AFFINE SYMMETRIES IN QUANTUM COHOMOLOGY:
CORRECTIONS AND NEW RESULTS

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Abstract. In [CMP09] a general formula was given for the multiplication by
some special Schubert classes in the quantum cohomology of any homogeneous
space. Although this formula is true in the non equivariant setting, the stated
equivariant version was wrong. We provide correction for the equivariant for-
mula, thus giving a correct argument for the non equivariant formula. We also
give new formulas in the equivariant homology of the affine grassmannian that
could lead to non-equivariant Pieri formulas.

1. Introduction

In [CMP09] a general formula was given for the multiplication in the qua-
tum cohomology of any homogeneous space by some special Schubert classes
coming from cominuscule weights. Although this formula is true in the non equi-
variant setting, the stated equivariant version is wrong. We provide correction for
the equivariant formula, thus giving a correct argument for the non equivariant
formula. We also provide new product formulas in the equivariant homology of the
affine grassmannian.

Let \( G \) be a semisimple simply connected algebraic group and fix \( T \subset B \) a
maximal torus and a Borel subgroup containing it. Denote by \( P^\vee \) and \( Q^\vee \)
be the coweight and corroot lattices. A dominant coweight \( \lambda^\vee \in P^\vee \) is
minuscule if \( \langle \lambda^\vee, \alpha \rangle \in \{0, 1\} \) for any positive root \( \alpha \). A
minuscule dominant coweight is a fundamental coweight.

Denote by \( I_m \) the subset of the set \( I \) of vertices of the Dynkin diagram of \( G \)
parametrising minuscule coweights.

We consider a finite group \( Z \) which has several interpretation. Define \( Z \) has
\[ Z := P^\vee / Q^\vee. \]

Representatives for this quotient are for example the opposites of the minuscule
fundamental coweights \( (\pm \varpi_i^\vee)_{i \in I_m} \). The group \( Z \) is also the center of \( G \) and if \( G^{\text{ad}} \)
the the adjoint group associated to \( G \), then \( Z = \pi_1(G^{\text{ad}}) \).

The group \( Z \) can be realised as a subgroup of the Weyl group \( W \) of \( G \) as follows.
Let \( w_0 \) be the longest element in \( W \). For \( i \in I_m \) define \( v_i \in W \) to be the
smallest element in \( W \) such that \( v_i \varpi_i = w_0 \varpi_i \). Then the family \((v_i)_{i \in I_m}\) forms a
finite subgroup of \( W \) isomorphic to \( Z \). Finally \( Z \) can be realised as a subgroup of the
extended affine Weyl group \( W_{\text{aff}} = W \ltimes P^\vee \) (see Section 2.2 below) by \( i \mapsto \tau_i := v_i \) \(-\varpi_i \).

For \( P \subset G \) a parabolic subgroup, let \( I_P \) be the set of vertices in the Dynkin
diagram such that, for \( i \in I \), the simple root \( \alpha_i \) is a root of \( P \) if and only if \( i \in I_P \).

\textit{Date}: June 18, 2020.
\textit{2000 Mathematics Subject Classification}. 14M15, 14N35.
For $w \in W$, denote by $\sigma^P(w)$ the Schubert class in $H^{2\ell(w)}(G/P, \mathbb{Z})$ defined by $w$. Denote by $Q^\vee$ the co-root lattice of $P$ and consider $\eta_P : Q^\vee \to Q^\vee/Q^\vee_p$, the quotient map. We define an action of the Weyl group $W$ of $G$ on the equivariant cohomology $H^*_T(G/P)$ using, for $w \in W$, the pull-back in cohomology of the left multiplication by $w$ (see Subsection 6.1). We denote this action by $w^*$. This action is trivial in non-equivariant cohomology and extends to an action on equivariant quantum cohomology $\text{QH}^*_T(G/P)$. In this paper we obtain the following formula in the quantum equivariant cohomology $\text{QH}^*_T(G/P)$ for any parabolic subgroup $P \subset G$ (see Theorem 6.9).

**Theorem 1.1.** Let $i$ be a cominuscule node. In $\text{QH}^*_T(G/P)$ we have

$$\sigma^P(v_i) \times v_i^*(\sigma^P(w)) = q_{\eta_P(\pi_i^w - w^{-1}(\pi_i^w))}\sigma^P(v_i w).$$

This result corrects our formula in [CMP09] Theorem 1 which was wrong in the equivariant setting (the action $v_i^*$ on the second factor on the LHS was missing). The error in [CMP09] comes from an incorrect description of the ring structure of $H^*_T(\Omega K^{ad})$ the equivariant homology of the adjoint affine Grassmannian (see Section 5). If $\Omega K$ is the affine Grassmannian for $G$, the incorrect claim ([CMP09, Page 12]) was that $H^*_T(\Omega K)$ should be isomorphic to $Z \otimes H^*_T(\Omega K)$. This is not true as explained in Section 5 (see Remark 5.13). This is corrected in the present paper. Especially, in Proposition 5.2 we prove the $S$-algebra isomorphism (here $S = H^*_T(\text{pt})$):

$$H^*_T(\Omega K^{ad}) \simeq S[P^\vee] \otimes_{S[Q^\vee]} H^*_T(\Omega K).$$

The incorrect product formula was then used only once in [CMP09, Proposition 3.16]. We give a correct version of Proposition 3.16 in [CMP09] in Proposition 5.14.

We tried to write this paper as independently from [CMP09] as possible and included many preliminary results on the algebra and the module structure of the extended affine Hecke algebra $\tilde{H}_{aff}$ (see Section 5) and on its module structure $\tilde{M}$ which is isomorphic to $H^*_T(\Omega K^{ad})$ the homology of the adjoint affine Grassmannian. We also added new results. Especially we provide a generalization of a formula in [Lam08, Proposition 5.4] to coweights for the map $j^{ad} : H^*_T(\Omega K^{ad}) \to Z_{\tilde{H}_{aff}}(S)$ (see Proposition 7.4).

**Proposition 1.2.** Let $\mu^\vee \in P^\vee$ be antidominant and set $W_{\mu^\vee} = \{ s_{\alpha_i} \mid i \in [1, r] \text{ and } \langle \alpha_i, \mu^\vee \rangle = 0 \} = \{ w \in W \mid w(\mu^\vee) = \mu^\vee \}$. Then

$$j^{ad}(\xi_{\mu^\vee}) = \sum_{w \in W/W_{\mu^\vee}} \tilde{A}_{w(\mu^\vee)}.$$ 

Finally, we use this formula to give an explicit formula for the image of the map $j : H^*_T(\Omega K) \to Z_{\tilde{W}_{aff}}(S)$ for the special elements $\tau_i(v_i) = \tau_i v_i \tau_i^{-1}$ (see Proposition 7.4). Here $\tilde{W}_{aff}$ denotes the set of minimal representatives of the quotient $W_{aff}/W$.

**Proposition 1.3.** We have $\tau_i(v_i) \in \tilde{W}_{aff}$ and

$$j(\xi_{\tau_i(v_i)}) = \sum_{w \leq L v_i} \sum_{v \leq l_i^{-1}} \tau_i(\xi_{\tau_i(v_i)}^w))A_{\tau_i(w)v_i w^{-1}} A_v,$$

where $\leq$ is the Bruhat order and $\leq_L$ the weak left Bruhat order.
We hope to use the above formula to prove Pieri type formulas in $H^*_T(\Omega K)$ in the spirit of what Lam, Lapointe, Morse and Shimozono [LLMS10] did in type $A$.

Acknowledgement: we thank Elizabeth Miličević for showing us a counterexample to [CMP09, Theorem 1] which lead to the present correction and development.

CONTENTS

1. Introduction
2. Notations
  2.1. Affine Lie algebras
  2.2. Affine Weyl groups
  2.3. Translations
3. extended nil-Hecke ring
  3.1. Definition
  3.2. Definition and properties of $A_\alpha$
4. Module and ring structures of $\tilde{A}_{aff}$
  4.1. $S$-module structure of $\tilde{A}_{aff}$
  4.2. Ring structure of $\tilde{A}_{aff}$
  4.3. Module over $\tilde{A}_{aff}$
5. Homology of the adjoint affine Grassmannian $\Omega K^{ad}$
  5.1. Cohomology of the finite-dimensional flag manifold $G/B$
  5.2. Affine Grassmannian and the Pontryagin ring structure
  5.3. Geometry of fixed points in $\Omega K^{ad}$
  5.4. Reminder on $H^*_T(\Omega K)$
  5.5. $S$-algebra structure on $H^*_T(\Omega K^{ad})$
  5.6. Compatibility between the ring and the $\tilde{A}_{aff}$-module structure
  5.7. Translations modulo $P$
6. Affine symmetries
  6.1. Peterson’s isomorphism
  6.2. A Weyl group action on $QH^*_T(G/P)$.
  6.3. Compatibility of Peterson’s isomorphism
  6.4. The result
7. Pieri formulas
References

2. Notations

In this section, we fix notation for affine Kac-Moody Lie algebras, we introduce the finite group $Z$ and define the extended affine Weyl group $\tilde{W}_{aff}$.

2.1. Affine Lie algebras. We denote by $\mathfrak{g}$ a simple finite-dimensional Lie algebra of rank $r$, and by $\mathfrak{h}$ a Cartan subalgebra. We denote by $G$ the simply-connected group corresponding to $\mathfrak{g}$ and by $G^{ad}$ the adjoint group. The affine Kac-Moody group corresponding to $G$ will be denoted by $\mathcal{G}$ and $\mathcal{P} \subset \mathcal{G}$ is the parabolic subgroup such that $\mathcal{G}/\mathcal{P}$ is the affine Grassmannian.

The corresponding affine Lie algebra will be denoted by $\mathfrak{g}_{aff}$, with Cartan subalgebra $\mathfrak{h}_{aff}$. The simple roots are denoted $(\alpha_i)_{i \in [1, r]}$ and the null-root, orthogonal
to all the simple roots \((\alpha_i)_{i \in [1,r]}\) will be denoted by \(\epsilon\). Recall that we have the equality \(\epsilon = \Theta + \alpha_0\), where \(\Theta\) is the highest root of \(\mathfrak{g}\). As in [Kac90, p.82] we will use the decompositions \(\mathfrak{h}_{\text{aff}}^+ = \mathfrak{h}^+ \oplus C\Lambda_0 \oplus \mathbb{C}\epsilon\) and \(\mathfrak{h}_{\text{aff}} = \mathfrak{h} \oplus CK \oplus \mathbb{C}d\). We denote by \(R_{\text{aff}}\) the set of roots of \(\mathfrak{g}_{\text{aff}}\) and by \(R\) those of \(\mathfrak{g}\).

We denote by \(Q,P,Q^\vee,P^\vee\) the root, weight, coroot, coweight lattices of \(\mathfrak{g}\). We also denote by \(S\) the symmetric algebra on \(P\).

### 2.2. Affine Weyl groups.

Let \(W\) be the Weyl group of \(\mathfrak{g}\) and let \(W_{\text{aff}} = Q^\vee \rtimes W\) be the affine Weyl group. For \(\lambda^\vee \in Q^\vee\), the corresponding element in \(W_{\text{aff}}\) will be denoted by \(t_{\lambda^\vee}\). The reflection associated to a root \(\alpha\) will be denoted by \(s_\alpha\).

The group \(W_{\text{aff}}\) is a Coxeter group with Coxeter generators \(s_i\) for \(1 \leq i \leq r\) and \(s_0 = t_{\Theta^\vee}s_\Theta\) ([Kum02, Prop 13.1.7], see also Lemma 2.7).

Define the extended affine Weyl group \(\tilde{W}_{\text{aff}} := P^\vee \rtimes W \supset W_{\text{aff}}\). The group \(W_{\text{aff}}\) acts on \(P \oplus \mathbb{Z}\epsilon\) while the group by \(\tilde{W}_{\text{aff}}\) acts only on \(Q \oplus \mathbb{Z}\epsilon\) via

\[
\begin{align*}
wt_{\lambda^\vee} \cdot (\mu + ne) &= w(\mu) + (n - \langle \mu, \lambda^\vee \rangle)\epsilon \\
wt_{\mu^\vee} \cdot (\lambda + ne) &= w(\lambda) + (n - \langle \lambda, \mu^\vee \rangle)\epsilon
\end{align*}
\]

where we have \(\lambda \in Q\), \(\lambda^\vee \in Q^\vee\), \(\mu \in P\), \(\mu^\vee \in P^\vee\). Note that in general \(\tilde{W}_{\text{aff}}\) does not act on \(P \oplus \mathbb{Z}\epsilon\) since \(\langle P,P^\vee \rangle \not\subseteq \mathbb{Z}\) in general.

We may however define actions of \(\tilde{W}_{\text{aff}}\) on \(P^\vee\) (and therefore on \(Q^\vee\)) by prescribing that translations do not act: we simply set \(wt_{\lambda^\vee}(\mu^\vee) = w(\mu^\vee)\) for \(w \in W\) and \(\lambda^\vee,\mu^\vee \in P^\vee\).

**Notation 2.1.** Since an element in \(Q^\vee\) is also an element in \(Q^\vee \oplus \mathbb{Z}\delta\), we will denote by \(w \cdot \lambda^\vee\) the result of the action of \(w \in \tilde{W}_{\text{aff}}\) on \(\lambda^\vee\) as an element in \(Q^\vee \oplus \mathbb{Z}\delta\) and by \(w(\lambda^\vee)\) the element in \(Q^\vee\).

