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Electromagnetic ELM and inter-ELM filaments detected in the COMPASS Scrape Off Layer

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Filamentary structures have been observed in all magnetic configurations with very similar features despite the difference in the magnetic geometry: theory and experiments suggest they exhibit a radial convective motion across the SOL, and the interest in blob dynamics is further motivated by their interaction with first wall and divertor. Despite their possible different generation mechanisms, turbulent structures and Edge Localized Mode (ELM) filaments share some common physical features, as the localization in the cross-field plane and the associated parallel current, with a convective radial velocity component somehow related to their dimension. The electromagnetic (EM) effects on filament structures deserve particular interest, among the others for the implication they could have for ELM, related for instance to their dynamics in the transition region between closed and open field lines or to the possibility, at high beta regimes, of causing line bending which could enhance the interaction of blobs with the first wall. The presence of ELMs and inter-ELM EM filaments was revealed in the SOL of COMPASS tokamak, where a new probe head was recently developed and commissioned. The diagnostic, based on the U-probe concept, allows the simultaneous measurements of electrostatic and magnetic fluctuations with high time resolution suitable for the identification of EM features of filaments, providing in particular the direct measurement of the current density associated to filaments. The probe head was inserted in the SOL of D-shaped diverted discharges. The COMPASS experiment was operated in these discharges in ohmic and NBI induced H-mode, with the clear presence of different type of ELMs. In addition, the diagnostic setup used allowed monitoring filamentary structures in different toroidal positions along the magnetic field line.

1. Introduction

Filamentary structures have been observed in all magnetic configurations with very similar features despite the difference in the magnetic geometry, they are magnetic-field aligned plasma structure considerably denser than the surrounding plasma and localized on the cross-field plane. Theory and experiments suggest these filament or blobs exhibit a radial convective motion across the Scrape Off Layer (SOL), and the interest in blob dynamics is further motivated by their interaction with first wall and divertor. Indeed by increasing particle and heat flux into the far SOL, blobs can increase interaction with limiters, RF antennas and first wall [1].

It is interesting to note that, despite their possible different generation mechanism, blobs and Edge Localized Mode (ELM) filaments share some common physical features, as the above mentioned localization in the perpendicular plane and the associated parallel current, with a convective radial velocity components somehow related to their dimension. Interestingly, the role of these turbulent eddies in providing substantial sheared flow in the external region has been recently considered as important in the process of LH transition [2,3]. Actually, since the vorticity drive provided by turbulent eddies gets stronger as heating power is increased, it should naturally lead to a very strong shear flow, which can ultimately lead to an H-Mode whether heating is enough. A further fundamental aspect of blob studies needs to be deeply investigated, namely the electromagnetic (EM) effects on filaments. These studies, only recently addressed from the experimental point of view [4,5,6] deserve additional effort, in particular for the implication they could have for ELM filaments. On the one hand, it is supposed, and experimentally observed, that at enough high beta, blobs can transport current, and the role of these current in ELM filaments dynamics is still an open issue. On the other hand at enough high beta blobs can also carry "frozen in" magnetic field lines, with the possibility of causing line bending which could enhance the interaction of blobs with the first wall, without letting those blob to hit divertor plates [1]. Another still unanswered question regards the dynamics of blobs/filaments in the transition region between closed and open field lines. This issue could also include the interaction of such structures with applied magnetic perturbation, as foreseen in Resonant Magnetic Perturbation technique (RMP), which breaks the 2D symmetry with the appearance of a 3D topology with the stable and unstable manifolds of the separatrix. Thus detailed comprehension of generation mechanism, dynamics and characteristic of filaments represents a fundamental physical issue for both present and future devices.

In this contribution the presence of ELMs and inter-ELM EM filaments will be investigated on their EM features in the COMPASS tokamak, where a new probe head was recently developed and successfully commissioned [7].

The diagnostic, based on the U-probe concept [8], allows the simultaneous measurements of electrostatic and magnetic fluctuations, with high time resolution suitable for the identification of EM features of filaments, providing in particular the direct measurement of the current density associated to filaments. The probe head was inserted in the SOL of D-shaped diverted discharges. The COMPASS experiment was operated in these discharges in ohmic and NBI assisted H-mode, with the clear presence of different type of ELMs.

The paper is organized as follows. In section 2 the main features of the COMPASS tokamak are described with the specific edge diagnostic and methods used in this paper, in section 3 the general features of a typical ELMy H-mode discharge are shown, in sections 4 and 5 the fine electrostatic and electromagnetic (EM) features detected respectively on ELM and inter-ELM filaments are described, in the last session some conclusions are drawn.

2. Experimental setup and method

The COMPASS tokamak [9] is a compact experimental device (R = 0.56 m, a = 0.2 m) operated in divertor plasma configuration with ITER-like plasma cross-section. The vacuum vessel of COMPASS is equipped with an open divertor covered by carbon tiles. Presently, COMPASS operates with plasma current up to 400 kA and toroidal magnetic field in the range 0.9 – 1.8 T and elongation up to 1.8. The data shown in this paper refer to Ip=300kA and B_t=1.15 T, D-shaped plasmas in Single Null (SN) configuration with the ion grad-B drift direction towards the X-point, see the poloidal section shown in Figure 1.

