EFDA–JET–PR(13)25

M. Gelfusa, A. Murari, I. Lupelli, N. Hawkes, P. Gaudio, M. Baruzzo, M. Brix, T. Craciunescu, V. Drozdov, A. Meigs, E. Peluso, M. Romanelli, S. Schmuck, B. Sieglin and JET EFDA contributors

Influence of Plasma Diagnostics and Constraints on the Quality of Equilibrium Reconstructions on JET

Influence of Plasma Diagnostics and Constraints on the Quality of Equilibrium Reconstructions on JET

M. Gelfusa[1], A. Murari[2], I. Lupelli[3], N. Hawkes[3], P. Gaudio[1], M. Baruzzo[2], M. Brix[3], T. Craciunescu[4], V. Drozdov[3], A. Meigs[3], E. Peluso[1], M. Romanelli[3], S. Schmuck[5], B. Sieglin[5] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Associazione EURATOM-ENEA - University of Rome "Tor Vergata", Roma, Italy.
[2]Consorzio RFX-Associazione EURATOM ENEA per la Fusione, I-35127 Padova, Italy.
[3]EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[4]EURATOM-MEdC Association, NILPRP, Bucharest, Romania
[5]Max-Planck-Institut für Plasmaphysik, Teilinstitut Greifswald, EURATOM Association, Wendelsteinstr.1,17491 Greifswald, Germany
** See annex of F. Romanelli et al, "Overview of JET Results", (24th IAEA Fusion Energy Conference, San Diego, USA (2012)).*

Preprint of Paper to be submitted for publication in
Review of Scientific Instruments

ABSTRACT
The free boundary equilibrium problem, described by the Grad-Shafranov equation in toroidal geometry and axisymmetric configurations, is mathematically very ill posed. Therefore the quality of the equilibrium reconstruction depends sensitively on the measurements used as inputs and on the imposed constraints. In this paper, it is shown how the different diagnostics (Magnetics Measurements, Polarimetry and Motional Stark Effect), together with the edge current density and plasma pressure constraints, can have a significant impact on the quality of the equilibrium on JET. Results show that both the Polarimetry and Motional Stark Effect internal diagnostics are crucial in order to obtain reasonable safety factor profiles. The impact of the edge current density constraint is significant when the plasma is in the H-mode of confinement. In this plasma scenario the strike point positions and the plasma last closed flux surface can change even by centimetres, depending on the edge constraints, with a significant impact on the remapping of the equilibrium-dependent diagnostics and of pedestal physics studies. On the other hand and quite counter intuitively, the pressure constraint can severely affect the quality of the magnetic reconstructions in the core. These trends have been verified with several JET discharges and consistent results have been found. An interpretation of these results, as an interplay between degrees of freedom and available measurements, is provided.

1. INTRODUCTION
One of the possible approaches to nuclear fusion consists of confining high temperature plasmas with properly shaped magnetic fields in toroidal geometry (Tokamak). In the last decades, more advanced plasma scenarios have been developed, such as hybrid modes, optimised shear etc, in order to maximise performance. Since these more sophisticated configurations require a carefully controlled shaping of the current profile, the accurate determination of the magnetic topology has become even more crucial for both the running of the experiments and the scientific exploitation of the results [1]. With regard to the plasma boundary, various aspects of the edge physics, from the formation of the high confinement mode (H-mode) to the dynamics of the edge localized modes (ELMs), are neither fully understood not controlled. Even these aspects of Tokamak physics would benefit from a better reconstruction of the magnetic topology around a small region at the plasma edge, for example for accurate stability studies. Given the strong gradients, which develop in this radially localised region, again the reconstruction around the boundary poses significant challenges even if more measurements are available to constrain the codes.

The magnetic topology, in present-day Tokamak configurations, is typically obtained under the assumption of equilibrium between the magnetic and the kinetic pressure by solving the Grad-Shafranov equation [2, 3]. The solution of the Grad-Shafranov equation in toroidal geometry and axisymmetric configuration is unfortunately an ill posed problem. In particular, the available measurements are typically compatible with multiple current profiles inside the plasma. This fact has been realised for quite a long time and the impact of the internal magnetic measurements as constraints in the solution of the equilibrium problem, such as Polarimetry and Motional Stark

Effect (MSE), on the final magnetic topology in the core is a well known fact. Recently, these qualitative considerations have been quantified using new mathematical tools, which prove that magnetic internal measurements are indispensable to identify the more appropriate solutions among many, at first sight reasonable, candidates [4, 5]. The inverse problem in a Tokamak is also far from continuous in the sense that small variations in the inputs can have strong repercussions on the final output. This can result on the one hand in convergence problems and, on the other hand, in unexpected variations in the final topology in regions far from the ones directly affected the input modifications. In this paper, it is shown how the different diagnostic (Magnetics Measurements, Polarimetry and Motional Stark Effect), together with the edge current density and plasma pressure constraints, can have a significant impact on the quality of the equilibrium on JET. Results show that both the Polarimetry and Motional Stark Effect internal diagnostics are crucial in order to obtain reasonable safety factor profiles. The impact of the edge current density constraint is significant when the plasma operates in H-mode. In this plasma scenario the strike point positions and the plasma last closed flux surface can also change even by centimetres with relevant impact on the remapping of the equilibrium-dependent diagnostic and pedestal physics study. On the other hand and quite counter intuitively, the pressure constraint can severely affect the quality of the magnetic reconstructions in the core. These trends have been verified with several JET discharges with the new ITER Like Wall (ILW). The standard equilibrium code run on JET is the latest FORTRAN implementation of the EFIT (Equilibrium Fitting), namely EFIT.f90, and it is the one used in this paper to translate the measurements information from plasma diagnostics into useful constraints for the solution of the Grad-Shafranov equation. For the reconstruction of the plasma boundary, the results have been compared with other codes such as FELIX, which is the reference code for the real-time determination and control of the last closed magnetic surface on JET. More details about these two computational tools are given in section 2.1.

The main boundary conditions for the Grad-Shafranov solution at the edge are the derivatives of the current and pressure profile and they can have a major impact on the quality of the boundary reconstruction. The essential internal constraint on JET is the plasma pressure, derived from the Thomson-Scattering diagnostic and simulations of the fast ion contribution to the plasma pressure. The two diagnostic techniques, used to directly measure the internal magnetic fields on JET, are Polarimetry and MSE. All these systems are briefly introduced in section 2.2 together with the magnetic measurement systems used by EFIT_f90.

The validation of the results has been performed comparing the outputs of EFIT_f90 with a series of measurements independent or not too dependent on the magnetic configuration. The main ones, Infrared Thermography, the Visible Cameras, spectroscopy, together with MHD markers and the Michelson Interferometer are described in section 3. The discharge database and the main settings of EFIT_f90 for the analysis reported in this paper are the subject of section 4.

The effects of the internal measurements and constraints on the boundary reconstructions are described in section 5, whereas section 6 reports the optimization and validation of the global equilibria, investigating the best compromise for both the edge and the core. The discussion of these results from a theoretical point of view and the directions of future investigations are the subject of the final section 7 of the paper.

