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ABSTRACT.

Fast magnetic pickup coils are used in forward modeling to match parameters in a simple ELM filament model. This novel method allows to determine key parameters for the evolution of the ELM filaments, as effective mode number, radial and toroidal velocity and average current from standard magnetic diagnostics. Potential consequences of the localised removal of current from the pedestal are discussed.

INTRODUCTION

Tokamak devices usually work in a regime with improved confinement (H-mode) resulting from a transport barrier at t he edge region. The H-mode is forseen as the baseline operating scenario for ITER, leading to sustained fusion in a magnet-ically confined plasma. The edge transport barrier is subjec t to cyclic breakdowns known as Edge Localised Modes (ELMs), which deposit large amounts of energy (up to 1MJ on JET) to-ward the plasma facing material components. Handling these short and spatially localised powerfluxes poses strict dema nds on the design of tokamaks. Compatibility with material limits seems at present to demand control and mitigation of ELMs for fusion power producing devices. Therefore understanding the origin and development of ELMs is of utmost importance. The ELM is at present to be thought to originate from a com-bination of current and pressure gradient driven MHD modes [1]. ELMs are commonly identified by using integrating diagnostics, such a D_α radiation from the plasma edge. Only more recently and with the advent of fast cameras, the spa-tial fine structure of the ELMs has become accessible. It is now widely clear that an ELM event results in a low number ($n \approx 10–15$) of filamentary structures [2–5], which are well localised perpendicular to and extended parallel to the mag-netic field, to be expelled from the edge into the Scrape Off Layer (SOL). The filaments, which carry only a part of the en-ergy released during an ELM event, then propagate through the SOL, where they can be measured using f.x. Langmuir probes [6] or by observing their power load signature on the divertor targets [7].

Here we present results from a novel forward modeling method to characterise ELM filament properties based on a simple model for the outboard midplane part of the ELM fila-ments. We utilise fast magnetic pickup coils in the wall of the tokamak vessel. These measurements take place far from the filaments in comparison to the radial extend of theses structures. This makes it generally difficult to observe or to reconstruct the magnetic perturbation going along with individual filaments, so that it is challenging to examine the magnetic fine structure of the ELMs in that way. Moreover the coils pick up magnetic field fluctuations arising at a multitude of locations with varying frequencies. We thus consider only the low frequency part of the magnetic signal during an ELM. We assume that it originates mostly from the motion of the current carrying filaments. Our strategy is to use an ad-hoc mode l for the ELM filament current and to fit the free parameters in that model to observations from a number of magnetic pick up coils. More specifically we prescribe the current density in a magnetic field aligned filament to be centered at the outboard midplane with a Gaussian shape and halfwidth of about 30 degrees, motivated by investigations in Tore Supra [8] and in accordance with recent results reported from DIIID [9]. The poloidal shape of the current distribution assumed is shown in Figure 1. The model assumes n such filaments, toroidally spaced equidistantly, to be present. The current density is as-sumed to decay linearly with a decay rate a_j to zero. The filaments are further assumed to rotate toroidally with velocity v_ϕ, the velocity being subject to toroidal acceleration. Shaping of the plasma was ignored and a simple circular cross section torus prescribed for the geometry. From these assumptions the change in the magnetic field at the position of the magnetic pickup coils was calculated. The coils in the JET tokamak vessel considered are from the toroidal coil array positioned at the same poloidal angle ($\theta = 47.3^o$) and at toroidal angles $\theta = 2,97^o$, 77^o ,$222^o$and named T001, T003/H301, and T008 respectively. Their poloidal position in the vessel can be seen from Figure 1. Note that the model does not prescribe a closed or selfconsistent current distribution, as the probes measure close to the outboard midplane it is sufficient to describe th e local current density in that area. Taking more probes into consideration, however, might with time contribute to a better understanding of the whole edge current system during ELM events.

