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ABSTRACT
On JET the magnetic topology is normally derived from the code EFIT, which solves the Grad-Shafranov equation with constraints imposed by the available measurements, typically the pick-up coils. Both the code and the measurements are expected to perform worse during ELMs. To assess this hypothesis, various statistical indicators, based on the values of the residuals and their probability distribution, have been calculated. They all show that the quality of EFIT reconstructions is clearly better in absence of ELMs. How the responsibility, for the lower quality of the reconstructions, is shared between the measurements, EFIT and its constraints is a subject under investigation.

1. THE PROBLEMS OF EFIT AND THE PICK-UP COILS DURING ELMS

A proper reconstruction of the magnetic topology is a prerequisite to almost every investigation of Tokamak plasma physics. On JET, the magnetic reconstruction is obtained with the code EFIT [1], which solves the Grad-Shafranov equation trying to fit the available measurements. Normally in JET only the measurements of the pick-up coils are used as constraints for EFIT. A previous investigation of the quality of JET equilibria [2] analysed systematically 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 showed that the reconstructions of the pick-up coil measurements was typically of not excellent quality. A candidate to explain the not completely satisfactory results of the reconstructions are the instabilities called ELMs [3]. Since the vast majority of JET plasmas present an H mode phase, they are typically affected by these instabilities.

Both EFIT and the measurements of the pick-up coils are expected to present problems during the ELMs. With regard to the reconstruction code, two main assumptions underlie EFIT: toroidal symmetry and equilibrium between the kinetic and the magnetic pressure. The validity of both assumptions is questionable during ELMs. Indeed ELMs are instabilities, in which energy and material are ejected from the plasmas. Moreover, in JET, as in other machines, videos of visible cameras show that the ELMs are not axial symmetric helical structures [4]. It is also worth mentioning that some constraints used to run EFIT on JET, in particular imposing zero current at the separatrix, could also be even less appropriate during ELMs that during ELM-free phases of the H mode. 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. This delay is of course more relevant during ELMs, which are fast transients of sub millisecond scale. The measurements of the pickup coils are therefore also to be considered of lower quality during the fast transients induced by the ELMs.

With regard to the organization of the paper, in the next section 2, the quality of JET magnetic reconstructions is quantified with statistical indicators in the ELMy and ELM-free periods. The following section 3 is devoted to more detailed investigations to start assessing the relative importance of EFIT inadequacies during ELMs with respect to the problem of the pick-up coils delay.

2. THE STATISTICAL ANALYSIS OF THE RESIDUALS

The typical time evolution of the magnetic signals, during the steady state phase of an ELMy H mode plasma, is shown in Figure 1. The rapid variations of the magnetic measurements during the period of the instabilities appear very clearly. The main diagnostic used for the tomographic reconstructions reported in this paper are pickup coils and flux loops 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: V_{out} ϕ $d\phi/dt$ where V_{out} is the output voltage of the coil and ϕ the magnetic flux through the coil. Flux loops are simply coils of larger surface typically located further away from the plasma. There are several pickup coils and flux loops subsystems at JET placed in different poloidal and toroidal positions. The results reported in this paper have been obtained by EFIT, using all available pickup coils and flux loops available, located in different positions around the machine [2].

The reconstructions presented in this paper poloidal and toroidal positions. The results reported have been obtained by EFIT, using all available pickup coils and flux loops available, located in different positions around the machine [2]. The reconstructions presented in this paper have been obtained with the well known EFITJ code described in detail in [5]. This version of EFIT contains an iron core model validated with a series of tests also reported in [5]. The profile p' and f' are represented by first order polynomials, which is considered the most conservative solution when, as in this paper, only the magnetic measurements are used as inputs to the code.

In order to assess the quality of the equilibrium in the various phases of the discharge, statistical indicators are required. First of all, a parameter called χ, defined in the following relation (1), has been used:

$$\chi_i = \sqrt{\Sigma_j} \, (Bi_{meas}\,(j) - Bi_{rec}(j))^2 / N_i \tag{1}$$

where Bimeas is the magnetic field measured by the pickup coils i and Birec the value of the field at the same coil determined on the basis of the EFITJ equilibrium, while the sum is over is the number Ni of points used, one for each time slice available for any given shot. An individual χ, which describes the overall situation for a shot, is then obtained averaging the χ_i for the individual coils.

