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ABSTRACT

The JET Neutral Beam Injection (NBI) system is undergoing an upgrade of both beam power and pulse duration, which will be completed in 2011. In order to obtain an early assessment of the performance of the upgraded injectors, two Positive Ion Neutral Injectors (PINIs) with modified ion source and accelerator configuration were installed on Octant 8 Neutral Injector Box and successfully commissioned in summer 2009. Both PINIs were routinely delivering ~2MW of deuterium neutral beam power during the JET experimental campaign in autumn 2009. These early tests allowed us to predict with confidence that the JET NBI upgrade objective of injecting 34MW of total deuterium neutral beam power into the JET plasma will be achieved.

1. INTRODUCTION

The JET NBI system consists of two Neutral Injector Boxes (NIBs) equipped each with up to 8 PINIs [1]. During the last twenty five years various modifications and upgrades of the system were carried out with the objective to increase the injected neutral beam power, to increase beam pulse duration and to improve the reliability of the system.

The latest upgrade of the JET NBI system was launched in spring 2005 as part of the JET Enhanced Performance 2 (EP2) programme. The scope and the aims of this NBI upgrade were discussed in detail previously [2] and will be only briefly described here. The three goals of the current JET NBI system upgrade are:

a) To increase the total injected deuterium neutral beam power from present 24MW to at least 34 MW.
b) To increase the NBI pulse duration at maximum power from present 10s to 20s and at half power from 20 s to 40s.
c) To improve overall availability and reliability of the NBI system.

The increase in power is achieved by increasing the extracted ion current of the high current triode PINIs, which were developed during the earlier EP1 Octant 8 NIB upgrade [3], and by modifying the extracted ion species composition. The increase in pulse duration from 10s to 20s will be accomplished by the replacement of inter-pulse cooled beamline components with actively cooled equivalents, in particular the beam duct protection on both NIBs [4]. Finally, the availability and reliability of the JET NBI system will be improved by the replacement of four existing 160kV/60A high voltage power supply units with four 130kV/130A units similar to these installed for the Octant 8 NIB upgrade [5].

The main goal of the present NBI upgrade is the increase in neutral beam power. This is accomplished by the conversion of all present JET PINIs (80kV/52-58A tetrode PINIs and 130kV/56A triode PINIs) to triode PINIs operated at 125kV/65A in deuterium. The conversion includes modification of the magnetic configuration of all present JET ion sources from supercusp filter to pure chequerboard pattern and optimisation of the injector accelerator geometry for operation at

125kV/65A in deuterium [2]. A number of EP2 PINIs were assembled, successfully commissioned and characterised at the JET Neutral Beam Test Bed. These tests confirmed predictions of increased neutral beam power and higher transmission.

To verify the Test Bed results, two EP2 PINIs were installed on Octant 8 NIB and commissioned for beam injection into JET in 2009. The main objectives of these tests were to get early experience in operating upgraded high power PINIs, to measure the injected beam power and to assess whether power loads on various beamline components are within the predicted margins. The outcome of this experiment allows us to estimate with confidence future JET NBI system performance after the completion of the upgrade and the commissioning of the entire NBI system in 2011.

2. COMMISSIONING OF UPGRADED INJECTORS

In April 2009, two fully commissioned PINIs with EP2 accelerator grid configuration [2] were removed from the Octant 8 NIB. The ion source magnetic configuration of these two injectors was rearranged to chequerboard pattern and they were reinstalled in the same positions on Octant 8 NIB. Both injectors were conditioned (in deuterium) in July 2009 by gradually increasing the operating parameters up to the maximum operating voltage of 125 kV. PINI conditioning took two weeks and required ~900 beam pulses with a total accumulated beam on-time of ~300s for each PINI. It should be noted that a relatively short conditioning time was required since both PINIs (with supercusp ion source configuration) were fully commissioned previously and were operated on Octant 8 NIB in 2008 and 2009.

