Plasma geometry and current profile identification on ASDEX Upgrade using an integrated equilibrium generation and interpretation system.

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Abstract

The identification of ideal MHD equilibrium states on a tokamak is the starting point for interpreting any diagnostic data dependent on knowledge of the flux surface geometry. The method of Function Parameterization (FP) starts with the Monte Carlo generation of a simulated equilibrium database, regression analysis of which yields simple functional representations of plasma geometry whose arguments are information-rich, uncorrelated linear combinations of simulated diagnostic signals. Once calculated, these FP expressions can be rapidly evaluated using experimental data. FP using magnetic data is in routine realtime use on ASDEX Upgrade for plasma position and shape control and has been applied to diagnostic design studies for ITER. An extension to FP using MSE data has recently been developed for realtime identification and control of the current profile on ASDEX Upgrade. Post-discharge interpretive equilibrium solutions are generated by the CLISTE code, which best fits a set of specified diagnostic data. CLISTE can include kinetic data and poloidal halo currents in the scrape-off layer as constraints on the equilibrium solution, a valuable feature which has been applied to ELM analysis. The code has recently been extended to interpret dB/dt data from magnetics and $d\gamma/dt$ data from MSE to yield a best fit solution to the time derivative of the Grad-Shafranov equation $-\Delta^*\partial\psi/\partial t = 2\pi\mu_0 R\partial j_\phi/\partial t$. The $\partial\psi/\partial t$ solution is used to calculate the flux surface averaged profile $\langle \mathbf{E}\cdot\mathbf{B}\rangle$ which can be used to calculate current drive from auxiliary heating methods via the equation

$$\langle \mathbf{j}\cdot\mathbf{B}\rangle_{\text{aux. heating}} = \langle \mathbf{j}\cdot\mathbf{B}\rangle_{\text{equil}} - \sigma\langle \mathbf{E}\cdot\mathbf{B}\rangle - \langle \mathbf{j}\cdot\mathbf{B}\rangle_{\text{boot}}$$

where $\langle \mathbf{j}\cdot\mathbf{B}\rangle_{\text{boot}}$ is calculated from kinetic profiles and neoclassical theory and $\langle \mathbf{j}\cdot\mathbf{B}\rangle_{\text{equil}}$ is an equilibrium output. This technique is applied here to analyse current profile modification by off-axis NBI on ASDEX Upgrade.

1. Introduction

Realtime feedback control of the plasma position, shape and current profile on ASDEX Upgrade requires the processing of many ($\simeq 100$) signals on a millisecond time-scale to deliver plasma parameters for control algorithms. Interpretive equilibrium solutions constrained by multiple diagnostic data are generated after the discharge. These tasks are carried out using a combination of predictive and interpretive tools, all of which have as their common base the predictive free boundary Garching Equilibrium Code (GEC) originally written by Lackner [1] which has been developed over the past two decades into (a) a database generation and analysis package (DGAP) used to generate large equilibrium databases for both ASDEX Upgrade and ITER geometries [2] and (b) the CLISTE equilibrium code [3, 4] which is routinely used for full equilibrium reconstruction between discharges. Both GEC and CLISTE solve the Grad Shafranov (G-S) equation

$$\begin{aligned} -\frac{1}{2\pi\mu_0 R}\triangle^*(\psi) = -\frac{1}{2\pi\mu_0 R}\left(\frac{\partial^2\psi}{\partial R^2} - \frac{1}{R}\frac{\partial\psi}{\partial R} + \frac{\partial^2\psi}{\partial Z^2}\right) &= Rp'(\psi) + \frac{ff'(\psi)}{\mu_0 R} \\ &\equiv j_\phi. \end{aligned} \quad (1)$$

The source profiles $p'(\psi)$ and $ff'(\psi)$ are specified functions of the *a priori* unknown solution poloidal flux function $\psi(R,Z)$ in the case of GEC, whereas in CLISTE they are free functions of ψ which are determined by an iterative least squares best fit to diagnostic data. A noteworthy feature of both codes is the natural presence of scrape-off layer currents in the equilibrium solution. This is a result of decoupling the separatrix contour from the last current-carrying flux surface by allowing the source profiles to be non-zero on open flux surfaces. Constant pressure and force balance is assumed to hold along open fieldlines until a vessel structure is encountered whereupon the plasma current density and pressure fall to zero across one grid interval. The return current through the material structure is assumed to have negligible effect on force balance in the plasma. In the following sections we outline the approaches used in generating predictive equilibrium databases both for ASDEX Upgrade and ITER using the DGAP package and we present applications of the CLISTE code to several equilibrium identification problems on ASDEX Upgrade.

