Fusion Engineering and Design 96–97 (2015) 396–399

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

JET neutral beam duct Optical Interlock

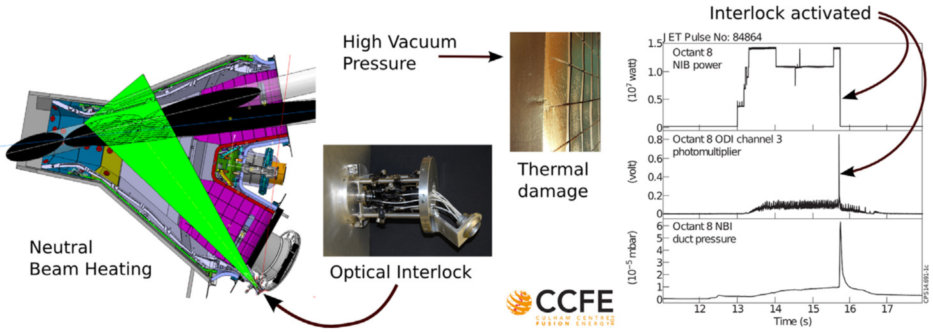
A.D. Ash*, T.T.C. Jones, E. Surrey, D. Ćirić, S.I. Hall, D. Young, M. Afzal, L. Hackett, I.E. Day, R. King, JET EFDA Contributors[1]

CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK

HIGHLIGHTS

- Optical Interlocks were installed on the JET NBI system as part of the EP2 upgrade.
- The system protects the JET tokamak and NBI systems from thermal load damage.
- Balmer-α beam emission is used to monitor the neutral beam-line pressure.
- We demonstrate an improved trip delay of 2 ms compared to 50 ms before EP2.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 2 October 2014
Received in revised form 28 January 2015
Accepted 5 March 2015
Available online 8 April 2015

Keywords:
Interlock
Plasma heating
Neutral Beam Injection
Beam emission spectroscopy
Balmer-α
JET

ABSTRACT

The JET Neutral Beam Injection (NBI) system is the most powerful neutral beam plasma heating system currently operating. Optical Interlocks were installed on the beam lines in 2011 for the JET Enhancement Project 2 (EP2), when the heating power was increased from 23 MW to 34 MW. JET NBI has two beam lines. Each has eight positive ion injectors operating in deuterium at 80 kV–125 kV (accelerator voltage) and up to 65 A (beam current). Heating power is delivered through two ducts where the central power density can be more than 100 MW/m^2. In order to deliver this safely, the beam line pressure should be below 2×10^{-5} mbar otherwise the power load on the duct from the re-ionised fraction of the beam is excessive. The new Optical Interlock monitors the duct pressure by measuring the Balmer-α beam emission (656 nm). This is proportional to the instantaneous beam flux and the duct pressure. Light is collected from a diagnostic window and focused into 1-mm diameter fibres. The Doppler shifted signal is selected using an angle-tuned interference filter. The light is measured by a photo-multiplier module with a logarithmic amplifier. The interlock activation time of 2 ms is sufficient to protect the system from a fully re-ionised beam—a significant improvement on the previous interlock. The dynamic range is sufficient to see bremsstrahlung emission from JET plasma and not saturate during plasma disruptions. For high neutron flux operations the optical fibres within the biological shield can be annealed to 350 °C. A self-test is possible by illuminating the diagnostic window with a test lamp and measuring the back scatter. We demonstrate an important technology for the protection of high power neutral heating beams and present the design and operational results.

---

* Corresponding author. Tel.: +44 01235464631.

[1] See Appendix of F. Romanelli et al., Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, USA.

http://dx.doi.org/10.1016/j.fusengdes.2015.03.010

1. Introduction

Magnetically confined fusion experiments use Neutral Beam Injection systems to provide auxiliary plasma heating, current drive and as a spectroscopic probe. JET has two Neutral Beam Injectors (NIBs) (octant 4 and octant 8) [1]. Each injector has capacity for eight PINI (Positive Ion Neutral Injector) beams. The configuration changes according to experimental requirements. The current configuration has all beams operating in deuterium at 80–125 kV with a maximum beam current per PINI of 65 A and a maximum injected power of 2.1 MW per PINI (34 MW total).

