Beam properties of the enhanced JET PINIs

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Two enhanced Positive Ion Neutral Injectors (PINIs) have been constructed and tested at the JET Neutral Beam Test Bed. Both were capable of producing ≥ 50 A of Deuterium beam at 140 kV acceleration and were conditioned within reasonable time (≤ 1500 beam on seconds). Two upgraded PINIs have excellent optical properties, particularly the PINI with the tetrode accelerator which has the lowest beam divergence ever seen for such positive ion multi-aperture source - 0.25°. Total extracted beam power of ≤ 8 MW for single PINI, and power density in the beam centre > 250 MW/m², are also record values obtained so far at JET. Beam power densities are above or very close to the design limits of present JET injector beamline components (scrapers, calorimeters and dumps). One neutral injector box fitted with eight such PINIs would be capable of delivering >15 MW of Deuterium neutral beam power and >19 MW of Tritium neutral beam power into the JET plasma.

1. INTRODUCTION

As a part of the study regarding the possibility of increasing the neutral beam heating power to JET, two upgraded Positive Ion Neutral Injectors (PINIs) have been constructed and tested at the JET Neutral Beam Test Bed (1). Preliminary computer simulation studies suggested that the design goal (≥50 A of Deuterium beam at 120-140 kV extraction voltage) could be accomplished by relatively simple modification of the accelerating grid structure, i.e. by changing only the inter-electrode spacing of the standard JET PINIs.

The main objective of the test was to determine the beam optical properties of the enhanced PINIs: optimum perveance, beam divergence and beam steering. The test had two additional objectives: a) to establish if these high power PINIs could be conditioned within acceptable time, and b) to provide data to determine if the PINI and the neutral injector beamline components would be able to sustain the increased power loading.

2. COMPUTER SIMULATION PREDICTIONS

The inter-electrode spacing for the two accelerator configurations was determined using the IONTRAK code - Culham version of the AXCEL two-dimensional Poisson solver. Accelerating grid structures of the standard JET 140 kV triode PINI and 80 kV high current tetrode PINI were implemented (1). The only mechanical modification to the accelerator structures was the change of the inter-electrode spacing: a) reduction of the acceleration gap from 27.2 mm to 17.5 mm in the triode case, and b) increase of the two acceleration gaps from 2.8 and 6 mm to 5.4 and 13.5 mm in the high current tetrode case.

The calculated trajectories of 140 kV Deuterium ions are shown in Figure 1 for the two accelerator geometries. The upgraded triode shows very strong beam compression with a minimum waist diameter of 1.6 mm, while the beam from the upgrade tetrode is virtually parallel with a minimum waist of 5 mm. This implies high space charge blow up of the beam in the triode case and virtually no blow up in the tetrode case.

The first-order thin lens approximation based on calculated potential distribution suggested that the beam steering (i.e. the focal lengths) of the upgrade tetrode will be similar to that of the standard tetrode (horizontal and vertical focal lengths f_H = 10 m, and f_V = 14 m), while the reduction of the focal lengths was expected for the enhanced triode case.

The predicted values of optimum perveance, i.e. the ratio between extracted current and the acceleration voltage at minimum beam divergence condition, were $I_{ex} / V_{acc}^{3/2} = 0.95\times10^{-6}$ A/V$^{3/2}$ for both upgrade triode and upgrade tetrode PINIs. This perveance corresponds to 50 A of extracted Deuterium current at 140 kV acceleration.

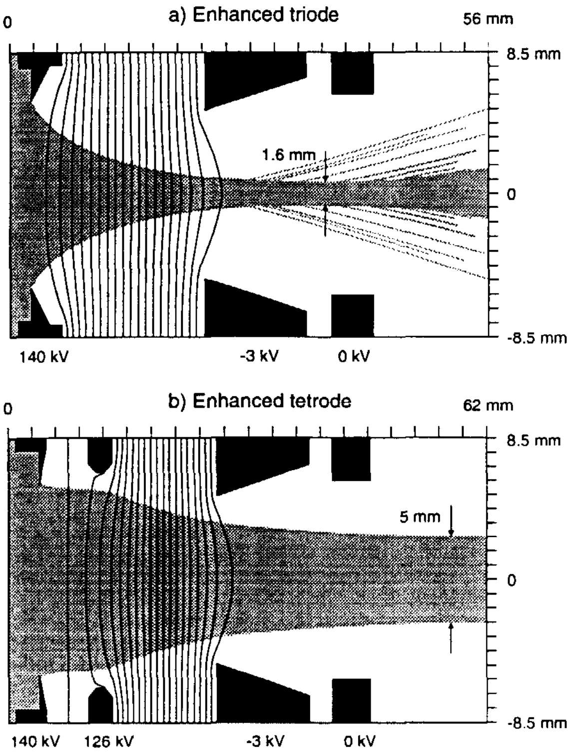

Figure 1. Trajectories of 140 kV Deuterium ions for a) enhanced triode and b) enhanced tetrode.

