Inter-ELM pedestal current density evolution in ASDEX Upgrade

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Edge Localised Modes (ELMs) are of great interest in both experimental and theoretical studies. The current favoured operating scenario for ITER is the Type-I ELMy H-mode. This gives the largest and most sustainable power output. However, the large number of particles expelled from the plasma during ELMs could cause problems for the longevity of the divertor[1, 2]. Studies of the predicted ELM energies in ITER show that such large outbursts are intolerable, given current material designs. This has generated a large interest in understanding ELMs, as well as in their control.

The currently most favoured explanation for the triggering of ELMs is magnetohydrodynamic (MHD) activity in the form of peeling-ballooning modes[3]. It is thought that the edge pressure gradient builds up to a peak value, along with the edge current density. When the stability boundary is breached up to 10% of the total plasma is released over a very short timescale.

At ASDEX Upgrade, the edge pressure gradient has previously been analysed[4, 5]. However, the current density is more challenging. Techniques such as Motional Stark Effect in the edge, used at MAST(MSE)[6], or Zeeman splitting of the edge Lithium beam[7] in D-IIID can be used. These are not presently available at ASDEX Upgrade, and are challenging measurements due to very small effects of a large current peak on a flat poloidal field profile. Another option for obtaining the edge current density comes from the Grad-Shafranov equation, of which the exact local current density is a direct output, given by

$$-\Delta^*\psi = \mu_0 R^2 \frac{dp}{d\psi} + f\frac{df}{d\psi} = \mu_0 R j_\phi \qquad (1)$$

Using the CLISTE code[8] as an equilibrium solver, the edge current density has been reconstructed for a full representative ELM cycle. One of the specific advantages of the CLISTE code is its ability to model current density in the scrape off layer.

In order to prepare an accurate equilibrium, several diagnostic constraints are required. The only necessary input set is the magnetic measurements. This consists of 38 poloidal magnetic field coils and 18 poloidal flux measurements. To increase the quality of the data, all signals were synchronised to an ELM. Events occurring faster than 100 Hz were excluded to ensure greater homogeneity of the data set. An example of this procedure, applied to discharge #23225 at 3.0-3.8 s can be seen in figure 1(a). The peak divertor current, shown in figure 2, was taken as the onset of the ELM.

It has been shown by McCarthy[9] that the magnetic measurements alone are sufficient to determine the edge current density. Following from this, it is expected that the magnetic

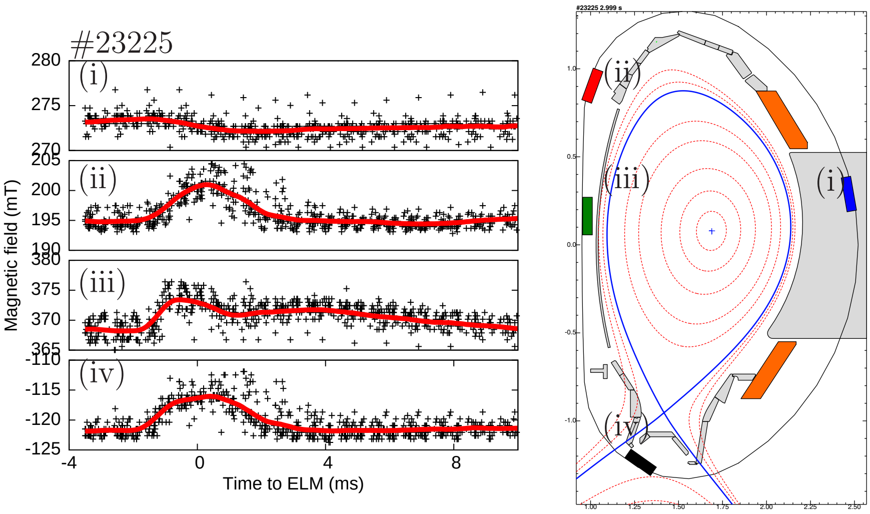

Figure 1: (i)-(iv) show the recorded magnetic signals at various points around the torus, as indicated in (b), which shows the equilibrium at -3 ms to an ELM.

signals in the vicinity of the x point would show the greatest reaction to an ELM crash. Comparing the measurements at different coil locations around the torus, as shown in figure 1(b), this is indeed the case. The coils close to the upper and lower divertors show the greatest relative reaction, as expected. This is due to the larger concentration of current at the outer flux surfaces towards the x-point and the upper portion of the elongated plasma.

