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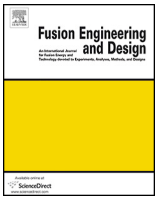

Analysis on acceleration of DT-mixed ion beams in a negative ion accelerator for a DT-mixed Neutral Beam Injector

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ABSTRACT

In order to reduce the tritium inventory in a fuel circulation system in fusion plants, a possibility of deuterium-tritium (DT) mixed neutral beam injectors with DT negative ion beams has been investigated by analyzing the beam optics of the DT-mixed negative ion beams for the first time. In a two-dimensional beam analysis, DT-mixed ion beams could be accelerated regardless of the DT current mixing ratio (T/D) from the identical acceleration geometry with the identical applied voltages by adjusting total space charge for the D and T components. However, in a three-dimensional beam analysis including magnetic fields, the DT-mixed ion beams were separated due to a mass dependence of the beam deflection by orthogonal magnetic fields of an electron suppression and transverse filter fields for negative ion production. In the case of the beamline for ITER, which requires beam deflection angle within ±1 mrad, the operational range for the DT-mixed ion beams was found to be the DT current mixing ratio of 0.7-1.5 and beam energy of 0.9-1.0 MeV. Although the operational range was not wide, the DT-mixed beam was found to be feasible in terms of the beam acceleration. These analyses also contribute to the study of the acceleration of other mixed ion beams such as impurity or heavy ions, which are useful techniques for diagnostic beams.

1. Introduction

A fusion power plant with deuterium-tritium (DT) fuel is one of promising power sources to realize long-term electric power generation in future. In such a plant, accumulation of the produced He ash must be avoided, and pumped out with other impurities. However, pumping of He gas is accompanied by a large amount of DT gas, several tens times larger than the He gas throughput. In order to maximize the full use of tritium, ITER and DEMO are planned to be equipped with a tritium processing plant system for an internal fuel circulation [1,2]. In this circulation system, the DT fuel exhausted from the vacuum vessel requires separation of impurities from a huge amount of deuterium (D) and tritium (T) gases with isotope separation based on cryogenic distillation [3]. After this isotope separation, the either D or T gas is used in pellet injectors [4] and NBI systems.

Although a large T gas throughput itself does not make serious inventory, a temporal liquid and its hold-up in the cryogenic isotope separation column for T enrichment [3] results in a large T inventory and is one of critical issues for a safety management in ITER and particularly in DEMO.

As a possibility to minimize tritium inventory in fusion system, fueling systems such as gas puffing, pellet and NBI system have been studied whether they could operate with DT mixed gas, without DT separation. Recently, fuel circulation with only the DT gas at fixed DT ratio was considered [5]. In this design, neutral beam injectors (NBI) were also planned to operate with the DT gas, however there were no theoretical background for the DT operation of the NBI.

So far, large current pure D or T beams [6] and H or D beams [7] have been accelerated from an ion source with the identical acceleration geometry by considering the mass dependence of the Child-Langmuir law [8]. However, acceleration of mixed negative ion beams has not been applied yet, because the beam optics of the mixed negative ion beams is not clear and the beams with poor optics can easily cause severe damage to acceleration grids in the case of large current beams such as ITER and DEMO [9]. Therefore, in order to examine the beam optics of the DT-mixed negative ion

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beams, theoretical and numerical approaches are discussed in order to clarify the operational range of the DT ratio in the DT-mixed NBI.

In this paper, several issues for the DT-mixed NBI system are discussed at first. After that, two-dimensional analysis of pure ion beam with different mass is carried out based on a theoretical approach. Then, the acceleration of the DT-mixed negative ion beams is investigated by two- and three- dimensional analyses. Finally, the operational parameters of the DT-mixed negative ion beams are evaluated.

2. NBI system for DT-mixed beams

2.1. Circulation of DT fuel in fusion reactor

In order to realize a self-sufficient power plant, the DT fuel is circulated in a fusion plant as shown in Fig. 1. In a conventional concept of the fusion plant, exhaust of DT gas from fusion plasmas including impurities is moved by pumping system into Tokamak Exhaust Processing (TEP) system. The recovered hydrogen isotopes are transferred to the isotope separation system (ISS), while the impurity gases are exhausted to environment after enough detritiation. In addition, tritium produced in the blanket is collected by Tritium Extraction System and is also transferred to the ISS in order to use it as fuel. In the ISS, the collected gases are required to be separated into D and T with high purity with eliminating H, because fueling and NBI systems use pure D_2 or T_2 gases or DT-mixed gas. This isotope separation requires high tritium throughput in the tritium plant system and increase the tritium inventory due to the cryogenic liquid hold-up of high T enrichment column, which is one of critical issues for the design, and which increases a possible risk to a safety management.

