1 MV Holding and Beam Optics in a Multi-aperture Multi-grid Accelerator for ITER NBI

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Abstract. At JAEA as the JApan Domestic Agency (JADA) for ITER, a multi-aperture multi-grid (MAMuG) accelerator has been developed for the ITER neutral beam heating & current drive (NB H&CD) system. A target is H^- ion beam acceleration of 0.5 A (200 A/m^2) at 1 MeV for several tens of seconds. In the tests to achieve the 1 MV holding, it was found that the voltage holding of the real accelerators was about a half of that obtained in an ideal small electrode. After applying necessary gap length and radii of edges of grid supports to lower the local electric field concentrations, the accelerator succeeded in sustaining 1 MV for more than one hour without feeding H_2 gas. In the beam acceleration, the beamlet was deflected due to magnetic field and space charge repulsion. Consequently these deflections caused high heat load to the grids, and limited the beam pulse length. The beamlet deflection and its compensation methods, which are an aperture offset and so-called “field shaping plate”, were examined by a three-dimensional beam analysis. And then, these compensation methods were applied to the MAMuG accelerator. As results, beam parameters achieved by the MAMuG accelerator were increased to 879 keV, 0.36 A (157 A/m^2) at perveance matched condition and 937 keV, 0.33 A (144 A/m^2) slightly under perveance from 796 kV, 0.32 A (140 A/m^2) reported in the previous conference.

1. Introduction

In a negative ion accelerator utilized in the ITER neutral beam heating & current drive (NB H&CD) system, the generation of 1 MeV, 40 A (200 A/m^2) deuterium negative ion (D^-) beams is required for 3600 s [1]. To meet the requirement, the Japan Atomic Energy Agency (JAEA) is developing a negative ion accelerator, called the “MeV accelerator” [2, 3]. The MeV accelerator is a five stage multi-aperture multi-grid (MAMuG) accelerator, which has been chosen as a baseline accelerator design for the ITER NB H&CD system [4]. A target of the MeV accelerator is to accelerate 0.5 A (200 A/m^2) H^- ion beam at the energy of 1 MeV for several tens of seconds.

After successes of beam acceleration at 796 keV, 0.32 A (140 A/m^2), 0.2 s presented at the previous conference of this series [4], an experimental campaign was dedicated to increase the pulse length. In the first attempt of long pulse test with water-cooled acceleration grids, 600 keV, 161 mA beam was accelerated for 10 s [5]. By this long pulse beam acceleration tests, two issues were revealed. One is insufficient voltage holding capability between grids and its support structures [6]. The other is excessive heat load to melt the grounded grids, which was caused by the beamlet deflection due to magnetic field and space charge repulsion among the beamlets [7].

In order to demonstrate stable beam acceleration for several tens of seconds, following studies have been performed; 1) improvement of the voltage holding capability, 2) beam optics study by a three-dimensional (3D) beam analyses. Then, high energy beam accelerations aiming at

1 MeV were demonstrated. This paper reports the status of these present R&D above and the result of beam acceleration test.