Maintaining a low pressure ($<2\times10^{-5}$ mbar) along the beam line is essential because the neutral beam can be ionised through electron stripping while travelling along the beam line. The ionised fraction will be deflected on to the beam line wall by the stray tokamak field causing localised heating. An interlock is needed to protect the system from excessive thermal load.

The neutral beams were upgraded during the 2009–2011 JET Enhancement Project 2 (EP2). The maximum power through each duct increased from 12 MW to 17 MW [2]. For EP2 the beam duct protection was upgraded from inertial water cooled tiles to actively cooled tiles (hypervapotrons). The removed duct protection tiles had extensive damage, with cracks and distortion, indicating that the maximum thermal load was exceeded many times. Operational experience has shown that a pressure excursion in the beam-line can escalate rapidly with the beam becoming totally ionised in a few milliseconds. Thermal load calculations indicate that an interlock with a response time of 2 ms will protect the EP2 beam-line under the worst-case conditions, however, the installed interlock uses a fast penning gauge and has a response time of 30–50 ms.

A faster measurement of duct pressure is possible by monitoring the neutral beam emission. Small angle collisions between the beam and the residual background gas excite Balmer-α emission (H_α at 656.3 nm, D_α at 656.1 nm). The feasibility of this has been investigated for the ITER neutral beam heating system [3] and measurement of the D_α beam emission has also been demonstrated in the JET neutral beam injectors [4,5].

Optical Duct Pressure Interlocks (ODIs) were installed during EP2. This paper describes the equipment and presents the first operational results collected during experimental campaigns.

2. The ODI Interlock

The Optical Duct Interlock (ODI) comprises of collection optics, fibre optic cables, detection optics, and signal conditioning/data acquisition. It provides inputs to and acts through the Fast Beam Interlock System (FBIS). Another input is from the fast penning gauges monitoring the neutral beam ducts (Duct Pressure Interlock).

Before EP2 the duct pressure limited the length of NB heating to 7–10 s per beam-line [6,7]. The duct pressure rises steadily when the beams are on until the heating pulse ends or is tripped. The rate of increase slows significantly after around 5 s. The duct trip pressure 2×10^{-5} mbar corresponds to a 4% re-ionised beam. Occasionally, rapid pressure rises are seen where the pressure reaches the trip level within milliseconds or faster. These are called fast pressure excursions.

The fast penning gauge protects against slow changes in the duct pressure but we know that it does not adequately protect against the fast pressure excursions or beam blocking. The role of the ODI is to add adequate protection against fast pressure excursions. The two systems complement each other providing complete coverage of fault conditions.

The ODI can be tested with a test lamp that illuminates the diagnostic window. The light scattered back from the window can be checked. This test is run automatically once per day.

3. Collection optics

Identical diagnostic windows (clear aperture = 32 mm) were installed on octant 4 and octant 8 diagnostic flanges. The windows are part of the torus vacuum boundary and have two quartz windows with a neon filled inter-space held at 0.5 bar. The location was chosen, within the practical constraints, to give the best visibility of the beams and minimum background light from the plasma. The collection optics has four lines of sight to monitor beam emission. These cover the full range of neutral beam pointing possible. For each channel, light is collected by a 7.5-mm aspheric lens and focused into a 1-mm core-diameter aluminium coated optical fibre. The location and pointing of the diagnostic windows were surveyed and an *as-built* CAD model was used to calculate alignment angles for each channel.

Aluminium coated fibres were chosen in order that optical fibres within the torus hall shielding could be annealed at up to 350 °C during high neutron flux experiments [8,9]. The bundle from each octant is enclosed in an industrial heating jacket (18 m long).

4. Detection optics

The beam emission must be distinguished from the background light of the tokamak plasma (line emission, bremsstrahlung, and emission from ELMS). The beam emission is Doppler shifted depending on angle of observation (57.8°, 59.0°, 62.8°, 64.6°, 65.7°, 68.3°, 69.0°, 73.7°) and the beam energy. This helps distinguish the beam emission from the background light from ELMs which are seen at the D_α wavelength (656.1 nm). An interference filter with a 10-nm band pass centred on 670 nm is angle-tuned (15°) to isolate beam emission and cut out the unshifted D_α.