Recall the definition of the fundamental alcove

\[
A_0 = \{ \lambda \in \mathfrak{h}_{\text{aff}}^+ | \langle \lambda, \alpha_i^\vee \rangle \geq 0 \text{ for all } i \in [1,r] \text{ and } \langle \lambda, \Theta^\vee \rangle \leq 1 \}.
\]

The stabiliser of \(A_0\) in \(\tilde{W}_{\text{aff}}\) will be denoted by \(Z\); it is a subgroup of \(\tilde{W}_{\text{aff}}\) isomorphic to \(P^\vee/Q^\vee\) [LS10, §10.1]. In loc. cit., the authors also prove the following result.

**Lemma 2.2.** Let \(\tau \in Z\). The conjugation by \(\tau\) is an automorphism of the Coxeter group \(W_{\text{aff}}\). In fact, there exists an automorphism \(f_{\tau}\) of the affine Dynkin diagram such that

\[
\forall i \in I \cup \{0\}, \quad \tau s_{\alpha_i} \tau^{-1} = s_{\tau^{-1} \alpha_i} = s_{\alpha_{f_{\tau}(i)}}.
\]

In particular, we have \(\tau \cdot \epsilon = \epsilon\).

**Notation 2.3.** For \(\tilde{x} \in \tilde{W}_{\text{aff}}\), set \(\tau(\tilde{x}) := \tau \tilde{x} \tau^{-1} \in \tilde{W}_{\text{aff}}\). We have \(\ell(\tau(\tilde{x})) = \ell(\tilde{x})\).

**Lemma 2.4.** An element \(\tau\) in \(Z\) permutes the positive real roots.

**Proof.** According to Lemma 2.2 we have \(\tau \cdot (\sum n_j \alpha_j + n\delta) = \sum n_j \alpha_{f_{\tau}(j)} + n\delta\). Since a real root \(\alpha + n\delta\) is positive if and only if \(n > 0\) or \(n = 0\) and \(\alpha > 0\), \(\tau\) indeed permutes positive roots. \(\square\)

As explained in [CMP09], \(\tilde{W}_{\text{aff}}\) is not a Coxeter group, but we have a well defined length function.

**Definition 2.5.** Every element \(x \in \tilde{W}_{\text{aff}}\) can be uniquely written as \(\tau \tilde{x}\) with \(\tau \in Z\) and \(\tilde{x} \in W_{\text{aff}}\).

1. Define the length function by \(\ell(x) := \ell(\tilde{x})\).
(2) Define a partial order on $\tilde{W}_{\text{aff}}$ by $\tau \hat{x} \leq \sigma \hat{y} \iff \sigma = \tau$ and $\hat{x} \leq \hat{y}$.

Covering relations in $\tilde{W}_{\text{aff}}$ for the above partial order are defined by $x \prec y$ if $x \leq y$ and $\ell(x) = \ell(y) - 1$.

**Remark 2.6.** The length of $x \in \tilde{W}_{\text{aff}}$ is also the number of inversions, namely the cardinal of the set $I(x) = \{\alpha \in R_{\text{aff}} \mid \alpha > 0, \alpha \text{ is real and } x(\alpha) < 0\}$. Indeed, for $x = \tau \hat{x}$, by Lemma 2.4, we have $I(x) = I(\hat{x})$.

### 2.3. Translations

We will need the following lemma.

**Lemma 2.7.** Let $\alpha \in R$. We have $t_{\alpha \vee} = s_{\varepsilon - \alpha} s_{\alpha}$.

**Proof.** Set $K^\perp = \{\mu \in \mathfrak{h}_{\text{aff}}^\vee \mid \langle \mu, K \rangle = 0\}$. By [Kac90, p.87], it is enough to compute $s_{\varepsilon - \alpha} s_{\alpha}(\mu)$ for $\mu \in K^\perp$. We have

$$s_{\varepsilon - \alpha} s_{\alpha}(\mu) = \mu - \langle \mu, (\varepsilon - \alpha)^\vee \rangle(\varepsilon - \alpha) - \langle \mu, \alpha^\vee \rangle \alpha + \langle \mu, \alpha^\vee \rangle \langle \alpha, (\varepsilon - \alpha)^\vee \rangle(\varepsilon - \alpha).$$

Now, for any $\beta \in R_{\text{aff}}$, we have by [Kac90, §2.3.5 and §6.2.3]:

$$\langle \mu, (\varepsilon + \beta)^\vee \rangle = \frac{2(\varepsilon + \beta, \mu)}{(\varepsilon + \beta, \varepsilon + \beta)} = \frac{2(\beta, \mu)}{(\beta, \beta)} = \langle \mu, \beta^\vee \rangle.$$

Therefore,

$$s_{\varepsilon - \alpha} s_{\alpha}(\mu) = \mu + \langle \mu, \alpha^\vee \rangle (\varepsilon - \alpha) - \langle \mu, \alpha^\vee \rangle \alpha - 2\langle \mu, \alpha^\vee \rangle (\varepsilon - \alpha) = \mu - \langle \mu, \alpha^\vee \rangle \varepsilon = t_{\alpha \vee}(\mu),$$

where the last equality follows from the definition of $t_{\alpha \vee}$ in [Kac90 §6.5.5]. □

**Corollary 2.8.** For $\alpha \in R$, $k \in \mathbb{Z}$ and $\mu^\vee \in P^\vee$, we have $s_{\alpha + k\varepsilon}(\mu^\vee) = s_{\alpha}(\mu^\vee)$.

**Proof.** We have $s_{\alpha + \varepsilon}(\mu^\vee) = s_{\alpha + \varepsilon} s_{\varepsilon - \alpha}(\mu^\vee) = s_{\alpha + \varepsilon} s_{\alpha}(\mu^\vee)$, by Lemma 2.7. The result follows by induction. □

### 3. Extended nil-Hecke Ring

The goal of this section is to extend the notion of the nil-Hecke ring defined by Kostant and Kumar [KK86]. This ring was used in [LS10] to compare the quantum cohomology of $G/P$ and the homology of affine Grassmannians $\Omega K$. We need a refined version of this nil-Hecke ring that enables dealing with $\Omega K^{\text{ad}}$ the adjoint affine grassmannian (see Section 3).

#### 3.1. Definition

We extend several classical object in particular the affine nil-Hecke algebra. Our reference for these classical objects is Kumar’s book [Kum02].

**Definition 3.1.** Recall that the ring $Q_{\text{aff}}$ is

$$Q_{\text{aff}} = \bigoplus_{w \in W_{\text{aff}}} \text{Frac}(S) \delta_w$$

We define the following extended version:

$$\tilde{Q}_{\text{aff}} = \bigoplus_{w \in \tilde{W}_{\text{aff}}} \text{Frac}(S) \delta_w$$

In both cases, the ring structure is defined by the equations $\delta_u \delta_v = \delta_{uv}$ and $\delta_u s = u(s)\delta_u$, for $u, v \in W_{\text{aff}}$ resp. $u, v \in \tilde{W}_{\text{aff}}$, and $s \in S$.

**Definition 3.2.** As in [Kum02], we consider particular elements in $Q_{\text{aff}}$. 

(1) For \( i \in I \), set \( A_i = \frac{1}{\alpha_i} (\delta_e - \delta_{s_i}) \). For \( i = 0 \), set \( A_0 = -\frac{1}{\ell_e} (\delta_e - \delta_{s_0}) \) (note that this is coherent with the forthcoming Definition 3.6).

(2) For \( w \in W_{\text{aff}} \) and for \( w = s_{i_1} \cdots s_{i_k} \) a reduced expression. We set:
\[
A_w = A_{i_1} \cdots A_{i_k}.
\]

By [Kum02, Theorem 11.1.2], the right hand side does not depend on the chosen reduced expression.

Recall that for \( x \in \tilde{W}_{\text{aff}} \), there is a unique decomposition \( x = \tau \tilde{x} \) with \( \tau \in \mathbb{Z} \) and \( \tilde{x} \in W_{\text{aff}} \).

**Definition 3.3.** Let \( x = \tau \tilde{x} \in \tilde{W}_{\text{aff}} \), we set \( \tilde{A}_w = \delta_x A_{\tilde{x}} \).

**Definition 3.4.** As in [KK86], the (extended) nil-Hecke ring is generated over \( S \) by the elements \( A_w \).

1. The nil-Hecke ring is
\[
\mathcal{A}_{\text{aff}} = \bigoplus_{w \in W_{\text{aff}}} S \cdot A_w \subset Q_{\text{aff}}.
\]

2. The extended nil-Hecke ring is
\[
\tilde{\mathcal{A}}_{\text{aff}} = \bigoplus_{w \in \tilde{W}_{\text{aff}}} S \cdot \tilde{A}_w \subset \tilde{Q}_{\text{aff}}.
\]

**Remark 3.5.** We will see below that both are indeed subrings of \( \tilde{Q}_{\text{aff}} \).

### 3.2. Definition and properties of \( A_\alpha \).

It will be helpful to generalize the definition of \( A_i \) in the following way.

**Definition 3.6.** For a real root \( \alpha = \gamma + k \epsilon \) with \( \gamma \in \mathbb{R} \), set \( A_\alpha = \frac{1}{\gamma} (\delta_e - \delta_{s_\alpha}) \).

These elements satisfy the following properties.

**Proposition 3.7.** Let \( w \in \tilde{W}_{\text{aff}}, \alpha \in R_{\text{aff}} \) a real root and \( \lambda \in Q \). Then we have:

1. \( \delta_w A_\alpha \delta_{w^{-1}} = A_{\mu(w)} \).
2. \( A_\alpha \lambda = s_\alpha(\lambda) A_\alpha + \langle \lambda, \alpha^\vee \rangle 1 \).

**Proof.** Let \( w = u_{\mu}, \alpha = \gamma + k \epsilon, \lambda \in P \) be as in the proposition. Then,
\[
\delta_w A_\alpha \delta_{w^{-1}} = \delta_w \frac{1}{\gamma} (\delta_e - \delta_{s_\alpha}) \delta_{w^{-1}} = \frac{1}{u(\gamma)} \delta_w (\delta_e - \delta_{s_{w\alpha}}) \delta_{w^{-1}} = \frac{1}{u(\gamma)} (\delta_e - \delta_{s_w}) = A_{w(\alpha)}.
\]

For the second point, we use [LS10 §6.1] and the above conjugation relation. Let \( w \in W_{\text{aff}} \) and \( i \in I \cup \{0\} \) be such that \( \alpha = w(\alpha_i) \). We have
\[
A_\alpha \lambda = \delta_w A_i \delta_{w^{-1}} \lambda = \delta_w A_i w^{-1}(\lambda) \delta_{w^{-1}} = \delta_w (s_i w^{-1}(\lambda) A_i + \langle w^{-1}(\lambda), \alpha_i^\vee \rangle) \delta_{w^{-1}} = w s_i w^{-1}(\lambda) \delta_w A_i \delta_{w^{-1}} = s_\alpha(\lambda) A_\alpha + \langle \lambda, \alpha^\vee \rangle.
\]

**Remark 3.8.** The second formula in the above proposition generalizes the usual relation satisfied by the elements \( A_i \) (see for example [LS10 §6.1]).

**Corollary 3.9.** For any real root \( \alpha \), we have \( A_\alpha \in \mathcal{A}_{\text{aff}} \).
Corollary 3.10. The (extended) nil Hecke rings \( \mathbb{H}_{\text{aff}} \) and \( \bar{\mathbb{H}}_{\text{aff}} \) are subrings of \( \bar{Q}_{\text{aff}} \).

Proof. The second formula above shows that for \( s, s' \in S \) and \( u, v \in W_{\text{aff}} \), the product \( sa_n s' a_v \) lies in \( \mathbb{H}_{\text{aff}} \) therefore \( \mathbb{H}_{\text{aff}} \) is a ring. The first formula proves that for \( \tau, \sigma \in Z \) and for \( u, v \in W_{\text{aff}} \), we have \( \delta_\tau A_u \delta_\sigma A_v = \delta_\tau \delta_\sigma A_{\sigma^{-1}(u)} A_v \in \mathbb{H}_{\text{aff}} \) proving that \( \mathbb{H}_{\text{aff}} \) is a ring.

4. Module and ring structures of \( \bar{\mathbb{H}}_{\text{aff}} \)

In this section we present three different descriptions of \( \bar{\mathbb{H}}_{\text{aff}} \) and describe its \( S \)-module structure and its ring structure in each case.

4.1. \( S \)-module structure of \( \bar{\mathbb{H}}_{\text{aff}} \). Recall that we have an injection of \( W_{\text{aff}} \) in the group of invertibles of \( \mathbb{H}_{\text{aff}} \), given by \( w \mapsto \delta_w \) in fact \( \delta_w = 1 - \alpha_i A_i \in \mathbb{H}_{\text{aff}} \) thus \( \delta_w \in \mathbb{H}_{\text{aff}} \) for all \( w \in W_{\text{aff}} \). Therefore the subgroup \( Q^\vee \subset W_{\text{aff}} \) also injects in \( \mathbb{H}_{\text{aff}} \), and since \( \mathbb{H}_{\text{aff}} \) is a ring we have an injection of the Laurent polynomial algebra \( \mathbb{Z}[Q^\vee] \) inside \( \mathbb{H}_{\text{aff}} \). Thus \( \mathbb{H}_{\text{aff}} \) is \( \mathbb{Z}[Q^\vee] \)-module via left multiplication. The natural \( \mathbb{Z} \)-module basis of \( \mathbb{Z}[Q^\vee] \) will be denoted by \( (h_{\lambda \vee})_{\lambda \vee \in Q^\vee} \).

We now introduce two new algebraic models of \( \bar{\mathbb{H}}_{\text{aff}} \).

