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Operational experience of the JET neutral beam actively cooled duct liner and implications for ITER operations

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ABSTRACT

We describe the operational experience of the JET actively cooled duct liner and compare it with the previous inertially cooled duct. The paper discusses the initial conditioning of the duct liner during restart commissioning and subsequent high power performance. The new duct was conditioned in 48 plasma pulses during its first time commissioning in only 35 plasma pulses in the following restart. The inertial duct liner conditioning typically required 100 plasma pulses. In a well conditioned beamline for a 15 MW beam pulse the duct liner temperature and pressure were observed to establish an equilibrium 5 s into the pulse and remain in a steady state to the end of the pulse. The observed behaviour is compared with the design basis predictions.

1. Introduction

Neutral beam injection systems have proved themselves to be the most effective form of auxiliary heating in tokamak plasmas. A fundamental limitation on pulse length has been the effect of re-ionised neutral particles in the restricted drift space or 'duct' between the beamline vacuum vessel and the tokamak vessel. These re-ionised particles are typically focused onto the duct wall by the tokamak magnetic field which can produce significant power density on the duct wall. In the case of JET these power densities can be of the order of 10 MW/m^2 which lead to significant temperature rises, evolution of gas trapped in the wall surface causing further re-ionisation and thus further heating of the duct wall.

In order to extend the beam pulse length in JET an actively cooled duct wall liner [1] was installed in 2011 as part of the EP2 upgrade [2] which would limit the temperature rise in the duct wall. The intention was to achieve a steady state with an equilibrium between duct pressure and duct wall temperature which would allow up to 20 s beam pulses in JET and demonstrate the feasibility of significantly longer beam pulses in future multi-megawatt beamlines such as those for ITER.

This paper summarises the duct conditioning experiences for the new actively cooled duct liner installed in 2010–2011 in both the 2011 and 2013 restarts and compares it with the previous inertial duct liner using data from the 2008 restart. Beamline pressures and temperatures are also compared once the ducts are well conditioned i.e. show no significant outgassing during high power pulses with durations >5 s. In both cases data for Octant 8 is used as the injectors were of a similar type. The comparison is made between duct performance at the highest levels of performance achieved to date in the inertial and actively cooled ducts.

Finally analysis of a range of pulses for both Octant 4 and Octant 8 beamlines has been carried out to study duct pressure rise as a function of beam energy.

2. Duct conditioning comparison

2.1. Inertial duct, previously well conditioned

In the 2008 restart Octant 8 beamline was equipped with 8, 130 kV/60 A EP1 triode injectors. As in previous restarts all injectors were conditioned to high power where possible (>110 kV) before commencing duct conditioning.

Fig. 1 shows the first torus pulse of the restart in 2008. Beam power (W) is shown in the upper trace with duct pressure (10^{-5} mbar) in the lower trace. A single injector fired for 0.21 s before the duct over pressure interlock terminated the pulse. The pressure rise recorded on the duct penning gauge was

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

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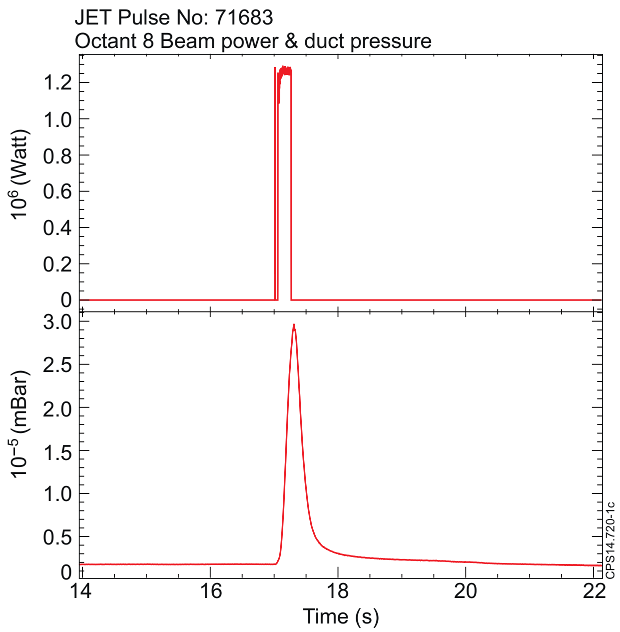

Fig. 1. Inertial duct. Single 130 kV EP1 PINI 114 kV, 1.3 MW, 0.21 s. Duct pressure rise ~3×10^{-5} mbar. JET Pulse Number (JPN) #71683.