2. Generation of Equilibrium Databases for ASDEX Upgrade and ITER

Equilibrium databases are generated using a well-developed methodology for evenly populating a high-dimensional ($> 20D$) parameter space with a tractable number of cases (of order 10^4). Use of the Monte Carlo approach ensures that the projection onto any 1-D sub-space will tend to be quasi-homogeneously distributed along that direction in parameter space, thus avoiding the "curse of dimensionality" where the choice of regularly spaced parameter values along each axis would require geometric growth in the number of cases with increasing dimension.

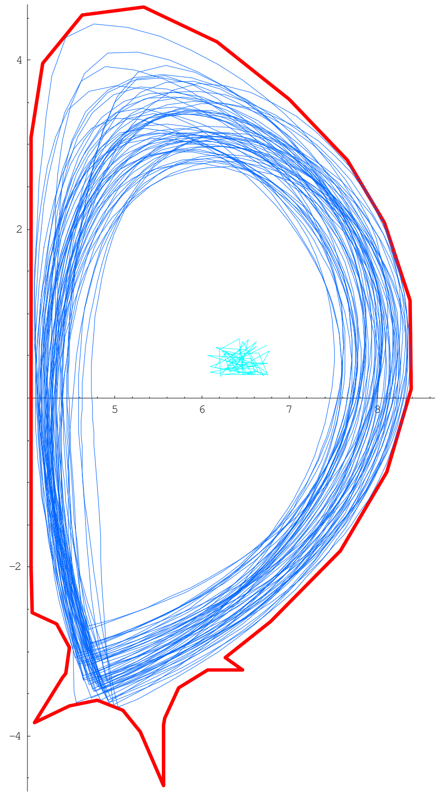


Figure 1: *ITER first wall and 60 randomly chosen separatrix contours with corresponding magnetic axis locations.*

Using the vacuum vessel and poloidal field coil geometry of ASDEX Upgrade (AUG) or ITER, randomly chosen candidate input parameters vectors specify the currents in the poloidal field coils, the in-vessel passive conductor currents in the case of AUG, the six dominant passive current modes in the vessel wall in the case of ITER [5], and the G-S source profiles $p'(\psi)$ and $ff'(\psi)$. The maximum and minimum values for each parameter are selected by a mixture of engineering limits (in the case of coil currents) and experience (in the case of the source profile parameters). If there are m input parameters in total, then each input parameter vector is chosen within an m-dimensional hypercuboid whose corner coordinates consist of the set of 2^m m-vectors constructed by combining together either a minimum or a maximum limit of each of the m input parameters. Typically, only a small fraction (several percent) of the candidate input vectors result in acceptable equilibrium solutions. This is due to the fact that most random input parameter combinations, in particular those where several parameters jointly take values close to their respective range limits, will not result in reasonable, or any solutions. The set of acceptable equilibria (whose input vectors are bounded by some m-1 dimensional surface inside the hypercuboid) are stored on disk and constitute the equilibrium database. This process is time-consuming (on the order of a week), and to avoid unnecessary repetition all simulated diagnostic signals are generated subsequently by a dedicated program within DGAP which reads the stored equilibria and (re-)evaluates the diagnostic signal values for each case in the database using the most recent diagnostic set-up.

Fig. 1 shows 60 sample lower single null boundary contours and magnetic axis locations from an ITER equlibrium database generated in 2003 and used in a number of diagnostic sensitivity studies, including that reported in [6].

