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ABSTRACT

In the period 2000–2003, the JET Neutral Beam Injection (NBI) System has been upgraded with the design goal of delivering more than 25MW of Deuterium beam power into the JET plasma. The programme of the JET Octant 8 Neutral Injector Box (NIB) upgrade is, to date, the largest modification of the JET machine completed within the current EFDA-JET framework. It involved modifications of various components of the JET NBI systems including significant changes to: a) Positive Ion Neutral Injectors (PINIs); b) beamline components; c) high voltage power supplies and d) control, interlock and data acquisition systems. The JET NBI upgrade project was completed in November 2003, when the last two upgraded PINIs were successfully commissioned for injection into the JET plasma. Various technical achievements that were accomplished during the lifetime of this project are discussed in the paper.Unforeseen technical difficulties that prevented achievement of the design goal (25MW injected into JET plasma) are also discussed, together with undertaken improvements that will enable JET NBI system to deliver 25MW in 2005.

INTRODUCTION

Neutral beam heating system of the JET tokamak consists of two Neutral Injector Boxes equipped with up to eight PINIs each [1]. Until spring 2001, the maximum total deuterium neutral beam power from two injectors was 20.5MW, with reliable high power operation achievable at 18-19 MW level. This neutral beam power was generated using 8 high current tetrode PINIs operating at 80 kV/55A (Octant 4 NIB) and delivering up to 13MW, and 8 triode PINIs (Octant 8 NIB) operating at 140kV/30 A and delivering up to 7.5MW to the JET plasma. Both injectors can be operated using H_2, D_2, T2, ^{3}He or ^{4}He gas.

In comparison to other plasma fusion facilities, JET neutral beam heating power is moderate with respect to the corresponding plasma volume. Analysis of options to increase neutral beam power to JET showed that the most cost effective gain would come from the additional High Voltage Power Supplies (HVPS) for Octant 8 NIB, i.e. from the increase in deuterium beam current of the corresponding PINIs from 30 to 60A.

The decision to carry out Octant 8 NIB upgrade was made in autumn 1999 with planned completion of the programme in October 2002. The project was carried out by the members of Heating and Fuelling Department and Operations Department of the Euratom/UKAEA Fusion Association. The scope and various engineering and physics aspects of the upgrade project were discussed in details elsewhere [2 – 5].

1. CHRONOLOGY OF THE JET NBI SYSTEM UPGRADE

The JET NBI upgrade project started in 2000 when the tests of several PINI prototypes were carried out at JET NB Test Bed. The aim of these tests was to determine the geometry of the PINI accelerator (grid spacing and aperture pattern) capable of producing 130kV/60A deuterium beam, while maintaining vertical and horizontal focal lengths to match the existing JET beamlines. These tests were completed by the end of year 2000, when the final accelerator geometry was adopted. In the same year the design work on new Box Scraper assembly based on improved performance hypervapotrons had started. One quadrant assembly of the new box scraper was successfully tested at the NB Test Bed at the beginning of 2001. In the first half of 2001 five upgraded PINIs were conditioned to full power at the NB Test Bed and new Box Scrapers were assembled and instrumented.

During 2001 JET Shutdown: four upgraded PINIs were installed into two lower quadrants of Octant 8 NIB in order to retain CXS diagnostic capability and maximise on-axis heating; the fifth PINI was installed at Octant 4 NIB; new Box Scrapers, defining the horizontal dimension of the JET neutral beams, were installed into both NIBs; and the existing NBI HVPS [6] had been re-configured with eight 80kV/60A grouped into four groups connected in series to provide acceleration voltage for the four upgraded PINIs.

To power the remaining four PINIs on Octant 8 NIB, two new HVPS units, each delivering 130A at 130kV, were procured in the period 2000 – 2003. Design and commissioning of these units are discussed in detail elsewhere [7,8].

In the first half of 2002, additional four upgraded PINIs were conditioned at NB Test Bed and installed on the Octant 8 NIB during short intervention period in summer 2002. Also in 2002, resistive load tests on the first completed HVPS unit were carried out by the manufacturer. These tests revealed some problems related to HV regulation and HV insulation, which were rectified in early 2003, when factory tests were successfully repeated.

