cdots, f_c)$ is a basis of $\mathbf{M}(G)$. Since F_M is horizontal for the connection ∇ (cf. 3.1(ii)), we have

$$\nabla(\phi_G(v_c^{(p)})) = \nabla(F_M(f_c^{(p)})) = 0.$$

In view of (4.11.2), we get

$$\begin{aligned} \nabla(e_1) &= \sum_{i=1}^{c} f_i \otimes da_i + \sum_{i=1}^{c} a_i \nabla(f_i) \\ &\equiv \sum_{i=1}^{c} f_i \otimes da_i \quad (\mathrm{mod}\ \mathfrak{m}_R). \end{aligned} \tag{4.11.3}$$

Let KS_0 and Kod_0 be respectively the reductions modulo $\mathfrak{m}_R$ of (3.2.1) and (3.2.2). Since $(\overline{v_i})_{1\leq i\leq c}$ is a base of $\mathrm{Lie}(G^\vee) \otimes k$, we can write

$$\mathrm{KS}_0(e_j) = \sum_{i=1}^{c} \overline{v_i} \otimes \theta_{i,j} \qquad \text{for } 1 \leq j \leq d,$$

where $\theta_{i,j} \in \Omega_{S/k} \otimes k$. From (4.11.3), we deduce that $\theta_{i,1} = da_i$. By the definition of Kod_0, we have

$$\mathrm{Kod}_0(\partial) = \sum_{j=1}^{d} \sum_{i=1}^{c} < \partial, \theta_{i,j} > \overline{e_j}^* \otimes \overline{v_i} \tag{4.11.4}$$

where $\partial \in \mathscr{T}_{S/k} \otimes k$, $< \bullet, \bullet >$ is the canonical pairing between $\mathscr{T}_{S/k} \otimes k$ and $\Omega^1_{S/k} \otimes k$, and $(\overline{e_i}^*)_{1\leq i\leq d}$ denotes the dual basis of $(\overline{e_i})_{1\leq i\leq d}$. Now assume that G is versal over S, *i.e.* Kod_0 is surjective by definition (3.2). In particular, there are $\partial_1, \cdots, \partial_c \in \mathscr{T}_{S/k} \otimes k$ such that $\mathrm{Kod}_0(\partial_i) = \overline{e_1}^* \otimes v_i$ for $1 \leq i \leq c$, *i.e.* we have

$$< \partial_i, da_j >= \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases} \quad \text{for } 1 \leq i, j \leq c, \tag{4.11.5}$$

and

$$< \partial_i, \theta_{j,\ell} >= 0 \qquad \text{for } 1 \leq i, j \leq c, 2 \leq \ell \leq d.$$

From (4.11.5), we see easily that $da_1, \cdots, da_c$ are linearly independent in $\Omega_{S/k} \otimes k \simeq \mathfrak{m}_R/\mathfrak{m}_R^2$; therefore, $(a_1, \cdots, a_c)$ is a part of a regular system of parameters of R. Statement (i) is proved.

For statement (ii), we assume $d=1$ and that $(a_1,\cdots,a_c)$ is a part of a regular system of parameters of R. Then the formula (4.11.4) is simplified as

$$\mathrm{Kod}_0(\partial)=\sum_{i=1}^{c} <\partial, da_i> \overline{e_1}^*\otimes\overline{v_i}.$$

Since $da_1,\cdots,da_c$ are linearly independent in $\Omega^1_{S/k}\otimes k$, there exist $\partial_1,\cdots,\partial_c\in\mathscr{T}_{S/k}\otimes k$ such that (4.11.5) holds, *i.e.* $(\overline{e_1}^*\otimes\overline{v_i})_{1\leq i\leq c}$ are in the image of Kod_0. But the elements $(\overline{e_1}^*\otimes\overline{v_i})_{1\leq i\leq c}$ form already a basis of $\mathscr{H}om_{\mathscr{O}_S}(\omega_G,\mathrm{Lie}(G^\vee))\otimes k$. So Kod_0 is surjective, and hence G is versal over S by Nakayama's lemma. Let G_0 be the special fiber of G. It remains to prove that when $d=1$, G is the universal deformation of G_0 if and only if $\dim(S)=c$ and G is versal over S. Let $\mathbf{S}$ be the local moduli in characteristic p of G_0. By the universal property of $\mathbf{G}$ (3.7), there exists a unique morphism $f:S\to\mathbf{S}$ such that $G\simeq\mathbf{G}\times_{\mathbf{S}}S$. Since S and $\mathbf{S}$ are local complete regular schemes over k with residue field k of the same dimension, f is an isomorphism if and only if the tangent map of f at the closed point of S, denoted by T_f, is an isomorphism. By the functoriality of Kodaira-Spencer maps (3.2.2), we have a commutative diagram

$$\begin{array}{ccc}\mathscr{T}_{S/k}\otimes_{\mathscr{O}_S}k & \xrightarrow{\mathrm{Kod}_0^S} & \mathrm{Hom}_k(\omega_{G_0},\mathrm{Lie}(G_0^\vee))\ , \\ \downarrow{\scriptstyle T_f} & & \| \\ \mathscr{T}_{\mathbf{S}/k}\otimes_{\mathscr{O}_{\mathbf{S}}}k & \xrightarrow{\mathrm{Kod}_0^{\mathbf{S}}} & \mathrm{Hom}_k(\omega_{G_0},\mathrm{Lie}(G_0^\vee))\end{array}$$

where horizontal arrows are the Kodaira-Spencer maps evaluated at the closed points (3.3.1). Since Kod_0^S and $\mathrm{Kod}_0^{\mathbf{S}}$ are isomorphisms according to the first part of this propostion, we deduce that so is T_f. This completes the proof. □

5. Monodromy of a HW-cyclic BT-group over a Complete Trait of Characteristic $p>0$

5.1. Let k be an algebraically closed field of characteristic $p>0$, A be a complete discrete valuation ring of characteristic p, with residue field k and fraction field K. We put $S=\mathrm{Spec}(A)$, and denote by s its closed point, by η its generic point. Let $\overline{K}$ be an algebraic closure of K, K^{sep} be the maximal separable extension of K contained in $\overline{K}$, K^{t} be the maximal tamely ramified extension of K contained in K^{sep}. We put $I=\mathrm{Gal}(K^{\mathrm{sep}}/K)$, $I_p=\mathrm{Gal}(K^{\mathrm{sep}}/K^{\mathrm{t}})$ and $I_t=I/I_p=\mathrm{Gal}(K^{\mathrm{t}}/K)$.

Let π be a uniformizer of A; so we have $A\simeq k[[\pi]]$. Let $\mathtt{v}$ be the valuation on K normalized by $\mathtt{v}(\pi)=1$; we denote also by $\mathtt{v}$ the unique extension of $\mathtt{v}$ to $\overline{K}$. For every $\alpha\in\mathbb{Q}$, we denote by $\mathfrak{m}_\alpha$ (*resp.* by $\mathfrak{m}_\alpha^+$) the set of elements $x\in K^{\mathrm{sep}}$ such that $\mathtt{v}(x)\geq\alpha$ (*resp.* $\mathtt{v}(x)>\alpha$). We put

(5.1.1) $$V_\alpha=\mathfrak{m}_\alpha/\mathfrak{m}_\alpha^+,$$

which is a k-vector space of dimension 1 equipped with a continuous action of the Galois group I.

5.2. First, we recall some properties of the inertia groups I_p and I_t [Se1, Chap. IV]. The subgroup I_p, called the *wild inertia subgroup*, is the unique maximal pro-p-group contained in I and hence normal in I. The quotient $I_t = I/I_p$ is a commutative profinite group, called the *tame inertia group*. We have a canonical isomorphism

$$\theta : I_t \xrightarrow{\sim} \varprojlim_{(d,p)=1} \mu_d, \tag{5.2.1}$$

where the projective system is taken over positive integers prime to p, μ_d is the group of d-th roots of unity in k, and the transition maps $\mu_m \to \mu_d$ are given by $\zeta \mapsto \zeta^{m/d}$, whenever d divides m. We denote by $\theta_d : I_t \to \mu_d$ the projection induced by (5.2.1). Let q be a power of p, $\mathbb{F}_q$ be the finite subfield of k with q elements. Then $\mu_{q-1} = \mathbb{F}_q^\times$, and we can write $\theta_{q-1} : I_t \to \mathbb{F}_q^\times$. The character θ_d is characterized by the following property.

PROPOSITION 5.3 ([Se3] Prop.7). *Let a, d be relatively prime positive integers with d prime to p. Then the natural action of I_p on the k-vector space $V_{a/d}$* (5.1.1) *is trivial, and the induced action of I_t on $V_{a/d}$ is given by the character $(\theta_d)^a : I_t \to \mu_d$. In particular, if q is a power of p, the action of I_t on $V_{1/(q-1)}$ is given by the character $\theta_{q-1} : I_t \to \mathbb{F}_q^\times$ and any I-equivariant $\mathbb{F}_p$-subspace of $V_{1/(q-1)}$ is an $\mathbb{F}_q$-vector space.*

5.4. Let G be a BT-group over S. We define $h(G)$ to be the valuation of the determinant of a matrix of φ_G if $\dim(G^\vee) \geq 1$, and $h(G) = 0$ if $\dim(G^\vee) = 0$. We call $h(G)$ the *Hasse invariant* of G.
(a) $h(G)$ does not depend on the choice of the matrix representing φ_G. Indeed, let c be the rank of $\mathrm{Lie}(G^\vee)$ over A, $\mathfrak{h} \in \mathrm{M}_{c\times c}(A)$ be a matrix of φ_G. Any other matrix representing φ_G can be written in the form $U^{-1} \cdot \mathfrak{h} \cdot U^{(p)}$, where $U \in \mathrm{GL}_c(A)$, U^{-1} is the inverse of U, and $U^{(p)}$ is the matrix obtained by applying the Frobenius map of A to the coefficients of U.
(b) By 2.11, the generic fiber G_η is ordinary if and only if $h(G) < \infty$; G is ordinary over T if and only $h(G) = 0$.
(c) Let $0 \to G' \to G \to G'' \to 0$ be a short exact sequence of BT-groups over T, then we have $h(G) = h(G') + h(G'')$. Indeed, the exact sequence of BT-groups induces a short exact sequence of Lie algebras (cf. [BBM] 3.3.2)

$$0 \to \mathrm{Lie}(G''^\vee) \to \mathrm{Lie}(G^\vee) \to \mathrm{Lie}(G'^\vee) \to 0,$$

from which our assertion follows easily.

PROPOSITION 5.5. *Let G be a BT-group over S. Then we have $h(G) = h(G^\vee)$.*

Proof. The proof is very similar to that of Lemma 4.6. First, we have

$$h(G) = \mathrm{leng}\big(\mathrm{Lie}(G^\vee)/\widetilde{\varphi_G}(\mathrm{Lie}(G^\vee)^{(p)})\big),$$

where $\widetilde{\varphi_G}$ is the linearization of φ_G, and "leng" means the length of a finite A-module (note that this formulae holds even if $\dim(G^\vee) = 0$). By the commutative diagram (3.1.3), we have

$$h(G) = \mathrm{leng}\,\mathbf{M}(G)/(\phi_G(\mathrm{Lie}(G^\vee)^{(p)}) + \omega_G).$$

On the other hand, by applying the functor $\mathrm{Hom}_A(\_, A)$ to the A-linear map $\widetilde{\varphi_{G^\vee}} : \mathrm{Lie}(G)^{(p)} \to \mathrm{Lie}(G)$, we obtain a map $\psi_G : \omega_G \to \omega_G^{(p)}$. If U is a matrix of $\widetilde{\varphi_{G^\vee}}$, then the transpose of U, denoted by U^t, is a matrix of ψ_G. So we have

$$h(G^\vee) = \mathtt{v}(\det(U)) = \mathtt{v}(\det(U^t)) = \mathrm{leng}\big(\omega_G^{(p)}/\psi_G(\omega_G)\big).$$

By diagram 3.1.3, we get

$$h(G^\vee) = \mathrm{leng}\,\mathbf{M}(G)/(\phi_G(\mathrm{Lie}(G^\vee)^{(p)}) + \omega_G) = h(G).$$

□

5.6. Let G be a BT-group over S, $c = \dim(G^\vee)$. We put

$$\mathrm{T}_p(G) = \varprojlim_n G(n)(\overline{K}) \tag{5.6.1}$$

the Tate module of G, where $G(n)$ is the kernel of $p^n : G \to G$. It is a free $\mathbb{Z}_p$-module of rank $\leq c$, and the equality holds if and only if the generic fiber G_η is ordinary. The Galois group I acts continuously on $\mathrm{T}_p(G)$. We are interested in the image of the monodromy representation

$$\rho : I = \mathrm{Gal}(K^{\mathrm{sep}}/K) \to \mathrm{Aut}_{\mathbb{Z}_p}(\mathrm{T}_p(G)). \tag{5.6.2}$$

We denote by

$$\overline{\rho} : I = \mathrm{Gal}(K^{\mathrm{sep}}/K) \to \mathrm{Aut}_{\mathbb{F}_p}\big(G(1)(\overline{K})\big) \tag{5.6.3}$$

its reduction mod p.