After the completion of the EP2 PINI conditioning, systematic measurements of the neutralisation efficiency were carried out over a wide range of beam energies (60-120kV) for both EP2 PINIs. Optimum beam parameters were determined at each beam energy, and calorimetric measurements of beam profiles were carried out for composite (neutrals and ions) and neutral beams. The neutralisation efficiency was calculated from the ratio of beam profile integrals of neutral and composite beams. The injected power was then evaluated as product of neutralisation efficiency, extracted power ($V_{beam} \times I_{beam}$) and beam transmission through the JET beamline, which was derived from measurements at The JET Neutral Beam Test Bed. The results of these measurements are discussed in section 4.

Off-line commissioning, which consists of firing short (< 0.5s) beam pulses into beamline calorimeters, was followed by on-line commissioning, i.e. injection of beams into the JET plasma. Beam voltage and beam pulse length were gradually increased and power loading on various beamline components was assessed. The maximum beam voltage was limited to 112kV to maintain the power loading on beamline components within present engineering limits – these limits will be increased following the replacement of several critical components during the JET shutdown in 2010.

Measurements carried out during on-line commissioning confirmed predicted power loads on various beamline components.

All Octant 8 injectors were also commissioned using helium gas. Neutralisation efficiency and injected power of helium beams were determined using the method described above and are given in section 4.

Both EP2 PINIs were used in support of the JET experimental programme in the period July-October 2009 and routinely injected ~2MW of deuterium beam power into the JET plasma. Summary of the designed and achieved deuterium beam parameters during this NBI operation is given in Table 1. It is clear that most of the upgrade objectives were already achieved in this initial test – the only remaining goal is the increased pulse length that could be only accomplished after the upgrade of various beamline components during the present JET shutdown.

3. DEUTERIUM BEAM POWER INCREASE

The considerable increase in beam power is achieved by the modification of the JET triode PINIs, which were developed during the EP1 Octant 8 NIB upgrade [3]. This will be illustrated by comparing measured deuterium beam parameters of EP1 and EP2 PINIs at accelerating voltage of 120kV.

3.1. ACCELERATOR MODIFICATION

The increase in beam current is accomplished by increasing the diameter of 262 PINI extraction apertures from 11 to 11.5mm and by reducing the accelerator gap from 16 to 15mm. At 120 kV acceleration, this modification results in the increase of optimum beam current, i.e. the current that corresponds to minimum beam divergence, from 48.0A to 56.5A.

3.2. ION SOURCE MODIFICATION

The main contribution to beam power increase comes from the conversion of the PINI ion source magnetic configuration to regular chequerboard pattern, which results in large field free volume in the extraction region of the source. As a consequence, the ion composition of the beam will change from 88.5%, 8% and 3.5% of D^+, D_2^+ and D_3^+ for a supercusp PINI at 120kV/48A to 73%, 22% and 5% for a chequerboard PINI at 120kV/56.5A.

The molecular ions in the beam have lower velocity and are more efficiently neutralised (and dissociated) in collisions with neutraliser gas molecules. Consequently, the power of fractional energy components will increase considerably. Chequerboard ion sources produce a uniform plasma in the vicinity of the extraction region. This results in highly uniform extracted beam, with lower average divergence, and higher beam transmission. An increase in transmission from ~70% (EP1 PINI) to ~75% (EP2 PINI) was confirmed by measurements at the JET NB Test Bed. The combined effect of the change of the accelerator geometry and ion source magnet configuration on beam power fractions and total power is given in Table 2.

3.3 INCREASE OF OPTIMAL BEAM CURRENT

Beams are usually operated at optimum perveance, i.e. at the optimum ratio of beam current and beam voltage ($I_{beam}/V_{beam}^{3/2}$) that corresponds to minimum beam divergence. Higher injected power can be achieved by operating beams at slightly higher current. This was observed in the past in numerous experiments at the JET NB Test Bed and confirmed by calorimetric beam profile measurements with the EP2 PINIs installed on Octant 8 NIB. Measurements showed that up to 8% more power is injected when beams are operated ~8% above optimal beam current. At the same time the beam size is increased by < 3%, which, in the case of JET beamlines, has negligible effect on beam transmission.

