Heat loading of MeV accelerator grids during long pulse beam operation

Naotaka UMEDA, Takatoshi MIZUNO, Masaki TANIGUCHI, Mieko KASHIWAGI, Koichiro EZATO, Hiroyuki TOBARI, Masayuki DAIRAKU, Kazuhiro WATANABE, Keishi SAKAMOTO and Takashi INOUE

Fusion Research and Development Directorate, Japan Atomic Energy Agency, 801-1 Mukoyama, Naka, Ibaraki, 311-0193 Japan

(Received: 20 November 2009 / Accepted: 19 February 2010)

To realize accelerations of high power negative ion beams up to 3,600 s for the ITER NBI, long pulse operations have been started at JAEA with a MeV accelerator. After a long pulse operation of 5 - 10 s, molten traces were observed around grid apertures due to collision of deflected negative ion beams. A three dimensional heat transfer analysis was carried out to design new acceleration grids and to estimate tolerance level of the beam deflection. A new grid whose aperture diameter is enlarged to 16 mm was designed to reduce the heat load. The tolerance of the beam deflection angle was estimated to be 6.4 mrad at full power beam acceleration.

Keywords: NBI, negative ion beam, electrostatic accelerator, beam deflection

1. Introduction

To realize ITER neutral beam injector (NBI), development of a high power negative ion accelerator is a key issue. Acceleration of 40 A (200 A/m^2) D^- ions at the energy of 1 MeV for 3,600 s is required for the ITER accelerator [1]. Japan Atomic Energy Agency (JAEA) has developed a Multi-Aperture Multi-Grid (MAMuG) accelerator (MeV accelerator) for R&D of the accelerator of ITER NBI [2]. A goal of the MeV accelerator is to accelerate 0.5 A (200 A/m^2) H^- ion beams at the energy of 1 MeV for several tens seconds. Acceleration of 320 mA (140 A/m^2) H^- beams at 796 keV has been succeeded [3]. The pulse length of the high power beams above was limited to 0.2 s because the acceleration grids were non-water cooled in these experiments.

Long pulse operation of the MeV accelerator has been started since 2009 using new water cooled acceleration grids. The pulse length has been extended with the beam energy and current, to 5 s for 750 keV, 221 mA and to 10 s for 600 keV, 66 mA [4]. After the long pulse operations, a few molten traces and beam footprints were found around the grid apertures. The avoidance of the grid damage is required for stable long pulse operation. The beam footprints showed that the negative ion beams were largely deflected in the accelerator. From a three dimensional (3D) beam trajectory calculation by OPERA-3d code, it was shown that the negative ion beam was deflected by magnetic field of electron suppression magnets and by beamlet-beamlet space charge repulsion [5]. It is necessary to compensate the beam deflection to reduce grid heat load by the beam direct interception for higher beam power acceleration for long pulses.

In this paper, analysis of the negative ion beams followed by the grid heat load is discussed and improvement of the acceleration grid structure with higher cooling performance is presented through an analysis of the temperature rise of the acceleration grid.

author's e-mail: umeda.naotakal@jaea.go.jp

2. Modeling of heat transfer analyses

Figure 1 shows a cross sectional view of the MeV accelerator. The hydrogen negative ions (H^-) are produced in the KAMABOKO source [6] at the top of the accelerator and extracted by extraction voltage applied between a plasma grid (PG) and an extraction grid (EXG) in the lattice pattern of 3 x 5 as shown in Fig.2 (a). In the EXG, magnets are embedded between apertures to suppress electron acceleration with the negative ions. The extracted negative ions are accelerated by the electrostatic

