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ABSTRACT
The configuration of the magnetic fields is an essential ingredient of Tokamak physics. In modern day devices, the magnetic topology is normally derived from equilibrium codes, which solve the Grad-Shafranov equation with constraints imposed by the available measurements. On JET the main code used for this purpose is EFIT and the diagnostic more commonly used are external pick-up coils. Both the code and the measurements present worse performance during ELMs. To quantify this aspect, various statistical indicators, based on the values of the residuals and their probability distribution, have been defined and calculated. They all show that the quality of EFIT reconstructions is clearly better in absence of ELMs. To investigate the possible causes of the detrimental effects of ELMs on the reconstruction, the pick-up coils have been characterised individually and both the spatial distribution and time behaviour of their residuals have been analysed in detail. The coils with a faster time response are the ones reproduced less well by EFIT. The constraints of current and pressure at the separatrix have also been varied but the effects of such modifications have not resulted in decisive improvements in the quality of the reconstructions. The interpretation of this experimental evidence is not absolutely compelling but strongly indicative of deficiencies in the physic model on which JET reconstruction code is based.

1. THE RECONSTRUCTION OF THE MAGNETIC FIELDS AND ELM INSTABILITIES

A proper reconstruction of the magnetic topology is a prerequisite to almost every investigation of Tokamak physics. The magnetic fields inside the plasma have indeed a strong impact on the performance of the devices, their operation and the interpretation of diagnostic measurements. In modern day Tokamaks the magnetic topology is normally obtained from equilibrium codes, which solve the Grad-Shafranov equation imposing the equivalence between the magnetic and the kinetic pressure in axisymmetric configurations inside the plasma column [1]. Given the fact that the magnetic fields inside the plasma cannot be measured directly with the necessary spatial and time resolution, the input measurements to the equilibrium codes are typically the external pick up coils. Solving the Grad-Shafranov equation with these constraints is a very complex inversion problem, which still presents various numerical issues and practical challenges.

Given the importance and the difficulties of determining the topology of the magnetic fields in a Tokamak, in the last years a critical review of the results has been undertaken. The existence of multiple solutions is a very important topic, to which new numerical techniques have been recently applied [2]. More advanced techniques to validate the results, adequate to the investigation of nonlinear MIMO systems, have also been recently deployed with interesting results [3]. The high order time correlations of the residuals can also be used to determine the more appropriate weights to be given to the various available measurements, both external and internal [4]. In this paper, the main goal is to assess the consequences of the ELMs on the quality of the equilibrium reconstructions on JET and a first investigation of the possible causes of their detrimental effects.

On JET the main code to solve the Grad-Shafranov equation is EFIT, which is the one used to obtain the reconstructions of the magnetic fields discussed in this paper [5]. A previous investigation of the quality of JET equilibria [3] focused on the systematic analysis of the residuals of the pickup coils, i.e. the difference between the original measurements and the ones reconstructed from EFIT output. The statistical indicators, used in that work, were based on the analysis of the residuals, the difference between the experimental measurements and their estimates based on the equilibrium code. They showed that the reconstructions of the pick-up coil measurements were typically no completely satisfactory. In particular, many coils present a multimodal residual distribution, i.e. a distribution with more than one local maximum, typically two. Moreover the non linear time correlations indicated that the residuals changed qualitatively not only between different discharges but also during the same pulse. This suggests that the presence of systematic errors, always possible, is not the main cause of the discrepancy between the measurements and their reconstruction by EFIT.

A prominent candidate to explain the not completely satisfactory results of the reconstructions are instabilities called ELMs [1]. Since the vast majority of JET plasmas access easily the H mode, they are typically affected by these instabilities. Moreover physical intuition suggests that indeed ELMs can pose additional significant difficulties to both the EFIT reconstructions and the measurements of the pick-up coils. Both are indeed expected to present significant additional problems during the ELMs. With regard to the reconstruction code, it must be remembered that two main assumptions underlie the equilibrium solver implemented in EFIT: toroidal symmetry and equilibrium between the kinetic and the magnetic pressure. The validity of both assumptions is more questionable during ELMs than in ELM-free phases. Indeed ELMs are abrupt instabilities, in which energy and material are rapidly ejected from the plasma. Moreover, in JET, as in other machines, videos of visible cameras show that the ELMs present a non axial symmetric helical component [4]. Another issue with EFIT, which is the one discussed more in this paper, concerns the constraints and how they should be optimised. One constraint particularly important for the evaluation of the ELMs consequences on the equilibrium is the one of zero current at the separatrix. The strong barrier at the very edge of H mode plasmas could not be completely compatible with this assumption. Also an appropriate constraint on the edge pressure can have a significant impact n the quality of the reconstructions.

The pick-up coils, in their turn, are typically surrounded by metallic casings, which constitute a shield introducing a delay in the response of the sensors. Eddy current in the near metallic structures can also affect the response of the coils. These effects are of course more relevant during ELMs, which are fast transients of sub millisecond scale. The measurements of the pick-up coils are therefore also to be considered of lower quality during the fast transients induced by ELMs.