Fig. 1 shows the calculated Doppler-shifted beam emission from eight beams operating in deuterium at 80 kV. The accelerated deuterium beam after neutralisation is composed of species $D^0(E)$, $D^0_2(E)$, $D^0(E/2)$, $D^0_2(2E/3)$ and $D^0(E/3)$ where the energy is given in brackets [2,10]. The calculated spectrum contains full energy, half energy and third energy components with approximate proportions and line widths. The 2E/3 component is less that 1% of the beam composition and is therefore ignored. Also shown is the unshifted D_α line and the response curve of the interference filter angle-tuned 15° off normal incidence. The observation looks downstream. The Doppler shift is to longer wavelength and the full energy component is shifted the most.

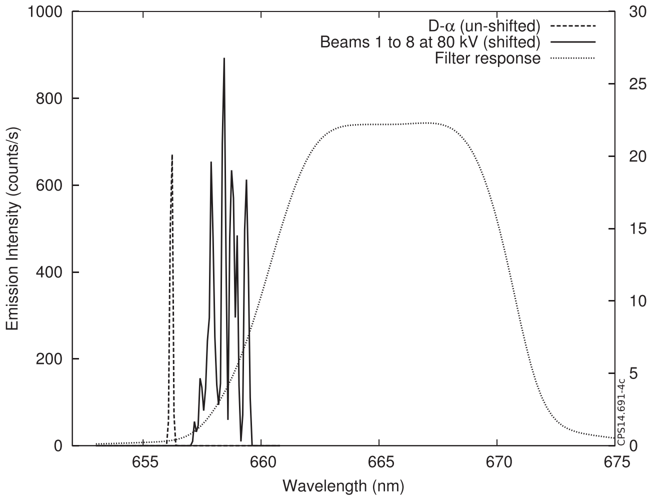


Fig. 1. Calculated beam emission for 80 kV deuterium beams. The Doppler shifted emission from full, half, and one third energy components is plotted. The transmission of the angle tuned (15°) interference filter is included.

The interference filter is effective at blocking the unshifted D_α line. However, also significantly reduces the beam emission of the third and half energy components. The emission from an 80 kV beam is the worst case because the accelerating voltage will normally be around 100 kV which gives an additional shift of 0.5 nm. Results given in Section 7 show that the arrangement works adequately.

5. Signal conditioning and data acquisition

The dynamic range in dB required from the measurement system was estimated over the range of conditions possible. The excitation cross-section for Balmer-α emission varies by a factor of 1.7 for beam voltages between 80 and 125 kV [11,3]. The range of duct pressure; the range of beam flux and the number of beams within the field of view are known. The dynamic range required is around 48 dB. To achieve this, light is measured by photomultiplier modules (>50 dB range) and the output is amplified by logarithmic amplifiers. The use of logarithmic signals preserves the dynamic range within 16-bit, 200 kHz digital sampling and it is also easier to set analogue trip levels against them.

6. Trip levels and calibration

The gain of the photomultiplier modules and the neutral density filtering were adjusted during commissioning of the interlock (C31 campaign). The strongest signals measured were from background light during plasma disruptions. The system has a large dynamic range and it was possible to set the filtering and photomultiplier gain to observe the background bremsstrahlung from the JET plasma and still not saturate during disruptions.

We found during the initial operation of the system that to calibrate each channel against duct pressure was not feasible. The reason was that there were limited opportunities to operate beams individually and that we had no control over the duct pressure.

The strategy for setting the trip levels is to set a trip level that is as low as possible but does not caused false trips when there is background light. The trip levels are selected after plotting histograms of signals recorded over a large set of pulses. Histograms are plotted for the following situations; beam injection, beam injection ended by a duct pressure trip, plasma operation with no beam injection, and plasma disruptions. By overlaying the histograms, it is possible to see what the trip level should be.

7. Results

For normal operating conditions and constant beam energy, the D_α emission is proportional to the background pressure and the neutral beam flux. Fig. 2 shows how the beam emission increases when the duct pressure increases for constant injected beam power of 6 MW.

