High energy, high current accelerator development for ITER NBI at JADA

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Abstract. At JAEA as the JApan Domestic Agency (JADA) for ITER, **a** MAMuG (multi-aperture multi-grid) accelerator has been developed for the ITER neutral beam injector (NBI). Beam parameters achieved by the MAMuG accelerator were increased to 0.32 A H^- at the ion current density of 140 A/m^2, from the 0.2 A reported at Chengdu, and 796 keV at the beam energy, which was almost the power supply limit (0.5 A) of the test facility. This was achieved as the result of countermeasures to handle unexpected heat load by backstream positive ions. A test of SINGAP (single-aperture single-gap) accelerator was performed at JAEA under an ITER R&D task agreement. The objective of this study was to compare the two different accelerator concepts (SINGAP and MAMuG) at the same test facility. As the result, it was concluded that the MAMuG accelerator is more suitable for the ITER NBI because of its better voltage holding and less electron acceleration. A simulation is in progress for space charge repulsion of beamlets in the JT-60U accelerator. An aperture offset steering is suggested effective at exit of extractor for compensation of the beamlet deflection due to its own space charge.

1. Introduction

The ITER neutral beam (NB) system is constructed so as to inject 33 MW of D^0 beams from two NB injectors at the beam energy of 1 MeV [1]. To meet the requirements for the ITER NB, development of a high current accelerator is in progress at Japan Atomic Energy Agency (JAEA), utilizing the MeV Test Facility (MTF) which is capable of 1 MeV and 0.5 A H^- ion acceleration [2]. The accelerator under development is a multi-aperture multi-grid (MAMuG) type electrostatic accelerator, called as MeV accelerator [3, 4]. In the previous conference at Chengdu, acceleration of high current density beams (836 keV, 0.2 A H^- at 146 A/m^2) was reported [5]. The present paper reports countermeasure against backstream positive ion beam as a new issue under high power operation and increase in the beam current from the MeV accelerator.

A SINGAP (single-aperture single-gap) accelerator [6] has been developed at CEA Cadarache as an alternative accelerator design for the ITER NBI. To assess the performance of SINGAP and MAMuG concepts at the same test facility under the same diagnostics, a collaborative R&D test was performed between JAEA and CEA Cadarache under an ITER task agreement. For this purpose, SINGAP accelerator was installed at the MTF of JAEA. The results of the test and the comparison of both concepts are reported in this paper.

One of the issues of negative ion based NB system for JT-60U is the beamlet deflection due to their mutual space charge. This causes excess heat load on the acceleration grids and the beamline components. Therefore, compensation of the beamlet deflection by the space charge is essential for long pulse operation of the JT-60SA N-NBI. A result of three dimensional analyses reproduces the beamlet deflection by space charge repulsion in the JT-60U N-NBI. The paper also discusses this beamlet repulsion followed by a proposal of compensation by aperture offset steering.

2. High power negative ion acceleration by MeV accelerator

Figure 1 shows a cross sectional illustration of the MeV accelerator developed at JAEA. To simulate the vacuum insulation required for the ITER NBI, the main structure of the MeV accelerator is installed in a vacuum vessel composed of a stack of five insulators made of FRP (fiber reinforced plastic). On the top of the accelerator, a negative ion source called "KAMABOKO source" is mounted to produce the high density H^- ions. During the operation, small amount of Cs is added to the source to enhance the H^- ion production. The extracted negative ions are accelerated by the potential difference between four intermediate grids and a grounded grid. Between each grid, 200 kV dc voltages are applied to accelerate the H^- ions up to 1 MeV. Although the ITER accelerator is required to accelerate 40 A of the H^- ion beams, power supply capability of the MTF is limited to 0.5 A. Therefore the accelerator development at JAEA was mainly dedicated to the acceleration of high current density beams (ITER requirement: 200 A/m^2). Up to 2005, 836 keV, 146 A/m^2 H^- beam (total H^- current; 206 mA) was successfully accelerated, as the highest record of the current density at MeV class energy beams [7].

