Current Density Profile Identification in the ASDEX Upgrade Pedestal Region from Kinetic and Magnetic Data using the CLISTE Interpretive Equilibrium Code

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Introduction

It has long been assumed that information provided by external magnetic measurements on the internal current density profile $j(R,Z)$ in a tokamak plasma is limited to the plasma current I_p,and, for elongated plasma cross-sections, beta poloidal and the internal inductance l_i. I_p and l_i correspond to the zeroth and first order moments of j while β_{pol} is effectively the zeroth moment of the equilibrium pressure profile. However, routine analysis of H-mode discharges on ASDEX Upgrade by the CLISTE interpretive equilibrium code [1] reveals a statistically very significant bootstrap-like peak in the pedestal region of the current density profile, typically for $0.93 < \rho_{pol} < 1$. For a given equilibrium, the height and width of the peak are somewhat dependent on the details of the current profile parameterization and curvature penalty, but the peak area I_{ped}, i.e. the current under the peak, is a fairly robust quantity. The identification of the I_{ped} by external magnetic measurements has been qualitatively explained in terms of the spatial localization of the current flowing in flux surfaces close to the X-point [2]. (The MSE diagnostic [3], which covers the region $0 < \rho_{pol} < 0.7$. provides only a moderate constraint on I_{ped}.) The consistency between this feature and current density calculations using high resolution measurements of edge density and temperature profiles which resolve the steep gradient region in the H-mode barrier was investigated via a comprehensive neoclassical bootstrap current model [4] to which CLISTE output is piped. Here, we present results which compare the neoclassically calculated current density with CLISTE equilibrium reconstructions using both external magnetic measurements and the high resolution pedestal pressure profiles.

Theory

The comparison between CLISTE and neoclassical calculations is based on the formula

$$\langle j_{||}B\rangle \;=\; \sigma_{neo}\langle E_{||}B\rangle - I_\phi(\psi)\,p(\psi)\Bigg[\mathcal{L}_{31}\frac{\partial \ln n_e}{\partial\psi} \;+$$

$$R_{pe}(\mathcal{L}_{31}+\mathcal{L}_{32})\frac{\partial \ln T_e}{\partial\psi} + (1-R_{pe})\times(\mathcal{L}_{31}+\mathcal{L}_{34}\,\alpha)\frac{\partial \ln T_i}{\partial\psi}\Bigg]$$

where $j_{||}$ is the current density parallel to $\mathbf{B}$, $I_\phi(\psi)$ is the toroidal current flowing inside the ψ flux surface and the angle brackets denote flux surface averages. $\sigma_{neo}E_{||}$ is the resistive current density and the remaining terms on the r.h.s. constitute the bootstrap current terms. The functions $\mathcal{L}_{31}, \mathcal{L}_{32}, \mathcal{L}_{34}$ (see [4], eqns. 13-17) were obtained by solving the full Fokker-Planck collision operator for a wide variety of collisionalities and equilibrium geometries. The local parallel current density for an axisymmetric equilibrium is given by

$$\mathbf{j}\cdot\mathbf{B} \;=\; F(\psi)\,p'(\psi) \;+F'(\psi)B^2/\mu_o$$

where $p'(\psi)$ and $FF'(\psi)$ are the source profiles for the Grad-Shafranov equation. Calculation of the flux-surface averaged value of B^2 results in the expression:

$$\langle \mathbf{j}\cdot\mathbf{B}\rangle\;(\psi) = \;F(\psi)\,p'(\psi)\;+\left(\frac{2\pi}{\mu_o}F(\psi)\;+\;\frac{I_\phi(\psi)}{q(\psi)}\right)F'(\psi)\Big/\frac{\partial V(\psi)}{\partial\phi}$$

This profile is calculated in CLISTE, thus allowing a direct comparison with the neoclassical expression above, which is evaluated, with the help of a routine supplied by O. Sauter (CRPP, Lausanne), using experimental temperature and density profiles and the equilibrium flux surfaces provided by CLISTE.