2. OVERVIEW OF THE EQUILIBRIUM RECONSTRUCTION CODES AND THEIR INPUTS

2.1 GOVERNING EQUATIONS

The free boundary equilibrium for plasmas, described by the Grad-Shafranov equation in toroidal geometry and axisymmetric configuration, is an ill posed problem. The plasma boundary is defined as the last closed magnetic flux surface inside the vacuum vessel of the machine. The Grad-Shafranov equation is derived from the combination of the magneto-static Maxwell's equations, which are satisfied in the whole space in presence of a magnetic field, and the equilibrium of the plasma itself, which is assumed to occur when the kinetic pressure is equal to the Lorentz force of the magnetic pressure. The Grad-Shafranov equation can be expressed in the following form:

$$-\Delta^{*}\psi = \mathrm{r}\mathrm{p}'^{(\psi)} + \frac{1}{\mu_0 r}\,(ff')\,(\psi) \tag{1}$$

in which μ_0 is the magnetic permeability of the vacuum, ψ (r,z) is the poloidal flux p (ψ), is the plasma pressure, f (ψ) the diamagnetic function and prime indicates derivative with respect to the poloidal flux ψ. Δ^* is the linear elliptic operator defined as:

$$\Delta^{*} = \frac{\partial}{\partial r}\left(\frac{1}{\mu r}\frac{\partial}{\partial r}\right) + \frac{\partial}{\partial z}\left(\frac{1}{\mu r}\frac{\partial}{\partial z}\right) \tag{2}$$

EFIT_f90

EFIT_f90 (Equilibrium Fitting) is a FORTRAN code that was developed to solve the Grad-Shafranov equation on the basis of the available measurements. The set of measurements used as inputs for EFIT_f90 are obtained from two different types of diagnostics: a) external-passive: such as magnetic probes and poloidal flux loops; b) internal-active: the Faraday rotation (Polarimetry) and the Motional Stark Effect (MSE). The Grad-Shafranov equilibrium equation is solved using all the available measurements as constraints on the toroidal current density. Since the current also depends on the solution of the Grad-Shafranov equation, the poloidal flux function, equation (1) represents a nonlinear optimization problem. The code determines the source term in the non linear Grad-Shafranov equation by a least-square minimization of the difference between the measurements and their estimates derived from the reconstructed fields.

FELIX

The second code, whose results are reported in this paper, is called FELIX. It is based on the previous code XLOC [6], which was originally introduced on JET in order to provide a fast and accurate determination of the plasma boundary in the neighbourhood of the X-point. This method has been extended to cover the whole plasma boundary and FELIX now routinely provides the boundary for arbitrary plasma configurations. It is also used for plasma shape realtime control on a daily basis. From this code, the main parameters of JET boundary, like the strike point position and the distance from the wall, are determined with a time resolution better than 1ms. Nowadays, after an extensive use and benchmarking with other diagnostics, FELIX provides the most reliable and precise determination of the plasma boundary on JET and is therefore considered the reference code in this respect. On the other hand, with this algorithm it is not possible to compute the internal magnetic flux configuration. At the basis of the calculation are 6th order expansions of the poloidal flux in five sections of the poloidal cross section of the machine: at the top, bottom, inboard, upper and lower outboard parts of the vessel.

The expansions are expressed mathematically by the relation:

$$\sum_{\substack{i=0\\ j=0\\ i+j\leq 6}}^{6} a_{ij}\,\rho^{i}\,z^{j} \tag{3}$$

where $r = R^2 - R_0^{\,2}$, $z = Z - Z_0$, with R the radial coordinate, Z the vertical coordinate, and (R_0, Z_0) the centre of the expansion. The variable ρ rather than $R - R_0$ is chosen because of the symmetry of the Grad-Shafranov equation about the major axis of the torus (R = 0). The coefficients a_{ij} are determined by imposing the vacuum equation:

$$-\Delta^{*}\psi = 0$$

$$\Delta^{*} = \frac{\partial}{\partial r}\left(\frac{1}{\mu r}\frac{\partial}{\partial r}\right) + \frac{\partial}{\partial z}\left(\frac{1}{\mu r}\frac{\partial}{\partial z}\right) \tag{4}$$

and by fitting to the local flux and magnetic field measurements. In addition, the five expansions are constrained to match at chosen points around the vessel [7].

The location of any X-points is found, by solving the equations

$$\frac{\partial\psi}{\partial\rho} = 0 \text{ and } \frac{\partial\psi}{\partial\rho} = 0 \tag{5}$$

The value of the flux at the plasma boundary is then determined by comparing the flux at the X-points with the flux at the 121 limiter points (points inside the private region of the X-points are ignored): the minimum ψ is taken as the value on the boundary of the plasma (I_{plasma}

$$\Psi_{bound} = \min\,(\Psi_{XP}, \Psi_{lim}) \tag{6}$$

2.2 DIAGNOSTICS INPUTS TO THE EQUILIBRIUM CODE AND INTERNAL CONSTRAINTS

This subsection is meant to provide a short description of the main diagnostics used to obtain the equilibrium reconstructions reported in this paper. The main diagnostics used as inputs to EFIT are the magnetic pick-up coils, polarimetry and MSE. The other main internal constraint is the pressure profile. The principal diagnostic used for the equilibrium reconstructions reported in this paper consists of pickup coils measuring the local magnetic field. A pickup coil is a single-turn or multipleturn coil of wire, used to measure the component of the local magnetic field perpendicular to the plane of the coil. The output voltage is proportional to the time derivative of the average magnetic flux linked with the windings. There are several measuring coils subsystems on JET, located in different poloidal and toroidal positions. The main types of coils are flux loops, saddle coils and small pickup coils. The reconstructions of the equilibrium reported in this paper have been obtained with a set of 4 flux loops and a set of 27 saddle coils. Several systems of pickup coils are installed on JET. Each system is typically classified according to its position around the plasma as shown in figure 1. The 135 coils placed inside the vacuum vessel wall are located in 18 different poloidal positions at 8 toroidal angles. Two different sets of divertor coils, for a total amount of 72, are located in the divertor region. Finally, there are 3 inner coils placed in the inner region outboard the plasma, 56 outer poloidal limiter coils in the region on the vessel outboard the plasma and 27 upper coils fitted in the upper part of the vessel. The results reported in this paper have been obtained by EFIT_f90 and FELIX, using a part of all pickup coils available, located in the same poloidal cross section. The positions and names of the coils used in this work are listed in [7]. All the coils on JET have been tested systematically and are considered to be affected by errors of the order of a few percent of the measured value.

The other main diagnostic, whose data have been used to obtain the results reported in this paper, is JET polarimeter. If a linearly polarized electromagnetic wave is sent into a magnetized plasma the following effects occur:

1. Faraday rotation of the polarization plane, proportional to the density times the magnetic field component parallel to the direction of the laser beam propagation.
2. Cotton–Mouton phase shift, proportional to the density times the square of the magnetic field component perpendicular to the propagation direction.

These effects can be described by the following equations:

$$\Delta\lambda \propto \lambda^2 \int n_e \cdot B_{\parallel}\, dz \tag{7}$$

$$\Phi \propto \lambda^3 \int n_e \cdot B_{\perp}^2\, dz \tag{8}$$

In equations (7) and (8), λ is the laser wavelength, n_e is the plasma electron density and $B_{\parallel}$ and $B_{\perp}$ are the components of the magnetic field parallel and perpendicular to the propagation direction of the laser beam respectively. To summarise, traversing a magnetised plasma, a polarised beam suffers a rotation of the polarisation plane due to the Faraday Rotation and acquires ellipticity due to the Cotton-Mouton effect.

On JET, the FIR diagnostic operates as a dual interferometer/polarimeter [8, 9]. The system probes the plasma with 4 vertical and 4 lateral laser beams. The diagnostic provides the line-integrated plasma density measurements, by means of interferometry, and Faraday rotation angle and Cotton-Mouton phase shift measurements by polarimetry. These measurements are preceded by an on-line calibration procedure performed before each shot (using half-wave plates). The calibration of the polarimetric measurements has been significantly improved in the last couple of years [8, 9]. The quality of the measurements is therefore higher than in the past and now an accuracy of about 10% can certainly be achieved. The layout of the instrument lines of sight is shown in figure 2. Due to instrumental issues, the polarimetric chords of good quality available to perform the analysis described in this paper are number 3, 5 and 7.