Definition 4.1. Let \( \varphi_1, \varphi_2 \) be the following morphisms of \( \mathbb{Z} \)-modules:

\[
\varphi_1 : \mathbb{Z}[P^\vee] \otimes_{\mathbb{Z}[Q^\vee]} \mathbb{H}_{\text{aff}} \rightarrow \bar{Q}_{\text{aff}}, \quad h_{\lambda \vee} \otimes A_w \mapsto \delta_{t_{\lambda \vee}} A_w,
\]

\[
\varphi_2 : \mathbb{Z}[Z] \otimes_{\mathbb{Z}} \mathbb{H}_{\text{aff}} \rightarrow \bar{Q}_{\text{aff}}, \quad \tau \otimes A_w \mapsto \delta_{\tau} A_w.
\]

Note that \( \mathbb{H}_{\text{aff}} \) has a structure of \( S \)-bimodule, thus also the two tensor products in this definition. Both maps \( \varphi_1 \) and \( \varphi_2 \) are \( S \)-linear on the right, moreover \( \varphi_1 \) is also \( S \)-linear on the left whereas \( \varphi_2 \) is not.

Proposition 4.2. With the above notations, \( \text{Im}(\varphi_1) = \text{Im}(\varphi_2) = \bar{\mathbb{H}}_{\text{aff}} \). Moreover, if \( J \subset \mathbb{H}_{\text{aff}} \) is a left ideal, then \( \varphi_1(\mathbb{Z}[P^\vee] \otimes_{\mathbb{Z}[Q^\vee]} J) = \varphi_2(\mathbb{Z}[Z] \otimes_{\mathbb{Z}} J) \).

Proof. Observe that \( \varphi_1 \) is well-defined: \( \varphi_1(h_{\lambda \vee} \otimes 1) = \varphi_1(1 \otimes \delta_{t_{\lambda \vee}}) = \delta_{t_{\lambda \vee}} \) for \( \lambda \vee \in Q^\vee \). We now prove that \( \varphi_1(\mathbb{Z}[P^\vee] \otimes J) \subset \varphi_2(\mathbb{Z}[Z] \otimes J) \). Let \( \lambda \vee \in P^\vee \): there exists \( \tau \in \mathbb{Z} \) and \( \bar{w} \in W_{\text{aff}} \) such that \( t_{\lambda \vee} = \tau \bar{w} \). Then for \( a \in J \), we have \( \varphi_1(h_{\lambda \vee} \otimes a) = \delta_{t_{\lambda \vee}} a = \delta_{\tau} \delta_{\bar{w}} a \in \varphi_2(\mathbb{Z}[Z] \otimes J) \) since \( \delta_{\bar{w}} a \in J \).

The reverse inclusion \( \varphi_2(\mathbb{Z}[Z] \otimes J) \subset \varphi_2(\mathbb{Z}[P^\vee] \otimes J) \) follows similarly from the fact that any element in \( \mathbb{Z} \) can be written as a product \( t_{\lambda \vee} u \) for some \( \lambda \vee \in P^\vee \) and \( u \in W \). Finally, the equality \( \text{Im}(\varphi_2) = \mathbb{H}_{\text{aff}} \) follows from the definition of \( \mathbb{H}_{\text{aff}} \) (Definition 3.4).

4.2. Ring structure of \( \bar{\mathbb{H}}_{\text{aff}} \). We give the description of the ring structure of \( \bar{\mathbb{H}}_{\text{aff}} \) according to the given three equivalent definitions of this module.

Proposition 4.3. Let \( x, y \in \bar{W}_{\text{aff}} \), then we have

\[
\bar{A}_x \bar{A}_y = \begin{cases} 
\bar{A}_{xy} & \text{if } \ell(xy) = \ell(x) + \ell(y) \\
0 & \text{otherwise}.
\end{cases}
\]
Proof. Write \( x = \sigma \hat{x} \) and \( y = \tau \hat{y} \) with \( \sigma, \tau \in Z \) and \( \hat{x}, \hat{y} \in W_{\text{aff}} \). Recall that for \( u, v \in W_{\text{aff}} \), we have:

\[
A_u A_v = \begin{cases} A_{uv} & \text{if } \ell(uv) = \ell(u) + \ell(v) \\ 0 & \text{otherwise.} \end{cases}
\]

By Lemma 2.2, we have

\[
A_x A_y = \begin{cases} \delta_{\sigma} \delta_{\tau} A_{\tau^{-1}(\hat{x}) \hat{y}} & \text{if } \ell(\tau^{-1}(\hat{x})\hat{y}) = \ell(\tau^{-1}(\hat{x})) + \ell(\hat{y}) \\ 0 & \text{otherwise} \end{cases}
\]

But \( \ell(\tau^{-1}(\hat{x})\hat{y}) = \ell(xy) \) since \( xy = \sigma \hat{x} \tau \hat{y} = \sigma \tau \tau^{-1}(\hat{x})\hat{y} \), and \( \ell(\tau^{-1}(\hat{x})) + \ell(\hat{y}) = \ell(\hat{x}) + \ell(\hat{y}) = \ell(x) + \ell(y) \). The result follows.

We now express the product in \( \widetilde{A}_{\text{aff}} = \varphi_1(Z[P^{\vee}] \otimes Z[Q^{\vee}] A_{\text{aff}}) \). Note that we need to compute the product \((\delta_{t_{\lambda \vee}} A_{\alpha}) (\delta_{t_{\lambda \vee}} A_{\beta})\). We therefore need to “move” \( \delta_{t_{\lambda \vee}} \) to the left of \( A_{\alpha} \). The following proposition gives formulas for this.

**Proposition 4.4.** Let \( \lambda \in P^{\vee} \) and let \( \alpha = \gamma + k\epsilon \in R_{\text{aff}} \). Then:

1. \( A_{\alpha} \delta_{t_{\lambda \vee}} = \delta_{s_{\alpha}(t_{\lambda \vee})} A_{\alpha} + \frac{1}{\gamma} (\delta_{t_{\lambda \vee}} - \delta_{t_{\alpha}^{(\lambda \vee)}}) \).
2. \( \delta_{t_{\lambda \vee}} - \delta_{t_{\alpha}^{(\lambda \vee)}} = \delta_{t_{\lambda \vee}}(1 - \delta_{t_{(\alpha, \lambda \vee)\alpha \vee}}) \).
3. \( 1 - \delta_{t_{\alpha}^{(\lambda \vee)}} = (1 + \delta_{t_{\alpha}} + \cdots + \delta_{t_{(\alpha - 1)\alpha \vee}})(1 - \delta_{t_{\alpha \vee}}) \) for \( n \in \mathbb{N} \),
4. \( 1 - \delta_{t_{-\alpha}} = \gamma (A_{\alpha} - \gamma A_{\alpha} A_{\epsilon - \alpha} + A_{\epsilon - \alpha}) \).

**Proof.** (1) From the equality \( s_{\alpha} t_{\lambda \vee} = t_{s_{\alpha}(\lambda \vee)} s_{\alpha} \), we get \( \delta_{s_{\alpha}} \delta_{t_{\lambda \vee}} = \delta_{t_{s_{\alpha}(\lambda \vee)}} \delta_{s_{\alpha}} \) in \( \widetilde{A}_{\text{aff}} \). By definition of \( A_{\alpha} \) (Definition 3.6), this relation implies

\[
(1 - \gamma A_{\alpha}) \delta_{t_{\lambda \vee}} = \delta_{t_{s_{\alpha}(\lambda \vee)}}(1 - \gamma A_{\alpha}) .
\]

Thus we get \( \gamma A_{\alpha} \delta_{t_{\lambda \vee}} = \gamma \delta_{t_{s_{\alpha}(\lambda \vee)}} A_{\alpha} + \delta_{t_{\lambda \vee}} - \delta_{t_{s_{\alpha}(\lambda \vee)}} \).

(2) and (3) are easy consequences of the product formulas in \( \widetilde{Q}_{\text{aff}} \).

(4) By Lemma 2.7, we have

\[
1 - \delta_{t_{-\alpha}} = 1 - \delta_{s_{\alpha}} s_{\alpha - \alpha} = 1 - (1 - \gamma A_{\alpha})(1 + \gamma A_{\epsilon - \alpha}) = \gamma A_{\alpha} - \gamma A_{\epsilon - \alpha} + A_{\epsilon - \alpha} = \gamma A_{\alpha} - \gamma A_{\epsilon - \alpha} + (s_{\alpha}(\gamma) A_{\alpha} + (\alpha^{\vee}, \gamma)) A_{\epsilon - \alpha} = \gamma A_{\alpha} + A_{\epsilon - \alpha} - \gamma^2 A_{\epsilon - \alpha} .
\]

where we used Proposition 3.7 on the fourth line.

The ring structure in \( \widetilde{A}_{\text{aff}} = \varphi_2(Z[Z] \otimes Z A_{\text{aff}}) \) is easy to describe:

**Proposition 4.5.** Let \( \sigma, \tau \in Z \) and let \( a, b \in \widetilde{A}_{\text{aff}} \). Then:

\[
\varphi_2(\sigma \otimes a) \cdot \varphi_2(\tau \otimes b) = \varphi_2(\sigma \tau \otimes \tau^{-1}(a)b) .
\]

**Proof.** This follows from the fact that in \( \widetilde{A}_{\text{aff}} \), we have \( \delta_{\sigma} a \delta_{\tau} b = \delta_{\sigma} \delta_{\tau}^{-1}(a)b \).

In the next proposition, we give an explicit formula for the commuting relation of the elements \( \widetilde{A} \) and \( \lambda \in P \), generalizing [KK86, Proposition 4.3.b]:
Proposition 4.6. Let \( x \in \widehat{W}_{\text{aff}} \) and let \( \lambda \in P \). We have:
\[
\tilde{A}_x \lambda = x(\lambda) \tilde{A}_x + \sum_{\alpha : \ x s_\alpha < x} \langle \lambda, \alpha^\vee \rangle \tilde{A}_{xs_\alpha} ,
\]
where the sum runs over positive real roots \( \alpha \) such that \( xs_\alpha < x \).

Proof. Let \( x = \tau \check{x} \in \widehat{W}_{\text{aff}} \) with \( \tau \in \mathbb{Z} \) and \( \check{x} \in W_{\text{aff}} \). Let \( \lambda \in P \). According to Definition 3.3, we have \( \tilde{A}_x = \delta_r A_{\check{x}} \). Using [KK86, Proposition 4.3.b], we get (sums always run over positive real roots):
\[
\tilde{A}_x \lambda = \delta_r A_{\check{x}} \lambda = \delta_r \check{x}(\lambda) A_{\check{x}} + \delta_r \sum_{\alpha : \ x s_\alpha < \check{x}} \langle \lambda, \alpha^\vee \rangle A_{\check{x}s_\alpha} \\
= \tau \check{x}(\lambda) \delta_r A_{\check{x}} + \sum_{\alpha : \ x s_\alpha < \check{x}} \langle \lambda, \alpha^\vee \rangle \delta_r A_{\check{x}s_\alpha} \\
= x(\lambda) \tilde{A}_x + \sum_{\alpha : \ x s_\alpha < \check{x}} \langle \lambda, \alpha^\vee \rangle \tilde{A}_{xs_\alpha} .
\]
Since, by Definition 3.3, the relation \( \check{x}s_\alpha < \check{x} \) holds if and only if the relation \( xs_\alpha < x \) holds, we get the result. \( \square \)

4.3. Module over \( \tilde{A}_{\text{aff}} \). We now define a natural module over \( \tilde{A}_{\text{aff}} \) which will be identified in the next section with the homology of the adjoint affine Grassmannian \( \Omega K^{\text{ad}} \).

Definition 4.7. Let \( W_{\text{aff}}^- \) resp. \( \tilde{W}_{\text{aff}}^- \) be the set of minimal length representatives of the quotient \( W_{\text{aff}}/W \) resp. \( \tilde{W}_{\text{aff}}/W \). By [LS10, Lemma 3.3], \( W_{\text{aff}}^- \) is the set of elements \( w = ut^{\lambda^\vee} \) such that \( \lambda^\vee \leq 0 \) and \( \forall i \in I, \langle \lambda^\vee, \alpha_i \rangle = 0 \implies u(\alpha_i) > 0 \).

We generalize the characterization of \( W_{\text{aff}}^- \) as follows:

Lemma 4.8. We have \( ut^{\lambda^\vee} \in \tilde{W}_{\text{aff}}^- \) if and only if \( \lambda^\vee \leq 0 \) and for all \( i \) in \( I \) it holds
\[
\langle \lambda^\vee, \alpha_i \rangle = 0 \implies u(\alpha_i) > 0 .
\]

Proof. Recall that we have a length formula in \( \tilde{W}_{\text{aff}} \) similar to the one in \( W_{\text{aff}} \):
\[
\ell(ut^{\lambda^\vee}) = \sum_{\alpha \in R^+} |\langle \lambda^\vee, \alpha \rangle + \chi(u(\alpha) < 0)| ,
\]
where \( \chi(P) = 1 \) if \( P \) is true and \( \chi(P) = 0 \) if \( P \) is false. This is proved in [CMP09, Corollary 3.13]. It follows that
\[
\ell(ut^{\lambda^\vee}s_i) - \ell(ut^{\lambda^\vee}) = |\langle \lambda^\vee, -\alpha_i \rangle + \chi(u(\alpha_i) > 0)| - |\langle \lambda^\vee, \alpha_i \rangle + \chi(u(\alpha_i) < 0)| .
\]
This is non-negative for all \( i \) in \( I \) if and only if for all \( i \), \( \langle \lambda^\vee, \alpha_i \rangle \leq 0 \), and \( \langle \lambda^\vee, \alpha_i \rangle = 0 \) implies \( u(\alpha_i) > 0 \). \( \square \)

Definition 4.9. For each \( w \in W_{\text{aff}}^- \), we define a variable \( \xi_w \) and we set
\[
M = \bigoplus_{w \in W_{\text{aff}}^-} S \cdot \xi_w .
\]
Recall [LS10 §6.2] that we may define a left \( A_{\text{aff}} \)-module structure on \( M \) via:
\[
A_w : \xi_u = \begin{cases} \xi_{wu} & \text{if } \ell(wu) = \ell(w) + \ell(u) \text{ and } wu \in W_{\text{aff}}^- , \\ 0 & \text{otherwise.} \end{cases}
\]
As left $\tilde{\mathcal{A}}_{\text{aff}}$-module, we have an isomorphism

$$M \cong \tilde{\mathcal{A}}_{\text{aff}} / J,$$

where $J = \bigoplus_{w \in \tilde{W}_{\text{aff}}} S \cdot A_w$.