The aim of this paper is to quantify the degradation of the reconstruction quality due to ELMs. To this need, for each discharges analysed, the steady state phase has been divided in ELM periods and ELM-free phases. A couple of examples of the ELMs evolution versus time and the choice of the time intervals affected by the ELMs are shown in figure 1. It has been verified that the obtained results do not change depending on the choice of the intervals supposedly affected by the ELMs (the results are so robust that they do not vary for any reasonable selection of these intervals).

Only the magnetic pick-up coils have been used as inputs to EFIT, since the main results are not expected to change if additional constraints, such as polarimetry, more relevant in the core, were added. The main aspects of the coils and their characterization are described in section 2, together with a short overview of JET version of EFIT. The assessment of the equilibrium quality has been performed with a series of sound statistical tests, which are described in detail in section 3. The analysis of the residuals, the differences between the EFIT estimates and the actual measurements, indicate quite clearly that the reconstruction is strongly affected by the ELMs as also quantified in section 3. To investigate the reasons why ELMs have such a clear detrimental effect on the equilibrium reconstruction, the analysis of the residuals has been particularised for each individual coils, as reported in section 4. With regard to the spatial location in the poloidal plane, the coils in the divertor region are the most affected by the ELMs (see section 4). An additional investigation has focussed on the time response, of the individual coils. This of course is a prerequisite to any analysis of the effects of the pick-up coils time response on the equilibrium quality. The characterisation has been performed using the signals acquired during specifically designed dry shots, in which the currents in the divertor coils have been energised to produce fast transients (see section 4). To interpret the obtained results, in section 5 of the paper the impact of modifying the constraints of current and pressure at the separatrix are investigated. In section 6 the obtained results are summarised and a tentative interpretation is proposed and discussed.

2. OVERVIEW OF THE RECONSTRUCTION CODE TESTED AND THE DIAGNOSTICS USED

The reconstruction of the plasma equilibrium is a free boundary problem, in which the plasma boundary is defined as the last closed magnetic flux surface or separatrix. The Grad-Shafranov equation is derived from the combination of the magnetostatic Maxwell's equations, which are satisfied in the whole space in presence of a magnetic field, and the equilibrium of the plasma itself, which occurs when the kinetic pressure is equal to the Lorentz force of the magnetic pressure.
The Grad-Shafranov equation is typically presented in the following form:

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

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

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

The function $f(\psi)$, on the right of equation (1), is not directly measured.

2.1. EFIT

EFIT (Equilibrium Fitting) is a computer code developed to derive the topology of the plasma internal magnetic fields and the boundary on the basis of the available magnetic measurements. The measurements used as inputs to EFIT can be obtained from external diagnostics such as magnetic probes, poloidal flux loops etc, and from internal measurements, the Faraday rotation and the Motional Stark Effect (MSE). The Grad-Shafranov equilibrium equation is solved using the available measurements as constraints on the toroidal current density. Since the current also depends on the solution of the equation, the poloidal flux function, this results in a nonlinear optimization problem. The equilibrium of a plasma, in a domain Ω representing the vacuum region, is a free boundary problem. The plasma free boundary is defined on JET as being the last closed magnetic surface or separatrix. The region Ω_p containing the plasma is defined as:

$$\Omega_p = \{x \in \Omega, \psi(x) \geq \psi_b\} \tag{3}$$

where $\psi_b = \psi(\mathrm{X})$ in the X point configuration. Assuming Dirichlet boundary conditions, h, are given on $\Gamma = \partial\Omega$, which is the poloidal cross section of the vacuum vessel, the final equations governing the behaviour of $\psi(r,z)$ inside the vacuum vessel are:

$$\begin{cases} -\Delta^* \psi = \left[\dfrac{r}{R_0} A(\overline{\psi}) + \dfrac{R_0}{r} B(\overline{\psi})\right] \chi\Omega_p \text{ in } \Omega \\ \psi = h \text{ on } \Gamma \end{cases} \tag{4}$$

with:

$$A\overline{\psi} = R_0\, p'(\overline{\psi}) \text{ and } B(\overline{\psi}) = \frac{1}{\mu_0 R_0} (f f')\,(\overline{\psi}) \tag{5}$$

where the normalized flux is introduced so that A and B are defined on the interval [0,1]:

$$\overline{\psi} = \frac{\psi - \max\limits_{\Omega_p} \psi}{\psi_b - \max\limits_{\Omega_p} \psi} \tag{6}$$

and $\chi\Omega_p$ is the characteristic function of Ω_p.

By means of least-square minimization of the difference between the measurements and their estimates derived from the reconstructed field topology, the code identifies the source term of the non linear Grad-Shafranov equation.

The results presented in this paper have been obtained with the well known EFIT code described in detail in [6,7]. This version EFITJ contains an iron core model which was validated with a series of dedicated tests also reported in [7]. The profile p' and f' are represented with nine knots cubic splines. The detailed weights used for the various pick-up coils are also given in [6].

