Long-pulse acceleration of 1MeV negative ion beams
toward ITER and JT-60SA neutral beam injectors

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Abstract. Pulse duration of the ITER-relevant high power density hydrogen negative ion beams at 1 MeV has been successfully extended from 0.4 s to 60 s by using a prototype Multi-Aperture and Multi-Grid accelerator for the ITER and JT-60SA neutral beam systems. This significant progress was achieved based on developments of technology for the design of a voltage holding capability and improvement of a beam optics, which are directly applicable to ITER and JT-60SA. In the design of the voltage holding capability, one of critical remaining issues was a multi-grid effect. This was experimentally investigated by using a multi-grid configuration. The voltage holding capability predicted based on this experimental investigation showed good agreement with experimental results obtained in the JT-60SA negative ion source within 10 % deviation. This result was also applied to improve the beam optics by tuning the acceleration gap. In addition, the extractor configuration was optimized. These tunings significantly contributed to reduce the grid power load from 15 % to 9 % of the total beam acceleration power and to increase the current density up to 1.4 times higher. As the result, 0.97 MeV, 190 A/m² negative ion beams were generated stably without any breakdowns and any thermal damages on the acceleration grids. This pulse length of the beams with the ITER-relevant energy and current density is the longest one in the world and contributes to assure the 1 MeV accelerator for the ITER NB system.

1. Introduction

In order to realize high performance fusion plasmas in ITER and JT-60SA tokamaks [1, 2], the neutral beam (NB) systems with injection powers of 16.5 MW and 10 MW and pulse durations of 3600 s and 100 s are required for the plasma heating and current drive, respectively [3-5]. In these NB systems, high energy and large current negative ion/beam sources to produce 1MeV, 40 A beams for ITER and 0.5 MeV, 22 A for JT-60SA are required. However, because developments of such negative ion/beam sources having a capability of long pulse duration are still challenging issues, R&Ds are being carried out in the world [6-9]. Particularly, in National Institutes for Quantum and Radiological Science and Technology (QST), electrostatic negative ion accelerators with 5- and 3-stage Multi-Aperture Multi-Gird (MAMuG) concept are being developed for ITER and JT-60SA [10, 11]. A lot of R&Ds have been carried out to solve
common issues for ITER and JT-60SA NB systems by utilizing the Megavolt Test Facility (MTF) and JT-60 negative ion sources.

In the past development in QST, the ITER-relevant beam energy and current density of 0.98 MeV, 185 A/m² have been achieved by improving voltage holding capability and starting to compensate the multi-beamlet deflections in 2010 [12]. However, the pulse duration was limited up to only 0.4 s due to excess power load on the acceleration grids. After that, compensations of the multi-beamlet deflections were optimized to reduce the power load on the acceleration grids by improving the beam optics in 2010-2014 [13, 14]. However, the pulse lengths with the achieved beam energies were limited to be less than 1 s and the stable beam acceleration was limited to be < 0.7 MeV due to the poor voltage holding capability and the grid power load on acceleration grids [15], which were remaining issues for ITER and JT-60SA NB systems.

Therefore, after the last FEC in 2014, technologies to design a voltage holding capability and improve a beam optics for reduction of grid power load have been developed in order to solve these issues and improve the accelerators. In this paper, the recent progress of the R&D for ITER and JT-60SA NB systems are reported.

### 2. Development of voltage holding prediction for the design and improvement of accelerators by taking into account multi-grid effect

The voltage holding capability is an essential performance of high energy accelerators, which strongly dominates not only the beam energy but also the beam current through the Child-Langmuir law (I~V^{1.5}). Therefore, prediction of the voltage holding capability is necessary for the design and improvement of accelerator, so far a lot of work has been made experimentally and theoretically [16, 17]. However, because physics of vacuum discharge is still unclear, there was no comprehensive prediction of the voltage holding capability of the MAMuG accelerators. In order to develop the techniques for the prediction and the design, the fundamental factors to determine the voltage holding capability on MAMuG accelerator have been investigated so far, such as gap length between grids, surface area and number of apertures (multi-aperture effect) and local electric field at edge as shown in Fig. 1. The remaining factor was so-called the multi-grid effect which was the most characteristic in MAMuG accelerators.