A series of 10 discharges, with different values of the main plasma quantities, has been analysed. In all of them, the parameter χ is significantly higher during the ELMs than in the ELM free period. This result is quantified for a series of discharges in Table I. To finally check 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 implies calculating for each shot the quantity:

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

In relation (2), χ_{NLEM} is the previous computed χ computed excluding the time intervals with ELMs, while χ_{WLEM} is computed only during ELMs; finally χ_{NELM} and χ_{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. Figure 2 shows that the Gaussian approximation is more than reasonable, even if there are small asymmetries in the pdfs indicating the presence of systematic errors. As can been seen also in Table I, 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_{WLEM} is always bigger than χ_{NLEM}.

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 2a. In the vast majority of cases, the second smaller peak is due to the ELMs; this is illustrated in Figure 2, in which the residual distribution of the ELMs (2c) and ELM free phases of the selected discharge are reported for a typical coil (2b). In practice, all or a substantial part of the second peak can be ascribed to the errors during the ELMs. This is coherent with what reported in [2], 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 discharges 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.

3. INVESTIGATION OF INDIVIDUAL COIL BEHAVIOR

The analysis of the residuals, amplitude and distribution, indicates quite clearly that the quality of the magnetic reconstruction is lower during the ELMs with respect to the ELM-free phases in JET. This conclusion is valid for all the discharges investigated and the statistical relevance of this conclusion is supported by the results of the Z-test.

Less clear is the main cause of the increased inadequacy of the reconstructions during ELMs. A possible culprit is the delay induced on the pickup coils by the shielding and the surrounding metallic structures. Another cause could be the assumption of equilibrium between the kinetic and magnetic pressures at the basis of the Grad-Shafranov equation and therefore of EFITJ. Moreover, some of the constraints used to run EFITJ on JET, such as imposing zero current at the separatrix, could also strongly contribute to decreasing the quality of the reconstructions during ELMs. Discriminating between these two hypotheses is not an easy task but certainly a closer look at the behaviour of the individual coils could shed some light on the issue. To this end, the χ_i parameter for the individual coils has been analysed again using the Z-test. This allows determining for which coils the χ_i are statistically different and therefore which individual coils are less accurately reconstructed during ELMs. In Table II the results of the Z-test, as applied to the mean values of the residuals distributions with or without ELMs for each shot, are reported. Practically all the coils are better reconstructed in the ELM-free period and therefore this analysis does not really allow discriminating between the two hypotheses. As a consequence, even if the analysis of individual coils is very informative and adds confidence to the conclusion that the reconstruction of the magnetic topology is of lower quality during ELMs, additional investigations are required to determine which is the real cause of the problem. A complementary approach consists of assessing whether the coils with less shielding, and therefore shorter delays, are systematically more affected during ELMs. Preliminary tests have been performed, using data of a dry run, in which the currents in the divertor coils have been designed explicitly to investigate the time response of the pick-up coils. They indicate that there are coils with statistically shorter time response and that the residuals of these coils during the ELMs have an average value significantly more different from zero.

ACKNOWLEDGMENTS

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Shot number	$\chi_{WELM} \cdot 10^{-4}$	$\chi_{NELM} \cdot 10^{-5}$	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 1: The χ parameters for 10 shots.

Pulse No:	Probe N^{O} with Z-test inferior to 1.96
75202	Ø
75203	1
75205	3,12,14,15,4 4,49,66,69
75208	Ø
75209	Ø
75210	10,55
75229	66
75230	35,66
75412	55,66
75554	40,42

Table 2: 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.

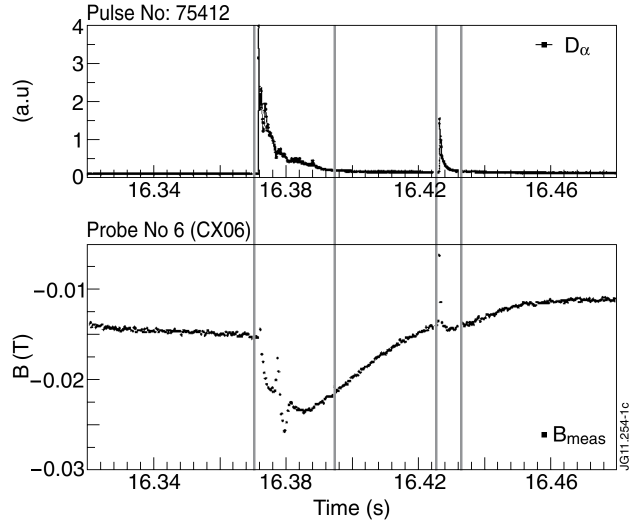

Figure 1: Top: D_α signal during an ELMy H mode phase; Bottom:the experimental measurement of coil CX06 for the Pulse No: 75412. The vertical lines indicate the time intervals assumed affected by the ELMs.

