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ABSTRACT

In the last years, JET diagnostic capability has been significantly improved to widen the range of physical phenomena that can be studied and to contribute to the understanding of some ITER relevant issues. The most significant results reported in this paper refer to the plasma wall interactions, the interplay between core and edge physics and the fast particles. A careful synergy between new infrared cameras, visible cameras and spectroscopy diagnostics has allowed investigating a series of new aspects of the plasma wall interactions. The power loads on the plasma facing components of JET main chambers have been assessed at steady state and during transient events like ELMs and disruptions. Evidence of filaments in the edge region of the plasma has been collected with a new fast visible cameras and the High Resolution Thomson scattering. The physics of detached plasmas and some new aspects of dust formation have also been devoted particular attention. The influence of the edge plasma on the core has been investigated with upgraded active spectroscopy, providing new information on momentum transport, the L-H transition physics and the effects of impurity injection on ELMs and ITBs. Given the fact that JET is the only machine with a plasma volume big enough to confine the alphas, a coherent programme of diagnostic developments for the energetic particles has been undertaken. With upgraded γ-ray spectroscopy and a new scintillator probe, it is now possible to study both the redistribution and losses of the fats particles in various plasma conditions.

1. INTRODUCTION

The JET mid-term research programme is aimed at addressing some of the scientific and technological issues more urgent for the design and construction of the next step device, ITER. In this perspective several upgrades have been implemented or are being procured, among which the two most important are the installation of a completely new first wall (made of Beryllium and Tungsten) [1], to better understand plasma wall interactions, and a significant increase in the additional heating power, to improve plasma performance and to understand the potential of the various heating schemes. Other very significant new tools being made available are a new pellet injector, an upgraded control system, routine operation at various levels of toroidal field ripple and upgraded power supplies of the error field correction coils [2].

Extending the operational space towards more reactor relevant parameters requires further understanding of various physical phenomena including a) the dynamics of low temperature plasmas close to the containment wall b) the effects of various instabilities and turbulence on the transport of energy, particles and momentum c) the burning plasma aspects linked to the interplay between collective instabilities and energetic particles generated by the fusion reactions.

Obtaining the necessary experimental information on these issues poses significant challenges for the measurement systems. Therefore, during the last couple of years, about thirty new or improved diagnostics have been installed and a similar number will be finalised during next campaigns, providing JET with state of the art instruments, covering all the main measuring techniques used in physics, from interferometry to scattering, from spectroscopy to tomography, from radar to thermography [3].

This paper describes some aspects of JET new diagnostic capability covering in particular plasma wall interactions and detachment (section 2), instabilities influencing the interplay between edge and core regions of the plasma and momentum transport (section 3), the physics of fast particles and their interactions with the magnetic topology and instabilities (section 4). A review of the future main lines of activity on diagnostic is the subject of the last section 5.

2. DIAGNOSTICS FOR PLASMA WALL INTERACTIONS AND DIVERTOR PHYSICS

The boundary region of fusion plasmas is particularly difficult to study because of the often non-linear mutual influences between plasma physics effects, atomic processes and material properties. Innovative detectors and techniques, from Quartz microbalances to visible and infrared spectroscopy [4], have provided new information on processes typical of low temperature plasmas, like erosion, re-deposition and material migration. They have also contributed to elucidate the main physical and chemical aspects of these phenomena. With regard to the global assessment of interactions of the plasma with the surrounding material surfaces, it was decided to improve the synergy between visible and InfraRed (IR) imaging. To this end, a new endoscope, providing a wide angle view of JET main chamber, has been designed and installed [5]. The endoscope comprises a tube holding the front head mirrors, a Cassegrain telescope, and a relay group of lenses connected to the camera body. To increase the ITER-relevance of the system, mainly reflective optical components have been chosen, because they are the only solution compatible with the typical neutron load of the next step device. Since the specifications required viewing the divertor, the inner wall, the outer poloidal limiters, the ITER-like ICRH antenna and the top limiter, the optical system has been designed to provide a field of view of 70 degrees.

The infrared range covered by a (In)Sb focal plane detector is between 3.5 and 5μm and the diagnostic is designed to measure from JET operating temperature of 200°C up to a maximum temperature of 2000°C. The visible view is equipped with a state of the art CMOS fast camera [6]. The diagnostic is diffraction limited as determined by on the bench measurements based on the Modulation Transfer Function (MTF) technique. This method proves that the system provides an overall spatial resolution of 2.5cm at three meters in the IR; in the visible the spatial resolution is of the order of 1.5cm.

The main aim of the visible fast camera is to provide data on fast instabilities and to help diagnose the effect of pellet injection. Clear evidence of filamentations has already been detected during type I ELMs, as shown in figure 1. These filamentary structures have also been detected by the new High Resolution Thomson Scattering (HRTS), a 90 degrees system with 63 measuring points covering the outer mid plane of JET plasmas with a spatial resolution of 1.5cm. An example of the filaments as seen by the HRTS is shown in figure 2, together with the schematic layout of the HRTS diagnostic. The synergy between these two and other systems is expected to provide some quantitative indications about the energy content and dynamics of the filamentary structures often present in the edge of JET plasmas.