Data Selection

The ASDEX Upgrade high resolution edge Vertical Thomson Scattering system (16 channels cycling through 6 radial positions with 2mm spacing every 50 msec) [5] has a useful radial mid-plane coverage of approx. 3cm. To obtain full coverage of the pedestal region, the plasma is moved approx. 3cm horizontally and quasi-statically (0.5s) to give a total effective radial coverage of about 6 cm. These radial scans are not common, and as the focus of this contribution is on the pedestal region, it was decided to seek good quality pedestal kinetic profiles at the expense of MSE data, since, to date, less than 10 radial scan discharges have MSE data present as well. We selected a neutral beam-heated discharge with well-spaced type 1 ELMs, so that Thomson profile data could be selected well away from the ELM crash times.

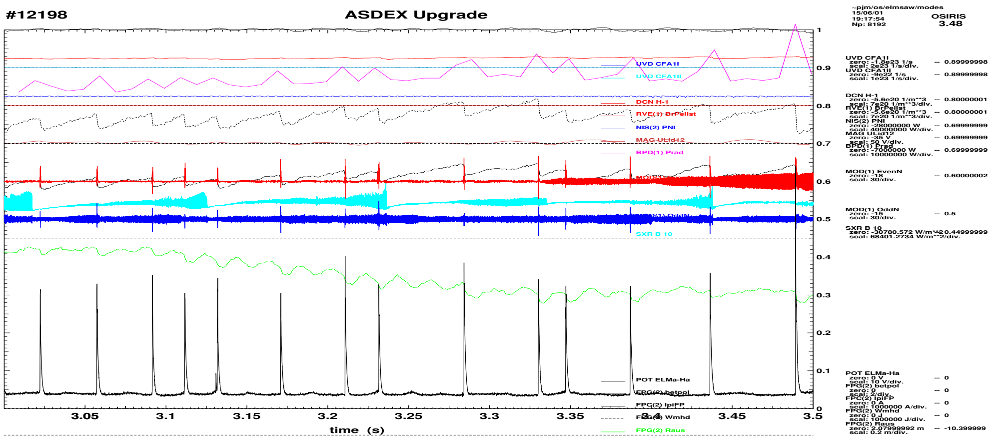

Fig.1 Diagnostic signal time traces during the radial scan for ASDEX Upgrade # 12198, t=3.0-3.5 s

Fig. 1. shows time traces for a variety of diagnostic signals for ASDEX Upgrade discharge $\#12198(I_p = 1MA, B = -2T, n_e = 9E+19\text{m}^{-3}$, $\text{P}_{heat} = 5\text{MW})$ between 3 and 3.5 s. The green trace is Raus, the outermost R coordinate of the plasma boundary, which moves 2.5 cm inwards with 5mm oscillations caused by the feedback system superimposed on the linear motion.

CLISTE equilibria using only equilibrium magnetic measurements were calculated every 2 ms during this time window on a 128 x 256 grid (grid spacing: 15 x 12 mm) and the position of the 16 vertical Thomson channels mapped onto the magnetic midplane was stored relative to the separatrix position. In this manner, a single pedestal profile was constructed over 500 msec. Data falling within a time window of 8 msec immediately following each ELM crash were excluded. All remaining ne and Te raw data (up to 1 cm outside the separatrix) are plotted in Fig. 2. (Given the unrealistically low separatrix temperature (20 eV), there is likely to be a systematic error in the CLISTE separatrix location and/or an error in the radial location of the edge Thomson system. This discrepancy is presently unresolved.) A nonlinear least squares best-fit is superimposed on the data using the function $f(x) = b + (p + s\,x)\text{Tanh}[(x + xoff)2/width] - s\,x$. The maximum electron pressure gradient, which occurs 18 mm inside the separatrix is 430 kPa/m. Ion temperature diagnostics have insufficent spatial resolution to resolve the pedestal gradient. Making a conservative assumption of Ti = Te and Zeff = 2 as suggested by transport modelling using BALDUR [6] yields a maximum equilibrium pressure gradient of 810 kPa/m. Such high edge pressure gradients fit well to theoretical expectations concerning the excitation of ballooning modes in ASDEX Upgrade where a previous analysis which considered values of $\nabla p \approx 500\,\text{kPa/m}$ near the separatrix required a substantial scaling factor of 1.8 to reach ideal-ballooning unstable behaviour [7].