The ***Motional Stark effect*** diagnostic Technique (MSE) allows measuring the plasma internal magnetic field pitch angle and hence derive the safety factor q throughout the plasma volume. The technique is based on the Stark splitting of a spectral line produced by the electric field associated with an atom's motion across a magnetic field. The Stark components of the line are polarized either parallel or perpendicular to the electric field. In the case of neutral deuterium injected into a tokamak for plasma heating or diagnostic, the direction of the polarization can be related to the magnetic field pitch angle, which can be used in the calculation of the plasma current profile. On JET, the MSE diagnostic sees the neutrals injected by the heating beams. Crossing the plasma magnetic field, the beam atoms experience an electric field of around 5MV m^{-1} and the collisions with plasma ions cause excitation and emission from these atoms with intense radiation, in particular at D_α ~656.3nm. The electric field causes Stark splitting of the energy levels of the atoms which, in the case of hydrogen, is an especially large effect. Emission from different transitions within the Stark multiplet produces line radiation at different wavelengths, which is polarized either perpendicular (σ) or parallel to (p) the electric field. The diagnostic uses the conventional approach of a dual photoelastic modulator (PEM) and the overall layout of the system is shown in Fig.3. In the reconstructions, whose results are reported in this paper, the plasma pressure is calculated as the following scalar sum in the unmodified Grad-Shafranov equation

$$p_{MHD} = p_e + p_i + 0.5\,(p_{perp} + p_{par}) \tag{9}$$

In equation (9), p_e is the pressure of the electron fluid, measured by JET High Resolution Thomson Scattering; p_i is the pressure of the ions under the assumption the temperature of the two fluids is the same. $p_{perp} + p_{par}$ are the parallel and perpendicular fast particle pressures [10]. They are obtained by a set of codes which determine mainly the energy densities of the beam born fast ions. It is worth mentioning that during these last campaigns, due to a lack of good ion temperature data, it has been assumed that T_e is equal to T_i.

3. DIAGNOSTICS USED FOR THE VALIDATION OF THE RECONSTRUCTIONS

This section contains a rapid overview of the main diagnostics used to validate the equilibria obtained with EFIT_f90. In this respect, the most useful measurements have proved to be infrared thermography, visible spectroscopy, the visible cameras, the MHD markers and the Michelson Interferometer. The first three do not depend on the magnetic measurements and therefore can be considered a completely independent validation of the results of the equilibrium reconstructions.

The MHD markers and the Michelson Interferometer make use of the magnetic measurements but also of other information and therefore constitute another very important additional check of the global coherence of the obtained equilibria. Since the following analysis is structured in two different parts, one focused on the reconstruction of the boundary and one on the quality of the reconstruction in the core, also the description of the diagnostics reflects this conceptual distinction. Section 3.1 introduces the diagnostics used to validate the boundary and section 3.2 the measurements used to validate the core.

3.1 VALIDATION OF THE BOUNDARY RECONSTRUCTION

In the last years, the emphasis of the studies of plasma wall interactions on JET has motivated the installation of a series of IR cameras. One of the most advanced is a camera located on top of the machine to perform thermography studies in the JET divertor. The layout of the diagnostic and the view of the divertor are provided in figure 4. The system can measure the emission from the outer strike point and therefore determine its position. The camera has a very high frame rate and is coupled to infrared optics which provides a spatial resolution of the order of a few mm. Given some additional uncertainties, mainly linked to the vibrations of the machine during ELMs, the accuracy in the determination of the strike point position is certainly not worse than 10mm.

Since 1994 JET has had a mirror-link spectroscopy system with a poloidal view of 150mm of the outer divertor; this system is called KT3. The diagnostic can detect radiation in three ranges: near-UV (~300-450nm), visible (450-750nm) and near-IR (750-1200nm). The system consists of 3 Czerny-Turner/CCD pairs: 1-meter focal length for the near-UV, imaging 0.75 m for the visible, and imaging 0.5m for the near-IR. The view of the divertor has been upgraded during the last shut down for the installation of the ILW. The new field of view of the diagnostic is shown in Figure 5. From such a figure it can be seen that the diagnostic now covers a quite large region of the divertor and can be used to detect quite accurately the position of the outer strike point (in the vast majority of the configurations). For this purpose, with the new ITER-Like Wall, the line used to determine the position of the outer strike point is the W1 at 401nm. The spatial resolution of the estimate provided by KT3 is about 2cm.

Nowadays JET is also equipped with a quite impressive set of visible cameras for operation and protection. Some of these cameras see the plasma boundary and can be used to validate the results of EFIT_f90, particularly on the high field side, where noy many magnetic coils are still operational. Figure 6 shows a frame of the visible camera KL1 (KL1-o4wb), in which the plasma boundary on the high field side is clearly visible. Since only a thin shell at the plasma edge around the last closed magnetic surface is expected to emit a significant amount of visible light, it is possible use this emission to try to locate the position of the separatrix. Contrary to MAST, where the camera position and the plasma emission permit to reconstruct completely the separatrix [11] , on JET the KL1 camera allows visualisation of only a small part of the plasma boundary [12]. As shown in Figure 6, only the plasma emission of the lower part of the plasma on the high field side is strong enough to be detected.

In this perspective, the frames of some JET visible cameras have been analysed with the phase congruency method to extract the position of the emission at the boundary [12]. This technique is a consolidated approach to determine the edges in images and is based on the observation that the edges of objects tend to be the regions where the Fourier or wavelet components of the images are most in phase.

In principle, to obtain a reasonable estimate of the distance between the plasma boundary and the limiter, the exact geometry of the camera field of view is required. In the ideal case, a perfect pinhole camera should have its axis normal to the object surface. In the case of the visible KL1 operation camera, the angle between the perpendicular to the camera detector and the poloidal plane containing the inner "Guard Limiter" is almost 90 degrees (95.108^{o}). Therefore the projection of the plane containing the guard limiter on the camera plane implies an almost negligible elongation of the distances on the horizontal axis direction [11]. In any case, the accuracy of the approach has been tested evaluating the position of the internal guard limiter, which appears in the frames. Since the discrepancy between the estimate of the Guard Limiter position derived from the videos and its actual coordinates (obtained from JET CATIA model) is always less than 2cm, this can be considered the error to be associated with the developed image processing method.

3.1 VALIDATION OF THE RECONSTRUCTION OF THE CORE

Whereas edge diagnostics, such as the cameras, can provide a lot of information about the edge, the plasma core of JET is not so well diagnosed. Indeed finding measurements with accuracy good enough to benchmark equilibrium codes in the core is not a simple task. On the other hand, MHD instabilities are often strictly linked to specific magnetic surfaces. They have therefore been used a lot in the past to derive information about the current profile and in general about the magnetic field configuration.

Michelson interferometers are capable of measuring broad band intensity spectra in the microwave and near infrared spectral range. Therefore, this type of diagnostic is routinely used on many fusion devices to probe the full electron cyclotron emission (ECE) spectrum emitted by high-temperature plasmas. On JET the electron cyclotron emission is measured also with a Michelson interferometer diagnostic [13,14]. Since the system is calibrated absolutely, using the hot/cold technique, the interferometer can profile detailed information about the electron temperature profile. The calibration procedure, recently refined, allows performing measurements of very good quality. Statistically, the relative uncertainty is below the 5% level in the spectral range 80-500GHz and even below 2% for 100-350GHz. In JET the diagnostic has a horizontal line of sight in the equatorial plane and it has been always found [14] that the peak of the electron temperature provided by the Michelson interferometer is a very good estimate of the magnetic axis radial position. This potential of the diagnostic can be used to validate the quality of the equilibria as described in section 6.

4. THE DATABASE, H-MODE VERSUS L-MODE AND EFIT_F90 SETUP

The analysis of the results has been performed using a validated database of about 10 JET discharges.

The choice has been mainly driven by the availability of the diagnostics so these discharges are not expected to be biased and cover a quite representative fraction of JET operational space. The analysis presented is therefore considered more than adequate to show the potential of the methodology proposed in the paper. For more specific physical studies, the approach could be of course particularised for the required configurations (of both the plasma and the available diagnostics; see also section 7).

