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Overview of the JET Neutral Beam Enhancement Project

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ABSTRACT
The JET Neutral Beam (NB) heating system is being upgraded as a part of the ongoing JET Enhancement Programme. This is one of the largest upgrades of the JET machine carried out within the EFDA-JET framework. The main goals of the project are to increase the NB power delivered to JET plasma, to increase the beam pulse duration and to improve the availability and reliability of the JET NB system. The upgrade of the system is being carried out through the modification of the two existing Neutral Injector Boxes (NIBs), each equipped with up to eight Positive Ion Neutral Injectors (PINIs). Significant changes of the JET NB system will be carried out within the next few years and will include modification of all PINIs, modification or replacement of various beamline components and corresponding instrumentation, procurement and installation of new High Voltage Power Supply (HVPS) units and corresponding control systems and refurbishment of the 36kV power distribution. Various physics, engineering and planning issues related to this project, as well as the current status of the project are discussed in detail. Particular attention is given to the results of a PINI prototype test, which are of crucial importance for the successful completion of the entire Enhancement Programme. Upon the completion of the project in 2009, JET NB system should be capable of delivering more than 34MW of deuterium beam power into the JET plasma for a duration of up to 20 seconds with improved reliability. This will significantly enhance overall capabilities of the JET machine in support of ITER development.

1. INTRODUCTION
The neutral beam heating system of the JET tokamak consists of two Neutral Injector Boxes equipped with up to eight PINIs each [1]. During the last twenty years the system has been continuously modified and improved, with main goals being the increase of power delivered to JET, the increase of the duration of the beam pulse and the improvement of the reliability of NB system. Until 2001, the maximum deuterium neutral beam power delivered to JET was ~20MW, with reliable high power operation achievable at ~18 MW level, while the average pulse duration was ~4 seconds.

During the period 1999-2003, a major upgrade of the JET NB system was carried out [2]. The main tasks within that project were the replacement of 140kV/30A triode PINIs of Octant 8 NIB with 130kV/56A upgraded triode PINIs, the installation of two new HVPS units and corresponding control systems [3, 4] and the upgrade of the Box Scrapers (beam size limiters at the exit of two NIBs) to accommodate higher power loading and to allow an increase in pulse duration. The design goal of this upgrade of 27MW of delivered deuterium neutral beam power has not been achieved due to lower neutralisation efficiency of the upgraded PINIs caused by the heating of the neutraliser gas [5, 6]. Even with this power deficit, a new record neutral beam power (22.7MW) was injected into JET plasma in January 2004.

At present, the JET NB System is capable of delivering maximum deuterium neutral beam power of >24MW with reliable high power operation achievable at the 20-21MW level. The maximum neutral beam pulse duration for high power operation is 10 seconds, but is very often restricted to ≤7 s to avoid overheating of neutral beam duct protection by re-ionised beam particles at the beam entry into the JET vessel.

The performance of the JET NB System in the last ten years has been analysed recently [7]. This analysis clearly showed that there is constant demand to increase both the neutral beam power and beam pulse duration. It also showed that the reliability of the JET NB system is governed almost entirely by the performance of twenty year old HVPS/Protection units [8].

In comparison to other plasma fusion facilities, JET neutral beam heating power per unit plasma volume is relatively modest. The increase of both the total neutral beam power and the beam pulse duration and improved operational reliability of the NB system were considered as major factors that could significantly improve the capabilities of the JET machine in support of ITER development during the EFDA Framework 7 Programme. Various options to upgrade the JET NB System, including both positive ion and negative ion based third neutral injector boxes, were discussed in autumn 2004. The upgrade of the JET NB system based on the modification of two existing neutral injector boxes was considered as the most cost effective solution, which could be realised in the required time frame 2005-2009. The project was formally approved in spring 2005 with the planned completion of the upgrade in 2009. The project is being carried out by the members of Heating and Fuelling Department and Machine Operations Department of the EURATOM/UKAEA Fusion Association at Culham.

2. GOALS OF THE PROJECT

The three main goals of the present JET NB Enhancement project are:

- To increase the maximum total deuterium beam power delivered to JET from present ~24MW to >34MW.
- To increase the beam pulse length, at maximum power, from present 7-10s to 20s, and at half power from 20 to 40s.
- To improve overall availability and reliability of the NB system.