To avoid the hazard of under-parameterization which leads to misleadingly accurate reconstruction results when the database is used, for example, to "train" a neural network-type reconstruction algorithm, DGAP has evolved a strategy of using richly featured source profile shapes with a large number of free parameters. The $p'(\psi)$ and $ff'(\psi)$ profiles are currently parameterized as linear combinations of up to 25 basis functions generated from the Discrete Cosine Transform on a grid consisting of equally spaced ψ values in the interval $[0,1]$ where 0 and 1 correspond to the last current-carrying surface and the magnetic axis, respectively. The ith component of the jth basis function $\mathbf{b_j}$ is given by

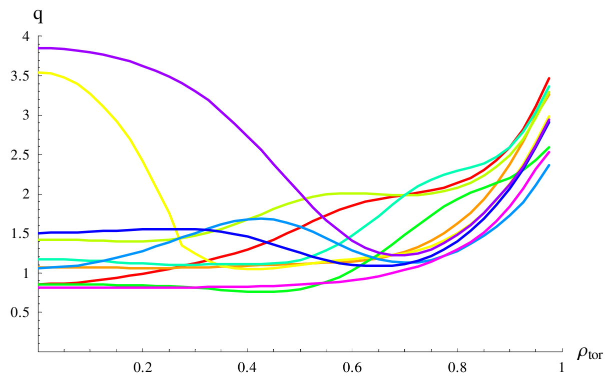


Figure 2: *Ten sample q profiles from the ITER equilibrium database* $(0 \leq \rho_{tor} \leq 0.975)$.

$$b_{i,j} = \sqrt{\frac{\min(L,2)}{L}} \cos\left((2i-1)(j-1)\frac{\pi}{2L}\right); \qquad i = 1, L \tag{2}$$

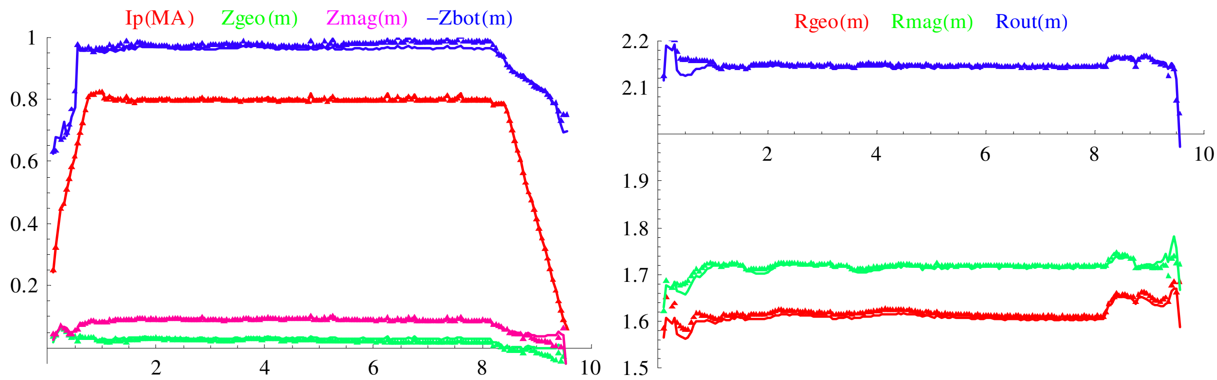
where $L = 1001$ is the number of ψ gridpoints for the source profiles. Smoothness conditions were imposed on the selected source functions by use of a spectral decay scheme whereby the amplitude of each profile moment was chosen from a normal probability distribution with zero mean whose standard deviation decreased geometrically with order, so that the finest details of the profile tended to have the lowest amplitude. To ensure that $p'(\psi)$ and $ff'(\psi)$ tend towards zero in the edge region, the profiles generated using eq. (2) are scaled by a monotonic envelope function $e(\psi)$ (with randomly chosen parameters) which vanishes at the last current-carrying surface. The source profiles are accordingly parameterized by $\sigma(\psi) = e(\psi)\sum_{j=1}^{N_b} \alpha_j \mathbf{b}_j$, where $\sigma(\psi)$ stands for $p'(\psi)$ or $ff'(\psi)$, $N_b \simeq 25$ is the number of linear combinations and α_j is the amplitude of the jth Fourier moment. Ten sample $q(\rho)$ profiles generated with this parameterization which belong to the ITER database used in [6] are plotted in Fig. 2.