Fig. 3 shows a plot of the neutral beam heating power from octant 8, the ODI signal from channel 3 and the duct penning gauge during a fast pressure excursion. The pressure spike is clearly visible on both the ODI signal and the duct penning gauge. This result was taken when the ODI system was being commissioned and its trip levels were disabled. During the heating phase, the duct pressure rises steadily as it did in Fig. 2. This is difficult to see because the graph scale includes the large pressure rise which occurs after 2.7 s of beam injection. This pressure excursion greatly exceeds the trip level (2×10^{-5} mbar). Channel 3 also shows an example of the background light from ELMs. These are seen as spikes on the graph. The ELM background is not significant compared with the signal from a rapid pressure excursion but is significant for the normal range of operations duct pressure.

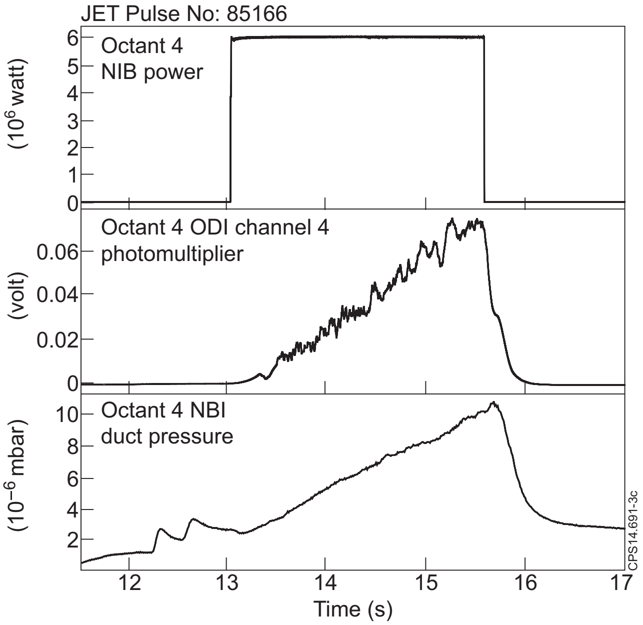


Fig. 2. Doppler shifted D_α emission measured from the neutral beams duct with constant beam power and increasing duct pressure [JET pulse 85166].

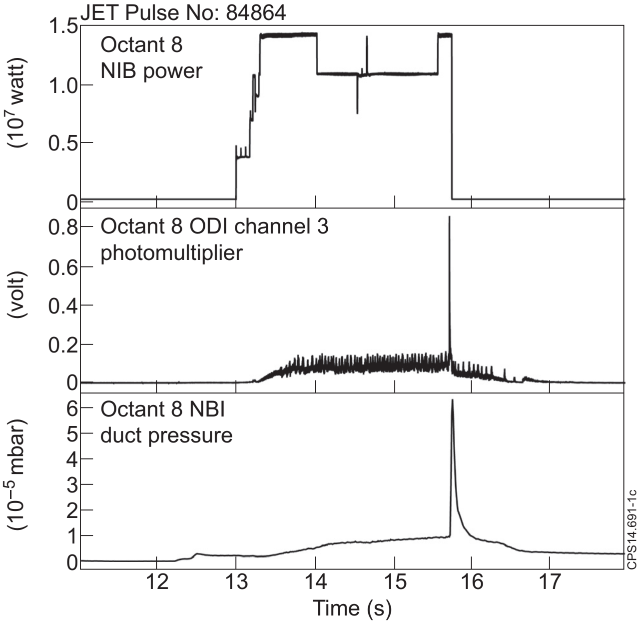


Fig. 3. Doppler shifted D_α emission measured from the neutral beams duct during a fast pressure excursion [JET pulse 84864].

Fig. 4 shows the same event on an enlarged time scale. This demonstrates the improved time response of the ODI compared with the duct pressure interlock. The pressure spike starts at 15.728 s. The ODI exceeds its trip level at 15.729 s but does not trip because it is disabled. The beams are then tripped by the penning gauge at 15.760 s. We see that the beam emission drops quickly after the peak value was reached. A small step in the emission, can be distinguished against the background, when the beams switch off.

