EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(04)06-24

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A Review of JET Neutral Beam System Performance 1994 to 2003

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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives",*
Fusion Energy 2002 (Proc. 19th IAEA Fusion Energy Conference, Lyon (2002)).

Preprint of Paper to be submitted for publication in Proceedings of the
23rd SOFT Conference,
(Venice, Italy 20-24 September 2004)

ABSTRACT

The operational performance of the JET Neutral Beam Injector (NBI) system during 2003 is presented and compared with NBI operation from 1994 to 2002. The paper also addresses different demands imposed on NBI operation during the JET Joint Undertaking (until the end of 1999) and the European Fusion Development Agreement (EFDA) JET Operating Contract (from 2000).

The material presented shows new operational performance records achieved in 2003, derived from data focused on average and maximum pulse lengths, pulse power and injected pulse energy. Over the last ten years the issue of JET NBI PINI reliability and availability has also been of significant interest. A discussion is presented where terminology is defined, specific technical systems causing unreliability and non-availability are analysed and operational practices are reviewed.

The performance analysis shows that during the period of JET operation under the EFDA contract, the NBI facility has successfully changed from high power - short pulse to high power - long pulse (10s) operation. It also shows that the sources of unreliability and non-availability have largely remained constant during this change.

1. JET NBI CONFIGURATION

During the period of 1994 to 2003 JET has been operating with two Neutral Beam Injection (NBI) systems [1]. The first Neutral Injection Box (NIB) was installed in 1986 at octant 8 (NIB8) with the addition of a second at octant 4 (NIB4) being completed in 1988. Since 1994 the 8 PINIs (Positive Ion Neutral Injectors) installed at octant 4 have been configured to accelerate ions up to 80keV using a tetrode (four grid) accelerator. The 8 PINIs at octant 8 have been configured to accelerate ions up to a maximum voltage of 140keV using a triode (three grid) accelerator.

2. JET NBI SYSTEM DURING 2003

During 2003 NIB4 was operated with six 80kV, 52A PINIs in positions 3 to 8 on the NIB, one 130kV, 60A PINI and one 140kV, 30A PINI in positions 1 and 2 respectively. Due to the limitations of the associated power supply it was not possible to operate PINIs 1 and 2 together above 105kV due to the current limitations of the power supply.

NIB8 was equipped with eight 130kV, 60A PINIs. Four of these PINIs, those in positions 5 to 8, were installed during the 2001 JET shutdown. Over the 2002 summer intervention the PINIs in positions 1 to 4 were installed.

During the first half of 2003 two new 130kV, 130A power supplies were installed for PINIs 1 to 4 on NIB8. Commissioning of the first power supply took place between March and August with the second between August and November. PINIs in positions 1 and 2 were commissioned and brought into full operation between July and September and PINIs 3 and 4 brought into full operation by November.

Considering the complex nature of the power supplies their commissioning was completed in a very short period of time. The use of structured commissioning procedures and integrated testing of the power supplies on dummy loads before connecting them to the unconditioned PINIs greatly facilitated this achievement. Approaching the work in such a systematic way significantly reduced the risk of damage to PINI and power supply. A more in-depth discussion of this work is presented elsewhere [2].

3. NBI PERFORMANCE COMPARED FOR 1994 TO 2003

The intensity of the operational requirements on the NBI system in 2003 lead to the breaking of many operational records set in previous years. The main measures of system performance discussed here are related to pulse length, pulse power, the number of pulses and total operating time.

The data presented in Figure 1 shows the average NBI pulse power for each year from 1994 to 2003. The noticeable drop in performance during 2002 is attributable to: only having 12 PINIs available; NIB8 power supply commissioning problems; the failure of NIB4 rotary torus isolation valve and a NIB8 PINI water leak.