Using Proposition 4.2, we define similarly a left ideal in $\tilde{\mathcal{A}}_{\text{aff}}$.

**Definition 4.10.** Let $\tilde{J} = \varphi_1(\mathbb{Z}[P^\vee] \otimes_{\mathbb{Z}[Q^\vee]} J) = \varphi_2(\mathbb{Z}[Z] \otimes_{\mathbb{Z}} J) = \bigoplus_{w \not\in \tilde{W}_{\text{aff}}} \tilde{A}_w$.

**Definition 4.11.** We introduce the following three modules.

- Let $\tilde{M}_1$ be the $S$-module $\mathbb{Z}[P^\vee] \otimes_{\mathbb{Z}[Q^\vee]} M$.
- Let $\tilde{M}_2 = \mathbb{Z}[Z] \otimes_{\mathbb{Z}} M$. This is an $\tilde{\mathcal{A}}_{\text{aff}}$-module with the action given by $(\sigma \otimes a) \cdot (\tau \otimes \xi) = \sigma \tau \otimes \tau^{-1}(a) \cdot \xi$, for $\sigma \otimes a \in \mathbb{Z}[Z] \otimes_{\mathbb{Z}} \tilde{\mathcal{A}}_{\text{aff}} = \tilde{\mathcal{A}}_{\text{aff}}$.
- Let $\tilde{M}_3 = \bigoplus_{w \in \tilde{W}_{\text{aff}}} S \cdot \tilde{A}_w$. This is an $\tilde{\mathcal{A}}_{\text{aff}}$-module with the action given by

$$\tilde{A}_w \cdot \tilde{c}_u = \begin{cases} \tilde{c}_{wu} & \text{if } \ell(uw) = \ell(w) + \ell(u) \text{ and } uw \in \tilde{W}_{\text{aff}}, \\ 0 & \text{otherwise}, \end{cases}$$

for $\tilde{A}_w \in \tilde{\mathcal{A}}_{\text{aff}} = \bigoplus_{w \in \tilde{W}_{\text{aff}}} S \cdot \tilde{A}_w$.

**Proposition 4.12.** With the above definitions,

1. Moding out by $\tilde{J}$, the morphism $\varphi_1$ induces an $S$-module isomorphism $\tilde{M}_1 \to \tilde{\mathcal{A}}_{\text{aff}} / \tilde{J}$.
2. Moding out by $\tilde{J}$, the morphism $\varphi_2$ induces an $\tilde{\mathcal{A}}_{\text{aff}}$-module isomorphism $\tilde{M}_2 \to \tilde{\mathcal{A}}_{\text{aff}} / \tilde{J}$ (which is not $S$-linear if we give $\tilde{M}_2$ the tensor product $S$-module structure).
3. The left $\tilde{\mathcal{A}}_{\text{aff}}$-modules $\tilde{\mathcal{A}}_{\text{aff}} / \tilde{J}$ and $\tilde{M}_3$ are isomorphic.

**Proof.** This proposition follows easily from Propositions 4.3 and 4.5.

**Remark 4.13.** The $\tilde{\mathcal{A}}_{\text{aff}}$-module structure induced on $\tilde{M}_1$ by the isomorphism in Proposition 4.12(1) can also be described via Proposition 4.4.

**Definition 4.14.** The $\tilde{\mathcal{A}}_{\text{aff}}$-module defined by one of the above equivalent definitions will be denoted by $\tilde{M}$.

5. Homology of the Adjoint Affine Grassmannian $\Omega K^\text{ad}$

In this section, we recall the adjoint affine Grassmannian $\Omega K^\text{ad}$, we prove that the $\tilde{\mathcal{A}}_{\text{aff}}$-module $\tilde{M}$ is isomorphic to the homology of $\Omega K^\text{ad}$, we define a ring structure on this module and study the compatibility of these two structures.

5.1. Cohomology of the finite-dimensional flag manifold $G/B$. Recall, see for example [Kum02 Chapter 11], that $H^*_T(G/B)$ has an $S$-basis $(\xi^w)_w \in W$ indexed by the Weyl group. The pull-back along the map $(G/B)^T \to G/B$ induces an inclusion

$$H^*_T(G/B) \to H^*_T((G/B)^T) = S^W.$$

Viewing $\xi^w$ as a function on $W$, Kumar [Kum02 11.1.6.(3)] sets $d_{u,v} = \xi^u(v) = \langle \xi^u, v \rangle$ and $D = (d_{u,v})_{u,v \in W}$. If $(f^w)_w \in W$ is the basis of $S^W$ given by $\langle f^u, v \rangle = \delta_{uv}$, we have

$$d_{u,v} = \langle f^u, v \rangle = \delta_{uv}.$$
$f^u(v) = \delta_{u,v}$, then we have $(\xi^u)_u = D(f^u)_u$. Given the identification \[Kum02\] 11.1.4(2)], we also have $(f^u, \delta_v) = \delta_{u,v}$.

The dual of $H^*_G(G/B)$ is $H^*_G(G/B)$ and identifies as an S-module with the $S$-subalgebra $A$ of $\mathbb{A}_{aff}$ generated by $(A_w)_{w \in W}$:

\[
H^*_G(G/B) \simeq \bigoplus_{w \in W} S \cdot A_w
\]

Note that $(A_w)_{w \in W}$ is the dual basis to $(\xi^u)_{w \in W}$ i.e. $(\xi^u, A_v) = \xi^u(A_v) = \delta_{u,v}$ (see \[Kum02\] 11.1.5), were $A_u$ is denoted by $x_u$). Over $F = \text{Frac}(S)$ we also have the basis $(\delta_w)_{w \in W}$ for $H^*_G(G/B)$. Kumar, in \[Kum02\] 11.1.2.(e)], describes the base change:

$$A_u = \sum_v c_{u,v} \delta_v$$

with $C = (c_{u,v})_{u,v \in W}$ a matrix with coefficients in $S$, in particular, we have $(A_v)_v = C(\delta_v)_v$. We have the following relation between the matrices $C$ and $D$.

**Fact 5.1** (See \[Kum02\] 11.1.7.(a)]. We have $D^{-1} = C^T$. Thus,

$$\delta_v = \sum_{w \leq v} \xi^w(v)A_w .$$

**Proof.** In fact, from the identity $(A_v)_v = C(\delta_v)_v$, we deduce that $(\delta_v)_v = C^{-1}(A_v)_v = D^T(A_v)$. Since $D^T_{v,w} = \xi^w(v)$ and the matrix $D$ is triangular, we get the result. \(\Box\)

Note also that an explicit formula for the coefficients $\xi^w(v)$ is known: see \[Kum02\] Proposition 11.1.11.

### 5.2. Affine Grassmannian and the Pontryagin ring structure

Let $G$ be the simply-connected almost simple group associated to $\mathfrak{g}$, and let $G^{ad}$ be the adjoint quotient of this group. Let $K$ resp. $K^{ad}$ be a maximal compact subgroup in $G$ resp. $G^{ad}$. Let $\Omega K$ resp. $\Omega K^{ad}$ be the group of loops $l$ with values in $K$ resp. $K^{ad}$ such that $l(0)$ is the unit element in $K$ resp. $K^{ad}$. By a loop we mean a map $l: S^1 \to K^{ad}$ that extends to a meromorphic map $\mathbb{D}^0 \to G^{ad}$, where $\mathbb{D}^0$ denotes the pointed disk. Modding out a loop by the center of $K$ yields an inclusion $\Omega K \subset \Omega K^{ad}$. The action of $T \cap K$ on $\Omega K$ resp. $\Omega K^{ad}$ is given by conjugation.

This implies that the equivariant homology of $\Omega K$ and $\Omega K^{ad}$ have a natural structure of an algebra, given by the Pontryagin product which is also $(T \cap K)$-equivariantly homotopy equivalent to the point-wise product of loops. In this section, we will recall an algebraic model for $H^*_T(\Omega K)$ and give one for $H^*_T(\Omega K^{ad})$. In particular we will describe the ring structure as well as an $\mathbb{A}_{aff}$-module structure on $H^*_T(\Omega K^{ad})$ extending the ring structure and the $\mathbb{A}_{aff}$-module structure on $H^*_T(\Omega K)$.

### 5.3. Geometry of fixed points in $\Omega K^{ad}$

Since $K \to K^{ad}$ is the universal cover of $K^{ad}$, the connected components of $\Omega K^{ad}$ are isomorphic to $\Omega K$ and are indexed by $\pi_1(G^{ad}) = \pi_1(K^{ad}) = \mathbb{Z}$. We now describe the $T$-fixed points in $\Omega K^{ad}$. We have, in the loop space picture

$$(\Omega K^{ad})^T = \{ \tilde{\psi}_{\lambda^v} : S^1 \to K^{ad} \mid \lambda^v \in P^\vee \},$$

where $\tilde{\psi}_{\lambda^v}(t) = \exp(2i\pi t\lambda^v)$ is the loop induced by the one-parameter subgroup $\lambda^v$ of $T^{ad}$ (the maximal torus of $K^{ad}$). For $\lambda^v \in P^\vee$, let $[\lambda^v]$ be its class in
$P^\vee/Q^\vee = \pi_1(K_{\text{ad}})$ and denote by $\Omega K_{\lambda^\vee}^{\text{ad}}$ be the connected component of $\Omega K_{\lambda^\vee}$ containing $\psi_{\lambda^\vee}$. We have

$$\Omega K_{\lambda^\vee}^{\text{ad}} = \prod_{[\lambda^\vee] \in P^\vee/Q^\vee} \Omega K_{[\lambda^\vee]}^{\text{ad}}.$$ 

Let $m_{\lambda^\vee} : \Omega K \to \Omega K_{[\lambda^\vee]}$ be the left multiplication by $\psi_{\lambda^\vee}$. Since $T$ and $\psi_{\lambda^\vee}$ commute, this is a $T$-equivariant isomorphism. Thus, $H^*_T(\Omega K^{\text{ad}}_{[\lambda^\vee]}) \simeq H^*_T(\Omega K)$.

5.4. **Reminder on $H^*_T(\Omega K)$**. Recall from [KK98] that $\Omega K$ has a cellular decomposition whose cells are index by $W_{\text{aff}}$. This implies that, as $S$-module, we have

$$H^*_T(\Omega K) = \bigoplus_{w \in W_{\text{aff}}} S \cdot \xi_w \simeq M.$$ 

Furthermore, according to [Lam08] (3.1) and (3.2)], $\mathcal{A}_{\text{aff}}$ acts on $H^*_T(\mathcal{G}/\mathcal{P})$ by

$$A_v : \xi_w \to \begin{cases} \xi_{vw} & \text{if } \ell(vw) = \ell(v) + \ell(w) \text{ and } vw \in W_{\text{aff}}^- \\ 0 & \text{otherwise} \end{cases}$$

and $\mathcal{A}_{\text{aff}}$ acts on $H^*_T(\mathcal{G}/\mathcal{P})$ by

$$A_v : \xi_w \to \begin{cases} \xi_{vw} & \text{if } \ell(vw) = \ell(v) - \ell(w) \text{ and } vw \in W_{\text{aff}}^- \\ 0 & \text{otherwise} \end{cases}$$

5.5. **S-algebra structure on $H^*_T(\Omega K_{\text{ad}})$**. We use the $T \cap K$-equivariant homology of the $T \cap K$-space $\Omega K_{\text{ad}}$, where $T \cap K$ acts on $\Omega K_{\text{ad}}$ via $T \cap K \to (T \cap K)^{\text{ad}} \to G_{\text{ad}}$. The inclusion $T \cap K \to T$ induces an isomorphism in equivariant cohomology $H^*_T(pt) \to H^*_{T \cap K}(pt)$. Note that we have $H^*_{T \cap K}(\Omega K) \simeq H^*_{T \cap K}(\mathcal{G}/\mathcal{P}) \simeq H^*_T(\mathcal{G}/\mathcal{P})$, where $\mathcal{G}/\mathcal{P}$ is the affine Grassmannian. Abusing notations slightly, we will denote in the following $H^*_T(\Omega K)$ simply by $H^*_T(\Omega K)$, and similarly for $H^*_T(\Omega K_{\text{ad}})$. The $T$-equivariant cohomology of the point is the symmetric algebra on $P$, namely $S$, see [Br98] p.5, so that the homology $H^*_T(\Omega K_{\text{ad}})$ will be an $S$-module and even an $S$-algebra. We are not considering $T^{\text{ad}}$-equivariant homology.

**Proposition 5.2.** As $S$-algebras, we have: $H^*_T(\Omega K_{\text{ad}}) \simeq S[P^\vee] \otimes_{S[Q^\vee]} H^*_T(\Omega K)$.