The raw magnetic signals from the coils show a plethora of magnetic activity, with very distinct broad spectrumevents coinciding with peaks in the divertor D_α radiation used to identify ELM events. To extract the low frequency components from the raw signal wavelet filtering was used and all signal components belonging to frequencies above 30kHz were removed, the cutoff frequency chosen at a change in the slope of the wavelet energy spectrum, with typically less than one percent of the energy in the frequencies which were cut off. ELMevents were taken from pulses of a JET session aimed at studying carbon ablation by large Type I ELMs, with characteristically $B_{tor} = 3$ T at 3MA, with between 16 and 19MW heating by neutral beams. Specific ELM events were selected on the basis of absence of any significant MHD activity in the low frequency range in the time before and after the ELM event. Thus Figure 2 shows the raw and filtered signal from Pulse No: 70223. The high frequency signal contains f.x. any activity of Alfvénic type associated with the ELM perturbation. It can be noted that the raw signal sometimes reaches saturation, a fact that we assume not to put significant restrictions on our analysis. Figure 3 shows the synthetic signal and the experimental one from coils T001 and H301, respectively. The data are taken from Pulse No: 70737 at t = 41.4398s. Using the filtered magnetic signals the model parameters were varied to give the best fit against the data. To have a measure of the deviation of the synthetic signal based on the model from the experimental data we calculate the normalised error as

$$\varepsilon_{probe}(T) = \frac{\int_{t_0}^{T} (\dot{B}_{Probe} - \dot{B}_{mod})^2 \, dt}{\int_{t_0}^{T} \dot{B}_{Probe}^2 \, dt} \tag{1}$$

This error norm is used to quantify the optimal match of parameters within the model assumptions and should not be interpreted as an absolute measure of the quality of the fit. For example it would be rather simple to improve the quality of the fit by introducing more free parameters, one of the most obvious ones would be to individually vary the current or the toroidal position of each filament. We have abstained fromdoing so to keep the number of fitting parameters and model assumptions as small as possible. Instead we consider the variation of the error norm as an indicator for a match with the experimental data within the model. In Figure 4 the dependence of the error with change of the number of filaments and the toroidal velocity in the model is shown. The dependence on the number of filaments n and their toroidal velocity vf is clearly connected as combinations $v_{\phi}n = const$ will reproduce the same number of peaks in the signal, nevertheless the error norm shows a clear absolute minimum. Final values for the model are taken to be the ones that minimize the overall error. According to the fitting analysis, this ELM generates n = 10 filaments which travel outward with a constant radial velocity $v_r = 310$m/s. They rotate toroidally with an initial speed of $v_{\phi} = 52$km/s, the toroidal velocity decreasing linearly with a constant deceleration of $a = 1.410^{7}$rad s^{2}. One should note that this velocity is not directly relatedt to the toroidal plasma velocity in the pedestal, as the motion of a one dimensional filament structure is a combination of parallel and perpendicular plasma motion, with the perpendicular to the magnetic field component determined by the local radial electric field. Each filament carries a current whose peak at $t0$ and at the mid-plane is I_{peak} =320A. The filament current decreases linearly with a factor $AJ = 2900$A m^{2}/s. Thus the current ceases after $t = 350\mu$s. The synthetic signals match very well the de-noised signals spikes, which are produced by the various filaments passing the probes, even though the error norms are 65% and 80% respectively, mostly originating, however, from mismatches in the tail of the signal.