The increase in the beam power will be accomplished by the replacement of all PINIs on both Octant 4 and Octant 8 NIBs with upgraded triode PINIs capable of operating at ~125kV/65A and delivering ~2.2 MW of neutral beam power. Present JET PINIs are all equipped with so called supercusp ion sources [1], which include magnetic filters to enhance the production of monatomic ions, leading to a high fraction of fullenergy neutrals. Upgraded PINIs will be equipped with ion sources with pure chequerboard magnetic configuration. These ion sources produce higher fractions of molecular ions, which are neutralised more efficiently, resulting in a considerable increase of the total neutral beam power. The absence of the magnetic filter also improves the uniformity of the plasma within the ion source, which results in superior ion-optical properties (lower beam divergence), leading to higher beam transmission and higher injected power.

The increase of the pulse length will be accomplished by the replacement of interpulse cooled beamline components, which limit the maximum beam pulse length to 10s. At present, the main components that are restricting pulse duration at high power levels are copper duct liners that are protecting the vacuum vessel at the beam entry into the JET machine from excessive re-ionised power. Both Octant 4 and Octant 8 NIB duct liners also show signs of ageing (cracks, localised melted regions) and will be replaced with actively cooled liners based on proven hypervapotron technology [9]. Several other components of the JET beamlines will be either modified or replaced.

The reliability and availability of the JET NB system will be improved by the replacement of four existing 160kV/60A HVPS/Protection units with four 130kV/130A HVPS units similar to these installed in the recent Octant 8 NIB upgrade [3]. Each of the new units will be used to operate two PINIs, which means that, after the completion of this NB Enhancement programme, 12 out 16 PINIs will be operated using new HVPS units based on modern IGBT technology. This would certainly improve both, availability and reliability of the JET NB system. In addition, the new HVPS units can operate at >65A output current, which means that 12 out of 16 PINIs will be operated at their full rating of 125kV/65A. The remaining four PINIs, which will be operated using existing HVPS units, will run at 120kV/60A.

3. SCOPE OF THE PROJECT

3.1 BEAMLINE PHYSICS ISSUES

Extensive physics studies have been carried out in the last 18 months in order to prepare the basis for the engineering analysis and design of both PINI and beamline components.

The first task was to establish the geometry of the upgraded PINI accelerator (grid spacing and aperture diameter), which would be capable of producing 65A of deuterium beam at 125kV acceleration, while maintaining the vertical and horizontal focal points at 10 and 14 metres respectively, to match the geometry of the existing JET beamlines. Three-dimensional beam simulation code KOBRA-INP [10] was used to determine accelerator geometry: aperture diameter of $\geq$ 11.5mm and first acceleration gap of 15 mm. The code also predicted that the aperture pattern should be identical to the one of the present 130kV/56A supercusp triode PINIs to maintain horizontal and vertical focal lengths.

PINIs fitted with chequerboard ion sources have been tested on several occasions in the JET Neutral Beam Test Bed, so some important parameters (ion species composition and beam divergence) were readily available. Previously measured ion species composition was combined with known cross sections for various atomic collisions processes in the PINI neutraliser to calculate total beam power and various neutral and ion beam fractions. These were then used to predict total power and power density distributions at various beamline components (neutralisers, full and fractional energy ion dumps, beam scrapers, duct liners). Thermo-mechanical engineering analysis was then carried out to verify whether specific beamline components have to be modified or replaced.

Particular attention was dedicated to the study of the gas balance in the duct region of the beamline. High pressure in the duct region increases the re-ionised beam power falling on the duct protection plates, and this re-ionised power increases the temperature of the protection plates to the values that are very close to the present engineering limits. Thus high pressure in the duct region is the major factor that limits the beam pulse length during JET operation, and it was clear from the very beginning of the project that present inter-pulse cooled duct protection would have to be replaced with actively cooled components. Both physics and engineering design of the new duct protection are discussed in detail in a separate paper [9].

Protection of the JET inner wall is another area of concern, due to increased PINI power which leads to increased shine-through power on various in-vessel components. Inner wall protection tiles are being redesigned as part of another JET Enhancement Programme – First Wall Project.

3.2 MECHANICAL ENGINEERING ISSUES

A total of eighteen PINIs (sixteen installed on two NIBs and two spares) have to be built as part of this enhancement programme. Most of the components of the present JET PINIs will be re-used. The only ion source modification is the rearrangement of the permanent magnets, which does not require any design or procurement. Only one accelerator grid per PINI has to be designed, manufactured and installed (a total of eighteen grids).