THEOREM 5.7 (Reformulation of Igusa's theorem). *Let G be a connected BT-group over S of height 2 and dimension 1. Then G is versal* (3.2) *if and only if $h(G) = 1$; moreover, if this condition is satisfied, the monodromy representation $\rho : I \to \mathrm{Aut}_{\mathbb{Z}_p}(\mathrm{T}_p(G)) \simeq \mathbb{Z}_p^\times$ is surjective.*

Proof. Since $\mathrm{Lie}(G^\vee)$ is an $\mathscr{O}_S$-module free of rank 1, the condition that $h(G) = 1$ is equivalent to that any matrix of φ_G is represented by a uniformizer of A. Hence the first part of this theorem follows from Proposition 4.11(ii).
We follow [Ka2, Thm 4.3] to prove the surjectivity of ρ under the assumption that $h(G) = 1$. For each integer $n \geq 1$, let

$$\rho_n : I \to \mathrm{Aut}_{\mathbb{Z}/p^n\mathbb{Z}}(G(n)(\overline{K})) \simeq (\mathbb{Z}/p^n\mathbb{Z})^\times$$

be the reduction mod p^n of ρ, K_n be the subfield of K^{sep} fixed by the kernel of ρ_n. Then ρ_n induces an injective homomorphism $\mathrm{Gal}(K_n/K) \to (\mathbb{Z}/p^n\mathbb{Z})^\times$. By taking projective limits, we are reduced to proving the surjectivity of ρ_n for every $n \geq 1$. It suffices to verify that

$$|\,\mathrm{Im}(\rho_n)| = [K_n : K] \geq p^{n-1}(p-1)$$

(then the equality holds automatically).

We regard G as a formal group over S. Then by [Ka2, 3.6], there exists a parameter X of the formal group G normalized by the condition that $[\xi](X) = \xi(X)$ for all $(p-1)$-th root of unity $\xi \in \mathbb{Z}_p$. For such a parameter, we have

$$[p](X) = a_1 X^p + \alpha X^{p^2} + \sum_{m\geq 2} c_m X^{p(1+m(p-1))} \in A[[X]],$$

where we have $\mathtt{v}(a_1) = h(G) = 1$ by [Ka2, 3.6.1 and 3.6.5], and $\mathtt{v}(\alpha) = 0$, as G is of height 2. For each integer $i \geq 0$, we put

$$V^{(p^i)}(X) = a_1^{p^i} X + \alpha^{p^i} X^p + \sum_{m\geq 2} c_m^{p^i} X^{1+m(p-1)} \in A[[X]];$$

then we have $[p^n](X) = V^{(p^{n-1})} \circ V^{(p^{n-2})} \circ \cdots \circ V(X^{p^n})$. Hence each point of $G(n)(\overline{K})$ is given by a sequence $y_1, \cdots, y_n \in K^{\mathrm{sep}}$ (or simply an element $y_n \in K^{\mathrm{sep}}$) satisfying the equations

$$\begin{cases} V(y_1) = a_1 y_1 + \alpha y_1^p + \cdots = 0; \\ V^{(p)}(y_2) = a_1^p y_2 + \alpha^p y_2^p + \cdots = y_1; \\ \vdots \\ V^{(p^{n-1})}(y_n) = a_1^{p^{n-1}} y_n + \alpha^{p^{n-1}} y_n^p + \cdots = y_{n-1}. \end{cases}$$

Let $y_n \in K^{\mathrm{sep}}$ be such that $y_1 \neq 0$. By considering the Newton polygons of the equations above, we verify that

$$\mathtt{v}(y_i) = \frac{1}{p^{i-1}(p-1)} \qquad \text{for } 1 \leq i \leq n.$$

In particular, the ramification index $e(K_n/K)$ is at least $p^{n-1}(p-1)$. By the definition of K_n, the Galois group $\mathrm{Gal}(K^{\mathrm{sep}}/K_n)$ must fix $y_n \in K^{\mathrm{sep}}$, *i.e.* K_n is an extension of $K(y_n)$. Therefore, we have $[K_n : K] \geq [K(y_n) : K] \geq e(K(y_n)/K) \geq p^{n-1}(p-1)$. □

PROPOSITION 5.8. *Let G be a HW-cyclic BT-group over S of height $c+d$ and dimension d such that $G \otimes K$ is ordinary,*

$$\mathfrak{h} = \begin{pmatrix} 0 & 0 & \cdots & 0 & -a_1 \\ 1 & 0 & \cdots & 0 & -a_2 \\ 0 & 1 & \cdots & 0 & -a_3 \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & \cdots & 1 & -a_c \end{pmatrix}$$

be a matrix of φ_G. Put $q = p^c$, $a_{c+1} = 1$, and $P(X) = \sum_{i=0}^{c} a_{i+1} X^{p^i} \in A[X]$.
(i) *Assume that G is connected and the Hasse invariant $h(G) = 1$. Then the representation $\overline{\rho}$ (5.6.3) is tame, $G(1)(\overline{K})$ is endowed with the structure of an $\mathbb{F}_q$-vector space of dimension 1, and the induced action of I_t is given by the character $\theta_{q-1} : I_t \to \mathbb{F}_q^\times$.*
(ii) *Assume that $c > 1$, $\mathtt{v}(a_i) \geq 2$ for $1 \leq i \leq c-1$ and $\mathtt{v}(a_c) = 1$. Then the order of $\mathrm{Im}(\overline{\rho})$ is divisible by $p^{c-1}(p-1)$.*

(iii) *Put* $i_0 = \min_{0\leq i\leq c}\{i; \mathtt{v}(a_{i+1}) = 0\}$. *Assume that there exists* $\alpha \in k$ *such that* $\mathtt{v}(P(\alpha)) = 1$. *Then we have* $i_0 \leq c-1$ *and the order of* $\mathrm{Im}(\overline{\rho})$ *is divisible by* p^{i_0}.

Proof. Since G is generically ordinary, we have $a_1 \neq 0$ by 2.11(d). Hence $P(X) \in K[X]$ is a separable polynomial. By 4.4, $G(1)(\overline{K}) \simeq (\mathrm{Ker}\, V_G)(K^{\mathrm{sep}})$ is identified with the additive group consisting of the roots of $P(X)$ in K^{sep}.
(i) By definition of the Hasse invariant, we have $\mathtt{v}(a_1) = h(G) = 1$. By 4.4(ii), the assumption that G is connected is equivalent to saying $\mathtt{v}(a_i) \geq 1$ for $1 \leq i \leq c$. From the Newton polygon of $P(X)$, we deduce that all the non-zero roots of $P(X)$ in K^{sep} have the same valuation $1/(q-1)$. We denote by

$$\psi : G(1)(\overline{K}) \to V_{1/(q-1)}$$

the map which sends each root $x \in K^{\mathrm{sep}}$ of $P(X)$ to the class of x in $V_{1/(q-1)} = \mathfrak{m}_{1/(q-1)}/\mathfrak{m}^+_{1/(q-1)}$ (5.1.1). We remark that $G(1)(\overline{K})$ is an $\mathbb{F}_p$-vector space of dimension c. Hence $G(1)(\overline{K})$ is automatically of dimension 1 over $\mathbb{F}_q$ once we know it is an $\mathbb{F}_q$-vector space. By 5.3, it suffices to show that ψ is an injective I-equivariant homomorphism of groups. By 4.4(i), ψ is obviously an I-equivariant homomorphism of groups. Let x_0 be a root of $P(X)$, and put $Q(y) = P(x_0y)$. Then the polynomial $Q(y)$ has the form $Q(y) = x_0^q Q_1(y)$, where

$$Q_1(y) = y^q + b_c y^{p^{c-1}} + \cdots + b_2 y^p + b_1 y$$

with $b_i = a_i/x_0^{(q-p^{i-1})} \in K^{\mathrm{sep}}$. We have $\mathtt{v}(b_i) > 0$ for $2 \leq i \leq c$ and $\mathtt{v}(b_1) = 0$. Let $\overline{b}_1$ be the class of b_1 in the residue field $k = \mathfrak{m}_0/\mathfrak{m}_0^+$. Then the images of the roots of $P(X)$ in $V_{1/(q-1)}$ are $x_0\overline{b}_1^{1/(q-1)}\zeta$, where ζ runs over the finite field $\mathbb{F}_q$. Therefore, ψ is injective.
(ii) By computing the slopes of the Newton polygon of $P(X)$, we see that $P(X)$ has $p^{c-1}(p-1)$ roots of valuation $1/(p^c - p^{c-1})$. Let L be the sub-extension of K^{sep} obtained by adding to K all the roots of $P(x)$. Then the ramification index $e(L/K)$ is divisible by $p^{c-1}(p-1)$. Let $\widetilde{L}$ be the sub-extension of K^{sep} fixed by the kernel of $\overline{\rho}$ (5.6.3). The Galois group $\mathrm{Gal}(K^{\mathrm{sep}}/\widetilde{L})$ fixes the roots of $P(x)$ by definition. Hence we have $L \subset \widetilde{L}$, and $|\,\mathrm{Im}(\overline{\rho})| = [\widetilde{L} : K]$ is divisible by $[L : K]$; in particular, it is divisible by $p^{c-1}(p-1)$.
(iii) Note that the relation $i_0 \leq c-1$ is equivalent to saying that G is not connected by 4.4(ii). Assume conversely $i_0 = c$, *i.e.* G is connected. Then we would have

$$P(X) \equiv X^q \mod (\pi A[X]).$$

But $\mathtt{v}(P(\alpha)) = 1$ implies that $\alpha^{p^c} \in \pi A$, *i.e.* $\alpha = 0$; hence we would have $P(\alpha) = 0$, which contradicts the condition $\mathtt{v}(P(\alpha)) = 1$.
We put $Q(X) = P(X+\alpha) = P(X) + P(\alpha)$. As $\mathtt{v}(P(\alpha)) = 1$, then $(0,1)$ and $(p^{i_0}, 0)$ are the first two break points of the Newton polygon of $Q(X)$. Hence there exists p^{i_0} roots of $Q(X)$ of valuation $1/p^{i_0}$. Let L be the subextension of K in K^{sep} generated by the roots of $P(X)$. The ramification index $e(L/K)$ is divisible by p^{i_0}. As in the proof of (ii), if $\widetilde{L}$ is the subextension of K^{sep}

fixed by the kernel of $\overline{\rho}$, then it is an extension of L. Therefore, we have $|\operatorname{Im}(\overline{\rho})| = [\widetilde{L}:K]$ is divisible by $[L:K]$, and in particular, divisible by p^{i_0}. □

5.9. Let G be a BT-group over S with connected part G°, and étale part $G^{\text{ét}}$ of height r. We have a canonical exact sequence of I-modules

$$0 \to G^\circ(1)(\overline{K}) \to G(1)(\overline{K}) \to G^{\text{ét}}(1)(\overline{K}) \to 0 \tag{5.9.1}$$

giving rise to a class $\overline{C} \in \operatorname{Ext}^1_{\mathbb{F}_p[I]}(G^{\text{ét}}(1)(\overline{K}), G^\circ(1)(\overline{K}))$, which vanishes if and only if (5.9.1) splits. Since I acts trivially on $G^{\text{ét}}(1)(\overline{K})$, we have an isomorphism of I-modules $G^{\text{ét}}(1)(\overline{K}) \simeq \mathbb{F}_p^r$. Recall that for any $\mathbb{F}_p[I]$-module M, we have a canonical isomorphism ([Se1] Chap.VII, §2)

$$\operatorname{Ext}^1_{\mathbb{F}_p[I]}(\mathbb{F}_p, M) \simeq H^1(I, M).$$

Hence we deduce that

$$\overline{C} \in \operatorname{Ext}^1_{\mathbb{F}_p[I]}(G^{\text{ét}}(1)(\overline{K}), G^\circ(1)(\overline{K})) \simeq H^1(I, G^\circ(1)(\overline{K}))^r. \tag{5.9.2}$$

Proposition 5.10. *Let G be a HW-cyclic BT-group over S such that $h(G)=1$, $\overline{\rho}$ (5.6.3) be the representation of I on $G(1)(\overline{K})$. Then the cohomology class $\overline{C}$ does not vanish if and only if the order of the group $\operatorname{Im}(\overline{\rho})$ is divisible by p.*

First, we prove the following result on cohomology of groups.