3. Geometry and current profile recovery on AUG using Function Parameterization

The statistically based method of Function Parameterization (FP) [7] in the plasma physics context involves analysis of equilibrium databases to derive simple functional representations of plasma parameters whose arguments are information-rich, uncorrelated linear combinations of diagnostic signals stored in the database. These are identified by the technique of Principal Component Analysis (PCA) which entails diagonalization of the covariance matrix $\mathbf{S} = \mathbf{X}^T\mathbf{X}/n$ where $\mathbf{X}$ is the $n \times k$ data matrix consisting of n cases of k diagnostic signals shifted with respect to their database mean values. PCA yields a set of eigenvectors representing k linear combinations of the signals which are uncorrelated in the database. Collinearities between the signals or noise-dominated linear combinations are identified by eigenvectors of $\mathbf{S}$ whose eigenvalues are close to zero or smaller than the experimental noise variance, respectively. Discarding these, the remaining p eigenvectors of the covariance matrix are pre-multiplied by $\mathbf{X}$ to form p columns of transformed, uncorrelated measurements $\phi_1, \ldots, \phi_p$. A quadratic FP model in these p variables is now constructed for each equilibrium parameter g_j as follows:

$$g_j = a_j + \sum_{r=1}^{p} b_{rj}\phi_r + \sum_{\substack{r=1 \\ s=r}}^{p} c_{rsj}\phi_r\phi_s \tag{3}$$

where the coefficients a_j, b_{rj} and c_{rsj} are determined by linear least squares regression. Once calculated, these FP expressions can be rapidly evaluated using experimental data. FP has been in use for position and shape control on ASDEX Upgrade since first plasma in March 1991 [8]. With two distinct methods of equilibrium parameter identification available, it is possible to routinely compare the results for consistency. Fig. 3 displays a comparison for a selection of geometric and q-profile parameters for AUG lowersingle null discharge # 21160 where only magnetic measurements were used in both FP and CLISTE reconstructions. The agreement is



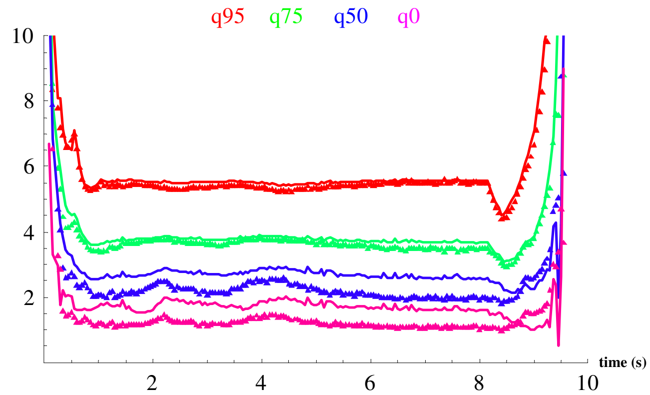


Figure 3: *Comparison of FP-recovered plasma parameters (continuous curves) with CLISTE results (triangles) versus time for ASDEX Upgrade # 21160 using magnetic measurements only. The parameters compared are: plasma current, Zgeo, Z(mag.axis) and -Zbottom (upper left panel), geometric, magnetic axis and outer R-coordinates (upper right panel) and q at the 95%, 75%, 50% ψ surfaces and axial q (lower panel).*

in general very satisfactory, with typical FP-CLISTE discrepancies for geometric parameters in the range 0-10 mm in the flat-top phase ($1 < t < 8$ s). The comparison of the q-recovery at four fixed ψ surfaces illustrates nicely the increasing uncertainty in determining q from magnetic measurements as one moves in from the boundary. The median FP-CLISTE discrepancies in flat-top were, starting at the q_{95} surface and moving inwards, (0.12, 0.38, 0.47, 0.35) or, expressed as percentages, (2%, 11%, 21%, 25%).

