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ICRH assisted breakdown study on JET

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Abstract.

Ion Cyclotron wave (IC) assisted breakdown can be considered to provide robust plasma initiation during the ITER pre-fusion operation phase. Studies were performed at JET at ITER relevant loop electric field, $E_{loop} \lesssim 0.33\ V/m$, and a range of toroidal fields, including at the low toroidal field of 1.7 T for which breakdown had not been achieved previously on JET. The study covered a range of H_2 and D_2 gas prefill pressures and timings, pumping conditions, and residual impurity levels. IC assisted breakdown was achieved for a lower and wider range of gas prefill pressures. IC assisted breakdown works by activating wall pumping before the current rise, changing the relation between fuelling and torus pressure in this phase compared to Ohmic breakdown. IC assisted breakdown enables plasma initiation with a higher level and significantly wider range of injected plasma prefill gas. As the injected prefill gas is the controlled parameter, this significantly improves the robustness of plasma initiation operationally. IC assistance is found to be more robust at ITER-like E_{loop}, succeeding with higher low-Z impurity content. Moreover, it does not introduce an impurity source that may hamper the subsequent burn though and current ramp-up phase. For both the IC assisted and pure Ohmic breakdown, the initial current rise rate is found to scale with n_e/E_{loop}. The results and implications for ITER are presented.

PACS numbers: 52.25.Fi, 52.50.Gj

1 Introduction

Plasma initiation in a tokamak begins with a Townsend avalanche phase where residual electrons in the vacuum vessel are accelerated by an induced toroidal electric field, producing secondary electrons through collisional ionisation of prefilled neutrals. This is followed by a burn through phase where, locally, most atoms are stripped of their electrons and the temperature of the plasma is increased through Ohmic heating until the plasma energy losses from interaction with neutrals (electron impact reactions and charge exchange collisions) become small with respect to thermal losses. Predicting the criteria and evolution of breakdown and burn through requires detailed modelling [1], but can be approximated by the Townsend avalanche breakdown criteria:

$$\frac{L_f}{\lambda_i} \gg 1 \qquad \text{with} \qquad \lambda_i = \left(\frac{a}{p}\right) e^{bp/E_{loop}} \qquad (1)$$

where L_f is the is the average length of open magnetic field lines (i.e. effective connection length), λ_i the mean length for an electron to be accelerated and make a collisional ionization of a neutral particle, p is the prefill gas pressure, E_{loop} is the toroidal (loop) electric field, and a and b are constants [2] which, at room temperature (300 K) for H_2, D_2, or T_2, are taken as $a = 0.258\, mPa^{-1}$ and $b = 950\, Vm^{-1}Pa^{-1}$ [3]. Based on the equation, L_f/λ_i can be used as a predictor for successful plasma breakdown. The breakdown criteria of equation 1 can be seen to have an optimal pressure but increasing E_{loop} is always favourable for breakdown and lower E_{loop} unfavourable with the range of allowable prefill pressures decreasing with decreasing E_{loop} until a value of E_{loop} below which no breakdown is possible. The maximum E_{loop} for ITER is expected to be $0.33\, Vm^{-1}$ which is considerably lower than that of existing tokamak (for JET $E_{loop} \lesssim 1\, Vm^{-1}$). This implies relatively long λ_i and so presents a challenge for plasma initiation in ITER. Purely Ohmic plasma initiation is sufficient for JET and many existing tokamaks. Studies indicate that Ohmic plasma initiation in ITER may be challenging in the case of a high hydrogenic background pressure or when there are large amounts of residual in-vessel impurities such as those that may be injected for plasma optimisation or disruption mitigation [4] [1]. This has motivated the study of electron cyclotron wave (EC) assisted plasma initiation both applying EC power to form a pre-ionised plasma prior to Ohmic breakdown and applying EC heating power later to assist the burn through phase. These studies have demonstrated EC assisted plasma initiation on several machines [2] [5] [6] [7] [8] [9] and provided a physics basis from which it has been concluded that the method can improve the reliability of plasma initiation on ITER [3] [1] [10].

During the initial ITER Pre-fusion Plasma Operation phase (PFPO-1), ITER will operate at low magnetic field ($B_t = 1.8\, T$) to enable H-mode access, for which the required heating power has been found empirically to scale near linearly with magnetic field, for H plasma. As the connection length scales linearly with B_t, plasma initiation will be less robust than for the later ITER Fusion Plasma Operation phase. Moreover, studies have shown that the planned 170 GHz ITER EC system will not be able to effectively heat at the third harmonic resonance that would be required at $B_t = 1.8\ T$ [11]. As is the case at higher field, Ohmic plasma initiation for ITER at 1.8 T is expected to be adequate, but ion cyclotron wave (IC) assisted breakdown would reduce risk of failed plasma initiation in the case of poor vacuum conditions [1]. Even though the present ITER research plan does not foresee IC heating capabilities for PFPO-1, a case for IC assisted breakdown needs to be developed. This motivates the present study which aims to demonstrate and optimise the method on JET and provide a physics basis for extrapolation to ITER. IC plasma formation has previously been demonstrated and optimised at JET for wall cleaning [12], but it has not been used before for main plasma initiation.

The structure of this paper is as follows. Section 2 outlines the experimental method used for the studies. Section 3 presents the experimental results related to the criteria for successful plasma initiation. Section 4 presents the results related to the subsequent evolution of the plasma. In Section 5, the results are summarised, and their implications discussed.

2 Experimental method

JET plasma initiation is performed [13] by using a set of poloidal field coils to generate a hexapole null in the poloidal field inside the vacuum vessel at the instance when the loop voltage, induced by the central solenoid, has reached its set steady value. In the region around the null, poloidal fields are small, hence the connection lengths are long and so favourable for breakdown. Once an initial plasma carrying a current higher than a few kA is established, the central solenoid controls the plasma current and the poloidal field coils control the plasma position and shape until the required plasma configuration is established.

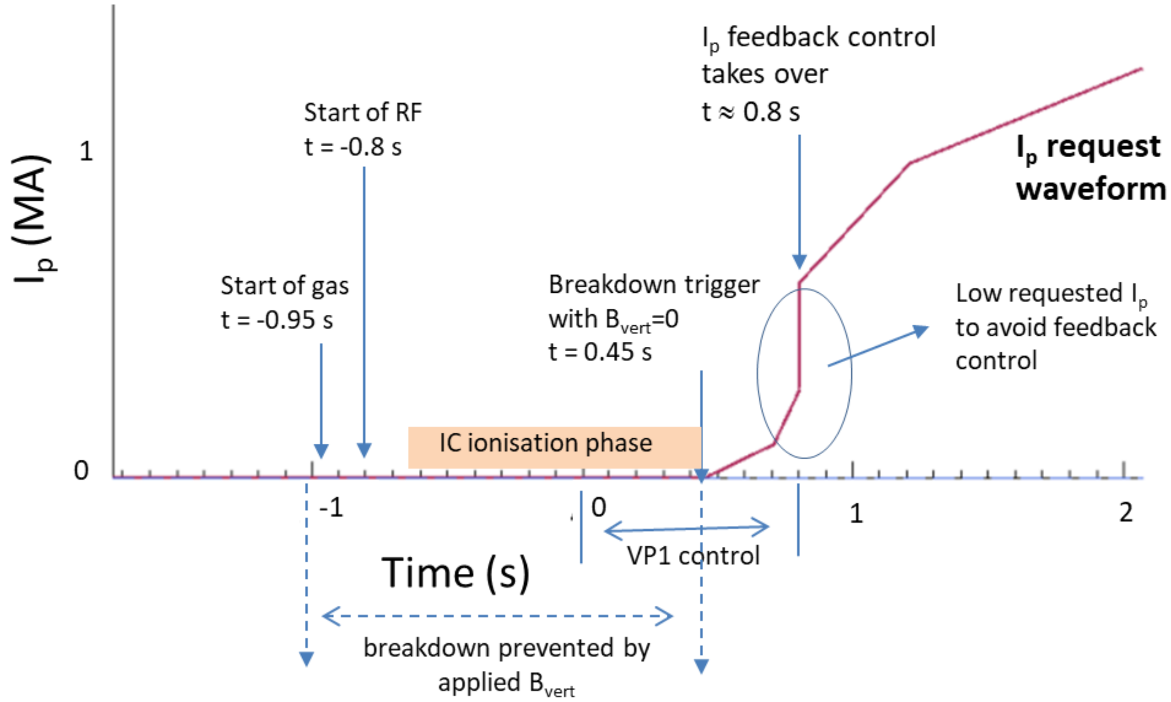

Figure 1. Schematic of a JET Ion Cyclotron (IC) assisted breakdown.