~3×10^{-5} mbar. Subsequent single injector pulses with longer durations and then with greater numbers of injectors firing simultaneously were used to condition the duct liner.

Fig. 2 shows the duct pressure rise close to the end of the duct conditioning sequence. In this pulse the characteristic rapid increase in duct pressure rise gradient is evident. 3 pulses later a 8 s pulse was achieved without a duct over pressure trip and the duct was considered to be fully conditioned. The injector alignment and duct conditioning sequence took ~100 pulses over 6.5 days to complete.

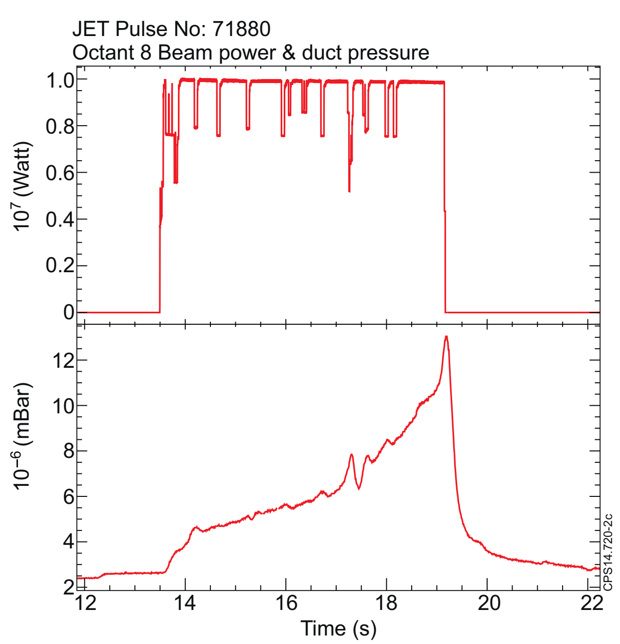

Fig. 2. Inertial duct. 8 × 130 kV EP1 PINIs 86–115 kV. Duct pressure trip ~5.6 s. JPN #71880.

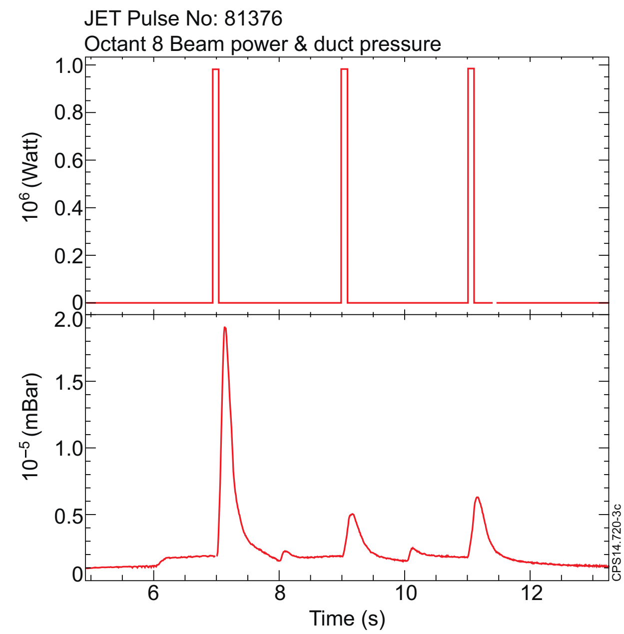

Fig. 3. Actively cooled duct, newly installed. Single EP2 PINIs 78 kV, 1.0 MW, 0.1 s. Duct pressure rise ~0.5×10^{-5}–2×10^{-5} mbar. JPN #81376.