First stage neutralisers are not compatible with the 20 s operation and will be replaced with the new design, which has higher thermal capacity (thicker walls) and improved cooling. A water cooled “septum” that divides the first stage neutraliser into two halves was also designed. Earlier tests carried out at Neutral Beam Test Bed suggested that the presence of the septum would increase the neutralisation efficiency.

The decision to include the septa in the final neutraliser design will depend on the analysis of the recent power measurement for 130kV/56A supercusp PINIs. Full Energy Ion Dump hypervapotron elements are adequate for slightly reduced full energy ion power from upgraded chequerboard 125kV/65A PINIs. Some minor modification of the inertial copper plates (increased heat capacity and improved cooling) is required.

Fractional Energy Ion Dump hypervapotron elements are also adequate for handling the power from upgraded PINIs. They were originally designed for 80kV/60A chequerboard PINIs [11] operated in hydrogen and were fully optimised. Although the fractional ion power from125kV/65A PINIs operated in deuterium will increase four times compared to present 130kV/56A supercusp PINIs, it represents an increase of only ~30% when compared to the 80kV/60A hydrogen case. Thermo-mechanical analysis showed that this power can be handled by the existing hypervapotron elements, providing the design water velocity of ~6 m/s could be achieved. Recent flow measurements on fractional energy ion dumps on the NIB spare Central Support Column confirmed that the present water flow is a factor of 2 below the design value. This means that the rather complicated water manifold used to feed fractional energy ion dumps will be simplified and re-designed.

The new actively cooled duct protection will be installed on both NIBs. The design is based on proven hypervapotron technology. This design was certainly the most challenging engineering task of the entire NB Enhancement Programme and is discussed in detail in a separate paper [9].

A survey of various inertial beamline components is being carried out and some components that need improvement (higher heat capacity) were identified.

3.3 POWER SUPPLIES

During the recent Octant 8 NIB upgrade two new 130kV/130A switched mode HVPS units were installed and commissioned [3, 4]. As a part of the NB Enhancement programme an additional four units are being procured. They will be used to provide high voltage to 6 PINIs on Octant 4 NIB and 2 PINIs on Octant 8 NIB. Two existing protection units will be re-configured to provide high voltage for PINIs 1 and 2 in the first quadrant of the Octant 4 NIB. The control system for the new HVPS units was also redesigned and is being procured. In addition, two new buildings have to be designed and built to accommodate the new HVPS units. HVPS load resistors are not compatible with 20 s pulse duration and will be replaced.

A survey of long pulse compatibility for the auxiliary power supplies is being carried out to verify whether some of the components need to be upgraded. Finally, the 36kV power distribution system will be refurbished to cope with the increased power required for the operation of the new HVPS units.

4. PINI PROTOTYPE TEST

In the early stages of the project it was decided that the test of the prototype of the new JET PINI should be carried out to verify that various design parameters (voltage, current, ion species composition, beam divergence, power loading of components, etc.) could be achieved.

A prototype injector 22FT was built using one of the spare 130kV/56A PINIs. The PINI was fitted with the ion source with chequerboard magnetic configuration. The spare PINI extraction grid was modified by enlarging the extraction aperture diameters from 11 to 11.5mm and reducing the extraction electrode gap to 15mm.

This extraction gap was expected to produce deuterium beams with minimum divergence at 125kV/65A, i.e. with optimum perveance of 65A/(125kV) 3/2 = 1.47μA/V3/2. The prototype PINI 22FT was installed at JET Neutral Beam Test Bed in March 2006 and conditioned to the maximum operating voltage of 120kV.

Conditioning to full operating voltage of 125kV using deuterium gas was not possible as it required extracted currents in excess of 60A, i.e. above the rating of the high voltage power supply.

Full characterisation of the prototype PINI was completed by the end of June 2006. The data are still being analysed and some important preliminary results are presented here.

Extracted deuterium beam current variation with ion source arc current at nominal gas flow (12 mbar×l/s fed to the ion source and 18 mbar×l/s fed to the neutraliser) is given in Figure 1. Extrapolated arc current required to produce 65A is ~1330A. This arc current value is very close to the practical limit of the existing arc power supply and such high current value would reduce the lifetime of ion source filaments. It was thus decided to increase the extraction aperture diameter in the final grid design to 11.7mm, which would reduce the required arc current to the acceptable level of ~1280A.

The variation of the optimum deuterium beam perveance with extraction voltage is shown in Figure 2. Extrapolated value at 125kV is $1.42\mu A/V^{3/2}$, which is slightly lower than the design value of $1.47\mu A/V^{3/2}$. This means that some minor correction of the accelerator gap might be required to match the required optimum perveance.