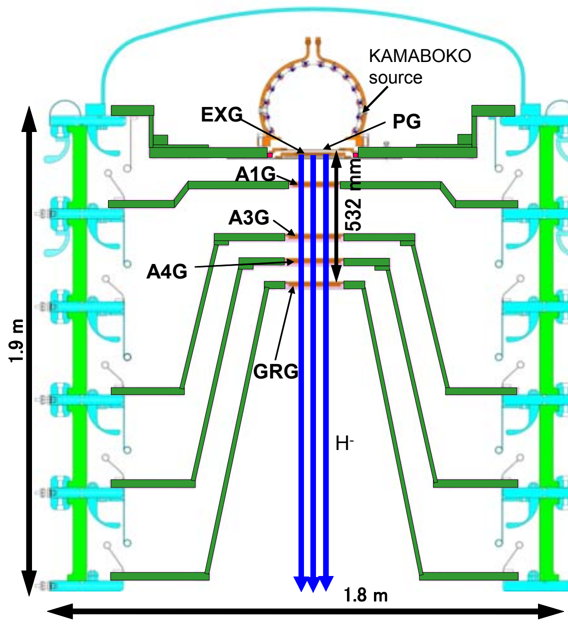
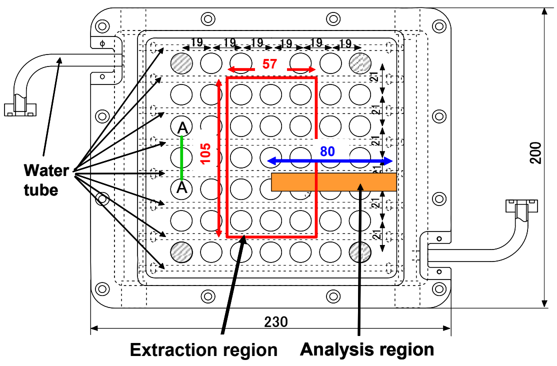
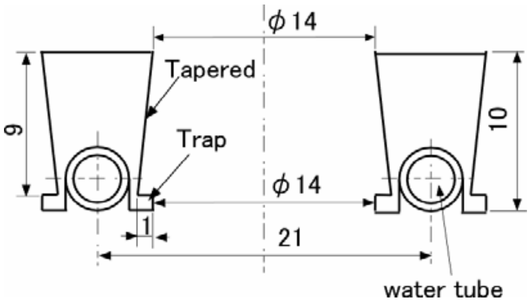


Fig.1 Illustration of the MeV accelerator



(a)



(b)

Fig.2 (a) Plane view of the acceleration grid

(b) Cross section of the acceleration grid aperture on line A in (a)

accelerator, which is composed of three intermediate grids called as A1G, A3G, A4G and a grounded grid (GRG). In this test, A2G is removed for simplicity. Distance from the PG to GRG is 532 mm in total.

Figure 3 shows the photograph of the acceleration grids after the long pulse operations. The molten traces were observed on A3G and GRG. It seemed that whole beamlets were deflected in same direction (left direction).

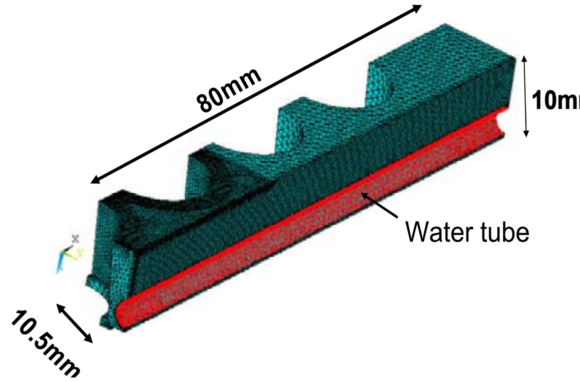


Fig.4 Analytical model

This was caused by declination of PG against EXG. The heat load of A3G is higher than that of A4G since the divergent beam collide on A3G for long gap between A1G and A3G. The observed damage around the aperture near the molten spots on the GRG was severer than that on the A3G. It is supposed due to the collision of the higher energy beams. Then, the analysis was carried out on the GRG.

Figure 2 (b) shows the cross sectional view of the acceleration grid aperture. The acceleration grids were made of oxygen free copper (OFCU). The diameters at the top and bottom surfaces of the apertures are 14 mm. The side wall of the aperture has tapered shape in order to reduce the collision of the H^- ion beams and the resultant emission of secondary electrons. In addition, the trap was also designed to prevent acceleration of secondary electrons from intermediate acceleration grids. Water tubes, whose inner diameter is 3 mm, are brazed at the back side of the grid.

Figure 4 shows an analytical model of the GRG.