**Proof.** We have the following inclusions that are compatible with pointwise multiplication and $T$-equivariant inducing $S$-algebra morphisms

$$\Omega K \hookrightarrow \Omega K_{\text{ad}} \quad \text{and} \quad H^*_T(\Omega K) \hookrightarrow H^*_T(\Omega K_{\text{ad}}).$$

Recall that we have bijections $(\Omega K_{\text{ad}})_{[\lambda^\vee]} \simeq P^\vee$ and $\Omega K_{[\lambda^\vee]} \simeq Q^\vee$ that are group homomorphisms since $\psi_{\lambda^\vee} \psi_{\mu^\vee} = \psi_{\lambda^\vee + \mu^\vee}$. We thus have $H^*_T((\Omega K_{\text{ad}})_{[\lambda^\vee]}) \simeq S[P^\vee]$ and $H^*_T((\Omega K_{[\lambda^\vee]})_{[\lambda^\vee]}) \simeq S[Q^\vee]$. In particular, the above diagram induces an $S$-algebra morphism $S[P^\vee] \otimes_{S[Q^\vee]} H^*_T(\Omega K) \to H^*_T(\Omega K_{\text{ad}})$. The restriction of this map to $H^*_T((\Omega K_{[\lambda^\vee]})_{[\lambda^\vee]})$ is the multiplication $m_{\lambda^\vee}$. The above decomposition of $\Omega K_{\text{ad}}$ in connected components gives an isomorphism of $S$-modules

$$H^*_T(\Omega K_{\text{ad}}) = \bigoplus_{[\lambda^\vee] \in P^\vee/Q^\vee} H^*_T((\Omega K_{[\lambda^\vee]})_{[\lambda^\vee]})$$
proving that the map \( S[P^\vee] \otimes_{S[Q^\vee]} H^T_\ast(\Omega K) \to H^T_\ast(\Omega K_{\text{ad}}) \) is surjective.

To prove injectivity, first note that, since \( H^T_\ast(\Omega K) \) is a free \( S \)-module and \( S[P^\vee] \) is a free \( S[Q^\vee] \)-module, the \( S \)-module \( S[P^\vee] \otimes_{S[Q^\vee]} H^T_\ast(\Omega K) \) is free. We therefore only need to prove the injectivity of the map after base extension to \( F = \text{Frac}(S) \) the field of fractions of \( S \). Now recall the following general result (see [Kum02, C.8 Theorem]): on the level of \( T \)-equivariant cohomology we have isomorphisms 
\[
H^T_\ast(\Omega K) \otimes_S F \simeq H^T_\ast(\Omega K^T) \otimes_S F 
\]
and 
\[
H^T_\ast(\Omega K^T) \otimes_S F \simeq H^T_\ast((\Omega K^T)^S) \otimes_S F.
\]
This induces isomorphisms in \( T \)-equivariant homology:
\[
H^T_\ast(\Omega K^T) \otimes_S F \simeq H^T_\ast(\Omega K) \otimes_S F 
\]
\[
H^T_\ast(\Omega K^T) \otimes_S F \simeq H^T_\ast((\Omega K^T)^S) \otimes_S F.
\]
After base change to \( F \), since \( H^T_\ast(\Omega K^T) \simeq F[Q^\vee] \) and \( H^T_\ast((\Omega K^T)^S) \otimes_SF \simeq F[P^\vee] \), our map is given by 
\[
F[P^\vee] \otimes F[Q^\vee] F[Q^\vee] \to F[P^\vee]
\]
and is therefore injective.

Recall that, as \( S \)-module, we have an isomorphism \( H^T_\ast(\Omega K) = M \). In particular the above results identifies \( H^T_\ast(\Omega K_{\text{ad}}) \) with the \( S \)-module \( M \) of Definition 4.14.

**Corollary 5.3.** As \( S \)-modules, we have:
\[
H^T_\ast(\Omega K_{\text{ad}}) \simeq \tilde{M}.
\]

**Corollary 5.4.** The exists an \( \tilde{\mathcal{A}}_{\text{aff}} \)-module structure on \( H^T_\ast(\Omega K_{\text{ad}}) \) compatible with the \( \mathcal{A}_{\text{aff}} \)-module structure on \( H^T_\ast(\Omega K) \). Furthermore, for this structure, we have an isomorphism of \( \tilde{\mathcal{A}}_{\text{aff}} \)-modules \( H^T_\ast(\Omega K_{\text{ad}}) \simeq \tilde{M} \).

**Proof.** We define the \( \tilde{\mathcal{A}}_{\text{aff}} \)-module structure on \( H^T_\ast(\Omega K_{\text{ad}}) \). Since we have the isomorphism of \( S \)-modules \( H^T_\ast(\Omega K_{\text{ad}}) \simeq \tilde{M}_1 = S[P^\vee] \otimes_{S[Q^\vee]} M \), we may extend the \( \mathcal{A}_{\text{aff}} \)-module structure on \( M \) to the \( \tilde{\mathcal{A}}_{\text{aff}} \)-module structure \( \tilde{M} \).

**Remark 5.5.** The above \( \tilde{\mathcal{A}}_{\text{aff}} \)-module structure on \( H^T_\ast(\Omega K_{\text{ad}}) \) also has a geometric description, see [CMP09, Proposition 3.3].

**Remark 5.6.** The above result shows that our claim on [CMP09, Page 12] that \( H^T_\ast(\Omega K_{\text{ad}}) \) is the tensor product ring \( \mathbb{Z}[\mathcal{Z} \otimes_S H^T_\ast(\Omega K) \) is wrong: by localization \( H^T_\ast(\Omega K_{\text{ad}}) \) is a subring of \( F[P^\vee] \) and this Laurent polynomial algebra contains no roots of unity, whereas \( \mathbb{Z}[\mathcal{Z} \otimes_S H^T_\ast(\Omega K) \) does.

Recall that \( \tilde{W}_{\text{aff}} \) can be embedded in \( \tilde{\mathcal{A}}_{\text{aff}} \) via \( w \mapsto \delta_w \). The induced action is denoted by \( x \cdot \xi := \delta_x \cdot \xi \) for \( x \in \tilde{W}_{\text{aff}} \) and \( \xi \in H^T_\ast(\Omega K_{\text{ad}}) \).

**Corollary 5.7.** Let \( w \in \tilde{W} \) and \( \lambda^\vee, \mu^\vee \in P^\vee \), we have 
\[
w_{\tilde{t}^\vee} := \delta_w \tilde{t}^\vee = \tilde{\psi}^\vee \in \tilde{W}_{\text{aff}}(\lambda^\vee + \mu^\vee) \).
\]

**Proof.** As already explained in the proof of Proposition 5.2, we have 
\[
\delta_w \tilde{t}^\vee = \tilde{\psi}^\vee.
\]
But our identification of \( H^T_\ast(\Omega K_{\text{ad}}) \) with \( \tilde{M} \) identifies \( \tilde{\psi}^\vee \) with \( h_{\mu^\vee} \otimes 1 \). Recall that \( 1 = [\delta] \in \tilde{\mathcal{A}}_{\text{aff}}/\tilde{J} \), so that \( h_{\mu^\vee} \otimes 1 = [\delta_{\mu^\vee}] \) and \( \delta_w \tilde{t}^\vee = \delta_w \tilde{t}^\vee = [\delta_{\mu^\vee}] = [\delta_w \delta_{\mu^\vee} \delta_{\mu^\vee - 1}] \) since \( \delta_{\mu^\vee - 1} \in \tilde{J} \). We get 
\[
\delta_w \tilde{t}^\vee = [\delta_w \delta_{\mu^\vee} \delta_{\mu^\vee - 1}] = [\delta_{w_{\mu^\vee}}] = \tilde{\psi}^\vee
\]
proving the result.
5.6. Compatibility between the ring and the $\mathring{A}_{\text{aff}}$-module structure. The above description of $H^T_*(\Omega K^{\text{ad}})$ as ring and as $\mathring{A}_{\text{aff}}$-module is not enough for our purposes: we need to be able to multiply two classes of the form $\sigma \otimes \xi_x$ and $\tau \otimes \xi_y$, see also Remark 5.6. To this end, we recall the definition and properties of $j^{\text{ad}}$ given in \cite{CMP09} §3.3.

**Proposition 5.8.** There is an $S$-algebra isomorphism $j^{\text{ad}} : H^T_*(\Omega K^{\text{ad}}) \to Z_{\mathring{A}_{\text{aff}}}(S)$. It satisfies:

1. $j^{\text{ad}}(\xi) \cdot \xi' = \xi \xi'$ for $\xi, \xi' \in H^T_*(\Omega K^{\text{ad}})$;
2. $j^{\text{ad}}(\psi_{t_s}) = \delta_{t_s}$ for $\lambda^\vee \in P^\vee$.

For $w \in \mathring{W}_{\text{aff}}$, $j^{\text{ad}}(\tilde{\xi}_w)$ is characterized by the two following properties:

1. $j^{\text{ad}}(\tilde{\xi}_w)$ is congruent to $A_w$ modulo $\sum_{x \in W \setminus \{e\}} \mathring{A}_{\text{aff}} \cdot A_x$;
2. $j^{\text{ad}}(\tilde{\xi}_w)$ belongs to $Z_{\mathring{A}_{\text{aff}}}(S)$.

The map $j^{\text{ad}}$ has the following equivariance property:

**Proposition 5.9.** Let $u \in W, \lambda^\vee \in P^\vee, \tilde{\xi} \in H^T_*(\Omega K^{\text{ad}})$. Then

1. $j^{\text{ad}}(ut^\vee \cdot \tilde{\xi}) = \delta_{u^\vee} \cdot j^{\text{ad}}(\tilde{\xi})$;
2. $\delta_{u^\vee} \cdot j^{\text{ad}}(\tilde{\xi}) = j^{\text{ad}}(\tilde{\xi}) \delta_{u^\vee}$.

**Proof.** (1) Let $s \in S$ be a scalar, we have:

- $j^{\text{ad}}(ut^\vee \cdot s\tilde{\xi}) = j^{\text{ad}}(u(s)t^\vee \cdot \tilde{\xi}) = u(s)j^{\text{ad}}(t^\vee \cdot \tilde{\xi})$;
- $\delta_{(u(s)t^\vee)} \cdot j^{\text{ad}}(s\tilde{\xi}) \delta_{u^\vee} = \delta_{u} j^{\text{ad}}(\tilde{\xi}) \delta_{u^\vee} = u(s) \delta_{u^\vee} j^{\text{ad}}(\tilde{\xi}) \delta_{u^\vee}$.

Thus, by semi-linearity, it is enough to prove the result for $\tilde{\xi} = \tilde{\psi}_{t^\vee}$. For $\tilde{\xi} = \tilde{\psi}_{t^\vee}$, we have $j^{\text{ad}}(ut^\vee \cdot \tilde{\psi}_{t^\vee}) = j^{\text{ad}}(u \cdot \tilde{\psi}_{ut^\vee}) = j^{\text{ad}}(\tilde{\psi}_{ut^\vee}) = \delta_{u} \delta_{u^\vee}$.

We also have $\delta_{u^\vee} \cdot j^{\text{ad}}(\tilde{\psi}_{t^\vee}) = \delta_{u^\vee} \cdot \delta_{u^\vee} = \delta_{u^\vee} \delta_{u^\vee} = \delta_{u^\vee} \delta_{u^\vee}$. Thus the result is proved.

(2) Both terms are $S$-linear so we only need to check this for $\tilde{\xi} = \tilde{\psi}_{t^\vee}$ but we have $\delta_{u} \cdot j^{\text{ad}}(\tilde{\psi}_{t^\vee}) = \delta_{u} \delta_{u^\vee} = \delta_{u^\vee} \delta_{u^\vee} = j^{\text{ad}}(\tilde{\psi}_{t^\vee}) \delta_{u^\vee}$. \qed

In particular, the previous Proposition allows computing $j^{\text{ad}}$ in terms of $j$:

**Example 5.10.** Let $\tau_i = v_i t_{-\tau_i} \in Z$ and let $\xi \in H^T_*(\Omega K)$. Then

$$j^{\text{ad}}(\tau_i \cdot \xi) = \delta_{\tau_i} \cdot j(\xi) \delta_{\tau_i}^{-1}.$$

We deduce a formula allowing reducing products in the homology of $\Omega K^{\text{ad}}$ to products in the homology of $\Omega K$:

**Corollary 5.11.** Let $\sigma = ut^\vee, \tau = vt^\vee$ be elements in $Z$. Let $\tilde{\xi}, \tilde{\xi}' \in H^T_*(\Omega K^{\text{ad}})$. Then

$$\psi_{\sigma, \tau} = \psi_{u^{-1}(\mu^\vee) - \mu^\vee} \psi_{v^{-1}(\lambda^\vee) - \lambda^\vee}.$$
Using Proposition 5.3, we compute:

\[(\sigma \cdot \tilde{\xi}) \times (\tau \cdot \tilde{\xi}') = j_{\text{ad}}(\sigma \cdot \tilde{\xi}) \cdot (\tau \cdot \tilde{\xi}')
\]

\[
= \delta_\nu \delta_{\nu'} j_{\text{ad}}(\tilde{\xi}) \delta_{\nu-1} \delta_v \delta_{\nu'} \cdot \tilde{\xi}'
\]

\[
= \delta_\nu \delta_{\nu'} j_{\text{ad}}(\tilde{\xi}) \delta_{\nu-1} \cdot \tilde{\xi}'
\]

\[
= \delta_\nu \delta_{\nu'} \delta_v \delta_{\nu'} j_{\text{ad}}(\tilde{\xi}) \delta_{\nu-1} \cdot \tilde{\xi}'
\]

\[
= \delta_\nu \delta_{\nu'} \delta_v \delta_{\nu'} \delta_{\nu-1} \cdot j_{\text{ad}}(\tilde{\xi}) \delta_{\nu-1} \cdot \tilde{\xi}'
\]

\[
= \delta_\nu \delta_{\nu'} \delta_v \delta_{\nu'} \delta_{\nu-1} \cdot j_{\text{ad}}(\tilde{\xi}) \cdot \tilde{\xi}'
\]

\[
= \sigma \tau \cdot (v_{\sigma,\tau} \times (u_{\nu-1} \tilde{\xi}) \times (u_{\nu-1} \tilde{\xi}')).
\]

\[\square\]

Remark 5.12. In [CMP09, p.12], it is claimed that $H^T_\ast(\Omega K_{\text{ad}})$ is the tensor product ring $\mathbb{Z}[\Omega] \otimes_\mathbb{Z} H^T_\ast(\Omega K)$. As explained in Remark 5.6, this is not true. However as the next corollary shows, this is true in the non equivariant homology.