2.2. *Actively cooled duct, initial commissioning*

In the 2011 EP2 restart Octant 8 was equipped with 8, 125 kV/65 A EP2 triode injectors. In order to gain experience with the newly installed metal wall in JET the injectors were conditioned to half power ~1.0 MW, 80 kV before duct conditioning started. Only 6 injectors were available during duct conditioning due to commissioning newly installed power supplies.

Fig. 3 shows the duct pressure rise during the first torus pulse of the restart in 2011 #81376. Beam pulse length is 0.1 s. The duct pressure rise varies from 0.5×10^{-5} mbar to ~2×10^{-5} mbar. Since this was the first time the newly installed actively cooled duct had been conditioned considerable care was taken with the conditioning lest a beam blocking event were to overload the hypervapotron elements leading to a water leak in the main JET vacuum vessel. However the duct conditioned very quickly compared with the inertial duct and was conditioned in only 48 pulses over 3 days, starting with pulse #81376 and ending with pulse #81463 shown in Fig. 4. Note duct temperature rises as measured by thermocouples 3 mm below the surface of the duct hypervapotrons were limited to 200 °C as a very conservative operating limit. Normal engineering limits for this type of hypervapotron are 310 °C. Allowed temperature rises on the inertial duct liner were 425 °C.

2.3. *Actively cooled duct, previously well conditioned*

During the restart in 2013 the duct conditioning was again carried out at ~80 kV but this time with 8 operational injectors. It was noticeable during this restart that the duct pressure rises were significantly less than in the previous 2011 conditioning when the duct liner was newly installed. Since the duct pressure rises seen with single injectors and pairs of injectors were minimal the conditioning moved rapidly to simultaneous injection with multiple injectors. The duct conditioned very quickly and was conditioned in only 35 pulses over 3 days, starting with pulse #84289 and ending with pulse #84345.

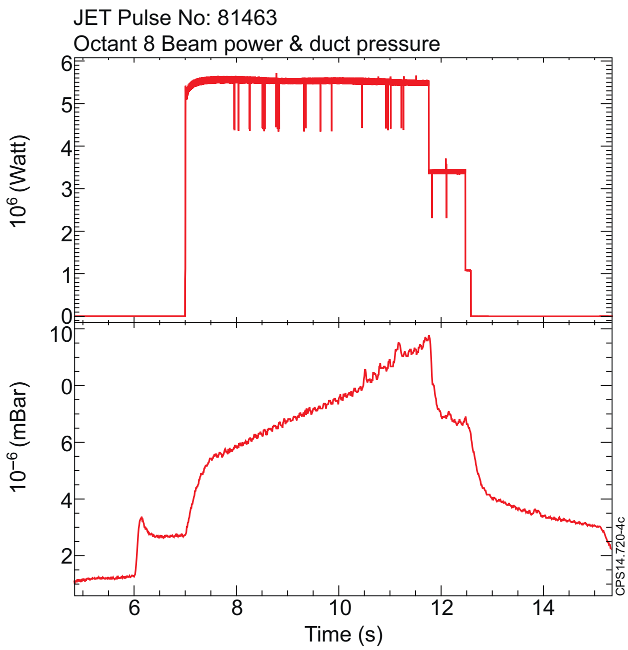

Fig. 4. Actively cooled duct. 6 × 125 kV/65 A EP2 PINIs 78 kV. Duct pressure rise ~1 × 10^{-5} mbar. JPN #81463.