Lemma 5.11. *Let F be a field, Γ be a commutative group, and $\chi : \Gamma \to F^\times$ be a non-trivial character of Γ. We denote by $F(\chi)$ an F-vector space of dimension 1 endowed with an action of Γ given by χ. Then we have $H^1(\Gamma, F(\chi)) = 0$.*

Proof. Let C be a 1-cocycle of Γ with values in $F(\chi)$. We prove that C is a 1-coboundary. For any $g, h \in \Gamma$, we have

$$C(gh) = C(g) + \chi(g)C(h),$$
$$C(hg) = C(h) + \chi(h)C(g).$$

Since Γ is commutative, it follows from the relation $C(gh) = C(hg)$ that

$$(\chi(g)-1)C(h) = (\chi(h)-1)C(g). \tag{5.11.1}$$

If $\chi(g) \neq 1$ and $\chi(h) \neq 1$, then

$$\frac{1}{\chi(g)-1}C(g) = \frac{1}{\chi(h)-1}C(h).$$

Therefore, there exists $x \in F(\overline{\chi})$ such that $C(g) = (\chi(g)-1)x$ for all $g \in \Gamma$ with $\chi(g) \neq 1$. If $\chi(g) = 1$, we have also $C(g) = 0 = (\chi(g)-1)x$ by (5.11.1). This shows that C is a 1-coboundary. □

Proof of 5.10. By 4.3(ii) and 5.4(c), the connected part G° of G is HW-cyclic with $h(G^\circ) = h(G) = 1$. Assume that $\mathrm{T}_p(G^\circ)$ has rank ℓ over $\mathbb{Z}_p$, and $\mathrm{T}_p(G^{\text{ét}})$ has rank r. Then by 5.8(a), $G^\circ(1)(\overline{K})$ is an $\mathbb{F}_q$-vector space of dimension 1 with $q = p^\ell$, and the action of I on $G^\circ(1)(\overline{K})$ factors through the character $\overline{\chi} : I \to I_t \xrightarrow{\theta_{q-1}} \mathbb{F}_q^\times$. We write $G^\circ(1)(\overline{K}) = \mathbb{F}_q(\overline{\chi})$ for short. If the cohomology class $\overline{C}$ is zero, then the exact sequence (5.9.1) splits, *i.e.* we have an isomorphism

of Galois modules $G(1)(\overline{K}) \simeq \mathbb{F}_q(\chi) \oplus \mathbb{F}_p^r$. It is clear that the group $\mathrm{Im}(\overline{\rho})$ has order $q-1$.
Conversely, if the cohomology class $\overline{C}$ is not zero, we will show that there exists an element in $\mathrm{Im}(\overline{\rho})$ of order p. We choose a basis adapted to the exact sequence (5.9.1) such that the action of $g \in I$ is given by

$$\overline{\rho}(g) = \begin{pmatrix} \overline{\chi}(g) & \overline{C}(g) \\ 0 & \mathbf{1}_r \end{pmatrix}, \tag{5.11.2}$$

where $\mathbf{1}_r$ is the unit matrix of type (r,r) with coefficients in $\mathbb{F}_p$, and the map $g \mapsto \overline{C}(g)$ gives rise to a 1-cocycle representing the cohomology class $\overline{C}$. Let I_1 be the kernel of $\overline{\chi} : I \to \mathbb{F}_q^\times$, Γ be the quotient I/I_1, so $\overline{\chi}$ induces an isomorphism $\overline{\chi} : \Gamma \xrightarrow{\sim} \mathbb{F}_q^\times$. We have an exact sequence

$$0 \to H^1(\Gamma, \mathbb{F}_q(\overline{\chi}))^r \xrightarrow{\mathrm{Inf}} H^1(I, \mathbb{F}_q(\overline{\chi}))^r \xrightarrow{\mathrm{Res}} H^1(I_1, \mathbb{F}_q(\overline{\chi}))^r,$$

where "Inf" and "Res" are respectively the inflation and restriction homomorphisms in group cohomology. Since $H^1(\Gamma, \mathbb{F}_q(\overline{\chi}))^r = 0$ by 5.11, the restriction of the cohomology class $\overline{C}$ to $H^1(I_1, \mathbb{F}_q(\overline{\chi}))^r$ is non-zero. Hence there exists $h \in I_1$ such that $\overline{C}(h) \neq 0$. As we have $\overline{\chi}(h) = 1$, then

$$\overline{\rho}(h)^p = \begin{pmatrix} \mathbf{1}_\ell & p\overline{C}(h) \\ 0 & \mathbf{1}_r \end{pmatrix} = \mathbf{1}_{\ell+r}.$$

Thus the order of $\overline{\rho}(h)$ is p. □

COROLLARY 5.12. *Let G be a HW-cyclic BT-group over S,*

$$\mathfrak{h} = \begin{pmatrix} 0 & 0 & \cdots & 0 & -a_1 \\ 1 & 0 & \cdots & 0 & -a_2 \\ 0 & 1 & \cdots & 0 & -a_3 \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & \cdots & 1 & -a_c \end{pmatrix}$$

be a matrix of φ_G, $P(X) = X^{p^c} + a_c X^{p^{c-1}} + \cdots + a_1 X \in A[X]$. If $h(G) = 1$ and if there exists $\alpha \in k \subset A$ such that $\mathrm{v}(P(\alpha)) = 1$, then the cohomology class (5.9.2) *is not zero,* i.e. *the extension of I-modules* (5.9.1) *does not split.*

Proof. Since $\mathrm{v}(a_1) = h(G) = 1$, the integer i_0 defined in 5.8(iii) is at least 1. Then the corollary follows from 5.8(iii) and 5.10. □

6. LEMMAS IN GROUP THEORY

In this section, we fix a prime number $p \geq 2$ and an integer $n \geq 1$.

6.1. Recall that the general linear group $\mathrm{GL}_n(\mathbb{Z}_p)$ admits a natural exhaustive decreasing filtration by normal subgroups

$$\mathrm{GL}_n(\mathbb{Z}_p) \supset 1 + p\mathrm{M}_n(\mathbb{Z}_p) \supset \cdots \supset 1 + p^m\mathrm{M}_n(\mathbb{Z}_p) \supset \cdots,$$

where $\mathrm{M}_n(\mathbb{Z}_p)$ denotes the ring of matrix of type (n,n) with coefficients in $\mathbb{Z}_p$. We endow $\mathrm{GL}_n(\mathbb{Z}_p)$ with the topology for which $(1 + p^m\mathrm{M}_n(\mathbb{Z}_p))_{m\geq 1}$ form a fundamental system of neighborhoods of 1. Then $\mathrm{GL}_n(\mathbb{Z}_p)$ is a complete and separated topological group.

6.2. Let $\mathfrak{G}$ be a profinite group, $\rho : \mathfrak{G} \to \mathrm{GL}_n(\mathbb{Z}_p)$ be a continuous homomorphism of topological groups. By taking inverse images, we obtain a decreasing filtration $(F^m\mathfrak{G}, m \in \mathbb{Z}_{\geq 0})$ on $\mathfrak{G}$ by open normal subgroups:

$$F^0\mathfrak{G} = \mathfrak{G}, \quad \text{and} \quad F^m\mathfrak{G} = \rho^{-1}(1 + p^m\mathrm{M}_n(\mathbb{Z}_p)) \text{ for } m \geq 1.$$

Furthermore, the homomorphism ρ induces a sequence of injective homomorphisms of finite groups

$$\rho_0 \colon F^0\mathfrak{G}/F^1\mathfrak{G} \longrightarrow \mathrm{GL}_n(\mathbb{F}_p) \tag{6.2.1}$$

$$\rho_m \colon F^m\mathfrak{G}/F^{m+1}\mathfrak{G} \to \mathrm{M}_n(\mathbb{F}_p), \quad \text{for } m \geq 1. \tag{6.2.2}$$

Lemma 6.3. *The homomorphism ρ is surjective if and only if the following conditions are satisfied:*
(i) *The homomorphism ρ_0 is surjective.*
(ii) *For every integer $m \geq 1$, the subgroup $\mathrm{Im}(\rho_m)$ of $\mathrm{M}_n(\mathbb{F}_p)$ contains an element of the form*

$$\begin{pmatrix} x & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 \end{pmatrix}$$

with $x \neq 0$; or equivalently, there exists, for every $m \geq 1$, an element $g_m \in \mathfrak{G}$ such that $\rho(g_m)$ is of the form

$$\begin{pmatrix} 1+p^m a_{1,1} & p^{m+1}a_{1,2} & \cdots & p^{m+1}a_{1,n} \\ p^{m+1}a_{2,1} & 1+p^{m+1}a_{2,2} & \cdots & p^{m+1}a_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ p^{m+1}a_{n,1} & p^{m+1}a_{n,2} & \cdots & 1+p^{m+1}a_{n,n} \end{pmatrix},$$

where $a_{i,j} \in \mathbb{Z}_p$ for $1 \leq i,j \leq n$ and $a_{1,1}$ is not divisible by p.

Proof. We notice first that ρ is surjective if and only if ρ_m is surjective for every $m \geq 0$, because $\mathfrak{G}$ is complete and $\mathrm{GL}_n(\mathbb{Z}_p)$ is separated [Bou, Chap. III §2 n°8 Cor.2 au Théo. 1]. The surjectivity of ρ_0 is condition (i). Condition (ii) is clearly necessary. We prove that it implies the surjectivity of ρ_m for all $m \geq 1$, under the assumption of (i). First, we remark that under condition (i), if A lies in $\mathrm{Im}(\rho_m)$, then for any $U \in \mathrm{GL}_n(\mathbb{F}_p)$ the conjuagate matrix $U \cdot A \cdot U^{-1}$ lies also in $\mathrm{Im}(\rho_m)$. In fact, let $\widetilde{A}$ be a lift of A in $\mathrm{M}_n(\mathbb{Z}_p)$ and $\widetilde{U} \in \mathrm{GL}_n(\mathbb{Z}_p)$ a lift of U. By assumption, there exist $g, h \in \mathfrak{G}$ such that

$$\rho(g) \equiv 1+p^m\widetilde{A} \mod (1+p^{m+1}M_n(\mathbb{Z}_p)) \text{ and } \rho(h) \equiv \widetilde{U} \mod (1+p\mathrm{M}_n(\mathbb{Z}_p)).$$

Therefore, we have $\rho(hgh^{-1}) \equiv (1 + p^m\widetilde{U} \cdot \widetilde{A} \cdot \widetilde{U}^{-1}) \mod (1 + p^{m+1}\mathrm{M}_n(\mathbb{Z}_p))$. Hence $hgh^{-1} \in F^m\mathfrak{G}$ and $\rho_m(hgh^{-1}) = U \cdot A \cdot U^{-1}$.
For $1 \leq i,j \leq n$, let $E_{i,j} \in \mathrm{M}_n(\mathbb{F}_p)$ be the matrix whose (i,j)-th entry is 0 and the other entries are 0. The matrices $E_{i,j} (1 \leq i,j \leq n)$ form clearly

a basis of $\mathrm{M}_n(\mathbb{F}_p)$ over $\mathbb{F}_p$. To prove the surjectivity of ρ_m, we only need to verify that $E_{i,j} \in \mathrm{Im}(\rho_m)$ for $1 \le i,j \le n$, because $\mathrm{Im}(\rho_m)$ is an $\mathbb{F}_p$-subspace of $\mathrm{M}_n(\mathbb{F}_p)$. By assumption, we have $E_{1,1} \in \mathrm{Im}(\rho_m)$. For $2 \le i \le n$, we put $U_i = E_{1,i} - E_{i,1} + \sum_{j\neq 1,i} E_{j,j}$. Then we have $U_i \in \mathrm{GL}_n(\mathbb{Z}_p)$ and $U_i \cdot E_{1,1} \cdot U_i^{-1} = E_{i,i} \in \mathrm{Im}(\rho_m)$. For $1 \le i < j \le n$, we put $U_{i,j} = I + E_{i,j}$ where I is the unit matrix. Then we have $U_{i,j} \cdot E_{i,i} \cdot U_{i,j}^{-1} = E_{i,i} + E_{i,j} \in \mathrm{Im}(\rho_m)$, and hence $E_{i,j} \in \mathrm{Im}(\rho_m)$. This completes the proof.