A database containing 30 ELM events without surrounding MHD activity from JET Pulse No's: 70221 to 70226 and from Pulse No: 70737 ($B_{tor} = 2.2$T at 1.6MA with 9MW neutral beam heat-ing) was constructed, for each ELM event carefully adjusting the parameters of the synthetic data. This allowed statisti-cal evaluation of the fitting parameters. Figure 5 shows the obtained histograms for various fitting parameters. The actual values of the fitted parameters can be compared to ELM filament data obtained varying methods, such a probe mea-surements and fast camera observations. It should be noted that most of these methods measure usually a subset of the characteristic values fitted here, and we use the reference v alues given by other machines to see if this new method provides values which are in the right order of magnitude. The number of filaments observed is in good agreement with other observations on tokamaks, such as MAST n = 7-15 [2] , Alcator C-MOD n = 5-15 [10] and Asdex Upgrade $n \approx 15$ [11]. For the radial velocities a rather wide distribution is found, the actual values being of the same order of magnitude 250-300 m/s, but a bit smaller than the ones reported from probe measurements on JET 1km/s [12], while the smaller Asdex Upgrade reports 450m/s [11], and DIIID values between 150m/s and 140m/s [13]. Due to the fact that probe measure-ments potentially pick up the peak velocity inside the filament structure they might overestimate the overall radial velocity by which the filament as a whole moves radially. The variation in toroidal velocity is even larger, but clusters around a few tenth of km/s, where from magnetic signals correlations ASDEX Upgrade recently reported about 100km/s [14]. From the time the filaments are seen with the magnetics, their toroidal velocity decreases and the distribution of toroidal deceleration factors is presented as well. One should note that the large amount of deceleration means that further away from the separatrix the toroidal velocity has dropped to about 20-30km/s for JET. This value compares to 15-20km/s for MAST [15], 10-20km/s on ASDEX Upgrade [11] or about 22 km/s reported from DIIID [13]. Interesting is naturally the amount of current car-ried in a filament, where the peak value seldom exceeds about 400 Amperes. MAST [2] has reported values modelled on a single filament in agreement with 190 Amperes peak current.

The order of magnitude for the current in the filaments is however too low to allow for the filaments to cause very large deviations of the magnetic field lines from their steady state equilibrium positions, indicating that at least in the propaga-tion phase of the filament it is no longer magnetically con-nected to the pedestal [16].

However, one has also to consider that the ELM filament, as it leaves the edge, leaves behind a hole in the edge cur-rent shell, as it would leave behind a hole depleted of pres-sure. The size of the hole corresponds to the amount of cur-rent that the filament convects out. It is perceivable that this local perturbation in the edge current stays behind for a time and arranges for locally increased transport from the affected edge region into the SOL. Thus there would be an increased transport over the last closed flux surface for as long as it ta kes for the edge to dissipate these current hole structures, which arise in the early phase of the ELM event. The hole structure would propagate radially inwards, filling rapidly both due to perpendicular diffusion, but more importantly due to fast parallel inflow at the high pedestal temperature. This would lead to a much lower lifetime of the hole structures compared to the filaments. At this point one can only speculate that if the hole structure reaches a low rational q surface its lifetime could be long enough to lead to actual observation. First on a rational q surface the hole-filament would close on itself, limiting the amount of plasma accessible along B to fill it, so that only perpendicular diffusion would remain for filling the ho le. Secondly on a rational q-surface the radial motion of the hole might be arrested, due to short circuiting the driving potential structure [17]. This would lead to a slowly dissipating negative current filament living on a low rational surface close t o the pedestal, with characteristics alike the so called Palmtree mode [18].

In conclusion we have demonstrated on a selected set of data that using forward modeling matching a synthetic signal to filtered magnetic pickup coil data, we are able to determine key parameters for the temporal evolution of ELM filaments. Besides the actual number of filaments we could determine their respective velocities in radial and toroidal direction (note that the toroidal velocity is for an ideal filamentary struct ure and reasonable safety factor q not to be distinguished from its poloidal velocity v_θ as $v_\phi = qv_\theta$). Moreover we can from fitting the model parameters provide an estimate for the current carried by the filaments. The current in the filament will partially be locally generated, but to a larger part be convected out with the filament after separation from the pedestal. Thus investigating the ELM filament currents one might hope to deduce the amount of magnetic perturbation remaining in the pedestal in the form of current “holes”. This would demand more extensive use of the magnetic coil data by using more coils. Using forward modeling on a larger number of magnetic coils distributed over the tokamak it would be possible to determine the SOL current system during ELM filament propagation with fair accuracy. The principal value of using mag-netic pickup coils data in that novel way was demonstrated here. More extensive and refined use of this method could prove to provide crucial information about f.x. the instability mechanism of ELMs or their contribution to momentum transport on a regular basis, as many tokamaks are equipped with fast magnetic probes. Finally it should be remarked that changes and refinements to the underlying assumed filament model would allow for changes in the derived filament para-meters, with parameters such as the number of filaments and their toroidal velocity being more robust than details of the ac-celeration or amount of current in the filaments. The latter one would for example be more prone to details in the, finally, not sufficiently well known radial current structure. For this point to be remedied it would be very beneficial to have localised measurements of the current structure within ELM filaments, by for example local magnetic probes.