Recently, the model has been extended beyond equilibrium magnetic measurements to also include MSE measurements of the poloidal magnetic field in the plasma which allows identification of the q profile on a timescale compatible with realtime feedback control of the current profile [9]. An example of this expanded "FPJ" algorithm applied to shot 12036 is shown in Fig. 4 where a CLISTE reconstruction from the same set of diagnostic data is shown for comparison. Note the consistency of the FPJ and CLISTE result, in contrast to the magnetics-only recovery of q shown in Fig. 3. Included in Fig. 4 are "experimental" q values (green triangles) obtained by scaling the poloidal field by a scaling factor such that $\tan\gamma$, evaluated using the geometry of the local MSE channel agrees with the experimental value. If this scaling factor is s_{exp} then by making the ansatz that the topology of the flux surfaces is not affected by the change in the poloidal field (geometric uncertainties can be taken into account in a further step) we use the exact local formula for q (ignoring the sense of the helicity):

$$q = \frac{\|\nabla\phi\|}{\|\nabla\psi_{pol}\|} \equiv \frac{\|\nabla\phi\|}{2\pi R B_{pol}} \tag{4}$$

where ϕ is the toroidal flux, ψ_{pol} is the poloidal flux (in Wb) and B_{pol} is the magnitude of the poloidal magnetic field. This gives the simple scaling $q \propto B_{pol}^{-1}$ at the channel position, since $\|\nabla\phi\|$ is conserved by the assumption of unperturbed geometry and hence we obtain $q_{exper} = q_{\mathrm{CLISTE}}/s_{exp}$ where q_{CLISTE} is the CLISTE q-profile value at the flux surface intersecting the channel location. Using the same method, the red error bars are obtained by varying the experimental $\tan\gamma$ value by $\pm\delta(\tan\gamma)$ and recalculating q using the perturbed values of B_{pol}. Here $\delta(\tan\gamma) \approx \delta(\gamma)$, the uncertainty in the experimental MSE measurement, is typically 0.2°. In the case of channels near the magnetic axis, a variation of 0.2° may result in the perturbed value of B_{pol} passing through zero, corresponding to infinite q. This occurs in the case of the third channel from the left in Fig. 4 resulting in an unbounded upper experimental uncertainty on the local q value. This method of calculating errors in the q-profile has the advantage that it is independent of the choice of regularization used in the parameterization of the G-S source profiles (see next section).

4. The CLISTE equilibrium code

The CLISTE (CompLete Interpretive Suite for Tokamak Equilibria) code finds a numerical solution to the Grad-Shafranov equation for a given set of poloidal field coil currents and in-vessel structures by varying the free parameters in the parameterization of the $p'(\psi)$ and $ff'(\psi)$ source profiles which define the toroidal current density profile j_ϕ so as to obtain a best fit in the least squares sense to a set of experimental data. Under development since 1996, it is the standard ideal MHD equilibrium solver on ASDEX Upgrade. During each iteration cycle, using the same basic algorithm as the EFIT code [11], an updated optimized set of free parameters which minimize the fit error is obtained using the following linear parameterization of the $p'(\psi)$ and $ff'(\psi)$ profiles:

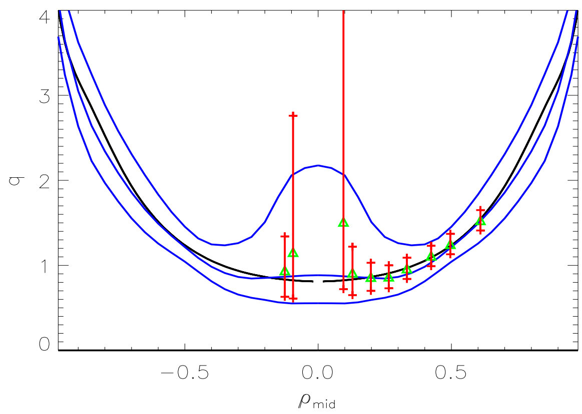


Figure 4: *FPJ q-profiles with 95% confidence bands from equilibrium database analysis (blue curves) for #12036, t=2.0 s. The black curve is the CLISTE reconstruction. "Experimental" q-values and error bars are shown as green triangles and red lines, respectively (see text).*

$$p'(\psi) = \sum_{i=1}^{n_s} c_i \pi_i(\psi)\,; \qquad ff'(\psi) = \sum_{j=1}^{n_s} d_j \varphi_j(\psi) \tag{5}$$

