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Determination of neutral beam injection accelerator grid deformation using beam emission measurements

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Theoretical modeling of 1–2 MW positive hydrogen ion neutral injectors developed at Oak Ridge National Laboratory (ORNL) has suggested that the plasma grid temperature could rise by up to 180 °C at pulse lengths above 0.5 s, leading to a grid deformation on the order of 5 mm, with a consequent change in focal length (from 4 to 2 m) and beamlet focusing. One of these injectors (on loan from ORNL) was used to achieve record β values on the Small Tight Aspect Ratio Tokamak at Culham, and two more are to be used on the Mega-Ampere Spherical Tokamak (MAST) at pulse lengths of up to 5 s. Since the grid modeling has never been tested experimentally, a method for diagnosing changes in beam transport as a function of pulse length using light emitted by the beam is now under development at Culham to see if grid modifications are required for MAST. Initial experimental results, carried out using a 50 A 30 keV hydrogen beam, are presented (including comparison with thermocouple data using an EK98 graphite beam stop). These confirm that emission measurement should allow the accelerator focal length and beamlet divergence to be determined to accuracies of better than ±0.45 m and ±0.2°, respectively (compared to nominal values of 4 m and 1.2°). © *1999 American Institute of Physics.* [S0034-6748(99)53101-8]

I. INTRODUCTION

Neutral beam injection on the Mega-Ampere Skeletal Tokamak (MAST) will be carried out using two injectors of the design shown in Fig. 1 that have been loaned to UKAEA by Oak Ridge National Laboratory (ORNL). The requirement for MAST neutral beam injection (MNBI) is a total injected *deuterium* beam power from two injectors of 5 MW at pulse lengths of up to 0.5 s, and 4 MW at pulse lengths up to 5 s for advanced tokamak tests. The present injectors were designed for a maximum pulse length of 500 ms, which was achieved at both ORNL and Princeton Plasma Physics Laboratory (PPPL) following modifications to the neutralizer gas flow. It is clear, therefore, that modifications to the ORNL injectors will be required to achieve the MNBI specification of 5 s. High power positive ion injection has been carried out at pulse lengths up to 30 s, however, in a number of fusion laboratories worldwide, and it is feasible to modify the ORNL hardware.

Table I shows the principle design issues involved in increasing the pulse length to 5 s, and the solutions presently envisaged for MAST NBI. Of the issues listed, the principle uncertainty lies in the area of grid distortion, which will arise due to the impact of stray beam ions, back accelerated electrons, and source plasma particles onto the grids during a beam pulse. Such distortion leads to changes to both the focal length of the ion optics and the divergence of individual beamlets. Both effects will modify the power density distribution at the ion dumps and beam scrapers (possibly leading to damage) and could decrease the power transmission to the tokamak. As discussed below, the existing ORNL grids may be capable of meeting the MAST long pulse specification, and designing replacement grids may be unnecessary. Quantification of the level of distortion for the present grids is therefore a priority.

II. THE EXISTING ORNL ACCELERATOR GRIDS

The ORNL duopigatron source uses a triode accelerator with 1981 apertures arranged in a 30 cm diam circular extraction pattern, with 1.59 mm outer diameter (o.d.) 0.25 mm wall copper cooling pipes located between pairs of apertures. The dimensions of the grids are shown in Table II. ORNL staff have published two articles discussing the thermal properties of the ORNL grid design.[1,2] These concluded that:

(i) The present design of ORNL grids should be capable of operation up to pulse lengths of 0.5 s at 6 MW extracted ion power (beam current×beam energy), but that this is close to the limit in pulse length for this grid geometry and power level due to thermal distortion of the first and third grids
(ii) The power loading on the *first* grid is estimated to be (worst case) 2% of the extracted ion beam power. At

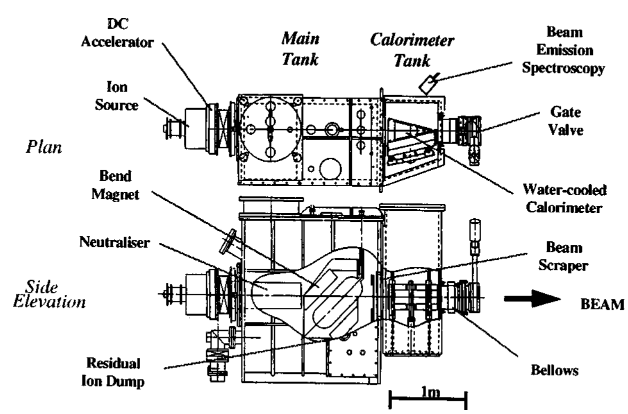

FIG. 1. Plan and elevation of the ORNL injectors.