Two neutral beam injectors provide nominal power of 2 x 0.4 MW at the beam energy of 40 keV for additional plasma heating. Ohmic as well as NBI assisted H-mode have been successfully achieved on the COMPASS tokamak after application of boronization of the vacuum vessel interior. The L–H power threshold PLH has a minimum at line-average density in the range of 3.5–4 $10^{19}m^{-3}$.

The L-H transition is followed either by an ELM-free period or ELMs with frequency in the range of 80 – 1 000 Hz. In this paper the case of type-I ELMs will be analyzed.

The edge measurements presented in this paper are mainly provided from a specifically developed insertable probe head and described in [7], the COMPASS U-probe. This diagnostics is based on the U-probe concept [5,8] and allows the simultaneous measurements of electrostatic and magnetic fluctuations, with high time resolution suitable for the identification of EM features of filaments, providing in particular the direct measurement of the current density associated to filaments. The probe, see figure 1, is based on two identical towers poloidally spaced by 40 mm covered by a BN case, each of them equipped with 6 lateral electrostatic pins radially spaced by 6 mm, and three pins on top. Inside the case are located three 3-axial magnetic pickup coils. They are arranged to form a 2D configuration among the two towers, lying on the cross-field plane. The concept would allow the direct estimate of the parallel current density fluctuation estimate from the Ampere's law $J_{par}=(\nabla\times B)_{par}/\mu_0$, where B is the local average magnetic field.

This method represents a simplified 2D version of the one adopted in the Cluster mission for the measurement of currents in the magnetosphere [10] and was applied for the first time in a fusion experiment in RFX-mod [11]. All signals are acquired with a 5Ms/s acquisition frequency. The probe is inserted in the SOL region from the port on the bottom part of the machine, as shown in figure 1. Its radial position can be modified on a shot-to-shot basis.

The COMPASS tokamak is also equipped with one array of 39 Langmuir probes (LP) in the divertor region, their poloidal spatial resolution is about 5 mm. The divertor sensor system is completed by an array constituted by 10 Ball Pen Probes (BPP) and 4 additional LPs toroidally spaced by placed in the toroidal opposite side of the machine [12,13].

3. ELMy H-mode discharges in COMPASS tokamak

An example of discharge with a long lasting H-mode transition is shown in figure 2, where some general plasma signals for the shot #9334 are represented.
In this case a flattop plasma current I_p of about 300kA was obtained, with an edge safety factor q_{95}~2.5 and a central density n_e~6 10^{19} m^{-3}. In this shot additional heating was applied through the NBI system operating in the time window from 1100 to 1200 ms with ~190 kW injected power. The transition to the H-mode is clearly visible after t=1065 ms, where a sudden drop of the D_α signal is observed as well as an abrupt increase of the core density. It can be also observed that huge peaks in the D_α signal characterize the H-mode phase. Those strong events are commonly [14] associated to the ELM filaments interacting with the first wall. Most of the time during the H-mode phase, their occurrence frequency is relatively low, of the order of 250 Hz increasing up to 500 Hz in the time window from 1090 and 1110 ms, corresponding to a main density decrease. The power density threshold at the separatrix for the L-H transition was ~37kW/m^2, see figure 2bis. The time evolution of the power at the separatrix, provides a clear correlation with the ELM frequency from 1000 and 1190 ms (fig. 2bis). According to the classification described in [15] this observation suggests the identification of such events as type-I ELMs.
Figure 2 shows also some representative electrostatic and magnetic signals provided by the COMPASS U-probe. In particular the ion saturation current, I_{sat}, indicative of the local plasma density value and the floating potential, V_f, were measured in the most inserted position available at one of the probe towers. For the shot 9334, the U-probe was inserted at 15 mm depth from the first wall, corresponding to a position of approximately 50 mm radially outside from the estimated local radial position of the LCFS (see the figure 1 insert).
It can be observed that the I_{sat} signal as well exhibits, during the H-mode phase, huge peaks. Those are indication of strong density burst and clearly associated to the ELM events observed in the D_α signal. On the other hand also the local V_f exhibits events with the same periodicity, in particular in this case V_f bursts are generally dipolar, i.e. a roughly double structure, positive and negative peak, appears associated to each event. A more detailed analysis of this behavior will be presented in the next paragraphs. As representative of magnetic signals, the time behavior of the radial component db_r/dt fluctuations is shown together with the corresponding evaluation of the local cross-field current density fluctuations, δJ_{tor}. The δJ_{tor} was evaluated via the cross-field circuitation and strong events related to the ELMy behavior are very well identified. The time evolution of the δJ_{tor} with strong peaks corresponding to D_α events provides a clear indication of the electromagnetic features of these ELMs.
More detail on this aspect can be found in figure 3, where a spectrogram of the poloidal magnetic field fluctuation, δb_{pol}, is shown as a matter of example during the type-I ELM phase. The signal of I_{sat} is chosen as trigger identification of the presence on the probe location of an ELM occurrence and overlapped to the δb_{pol} spectrogram. It can be seen that corresponding to each one of the I_{sat} peaks, the magnetic

spectrogram exhibit an abrupt spreading so that the magnetic activity indicates that a magnetic structure localized in time is associated to these events. In the inter-ELM phases the power spectrum level is strongly reduced, however some features can be highlighted. In particular other spectrum spreading bursts are observed but with much lower intensity and not correlated to the occurrence of local I_{sat} strong peaks. It is worth mentioning that they are instead well correlated to the SXR drops and related to sawtooth activity. In addition a systematic magnetic activity is observed in the range 50-70 kHz in the phase preceding the ELM occurrence and disappears in the right after phase. Analogous features are detected in all the three component of the magnetic field fluctuations.

