# ELM-resolved interpretive MHD equilibria on ASDEX Upgrade using SOL tile currents and kinetic data

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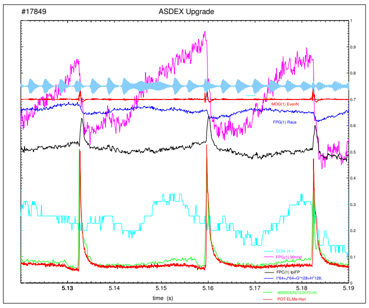
## Introduction

The determination of the edge current density profile in tokamaks is challenging for diagnostics such as the Motional Stark Effect which typically measures the poloidal magnetic field in the vicinity of the midplane and hence delivers only integral information on $j(R, \psi)$. Recently, it has been recognized that for X-point plasma configurations, an interpretive equilibrium code using standard equilibrium magnetic measurements can identify the toroidal current flowing in the vicinity of an X-point due to the topological properties of the flux surfaces close to the X-point [1]. The availability of edge kinetic profiles provides some constraints on the $j_{edge}$ profile shape [2]. Here we extend this work to include measurements of poloidal currents flowing in the scrape-off layer (SOL) of divertor plasmas on the ASDEX Upgrade tokamak [3]. Due to flux expansion near the X-point these currents, which flow along open field lines and through divertor tiles, yield sub-centimeter radial resolution in the magnetic midplane. They are measured as they pass through shunt resistances connecting the divertor tiles to the vacuum vessel. If such data are available on a sufficiently fast time scale, their inclusion in an equilibrium code has the potential to provide important information on current flow during an ELM crash. The CLISTE equilibrium code [4] has been extended to interpret individual tile currents under the assumption of axisymmetry and force balance in the SOL. The poloidal current through each tile is easily modelled in the code by noting the change in the equilibrium quantity $F(\psi) = RB_\phi$ between the poloidal extremities of each tile and adding the measured currents to the set of diagnostic data that constrains the equilibrium fit. At each iteration the current density on gridpoints lying in the shadow of material structures is zeroed. Thus the current on open fieldlines is abruptly terminated at the point of intersection with material structres. In-out asymmetries due to SOL current flowing between lower and upper divertor plates instead of completing a poloidal circuit from low field to high field side are taken into account. Any influence on force balance in the SOL caused by the flow of these currents through material structures is neglected.

## Data Selection

The requirement for sub-millisecond time resolution, needed to resolve ELM timescales, places significant restrictions on data availability. On ASDEX Upgrade, tile currents are measured up to a frequency of 35 kHz. Most of these are intended to monitor current flow during a disruption and their bit resolution is too low for our purposes. A number of slower but more sensitive 5kHz signals covering the innner and outer lower divertor plates are, however, available. Although equilibrium magnetic measurements are normally acquired at a rate of 1 kHz, data is routinely acquired at a higher 10kHz rate between 4.2 and 5.2 seconds into the discharge. The edge Thomson scattering diagnostic provides 120 profiles per second and hence falls short of the required time resolution. However, by mapping all profiles onto a time relative to the nearest ELM, reasonable coverage of the mean ELM cycle over a long, stable ELM phase can be obtained.




*Diagnostic signals for # 17849*

Fig. 1 shows timetraces of diagnostic signals across three Type 1 ELMSs for ASDEX Upgrade discharge # 17849 ($I_p$ = 1.15$MA$, B= -2T, $n_e$ = 8E19m$^{-3}$,P$_{heat}$= 5MW) for $5.12 \leq t \leq 5.19$ s. The plasma current (black trace), midplane line averaged density (cyan) and plasma energy (magenta) are scaled so that full scale corresponds to 10% variation of these signals. The behaviour of the total SOL poloidal current (green) leaving the low field side or the lower divertor closely follows that of the outboard H-alpha signal (red). The discharge parameters remained stable in the window $5.0 \leq t \leq 6$. CLISTE equilibria were generated at each Thomson timepoint in this window and the Thomson channel locations were mapped onto $\rho_{poloidal}$. A 5-parameter Tanh function of $\rho_{pol}$, whose coefficents were fitted to linear and quadratic ELM-relative time dependences, (determined from the outboard $H\alpha$ signal) was then fitted to the $Te$ and $Ne$ data, the latter calibrated to agree with the steady state density profile obtained from lithium beam and interferometer data. For these data there were no significant quadratic dependences and only the pedestal height and location relative to the separatrix had significant linear dependences. Fig. 2 shows the Electron

