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New Developments in the Diagnostics for the Fusion Products on JET in Preparation for ITER

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** See annex of F. Romanelli et al, "Overview of JET Results", (Proc. 22nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).*

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ABSTRACT.
Notwithstanding the advances of the last decades, significant developments are still needed to satisfactorily diagnose "burning plasmas". D-T plasmas indeed require a series of additional measurements for the optimisation and control of the configuration: the14MeV neutrons, the isotopic composition of the main plasma, the helium ash and the redistribution and losses of the alpha particles. Moreover a burning plasma environment is in general much more hostile for diagnostics than purely deuterium plasmas. Therefore, in addition to the development and refinement of new measuring techniques, technological advances are also indispensable for the proper characterization of the next generation of devices. On JET an integrated programme of diagnostic developments, for JET future and in preparation for ITER, has been pursued and many new results are now available. In the field of neutron detection, the neutron spectra are now routinely measured in the energy range 1-18 MeV by TOFOR and they have allowed studying the effects of RF heating on the fast ions. A new analysis method for the interpretation of the neutron cameras measurements has been refined and applied to the data of the last trace tritium campaign (TTE). With regard to technological upgrades, CVD diamond detectors have been qualified both as neutron counters and as neutron spectrometers, with a potential energy resolution of about one percent. The in situ calibration of the neutron diagnostics, in preparation for the operation with the ITER like wall, is also promoting important technological developments. With regard to the fast particles, for the first time the temperature of the fast particle tails has been obtained with a new High purity Germanium detector measuring the gamma emission spectrum from the plasma. The effects of TAE modes and various MHD instabilities on the confinement of the fast particles have been determined with a combination of gamma ray cameras, NPAs, scintillator probe and Faraday cups. From a more technological perspective, various neutron filters have been tested to allow measurement of the gamma ray emission also at high level of neutron yield.

1. THE DETECTION OF FUSION PRODUCTS

In a "Burning Plasma", a plasma in which a significant amount of fusion reactions takes place, it becomes essential to properly detect the fusion products, since they are a fundamental ingredient both to assess the performance of the plasma and to control it. On the other hand, properly diagnosing the fusion products is a challenge not only for the inherent difficulties in the measurements but also because limited information is available since not many devices can produce really relevant burning plasmas. Indeed in general D-T plasmas would be required to properly assess the potential of the various diagnostic techniques. In JET experience has been gathered on the fusion products in three D-T campaigns (15% T in 1991, 50−50% in 1997 and between 1 and 3% T in 2003) and the diagnostics developed for these experiments are being continuously developed in more traditional high performance D-D experiments. Another important aspect of the fusion product detection, which is often underestimated, is the severity of the environment, which very often requires not only technological developments but also significant refinement in the measuring techniques. The high neutron background indeed can not only jeopardise certain measurements, such as the detection of γ-rays emitted by the fast ions, but can even damage detectors.

As far as the physical parameters are concerned, the specific measurements to be performed, to characterize the fusion products in burning plasmas, are: the neutrons (see section II), the alpha particles (see section III), both their redistribution and their losses, and the He ash. The neutrons constitute the ultimate indicator of the quality and reactor relevance of thermonuclear plasmas. The alpha particles are expected to remain confined and, by transferring their energy to the main plasma, contribute to the efficiency of the energy production. The He ash is on the contrary an undesired side effect of the fusion reactions, which must be eliminated otherwise it can dilute the plasma and adversely affect its reactivity. With regard to technological developments, to perform better measurements in the hostile environment of burning plasmas, the most significant results have been obtained in the field of radiation hard detectors (see section II) and in the development of neutron filters (see section III) to modify the radiation field and allow measurements of the g-ray emission even in plasmas with high neutron emission.

