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Time-dependent ELM-resolved equilibrium reconstruction on ASDEX Upgrade.

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Introduction and Motivation

Type I edge-localized modes (ELMs) on ASDEX Upgrade are accompanied by negative voltage spikes of magnitude $\simeq 10\,\mathrm{V}$ measured near the lower divertor, current spikes $\simeq 10\,\mathrm{kA}$ in measured poloidal SOL currents corresponding to several tens of kA of SOL current flowing toroidally, and a $\simeq 10\,\mathrm{kA}$ transient increase in the typically 1 MA plasma current (including the SOL toroidal current) [1]. Inboard and outboard poloidal SOL currents, which are measured at a number of toroidal locations, are reasonably axisymmetric (see fig. 1) and hence ELM-resolved equilibrium reconstruction using an axisymmetric equilibrium code incorporating the SOL poloidal current measurements becomes feasible, despite the known 3D character of ELMs [2]. The task of generating loop voltage profiles from numerical differentiation of a sequence of static equilibrium reconstructions is a challenging one, since there is a trade-off between noisiness and time resolution of such reconstructed loop voltages. Nevertheless, the validity of results such as those presented in [1], in particular the modelling of strong, transient SOL currents during and immediately following a Type I ELM crash, can be questioned as long as the voltage spikes, examples of which are included in fig. 2 cannot be reconstructed. Accordingly, the present work is motivated by the advantages that would result from a method of solving the time-dependent Grad-Shafranov equation (GSE) in the form

$$-\frac{\partial}{\partial t}\Delta^*\psi(R,Z,t) = \mu_0 R^2 \frac{\partial}{\partial t}p'(\psi) + \frac{\partial}{\partial t}ff'(\psi) \qquad (1)$$

that avoids (a) the above-stated problem of noise or poor time resolution for loop voltage profiles calculated from a sequence of independent static equilibria or (b) having to resort to predictive current diffusion calculations [3].

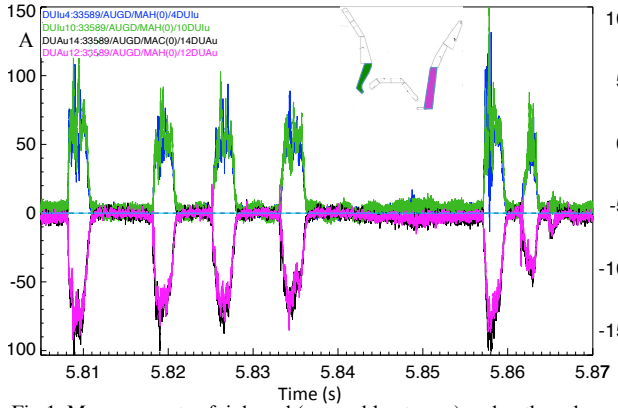


Fig 1. Measurements of inboard (green, blue traces) and outboard (magenta, black) divertor tile currents at 4 separate toroidal locations spanning six Type I ELMs for ASDEX Upgrade discharge #33589.

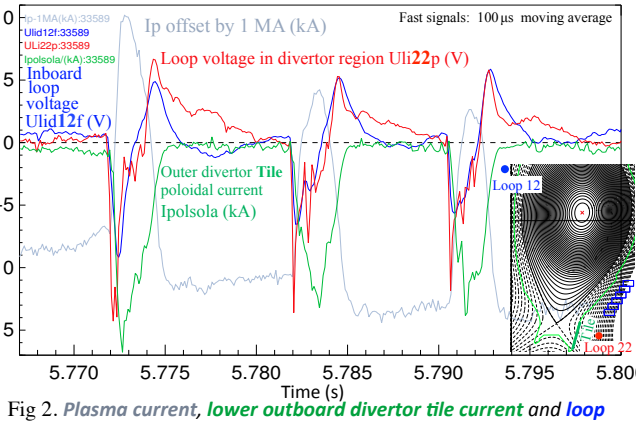


Fig 2. *Plasma current, lower outboard divertor tile current and loop voltages* at displayed locations for a 30 msec time window containing 3 Type I ELMs for ASDEX Upgrade standard H-mode discharge #33589.