High current density beams have been accelerated up to MeV level energy since 2005, however, a rapid decrease of the H^- ion current was observed right after the acceleration of such high power density beams [8]. This was found due to air leak from an un-cooled port plug located at the top of the ion source. The port plug (made of SS) was partly melted indicating excess temperature rise as a consequence of high heat load input due to back stream positive ions. Due to the air leak, caused by the back

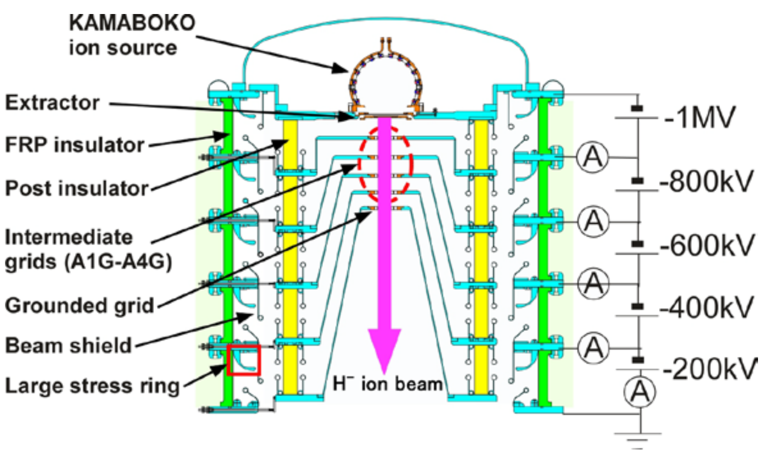


Fig.1 Cross sectional illustration of MeV accelerator.

stream positive ions, the Cs effect was degraded to cause the reduction in the negative ion density in the source. To protect the port plug from the heat load by backstream positive ions, a water cooled beam dump was equipped on the top of the ion source. After mounting the beam dump, high current beam production lasted for more than one month, and high current H^- ion beams of 0.32 A (140 A/m^2) have been accelerated up to 796 keV. In a wide range of operation window but maintaining the perveance, beam divergence angle of about 5 mrad was attained, which fulfills the ITER requirement (≤ 7 mrad). The progress of the MeV accelerator is summarized in Fig. 2. In the high power beam acceleration above, the drain current (H^- ion plus co-accelerated electrons) reached 0.42 A which is close to the limit of the power supply.

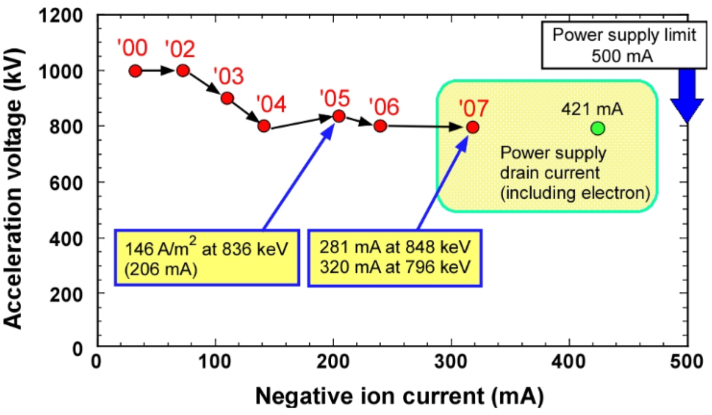


Fig.2 Progress of MeV accelerator.

3. The SINGAP accelerator test at JAEA MeV test facility

Test of a SINGAP accelerator has been performed at the MTF under the ITER R&D task agreement. A unique feature of the SINGAP is in the simplicity, a large single aperture in the grounded grid, and no intermediate grids. On the other hand, this simple geometry may cause relatively high current of backstream positive ions, and electrons to be accelerated up to high energy. This causes decrease in acceleration efficiency as well as excess heat load on the beam line components. The purpose of this study was to compare the SINGAP and the MAMuG accelerators in the same test facility with same diagnostics, and to obtain the experimental results from various tests to choose an accelerator concept that would be suitable for the ITER NBI. Figure 3 shows the SINGAP accelerator installed on the MTF. Originally, pre-acceleration voltage of the SINGAP was designed to 60 kV [6]. However, in the present SINGAP test at the MTF, the first stage of the MAMuG (A1G, -800