2. Improvement of accelerator voltage holding

Cross sectional views of the MeV accelerator are shown in FIG.1. FIGURE 1 (a) and (b) show the configurations used in the first long pulse test [5] and modified to improve the voltage holding, respectively. The H^- ions are produced in the KAMABOKO ion source [8] on the top of the accelerator. The produced H^- ions are extracted up to several kV through apertures (14 mm in diameter) drilled in a lattice pattern of 5×3 in the extractor, and then accelerated up to 1 MeV. The accelerator consists of four intermediate acceleration grids (A1G-A4G) and the grounded grid (GRG). The applied voltage between each grid is 200 kV at the maximum and 1 MV by the stack of five stages. The minimum gap lengths between metals (grid and grid supports) in each acceleration stage were 102/94/87/78/72 mm respectively in the original configuration [2]. In the long pulse test, the A2G was removed to examine simplicity of the number of acceleration stage. Then, the minimum gap lengths between metals were changed to 102/181/78/72 mm as shown in FIG.1 (a). Each acceleration grid and the GRG are supported by Fiber-Reinforced-Plastic (FRP) insulator columns. To suppress the surface flashover along the FRP surface, specially designed large stress ring has been installed [9]. It was confirmed that the voltage holding capability of the FRP insulator is 300 kV in one stage by installing the large stress ring. This is 1.5 times larger than the rated voltage (200 kV in one stage to sustain 1 MV in five stages). However, the voltage holding of the MeV accelerator including the grids and the grid supports was only 835 kV. The high voltage of 1 MV was sustained when the H_2 gas of 0.1 Pa was fed in the accelerator. This was not sufficient for the stable H^- beam acceleration. The current and energy achieved in the MeV accelerator was 796 keV, 0.32 A (140 A/m^2) in 2008 [4]. To fulfill the ITER requirement (1 MeV, 200 A/m^2), stable 1 MV holding without gas feeding had been strongly desired.

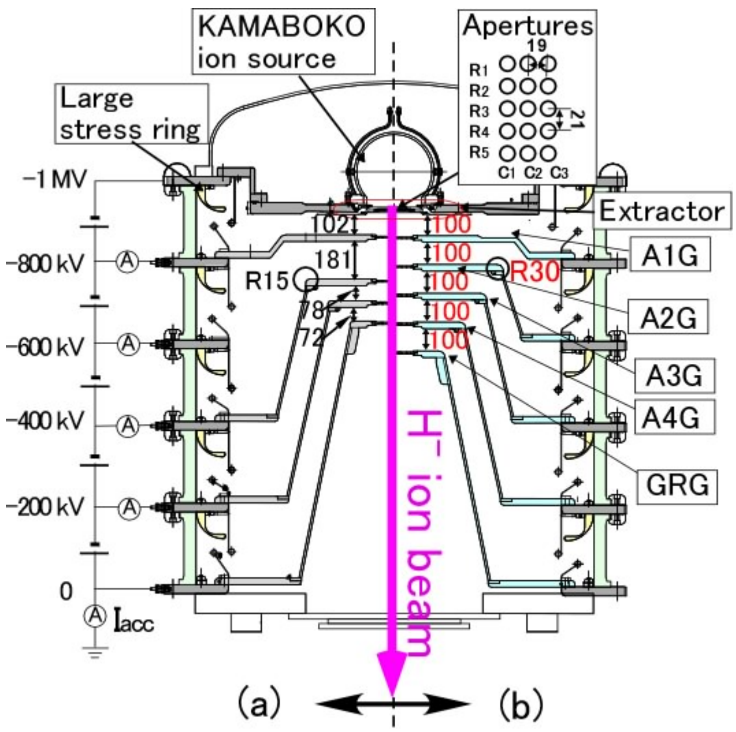


FIG.1 MeV accelerator configurations,
of (a) long pulse test and (b) modified one with longer gap.