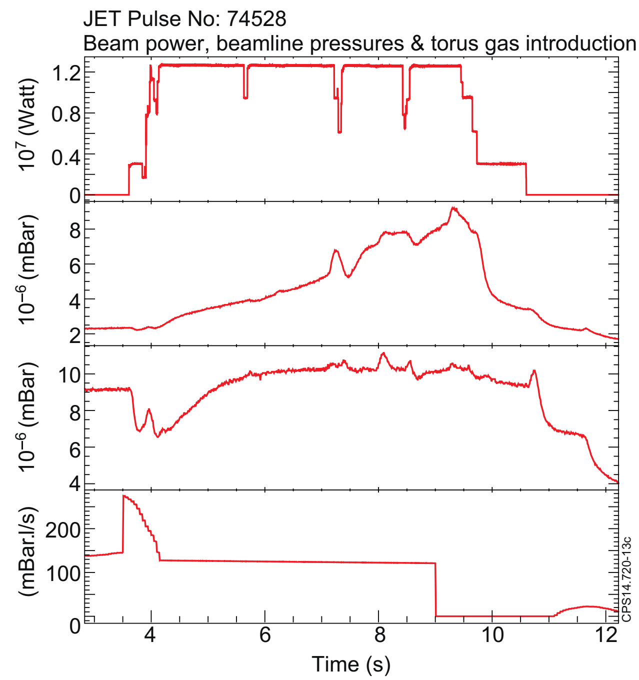

Fig. 5. Inertial duct. 8 × 130 kV EP1 PINIs 111–118 kV, 12.7 MW. Beam power, duct and NIB pressures (mbar) and Torus gas injection rate. JPN #74528.

3. Comparison of Performance of well conditioned ducts

In the following sections beamline pressures and duct temperatures are compared for the inertial and actively cooled duct liners. These pulses are representative of the highest levels of performance of the duct liners. The pulses chosen have a relatively constant or falling torus fuelling rate so pressure rises due to duct heating alone can be studied and so that changes in the neutral gas around the plasma should not significantly affect the duct pressure measurements.

3.1. Inertial duct, well conditioned 12.7 MW, 5.5 s

Data from #74528 illustrates well typical behaviour of a well conditioned inertial duct liner operating at high power.

Though the rest of the beamline was capable of sustaining 10 s pulses, temperature rises in the duct limited beam pulses to 5.5 s in this case. Beam power, beamline pressures and torus gas injection rate for this 12.7 MW, 5.5 s pulse can be seen in Fig. 5. During the beam pulse duct pressure rises to ~9 × 10^{-6} mbar in 5 s. Duct temperature at the hottest point rises to ~400 °C. The corresponding temperature rise on the hottest section of the inertial duct liner can be seen in Fig. 6 along with a contour map of the temperature rises.

Pulse length was limited by duct pressure rise and by duct liner temperature. The administrative limit on the measured duct temperature rise was 425 °C.

3.2. Actively cooled duct, well conditioned 15.2 MW/10.9 s

Data from #85440 shows the behaviour of the actively cooled duct with the longest pulse to date at powers close to the design limit of the EP2 injectors. Beam power, beamline pressures and torus gas injection rate for a 15.2 MW, 10.9 s pulse can be seen in Fig. 7. The corresponding temperature rise on the hottest section of the inertial duct liner can be seen in Fig. 8.

Duct pressure rises to ~9.2 × 10^{-6} mbar after ~4.5 s (~3 s after full beam power established) and remains in equilibrium from that point. Duct temperature at the hottest point rises ~145 °C and again appears to have reached equilibrium after ~ 5 s as shown in Fig. 8. Calculations using the ION code [3] show the peak duct power

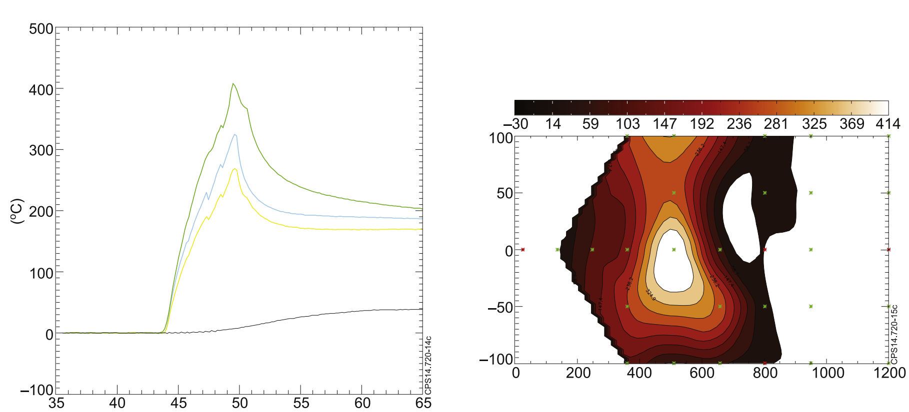

Fig. 6. Inertial duct. 8 × 130 kV EP1 PINIs 111–118 kV, 12.7 MW. Temperatures on hottest duct thermocouples and contour plot. JPN #74528.