2. THE DETECTION OF NEUTRONS

In JET, the spectra of the 2.45MeV neutrons are measured routinely by the TOFOR spectrometer [1]. The diagnostic is a time of flight spectrometer and has been designed to detect rates between 10^{14} and 10^{17} n/s for a maximum count rate of 400kHz. The energy resolution of the diagnostic is 7.4%. The spectrometer is located in the roof lab of JET, about 19 meter from the centre of the vacuum vessel, and has been operated routinely in the last campaigns. Among other things, it has been very useful to measure the neutron spectra of the recent high current experiments and assess the global performance of these plasmas. The results obtained by TOFOR are presented in figure 1 and show that almost 70% of the neutron emission is due to thermo-nuclear reactions for this 4.5MA discharge at 3.6T of toroidal field [2]. The thermal dominated phase lasts for about 4 seconds, indicating that this high neutron yield is not a transient effect but a quite stable property of the discharge. The neutron spectrum allows also determining the ion temperature of the main plasma, not of the impurities as provided by spectroscopy. The ion temperature determined with TOFOR is compared with the Thomson Scattering measurements in figure 1, proving that in plasmas, in which the majority of the neutrons are thermal, neutron spectrometry can provide a very good estimate of the ion temperature.

The spectra of the emitted neutrons can provide interesting information not only about the overall performance of the plasma but also about various instabilities and about the impurity content of the discharge. An example of the signature left on the neutron emission by plasma instabilities is shown in figure 2. The neutron spectrum has been studied in two different deuterium energy ranges: for energies above 0.5MeV and for energies above 1.3MeV. After switching on the RF heating at 12s, the flux of neutrons in both energy intervals increases. At 14.2s TAE modes are detected in the magnetic measurements and these instabilities affect the neutrons from the two deuteron energy ranges in a different way. The flux of neutrons due to deuterons in the energy range E_d above 0.5MeV continues to increase, whereas the one of neutrons due to deuterons with energy above 1.3MeV start to clearly decrease. The sawtooth crash at 15s has the effect of causing strong losses of the deuterons with energy above 0.5MeV affecting the deuterons above 1.3MeV less significantly. The main interpretation of this behaviour is based on the facts that the TAE modes interact with the ICRF accelerated ions through trapped ion precession resonance, i.e., at the ion energies for which the precession frequency, in the toroidal direction, matches the resonance condition with the TAE, e.g. n = 3 and 4 TAE resonate with E_d = 1.4 and 1.1MeV, respectively. For these fast deuterons the energy can be transferred resonantly between the ions and the wave. Since the ICRF heating accelerates ions from the beam energy and upwards, the entire ion population above the resonance energy is affected, which explains the observation for E_d > 1.3MeV.

The neutron spectrum can also provide information about the species composition of the plasma. In particular, a quite important subject in the perspective of ITER and JET with a metallic wall, the signature of Be can be found in the neutron spectra. In the case of the present JET wall, Be is seeded into the plasma mainly by Be evaporation. A reaction which produces the detectable neutrons in RF heated discharges is ^{9}Be (^{3}He,n)^{11}C. The signature of Be in the spectrum is shown in figure 3. Further studies will be carried out to study the signature of Be in the neutron spectra after the installation of JET new ITER-like wall. Indeed the neutron emission due to the presence of this impurity could constitute an issue for the low activation phase of ITER.

Another main diagnostic for the detection of the neutrons in JET are the neutron cameras [2]. They consist of two fan shaped arrays of detectors as shown in figure 4. The diagnostic consists of 10 horizontal lines of sight and 9 vertical lines of sight for a total of 19 channels which are enough to perform tomographic inversion and therefore to derive information about the spatial distribution of the neutron emission. Each line of sight is equipped with two detectors: a NE213 detector which can measure both the 2.45 and the 14MeV neutrons and a Bicron detector for the 14MeV neutrons. An example of the type of information, which can be derived by this diagnostic, is provided in figure 5. This figure shows the penetration of tritium in a deuterium plasma after gas puffing. The analysis is based n the ratio method, which has been developed for JET as reported in [3]. The main characteristic of the approach is the use of both the 2.45 and 14MeV neutron emission. The ratio of the two neutron components allows deriving information about the isotopic ratio of the plasma directly without any forward modelling and, what is more important, independently from the absolute calibration of the diagnostic. In the last years, advanced tomographic inversion methods, based on the Minimum Fisher Information regularization, Maximum Likelihood statistical principle [4] and neural networks [5] have also been developed. They allow fast tomographic inversion. Therefore the evolution of the neutron emissivity can be followed with a high temporal resolution and can be used to perform systematic studies of particles transport. It is also worth mentioning that a thorough assessment of the inversion techniques used at JET has been performed, to determine the strengths and weaknesses of the various approaches.