With this new endoscope, it has been possible for the first time to perform thermography in JET main chamber. Power loads have been determined for the most severe transient phases, like ELMs and disruptions. Before density limit discharges, a MARFE instability is routinely detected [7]. An IR image of this instability moving along the inner wall is shown in figure 3. Since in some cases MARFE instabilities have been detected even between one and two seconds before a disruption, the potential of IR imaging for disruption prediction will be further investigated in the future.

High density operation, even if potential hazardous because it can trigger disruptions, is supposed to become routine in ITER, whose plasmas will have to be detached in both legs of the divertor. Detachment is a particular plasma state [8], occurring close to the target tiles, whereby, due to the high density, low temperature and the presence of a high level of neutral particles, the pressure is not longer constant along the magnetic field lines.

Diagnosing this type of plasmas is particularly demanding. First of all, given the gradients in the plasma parameters along the field lines, Langmuir probes do not provide measurements indicative of the plasma state away from the target plates. This can be seen in figure 4, where the density given by the Langmuir probes is compared with the one obtained by spectroscopy before an after plasma detachment in the outer leg of JET divertor. It appears very clearly how the plasma parameters present strong gradients along magnetic surfaces and therefore specific diagnostic methods have to be developed. Spectroscopy is particularly suited, since the spectrum emitted by deuterium in the UV range is very sensitive to plasma density and temperature through Stark broadening [9]. Significant modelling efforts are under way to simulate the Balmer/Paschen spectra, in order to improve the estimate of the density and temperature. The first attempts to feedback control detached plasmas using these spectroscopic measurements have already been successful.

3. DIAGNOSTICS FOR THE INTERACTIONS BETWEEN THE EDGE AND THE CORE

In the plasma core, the energy, particle and momentum confinement is crucially determined by the non-linear saturation level of the turbulence and its effects on transport. In order to understand the impact of these phenomena on the global machine performance, the main plasma parameters have been measured with higher spatial and time resolution using upgraded active spectroscopy, Thomson scattering and microwave diagnostics. Both JET active charge exchange (CXRS) systems, with poloidal and toroidal views, have been recently upgraded [10,11] mainly to improve their time and spatial resolution and to measure more spectral lines in parallel. These two systems have now a time resolution which can reach 10 ms and a spatial resolution of the order of a few centimetres (depending on the magnetic configuration). The enhanced versions of the CXRS systems have allowed performing sophisticated experiments, on impurity tansport and rotation, which had not been satisfactory in the past due to the limited performance of the diagnostics.

Recently particular attention has been devoted to an issue whose importance is sometimes not fully appreciated: the interactions between the edge and the core of the plasma and the effects that instabilities in one region can have on the other. An important example is represented by the effects of the ELMs on the sustainment of Internal Transport Barriers (ITBs). This issue can have a significant impact on ITER non-inductive scenario, whose requirements are $\beta_N > 3$ and HIPB98(y,2) > 1.5. This performance can be achieved only by Advanced Tokamak (AT) configurations with ITBs at large radius ($\rho > 0.5$ corresponding for JET to a mid-plane radius Rmid ~ 3.50m), combined with a strong edge pedestal. However, large ELM crashes, often associated with steep pedestal gradients, affect significantly the quality of the ITBs and can even destroy them completely [12].

To understand the interactions between the edge instability and the ITBs on JET, impurity and deuterium injection experiments have been performed in high triangularity AT scenarios. The discharges specifically devoted to this issue have been run with $B_t = 3.1$T and $I_p = 1.9$MA. The radiated power fractions ranges from 20% (mainly from carbon the natural impurity in JET with the present wall) for the reference shot (with D2 only gas puffing) to a maximum of 60% for the pulse with the highest level of neon puffing. The total injected levels of Ne and D2 are summarised in Table I, in which the shots are listed in order of increasing neon injection. At higher neon puffing, the amplitude of the ELMs is clearly reduced, as shown in figure 5, and therefore it has been possible to sustain an ITB, whereas this had proved impossible in the original reference scenario with only deuterium puffing. The most evident difference in the edge parameters, potentially explaining the change in the ELM regime and therefore the presence of a more stable barrier, is the significant increase in the radial electric field (E_r) shear as shown in figure 6. The evolution of E_r has been determined using the force balance equation based on the measurements of the CXRS systems. The direct mechanism whereby this improved gradient could affect the ELMs behaviour is under study. In any case the change in the radial electric field is mainly due to the increased share of both the poloidal and the toroidal velocities.

The upgraded charge exchange systems of JET are also providing very useful information on other important issues involving the interplay between the core and edge regions of the plasma. Among the most relevant are the studies of momentum transport [13], which have proven the existence of a significant anomalous pinch velocity, and the transition between the L and H modes of confinement [14]. With regard to the transport of momentum, the increased time resolution of the CXRS diagnostics is now sufficient for the interpretation of perturbative experiments, like the one shown in figure 7. In this discharge whose parameters have been designed for the turbulence to be in a clear ITG regime, the power of the neutral beams has been modulated to dynamically modify the toroidal rotation. With these perturbative experiments, it is possible to separate the contribution of the diffusion and pinch velocity of the momentum transport. The applied torque has been simulated with TRANSP and the modulation of the plasma momentum with JETTO [13]. As reported in figure 8, in order to properly reproduce the evolution of the experimental quantities, a significant pinch velocity of the order of about 15m/s must be introduced in the simulations. This is a positive results in the perspective of ITER, because it proves that, even with limited momentum input, the plasma can auto-organise itself to produce a significant velocity shear in the core, which is known to have a positive effect on the stabilisation of turbulence.