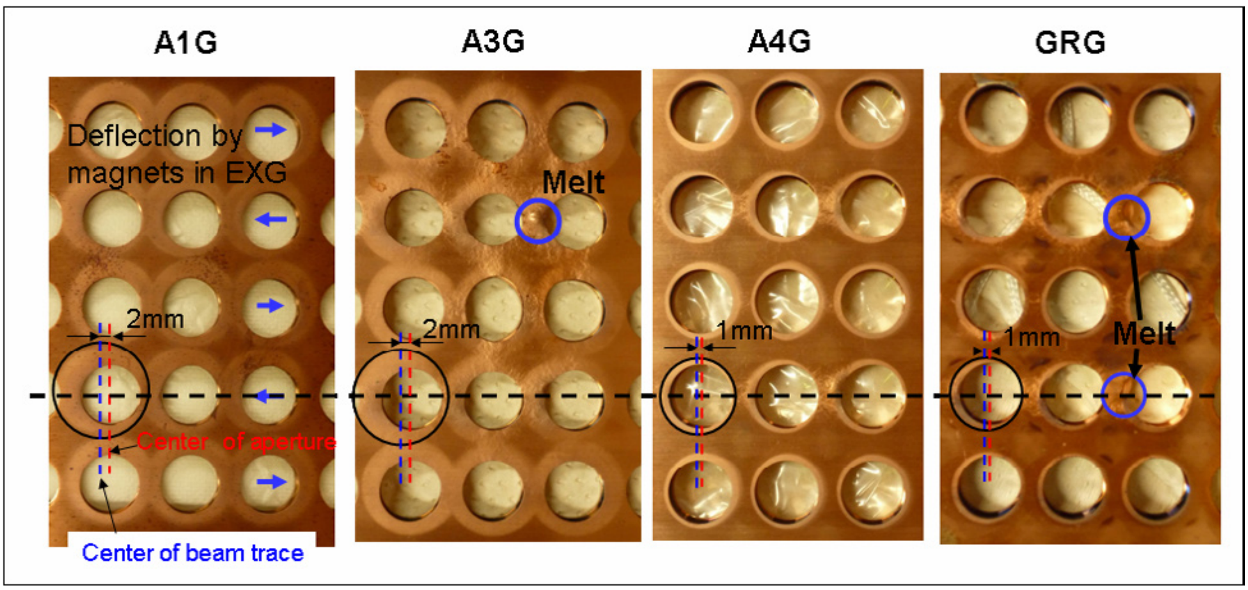


Fig.3. Photograph of the acceleration grids after the test

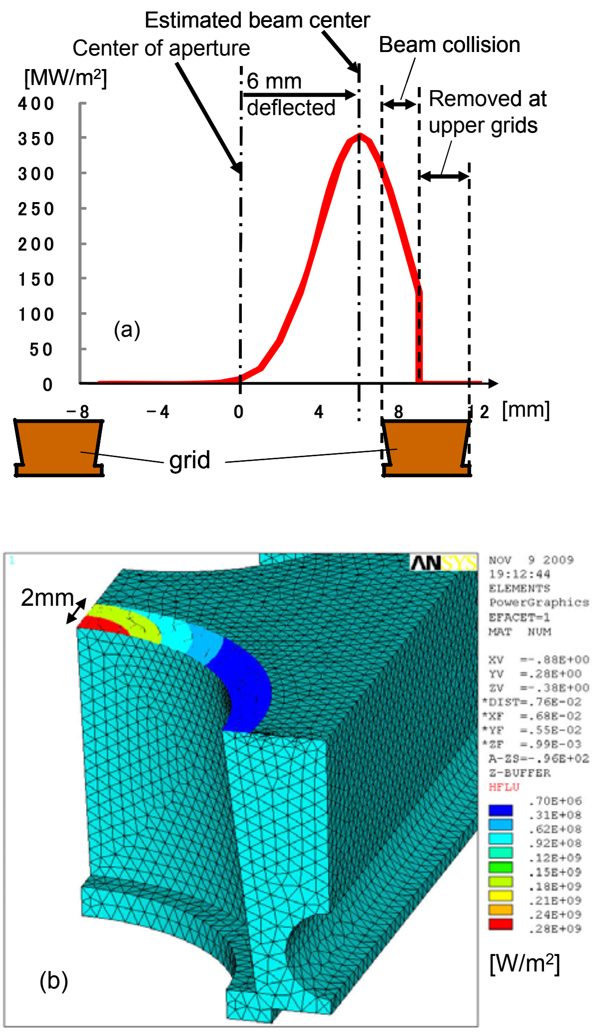


Fig.5 (a) Estimated one dimensional heat flux profile at GRG
(b) Boundary condition of heat flux

Analyses were carried out using ANSYS code [7]. Analytical region drawn in Fig.2 (a) is a quarter part of one row of apertures (80 mm x 10.5 mm x 10 mm), from center of the apertures to center of the neighboring water tube. The grid temperature was set at 20 degree C as an initial condition. For simplification, it is assumed that the temperature of the cooling water was kept at 20 degree C. As a boundary condition, a heat transfer coefficient at the interface between water tube and the cooling water was calculated as a function of wall temperature of the water tube and water flow velocity. The water flow velocity in the GRG was estimated to be 4.5 m/s in the experiments. Heat transfer coefficient was calculated from the Dittus-Boelter's equation of forced convection under saturation temperature, while heat transfer coefficient over saturation temperature was estimated from Ikeda-Araki's relation [8]. The saturation temperature was assumed 152 degree C in case of 0.5 MPa of water pressure at the grid.