The analysis is typically more focused on the steady state phase of the discharges. Transient phases in principle do not present any conceptual problem but the flat top of the plasma current, when the additional heating systems inject the highest power, is the most challenging for the equilibrium reconstructions. Indeed this is normally the part of the discharge in which the plasma achieves the H mode of confinement. With higher plasma pressure and the strong gradients at the edge, the magnetic topology of H mode plasmas is more problematic to reconstruct than that of L mode configurations. This fact has been systematically verified and confirmed even when, as it is typical on JET, the measurements are of better quality during the steady state part of the discharge. In particular, using the same approach and in particular exactly the same indicators, it has been found that the internal constraints are far less influential during the L mode phase of the discharges, including the transients such as the current ramp up and ramp down. On the other hand, they are absolutely essential to obtain reconstructions of decent quality when the plasma is in the H mode. This is the main reason why the cases reported in the rest of the paper refer mainly to the H mode phase of the discharges

With regard to the diagnostic inputs to the various versions of the code, the basic version of EFIT_f90 utilizes only the pick-up coils (and it is called simply EFIT). The other important version of the reconstruction includes the plasma pressure a constraint (and it is therefore identified by the acronym EFTP). Other runs have then been performed adding also the internal magnetic measurements, mainly the polarimeter (and it is called simply EFTF) and, when available, also the MSE (EFTM). The results of the various EFIT_f90 runs have then been compared with the available independent measurements and with the outputs of FELIX.

With regard to the reconstruction of the plasma boundary, the constraints imposed on p’ and ff’ at the separatrix can have a significant impact on the quality of the final equilibrium. The impact of the basis functions can also be important and therefore both these aspects have to be considered carefully. In the following table I the versions of EFIT, which are routinely run on JET, and their configurations, in terms of basis functions and edge constraints at the separatrix, are reported.

5. EFFECTS OF THE EFIT SETTINGS AND THE PRESSURE CONSTRAINT ON THE EQUILIBRIUM RECONSTRUCTION OF THE BOUNDARY

5.1 EFFECTS OF THE SETTINGS AND INTERNAL CONSTRAINTS ON THE STRIKE POINT POSITION

To assess the effects of the different settings and of the internal constraints on the reconstruction of the boundary, a series of EFIT_f90 runs have been performed. In figure 7 the radial position of the outer strike plot is plotted versus time. The estimates of the various EFIT_f90 runs are compared with the measurements provided by the infrared thermography. The EFIT_f90 estimates have also been compared with the outputs of FELIX.

From figure 7, it emerges very clearly that EFIT can overestimate the strike point position by even 8 cm. EFTP provides by far the best estimate of the strike point position. This improvement is obtained by increasing the degrees of freedom of the code, a combined effect of the different basis functions (tensioned splines instead of polynomials of order 2) and relaxed constraints on f' and pp'. To obtain reasonable converge of EFTP with these settings, it is vital to include additional measurements and the pressure seems to be the best one in this respect. On the contrary, the internal magnetic measurements, MSE and polarimetry, are typically not enough to guarantee a good reconstruction of the strike point position if the pressure constraint is not introduced. On the other hand, these additional measurements do not cause any major degradation of the strike point position determination and, as described in detail in section 6, they are essential to obtain a detailed reconstruction in the plasma core.

The same conclusions can be reached if the position of the strike point is estimated from the visible spectroscopy (KT3), as shown in Figure 8. Again EFTP boundary is in better agreement with spectroscopy than EFIT with magnetic only (and the other constraints, MSE and polarimetry, do not cause any major degradation of the strike point estimates).

The problems encountered by EFIT in detecting the position of the external strike point are confirmed by a comparison with the results of FELIX. As shown in Figure 7, FELIX provides a much better estimate of the strike point position compared with EFIT using the magnetics only. So when the two codes are given a inputs the same measurements, FELIX systematically produces a significantly better estimate of the strike point position. Only by increasing the degrees of freedom. and introducing the pressure constraint, EFTP manages to obtain a competitive estimate of the strike point position. this is due to the fact that the conditions $p' = 0$ and $ff' = 0$ are too rigid to provide a satisfactory reconstruction of the edge for H mode plasmas. On the other hand, they cannot be relaxed without adding additional measurements (see section 7).

The aforementioned trends are illustrated statistically in Figure 9, in which EFIT (magnetic only) and EFTP (with the pressure constraint) estimates of the strike point position are compared with the IR measurements and FELIX. Again, from these histograms it emerges very clearly that the EFTP settings are the best to provide a reasonable estimate of this quantity. In particular the distribution of EFTP residuals is much narrower and better centered around zero than the one of the other versions. This is again the results of the increased flexibility in EFTP ($p' \neq 0$ and $ff' \neq 0$) coupled with additional measurement constraints (see section 7 for a more detailed discussion).

5.2 EFFECTS OF THE SETTINGS AND INTERNAL CONSTRAINTS ON THE BOUNDARY

A more general validation of the boundary, and not only of the strike point position, can be obtained using the phase congruency identification of the emission halo corresponding to the plasma boundary and sometimes appearing in the visible cameras. The statistical basis of these results is not very high, since the halo is not always present in JET videos. On the other hand, when the frames are of good quality, it has been consistently found that the agreement between the position of the boundary determined by EFTP and EFTF agrees better with the cameras than the boundary of EFIT. This is illustrated for an indicative example in Figure 10 for two different Pulse No's: 82080 and 82800 (a traditional H-mode and a 'hybrid' scenario). The images acquired with the visible operation camera during the flat top of the discharges have been analyzed. The separatrix obtained from the various versions of EFIT and the boundary derived from the visible images (green stars) are compared. In the low part of the high field side, the two estimates for the two analyzed shots present always a difference smaller than 10cm. When EFTF version is run, the agreement between the equilibrium reconstructions is better and the evaluation of the boundary position from the camera improves systematically (practically for all time slices), in some cases by several centimeters. The discrepancies between the two estimates of the boundary are unfortunately quite significant. Moreover the absolute value of the discrepancy can change appreciably during a shot and for the moment no clear correlation to explain such behavior has been found. On the other hand, the agreement always improves when EFTP or EFTF are compared with the simple version EFIT using the magnetic pickup coils as only inputs. As discussed in more detail in the last section of the paper, this evidence can be interpreted considering that all the versions of EFIT solve simultaneously the external and internal problem. Therefore adding internal measurements can have a positive effect not only in the core but also in the reconstruction of the boundary.

To obtain a more general overview of the reconstruction of the boundary, the outputs of the various EFIT_f90 runs have been compared with the boundary reconstructed by FELIX. To quantify the quality of the boundary reconstruction, the plasma wall distance is calculated along some predefined directions, called GAPs. The GAPs, used for the validation of EFIT_f90 performed in this paper, are reported in figure 11. The difference between the GAPs calculated by FELIX and EFIT_f90 has been averaged over the H mode phase of the discharges in the database. A typical result is reported in figure 11, from which it is easy to deduce that there is no statistically significant difference in the estimates of the GAP provided by EFIT and EFTP compared to FELIX. The reported statistics is based on 480 shots between Pulse No's: 82200 and 82900.

6. VALIDATION OF THE EQUILIBRIUM RECONSTRUCTION QUALITY IN THE CORE

As mentioned in the introduction, the quality of the reconstructions in the core can be assessed using the MHD markers and the Michelson interferometer. This is the subject of the next two subsections, which show how the measurements of the MSE and polarimetry are essential to obtain acceptable magnetic topologies in the core, since the pressure has a strong detrimental effect on the q profile in the core.

6.1 VALIDATION SURFACE RADIAL POSITION WITH THE MHD MARKERS

The quality of the reconstructions in the plasma core can be verified with measurements of the

MHD instabilities, whose localisation on the q profile can be determined independently from the equilibrium. This approach is based on the fact that magnetic islands due to tearing instabilities give rise to magnetic oscillations, which can be detected by pickup coils at the plasma edge. These oscillations are characterized by toroidal (n) and poloidal (m) mode numbers, associated with the mode periodicity in the torus angles and correspond to surfaces of rational q=m/n values resonating with the island helicity. The identification of the modes can be obtained by Fourier analysis of the pickup coil signals and phase comparison between coils at different toroidal and poloidal locations. In general on JET, given the location of the coils, this approach leads to a clear identification of the n number, whereas the m number is determined with a higher degree of uncertainty.

On JET a main localization technique based on the ECE is now used [15, 16]. The approach relies on the analysis of the temperature oscillations induced on the measurements of the electron cyclotron emission by the magnetic islands rotating inside the plasma. Temperature signals from the JET ECE radiometer are cross-correlated with a reference signal from a Mirnov coil, so that amplitude, phase and coherence are obtained as a function of the plasma major radius. A typical example of this type of analysis is reported in figure 12.

