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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

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ABSTRACT.
As part of the upgrade to the JET neutral beam heating system a new Positive Ion Neutral Injector (PINI) design has been commissioned. The new PINI delivers 60A total beam current at 130kV, approximately doubling the neutral beam power delivered to JET. A programme of testing on the Neutral Beam Test Bed established the preferred geometry to maintain horizontal and vertical beam focal lengths of 10m and 14m respectively. The results of these tests and the characterisation of the beam using a number of diagnostic techniques are described, together with predictions for neutral power delivery to the JET plasma.

1. INTRODUCTION

HE neutral beam heating system on the JET Octant 8 will be upgraded to deliver 15MW of neutral deuterium beam power by 2002. To achieve this doubling of power capability, the Positive Ion Neutral Injectors (PINIs) have been modified from 140kV/30A to 130kV/60A operation, the limits being set by the power supply. To minimise additional costs, the original vertical and horizontal focal lengths of 14m and 10m respectively have been preserved thus recreating the original balance between power loading on the beamline elements and power delivered to the JET plasma. The only new component required is the plasma grid; all other components (deceleration grid, neutraliser, etc.) can be re-used.

The increase in perveance has been achieved by shortening the accelerating gap of the triode, whilst simultaneously modifying the off set aperture steering to maintain the vertical and horizontal focal lengths. The KOBRA3-INP [1] beam simulation code was initially used to determine probable geometries and several prototype plasma grids were tested on the Neutral Beam Test Bed at JET. The paper presents the results of the tests of the upgraded PINI.

2. DESCRIPTION OF THE MODIFIED PINI

An overall description of the JET PINI is given in [2]. The PINI beams are produced from triode or tetrode accelerator geometries, with the triode being used for higher energy operation. The PINI source is a magnetically confined bucket type of dimensions 500x300x200mm with magnetic filter to enhance proton yield. Each accelerator grid is formed from two half grids inclined at an angle of 8mrad from the vertical plane, each half containing 131 extraction apertures.

The increase in beam power was achieved by reducing the gap between the plasma grid (G1 in Fig.1) and the decelerating grid (G3) to increase the perveance of the injector. The aperture sizes remained the same as for the standard PINI.

To produce the required vertical and horizontal focal lengths, the apertures in the plasma grid are offset with respect to those in the decelerating and earth grid to produce a steering effect. The degree of steering is a function of the electric field in the first gap, it follows therefore that to maintain the beam focal length whilst shortening the first gap, the aperture offset should be modified.

Simulation using the KOBRA3-INP code suggested that the offset aperture steering constant would increase by ~48% as a result of shortening the gap in the upgrade triode [3], implying a reduction in the offset of ~50%. The uncertainty in the modelling was such that three combinations of gap and offset were tested experimentally before selecting the optimum geometry; the combinations and the PINI designations are given in Table I.

PINI Designation	G1-G3 Gap (mm)	Offset Steering (% of Standard PINI)
S	27.2	100
U1	15.0	63
U2	16.0	50
U3	16.0	63

Table 1: PINI Geometries

The Neutral Beam Test Bed at JET contains a number of diagnostic devices for beam characterisation. Most of the measurements are performed using inertial, water and infra red calorimetry [4], although some Doppler shift Hα spectroscopy was performed.

3. CHARACTERISATION OF THE PINI GEOMETRY

Figure 1 shows the modification to the grid gap in the triode; the upper half illustrates the standard triode and the lower half the upgrade triode. Values of grid gap of 16mm and 15mm were tested with aperture offsets of 63% and 50% of the standard arrangement.

Figure 2 shows the results of perveance scans onto the beam dump, approximately 12m from the injector, for the three upgrade geometries and the standard PINI. The increase in perveance is obvious, with geometry U1 giving a perveance match at 1.3P at 100kV, corresponding to a total extracted beam current of 40.9A. Extrapolating to the maximum operating voltage of 130kV (including the change in species ratio with arc current) implies a current of 63.3A, above the specified value. Geometry U1 therefore delivered a higher perveance beam than required hence the increase in gap length from 15 to 16mm for geometries U2 and U3. The increase in minimum beam width at the dump can be attributed to an increase in the space charge of the residual charged species for geometries U1 and U3, with an additional contribution from the steering for U2.