The dark shaded bars on Figures 1 to 4 indicate operation under the JET Joint Undertaking, the blue bars indicate operation under the EFDA Agreement. It can be seen in Figure 1 that the performance in 2003 is equal to that of any previous year, which is all the more significant as only 12 PINIs were available until August of 2003. In combination with this, operating the tritium gas feed [3] forced the maximum operating voltage of the NIB8 PINIs to be reduced from 130kV to 110kV for part of the year, again reducing the power available. Figure 2 shows the average NBI pulse length for each year from 1994 to 2003.

In 2003 a new maximum average pulse length of 6.8s was achieved. The combination of sustained average power and increasing average pulse length indicate how under the EFDA Agreement, the JET NBI system is increasingly being used for high power long pulses. Under the JET Joint Undertaking the emphasis was still on high power but for much shorter pulses.

This is clearly illustrated by the data presented in Figure 3, which shows the Average NBI Pulse Energy 1994 to 2003. The only exception for this being 2002 for the reasons described earlier.

In 2003 the average energy injected per pulse reached a new maximum of 56.8MJ, approximately 50% higher than in any year under the JET Joint Undertaking. Also, during the years from 2000 to 2003 there was an increase in the use of beam modulation, feedback control and Real Time Central Control (RTCC). These systems all add to the increasing complexity of the NBI power waveforms.

The intensity of NBI operation during 2003 is clearly shown in Figure 4. In 2003 an injected energy of 163GJ was achieved; almost two and a half times that of any other year. In Table 1 all the records set in 2003 are shown together with the previous records.

4. NBI PINI AVAILABILITY AND RELIABILITY

Since the original installation of the NBI system on JET there has been extensive interest in its reliability and availability [4]. **Availability** is expressed per NIB, and quantifies the percentage of time when an injector is available for operation. As each NIB is a complex system it is possible to have partial availability. Reliability refers to the ratio of Energy Delivered in a JET pulse with the energy requested before the JET pulse, expressed as a percentage.

4.1. AVAILABILITY

The availability of a PINI, (comprising ion source and accelerator) pair of PINIs or whole NIB can be affected by many systems. The availability of the PINI components themselves was very high. However, considering the more complete system including control hardware, software and associated power supplies the overall availability tends to be lower. This issue is further complicated as not all pulses require all PINIs. A degree of redundancy therefore exists and although some PINIs may not be available those that are can often meet the requirements.

4.2. RELIABILITY

According to the definition presented the reliability of the NBI system, including all associated power supply trips over 2003 was approximately 91%. There are however, many aspects of JET operation that cause an NBI pulse to be prematurely terminated which can lead to a lower interpretation of reliability. The majority of pulses that are terminated prematurely, 35% under JET Joint Undertaking and 43% under the EFDA Agreement, are due to other JET protection systems, which are described in Table 2. These include the Fast Beam interlock System [5] designed to provide fail-safe fast protective termination (~10ms response) for a range of beamline and plasma fault conditions.

Figures 5 and 6 show graphically how, for yearly operation from 1994 to 2003 the percentage of pulses terminated is distributed amongst these protection systems.

Only two of the reasons shown in Figures 5 and 6 are directly attributable to neutral beam operation and these are NIBP and BLIPS which account for less than 1% of all prematurely terminated pulses. The data is split into JET Joint Undertaking and EFDA Agreement periods of operation to illustrate that the main six reasons for terminating a pulse remain the same, although the distribution between them differs. There is one exception to this, being the number of pulses terminated by high levels of stray field from the tokamak, transiently exceeding the capability of the NIB field compensation system [7] (FIELD) under the JET Joint Undertaking. Neutral beam power supply trips also have a significant impact on the operational performance of JET. Under the JET Joint Undertaking approximately 19.0% of all pulses had a power supply trip on one or more PINIs during the pulse, with 18.0% under the EFDA Agreement. However, as there are often ‘back-up’ PINIs available if one fails due to a power supply problem the effect of the failure on pulse termination is reduced.

CONCLUSIONS

The performance and operation of the JET neutral beam injection system during 2003 was by previous historical standards, exceptional. The outstanding number of synchronous pulses (in excess of 3000), total operating time (19500s) and total injected energy (169GJ) immediately demonstrates this. The performance was achieved through the very high levels of neutral beam reliability and availability and was a result of the increasing demands of the JET experimental programme under the EFDA contract.