The increase of optimum beam current from 56.5 to 61.0 A at 120 kV acceleration voltage results in the total deuterium power of 2.14 MW delivered to plasma.

4. MEASURED AND PREDICTED NEUTRAL BEAM POWER

4.1. DEUTERIUM

The neutralisation efficiency and corresponding injected neutral beam power of two EP2 PINIs were determined using the method described in section 2. The results are represented by large symbols in Figure 1. This figure also shows results obtained previously for a number of EP1 type PINIs. All measurements were carried out with beams at optimum perveance. Thin solid lines represent polynomial approximations of measured data, while the thick solid line shows the predicted power for EP2 PINIs operated at beam currents 8% above optimum perveance.

At beam energies below ~100keV experimental data could be well described by assuming neutralisation target line density of 5.6×10^{19} m^{-2} . At higher beam energies, measured neutralisation efficiency could be only interpreted by the reduction of target density due to the gas heating effect [6]. This effect becomes visible at extracted ion power of ~4MW (corresponds to 100keV) and the neutraliser target line density decreases gradually to the minimum value of 3.7×10^{19} m^{-2} at full power.

Deuterium beam power fractions could be deduced from known cross sections for various atomic collision processes occurring in the neutraliser by varying the target line density in the calculation to match the measured neutralisation efficiency. The results for deuterium beams operated at optimum perveance are shown in Figure 2.

4.2. HELIUM

Neutralisation efficiency of helium beams was also measured for EP2 PINIs equipped with ion sources with chequerboard or supercusp magnetic configuration. The injected power of helium beams is derived assuming beam transmission of 75%. The results for helium beams operated at optimum perveance are given in Figure 3. In the case of helium beams, the increase in neutral beam power comes only from the increase in beam current. The maximum operating beam voltage of 120kV is determined by the maximum available current of the bending magnet power supplies.

4.3. HYDROGEN

NB Test Bed results indicate higher molecular hydrogen ion fractions compared to the deuterium results: 60.1%, 26.5% and 13.4% of H^+, H_2^+ and H_3^+ compared to 70.0%, 22.4% and 7.6% of D^+, D_2^+ and D_3^+ at 50 A beam current. This trend is also confirmed by applying the ion source modelling code [7] to chequerboard ion sources. Test Bed results also suggest a lower transmission of 70% for hydrogen beams. By applying measured ion beam species composition and assuming neutralisation target reduction with extracted ion power similar to that discussed in section 4.1, hydrogen neutral beam power fractions can be calculated. The results for hydrogen beams operated at optimum perveance are shown in Figure 4. The maximum beam voltage is limited to ~90kV to maintain the power load on the fractional energy ion dump within engineering limits. This results in a maximum hydrogen beam power of ~1MW per PINI with a dominant half energy beam component (Fig.4).

4.4 TRITIUM

The prediction of tritium beam power is based on experimental data obtained for deuterium and hydrogen beams. Neutraliser gas line density of $4\times10^{19}\ m^{-2}$ was assumed at low beam power, based on the measurements with tritium beams during the JET Trace Tritium Experiment [8]. The reduction of neutralisation target with beam power was implemented in the manner described in section 4.1. To account for the isotopic effect on tritium ion species composition predicted by modelling [7], the measured deuterium atomic species fraction was increased by ~8%, with a corresponding reduction of the two molecular ion fractions. In the case of tritium beams, the maximum operating voltage is determined by the maximum ion current that can be extracted from the EP2 PINIs. JET PINIs use a tritium gas manifold, which does not supply gas directly into the ion source, resulting in low ion source pressure that limits the extracted current. Maximum tritium current is estimated to be 45A. This maximum current is derived from data obtained with deuterium beams operated using the tritium gas feed. The modification of the tritium gas feed that would make possible an increase of tritium beam current is being assessed.