4. DIAGNOSTICS FOR THE FAST PARTICLES

Since JET is the only device with a plasma volume big enough to confine the alpha particles, so that their vast majority is not lost already during their first orbit, a multi year upgrade programme has been devoted to the detection of energetic particles. For the particles in the highest energy range, the technique of detecting them with γ-ray spectroscopy, an approach pioneered by JET [15,16], is being continuously upgraded. New detectors have been installed on the γ-ray cameras and new acquisition and processing electronics is being developed. Tomographic inversions of the γ-ray camera line integrals provide information about the fast particle orbits for scenarios with various heating schemes. One example is shown in figure 9, to emphasize the importance of proper modelling of the fast particle behaviour to interpret the tomographic reconstructions. Since the He-3 fast particles, accelerated with 90 degrees ICRF phasing, spend most part of their time near the stagnation points, their γ-ray emission is higher on the high field side and does not reflect directly the shape of the banana orbits. These results have been confirmed by simulations performed with the SELFO code, which manage to properly reproduce the line integrals of the γ-ray cameras. The high performance of the system allows also studying the redistribution of the fast particles during fast events like sawteeth, as illustrated in figure 10. Given the very positive results obtained so far, particular attention is being devoted to improve the ITER compatibility of this technique. To this end, various neutron absorbers are going to be tested to reduce their detrimental effects on the measurement of the γ-rays.

Even if the potential of γ-ray spectrometry is very high, as testified by the reported results, this diagnostic technique is limited to the high energy range, because of the nuclear reactions the method is based on. To complement the measurements of γ-ray spectrometry, JET neutral particle analyzers are also being improved. New detectors, based on Silicon on Insulator technology, are being developed for the detection of the neutral particles, to reduce the sensitivity of these sensors to the neutrons. This is meant to extend the energy operational range of present day neutral particle analysers well below 100 keV, to investigate wave particle interactions of more ITER relevance than what can be done today. For the losses, a new scintillator probe [17] has been operated during the last campaigns, with the main objective of studying the interplay between energetic particles and collective Magneto-Hydro-Dynamic instabilities, which can significantly increase their losses. The simultaneous use of the diagnostics for the redistribution and the losses of the fast particles is expected to provide a lot of new information. An example is shown in figure 11, where the decay time of the fast particles measured with a high resolution γ-ray spectrometer and the scintillator probe are reported. The measurements have been taken in notches of the ICRH heating. The redistribution of the fast particles in the core increase their effective confinement time compared to the ones already at the edge which are lost on a faster time scale.

5. FUTURE DEVELOPMENTS

Even if JET measurements have been significantly improved in the last years and the present set of diagnostics normally provides good support to the experimental programme, there are some aspects of the present day diagnostic capability which it would be worth upgrading.

With regard to the diagnostic techniques which need further developments in the perspective of ITER, detection of He ash is a particularly delicate issue. Spectroscopic detection of line radiation, emitted following double charge exchange between the He ash and the atoms of He beams, has been proposed and attempted in the past [18]. A final experimental validation of the approach would be required but has not been possible yet. As far as the JET scientific programme is concerned, the main weakness is probably reflectometry. A new sweeping reflectometer is being designed to be able to measure the density profile over the entire minor radius with sub centimetre spatial resolution and ms time resolution.

The diagnostic capability for the plasma edge has been upgraded significantly in the last years and further developments are under way, particularly to improve the infrared thermography in the divertor. On the other hand evidence of new physical phenomena occurring at the edge is emerging. In addition to the filamentary structures already discussed in section 1, a body of evidence is being collected that shows a potentially new route for dust formation in the divertor region for low temperature, high density plasmas close to detachment.

For ne > 10^{18} m^{-3} and Te < 10 eV simulations indicate that the carbon present in the plasma can coagulate and undergo a process of accretion to form hydrocarbon nanoparticles (up to diameters of 1mm), following the process described in figure 12. These nanoparticles have also been detected in Ar low temperature plasmas [19]. At JET these particles were recovered from the region below the divertor during the 1999 shutdown (figure 13). New evidence has emerged since the installation of the new wide angle infrared camera. Careful calculations have indeed proved that the MARFE emission in the IR shown in figure 3 is not due to brehmsstrahlung and can be explained by the infrared emission of these hydrocarbon nanoparticles. If the amount of these nanoparticles, whose presence is very likely, proved to be significant, they could have implications for the tritium retention in ITER, since they absorb and retain a significant amount of hydrogen. The amount of hydrogen particles retained by these nanoparticles is relatively well known by low temperature plasma experiments. On the other hand quantifying the amount of these particles in the edge of JET plasmas remains an open issue.

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Table I Level of puffing in the various dischargesto study the effect of the ELMs on wide ITBs.