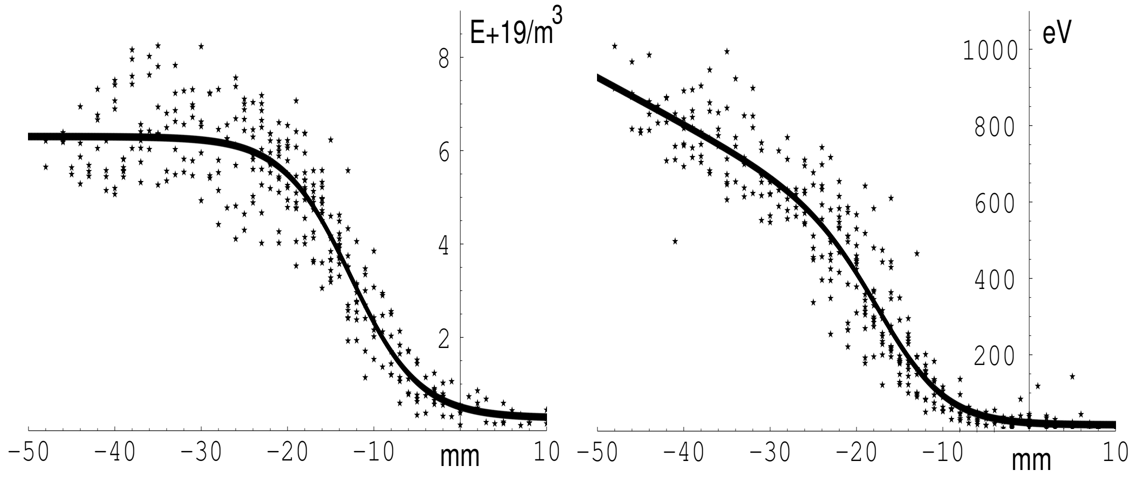

Fig.2 Electron density and temperature data from the Edge Thomson Scattering system mapped onto a midplane position relative to the separatrix.

Results

To allow flexibility in fitting the edge kinetic data, a CLISTE equilibirum calculation was made with a current profile parameterization with a twelve-parameter spline for each source profile with knots at the following ρ percentiles: 0 60 85 88 90 92 94 95 96 97 98 99. Flux surface contours and j(R) and p(R) profiles for equlibrium interpretations using magnetics only (upper j(R) and p(R) profile pair) and magnetics + the pedestal pressure profile assuming Zeff=1.5 and Ti=Te (lower set of profiles) are shown in Fig. 3. Note the large error bars in j in the centre reflecting the absence of MSE measurements.