Figure 3 shows measured fractions of the ion species extracted from the prototype chequerboard PINI as a function of extracted beam current for the nominal deuteriumgas flow. The ion density species composition $D^+:D2^+:D3^+$ at ≥60A extracted current is 74%:21%:5%.

The neutral beam power transmission to the JET plasma was estimated to be 75%. This value was derived from calorimetric measurements of the beam properties (total power and two-dimensional profiles) of the prototype PINI. The transmission of the prototype PINI is slightly lower than that measured in the past for both triode and tetrode chequerboard PINIs (78%). This reduction in transmission could be attributed to the misalignment of the accelerator grids of the prototype PINI.

From the results of the prototype PINI test and known cross-sections for various atomic collision processes in the neutraliser, it is possible to predict the power delivered to JET from the upgraded chequerboard PINI. The result is shown in Figure 4, where the predicted injected power of a 125kV/65A chequerboard PINI is compared to the recently measured power from eight 130kV/56A supercusp PINIs.

The neutralisation target line density of 4.5×10^{15} cm^{-2} was derived from recent supercusp PINI power calibration on the JET beamlines. Measured ion species composition and transmission of 75% were used to estimate the delivered PINI power. The maximum injected deuterium power of the upgraded 125kV/65A chequerboard PINI is ~2.2MW, which results in the total power of the upgraded JET NB system of >34 MW.

During prototype PINI characterisation, particular attention was dedicated to the measurements of the power loading on various injector components (ion source body and backplate, accelerator grids and the neutraliser). It was important to verify that the loading of all components is below corresponding thermo-mechanical engineering limits. The results for the ion source are shown in Figure 5 as a function of the extracted beam power, i.e. the product of the beam voltage and beam current. Data points represent measurements at beam extraction voltages of 90, 100, 110 and 120kV. Values for the maximum power (125kV×65A = 8.12MW) could be determined by extrapolation. Maximum power loading on various source components for the present 130kV/56A supercusp PINI and 125kV/65A chequerboard PINI are compared in Table 1. As expected, an increase in power loading on various source components is observed, and measured values are below the corresponding engineering limits.

Note also that the loading of the second stage neutraliser is considerably reduced due to the superior beam properties of the beams extracted from chequerboard ion sources.

5. PLANNING ISSUES AND PRESENT STATUS

The whole NB Enhancement programme has to be carried out with minimum impact on JET operation. This makes the planning of various stages of the upgrade particularly difficult.

The majority of the beamline components will be installed during the one-year long JET shutdown planned for autumn 2008. Since it is impossible to build and condition 16 PINIs during a one-year shutdown, the construction and conditioning of upgraded PINIs have to start considerably earlier. The consequence is that the procurement of the new PINI grids determines the critical path of the entire project. The first set of four PINI grids will be delivered in September 2006. These will be used to build four PINIs from available spare components. The PINIs will be conditioned in JET Neutral Beam Test Bed in 2006/07. During a short intervention in 2007, four PINIs with new grids but fitted with supercusp ion sources will be installed in the upper four positions on Octant 8 NIB. This will allow an early test of the operation of the PINIs at 65A, since these four PINIs are powered by the new HVPS units. The four PINIs removed from the Octant 8 NIB will be re-built and conditioned during 2007/08, i.e. prior to the main 2008 shutdown. The remaining eight PINIs will be re-built and conditioned during the 2008 shutdown. All other mechanical engineering tasks should be completed prior to the installation in 2008.

The new HVPS units and corresponding control systems will be delivered in phases, starting in summer 2007. The first unit will be commissioned in parallel with JET operation using the spare 36kV feed. The remaining three units will be commissioned during the 2008 JET shutdown.

At present, the NB Enhancement programme is progressing according to the initial plan, with few small delays, which are not affecting the overall project.

SUMMARY AND CONCLUSIONS

A major upgrade of the JET NB heating system is being carried out. Various physics and engineering issues related to this programme have been summarised. The results of the prototype PINI test suggest that the design goal of delivering >34MW of deuterium power is achievable. The NB Enhancement programme is progressing according to the initial project plan and should be completed on time in 2009. The successful completion of this upgrade will significantly enhance the capabilities of the JET machine in support of ITER development. This is illustrated in Figure 6, where future operating range of the JET NB system is compared to the present one.