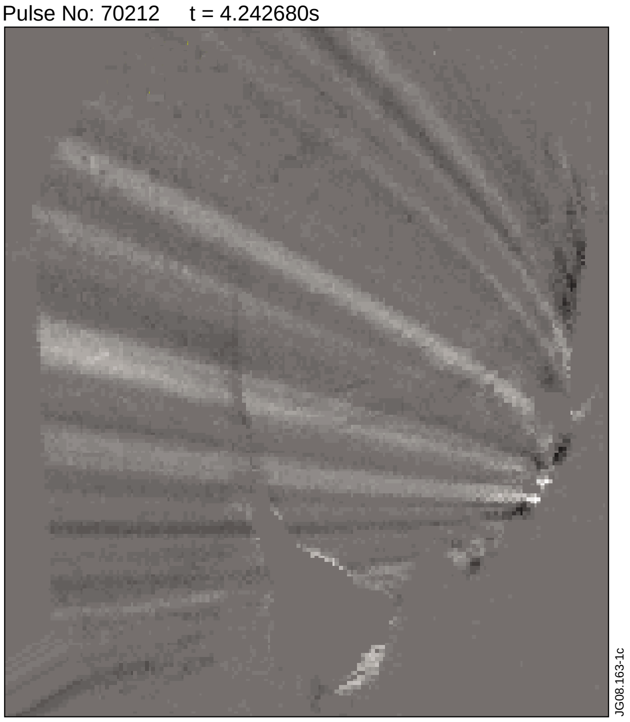


Figure 1: Filaments seen with the fast visible camera during a type 1 ELMy H mode phase.

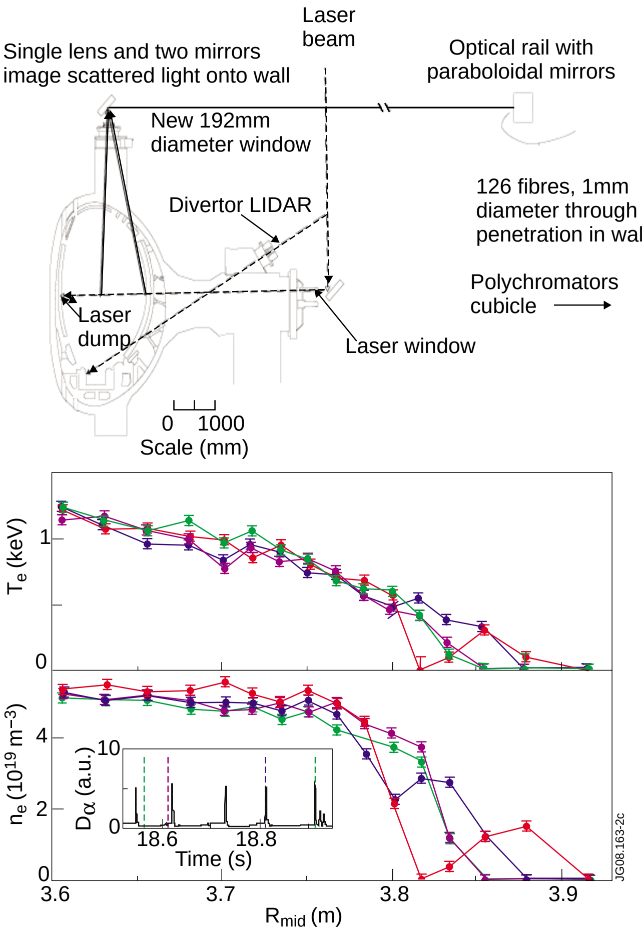


Figure 2: Filaments in the edge of JET plasmas seen by the High Resolution Thomson Scattering diagnostic during ELMy H mode phase.

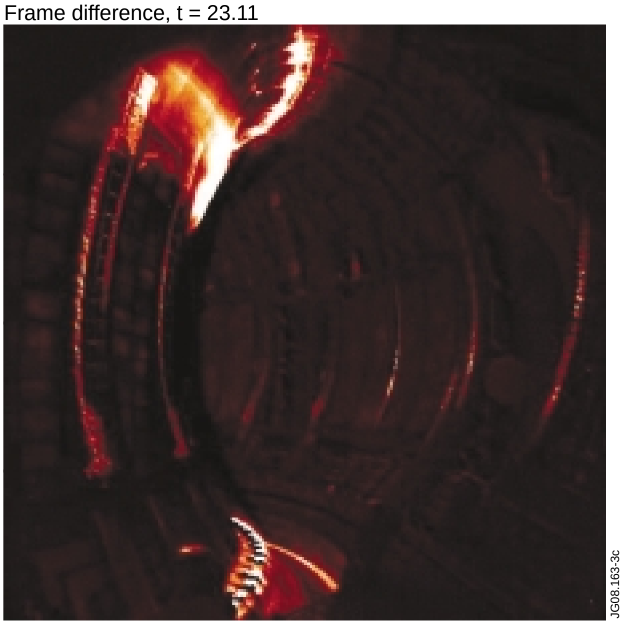


Figure 3: MARFE instabilities clearly seen in the IR image before a density limit disruption.