Figure 1 shows the waveform used for the IC assisted breakdown experiments. Breakdown is initially avoided by applying, from $t = -1\ s$, a vertical magnetic field which ensures a short connection length. The required E_{loop} and prefill gas pressure is then developed. The applied vertical magnetic field is removed at $t = 0.45\ s$ and breakdown attempted. The exact time of the breakdown and its development depends upon the experimental conditions. A plasma current waveform is requested from $t = 0.45\ s$ and the JET plasma control system essentially limits E_{loop} to deliver this current. Before $t = 0.8\ s$ s, the requested plasma current is kept low to avoid a strong increase in the loop voltage. The feed forward request of the loop voltage is gradually reduced over 200 ms to obtain a fully feedback controlled electric field at or before $t = 0.8\ s$. During this time, the breakdown and burn through phases evolve freely. From $t = 0.8\ s$, the requested plasma current is raised and E_{loop} is controlled to deliver this. As the plasma resistivity is low at this time, the required electric field is well below the 0.33 Vm^{-1} limit of ITER.

Following previous studies of IC discharges for ion cyclotron wall conditioning (ICWC) in JET [12], the IC frequency is selected for an on-axis fundamental H resonance with the, toroidally distributed, antenna straps all in phase – referred to as “*monopole*” phasing. The resulting IC heating scheme is H minority for D plasma and H majority for H plasma. The antenna protection settings are identical to those for JET ICWC operation, following Ref [12]. The interlock for the pressure in the IC vacuum transmission lines is lowered to 5 mPa with the same limit for the torus pressure. The number of trips per IC amplifier is limited to 10 per discharge and 100 per experimental session. The maximum permitted Voltage Standing Wave Ratio for the IC antenna is increased, but the maximum permitted voltages on the transmission lines is limited to 20 kV. The External Conjugate-T matching system is not used.

Following the JET ICWC scheme, pre-fill gas fuelling is from valves in the divertor for all discharges to avoid fuelling gas too close to an IC antenna and to obtain a uniform torus pressure. This contrasts with the mid-plane pre-fill gas fuelling more commonly used for breakdown. Compared to mid-plane fuelling, divertor fuelling on JET requires more injected gas to produce the same change in vessel pressure. This is experimentally and operationally advantageous, as it allows finer control of vessel gas pressure. Divertor fuelling on JET results in toroidally symmetric gas pressure in contrast to mid-plane fuelling where vessel gas pressure is larger in the toroidal location close to the injecting valve. The toroidally symmetric gas pressure distribution means that divertor fuelled breakdowns are easier to interpret which experimentally and operationally advantageous.

Ohmic breakdown references were performed using the same setup as for the IC assisted breakdowns only with the IC power turned off.

Since JET began operating with the ITER-like Be/W wall, plasma initiation has been robust with failed plasma initiations being rare [14]. This is when operating with breakdown $E_{loop} \approx 0.9\ Vm^{-1}$ and $B_t \geq 2.3\ T$ to ensure sufficiently long connection lengths. To study an ITER relevant regime where E_{loop} and connection lengths may be low enough that plasma initiation becomes marginal, these studies were performed with $E_{loop} \lesssim 0.33\ Vm^{-1}$ and $B_t \approx 1.7\ T$. JET plasma initiation had not previously been achieved in such conditions.

Diagnosis follows the approach used in previous JET breakdown studies [14]. The loop electric field is inferred from the central solenoid (P1 coil) voltage, V_{P1}. The P1 coil has $N_T = 710$ turns, so $V_{P1} = 2\pi R_0 N_T E_{loop}$, where $R_0 = 2.96\ m$ is the JET geometric radius. This gives In-vessel neutral gas pressure is measured with Penning gauges [15] [16]. The line integrated density is measured with the JET far-infrared interferometer using a vertical line of sight passing through the centre of vessel with a time resolution of 10 μs [17] [18]. Bremsstrahlung and D Balmer-α emission is measured by a visible spectroscopy system with multiple lines of sight and 1 ms time resolution [19]. Z-effective is inferred from Bremsstrahlung radiation. The JET VUV emission spectroscopy system is used to measure line radiation from impurities, including Be III, C III, C IV, O VI, Ne VII, Ne VIII, Ne IX, Ar XVI, Fe XXIII, Ni XVIII and W (multiple lines) [20].

3 Criteria for successful plasma initiation

3.1 Overview of the JET IC assisted breakdown results

Plasma initiation with IC assisted breakdown has been successfully established in the regime of interest for ITER, $E_{loop} < 0.33\,Vm^{-1}$, for a range of fields $B_t = 1.7 - 2.3\,T$. Figure 2 shows a typical discharge (red, #100624) compared with an Ohmic breakdown (blue, #100636) at matched $E_{loop} \lesssim 0.33\,Vm^{-1}$ and $B_t = 1.7\,T$. In the period before the main breakdown phase, a low density, $n_e \leq 5 \times 10^{18}\,m^{-3}$, plasma is produced in the vacuum vessel by powering the IC antennas. After an initial increase of the torus gas pressure due to gas fuelling in vacuum, the pressure falls at the onset of the IC discharge due to wall pumping. This process eventually saturates as shown by the gradual pressure increase from $\approx 0.25\,s$. The, so-called, ‘pre-ionisation’ plasma is maintained until the start of the main breakdown phase. The torus pressure at breakdown can be tuned by the gas fuelling rate and the launched IC power. The plasma density rise rate through the breakdown and plasma burn through phases is much higher than for the Ohmic reference. The following analysis will look more carefully into successful and unsuccessful plasma initiation attempts for both Ohmic only and IC assisted scenarios. It is important to note that most of pulses achieved breakdown while many failed in the burn through phase. Hence, a successful plasma initiation is hereafter defined by a successful completion of the plasma burn through phase. Consistent with previous studies, the time point at which the JET plasma current reaches $100\,kA$ is used to define the loop electric field and neutral gas pressure of the plasma breakdown [14].

