Progress in long pulse production of powerful negative ion beams for JT-60SA and ITER


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Abstract. Significant progress in the extension of pulse durations of the powerful negative ion beams has been made to realize the neutral beams injectors for JT-60SA and ITER.

As for the long pulse production of high-current negative ions for JT-60SA ion source, the pulse durations have been successfully increased from 30 s at 13 A on JT-60U to 100 s at 15 A by modifying the JT-60SA ion source, which satisfies 70% of the rated beam current for JT-60SA. This progress is based on the R&D efforts about the temperature control of the plasma grid and uniform negative ion productions with the modified tent-shaped filter field configuration.

As for the long pulse acceleration of high power density beams in the MeV accelerator for ITER, the pulse duration of MeV-class negative ion beams has been extended by more than 2 order of magnitude from the last IAEA conference. A long pulse acceleration of 60 s has been achieved at 70 MW/m² (683 keV, 100 A/m²) by modifying the extraction grid with high cooling capability and high-transmission of negative ions.

These results are the longest pulse durations of high-current and high-power-density negative ion beams in the world.

1. Introduction

To proceed the JT-60SA [1] and ITER [2] projects successfully, negative-ion-based neutral beam injectors (N-NBIs) providing 10 MW D³ beam for 100 s and 16.5 MW for 3600 s are necessary for actuators of the plasma heating/current drive. For the realization of these N-NBIs, the long pulse generations of the powerful negative ion beams of 500 keV, 22 A (130 A/m²) and 1 MeV, 40 A (200 A/m²) are essential challenges [3]. In order to obtain these negative ion beams, lots of R&D efforts to improve negative ion productions [4-5], beam optics [6] and voltage holding capability [7] have been made in the world.

In Japan Atomic Energy Agency (JAEA), high energy accelerations with multi-stage multi-aperture accelerators were the priority of R&D activities [8]. In order to design the acceleration gaps for JT-60SA and ITER, the voltage holding capability of large-size multi-aperture grids has been intensively investigated. Up to the last IAEA conference, the required beam energies for JT-60SA [9] and ITER [10] have been realized by modifying the accelerators based on the experimental database.

After that, one of the remaining common issues for JT-60SA and ITER is the extensions of pulse durations. Toward this issue, the development of the key technologies for the long pulse production/acceleration of the negative ions has been concentrated by using the JT-60SA ion source and the MeV accelerator. This paper reports the recent activities and progresses on the development of the long-pulse negative ion beams toward the realization of JT-60SA and ITER N-NBIs.

2. Long Pulse Production of Negative Ions
In JT-60U, the longest pulse duration was 30 s with the beam current of 13 A [11], which was limited by the increase of a grid heat load due to a deviation from an optimum perveance condition. Since the JT-60U negative ion source was originally designed for short-pulse of 10 s with an inertially-cooled plasma grid (PG), the PG was overheated according to the pulse duration. This overheat of the PG resulted in a degradation of cesium (Cs) coverage on PG, namely negative ion current. To suppress this degradation for the long pulse production, the active control of the PG temperature has been developed for the JT-60SA ion source [12]. Moreover, in order to increase an extractable negative ions, the improvement of the beam uniformity has been tried by changing the magnetic field configuration of an arc discharge chamber to the tent-shaped filter configuration [13].

In order to overcome these issues, a teststand by using the JT-60SA ion source and power supplies was constructed in 2012. Since the 500 kV acceleration power supply is not available in this teststand, the long pulse production/extraction of 10 keV hydrogen negative ion beam are carried out. Fig. 1(a) shows the JT-60SA negative ion source which is basically reuse of that for JT-60U. Source plasmas are produced by filament-driven arc discharges in the
KAMABOKO type chamber and confined with permanent magnets and the PG filter field [14]. The negative ions are mainly produced on a surface of Cs covered PG made of molybdenum. The PG composed of 5 segments with 1080 apertures in the extraction area of 110 cm x 45 cm. To receive 10 keV, 22 A beams for 100 s, a beam target was installed below the EXG, instead of the acceleration grids for this teststand.

### 2.1 Temperature Control of Plasma Grid

Since the negative ion production strongly depends on the work function on the PG given by the coverage of Cs, the negative ion production can be controlled by the Cs coverage via the temperature of the PG. According to the previous studies [15], the temperature of the PG should be kept within 150-250 °C in order to obtain an optimum negative ion production.

In order to extend the pulse duration with keeping the negative ion current, the active-control system of the PG temperature has been newly developed as shown in Fig. 2(a)(b). In this system, the PG is cooled and heated by the fluid, at the same time, a heat flux of maximum 0.1 MW/m² is removed by the fluid. In some candidates of the primary fluid, the fluorinated fluid (GALDEN HT-270) was applied in this system, which gives a big advantage of a high boiling point of 270 °C at 0.1 MPa with low viscosity [12].

The key parameter to design the system was the time constant of the temperature control of the PG. The saturation time of the PG temperature during the arc discharge was designed to be 7 s which was shorter than the decay time of the negative ion current which had been found to be about 30 s from the past experimental results.