Predicted power fractions for tritium beams operated at optimum perveance are shown in Figure 5. Since many assumptions have to be made in this evaluation, larger uncertainties should be assumed for tritium power prediction, particularly in estimating beam power fractions. Nevertheless, a sensitivity study carried out by varying the neutralisation target density and species composition suggests that more than 2MW of tritium beam power will be achieved at 118kV/45A with a dominant full energy component.

CONCLUSIONS

Successful early tests of upgraded JET EP2 injectors enable us to predict with a high degree of confidence the future performance of the JET NBI system. These tests confirmed that the design goal of more than 34MW of injected deuterium beam power could be achieved and that considerable increase in beam power using other gas species could be expected, as summarised in Table 3.

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Parameter	Designed Value	Achieved value on-line	Achieved value off-line
Maximum voltage (kV)	125	112	125
Maximum current (A)	65.0	54.0	65.7
Maximum power (MW)	>2.13	2.08	2.16
Maximum pulse length (s)	20.0	9.3	–

Table 1: Designed and achieved deuterium beam parameters for JET EP2 PINIs.

PINI type	Beam power fractions (MW) Full	Half	Third	Total
EP1 PINI (120kV/48.0A)	1.03	0.21	0.13	1.37
EP2 PINI (120kV/56.5A)	1.04	0.72	0.23	1.99

Table 2: Measured deuterium beam power fractions for EP1 and EP2 PINIs operated at 120kV.

Parameter	Gas species H_2	D_2	T_2	^4He
Max. beam energy (keV)	90	125	118	120
Max. beam current (A)	50	65	45	42
Max. power per PINI (MW)	1.0	2.16	2.2	1.56
Max. power per NIB (MW)	8.0	17.3	17.6	12.5
Max. total power (MW)	16.0	34.6	35.2	25.0

Table 3: Measured (D_2 and ^4He) and predicted (H_2 and T_2) parameters of the JET NBI system after the completion of EP2 upgrade.

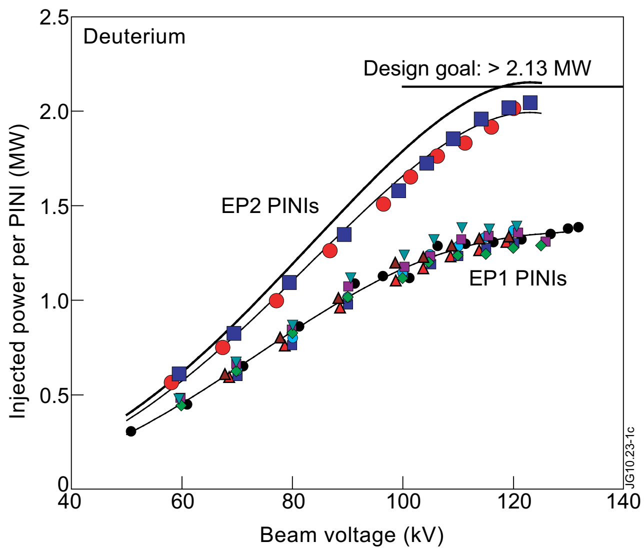

Figure 1: Measured deuterium beam power.

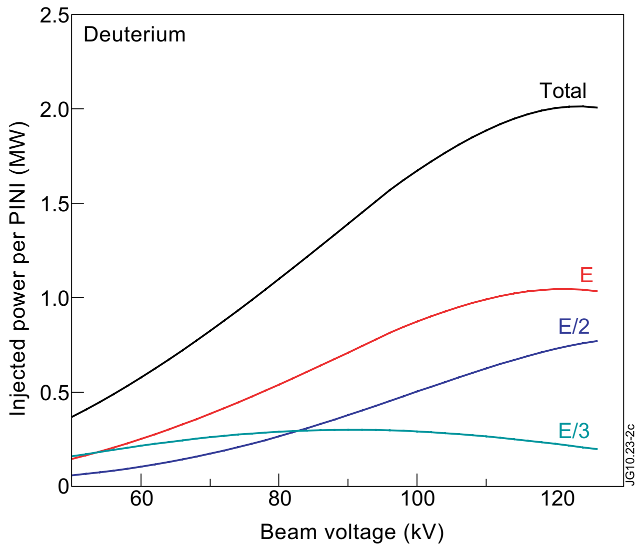

Figure 2: Predicted deuterium beam power fractions.