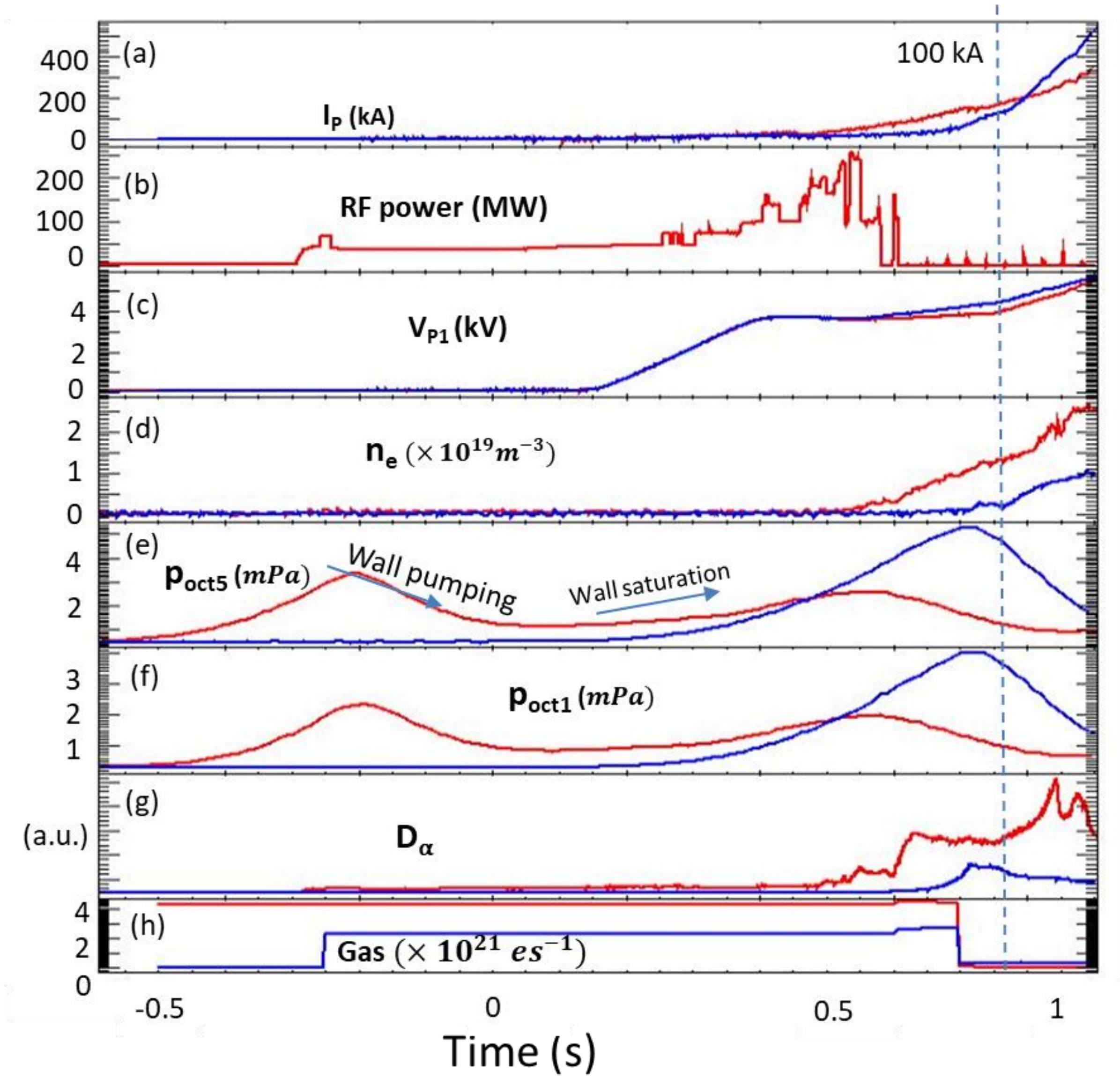

Figure 2. Time trace of plasma parameters for an IC assisted breakdown (red, #100624) and an Ohmic breakdown (blue, #100636) with D_2 fuelling. (a) Plasma current; (b) coupled RF power; (c) P1 coil voltage; (d) the line average density; (e) in-vessel gas pressure in octant 1; (f) in-vessel gas pressure in octant 5; (g) D-α emission; and (h) injected gas.

Figure 3 shows the full set of IC assisted breakdown discharges in this study. A range of breakdown pressures and toroidal (loop) electric fields were attempted with D_2 fuelling at three different toroidal magnetic fields, $B_t = 1.7, 2.0, and\ 2.3\ T$. A range of breakdown pressures and toroidal (loop) electric fields were also attempted with H_2 fuelling at $B_t = 2.3\ T$. The minimum E_{loop} for plasma initiation is $0.22\ Vm^{-1}$ for both $B_t = 1.7\ T$ and $B_t = 2.3\ T$. A full pressure scan was conducted at $B_t = 1.7\ T$ with $E_{loop} \leq 0.33\ Vm^{-1}$ with the pressure range for successful plasma initiation identified as $0.5 - 2.4\ mPa$. The minimum pressure for successful IC assisted initiation appears to be independent of toroidal magnetic field ($\approx$

0.5 mPa), but IC assisted initiation was still successful for the highest pressure attempted at $B_t = 2.0\,T$ ($\approx 5\,mPa$). It is preliminarily concluded that the operational space of pressure is larger for higher B_t, in line with the fact that connection length scales linearly with field. H_2 breakdowns appear to show the same trends as for D_2 ones, although the dataset of H_2 breakdowns is more limited.

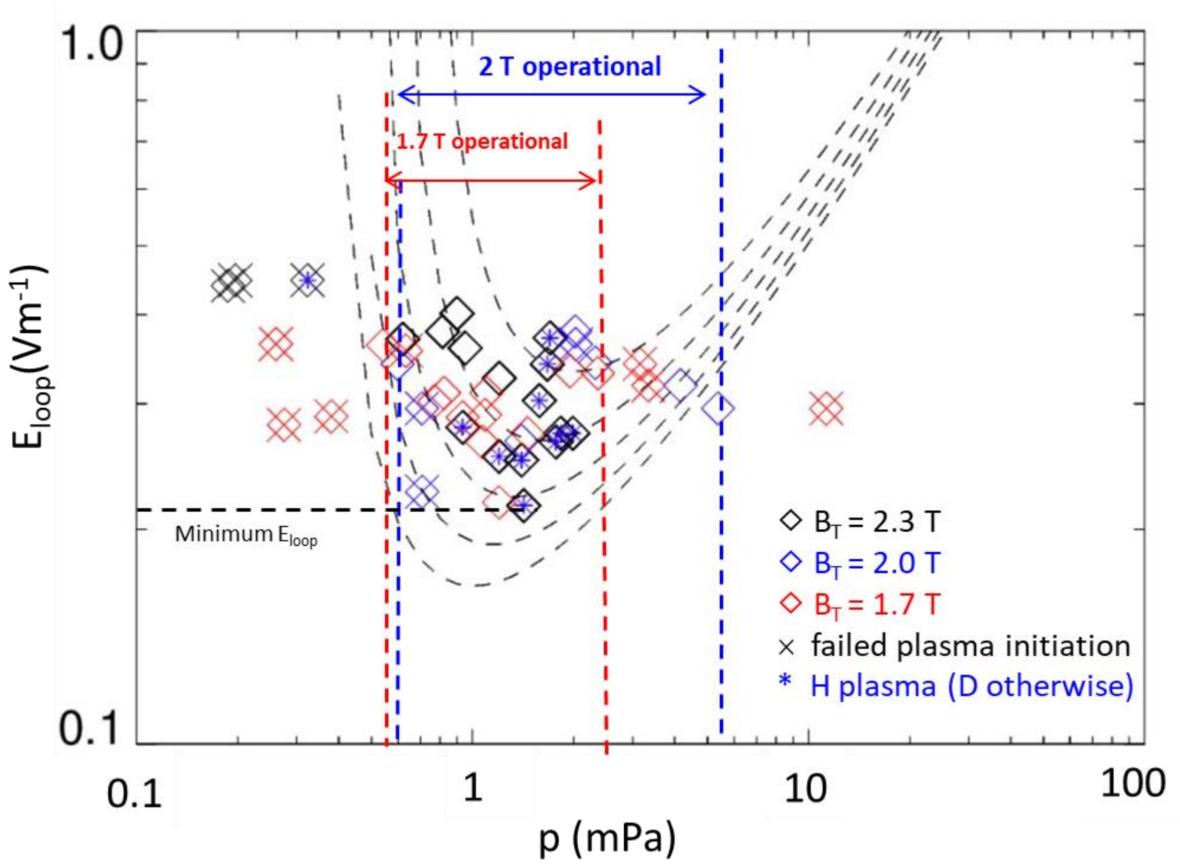

Figure 3. Toroidal (loop) electric field versus prefill gas pressure, both at the time of breakdown, for all attempted IC assisted breakdown discharges in this study. Dashed grey contours denote contours of constant λ_i using the breakdown criteria of equation 1. Dashed vertical lines show the operational range for successful plasma initiation at $B_t = 1.7\,T$ (red) and $B_t = 2.0\,T$ (blue). Dashed black line shows the minimum $E_{loop} = 0.22\,Vm^{-1}$ at which plasma initiation was achieved.

3.2 Comparison of Ion Cyclotron assisted and Ohmic breakdowns

As part of the study, Ohmic breakdowns with D_2 fuelling at $E_{loop} \leq 0.33\,Vm^{-1}$ and $B_t = 1.7\,T$ were also attempted as references. Some of these were also successful, representing the first Ohmic breakdowns established at ITER-PFPO-like E_{loop} and B_t in JET. As for the IC assisted breakdowns, a full pressure scan was completed at $B_t = 1.7\,T$, figure 4(a). The pressure range for successful plasma initiation with Ohmic breakdown at $B_t = 1.7\,T$ was observed to be $2.5 - 4.0\,mPa$, Hence, IC assisted breakdown enables plasma initiation with 5 times lower gas prefill pressure and a much wider range ($0.5 - 2.4\ mPa$). This gives access to the $1\ mPa$ prefill pressure that is proposed for ITER [21].

The amount of injected prefill gas for successful plasma initiation with IC assisted breakdown ($7.7 - 10.9\ kPa\ l$) is greater than for Ohmic breakdown ($4.3 - 4.4\ kPa\ l$) with a considerably larger range, figure 4(b). As the amount of injected prefill gas is the controlled parameter experimentally, Ohmic breakdown at $E_{loop} \leq 0.33\ Vm^{-1}$ and $B_t = 1.7\ T$ requires careful gas control, and is presumably sensitive to vessel condition, whilst IC assisted breakdown is more robust.