Corollary 5.13. In non equivariant homology, let $\tilde{\xi}, \tilde{\xi}' \in H_\ast(\Omega K_{\text{ad}})$ and $\sigma, \tau \in \mathbb{Z}$, then

\[(\sigma \cdot \tilde{\xi}) \times (\tau \cdot \tilde{\xi}') = \sigma \tau \cdot (\tilde{\xi} \times \tilde{\xi}').\]

Proof. Indeed, push-forwards $u_{\sigma}^{-1}$ and $v_{\tau}^{-1}$ are trivial in non equivariant homology. Moreover, the equivariant classes $\tilde{\psi}_\lambda \cdot \tilde{\xi}$ restrict to the class of a point in $H_\ast(\Omega K_{\text{ad}})$, which is the unit in $H_\ast(\Omega K_{\text{ad}})$.

\[\square\]

5.7. Translations modulo $P$. We use [LS10 Lemma 10.1] and [CMP09 Corollary 3.15] as a definition:

(5) \[
(W^P)_\text{aff} = \left\{ ut_{\nu'} | \forall \gamma \in R^+_P, \langle \nu', \gamma \rangle = \begin{cases} 0 & \text{if } u(\gamma) > 0 \\ -1 & \text{if } u(\gamma) < 0 \end{cases} \right\}
\]

(6) \[
(\tilde{W}_P^P)_\text{aff} = \left\{ ut_{\nu'} \in \tilde{W}_\text{aff} | \forall \gamma \in R^+_P, \langle \nu', \gamma \rangle = \begin{cases} 0 & \text{if } u(\gamma) > 0 \\ -1 & \text{if } u(\gamma) < 0 \end{cases} \right\}.
\]

Following [LS10 §10.2 and 10.3], we also define $(W^P)_\text{aff} = \{ wt_{\lambda'} | w \in W_P, \lambda' \in Q^+_P \}$. Recall, from [CMP09 Section 3.4] that any element $w \in \tilde{W}_\text{aff}$ can be uniquely factorized as $w_1 w_2$ with $w_1 \in (\tilde{W}^P)_\text{aff}$ and $w_2 \in (W^P)_\text{aff}$ and $\ell(w) = \ell(w_1) + \ell(w_2)$. We denote $w_1 = \pi_P(w)$. Thus $(W^P)_\text{aff}$ is a set of representatives for the quotient $\tilde{W}_\text{aff}/(W^P)_\text{aff}$ which will be relevant for Peterson’s isomorphism [7].

Following [LS10 Section 10.4] and [CMP09 Section 3.4], define the ideals $J_P \subset M$ and $\bar{J}_P \subset M$ as follows:

\[J_P = \sum_{x \in \tilde{W}_\text{aff} \setminus (W^P)_\text{aff}} S\xi_x \text{ and } \bar{J}_P = \sum_{x \in \tilde{W}_\text{aff} \setminus (\tilde{W}_P^P)_\text{aff}} S\xi_x.\]

The following result corrects [CMP09 Proposition 3.16] which used the wrong product structure, see Remark 5.6.

Proposition 5.14. Let $x \in \tilde{W}_\text{aff} \cap (\tilde{W}^P)_\text{aff}$ and let $\nu' \in P^\vee$. Then $x \pi_P(t_{\nu'}) \in \tilde{W}_\text{aff} \cap (\tilde{W}^P)_\text{aff}$. Let us write as usual $x = \sigma \hat{x}$ and $\pi_P(t_{\nu'}) = \tau \overline{\pi_P(t_{\nu'})}$ with $\sigma = ut_{\lambda'}, \tau = vt_{\nu'}$. Then

\[\left( u_{\sigma-1} \xi \right) \times \left( u_{\tau-1} \xi \overline{\pi_P(t_{\nu'})} \right) = \psi_{\sigma,\tau} \xi \overline{\pi_P(t_{\nu'})} \text{ modulo } J_P.\]
Proof. The proof follows the arguments in [CMP09]. In particular, we get
\[(\sigma : \xi \hat{\varepsilon}) \times (\tau : \xi \pi P(t_{\nu})) = \sigma \tau : \xi \pi P(t_{\nu}) \] modulo $\tilde{J}_P$.

Using the correct product formula given in Corollary 5.11, the left hand side is
\[\sigma \tau : (\psi_{\sigma, \tau}(v_{\pi P(t_{\nu}))} - \xi \pi P(t_{\nu})) \cdot \xi \pi P(t_{\nu}) \].

This proves the result since $\tilde{J}_P \cap M = J_P$ (as $\sigma \hat{x} \in \tilde{W}_0 \Leftrightarrow \hat{x} \in W_0$). □

In particular, the case $P = B$ yields:

**Corollary 5.15.** Let $x \in \tilde{W}_0$ and let $\nu^\vee \in P^\vee$. Then $xt_{\nu^\vee} \in \tilde{W}_0$. Let us write as usual $x = \sigma \hat{x}$ and $t_{\nu^\vee} = \pi t_{\nu^\vee}$ with $\sigma = ut_{\lambda^\vee}, \tau = vt_{\mu^\vee}$. Then
\[(u_{\pi P(t_{\nu^\vee}))} - \xi \pi P(t_{\nu^\vee})) \cdot (\psi_{\sigma, \tau}(v_{\pi P(t_{\nu^\vee}))} - \xi \pi P(t_{\nu^\vee})) \cdot \xi \pi P(t_{\nu^\vee}) \].

6. Affine symmetries

In this section, we correct [CMP09 Section 3.5], see Remark 6.6, using the correct product formula given in Corollary 5.11 and Proposition 5.14. In particular, we prove that the formulas given in [CMP09] are correct in the equivariant setting.

6.1. Peterson’s isomorphism. Proposition 5.14 is our needed result in the equivariant homology of the affine Grassmannian. Translating this formula in the quantum cohomology of $G/P$, we prove our main theorem. We use Peterson’s isomorphism proved in [LS10] to relate $H^T(\Omega K)$ and $QH^T(G/P)$.

Let $\eta_P : Q^\vee \to Q^\vee_P$ be the projection on the coroot subspace generated by simple roots $\alpha_i$ with $\alpha_i \notin R_P$. Peterson’s isomorphism is the map
\[(\nu^\vee) : H^T(\Omega K)_P \to \mathbb{Z}[Q^\vee_P] \otimes_\mathbb{Z} H^T_P(G/P)\]
\[\xi_{w \pi P(t_{\lambda^\vee})} \xi^{\pi P(t_{\mu^\vee})} := q_{\eta P}(\lambda^\vee - \mu^\vee) \sigma^P(w)\]
where $w \in W$ and $\lambda^\vee, \mu^\vee \in Q^\vee$ with $Q^\vee$ the set of antidiagonal elements in $Q^\vee$.

**Remark 6.1.** In the above statement, we have:

1. The space $H^T(\Omega K)_P$ is a quotient and a localization of $H^T(\Omega K)$ defined in [CMP09 Section 2.2]. The family $\{\sigma^P(w), w \in W/W_P\}$ is the Schubert base of $H^T_P(G/P)$, and the element in $\mathbb{Z}[Q^\vee_P]$ corresponding to $\nu^\vee$ in $Q^\vee_P$ is denoted by $q_{\nu^\vee}$. We have for $\nu^\vee \in Q^\vee$ the formula
\[\deg(q_{\nu^\vee}) = \sum_{\alpha \in \mathbb{R}^+ \setminus R_P} (\nu^\vee, \alpha) = -\ell(t_{\nu^\vee}).\]

2. This isomorphism is graded. In fact, for very negative coweights $\lambda^\vee, \mu^\vee$, the element $\xi_{w \pi P(t_{\lambda^\vee})} \xi^{\pi P(t_{\mu^\vee})}$ has homological degree $\ell(\pi P(t_{\lambda^\vee})) - \ell(w) - \ell(\pi P(t_{\mu^\vee}))$, by [LS10] Lemma 3.3. On the other hand, in quantum cohomology, the element $q_{\eta P}(\lambda^\vee - \mu^\vee) \sigma^P(w)$ has degree $-\ell(\pi P(t_{\lambda^\vee})) + \ell(\pi P(t_{\mu^\vee})) + \ell(w)$.
6.2. A Weyl group action on $\text{QH}^*_T(G/P)$. In this subsection, we define an action of the Weyl group on $H_T^*(G/P)$ and on $\text{QH}^*_T(G/P)$ by left translation. We will prove the compatibility of this action with Peterson’s isomorphism in the next subsection. Since this action is different from the action defined in Kumar [Kum02, 11.3.4] we define it carefully. We start with the action on $G/B$ and then deal with the general situation for $G/P$.

We define an algebraic and a geometric action of the Weyl group $W$ on $H_T^*(G/B)$. We then prove that these actions coincide.

Let $n \in G$ be in the normalizer of $T$ and let $w$ be the corresponding element of the Weyl group. Define the left action $L_n : G/B \to G/B$ by left multiplication: $L_n : [x] = [n^{-1}x]$. This action is $T$-equivariant if we consider the $w$-twisted action of $T$ on $G/B$ given by $t \cdot [x] = [wt(x)]$. It therefore induces a $w$-semilinear map $H_T^*(G/B) \to H_T^*(G/B)$, denoted $L^*_n$: $L^*_n(s\xi) = w(s)L^*_n(\xi)$ for $s \in S$ and $\xi \in H_T^*(G/B)$.

Fact 6.2. The above action $L^*_n$ satisfies the following properties:

1. $L^*_n$ depends on $w$ and not on $n$ itself; it will be denoted by $w^*$ in the sequel.
2. Via the inclusion $H^*_T(G/P) \subset H^*_T(G/B)$ given by pulling back the projection $G/B \to G/P$, we have $w^*H^*_T(G/P) \subset H^*_T(G/P)$.
3. The induced action of $w^*$ on the non equivariant cohomology $H^*(G/B)$ is trivial.

Proof. (1) Let $N$ denote the normalizer of $T$. The map $N \times G/B \to G/B, (n, [x]) \mapsto L_n \cdot [x]$ is continuous and therefore for $\xi \in H_T^*(G/B)$, the map $N \to L^*_n \xi$ is locally constant.

(2) For $n$ in the normalizer of $T$, we have a commutative diagram:

$$
\begin{array}{ccc}
G/B & \xrightarrow{L_n^B} & G/B \\
\downarrow & & \downarrow \\
G/P & \xrightarrow{L_n^P} & G/P
\end{array}
$$

Here we made a difference between the action of $n$ on $G/B$ and $G/P$ using superscripts. It follows that for $\xi \in H_T^*(G/P)$, we have $w^*\xi = (L_n^B)^*\xi = (L_n^P)^*\xi \in H_T^*(G/P)$.

(3) For $g \in G$, we can consider the action of left translation $L^*_g$ on non equivariant cohomology $H^*(G/B)$. By the same argument as in (1), this action is trivial. In particular, for $g = n$ in $N$, we obtain that the action $L^*_n$ on non equivariant cohomology is trivial. $\Box$

Recall that $W$ can be embedded in $A_{\text{aff}}$ via $v \mapsto \delta_v$.

Definition 6.3. Let $w \in W$. Consider $H_T^*(G/B)$ as the dual of $H^*_T(G/B) \subset A_{\text{aff}}$ and set

$$(w \bullet f)(x) = f(\delta_{w^{-1}}x) \text{ for } x \in H_T^*(G/B) = A.$$

Proposition 6.4. For $f \in H_T^*(G/B)$ and $w \in W$, we have $w \bullet f = w^*f$.

Proof. Using Frac($S$)-linearity, we only need to compare these actions on the elements $\xi^v$. We have $(w \bullet \xi^v)(\delta_u) = \xi^v(\delta_{w^{-1}}\delta_u) = \xi^v(\delta_{w^{-1}}u) = \delta_{v,u^{-1}}u = \xi^v(w^{-1}u) = (w^*\xi^v)(u)$, proving the result. $\Box$
Corollary 6.5. Let $\alpha$ be a simple root and $w \in W^P$. We have

\[(s_\alpha)^*\sigma^P(w) = \begin{cases} \sigma^P(w) & \text{if } s_\alpha w > w; \\ \sigma^P(w) - \alpha\sigma^P(s_\alpha w) & \text{if } s_\alpha w < w. \end{cases}\]

Proof. We compute $((s_\alpha)^*\sigma^P(w))(A_u) = \sigma^P(w)(\delta_{s_\alpha A_u}) = \sigma^P(w)((1 - \alpha A_\alpha)A_u) = \sigma^P(w)(A_u) - \alpha\sigma^P(w)(A_\alpha A_u)$. Now we have

\[A_\alpha A_u = \begin{cases} 0 & \text{if } s_\alpha u < u \\ A_{s_\alpha u} & \text{if } s_\alpha u > u. \end{cases}\]

Since $\sigma^P(w)(A_v) = \delta_{v,w}$, we get

\[((s_\alpha)^*\sigma^P(w))(A_u) = \begin{cases} \delta_{u,w} & \text{if } s_\alpha u < u \\ \delta_{u,w} - \alpha\delta_{s_\alpha u,w} & \text{if } s_\alpha u > u. \end{cases}\]

This in turn gives the result. \qed

Remark 6.6. (1) Note that, for $\alpha$ simple, the two conditions $w \in W^P$ and $s_\alpha w < w$ imply the inclusion $s_\alpha w \in W^P$ since the inversion set of $s_\alpha w$ is contained in the inversion set of $w$. In particular, in the second case of the above formula, the class $\sigma^P(s_\alpha w)$ is well defined.