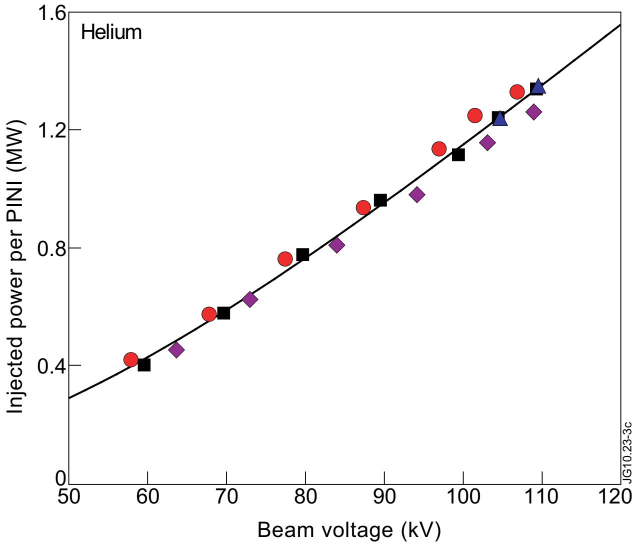

Figure 3: Measured helium beam power.

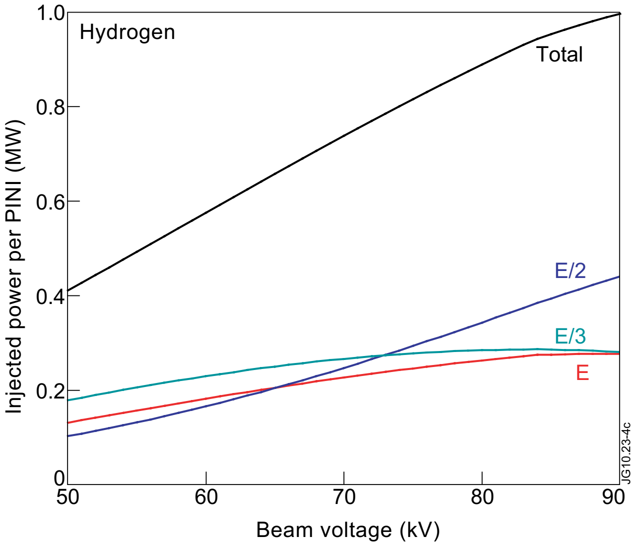

Figure 4: Predicted hydrogen beam power fractions.

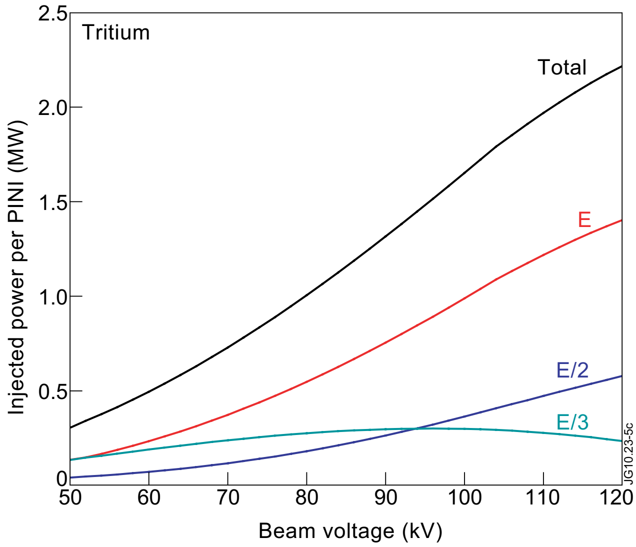

Figure 5: Predicted tritium beam power fractions.