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Dynamics of JET runaway electron beams in D₂-rich shattered pellet injection mitigation experiments

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Abstract

The publication provide further insights into the dynamics of JET runaway electron (RE) beams mitigated by D₂-rich shattered pellet injection (SPI) (Reux *et al* 2022 *Plasma Phys. Control. Fusion* **64** 034002). Multi-diagnostic analyses show that mechanisms causing continuous RE losses and energy transfer from hot electrons to cold background plasma can act before the SPI. After the SPI, measurements are compatible with a reduction of the maximum energy and pitch angle of the RE distribution while the population of supra-thermal electrons increases. The RE population growth is likely due to electron avalanche. Dark island-like pattern chains, characterised by an integer poloidal mode number and a certain minor radius, are identified in the JET RE beam synchrotron radiation videos. The synchrotron island dynamics is studied via

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a newly developed computer vision code (Sommariva and Silburn <https://c4science.ch/source/pSpiPTV/>). The radial motion of synchrotron island chains is found to be consistent with the most plausible time evolution of the radial current density profile compatible with both the RE synchrotron videos and the total RE current time trace. Similarly, correlations are identified between the temporal progression of the synchrotron islands poloidal rotation frequency and sudden MHD relaxation events. Loss-of-RE events probably caused by non-linear interactions between synchrotron islands are observed for the first time. Experimental evidences suggest that synchrotron islands are possibly related to the existence of magnetic islands which may lead to the development of new RE beam mitigation strategies.

Keywords: runaway electrons, plasma disruptions, magnetic fusion

(Some figures may appear in colour only in the online journal)

1. Introduction

Relativistic, runaway, electron beams may be observed after tokamak plasma disruptions (global magnetohydrodynamics—MHD instability leading to the prompt loss of magnetic confinement and hence, of the plasma thermal energy, during a discharge [1]) [2–4]. In order to study the quenching of runaway electrons (REs), high-energy high-current RE beams have been successfully generated in large devices such as the JET tokamak [2, 5]. Uncontrolled termination of RE beams, having current of hundreds of kiloampères (kA), may damage the reactor first wall and coils if not properly mitigated [6, 7]. The ITER worst case scenario predicts full conversion of the pre-disruptive plasma current (15 MA) in RE current [8]. Despite being highly improbable, such an event represents a serious threat to the integrity of the ITER plasma facing components (PFCs) [9]. Therefore, effective RE avoidance, control and mitigation strategies must be developed for guaranteeing safe tokamak operations.

Focusing on the RE beam mitigation strategies, the shattered pellet injection (SPI) is the chosen mitigation method for ITER [10] and hence, is currently under extensive test [5, 10–12]. The SPI consists of the injection of pre-fragmented pellets of deuterium (D2) and/or heavy impurities for dissipating the energy of the relativistic carriers. SPI experiments in the DIII-D, JET and ASDEX-Upgrade tokamaks showed that harmless (benign) termination of RE beams up to the megaampère (MA) range can be obtained injecting deuterium rich (>80%) shattered pellets [13–15] in the hot electron population. Similar results have been obtained in the TCV tokamak using the massive gas injection method [15]. In JET, the RE current is observed to grow after the SPI arrival until the onset of a disruptive MHD instability [5, 13, 14]. Simulations show that the wall surface wetted by fast electrons is significantly increased by the 3D magnetic topology (magnetic chaos) resulting from the disruptive event reducing the heat flux on the PFC to acceptable levels [5, 13, 14, 16, 17]. The instability causing the benign RE beam termination is thought to be of the kink type in medium sized tokamaks such as DIII-D, ASDEX-Upgrade and TCV [14, 18]. Indeed, the disruptive MHD event is triggered for values of the edge safety factor below 2 in DIII-D, ASDEX-Upgrade and TCV. A different picture is provided by the JET tokamak experiments in which benign RE beam

terminations are triggered for edge safety factor above 3 [5, 16].

The evolution of the hot electron population in terms of the current density, the energy and the pitch angle distributions strongly influences the MHD dynamics of the relativistic electron beams. Different techniques have been used for trying to reconstruct the hot electron properties from experimental data. In this context, synchrotron radiation images are an invaluable source of information when trying to infer the properties of post-disruptive RE distributions from experimental data [19–22]. For instance, the temporal evolution and the spatial profiles of the synchrotron radiation intensity can be related respectively to the dynamics and the radial distributions of the RE current density, pitch angle and energy [20, 21]. Similarly, 2D features visible in synchrotron images have been related to the presence of MHD instabilities in the RE beam [19, 22]. In JET, images of the synchrotron radiation emitted by relativistic electrons in both the IR and visible spectra have been available since the 2018 experimental campaign [5, 16, 23, 24]. Preliminary analyses of the experimental videos showed the presence of features unique to the RE beam synchrotron emission of the JET tokamak. For example, multiple videos are characterized by a hollow distribution of the synchrotron radiation intensity which is higher at the beam edge and lower at its core [5, 16]. The rough map between the magnetic topology and the region of synchrotron emission is justified by the absence of splitting of the synchrotron spot and by the small pitch angle interval required for matching SOFT simulations to the experimental images [5, 16, 25, 26]. In addition, low-radiation island-like structures having a defined poloidal mode number have been observed as well [5, 16]. The visible hollow synchrotron profile and island-like structures have been assumed to be caused by a hollow radial current density profile and the presence of magnetic islands in the RE beam [5]. The assumptions have been used afterwards for performing simulations of the benign termination of RE beams using the JOREK code [16].

The aim of the present work is to provide support to the connection of the synchrotron images temporal and spatial features with the presence of a hollow current density profile and of magnetic islands in the JET RE beam. For doing so, the evolution of the synchrotron radiation of the JET relativistic electron beams is compared with measurements of multiple

diagnostics for providing an as exhaustive as possible picture of the evolution of both RE pitch and energy distributions. The deduction of the RE energy and pitch angle evolution is also obtained investigating the dynamics of the spatial synchrotron radiation profiles comparing the experimental data to the simulations performed with the CHEASE [27] and SOFT [28] codes (to be reported in a future publication [26]). Subsequently, the dynamics of the synchrotron islands is characterized using a newly developed computer vision code [29]. Video analysis results are then compared with the Mirnov coil signals, the total current and the edge safety factor profiles for establishing a relation between island-like synchrotron patterns and the possible presence of magnetic islands. Finally, a connection between the interactions of synchrotron islands and the loss of RE is also established. The present work considers a subset of all available JET discharges containing RE beams. More specifically, the experiments JET Pulse Number (JPN) 95135, 95775 and 95776 are investigated hereafter.

The publication is organized as follows: the first section introduces the diagnostics used for the analyses presented afterward highlighting their deficiencies when measuring the properties of RE beams. The second section presents an overview of the JET pulse 95135, 95775 and 95776 RE phases. Analyses of the evolution of the synchrotron radiation and of the visible island-like structure dynamics and their comparison with multiple measurements are provided in the third section. Conclusions and perspectives for future work are given at the end of the publication. We wish to note that the numerical framework and analyses used in the present work will be reported in a future publication [26].

2. Key experimental diagnostics

The JET tokamak has an extensive set of diagnostics measuring several plasma parameters during a plasma discharge. The subset of diagnostics considered in the present work, in addition to standard measurements such as the plasma current, the loop voltage and the main magnetic equilibrium quantities, includes fast visible and infrared cameras, inner discrete magnetic coils, bolometers, Hard x-ray (HXR) and visible spectrometers. The diagnostic toroidal positions and coverage sectors are depicted in figure 1 while their visual ranges and lines-of-sight in the poloidal plane are provided in figure 2. A brief description of each diagnostic of relevance is provided hereafter.

JET is equipped with two main fast visible cameras (KL8 and KLDT) with wide viewing angles. They are installed on two different octants and can capture the full poloidal cross-section of JET. KL8 can directly record the injection of fragments from the SPI system, but it is affected by vibrations. KLDT-E5WE, being protected from radiation and vibrations, can provide cleaner images. Another camera, KLDT-E5WC, captures infrared radiation and allows to visualize the synchrotron emission from REs.

As far as spectroscopy measurements are concerned, JET is equipped with photon multiplier tubes (PMTs—not shown

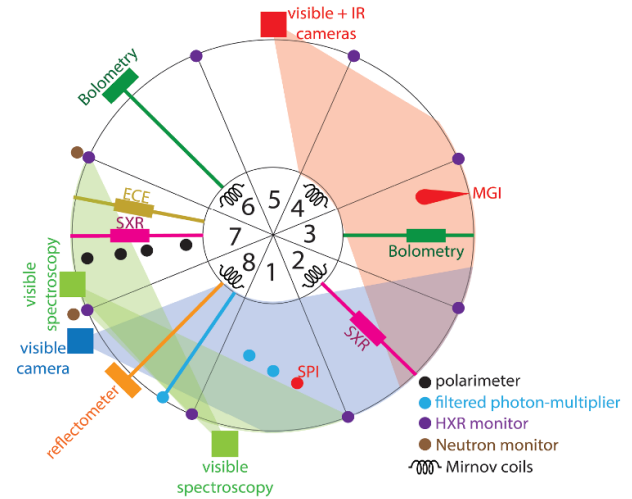


Figure 1. Schematic of the JET diagnostics, the massive gas and the shattered pellet injector positions: top-view.

here) and charge-exchange spectrometers, allowing to identify ionization-recombination events in the plasma, as well as the presence of heavy impurities in a plasma discharge.

Regarding the plasma density, the polarimeter systems provide the most reliable and better time-resolved measurements in the post-disruption phases.

Reflectometers can provide useful information as well if the RE beam is vertically stable and knowing that measurements are affected by relativistic effects and, *a priori*, have to be corrected as a function of the plasma electron temperature.

Another paramount aspect during the RE beam phase is the MHD activity. JET is equipped with a wide range of magnetic probes, which allow to identify and characterize MHD instabilities during stationary phases as well as during fast transient events, such as disruptions. Among the various systems of magnetic probes, the analysis presented in this paper is based on Inner Discrete Coils (IDCs), which provide one of the highest temporal resolutions among the various magnetic sensors installed on JET [30]. IDC probes are expected to be the most sensitive magnetic sensors to the MHD instabilities of RE beams and they offer a reasonably good toroidal coverage, therefore they represent the primary MHD diagnostic used in the subsequent sections.

Hard x-ray provides information on the generation of REs by detecting hard x-rays from its Bremsstrahlung radiation.

A detailed description of each JET diagnostic analyzed in the present work can be found in appendix B.

3. Overview of the JET RE beams: pulse 95135, 95775 and 95776

The plasma discharges (pulses) 95135, 95775 and 95776 are a series of three experiments conducted using the JET tokamak aimed to investigate the effect of different SPI compositions on the mitigation of post-disruptive RE beams. Benign termination of RE beams by pure D₂ SPI was firstly demonstrated in the pulse 95135 [5, 13]. The three discharges have

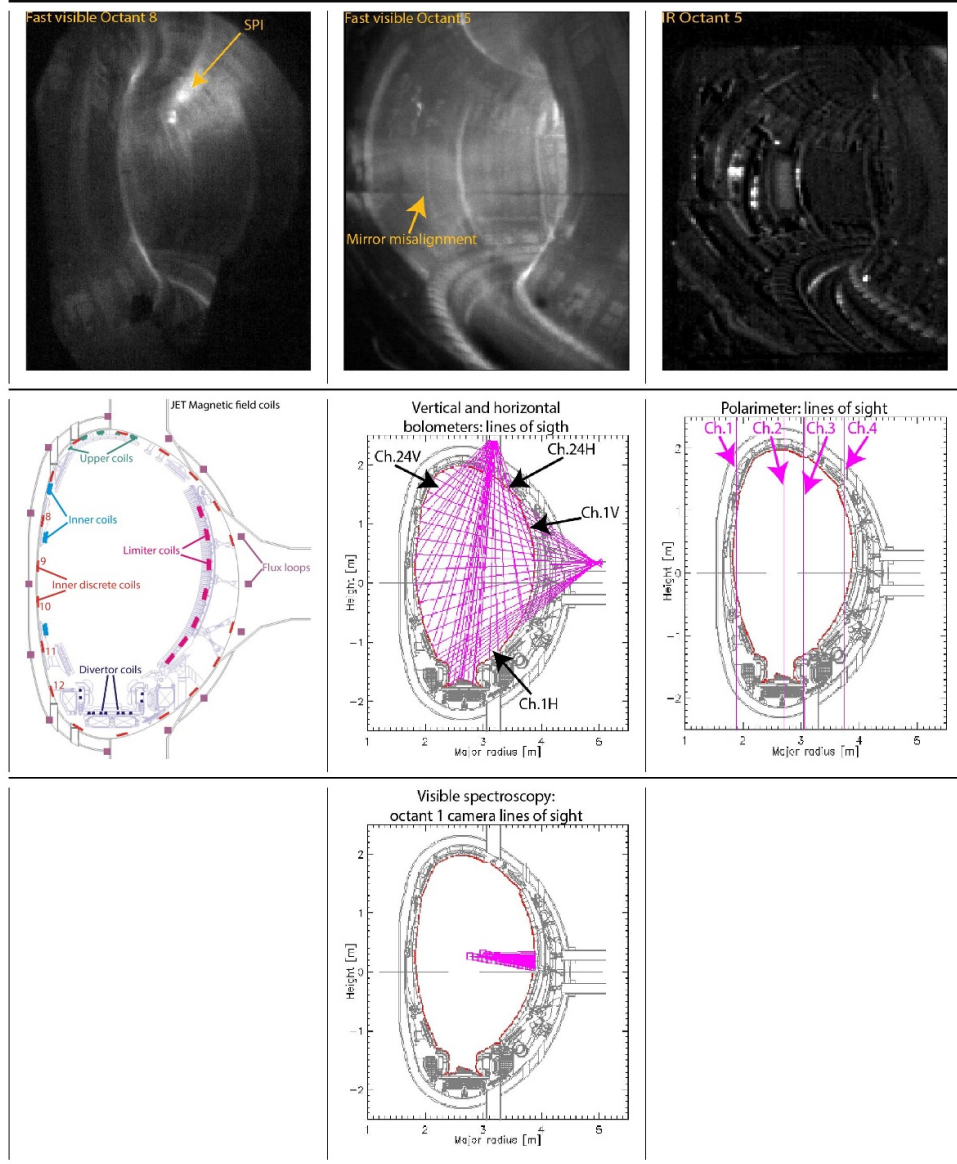


Figure 2. JET diagnostic poloidal plane positions, view sectors and lines of sight. Top row (from left to right): images of the SPI of the pulse 98766 respectively recorded with the fast visible cameras having ports in octants 8 and 5 and the infrared (IR) camera of octant 5. The second row of the table shows the JET magnetic coils position in the poloidal plane (left plot—for accurate plan and 3D views of the JET coil system the interested reader can refer to [30]), the lines of sight of the JET bolometers (center plot) and of the far infrared polarimeters (right). The bottom row center plot shows the lines of sight of the octant 1 visible charge-exchange spectrometer.

similar initial conditions and control system settings. The only remarkable difference is in the SPI pellet composition which is respectively of: 100%D₂, 10%Ne + 90%D₂ and 20%Ne + 80%D₂. We report that the pellet composition is in % of the volume of gas constituting the pellet at the reference temperature of 300 K. The vacuum toroidal magnetic field and the pre-disruptive plasma current are respectively of 3 T and 1.46 MA. Table 1 reports the remaining plasma parameters for all the three experiments taken 1 s before disruption ($t: 7$ s). The plasma disruption is triggered by MGI. The disruption time for all three pulses is of 8.02 s. The DMV used for the