(2) This formula also shows that the action $w^*$ is trivial in the non-equivariant setting (indeed, in that case wet set $\alpha = 0$).

The action $w^*$ is extended to $\text{QH}_*^P(G/P)$ by linearity on quantum parameters.

6.3. Compatibility of Peterson’s isomorphism. In this subsection we prove that Peterson’s isomorphism is compatible with the actions $u_\alpha$ in homology and $u^*$ in cohomology. We start with a useful lemma.

Lemma 6.7. Let $w \in W^P$ and let $\lambda^\vee \in Q^\vee_\mathbb{P}$ be such that $x = w\pi_P(t_{\lambda^\vee}) \in (W^P)_{\text{aff}}$. Write $x = w\pi_P(t_{\lambda^\vee}) = vt_{\mu^\vee}$ with $v \in W$ and $\mu^\vee \in Q^\vee$. Let $\alpha$ be a simple root and let $\beta = w^{-1}(\alpha)$, $\beta' = v^{-1}(\alpha)$.

(1) We have $w^{-1}v \in W_P$ and $\mu^\vee \in Q^\vee_\mathbb{P}$.

(2) We have $\beta \in R_P \iff \beta' \in R_P$.

(3) We have $s_\alpha x \in W_{\text{aff}} \iff (\mu^\vee, \beta) \neq 0$.

(4) We have $s_\alpha x \in (W^P)_{\text{aff}} \iff \beta \notin R_P \iff s_\alpha w \in W^P$.

(5) We have the equivalence:

\[(s_\alpha x \in W_{\text{aff}} \cap (W^P)_{\text{aff}} \text{ and } \ell(s_\alpha x) > \ell(x)) \iff (s_\alpha w \in W^P \text{ and } \ell(s_\alpha w) < \ell(w)).\]

Proof. (1) By [LS10, Lemma 10.7], we have $\pi_P(t_{\lambda^\vee}) = ut_{\mu^\vee}$ with $u \in W_P$. This gives $w^{-1}v = u \in W_P$. Since $vt_{\mu^\vee} \in W_{\text{aff}}$ we have $\mu^\vee \in Q^\vee_\mathbb{P}$.

(2) Since $u = w^{-1}v \in W_P$ and $\beta = u(\beta')$, we have $\beta \in R_P \iff \beta' \in R_P$.

(3) We have $vt_{\mu^\vee} \in W_{\text{aff}}$ therefore $\mu^\vee \in Q^\vee_\mathbb{P}$ and for $\gamma > 0$, we have the implication $(\langle \mu^\vee, \gamma \rangle = 0 \implies v(\gamma) > 0)$. The condition $s_\alpha vt_{\mu} \in W_{\text{aff}}$ is thus equivalent to $(\langle \mu^\vee, \gamma \rangle = 0 \implies s_\alpha v(\gamma) > 0)$ for $\gamma > 0$. But since for $\gamma = \beta'$, the roots $v(\gamma)$ and $s_\alpha v(\gamma)$ have opposite signs, the condition $s_\alpha vt_{\mu^\vee} \in W_{\text{aff}}$ is equivalent to $\langle \mu^\vee, \beta' \rangle = 0$.

(4) We have $vt_{\mu^\vee} \in (W^P)_{\text{aff}}$ therefore, for $\gamma \in R^+_P$, we have the equivalences $(\langle \mu^\vee, \gamma \rangle = 0 \iff v(\gamma) > 0)$ and $(\langle \mu^\vee, \gamma \rangle = -1 \iff v(\gamma) < 0)$. The condition $s_\alpha vt_{\mu} \in (W^P)_{\text{aff}}$ is equivalent to having the equivalences $(\langle \mu^\vee, \gamma \rangle = 0 \iff s_\alpha v(\gamma) > 0)$ and $(\langle \mu^\vee, \gamma \rangle = -1 \iff s_\alpha v(\gamma) < 0)$. Since for $\gamma = \beta'$, the roots $v(\gamma)$ and $s_\alpha v(\gamma)$ have
opposite signs, the last equivalences occur if and only if $\beta' \notin R_P$. This in turn is equivalent to $\beta \notin R_P$ by (2).

For the last equivalence, note that by definition, we have $(s_{a}w \in WP) \iff s_{a}w(R_{P}^{+}) \subset R^{+}$. Since $w \in WP$, we have $w(R_{P}^{+}) \subset R^{+}$. Since the inversion sets of $w$ and $s_{a}w$ only differ by $\beta$ (or its opposite, depending on the sign of $\beta$) we get the last equivalence.

(5) Note that we have the equivalence $(\ell(s_{a}w) < \ell(w) \iff \beta < 0)$. We therefore need to prove that the left hand side of the equivalence is equivalent to $\beta \notin R_P$ and $\beta < 0$. Note that since $w \in WP$, this is equivalent to $\beta < 0$.

First assume that $s_{a}x \in \tilde{W}_{aff} \cap (WP)_{aff}$ and $\ell(s_{a}x) > \ell(x)$. By [LS10] Lemma 3.3, since $vt_{\mu}^{\vee}, s_{a}vt_{\mu}^{\vee} \in W_{aff}m$, we have $\ell(s_{a}x) = \ell(t_{\mu}^{\vee}) - \ell(s_{a}v)$ and $\ell(x) = \ell(t_{\mu}^{\vee}) - \ell(v)$. In particular, we have $\ell(s_{a}v) < \ell(v)$, thus $\beta < 0$. Since $s_{a}x \in (WP)_{aff}$, we also have $\beta \notin R_P$ thus $\beta' \notin R_P$. Now, since $u \in WP$, this implies $\beta < 0$.

Conversely, assume $\beta < 0$. By the above arguments, this implies $\beta \notin R_P$ and thus $s_{a}x \in (WP)_{aff}$. This also implies $\beta' \notin R_P$ and since $u \in WP$ and $\beta = u^{-1}(\beta)$, we get $\beta' < 0$. Since $vt_{\mu} \in \tilde{W}_{aff}$, $-\beta > 0$ and $v(-\beta') = -\alpha < 0$, we must have $\langle \mu', \beta' \rangle \neq 0$ and by (3), this implies $s_{a}x \in \tilde{W}_{aff}$. □

We have the following equivariance property of $\psi_{p}$.

**Proposition 6.8.** For $\xi \in H_{T}^{*}(\Omega K)_{P}$, we have $\psi_{p}(u_{*}\xi) = u^{*}\xi$.

**Proof.** We may assume that $u = s_{i}$, with $\alpha_{i}$ a simple root. Then $u_{*}\xi_{w\pi\nu}(t_{\lambda}^{\vee}) = \delta_{u} \cdot \xi_{w\pi\nu}(t_{\lambda}^{\vee}) = (1 - \alpha_{i}A_{i}) \cdot \xi_{w\pi\nu}(t_{\lambda}^{\vee})$. If $\ell(s_{i}w\pi\nu(t_{\lambda}^{\vee})) > \ell(w\pi\nu(t_{\lambda}^{\vee}))$ and $s_{i}w\pi\nu(t_{\lambda}^{\vee}) \in (WP)_{aff} \cap \tilde{W}_{aff}$, then this is equal to $\xi_{w\pi\nu}(t_{\lambda}^{\vee}) - \alpha_{i}\xi_{w\pi\nu}(t_{\lambda}^{\vee})$. Otherwise, this is equal to $\xi_{w\pi\nu}(t_{\lambda}^{\vee})$.

The action $s_{i}^{*}\sigma^{P}(w)$ is computed in Corollary [6.5]. If $\ell(s_{i}w) < \ell(w)$ and $s_{i}w \in WP$, then this is equal to $\sigma^{P}(w) - \alpha_{i}\sigma^{P}(s_{i}w)$. Otherwise, this is equal to $\sigma^{P}(w)$.

Let $\beta = w^{-1}(\alpha_{i})$. The condition $s_{i}w \in WP$ and $\ell(s_{i}w) < \ell(w)$ is equivalent to the condition $\ell(s_{i}w\pi\nu(t_{\lambda}^{\vee})) > \ell(w\pi\nu(t_{\lambda}^{\vee}))$ and $s_{i}w\pi\nu(t_{\lambda}^{\vee}) \in (WP)_{aff} \cap \tilde{W}_{aff}$ by Lemma [6.7] (5). This proves the result. □

**6.4. The result.** We now prove our main result. For $i$ a cominuscule node, i.e. such that $\varpi_{i}^{\vee}$ is a minuscule coweight, we let $v_{i}$ be the smallest element in $W$ such that $v_{i}(\varpi_{i}^{\vee}) = w_{0}(\varpi_{i}^{\vee})$ ($w_{0}$ is the longest element in $W$). The coweight $v_{i}(\varpi_{i}^{\vee}) = w_{0}(\varpi_{i}^{\vee})$ is the opposite of a fundamental coweight: there exists $f(i) \in I$ such that $v_{i}(\varpi_{i}^{\vee}) = -\varpi_{f(i)}$'. Actually we have $\alpha_{f(i)} = -w_{0}(\alpha_{i})$ and $v_{f(i)} = v_{i}^{-1}$.

**Theorem 6.9.** Let $i$ be a cominuscule node. In $QH_{T}^{*}(G/P)$ we have

$$
\sigma^{P}(v_{i}) \times v_{i}^{*}(\sigma^{P}(w)) = q_{np}(\varpi_{i}^{-w_{0}^{-1}(\varpi_{i}^{\vee})})\sigma^{P}(v_{i}w).
$$

**Proof.** Let $w \in WP$, we have $\pi_{p}(w) = w$. Let $\varpi_{i}^{\vee}$ be the minuscule coweight associated to $i$ and let $\mu^{\vee}$ and $\nu^{\vee}$ be in $Q^{\vee}$ and dominant enough. As in [CMP09] §3.5], we get

$$
\pi_{p}(t_{-w_{0}^{-1}(\varpi_{i})}) = \tau_{i}\pi_{p}(v_{f(i)}w)\pi_{p}(t_{-w_{0}^{-1}(\varpi_{i})}^{\vee}) \quad \text{and}
$$

$$
\pi_{p}(vt_{\mu}^{-w_{0}^{-1}(\varpi_{i})}) = \tau_{i}\pi_{p}(v_{f(i)}w)\pi_{p}(t_{-w_{0}^{-1}(\varpi_{i})}^{\vee} + \mu) + \pi_{p}(t_{-w_{0}^{-1}(\varpi_{i})}^{\vee} + \mu + \nu).
$$

For $\mu$ and $\nu$ dominant enough, the elements $wt_{\nu}, t_{w_{0}^{-1}(\varpi_{i})}$ and $wt_{\nu}t_{w_{0}^{-1}(\varpi_{i})}$ are in $\tilde{W}_{aff}$ and their image by $\pi_{p}$ are in $(WP)_{aff} \cap \tilde{W}_{aff}$. We may therefore apply
Proposition 5.14 to the elements $w t_\nu$ and $t_\mu$ to get:

\[ (v_f(i))_\ast \xi w_{\pi P}(t_\mu) \ast \xi_{\pi P}(v_f(i)) \pi P(t_\nu) (\omega_i^\gamma + \omega_i^\rho) \equiv \xi_{\pi P}(v_f(i) w) \pi P(t_\nu) (\omega_i^\gamma + \omega_i^\rho), \]

where \( \equiv \) means equality in \( H^2_t(\Omega K)_P \) or equivalently equality modulo \( J_P \). Applying Peterson's map \( (7) \), we get thanks to Proposition 6.8 the corresponding formula in the quantum cohomology ring:

\[ v_f(i) \sigma^P(w) q_{-\eta P(\nu \gamma)} \ast \sigma^P(v_f(i)) q_{-\eta P(\omega_i^\gamma + \omega_i^\rho)} = \sigma^P(v_f(i) w) q_{-\eta P(\omega_i^\gamma + \omega_i^\rho)}, \]

hence finally:

\[ v_f(i) \sigma^P(w) \ast \sigma^P(v_f(i)) = q_{\eta P(\omega_i^\gamma + \omega_i^\rho)} \sigma^P(v_f(i) w). \]

This concludes the proof of the theorem. \( \square \)

**Corollary 6.10.** Let \( i \) be such that \( \omega_i^\gamma \) is a minuscule coweight. In \( QH^*(G/P) \), we have

\[ \sigma^P(v_i) \times \sigma^P(w) = q_{\eta P(\omega_i^\gamma + \omega_i^\rho)} \sigma^P(v_i w). \]

**Example 6.11.** Let \( G \) be of type \( A_1 \), so that \( G/B = \mathbb{P}^1 \). Let \( s \) be the non trivial element of \( W \) and \( \alpha \) the simple root. We have

\[ \sigma^B(s) \ast (\sigma^B(s) - \alpha) = q. \]

**Proof.** Let \( i \) be the unique node of the Dynkin diagram of \( G \). Then \( v_i = s \). To apply Theorem 6.9, we also set \( w = s \). Let \( x \) resp. \( y \) be the \( B \)-stable resp. \( B^- \)-stable point in \( \mathbb{P}^1 \). The class \( \sigma^B(s) \) is the \( T \)-equivariant class of \( x \), and \( v_i^* \sigma^B(s) \) is the \( T \)-equivariant class of \( y \). Since \( [x] - [y] = \alpha \), we have \( v_i^* \sigma^B(s) = \sigma^B(s) - \alpha \).