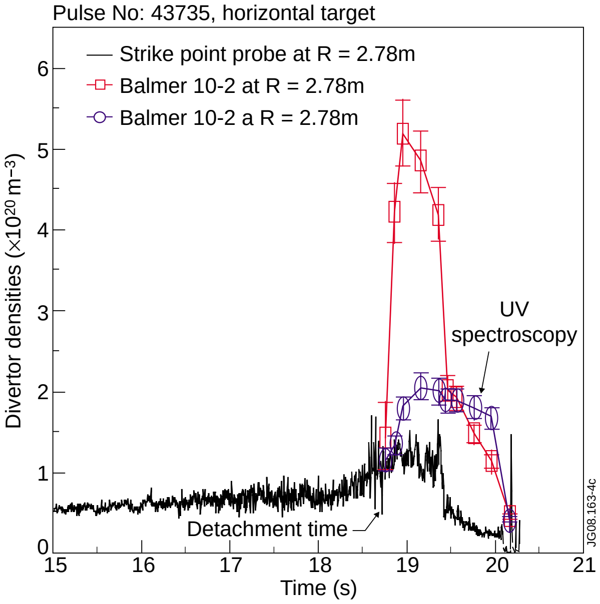


Figure 4: Comparison of the Langmuir probe and spectroscopy measurements before and after detachment of JET divertor outer leg.

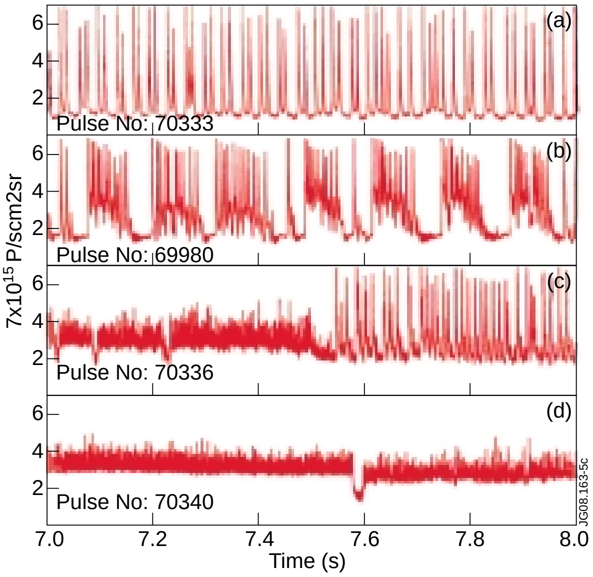


Figure 5: Change in the ELM behaviour following the different levels of Neon injection. Neon injection increasing from top to bottom.

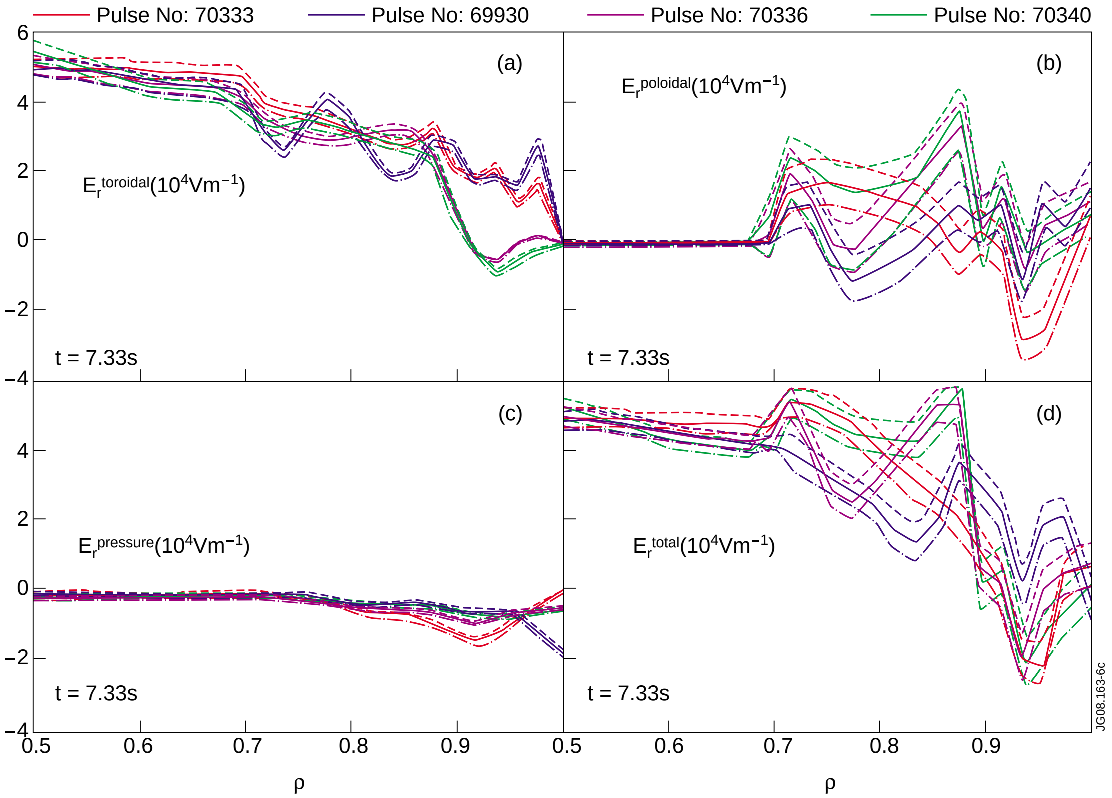


Figure 6: The radial magnetic field of the discharges with different levels of Ne injection. The highet shear of the E_r (green curve) corresponds to the discharge with the strongest Ne puffing and shows the steepest gradient of the radial electric field.