Equilibrium reconstruction with multiple timepoints

A "multipoint mode" has recently been developed within the CLISTE equilibrium code [4] based on a single solution of the GSE to a narrow window of timepoints. The method, which simultaneously determines ψ(R,Z) and $\partial\psi/\partial t$(R,Z), parameterizes the source terms in the Grad Shafranov equation by free parameters that fit both static amplitudes and time derivatives to a set of spline basis functions, and takes account of the dynamics of active coil currents and eddy currents. So far, the time-dependent terms are constrained by multi-timepoint magnetic data (10 kHz acquisition rate) and SOL tile current data (200 kHz acquisition rate) in an interval $<$ 1 msec centred on the selected

static equilibrium timepoint. The method is implemented in CLISTE, which extends force balance into the open fieldline region and can achieve high fidelity reconstructions of edge pressure data in both pedestal and SOL regions [5]. Though CLISTE contains an explicit model for vacuum vessel currents, the routine method for taking account of passive currents in equilibrium reconstructions, particularly those driven by rapid changes in the fast control coils which lie inside the toroidal field coils on ASDEX Upgrade, is to allow deviations from the measured values of poloidal field (PF) coil currents, with the exception of the central solenoid OH current. This method, whose justification relies on the vacuum vessel acting to delay the penetration through the vessel wall of changes in PF currents on timescales shorter than the resistive time $\tau_R \approx 5\,\mathrm{msec}$, succeeds in fitting magnetic data in the presence of significant eddy currents with a quality similar to that of more quiescent phases of the discharge. The favourable results that will be presented here support this approach.

In what follows, sample results for an ASDEX Upgrade discharge with Type I ELMs (#33589) are presented, and the new method will be seen to agree quantitatively with experiment once a necessary pre-reconstruction data processing step is taken. It should be noted that the measured loop voltage at the location of 'loop 22' (see fig. 2) played no part in the reconstructions.