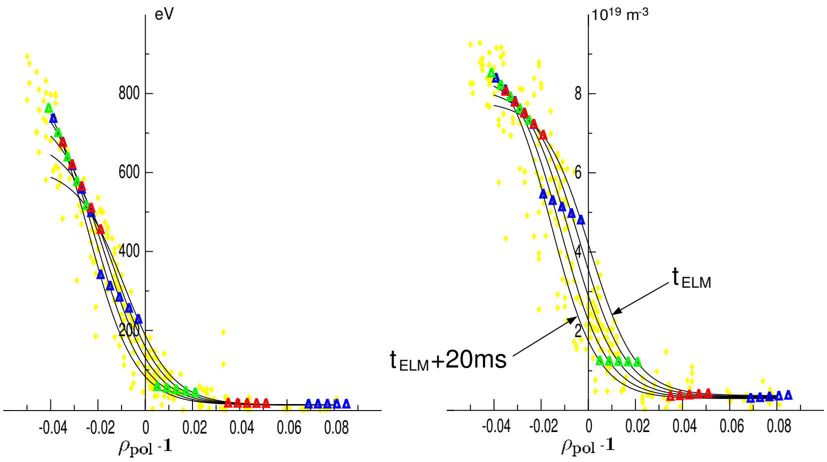
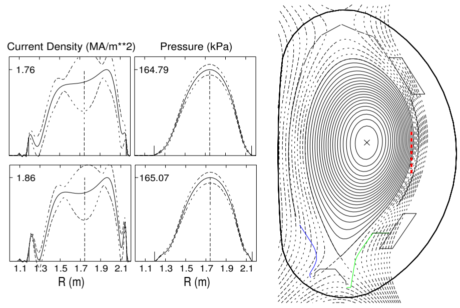



*Figure 1: $t_{ELM}$-relative pedestal evolution fit*

temperature and calibrated density data (yellow) from the edge Thomson scattering diagnostic mapped onto $\rho_{pol} - 1$. The set of curves is the fitted profile at t= 0, 5, 10, 15, 20ms after a Type 1 ELM crash. The large triangles indicate the evolution in magnitude and position relative to the separatrix of each of the seven channels used in the fit. The curves are evaluated for $R_{\rm Laser} = 2.138$ m.

## Results

CLISTE interpretive equilibria with a 0.1ms timestep were generated for a time window covering the second and third ELMs in fig.1 using (i) equlibrium magnetics+SOL tile currents and (ii) the fitted time-dependent pedestal function shown in fig. 2.




*CLISTE equilibrium 18 ms after ELM*

Fig. 3 shows an equilibrium at $t = 5.18\,\mathrm{s}$, 18 ms after the ELM crash at $t = 5.1824\,\mathrm{s}$. The upper pair of interpreted profiles were obtained from magnetic measurements and 8 tile currents, 4 of which measure the poloidal SOL current flowing through contiguous sections of the lower inboard divertor plate (blue). The remaining 4 see SOL currents through the outer divertor plate (green). The lower profile pair were obtained from CLISTE fits with additional constraints on the edge pressure using the pedestal function in fig. 2 which was fitted to the Thomson data whose positions are shown as red boxes. The detailed time evolution of the midplane current density profile over a 7ms interval around the middle ELM crash is shown in Fig. 4. The left-hand plot was obtained from CLISTE with magnetic measurements and SOL currents. The right-hand plot was obtained with the additional constraints from the Thomson data. In both plots there is an abrupt fall of ≈40% in the height of the bootstrap-driven edge current peak and a simultaneous jump in the SOL toroidal current. The distribution of plasma/SOL

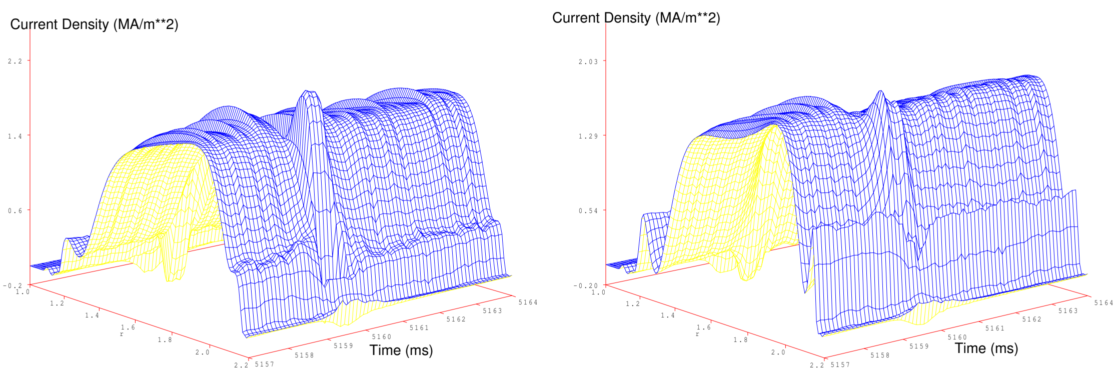



*Figure 2: Time evolution of midplane $j(R)$ profile for # 17849,* $5157 \leq t \leq 5164\,ms$.