2.2. THE MAGNETIC DIAGNOSTIC

The main diagnostics used for the tomographic reconstructions reported in this paper are pickup coils measuring the local magnetic field. A pickup coil is a small cross-section, multiple-turn coils 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 pickup coils subsystems at JET placed in different poloidal and toroidal positions. Each system is classified according to the position as shown in figure 2 and 3. The names of the coils used in this work are listed in [3]. The pickup coils are the only ones on which the ELMs leave a clear signature and therefore these are the ones analysed in the present work. An important diagnostic aspect to be mentioned is the toroidal field compensation, since the poloidal field coils are not perfectly aligned and therefore they can pick up a small but significant part of the toroidal field. To overcome this problem, before any campaign, and in any case after any potentially relevant modifications implemented on the machine, a series of dry shots at various toroidal fields are performed. The detected signals are used to compensate the measurements during plasma shots. This compensation has been performed for all the discharges in the database used in the paper and the results indicate that there is no evidence that the toroidal field compensation is an issue. Indeed, to check the quality of the compensation, toroidal field only pulses have been run and the errors detected are certainly less than 1 % and can be of a few 0.1% during the steady state phase of the discharges (for the magnetic field levels of the discharges discussed in this paper). Moreover the trend of the residuals, both distributions and correlations, with the toroidal field has also been analysed. No trend has been found, which confirms that the remaining errors after the toroidal field compensation should not have any major impact on the quality of the equilibrium reconstructions.

2.3. DETERMINATION OF THE COILS RESPONSE

For the assessment of transient effects, it would be important to know exactly the time response of the coils. This is a delicate issue because the coils are not completely characterised. Moreover the effects of the surrounding structures are very difficult to model. Therefore a practical approach has been adopted. In a dry shot, the currents in the divertor coils have been ramped up and down to generate transients and their effect on the measurements of the coils have been determined. The time evolutions of the currents in the four divertor coils are reported in figure 4. The response of one representative coil to the forcing term, the current in the divertor coils, is also shown in figure 4. The pick-up coil signals acquired during this dry run provide a clear indication of the individual coil dynamics. In reality, as usual, the signals of the pick-up coils are affected by low but appreciable level of noise. Therefore two different approaches have been adopted to determine their time constants from the response to the stimulus of figure 4; both time constants have been determined with appropriate fitting techniques applied to the currents in the divertor coils and to the outputs of the pick-up coils. First, the difference between the rise time of the pick-up coils and the currents in the divertor coils has then been calculated as follows:

$$\tau_{coils} = \tau_{rise\ time\ coil} - \tau_{rise\ time\ current} \qquad (7)$$

Where $\tau_{rise\ time\ coil}$ is the rise time of the current in the pick up coils and $\tau_{rise\ time\ current}$ is the time rise of the current in the divertor coils.

The second approach to the determination of the characteristic time response of the coils involves the determination of the interval between the time the divertor currents reach a steady state and the time the pick-up coils reach the corresponding flat top (the equation is similar to the previous one). Both estimates, the difference in the rise times and the delay in reaching the steady state, can be considered indicators of the coil capability to follow a rapid transient such as an ELM.

3. THE DATABASE AND THE GENERAL OVERVIEW OF THE RESIDUALS

The analysis reported in this paper has been performed on a series of 10 discharges, with different values of the main plasma quantities, covering a quite wide region of JET operational space**;** the plasma current, during the time intervals selected, covers a range from 2.20 MA up to 3.00 MA, while the toroidal magnetic field in varies in the interval between 2 and 2.7 T. In total 350 Type I ELMs have been analysed individually, see table 1 for the details. The results are so consistent, not only for all discharges but also for practically all the coils, that the statistical basis of the conclusions is considered more than adequate.

In order to assess the quality of the reconstructions during and between ELMs, it is important to perform a thorough analysis, with appropriate statistical indicators. With this aim, a parameter called χ_i, defined in the following relation (8), has been used:

$$\chi_i = \sqrt{\textstyle\sum_j (Bi_{meas}(j) - Bi_{rec}(j))^2} \ / \ N \qquad (8)$$

where B_{imeas} is the magnetic field measured by the pickup coils i and B_{irec} the value of the field at the same coil determined on the basis of the EFITJ equilibrium, while the sum is over the number N_i of points used, one for each time slice available for any given shot. An individual χ, which describes the overall quality of the reconstruction for a shot, is then obtained averaging the χ_i for the individual coils:

$$\chi = \sqrt{\textstyle\sum_j (\chi_i)} \ / \ n_i \qquad (9)$$

where n_i is the number of coils used in EFITJ for a given shot. In all the discharges analysed, the parameter χ is significantly higher during ELMs than in ELM free periods. This result is quantified in Table 2. To finally confirm that the different values of χ for the ELMy and ELM-free phases are indeed significantly different, in the statistical sense, the zeta test has been performed. This is achieved by calculating for each shot the quantity:

$$Z = |\chi_{NELM} - \chi_{WELM}|/\sqrt{(\sigma_{NELM}^2 + \sigma_{WELM}^2} \quad (10)$$

In relation (9), χ_{NLEM} is the previous computed χ computed excluding the time intervals with ELMs, while χ_{WLEM} is computed only during ELMs; finally σ_{NELM} and σ_{WELM} are the corresponding statistical errors. In the hypothesis that the pdf of the residuals are Gaussians, if Z is larger than 1.96, then the two values are considered statistically significantly different, with a confidence higher than 95%. As can been seen also in Table 2, for all the shots the Z value is 2.64 or higher. In addition, the quality of the reconstructions during the ELMs are worse than in ELM-free periods since χ_{WELM} is always larger than χ_{NELM}.