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TABLE I. MAST NBI long pulse issues.

Long pulse issue	MAST NBI solution
Outgassing of epoxy insulator	Switch to porcelain insulators
Survivability of calorimeters and ion dumps	Use hypervapotrons
Survivability of oxide-coated cathodes	Switch to tungsten filaments or indirectly heated cathodes
Neutralizer pressure increases	Control of neutralizer gas feed
Grid distortion	Need to assess

the 6 MW extracted ion beam power, the first grid is predicted to rise to 155–160 °C in 0.5 s (85% of steady-state value), compared to a steady-state value of 180–190 °C after 2 s.

(iii) Thermal deflection of the first grid after 0.5 s at 6 MW is predicted to be on the order of 4.6 mm. As a result, ORNL suggested that the focal length of the accelerator might change from 4 to 2 m, *but noted that this was not consistent with the measured performance*.

Since operating the MAST NBI at ion beam powers of up to 4 MW for pulse lengths above 0.5 s has been proposed, the steady-state grid 1 temperature should remain less than the 155–160 °C value stated by ORNL to be acceptable (assuming that the steady-state grid temperature rise is linearly dependent on grid power loading). This suggests that the present grids may be usable for MAST. Two possible options for circumventing problems if excessive distortion of the present ORNL grids is found to apply are: (a) remounting of the grids in order to allow some degree of grid movement during heating, and (b) use of grids specifically designed for long pulse operation [similar to those in use at the Joint European Torus (JET)].

Given the critical importance of achieving acceptable levels of grid distortion for long pulse operation, a means of quantifying the level of true deformation for the ORNL grids is required. Martin[3] has used COSMOS[4] to predict significant distortion of the JET grids at pulse lengths above 1 s; a result which does not agree with experimental beam performance. For this reason, it is proposed here that *experimental* measurement of grid distortion via its effects on the beam properties is the surest method for determining the importance of grid distortion for MAST NBI. Such a measurement can be carried out at Culham Science Centre on the Small Tight Aspect Ratio Tokamak (START) NBI facility, which is equipped with an ORNL 30 cm source which was used to inject into START, and is now available as a test stand. At present, this facility can operate at pulse lengths up to 80 ms,

TABLE II. ORNL grid dimensions.

Grid	Thickness (mm)	Aperture (mm)
Plasma	2.286	4.445/5.08
ACCEL	3.175	5.08
DECEL	3.175	5.08

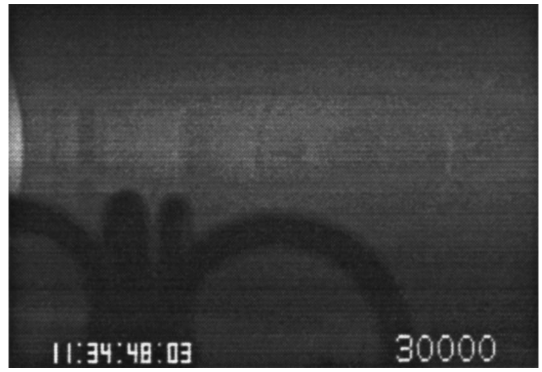

FIG. 2. CCD image of a perveance matched beam within the calorimeter tank.

but an upgrade of the water cooling system to allow long pulse operation is underway. As part of this upgrade, diagnostics are to be installed to allow time-dependent thermal effects, such as grid distortion, to be assessed.

III. DEVELOPMENT OF A TECHNIQUE FOR GRID DISTORTION MEASUREMENT

A. Experimental measurements

Given the high peak power densities in the ORNL beamline (on the order of 130 MW/m^2 at the proposed MAST NBI calorimeter), it is essential to use a noninterceptive technique for measuring beam profiles at pulse lengths above 0.1 s. Since it has been well established that beam profiles can be measured using the emission induced in the beam channel by excitation of background gas and beam neutrals,[5] development of a noninterceptive beam profile diagnostic based upon measurement of beam size at two or more positions has been proposed to determine the focal length and beamlet divergence as a function of time for comparison with results from ORNL modeling and for calculation of the beam size at key components.