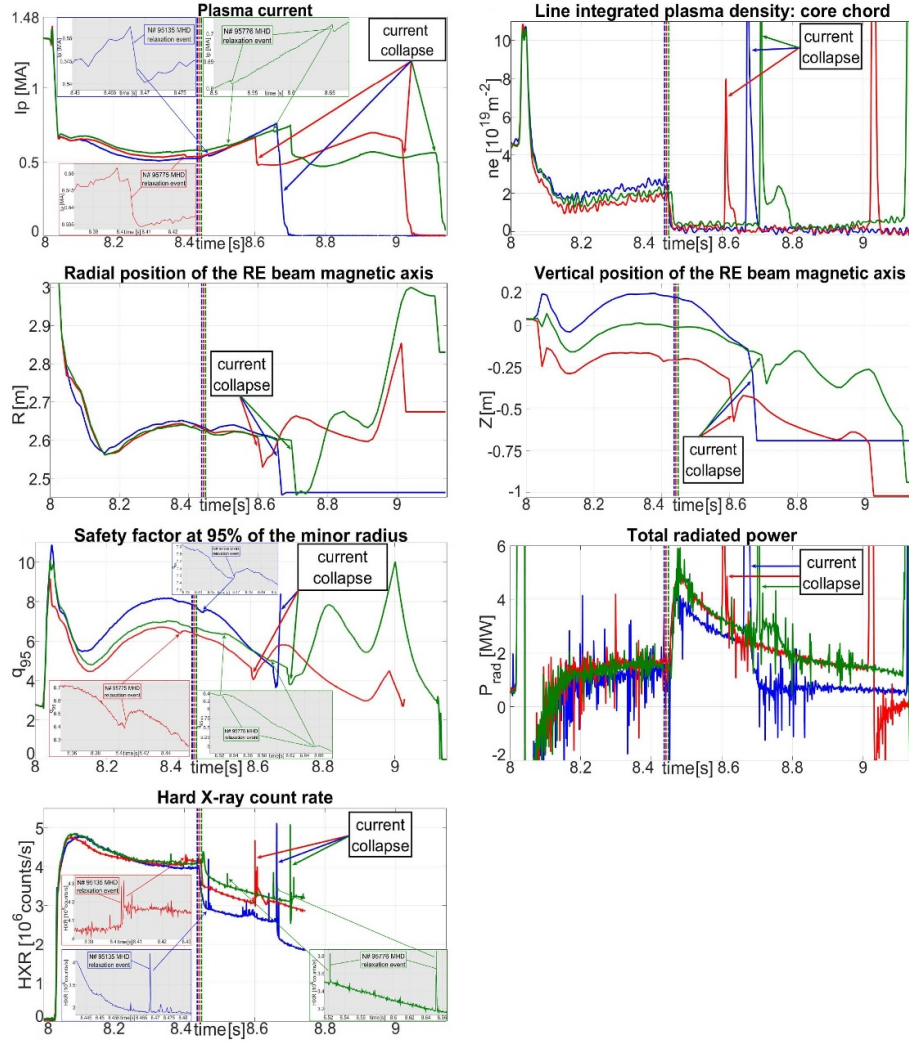
MGI is located in oct.3 at mid-plane and loaded with a number of Ar atoms between $7 \cdot 10^{20}$ and $8 \cdot 10^{20}$ (pure Ar MGI).

RE beams appear approximately 36 ms after the plasma disruption as shown by the first sign of synchrotron radiation in the IR images, the sudden increase of the HXR count rate and of the total radiated power (figure 3). The main measurements which can be used for characterizing the dynamics of RE beams in JET are provided in figure 3.

We remark that negative values of the total radiated power visible after the plasma disruption in figure 3 are not physical. Negative values of the total radiated power are caused

Table 1. Main plasma scenario parameters taken 1 s before the MGI ($t: 7$ s). n_e , T_e and N refer respectively to the core electron density, the core electron temperature and the number of argon atoms in the DMV reservoir.

Pulse	n_e (10^{19} m^{-3})	T_e (keV)	N 10^{20} Argon
95135	4.18	2.6	8.154
95775	3.73	3	7.267
95776	4.03	2.6	7.267

**Figure 3.** Overview of the main plasma parameters for the pulses: 95135 (in blue), 95775 (in red) and 95776 (in green). From top left to bottom right: plasma current, electron line integrated density (from polarimetry), plasma radial and vertical positions, edge safety factor, total radiated power, HXR count rates. Plasma profiles are reported with solid lines while dot-dashed lines denote the SPI time.

by the extreme radiative transients typical of mitigated plasma disruptions.

3.1. RE beam dynamics before the SPI

The RE beams of the pulses 95135, 95775 and 95776 present a comparable evolution in the pre-SPI phase. The pre-SPI phase is defined as the time interval between the maximum of the HXR count rate identified just after the disruption and the time-of-arrival of the SPI plume as observed by the oct.8 fast visible camera.

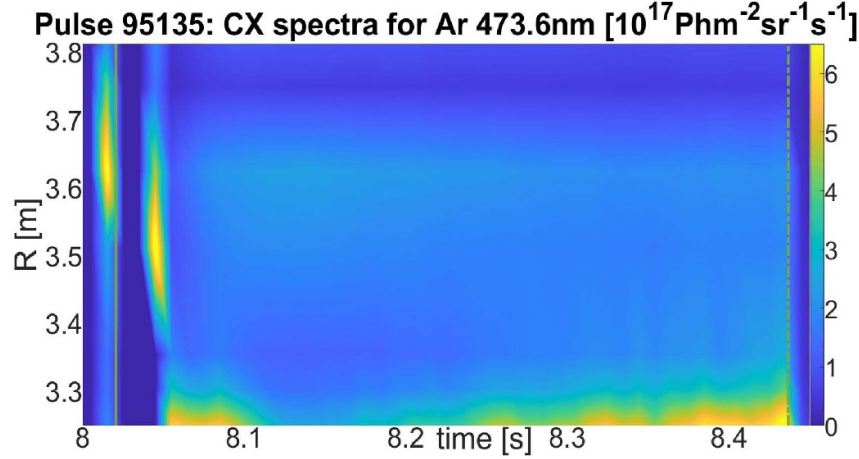
The values of the plasma current, of the core (chord N#3) line-integrated electron density, of the poloidal position and of the q_{95} for the three pulses at the beginning of the RE phase (time of the peak of the HXR emission) are given in table 2.

Table 2 shows that pulses 95135, 95775 and 95776 RE beams have similar initial states in terms of integrated quantities. The only notable differences are the core line integrated electron density and q_{95} of the pulse 95776 being respectively 16% and 15% higher than the pulse 95135 values.

HXR emission during a RE phase is typically caused by bremsstrahlung emission [31] of REs colliding with ions. The

Table 2. RE beam characteristics measured at the maximum of the HXR emission. The time at which the HXR number of counts reaches its maximum is considered as the initial time of the fully developed RE beam.

Pulse	95135	95775	95776
I_{RE} (kA)	651	642	667
$ne \cdot 10^{19}$ (m ⁻²)	2.755	2.676	3.189
R / Z (m)	2.568 / -0.024	2.647 / -0.169	2.601 / -0.036
q_{95}	6.2	6.9	7.15

**Figure 4.** Plasma Argon-II line emission for the RE phase of the pulse 95135 before the SPI. Solid and dash-dot green lines indicate respectively the disruption and SPI time.

collision targets are ions constituting the background plasma or the reactor first wall material. Being collision processes, the bremsstrahlung emission depends on the phase space distribution and confinement of the fast electrons, density and composition of the background plasma and on the material used for the first wall. Figure 3 reports that both the plasma current and the HXR decay with time while a growth is seen for the line-integrated electron density and the total radiated power. A decay of the HXR caused by a depletion of the background plasma must be discarded since the line integrated electron density increases with time and the radial movement of the RE beam is negligible. Therefore, the pre-SPI decrease of the HXR count rate can be imputed to a reduction of the RE population and/or of their energy distribution. In addition, the total radiated power (figure 3) and the Argon-II emission (figure 4) measured respectively by the bolometer and the visible spectrometer grow until the triggering of the SPI. Both measurements suggest an improved dissipation of energy of the RE beam—background plasma system through radiation. As a note of warning, we remark that the increase of the total radiated power is, at least, partially caused by the recovery of the measurements from negative values. The energy sources heating the background plasma are (1) the RE beam and (2) the ohmic heating. Analyses reported in [32] claim a temperature of ~ 10 eV for the background plasma. The high resistivity connected to the ~ 10 eV temperature prevents the generation of a significant ohmic current and hence, the ohmic heating of

the companion plasma. Moreover, the absence of a ohmic current also implies that all the plasma current is actually RE current. Consequently, the existence of a mechanism transferring energy for the RE beam to the background plasma and hence, reducing the RE energy, would explain the evolution of the HXR, the line integrated electron density, the total radiated power and of the Argon recombination rate measurements. The energy received from the hot electron population would be (partially) dissipated through radiation by the background plasma. We wish to point out that an energy transfer between hot electrons and background plasma is not the only possible explanation to the dynamics of the HXR time trace. Indeed, the decay of the HXR measurement correlates with a flattening followed by a mild increase of the RE current until the triggering of the SPI (figure 3). The reduction of the HXR counting rate together with the flattening of the RE current may indicate an improved confinement of the hot electrons. Indeed, fewer RE losses would imply fewer collisions of relativistic electrons with the reactor first wall and, hence, lower HXR emissions [33].

As final remark, we report that MHD relaxations causing a sudden RE deconfinement of 18 kA and 8 kA are respectively seen in the pulse 95775 at 8.4 s and in the pulse 95776 at 8.36 s. The RE losses are identified by sudden drops of the plasma current connected with spikes in the HXR signal of figure 3. The presence of MHD instabilities is stressed here since both relaxation events are correlated with the appearance

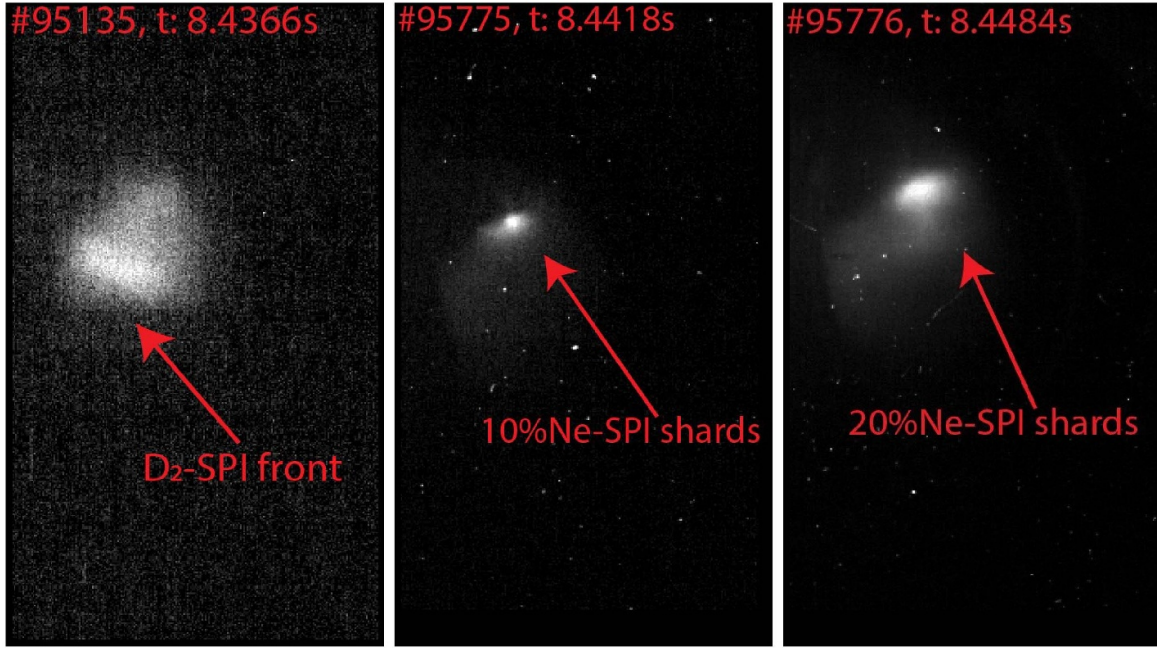


Figure 5. Fast visible images of the JET SPI in the RE beams of the JET pulses: 95135 (left), 95775 (center) and 95776 (right). The light composing the pulse 95135 image is unfiltered while the NeI filter has been used for the pulses 95775 and 95776 videos.

of island-like structures in the RE synchrotron images. A complete analysis of the relations between synchrotron islands and MHD instabilities is reported in section 4.2.

3.2. RE dynamics during the SPI

For all three pulses, the mitigation of the RE beam is attempted triggering the SPI at 8.4 s. The D_2 content is of $142.3 \cdot 10^{21}$, $129.8 \cdot 10^{21}$ and $117.4 \cdot 10^{21}$ molecules respectively for the pulses 95135, 95775 and 95776. $8.9 \cdot 10^{21}$ and $17.79 \cdot 10^{21}$ atoms of Ne are also added to the pellet composition of the pulses 95775 and 95776. Signals from the SPI microwave diagnostics [34–37] reveal that in the pulses 95135 and 95775 pellets broke into two pieces before fragmentation. Finally, a comparable time of SPI arrival within 8.4366 s and 8.4484 s is estimated for all three pulses. The SPI arrival time is extracted identifying the first bright features visible at the SPI port in the oct.8 fast visible camera as shown in the images of figure 5.

A possibly interesting difference between pure D_2 SPI and pellets containing Ne impurities is the dynamics of the shard sublimation. Shard sublimation is caused by the intense volumetric heating resulting from the interactions with the REs [38]. SPI shards containing Ne impurities are visible during the injection into RE beams (center and right plot of figure 5). The SPI shards are mainly ablated at the RE beam edge with ablation cloud spreading toroidally and poloidally. Conversely, no shards and no ablation processes are visible for pure D_2 SPI. Instead, a gas blast is observed to instantly cross the entire RE beam volume (figure 5 left plot). We remark that the differences between the ablation videos are also observed for unfiltered videos of Ne SPI and for filtered videos of pure D_2 SPI ($D - \alpha$ Balmer line filter). Therefore, light filtering effects

must be discarded as possible explanations of the peculiar pure D_2 SPI ablation process.

The response to the SPI injection into the RE beam consists of a sudden neutralization of the background plasma in all the three pulses. The neutralization process is revealed by a drop from approximately $\sim 2.87 \cdot 10^{19} \text{ m}^{-2}$ to $\sim 1.5 \cdot 10^{18} \text{ m}^{-2}$ in the line-integrated electron density for the pulse 95135 and between $\sim 2 \cdot 10^{19} \text{ m}^{-2}$ ($\sim 2.34 \cdot 10^{19} \text{ m}^{-2}$) and $\sim 2 \cdot 10^{18} \text{ m}^{-2}$ ($\sim 4.2 \cdot 10^{18} \text{ m}^{-2}$) for the pulse 95775 (95776) (figure 3). The fall of the line integrated density is followed by a peak of the total radiated power (figure 3). The peak in the total radiated power is attributed to the line emission of the recombining atoms and excited neutrals (radiation peaks are observed in the visible camera and spectrometers as well). Similarly, the HXR count rate instantly decays suggesting a reduced collisionality between relativistic electrons and the companion plasma. The time scale of the companion plasma neutralization is approximately $\sim 10 \text{ ms}$.