In addition to the development of specific diagnostics and the refinement of analysis methods, the detection of neutrons requires also some technological advances. One of the main technological fields which has witnessed significant progress in the last years is solid state chemistry for the developments of radiation hard detectors. In the case of reactor machines such as JET and even more ITER, various technologies are not sufficiently robust. Therefore new detector based on Si on insulator technologies, for NPA detectors with low sensitivity to the neutron background, and new radiation hard Hall probes are being developed. One of the technologies which have progressed more in the last years is Chemical Vapour Deposition for the manufacturing of radiation hard diamond detectors for neutron counting and neutron spectrometry [6]. These detectors are produced in vacuum chambers with radiofrequency sustained plasmas. Some of the most relevant properties of diamond for the application to neutron detection are: the high energy bandgap of 5.48eV at 300K, the high carrier mobility (2200cm^2/Vs for electrons and 1600cm^2/Vs for holes). In particular the high bandgap guarantees proper operation at high temperatures, which is a not negligible advantage in the perspective of ITER. In any case the main added value of this technology is the robustness of the diamond detectors with respect to neutron damage. It has been experimentally demonstrated that these detectors preserve their properties at room temperatures up to fluences of 2×10^{16} n/cm^2.

Nowadays in JET practically only monocrystalline CVD diamond detectors are used, since they provide much cleaner signals and in particular can be used for spectrometry. The manufacturing of good quality monocrystalline diamond detectors is not simple task but they are now produced routinely, providing an energy resolution of the order of 1% at 14MeV, a fact that positions this technology among the most accurate for the measurement of the D-T neutron spectra. Another important issue, which has pushed is the fact that diamond can detect only 14MeV neutron since the reaction $^{12}C(n,\alpha)^{9}Be$ has a threshold around about 9MeV. In order to be able to count also the 2.45MeV neutrons, a new generation of detectors has been developed. On the surface of the monocrystalline diamond detectors a layer of LiF is deposited. The interaction between the Li and the neutrons produces T and alpha particles which deposit their energy in the diamond and allow detection of the 2.45MeV neutrons (but not spectrometry). Various generations of these detectors have already been installed and operated successfully on JET. Their counting rates have been validated by comparison with the measurements of the fission chambers, the reference diagnostics for the neutron yield in JET. The spectrometric capability of the monocrystilline diamond detectors has also been verified by comparison with the other JET spectrometers. The main line of research is now in the field of signal processing electronics, particularly preamplifiers. Indeed diamond detectors produce quite small peaks, of the order of mV; moreover these peaks are very short in time (order of tens of picoseconds). Specific preamplifiers have already been operated successfully on JET even 90 meters from the detectors. Nonetheless a new generation of amplifiers, based on the physics properties of the transistor junction, which renders the amplifiers practically insensitive to the cable length connecting them to the detectors, are being developed and tested.

In preparation of the operation of JET with the ITER-like wall, a new calibration of the neutron diagnostics is planned. This update of the previous calibration, performed in the eighties, becomes particularly necessary because Be, the new material of JET plasma facing components in the main chamber, is a neutron multiplier. Indeed ^{9}Be, when hit by a neutron, can decade into two alpha particles and emit two neutrons. This requires a recalibration of the neutron detectors, fission chambers, activation foils and diodes, which are used to provide the neutron yield. Also the channels of the neutron cameras need to be recalibrated since the materials in front of them will also change significantly. The planned in situ calibration is to be performed with a quite powerful ^{252}Cf source emitting 10^{9} n/s (γ-ray emission: ~ Air kerma rate at 1m of ~ 470uSv/hour; neutron: dose rate at 1 m of ~ 10mSv/hour). The source will be moved inside the vacuum vessel using JET remote handling mascot. The source is planned to be located in 40 toroidal positions. In order to simulate an extended source, such as the one constituted by JET plasmas, for each toroidal position the source will not be located only on the axis of the machines but both a horizontal and a vertical scan will be performed. All together the calibration is expected to take about a week of JET shutdown at the usual pace of two shifts per day, 7 day per week.