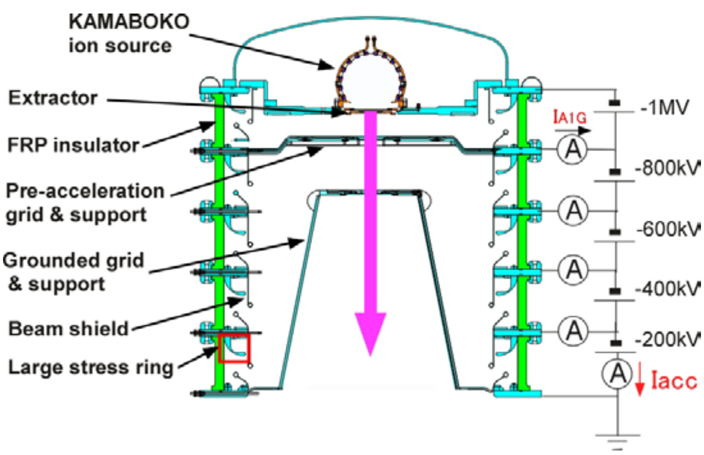


Fig.3 The SINGAP accelerator installed at MTF.

kV) was utilized as a pre-accelerator. The grounded grid has one large aperture of 114 mm x 106 mm. The negative ion source, the extractor, and the FRP insulator columns were the same as those used for the test of the MAMuG accelerator.

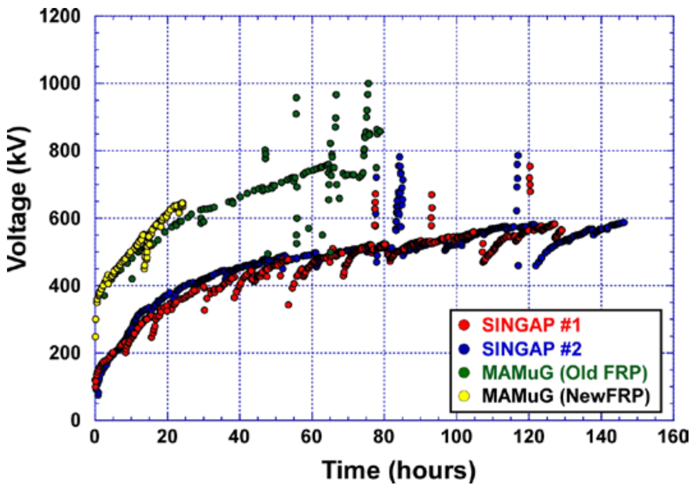


Fig.4 Conditioning history of the SINGAP accelerator.

Figure 4 shows the high voltage conditioning curve of the SINGAP for two test campaigns. The data of the MAMuG are also plotted for comparison. The conditioning history of the SINGAP was almost the same for two test campaigns. The progress of voltage holding for the SINGAP was slow compared with that of the MAMuG. In the case of the MAMuG, 757 kV has been sustained after 60 hours of conditionings, and voltage holding was increased up to 1 MV by adding H_2 gas of 0.2 Pa. However, in the SINGAP case, maximum voltage holding was 572 kV after 120 hours of conditioning and seemed to be saturated at the level below 600 kV. With adding the H_2 gas to the accelerator (0.25 Pa), voltage holding was increased to 800 kV, but the rated voltage of 1 MV could not be achieved.