3.3. Evolution of the RE beams after the SPI

After the SPI, the RE beam current increases almost linearly until a maximum respectively of $\sim 760 \text{ kA}$, $\sim 670 \text{ kA}$ and $\sim 760 \text{ kA}$ for the pulses 95135, 95775 and 95776 (figure 3). Conversely, the HXR count rate steadily reduces with time. A more detailed discussion of the dynamics of the RE beam and the evolution of the plasma current and HXR rate is reported in section 4.1.

Two different types of MHD events are also observed after the SPI (figure 3). The first are MHD events causing the loss of supra-thermal electrons as revealed by the associated drop in the plasma current and spikes in the HXR count rate. The

second are instabilities causing a breakdown or re-heating of the companion plasma without losses such as the anomalous Doppler instability [39–42]. An example of anomalous Doppler instability observed during the post-SPI phase of the pulse 95135 is provided in appendix A [39–42].

The RE beams of the pulses 95135 and 95775 terminate benignly [43, 44]. In contrast, a harmful termination characterizes the pulse 95776 RE beam ending [43, 44]. Experiments conducted in the ASDEX-Upgrade and the TCV tokamaks revealed that a low companion plasma density is required for achieving benign RE beam termination. Conversely, harmful beam termination has been systematically obtained for high enough companion plasma densities. An increase of the background plasma density has been observed for the pulse 95776 RE beam concomitant to an MHD event taking place before the final collapse. The increase of the plasma density is revealed by the growth of the line integrated density measurement (figure 3). Therefore, the harmful termination of the pulse 95776 RE beam might be explained with the reaching of background plasma density levels at which benign termination cannot occur.

4. Analysis of the synchrotron radiation of the JET RE beams

4.1. Overview of the synchrotron radiation of the JET RE beams

Information of the dynamics of RE beams can be extracted considering the time evolution of the total radiation received by the camera and of its integrated radiation profiles as reported in figure 6. Together with the camera integrated intensities, figure 6 reports also the loop voltage and the total plasma current.

A fast decay of the RE synchrotron radiation is observed after the arrival of the SPI (≈ 8.45 s) for all pulses (first, and second rows of figure 6). We remark that the line integrated intensity of the oct.8 camera does not drop after the neutralization of the background plasma (fourth row of figure 6) since no synchrotron emission is visible to this camera. At present, the phenomena inducing the drop in the synchrotron radiation emission are still unknown. Different hypotheses capable to explain the observed behavior of the synchrotron radiation intensity can be formulated. For instance, a reduction of the overall emitted synchrotron power can be caused by: (1) a depletion of the RE population, (2) a contraction of the RE pitch angle distribution and (3) the slowing down of REs to lower energies. Significant losses of RE are excluded by the increase of the plasma current after the SPI (right plot—third row of figure 6). Actually, the growth of the plasma current is a sign of an increase of the RE population given that all the plasma current is carried by REs as already discussed in section 3.1. A reduction of the maximum pitch angle distribution may also explain the observed synchrotron emission decay. The shrinking of the pitch angle distribution can be related to the presence of a toroidally accelerating electric field, as suggested by a non-zero loop voltage (figure 6 left

plot fourth row) and, eventually, by a reduction of the plasma collisionality [45]. Collisions between REs and the companion plasma have the effect of increasing the maximum pitch angle of the RE distribution and hence, the emitted synchrotron power [28]. The initial drop of the companion plasma collisionality [45] is caused by the decrease of both the background plasma density and the neutralization of the ionized heavy impurity populations induced by the SPI as discussed in section 3. Hints of an additional slow decay of the Ar-II and of the Ne-I populations during the post-SPI phase are provided by (1) the slower decay of the RE synchrotron power for the Ne-rich (pulse 95775 and 95776) SPI with respect to the pure D2 (pulse 95135) injection and (2) by the reduction of the oct.8 camera total number of counts (first, second and last rows of figure 6). Indeed, a slower recombination of the Ne impurities would cause a slower decay of the RE-companion plasma collisionality and hence, of the synchrotron power. We note that no significant differences are found between the 10% and the 20% Ne SPI experiments. Consequently and if confirmed, the slow post-SPI neutralization of heavy impurities would decrease the effective charge of the companion plasma further reducing the collisionality.

An unclear picture emerges when the maximum RE energy is considered. The experimental time traces (last row of figure 3) show a reduction with time of the HXR counts after the SPI. As reported in section 3.1, the decay of the HXR signal can be attributed to both a drop of the maximum RE energy and (or) of the background plasma collisionality. Therefore, no conclusion can be drawn. We wish to remark that different analyses methods, based on magnetic measurements and on the deconvolution of HXR spectra, suggest that the RE kinetic energy decays with time after the D2 SPI [25, 46, 47].

Additional information concerning the evolution of the RE momentum distribution can be extracted analyzing the spatial features of the synchrotron spots such as the vertically and horizontally integrated emission profiles. The vertically and horizontally integrated profiles and intensity contour plots for the pulse 95135 RE beam normalized to the frame total number of counts are given respectively in the left and right columns of figure 7. The procedure developed for generating the image-to-physical coordinate maps is reported in appendix C.1.

The evolution of the vertically integrated synchrotron emission after the SPI (left column of figure 7) is characterized by an asymmetric contraction of the synchrotron image towards the high field side with time. The dynamics is particularly evident from the vertically integrated intensity contours (left-column lower plot) which contract toward the high field side. Similarly, the time evolution of the horizontally integrated synchrotron radiation (right column) presents (1) a rigid displacement towards lower vertical positions and (2) a contraction of the synchrotron spot from top (above mid-plane) to bottom (below mid-plane). While probably not evident from the right column of figure 7, the vertical contraction of the synchrotron spot can be clearly visualized analyzing the variation of the distance between isolines of equal normalized horizontally integrated synchrotron emission. The time variations of the

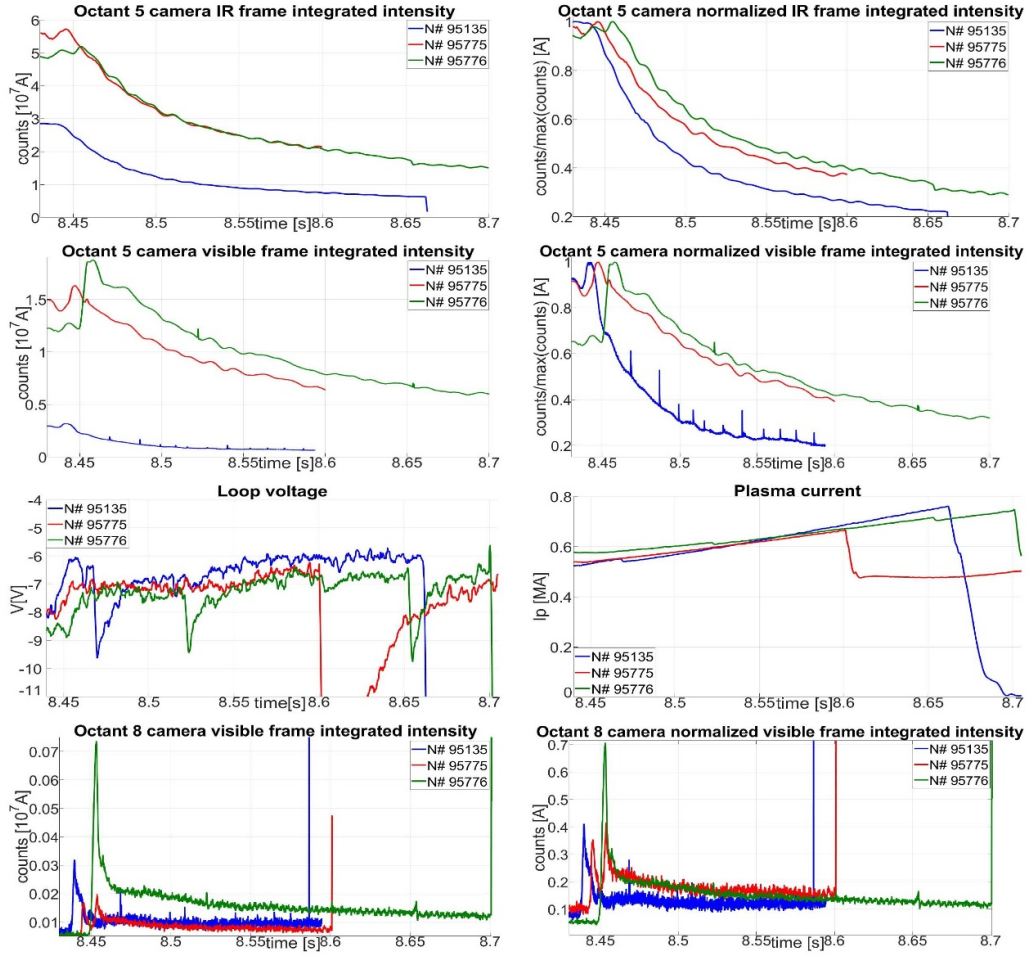


Figure 6. Frame integrated light intensities of the oct.5 IR and fast visible cameras with comparison to the RE beam loop voltage and plasma current for the pulses 95135 (blue solid line), 95775 (red solid line) and 95776 (green solid line). The considered time interval is between the SPI injection (8.4 s) and the RE beam (partial) collapse. From top-left to bottom-right plots: absolute (left plot) and normalized to the maximum value (right plot) frame integrated IR light intensities, absolute (left plot) and normalized to the maximum value (right plot) frame integrated visible light intensities, RE beam loop voltage (left plot), plasma current (right plot), absolute (left plot) and normalized (right plot) frame integrated light intensity of the oct.8 camera.

distance between two isolines located above and below mid-plane for different normalized horizontally integrated synchrotron emission values are provided in figure 8. Figure 8 shows that the vertical separation between two isolines reduces with time. The reduction is more pronounced for isolines located at the edge of the synchrotron spot i.e. having lower emission levels. A comparison with the numerical experiments discussed in [26] reveals that the dynamics of the vertically integrated emission is compatible with a reduction of the maximum RE kinetic energy. Similar comparisons with the results of [26] shows that the asymmetric vertical contraction of the RE beam image can be related to a reduction of the maximum pitch angle reachable by the relativistic electrons for maximum pitch angles above $7.5 \cdot 10^{-2}$ radians. The rigid vertical shift is attributed to the RE beam downward motion (figure 3 and [26]). Therefore, the spatial evolution of the synchrotron images in concert with the numerical experiments of [26] suggests that both the maximum achievable pitch angle and kinetic energy by the supra-thermal electrons reduce with time after the D2-SPI. We point out that the synthetic synchrotron

images of [26] have been obtained using the CHEASE [27] and the SOFT [48] codes and have been based on the pulse 95135 experimental data. The relativistic electrons pitch angle and energy distribution used in [26] are respectively uniform and almost mono-energetic (uniform-narrow bounded).

The simultaneous decay of the RE maximum energy and growth of the relativistic beam current may be the result of the electron avalanche mechanism [49–51]. Indeed, the electron avalanche would (1) produce mildly energetic REs and (2) limit the maximum energy reachable by relativistic electrons due to knock-on collisions with the cold background plasma. This last would counteract the acceleration of the driving electric field which should populate the high energy tail of the hot electron distribution. Numerical simulations are required for verifying the compatibility of the presence of electron avalanche with an overall contraction of the RE pitch angle distribution.

The time evolution of the vertically and horizontally integrated synchrotron emission profiles (not reported here) of the

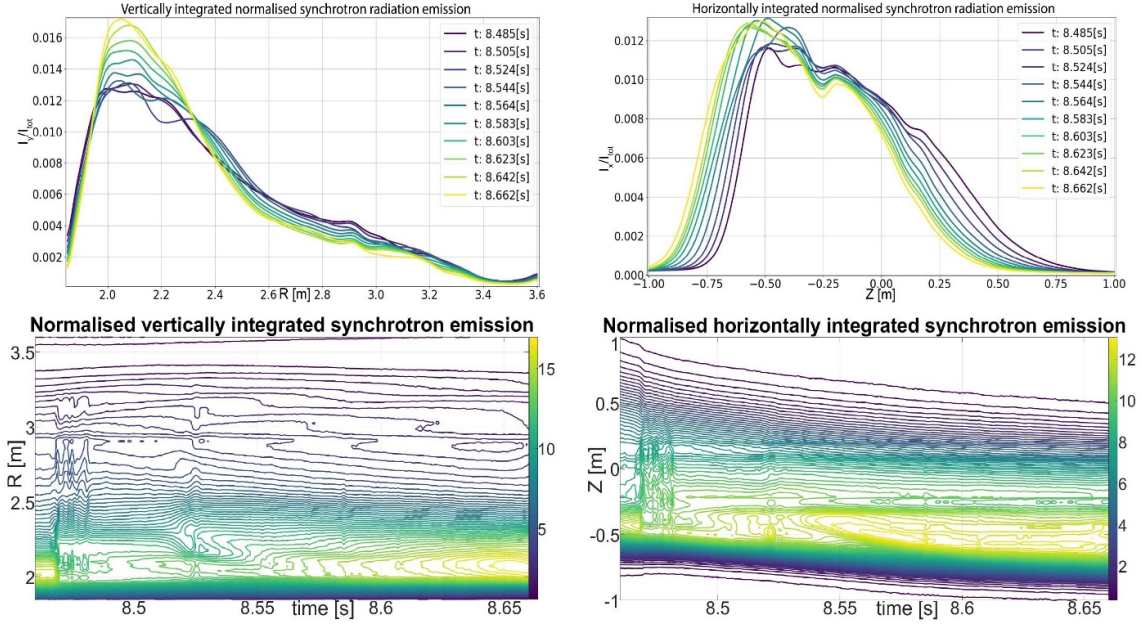


Figure 7. Normalised vertically (left column) and horizontally (right column) integrated synchrotron radiation number of counts (IR camera) of the pulse 95135 after the SPI arrival (t : 8.485s–8.662s). The upper plots are respectively the vertically and horizontally integrated number of counts profiles at different times (the increasing time is denoted with brighter colors). Contour plots of the vertically and horizontally integrated IR number of counts as a function of the temporal and spatial coordinates are reported in the lower row. The intensity of the contour plots is scaled with a factor of 10^3 . The normalization is with respect to the total number of counts per each frame. Please, refer to appendix C.1. for a discussion of the image to physical coordinates mapping procedure.

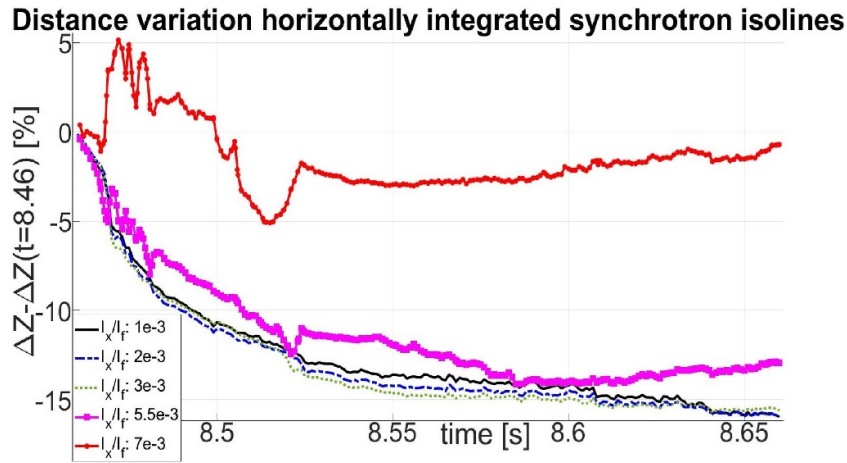


Figure 8. Time variation of the vertical distance between lines of constant normalized horizontally integrated synchrotron emission. Solid black, blue dash-dot, green dotted, magenta solid-square and red solid-star lines denote the variation of distance between isolines having a normalized horizontally integrated synchrotron emission respectively of 10^{-3} , $2 \cdot 10^{-3}$, $3 \cdot 10^{-3}$, $5.5 \cdot 10^{-3}$ and $7 \cdot 10^{-3}$.