The effect of the offset aperture steering is further demonstrated in Fig.3, which shows a normalised vertical profile of a deuterium beam generated by geometries U2 and U3. The profile is obtained by analysis of the infra red image of the beam formed on a CFC tile situated 4.8m along the beamline from the PINI. The reduced offset aperture steering of the U2 geometry gives a wider beam profile. The vertical focal length can be estimated form this data to be approximately 16m for geometry U2 and 13m for U3; comparison with the desired value of 14m demonstrates the superiority of geometry U3 for the upgrade PINI design.

4. OPERATION OF THE UPGRADE PINI

To date, four upgrade PINIs have been operated up to 134kV on the Test Bed in preparation for installation on Octant 8 of JET in November. The average conditioning time required to achieve full power is approximately 5000s of beam time, which represents some 1500 pulses or 112 hours of Test Bed operation. Conditioning statistics, shown in Fig.4, indicate the increase in extraction voltage over the conditioning period. "Reliability" is defined as the ratio of actual beam on time to the set beam on time and "normalised power" is defined as the deuteron equivalent power multiplied by the reliability.

Despite the increase in beam power, the power loading of the PINI and beamline components remains within design limits. Figure 5 shows the power loading on the intermediate grids, neutraliser and Box Scraper for the standard geometry and the U3 geometry. (The Box Scraper simulates the position of the Neutral Injector Box exit beam scrapers on the actual Torus Injection System [2]). Power loading on the Box Scraper is typically 8% of extracted beam power at perveance match, a value similar to the standard PINI, indicating no significant deterioration of beam optics as a result of increasing the perveance of the injector. The power loading on the Test Bed beam dump (>5MW) restricts the pulse length to <2s at full beam power.

Figure 6 shows vertical beam radius (1/e) measured by water calorimetry at the beam dump. Optimum perveance in deuterium is 1.2×10^{-6} $AV^{-3/2}$ at 110kV, which extrapolates to 1.23×10^{-6} $AV^{-3/2}$ at nominal operating voltage of 130kV. The optimum perveance in tritium is expected to be 1.0×10^{-6} $AV^{-3/2}$, giving a current of 47A at 130kV. The maximum deuterium current achieved is 56.8A at 128kV (total extracted power 7.3MW) at a set arc current of 1200A and total gas flow ~24mbar litres/s. The maximum voltage achieved during conditioning is 134kV using deuterium in the source and neon in the neutraliser. Using grid gas feed (necessary for tritium compatibility) 50A total beam current is extracted in deuterium for a set arc current of 1400A and gas flow of ~28mbar litres/s.

The two dimensional beam power density profile is routinely measured at 4.8m and 8.3m from the PINI using an infra red inertial calorimetric technique [4]. The image can be displayed either as false colour or power density contours, as shown in Fig.7, which demonstrates the evolution of the beam along the beamline. Figure 7(a) shows power density contours of a deuterium beam at 4.8m where the density distribution still retains the character of the two grid halves. At 8.3m distance (Fig.7(b), the two beams have merged to form a single distribution. Note also that the beams extracted from each half of the grid are well aligned in the vertical plane. This degree of alignment is obtained through the use of a precise measurement of grid positions and simulation of the resulting beam profile during assembly of the PINI [5]. This technique permits the correction of poorly aligned PINIs before installation on the Neutral Beam Test Bed.

5. EXTRAPOLATION TO OPERATION ON JET

From the performance of the upgrade PINIs on the Neutral Beam Test Bed, the power delivered to JET from each PINI can be estimated. The overall beam transmission is known to be approximately 70% of total extracted beam current, which for a typical target density of $7.5\times10^{19}m^2$ in the neutraliser gives a neutral beam power of 1.94MW per PINI in deuterium. Figure 8 shows the calculated deuterium neutral beam power for the standard and upgrade PINIs as a function of neutraliser target density. The total deuterium neutral beam power from the Octant 8 injector box will be in excess of 15MW.

For operation in tritium at 130kV/47A the total neutral injected power will be 2.4MW per PINI or approximately 19MW for the injector box.