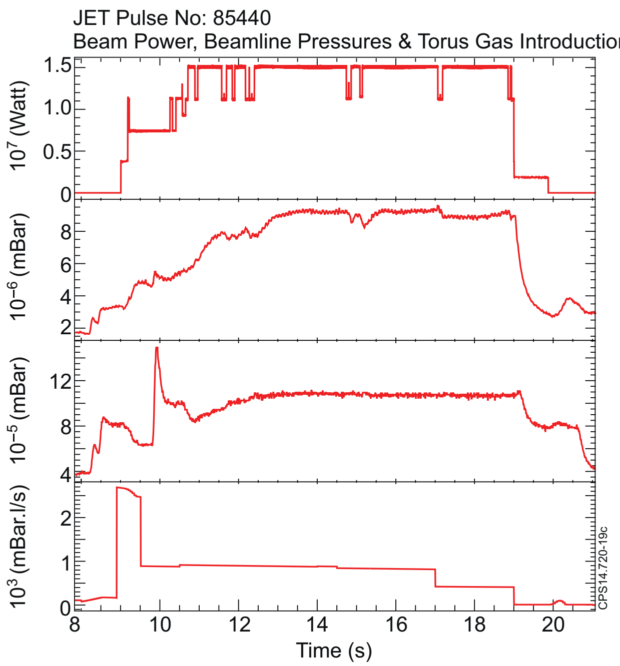

Fig. 7. Actively cooled duct. 8 × 125 kV EP2 PINIs ∼110 kV, 15.2 MW/10.9 s. Beam power, duct and NIB pressures (mbar) and Torus gas injection rate. JPN #85440.

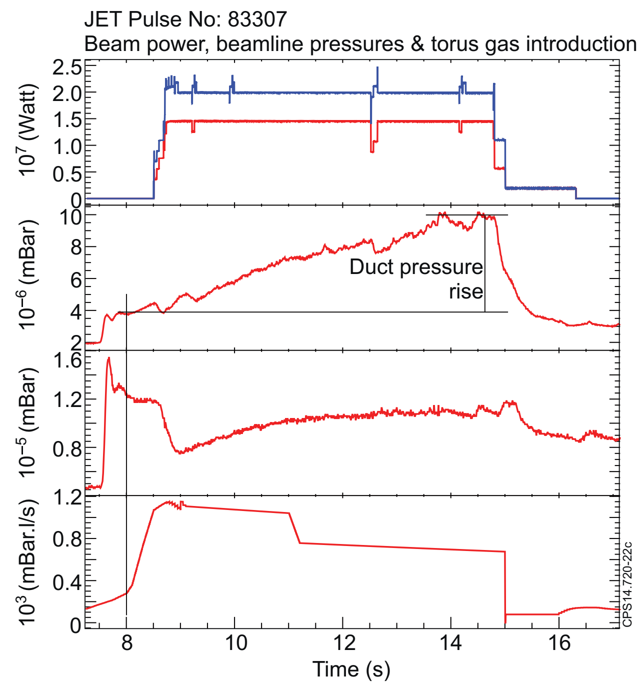

Fig. 9. Illustrating duct pressure rise during beam heating phase. Beam power; total (blue) and octant 8 (red), duct and NIB pressures (mbar) and Torus gas injection rate. JPN #83307. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

density to be ∼6 MW/m^2 excluding direct beam interception. The achievement of a steady state is therefore in line with the design basis for the actively cooled duct liner which anticipated an average duct power load of 5 MW/m^2 with a temperature rise of <200 °C [1].