Denoting \( h = \sigma^B(s) \), the theorem yields \( h \times (h - \alpha) = q \), as claimed. Note that \( h^2 = q + \alpha h \) is also predicted eg by [M07 Theorem 1]. \( \square \)

### 7. Pieri formulas

We now give another application of Proposition 5.8 to prove a formula for \( j(\xi_{\tau_i(v_i)}) \), see Proposition 7.2. This gives the multiplication in \( H^2_t(\Omega K) \) by the class \( \xi_{\tau_i(v_i)} \). We hope in subsequent work to deduce Pieri formulas for the non-equivariant multiplication by classes generating \( H_*(\Omega K) \) in all classical types.

We first provide a generalization of [Lam08 Proposition 5.4] to coweights. For \( \mu^\gamma \in P^\gamma \), set \( W_{\mu^\gamma} = \{ s_{\alpha_i} \mid i \in [1, r] \} \) and \( \{ w(\mu^\gamma) = 0 \} = \{ w \in W \mid w(\mu^\gamma) = \mu^\gamma \} \).

**Proposition 7.1.** Let \( \mu^\gamma \in P^\gamma \) be antidiominant. Then

\[ j^\text{ad}(\xi_{\mu^\gamma}) = \sum_{w \in W/W_{\mu^\gamma}} \tilde{A}_{t_{w(\mu^\gamma)}}. \]

**Proof.** We follow the idea of proof given in [Lam08 Proposition 5.4]. Using Lemma 4.8, we see that for \( w \in W/W_{\mu^\gamma} \) non trivial, \( t_{w(\mu^\gamma)} \notin \tilde{W}_{\text{aff}} \), so that \( A_{t_{w(\mu^\gamma)}} \) belongs to the ideal \( \sum_{x \in W \backslash \{ e \}} \tilde{A}_{\text{aff}} \cdot A_{x} \) of Proposition 5.8. Thus, using Proposition 5.8, we only need to prove that \( \sum_{w \in W/W_{\mu^\gamma}} A_{t_{w(\mu^\gamma)}} \in Z_{\tilde{A}_{\text{aff}}}(S) \).

To prove that \( c := \sum_{w \in W/W_{\mu^\gamma}} \tilde{A}_{t_{w(\mu^\gamma)}} \) centralizes \( S \), or equivalently commutes with any \( \lambda \) in \( P \), we use Proposition 4.6 to compute \( \tilde{A}_{t_{\mu^\gamma}} \lambda \). In this formula, the
term $t_{\nu^\vee}(\lambda)$ is equal to $\lambda$ by \(1\) in \(2.2\). Let $\mathcal{P}$ be the set of pairs $(\nu^\vee, \beta)$ where $\nu^\vee \in W \cdot \mu^\vee$, $\beta$ is a positive real root, and $t_{\nu^\vee}s_\beta < t_{\nu^\vee}$. We have:

$$c\lambda - \lambda c = \sum_{(\nu^\vee, \beta) \in \mathcal{P}} \langle \lambda, \beta \rangle \tilde{A}_{t_{\nu^\vee}s_\beta},$$

so our concern now is to prove that this sum vanishes.

We consider the map $\iota : \mathcal{P} \to \mathcal{P}$ defined by $\iota(\nu^\vee, \beta) = (s_\beta(\nu^\vee), -t_{\nu^\vee}(\beta))$. Let $(\nu^\vee, \beta) \in \mathcal{P}$. We have

$$t_{\nu^\vee}s_\beta = t_{\nu^\vee}s_\beta t_{-\nu^\vee}t_{\nu^\vee} = s_{t_{\nu^\vee}(\beta)}t_{\nu^\vee} = t_{s_{t_{\nu^\vee}(\beta)}(\nu^\vee)}s_{t_{\nu^\vee}(\beta)} = t_{s_{\beta}(\nu^\vee)s_{-t_{\nu^\vee}(\beta)}},$$

where the last equality follows from \(1\) and Lemma 2.8. By the length formula in [CAMP09 Corollary 3.13], $\ell(t_{s_{\beta}(\nu^\vee)}) = \ell(t_{\nu^\vee})$ and by definition of $\mathcal{P}$, $\ell(t_{\nu^\vee}s_\beta) = \ell(t_{\nu^\vee}) - 1$. Thus, $\ell(t_{s_{\beta}(\nu^\vee)s_{-t_{\nu^\vee}(\beta)}}) = \ell(t_{s_{\beta}(\nu^\vee)}) - 1$. Moreover, by [BB05 Proposition 4.4.6], $t_{\nu^\vee}(\beta) < 0$, which implies $t_{s_{\beta}(\nu^\vee)s_{-t_{\nu^\vee}(\beta)}}< t_{s_{\beta}(\nu^\vee)}$ and $-t_{\nu^\vee}(\beta) > 0$, so $(s_{\beta}(\nu^\vee), -t_{\nu^\vee}(\beta)) \in \mathcal{P}$ as claimed.

We also observe that $\langle \lambda, -t_{\nu^\vee}(\beta) \rangle = -\langle \lambda, \beta \rangle$. Finally,

$$-t_{s_{\beta}(\nu^\vee)}(-t_{\nu^\vee}(\beta)) = t_{s_{\beta}(\nu^\vee)t_{\nu^\vee}(\beta)} = s_\beta t_{\nu^\vee}s_\beta t_{\nu^\vee}(\beta).$$

One can check that this root is equal to $\beta$, so that $\iota$ is an involution and the terms in (8) cancel pairwise.

We now prove some preliminary lemmas.

**Lemma 7.2.** Let $i \in I_{aff}$. We have $j^{ad}((\xi_{w_0}(\pi^\vee_0))) = \delta_{t_i}^{-1} \sum_{w \leq w_{t_i}} A_{t_i(w)v_iw^{-1}}$.

**Proof.** Since $w_0(\pi^\vee_0) \leq 0$ we may apply Proposition 7.1 and get

$$j^{ad}((\xi_{w_0}(\pi^\vee_0))) = \sum_{\mu^\vee \in W \cdot \pi^\vee_0} A_{i_{\mu^\vee}}.$$  

Thus,

$$j^{ad}((\xi_{w_0}(\pi^\vee_0))) = \sum_{\mu^\vee \in W \cdot \pi^\vee_0} A_{i_{\mu^\vee}} = \sum_{w \leq w_{t_i}} A_{w_{t_i}^{-1}v_iw^{-1}} = \sum_{w \leq w_{t_i}} A_{t_i^{-1}t_i(w)v_iw^{-1}} = \delta_{t_i}^{-1} \sum_{w \leq w_{t_i}} A_{t_i(w)v_iw^{-1}}.$$  

**Lemma 7.3.** Let $s \in S$ and $i \in I_{aff}$. We have

$$\left( \sum_{w \leq w_{t_i}} A_{t_i(w)v_iw^{-1}} \right) s = \tau_i(s) \left( \sum_{w \leq w_{t_i}} A_{t_i(w)v_iw^{-1}} \right).$$

**Proof.** Let $i \in I_{aff}$. Since $j^{ad}((\xi_{w_0}(\pi^\vee_0))) = \delta_{t_i}^{-1} \sum_{w \leq w_{t_i}} A_{t_i(w)v_iw^{-1}}$, we deduce that

$$\delta_{t_i}^{-1} \sum_{w \leq w_{t_i}} A_{t_i(w)v_iw^{-1}} \in Z_{h_{aff}}(S).$$

Let $s \in S$, we have:

$$\delta_{t_i}^{-1} \left( \sum_{w \leq w_{t_i}} A_{t_i(w)v_iw^{-1}} \right) s = s \delta_{t_i}^{-1} \sum_{w \leq w_{t_i}} A_{t_i(w)v_iw^{-1}} = \delta_{t_i}^{-1} \tau_i(s) \sum_{w \leq w_{t_i}} A_{t_i(w)v_iw^{-1}},$$

which proves the lemma.
Proposition 7.4. Let \( i \in I_{\text{aff}} \), let as above \( v_i \) the maximal element in \( W^{P_i} \) and \( \tau_i \) the automorphism of the affine Dynkin diagram defined by \( L \).

and we have:

\[
j(\xi_{\tau_i(v_i)}) = \sum_{w \leq L \, v_i} \sum_{v_i w^{-1}} \tau_i(\xi^v(v_i^{-1}))A_{\tau_i(w)v_i w^{-1}}A_v.
\]

Proof. We first prove that \( \tau_i(v_i) \in W^-_{\text{aff}} \). We know that \( \tau_i(\alpha_i) = \alpha_0 \). Since \( v_i \in W^{P_i} \), we have for \( 1 \leq j \leq n \) with \( j \neq i \), \( \ell(v_i s_j) < \ell(v_i) \). Applying \( \tau_i \), we deduce that for all \( k > 0 \), \( \ell(\tau_i(v_i) s_k) < \ell(\tau_i(v_i)) \). Thus, \( \tau_i(v_i) \in W^-_{\text{aff}} \).

Moreover, we know that \( \tau_i = v_i t_{-\pi_i} \). Therefore, \( v_i = \tau_i t_{-\pi_i} = t_{\alpha_0(\pi_i)} t_{-\pi_i} \), so that \( t_{\alpha_0(\pi_i)} = v_i t_{-\pi_i} \). By Proposition 5.3, we deduce that \( j^d(\xi_{\alpha_0(\pi_i)}) = \delta_{\tau_i^{-1}}(\xi_{\tau_i(v_i)}) \delta_{v_i} \).

By Lemma 7.2, we deduce that

\[
\delta_{\tau_i^{-1}}(\xi_{\tau_i(v_i)}) \delta_{v_i} = \delta_{\tau_i^{-1}} \sum_{w \leq L \, v_i} A_{\tau_i(w)v_i w^{-1}}.
\]

Therefore, using Fact 5.1 and then Lemma 7.3 we find

\[
j(\xi_{\tau_i(v_i)}) = \sum_{w \leq L \, v_i} A_{\tau_i(w)v_i w^{-1}} \delta_{v_i}^{-1} = \sum_{w \leq L \, v_i} A_{\tau_i(w)v_i w^{-1}} \sum_{v_i w^{-1}} \xi^v(v_i^{-1}) A_v
\]

\[
= \sum_{w \leq L \, v_i} \sum_{v_i w^{-1}} \tau_i(\xi^v(v_i^{-1})) A_{\tau_i(w)v_i w^{-1}} A_v.
\]

\[
\square
\]

Remark 7.5. Let \( x \in W^-_{\text{aff}} \). In the non equivariant homology, we thus have

\[
\xi_{\tau_i(v_i)} \cdot x = \sum \xi_{\tau_i(w)v_i w^{-1}} x,
\]

where the sum is over \( w \leq L \, v_i \) such that \( \ell(\tau_i(w)v_i w^{-1} x) = \ell(v_i) + \ell(x) \) and \( \tau_i(w)v_i w^{-1} x \in W^-_{\text{aff}} \).

By Corollary 5.13, we know that there is only one Schubert class in the product \( \xi_{\tau_i(v_i)} \cdot x \), from which we deduce that there is exactly one \( w \leq L \, v_i \) such that \( \ell(\tau_i(w)v_i w^{-1} x) = \ell(v_i) + \ell(x) \) and \( \tau_i(w)v_i w^{-1} x \in W^-_{\text{aff}} \).

Example 7.6. Let us assume we are in type \( A_3 \) and let us write for short \( A_{210} \) instead of \( A_{s_2 s_1 s_0} \) and similarly for \( \xi_{210} \) and \( \delta_{210} \). Let \( i = 1 \) so that \( v_i = s_3 s_2 s_1 \) and \( \tau_i(v_i) = s_2 s_1 s_0 \). First we observe that

\[
\delta_{\tau_i^{-1}} = \delta_{123} = (1 - \alpha_1 A_1)(1 - \alpha_2 A_2)(1 - \alpha_3 A_3)
\]

\[
= 1 - \alpha_1 A_1 - (\alpha_1 + \alpha_2) A_2 - (\alpha_1 + \alpha_2 + \alpha_3) A_3
\]

\[
+ \alpha_1(\alpha_1 + \alpha_2) A_{12} + (\alpha_1 + \alpha_2 + \alpha_3) A_{13} + (\alpha_1 + \alpha_2)(\alpha_1 + \alpha_2 + \alpha_3) A_{23}
\]

\[
= \alpha_1(\alpha_1 + \alpha_2)(\alpha_1 + \alpha_2 + \alpha_3) A_{123}.
\]
Since $\tau_i(\alpha_1) = -\theta = -(\alpha_1 + \alpha_2 + \alpha_3)$, $\tau_i(\alpha_2) = \alpha_1$ and $\tau_i(\alpha_3) = \alpha_2$, we get:

\[
\begin{align*}
    j(\xi_{210}) &= A_{210} + A_{321} + A_{032} + A_{103} \\
    &+ \alpha_3(A_{2103} + A_{3213} + A_{0323}) \\
    &+ (\alpha_2 + \alpha_3)(A_{2102} + A_{3212} + A_{1032}) \\
    &+ (\alpha_1 + \alpha_2 + \alpha_3)(A_{2101} + A_{3211} + A_{1031}) \\
    &+ \alpha_3(\alpha_1 + \alpha_2 + \alpha_3)(A_{21012} + A_{3212} + A_{10312}) \\
    &+ \alpha_3(\alpha_2 + \alpha_3)(\alpha_1 + \alpha_2 + \alpha_3)(A_{210123} + A_{32123} + A_{103123}).
\end{align*}
\]

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