3. THE DETECTION OF ALPHA PARTICLES

A. FAST PARTICLE REDISTRIBUTION

In JET one of the main techniques to characterise the population of fast particles is the detection of gamma rays. When fast particles collide with the natural impurities in the plasma, they can cause nuclear reactions which emit specific gamma ray lines. The spectral identification of these lines allows determining the species inducing the reaction and the absolute measurement of the emitted radiation, together with the density of the target impurities, can give indications about the density of the fast particle population. An example is the reaction ^{9}Be (a,gn)^{12}C, which has been used historically to detect the alpha particle redistribution at JET. Traditionally the spectra of the emitted γ-rays have been measured with Na(I) and BGO scintillators. In the last years significant efforts have been devoted to the development and use of new detectors, which can provide better performance. The two main materials tested are LaBr3 scintillators and HPGe semiconductor detectors. The first material provides a very high light response whereas the HPGe is characterised by a very good energy resolution. Indeed HPGe presents an energy resolution DE/E of about 0.3% in the MeV energy range of interest for JET, whereas the value for LaBr3 is 2%. The very good energy resolution of the HPGe detectors has allowed determining the temperature of the fast ion population in JET [7]. Indeed the energy resolution of a fraction of percent is enough to resolve the Doppler broadening of the gamma lines emitted by impurities after the collision with the fast ions. This is shown in figure 6 in which an example of a very high resolved spectrum in the g-ray region is shown. The bottom plot shows how the line at 4.439MeV is resolved to give the temperature of the fast ion tail, assuming of course that its distribution function is maxwellian. The capability to resolve the temperature of the fast ion tails is a new result, made possible by the very high purity of the Ge detector used and opening new horizons in this line of research on JET. It is also worth mentioning that the new diagnostic capability provided by this detector has motivated the development of various models to simulate the nuclear interactions between the fast ions and the impurities nuclei. In the course of this work, it has emerged quite clearly that some relevant cross sections have been measured a long time ago and more recent and complete data would be very beneficial. Therefore a proposal for the determination of the different cross section of various reactions is being considered.

In addition to the energy resolved measurements provided by the neutron spectrometers, the neutron cameras shown in figure 4 can also provide the γ-ray emission along their lines of sight, since Cs(I) scintillators can be located in front of the neutron detectors.
Tomographic inversion of the line integrated measurements has allowed determining the influence on the spatial distribution of the fast particles of various factors, ranging from the current profile to various MHD instabilities. The effects of the various ICRH heating schemes have also been studied in detail and, by selecting different lines, these studies have been particularised for different fast particle populations.

An important issue for the proper detection of the γ-rays is of course the subtraction of the neutron-induced γ-ray background. Unfortunately in JET already a few MWs of addition heating power can jeopardise the CS(I) measurements of the γ-rays. Therefore in the last years various neutron filters have been modelled and tested. The effectiveness of 6LiH as neutron filter has been verified in various experiments, proving that the 2.45MeV neutrons can be reduced of a factor 100 by 30 cm of this material, for a penalty of only 50% in the transmission of γ-rays. For the γ-rays cameras, reservoirs of demineralised waters are being manufactured, since various MCNP calculations have shown that they should be enough to guarantee good measurements in deuterium for any value of the NBI power. On the contrary ^{6}LiH filters would be necessary in case of 50-50% D-T operation.

B. FAST PARTICLES LOSSES

In the last years, one of the most active areas of research in JET has been the development of diagnostics for the fast particle losses. Three different systems have been installed and operated successfully for the first time in a Tokamak of the class of JET. The first one to provide result has been a new scintillator probe housed in a shielded cup and located approximately in the equatorial plane on the low field side of the machine. The diagnostic allows determining the energy and the pitch angles of the lost particles. The measurements are time resolved (time resolution of the order of 2ms) and therefore the losses can be correlated with the phenomena taking place in the plasma. In particular a lot of studies have been performed on the influence of the MHD instabilities on the confinement of the ions. One of the most interesting recent results has been the correlation between the fast ion losses and the fishbone instabilities. Indeed measurements obtained with JET 2-D scintillation detector reveal the existence of highly energetic (MeV-range) fast ion losses induced by fishbones. The losses are identified as losses of non-resonant type. The results discussed in this paper have been obtained in an ELMy H-mode discharge with conventional (fully relaxed) q-profile. The main parameters of the shot are: toroidal field $B_0 = 2.7T$, plasma current $I_p = 1.2MA$, safety factor $q_{95} \sim 6.5$, $\beta_{pol} = 1.8$, $n_e/n_{GW} = 0.77$, triangularity d ~ 0.4. The discharge is a deuterium shot with about 5% of H as measured by visible spectroscopy. The plasma heating consists of 15MW of NB power and 6MW of ICRH. The frequency of the RF is 42MHz, which corresponds to a central resonance for H minority at a major radius of R = 2.82m. In this discharge a clear signature of fishbone instabilities, destabilised by the beam injected ions, has been detected. The fishbone present an average amplitude DBq/B0 of about $1\text{-}4.5\times10^{-4}$ (measured outside the plasma). At the time of maximum amplitude, the radial displacement due to the instability is in the range of 3-8cm (±20%) inside the q=1 surface. These topological effects have been determined with the help of the soft-X ray and ECE diagnostics.