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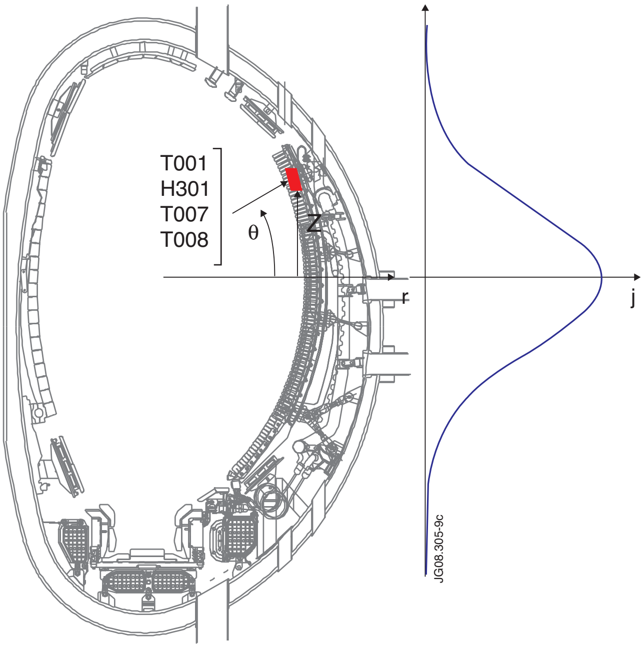

Figure 1: Poloidal position of fast magnetic pickup coils used (left) and projection of the poloidally varying currentdensity profile assumed for the ELM filament.

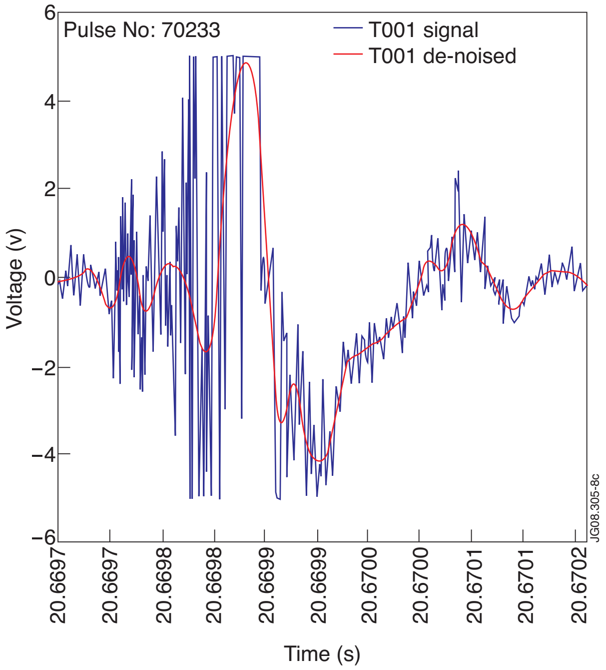

Figure 2: Raw and smoothed signal from coil T001 for JET Pulse No: 70223.