The most striking result emerging from Figure 12 is the very significant disagreement of the q profile in the core obtained with EFTP, compared to the other versions of the code. This is a very consistent result, the case of Figure 12 is quite typical, but gives a quite counter intuitive global picture. Indeed, on the basis also of the evidence of section 5, the main effect shown by EFTP seems to be an improvement in the reconstruction of the boundary and a degradation of the q profile in the core. This is indeed a quite unexpected outcome for the introduction of an internal constraint but it is confirmed by the analysis of the Alfven Cascades (AC). For the discharge reported in figure 13, there is clear evidence of the presence of AC and therefore the q profile is expected to be inverted. On the other hand, again only the EFTF version of the equilibrium does not give a monotonic q profile.

The interpretation of the validation with the MHD activity is linked to the global interplay between the additional measurements, the degrees of freedom and the edge constraints. Indeed it has been shown that the improvement at the edge is due not only to the pressure but also due to the relaxed conditions on p' and ff' and the increased spatial resolution of the grid. On the other hand, this increased number of degrees of freedom causes significant errors in the q profile in the core, if no additional measurements, such as polarimetry, are introduced as inputs.

6.2 VALIDATION OF THE MAGNETIC AXIS RADIAL POSITION WITH THE ELECTRON TEMPERATURE

As mentioned in subsection 3.3, JET Michelson interferometer has often provided a very good estimate of the radial position of the magnetic axis. Moreover it is common knowledge that properly identifying the position of the magnetic axis is a crucial step in providing good magnetic reconstructions. Particularly in the core the quality of the equilibrium is strongly dependant on the accuracy of the magnetic axis position. These reasons motivate the validation of the choice of the weights with an assessment of their effects on the magnetic axis position. Unfortunately the

Michelson interferometer is not properly calibrated for all the discharges of the analysed database. On the other hand, in the cases available, it is quite evident that the polarimetric or MSE inputs are indispensable to obtain a realistic localisation of the magnetic axis. An example is reported in figure 14, where it is shown that only EFTF and EFTM provide an estimate within the error bars (about ±10cm) of the Michelson interferometer measurements.

7. DISCUSSION, CONCLUSIONS AND FURTHER DEVELOPMENTS

A series of equilibrium reconstructions have been run with different input measurements and constraints. These reconstructions have been performed with the last set of EFIT codes indicated collectively with the name EFIT_f90. The main new results concern the systematic analysis of equilibrium sensitivity to the different measurement inputs, edge constraints and basis functions. The simple version EFIT, using magnetics only, polynomial basis functions and forcing p' and ff' to zero at the separatrix can overestimate the strike point position by even 8cm. In general, the full boundary can be poorly identified. The different inputs and constraints of EFTP basically bring the strike point position in agreement with the independent measurements (IR thermography and spectroscopy). EFTF does not show great difference with respect of EFTP in terms of the boundary. Unfortunately the plasma pressure constraint and the increased degrees of freedom of EFTP have a very detrimental effect on the quality of the reconstructions, and in particular on the q profile, in the core. The internal magnetic measurements, polarimetry and MSE, are therefore indispensable to obtain a realistic current profile in the core.

The aforementioned results can be interpreted considering that EFIT_f90 solves a free boundary problem and therefore tries to maximize the fitting of all the measurements at the same time. This problem is mathematically not well posed. Moreover on JET in general the magnetic topology can be quite complex. Therefore, on the one hand sufficient degrees of freedom, in terms of basis functions and $p' \neq 0$ $ff' \neq 0$, have to be provided for EFIT_f90 to converge on realistic equilibria. On the other hand, these degrees of freedom have to be properly constrained by sufficient measurements, particularly of the current profile in the core, otherwise the magnetic topology can be significantly wrong. The most important example is the introduction of the polarimetric measurements to complement the pressure constraint in order to obtain a reasonable estimate of the q profile in the core.

ACKNOWLEDGMENTS

This work, supported by the European Communities under the contract of Association between EURATOM/CCFE/ENEA/MedC, was carried out under the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

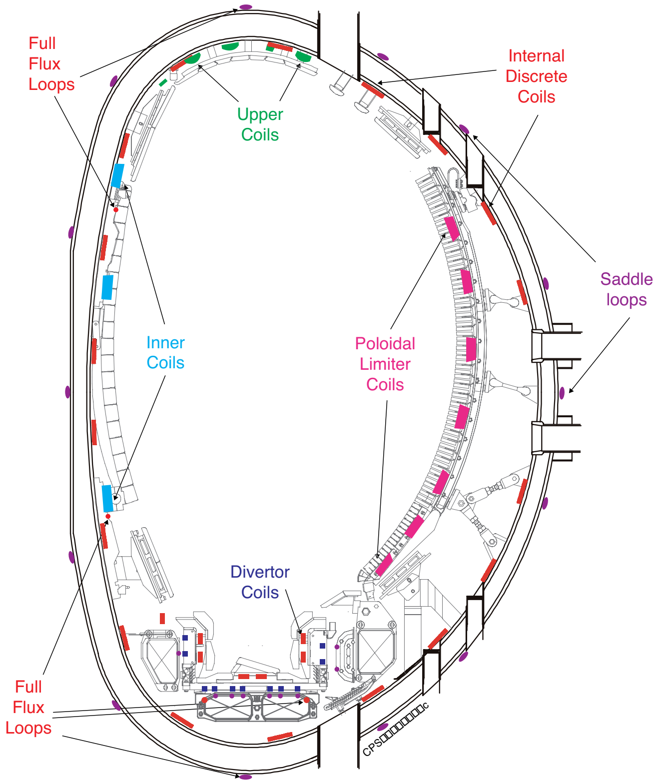
[1]. J.Wesson "Tokamaks" Clarendon Press, Oxford, third edition, 2004

[2]. Lao L.L., et.al., Nuclear Fusion **30**, 1035 (1990).

[3]. Lao L.L., et al. Fusion Science and Technology **48** (2005) 968
[4]. F.S. Zaitsev, D.P. Kostomarov, E.P. Suchkov. Existence of substantially different solutions in an inverse problem of plasma equilibrium reconstruction. 35th EPS Plasma Physics Conference. Crete, Greece, 2008. P-1.091, 4p. (http://epsppd.epfl.ch/Hersonissos/pdf/P1_091.pdf).
[5]. F.S. Zaitsev et. al. Nuclear Fusion **51** (2011) 103044.
[6]. D.P. O'Brien, J.J. Ellis and J. Lingertat Nuclear Fusion **33** (1993) 467
[7]. A.Murari et al Nuclear Fusion **51** (2011) 053012 (18pp)
[8]. M.Gelfusa et al Review of Scientific Instruments **81**, 1 (2010) F
[9]. M.Gelfusa et al Meas. Sci. Technol. 21 (2010) 115704 (11pp) [10] Brix et al, Review of Scientific Instruments **79**, 10F325 (2008)
[11]. G. Hommen, M. de Baar, P. Nuij, G. McArdle, R. Akers, M. Steinbuch1, "Optical boundary reconstruction of tokamak plasmas for feedback control of plasma position and shape", Review of Scientific Instruments **81**, 113504 (2010)
[12]. P. Gaudio, T. Craciunescu, M. Gelfusa, N. Hawkes, I. Lupelli, A. Murari, E. Peluso "Preliminary investigation of the use of visible images to validate the magnetic reconstructionof the boundary on JET" accepted for publication in Fusion Engineering and Design.
[13]. A.E. Costley et al. An Overview of the JET ECE System. Proc. of 3rd Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, 1982.
[14]. S. Schmuck, J. Fessey, T. Gerbaud, B. Alper, M.N.A. Beurskens, et al., Electron cyclotron emission measurements on JET: Michelson interferometer, new absolute calibration, and determination of electron Temperature, Review of Scientific Instruments **83**, 125101 (2012); doi: 10.1063/1.4768246
[15]. S.E. Sharapov, B. Alper, J. Fessey, N.C. Hawkes, N.P. Young, R. Nazikian, G. J. Kramer, D.N. Borba, S. Hacquin, E. De La Luna, S.D. Pinches, J. Rapp, D. Testa
[16]. M. Baruzzo et al 2010 Plasma Physics and Controlled Fusion **52** 075001

	EFIT	EFTP	EFTF and EFTM
Basis Functions	Second order polynomials	Tensioned splines with 9 knots	Tensioned splines with 9 knots
Edge constraints: p' and ff' at the separatrix	Zero value	Non Zero value	Non Zero value
Grid	33×33	33×33	33×33

Table I: The different settings for the various versions of EFIT_f90. By "zero value" it is meant that p' and ff' are forced to be zero at the separatrix (Non Zero value means that p' and ff' are left free).