To gain further insight into the issue, the statistical distribution of the residuals has also been calculated for each probe. As mentioned, the residual distribution is often multimodal in EFITJ reconstructions. An example is shown in Figure 5a. In the vast majority of cases, one of the peaks is due to the ELMs; this is illustrated in Figure 5, in which the residual distribution of the ELMs (5c) and ELM free phases of the selected discharge are reported for a typical coil (5b). In practice, all or a substantial part of one of the peaks can be ascribed to the errors during the ELMs. This is coherent with what reported in [3], in which it was shown, using linear and nonlinear correlations of the residuals, that it was unlikely that the multimodal character of the residual distribution function could be due only to systematic errors in the measurements. Residuals are indeed too uncorrelated even during different phases of the same discharge to be attributed only to systematic errors in the measurements and have to be linked to the behavior of the plasma, such as ELM instabilities. It is worth mentioning that in figure 5 the distribution of the residuals in the two peaks present a distribution which is very similar to a Gaussian. Therefore the Gaussian approximation at the basis of the Z-test is more than reasonable, even if there are small asymmetries in the pdfs.

4. DETAILED ANALYSIS OF THE INDIVIDUAL COILS RESIDUALS

To gain further insight into the possible causes of the degradation due to the ELMs on the EFITJ output, a detailed analysis of the individual coils is necessary. A careful investigation of the spatial and time dependence of the residuals has therefore been carried out for the individual coils and the results are reported in the next two subsections.

4.1. SPATIAL DISTRIBUTION OF THE COIL RESIDUALS

First of all, the individual χ_i parameter for each coil has been analyzed again, checking if the residuals during ELMs are higher than the residuals during the ELM free periods. Only one coil of one shot has been found have residuals smaller during ELMs. In other words, the better reconstruction during the ELMs free phase, shown in table 2, is not only the result of a mean over all the coils, but also the outcome of each individual probe.

Table 3 reports another test performed for each coil, showing the results of the Z-test applied to the mean values of the two residuals distributions, the ELMy and ELMs free one. As can be seen, it allows assessing when the two pdfs are statistically different.

4.2. TIME RESPONSE AND COIL RESIDUALS

An investigation, complementary to the analysis of the spatial distribution of the coils residuals, consists of assessing whether the coils with less shielding, and therefore shorter delays, are systematically more affected during ELMs.

Systematic tests have been performed, using the data of the dry run mentioned in section 2.3, in which the currents in the divertor coils have been varied explicitly to investigate the time response of the pick-up coils. Both approaches to the determination of the time response of the coils, the difference in the rise times and the delay in reaching the steady state, indicate that there are coils with statistically shorter time response. These times can be related to the difference of the average residuals in the ELMy and ELM-free phases for each class of coils. The correlation between these quantities is shown in figure 6 for a representative shot. Even if there is a certain scatter in the results, a quite solid conclusion emerges from this analysis.

The coils more rapid, the ones on the left hand side of the plots in figure 6, present consistently a larger difference between the mean of their residuals during ELMs and the one in the ELM free phases. This conclusion is the same irrespective of the way chosen to determine the response time of the coils: the rise time or the delay in reaching the steady state (see section 2.3). This means that the fast coils are the ones that EFITJ has consistently more problems to reproduce during ELMs. In the poloidal plane these coils are mainly situated in the divertor region.

5. EFFECTS OF THE CONSTRAINTS IN EFITJ

To shed some light on the issue of the use of EFITJ constraints, it has been decided to intervene on two important constraints to EFITJ: the pressure constraint and the plasma current at the separatrix. The results shown so far in the paper have been obtained imposing the *p*' and *ff*' to be zero at the separatrix (see equation 1). If these two constraints are removed and these two quantities are left free, the results of EFITJ can change significantly, mainly the ELMs free residual distribution can be significantly affected. In figure 7 this is shown quite clearly.

This issue has been investigated running a systematic series of tests. EFITJ has been run varying these two constraints. The results are reported in table 4, where the 00 case indicates that both *p*' and *ff*' are left free to assume the value at the separatrix determined by EFITJ. The classification 11 indicates that both *p*' and *ff*' are constrained to be strictly zero at the separatrix. 01 identify the case when *p'* is forced to zero whereas in the case 10 it is the constraint of *ff'* to be zero at the separatrix which is imposed.

In order to assess whether the increased flexibility given to the code could improve the reconstruction, it has been decided to discriminate between monomodal gaussian distributions and bimodal ones for each coil of each shot and for each combination of the ff' and p' constraints.

The monomodal behaviour has been preferred if the χ value, redefined as

$$\chi = \frac{\sqrt{\Sigma_{i=1}^{n_{bins}} \ (f_i - f_i)^2}}{v} \tag{11}$$

is smaller than the bimodal one or if the two peaks of the bimodal fit are not statistically different ($Z<1.96$). In the previous equation f_i is the value of the function computed in the centroid numbered by the letter i while υ is the number of degree of freedom. This choice allows computing a model independent χ value. The results can be seen in the figure 7 for the four cases analysed. The analysis allows computing the mean number of coils having a monomodal or a bimodal pdfs during the ELMy or ELMs free phases.