Work to enhance the flexibility of the neutral beam injection system and re-commission existing sub-systems was co-ordinated and integrated very successfully with JET operation. This work included modifying NIB4 to operate with mixed gases (i.e. the possibility of running one PINI in helium and the others in deuterium), re-commissioning of the NIB8 tritium gas system for the Trace Tritium Experiment (TTE), commissioning two new 130kV, 130A power supplies and conditioning four 130kV, 60A PINIs.

The newly installed power supplies on NIB8 were commissioned quickly and efficiently as were the four PINIs connected to them. The success of this work was primarily due to the use of very structured commissioning procedures and the strategy adopted to commission the power supplies extensively on dummy loads.

ACKNOWLEDGEMENTS

This work was funded by EURATOM through the European Fusion Development Agreement.
The authors would like to thank the JET Neutral Beam Operations team.

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Campaign	Additional Neutral Beam Requirements
C7b, C8, C10 and C12	Fully conditioned PINIs, with high reliability and availability, to consistently deliver high long (up to 10s) pulses.
C9	Realignment of all PINIs to provide "counter injection" additional heating for reversed JET magnetic field operation.
C11	1. Establish mixed gas operation on NIB4. 2. Commision the dedicated NIB4 argon frosting system. 3. Re-commision the NIB4 tritium gas delivery system. 4. Commission all 8 PINIs for operation with this system. 5. Operate PINIs 1 & 2 in tritium fir Trace Tritium Experiment (TTE) campaign.
All Campaigns	1. Install two new 130kV, 130A power supplies on NIB8. 2. Condition and commission PINIs 1 to 4 on NIB8.

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Table 1 : Specific NBI Requirements for operation in 2003

Description	2003	Previous
Maximum energy / pulse	56.8MJ	48.5MJ
Maximum average pulse lenth	6.8s	6.55s
Maximum injected energy in a single pulse	170MJ	161MJ
Maximum deuterium pulse power	21.6MW	21.0MW
Total NBI SYNC time in one year	19500s	9950s
Total injected energy in one year	163GJ	69GJ
Number of NBI SYNC pulses in a year	> 3000	2100

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Table 2 : NBI Operational Performance Records in 2003

Acronym	Description
PDOK	The pulses has been terminated by the Fast Beam Interlock System [5] but none of the following alarms have been identified as the first fault.
NIBP	Excessive NIB pressure.
DUCT P	The pulse is terminated if the pressure in the neutral beam duct increases beyond a safe level.
SLOW and PEWS	The JET 'Plant Enabling Windows System' (PEWS) monitors plasma perameters against set limits during a pulse providing fast pulse termination if a limit is violated.
ESD	The JET machine central Interlock [1] continuously monitors plant conditions and forces a transition to 'Emergency Shutdown' (ESD) if a fault occurs.
RTPC	Real Time Plasma Control Failure.
BBI	A primary Neutral Beam System Interlock [6] that measures the plasmas Bremsstrahlung radiation to asses the JET plasma density. The pulse is terminated if the desity drops too low.
SYNCTEST	The neutral beam system has been inappropriately set for Synchronous Test Mode [1] operation.
BLIPS	Failure of the bending magnet to accurately track the beam parameters.
DISRUPTION	The pulse is terminated due to a JET plasma disruption.
MULTIPLE	The pulse has terminated due to a violation of more than one interlock system.