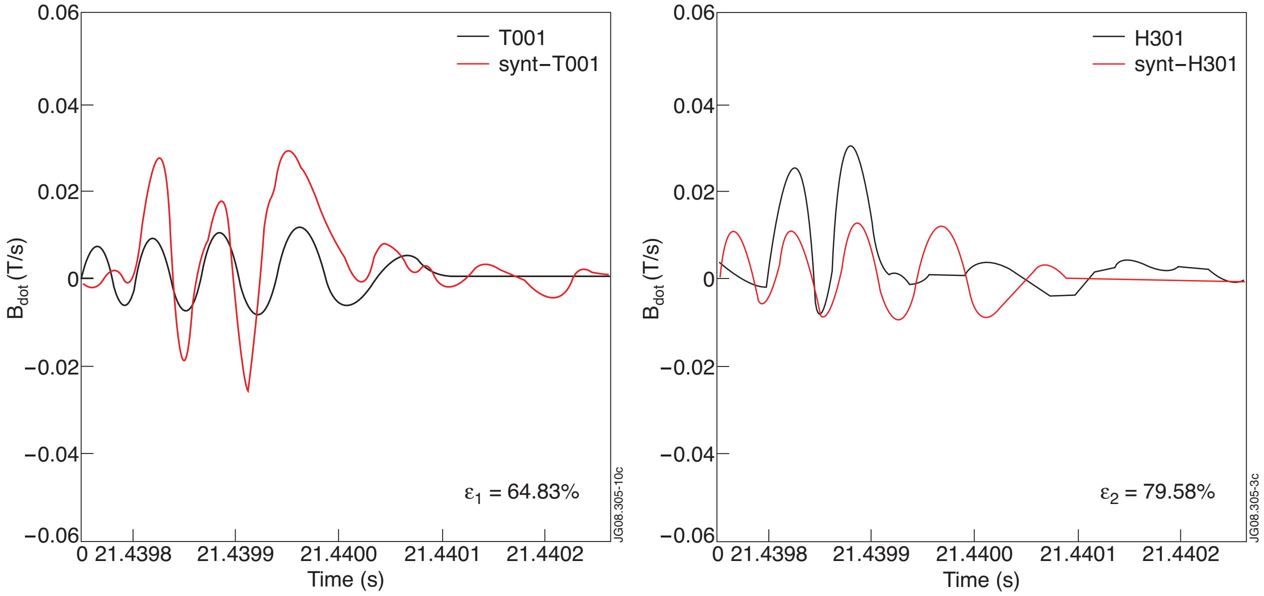

Figure 3:Synthetic signal and signal from coils T001 and H301 for moved, the cut-off frequency chosen at a change in the slope Pulse No: 70737.