Finally it can be stated that, as reported in the tables 4 and 5, relaxing the constraints on *p*' and *ff*' improves the situation slightly particularly in the ELM free periods. In fact, during the ELMs free intervals more coils are better reconstructed and the pdf of their residuals becomes monomodal. On the other hand, no significant change is detected in the number of coils having a monomodal or bimodal pdf during ELMs and the increase in the number of coils presenting a monomodal pdf of the residuals is indeed negligible during ELMs.

6. DISCUSSION AND FURTHER DEVELOPMENTS

In this paper, in the framework of assessing the quality of EFITJ reconstructions on JET, a statistical analysis of the residuals, amplitude and distribution, has been performed and particularized for the ELM-free and ELMy phases of the discharges. This investigation indicates quite clearly that the quality of the magnetic reconstruction is lower during ELMs with respect to ELM-free phases. This result is valid for all the discharges investigated and the statistical relevance of this conclusion is fully supported by the results of the Z-test.

Unfortunately the main cause of the increased inadequacy of the reconstructions during ELMs is much less clear. Three main hypotheses can be formulated: a) the difficulties with the reconstructions of the equilibrium during the ELMs is an instrumental issue, linked mainly to the delay induced on the pickup coils by the shielding and the surrounding metallic structures b) the constraints used to run the equilibrium code, namely the condition of zero current at the separatrix, are less adequate to reconstruct the magnetic topology during ELMs c) the last explanation would identify in the EFITJ code, and in particular in the underlying assumptions of equilibrium between the kinetic and magnetic pressures and the axis-symmetry, the main sources of the degraded quality of the magnetic reconstructions during ELMs.

Discriminating between these alternative explanations is not an easy task. Verifying the last hypothesis would require significant modifications to the EFITJ code, which is beyond the scope of the present paper. On the other hand, interesting indications can be derived by exploring the other two alternatives. A detailed analysis of the coils response has been carried out; it is statistically very evident that the shorter the time response of the coils the worse is their reconstruction by EFITJ. This could be interpreted as evidence that EFITJ has more difficulties to reproduce fast events, which do not satisfy either the constraints or equilibrium and axis-symmetry hypotheses. On the other hand, caution in the interpretation is in place. Since the number of fast coils is quite limited, the fact they are reproduced less accurately could be also a consequence of their being a minority. Since EFITJ performs a minimisation of the residuals in the least square sense, the measurements which are underrepresented can be penalised, as shown in [4]. On the other hand, at the moment on JET there are not enough fast coils operational to perform equilibrium reconstructions only with them.

Varying the constraints on the pressure and current at the separatrix has revealed that the increased flexibility, given to EFITJ when *f'* and *pp'* are not forced to zero, can improve the quality of the reconstructions. On the other hand, the final reconstruction remains far from satisfactory, for example the pdf of the residuals remains bimodal for the majority of the coils.

Overall, not definitive conclusion can be drawn form the performed investigation. However, the modest improvements obtained by relaxing the constraints on *f'* and *pp'* at the separatrix and the reduced capability of EFITJ to reconstruct fast coils strongly indicate that the version of EFITJ run at JET is not completely satisfactory. The approximations of the model implemented (equilibrium, axial-symmetry, no effect of the plasma velocity etc) probably affect significantly the capability of the reconstruction code to properly reproduce the complexity of the physics of JET plasmas. A definitive answer to this point can on the other hand be obtained only by trying to upgrade the code to include more realistic physics.

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Pulse Number	Time interval (s)	Number of ELMs	Number of probes used
75202	t ∈ (52.03, 54.30)	36	54
75203	t ∈ (50.56, 52.56)	26	53
75205	t ∈ (50.49, 52.49)	36	53
75208	t ∈ (56.00, 58.00)	22	52
75209	t ∈ (56.00, 58.00)	24	52
7521 0	t ∈ (54.00, 57.36)	35	51
75229	t ∈ (50.51, 52.51)	57	54
75230	t ∈ (50.55, 52.50)	45	54
75412	t ∈ (56.00, 58.00)	13	53
75554	t ∈ (59.64, 63.01)	48	55

Table 1: Shots and ELMs analysed.

Pulse Number	$\chi_{WELM} \times 10^{-4}$	$\chi_{NELM} \times 10^{-4}$	Z-test
75202	1.51 ± 0.16	9.05 ± 0.97	3.23
75203	1.69 ± 0.17	9.7 ± 1.0	3.65
75205	1.81 ± 0.19	6.49 ± 0.68	5.75
75208	1.70 ± 0.16	8.61 ± 0.89	4.58
75209	1.77 ± 0.16	8.65 ± 0.88	4.96
75210	1.65 ± 0.15	6.50 ± 0.67	6.09
75229	1.35 ± 0.13	9.31 ± 0.91	2.64
75230	1.45 ± 0.14	8.95 ± 0.86	3.38
75412	1.68 ± 0.15	7.94 ± 0.80	5.21
75554	0.95 ± 0.10	5.78 ± 0.62	3.16

Table 2: The χ parameters for 10 shots and the results of the Z -test.