At first, for the proof-of-principle (PoP) of the long pulse production, the PG temperature control was applied to only 1 of 5 segments of the PGs. This PoP-PG was made of Cu and had 14 cooling channels with size of 3 x 6 mm² between 110 apertures corresponding to 10% of the extraction area. Fig. 3 shows that the saturation time of the PG temperature is decreased with the temperature increase of the fluid by improving the cooling capability due to the physical property of the fluid, and the design value of 7 s has been satisfied in the operational range of 150 °C-200 °C at a flow speed of 1.3 m/s.

By applying the temperature control of the PG, the long pulse capability of the negative ion current was increased.
production has been significantly improved as shown in Fig 4(a)(b). This improvement implies the success of the sustainment of the Cs coverage on the PG. As a results, the sustainable current density for 100 s was 5 times higher than the original inertially-cooled PG.

Based on the results, 5 segments of the prototype PGs having 1080 aperture corresponding to 100% of the extraction area have been developed. The PGs were made of molybdenum for 3 segments, oxygen free copper for 2 segments. 10 cooling channels with the same size as PoP-PG are arranged between each aperture lines. Due to the size limitation between apertures, the thickness of the PG was increased from 6 mm to 9mm, and the shape of the apertures was modified to the 75° taper-type. Although the configuration of the PG aperture was varied from the original one, the extraction of the required current density of 130 A/m² has been confirmed by the dedicated experiments for negative ion extractions from various aperture shapes.

Since the time constant of the prototype PG was designed to be same as the PoP-PG, the similar saturation time of the PG temperature has been obtained as shown in Fig. 3, which is also enough shorter than the decay time of the negative ions. By using the prototype PG, the long pulse production has been tried with the prototype PG.

### 2.2 High Current Production with Uniform Negative Ion Profile

In order to realize high-current long-pulse production, one of remaining issues is a uniformity of beam profile. Since the beam current is determined by ensemble of each beamlets, each beamlets should be produced and accelerated in the same focusing property. If un-uniform plasma is

**FIG.5.** (a) Schematic view of the concept of the original filter field (left) and calculated population profile of primary electrons (right) (b) The modified tent-shaped filter concept with 2D-mentionally rotated filter field (left) and its population profile

**FIG.6.** The temperature increase \( \Delta T \) profile on the beam target at 45mm below the EXG. Beam pulse duration is 1 s. \( \Delta T \) is proportional to the beam intensity. Cooling pipes are arranged transversely.
produced, lower beam current with higher grid heat load is expected due to the un-uniform negative ion extraction/acceleration.

In JT-60U, past experimental results suggested that the magnetic field configuration with the PG filter field caused the low beam uniformity of 70%, where the uniformity is defined as the ratio of the beam current and the estimated beam current where maximum current density is uniformly assumed \((\propto I/\int j_{\text{max}}\,ds)\). In order to increase the negative ion current by improving the plasma uniformity, the tent-shaped filter configuration was tested, which had been developed in JAEA by using the small ion source \([16]\).

From the past results \([13]\), the key factor for the beam uniformity was found to be a uniform plasma production with control of the magnetic drift for primary electrons emitted from filaments. The calculated electron population profile for the original configuration shows the localized profile due to one way grad-B drift by the PG filter field as shown in Fig. 5(a).

In order to resolve the localization of the primary electron, the tent-shaped filter concept has been designed for the JT-60SA ion source as shown in Fig. 5(b). By adjusting the permanent magnets from asymmetry to axial symmetry, the orbits of the primary electrons were designed to go around the magnetic filter by the rotational grad-B drift.

As a result, by applying the tent-shaped filter concept, the uniformity of the extracted beam profile has been significantly improved from 68% to 83% as shown in Fig 6, where 32 A negative ions has been produced. Moreover, 22 A negative ion has been obtained only from the 3 segments of Seg.2~4. Because the extractable negative ion current for this configuration become 1.14 times higher than the original one at the same condition, the negative ion current of 22 A has been realized at the arc power of 200 kW, the extraction voltage of 7.4 kV and the PG temperature of 250 °C. Although the co-extracted electrons accompanied with the negative ion extraction was increased from 20% to 50% of the total extraction current due to the reduction of the filter field strength from 0.7 to 0.4 mTm, this heat flux was below the allowable level of the cooling capability of the EXG (1 MW/m²). The high-current production for JT-60SA has been realized by this modified tent-shaped filter concept.

2.3 Long Pulse Production of High Current Negative Ions for JT-60SA

In 2013, the long pulse production of 2A negative ions has been demonstrated with the PoP-PG from 10% extrication area \([12]\). In 2014, the prototype PG having 100% extraction area and the tent-shaped filter configuration has been installed in the JT-60SA ion source. By utilizing these Fig.7. (a) The progress of the long pulse production started from 2013 with proof-of principle PG and prototype PG for the PG temperature control. (b) Progress of the achieved performance required for JT-60SA.
new techniques, the long pulse production of high current negative ions has been tried. As a result, 15 A negative ions with pulse duration of 100 s has been achieved for the first time as shown in Fig.7(a). This performance has reached to 70% of the required current for JT-60SA and fulfil the required pulse duration which is 3 times longer than the result on JT-60U. The long pulse production is going on in the teststand.