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PINI Component	Power Loading Supercusp (kW)	 Chequerboard (kW)	 Change (%)
Ion source	258	285	+10
Source body	–	117	–
Source backplate	–	168	–
Extraction grid	82	112	+37
Electron suppression grid	20	26	+30
Ground grid + 1st stage neutraliser	90	128	+42
2nd stage neutraliser	208	130	–38
TOTAL	**658**	**681**	**+3**

Table 1: Comparison of power loading on various PINI components for the present 130kV/56A supercusp PINI and upgraded 125kV/65A chequerboard PINI. Separate source body and backplate measurements are available only for the chequerboard PINI.

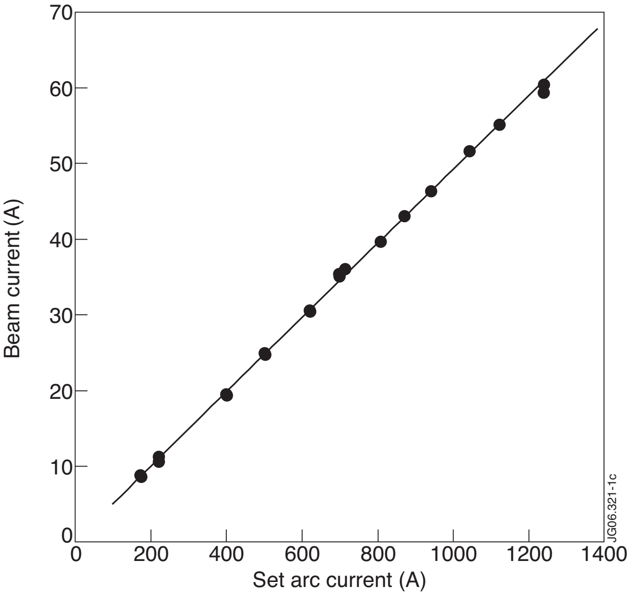

Figure 1: Variation of the extracted beam current with set arc current for the chequerboard PINI prototype 22FT.

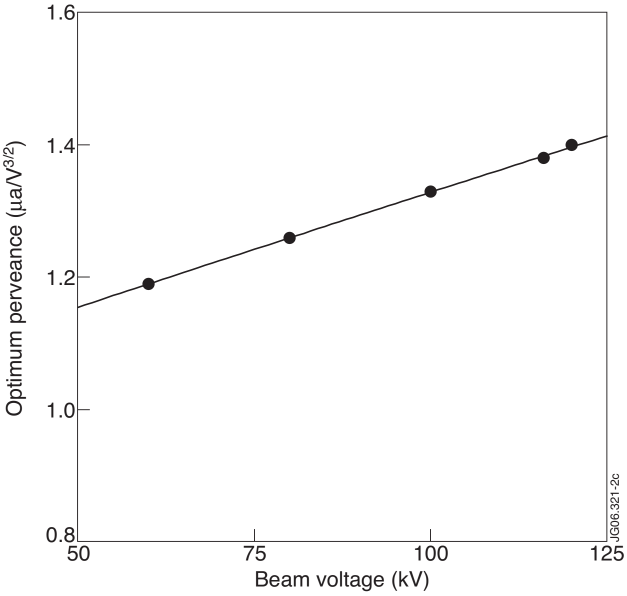

Figure 2: Variation of the optimum deuterium beam perveance with beam voltage.

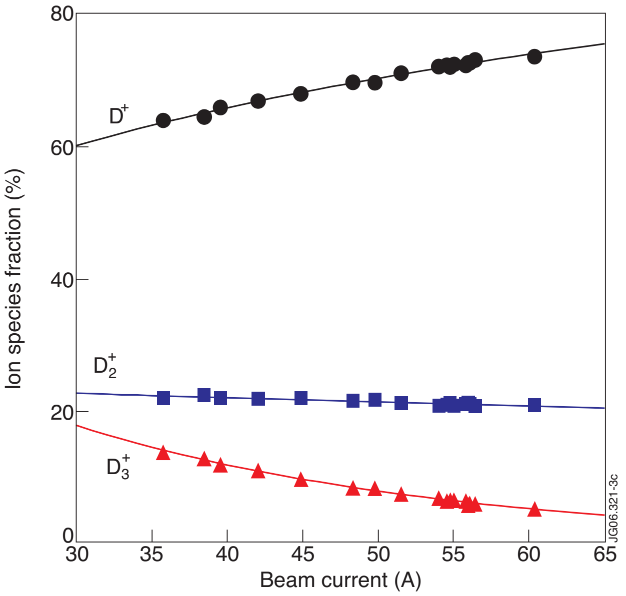

Figure 3: Density ion species composition for the prototype PINI 22FT equipped with the chequerboard ion source.