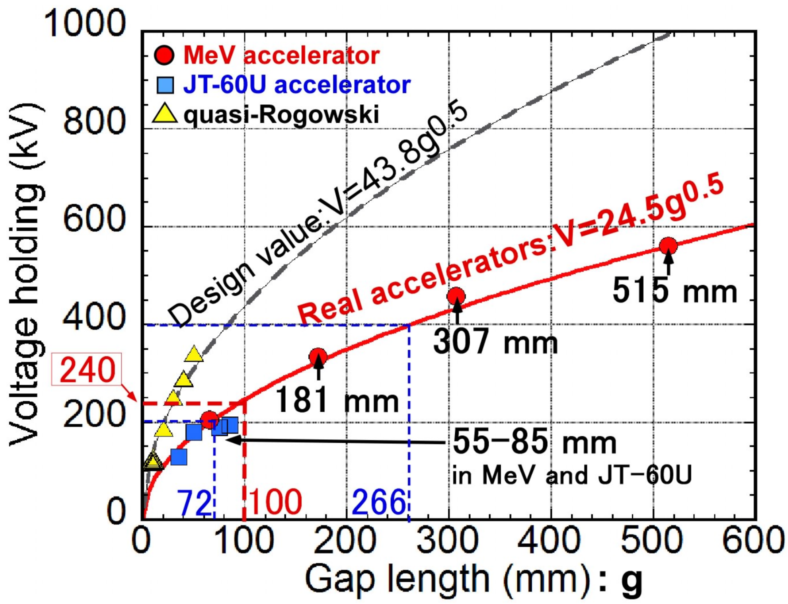


FIG.2 Voltage as a function of gap length

The voltage holding tests were performed in various accelerator configurations of the MeV accelerator [5, 10, 11]. The gap length was widely changed from 72 mm to 515 mm by removing the intermediate acceleration grids. One of them is the accelerator used for the long pulse test as shown n FIG.1 (a). The maximum voltage as a function of gap length is summarized in FIG.2. Results from JT-60U accelerator [12] and those from small quasi-Rogowski electrode (160 mm in diameter) [13] are also shown in FIG.2. FIGURE 2 shows the voltage holding capability follows the clump theory in wide range of 50 - 515 mm gap. Although structure and grid area are different, voltage holding capability of the MeV accelerator and JT-60U accelerator shows the same dependence on the gap length. Moreover, sustainable voltage of these accelerators at JAEA is almost a half of that in the small quasi-Rogowski electrode used for design of these accelerators. In the interior observation of the accelerator after the test, various discharge marks were found on metal surfaces of both cathode and anode sides, in particular on the opposite side of edges and small steps of the order of a few mm on grids and grid supports. This fact shows that the local electric field concentrations at these edges and steps also influence the voltage holding. As one of possible models, it is considered that the clumps emitted from parts with the local electric field concentrations are easily accelerated in a long vacuum gap and caused breakdowns. The data in FIG.2 indicates that the minimum gap length (72 mm) in the MeV accelerator is considered to be marginal to sustain 200 kV. In the four stage MAMuG accelerator as shown in FIG.1 (a), the gap length after removing the A2G (181 mm) was not enough and the gap length of 266 mm was necessary to sustain 400 kV. This result shows that accelerators with less acceleration stages require longer gap length to hold the same acceleration voltage.

Then, the accelerator was modified as shown in FIG.1 (b). The A2G was installed again. The gap length in each stage was extended to 100 mm to hold 200 kV stably (1 MV for five stages) including the margin of 20 %. The margin was decided by the past results that the voltage with beams lowered to be 20 % of that without beams [4]. In the beam optics study using a two-dimensional (2D) beam analysis [14], it was confirmed that the increase of the beam divergence due to the gap expansion was from 3.1 mrad in the original configuration to 3.7 mrad in the modified one, and was within allowable level compared with the requirement for the ITER (7 mrad). In addition, edges of the grid supports were rounded from 15 mm to 30