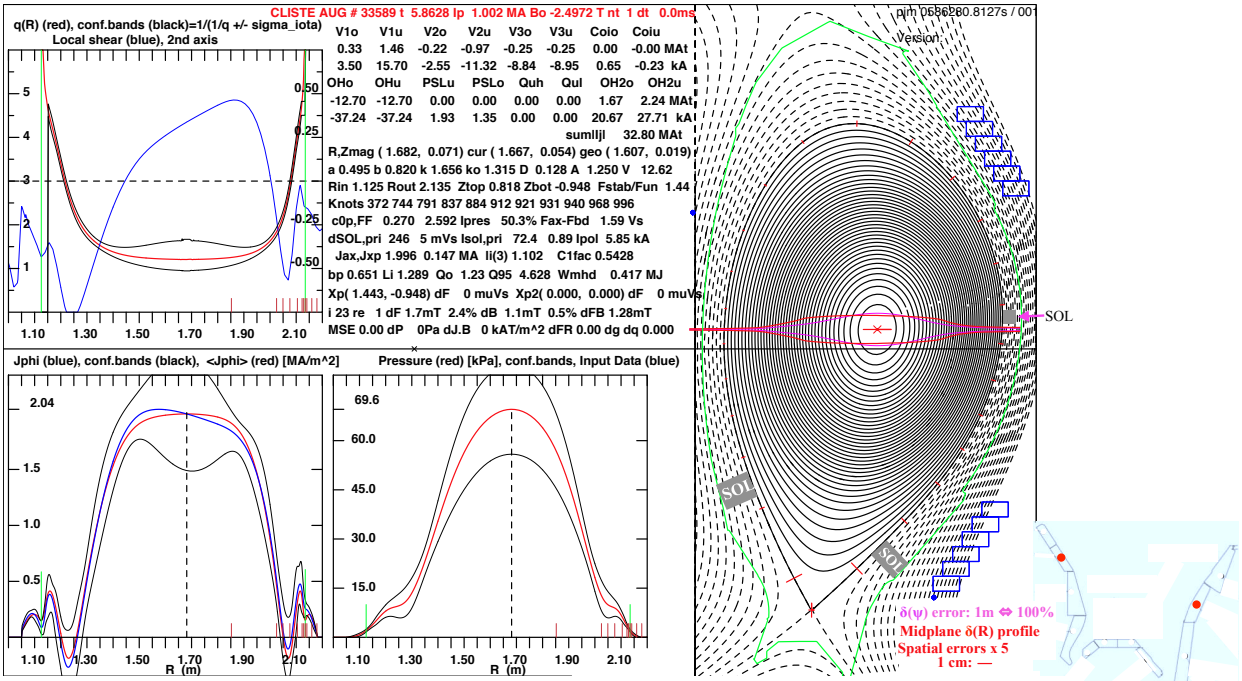


Fig 3 CLISTE equilibrium reconstruction during an ELM crash. PF currents (except for OH current) are allowed to deviate from measured values to mimic vessel currents. RMS fit error for 59 magnetic signals: **1.28 mT ⇔ 1.4%** of RMS magnitude. Toroidal **SOL current**: 72 kA = **7.2% of Ip**. A wide SOL width (shown) is necessary to successfully model large SOL currents during ELM crashes when remote divertor tiles (see red dots in graphic to the right of main plot) carry currents which, while smaller than those flowing in the tiles highlighted in the inset in fig. 1, are nevertheless significant.

Examples of CLISTE equilibrium reconstructions during ELM crashes

Before proceeding to the application of the new method, we present some examples of CLISTE reconstructions during an ELM crash and compare pre-ELM and within-ELM cases. Fig. 3 shows a typical equilibrium reconstruction during an ELM crash, approximately 1 msec after ELM onset. A noteworthy feature is the wide current-carrying SOL magnetic depth (depicted in fig. 3) which extends to $\rho_{pol} = 1.075$ and is required because in addition to the tiles shown in the inset to fig. 1 which carry the largest SOL currents, more remote tiles such as those highlighted by red dots in the graphic to the right of fig. 3 also carry significant current during an ELM crash. The root mean squared fit error to the 59 magnetic signals (17 flux differences and 42 magnetic pick-up coils) was 1.42 mT (where each flux difference was converted to an average $\langle B_{\theta,\perp} \rangle = \Delta\psi/A$, with A being the area between the two participating loops) corresponding to 1.4% of the rms signal magnitude. This is similar to the magnetic signals fit error for inter-ELM timepoints. The measured poloidal

SOL current of 5.85 kA, which is accurately matched by the reconstructed value, corresponds for this case to a toroidal SOL current of 72 kA, or 7.2% of the 1 MA plasma current.

An example comparing magnetic midplane profiles of toroidal current density j_ϕ and equilibrium pressure 0.3 msec before and 0.5 msec after an ELM onset is shown in Fig. 4. In this case, the j_ϕ peak in the pedestal region which, prior to the ELM, lies ≈ 8 mm inside the separatrix (see vertical green markers on the horizontal axes) has moved out to the separatrix at $t_{ELM} + 0.5$ msec. The pressure pedestal has weakened considerably. These reconstructions were constrained both by magnetics+tile currents and edge kinetic data interpolated between available Integrated Data Analysis timepoints [6].