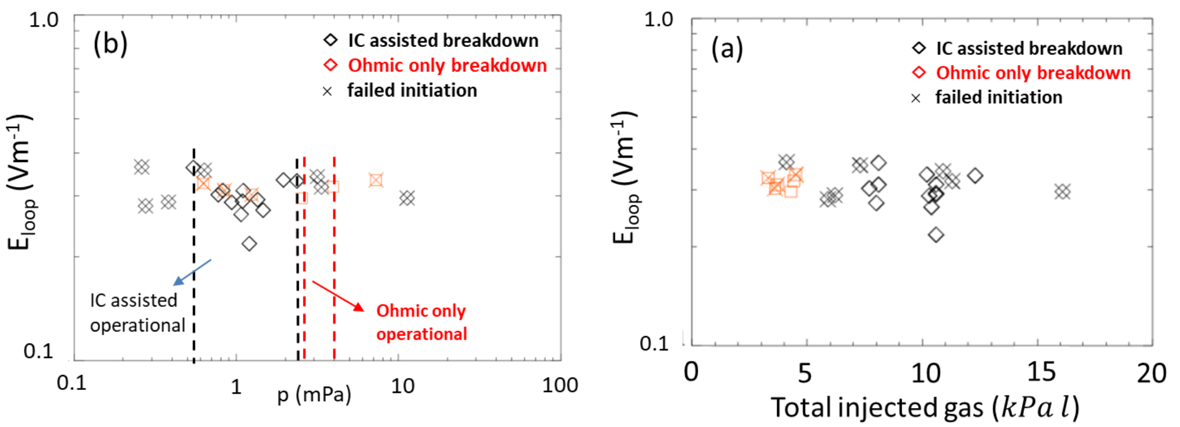

Figure 4. E_{loop} against (a) torus pressure immediately prior to breakdown; and (b) total injected gas prior to breakdown for Ohmic only (red squares) and IC assisted (black diamonds) breakdowns in JET with D_2 fuelling at $B_t = 1.7\ T$. Failed plasma initiations are marked with an "X".

3.3 The impact of pumping

The impact of divertor cryo-pump condition was explored by comparing breakdowns attempted with the cryo-pump cooled by liquid N_2 and liquid He, which affect the pumping efficiency of hydrogen. For both H_2 and D_2 gas fuelling the JET divertor cryo-pump is found to pump at $\approx 150\ m^3s^{-1}$ when liquid He cooled and at $\approx 5\ m^3s^{-1}$ when liquid N_2 cooled. At both temperatures, scans of pre-fill gas pressure were performed with IC assisted breakdown with $E_{loop} < 0.33\ Vm^{-1}$ at $B_t = 1.7\ T$. A pre-fill gas pressure scan was also performed with the cryo-pump cooled by liquid N_2 for Ohmic breakdown with the same E_{loop} and B_t. The impact of this on the breakdown studies can be seen by comparing the IC assisted D breakdown discharges at $B_t = 1.7\ T$ with the two divertor cryo-pump coolants, figure 5. For both pumping conditions, a similar range of gas prefill pressure, $\approx 0.6 - 3.0\ mPa$, is observed for successful IC assisted breakdowns, figure 5(a). The range of pre-fill gas fuelling that is required to achieve these pressures is also similar with the two cryo-pump coolants, $\approx 75 - 110\ mbar\ l$, figure 5(b). Thus, for IC assisted breakdown, cryo-pump condition doesn't seem to obviously affect the breakdown pressure or the total injected pre-fill gas.

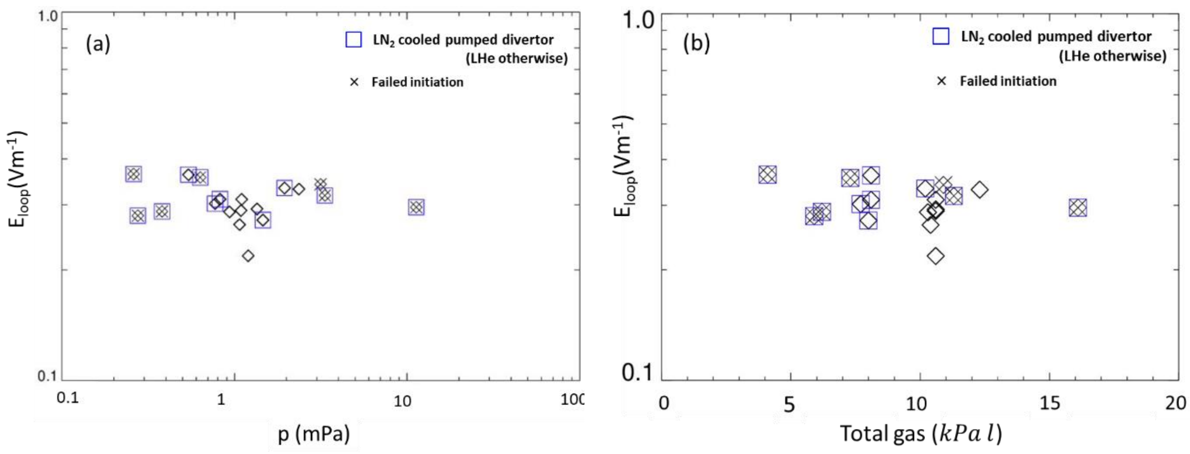

Figure 5. E_{loop} against (a) torus pressure immediately prior to breakdown; and (b) total injected gas prior to breakdown for IC assisted breakdowns in JET at $B_t = 1.7\ T$ with D_2 fuelling. Discharges with liquid N_2 cooled pumped divertor (pump speed $\approx 5\ m^3s^{-1}$) marked by blue open squares; other discharges have liquid He cooled pumped divertor (pump speed $\approx 150\ m^3s^{-1}$). Failed plasma initiations are marked with an "X".

3.4 The role of ion cyclotron wave injection in breakdown

Comparing IC assisted with Ohmic breakdown with the cryo-pump at liquid N_2 temperature, clearly the breakdown pressure and the total injected pre-fill gas ranges differ significantly, figure 6. The effective pumping speed, S, can be calculated from the expression for the time evolution of the gas prefill pressure $p(t)$

$$V\frac{dp(t)}{dt} = -S[p(t) - p_L] + F(t), \qquad (2)$$

where V is the total pumped torus volume, $\approx 180\ m^3$; p_L is the stable torus pressure, ≈ 0.03 mPa for the N_2 cooled pump divertor; and $F(t)$ is the time dependent gas injection rate. The total pumping speed is found to be $\approx 20\ m^3s^{-1}$ for Ohmic breakdown pulses and $\approx 1000\ m^3s^{-1}$s for the IC assisted breakdown pulses. The applied IC acts as a pump which greatly increases the amount of gas consumed by breakdown. As outline in [22], IC power applied to breakdown the plasma creates a flux to the wall primarily from isotropic neutral hydrogenic species either desorbed from the wall surfaces or created by dissociation of molecular hydrogen by electron collisions, having Franck-Condon energies of a few eV. In addition to ion fluxes parallel to the magnetic field lines, fast neutrals are produced by charge exchange between protons or deuterons accelerated in the IC resonant layer and the background neutral gas, with temperatures above 1 keV and energies up to 50 keV.