For the duct penning gauge signal, the time to trip was 32 ms. For this example the ODI reached its trip level after 1 ms. However, we should include the additional signal delays (around 0.4 ms) and

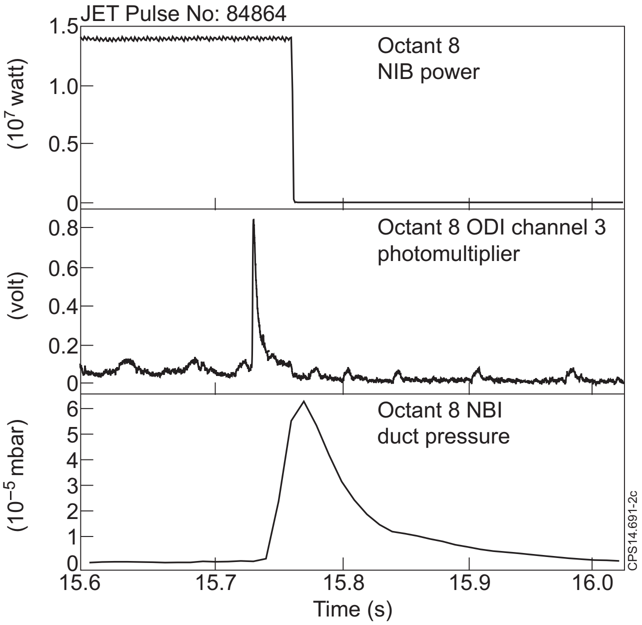


Fig. 4. Comparison of time response of the Doppler shifted D_α emission and the duct penning gauge during a fast pressure excursion [JET pulse 84864].

the PINI power supply switching time around 1.1 ms. This implies that ODI time to trip is around 2.5 ms.

8. Conclusions

Plasma heating pulses after the EP2 upgrade are no longer limited to 7–10 s before there is a duct pressure trip. Following EP2 duct pressure trips are rare. Replacing the inertial water cooled duct protection with hypervapotrons has been highly successful [7].

The time response of the duct penning gauge (50 ms before EP2) was shown not to be sufficient to protect the duct protection from damage as the removed tiles had extensive damage. Thermal load calculation shows that under the most severe fault conditions when there is a fast pressure excursion leading to complete beam blocking in the duct, a 2-ms response time is sufficient to protect the hypervapotron elements from damage.

The operation of a pressure interlock based on neutral beam emission has been demonstrated. We have presented some of the initial results from its operation. Results presented in Section 7 show that the ODI interlock time-to-trip for a fast pressure excursion is about 2.5 ms.

Acknowledgements

This work, part-funded by the European Communities under the contract of Association between EURATOM/CCFE, was carried out within the framework of the European Fusion Development Agreement.

This work was also part-funded by the RCUK Energy Programme under grant EP/I501045.

The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] G. Duesing, H. Altmann, H. Falter, A. Goede, R. Haange, Hemsworth, et al., Fusion Technol. 11 (1987) 163–202.
[2] D. Ćirić, A. Ash, B. Crowley, I. Day, S. Gee, L. Hackett, et al., Fusion Eng. Des. 86 (2011) 509–512.
[3] A. Ash, E. Surrey, Fusion Eng. Des. 84 (2009) 413–417.
[4] A.P.H. Goede, S. Papastergiou, J. Simkin, C. Challis, G. Duesing, R. Haange, et al., Twelfth Symposium on Fusion Engineering (SOFE), Monterey, USA, 12–16th October, 1987, pp. 1115–1118.
[5] A.J. Bickley, T.T.C. Jones, T. Norman, D. Stork, J. Wight, Fusion Technol. 1 (1990) 607–611, Sixteenth Symposium on Fusion Technology (SOFT), London.
[6] D. Ciric, D. Brown, C. Challis, B. Chuilon, S. Cox, B. Crowley, et al., Fusion Eng. Des. 82 (2007) 610–618.
[7] I.E. Day, T.T.C. Jones, Operational experience of the JET neutral beam actively cooled duct liner and implications for ITER operations, Fusion Eng. Des. (2015), http://dx.doi.org/10.1016/j.fusengdes.2015.02.038 (in this issue).
[8] H. Böck, J. Siehs, N. Vana, Radiat. Effects 65 (1982) 75–78.
[9] A. Maas, P. Andrew, P. Coad, A. Edwards, J. Ehrenberg, Gibson, et al., Fusion Eng. Des. 47 (1999) 247–265.
[10] K. Berkner, R. Pyle, J. Stearns, Nucl. Fusion 15 (1975) 249.
[11] C.F. Barnett, in: C.F. Barnett (Ed.), Atomic Data for Fusion, vol. 1 of ORNL-6086, Oak Ridge National Laboratory's Physics Division, 1990.