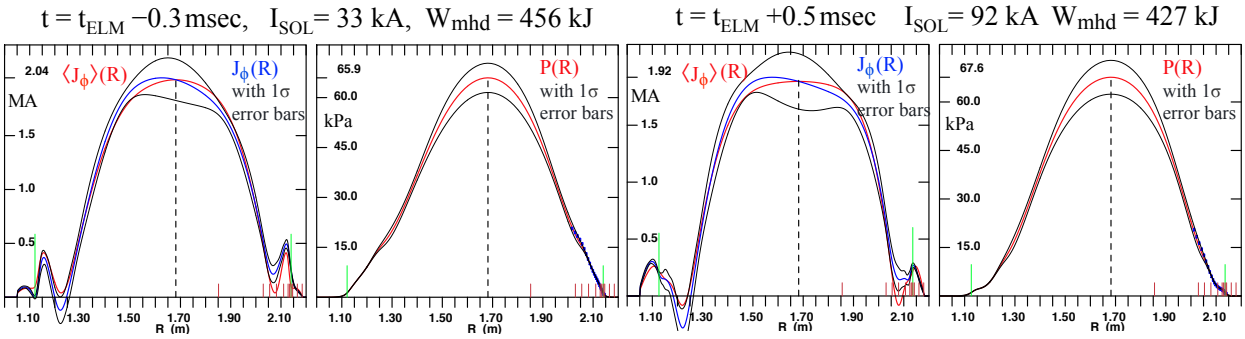


Fig 4. Magnetic midplane profiles of current density and pressure from CLISTE reconstructions at t_{ELM} −0.3 msec and t_{ELM} +0.5 msec constrained by magnetics and edge kinetics, the latter interpolated from available IDA timepoints [6] (see pressure profile edge region). The dark red vertical markers on the horizontal axes indicate the 11 knot locations for the $p'(\psi)$ and $ff'(\psi)$ spline basis functions.

Application of multipoint mode to an ASDEX Upgrade standard H-mode discharge

To illustrate the operation of the new multipoint method, it has been applied to equilibrium and loop voltage reconstruction during a sequence of Type I ELMs for ASDEX Upgrade standard H-mode discharge #33589, relevant signals of which have been plotted in figs. 1 and 2. We present results generated by running CLISTE in multipoint mode to obtain $\partial\psi/\partial t\,(R,Z)$ (as well as $\psi(R,Z)$) constrained by magnetics and tile current data at 100 μs intervals across a 65 msec time window containing four Type I ELMs. At each timepoint, data from three neighbouring timepoints on either side of the central point are used to identify the temporal gradients of the spline basis function amplitudes that parameterize the right-hand side of eq. (1). Thus the temporal resolution of the reconstructed loop voltage function is $\pm 300\,\mu$s. First results are shown in fig. 5, which displays time traces of $-(\partial\psi/\partial t)_{equilibrium}$ (blue trace), the plasma flux contribution $-(\partial\psi/\partial t)_{plasma}$ (green trace), and the experimental loop voltage (red trace) at the location of 'Loop 22', at the location of the red dot in fig. 2. The experimental signal is a moving average of the data with a 300 μs window. The qualitative agreement is good, insofar as the reconstructed voltage spikes are almost perfectly coincident with experiment. However, the magnitudes of the spikes are systematically stronger, and the inter-ELM reconstructed signal is noisier.

Detailed analysis of the results identified the OH (transformer) current as the cause of the problems. As remarked earlier, this current, unlike other PF currents is not allowed to deviate from its measured value in mimicing the effects of otherwise neglected vessel currents. Since the OH current, by design, generates a very weak in-vessel magnetic field, it would be counterproductive to allow deviations from experimental values, since these would be very poorly defined by poloidal field measurements. However, on timescales shorter than the vessel resistive time of $\approx$ 5 msec, changes in the OH current, and hence the in-vessel loop voltage will be shielded. This can be taken into account in a deterministic manner by pre-filtering the OH current signal as follows:

$$I^*_{OH}(t) = \int_{-\infty}^{t} I_{OH}(x) e^{-(t-x)/\tau_R}\, dx \qquad (2)$$

The filtered signal $I^*_{OH}(t)$ is then used in the equilibrium reconstructions where it will have little or no effect on the $\psi(R,Z)$ solution, but can dramatically affect $\partial\psi/\partial t\,(R,Z)$. Reconstructions identical to those shown in fig. 5, except for the substitution of $I^*_{OH}(t)$ for the measured OH current,

are reported in fig. 6. Here, in contrast to fig. 5, the peak amplitudes of $-(\partial\psi/\partial t)_{equilibrium}$ agree very well in all cases with the experimental data (as before, averaged over 300 μs) and the inter-ELM behavior is smoother, in closer agreement with experiment, although for two of the four ELM cycles, the experimental loop voltage decays more slowly than the reconstructed signal.