In the new DT fuel circulation concept, instead of the separated pure DT gases, the DT mixed gas is supplied to the fueling and NBI systems without DT isotope separation. Only H isotope is removed by the ISS after He ash and other impurities are removed by the TEP. Although the fueling gas and pellet with the DT mixed gas are feasible even in a present technology [4], a possibility of the DT mixed NBI has not been investigated technically so far. Therefore, technical issues of the DT-mixed NBI are discussed for the first time.

2.2. Technical issues of DT-mixed NBI system

In the DT-mixed NBI, the DT-mixed gas is supplied to the ion source and the neutralizer, and the DT-mixed beams are injected to a plasma as shown in Fig. 2.

At first, DT plasmas are produced in the ion source for the DT-mixed ion beams. Considering the plasma parameters on ITER and DEMO, a negative ion source is used for the DT-mixed NBI. In such a case, one of technical issues is an isotope effect on negative ion production due to the incident velocities for the surface production of negative ions, which might cause a difference of extracted negative ion current between D and T [10]. In addition, suppression of higher current of co-extracted electrons is also one of the issues of long pulse operations [11].

As for the acceleration part, the DT-mixed ion beams are accelerated through a negative ion accelerator with a multi-aperture multi-grid (MAMuG) concept [12,13], which strongly dominates the performance of the NBI such as beam energy, injection power and pulse length. However, due to unclear beam optics for the mixed-ion beams, the simultaneous acceleration of the DT-mixed ion beams is the largest issue for the DT-mixed NBI. Therefore, the beam optics for the mixed-ion beams in the accelerator is investigated in this paper.

After the DT-mixed ion beams are accelerated, 60% of the beam is neutralized by collisions between the supplied DT gases in the neutralizer. Remaining 40% of the beams is dumped on the residual ion dump (RID) [14], which can be chosen among 2 kinds of separation techniques: electric and magnetic deflections. Because the electric separation of the residual ions depends on the beam energy only, the electric RID in the DT-mixed NBI can be commonly operated as well as the NBI with the D beam. On the other hand, because the magnetic separation depends on the mass and the energy, the DT-mixed ion beams are separated in the RID according to the mass of the beams, which can contribute the reduction of the power load on the RID. Both of the RID systems have each advantage in terms of the operations.

Other issues are the production of neutrons by the DT reaction in the DT-mixed NBI system. Along the beamline, the DT reaction occurs due to collisions between the DT beams and the accumulated DT gases on the surface of the RID and a beam dump. Although these neutrons strongly radioactivate the beamline components, an estimation of the neutron production rate and the influences on the beamline components will be investigated in future.

After all, one of the critical issues of the DT-mixed NBI is considered to be the acceleration of the DT-mixed ion beams in the accelerator. Therefore, the beam optics of the mixed ion beams is investigated by theoretical and numerical approaches in order to explore a possibility of the DT-mixed NBI.

3. Two-dimensional analysis of beam optics in different mass

3.1. Theoretical approach for beam acceleration with different mass

In order to investigate the beam optics of the mixed ion beams, the mass dependence of the beam optics is discussed from the theoretical and numerical viewpoints.

The beam optics is basically determined by balance between space charge and electrostatic lens. In the accelerator, the space charge corresponds to the current density of the ion beam, and the electrostatic lens corresponds to a geometry of acceleration grids and applied potential. In order to accelerate the ion beams with the different mass from the identical acceleration geometry, the space charge, that is, the current density should be adjusted to match the beam optics.

As the current density is written by $j_i = z_i n_i v_i$, the space charge on a beam trajectory is given by

$$z_i n_i = \frac{j_i}{v_i} = j_i \sqrt{\frac{m_i}{z_i}} \frac{1}{\sqrt{2E}} \tag{1}$$

where z_i, n_i and v_i are a charge number, density and velocity of the beam, and m_i and E_i are the mass and energy of the beam, respectively [15]. Therefore, this space charge can be kept by satisfying $j_i\sqrt{m_i} = \text{cons}\tan\text{t}$ where mass dependence is shown. Therefore, this indicates that the identical beam trajectories in the identical accelerator geometry can be obtained if the operational current density between D and T beams satisfies $j_D\sqrt{m_D} = j_T\sqrt{m_T}$.

3.2. Numerical simulation for beam acceleration with different mass

In order to confirm this relationship, a two-dimensional analysis of the beam trajectory was carried out on ITER-like 5-stage acceleration geometry which is optimized for the D beam with the beam energy of 1 MeV and the current density of 250 A/m^2 as shown in Fig. 3. In this acceleration geometry, an extractor consists of a plasma grid (PG) and an extraction grid (EXG) with an aperture diameters of 14 and 13 mm. The accelerator consists of 5 acceleration grids (A1G-A4G, GRG) with aperture diameters of 14 mm for