10% and the 20% Ne SPI experiments (95775 & 95776) is similar to the profile dynamics of the pure D2 SPI plasma discharge (95135). The main difference is the reduction of the profile peaking and contraction for larger Ne content in the pellet composition. The trend is compatible with an enhancement of the RE pitch angle (collision) scattering and hence, of the maximum pitch angles reachable by the RE distribution, with the increase of the total number of injected Ne atoms [45].

4.2. Dynamics of rotating synchrotron islands in JET RE beams during and after MHD relaxation events

At least two JET-specific features have been found in videos capturing the synchrotron radiation of RE beams. The first feature is the presence of hollow synchrotron spots. Hollow spots are synchrotron images having an intensity of the synchrotron emission lower at the core than at the edge. The second feature is the presence of natural island-like patterns organized in chains within the RE beam. The adjective ‘natural’ here

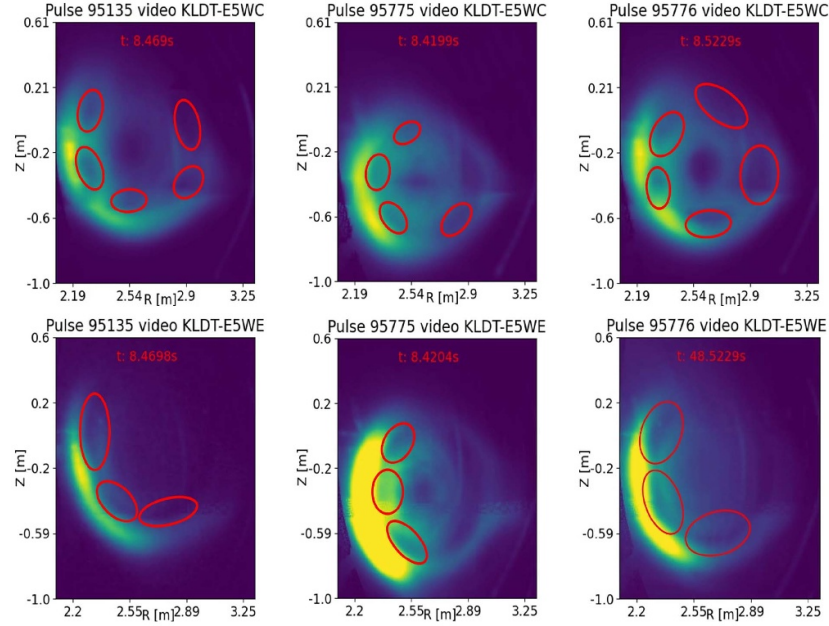


Figure 9. Examples of synchrotron island-like patterns visible in the IR (top row) and visible (bottom row) videos of the pulses 95135 (left column), 95775 (central column) and 95776 (right column). Island-like patterns are highlighted by red ellipses.

indicates that the synchrotron islands do not result from the injection of killer pellets [19, 52] or the application of resonant magnetic perturbations [22, 53, 54]. Previous work [5, 16] assumed island-like structures in the synchrotron emission to be related with the presence of magnetic islands in the RE beam magnetic topology. The characterization of the synchrotron island dynamics jointly to sensitivity scans of the synchrotron emission performed using the SOFT code associated the hollow synchrotron images with the presence of hollow current profiles [5, 16]. We remark that monotonic current profiles may also result in hollow synchrotron images if the electron maximum pitch angle and/or the energy abruptly increase towards the beam edge [26]. Examples of synchrotron islands for the pulses 95135 (post-SPI), 95775 (pre-SPI) and 95776 (post-SPI) are provided in figure 9.

Figure 9 shows that island-like structures in the JET RE beam images are multiple localized regions of reduced synchrotron emission. The low radiation regions have island-like shapes and are symmetrically laid on a poloidal circle at similar minor radius. Single chains of island-like patterns having poloidal mode number respectively of $m = 6$, $m = 5$ and $m = 5$ are visible in the images of the pulses 95135, 95775 and 95776 of figure 9. The synchrotron island chains treated hereafter are visible before the SPI shards arrival for the pulse 95775 and after the SPI for the pulses 95135 and 95776. As discussed in section 4.1, the features are specific of the synchrotron radiation because visible at the same time in both the visible and the IR spectrum images while invisible to the oct.8 camera. An analysis of the synchrotron spot sensitivity to the maximum RE pitch angle (uniformly distributed) using the SOFT code suggests that the synchrotron images reported in figure 9 capture the overall RE beam emission without incurring in synchrotron spot splitting [26]. Therefore, the synchrotron

emission can be considered as a rough map of the drift orbit surfaces for the experiments treated here. A possible reason explaining the presence of island pattern chains in the JET synchrotron images is the generation of magnetic islands in the RE beam via current suppression. Indeed, a direct comparison of figure 9 with the data of [19, 22, 52–54] reveals that magnetic islands in RE beams are observed as island patterns appearing in relativistic electron beams. Magnetic islands trapping RE are observed as regions of strong synchrotron emission in TEXTOR and DIII-D [19, 22, 52–54]. Conversely, the patterns visible in JET are regions of lower emission with respect to the overall synchrotron spot (figure 9). Consequently, the JET island patterns seem to be characterized by regions of reduced RE density and hence, of reduced current. A first numerical investigation aimed to identify possible relations between dark synchrotron islands and magnetic islands with reduced RE current density has been performed using the JOREK code. Indeed, preliminary 3D JOREK synchrotron simulations of magnetic configurations with double $m = 4$ $n = 1$ magnetic island chains show that darker synchrotron island-like features can correspond to regions of reduced current within the magnetic islands [55]. Unfortunately, a direct connection between the presence of synchrotron and of magnetic islands has not been established yet in JET. Indeed, spectrograms of the JET magnetic measurements do not present signatures of coherent MHD modes having toroidal mode numbers larger than 0. As reported afterwards, signals of the magnetic measurements are likely dominated by the MHD relaxation processes occurring concomitantly to the rotation of the synchrotron islands. The presence of MHD relaxation events during the island rotation prevents the detection of possible MHD coherent modes. In addition, no locked mode has been detected by the JET saddle coil system during the non-rotating phase of

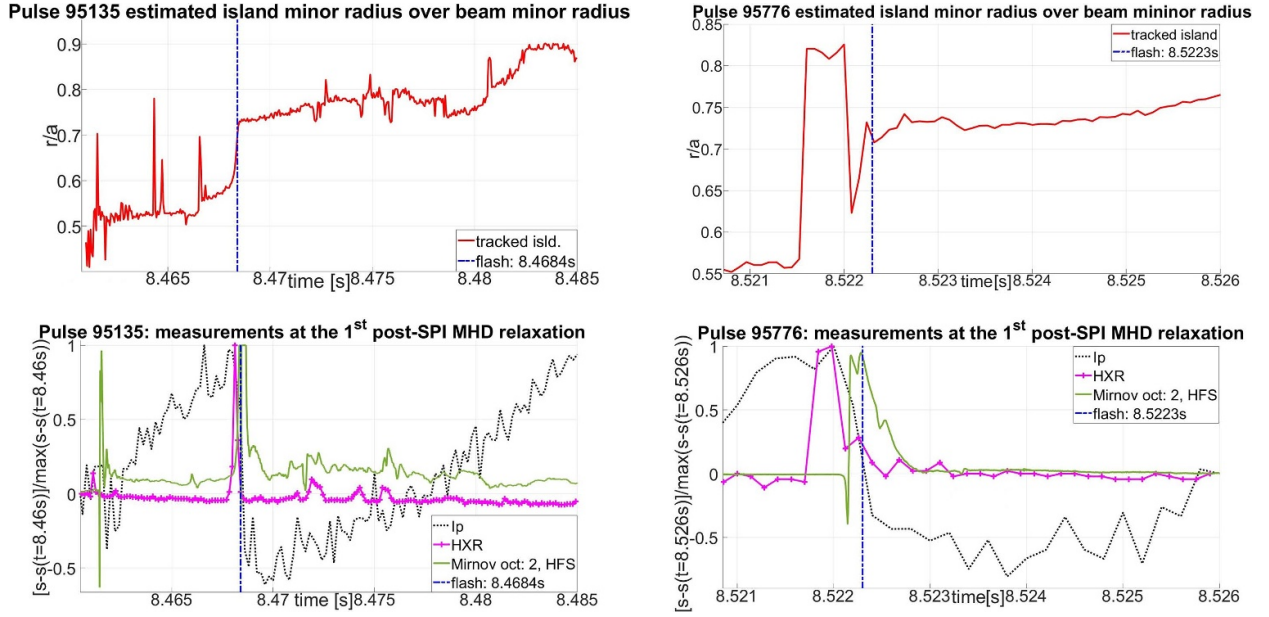


Figure 10. Comparison between the evolution of the synchrotron island chain (visible spectrum) radial position with respect to the experimental measurements of the pulses 95135 ($m = 6$ island chain, left column) and 95776 ($m = 5$ island chain, right column) during a MHD relaxation event. The first row reports the evolution of the average estimated island minor radius normalized to the beam minor radius (red solid line). The second row reports the evolution of the plasma current (dotted black line), the HXR signal (magenta line with plus markers) and the mid-plane—HFS Mirnov coil signal located in the oct.2 (light green solid line). In all plots, the vertical dash-dot blue line denotes the time of the instability seen in images as a sudden increase of the count number (flash).

the synchrotron islands section 4.3 probably due to too low sensitivity. Similarly, no coherent mode has been observed in the ECE and SXR data. The absence of mode observation may be caused by RE-induced relativistic Doppler effects and by a too low signal-to-noise ratio for respectively the ECE and the SXR measurements appendix B. For establishing a connection between the dynamics of synchrotron island chains with the presence of MHD instabilities, figure 10 compares the time traces of the estimated island chain minor radius and rotation frequency against the plasma current, HXR and Mirnov coil signals (oct.2 mid-plane-HFS) for the pulses 95135 and 95775.

While synchrotron islands appear in the visible images between 3 ms and 1 ms before the MHD instabilities, a sudden change of their properties occurs in proximity of the MHD event. As a matter of fact, both the $m = 6$ chain of the pulse 95135 (left plot) and the $m = 5$ chain of the pulse 95776 (right plot) exhibit a sudden and explosive increase of the chain estimated minor radius (top row figure 10). Indeed, the estimated minor radius increases of approximately 25% (22.5%) in 0.61 ms (1.1 ms) for the pulse 95135 (95776). The fast radial motion of the patterns associated to the fast MHD relaxation is compatible with the non linear dynamics of double tearing modes [56, 57]. Indeed, double tearing mode simulations show that external and internal magnetic island chains promptly swap positions during the fast relaxation phase (cf figure 11 of [56] for example). This phase is also characterized by partial stochasticization of the magnetic fields compatible with the loss of RE revealed by the spikes in the HXR signal and the loss of current [56, 57]. Unfortunately, the presence of a second

$m = 6$ synchrotron island chain has not been currently identified in experimental videos.

Apart from the relaxation dynamics described in the previous paragraph, synchrotron islands are sometimes observed to rotate. The island rotation frequency is shown in figure 11 where it is compared to mid-plane-HFS Mirnov coil signals for the pulse 95775 (pre-SPI).

Figure 11 shows that the island rotation frequency is not constant with time but presents phases of acceleration and deceleration. These phases are correlated to the growth and the decay of Mirnov coil signal intensity. Note that the signals of the octant 4, 6 and 8 (not reported here) are superimposed to the octant 2 measurement. Therefore, the Mirnov data is dominated by an $n = 0$ mode possibly related to interference of multiple island chains rotating at different frequencies.

Figure 12 reports images (visible spectrum) of the relaxation process triggering dark synchrotron islands in the pulse 95775 RE beam.

A hollow synchrotron spot is observed before the relaxation process. During the MHD instability, a $m = 5$ dark island chain appears in the synchrotron image (red ellipses—top middle plot figure 12). At the same time, a chain of bright island-like structures is visible within the synchrotron spot as well (light orange ellipses—top middle plot figure 12). The bright islands are identified in both visible and IR images hence, they are features of the RE beam synchrotron emission. Dark and bright island chains have opposite dynamics: dark synchrotron islands propagate towards the RE beam edge while a radial motion towards the beam core is seen for the bright islands.

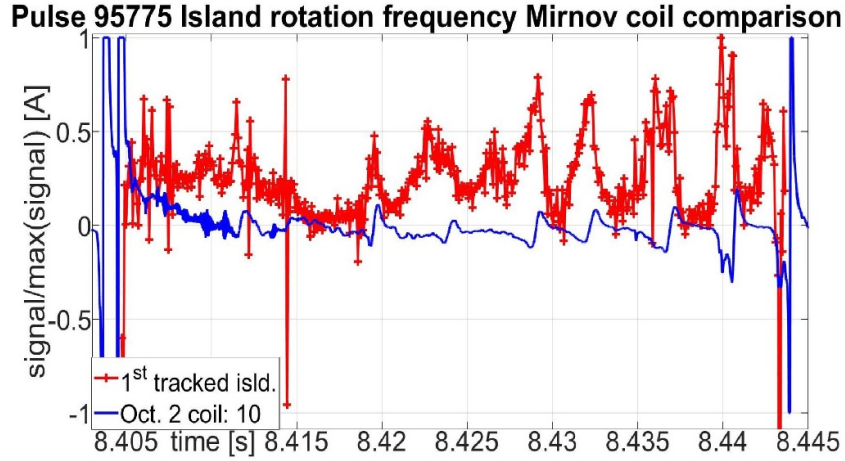


Figure 11. Average estimated $m = 5$ island rotation frequency of the pulse 95775. Blue solid denotes the signal of the mid-plane-HFS Mirnov coils of the octant 2. The red-star line is the average estimated island $m = 5$ rotation frequency.

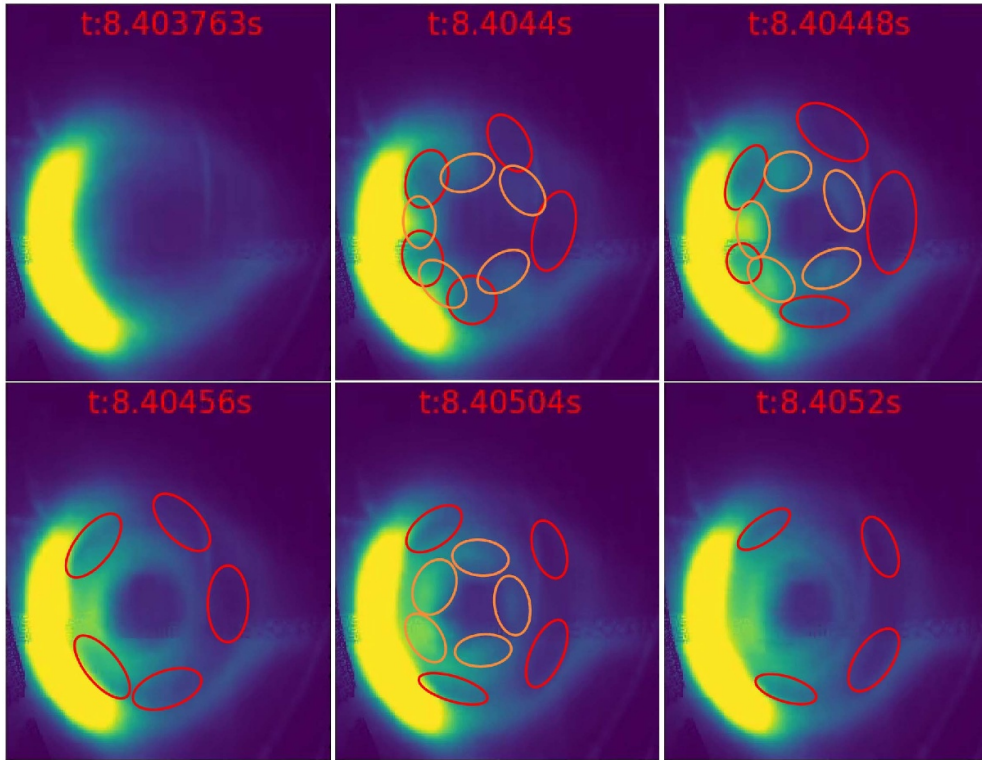


Figure 12. Images of the MHD relaxation generating dark synchrotron islands during the pulse 95775 RE phase. Images are time ordered from top-left to bottom-right. Red and light orange ellipses denote respectively dark and bright synchrotron island chains.