The heat flux on the grid was estimated from the H^- ion beam profile. It was assumed that the beam profile is the Gaussian distribution. It was considered that the H^- ion beam colliding with the GRG have a larger divergence than that on the perveance matched. Then, the beam divergence angle, which was obtained as the 1/e half width of the Gaussian distribution, was assumed to be 6 mrad as a light source of PG.

The normalized constant of the Gaussian distribution was determined by the beam power per one beamlet of 10 kW for 750 keV, 221 mA beam acceleration, which was record of the long pulse operations

The deflection of the beam center was estimated from the beam footprints on the acceleration grids as shown in Fig.3. The deflection was obtained from a difference between center of aperture and center of beam trace. The difference on each grid was 2 mm on A1G, 2 mm on A3G, 1 mm on A4G and 1 mm on GRG, respectively. It was supposed that the beam was deflected 6 mm at the GRG by summation of the difference on each grid. It corresponds to 11 mrad of deflection angle at the GRG under the assumption of the beam traveled in the straight line from the PG. The foot prints on GRG drew a circle only 2 mm from the aperture edge. This suggests that the outer beam trace was intercepted and removed at upper grids. From these assumptions, one dimensional heat flux profile was given as shown in Fig.5 (a). On the basis of this profile, two dimensional heat flux profile was given as shown in Fig.5 (b) for 5 s as a boundary condition. The highest heat flux by the beam collision was 280 MW/m^2 and heat fluxes by other particles such as electrons, neutral particles and positive ion were enough low in this condition.

3. Results and discussions

Figure 6 shows an analytical result of a temperature distribution for the beam of 6 mrad divergence, after 5 s of beam acceleration. Maximum temperature exceeds melting point of copper (1084 degree C). Thus it is necessary to reduce grid heat load by the direct

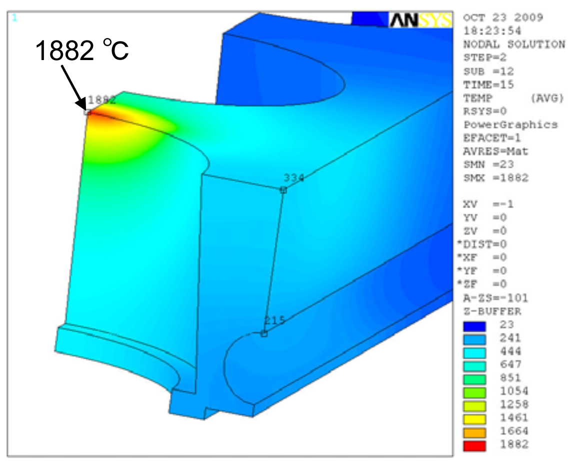


Fig6. An analytical result of temperature profile

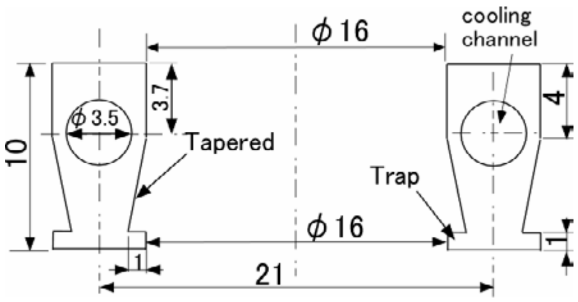


Fig.7. Cross section of the aperture of the modified acceleration grid

interception for higher beam power and longer pulse beam acceleration. Also cooling capability improvement of the acceleration grids would help experiments of such high power beam acceleration.

It was expected that expansion of the aperture diameter was effective to reduce the heat flux on the grids. The acceleration grid has been modified as shown in Fig.7. Cooling channels are drilled near upper surface instead of brazing water tube at the back side. This has an advantage to make space for larger aperture diameter from 14 mm to 16 mm. This also leads to improvement of cooling performance by enlarging the diameter of cooling channel from 3 mm to 3.5 mm.