current is shown in the left-hand plot in fig. 5 which gives the temporal evolution of the total toroidal current (offset by 1.15 MA), and toroidal and poloidal SOL currents for the two ELMs at 5.1596s and 5.1824s. The blue traces are experimental data, red traces are CLISTE interpretations using magnetics + SOL currents. Green traces are intepretations additionally constrained by the edge Thomson data. Though the between-ELM steady-state interpreted toroidal SOL currents differ in the two cases,

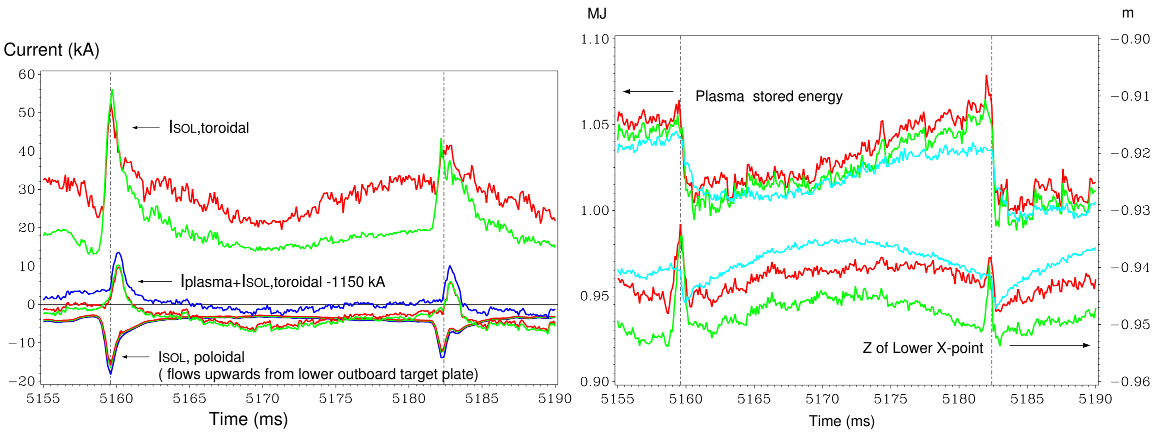



*Figure 3: Time evolution of plasma and SOL currents (left) and plasma energy and Xpoint location (right) for # 17849,* $5157 \leq t \leq 5164\,ms$.

the maximum value at the ELM crashes are consistent. These substantial currents (here in the range 40-56kA) cannot be explained by a rise in the robustly determined total (plasma+SOL) toroidal current rise of $\leq$ 10kA which could be due to currents transiently generated in the SOL itseelf. The present results suggest that a very rapid ($< 1\,$ms) and substantial flow of toroidal current from the plasma into the SOL takes place durung an ELM crash. This hypothesis is consistent with the behaviour of the vertical position of the lower X-point which jumps upwards by 10-15mm as shown on the right-hand plot (lower triplet of traces)in fig. 5 which also shows the time dependence of the plasma stored energy (upper triplet). The cyan traces show the evolution of these parameters as determined by the Function Parameterization algorithm used to determine plasma parameters in realtime for the feedback control system. Unlike the CLISTE results, the Xpoint position drops at the ELM crash (by 5mm) according to FP. This is very likely due to the fact that there are no SOL currents in the database of predictive equilibria used in the offline training of the FP coefficients so that FP sees a 10kA increase in $Ip$ whereas CLISTE sees a 15-25kA decrease.

## Conclusions

Substantial (50kA) toroidal SOL currents have been identified on ASDEX Upgrade following Type 1 ELM crashes from interpretive equilibria using measured tile currents and edge kinetic data. The results suggest that these currents are prediminantly due to a redistribution of current on a $< 1\,$ms timescale from the main plasma to the SOL and cannot be explained by currents generated in the SOL.

## References:

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4. P.J. Mc Carthy et al., IPP Report 5/85, 1999.