□

REMARK 6.4. By using the arguments in [Se2, Chap. IV 3.4 Lemma 3], we can prove the following stronger form of Lemma 6.3: *If $p = 2$, condition* (i) *and* (ii) *for $m = 1, 2$ are sufficient to guarantee the surjectivity of ρ; if $p \ge 3$, then* (i) *and* (ii) *just for $m = 1$ suffice already.*

A subgroup C of $\mathrm{GL}_n(\mathbb{F}_p)$ is called a *non-split Cartan subgroup*, if the subset $C \cup \{0\}$ of the matrix algebra $\mathrm{M}_n(\mathbb{F}_p)$ is a field isomorphic to $\mathbb{F}_{p^n}$; such a group is cyclic of order $p^n - 1$.

LEMMA 6.5. *Assume that $n \ge 2$. We denote by H the subgroup of* $\mathrm{GL}_n(\mathbb{F}_p)$ *consisting of all the elements of the form* $\begin{pmatrix} A & b \\ 0 & 1 \end{pmatrix}$, *where $A \in \mathrm{GL}_{n-1}(\mathbb{F}_p)$ and* $b = \begin{pmatrix} b_1 \\ \vdots \\ b_{n-1} \end{pmatrix}$ *with $b_i \in \mathbb{F}_p (1 \le i \le n-1)$. Let G be a subgroup of* $\mathrm{GL}_n(\mathbb{F}_p)$. *Then $G = \mathrm{GL}_n(\mathbb{F}_p)$ if and only if G contains H and a non-split Cartan subgroup of* $\mathrm{GL}_n(\mathbb{F}_p)$.

Proof. The "only if" part is clear. For the "if" part, let C be a non-split Cartan subgroup contained in G. For a finite group Λ, we denote by $|\Lambda|$ its order. An easy computation shows that $|\mathrm{GL}_n(\mathbb{F}_p)| = |H| \cdot |C|$. So we just need to prove that $U \cap C = \{1\}$; since then we will have $|\mathrm{GL}_n(\mathbb{F}_p)| = |G|$, hence $G = \mathrm{GL}_n(\mathbb{F}_p)$. Let $g \in H \cap C$, and $P(T) \in \mathbb{F}_p[T]$ be its characteristic polynomial. We fix an isomorphism $C \simeq \mathbb{F}_{p^n}^\times$, and let $\zeta \in \mathbb{F}_{p^n}^\times$ be the element corresponding to g. We have $P(T) = \prod_{\sigma \in \mathrm{Gal}(\mathbb{F}_{p^n}/\mathbb{F}_p)} (T - \sigma(\zeta))$ in $\mathbb{F}_{p^n}[T]$. On the other hand, the fact that $g \in H$ implies that $(T-1)$ divises $P(T)$. Therefore, we get $\zeta = 1$, *i.e.* $g = 1$. □

REMARK 6.6. E. Lau point out the following strengthened version of 6.5: *When $n \ge 3$, a subgroup $G \subset \mathrm{GL}_n(\mathbb{F}_p)$ coincides with $\mathrm{GL}_n(\mathbb{F}_p)$ if and only if G contains a non-split Cartan subgroup and the subgroup* $\begin{pmatrix} \mathrm{GL}_{n-1}(\mathbb{F}_p) & 0 \\ 0 & 1 \end{pmatrix}$. This can be used to simplify the induction process in the proof of Theorem 7.3 when $n \ge 3$.

7. Proof of Theorem 1.3 in the One-dimensional Case

7.1. We start with a general remark on the monodromy of BT-groups. Let X be a scheme, G be an ordinary BT-group over a scheme X, $G^{\text{ét}}$ be its étale part (2.10.1). If $\overline{\eta}$ is a geometric point of X, we denote by

$$\mathrm{T}_p(G,\overline{\eta}) = \varprojlim_n G(n)(\overline{\eta}) = \varprojlim_n G^{\text{ét}}(n)(\overline{\eta})$$

the Tate module of G at $\overline{\eta}$, and by $\rho(G)$ the monodromy representation of $\pi_1(X,\overline{\eta})$ on $\mathrm{T}_p(G,\overline{\eta})$. Let $f: Y \to X$ be a morphism of schemes, $\overline{\xi}$ be a geometric point of Y, $G_Y = G \times_X Y$. Then by the functoriality, we have a commutative diagram

$$\begin{tikzcd} \pi_1(Y,\xi) \arrow[r, "\pi_1(f)"] \arrow[d, "\rho(G_Y)"'] & \pi_1(X, f(\overline{\xi})) \arrow[d, "\rho(G)"] \\ \mathrm{Aut}_{\mathbb{Z}_p}(\mathrm{T}_p(G_Y,\overline{\xi})) \arrow[r, equal] & \mathrm{Aut}_{\mathbb{Z}_p}(\mathrm{T}_p(G, f(\overline{\xi}))) \end{tikzcd} \tag{7.1.1}$$

In particular, the monodromy of G_Y is a subgroup of the monodromy of G. In the sequel, diagram (7.1.1) will be refereed as the *functoriality of monodromy* for the BT-group G and the morphism f.

7.2. Let k be an algebraically closed field of characteristic $p > 0$, G be the unique connected BT-group over k of dimension 1 and height $n+1 \geq 2$ (4.10). We denote by $\mathbf{S}$ the algebraic local moduli of G in characteristic p, by $\mathbf{G}$ the universal deformation of G over $\mathbf{S}$, and by $\mathbf{U}$ the ordinary locus of $\mathbf{G}$ over $\mathbf{S}$ (3.8). Recall that $\mathbf{S}$ is affine of ring $R \simeq k[[t_1, \cdots, t_n]]$ (3.7), and that G and $\mathbf{G}$ are HW-cyclic (cf. 4.3(i) and 4.10). Let $\overline{\eta}$ be a geometric point of $\mathbf{U}$ over its generic point. We put

$$\mathrm{T}_p(\mathbf{G},\overline{\eta}) = \varprojlim_{m\in\mathbb{Z}_{\geq 1}} \mathbf{G}(m)(\overline{\eta})$$

to be the Tate module of $\mathbf{G}$ at the point $\overline{\eta}$. This is a free $\mathbb{Z}_p$-module of rank n. We have the monodromy representation

$$\rho_n : \pi_1(\mathbf{U},\overline{\eta}) \to \mathrm{Aut}_{\mathbb{Z}_p}(\mathrm{T}_p(\mathbf{G},\overline{\eta})) \simeq \mathrm{GL}_n(\mathbb{Z}_p).$$

The following is the one-dimensional case of Theorem 1.3.

Theorem 7.3. *Under the above assumptions, the homomorphism ρ_n is surjective for $n \geq 1$.*

7.4. First, we assume $n \geq 2$. By Proposition 4.11(ii), we may assume that

$$\mathfrak{h} = \begin{pmatrix} 0 & 0 & \cdots & 0 & -t_1 \\ 1 & 0 & \cdots & 0 & -t_2 \\ 0 & 1 & \cdots & 0 & -t_3 \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & \cdots & 1 & -t_n \end{pmatrix} \tag{7.4.1}$$

is a matrix of the Hasse-Witt map $\varphi_{\mathbf{G}}$. Let $\mathfrak{p}$ be the prime ideal of R generated by $t_1, \cdots, t_{n-1}$. Then the closed subscheme of $\mathbf{S}$ defined by $\mathfrak{p}$ is just the locus where the p-rank of $\mathbf{G}$ is ≤ 1 by 4.4(ii). Let $K_0 \simeq k((t_n))$ be the fraction field of $R/\mathfrak{p}$, $R' = \widehat{R}_{\mathfrak{p}}$ be the completion of the localization of R at $\mathfrak{p}$, and $\mathscr{G}_{R'} = \mathbf{G} \otimes_R R'$. Since the natural map $R \to R'$ is injective, for any $a \in R$, we will denote also by a its image in R'. Since the Hasse-Witt map commutes with base change, the image of $\mathfrak{h}$ in $\mathrm{M}_{n\times n}(R')$, denoted also by $\mathfrak{h}$, is a matrix of $\varphi_{\mathscr{G}_{R'}}$. We see easily that the étale part of $\mathscr{G}_{R'}$ has height 1 and its connected part $\mathscr{G}^{\circ}_{R'}$ has height n. We have an exact sequence of BT-groups over R'

$$0 \to \mathscr{G}^{\circ}_{R'} \to \mathscr{G}_{R'} \to \mathscr{G}^{\text{ét}}_{R'} \to 0. \tag{7.4.2}$$

We fix an imbedding $i : K_0 \to \overline{K}_0$ of K_0 into an algebraically closed field. Put $\mathscr{G}^{*}_{\overline{K}_0} = \mathscr{G}^{*}_{R'} \otimes \overline{K}_0$ for $* = \emptyset, \text{ét}, \circ$. We have $\mathscr{G}^{\text{ét}}_{\overline{K}_0} \simeq \mathbb{Q}_p/\mathbb{Z}_p$, and $\mathscr{G}^{\circ}_{\overline{K}_0}$ is the unique connected one-dimensional BT-group over $\overline{K}_0$ of height n (cf. 4.10). We put $\widetilde{R'} = \overline{K}_0[[x_1, \cdots, x_{n-1}]]$, and

$$\Sigma = \{\text{ring homomorphisms } \sigma : R' \to \widetilde{R'} \text{ lifting } R' \to K_0 \xrightarrow{i} \overline{K}_0\} \tag{7.4.3}$$

Let $\sigma \in \Sigma$. We deduce from (7.4.2) by base change an exact sequence of BT-groups over $\widetilde{R'}$

$$0 \to \mathscr{G}^{\circ}_{\widetilde{R'},\sigma} \to \mathscr{G}_{\widetilde{R'},\sigma} \to \mathscr{G}^{\text{ét}}_{\widetilde{R'},\sigma} \to 0, \tag{7.4.4}$$

where we have put $\mathscr{G}^{*}_{\widetilde{R'},\sigma} = \mathscr{G}^{*}_{R'} \otimes_{\sigma} \widetilde{R'}$ for $* = \circ, \emptyset, \text{ét}$. Due to the henselian property of $\widetilde{R'}$, the isomorphism $\mathscr{G}^{\text{ét}}_{\overline{K}_0} \simeq \mathbb{Q}_p/\mathbb{Z}_p$ lifts uniquely to an isomorphism $\mathscr{G}^{\text{ét}}_{\widetilde{R'},\sigma} \simeq \mathbb{Q}_p/\mathbb{Z}_p$. Assume that $\mathscr{G}^{\circ}_{\widetilde{R'},\sigma}$ is generically ordinary over $\widetilde{S}' = \mathrm{Spec}(\widetilde{R'})$. Let $\widetilde{U}'_{\sigma} \subset \widetilde{S}'$ be its ordinary locus, and $\overline{x}$ be a geometric point over the generic point of $\widetilde{U}'_{\sigma}$. The exact sequence (7.4.4) induces an exact sequence of Tate modules

$$0 \to \mathrm{T}_p(\mathscr{G}^{\circ}_{\widetilde{R'},\sigma}, \overline{x}) \to \mathrm{T}_p(\mathscr{G}_{\widetilde{R'},\sigma}, \overline{x}) \to \mathrm{T}_p(\mathscr{G}^{\text{ét}}_{\widetilde{R'},\sigma}, \overline{x}) \to 0 \tag{7.4.5}$$

compatible with the actions of $\pi_1(\widetilde{U}'_{\sigma}, \overline{x})$. Since we have $\mathrm{T}_p(\mathscr{G}^{\text{ét}}_{\widetilde{R'},\sigma}, \overline{x}) \simeq \mathrm{T}_p(\mathbb{Q}_p/\mathbb{Z}_p, \overline{x}) = \mathbb{Z}_p$, this determines a cohomology class

$$C_{\sigma} \in \mathrm{Ext}^1_{\mathbb{Z}_p[\pi_1(\widetilde{U}'_{\sigma},\overline{x})]}(\mathbb{Z}_p, \mathrm{T}_p(\mathscr{G}^{\circ}_{\widetilde{R'},\sigma}, \overline{x})) \simeq H^1(\pi_1(\widetilde{U}'_{\sigma}, \overline{x}), \mathrm{T}_p(\mathscr{G}^{\circ}_{\widetilde{R'},\sigma}, \overline{x})). \tag{7.4.6}$$

We consider also the "mod-p version" of (7.4.5)

$$0 \to \mathscr{G}^{\circ}_{\widetilde{R'},\sigma}(1)(\overline{x}) \to \mathscr{G}_{\widetilde{R'},\sigma}(1)(\overline{x}) \to \mathbb{F}_p \to 0,$$

which determines a cohomology class

$$\overline{C}_{\sigma} \in \mathrm{Ext}^1_{\mathbb{F}_p[\pi_1(\widetilde{U}'_{\sigma},\overline{x})]}(\mathbb{F}_p, \mathscr{G}^{\circ}_{\widetilde{R'},\sigma}(1)(\overline{x})) \simeq H^1(\pi_1(\widetilde{U}'_{\sigma}, \overline{x}), \mathscr{G}^{\circ}_{\widetilde{R'},\sigma}(1)(\overline{x})). \tag{7.4.7}$$

It is clear that $\overline{C}_{\sigma}$ is the image of C_{σ} by the canonical reduction map

$$H^1(\pi_1(\widetilde{U}'_{\sigma}, \overline{x}), \mathrm{T}_p(\mathscr{G}^{\circ}_{\widetilde{R'},\sigma}, \overline{x})) \to H^1(\pi_1(\widetilde{U}'_{\sigma}, \overline{x}), \mathscr{G}^{\circ}_{\widetilde{R'},\sigma}(1)(\overline{x})).$$

LEMMA 7.5. *Under the above assumptions, there exist $\sigma_1, \sigma_2 \in \Sigma$ satisfying the following properties:*
(i) *We have $\mathscr{G}^{\circ}_{\widetilde{R}',\sigma_1} = \mathscr{G}^{\circ}_{\widetilde{R}',\sigma_2}$, and it is the universal deformation of $\mathscr{G}^{\circ}_{\overline{K}_0}$.*
(ii) *We have $C_{\sigma_1} = 0$ and $\overline{C}_{\sigma_2} \neq 0$.*

Before proving this lemma, we prove first Theorem 7.3.