In order to investigate this multi-grid effect experimentally, the 5-stage cylindrical electrode having similar surface area to that of the accelerators for ITER and JT-60SA with uniform electric field profile was developed as shown in Figure 2(a) and tested in MTF [18]. In this experiment, the breakdown probability and the conditioning speed to increase the applied voltage were investigated in vacuum by applying a high voltage to each single stage and 2-5 multi-stages to simulate a 5-stage accelerator. According to the number of stages, the sustainable voltage per single stage and the conditioning speed to reach the maximum voltage with multi-grid was reduced. Totally, the voltage holding capability was reduced by 30% from single stage to 5-stages. Because the increase of the number of the stages corresponds to the increase of the total surface area including the multi-grids, the obtained results were compared with the previous surface area effect as shown in Fig. 2(c). In this figure, VHC is defined

![Fig. 1. Essential factors for the design of voltage holding capability.](image-url)
as an indicator of the voltage holding capability, which is the sustainable voltage normalized by $g^{0.5}$ based on the Clump theory ($V \sim g^{0.5}$) [19]. The obtained results in single to multi stages agreed with the extrapolation of the previous area effect on single stages. Therefore, it was found that the multi-grid effect on the voltage holding capability could be considered as the area effect of total surface area integrated over the multi-stage accelerator, which was derived to be $V/g^{0.5} = 33.5$ S$^{0.12}$.

By taking the multi-grid effect into account, the techniques of the prediction and design of the MAMuG accelerators have been developed as shown in Fig. 3(a). In this method, the nested structure of intermediate grid supports in the MAMuG accelerators was decided to maximize the voltage holding capability based on the experimental results within given boundary conditions of the diameter of the top and bottom grids and outermost boundary of insulators. By using this method, the 3-stage MAMuG accelerator for JT-60SA has been designed and experimentally tested as shown in Fig. 3(b). As the result, the predicted gap dependence of the voltage holding capability agreed with the experimental results within an error of 10 %, which indicated good reliability of this design technique. From these results, the design of the MAMuG accelerator for JT-60SA has been completed in terms of the voltage holding capability.

This is a useful technique to design the voltage holding capability of the MAMuG accelerator, and directly applicable to not only the accelerators for ITER and JT-60SA but also multi-grid system such as the high voltage busing for ITER [20]. Furthermore, this technique was successfully used for the gap tuning to compromise between the voltage holding and the beam optics for the long pulse acceleration of 1 MeV beam by using the prototype accelerator for ITER.
3. Tuning of the beam optics for long pulse acceleration of high energy beams

Demonstration of long pulse acceleration of high energy negative ion beams is one of critical issues for ITER and JT-60SA. Before last FEC in 2014, the pulse lengths with the rated beam energies were limited to be less than 1 s due to the power load on acceleration grids, and also available beam energies for long pulse accelerations were limited to be 70% of the rated beam energies [3]. Therefore, further reduction of the grid power load was one of remaining issues for ITER and JT-60SA NB systems.

In order to overcome this issue, the technology for the tuning of the beam optics was developed by using the prototype accelerator for ITER in MTF as shown in Fig. 4. In the past results, after the improvement of the voltage holding of the accelerator [12] and the application of the compensations of the beamlet deflections at the extractor [10], the extractor was modified again to reduce the grid power loads by improving the transmission of the high current density negative ion beams [13]. In this modifications, a diameter of the beam steering control grid (SCG) of the extractor was enlarged to avoid the direct interception of negative ion to the extractor and suppress the emission of secondary electrons from the extractor, which increased the extracted current density and reduced the grid power load at upstream grids significantly [14].

However, the grid power load on the grounded grid (GRG) was still high more than 3% of the total acceleration power at the high current density beam of 1 MeV 200 A/m², which was not acceptable for long pulse acceleration. From the results of the beam analysis, it was found that this high grid power load on the grounded grid was caused by the mismatch between the available current density by the improved extractor and the acceleration electric field which became relatively weak, because the beam optics was mainly determined by the ratio of the electric fields of the extraction gap and the first acceleration gap. Therefore, the tuning of the acceleration electric field was carried out to achieve the long pulse acceleration of 1 MeV beams.