Inter-ELM magnetic activity with similar features was observed in DIII-D and C-Mod experiments [16,17]. In this case the onset of these so called quasi-coherent-modes was related to the time evolution and saturation of the pedestal temperature profile associated to the phases preceding the ELM occurrence.

The spectrogram was calculated in the same time window also for the electrostatic quantities. As representative the case of a V_f signal spectrogram is shown in the bottom panel of figure 3 case and shown in the same time window. The abrupt spreading of spectrum at the I_{sat} ELMy bursts is as well visible, indicating the presence of a spatially localized structure at the ELM event occurrence. In the inter-ELM phase a series of spectrogram spreading events follow the ELM time occurrence, with a generally decreasing intensity. On the other side no modes in the inter-ELM phase of the electrostatic spectrogram is detected, indication of a purely magnetic activity.

4. ELM fine structure

4.1 Electrostatic features and radial behavior

Information on the events features along the radial direction can be obtained by exploiting the radially distributed electrostatic pins in the COMPASS U-probe. An example is shown in figure 4, where the radial array on one tower was configured for I_{sat} measurements, while the array on the other tower measured V_f and I_{sat} every second one. In the top panel of figure 4 the time evolution of V_f signals measured at four different distances from the LCFS is shown in the same ELMy-phase time window of figure 3. The behavior of V_f signals is analogous to the one shown in the example of figure 2, it is confirmed that both positive and negative strong peaks are associated to the ELM occurrence and this behavior is reproduced with different intensities along the radial direction. It can then be concluded that the ELM V_f structure involves all the radially distributed pins in the probe head, indicating a radial extension covering at least the 4 cm monitored by the probe. Analogous considerations can be deduced from the radial array of I_{sat} measurements, even if performed in a different tower poloidally spaced by 4 cm. The four I_{sat} signals, in the bottom panel of figure 4, indicate a bursty behavior at the ELM occurrence involving all the probe location measurements, see also [18]. A series of generally decreasing intensity peaks are observed right after the first huge one and this fine behavior with strong and weaker events are well replicated along the radial direction. These features suggest a more complex structure in the density behavior and this can be observed by zooming on a single event. Figure 5 shows the time evolution during a single event of the local density fluctuation radial profile at the probe location. The three panels of figure show increasing detailed time behavior around the single event. It can be observed that the apparent single burst in I_{sat} signals examined in figure 2 is composed by multiple bursts radially extended and in some cases a radial propagation can also be guessed by the time behavior of the $I_{sat}(r)$, see for instance last bottom panel. The ELM density structure, confirming the indication of multiple peaks for each event in figure 3, provides a picture of a ELM density feature composed by multiple fragmented structures rather that a single one, and those structures are evolving in time. The typical time window for the ELM manifestation at the probe location is of the order of ~200μs.

4.2 ELM electromagnetic features

The detailed features of a single ELM as revealed by the magnetic and electrostatic quantities measured by the COMPASS U-probe are shown in figure 6. The chosen event is the same selected for the figure 5. In the bottom panel the time behavior of V_f and I_{sat} locally measured. Data are normalized to their respective maximum to make easier the comparison. In particular the multiple structures are evident both on I_{sat} as already stated but on the V_f as well. In particular the V_f time evolution exhibits positive and negative peaks oscillations and in this specific case three major oscillations can be recognized. The time behavior of the fluctuations of the cross-field components of magnetic field, δb_r and δb_p, as measured by one of the 3-axial coils, is shown for the same time window. Three periodic oscillation with variable intensity are observed, with a phase-shift between δb_r and δb_p, in the range from $\pi/4$ and $\pi/2$. The corresponding parallel current density estimate, δJ_t, is than provided in the top panel of the figure. A main peak of about 50kA/m^2, is detected and also for the current density an oscillation between positive and negative peaks is visible. This behavior could be interpreted as a current path within the ELM closing within the structure itself. A further detail can be captured by plotting the odogram of the components δb_r and δb_p, left panel of figure 5. The picture is obtained in the same time window of the graphs on the left column and describes the pattern of the cross-field magnetic field component at the occurrence of the ELM. Ideally for a simple single homogeneous current filament this pattern is expected to be a closed circular. The red dots highlight the time window around the main peak observed in the δJ_{tor}. This main peak is clearly associated to the closed pattern in red also in the odogram graph. This observation provides the clear identification of the ELM structure as a current filament. In addition other closed patterns are observed, so that beside a composite electrostatic structure also a composite filamentary current density feature is associated to ELMs.