PROOF OF 7.3. First, we notice that the monodromy of a BT-group is independent of the base point. So we can change $\overline{\eta}$ to any geometric point of $\mathbf{U}$ when discussing the monodromy of $\mathbf{G}$. We make an induction on the codimension $n = \dim(G^{\vee})$. The case of $n = 1$ is proved in Theorem 5.7. Assume that $n \geq 2$ and the theorem is proved for $n-1$. We denote by

$$\overline{\rho}_n : \pi_1(\mathbf{U}, \overline{\eta}) \to \mathrm{Aut}_{\mathbb{F}_p}(\mathbf{G}(1)(\overline{\eta})) \simeq \mathrm{GL}_n(\mathbb{F}_p)$$

the reduction of ρ_n modulo by p. By Lemma 6.3 and 6.5, to prove the surjectivity of ρ_n, we only need to verify the following conditions:
(a) $\mathrm{Im}(\overline{\rho}_n)$ contains a non-split Cartan subgroup of $\mathrm{GL}_n(\mathbb{F}_p)$;
(b) $\mathrm{Im}(\rho_n)$ contains the subgroup $H \subset \mathrm{GL}_n(\mathbb{Z}_p)$ consisting of all the elements of the form $\begin{pmatrix} B & b \\ 0 & 1 \end{pmatrix} \in \mathrm{GL}_n(\mathbb{Z}_p)$, with $B \in \mathrm{GL}_{n-1}(\mathbb{Z}_p)$ and $b \in \mathrm{M}_{(n-1)\times 1}(\mathbb{Z}_p)$;
For condition (a), let $A = k[[\pi]]$, $T = \mathrm{Spec}(A)$, ξ be its generic point, $\overline{\xi}$ be a geometric point over ξ, and $I = \mathrm{Gal}(\overline{\xi}/\xi)$ be the absolute Galois group over ξ. We keep the notations of 7.4. Let $f^* : R \to A$ be the homomorphism of k-algebras such that $f^*(t_1) = \pi$ and $f^*(t_i) = 0$ for $2 \leq i \leq n$. We denote by $f : T \to \mathbf{S}$ the corresponding morphism of schemes, and put $G_T = \mathbf{G} \times_{\mathbf{S}} T$. By the functoriality of Hasse-Witt maps,

$$\mathfrak{h}_T = \begin{pmatrix} 0 & 0 & \cdots & 0 & -\pi \\ 1 & 0 & \cdots & 0 & 0 \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & \cdots & 1 & 0 \end{pmatrix}$$

is a matrix of φ_{G_T}. By definition 5.4, the Hasse invariant of G_T is $h(G) = 1$. Hence G_T is generically ordinary; so $f(\xi) \in \mathbf{U}$. Let

$$\overline{\rho}_T : I = \mathrm{Gal}(\overline{\xi}/\xi) \to \mathrm{Aut}_{\mathbb{F}_p}(G_T(1)(\overline{\xi}))$$

be the mod-p monodromy representation attached to G_T. Proposition 5.8(i) implies that $\mathrm{Im}(\overline{\rho}_T)$ is a non-split Cartan subgroup of $\mathrm{GL}_n(\mathbb{F}_p)$. On the other hand, by the functoriality of monodromy, we get $\mathrm{Im}(\overline{\rho}_T) \subset \mathrm{Im}(\overline{\rho}_n)$. This verifies condition (a).
To check condition (b), we consider the constructions in 7.4. Let $S' = \mathrm{Spec}(R')$, $f : S' \to \mathbf{S}$ be the morphism of schemes corresponding to the natural ring homomorphism $R \to R'$, U' be the ordinary locus of $\mathscr{G}_{R'}$, and $\overline{\xi}$ be a geometric point of U'. From (7.4.2), we deduce an exact sequence of Tate modules

$$0 \to \mathrm{T}_p(\mathscr{G}^{\circ}_{R'}, \overline{\xi}) \to \mathrm{T}_p(\mathscr{G}_{R'}, \overline{\xi}) \to \mathrm{T}_p(\mathscr{G}^{\text{ét}}_{R'}, \overline{\xi}) \to 0. \tag{7.5.1}$$

Let $\rho_{\mathscr{G}'}: \pi_1(U', \overline{\xi}) \to \mathrm{Aut}_{\mathbb{Z}_p}(\mathrm{T}_p(\mathscr{G}_{R'}, \overline{\xi})) \simeq \mathrm{GL}_n(\mathbb{Z}_p)$ be the monodromy represention of $\mathscr{G}_{R'}$. Under any basis of $\mathrm{T}_p(\mathscr{G}_{R'}, \overline{\xi})$ adapted to (7.5.1), the action of $\pi_1(U', \overline{\xi})$ on $\mathrm{T}_p(\mathscr{G}_{R'}, \overline{\xi})$ is given by

$$\rho_{\mathscr{G}_{R'}}: g \in \pi_1(U', \overline{\xi}) \mapsto \begin{pmatrix} \rho_{\mathscr{G}^{\circ}_{R'}}(g) & * \\ 0 & \rho_{\mathscr{G}^{\text{ét}}_{R'}}(g), \end{pmatrix}$$

where $g \mapsto \rho_{\mathscr{G}^{\circ}_{R'}}(g) \in \mathrm{GL}_{n-1}(\mathbb{Z}_p)$ (*resp.* $g \mapsto \rho_{\mathscr{G}^{\text{ét}}_{R'}}(g) \in \mathbb{Z}_p^{\times}$) gives the action of $\pi_1(U', \overline{\xi})$ on $\mathrm{T}_p(\mathscr{G}^{\circ}_{R'}, \overline{\xi})$ (*resp.* on $\mathrm{T}_p(\mathscr{G}^{\text{ét}}_{R'}, \overline{\xi})$). Note that $f(U') \subset \mathbf{U}$. So by the functoriality of monodromy, we get $\mathrm{Im}(\rho_{\mathscr{G}'}) \subset \mathrm{Im}(\rho_n)$. To complete the proof of Theorem 7.3, it suffices to check condition (b) with ρ_n replaced by $\rho_{\mathscr{G}_{R'}}$ under the induction hypothesis that 7.3 is valide for $n-1$. Let $\sigma_1, \sigma_2 : R' \to \widetilde{R'}$ be the homomorphisms given by 7.5. For $i = 1, 2$, we denote by $f_i : \widetilde{S}' = \mathrm{Spec}(\widetilde{R'}) \to S' = \mathrm{Spec}(R')$ the morphism of schemes corresponding to σ_i, and put $\mathscr{G}_i = \mathscr{G}_{\widetilde{R'}, \sigma_i} = \mathscr{G}_{R'} \otimes_{\sigma_i} \widetilde{R'}$ to simply the notations. By condition 7.5(i), we can denote by $\mathscr{G}^{\circ}$ the common connected component of $\mathscr{G}_1$ and $\mathscr{G}_2$. Let $\widetilde{U'} \subset \widetilde{S}'$ be the ordinary locus of $\mathscr{G}^{\circ}$. Then we have $f_i(\widetilde{U'}) \subset U'$ for $i = 1, 2$. Let $\overline{x}$ be a geometric point over the generic point of $\widetilde{U'}$. We have an exact sequence of Tate modules

$$0 \to \mathrm{T}_p(\mathscr{G}^{\circ}, \overline{x}) \to \mathrm{T}_p(\mathscr{G}_i, \overline{x}) \to \mathrm{T}_p(\mathbb{Q}_p/\mathbb{Z}_p, \overline{x}) \to 0 \tag{7.5.2}$$

compatible with the actions of $\pi_1(\widetilde{U'}, \overline{x})$. We denote by

$$\rho_{\mathscr{G}_i}: \pi_1(\widetilde{U'}, \overline{x}) \to \mathrm{Aut}_{\mathbb{Z}_p}(\mathrm{T}_p(\mathscr{G}_i, \overline{x})) \simeq \mathrm{GL}_n(\mathbb{Z}_p)$$

the monodromy representation of $\mathscr{G}_i$. In a basis adapted to (7.5.2), the action of $\pi_1(\widetilde{U'}, \overline{x})$ on $\mathrm{T}_p(\mathscr{G}_i, \overline{x})$ is given by

$$\rho_{\mathscr{G}_i}: g \mapsto \begin{pmatrix} \rho_{\mathscr{G}^{\circ}}(g) & C_{\sigma_i}(g) \\ 0 & 1 \end{pmatrix},$$

where $\rho_{\mathscr{G}^{\circ}}: \pi_1(\widetilde{U'}, \overline{x}) \to \mathrm{GL}_{n-1}(\mathbb{Z}_p)$ is the monodromy representation of $\mathscr{G}^{\circ}$, and the cohomology class in $H^1(\pi_1(\widetilde{U'}, \overline{x}), \mathrm{T}_p(\mathscr{G}^{\circ}))$ given by $g \mapsto C_{\sigma_i}(g)$ is nothing but the class defined in (7.4.6). By 7.5(i) and the induction hypothesis, $\rho_{\mathscr{G}^{\circ}}$ is surjective. Since the cohomology class $C_{\sigma_1} = 0$ by 7.5(ii), we may assume $C_{\sigma_1}(g) = 0$ for all $g \in \pi_1(U', \overline{x})$. Therefore $\mathrm{Im}(\rho_{\mathscr{G}_1})$ contains all the matrix of the form $\begin{pmatrix} B & 0 \\ 0 & 1 \end{pmatrix}$ with $B \in \mathrm{GL}_{n-1}(\mathbb{Z}_p)$. By the functoriality of monodromy, $\mathrm{Im}(\rho_{\mathscr{G}_{R'}})$ contains $\mathrm{Im}(\rho_{\mathscr{G}_1})$. Hence we have

$$\begin{pmatrix} \mathrm{GL}_{n-1}(\mathbb{Z}_p) & 0 \\ 0 & 1 \end{pmatrix} \subset \mathrm{Im}(\rho_{\mathscr{G}_1}) \subset \mathrm{Im}(\rho_{\mathscr{G}_{R'}}). \tag{7.5.3}$$

On the other hand, since the cohomology class $\overline{C}_{\sigma_2} \neq 0$, there exists a $g \in \pi_1(\widetilde{U'}, \overline{x})$ such that $b_2 = \overline{C}_{\sigma_2}(g) \neq 0$. Hence the matrix $\rho_{\mathscr{G}_2}(g)$ has the form $\begin{pmatrix} B_2 & b_2 \\ 0 & 1 \end{pmatrix}$ such that $B_2 \in \mathrm{GL}_{n-1}(\mathbb{Z}_p)$ and the image of $b_2 \in \mathrm{M}_{1\times n-1}(\mathbb{Z}_p)$

in $\mathrm{M}_{1\times n-1}(\mathbb{F}_p)$ is non-zero. By the functoriality of monodromy, we have $\mathrm{Im}(\rho_{\mathscr{G}_2}) \subset \mathrm{Im}(\rho_{\mathscr{G}_{R'}})$; in particular, we have $\begin{pmatrix} B_2 & b_2 \\ 0 & 1 \end{pmatrix} \in \mathrm{Im}(\rho_{\mathscr{G}_{R'}})$. In view of (7.5.3), we get

$$\begin{pmatrix} \mathrm{GL}_{n-1}(\mathbb{Z}_p) & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} B_2 & b_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \mathrm{GL}_{n-1}(\mathbb{Z}_p) & 0 \\ 0 & 1 \end{pmatrix} \subset \mathrm{Im}(\rho_{\mathscr{G}_{R'}}). \tag{7.5.4}$$

But the subset of $\mathrm{GL}_n(\mathbb{Z}_p)$ on the left hand side is just the subgroup H described in condition (b). Therefore, condition (b) is verified for $\rho_{\mathscr{G}_{R'}}$, and the proof of 7.3 is complete.