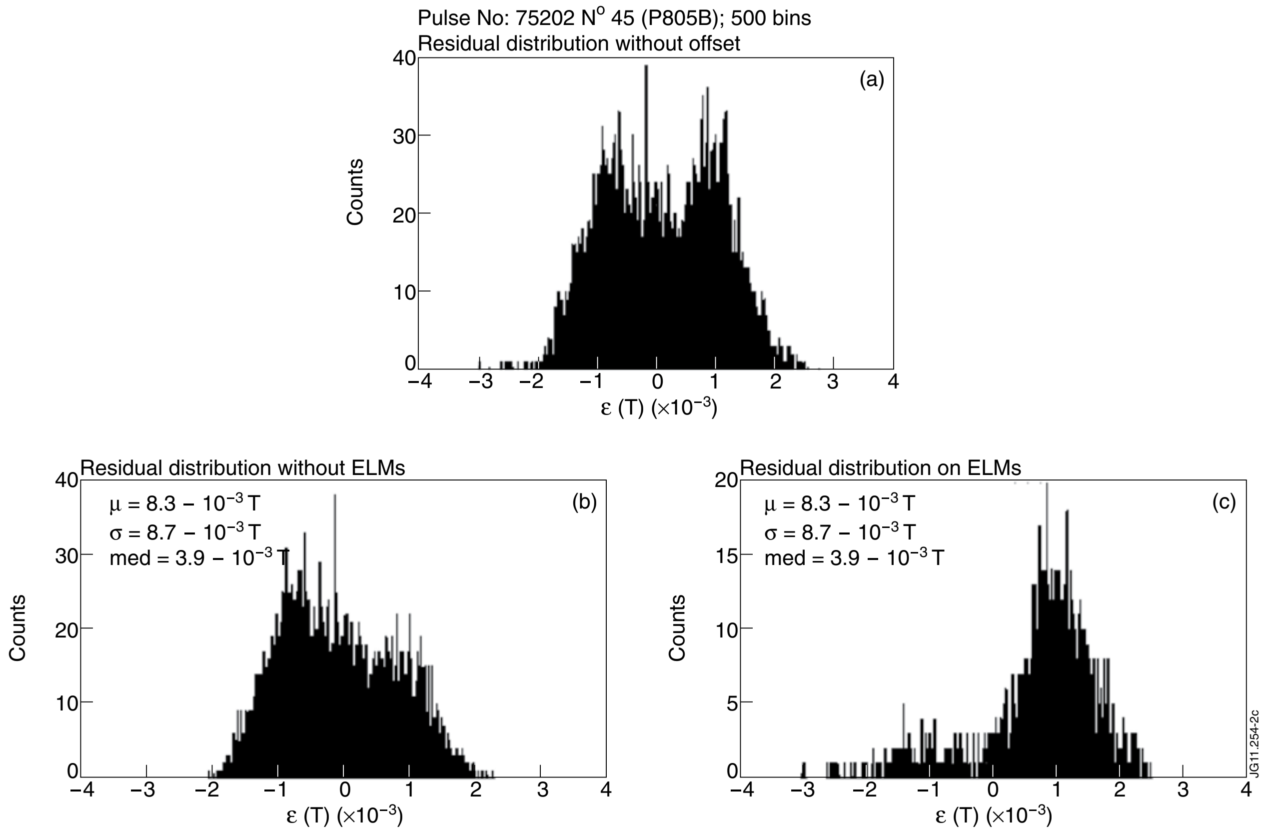

Figure 2: Residual distributions for the coil P805B of the Pulse No: 75202: a)Total distribution ; b) Without ELMs; c) Only during ELMs.