To date few pulses have been carried out at high powers (>14 MW) and long pulse lengths (>6 s) to establish the time to achieve equilibrium in the duct in a range of operating scenarios at high powers. It is interesting to note that in both cases the pressure in the vicinity of the ion dumps reaches an equilibrium value of 1×10^{-5} mbar.

In order to get a better picture of the response of the actively cooled duct liner over a range of operating scenarios pressure rise data has been collated from a range of high power pulses. The data was collated from both Octant 4 and Octant 8 beamlines. The methodology is described in more detail in the next section.

4. Duct pressure rise analysis

In order to assess the duct pressure rise over a range of operating scenarios the following methodology was used. Pulses were selected with peak pulse power per beamline of >10 MW and average pulse power per beamline of >8 MW. All pulses with pulse energies >80 MJ were analysed and ∼5 pulses in each 5 MJ range down to a pulse energy around 20 MJ. This was repeated for both beamlines.

Fig. 9 shows the determination of duct pressure rise. The initial duct pressure was taken following the peak in NIB tank pressure seen just before the beam pulse starts at the time when the injector gas flow has been established.

This accounts for the duct pressure rise from the injector gas flows. The final duct pressure is simply the duct pressure at the end of the beam heating phase. The pressure rise is simply the difference of the two. The pressure rise in the duct will be due to a combination of gas evolved from the duct liner as re-ionised power heats the duct liner and the neutral gas surrounding the plasma.

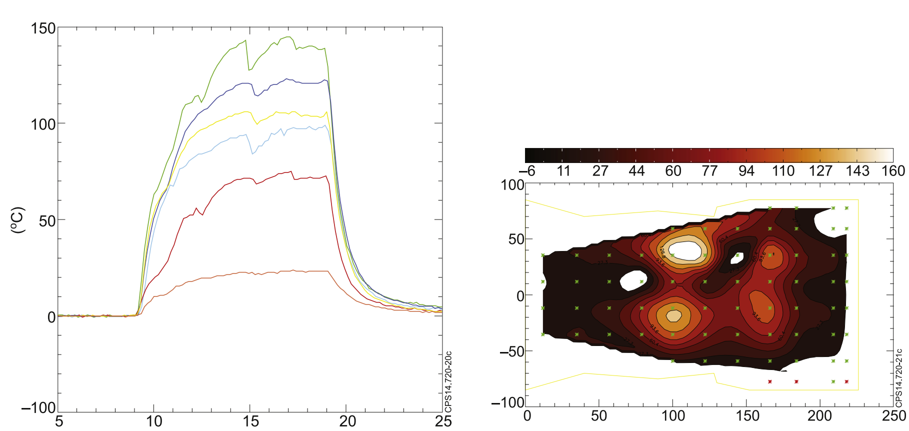

Fig. 8. Actively cooled duct. 8 × 125 kV EP2 PINIs ∼110 kV, 15.2 MW/10.9 s. Temperatures on hottest duct thermocouples and contour plot. JPN #85440.

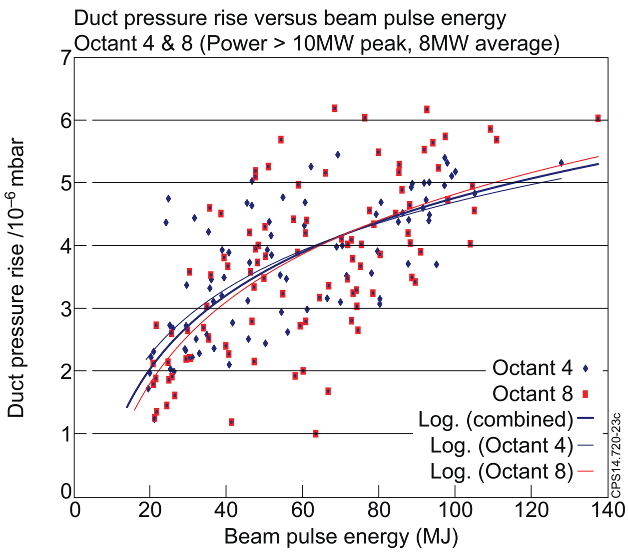

Fig. 10. Duct pressure rise as a function of beam pulse energy for Octant 4 & 8 beamlines. Peak beam power >10 MW per beamline, average power >8 MW per beamline.