In order to provide an early test of the proposed technique, measurements were carried out at a reduced pulse length (80 ms) and power (30 keV/50 A) during February 1998 on the ORNL injector used on START until March 1998. A Hitachi KP-M1 charge coupled device (CCD) camera was positioned to view the beam after the beam scrapers inside the calorimeter tank (2.72 m from the accelerator plasma grid), and a typical image is shown in Fig. 2. An example of the resultant profile is shown in Fig. 3 for a perveance of 9.5 μPv, which is close to perveance match. The radius scale was calibrated using the positions within the CCD image of the light reflected off the edge of items of known spacing lying above and below the beam center line. The level of noise on the detected images, and the degree of shot to shot repeatability, suggest that these images allow the beam profile ($1/e$) width to be derived to an accuracy of $\pm$0.25 cm. Full implementation of this technique will require the installation of a further window and light baffles to facilitate measurements within the main tank to provide the required second measurement position (existing ports do not provide a suitable view for such measurements).

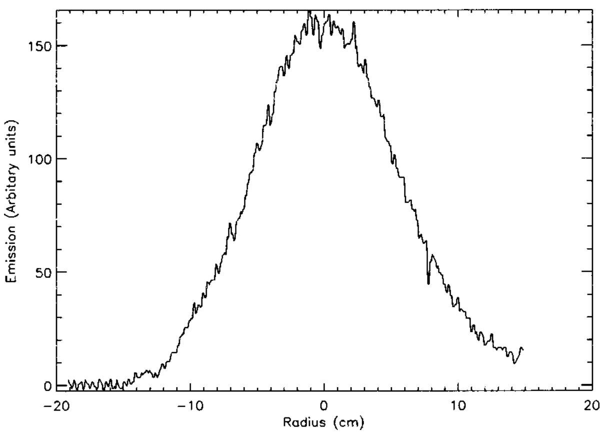

FIG. 3. Raw data for the measured emission profile (calorimeter tank).

In order to verify that the technique provides a realistic value for the beam size, measurements were made at varying perveance values of both the emission profiles and power deposition profiles measured at an EK98 graphite beam stop located within START. This beam stop is equipped with a vertical row of 13 thermocouples, which provide the (1/*e*) width of the Gaussian beam power distribution at the beam stop. The measured beam stop profile widths are consistent with values for the accelerator focal length and (1/*e*) beamlet divergence of 4 m and 1.2°, respectively. Using these values, the beam profile (1/*e*) widths shown in Fig. 4 have been derived. The agreement between the widths derived from emission measurements and those derived from the beam stop is very encouraging, and it confirms that this technique allows the beam width to be determined to within ±0.25 cm.

B. Modeling

In the absence of main tank profiles, a full experimental test of the technique is not possible, and so modeling has been used to assess the suitability of this technique. The beam size at the two camera positions has been calculated as a function of beamlet divergence and accelerator focal length, assuming: (a) uniform grid curvature, (b) a Gaussian beamlet divergence distribution, and (c) a uniform source current density distribution. Figures 5(a) and 5(b) show the resultant contours of constant beam size (in bands of ±0.5 cm) predicted for the main and calorimeter tank, respectively. Figure 6 shows the result that would be obtained if the beam (1/*e*) radii of 8±0.25 and 7±0.25 cm predicted for a 4 m focal length 1.2° divergence beam at the main and calorimeter tank camera positions, respectively, were observed. This demonstrates that the focal length and divergence could be derived from the crossover in the two contours to accura-