3. TEST SEQUENCE

Two PINIs with modified accelerating grid structures were constructed. To minimise the influence of the non-uniform source plasma density on beam optical properties, both PINIs were fitted with the same ion source with chequerboard magnetic configuration. It is known from previous work that this type of ion source provides uniform plasma density across the large extraction region (2).

Both PINIs were initially conditioned using Hydrogen beams up to the available power supplies limit (60 A of extracted current). The upgrade triode PINI was also conditioned in Deuterium up to the full acceleration voltage of 140 kV.

Helium beams were used to determine the beam optical properties. Horizontal and vertical beam profiles were measured using inertial cross calorimeter located at 6.3 metres from the source and using water and inertial calorimetry of the Test Bed beam dump at 12 metres from the source. Two-dimensional beam profiles were measured at several positions along the beam axis (4.75 - 10 metres from the source) using a mobile carbon fibre composite inertial calorimeter viewed by an infrared camera.

Doppler shifted Balmer-α spectroscopy was used to measure the species composition of Hydrogen and Deuterium beams.

4. RESULTS

4.1. Conditioning

Both PINIs were conditioned within acceptable time. The accumulated beam on time (≤1500 s) was comparable to the one required to condition the standard JET PINIs to the same reliability level. No difficulties (excessive number of high voltage breakdowns, short circuits, etc.) were experienced during the conditioning procedure.

4.2 Optimum perveance

The optimum beam perveance was determined as the ratio of extracted current and acceleration

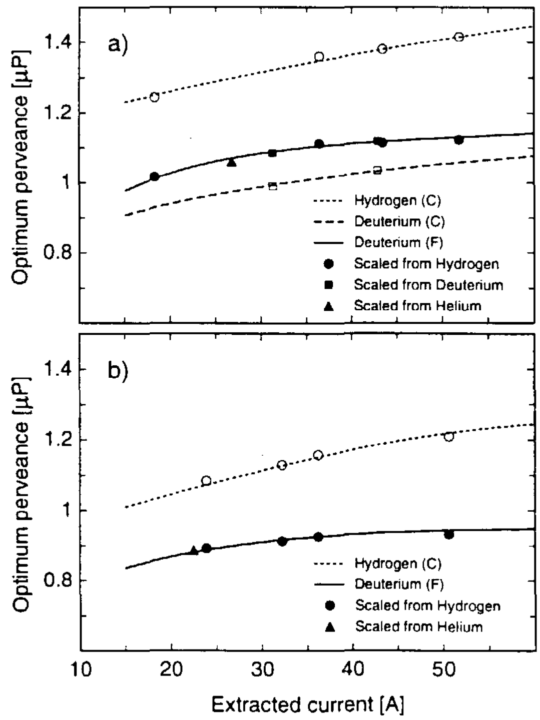

Figure 2. Optimum perveance for a) enhanced triode and b) enhanced tetrode PINIs: measured values for chequerboard (C) source and extrapolated values for filter (F) source