While the $m = 5$ dark synchrotron island chain remains visible until the arrival of the SPI (figure 11), the bright synchrotron islands are seen to relax to a circular radiating belt enclosing the dark RE core. A sequence of five events concerning the appearance and the relaxation of the bright synchrotron islands is identified. The low emission region at the core of the RE beam is contracted at each event. Unfortunately, the relaxation dynamics shown in figure 12 has not been captured by standard plasma diagnostics, such as the ECE or reflectometer. Consequently, different physical explanations can be theorized

for interpreting the sequence of events reported in figure 12. A possible explanation invokes a relaxation process mediated by double tearing instability [56, 58–62]. Assuming the presence of a hollow current density profile before the relaxation (compatible with the hollow synchrotron profile), the growth of the plasma current characterizing the pre-relaxation phase would increase the off-axis peaking of the current density. When the $q_{\min}$ goes below 5, an $m = 5$ double tearing mode is destabilized generating the dark and the bright $m = 5$ synchrotron island chains as recorded in the videos. Similarly to

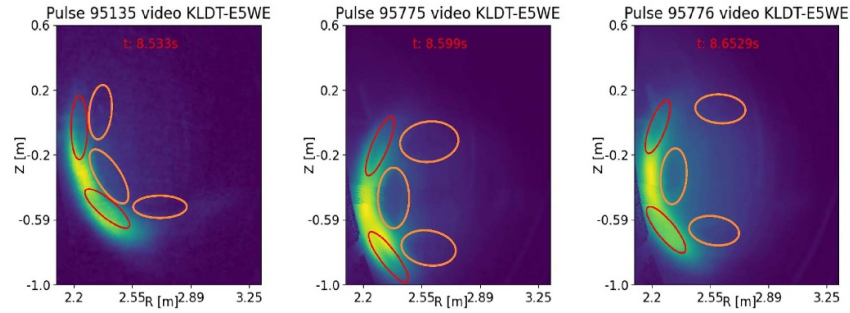


Figure 13. Examples of images in the visible spectrum of multiple locked synchrotron island chains appearing during the RE beam current ramp-up phase of the pulses 95135 (left), 95775 (center) and 95776 (right). The outermost and innermost island chains are highlighted respectively by red and light orange ellipses.

the previously discussed relaxation cases in the pulses 95135 and 95776, we speculate that non-linear interaction causes the interchange of the radial position of the two island chains with partially chaotic magnetic fields. The resulting magnetic chaos can be responsible of the deconfinement of hot electrons. We also speculate that the external islands are generated in region of higher RE current densities hence, of brighter synchrotron emission before moving towards the center. Therefore, the bright synchrotron islands can be associated to the originally external and finally internal island chain.

Summarizing, the island-like patterns observed in the synchrotron images of JET RE beam can be connected to the presence of magnetic islands with reduced RE density. The lower RE density and hence, RE current, is suggested by the fact that JET synchrotron islands result to be darker than the overall synchrotron spot. The reduction of RE density as cause of dark synchrotron islands is supported by preliminary JOREK simulations as well [55]. Contrarily, magnetic islands trapping a RE population resulted in bright island structures as visible in the synchrotron images of TEXTOR and DIII-D tokamaks [19, 22, 52–54]. A direct relation between synchrotron and magnetic islands have not been established yet in JET due to the absence of signatures of coherent MHD modes with toroidal mode number different than 0. Conversely, correlations between the synchrotron pattern dynamics and the RE beam MHD activity exist, supporting the MHD nature of the synchrotron islands. Indeed, explosive island radial displacements have been observed during MHD events characterized by a sudden loss of current. Such a radial displacement may be related to variations in the position of the resonance surfaces. Correlations also exist between the synchrotron island rotation frequency and the beam MHD activity. An acceleration of the island rotation is seen at the destabilization of the RE beam MHD while a relaxation of the MHD instability correlates with a deceleration of the synchrotron islands. Finally, the relaxation process triggering the dark $m = 5$ synchrotron islands identified in the pulse 95775 RE phase may be related to non-linear interactions between double $m = 5$ tearing modes or $m = 5$ tearing and core MHD instabilities. It is worth noting that the absence of signature in the magnetic signals of coherent MHD modes while synchrotron islands are visible may be caused by a difference in the width of the islands in the

magnetic and in the drift orbit topologies. Indeed, the width of islands in the drift orbit topology is expected to increase with the energy of the RE as described in [63].

4.3. Long term evolution of the synchrotron islands

Multiple synchrotron island chains are observed to evolve during the post-SPI current ramp-up of the pulse 95135, 95775 and 95776 RE beams. Examples of synchrotron visible images with multiple island chains are reported in figure 13 for the three pulses. We note that the poloidal mode number of synchrotron islands appearing at later time is in decreasing order starting from $m = 6$ for 95135 and $m = 5$ for the other two experiments. During the RE beam current increase phase, the rotation of the synchrotron islands is suppressed (locked islands) while an outward radial motion towards the RE beam edge is observed. The estimated radial positions of the outer (in blue) and inner (in red) synchrotron island chains for the pulses 95135 (top-left), 95775 (top right) and 95776 (bottom) pulses are provided in figure 14.

Figure 14 shows that the synchrotron island chains move towards the RE beam synchrotron spot edge at almost constant velocity during the RE current ramp-up phase of all three pulse. The only exception is the second island chain of the pulse 95775 which shows an explosive growth. Assuming the synchrotron islands to be related to the presence of magnetic islands, the simplest explanation of the radial movement towards the RE beam edge is a reduction of the RE beam safety factor. We attribute the decay of the safety factor to the growth of the RE current since the shrinking in diameter of all RE beams considered here is below 5.33% before collapse. The growth of the RE current is probably caused by the generation of relativistic carriers due to electron avalanche [49–51]. Experimental evidences supporting such a theory would be (1) an edge safety factor profile allowing the presence of resonant surfaces compatible with the synchrotron island poloidal mode number (2) a correlation between the growth (decay) rate of the plasma current (safety factor) time traces and the synchrotron island radial velocity. The electron avalanche may also provide hints on the connection between hollow synchrotron and current density profiles. Indeed, the electron avalanche is proportional to the RE current density. Therefore, the growth

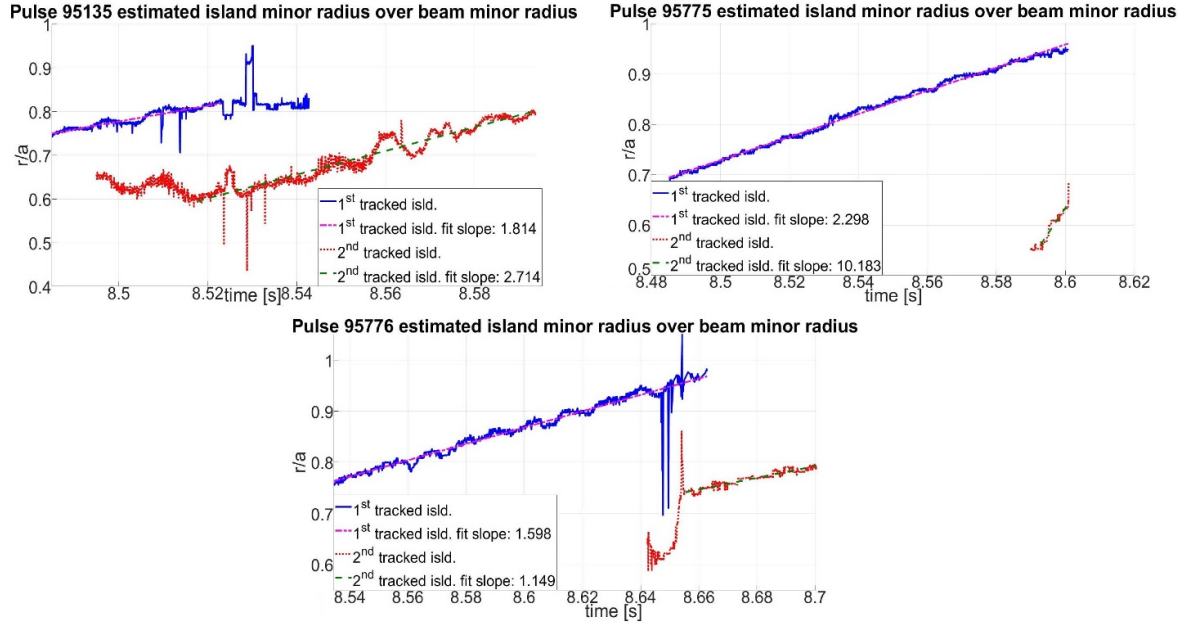


Figure 14. Estimated average minor radius (normalized to the beam minor radius) of the pulse 95135 (top-left), 95775 (top-right) and 95776 (bottom) synchrotron islands. The minor radius of the first and second island chains and of their linear fits are denoted using respectively solid blue, red dot, magenta dash-dot and green dash lines.

Table 3. Linear interpolation of the experimental q_{95} values at the appearance ($q_{95_{\text{init}}}$) and at the disappearance ($q_{95_{\text{end}}}$) of locked island chains.

Sync. Island Chain	Poloidal mode number	$q_{95_{\text{init}}}$	$q_{95_{\text{end}}}$
N# 95135 2nd isld.	6	7.55	6.74
N# 95135 3rd isld.	5	7.47	5.72
N# 95775 1st isld.	5	6.09	4.62
N# 95775 2nd isld.	4	4.81	4.64
N# 95776 1st isld.	5	6.34	4.97
N# 95776 2nd isld.	4	5.12	4.38

rate of the RE density is expected to be higher at the beam edge for hollow current configurations and in the absence of radial transport [49–51]. Since the synchrotron radiation is also proportional to the RE density, the synchrotron intensity received from minor radii close by the RE beam edge would also increase at higher rates. The last point has to be considered as ‘weak’ evidence since sharp radial variations of the RE momentum distribution can produce similar synchrotron images from RE beams having different current density profiles [26]. Table 3 reports the values of q_{95} , obtained from the EFIT code [64], at the appearance ($q_{95_{\text{init}}}$) and the disappearance ($q_{95_{\text{end}}}$) of each magnetic island chain shown in figure 14. The q_{95} values are linearly interpolated at the initial and final island chain time.

The values of q_{95} measured at the appearance and the disappearance of the locked synchrotron island chains reported in figure 14 shows that synchrotron patterns appear for values of q_{95} higher than the estimated poloidal mode number of the synchrotron island chain. The analysis assumes a toroidal mode number of the magnetic islands possibly associated to the island-like patterns of $n = 1$ [5, 16, 26]. Similarly, synchrotron

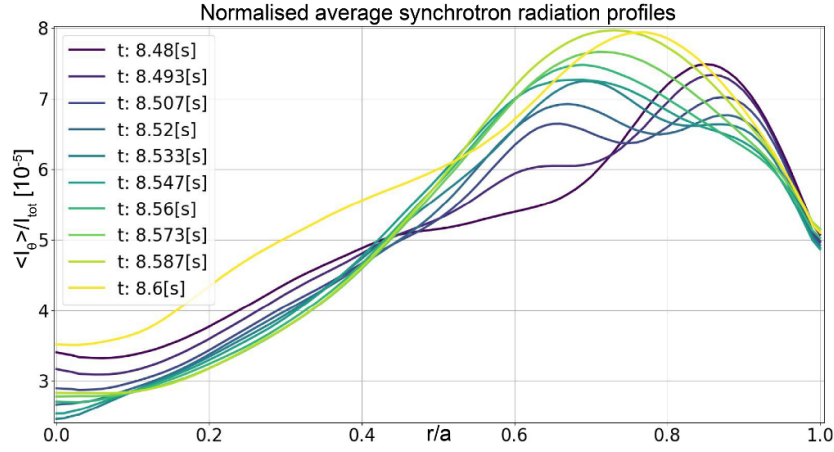
chains disappear when the q_{95} approaches the island-like patterns poloidal mode number or when the RE beam (partial) collapse is triggered. Therefore, the data of table 3 supports a relation between the appearance of synchrotron island chains and the presence within the RE beam of a resonant surface having the same poloidal mode number as observed in the synchrotron patterns (under the assumption of $n = 1$).

As second test of the claim, table 4 compares the estimated average radial velocity of the synchrotron island chain (first column) to the growth rate of the plasma current (second column). Comparisons with the decay rate of q_{95} are not required since it is related to the growth of the RE current. The pattern radial velocity is estimated via linear fitting of the island positions reported in figure 14. Similarly the growth rates of the plasma current are obtained via linear fit of the experimental time traces.

Table 4 shows that for almost all synchrotron island chains the fitted island-like pattern radial velocity is comparable with both the plasma current growth and q_{95} decay rates. The only outlier is the second synchrotron island chain of the pulse 95775 which presents a ~ 7.87 times faster radial motion

Table 4. Linearly fitted synchrotron island radial velocity (second column), plasma current growth rate (third column). The RE beam minor radius and maximum plasma current are used for normalizing the rates.

Sync. Island Chain	$\frac{\Delta r}{a \Delta t} (\text{s}^{-1})$	$\frac{\Delta I_p}{\max I_p \Delta t} (\text{s}^{-1})$
N# 95135 2nd isld.	1.814	1.577
N# 95135 3rd isld.	2.714	1.577
N# 95775 1st isld.	2.298	1.293
N# 95775 2nd isld.	10.183	1.293
N# 95776 1st isld.	1.5975	1.088
N# 95776 2nd isld.	1.1286	1.088

**Figure 15.** Poloidal (geometric) average synchrotron radiation profiles (IR camera) of the pulse 95775 during the locked island phase: darker to lighter lines denote profiles at increasing time. The average number of counts are normalized to the total frame number of counts. the radial coordinate is normalized to the RE beam minor radius.

towards the spot edge probably due to non-linear effects. Summarizing, the experimental evidences supports the claim that the radial dynamics of the locked synchrotron island chains is related to the modifications of the RE radial current density profile and hence, of the safety factor profile. Such observations strengthen the hypothesis that synchrotron islands result from the presence of islands in the RE beam magnetic topology.

Hereafter, a hollow current profile and a smoothly varying momentum distribution for the RE beam are assumed [5, 16, 26]. Under these assumptions, an increase of the electron current density at the edge of the RE beam would result in a peaking of the received synchrotron radiation nearby the RE beam edge as well. The peaking of the synchrotron emission can be identified computing the poloidal average intensity of the synchrotron emission defined as:

$$I_\theta(r) = \frac{1}{2\pi} \sum_{i=1}^{N_\theta} I_{\text{sync}} \left(r, \frac{\theta_{i+1} + \theta_i}{2} \right) (\theta_{i+1} - \theta_i). \quad (1)$$

We remark that the minor radius r and the poloidal angle θ of equation (1) have to be interpreted as geometric coordinates.