CONCLUSIONS

The standard JET PINI has been successfully upgraded to double the neutral beam power delivered to the JET plasma; all the requirements with respect to power loading and beam transmission have been fulfilled. The high power density of the beam limits the pulse length during conditioning at high voltages and similar problems can be expected during operation on the Torus. To minimise the conditioning time required on the Torus, the new PINIs will be conditioned on the Neutral Beam Test Bed to voltages above nominal using a deuterium/neon gas mixture.

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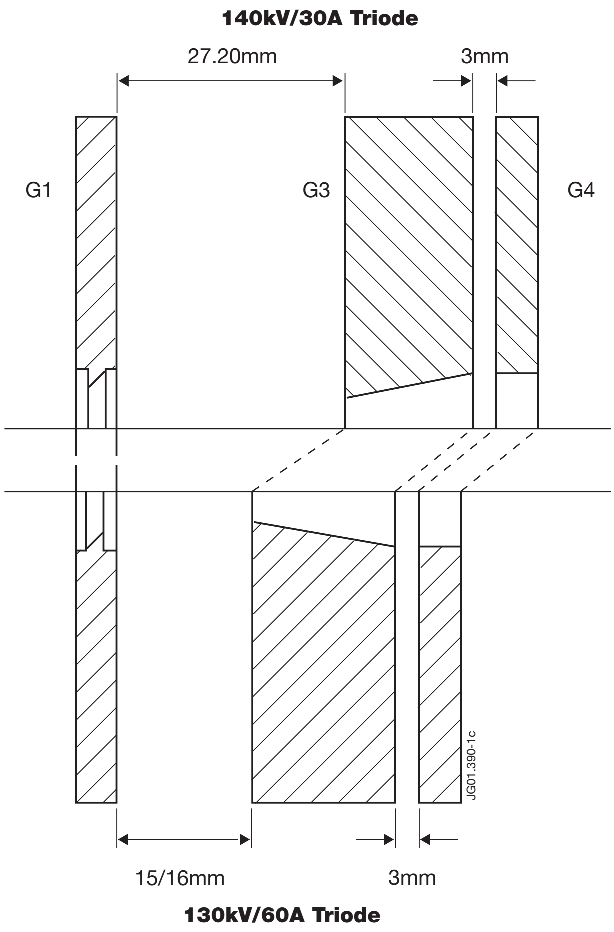

Figure 1: Modification of the triode geometry in the upgrade injector

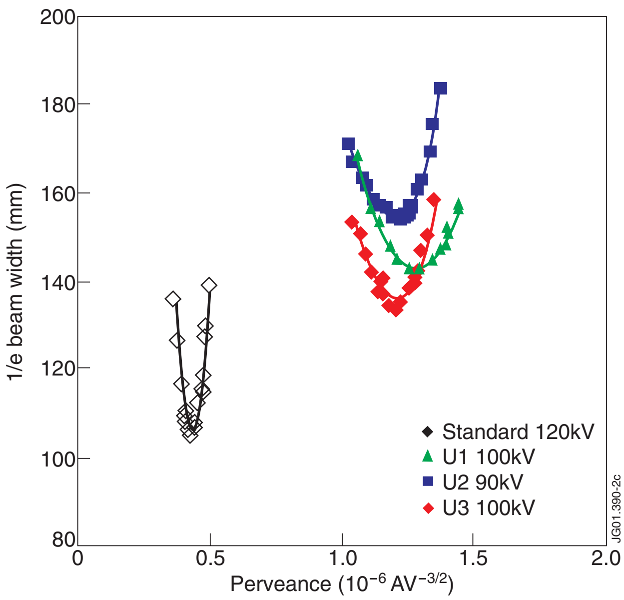

Figure 2: Perveance scans in deuterium for the standard & upgrade geometries. (◇) S 120kV, (▲) U1 100kV, (■) U2 100kV, (◆) U3 90kV.