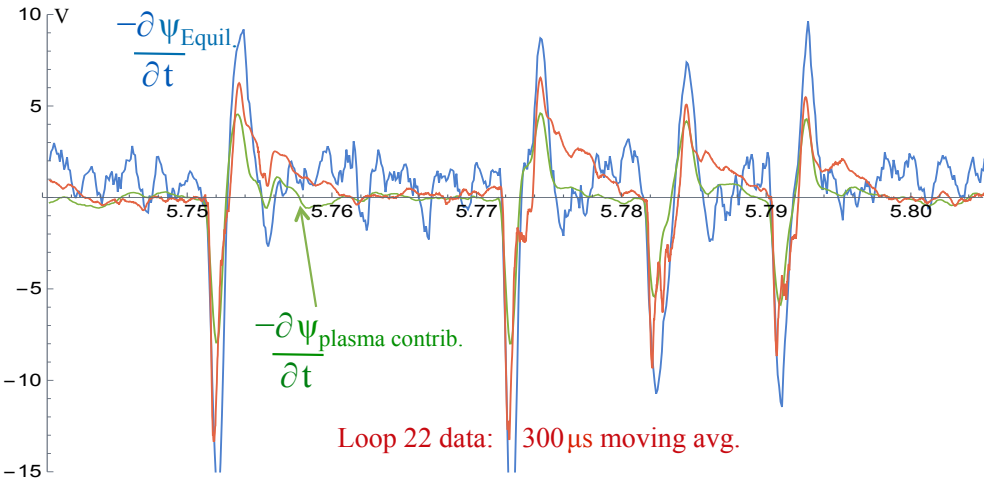


Fig. 5: **Experimental loop voltage data** and **CLISTE equilibrium loop voltage**, with the **plasma contribution** shown separately, from a multipoint analysis evaluated at the location of flux **loop 22** for a 65 msec window containing 4 ELMs in ASDEX Upgrade disch. #33589. The loop voltage data is smoothed with a 300 µs window.

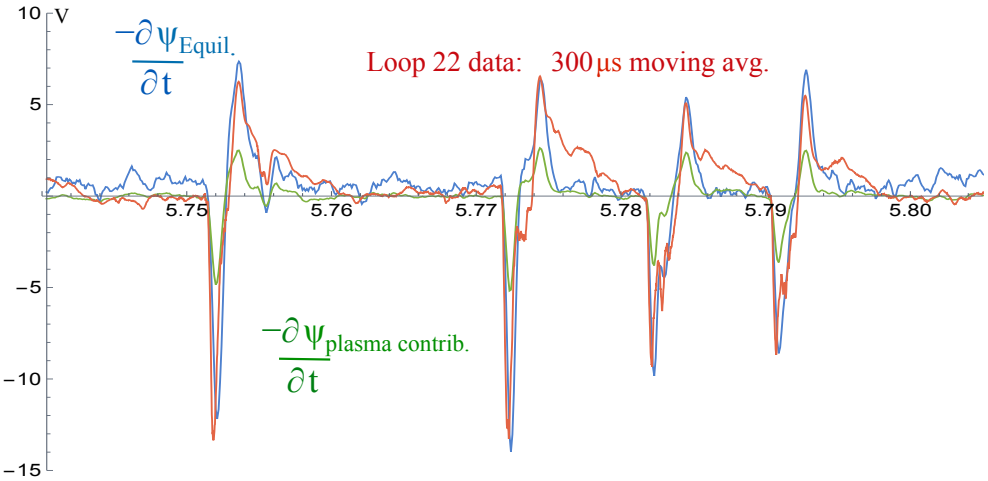


Fig. 6: Same analysis as in Fig. 5, but this time with OH currents filtered using a 5 msec delay. This mimics the ≈ 5msec resistive time of the AUG vacuum vessel and results in much better agreement between peak values in the CLISTE and experimental loop voltage signals at each ELM crash as well as less noisy inter-ELM behaviour.

Summary

By extending the SOL range to include remote tile currents, CLISTE can model an ELM crash with inter-ELM goodness of fit. A new multipoint mode with time derivative parameters allows multi-timepoint magnetic and current data to be fitted with a single GSE solution. Loop voltages derived from the multipoint fit, while in good qualitative agreement with experiment, were still not satisfactory. Pre-filtering the OH current with a time constant of 5 msec, a representative resistive time for the ASDEX Upgrade vacuum vessel, is a necessary prerequisite for the good quantitative agreement between CLISTE reconstructions and experimental loop voltages shown in fig. 6.

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