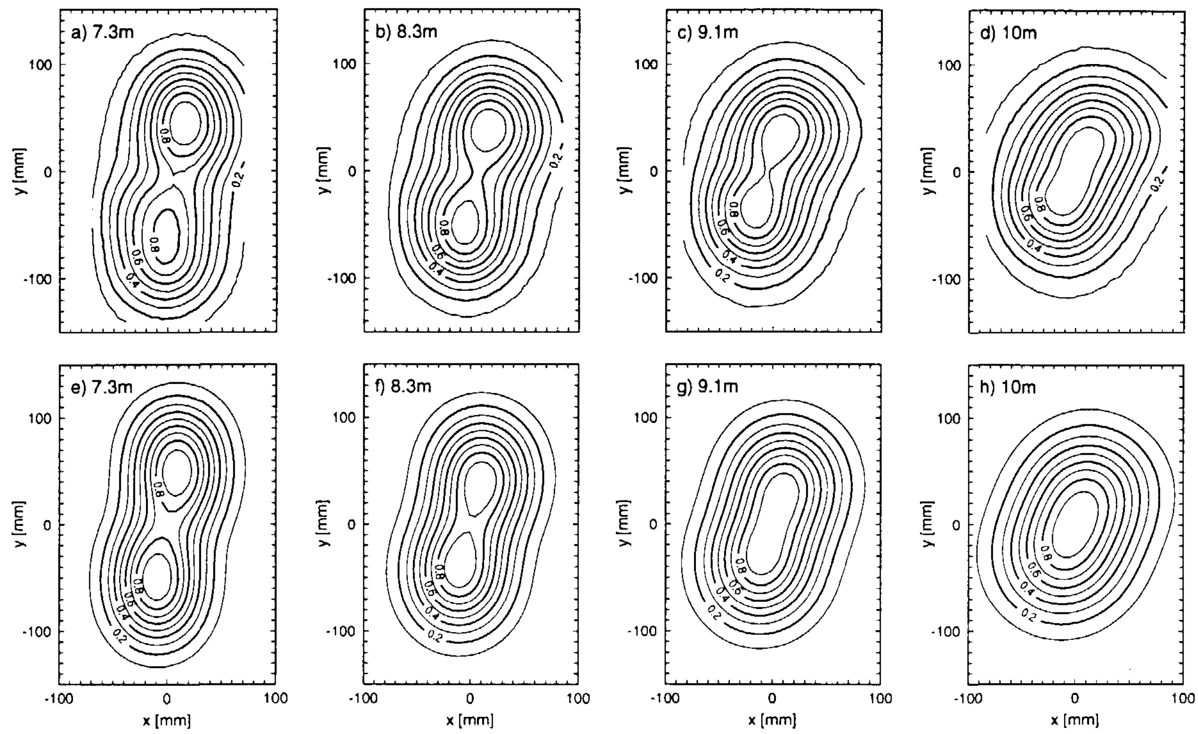

Figure 3. Measured (a-d) and calculated (e-h) normalised power density distributions for the enhanced tetrode PINI (100 kV Helium beam at optimum perveance) at various distances from the source. Best fit to the measured data is obtained for the beam divergence of 0.25° and vertical and horizontal focal lengths of f_V = 12 m and f_H = 8 m.

voltage (I_{ex} / $V_{acc}^{3/2}$) corresponding to the minimum beam divergence, i.e. the minimum beam profile width. Since both enhanced PINIs were fitted with the chequerboard ion source (which has different species composition than the standard JET filter sources) the optimum perveance of the enhanced PINIs fitted with the standard JET filter source was estimated using the effective mass scaling (Figure 2). The effective mass was determined from the measured beam species composition.

Optimum perveance of a Deuterium beam above 50 A is 1.15×10^{-6} A/V$^{3/2}$ for the enhanced triode and 0.95×10^{-6} A/V$^{3/2}$ for the enhanced tetrode. This means that the optimum extracted Deuterium current at 140 kV acceleration for the PINI fitted with a filter source would be 60 A and 50 A for the upgrade triode and upgrade tetrode PINIs respectively.

4.3 Beam optical properties

Beam divergence and steering (vertical and horizontal focal lengths) were determined from the comparison of the measured two-dimensional profiles to the simulated power density distribution (Figure 3). Power density distribution was simulated as a sum of 262 individual beamlets (JET PINIs have 262 apertures in the acceleration grid structures). Beamlet divergence and vertical and horizontal focal lengths were used as free parameters in this procedure and the corresponding values were determined from the best fit to experimental data.

Vertical and horizontal focal lengths and beam divergence are: f_V = 9 m, f_H = 6.5 m, and α = 0.47° for the enhanced triode, and f_V = 12 m, f_H = 8 m, and α = 0.25° for the enhanced tetrode. This means that both accelerators require the modification of the aperture offset between the extraction and deceleration (negative) grids to adjust the focal lengths to the nominal values of 14 and 10 metres respectively.