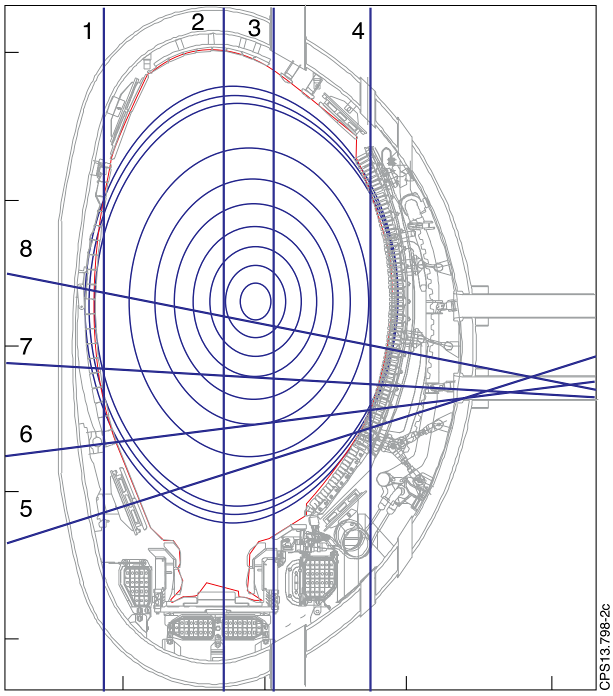


Figure 1: Equilibrium Magnetics: Pickup coils, Saddle coils and Flux Loops

Figure 2: The layout of JET polarimeter lines of sight.

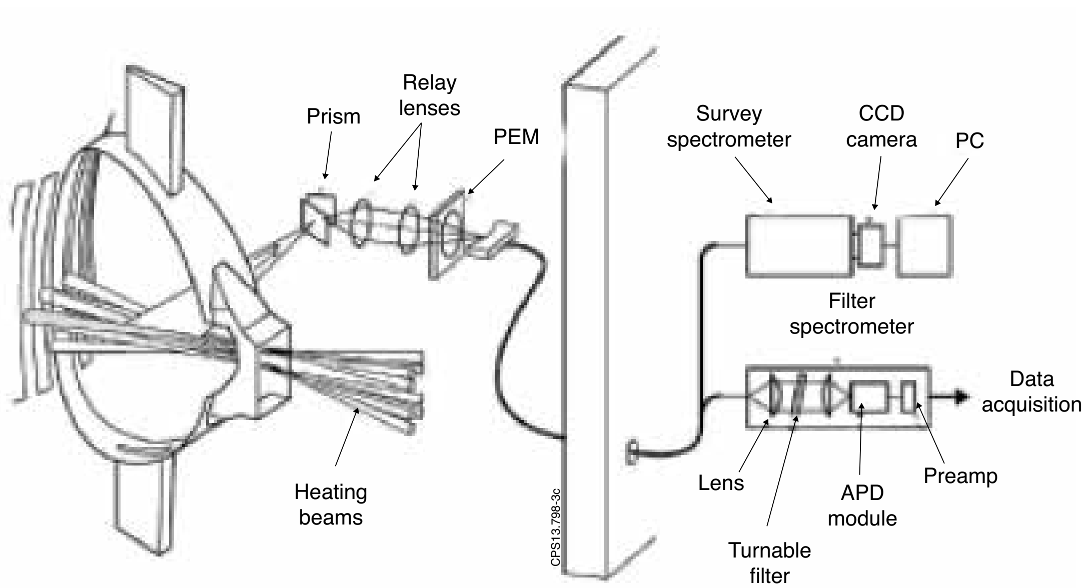


Figure 3: Overview of the Motional Stark Effect (MSE) diagnostic as implemented on JET.

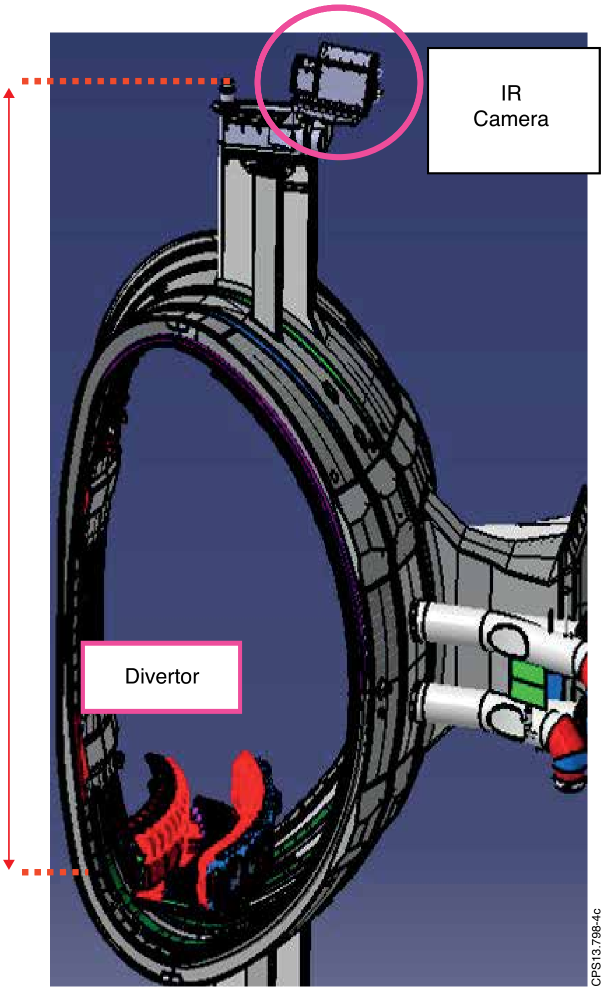


Figure 4: The IR camera located on top of JET to see the divertor.

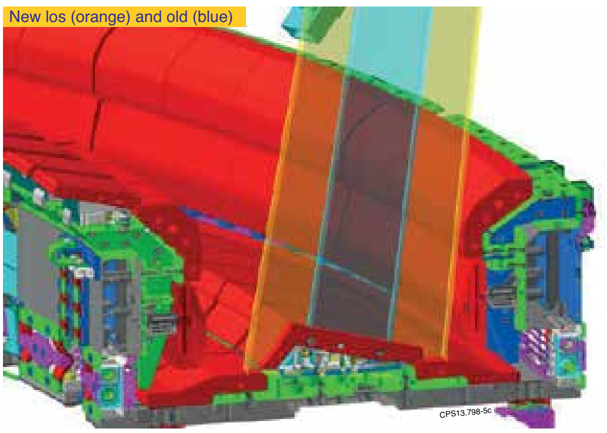


Figure 5: In orange the new KT3 view of JET divertor (in light blue the old one).