The fishbones are accompanied by a sudden increase in flux of lost ions detected by the scintillator probe. In the case reported in figure 7 the increment in the losses is of a factor between 10 and 20 enhancement with respect to the background level between fishbones. The energy losses peak at 1.55 (±0.35) MeV, with the tail exceeding 3MeV. The pitch angle distribution of the lost ions shows a single peak centred at 58.5 (±2) degrees; this corresponds to trapped orbits whose turning points are in the vicinity (within 6cm or less than a gyroradius) from the RF resonant layer. Therefore the energies of the lost particles are at least an order of magnitude higher than the beam injected ions destabilising the fishbones ($E < 130keV$). As a consequence the losses must originate from the RF accelerated protons themselves, since the cross-section for fusion products is too small to cause such a big signal on the scintillator probe. The dependence on the fishbone amplitude, the time evolution of losses during a fishbone, and the energy and pitch angle distribution of the losses has been modelled compared with drift-kinetic code simulations using HAGIS, SELFO and MISHKA [8]. In particular the drift-kinetic code HAGIS follows the guiding centre trajectories in the presence of the kink perturbation during a fishbone period (11ms). The radial origin of lost ions predicted by HAGIS for a fishbone with amplitude $A_{sat} = 1.0\times10^{-2}$ is shown in figure 8. The quantity rmax is defined as the highest minor radius that an unperturbed guiding centre orbit reaches on the outer midplane. The simulations have been interpreted as the result of two main types of orbit losses, which are also shown in figure 8.

The scintillator probe has been complemented with a set of 9 Faraday cups located in five different poloidal positions covering about 20 degrees in the lower part of JET vessel again in the low field side of the machine. In the case of JET, these detectors are made of Ni foils separated by mica insulator sheets to provide a rough energy resolution. This is a quite robust technology which is expected to be of relevance for ITER; moreover these detectors can be calibrated absolutely and therefore constitute a good complement to the scintillator probes, which are difficult to calibrate absolutely and which are expected to be less stable in terms of light emission in an hostile environment like a reactor relevant Tokamak. Unfortunately the diagnostic was affected for a long time by a very strong pickup noise induced by the operation of the RF heating systems. Indeed fast ions detectable by the Faraday cups can be generated in JET only by the ICRH and therefore a lot of efforts have been exerted to reduce the pickup noise. Better earthing and the insertion of RF filters in series of the signal cables connected to the foils of the Faraday cups have been the two most effective measures. Once the noise has been reduced to the level of a few tens of nA, the first clear measurements have become possible. An example is provided in figure 9, showing the results obtained in He plasmas. Also in this case, the fast particles have been accelerated by RF heating (see figure 9). The losses are detected as expected by the foils which correspond to energies between 2.3 and 5.9MeV, whereas the most internal foils, corresponding to energies between 6.3 and 7.2MeV, do not show any appreciable increase during the RF phase. It has also been possible to correlate the amount of signals with the power of the RF injected in the plasma. The good correlation, also reported in figure 9, confirms that the charge collected by the Faraday cups are indeed fast ions. A quantitative interpretation of these measurements is under way.

The third diagnostic approach consists of a set of activation foils, which have been located near the plasma edge in the top part of the vacuum vessel using the manipulator normally used for inserting JET reciprocating probes. The foils are activated by the impact of the lost ions and by measuring the radiation emitted by them, once they are extracted from the machine, it is possible to quantify the fast particle losses. This third technique has been demonstrated on JET but it is still at a proof of principle stage so it has not been possible to obtain many results about the physics of the fast particle losses. On the other hand, it is a significant result that fast particle losses have been detected even on the upper part of the machines.