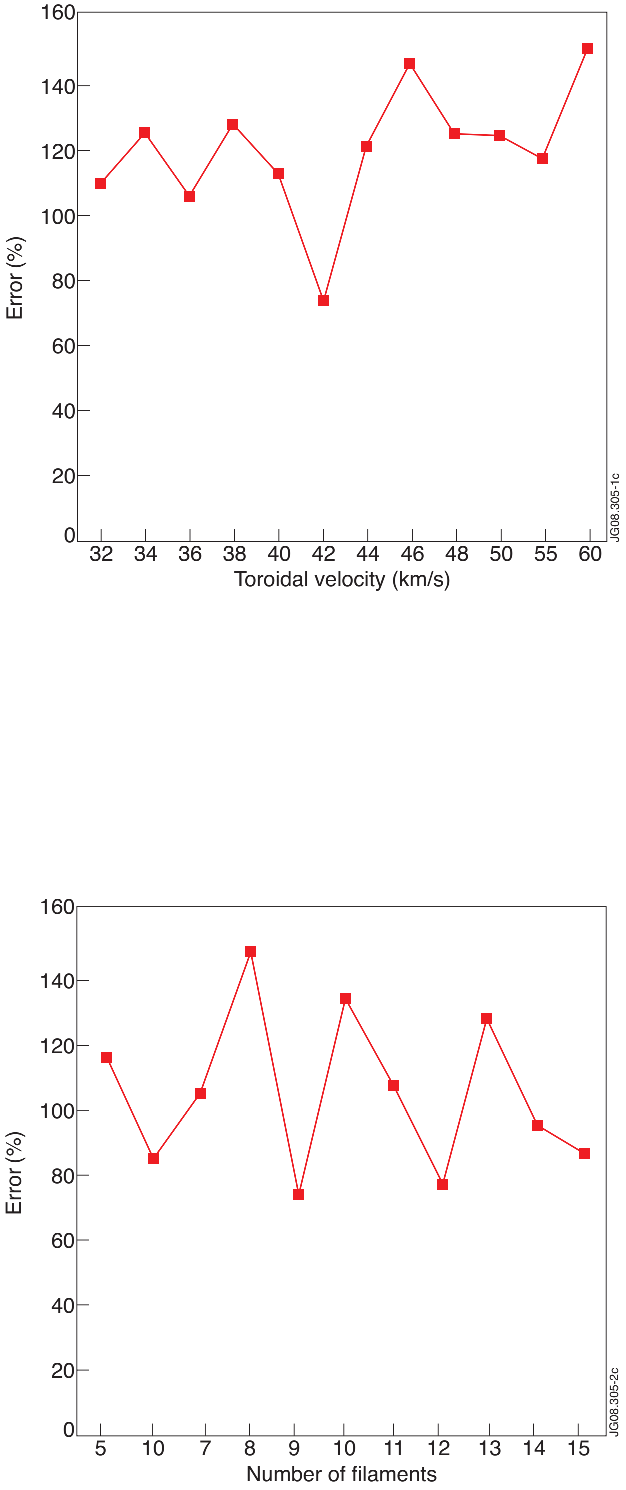

Figure 4: Dependence of the error on fitting the toroidal velocity (top panel) and the number of filaments (bottom panel) showing a clear correlation.

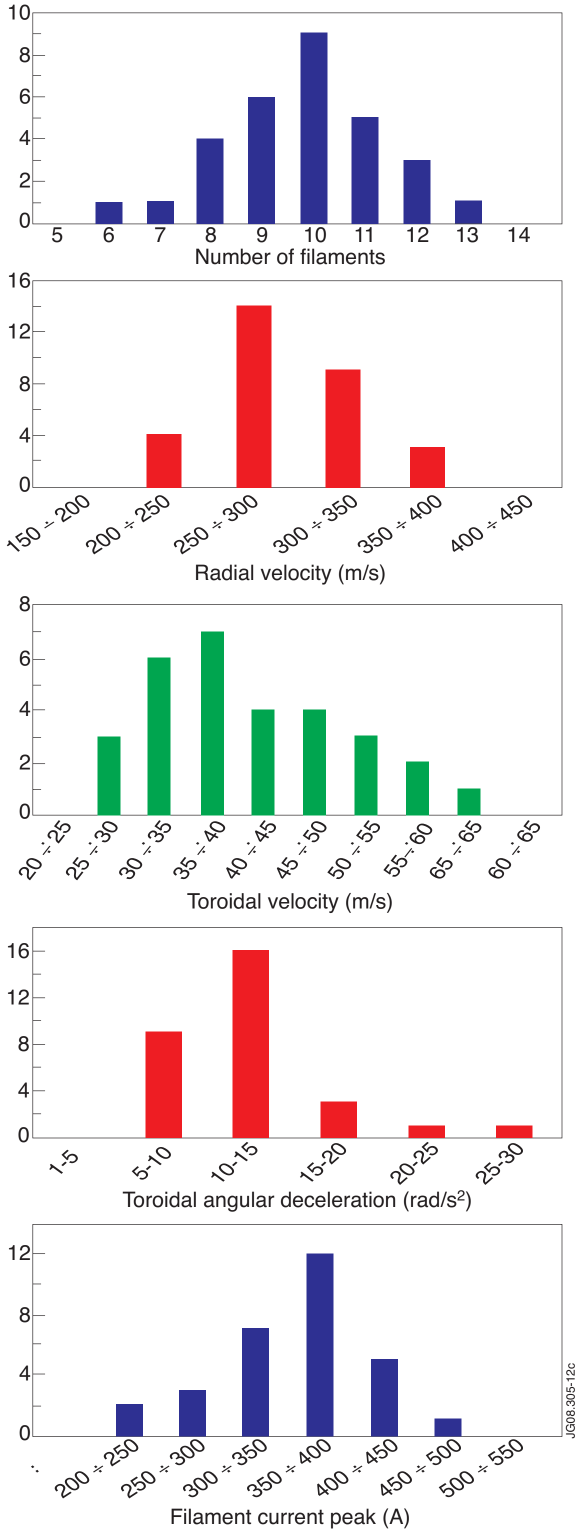

Figure 5: Histogramms for the number of filaments (top panel), their radial (2nd panel) and toroidal velocities (3rd panel), as well as their toroidal deceleration (4th panel) and peak current (bottom panel).