Pulses selected for analysis were filtered for those with a constant or falling Torus fuelling rate (4th trace in Fig. 9). Pulses with a fuelling rate of >1200 mbar l/s for a significant proportion of the beam heating phase were excluded as duct pressure appeared to be dominated by torus fuelling in these cases.

The results of the analysis are shown in Fig. 10 with the results for Octant 4 beamline in blue and Octant 8 beamline in red.

Both beamlines show a duct pressure rise rising to a level around 6×10^{-6} mbar and then levelling off. A logarithmic fit is shown for both beamlines individually and for the combined data set as a guide to the eye. In the mid range of pulse energies between 50 and 80 MJ there is considerable scatter in the data which may be due to different torus fuelling rates. However at higher pulse energies the scatter appears to be reduced though the number of pulses requested with pulse energies >90 MJ has been limited.

The trends in the data indicate that the actively cooled duct liner is able to limit the duct pressure rise at high pulse energies allowing a steady state to be achieved over a range of plasma scenarios with beam powers close to the maximum possible in the EP2 beamline configuration. From this data and the clear evidence of achieving a steady state in Section 3.2 it would be expected that longer pulse lengths at >15 MW up to the full 20 s design specification of the EP2 upgrade should be achievable.

5. Conclusions

The inertial duct liner required ~100 pulses to achieve an acceptable level of condition which would allow all injectors to fire simultaneously for at least 5 s. This process required 6.5 days of machine time. The new actively cooled duct liner conditioned significantly more quickly. The first time the new duct was conditioned in 2011 required 48 pulses and was completed in 3 days. The subsequent 2013 restart is arguably a better comparison to the 2008 data as in both cases the duct liner had been previously well conditioned. In this case only 35 pulses were required over 3 days.

Comparison of beamline pressures in well conditioned beamlines shows that at high power, for the inertial duct a beam power of 12.7 MW with duration of 5.5 s caused a duct temperature rise of ~400 °C and a duct pressure of 9×10^{-6} mbar. This pulse is representative of pulses at the limit of performance of the inertial duct liner with duct temperatures close to allowed limits. For the actively cooled duct we demonstrate performance at beam powers of ~15 MW for pulses length of 10.9 s. In this case duct pressure rises to ~1×10^{-5} mbar with duct temperatures reaching an equilibrium in ~5 s at ~150 °C. The duct temperature and pressure remain constant after ~5 s for the remainder of the pulse demonstrating an equilibrium has been achieved. This performance is in line with the design basis for the actively cooled duct liner.

Finally analysis of a range of pulses for both Octant 4 and Octant 8 beamlines has been carried out to study duct pressure rise as a function of beam energy for pulses with beam powers >10 MW (peak) and >8 MW (average). This demonstrates that over a range of plasma types and plasma fuelling scenarios that maximum duct pressure rises reach a maximum of 6×10^{-6} mbar for pulse energies above 60 MJ. Therefore the full high power 20 s design specification of the EP2 duct liner should be achievable.

Acknowledgments

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References

[1] D.J. Wilson, D. Ciric, S.J. Cox, T.T.C. Jones, M. Kovari, A. Li Puma, et al., Physics basis and mechanical design of the actively cooled duct scraper protection for the JET neutral beam enhancement, Fusion Eng. Des. 82 (2007) 845–852.
[2] D. Ciric, D.P.D. Brown, C.D. Challis, B. Chuilon, S.J. Cox, B. Crowley, et al., Overview of the JET neutral beam enhancement project, Fusion Eng. Des. 82 (2007) 610–618.
[3] H.P.L. de Esch, T.T.C. Jones, D. Stork, Reionised power deposition in the JET neutral beam duct and plasma facing components, Fusion Technol. 1990 (1991) 493–497.