Pulse Number	Probe N° with Z-test inferior to 1.96
75202	Ø
75203	1
75205	3,12,14,15,44,49,6 6,69
75208	Ø
75209	Ø
75210	10,55
75229	66
75230	35,66
75412	55,66
75554	40,42

Table 3: Zeta-test results after comparing the mean values for the two residuals distributions for each probe. For each shot more than 50 probes have been found to work properly and have been therefore included in the analysis.

	ELMs free	ELMy phase
00	17	19
01	14	19
10	17	19
11	8	17

Table 4: Number of coils with monomodal pdf of the residuals: mean over the analysed database for the various constraints.

	ELMs free	ELMy phase
00	37	30
01	39	30
10	37	30
11	45	34

Table 5: Number of coils with binomodal pdf of the residuals: mean over the analysed database for the various constraints.

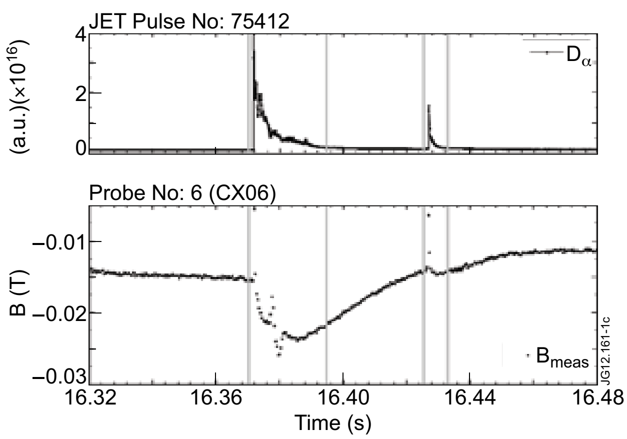

Figure 1:Top: Dα signal during an ELMy H mode phase; Bottom:the experimental measurement of coil CX06 for the Pulse No: 75412. The vertical lines indicate the time intervals assumed affected by the ELMs.

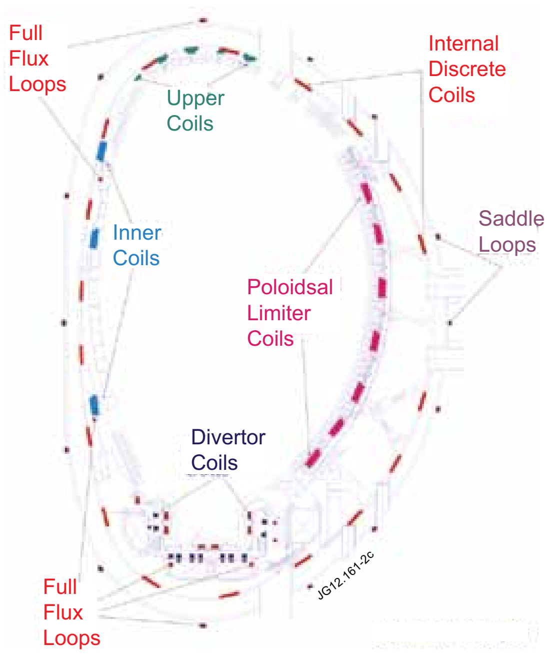

Figure 2: Equilibrium Magnetics: Pick-up coils and Flux Loops.

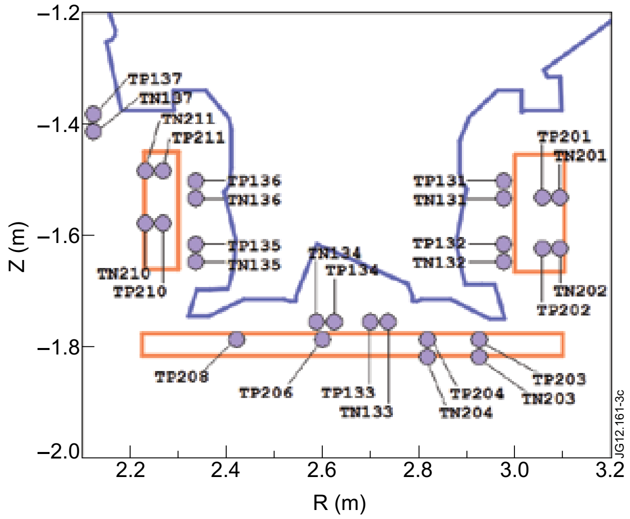

Figure 3: Position of the pickup coils in the divertor region.