Both new HVPS units were installed at the JET site in the period January – July 2003. Integral commissioning of the new HVPS and related control system were carried out at JET during 2003: the first unit was commissioned during May-July and the second unit during July – October. 2.

2. PERFORMANCE OF THE UPGRADED NBI SYSTEM

Upgraded 130kV/60A PINIs were used in JET operation in the period March 2002 – March 2004. Conditioning of these PINIs did not require longer conditioning times or higher number of pulses compared to other PINI types used at JET. In terms of reliability, these PINIs are also comparable to other PINI types with dominant fault conditions being the HVPS protection actions and alarms. It should be noted that the two new switched-mode HVPS units have proved to be more reliable than the existing, 20 years old HVPS units, employing tetrode tubes.

High power loading of JET beamline components had historically limited the beam pulse duration at maximum beam power, mainly due to high intercepted power caused by PINI grid misalignment. The better power handling of the new Box Scrapers and better upgraded PINI optics, resulting from improved grid alignment procedure [5], improved this limit significantly.

Operating voltage of the upgraded PINIs was limited to 125kV (see section 5). At this voltage, the power loading on various beamline components is within specified engineering limits, allowing the operation each upgraded PINI for the full pulse duration of 10 seconds.

The main factor limiting the NBI pulse length at full box (eight PINI) operation was the pressure in the beam duct, due to higher power and location of the deposited ionised power. The predicted values [4] were confirmed experimentally, resulting in the maximum pulse duration of < 7s when operating full injector at high power at moderate JET plasma currents and high gas fuelling rates.

The design goal of 1.8MW of delivered deuterium neutral beam power per upgraded PINI was not achieved due to limitation of the operating voltage and to lower neutralisation efficiency caused by the heating of the neutraliser gas [9,10]. These two factors limited the maximum delivered power per PINI to 1.3 – 1.4MW. Even with this power deficit, a new record neutral beam power (22.7 MW) was delivered to JET plasma in January 2004 (Figure 1).

3. OPERATIONAL EXPERIENCE - TECHICAL ACHIEVEMENTS

2002 and 2003 were very demanding regarding the JET NBI Operations. In addition to providing plasma heating and diagnostic support to the JET experimental programme, the commissioning of various NBI subsystems had to be carried out in parallel. 2003 was the most intensive operational year in the history of JET. NBI systems were operated for a total of 209 days, i.e. 42 weeks of double-shift operation, including 141 JET campaign days. Numerous records that had been achieved during 2003 are discussed in detail in a companion paper [11] - only few technical highlights will be discussed here.

3.1. COMMISSIONING OF THE UPGRADED PINIS USING NEW HVPS UNITS

Commissioning of the upgraded PINIs powered by the new HVPS units (PINIs 1 - 4 on Octant 8 NIB) had to be carried out during JET operation, with minimum disruption to the experimental campaigns. This was achieved through extensive use of parasitic commissioning using the following HVPS-PINI configuration:

- All systems, including HVPS and auxiliary PS were operated under full JET integrated computer control and data acquisition system as per normal pulse operation.
- HVPS was disconnected from the PINI and connected to the local resistive load.
- All other systems (gas introduction, timing, etc.) and auxiliary power supplies (filament, arc, snubber) were energised normally, with deceleration grid (Grid 3) energised normally but disconnected from the PINI.

This approach allowed all systems, and in particular controls, interlocks and load protection to be debugged with no risk to the PINI and minimal interference with JET operation – only three campaign shifts were conceded for initial arc-only operational tests of the new Local Control Panel. This approach also allowed quick transition form HVPS/Control commissioning to PINI conditioning phase. The final adjustment of the power supplies timing sequence for PINIs 1 & 2 was carried on 27 July 2003. PINIs were connected to HVPS overnight and PINI conditioning started the following morning. By the end of the early shift, both PINIs were successfully operating at 60kV extraction voltage!

3.2. TRITIUM BEAM OPERATION

A Trace Tritium Experiment (TTE) was successfully carried out at JET in October 2003, the first tritium operation since DTE1 experiment in 1997. Tritium was introduced into JET in the form of gas puffs or short (< 300ms) 1.1MW tritium beam pulses [12-14]. This operation required extensive preparation, which started in summer 2002. All NBI-related machine protection systems were re-commissioned during summer 2003, a formal requirement for the Authority To Operate with tritium. The DT Gas Introduction System was re-commissioned after six years without use. Finally, two PINIs on Octant 8 NIB (operated by the new HVPS) were commissioned for tritium operation and injected tritium beams into JET plasma on 24 September 2003, a date which had been planned more than a year earlier.