CONCLUSIONS AND DIRECTIONS OF FURTHER RESEARCH

On JET a series of diagnostics are routinely available to measure the neutrons and the fast particles. They have been developed in the last years and have already achieved a quite good level of maturity. Nonetheless, a programme of further developments is continuously being pursued. In this perspective, the weakest point, with regard to detection of the fusion products, remains the measurement of the He ash. Spectroscopy is still experiencing severe difficulties, due mainly to the strong He emission from the edge of JET plasmas, which makes it difficult to obtain the fuel ratio in the core. To solve this problem, the double charge exchange of He beam particles with the thermalized He is being actively investigated. Recently some additional experiments have been performed but they require further analysis. The other parameter, very important to control “burning plasmas”, is the isotopic composition. On JET a specific Neutral particle Analyser has been designed and installed to measure exactly the fuel ratio. The diagnostics unfortunately showed some significant problems with the neutron background in the TTE campaign in 2003. Recently therefore new Si on insulator detectors have been developed. Their active area has a thickness of the order of 5 mm and therefore they are quite insensitive to the neutrons. They have been properly tested and characterised and they are planned to be deployed on JET in the next campaigns.

ACKNOWLEDGMENTS

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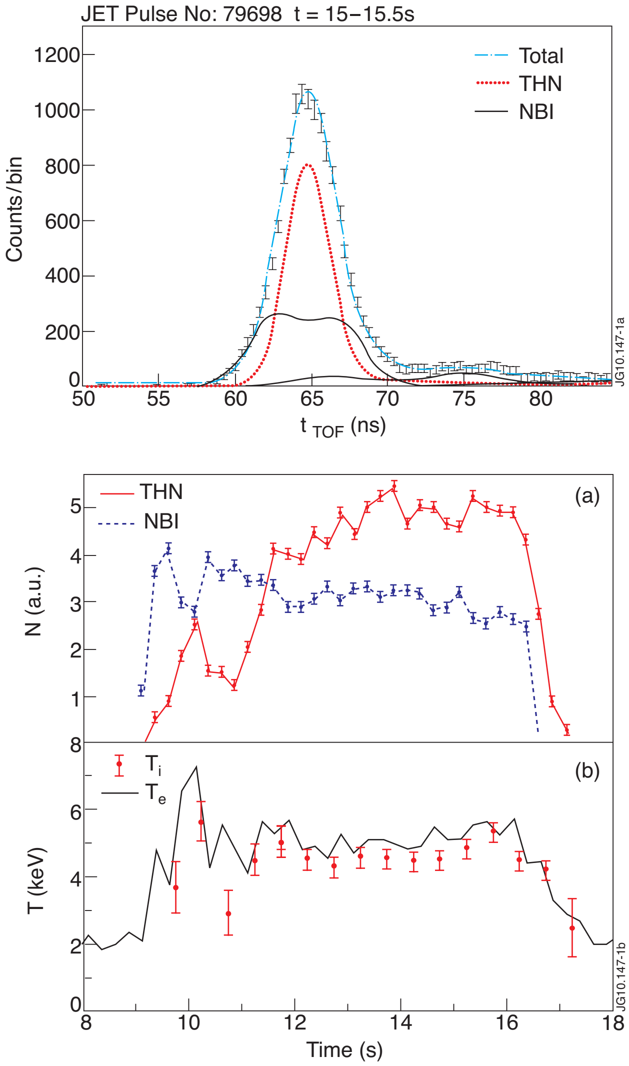

Figure 1: Top- the neutron (TOF) spectrum measured by TOFOR for a 4.5MA, 3.6 T discharge. Almost 70% of the emission is thermal (THN) in the high heating phase of the discharge and the rest is due to the beam plasma interaction (NBI) Middle: the time evolution of the neutron emission shows that the thermal dominated period lasts for about 4 seconds. Bottom: the estimate of the ion temperature from TOFOR compared with the electron temperature determined with Thomson Scattering.