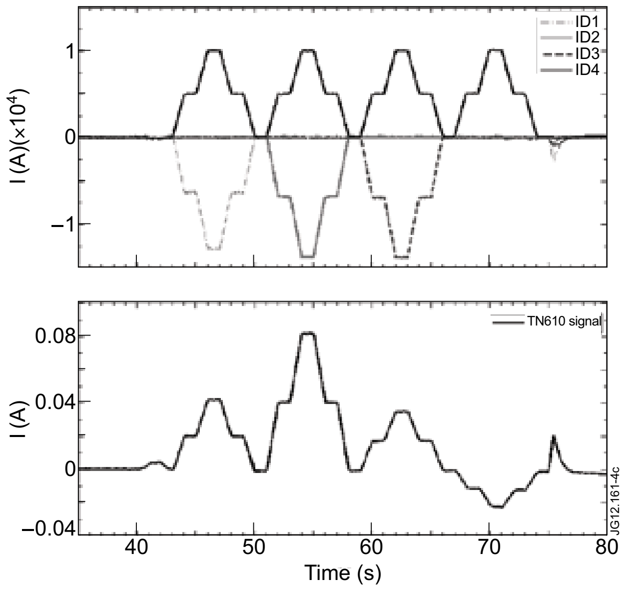

Figure 4: Top: Time evolution of the four divertor coils for the Pulse No: 72120 (dry run).Bottom: example of the signals of a pick up coil (TN610)

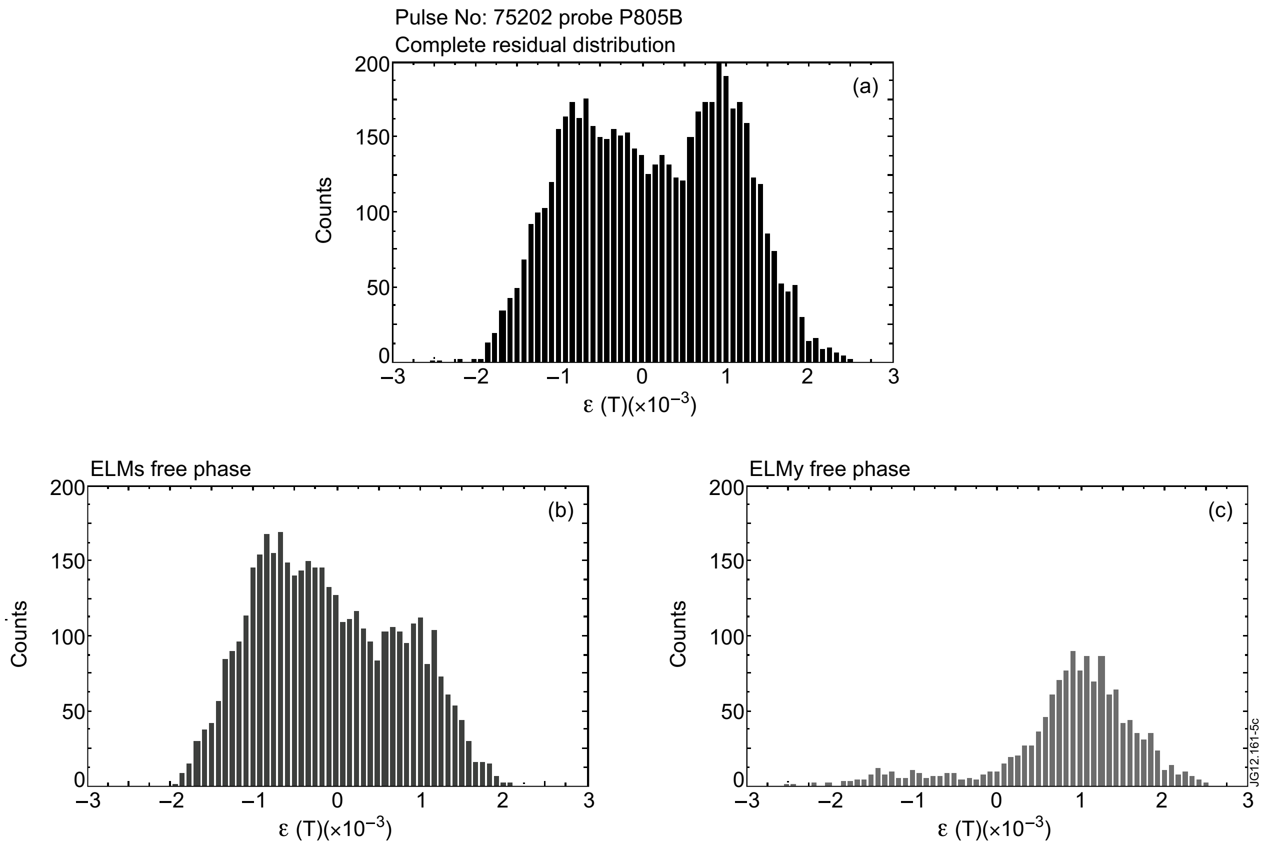

Figure 5 – Residual distributions for the coil P805B of the Pulse No: 75202: a)Total distribution ; b) Without ELMs; c) Only during ELMs.