3.3. MIXED DEUTERIUM/HELIUM BEAM OPERATION

A new mode of operation was established on NIB 4 in 2003, which allows the operation of a single PINI using helium gas while operating the remaining PINIs in the same NIB in deuterium gas. This mode is of particular importance for the studies of helium ash exhaust from the core of high-power deuterium heated plasma and is unique to JET. It was accomplished by using the helium gas feed originally used for helium doping of deuterium beam. The implementation of this new mode required: helium flow calibration; modification to the control software and interlocks; and the commissioning of a dedicated argon frosting system enabling simultaneous deuterium and helium gas pumping (this system was successfully commissioned for the first time in summer 2003). Mixed (D_2/He) beam operation mode was commissioned in early autumn 2003 and successfully used in JET experimental programme at the end of TTE in November 2003.

4. OPERATIONAL EXPERIENCE - TECHICAL PROBLEMS

During JET NBI operation 2002 – 2004 ion source backplates of the upgraded 130kV/60A PINIs were damaged by the excessive flux of back-streaming electrons on two occasions. This is the first time that ion source backplates were damaged at JET. Calculations using the AXCEL code showed that, in the case of upgraded PINIs, back-streaming electrons are not entirely suppressed by the nominal voltage of –2.8kV applied to Grid 3 (deceleration grid), due to higher electric field in the first gap. After the first event, which happened in September 2002, Grid 3 voltage was increased to –3kV and maximum beam operating voltage of the upgraded PINIs was reduced to 125kV. This did not prevent the re-occurrence of the same event in January 2004, and the reasons of the damage are not clearly understood yet. Both events took Octant 8 NIB out of action.

A water leak happened in January 2004 on the Central Support Column (CSC) of Octant 8 NIB. This leak was identified only after the second leak on a PINI (see above) was detected and isolated. In contrast to PINI water leaks, which can be removed by replacing the PINI in relatively short time (few weeks), the CSC water leak took NIB 8 out of action for the rest of the planned JET operation in 2004. CSC was removed from NIB 8 by the end of March 2004. Water leak localisation and repair were hindered by the fact that NIB 8 was operated in tritium in 1997 and 2003 and the CSC was tritium contaminated requiring special handling. To allow vacuum leak detection it was necessary to remove water from various water-cooled CSC components. This was a complex operation and leak checks of the NIB 8 CSC started only in July, more than 5 months after the event and more than 3 months after the CSC was removed from NIB 8. Helium vacuum leak checks revealed one single leak on the braze joint between the stainless steel water pipe and hypervapotron panel of the Quadrant 1 full energy ion dump. This indicates that the leak was not caused by fatigue or excessive power load, which could be a conclusion if the leak was found on the ion dump bellows or hypervapotron elements. The cause of the leak is not clear yet and, after the defective element is being removed from the CSC, the faulty braze joint will be fully analysed. The NIB 8 CSC is being repaired at present and is planned to be reinstalled in the Octant 8 NIB at the end of the present JET shutdown.

5. FURTHER TECHNICAL IMPROVEMENTS OF THE JET NBI SYSTEM

In addition to the NIB 8 CSC repair, a few other tasks are being carried out with the goal to improve the protection and to increase the power output of upgraded 130kV/60A PINIs. All Grid 3 power supplies are being modified to enhance PINI protection from excessive flux of back-streaming electrons. Tests carried at on the NB Test Bed on a prototype of the modified Grid 3 power supply showed that increase of the output voltage up to –4.5kV can be achieved via relatively simple and cost effective circuit modification.