Following to the high voltage conditioning, beam acceleration test was performed. The KAMABOKO ion source was operated with Cs seeding. At the perveance matched condition, 626 keV, 225 mA (97 A/m^2) beam was successfully accelerated. At lower perveance condition, 672 keV, 220 mA beam was obtained. However, the higher acceleration voltage above 700 keV could not be attained due to the poor voltage holding. The maximum voltage with the H^- ion beam was 775 keV, but the current was limited to 75 mA at this voltage. During the beam acceleration by the SINGAP accelerator, it was found that the ratio of co-accelerated electrons was large. The amount of accelerated electrons was estimated as the difference between power supply drain current (I_{acc}) and the H^- ion current ($I_e^- = I_{acc} - I_H^-$). As the result, the ratio of electron to H^- ion (I_e^-/I_H^-) for SINGAP was estimated to be 1.09 at the beamline pressure of 0.08 Pa (source pressure: 0.16 Pa). This is three times larger than that of the MAMuG (I_e^-/I_H^- = 0.29). In the present experiment, the gas pressure was 0.08 Pa at the accelerator downstream to maintain the voltage holding of the SINGAP. Note that the pressure was about three times higher than the designed gas pressure of the ITER NB, < 0.03 Pa [9]. Under such high pressure, not only stripping losses and ionization of the background gas but also ionization by secondary neutrals and secondary electrons by positive ion impact on the pre-acceleration grid are important. The positive ions are generated by ionization of beam particles by collision with background gases in the gap between the pre-acceleration grid and the grounded grid, or extracted from beam plasma through the large openings of the grounded grid of the SINGAP accelerator. These positive ions are accelerated backwards and either hit the pre-acceleration grid, the extraction grid, the PG or the rear of the ion source with an energy that depends on their "birth" point. Positive ions that hit the pre-acceleration grid will generate secondary electrons. A numerical analysis utilizing EAMCC code also indicated that a significant amount of electrons leaked from the large opening of the grounded grid in the SINGAP test at MTF [10]. The fraction of the total beam power transmitted out of the SINGAP accelerator as electron power (P_{e-}) and H^- ion power (P_{H^-}) were estimated to be 0.26 and 0.74, respectively. Though the gas pressure was high in the experiments at MTF, these results indicate that the SINGAP configuration permits easily to accelerate many electrons up to the high energy.

An estimation of the electron currents in both accelerators at the ITER relevant gas pressure was studied by Fubiani and de Esch et al. utilizing EAMCC code [11, 12]. The results showed that electron power of 7.3 MW was transmitted from the large openings of the grids in the SINGAP accelerator [12]. In the ITER MAMuG, electron power transmitted out of the accelerator was only 800 kW because most of electrons were intercepted on the intermediate grids [11].

Table 1 Summary of experimental results in MAMuG and SINGAP tests at MTF.

	MAMuG	SINGAP (at MTF)
Voltage holding	1 MV With H_2 gas of 0.21 Pa	787 kV with H_2 gas of 0.25 Pa
Beam current	320 mA (140A/m^2) at 796 keV	220 mA (95 A/m^2) at 672 keV
Optics	5.5 mrad at 750 keV	2.6 - 4.5 mrad at 450 keV
Electron to ion ratio (background pressure at 0.08 Pa)	$I_{e-}/I_{H^-} = 0.28$	$I_{e-}/I_{H^-} = 1.09$
Estimated electron power transmitted out of the SINGAP accelerator [10] (background pressure at 0.09 Pa)		$P_{e-}/P_{H^-} = 0.17$
Estimated electron power transmitted out of the ITER accelerator [11, 12] (< 0.03 Pa at ITER pressure)	800 kW (ITER MAMuG)	7.3 MW (ITER SINGAP)

Table 1 summarizes the comparison of SINGAP and MAMuG accelerator tested at the MTF. From the viewpoint of voltage holding, maximum beam current and electron co-acceleration, the MAMuG showed better performance. Based on these results, it was decided to adopt the

MAMuG accelerator for the ITER NBI in SINGAP / MAMuG discussion meeting held at the ITER Organization on 28 May 2008.

4. Compensation of beamlet repulsion

In the JT-60U NB system, excess heat loads on the accelerator grids and downstream components are one of issues in an attempt of long pulse operation. The heat loads are generated by deflected beamlets due to mutual space charge repulsion between them. At present, metal bars were attached around the aperture area at the exit of the electron suppression grid (ESG, 3rd grid) [12]. Forming electric field distortion, beamlets from outermost apertures are steered to counteract to the beamlet deflection. However, the beamlet steering by this method is only effective to the outermost beamlets since the field distortion does not propagate far away. In order to steer all beamlets properly, the space charge repulsion of beamlets and beamlet steering by offset aperture have been simulated utilizing a three dimensional beam calculation code, OPERA-3d [13].