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Table 3 : Description of the most common reasons for NBI Pulse Termination

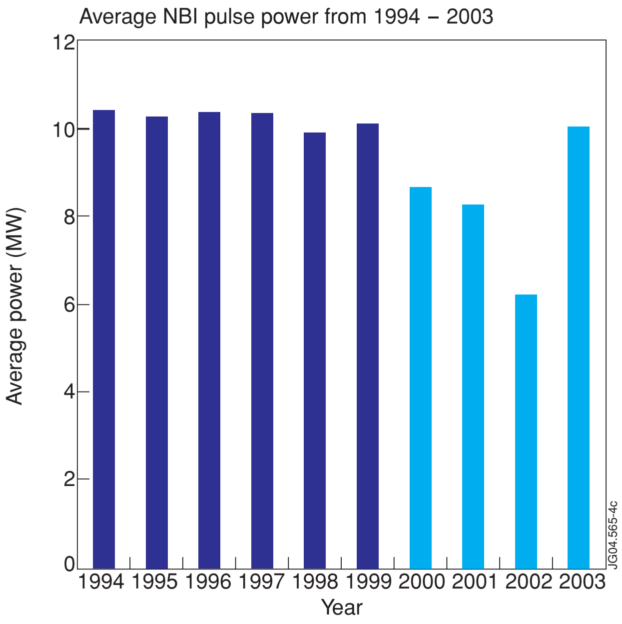

Figure 1: NBI Average Pulse Power (MW) 1994 to 2003

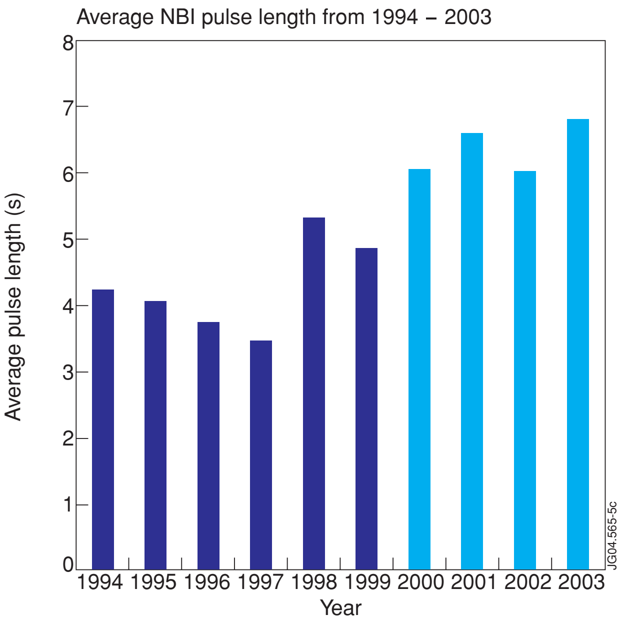

Figure 2: NBI Average Pulse Length (s) 1994 to 2003

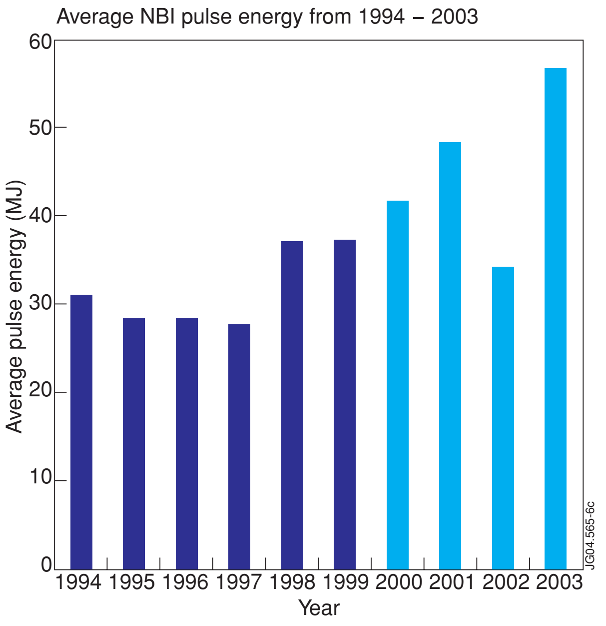