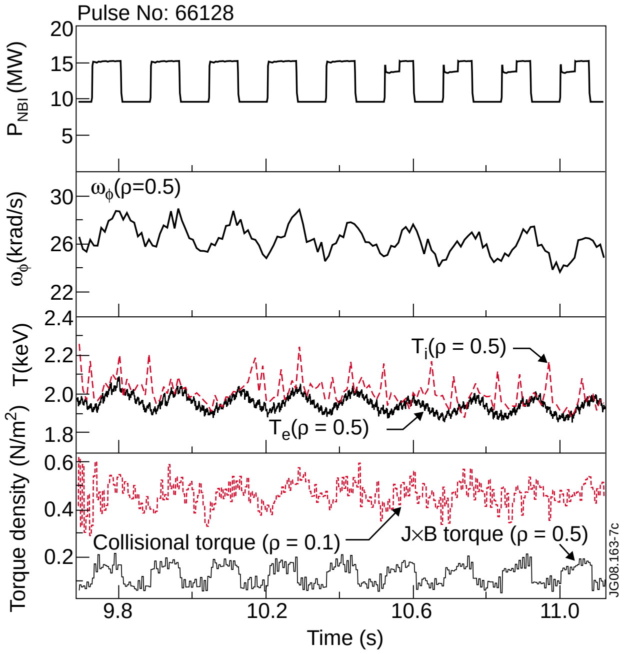


Figure 7: Modulation of the neutral beam power (P_{NBI}), toroidal angular velocity ω_ϕ ,ion and electron temperatures and the two main components of the torque.

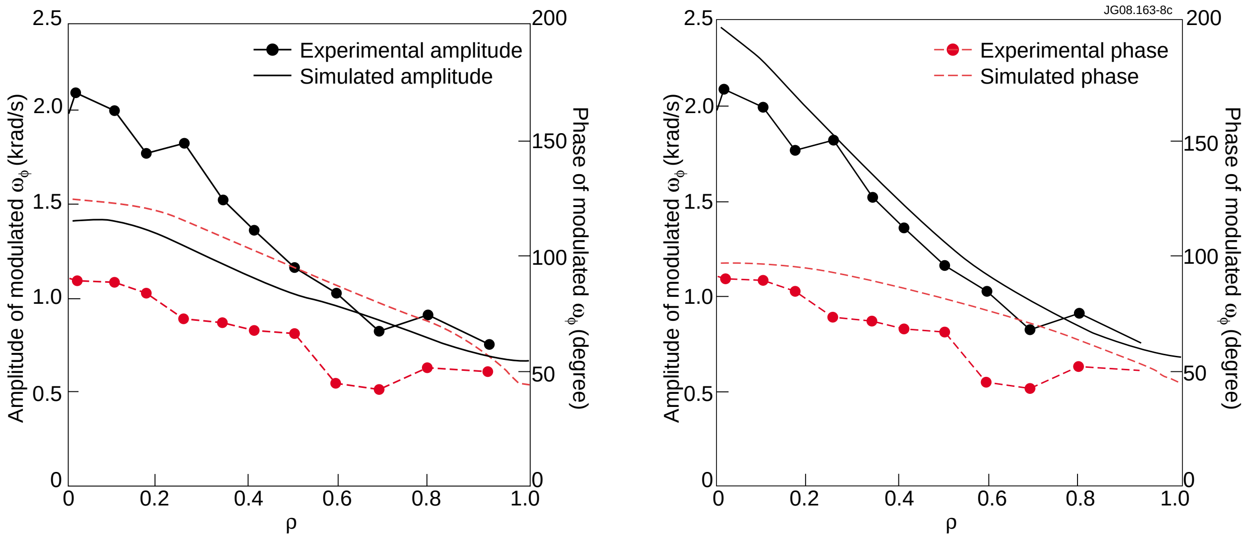


Figure 8: Amplitude and phase of the toroidal angular velocity. Left: results of the JETTO simulations without momentum pinch Right: results of the JETTO simulations with pinch velocity.