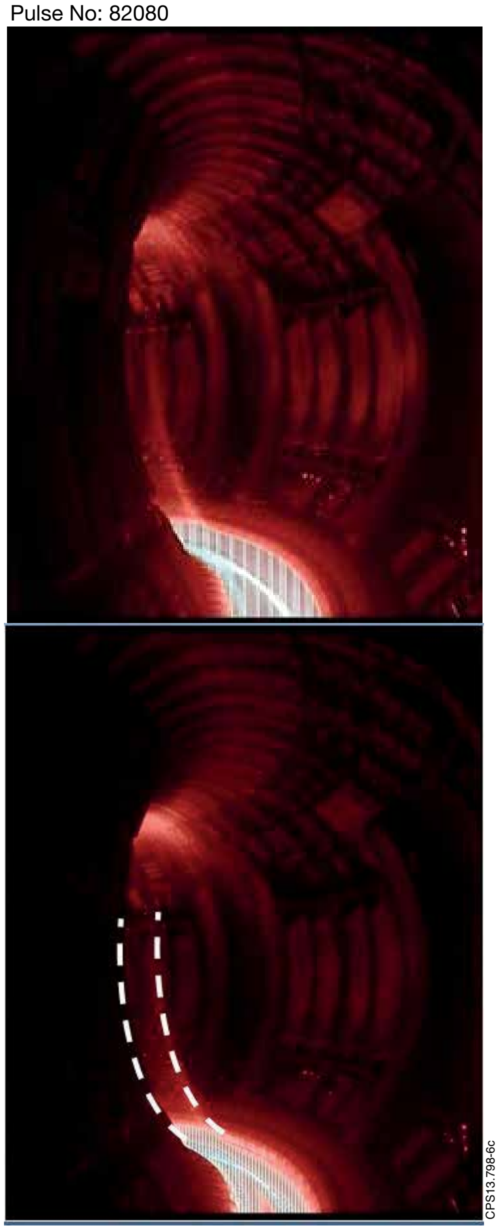


Figure 6: Top: a frame of the operation visible camera KL1. A halo of increased emission, which is believed to indicate the position of the plasma boundary, is clearly visible (shot 82080). Bottom: position of the halo and the poloidal guard limiter identified with the method of the phase contrast.

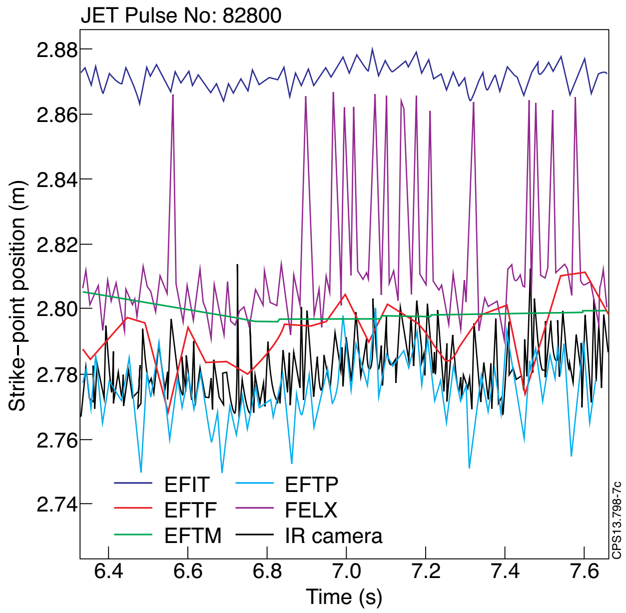


Figure 7: Strike point position. Pulse No: 82800.

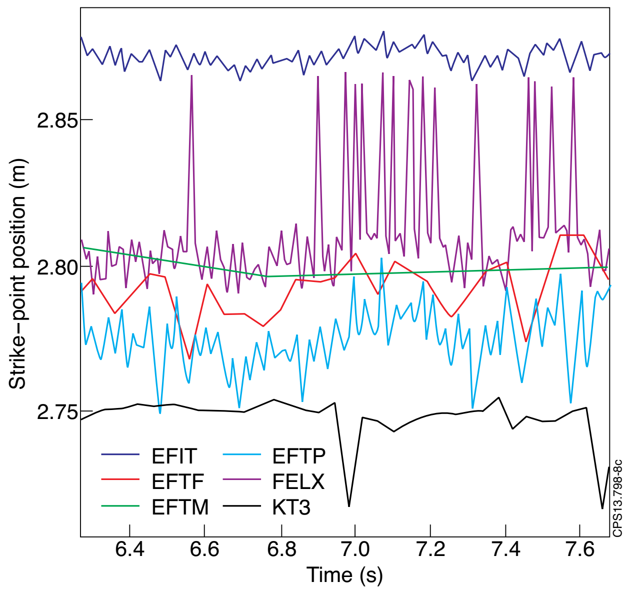


Figure 8: Strike point position from the visible spectroscopy (KT3) compared with the estimates of the various EFIT versions.

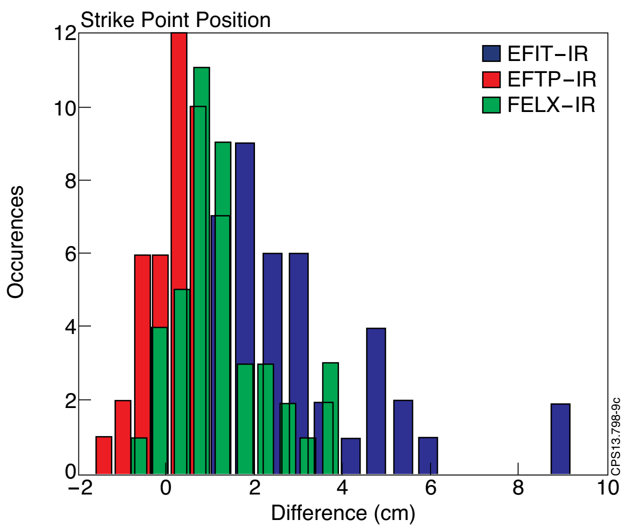


Figure 9: Histogram of the residuals, the difference between the strike point position estimated by EFIT, EFTP, FELIX and the IR measurement. The database used to derive the reported histogram contains about 40 shots.

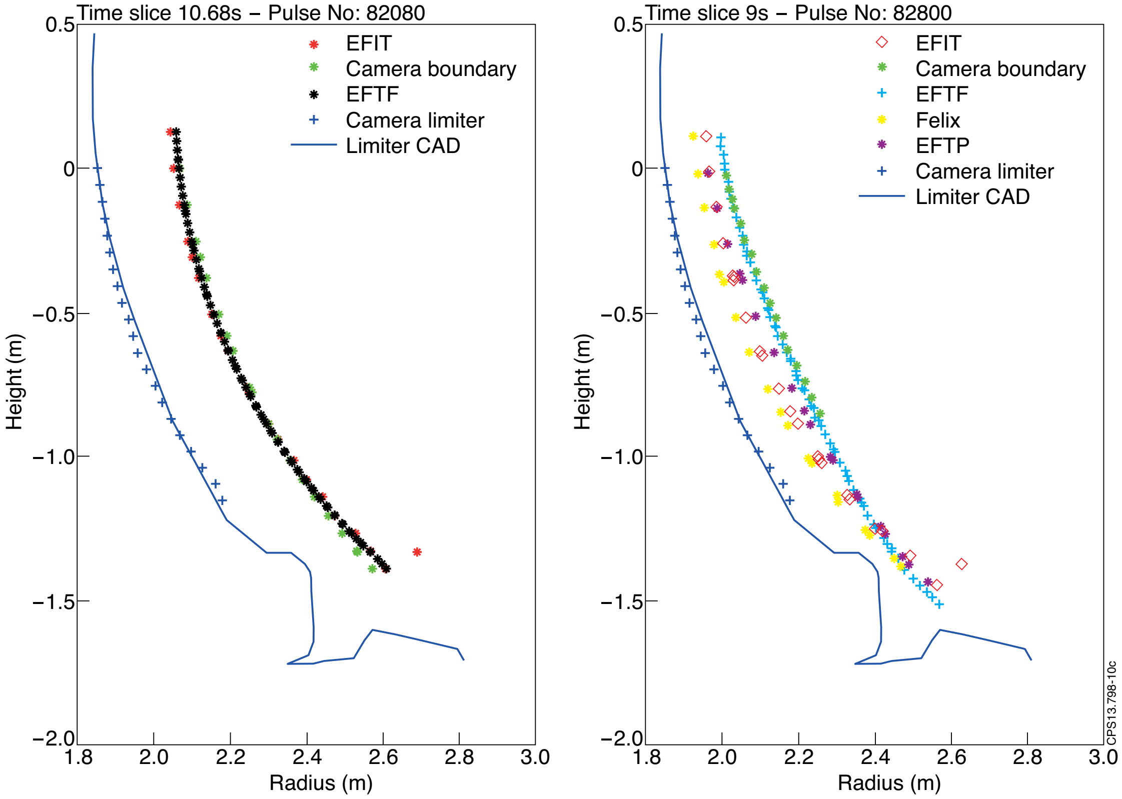


Figure 10: a) left (Pulse No: 82080) b) right (Pulse No: 82800). Comparison between the optical plasma boundary reconstruction and the last magnetic flux surface of the equilibrium code EFIT for a time slice. The coordinates of the inner guard limiter (blue continuous line) and position of the same guard limiter evaluated from the visible images (blue crosses) seem to be in good agreement and confirm the potential of the method adopted for the analysis. The two figures show the comparison of the optical plasma boundary reconstruction (green stars) and the equilibrium reconstruction using only magnetic coils and plasma pressure (red stars) or magnetic coils, plasma pressure and polarimeter measurements (black stars)..