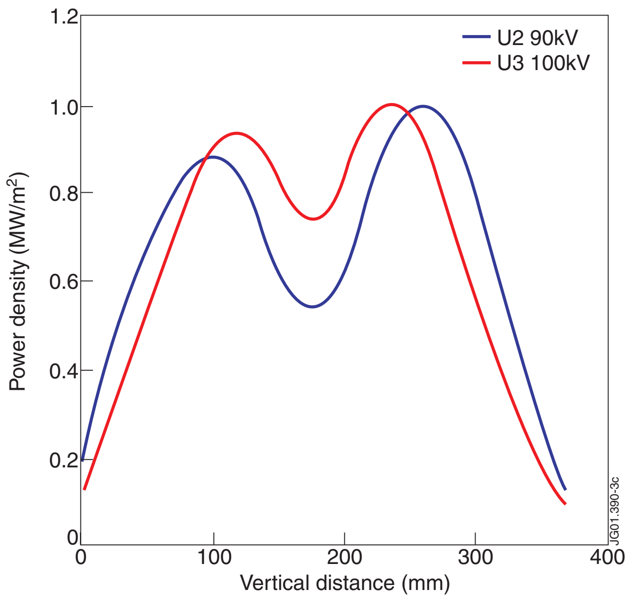

Figure 3: Normalised vertical profiles of deuterium beams from geometries – U2 and – U3 at optimum perveance. Measured at 4.8m from the PINI .

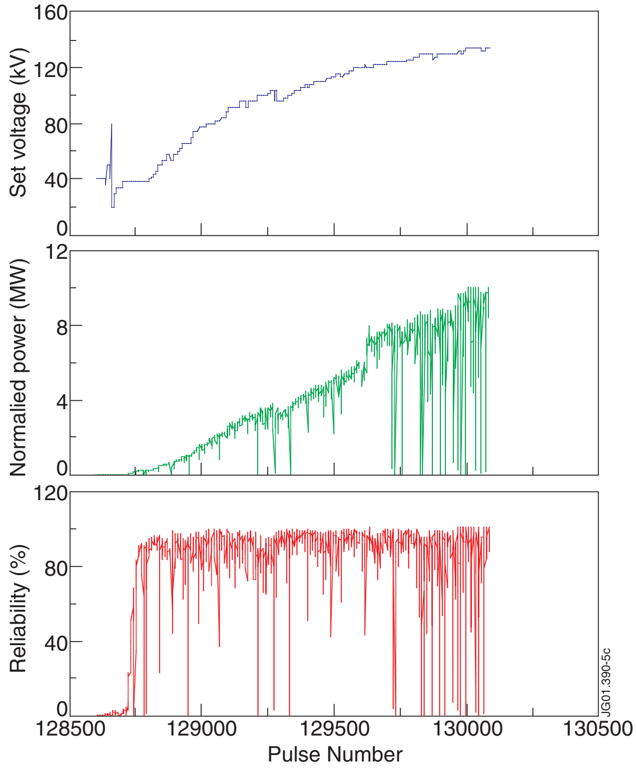

Figure 4: Conditioning statistics for upgrade PINI. Reliability is defined as the ratio of actual beam on time to set time. Normalised power is the deuteron equivalent beam power multiplied by the reliability.

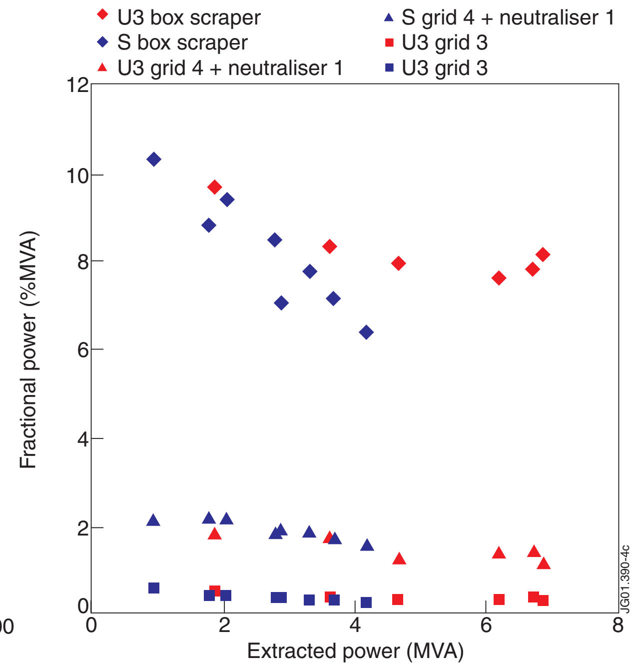

Figure 5: Power loading on the intermediate grids and Box Scraper element for standard, S, and upgrade geometry, U3. Values are expressed as percentage points of extracted power for operation in deuterium at optimum perveance. (◆) U3 box scraper; (◇) S box scraper; (▲) U3 grid4 + neutraliser1; (△) S grid4+neutraliser1; (■) U3 grid3; (□) S grid3.