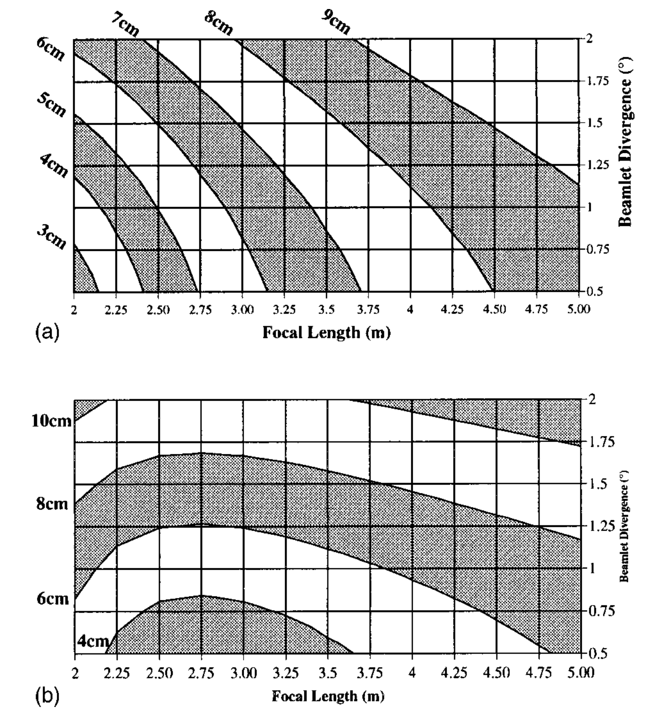

FIG. 5. Contours of constant beam (1/*e*) radius predicted as a function of accelerator focal length and beamlet divergence at: (a) top trace—main tank, and (b) bottom trace—calorimeter tank.

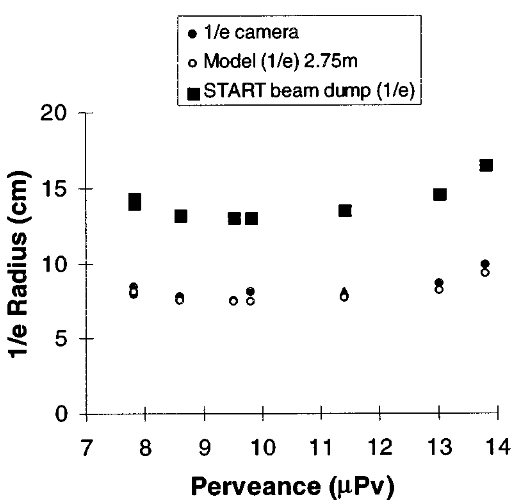

FIG. 4. (1/*e*) beam profiles (a) measured at 2.75 m from the source using the CCD camera (closed circles), (b) measured at 5.5 m from the source using the beam stop (closed squares), and (c) derived using the beam stop measurements for 2.75 m from the source (open circles).

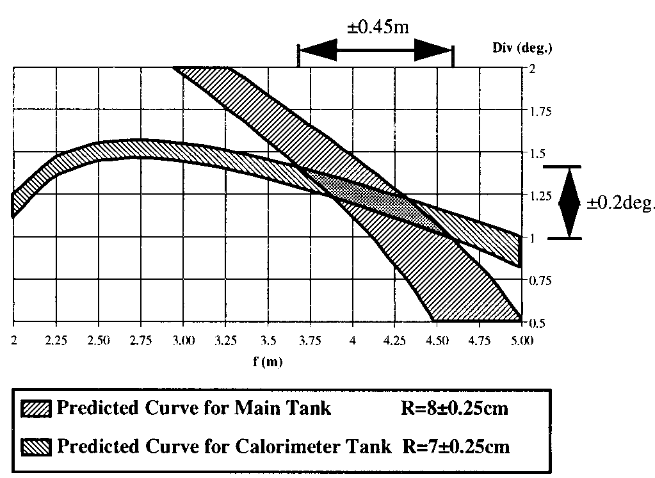

FIG. 6. Demonstration that crossover of the contours measured at the main and calorimeter tank positions provides quantification of the focal length and beamlet divergence [using the beam sizes corresponding to the nominal 4 m focal length and 1.2° (1/*e*) divergence].

cies on the order of ±0.45 m and ±0.2°, respectively, which is sufficient for determining gross changes in the beam transport if grid distortion occurs.

IV. CONCLUSIONS

Existing ORNL duopigatron injectors are to be used for NBI on MAST at pulse lengths up to 5 s, but modeling at ORNL has suggested that the existing grids may distort unacceptably at such pulse lengths. A technique for assessing whether grid deformation is significant at long pulse length has been successfully tested on the START neutral beam injector at UKAEA. At present, the full measurement cannot be carried out due to the limitations of a pulse length of <80 ms on START. Upgrades to the water cooling system, presently planned for late 1998, should allow grid distortion at pulse lengths above 0.5 s to be assessed.

ACKNOWLEDGMENTS

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