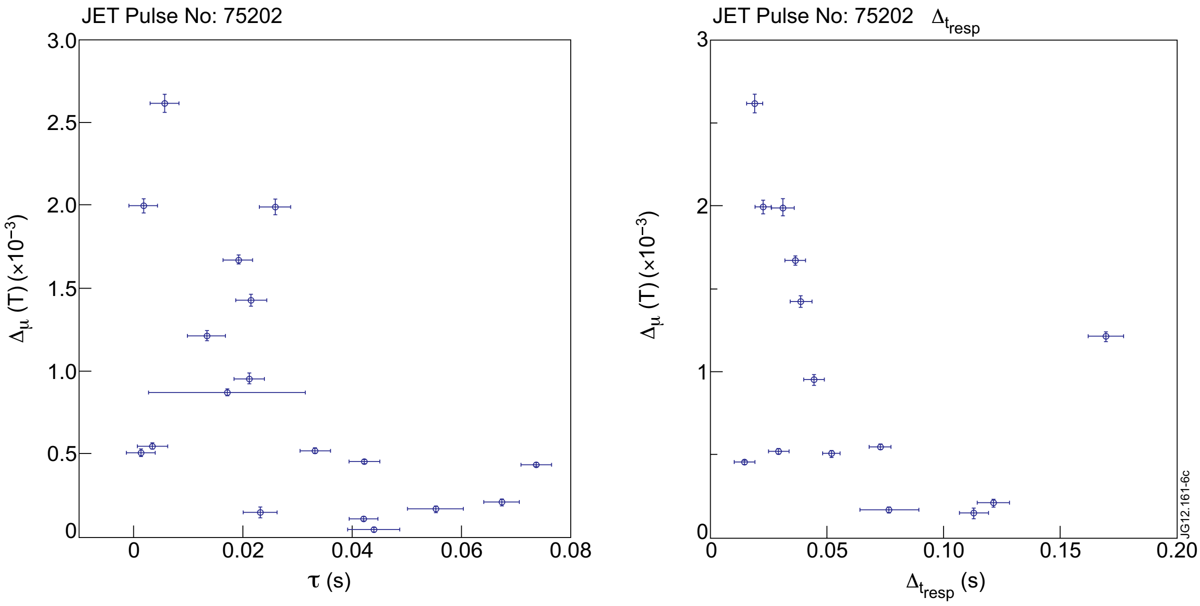

Figure 6: Left: difference Δ_μ of the residuals means between the ELMy and ELM –free phases versus the difference τ between the rise time of the signals of the pick-up coils and the divertor currents. Right: difference Δ_μ of the residuals means between the ELMy and ELM –free phases versus the delay Δt_{resp} in the coils signals reaching the flat top compared to the moment the divertor currents reach the plateau.

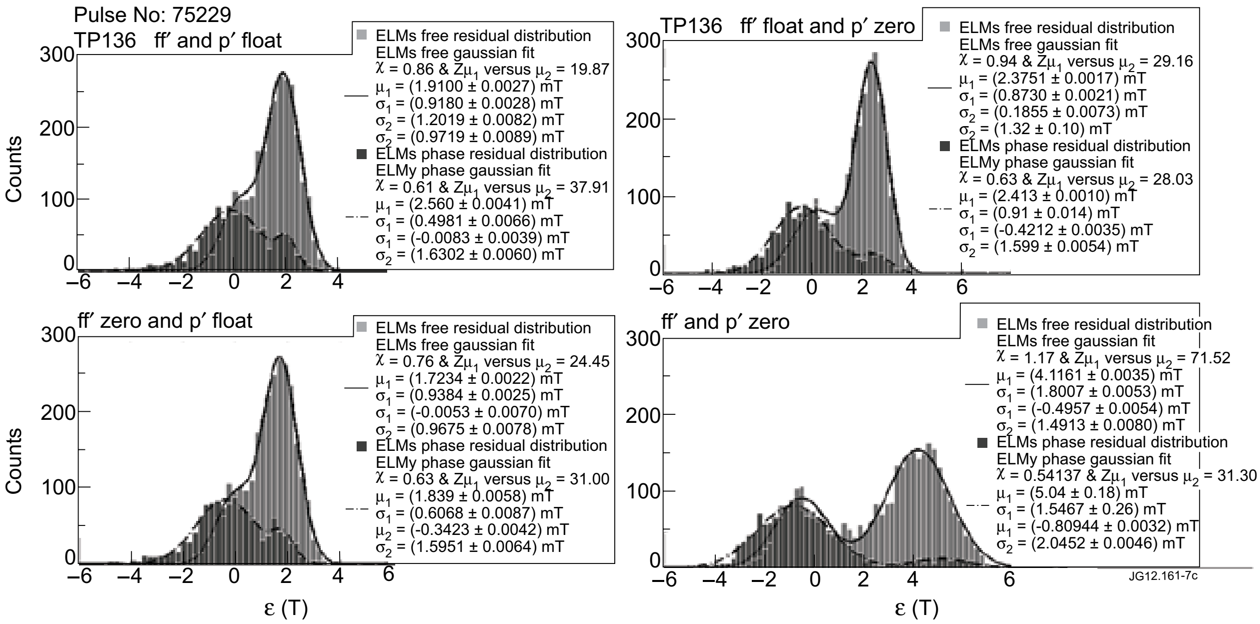

Figure 7: Different behaviour of the residuals of one coil constraints for different constraints on ff' and p' at the edge. Top left: both ff' and p' are free; Top right: ff' is free whereas p' is zero; Bottom left: ff' is zero and p' is free; Top right: both of them are forced to zero at the edge.