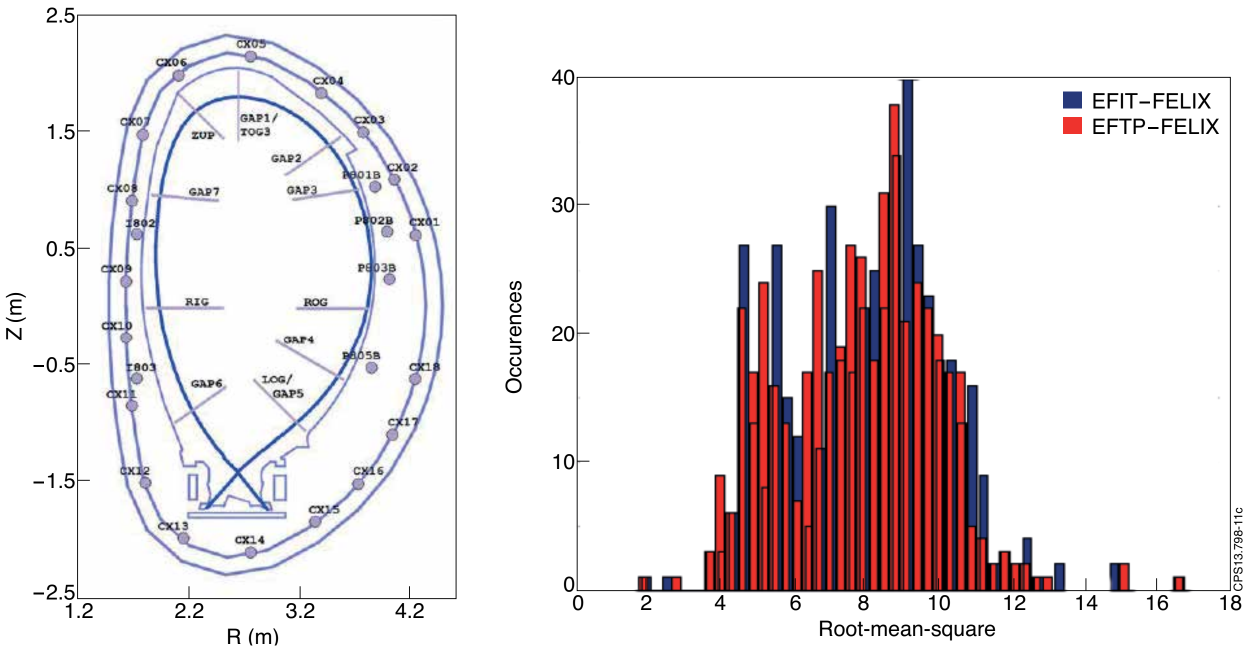


Figure 11: Left: location of the GAPs included in the statistical study reported. Right: histogram of the residuals.

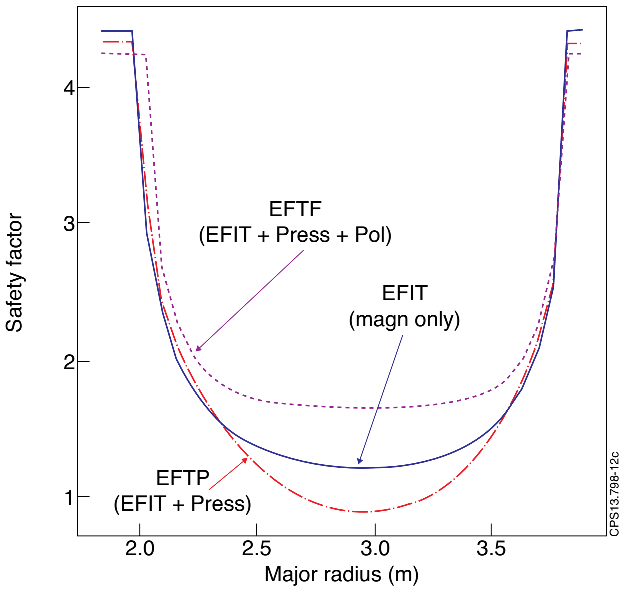


Figure 12: Comparison of the q profile obtained with the various versions of EFIT-f90. For this time slice the q min obtained from the MHD analysis is of the order of 1.5, coherent only with the output of EFTF. SHOT = 82800 – time = 4 sec.

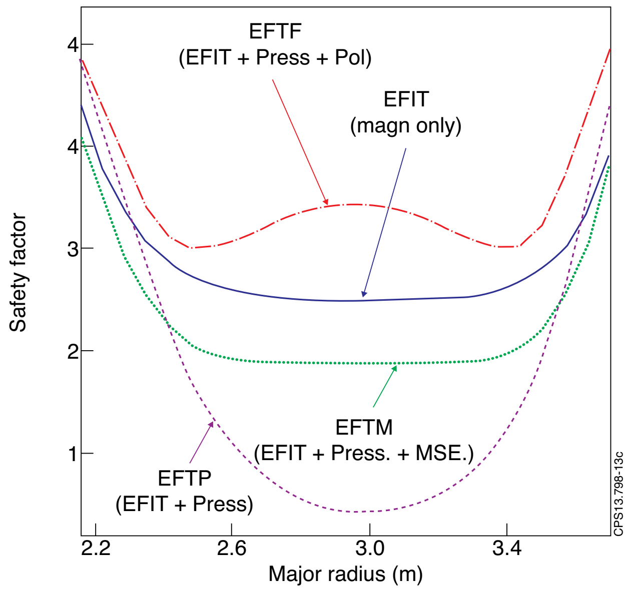


Figure 13: Comparison of the q profile obtained with the various versions of EFIT_f90 for a discharge interval with strong Alfven cascades (AC). The experimental evidence of AC is coherent only with the output of EFTF. SHOT=82700 – time = 4.1 sec.

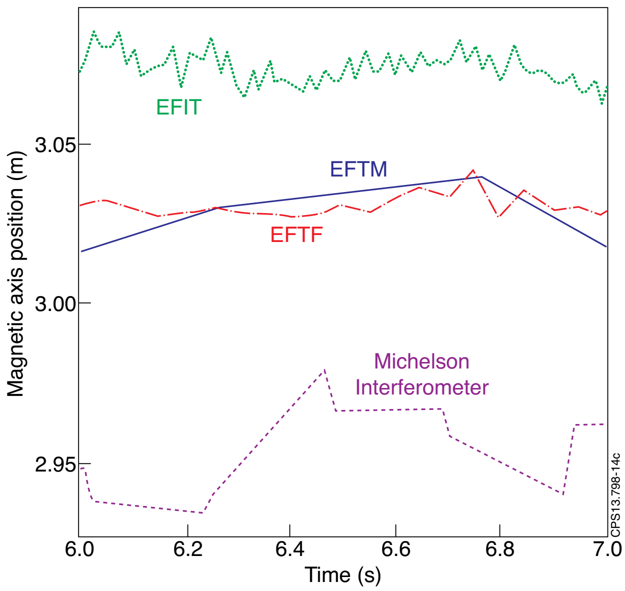


Figure 14: Magnetic axis position. Shot = 82800. The internal constraints are again essential to improve the estimate of the equilibrium codes.