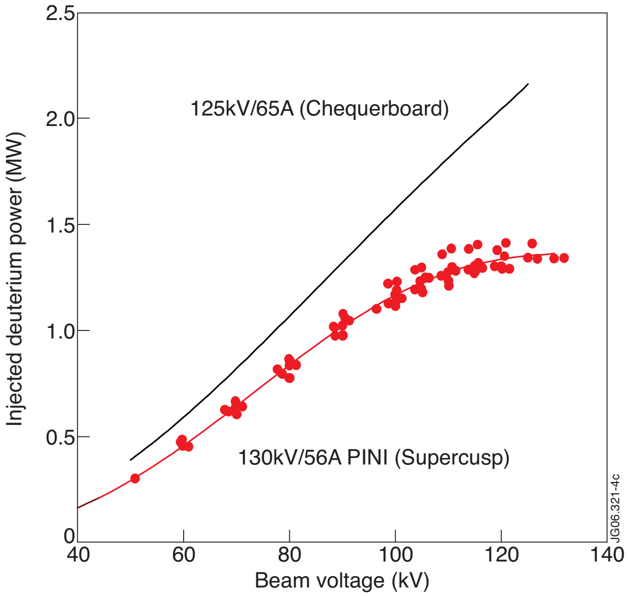

Figure 4: Comparison of the predicted neutral beam power of the upgraded 125kV/65A PINI (chequerboard ion source) with measured power from present 130kV/56A PINIs (supercusp ion source).

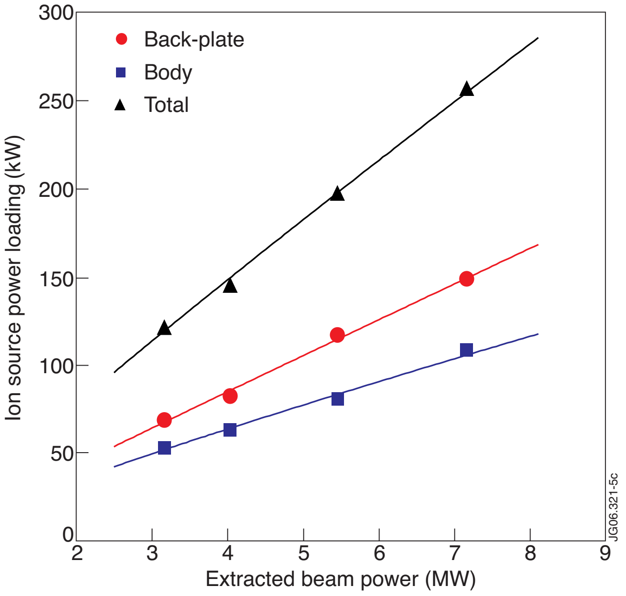

Figure 5: Ion source power loading of the prototype chequerboard PINI.

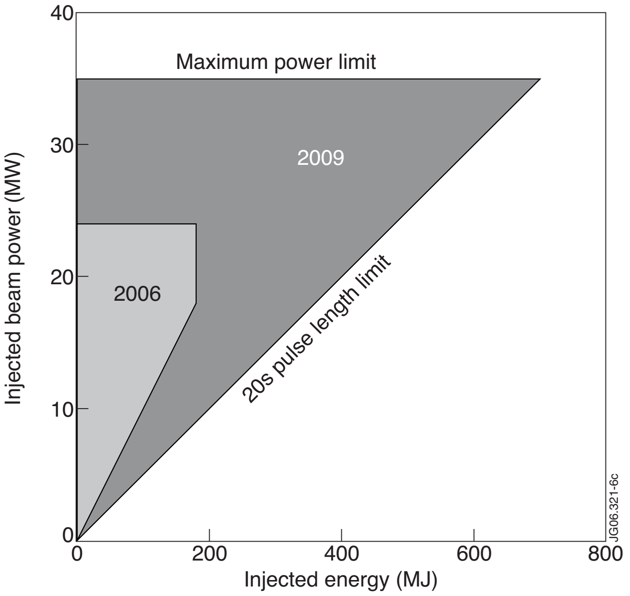

Figure 6: Operating range of the present (2006) and upgraded (2009) JET NB System.