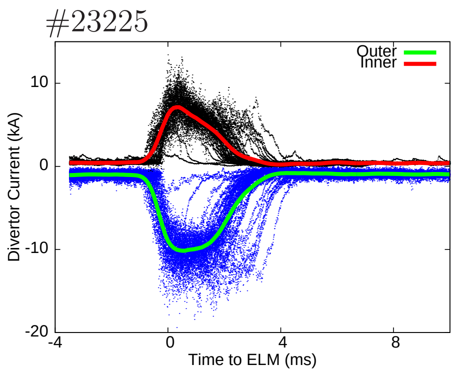

Figure 2: ELM averaged divertor currents. The currents are measured as flowing into a divertor tile.

However, since the magnetic measurements are insufficient to recover moments of the pressure profile, pressure data, in the form of fitted profiles, is required for an accurate reconstruction. Fortunately, ASDEX Upgrade is well diagnosed with edge electron temperature and density diagnostics. Electron temperature used in this work is measured using Electron Cyclotron Emission (ECE) and density with a combination of Lithium beam and Deuterium-Cyanide-Nitrogen (DCN) interferometry. Pressure due to fast particles has been assumed to be negligible in the edge and as such was not included.

Integrated Data Analysis (IDA)[10] is a Bayesian approach to data analysis. It combines complementary diagnostics, such as the Lithium beam and DCN interferometer in the case of density, to obtain more accurate profiles. These fits are then ELM synchronised in the same fashion as the magnetic measurements. The final diagnostic input is the divertor currents, shown in figure 2, determined from a tile shunt resistance. This acts as a constraint on the poloidal scrape off layer (SOL) current, and hence the ff' source profile of the Grad-Shafranov equation.

Due to the relatively slow time resolution of the charge exchange diagnostics at the time of the discharges analysed in this study, ion temperatures have not been included in the analysis. They have been assumed to be equal to the electron temperature. This has been shown to be a reasonable approximation in the pedestal at high collisionality by Wolfrum et al.[5]. The ion density is less well known and relies on an effective charge relation to the electron density.

Sample ELM synchronised pressure and current density profiles output from CLISTE are shown for discharge #23225 at -1.5 ms to an ELM in figure 3 with input constraints, where appropriate. Data was taken between 3 and 3.8 s during the discharge. This has a -2.5 T toroidal magnetic field, 1 MA plasma current, 7.5 MW of neutral beam injection heating, 0.7 MW of electron cyclotron resonance heating and a $9 \times 10^{21} s^{-1}$ deuterium gas fuelling. The kinetic constraints act in this case to strongly localise the edge current density peak. While the integral current densities agree quite well between the red and blue curves up to the point of maximum pressure gradient, the pressure is required for more precise information. This information, combined with an accurate pressure gradient profile, is important for stability analysis. It is important to note at this point that, although the current density can be constrained by calculating the bootstrap current, $\langle j_{neo} \cdot B \rangle$, with the formula given by Sauter et al.[11, 12] and a neoclassical resistivity profile for the Ohmic current, this was not done in this case.