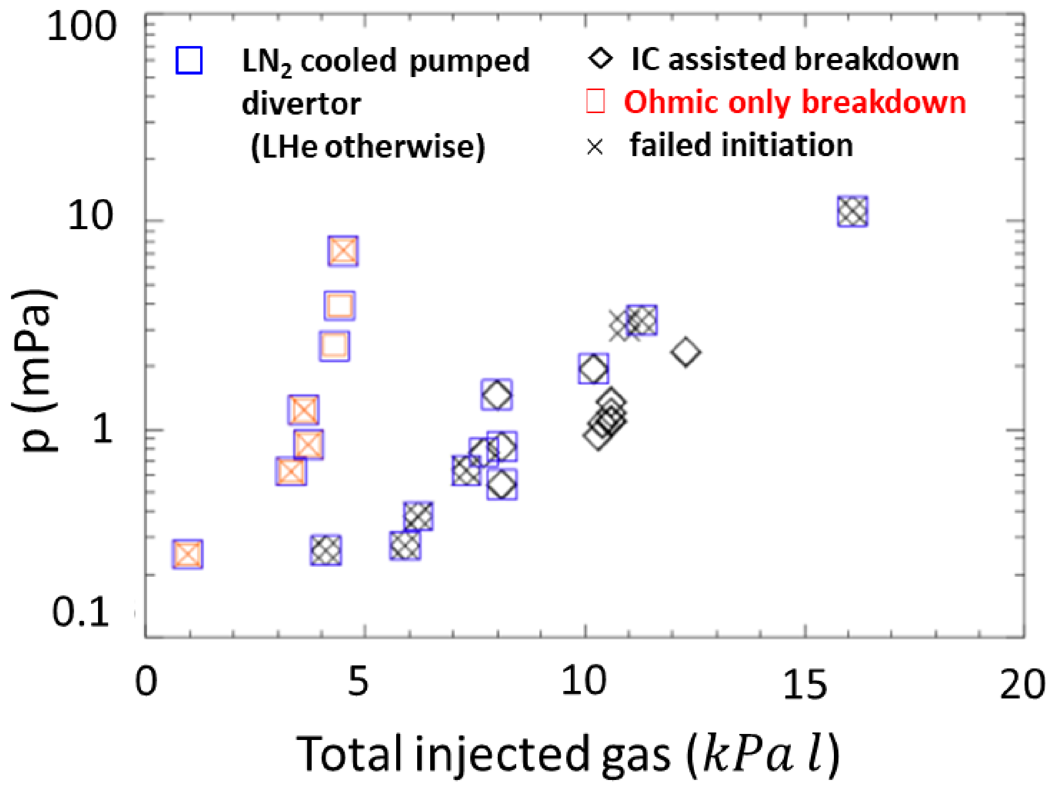

Figure 6. Pressure at which breakdown is achieved versus the total injected gas prior to breakdown for Ohmic only (red squares) and IC assisted (black diamonds) breakdowns in JET with D_2 fuelling. Discharges with liquid N_2 cooled pumped divertor (pump speed $\approx 5\ m^3s^{-1}$) marked by blue open squares; other discharges have liquid He cooled pumped divertor (pump speed $\approx 150\ m^3s^{-1}$). Failed plasma initiations are marked with an "X".

There is no strong trend across the dataset of a correlation between IC coupled power and successful plasma initiation. Some pulses with poor coupling (lower ICWC n_e) during IC pre-ionisation phase succeeded in plasma initiation, while some failed with well coupled power. There was no strong trend between the IC preionisation plasma density and breakdown either. Figure 7 illustrates this for a D_2 breakdown assisted with 33 MHz IC. Discharge #100416 (blue trace) is a successful $E_{loop} < 0.33\ Vm^{-1}$, $B_t = 1.7\ T$ IC assisted discharge. Discharge #100408 (red trace) with similar loop voltage failed in plasma initiation. Coupled IC power is higher for this discharge and is associated with considerably ($\approx 2\ times$) higher preionisation electron density. Despite this, the current fails to take off.

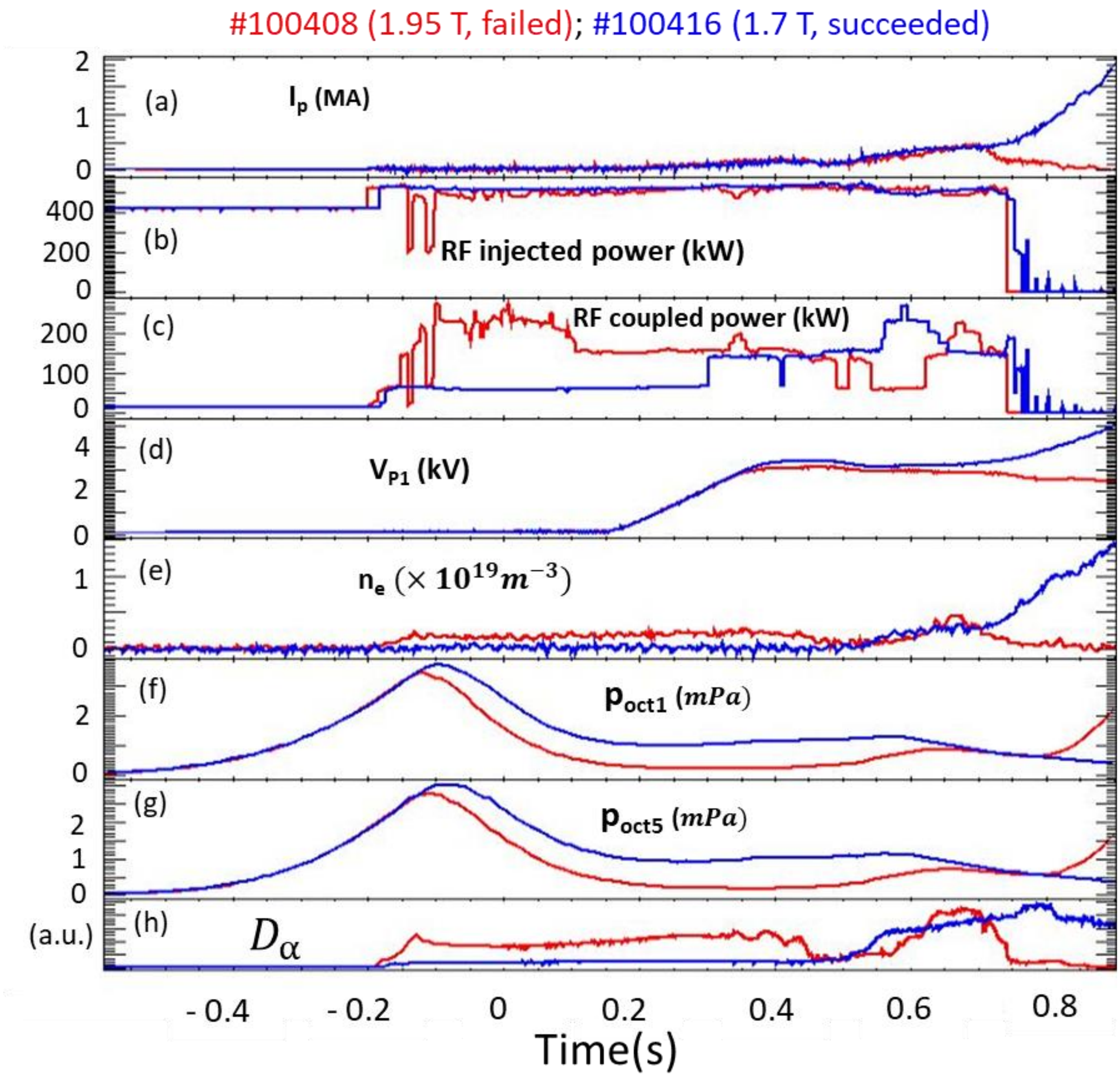

Figure 7. Time trace of plasma parameters for a successful (blue, #100416) and a failed (red, #100408) plasma initiation with IC assisted breakdown and D_2 fuelling. (a) Plasma current; (b) injected RF power; (c) coupled RF power; (d) P1 coil voltage; (e) line average density; (f) in-vessel gas pressure in octant 1; (g) in-vessel gas pressure in octant 5; and (h) D-α emission.

Across all the IC assisted discharges, the IC preionisation plasma has low density, $n_e < 5 \times 10^{18}\ m^{-3}$, and there is no correlation observed between IC plasma density and density at the end of the burn through. The time when $I_p = 100\ kA$ may be taken as the approximate end of the burn through. At this time the IC assisted breakdown pulses have higher electron density than Ohmic breakdowns, even at similar prefill gas pressures, figure 8(a). Even though the total injected gas is lower in Ohmic only breakdowns than IC assisted ones, the density at breakdown is similar, figure 8(b).