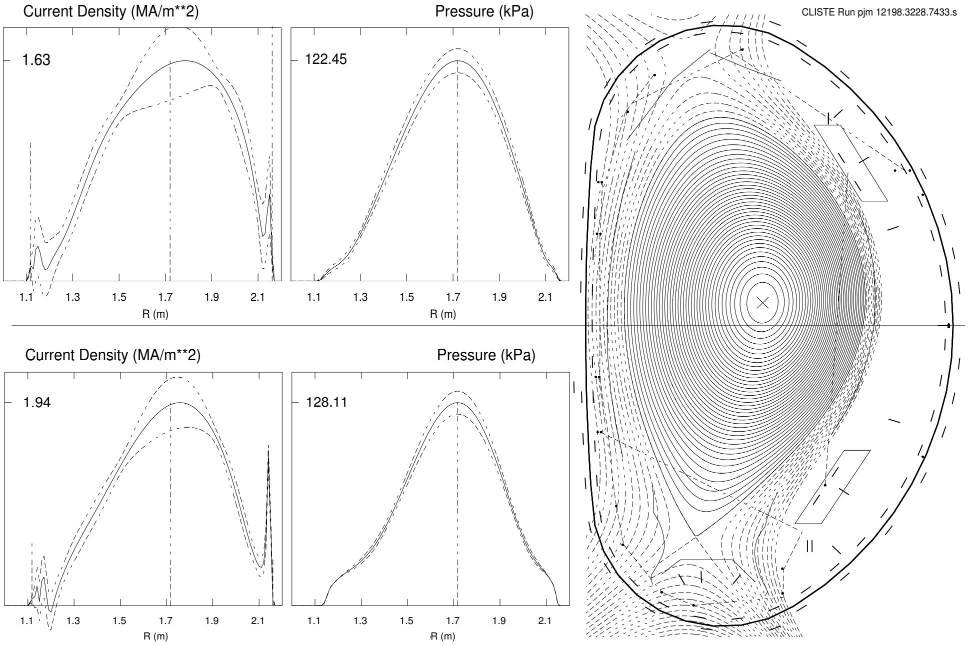

Fig.3 Flux surfaces and current density and equilibrium pressure profiles for #12198 t=3.328 s.

The rms magnetics error was 1.2 mT in both cases. The density of knots near the edge allows an almost perfect fit to the smooth edge pressure profile constructed from the Tanh fits to the n_e and T_e data: rms error = 28 Pa. The magnetics-only j profile has a pronounced edge peak consistent with [2]. This peak is even more pronounced in the case of the magnetics+kinetic equilibrium. The results of the neoclassical calculation for this case are shown in Fig. 4. The solid green curve is the $\langle j_{||} \rangle$ profile calculated in CLISTE while the red curve is the neoclassical equivalent.

The agreement in the upper plot is impressive at the location of maximum pressure gradient. The lower plot is the result of a subsequent CLISTE run where the curvature penalty on the current profile (but not the pressure) was increased significantly. The pressure-driven current density (solid black curve) is unchanged, but the FF' term (dotted black curve) is more negative leading to a flatter j_ϕ (dotted green curve) which results in a dip in $\langle j_{||} \rangle$. The current outside R=2.11m ($\rho = 0.91$) is 142 ± 1 kA in the two cases, i.e. I_{ped} is conserved. The goodness of fit was the same for both runs.

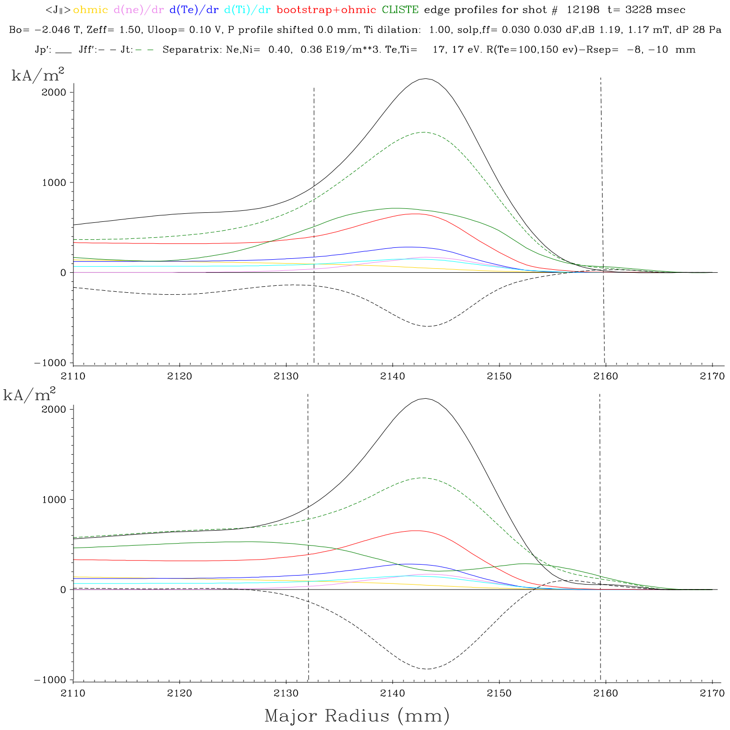

Fig.4 Comparison between equilibrium and neoclassical $\langle j_{||} \rangle$ calculations.

Conclusions and Acknowledgments

Neoclassical calculations are consistent with a sharp edge peak in the current density profile as calculated by the CLISTE interpretive equilibrium code and reconfirm the earlier finding that, for an X-point geometry, the total current under this peak, I_{ped}, can be identified from magnetic measurements only.

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References

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