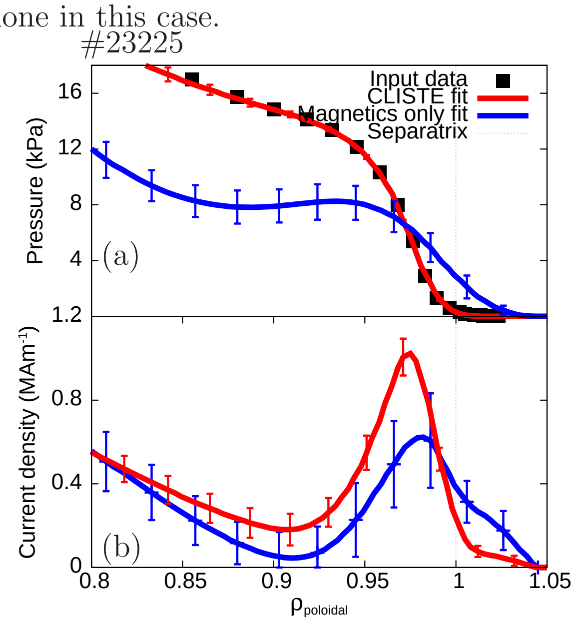

Figure 3: (a) Pressure profile. (b) current density profile. The blue line denotes a fit made only with magnetics constraints, while the red line is the fit using a prescribed pressure profile. Black boxes represent input data points. Error bars are 1 sigma confidence bands.

Since there are only three dominant contributions to the edge current density, Ohmic current, bootstrap current and Pfirsch-Schlüter currents, a comparison of the CLISTE output can be made with theoretical predictions. Current drive due to fast ions was assumed to be negligible in the pedestal region. By default, the output from the Sauter et al. formula is of the form of a flux surface averaged $j \cdot B$. This is also a standard output of the CLISTE code. Since the Pfirsch-Schlüter currents cancel out on a flux surface, we require only the calculated $\langle j_{neo} \cdot B \rangle$ and the Ohmic current for this comparison.

In order to calculate the Ohmic current contribution, the plasma toroidal electric field was calculated using the method described in Burckhart et al.[4]. This was combined with a calculated neoclassical resistivity profile to give $\langle j_{Ohmic} \cdot B \rangle$ at the same position as the maximum $\langle j_{neo} \cdot B \rangle$. Figure 4(a) shows the calculated electric field. The initial value corresponds well with the steady state loop voltage measured outside the plasma. This diverges during the recovery phase of the

ELM cycle, with a negative electric field being modelled.

Figure 4(b) shows the edge peaks of the CLISTE output (red) and the calculated profile (black). The error bars on the CLISTE fit correspond to a 1 sigma value of the confidence band. There is excellent agreement between the two curves, especially in the pre-ELM phase. Further improvements to the Ohmic model can be made by using the actual plasma geometry rather than a cylindrical approximation, by combining it with ASTRA calculations to determine the current drive due to external sources, and by making a neoclassical correction to the resistivity.

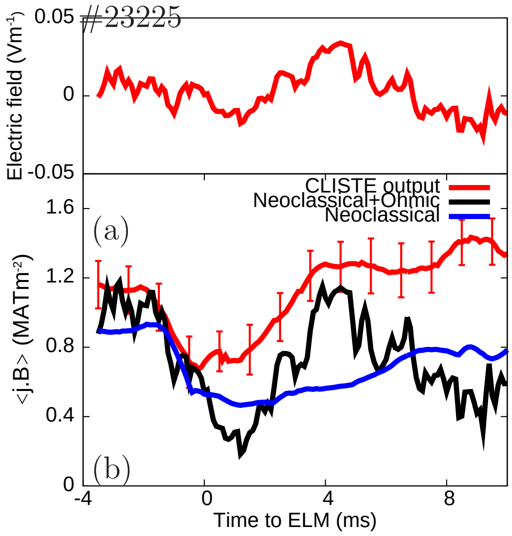

Figure 4: (a) shows the electric field calculated at the peak bootstrap position using a resistive current propagation model. (b) shows the flux surface averaged current density from CLISTE (red), $\langle j_{neo} \cdot B \rangle$ (blue) and $\langle j_{neo} \cdot B \rangle + \langle j_{Ohmic} \cdot B \rangle$ (black).

The neoclassical formula for bootstrap current from Sauter et al. has been validated by comparing to CLISTE output, which was constrained with magnetic signals and input kinetic profiles. This allows the separate temperature and density gradient contributions to the current density to the analysed, which is quite valuable in the search for an ELM trigger. Further work will focus more specifically on the growth of the ion temperature gradient contribution to both the pressure gradient and bootstrap current. The movement of the strikepoints, which has been observed to vary by 10-20 mm over an ELM cycle with CLISTE, will also be analysed in more detail. Individual ELMs, rather than ELM-synchronised data, will also be analysed in order to evaluate differences between slow and fast ELM cycles.

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