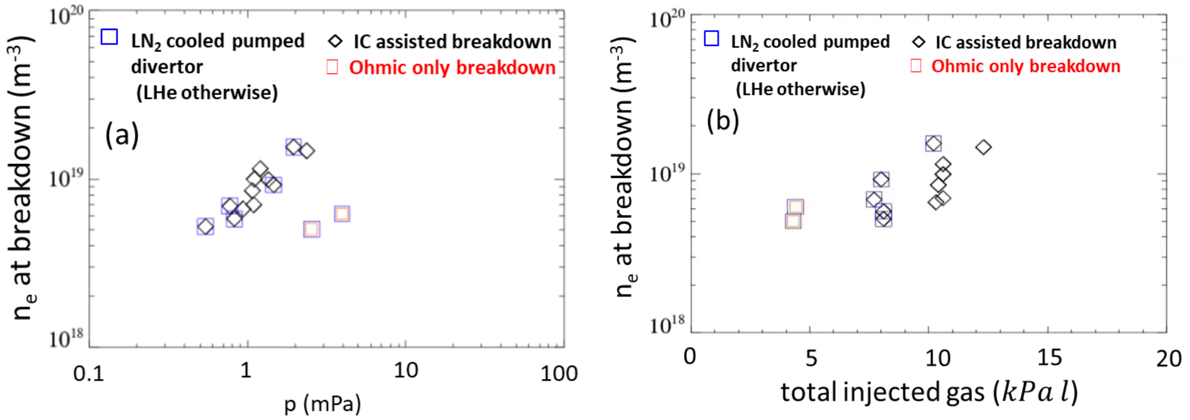

Figure 8. Electron density, at the time in the breakdown where $I_p = 100\ kA$, against (a) torus pressure at the same time; and (b) total injected gas prior to breakdown for Ohmic and IC assisted breakdowns in JET.

3.5 The impact of impurities

Compared with Ohmic only assisted breakdown, IC assisted breakdown can initiate plasma in the presence of higher levels of impurities, such as Ne. This was demonstrated with a study of breakdown with D_2 fuelling in the presence of high in-vessel Ne concentrations. Ohmic breakdown was first attempted at $E_{loop} \lesssim 0.33\ Vm^{-1}$. Despite three consecutive attempts at different pressures around the optimal value, Ohmic breakdown was unsuccessful. Figure 9 shows one of the unsuccessful Ohmic only breakdowns (#100401, red) which was based on a reference successful Ohmic only breakdown (#98343, blue). Despite similar prefill fuelling, prefill gas pressure, and loop electric field to the reference at $t = 0.45\ s$, the breakdown for #100401 is clearly un-sustained. IC assisted initiation #100404 was then attempted and was successful straight away. Figure 10 shows plasma parameters for the successful IC assisted breakdown discharge (#100404, red) against that of the previously successful Ohmic pulse (#98343, blue). The Ohmic reference has line radiation from Ne lines which are essentially at or below the background noise. #100404 has much higher neon levels, but these do not prevent plasma initiation. The high neon content comes from the previous session which actively injected neon for experimental purposes. The failure of the Ohmic only breakdown and the success of the IC assisted breakdown for the same high Ne level vessel conditions shows that IC assisted breakdowns can tolerate higher impurity levels than Ohmic only ones in JET with the ITER-like wall.

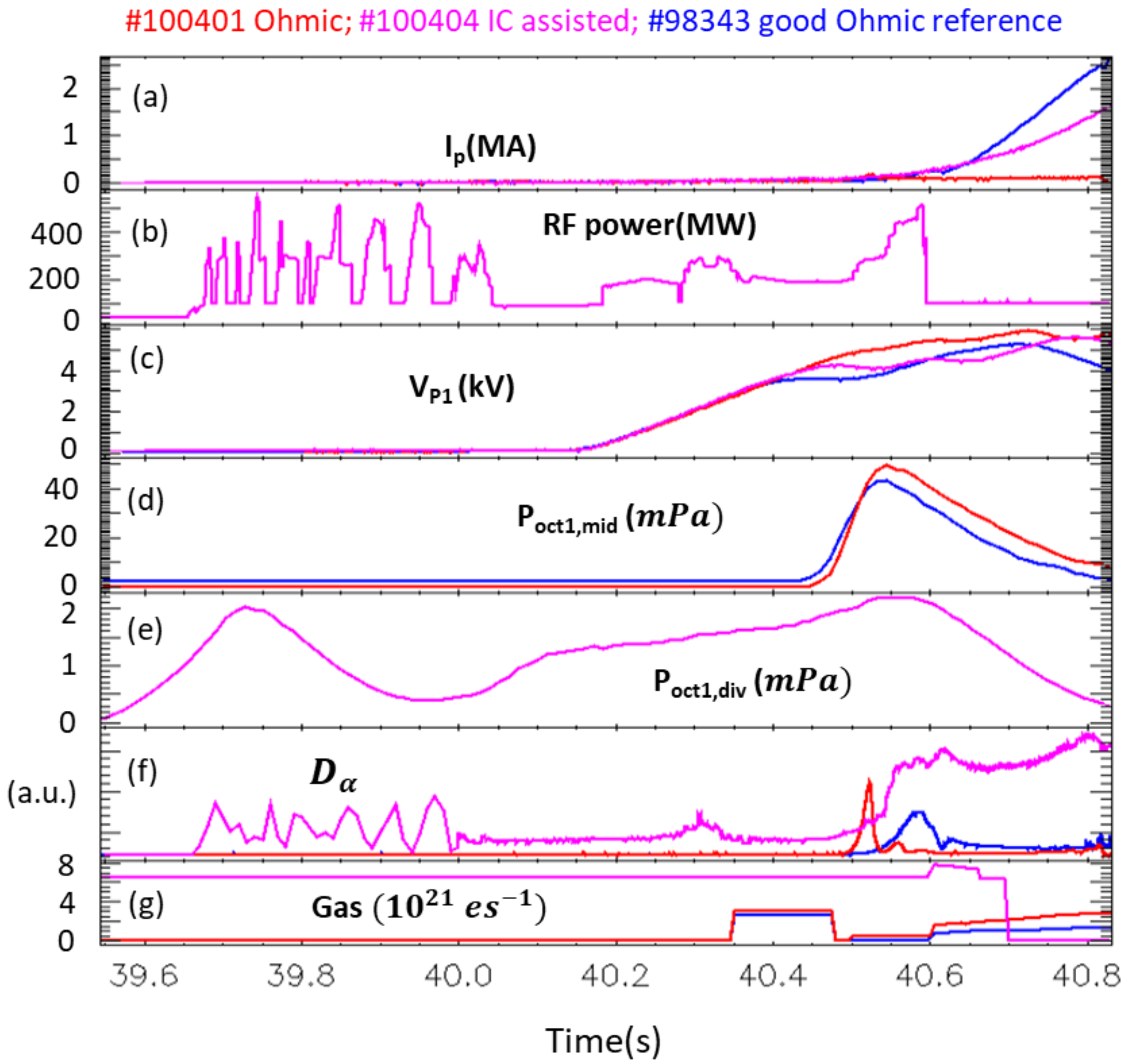

Figure 9. Time trace of plasma parameters for an unsuccessful Ohmic breakdown (red, #100401), the immediately following successful IC assisted breakdown (magenta, #100404) both are D_2 fuelled with high intrinsic impurity levels. The reference successful Ohmic breakdown (blue, #98343) is also shown. (a) Plasma current; (b) coupled RF power; (c) P1 coil voltage; (d) in-vessel gas pressure in octant 1; (e) in-vessel gas pressure in octant 1; (f) D-α emission; and (g) injected gas.