The rest of this section is dedicated to the proof of Lemma 7.5.

Lemma 7.6. *Let k be an algebraically closed field of characteristic $p > 0$, A be a noetherian henselian local k-algebra with residue field k, G be a BT-group over A, and $G^{\text{ét}}$ be its étale part. Put*

$$\mathrm{Lie}(G^\vee)^{\varphi=1} = \{x \in \mathrm{Lie}(G^\vee) \text{ such that } \varphi_G(x) = x\}.$$

Then $\mathrm{Lie}(G^\vee)^{\varphi=1}$ is an $\mathbb{F}_p$-vector space of dimension equal to the rank of $\mathrm{Lie}(G^{\text{ét}\vee})$, and the A-submodule $\mathrm{Lie}(G^{\text{ét}\vee})$ of $\mathrm{Lie}(G^\vee)$ is generated by $\mathrm{Lie}(G^\vee)^{\varphi=1}$.

Proof. Let r be the rank of $\mathrm{Lie}(G^{\text{ét}\vee})$, G° be the connected part of G, and s be the height of $\mathrm{Lie}(G^{\circ\vee})$. We have an exact sequence of A-modules

$$0 \to \mathrm{Lie}(G^{\text{ét}\vee}) \to \mathrm{Lie}(G^\vee) \to \mathrm{Lie}(G^{\circ\vee}) \to 0,$$

compatible with Hasse-Witt maps. We choose a basis of $\mathrm{Lie}(G^\vee)$ adapted to this exact sequence, so that φ_G is expressed by a matrix of the form $\begin{pmatrix} U & W \\ 0 & V \end{pmatrix}$ with $U \in \mathrm{M}_{r\times r}(A)$, $V \in \mathrm{M}_{s\times s}(A)$, and $W \in \mathrm{M}_{r\times s}(A)$. An element of $\mathrm{Lie}(G^\vee)^{\varphi=1}$ is given by a vector $\begin{pmatrix} x \\ y \end{pmatrix}$, where $x = \begin{pmatrix} x_1 \\ \vdots \\ x_r \end{pmatrix}$ and $y = \begin{pmatrix} y_1 \\ \vdots \\ y_s \end{pmatrix}$ with $x_i, y_j \in A$, satisfying

$$\begin{pmatrix} U & W \\ 0 & V \end{pmatrix} \cdot \begin{pmatrix} x^{(p)} \\ y^{(p)} \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} \quad \Leftrightarrow \quad \begin{cases} U \cdot x^{(p)} + W \cdot y^{(p)} = x \\ V \cdot y^{(p)} = y. \end{cases} \tag{7.6.1}$$

where $x^{(p)}$ (*resp.* $y^{(p)}$) is the vector obtained by applying $a \mapsto a^p$ to each $x_i (1 \leq i \leq r)$ (*resp.* $y_j (1 \leq j \leq s)$). By 2.9, the Hasse-Witt map of the special fiber of G° is nilpotent. So there exists an integer $N \geq 1$ such that $\varphi^N_{G^\circ}(\mathrm{Lie}(G^{\circ\vee})) \subset \mathfrak{m}_A \cdot \mathrm{Lie}(G^{\circ\vee})$, *i.e.* we have $V \cdot V^{(p)} \cdots V^{(p^{N-1})} \equiv 0 \pmod{\mathfrak{m}_A}$. From the equation $V \cdot y^{(p)} = y$, we deduce that

$$y = V \cdot V^{(p)} \cdots V^{(p^{N-1})} \cdot y^{(p^N)} \equiv 0 \pmod{\mathfrak{m}_A}.$$

But this implies that $y^{(p^N)} \equiv 0 \pmod{\mathfrak{m}_A^{p^N}}$. Hence we get $y = V \cdot y^{(p)} \equiv 0 \pmod{\mathfrak{m}_A^{p^N+1}}$. Repeting this argument, we get finally $y \equiv 0 \pmod{\mathfrak{m}_A^{\ell}}$ for all integers $\ell \geq 1$, so $y = 0$. This implies that $\mathrm{Lie}(G^\vee)^{\varphi=1} \subset \mathrm{Lie}(G^{\text{ét}\vee})$, and the equation (7.6.1) is simplified as $U \cdot x^{(p)} = x$. Since the linearization of $\varphi_{G^{\text{ét}}}$ is bijective by 2.11, we have $U \in \mathrm{GL}_r(A)$. Let $\overline{U}$ be the image of U in $\mathrm{GL}_r(k)$, and Sol be the solutions of the equation $\overline{U} \cdot x^{(p)} = x$. As k is algebraically closed, Sol is an $\mathbb{F}_p$-space of dimension r, and $\mathrm{Lie}(G^{\text{ét}\vee}) \otimes k$ is generated by Sol (cf. [Ka2, Prop. 4.1]). By the henselian property of A, every elements in Sol lifts uniquely to a solution of $U \cdot x^{(p)} = x$, *i.e.* the reduction map $\mathrm{Lie}(G^\vee)^{\varphi=1} \xrightarrow{\sim} \mathrm{Sol}$ is bijective. By Nakayama's lemma, $\mathrm{Lie}(G^\vee)^{\varphi=1}$ generates the A-module $\mathrm{Lie}(G^{\text{ét}\vee})$. □

7.7. We keep the notations of 7.4. Let $\mathbf{Comp}_{\overline{K}_0}$ be the category of noetherian complete local $\overline{K}_0$-algebras with residue field $\overline{K}_0$, $\mathcal{D}_{\mathscr{G}_{\overline{K}_0}}$ (*resp.* $\mathcal{D}_{\mathscr{G}^\circ_{\overline{K}_0}}$) be the functor which associates to every object A of $\mathbf{Comp}_{\overline{K}_0}$ the set of isomorphsm classes of deformations of $\mathscr{G}_{\overline{K}_0}$ (*resp.* $\mathscr{G}^\circ_{\overline{K}_0}$) . If A is an object in $\mathbf{Comp}_{\overline{K}_0}$ and G is a deformation of $\mathscr{G}_{\overline{K}_0}$ (*resp.* $\mathscr{G}^\circ_{\overline{K}_0}$) over A, we denote by $[G]$ its isomorphic class in $\mathcal{D}_{\mathscr{G}_{\overline{K}_0}}(A)$ (*resp.* in $\mathcal{D}_{\mathscr{G}^\circ_{\overline{K}_0}}$).

Lemma 7.8. *Let Σ be the set defined in* (7.4.3).
(i) *The morphism of sets $\Phi : \Sigma \to \mathcal{D}_{\mathscr{G}_{\overline{K}_0}}(\widetilde{R'})$ given by $\sigma \mapsto [\mathscr{G}_{\widetilde{R'},\sigma}]$ is bijective.*
(ii) *Let $\sigma \in \Sigma$. Then there exists a basis of $\mathrm{Lie}(\mathscr{G}^{\circ\vee}_{\widetilde{R'},\sigma})$ such that $\varphi_{\mathscr{G}^\circ_{\widetilde{R'},\sigma}}$ is represented by a matrix of the form*

$$\mathfrak{h}^\circ_\sigma = \begin{pmatrix} 0 & 0 & \cdots & 0 & a_1 \\ 1 & 0 & \cdots & 0 & a_2 \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & \cdots & 1 & a_{n-1} \end{pmatrix} \tag{7.8.1}$$

with $a_i \equiv \alpha \cdot \sigma(t_i) \pmod{\mathfrak{m}^2_{\widetilde{R'}}}$ for $1 \leq i \leq n-1$, where $\alpha \in \widetilde{R'}^\times$ and $\mathfrak{m}_{\widetilde{R'}}$ is the maximal ideal of $\widetilde{R'}$. In particular, $\mathscr{G}^\circ_{\widetilde{R'},\sigma}$ is the universal deformation of $\mathscr{G}^\circ_{\overline{K}_0}$ if and only if $\{\sigma(t_1), \cdots, \sigma(t_{n-1})\}$ is a system of regular parameters of $\widetilde{R'}$.

Proof. (i) We begin with a remark on the Kodaira-Spencer map of $\mathscr{G}_{R'}$. Let $\mathscr{T}_{\mathbf{S}/k} = \mathscr{H}om_{\mathscr{O}_\mathbf{S}}(\Omega^1_{\mathbf{S}/k}, \mathscr{O}_\mathbf{S})$ be the tangent sheaf of $\mathbf{S}$. Since $\mathbf{G}$ is universal, the Kodaira-Spencer map (3.2.2)

$$\mathrm{Kod} : \mathscr{T}_{\mathbf{S}/k} \xrightarrow{\sim} \mathscr{H}om_{\mathscr{O}_\mathbf{S}}(\omega_\mathbf{G}, \mathrm{Lie}(\mathbf{G}^\vee))$$

is an isomorphism. By functoriality, this induces an isomorphism of R'-modules

$$\mathrm{Kod}_{R'} : T_{R'/k} \xrightarrow{\sim} \mathrm{Hom}_{R'}(\omega_{\mathscr{G}_{R'}}, \mathrm{Lie}(\mathscr{G}^\vee_{R'})), \tag{7.8.2}$$

where $T_{R'/k} = \mathrm{Hom}_{R'}(\Omega^1_{R'/k}, R') = \Gamma(\mathbf{S}, \mathscr{T}_{\mathbf{S}/k}) \otimes_R R'$.

For each integer $\nu \geq 0$, we put $\widetilde{R'}_\nu = \widetilde{R'}/\mathfrak{m}^{\nu+1}_{\widetilde{R'}}$, Σ_ν to be the set of liftings of $R \to K_0 \to \overline{K}_0$ to $R \to \widetilde{R'}_\nu$, and $\Phi_\nu : \Sigma_\nu \to \mathcal{D}_{\mathscr{G}_{\overline{K}_0}}(\widetilde{R'}_\nu)$ to be the morphism of sets $\sigma_\nu \mapsto [\mathscr{G}_{R'}\otimes_{\sigma_\nu}\widetilde{R'}_\nu]$. We prove by induction on ν that Φ_ν is bijective for all $\nu\geq 0$. This will complete the proof of (i). For $\nu=0$, the claim holds trivially. Assume that it holds for $\nu-1$ with $\nu\geq 1$. We have a commutative diagram

$$\begin{tikzcd} \Sigma_\nu \arrow[r, "\Phi_\nu"] \arrow[d] & \mathcal{D}_{\mathscr{G}_{\overline{K}_0}}(\widetilde{R'}_\nu) \arrow[d] \\ \Sigma_{\nu-1} \arrow[r, "\Phi_{\nu-1}"] & \mathcal{D}_{\mathscr{G}_{\overline{K}_0}}(\widetilde{R'}_{\nu-1}), \end{tikzcd}$$

where the vertical arrows are the canonical reductions, and the lower arrow is an isomorphism by induction hypothesis. Let τ be an arbitrary element of $\Sigma_{\nu-1}$. We denote by $\Sigma_{\nu,\tau}\subset\Sigma_\nu$ the preimage of τ, and by $\mathcal{D}_{\Phi_{\nu-1}(\tau)}(\widetilde{R'}_\nu)\subset \mathcal{D}_{\mathscr{G}_{\overline{K}_0}}(\widetilde{R'}_\nu)$ the preimage of $\Phi_{\nu-1}(\tau)$. It suffices to prove that Φ_ν induces a bijection between $\Sigma_{\nu,\tau}$ and $\mathcal{D}_{\Phi_{\nu-1}(\tau)}(\widetilde{R'}_\nu)$. Let $I_\nu=\mathfrak{m}^{\nu}_{\widetilde{R'}}/\mathfrak{m}^{\nu+1}_{\widetilde{R'}}$ be the ideal of the reduction map $\widetilde{R'}_\nu\to\widetilde{R'}_{\nu-1}$. By [EGA, $0_{\rm IV}$ 21.2.5 and 21.9.4], we have $\Omega^1_{R'/k}\simeq\widehat{\Omega}^1_{R'/k}$, and they are free over A of rank n. By [EGA, $0_{\rm IV}$ 20.1.3], $\Sigma_{\nu,\tau}$ is a (nonempty) homogenous space under the group

$$\mathrm{Hom}_{K_0}(\Omega^1_{R'/k}\otimes_{R'}K_0, I_\nu)=T_{R'/k}\otimes_{R'}I_\nu.$$