Power density distributions of the beams from different JET PINIs are compared in Figure 4. As a

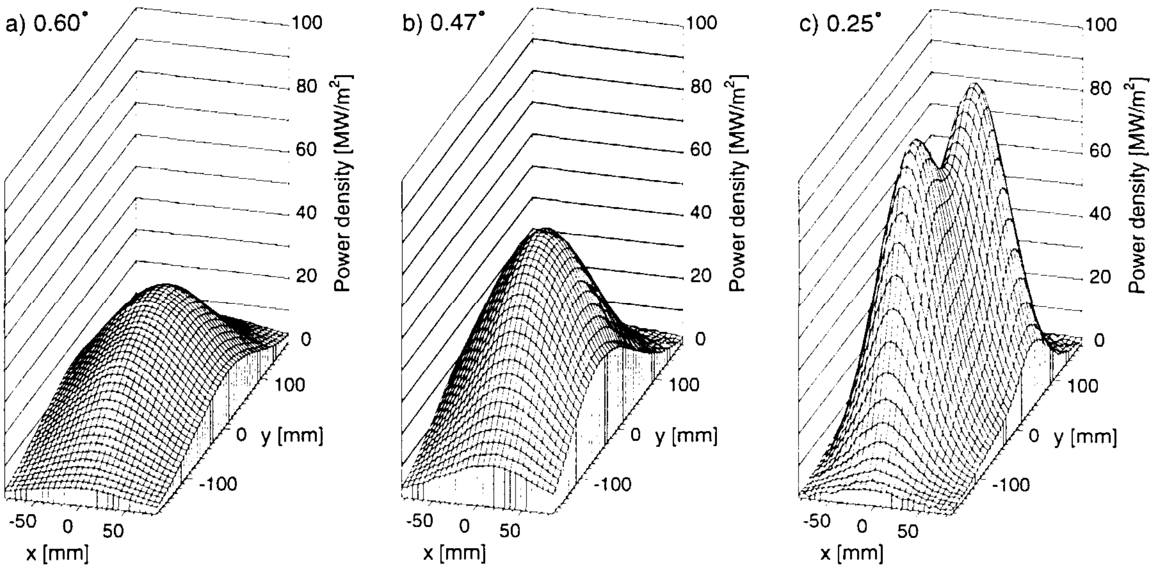

Figure 4: Measured Helium beam power density distribution at 8.3 metres from the source for different JET PINIs fitted with the chequerboard ion source: a) standard JET triode: V_{acc} = 103 kV, I_{ex} = 13 A, p_{max} = 37 MW/m², b) enhanced triode: V_{acc} = 100 kV, I_{ex} = 25.1 A, p_{max} = 74 MW/m², and a) enhanced tetrode: V_{acc} = 100 kV, I_{ex} = 22.6 A, p_{max} = 100 MW/m².

consequence of very low beam divergence and excellent optics, the peak power density of the beam extracted from the upgraded tetrode is extremely high. The two peaks in the distribution correspond to the beams from two grid halves. Note that more than 95% of the beam is contained within an area 150 mm wide and 360 mm high (Figure 4c).

4.4 Power loadings

Power densities of the beams from the enhanced PINIs are extremely high (Figure 4). If those PINIs are installed into JET Neutral Injectors, the power loading on various beamline components (scrapers, dumps and calorimeters) will be considerably higher compared to present situation. Excellent beam properties of the enhanced tetrode PINI practically disqualifies this injector as candidate for neutral injector upgrade whilst keeping the present Ion Dumps. The dump elements could, on the other hand, be subjected to several hundred full power 10s pulses without any danger, if the enhanced triode PINI were used. Longer lifetime of the beamline components (the most critical being the full energy ion dump) can be accomplished by correcting the beam steering to achieve longer focal lengths, or by reducing the injection energy to ~ 120 kV.

CONCLUSIONS

- Conditioning time is within acceptable limits for both PINI designs (≤ 1500 beam seconds).
- Optimum Deuterium beam current at 140 kV acceleration for PINIs fitted with a filter ion source: 59 A (enhanced triode) and 50 A (enhanced tetrode).
- Beam divergence : 0.47° (enhanced triode) and 0.25° (enhanced tetrode).
- Beam steering: grid modification required for both PINI designs.
- Power density: too high for present beamline components (enhanced tetrode) and just within the design limits (enhanced triode).
- Predicted injected neutral beam power into JET plasma (one injector box fitted with eight enhanced triode PINIs): >15 MW (140kV/60A Deuterium) and >19 MW (140kV/41A Tritium).

REFERENCES

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2. T. S. Green et al, 10^{th} Int. Conf. on Plasma Phys. and Contr. Nucl. Fusion Research, London, 1984 (IAEA-CN-44/H-I-5).