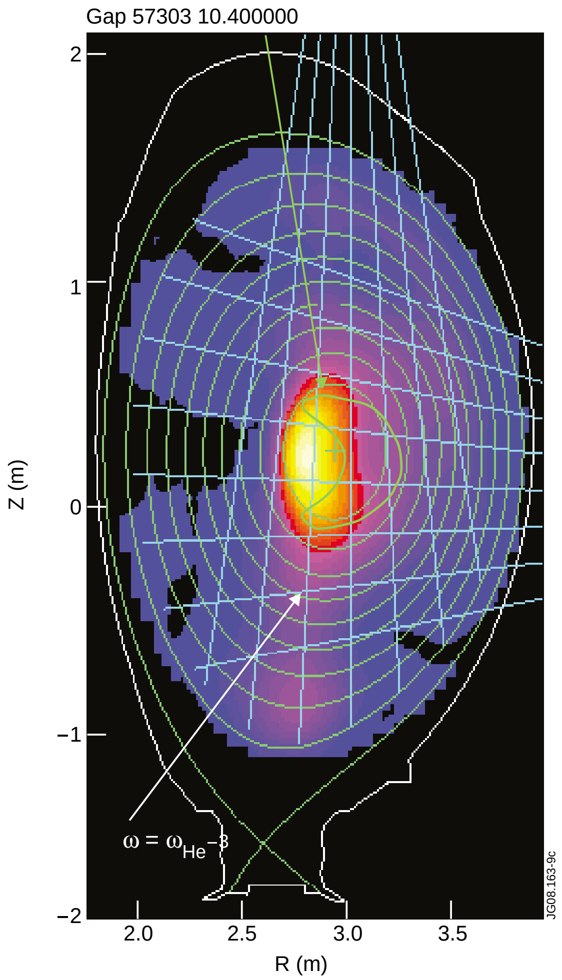


Figure 9:Top He-3 fast particles distribution determined with the γ-ray cameras .

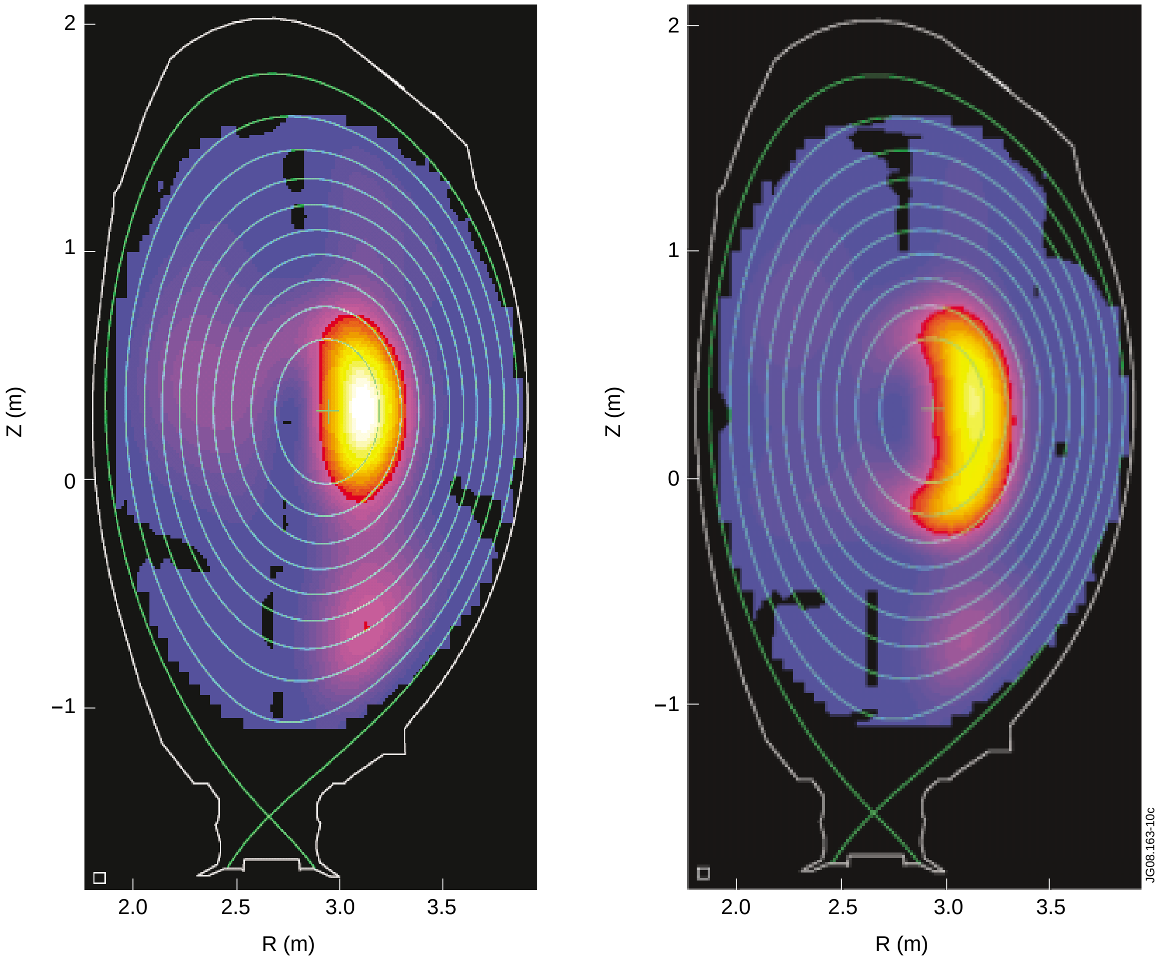


Figure 10:Fast particles redistribution after a sawtooth. γ-ray emission before (right) and after (left) the sawtooth crash.