As a matter of comparison the corresponding ELM peak detected in the D_α signal is shown in the bottom left panel, evidencing a wider peak with respect to the local measurements provided by the probe. This different behavior is likely related to a less localized and line integrated feature of D_α signal. A time delay is observed with respect to the probe signals, likely due to the different location in the COMPASS machine. It is interesting to note also the detailed comparison with Langmuir probe measurements in the divertor plate. In particular a very similar time behavior is observed between the U-probe V_f measurement and the V_f measured on the probe L39 located on the field line connected with the U-probe location, larger differences are observed instead with the probe L1 on the opposite side of divertor and not connected to the U-probe. This observation suggests that the fine ELM structure observed by the COMPASS U-probe is elongated along the field line, and in this case is connected to the divertor [19].

5. Inter-ELM structures

The phase in between ELMs is populated as well by structures but with a shorter time scale. As an example the focus is concentrated in one inter-ELM time window in figure 7. Analogously to what shown in the figure 3 the spectrogram of the δb_{pol} is provided and as a reference for localized bursty events the I_{sat} signal is over-plotted in green, in a.u. units. The mode at 50-70 kHz is present continuously from t=1125s onward, while in the phase immediately after the ELM this magnetic activity is absent and later on start to appear with much lower intensity with respect to the phase closely preceding the subsequent ELM. The investigation of the electromagnetic features of structures was focused in this phase where the mode 50-70 kHz does not dominates the magnetic fluctuations. As can be deduced through the comparison with the figure 3, these I_{sat} events are by far smaller than the ELM related ones, however this zooming on inter-ELM phase allow appreciating their bursty behavior. Figure 8 shows the fluctuations time behavior during 0.5 ms in the inter-ELM phase of δJ_{tor}, and of δI_{sat} and δV_f, the latter ones normalized to their maximum value. The I_{sat} bursts are associated also in the inter-ELM phase to bipolar, generally asymmetric, structures in δV_f . Strong fluctuations are also observed in the δJ_{tor}. As a further detail the right column of figure 8 shows the time evolution of a single density burst. Resulting associated with a peak and valley of δV_f and a peak of parallel current density fluctuation, of about 0.65 kA/m^2, indicative of the presence of a EM filamentary structure, developed on a time scale of the order of tens of microseconds. It can be concluded that the inter-ELM structures studied exhibit features similar to the ELM, but characterized by a more that one order of magnitude smaller in amplitude and time scale.

6. Discussion and conclusions

The ELM events obtained during H-mode NBI assisted COMPASS discharges were clearly detected in the SOL region and investigated in detail by the COMPASS U-probe, from the point of view of their electrostatic and magnetic properties. In particular a magnetic activity onset around 50-70 kHz was observed to precede the ELM occurrence, in analogy to what observed in DIII-D experiment.

In particular they are identified as strong burst of density and generally dipolar structures in potential. Thanks to the high time and space resolution of the COMPASS U-probe their fine composite structure was revealed, consisting in multiple fragmented smaller structures rather that a single larger one. The EM features were investigated in the cross-field plane providing a clear fingerprint of filamentary EM structures, constituted by multiple parallel current density filament associated to one single ELM occurrence. Both positive and negative peaks are detected indicating the possibility of a return current pattern within the filament itself. This observation is in agreement to the equivalent circuit model proposed for the EM filaments in the SOL

[20] which foresees the closure pattern via the limiter sheath. Along this line another interesting observation is represented by the correlation observed on one single filament monitored on V_f along the same field line on the divertor region, confirming its elongated structure along the field line up to the divertor.
In the case studied in this paper an ELM filament current density of the order of 50kA/m^2 was observed. On the other hand the inter-ELM features were investigated as well. It can be concluded that the inter-ELM structures studied exhibits features similar to the ELM, but characterized by a more than one order of magnitude smaller in amplitude and time scale.
Similar observations were obtained also for type-I ELM in ohmic H-mode discharges and work is in progress in order to perform a comparison between different ELM types and H-mode regimes.

Acknowledgments

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Figure captions

Fig. 1 Inner view of the COMPASS camera with the porthole where the probe head was inserted is shown. The scheme of the probe poloidal section with the LCFS in green is shown in the inner square. Picture on the right shows the U-probe for COMPASS experiment and the detail of the pick-up coils equipping the probe.

Fig. 2 Example of an H-mode shot (#9334) obtained with NBI additional heating (~190 kW from 1100 to 1200). Left column shows some general shot signals: plasma current, q_{95}, plasma density, D_{α}. Right column shows some representative electrostatic and magnetic signals obtained from the COMPASS U-probe.

Fig. 2bis Power density estimate at the separatix , P_{sep}, and D_{α}.signal (top), ELM frequency and indication NBI power time trace (bottom). All quantities refer to shot #9334.

Fig. 3 Top panel: spectrogram of the poloidal component of magnetic field fluctuation during the H-mode phase, in green the I_{sat} local measure is over plotted. Bottom panel: spectrogram of the local floating potential in the same time window. Measures provided by the COMPASS U-probe.

Fig. 4 Top panel: Time evolution of the floating potential measured at four different radial positions during ELMy H-mode, r_0 represents the probe head inner edge distance from the LCFS, r_0 = 50 mm in this case. Bottom panel: the same for I_{sat} measurements in for different radial position with respect to the LCFS.

Fig. 5 Time evolution of the local I_{sat} radial profile measurement during a single ELM. From top to bottom increased zoom details are shown.