The first stage neutralisers of the nine upgraded PINIs have also been modified by introducing a copper “septum” in the horizontal plane, dividing the first stage neutraliser into two halves. This modification influences neutraliser gas flow and volume to surface ratio resulting in the decrease of neutraliser gas temperature. As a consequence, a higher neutraliser target and an increase in neutralisation efficiency are expected. Initial tests at JET NB Test Bed indicate that neutral beam power per PINI could be increased to ~1.7MW. This is illustrated in Figure 2, where JET NIB 8 calorimetric data are compared to the NB Test Bed results obtained using two neutraliser prototypes and two different methods of determining neutral beam power (Rogowski-coil residual ion current measurements and neutraliser pressure measurements). Calorimetric data below 90keV were determined directly, by switching the beam bending magnet on and off. Above this energy, data were derived indirectly from the neutral beam profile integrals, causing larger data scattering.

Further increase of the JET NBI system total neutral beam power by 0.3MW is expected from the replacement of two 80kV/55A PINIs with two recently developed 80kV/60A high current tetrode PINIs.

The mixed D^2/He beam operation, already implemented on Octant 4 NIB, is also being implemented on Octant 8 NIB, further improving JET machine capabilities to study helium ash transport from the core of the plasma.

CONCLUSIONS

The upgrade of the JET NBI system was successfully completed in 2003. The design goal of 25MW of neutral beam power delivered to JET was not achieved yet. It is expected that improvements of the NB system carried out during present JET shutdown will result in maximum NBI power level of 25MW and routine (>90% achievement probability) power level of 23MW during JET operation in 2005.

ACKNOWLEDGEMENTS

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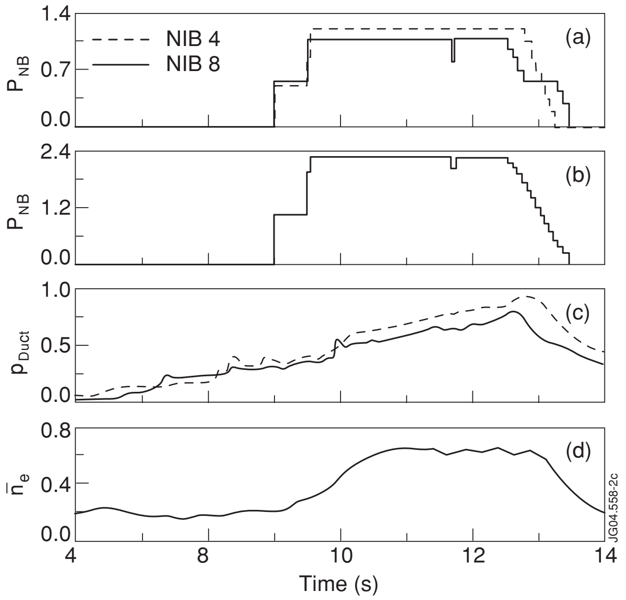

Figure 1. Record JET NBI power Pulse No: 62620. Time traces of: (a) NIB neutral beam power in 10^7W; (b) total Neutral beam power in 10^7 W; (c) duct pressures in 10^{-5} mbar; and (d) line averaged plasma density in 10^{20} m^{-3}.

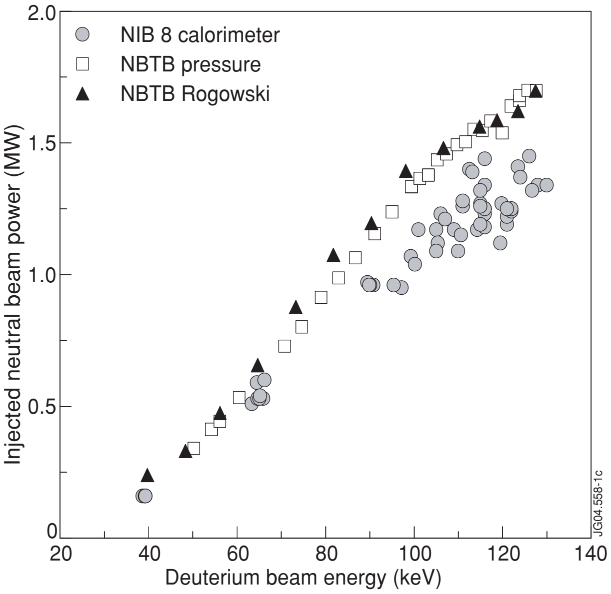

Figure 2. Deuterium neutral beam power determined using calorimetric data (JET NIB 8 – standard neutralisers) and using Rogowski-coil residual ion current and neutraliser pressure measurements (JET NB Test Bed – “septum” neutralisers).