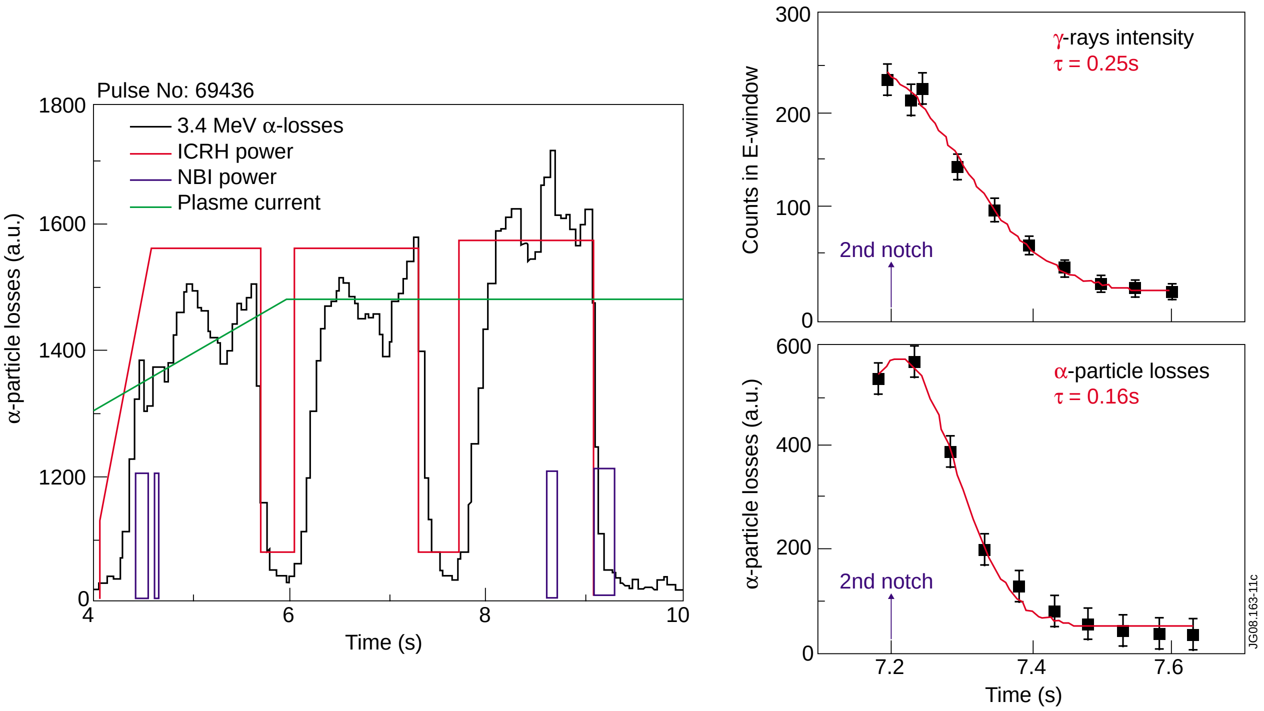
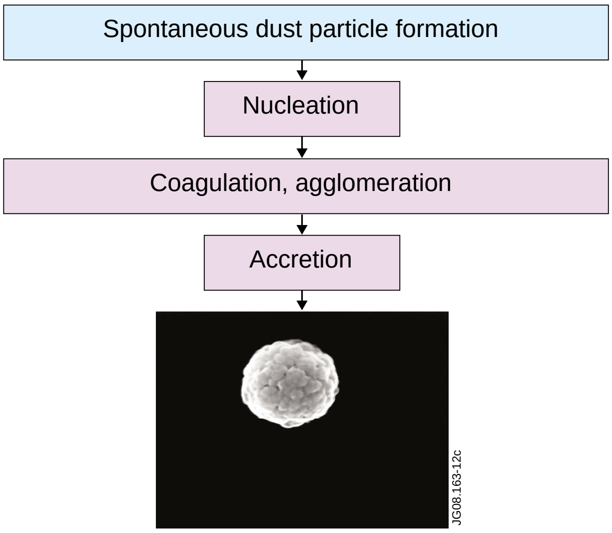


Figure 11: Fast particles decay time measured during notches in the ICRH power (left) as measured with the γ-ray spectroscopy and with the scintillator probe.



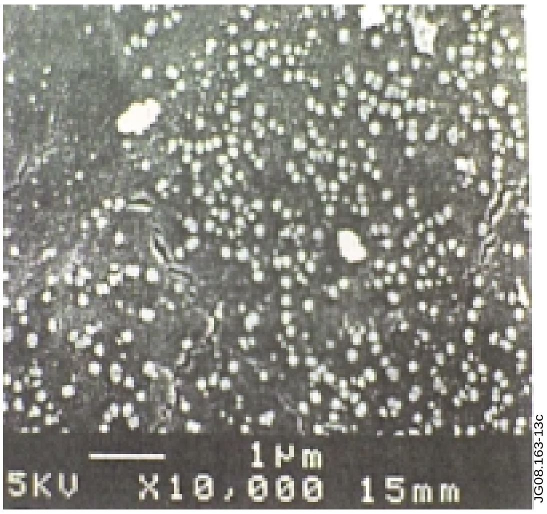


Figure 12: Hydrocarbon nanoparticle formation.

Figure 13:Dust extracted from the region below the divertor in 1999.