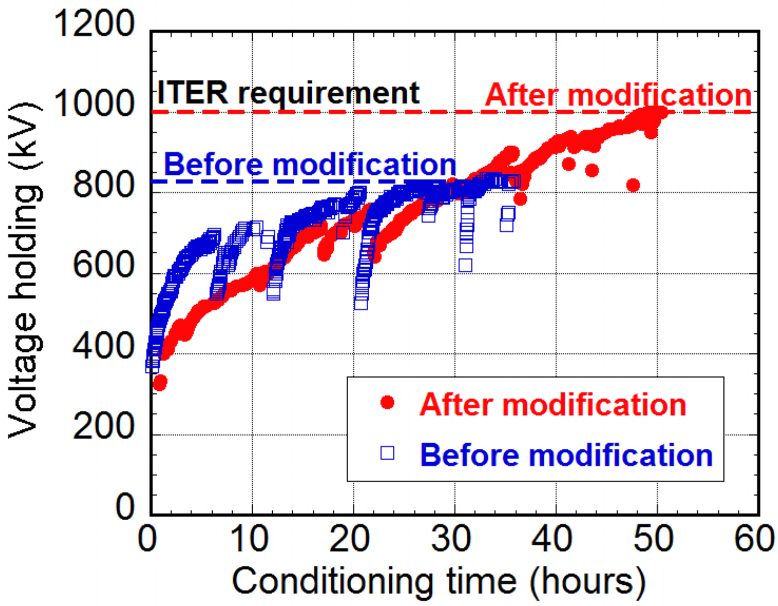


FIG.3 Trend of accelerator conditioning

mm in radius to reduce the electric field concentrations to less than 4.3 kV/mm [6]. The voltage holding as a function of the conditioning time is shown in FIG.3. Before the modification, the voltage holding saturated around 800 kV. After the modifications, the voltage increased proportional to the conditioning time and was stopped at 1 MV because of power supply limit. Then, the MeV accelerator achieved stable voltage holding of 1 MV without H_2 gas feeding (base pressure; 2 x 10^{-4} Pa) for 4000 s [6].

3. Beam optics study

In the accelerator configuration of FIG.1 (a), the pulse length was extended up to 10 s at 600 keV under perveance matched conditions [5]. After this test, the GRG was found to be melted around the grid apertures [15]. A three-dimensional (3D) multi beamlet analysis using OPERA-3d code [16] was applied to investigate the cause of grid melt [7]. In the 3D beam analysis [17, 18], it was shown that the beamlet was deflected 11 mrad at 600 keV and partly intercepted at the grids causing excessive heat loads to melt the grids. Such large beamlet deflection was caused by superposition of the beamlet deflections due to i) dipole magnetic field and ii) space charge repulsion among beamlets [7]. To compensate these beamlet deflections, aperture offset and so-called "field shaping plate [19]" were examined in the 3D beamlet analysis. The first attempt to demonstrate the compensation methods in a MeV-class accelerator for ITER has been started in the modified accelerator shown in FIG.1 (b).

In the 3D beam analysis, precise calculation models were constructed. The detailed geometries of grids and grid supports, magnetic fields and the process of the H^- ion current reduction due to stripping loss were included. The extractor of the MeV accelerator consists of the plasma grid (PG), the extraction grid (EXG) and the electron suppression grid (ESG). Arrangement of aperture array to extract the beamlet was a lattice pattern of 5 rows (R_1-R_5)$\times$ 3 columns (C_1-C_3) as shown in FIG.1. In the EXG, the dipole magnetic field was generated by permanent magnets embedded between aperture rows to suppress the electron acceleration. The beamlets were deflected in the ±X directions alternatively in each row due to i) the dipole magnetic field. The beamlets were also deflected outwards of the aperture array due to ii) the space charge repulsion. Then, the beamlets distributed as shown in FIG.4 (a) at the