On the other hand, according to 3.5(i), $\mathcal{D}_{\Phi_{\nu-1}(\tau)}(\widetilde{R'}_\nu)$ is a homogenous space under the group

$$\mathrm{Hom}_{\overline{K}_0}(\omega_{\mathscr{G}_{\overline{K}_0}},\mathrm{Lie}(\mathscr{G}^\vee_{\overline{K}_0}))\otimes_{\overline{K}_0}I_\nu=\mathrm{Hom}_{R'}(\omega_{\mathscr{G}_{R'}},\mathrm{Lie}(\mathscr{G}^\vee_{R'}))\otimes_{R'}I_\nu.$$

Moreover, it is easy to check that the morphism of sets $\Phi_\nu:\Sigma_{\nu,\tau}\to\mathcal{D}_{\Phi_{\nu-1}(\tau)}(\widetilde{R'}_\nu)$ is compatible with the homomorphism of groups

$$\mathrm{Kod}_{R'}\otimes_{R'}\mathrm{Id}:T_{R'/k}\otimes_{R'}I_\nu\to\mathrm{Hom}_{R'}(\omega_{\mathscr{G}_{R'}},\mathrm{Lie}(\mathscr{G}^\vee_{R'}))\otimes_{R'}I_\nu,$$

where $\mathrm{Kod}_{R'}$ is the Kodaira-Spencer map (7.8.2) associated to $\mathscr{G}_{R'}$. The bijectivity of Φ_ν now follows from the fact that $\mathrm{Kod}_{R'}$ is an isomorphism.

(ii) The second part of the statement follows immediately from 4.11. It remains to compute the Hasse-Witt map of $\mathscr{G}^\circ_{\widetilde{R'},\sigma}$. We determine first the submodule $\mathrm{Lie}(\mathscr{G}^{\text{ét}\vee}_{\widetilde{R'},\sigma})$ of $\mathrm{Lie}(\mathscr{G}^\vee_{\widetilde{R'},\sigma})$. We choose a basis of $\mathrm{Lie}(\mathbf{G}^\vee)$ over $\mathscr{O}_{\mathbf{S}}$ such that $\varphi_{\mathbf{G}}$ is expressed by the matrix $\mathfrak{h}$ (7.4.1). As $\mathscr{G}_{\widetilde{R'},\sigma}$ derives from $\mathbf{G}$ by base change $R\to R'\xrightarrow{\sigma}\widetilde{R'}$, there exists a basis $(e_1,\cdots,e_n)$ of $\mathrm{Lie}(\mathscr{G}^\vee_{\widetilde{R'},\sigma})$ such that $\varphi_{\mathscr{G}_{\widetilde{R'},\sigma}}$ is expressed by

$$\mathfrak{h}^\sigma=\begin{pmatrix}0&0&\cdots&0&-\sigma(t_1)\\1&0&\cdots&0&-\sigma(t_2)\\\vdots&&\ddots&&\vdots\\0&0&\cdots&1&-\sigma(t_n)\end{pmatrix}.$$

By Lemma 7.6, $\mathrm{Lie}(\mathscr{G}^{\text{ét}\vee}_{\widetilde{R'},\sigma})$ is generated by $\mathrm{Lie}(\mathscr{G}^\vee_{\widetilde{R'},\sigma})^{\varphi=1}$. If $\sum_{i=1}^n x_ne_n\in\mathrm{Lie}(\mathscr{G}^\vee_{\widetilde{R'},\sigma})^{\varphi=1}$ with $x_i\in\widetilde{R'}$ for $1\leq i\leq n$, then $(x_i)_{1\leq i\leq n}$ must satisfy the equation $\mathfrak{h}^{\sigma}\cdot\begin{pmatrix}x_1^p\\ \vdots\\ x_n^p\end{pmatrix}=\begin{pmatrix}x_1\\ \vdots\\ x_n\end{pmatrix}$; or equivalently,

$$\begin{cases}x_1=-\sigma(t_1)x_n^p\\ x_2=-\sigma(t_2)x_n^p-\sigma(t_1)^px_n^{p^2}\\ \cdots\\ x_{n-1}=-\sigma(t_{n-1})x_n^p-\cdots-\sigma(t_1)^{p^{n-2}}x_n^{p^{n-1}}\\ \sigma(t_1)^{p^{n-1}}x_n^{p^n}+\sigma(t_2)^{p^{n-2}}x_n^{p^{n-1}}+\cdots+\sigma(t_n)x_n^p+x_n=0.\end{cases}\tag{7.8.3}$$

We note that $\sigma(t_i)\in\mathfrak{m}_{\widetilde{R'}}$ for $1\leq i\leq n-1$ and $\sigma(t_n)\in\widetilde{R'}^{\times}$ with image $i(t_n)\in\overline{K}_0$, where $i:K_0\to\overline{K}_0$ is the fixed immbedding. By Hensel's lemma, every solution in $\overline{K}_0$ of the equation $i(t_n)x_n^p+x_n=0$ lifts uniquely to a solution of (7.8.3). As $\mathrm{Lie}(\mathscr{G}^{\text{ét}\vee}_{\widetilde{R'},\sigma})$ has rank 1, by Lemma 7.6, these are all the solutions of (7.8.3). Let $(\lambda_1,\cdots,\lambda_n)$ be a non-zero solution of (7.8.3). We have

$$\lambda_n\in\widetilde{R'}^{\times}\quad\text{and}\quad\lambda_i\equiv-\lambda_n^p\sigma(t_i)\pmod{\mathfrak{m}^2_{\widetilde{R'}}}.\tag{7.8.4}$$

We put $v=\lambda_1e_1+\cdots+\lambda_ne_n$; so v is a basis of $\mathrm{Lie}(\mathscr{G}^{\text{ét}\vee}_{\widetilde{R'},\sigma})$ by 7.6. For $1\leq i\leq n$, let f_i be the image of e_i in $\mathrm{Lie}(\mathscr{G}^{\circ\vee}_{\widetilde{R'},\sigma})$. Then $f_1,\cdots,f_n$ clearly generate $\mathrm{Lie}(\mathscr{G}^{\circ\vee}_{\widetilde{R'},\sigma})$. By the explicit description above of $\mathrm{Lie}(\mathscr{G}^{\text{ét}\vee}_{\widetilde{R'},\sigma})$, we have $f_n=-\lambda_n^{-1}(\lambda_1f_1\cdots+\lambda_{n-1}f_{n-1})$. Hence $f_1,\cdots,f_{n-1}$ form a basis of $\mathrm{Lie}(\mathscr{G}^{\circ\vee}_{\widetilde{R'},\sigma})$. By the functoriality of Hasse-Witt maps, we have $\varphi_{\mathscr{G}^{\circ}_{\widetilde{R'}}}(f_i)=f_{i+1}$ for $1\leq i\leq n-1$, or equivalently,

$$\varphi_{\mathscr{G}^{\circ}_{\widetilde{R'},\sigma}}(f_1,\cdots,f_{n-1})=(f_1,\cdots,f_{n-1})\cdot\begin{pmatrix}0&0&\cdots&0&-\lambda_n^{-1}\lambda_1\\ 1&0&\cdots&0&-\lambda_n^{-1}\lambda_2\\ \vdots&&\ddots&&\vdots\\ 0&0&\cdots&1&-\lambda_n^{-1}\lambda_{n-1}\end{pmatrix}.$$

In view of (7.8.4), we see that the above matrix has the form of (7.8.1) by setting $\alpha=\lambda_n^{p-1}\in\widetilde{R'}^{\times}$. The second part of statement (ii) follows immediately from Proposition 4.11(ii) and the description above of $\varphi_{\mathscr{G}^{\circ}_{\widetilde{R'},\sigma}}$. □

Now we can turn to the proof of 7.5.

7.9. Proof of Lemma 7.5. First, suppose that we have found a $\sigma_2\in\Sigma$ such that $\overline{C}_{\sigma_2}\neq0$ and $\mathscr{G}^{\circ}_{\widetilde{R'},\sigma_2}$ is the universal deformation of $\mathscr{G}^{\circ}_{\overline{K}_0}$. Since $\Phi:\Sigma\xrightarrow{\sim}\mathcal{D}_{\mathscr{G}_{\overline{K}_0}}(\widetilde{R'})$ is bijective by 7.8(i), there exists a $\sigma_1\in\Sigma$ corresponding to the deformation $[\mathscr{G}^{\circ}_{\widetilde{R'},\sigma_2}\oplus\mathbb{Q}_p/\mathbb{Z}_p]\in\mathcal{D}_{\mathscr{G}_{\overline{K}_0}}(\widetilde{R'})$. It is clear that $\mathscr{G}^{\circ}_{\widetilde{R'},\sigma_1}\simeq\mathscr{G}^{\circ}_{\widetilde{R'},\sigma_2}$. Besides, the exact sequence (7.4.5) for σ_1 splits; so we have $C_{\sigma_1}=0$. It remains to prove the existence of σ_2. We note first that $\overline{K}_0$ can be canonically imbedded into $\widetilde{R'}$, since it is perfect. Since R' is formally smooth over k and

$(t_1, \cdots, t_n)$ is a p-basis of R' over k, by [EGA, 0_{IV} 21.2.7], there is a $\sigma \in \Sigma$ such that $\sigma(t_i)$ $(1 \leq i \leq n-1)$ form a system of regular parameters of $\widetilde{R'}$ and $\sigma(t_n) \in \overline{K}_0 \subset \widetilde{R'}$. We claim that $\sigma_2 = \sigma$ answers the question. In fact, Lemma 7.8(ii) implies that $\mathscr{G}^\circ_{\widetilde{R'},\sigma}$ is the universal deformation of $\mathscr{G}^\circ_{\overline{K}_0}$. It remains to verify that $\overline{C}_\sigma \neq 0$.

Let $A = \overline{K}_0[[\pi]]$ be a complete discrete valuation ring of characteristic p with residue field $\overline{K}_0$, $T = \mathrm{Spec}(A)$, ξ be the generic point of T, $\overline{\xi}$ be a geometric over ξ, and $I = \mathrm{Gal}(\overline{\xi}/\xi)$ the Galois group. We define a homomorphism of $\overline{K}_0$-algebras $f^* : \widetilde{R'} \to A$ by putting $f^*(\sigma(t_1)) = \pi$ and $f^*(\sigma(t_i)) = 0$ for $2 \leq i \leq n-1$. This is possible, since $(\sigma(t_1), \cdots, \sigma(t_{n-1}))$ is a system of regular parameters of $\widetilde{R'}$. Let $f : T \to \widetilde{S}'$ be the homomorphism of schemes corresponding to f^*, and $\mathscr{G}_T = \mathscr{G}_{\widetilde{R'},\sigma} \times_{\widetilde{S'}} T$. By the functoriality of Hasse-Witt maps,

$$\mathfrak{h}_T = \begin{pmatrix} 0 & 0 & \cdots & 0 & -\pi \\ 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & \cdots & 1 & -f^*(\sigma(t_n)) \end{pmatrix} \in \mathrm{M}_{n\times n}(\widetilde{R'})$$

is a matrix of $\varphi_{\mathscr{G}_T}$. By definition (5.4), the Hasse invariant of $\mathscr{G}_T$ is $h(\mathscr{G}_T) = 1$. In particular, $\mathscr{G}_T$ is generically ordinary. Let $\widetilde{U}'_\sigma \subset \widetilde{S}'$ be the ordinary locus of $\mathscr{G}_{\widetilde{R'},\sigma}$. We have $f(\xi) \in \widetilde{U}'_\sigma$. By the functoriality of fundamental groups, f induces a homomorphism of groups

$$\pi_1(f) : I = \mathrm{Gal}(\overline{\xi}/\xi) \to \pi_1(\widetilde{U}'_\sigma, f(\overline{\xi})) \simeq \pi_1(\widetilde{U}'_\sigma, \overline{x}).$$

