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# MAST neutral beam long pulse upgrade

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**Abstract**

Until summer 2003 two Neutral Beam Injectors (NBI), each equipped with one duopigatron ion source on loan from Oak Ridge National Laboratory (ORNL), were delivering up to 3 MW of deuterium neutral beam power into the Mega Amp Spherical Tokamak (MAST) plasma for a duration of up to 300 ms. The two ORNL injectors are now being replaced with JET type Positive Ion Neutral Injectors (PINIs). The MAST PINI design is a modification of the JET high current tetrode injector, with nominal deuterium beam voltage and current of 75 kV and 65 A, respectively. Each injector will deliver up to 2.5 MW of deuterium neutral beam power (in excess of 1 MW in hydrogen) for pulse lengths of up to 5 s.

In addition to the replacement of the two injectors, many other components of the MAST NBI system are being replaced or modified. The various design issues of the upgraded MAST NBI system are addressed.


*Keywords:* Neutral beam injection; Neutral beams; Plasma heating; Spherical tokamak

## 1. Introduction

Neutral Beam Injection (NBI) is the main auxiliary plasma heating system on the Mega Amp Spherical Tokamak (MAST) [1] at Culham. The original MAST NBI specification was for a deuterium neutral beam power per injector of 2.5 MW for 0.5 s or 2 MW for 5 s pulses when operated at 70 kV, 80 A and 61 kV, 60 A, respectively [2]. To this end two beam lines on loan from Oak Ridge National Laboratory (ORNL), each equipped with a duopigatron ion source, were installed during 1999 and 2000 onto MAST, based on the 1 MW 40 ms hydrogen pulses previously achieved on START [3]. Substantial progress towards this goal has been achieved—the highest injected deuterium power from a single injector of 2.2 MW and the longest pulse of 0.43 s (at 1.5 MW), have been recorded. Although good progress has been made, it was recognised that significant technical challenges still remain in order to achieve reliable operation at higher powers and longer pulse lengths. The decision was therefore taken to replace the duopigatron ion sources and ORNL accelerators [4] with JET type Positive Ion Neutral Injectors (PINIs) [5]. The PINIs have other advantages such as a smaller

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footprint which provides a brighter and more localised source for the MAST charge exchange recombination spectroscopy diagnostics, and better species mix which results in more power being deposited in the plasma core.

In July 2003, engineering work started to upgrade the MAST NBI systems for long pulse operation. The design goal of the MAST NBI upgrade project is the injection of 5 MW of total deuterium neutral beam power into the MAST plasma for pulse lengths up to 5 s.

## 2. MAST PINI design specification

The MAST PINI is a modification of the JET high current tetrode; a comparison of the design parameters of both injectors is outlined in Table 1. The primary differences from the JET high current tetrode are that the grid spacing, grid half-tilt angles, grid three hole pattern and operating voltage, all have been changed. The resultant accelerator focal lengths were chosen to match the MAST beamline geometry by minimising the local power density at the calorimeter and residual ion dump, which were designed for lower beam power densities from the ORNL injectors.

The reduced grid spacing results in a high steering constant of 55 mrad mm$^{-1}$, considerably higher than any PINI currently in use, meaning that the accelerator grid alignment has to be done with very high precision (<100 μm). Fig. 1 shows the predicted power density profiles at different axial positions along the beamline derived from the measured small accelerator grid misalignment of the first MAST PINI. Misalignment data were obtained using a high precision (25 μm) 3D co-ordinate measuring device using the procedure described in ref. [6]. There is some beam interception (∼3–4%) by the second stage neutraliser, but there is practically no interception with downstream beamline components. It should be noted that the reduced grid gaps and the applied accelerator potentials mean that the MAST PINI operates very near to the empirical Kilpatrick limit [7], implying longer conditioning times. Nevertheless, recent tests carried out on a similar

Table 1
Comparison of the MAST PINI and JET high current tetrode design parameters

| Parameter | MAST PINI | | JET high current tetrode |
|---|---|---|---|
| Source gas | $D_2$ | $H_2$ | $D_2$ |
| PINI gas flow rate (mbar s$^{-1}$) | 11 | 11 | 11 |
| Neutraliser flow rate (mbar s$^{-1}$) | 14 | 14 | 14 |
| Beam energy range (keV) | 35–75 | 35–56 | 35–80 |
| Maximum beam current (A) | 60 (65) | 55 | 55 |
| Optimum beam perveance ($10^{-6}$ A/V$^{3/2}$) | 2.9 | 4.1 | 2.3 |
| Grid spacing G1–G2:G2–G3:G3–G4 (mm) | 2:4.4:5.3 | 2:4.4:5.3 | 2.8:6.0:3 |
| Aperture diameter G1, G2, G4 (mm) | 12 | 12 | 12 |
| Aperture diameter G3 (mm) | 10 | 10 | 10 |
| Half-grid tilt angle (mrad) | 19 | 19 | 8.5 |
| Steering constant (mrad/mm) | 55 | 55 | 42 |
| Minimum beamlet divergence (mrad) | 9 | 16 | 9 |
| Ion source flux fractions $Z^+:Z_2^+:Z_3^+$ (%) | 92:6:2 | 91:7:2 | 91:7:2 |
| Ion source plasma density non-uniformity (%) | 10 | 10 | 10 |
| Neutraliser target line density ($10^{16}$ cm$^{-2}$) | 0.55 | 0.55 | 0.55 |
| Maximum beam power (MW) | 2.2 (2.5) | 1.1 | 1.7 |
| Beam pulse length (s) | 0.05–5 | 0.05–5 | 0.05–10 |
| Horizontal focal length (m) | 14 | 14 | 10 |
| Vertical focal length (m) | 6 | 6 | 14 |
| Overall beam transmission (%) | 85 | 80 | 70 |
| Beam shape on plasma axis | Gaussian | Gaussian | Gaussian |
| 1/e beam half width on plasma axis (cm) | 7.8 (8.8) | 12.6 | 12 |
| 1/e beam half height on plasma axis (cm) | 7.6 (8.6) | 12.5 | 12 |

Numbers in brackets correspond to operation 10% above optimum perveance. G1, ACCEL grid; G2, intermediate ACCEL grid; G3, DECEL grid; G4, grounded grid.