The poloidal averaged synchrotron profiles at different times for the pulse 95775 (IR spectrum) are reported in figure 15. The profiles are normalized to the total number of counts of the related frame while the RE beam minor radius is

used for normalizing the radial coordinate. The time evolution of the profiles is denoted by the line colors which evolve from darker to lighter shades. We report without showing it that the plasma boundary reconstructed by the EFIT code closely matches the synchrotron spot edge at the high field side. The profiles of figure 15 reveal that the poloidal average intensity constantly increases with time in proximity of the RE synchrotron spot edge. Conversely, the average intensity at the core of the spot presents a first decrease with time for then being roughly constant until the RE beam partial collapse (~ 8.6 s). Under the hypotheses of hollow current profile and constant and spatially uniform momentum distribution, SOFT simulations reported in [26] suggest that the increase of the poloidally average intensity close by the RE synchrotron spot edge is related to the growth of the current density in this region and hence, with a drop of the safety factor. The drop of the safety factor in proximity of the RE beam edge causes the outward shift of the resonance surfaces and, hence, of the magnetic islands. In case of parabolic-like hollow safety factor profile, the magnetic island must be located at a minor radius larger than the maximum of the current density for experiencing an outward shift [26]. The final result of the radial motion of the magnetic island is a radial displacement of the synchrotron island minor radius. Therefore, the evidences of figure 15 support a direction connection between synchrotron and underlying magnetic islands. Finally, we remark that the

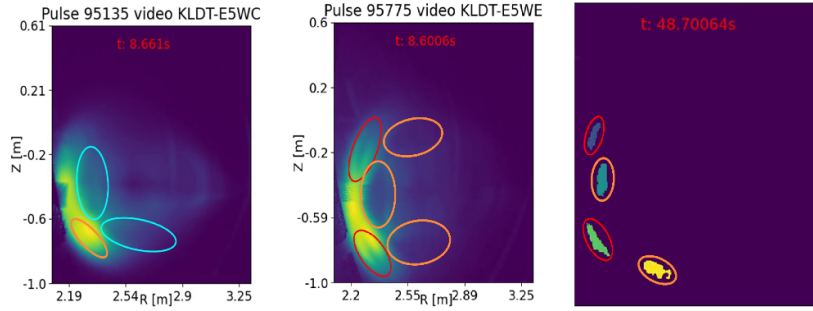


Figure 16. Examples of the double synchrotron pattern chain configuration before the collapse of the RE current in the pulses 95135 (left plot), 95775 (center plot) and 95776 (right plot). The snapshots are taken respectively 1 ms (95135), 0.4 ms (95775) and 0.36 ms (95776) before RE beam collapse. The left and center snapshots are respectively in the IR and visible spectra. The right plot is the visible image of the pulse 95776 after post-processing for enhancing the feature visibility.

non-monotonic feature of the poloidally average synchrotron profiles shifting towards the RE beam edge with time is caused by the radial motion of the synchrotron islands.

4.4. Synchrotron islands and RE beam benign termination

Multiple chains of synchrotron island-like patterns are seen to precede the RE beam (partial) current collapse of the pulse 95135, 95775 and 95776 as reported in figure 16. The dynamics of the synchrotron islands before collapse is similar for all three pulses. A first island chain, probably the external $m = 5$ island chain reported in figure 14, is localized at the RE beam synchrotron spot edge. A second synchrotron island chain of lower poloidal mode number ($m = 4$) is generated at the spot core and shows a fast growth and radial displacement towards the edge. A global MHD instability causing a partial or total collapse of the RE current (benign termination) is triggered when the internal $m = 4$ chain is in proximity of the external $m = 5$ one. A similar process involving the growth and non-linear interactions of $m = 4$ double tearing modes have been simulated using the JOREK code [16]. Unfortunately, a direct connection between the triggering of the RE collapse and the non-linear interaction of multiple chains of synchrotron islands cannot be directly drawn from the JET experimental data, due to the fast time scale of the event. Conversely, a minor loss of RE current which can be directly related to the interaction between two synchrotron island chains has been identified in the pulse 95776.

During the ramp-up phase of the pulse 95776 $m = 5$ (external) and $m = 4$ (internal) synchrotron island chains are observed to come in close contact before the loss of the RE current. The distance between the two island chains is reported in figure 17. Indeed, figure 17 shows the presence of a sudden drop of the distance between the two island chains up to 17% of the RE beam minor radius at the MHD relaxation. Unfortunately, a robust computation of the distance between the $m = 5$ and $m = 4$ synchrotron island separatrices is not available at the moment of the writing. The reason is a noise-dominated estimation of the synchrotron island width caused by visible light fluctuations.

Visible images of the interactions between synchrotron islands are reported in figure 18. Within 2 ms, the innermost

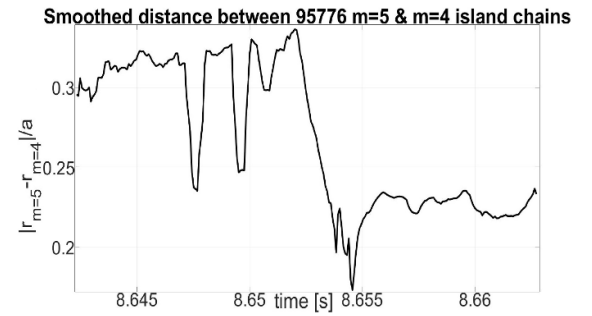


Figure 17. Distance between the pulse 95776 $m = 5$ and $m = 4$ synchrotron island center of mass positions during the MHD event. The distance is normalized to the RE beam minor radius. A seven points smoothing filter is applied for suppressing fast oscillations.

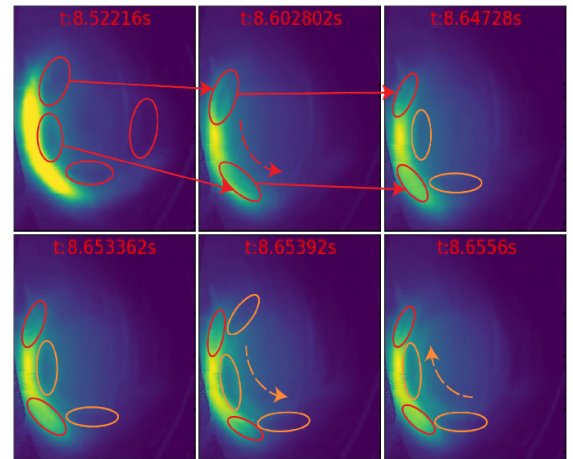


Figure 18. Visible images of the interaction between the two synchrotron island chains of the pulse 95776 : images are ordered by increasing time from top-left to bottom-right. Red and light orange ellipses denote respectively the outermost $m = 5$ and the innermost $m = 4$ synchrotron island chains. Red arrows denote the position of the same $m = 5$ synchrotron islands at different times. Dashed light orange lines indicate the direction of the island rotation during the interaction phase.

$m = 4$ pattern chain approaches the outermost $m = 5$ pattern via a fast growth and an outward radial displacement (figures 17 and 18). Rotation and radial fluctuations of both

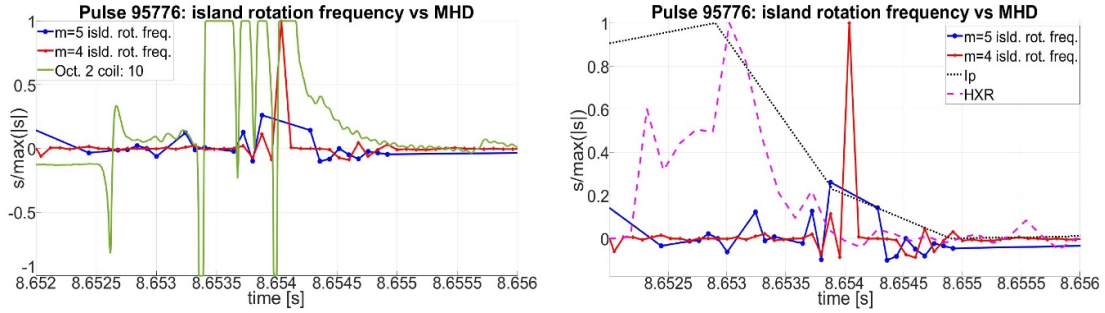


Figure 19. Comparison between the average estimated rotation frequency of both the outermost (blue circle-solid line) and innermost (red plus-solid line) synchrotron island chains, the oct.2 mid-plane-HFS Mirnov coil signal (left plot-solid line), the plasma current (right plot—dot black line) and the HXR signals (right plot—magenta dash line).

island chains are observed when their radial positions reach the nearest point (figure 17 and bottom center and right plots of figure 18) suggesting a non-linear interaction between the synchrotron islands. An inward radial displacements and a reduction of the synchrotron island width increases the gap between the two synchrotron island chains at the end of the interaction phase locking the pattern dynamics (figure 17).

The average estimated rotation frequency of both the $m = 5$ and $m = 4$ are compared with the evolution of the oct.2 mid-plane-HFS Mirnov coil signals (left plot), the HXR signal and the plasma current evolution (right plot) in figure 19. Fluctuations of the Mirnov coil signal are observed during the interaction of the two synchrotron island chains. The RE beam MHD instability correlates with both a spike in the HXR emission and a drop in the beam current which are both signs that RE are lost to the wall. The delay of approximately 1 ms between the spikes of the HXR emission and the rotation of the synchrotron islands can be attributed to small delays due to filtering and post processing of the diagnostic data. Consequently, the interaction of multiple synchrotron island chains is probably related to the triggering of MHD instabilities in the RE beam leading to a loss of relativistic electrons. A similar chain of events may explain the global MHD destabilization which lead to the (partial) collapse of the pulse 95135, 95775 and 95776 RE beams. Experimental data also partially support the JOREK simulations as far as the RE current collapse is concerned [16].

In JOREK simulations [16], the growth of two magnetic island chains having equal poloidal and toroidal (n) mode numbers of respectively 4 and 1 is observed (double tearing modes). The $m = 4, n = 1$ double tearing modes are triggered using a hollow current profile configuration with two 4/1 resonant surfaces as initial RE beam condition. Such initial conditions are thought to be representative of the pulse 95135 RE beam configuration just before the final collapse. The full stochastization of the RE beam magnetic field is developed by non-linear effects taking place at the overlapping of the two $m = 4, n = 1$ magnetic island chains. Therefore, RE beam final collapse is considered to be a consequence of the magnetic field stochastization [16]. JOREK simulations are partially congruent with the analysis of the JET experiments reported here. Indeed, RE beam collapse is observed when the two chains of synchrotron islands are at the closest point in

all three experiments. The main discrepancy between experiments and JOREK simulations resides in the poloidal mode number of the island chains. As a matter of fact, two $m = 4$ island chains are simulated by JOREK while, in JET experiments, the most probable poloidal mode number for the outermost and innermost island chains is respectively 5 and 4. We wish to stress that the discrepancy between simulations and experiments may be explained by (1) the presence of a $m = 4$ island chain not visible in the synchrotron images or (2) the existence of islands in the drift orbit topology with poloidal mode number different than the magnetic islands as described in [63].

5. Conclusions

Three JET RE beam mitigation experiments via SPI have been analyzed in the publication. The three experiments share similar initial conditions in terms of pre-disruptive target plasma and disruption-triggering MGI. In all three pulses, RE beams are generated after the disruption (induced by massive gas injection). Experimental measurements acquired before RE beam mitigation suggest the presence of mechanisms causing a continuous deconfinement of hot electrons and a transfer of energy between RE and cold background plasma. The mechanisms are probably particle collision based. In the JET pulses, the gas mixture used for mitigating the RE population via SPI has been varied (pure D2, 10%Ne + 90%D2, and 20%Ne + 80%D2,) but, in all cases a sudden recombination of the background plasma is obtained. The recombination of the companion plasma is observed to continue at decreasing rate until the triggering of the (partial) current collapse of the RE beam. The HXR, neutron, synchrotron emissions and plasma current measurements indicate a reduction in the maximum hot electron kinetic energy and pitch angles while the total number of RE is increased probably by electron avalanche. Dark island-like structure chains defined by an integer poloidal mode number on the same minor radius have been identified in the synchrotron images of JET RE beams. The radial dynamics of the synchrotron islands have been found consistent with both fast (loss of RE) and slow (post-SPI increase) variations of the plasma current. In addition, the acceleration and braking of the poloidal rotation of the synchrotron island-like structure

is correlated with $n = 0$ fluctuations of the Mirnov coils data. A possible hypothesis is that this behavior is related to the interaction of different islands chains with different rotation velocities. The connection between the synchrotron islands and the RE beam activity suggests that synchrotron islands are related to the presence of islands in the RE beam magnetic topology. As suggested by JOREK simulations [55], the magnetic islands are probably regions of low RE current given that the synchrotron islands are local minima of the synchrotron emission. It is worth noticing that no sign of MHD coherent modes has been identified during the RE phase of a JET disruption up to now. Finally, an MHD event causing losses of relativistic electrons and (possibly) triggered by non-linear interactions between two different synchrotron island chains has been observed for the first time. The observations support the numerical investigations identifying the non-linear interactions of multiple magnetic island chains, even with different poloidal mode number, as possible causes of RE beam collapses.

The present work may provide a new vision on the dynamics of RE beams in large machines. For instance, experimental data suggests that the evolution of the current density profile may destabilize multiple tearing instabilities generating magnetic islands. If present, non-linear interactions between multiple island chains can trigger abrupt MHD events inducing further RE losses. In this context, the generation of RE via electron avalanche mechanism may be the main driver of the evolution of the RE current density profile from stable to unstable configurations. If it is the case, relations between the RE current density evolution and the destabilization of the RE beam MHD may be investigated in controlled manner even in medium size tokamaks. The basic idea is to shape the RE current density profile, for example using the electron current drive, for forcing its evolution towards unstable configurations. Multiple steps are required for proving the feasibility of such an experiment. Firstly, the generation of magnetic islands via RE current drive and the evolution of current profiles towards MHD unstable configuration have to be demonstrated numerically. The goal can be achieved using current tools as, for example, the JOREK, LUKE and DREAM codes [65–67]. If supported by simulations, the second step would be to develop a RE-enabled equilibrium reconstruction code. For doing so, a coupling between an equilibrium reconstruction code, such as LIUQE [68], and a Fokker–Planck solver capable to evolve both RE and background plasma distributions, as DREAM, can be performed for computing the state variables of a RE beam. In addition to the standard plasma measurements, experimental data from the synchrotron videos, HXR, spectrometers and bolometers can be added for further constraining the phase space reconstruction. A preliminary example of a reduced framework for inferring the RE beam current density profile from experimental data is presented in [26]. The final step consists of the development of an actuator capable to modify the RE current density profile into a desired target shape. One possibility is to modify an antenna for emitting radio waves resonating with the relativistic electron cyclotron frequency. Ideally, the emitter should be able to locally accelerate, decelerate or induce

radial transport of fast electrons. It is worth remarking that the radial transport of RE via tagging with electron cyclotron frequency radio-waves have already been shown in the TCV and the DIII-D tokamak experiments [22, 53, 69]. If successful, the ability to control the RE current density profile via current drive may lead to the development of innovative RE beam mitigation strategies. Simulations focused in demonstrating the possibility to trigger magnetic islands in JET RE beams via local current suppression using the JOREK code are ongoing.