Let $\mathscr{G}^\circ_T$ be the connected part of $\mathscr{G}_T$, and $\mathscr{G}^{\text{ét}}_T$ be the étale part of $\mathscr{G}_T$. Then $\mathscr{G}^{\text{ét}}_T \simeq \mathbb{Q}_p/\mathbb{Z}_p$. We have an exact sequence of $\mathbb{F}_p[I]$-modules

$$0 \to \mathscr{G}^\circ_T(1)(\overline{\xi}) \to \mathscr{G}_T(1)(\overline{\xi}) \to \mathscr{G}^{\text{ét}}_T(1)(\overline{\xi}) \to 0,$$

which determines a cohomology class $\overline{C}_T \in H^1(I, \mathscr{G}^\circ_T(1)(\overline{\xi}))$. We notice that $\mathscr{G}_T(1)(\overline{\xi})$ is isomorphic to $\mathscr{G}_{\widetilde{R'},\sigma}(1)(\overline{x})$ as an abelian group, and the action of I on $\mathscr{G}_T(1)(\overline{\xi})$ is induced by the action of $\pi_1(\widetilde{U}'_\sigma, \overline{x})$ on $\mathscr{G}_{\widetilde{R'},\sigma}(1)(\overline{x})$. Therefore, $\overline{C}_T$ is the image of $\overline{C}_\sigma$ by the functorial map

$$H^1\big(\pi_1(\widetilde{U}'_\sigma, \overline{x}), \mathscr{G}^\circ_{\widetilde{R'},\sigma}(1)(\overline{x})\big) \to H^1\big(I, \mathscr{G}^\circ_T(1)(\overline{\xi})\big).$$

To verify that $\overline{C}_\sigma \neq 0$, it suffices to check that $\overline{C}_T \neq 0$. We consider the polynomial $P(X) = X^{p^n} + f^*(\sigma(t_n))X^{p^{n-1}} + \pi X \in A[X]$. According to 5.12, it suffices to find a $\alpha \in \overline{K}_0 \subset A$ such that $P(\alpha)$ is a uniformizer of A. But by the choice of σ, we have $\sigma(t_n) \in \overline{K}_0$ and $\sigma(t_n) \neq 0$; so $f^*(\sigma(t_n)) \neq 0$ lies in $\overline{K}_0$. Let α be a $p^{n-1}(p-1)$-th root of $-f^*(\sigma(t_n))$ in $\overline{K}_0$. Then we have $\alpha \in \overline{K}_0^\times$, and $P(\alpha) = \alpha\pi$ is a uniformizer of A. This completes the proof of 7.5.

8. End of the Proof of Theorem 1.3

In this section, k denotes an algebraically closed field of characteristic $p > 0$.

8.1. First, we recall some preliminaries on Newton stratification due to F. Oort. Let G be an arbitrary BT-group over k, $\mathbf{S}$ be the local moduli of G in characteristic p, and $\mathbf{G}$ be the universal deformation of G over $\mathbf{S}$ (3.8). Put $d = \dim(G)$ and $c = \dim(G^\vee)$. We denote by $\mathcal{N}(G)$ the Newton polygon of G which has endpoints $(0,0)$ and $(c+d,d)$. Here we use the normalization of Newton polygons such that slope 0 corresponds to étale BT- groups and slope 1 corresponds to groups of multiplicative type.
Let $\mathcal{NP}(c+d,d)$ be the set of Newton polygons with endpoints $(0,0)$ and $(c+d,d)$ and slopes in $(0,1)$. For $\alpha,\beta \in \mathcal{NP}(c+d,d)$, we say that $\alpha \preceq \beta$ if no point of α lies below β; then "$\preceq$" is a partial order on $\mathcal{NP}(c+d,d)$. For each $\beta \in \mathcal{NP}(c+d,d)$, we denote by V_β the subset of $\mathbf{S}$ consisting of points x with $\mathcal{N}(\mathbf{G}_x) \preceq \beta$, and by V_β° the subset of $\mathbf{S}$ consisting of points x with $\mathcal{N}(\mathbf{G}_x) = \beta$. By Grothendieck-Katz's specialization theorem of Newton polygons, V_β is closed in $\mathbf{S}$, and V_β° is open (maybe empty) in V_β. We put

$\diamondsuit(\beta) =$

$\{(x,y) \in \mathbb{Z}\times\mathbb{Z} \mid 0 \leq y < d, y < x < c+d, (x,y)\text{lies on or above the polygon } \beta\}$,

and $\dim(\beta) = \#(\diamondsuit(\beta))$.

Theorem 8.2 ([Oo2] Theorem 2.11). *Under the above assumptions, for each $\beta \in \mathcal{NP}(c+d,d)$, the subset V_β° is non-empty if and only if $\mathcal{N}(G) \preceq \beta$. In that case, V_β is the closure of V_β° and all irreducible components of V_β have dimension* $\dim(\beta)$.

8.3. Let G be a connected and HW-cyclic BT-group over k of dimension $d = \dim(G) \geq 2$. Let $\beta \in \mathcal{NP}(c+d,d)$ be the Newton polygon given by the following slope sequence:

$$\beta = (\underbrace{1/(c+1),\cdots,1/(c+1)}_{c+1},\underbrace{1,\cdots,1}_{d-1}).$$

We have $\mathcal{N}(G) \preceq \beta$ since G is supposed to be connected. By Oort's Theorem 8.2, V_β is a equal dimensional closed subset of the local moduli $\mathbf{S}$ of dimension $c(d-1)$. We endow V_β with the structure of a reduced closed subscheme of $\mathbf{S}$.

Lemma 8.4. *Under the above assumptions, let R be the ring of $\mathbf{S}$, and*

$$\begin{pmatrix} 0 & 0 & \cdots & 0 & -a_1 \\ 1 & 0 & \cdots & 0 & -a_2 \\ 0 & 1 & \cdots & 0 & -a_3 \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & \cdots & 1 & -a_c \end{pmatrix} \in \mathrm{M}_{c\times c}(R)$$

be a matrix of the Hasse-Witt map φ_G. Then the closed reduced subscheme V_β of $\mathbf{S}$ is defined by the prime ideal $(a_1,\cdots,a_c)$. In particular, V_β is irreducible.

Proof. Note first that $\{a_1, \cdots, a_c\}$ is a subset of a system of regular parameters of R by 4.11(i). Let I be the ideal of R defining V_β. Let x be an arbitrary point of V_β, we denote by $\mathfrak{p}_x$ the prime ideal of R corresponding to x. Since the Newton polygon of the fibre $\mathbf{G}_x$ lies above β, $\mathbf{G}_x$ is connected. By Lemma 4.4, we have $a_i \in \mathfrak{p}_x$ for $1 \leq i \leq c$. Since V_β is reduced, we have $a_i \in I$. Let $\mathfrak{P} = (a_1, \cdots, a_c)$, and $V(\mathfrak{P})$ the closed subscheme of $\mathbf{S}$ defined by $\mathfrak{P}$. Then $V(\mathfrak{P})$ is an integral scheme of dimension $c(d-1)$ and $V_\beta \subset V(\mathfrak{P})$. Since Theorem 8.2 implies that $\dim V_\beta = c(d-1)$, we have necessarily $V_\beta = V(\mathfrak{P})$. $\square$

We keep the assumptions above. Let $(t_{i,j})_{1\leq i\leq c, 1\leq j\leq d}$ be a regular system of parameters of R such that $t_{i,d} = a_i$ for all $1 \leq i \leq c$. Let x be the generic point of the Newton strata V_β, $k' = \kappa(x)$, and $R' = \widehat{\mathscr{O}}_{\mathbf{S},x}$. Since R is noetherian and integral, the canonical ring homomorphism $R \to \mathscr{O}_{\mathbf{S},x} \to R'$ is injective. The image in R' of an element $a \in R$ will be denoted also by a. By choosing a k-section $k' \to R'$ of the canonical projection $R' \to k'$, we get a (non-canonical) isomorphism of k-algebras $R' \simeq k'[[t_{1,d}, \cdots, t_{c,d}]]$. Let k'' be an algebraic closure of k', and $R'' = k''[[t_{1,d}, \cdots, t_{c,d}]]$. Then we have a natural injective homomorphism of k-algebras $R' \to R''$ mapping $t_{i,d}$ to $t_{i,d}$ for $1 \leq i \leq c$.
Let $S'' = \mathrm{Spec}(R'')$, $\overline{x}$ be its closed point. By the construction of S'', we have a morphism of k-schemes

$$f : S'' \to \mathbf{S} \tag{8.4.1}$$

sending $\overline{x}$ to x. We put $\mathscr{G} = \mathbf{G} \times_{\mathbf{S}} S''$. By the choice of the Newton polygon β, the closed fibre $\mathscr{G}_{\overline{x}}$ has a BT-subgroup $\mathscr{H}_{\overline{x}}$ of multiplicative type of height $d-1$. Since S'' is henselian, $\mathscr{H}_{\overline{x}}$ lifts uniquely to a BT-subgroup $\mathscr{H}$ of $\mathscr{G}$. We put $\mathscr{G}'' = \mathscr{G}/\mathscr{H}$. It is a connected BT-group over S'' of dimension 1 and height $c+1$.

Lemma 8.5. *Under the above assumptions, $\mathscr{G}''$ is the universal deformation in equal characteristic of its special fiber.*

This lemma is a particular case of [Lau, Lemma 3.1]. Here, we use 4.11(ii) to give a simpler proof.

Proof. We have an exact sequence of BT-groups over S''

$$0 \to \mathscr{H} \to \mathscr{G} \to \mathscr{G}'' \to 0,$$

which induces an exact sequence of Lie algebras $0 \to \mathrm{Lie}(\mathscr{G}''^\vee) \to \mathrm{Lie}(\mathscr{G}^\vee) \to \mathrm{Lie}(\mathscr{H}^\vee) \to 0$ compatible with Hasse-Witt maps. Since $\mathscr{H}$ is of multiplicative type, we get $\mathrm{Lie}(\mathscr{H}^\vee) = 0$ and an isomorphism of Lie algebras $\mathrm{Lie}(\mathscr{G}''^\vee) \simeq \mathrm{Lie}(\mathscr{G}^\vee)$. By the choice of the regular system $(t_{i,j})_{1\leq i\leq c,1\leq j\leq d}$, there is a basis $(v_1, \cdots, v_c)$ of $\mathrm{Lie}(\mathscr{G}''^\vee)$ over $\mathscr{O}_{S''}$ such that $\varphi_{\mathscr{G}''}$ is given by the matrix

$$\mathfrak{h} = \begin{pmatrix} 0 & 0 & \cdots & 0 & -t_{1,d} \\ 1 & 0 & \cdots & 0 & -t_{2,d} \\ 0 & 1 & \cdots & 0 & -t_{3,d} \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & \cdots & 1 & -t_{c,d} \end{pmatrix}.$$

Now the lemma results from Proposition 4.11(ii). □

8.6. PROOF OF THEOREM 1.3. The one-dimensional case is treated in 7.3. If $\dim(G) \geq 2$, we apply the preceding discussion to obtain the morphism $f\colon S'' \to \mathbf{S}$ and the BT-groups $\mathscr{G} = \mathbf{G} \times_{\mathbf{S}} S''$ and $\mathscr{G}''$, which is the quotient of $\mathscr{G}$ by the maximal subgroup of $\mathscr{G}$ of multiplicative type. Let U'' be the common ordinary locus of $\mathscr{G}$ and $\mathscr{G}''$ over S'', and $\overline{\xi}$ be a geometric point of U''. Then f maps U'' into the ordinary locus $\mathbf{U}$ of $\mathbf{G}$. We denote by

$$\rho_{\mathscr{G}} : \pi_1(U'', \overline{\xi}) \to \mathrm{Aut}_{\mathbb{Z}_p}(\mathrm{T}_p(\mathscr{G}, \overline{\xi}))$$

the monodromy representation associated to $\mathscr{G}$, and the same notation for $\rho_{\mathscr{G}''}$. By the functoriality of monodromy, we have $\mathrm{Im}(\rho_{\mathscr{G}}) \subset \mathrm{Im}(\rho_{\mathbf{G}})$. On the other hand, the canonical map $\mathscr{G} \to \mathscr{G}''$ induces an isomorphism of Tate modules $\mathrm{T}_p(\mathscr{G}, \overline{\eta}) \xrightarrow{\sim} \mathrm{T}_p(\mathscr{G}'', \overline{\eta})$ compatible with the action of $\pi_1(U'', \overline{\eta})$. Therefore, the group $\mathrm{Im}(\rho_{\mathscr{G}})$ is identified with $\mathrm{Im}(\rho_{\mathscr{G}''})$. Since $\mathscr{G}''$ is one-dimensional, we conclude the proof by Lemma 8.5 and Theorem 7.3.

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Yichao Tian
Department of Mathematics
Princeton University
Princeton
New Jersey
08544
USA
yichaot@princeton.edu