Fig.7(b) shows the progress of a performance diagram for the JT-60SA N-NBI. At present, the long pulse capability has been significantly improved. Therefore, long pulse accelerations with high-current negative ion beams are expected in JT-60SA operation. Moreover, for ITER, this R&D result contributes to the PG design of the ITER ion source in terms of the required time constant for the high-current long pulse production.

3. Long pulse acceleration of high power density beams with improved extractor

To realize the long pulse acceleration of the high-power density MeV-class beam for ITER, the reduction of the heat load and the heat removal from acceleration and extraction grids are essential techniques. Up to the last IAEA conference, the reduction of the heat load by controlling the beam trajectories to compensate the beam deflection was the key issue for the acceleration of ITER relevant beams [10].

After that, one of remaining issues is the heat removal of the co-extracted electrons from the EXG. Because the EXG has magnets to deflect the co-extracted electrons, the operational temperature is strongly restricted by the demagnetization temperature of the SmCo-magnets about 200 °C. In the MeV accelerator (Fig. 1(b)), since the EXG of JT-60 type was used, the pulse duration of the ITER relevant high power density beams was limited to 0.4 s. This was
because an allowable heat flux of the EXG was limited to 1MW/m² for JT-60 type where 20% of the electron current ratio was assumed. However, the heat flux of the co-extracted electrons for ITER-relevant beam was estimated to be over 2MW/m² due to higher current density and higher electron ratio of 50% were assumed. Therefore, a new EXG has been developed for the demonstration of the long pulse acceleration of high-power density beams for ITER [17].

The key parameters for the long pulse EXG are the cooling capability for the co-extracted electrons and the transmission of the extracted negative ions. In order to improve the cooling capability, the position of water-cooling channels was moved near the electron receiving area as shown in Fig. 8(a)(b). Moreover, the cross section of the cooling channels was enlarged by 3 times than that of JT-60 type. As a result, the maximum temperature of the EXG has been reduced from 257 °C to 104 °C in 3D thermal analysis.

In addition, the configuration of the EXG has been re-designed to enhance the transmission of the negative ions [18]. In the JT-60 type, a clearance of 0.4 mm between the beam outline and the electron suppression grid (ESG) was marginal to increase the beam current density. In this case, the direct interception of the negative ions to the ESG results in both of the low negative ion current and the production of the secondary electron flux to downstream grids. Therefore, the aperture size and its displacement of the EXG-ESG configurations has been modified as shown in Fig. 8(b). As a result, the clearance is increased to 1.4 mm in 3D beam analysis, which indicates the higher transmission is expected even in higher current density.

The long pulse acceleration has been tested in the MeV accelerator with the developed EXG-ESG from 2014. As a result, the negative ion current has been increased by 10% at the same condition as shown in Fig. 9(a), which indicate the improvement of the transmission in high-arc-power high-current condition. The higher transmission also affects to the reduction of the grid heat on the upstream acceleration grids of A1G-A3G as shown in Fig.9(b). Totally the grid heat load has been reduced from 17% to 12%, which is considered to be the effect of the suppression of secondary electrons production due to the direct interception of the negative ions to the ESG. This level of the grid heat load is enough lower than the ITER requirement (25%) even if assuming the increase of the stripping loss in the ITER accelerator.

**FIG. 9.** (a) Hydrogen negative ion current for the JT-60 and ITER type EXG. (b) Grid heat loads on the acceleration grids from A1G to GRG.

**FIG.10.** Progress of the long pulse accelerations for high-power density beams in the MeV accelerator.
At present, long pulse acceleration of 700 keV, 70 MW/m² beam for 60 s has been achieved as shown in Fig. 10. Although the pulse duration of 60 s is limited by the power supplies, no limitation has been observed to increase the power density.

4. Summary

Toward the realization of JT-60SA and ITER N-NBIs the key technologies to realize the high-current long-pulse negative ion beams have been developed to overcome the common issues.

As for the long pulse production of high current beams, the PG temperature control system successfully demonstrated the sustainment of the negative ion production. In addition, the beam uniformity has been improved to enhance the negative ion current. The improvement of the uniformity also contributes the reduction of the grid heat load. Since the JT-60SA ion source has been upgraded by these techniques, the negative ion production of 15 A for 100s has been achieved, which has reached to 70% of the target current.

As for the long pulse acceleration, the EXG with high cooling capability and high transmission has been developed to accelerate ITER relevant power density beams. By applying the developed EXG, the long pulse acceleration of 70 MW/m² beam for 60 s has been obtained successfully. This pulse duration was 2 orders higher than that for the last IAEA conference and has reached to the limit of the present power supplies.

Both of the obtained experimental results of the long pulse production/acceleration are the first breakthroughs to realize the long pulse production/acceleration of the high-current/high-power-density negative ion beams in the world.

References