Here, $\pi_i(\psi)$ and $\varphi_j(\psi)$, which are arbitrary but fixed functions of ψ, constitute the basis functions for j_ϕ. In contrast to the Fourier parameterization used for equilibrium database generation, CLISTE typically uses 6-12 fixed-knot cubic splines to represent each source profile. The free parameters whose values are determined by an iterative fit to the diagnostic data, thereby specifying the equilibrium solution, are the set of spline function amplitudes $\{c_i,\ d_j\}$. This is an ill-conditioned inverse problem which requires regularization, here imposed by penalizing the curvature of the solution $p'(\psi)$ and j_ϕ profiles. CLISTE, which is parallelized by use of a Message Passing Interface [10] and runs automatically after each discharge, can constrain the equilibrium solution using a wide variety of diagnostic information, currently consisting of :

(i). equilibium magnetic measurements
(ii). motional Stark effect pitch angle data
(iii). information on the location of resonant surfaces from soft X-ray, ECE, MHD mode analysis, etc.

(iv). kinetic data (Thomson scattering) combined with calculated fast pressure profiles
(v). line-integrated densities (DCN) combined with Lithium Beam edge densities
(vi). poloidal current measurements (halo currents) in the scrape-off layer
(vii). isoflux constraints from inboard/outboard reflectrometry data
(viii). separatrix strike positions from infra-red thermography
(ix). parallel current density profiles from neoclassical theory
(x). Processing of time differentiated magnetic/MSE data to recover loop voltage profiles.

In the pedestal region, where the significant current generation mechanisms are usually limited to Ohmic and bootstrap current drive, the current density can be tightly constrained with the combination of constraints (i), (iv), (v), (vi) and (ix). An example is shown in Fig. 5 for a discharge (#17151) with good quality pedestal kinetic data.

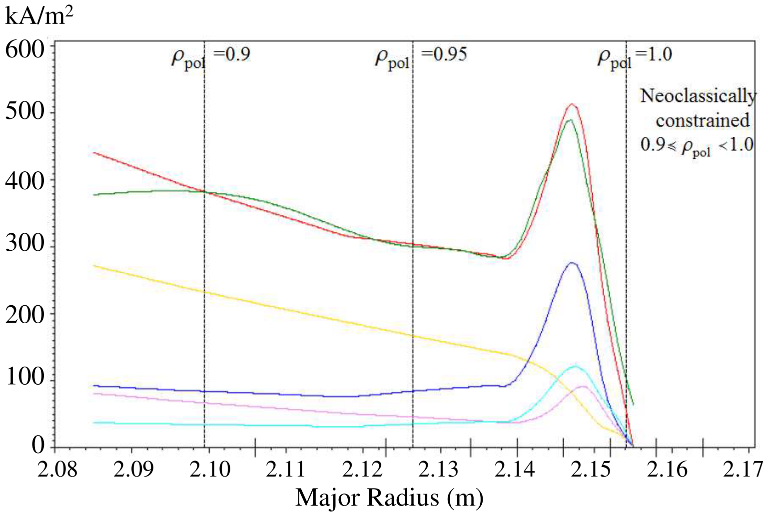


Figure 5: **Ohmic**,**∇n**, **∇Te**, **∇Ti**, **total neoclassically driven** *parallel current and* **CLISTE $\langle J \cdot B \rangle / \langle B \rangle$** *profiles in the pedestal region for ASDEX Upgrade discharge #17151, $t = 3.85s$, $Ip = 800kA$, $B_t = -2.0T$. Neoclassical constraints were imposed for $0.9 \leq \rho_{pol} < 1.0$ spanning 5.5cm radially in the midplane. A free cBoot scaling parameter was fitted by CLISTE: the red curve is* **0.914*(Jboot+Johmic)**.