Figure 3: NBI Average Pulse Energy (MJ) 1994 to 2003

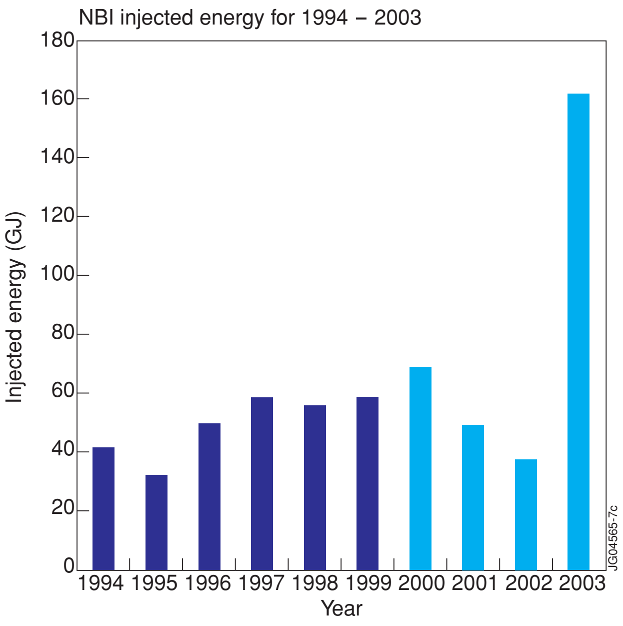

Figure 4 : NBI Total Injected Energy (GJ) Per Year 1994 to 2003

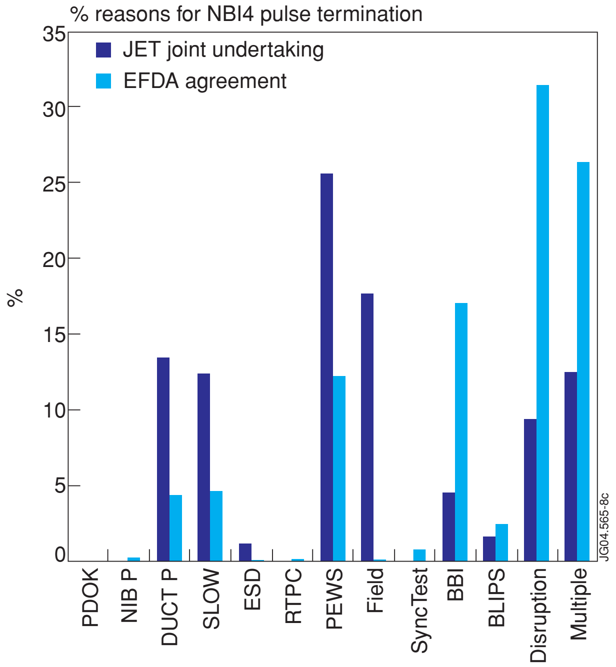

Figure 5: Percentage Reasons for NBI4 Pulse Termination

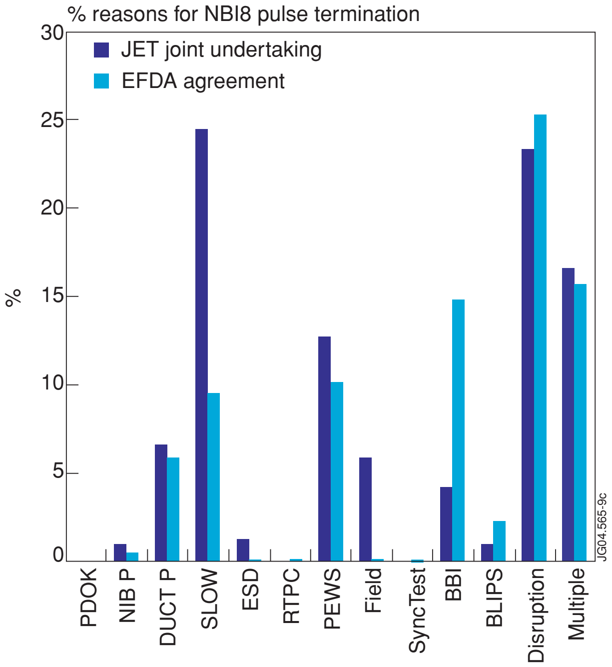

Figure 6: Percentage Reasons for NBI8 Pulse Termination