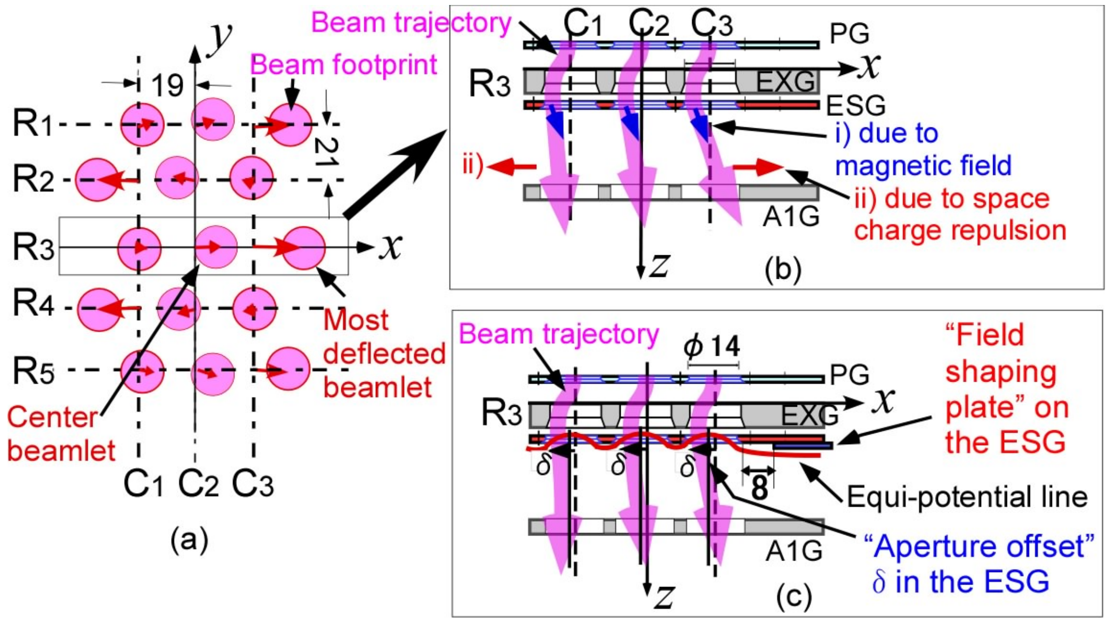
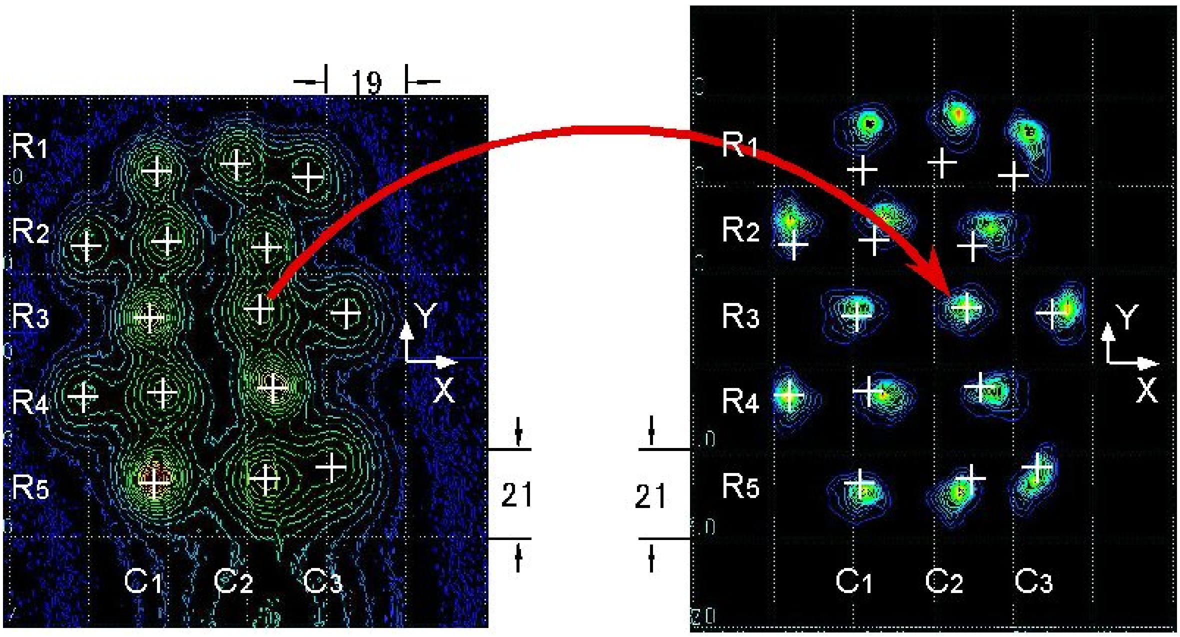