At first, the improvement of the acceleration electric field was designed by the beam analysis as shown in Fig. 5. In this calculation, divergence angles at the exit of the GRG were investigated by increasing the acceleration electric field at the fist acceleration gap by 0-14% from the original acceleration electric field. By increasing the acceleration electric field by 14%,

![Fig. 4. (a) Structure of the prototype accelerator for ITER in MTF. (b) A trajectory of a negative ion beam simulated by a 3D simulation with a schematic diagram of the extraction grid, acceleration grids, protection resistor and the power supplies.](image-url)
it was found that lower divergence angle even in higher current density of 200 A/m² could be obtained at the beam energy of 1 MeV. And also, higher voltage ratio of Vext/Vacc than the original case was expected at minimum divergence angle, which indicated that the beam optics could be tuned to the acceleration of higher current density beams.

In order to realize the increase of the acceleration electric field at the first acceleration gap, two modifications were carried out in this experiment. At first, the gap length of the first acceleration gap was tuned from 112 mm to 109 mm. Originally, this gap length had been tuned in terms of the voltage holding capability. Therefore, by applying the developed technique to design the voltage holding capability of the MAMuG accelerator, the gap length has been tuned again to compromise between the voltage holding capability and the beam optics. As for the second step, a voltage drop at the highest potential was optimized. In the high voltage acceleration power supply, the protection resistors were connected in series with the accelerator as shown in Fig. 5(a). Therefore, according to the total current, the applied voltage was dropped at the highest potential region only. In this experiment, this resistance was reduced to suppress...
the voltage drop by compromising the surge protection capability and the acceptable voltage drop. As a result, the acceleration electric field has been increased by 14% as designed.

After the tuning of the acceleration electric field, the available current density at the same beam energy of 0.8 MeV was significantly increased by 42% from the original case, and the optimum voltage ratio of \( \text{Vext} / \text{Vacc} \) was increased from \( 5.5 \times 10^{-3} \) to \( 6.1 \times 10^{-3} \) as designed (Fig. 6(a)). From these results, it was found that the tuning of the beam optics to the acceleration of higher current density has been achieved. Moreover, the total grid power load on the acceleration grids was reduced from 15% to 10% as shown in Fig. 6(b), and the power load on each of the grid below 3% has been achieved for the first time, which finally satisfied allowable level for the long pulse acceleration of 1 MeV beam.

By increasing the beam energy from 0.8 MeV to 1 MeV, further reduction of the grid power load was obtained at the 1 MeV, 200A/m\(^2\) ITER-relevant power density beams as shown in Fig. 7, because the compensation of the beamlet deflections has been tuned to 1 MeV beam. Finally, the total grid power load has been slightly reduced to about 9%.

This tuning of acceleration electric field with combination of the design technique of the voltage holding capability is a much useful technique to comprehensively design the beam optics of MAMuG accelerator and directly applicable to the accelerators for ITER and JT-60SA.

4. Achievement of acceleration of ITER-relevant power density beams for 60 s

After the improvement of the beam optics, the long pulse acceleration of the ITER-relevant high power density beam was tried with the modified prototype accelerator for ITER.

In order to obtain such high power density beam with long pulse, the conditioning procedure is also important technique for the operation of the NB systems. Basically the conditioning of the high energy negative ion beam/source consists of 3 phases which are increases of energy, current and pulse length. Particularly, conditioning with high acceleration voltages and low Cs injection was most essential to realize a stable operation of high power density and long pulse beams.

For this purpose, the condition of the acceleration voltage was kept at 1 MV with a daily conditioning during the experimental campaign regardless of Cs injection. As for the low Cs injection, during Cs injection of 3.4 \( \mu \)g/s, higher power arc discharges up to 30 kW with a pulse length of \( \sim 3 \) s were repeated to enhance the Cs recycling through a heating of the chamber wall, which contributed to the early realization of ITER-relevant 1 MeV 200 A/m\(^2\) beam in just 4 operational days after the Cs injection. Thanks to the short conditioning for energy and current by these procedures, the stable acceleration was realized with low Cs injection less than 1 g during the conditioning of the pulse length. After the extension of the pulse length with 17 conditioning shots at about 1 MeV, the long pulse accelerations of ITER-relevant beams (0.97 MeV, 190A/m\(^2\)) up to the power supply limitation of 60 s have been achieved.