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Appendix A. Anomalous Doppler instability in the pulse 95135 RE beam

The anomalous Doppler instability can be observed in RE dominated plasmas when the hot electron momentum distribution destabilises MHD waves, typically of the Langmuir type, via the Cherenkov resonance mechanism [39, 40]. The anomalous Doppler instability consists of limiting cycles during which relativistic electrons are accelerated reducing their maximum pitch angle. The acceleration is interrupted when the hot electron distribution trigger fast MHD waves via Cherenkov resonance mechanism. The energy of the MHD waves is then absorbed by the background plasma as heat provided to the ions [39, 40]. In addition, hot electrons are scattered by the MHD waves relaxing their pitch angle distribution [39, 40]. Macroscopic indicators suggesting the presence of the anomalous Doppler instability are (1) limit cycles of slow decay followed by sharp growth of the received ECE power, (2) sudden destabilisation of the MHD at the time of the increase in the ECE and (3) heating of the cold background ions eventually, with spikes in the loop voltage) [39, 41, 42]. Measurements of the pulse 95135 RE beam taken after the D2-SPI are found to be compatible with the presence of the anomalous Doppler instability as shown in figure 20.

The ECE measurements at different frequencies reported in figure 20 shows a first decay phase suggesting the reduction of

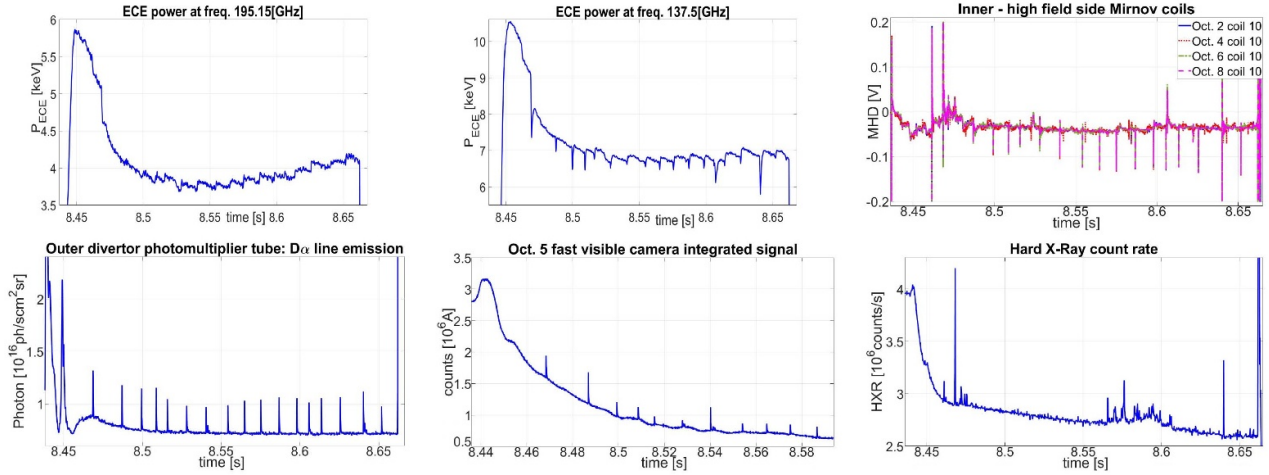


Figure 20. Measurements showing the presence of a possible Doppler instability of the RE beam during the post-SPI phase of the pulse 95135. From top-left to bottom-right: ECE signal at the frequency of 195.15 GHz, ECE 137.5 GHz channel, MHD signals of the octant two (blue solid lines), four (red dot line), six (green dash-dot line) and eight (magenta dash line) midplane—HFS Mirnov coils, D α emission from the outer-divertor PMT, integrated emission from the octant five fast visible camera, HXR count rate.

the maximum pitch angle of the electron distribution. Reached a local minima of the received ECE power, an abrupt MHD event is triggered (sequence of bursts in the Mirnov coil signals after 8.48 s—right plot figure 20). The ECE power suddenly increases at the MHD event indicating a relaxation of the electron pitch angle distribution. In parallel, spikes in both the D α and oct.8 fast visible camera time traces are observed. Visible radiation measurements can be connected to a re-heating of the background plasma causing its re-ionisation. The re-ionisation is followed by recombination when the energy drive terminates with consequent emissions in the visible spectrum (bottom left and middle plot of figure 20). The cycle is then repeated until RE beam collapse. Therefore, the results reported in figure 20 clearly suggest the presence of an anomalous Doppler instability acting in the post-SPI RE phase of the JET pulse 95135 [39, 41, 42]. We note that in the pulse 95135 the anomalous Doppler instability do not enhance RE losses as suggest by the HXR time trace provided in figure 20.

Appendix B. Extended description of the JET diagnostics and of the SPI

B.1. Fast visible and infrared imaging systems

The main experimental fast visible camera system of JET is composed of two Photron APX high speed cameras having a CMOS sensor of 1024×1024 pixels and a pixel size of $20 \mu\text{m}$. The spectral sensitivity interval of the sensor is estimated to be within $400 \text{ nm} \lesssim \lambda \lesssim 700 \text{ nm}$ [24]. The view angle of the two cameras is wide enough for recording the complete poloidal cross section of JET with a maximum achievable frame rate of 250 kHz [24]. Unfortunately, the JET control system allocates a maximum memory buffer of 2 GB per camera per pulse hence, the size of the Region-Of-Interest (ROI) and the frame rate have to be set so that the resulting video fits the 2GB allocation [24]. The first camera, called KL8, is connected to the endoscope of octant 8 and looks towards octant

3 (figure 1 blue square and blue shaded region). It is worth remarking that the SPI system is within the visual range of KL8. Therefore, the identification of the shard arrival time in plasmas or RE beams can be performed via the direct timing of the KL8 videos. An example of SPI shard images as recorded by KL8 is provided in the top-left plot of figure 2. Another important feature of the KL8 imaging system is the availability of a four slots filter wheel. Filters normally installed for disruption and RE experiments are Deuterium – α (D α), Neon-I (NeI) and Argon-II (ArII) which are the spectral lines emitted by the SPI pellet gasses [35]. Unfortunately, the tight mount of the KL8 camera system transmits vibrations from the tokamak structure to the optical guides. The mechanical vibration are recorded as oscillations in the videos of large plasma and RE beam instabilities [35]. The second fast visible system, identified as KLDT-E5WE, has a view point located in octant 5 and a view range extending up to octant 2 (red square and red shaded region of figure 1). The counter-RE (clockwise) looking direction of the KLDT-E5WE system allows the recording of synchrotron images of the RE beams. Differently from KL8, the sensor of KLDT-E5WE is not tightly connected to the endoscope but it is located outside the tokamak bioshield [23]. The optical connection between the sensor and the endoscope is granted by an optical relay based on mirrors [23]. The optical design of KLDT-E5WE as the advantages of (1) protecting the sensor from hard radiation and of (2) reducing the amount of vibrations transmitted to the camera. Therefore, images recorded by the KLDT-E5WE system are less afflicted by the problems of oscillation and hard radiation noise typical of the KL8 camera. On the other hand, the presence of a small misalignment of the mirrors resulted in a slight deformation of the above and below mid-plane images as shown in the top-center of figure 2. No filter wheel is available for the KLDT-E5WE camera. Similarly to KLDT-E5WE, KLDT-E5WC is a forward-looking infrared camera located outside the tokamak bioshield and connected to the endoscope by the same optical system of KLDT-E5WE. Therefore, KLDT-E5WC is

able to image the synchrotron radiation emitted by RE as well. The KLDTE5WC sensor is a FLIR SC7500 with a grid of 176×120 pixels and a maximum frame rate of 1 kHz. A typical image of the KLDTE5WC imaging system, showing deformation due to mirror misalignment, is reported in the top-right figure of figure 2.

B.2. Magnetic (Mirnov) coils

Different magnetic probes have been installed in the JET tokamak for revealing and characterising MHD instabilities occurring during a pulse [70–72]. The JET IDCs are the magnetic sensors chosen for the analyses discussed in the sections which follow. The choice is lead by the positioning of the RE beams which tend to be localised at the high field side of the JET vacuum vessel. As shown by the second row—left plot of the figure 2, the IDCs system covers all the JET cross section and are installed behind the tokamak first wall (red rectangles of figure 2) [70, 71]. Therefore, the IDC probes are expected to be the most sensitive magnetic sensors to the MHD instabilities of RE beams. In addition, four different toroidal sectors are covered by IDC arrays (octant 2, 4, 6 and 8 - figure 1) allowing basic identification of the instability toroidal mode number. The typical IDC sampling frequency is of 100 kHz for the raw voltage signals and of 5 kHz for the time-integrated measurements (poloidal field) [70].

B.3. Bolometers

Bolometers are diagnostics used for measuring the plasma radiated power along specific lines-of-sight. Vertical and horizontal-looking bolometers covering the overall poloidal cross section with 24 lines-of-sight each are installed in JET [73]. The bolometers are installed in two different toroidal sectors: octant 6 for the horizontal sensor and octant 3 for the vertical sensor (figure 1). A representation of the two camera lines-of-sight is provided in the second-row center plot of figure 2. The sensors of the JET bolometers is composed of a thin gold foil ($8 \mu\text{m}$ thick) deposited on a $20 \mu\text{m}$ -thick mica sublayer [73]. The sensitivity range of the JET bolometers is between 480 nm and 0.1 nm [73]. The synchrotron radiation spectrum of tokamak RE mainly involves the IR and the visible wavelengths hence, we expect that the amount of synchrotron radiation measured by the bolometers to be negligible [5, 25]. The diagnostic maximum acquisition frequency is of 5 kHz [73]. During the analyses, two anomalies have been found:

- 1 The radiated power measured by the divertor looking narrow channels (Ch.9-16) of the vertical sensor does not match the measures of the overlapping overview channels (Ch.6 & Ch.8) hence they have been discarded.
- 2 Intense radiation is measured by the vertical bolometer in sectors distant from the RE beams (high field side—upper port). We speculate that such an effect is due to reflections or neutrals hitting the sensor gold foil hence, measurements of the radiated power may be afflicted by errors difficult to identify and/or estimate.

B.4. Polarimeter

The plasma density in JET non-disruptive scenarios is measured using the far infrared interferometric technique [74]. Unfortunately, interferometry cannot be used for inferring the background plasma electron density after a disruption due to fringe jumps which add bias to the measurement [2, 5]. The polarimetric technique instead is not affected by the disruption dynamics as the interferometer hence, it can be safely used during the RE plateau phase [5]. The working principle consists of measuring the change of polarisation of a $195 \mu\text{m}$ (deuteride cyanide) laser passing through the plasma [75]. Then, the plasma density can be inferred from the variation of the laser beam polarisation and the local magnetic field [76]. The polarimeter is positioned in octant 7 (black dots of figure 1) and it is composed of one channel at the edge high field side (1), two core channels (2–3) and one edge channel at the low field side (4) (first row—left plot of figure 2). The channels 3 and 4 are the less afflicted by noise hence, they are the channels considered in the remaining sections. A new FPGA-based hardware and implementation [77] allows to achieve very high acquisition frequencies between 500 kHz and 2 MHz.

B.5. Electron Cyclotron Emission (ECE) radiometer

The ECE diagnostics measures the electromagnetic waves emitted by the gyration of electrons around the magnetic field lines [78]. In non-disruptive plasma conditions, ECE measurements can be used for reconstructing the radial electron temperature profile during stationary and transient conditions [79, 80] or identifying the presence of supra-thermal electrons [81, 82]. Unfortunately, the ECE diagnostic cannot be directly employed for establishing the energy of highly relativistic electrons. Indeed, relativistic effects cause the broadening and down-shift of the ECE harmonics which cannot be quantified without knowing the hot electron distribution in momentum space [83, 84]. Conversely, the ECE can be a useful diagnostic for identifying the presence of instabilities in RE beams [40–42]. The ECE diagnostic of the JET tokamak is composed of two instruments: a Michelson interferometer (X-mode interferometer with a frequency bandwidth between 90 GHz and 450 GHz, a frequency resolution of 3.66 GHz and a temporal resolution of 16 ms) and a heterodyne radiometer [79, 80, 85, 86]. Only the heterodyne radiometer is considered in the present work. The ECE radiation is collected from the low field side by an open waveguide antenna with dimensions $50 \times 65 \text{ mm}$ located in the octant 7 (dark yellow line of figure 1). The antenna vertical position is of 0.133 m. The collected ECE emission passes along a single oversize wave-guide to the Diagnostic Hall in which the heterodyne radiometer is installed. The JET heterodyne radiometer consists of twelve independent heterodyne receivers each of which has its own mixer and corresponding oscillator, band-filter for proper side-band selection and IF (6–18 GHz) amplifier chain. The ECE system has 96 channels covering a spectral range between 96 GHz and 207 GHz [79, 80]. The bandwidth of each channel is of 250 MHz [79, 80]. The system provides a wide

radial coverage for most of the magnetic fields used at JET $1.7\text{ T} \leq B_0 \leq 4\text{ T}$. For thermal plasmas, the close spacing of the channels allows a radial resolution approximately between 1 cm and 1.5 cm depending on the magnetic field gradient [79, 80]. The absolute electron temperature values are calibrated via direct comparison against the Michelson interferometer [80]. The output signal of the radiometer is then recorded by two acquisition systems. A first slow acquisition system with a sampling frequency of 5 kHz is used for electron temperature profile measurements with a temporal resolution of usually 1 ms. Conversely, a second fast acquisition system with a sampling rate of 200 kHz and with a 100 kHz anti-aliasing filter is suitable for studying fast events such as the instabilities in RE beams.

B.5.1. Visible spectrometers. Visible spectrometers are particularly useful diagnostic for (1) revealing ionisation-recombination processes and (2) identifying the presence of heavy impurities in a plasma discharge. The two JET spectrometric systems of interest are the visible photon multiplier tubes (PMTs) and the charge-exchange spectrometers [87, 88]. The PMTs are sensitive to the light in the visible spectrum [87]. Filters have been interposed in front of the PMTs for collecting light from spectral line emission (passing band $\sim 2\text{ nm}$) [87]. Hereafter, we focus our attention on the $D\alpha$ line emission (656 nm) for identifying ionisation-recombination events of the background plasma taking place during the RE phase of a discharge. In JET, the vertical PMTs are installed in octant 1 with three channels: vertical, inner and outer divertor targets while a horizontal PMT can be found in octant 8 at mid-plane (light blue circles and line in figure 1). The maximum acquisition frequency for this system is of 10 kHz [87]. The charge-exchange diagnostics is composed of two spectrometers situated respectively in octant 1 and 7 and looking at opposite directions (light green squares and shadowed regions of figure 1) [88]. Unfortunately, their view angles are limited to the mid-plane low field side sectors [88]. The diagnostic is composed of multiple spectrometers and CCD cameras capable to resolve the spectrum of visible light emitted due to charge-exchange collisions between high-energy neutral beams and the background plasma [88]. Given that the neutral beam injector is not used during RE plateaus, the charge-exchange diagnostics can be used for revealing the presence of spectral line radiation emitted by the recombination of heavy impurities. More specifically, the diagnostic can be used for assessing the presence of residual NeI or ArII impurities used for mitigating disruptions and/or RE beams. The system has a maximum acquisition frequency of 100 Hz.