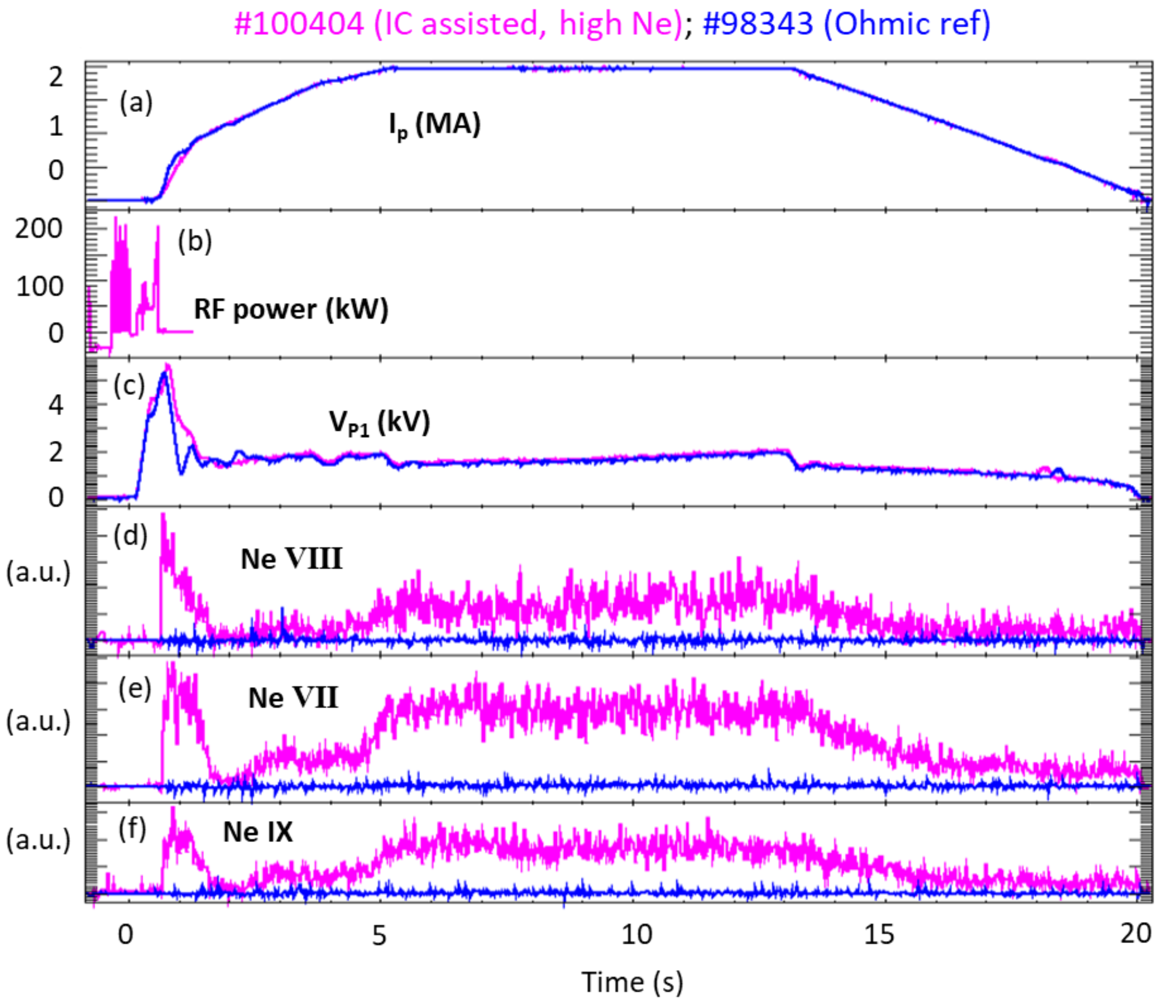

Figure 10. Time trace of plasma parameters for the D_2 fuelled, IC breakdown discharge with high levels of Ne impurity of figure 10 (magenta, #100404)) and the D_2 fuelled, Ohmic only breakdown reference discharge with low levels of Ne impurity of figure 10 (blue, #98343). (a) Plasma current; (b) coupled RF power; (c) P1 coil voltage; (d) Ne VII line emission intensity; (e) Ne VIII line emission intensity; and (f) Ne IX line emission intensity.

4 Breakdown and burn through evolution

4.1 The parametric dependency of the plasma current rise rate

The plasma current rise rate after breakdown is defined, for these studies, as the average of dI_p/dt over the period between $I_p = 100\ kA$ and $I_p = 200\ kA$. This is always before I_p is in feedback control and is freely evolving. For both IC assisted and Ohmic breakdown, the plasma current rise rate after breakdown inversely correlates with the electron density at breakdown and positively correlates with E_{loop}. This can be seen in figure 11 where breakdown n_e/E_{loop} is well, inversely correlated with the I_p rise rate. Higher E_{loop} drives faster I_p rise rate. Higher

n_e is associated with lower T_e for the same plasma energy, which results in higher resistance and so lower I_p rise rate. For Ohmic breakdown, I_p rises much faster, at similar pressure, than for IC assisted breakdowns. Comparing the breakdowns with the cryo-pump cooled by liquid N_2 and liquid He, there is no evidence of the divertor condition affecting the I_p rise rate.

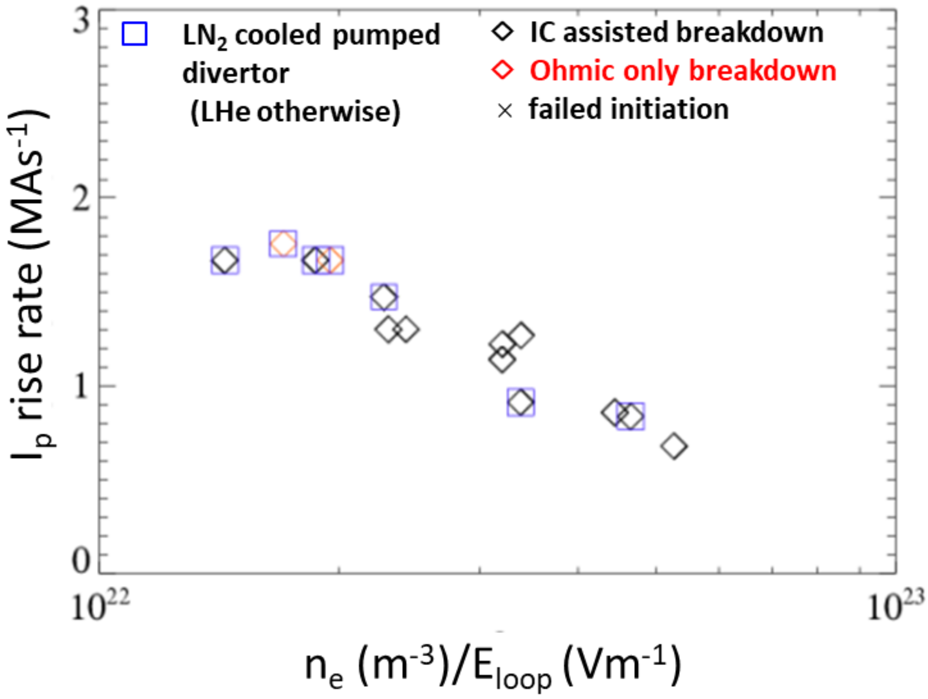

Figure 11. Plasma current rise rate, averaged over the period between $I_p = 100\,kA$ and $I_p = 200\,kA$, versus vessel pressure normalised to the toroidal electric field for a series of Ohmic (red diamonds) and IC assisted (black diamonds) JET breakdowns with $B_t = 1.7\,T$ and D_2 fuelling. Discharges with liquid N_2 cooled pumped divertor (pump speed $\approx 5\,m^3s^{-1}$) marked by blue open squares; other discharges have liquid He cooled pumped divertor (pump speed $\approx 150\,m^3s^{-1}$). Failed plasma initiations are marked with an "X".

Although Ohmic breakdown happens at higher vessel pressure, n_e is lower compared with IC assisted breakdown, as the examples (#100624 vs #100636) shown in figure 2. I_p rises faster for higher B_t for the same breakdown prefill gas pressure, figure 12(a). This is consistent with the observation that IC assisted breakdown pulses have higher electron density than Ohmic breakdowns at similar prefill gas pressures, section 3.4. There is no notable isotope effect. There is a strong, negative correlation between the I_p rise rate and n_e/E_{loop} across the whole dataset, figure 12(b).

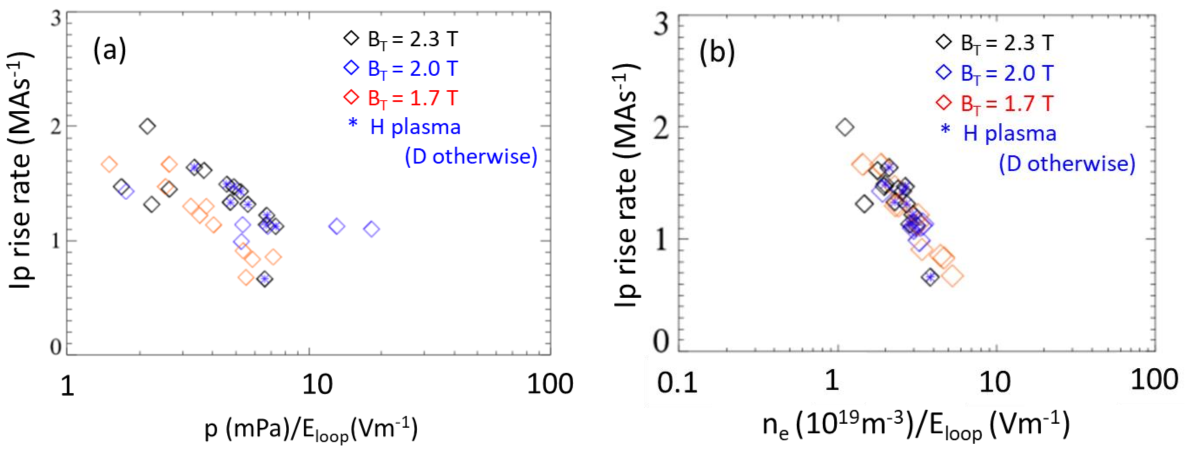

Figure 12. Plasma current rise rate, averaged over the period between $I_p = 100\ kA$ and $I_p = 200\ kA$, versus (a) vessel pressure normalised to toroidal electric field; and (b) electron density normalised to toroidal electric field for IC assisted JET breakdowns with $B_t = 1.7\ T$ (black diamonds), $B_t = 2.0\ T$ (blue diamonds), and $B_t = 2.3\ T$ (red diamonds). H_2 fuelled discharges are marked with a blue "" symbol; discharges are D_2 fuelled otherwise.*