FIG.4 Beamlet deflection (a)(b) and compensation methods (c)

downstream of the accelerator. Details of beam trajectories are shown in FIG.4 (b) showing a cross sectional view of the apertures of the R_3 row. The center beamlet of the C_2 column is deflected due to only i). The deflection of the peripheral beamlet in the C_3 column is larger than that of the beamlet in the C_1 and C_2 Columns. This is due to superposition of i) and ii) because the beamlet deflections due to i) and ii) are in the same direction. On the contrary, the peripheral beamlet in the C_1 column is the smallest because the beamlet deflections due to i) and ii) are in the opposite direction. To compensate the beamlet deflections, the aperture offset was applied to each row of apertures in alternate directions at the ESG. For the most deflected beamlet in the C_3 column, another compensation method was also provided. This is the field shaping plate, which is a metal plate of 1 mm thick attached at the ESG as shown in FIG.4 (c). It generates electric field distortions, which steer the peripheral beamlets inward.

The calculated deflection angles of the C_1, C_2 and C_3 columns were 0, 4.7 and 9.5 mrad at 1 MeV, respectively. When the beamlet deflection angle lowers below 1 mrad by only the aperture offset, the necessary aperture offsets of the C_2 and C_3 columns were 0.8 mm and 1.8 mm for the beamlet of 1 MeV. There is a possibility that such large aperture offset intercepts the beam at the ESG. Then, a conservative aperture offset of 0.5 mm and the field shaping plate were applied in the first compensation test in the modified MeV accelerator.

The measured footprint in the experiment and the calculated one by the 3D beam analysis are shown in FIG.5 (a) and (b), respectively for the case of beam energy at 700 keV as the typical operational conditions. These are the footprints at the 2.5 m downstream from the GRG exit. In the experiment, the beam footprint on a one dimensional carbon-fiber-composite (CFC) target was measured by an infrared camera. In the calculation, the extraction voltage and the current density were set to be the same as the experimental conditions, that is, 4.2 kV and 120 A/m^2, respectively. In FIG.5 (a), the center of measured beamlet is marked by "+" symbols. These "+" are superimposed on FIG.5 (b) to compare the beamlet positions directly. In horizontal direction, the positions of each beamlet are in good agreement between the experiment and the calculation.



(a) (b)

FIG.5 Beam footprints in (a) the experiment and (b) the 3D beam analysis.
The symbol "+" expressed the beamlet center in the measurement.

The deflection angles of the beamlet as a function of the beam energy are shown in FIG.6. These are the deflection angles of the beamlet from the C_1, C_2 and C_3 columns in the R_3 row. The deflection angle was changed inversely proportional to a square root of the beam energy. The beamlet deflection angles between the 3D beam analysis and the measurement were in good agreement. It was demonstrated that the beamlets were compensated as designed in the 3D beam analysis. However, more proper compensations are necessary for the beamlet in the C_2 and C_3 columns because the beamlet deflections still remained 3 and 5 mrad for 1 MeV beam, respectively. The aperture offset of 0.8 mm, which could lower the beamlet deflection to 0 and 2 mrad in the C_2 and C_3 columns, was installed and is to be tested.

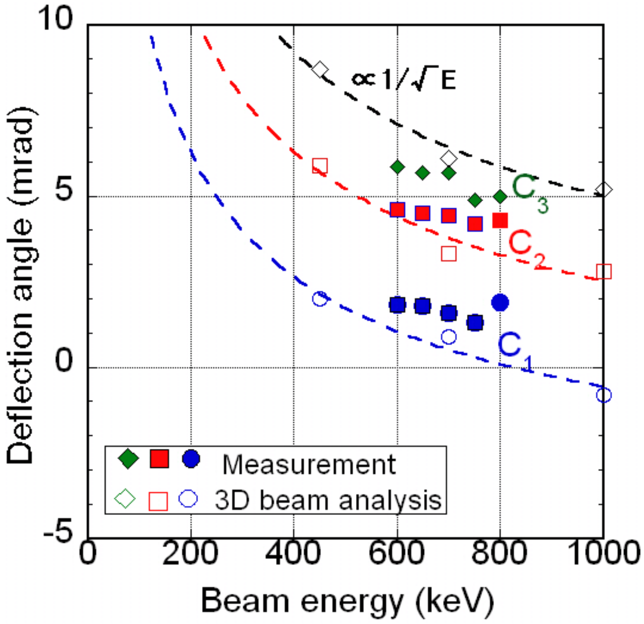


FIG.6 Beamlet deflection angle in R_3 row.
The aperture offset of 0.5 mm and field shaping plate were applied in the accelerator.