Fig. 6 Time evolution around a single ELM occurrence of the δJ_{tor}, δb_{rad}, δb_{pol} and of normalized I_{sat} and V_f to their maximum value fluctuations (left column). Cross-filed pattern odogram described by the δb_{rad}, δb_{pol} fluctuations during the same time window, red dot highlights the corresponding pattern and time range in δJ_{tor}.

Fig. 7 Spectrogram of the δb_{pol} during an inter-ELM phase. Analogously to fig. 3 the corresponding local I_{sat} time evolution (green line) is over-plotted in a.u.

Fig. 8 Time evolution during about half ms of an inter-ELM phase of δJ_{tor}, and of δI_{sat} and δV_f normalized to their maximum value fluctuations (left column). Detail on the same quantities zooming on a single event detected on δI_{sat} in the inter-ELM phase.

Figures

Fig. 1

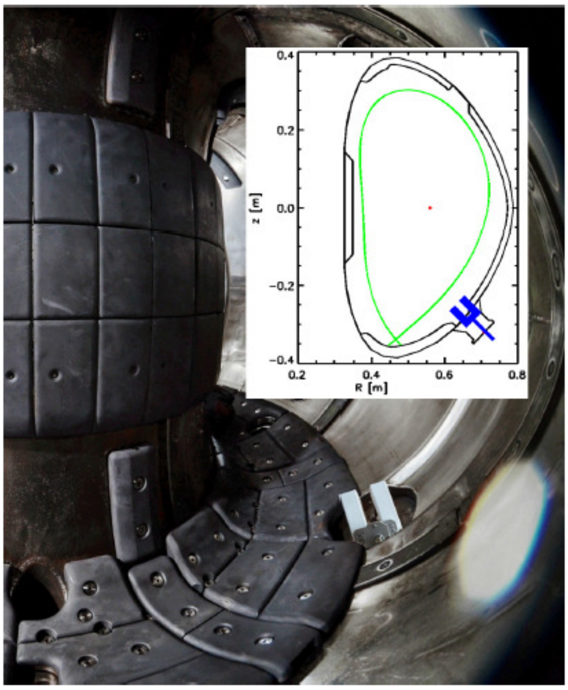


Fig. 2

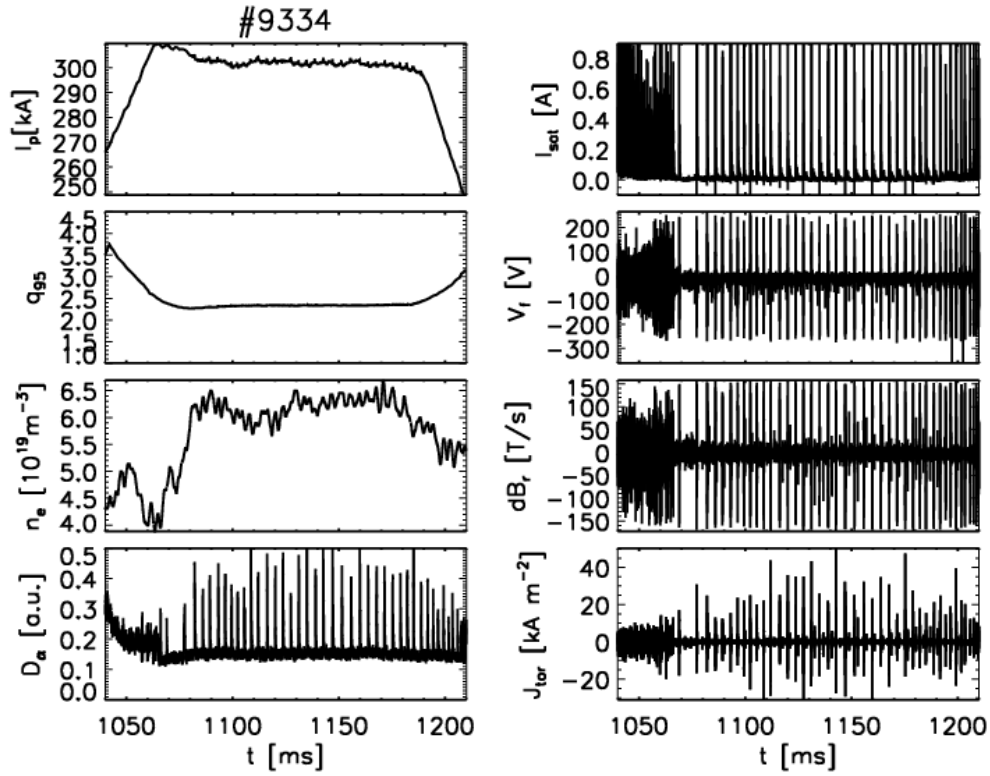


Fig. 2bis

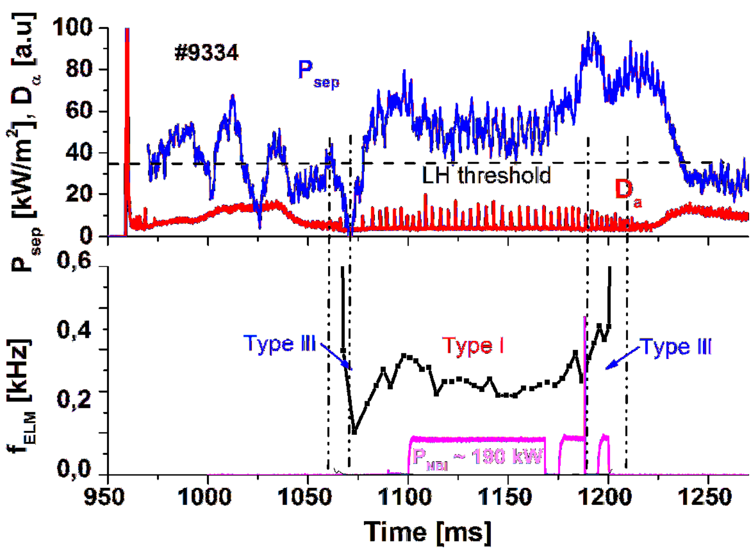


Fig. 3

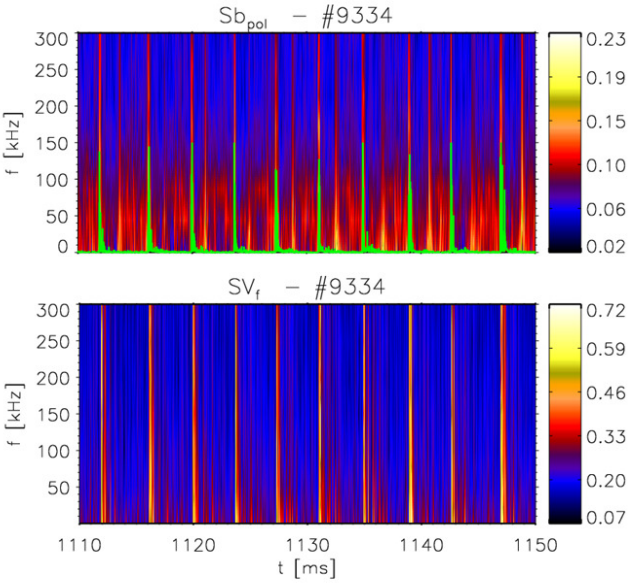

Sb_pol – #9334
f [kHz]
300
250
200
150
100
50
0
0.23
0.19
0.15
0.10
0.06
0.02
SV_f – #9334
f [kHz]
300
250
200
150
100
50
0.72
0.59
0.46
0.33
0.20
0.07
1110
1120
1130
1140
1150
t [ms]