CLISTE has recently being extended to interpret $\frac{\partial}{\partial t}B_\theta$, $\frac{\partial}{\partial t}(\psi(\mathbf{r}_1) - \psi(\mathbf{r}_2))$ magnetic data and MSE $\frac{\partial}{\partial t}\gamma$ data to yield a least squares best fit solution to the time derivative of the Grad-Shafranov equation $\Delta^* \frac{\partial}{\partial t}\psi = -2\pi\mu_0 R \frac{\partial}{\partial t} j_\phi$ (see [12] for the background to this method) where the free source profiles $\frac{\partial}{\partial t}p'(\hat{\psi})$ and $\frac{\partial}{\partial t}FF'(\hat{\psi})$ are functions of the poloidal flux solution to the equilibrium problem. The flux surface averaged profile

$$\langle \mathbf{E} \cdot \mathbf{B} \rangle = \langle E_\phi B_\phi \rangle + \langle E_\theta B_\theta \rangle = -\frac{F}{2\pi} \left\langle \frac{\partial \psi}{\partial t} \frac{1}{R^2} \right\rangle + \oint E_\theta \, d\ell \tag{6}$$

can be calculated from $\frac{\partial}{\partial t}\psi$ and $\frac{\partial}{\partial t}F$ noting the relation $\oint E_\theta \, d\ell = -\int (\frac{\partial}{\partial t}F/R) dA$ and this in turn determines the flux surface averaged inductively driven parallel current density $\langle j_{\Omega,\parallel} \rangle$ in the form $\langle \mathbf{j} \cdot \mathbf{B} \rangle_\Omega = \sigma \langle \mathbf{E} \cdot \mathbf{B} \rangle$. The bootstrap current profile is calculated in CLISTE using the Sauter-Angioni-Lin-Liu model [13]. The total parallel current density expressed in the form $\langle \mathbf{j} \cdot \mathbf{B} \rangle_{equil} = F(\hat{\psi}) p'(\hat{\psi}) \; + F'(\hat{\psi}) \langle B^2 \rangle / \mu_0$ is an equilibrium quantity which is identified by CLISTE when internal poloidal magnetic field information provided by MSE data is available. This is combined with $\langle j_{\Omega,\parallel} \rangle$ and $\langle j_{boot} \rangle$ to isolate the remaining current drive term, namely that generated by neutral beams and other auxiliary heating methods:

$$\langle \mathbf{j} \cdot \mathbf{B} \rangle_{aux.heating} = \langle \mathbf{j} \cdot \mathbf{B} \rangle_{equil} - \sigma \langle \mathbf{E} \cdot \mathbf{B} \rangle - \langle \mathbf{j} \cdot \mathbf{B} \rangle_{boot} \tag{7}$$

The quality of the fits is enhanced utilizing the fact that $\langle \mathbf{j} \cdot \mathbf{B} \rangle_{aux.heating}$ may frequently be neglected towards the edge of the plasma and hence the current profile can be tightly specified in this region by applying equilibrium pressure and neoclassical constraints as illustrated in Fig. 5.

This method of determining current drive provides an important alternative to the usual reliance on transport codes such as TRANSP and ASTRA. Here, we present an illustrative example of the change in the Neutral Beam Current Drive (NBCD) profile as identified by the present method when two 93 keV off-axis beam sources contributing 5MW (out of a total of 7.5MW) of heating power on ASDEX Upgrade are switched off and promptly replaced by two 60 keV on-axis beams, also contributing 5 MW. The discharge analyzed (# 19026) for which MSE data was available was designed to minimize the changes in the kinetic profiles following the switch in beam sources, so that the bootstrap current profile could be assumed to be unchanged (see [15] for more details). The left-hand plot in Fig. 6 shows loop voltage profiles before, 100 ms following and 150 ms following the switch from off-axis to on-axis beams which occurred at 5.15 s. As a necessary compromise between noisy derivatives and time resolution, the pre- and post-switch profiles were calculated across ± 100 ms time-windows. The difference profile $\delta V(\rho) = V_{post}(\rho) - V_{pre}(\rho)$ was used to calculate the change in the beam-driven current profile using

$$\delta\langle \mathbf{J}_{NBCD} \cdot \mathbf{B} \rangle = -\sigma\delta(\langle E_\phi B_\phi \rangle) \tag{8}$$

where $\sigma(\rho)$ is the neoclassical conductivity profile, E_ϕ is related to $V(\rho)$ as in eq. (6) and the term $\langle E_\theta B_\theta \rangle$ in eq. (6) vanishes because the calculations are performed on a fixed ρ_{tor} grid.