B.6. Shattered Pellet Injector

The SPI system of JET is composed of three barrels each of which having a different bore: 12.5 mm (A), 8.1 mm (B) and 4.5 mm (C) [34]. Pellets are formed by a cold plate capable to deposit hydrogen, deuterium, neon and argon or a mixture of

them with possibly a deuterium coating [34]. The number of atoms of deuterium per pellet for each barrel is respectively of: $1.4 \cdot 10^{23}$ (A), $4 \cdot 10^{22}$ (B) and $6.3 \cdot 10^{21}$ (C) [34]. Pellet acceleration is obtained via the injection of deuterium at a pressure between 50 and 60 bars or with the aid of a mechanical punch activated by the same working fluid (barrel A and B only) [34]. The propulsion system is design such that pellets hit the fragmentation plate with an excess of velocity of at least 20 ms^{-1} . The bent characterising the shatter plate is approximately of $\sim 20^\circ$. A microwave cavity is installed along the launching tube for assessing the pellet integrity before fragmentation [34]. A CAD schematic of the JET SPI can be found in [34]. The SPI is installed in octant 8 upper port (red circle in figure 1) and the injected fragments are visible in the KL8 fast camera videos (figure 2 upper-right).

Appendix C. The JET computer vision code

The identification and tracking of features in the JET experimental videos, such as the synchrotron videos of RE beams, have been performed using a newly developed computer vision code. The code is written in Python3 [89] and takes advantage of advanced computational libraries as, for example, NumPy [90] and SciPy [91], the OpenCV computer vision library [92] and the Matplotlib visualisation library [93]. The code is split in four different parts: (1) routines for reading data, (2) video pre-processing and image enhancement algorithms, (3) feature identification and tracking algorithms and (4) data post processing. The results of each section are stored in HDF5 files [94] and in MP4 videos. The code version control is based on the standard Git software [95]. The code Git repository can be accessed upon request to the authors.

C.1. Input data and video mapping

The code inputs are composed of three sets of data: an input file defining the paths and the parameters required for processing experimental videos, a dataset containing the video to be analysed and, optionally, three datasets containing respectively the physical time associated to each frame and two maps relating the pixel position in the frame reference system to the physical position in the tokamak reference system (major radius and vertical coordinates). Input data file must be provided as string with standard Python3 formatting for the different datatypes (lists, sets, tuples and dictionaries). A reading routine executes the conversion from string to the expected parameter datatype. The video and the mapping data can be provided using two different techniques. The first one is using a NPZ [90] compressed repository containing four NumPy files. The first one, *data*, contains a 3D NumPy array describing the video to be processed. The first index of the array denote the ordering number of the video frame. The second, *t*, third, *r* and fourth *z* files contain respectively a 1D NumPy array describing respectively the physical time vector, the pixel major radius and vertical coordinate mappings.

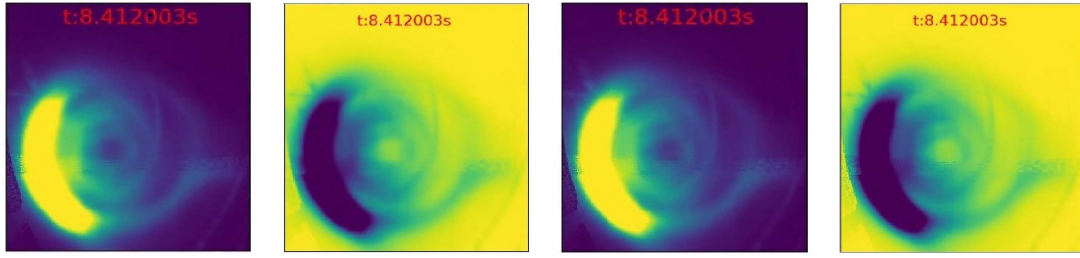


Figure 21. Example of pre-processing of a synchrotron image (visible spectrum) of the pulse 95775 at a time of 8.412 s. From left to right: mapped image using the JET synchrotron radiation coordinate maps, image with inverted grey-scale, image filtered using OpenCV Gaussian spatial filter (5×5 pixels kernel and a standard deviation of one) and time filtered image with inverted grey-scale (number of frames for time average: 500).

The second method loads all available data directly from the JET database using procedures included in the JET Photrons library.

The calibration of the JET synchrotron videos is a multi-step process. A first manual calibration between a video frame, in which details of the JET first wall are clearly visible, and the CAD model of the JET tokamak is performed. The calibration is performed using image feature identification routines implemented in the CALCAM code [96]. The results of the first calibration are the camera position, view direction, field of view and image distortion in the tokamak reference system. These data are then used for defining a line of sight for each image pixel. Secondly, the video is processed for correcting the rigid camera movement which may happen during a plasma discharge. The camera movement correction can be performed manually or automatically. The manual camera movement correction method is based on computing the shift between each single frame with respect to the reference frame via feature matching. The automatic one consists of taking 1D horizontal and vertical slices of two subsequent frames. Slices containing high contrast features are selected and their light intensity interpolated using splines. The relative position of two subsequent frames is then corrected computing the shift, scale and offset matching the horizontal and vertical 1D splines of the two frames. The pixel coordinate maps can be generated after having calibrated and corrected all frames of a video. Pixel coordinate maps are constructed assuming that the synchrotron emission of RE beams propagates roughly parallel to the magnetic field lines. The hypothesis is justified if the maximum pitch angle of the hot electron distribution is small enough so that no splitting of the synchrotron spot is visible in the videos [28, 48]. We highlight that significant synchrotron spot splitting is not observed in the JET experiments considered in the present publication [26]. For each frame, the line of sight of each pixel is uniformly discretised from the tokamak wall to the camera pupil with a length step of 1 cm. Then, the plasma equilibrium nearest to the frame physical time is selected and the magnetic field is computed at each node of the line of sight. The coordinate of a pixel in the tokamak reference system is identified finding the node on the line of sight minimizing the dot product between the line of sight and magnetic field directions ($\vec{l}_{\text{LoS}} \cdot \frac{\vec{B}}{\|\vec{B}\|} \simeq -1$).

C.2. Video pre-processing algorithms

Video pre-processing algorithms are procedures used for removing unwanted features in images while retaining and enhancing the visibility of the desired ones. Firstly, pixels belonging to a specific region of interest (ROI) can be selected setting to zero the light intensity of discarded pixels. The possibility of retaining only a specific ROI has been found useful for (1) improve code performances removing undesired background light and (2) discard data from faulty pixels. After the definition of an ROI, the grey scale of a video can be inverted. The inversion of the grey-scale allows the tracking of low intensity, ‘dark’, features. An example of an image with inverted grey-scale can be found in figure 21 second plot. Short wavelength fluctuations (noise) is efficiently removed applying one or more spatial smoothing filters to each frame. A subset of the smoothing filters implemented in the SciPy and OpenCV libraries is available in the particle tracking code. Available filters of the SciPy library are: Gaussian, median, uniform, maximum, Laplace, Sobel, Prewitt, gradient and Hessian while implemented filters based on the OpenCV library are: box, Gaussian, median, Laplace, Scharr and Sobel. Detailed descriptions of each smoothing filter can be found respectively in the SciPy and OpenCV user’s guides [91, 92]. The third image of figure 21 shows an example of a filtered image using a Gaussian filter. We remark that optimal filter parameters for the desired test case can be identified by the user directly during the code execution via terminal interface. Time filtering has also been found particularly useful for improving the visibility of fastly varying features such as rotating synchrotron islands, injected pellet shards and radiating plasmoids. The time filter implemented in the particle tracking code subtracts from the light intensity of a frame of interest the average of the light intensities of all frames within a time interval centred at the time of the frame of interest. The user can select the width of the time interval in which the averaging process is performed. An example of time averaged frame can be found in figure 21 right plot.

C.3. Feature identification and tracking

Routines allowing the identification and tracking of features in experimental videos are at the core of the particle tracking

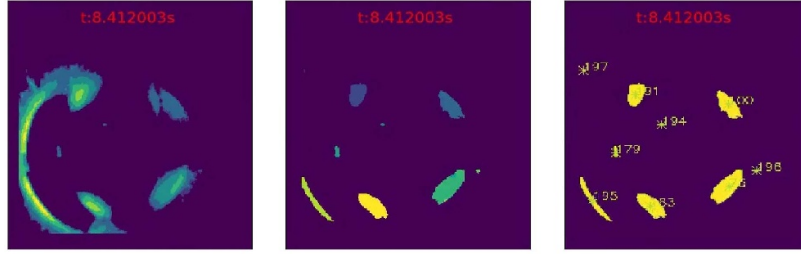


Figure 22. Example of the structure identification and pairing process using the synchrotron image (visible spectrum) of the pulse 95775 at a time of 8.412 s. From left to right: thresholded image, frame with identified structures and frame with matched structure labels.

code. Methods can be regrouped in three functional classes: algorithms for the thresholding of the light intensity, routines for the identification of features in images and procedures for the feature matching between two subsequent frame.

The objective of the image thresholding process is to remove all background light from an image while retaining only the structures to be analysed. The basic idea behind the thresholding process is to binarise an image assigning the white colour to pixels having their light intensity above a threshold [97]. The black colour is assigned to pixels with intensity below the threshold [97]. Evidently, white pixels must define the light structures to be retained for further analyses. The particle tracking code allows the application of multiple thresholds to a video. Each thresholds can be defined by the user or computed automatically. The automatic calculation of the thresholds can be performed either via routines native to the OpenCV library (triangle or Otsu's variance maximisation algorithms [92, 97]) or using a simulated annealing algorithm [98]. The simulated annealing method has the objective of maximising the weighted within-class variance of the light intensity (Otsu's criterion) [97]. The energy measure, used for accepting the result of the simulated annealing algorithm, is based on the difference of the Otsu's criterion between two different steps. The initial and final temperatures are provided by the user as input. An example of a binarised image via simulated annealing—Otsu's algorithm is shown in the left plot of figure 22.

The feature identification method relies on the OpenCV *findContours* algorithm [92]. The *findContours* algorithm labels each structure visible in a binarised image with a unique identifier. The identification process is performed for all binarised images and for all frames. It is worth remarking that no relationship exists between the identifiers of different images despite being attributed to the same structure. The total number of pixels and the indices of the pixels composing the perimeter of a structure are also returned. A minimum structure size (in terms of total number of pixels) can be set by the user. If the same structure is visible within different binary images of a same frame, the largest structure having the total number pixels closest to the user requested number is retained for the matching process. The decision of retaining or removing structures having size smaller than the desired value is left to the user. Retained structures are then assembled in a common

frame denoted *object image*, an example of which is shown in the center plot of figure 22.

The matching of light structures between two subsequent frames is the last step of the feature identification and tracking process. The objective of the matching algorithm is to assign the same identifier to the same light structure visible in two different frames. For doing so, multiple structure matching algorithms are combined via a common score. The simplest object matching procedures are the maximum overlap and minimum center-of-mass distance algorithms. The maximum overlap method computes the number of pixels shared by each structure composing the object image at the time t_i and all structures of the object image at the time t_{i+1} . A common identifier is provided to structures of the t_i and the t_{i+1} frames sharing the largest amount of pixels. The minimum center-of-mass distance method provides a common identifier to the structures of two subsequent frames having the smallest euclidean distance between their center-of-mass. The position of the center-of-mass of a feature is defined as:

$$\{x, y\}_{\text{com},j} = \frac{\sum_{k=1}^{N_j} I_{k,j} \{x, y\}_{k,j}}{\sum_{k=1}^{N_j} I_{k,j}} \quad (2)$$

Where $\{x, y\}_{\text{com},j}$ is the position of the j th structure center-of-mass in the image reference system, N_j is the total number of pixels composing the j th structure, $\{I, x, y\}_{k,j}$ are respectively the light intensity and the coordinates of the k th pixel composing the j th structure. The ratio between the center-of-mass distance of the matched structures with respect to the length of the frame diagonal is used as score. In addition, the OpenCV *template matching* and *feature matching* algorithms [92] are also implemented in the particle tracking code. The template matching method consists of extracting a template image, defined here as the image narrow bounding the light structure to match, from the frame at the time t_i and slide it over the frame at t_{i+1} . A similarity measure between the template image and the patch of pixels of the t_{i+1} -th frame covered by the template image is then compute. The resulting structure is then identified minimising (or maximising) the similarity measure between the template image and the pixel patch. The interested reader can refer to [92] for a detailed explanation of the template match algorithm and of the available similarity measures. Structures are considered paired if

their normalised similarity measure overcomes a user defined threshold. The threshold is also used as score for the template matching routine. We also note that, at present, all similarity measures implemented in the OpenCV library are available in the particle tracking code. Image feature pairing is a two step process. A detection/description algorithm is firstly used for extracting features from the two structures to be paired. In this context, image features are defined as regions of an image with sharp gradients in all directions [92]. A similarity measure is then computed between each feature of the structure at the time t_i and all features of the structure at t_{i+1} . The pairs of features minimising the similarity distance are then returned as best matches [92]. The light structures of two subsequent frames maximising the ratio between the number of paired features and the total number of extracted features from each structure at t_{i+1} are identified as equal. Similarly to the template match routine, all feature detectors, descriptors and similarity measures implemented in OpenCV are also available in the particle tracking code [92]. After having applied one or more matching algorithms, the final couple of paired structures is selected as the one maximising the overall score defined below:

$$S_{ij} = \frac{1}{N_M N_i} \sum_{k=1}^{N_M} W_k \frac{S_{ijk}}{\sum_{j=1}^{N_i} S_{ijk}}, W_k \in [0, 1] \quad (3)$$

where S_{ij} denotes the final pairing score between the i th and j th structures, N_M, N_i are respectively the total number of used matching algorithms and the total number of j th structures for the selected i th structure while S_{ijk}, W_k are respectively the score of the $\{i, j\}$ th-pair assigned by the k th matching method and the weight attributed by the user to the k th pairing algorithm. An example of image with matched structures is reported in the right plot of figure 22.

C.4. Data post-processing routines

The time evolution of the properties of light structures can be extracted and computed after the identification and tracking process. The particle tracking code characterises both position and size of a feature. The time evolution of a light structure position is obtained computing and recording its center-of-mass coordinates (equation (2)) for each frame. If a coordinate map exists between the image and the physical reference frame, the structure positions are remapped into the physical reference. Moreover, velocity profiles are also estimated by forward differentiating in time the position profiles. The time base for the forward differentiation is based on the camera sampling frequency. An example of center-of-mass position computed using the JET synchrotron map is given in the left plot of figure 23. The estimation of the light structure size can also be performed using the particle tracking code. For estimating the size, an ellipse circumscribing a structure is fitted in the least square sens. The fitting procedure is performed using the procedure *fitEllipse* of the OpenCV library [92]. The resulting fitted ellipses are shown in the right plot of figure 23. The coordinates of the ellipse major and minor axis endpoints are then mapped to the physical reference system. The lengths of

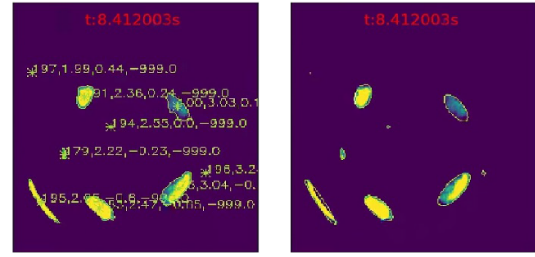


Figure 23. Examples of the structure position and size determination using the synchrotron image (visible spectrum) of the pulse 95775 at a time of 8.412 s. The left plot reports the structure labels, radial and vertical positions (unknown values are set at -999). The physical coordinates are obtained from the JET synchrotron coordinate map. The right plot shows the fitted ellipses used for computing the size of a structure.

the minor and major axes are computed and associated respectively to the estimated structure width and length. The width and length are then recorded for each frame generating the structure size profiles. The structure growth rates are estimated forward differentiating in time the size profiles.

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