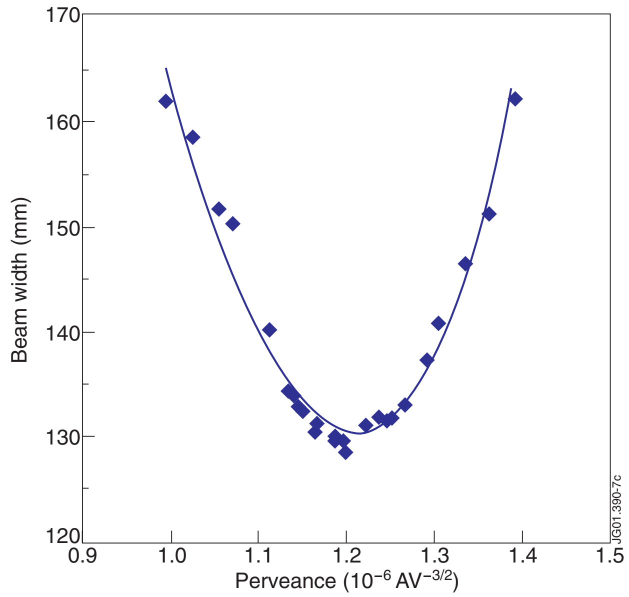

Figure 6: Vertical beam width (1/e) measured at the beam dump by water calorimetry. Composite deuterium beam at 110kV.

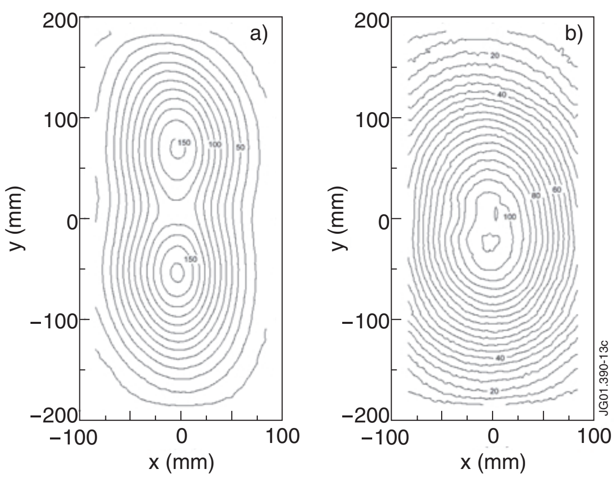

Figure 7: Power density profiles derived from the infra red calorimetry of a deuterium beam 110kV/44A at (a) 4.8m & (b) 8.3m from the PINI. Contour units are MWm^{-2}.

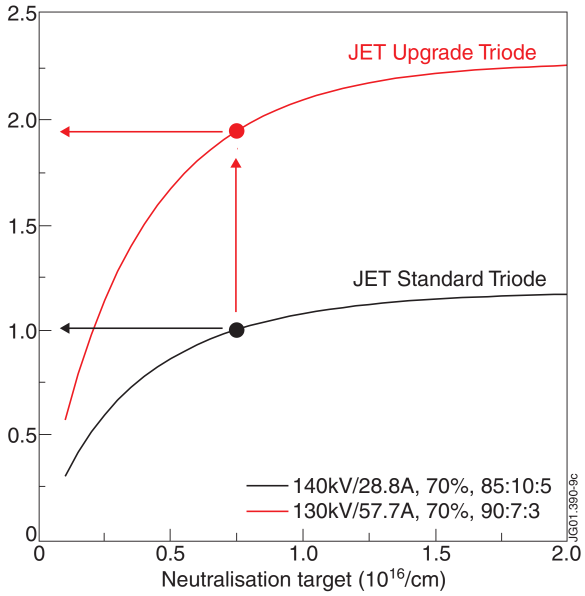

Figure 8: Calculated neutral deuterium beam power delivered to JET for standard and upgrade PINIs. Standard triode:140kV/28.8A D^+ 85%, $D2^+$ 10%, $D3^+$ 5% Upgrade triode: 130kV/57.7A D^+ 90%, $D2^+$ 7%, $D3^+$ 3% Total beam transmission 70%