Fig. 4

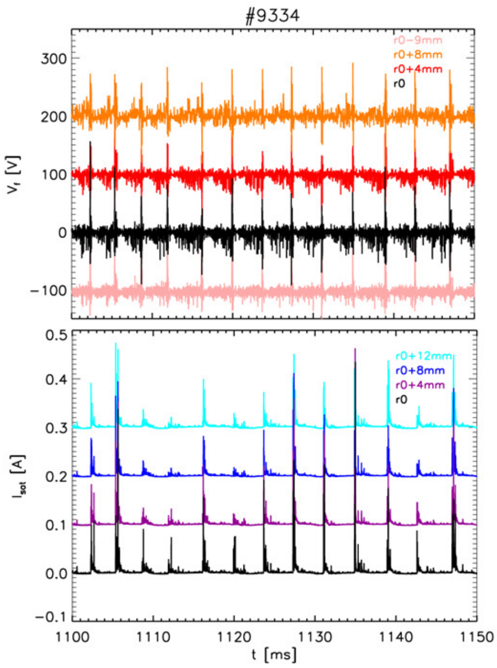
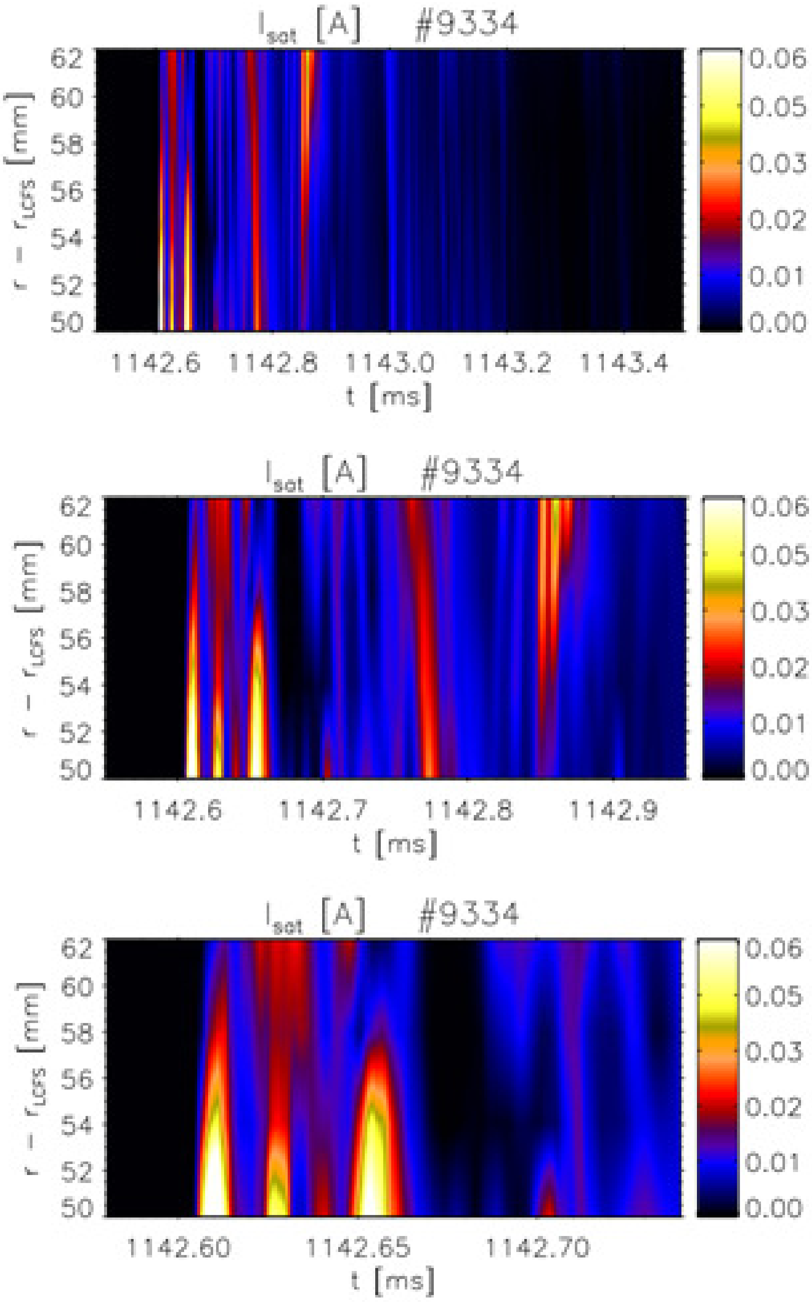
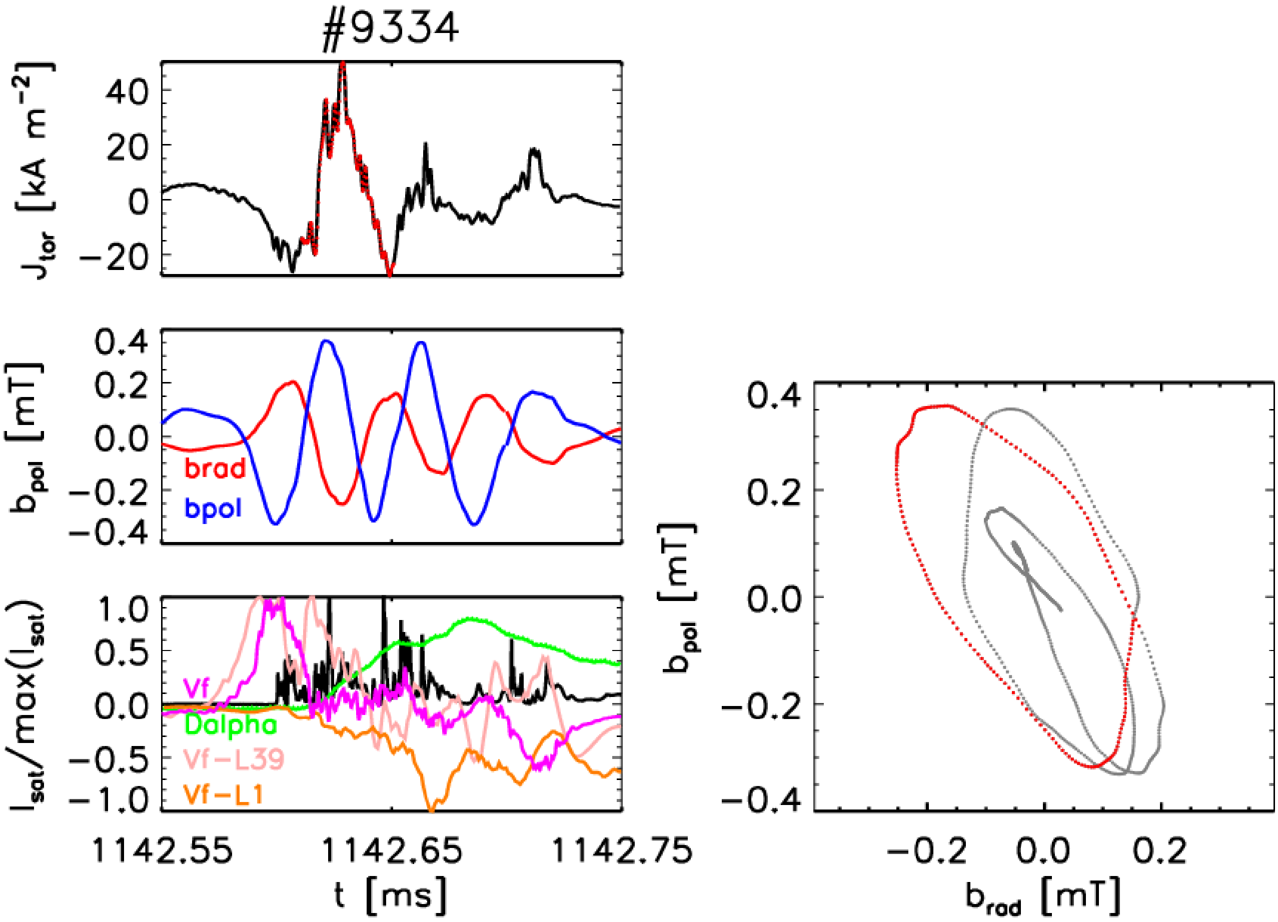