*Fig. 8. Time evolution of (a) accelerated current density, (b) acceleration voltage, (c) extracted current including ion and electron, (d) temperature increase of cooling water for GRG during the 60 s pulse of 0.97 MeV and 190 A/m\(^2\).*
for the first time as shown in Fig. 8. Moreover, this significant achievement was obtained in just 16 operational days, which could contribute to the effective operation of ITER and JT-60SA.

The significant progress after the last FEC has been achieved in terms of the long pulse acceleration of high power density beam as shown in Fig. 9 and Table I. Because the pulse duration of the ITER-relevant power density beam had been limited to be 0.4 s in the previous results, this achievement is one of breakthroughs for the development of the MAMuG type accelerators. Furthermore, total accelerated energy density of high power density beam has been increased rapidly up to 11058 MJ/m² beyond the requirement of the accelerator for JT-60SA (6500 MJ/m²) as shown in Fig. 10, which suggested that the MAMuG accelerator for JT-60SA is available based on the present technologies.

Toward the accelerator for ITER, because the achieved pulse length in this time is limited by the limitation of the power supply, longer pulse length up to 3600 s will be tried after the upgrading of the power supply and improving the negative ion production for long pulse. However, because no breakdown occurred up to 60 s and the temperature of the cooling water was saturated within 20~30 s, there is no problem to extend the pulse length in terms of the acceleration so far. Moreover, as for the cooling capability of the grids, the temperature increase of the accelerator for ITER can be estimated to be about 20 °C from the experimental results by taking the number of the apertures and the flow rates into account, which is low enough to design the cooling capability of the acceleration grids.

**TABLE I: ACHIEVEMENTS AND REQUIREMENTS FOR ITER AND JT-**

<table>
<thead>
<tr>
<th>Achievement</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td></td>
</tr>
<tr>
<td>FEC 2014</td>
<td>FEC 2016</td>
</tr>
<tr>
<td>0.98 MeV</td>
<td>0.97 MeV</td>
</tr>
<tr>
<td>Current</td>
<td></td>
</tr>
<tr>
<td>(Current density)</td>
<td>0.43 A (185 A/m²)</td>
</tr>
<tr>
<td>Pulse length</td>
<td></td>
</tr>
<tr>
<td>0.4 s</td>
<td>60 s</td>
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</table>

5. Conclusion

In order to realize the NB systems for ITER and JT-60SA, key technologies to design the voltage holding capability and to reduce the grid power loads in the MAMuG accelerators have been developed.
As for the design of the voltage holding capability, the multi-grid effect was investigated experimentally for the first time. Empirical scaling of voltage holding capability for total facing surface area of single- and multi-stage electrodes was obtained, which suggested the multi-grid effect could be interpreted as the area effect of total surface area integrated over the multi-stage. Based on the experimental result, the design technique taking the multi-grid effect into account was developed and applied to the 3-stage MAMuG accelerator for JT-60SA. As the result, the reliable prediction of the voltage holding capability within 10% deviation has been obtained. This technique was also applied to the prototype accelerator and the high voltage bushing for ITER.

As for reduction of the grid power load, acceleration electric field of the first acceleration gap and the extractor configuration of the ITER prototype accelerator were tuned to have the best optics at 1 MeV, 200A/m² by a 3D beam simulation. The beam optics and the voltage holding capability could be compromised by the developed technique of voltage holding prediction. The reduction of the grid power load from 15 % to 9 % in total within allowable level of 3% at each of the grids has been successfully achieved to ensure the long pulse acceleration. These developed technologies can be applied to the accelerator for ITER and JT-60SA directly.

By applying these developed technologies, the long pulse acceleration of negative ion beams of 0.97 MeV, 190 A/m² was demonstrated successfully for the power supply limitation of 60 s without any breakdown and any thermal damage on the acceleration grids. This is the first demonstration of the long pulse acceleration over the time constant of the cooling capability on the acceleration grids on the ITER-relevant power density beams.

Reference