4.2 The impact of IC assisted breakdown on plasma impurities

IC heating on JET has been observed to be associated with impurity production [23] [24] [25] [26] [27] [28]. For IC assisted breakdown pulses, no sign of increased impurities level in current ramp-up or later phases. Figurer 13 shows an example IC assisted breakdown discharge and its Ohmic only breakdown reference. Plasma initiation for both discharges is successful. Line radiation from low Z and high Z impurities and the Z-effective for the two discharges is similar throughout plasma burn through and later flat-top phase. There is no evidence of increased Be or Ni impurities from the Ni components of the IC antennas or the Be limiters around them.

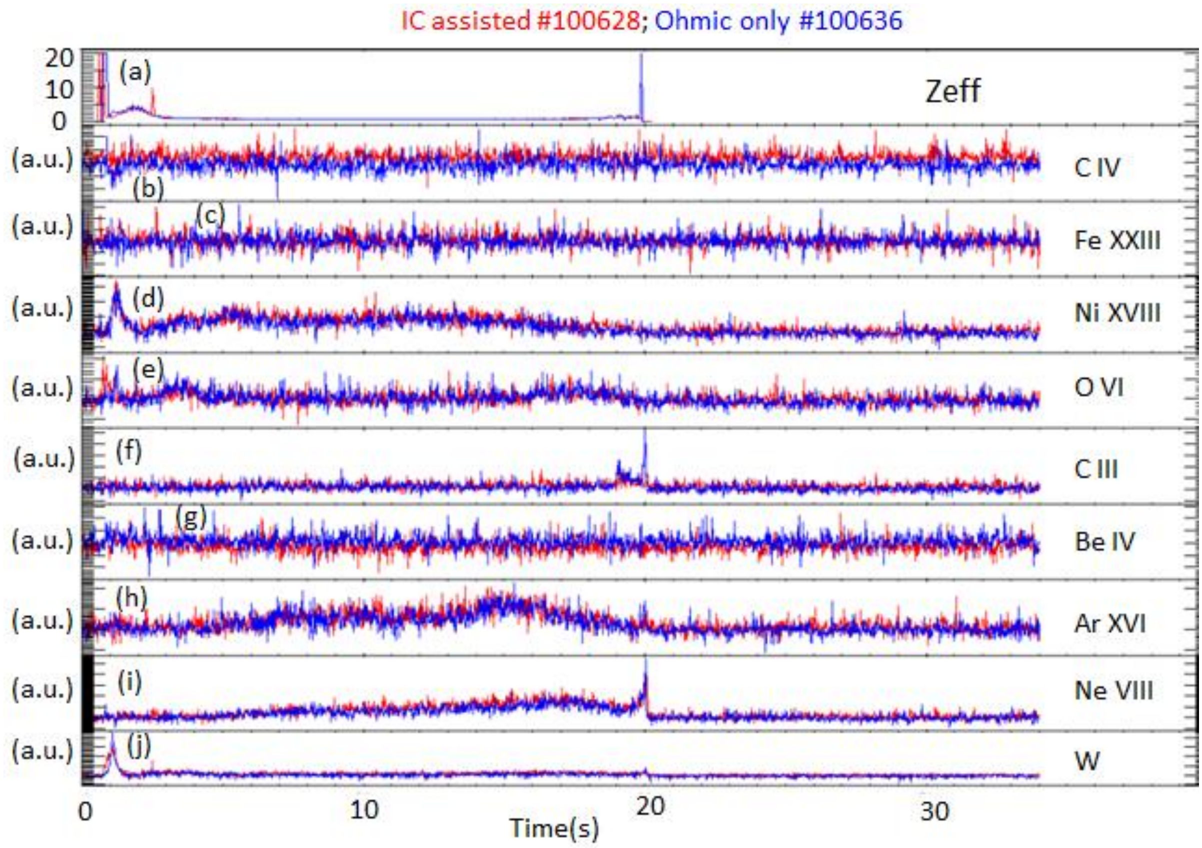

Figure 13. Time trace of various impurities for a successful IC assisted breakdown (red, #100628) and a successful Ohmic breakdown (blue, #100636). (a) Line average Z-effective and the line emission intensity of (b) carbon IV (c) iron XXIII, (d) nickel XVIII, (e) oxygen VI, (f) carbon III, (g) beryllium IV, (h) argon XVI, (i) neon VIII, and (j) tungsten.

5 Summary and implication of the results

For the first time on JET, a series of Ion Cyclotron wave (IC) assisted breakdown experiments have been performed to provide a physics basis for validating models for testing and optimising plasma initiation with IC assisted breakdown for ITER. RF operation and protection, fuelling time and location, and the range of breakdown pressure and E_{loop} were studied.

For the first time, both IC assisted and Ohmic breakdown were achieved in D for the regime planned for the first pre-fusion operation (PFPO-1) phase of ITER, $E_{loop} \lesssim 0.33\ V/m$ with $B_t = 1.7\ T$ and where EC breakdown assistance with $170\ GHz$ waves would not work. All discharges, IC assisted or otherwise, achieved breakdown; successful plasma initiation was determined by the success of the subsequent plasma burn through phase.

In the studies, plasma initiation with IC assisted breakdown was significantly more robust than Ohmic breakdowns with the same E_{loop} and B_t. For the IC assisted breakdowns at the lowest fields explored, $B_t = 1.7\ T$ and $E_{loop} \lesssim 0.33\ Vm^{-1}$, breakdown is achieved at lower pressures for a wider range and with significantly higher amounts of injected gas for a wider range than Ohmic only references. Plasma initiation with IC assisted breakdowns was also achieved with higher impurity content than for Ohmic breakdown references. To get the same prefill gas pressure, IC breakdowns required considerably higher injected prefill gas than Ohmic breakdowns showing that the IC acts as a pump. Thus, IC assisted breakdown enables plasma initiation with a higher level and wider range of injected plasma prefill gas. As the injected prefill gas is the controlled parameter, this significantly improves the robustness of plasma initiation operationally.

Divertor fuelling on JET provides a more symmetric torus pressure than the more common mid-plane fuelling, enabling easier control and analysis of breakdowns. It is recommended that divertor fuelling is used for future breakdown studies and that the toroidal asymmetry is considered when validating breakdown models on mid-plane fuelled discharges. No obvious influence of cryo-pump condition on breakdown pressure range was observed.

Turning to the evolution of the breakdown and plasma burn through, the I_p rise rate is well (negatively) correlated with the n_e/E_{loop} across the full dataset which includes Ohmic and IC assisted breakdowns and a wide range of B_t, bulk isotope species, and pumped divertor temperatures. There is no evidence of increased impurity level for IC assisted breakdown in the current ramp-up and later phases.

As successful burn through determines the success of plasma initiation, combining IC pre-ionisation with IC assisted burn through and ramp-up phases may further extend the operational range. Such a recipe on JET requires the use of different antennas one or more tuned for the pre-ionisation plasma and one or more for the later phases. This is intended to be the subject of future experiments.

Ohmic plasma initiation on JET-ILW has previously been shown to be consistent with the DYON plasma burn through simulator based on a parametrised confinement time and impurity fluxes based on a wall-sputtering model [29] [30]. The data from all the studies presented here will be provided as a basis for model validation for plasma initiation on ITER and other devices. However, the demonstration in the ITER relevant regime that IC assistance extends the access to breakdown without any evidence for enhanced impurities already gives significant confidence that its use on ITER will also be important for assisting breakdown in the pre-fusion operation phase.

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