To study the beamlet repulsion of the JT-60U N-NBI, the accelerator was modeled including the plasma grid (PG), the extraction grid (EXG) and the electron suppression grid (ESG) as well as three acceleration grids (A1G, A2G and GRG). The trajectory of fifty beamlets from 5 x 10 apertures can be traced by this model. OPERA code used in this work cannot model the extraction of the D^- ions from the plasma. Therefore, the 2D beam orbital code "BEAMORBIT" [14] was used to calculate the D^+ ion extraction from the source plasma. The position, velocity and direction of the D^+ ions at the exit of the extractor were obtained by the BEAMORBIT, and then, these values are used as the D^- ion extraction for OPERA calculation. This procedure is also effective to decrease the time for the OPERA calculation.

Figure 5 shows the accelerator model and trajectories of beamlets at 340 keV, 130A/m^2 D^- ion beam as a typical operation condition of the JT-60U. Deflection angle of each beamlet is shown in fig.6 as a function of aperture positions. The column numbers C1 to C10 represent the position of

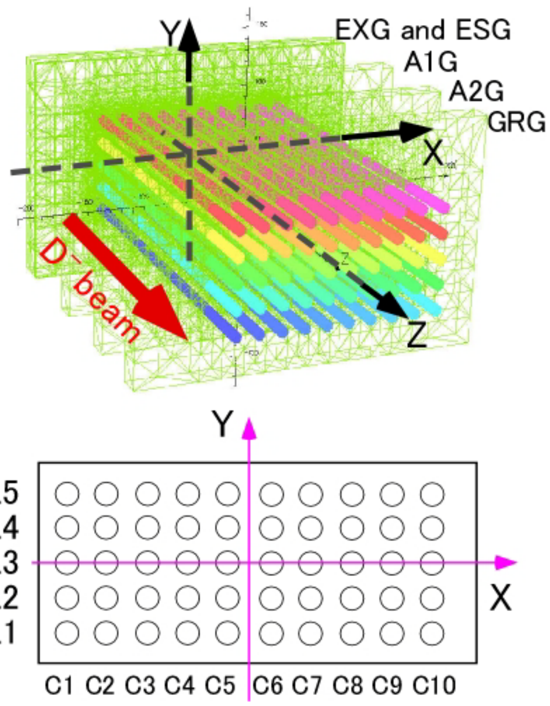
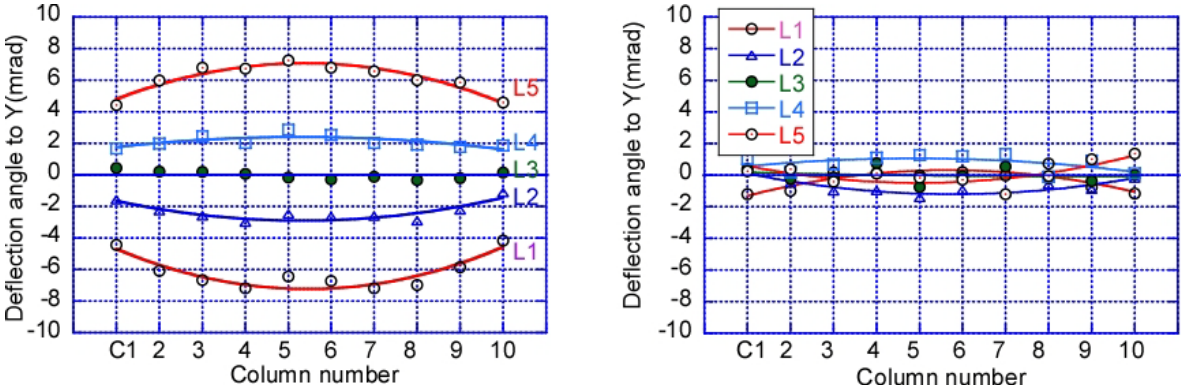


Fig.5 Beam trajectory of 340 keV, 130 A/m^2 beam of the JT-60U accelerator.