#9334
r0−9mm
r0+8mm
r0+4mm
r0
300
200
100
0
−100
V_f [V]
r0+12mm
r0+8mm
r0+4mm
r0
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
I_sat [A]
1100
1110
1120
1130
1140
1150
t [ms]

Fig. 5



I_sat [A] #9334
r − r_LCFS [mm]
62
60
58
56
54
52
50
1142.6 1142.8 1143.0 1143.2 1143.4
t [ms]
0.06
0.05
0.03
0.02
0.01
0.00
I_sat [A] #9334
1142.6 1142.7 1142.8 1142.9
t [ms]
I_sat [A] #9334
1142.60 1142.65 1142.70
t [ms]

Fig. 6



#9334
J_{tor} [kA m^{-2}]
40
20
0
−20
b_{pol} [mT]
0.4
0.2
0.0
−0.2
−0.4
brad
bpol
I_{sat}/max(I_{sat})
1.0
0.5
0.0
−0.5
−1.0
Vf
Dalpha
Vf−L39
Vf−L1
1142.55
1142.65
1142.75
t [ms]
b_{pol} [mT]
0.4
0.2
0.0
−0.2
−0.4
−0.2
0.0
0.2
b_{rad} [mT]

Fig. 7

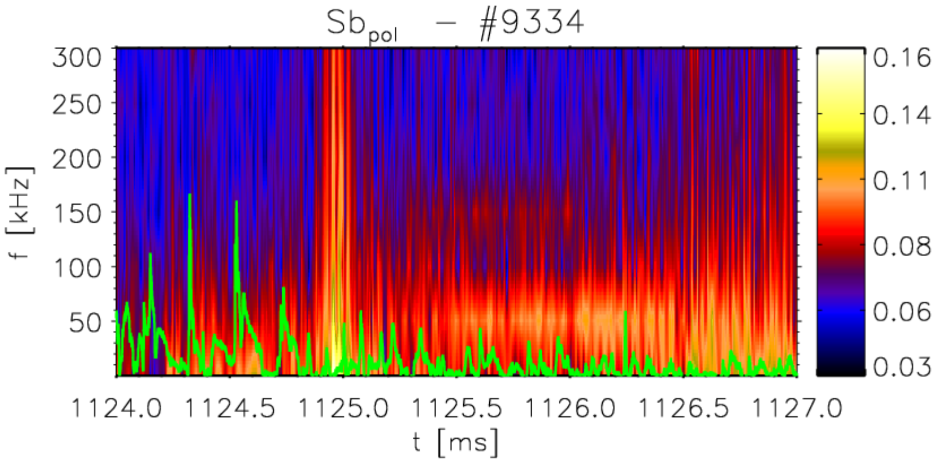
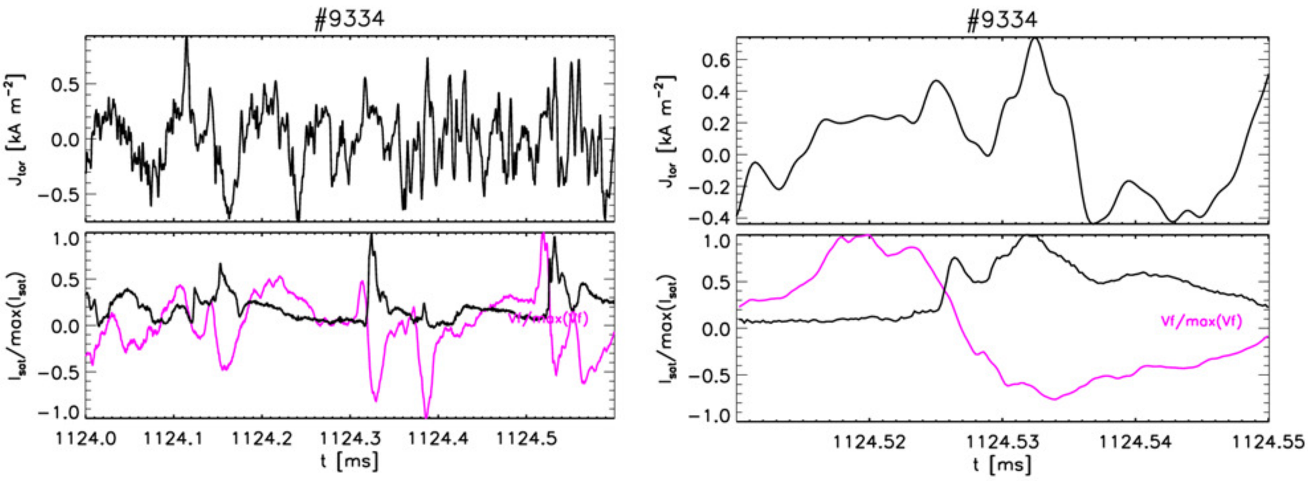


Fig. 8



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