Figure 8 shows a comparison of maximum temperature between the present grid and the modified grid as a function of beam divergence at 11 mrad of deflection angle. The temperature rise is reduced with the modified grids but the temperature is still high. For the next test, beam deflection will be compensated by aperture displacement of electron suppression grid located downstream of EXG [5]. It is necessary to determine tolerance level of beam deflection for full

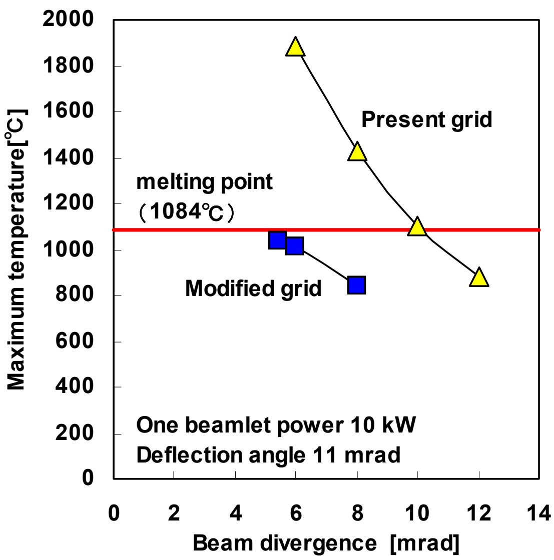


Fig.8 Comparison of maximum temperature between the present grid and the modified grid

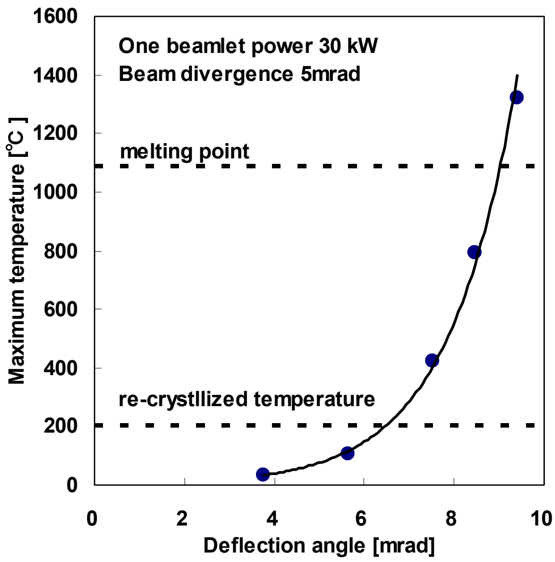


Fig.9 Dependence of maximum grid temperature on the beam deflection angle

power (1 MeV, 200 A/m^2) beam at optimum perveance. At the full power beam, beam power per one beamlet is estimated 30 kW. The heat analysis was carried out by varying the beam deflection angle at the beam divergence of 5 mrad, which is the design value of MeV accelerator, as shown in Fig.9. Deflection angle should be less than 6.4 mrad to suppress grid temperature under 200 degree C, which is re-crystallization temperature of Copper. It would be possible to compensate beam deflection less than 6.4 mrad by aperture displacement [9]. So higher power and longer pulse beam acceleration will be expected in the next long pulse experiments.

4. Summary

A three dimensional heat transfer analysis has been carried out to evaluate temperature rise of the grid assuming various beam parameters, in particular the beam deflection angles from footprints on the acceleration grids. To reduce temperature rise, a new acceleration grid structure was proposed to make the aperture diameter larger from 14 mm to 16 mm. Tolerance against the beam deflection angle was estimated and the deflection angle of 6.4 mrad could be sustained with the new grid even under acceleration of full power beam at optimum perveance.

[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 (unpublished)
[2] T. Inoue, Japan Atomic Energy Research Institute Report, JAERI-Tech 94-007,1994
[3] M. Tanighchi *et al.*, Rev. Sci.Instrm. 79, 02C110 (2008*)*
[4] M. Taniguchi *et al.*, submitted to Rev. Sci. Instrum.
[5] M. Kashiwagi *et al.*, to be published in Rev. Sci. Instrum.
[6] T.Inoue *et al.*, Rev.Sci.Instrum. 75, 1819 (2004)

[7] http://www.ansys.com/
[8] M. Araki *et al*., Japan Atomic Energy Research Institute Report, JAERI-Tech 95-022, 1995
[9] M. Kashiwagi, *et al*., Nucl. Fusion **49** 065008 (2009)