4. Beam Acceleration

In the modified accelerator configuration with the compensation methods discussed in chapter 3, the beam acceleration was demonstrated toward accelerations of 1 MeV beam. The H^- ion current is shown as a function of the acceleration voltage. In the previous test [4], acceleration of perveance matched beams was limited to 796 keV at 0.2 s pulse. In the present test, the operational

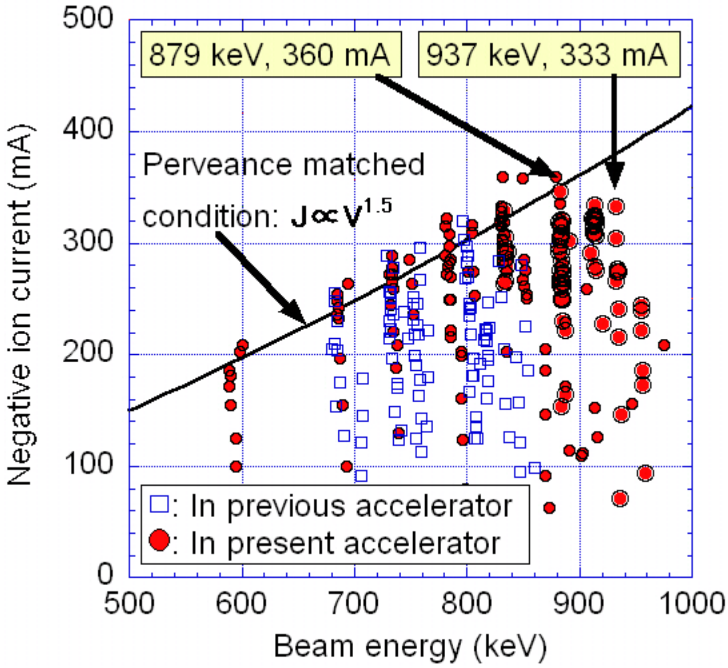


FIG.7 Beam acceleration toward to 1 MeV

energy was increased than 900 keV level. Finally, 879 keV, 360 mA H^- ion beam are successfully generated at the perveance matched condition. At slightly under-perveance condition, 937 kV, 333 mA H^- ion beams were achieved. The pulse length was set to 0.2 s to avoid the grid melting because the heat loads caused by the direct interception of H^- ion beams was still high in the GRG due to insufficient compensations of the beamlet deflection. The beam energy and the pulse length are to be increased with the progress of the compensation methods of the beamlet deflection.

5. Summary

In order to demonstrate stable accelerations of 1 MeV, 200 A/m^2 H^- ion beam, the voltage holding tests and the beam optics study were performed in the MeV accelerator. And then, beam acceleration tests were progressed. The results are summarized as follows.

- It was found that the voltage holding capability of the real accelerators is about a half obtained that of the ideal small electrode. Necessary gap length and radii of grid supports to suppress the local electric field concentrations were estimated and applied to the accelerator. As results, the accelerator succeeded in sustaining 1 MV for more than one hour without feeding H_2 gas.
- The beamlet deflections and its compensation method, the aperture offset in the ESG and the field shaping plate, were examined in the 3D beam analysis. In the first attempt of demonstration of the compensation methods in a MeV-class accelerator for ITER, the calculated results were in good agreement with the experimental ones.
- Beam parameters were increased to 879 keV, 0.36 A (157A/m^2) at perveance matched condition and 937 keV, 0.33 A (144 A/m^2) at slightly under-perveance condition from 800 keV level in the previous accelerator configuration.

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