(a) apertures are in original position *(b) with aperture offset at ESG*

Fig.6 Beamlet deflection angle in Y direction.

horizontal directions and lines L1 to L5 represent the position of vertical directions. Figure 6 (a) shows the beamlet deflection angle in Y-direction before applying the aperture offset. The deflection angle at the center columns (C5, C6) was larger than those at the corners (C1, C10). The maximum deflection angles in the outermost beamlets (L1, L5) were 7 mrad, and 3 mrad even in the inner beamlets (L2, L4). These results indicate that the beamlet deflection by the space charge repulsion strongly depends on the aperture position. Therefore, to compensate the beamlet deflection, the aperture offset must be designed for each beamlets. According to the thin lens theory, beamlet steering angle is proportional to the aperture offset length of ESG, and 8 mrad is expected by the offset of 1 mm. Thus, the aperture offset of 0.5 to 1.0 mm was applied with respect to the beamlet deflection angle. Figure 6 (b) shows the beamlet deflection angle after applying the aperture offset at ESG. The deflection angles of each beamlet are properly compensated and it was within the numerical error (±1 mrad). Thus effectiveness of the ESG aperture offset was demonstrated for compensation of the beamlet deflection by the space charge repulsion. This compensation technique is to be applied to the MeV accelerator for the verification.

5. Summary

The development of high energy, high current MAMuG accelerator is in progress at JADA toward the ITER NBI. The accelerated H^- ion current obtained at the MeV accelerator was increased to 320 mA, which is 1.5 times higher than the reported value at the previous conference in Chengdu. The SINGAP accelerator was tested at JAEA MeV test facility to compare the two accelerator concepts. As a result, the MAMuG showed better performance than the SINGAP, and it has been decided to choose the MAMuG as the baseline accelerator for the ITER NBI. The beamlet deflection due to the space charge repulsion was studied using OPERA-3d code. It was shown in the analysis that the beamlet steering by the aperture offset at the ESG is effective to compensate the beamlet deflection.

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References

[1] ITER EDA Final Design Report, ITER technical basis, Plant Description Document (PDD), G A0 FDR 1 01-07-13 R1.0, IAEA EDA documentation No. 24 (2002).

[2] K.Watanabe et al, “Development of a large volume negative-ion source for ITER neutral beam injector “, Rev. Sci. Instrum. 73 (2) (2002) 1090-1092.

[3] T.Inoue, et al., “1 MeV, ampere class accelerator R&D for ITER”, Nucl. Fusion 46(6) (2006) S379-385.

[4] M.Taniguchi et al., “Development of high performance negative ion sources and accelerators for MeV class neutral beam injector”, Nucl. Fusion 43 (2003) 665-669.

[5] M.Hanada et al., “R&D progress at JAEA towards production of high power and large-area negative ion beams for ITER”, Nucl. Fusion 47 (2007) 1142-1146.

[6] H.P.L. de Esch et al., “Updated physics design ITER-SINGAP accelerator”, Fusion Engin. Des., 73(2005)329.

[7] M.Taniguchi et al., “Acceleration of MeV class, high current density H^- ion beams for ITER NB system”, Rev. Sci. Instrum. 77 (2006) 03A514.

[8] M.Taniguchi et al., “Acceleration of ampere class H^- ion beam by MeV accelerator”, Rev. Sci. Instr. 79 (2008) 02C110.

[9] ITER Design Description Document (DDD) 5.3: Neutral Beam Heating & Current Drive (NB H & CD) system.

[10] H.P.L. de Esch et al., to be published in Fusion Eng. Des.

[11] G. Fubiani et al., "Modeling of secondary emission processes in the negative ion based electrostatic accelerator of the International Thermonuclear Experimental Reactor", Phys. Rev. Special Topics., Accele. and Beams 11(2008) 014202.

[12] G. Fubiani et al., to be submitted in Rev. Sci. Instrum.

[13] M. Kamada et al., “Beamlet deflection due to beamlet-beamlet interaction in a large-area multiaperture negative ion source for JT-60U”, Rev. Sci. Instrum., 79 (2008) 02C114.

[14] “OPERA-3d”, Vector Fields Co.Ltd., http://www.vectorfields.com/.

[15] Y. Ohara, “Simulation code for beam trajectories in an ion source”, JAERI-M 6757 (1976).