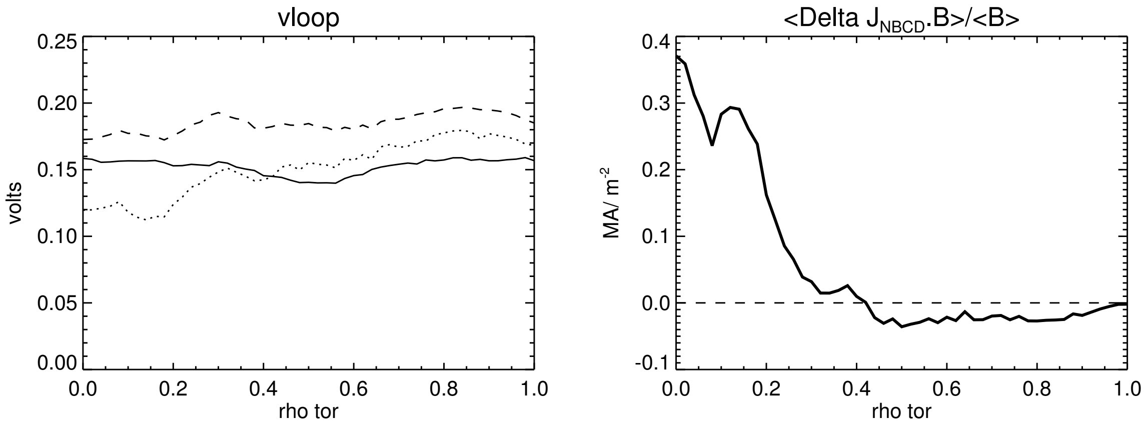


Figure 6: *Left plot: Loop voltage profiles calculated before (solid), 100 ms after (dotted) and 150 ms after (dashed curve) the substitution of 5MW of off-axis NBI heating by 5MW on-axis heating for #19026 ($I_p = 0.8MA$, $B_t = 2.5T$). Right plot: Change in the NBCD profile inferred from the difference in the solid and dotted loop voltage profiles.*

The resulting change in the NBCD profile corresponding to the difference between the solid and dotted voltage profiles is plotted in the right-hand panel in Fig. (6) which shows a significant current density driven in the region $\rho < 0.3$. The area integral of this profile, i.e. the cumulative change in the beam-driven current profile, peaks at $\rho = 0.42$ at a value of 19 kA and is less than 1 kA at the separatrix. The loop voltage 150 ms after the switch has flattened once more, albeit at a higher value. This may be due to the fact that the on-axis beams drive less overall current at the same power due to the lower CD efficiency associated with the less energetic ions and the more normal injection angle. The rapid timescale on which the voltage profile relaxes is likely to be due to the redistribution of fast ions caused by the combination of an NTM throughout the flat-top phase of this discharge and the effect of small scale turbulence [14, 15].

5. Summary and Outlook

The CLISTE interpretive code and the Function Parameterization method are two complementary approaches to MHD equilibrium identification whose routine availability provides ASDEX Upgrade with robust tools for recovering plasma geometry and current profile information with a high degree of confidence in their accuracy. CLISTE can constrain the equlibrium solution using a wide variety of diagnostic data and can also process time derivative data to generate loop voltage profiles. Halo currents are handled naturally by decoupling the last current-carrying flux surface from the plasma boundary surface. FP is part of a wider Database Generation and Analysis Package which has been used to generate large equilibrium databases for both ASDEX Upgrade and ITER geometries. For the future, it is intended, in the context of the International Tokamak Modelling Taskforce, that CLISTE will be generalized to handle data from other experiments as well as ITER. Further development, currently focusing on the incorporation of toroidal rotation into force balance calculations, is an ongoing process.

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