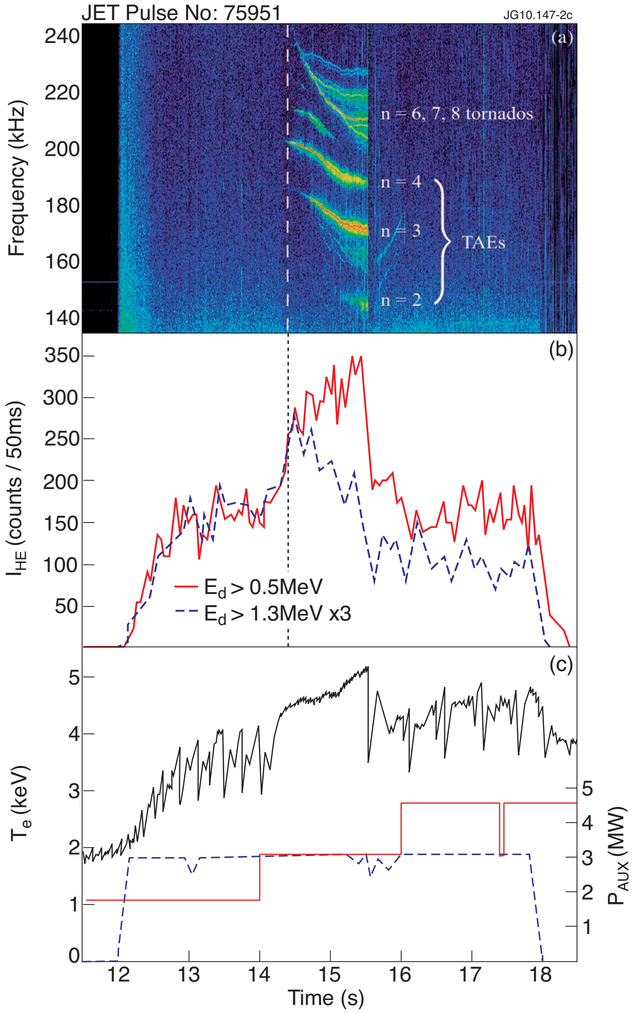

Figure 2: Top: signature of the TAE modes in the frequency spectra of the magnetic pick-up coils. Middle: evolution of the neutron emission due to deuterons in the energy intervals above 0.5MeV (red continuous line) and above 1.3MeV (blue dashed line) Bottom: electron temperature of the plasma and the additional heating powers: blue dashed line ICRH, red continuous line NBI.

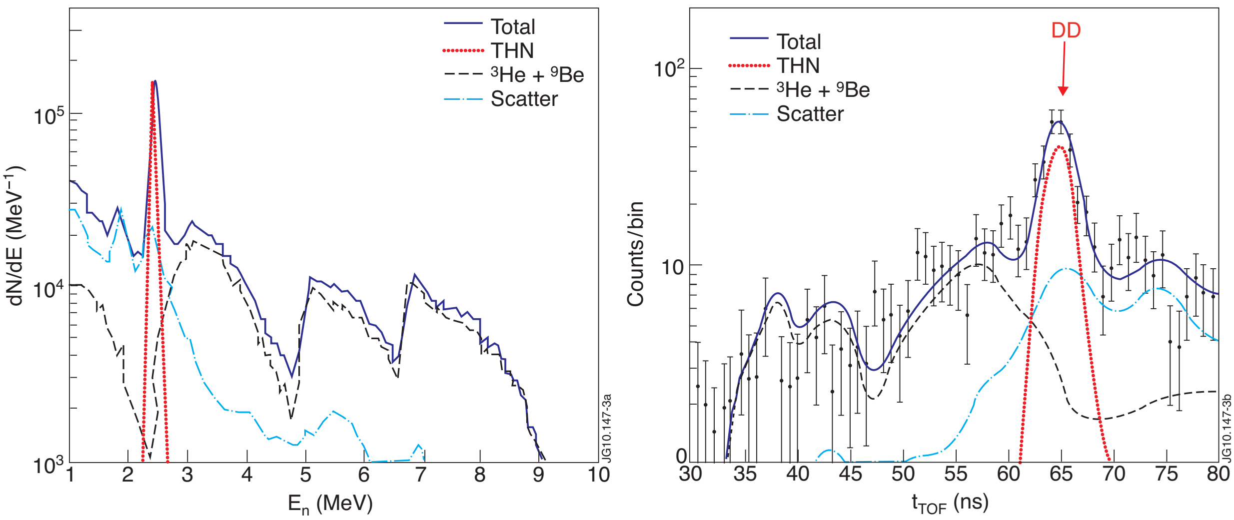

Figure 3: Various components of the neutron spectrum, versus time of flight (top) and energy (bottom).

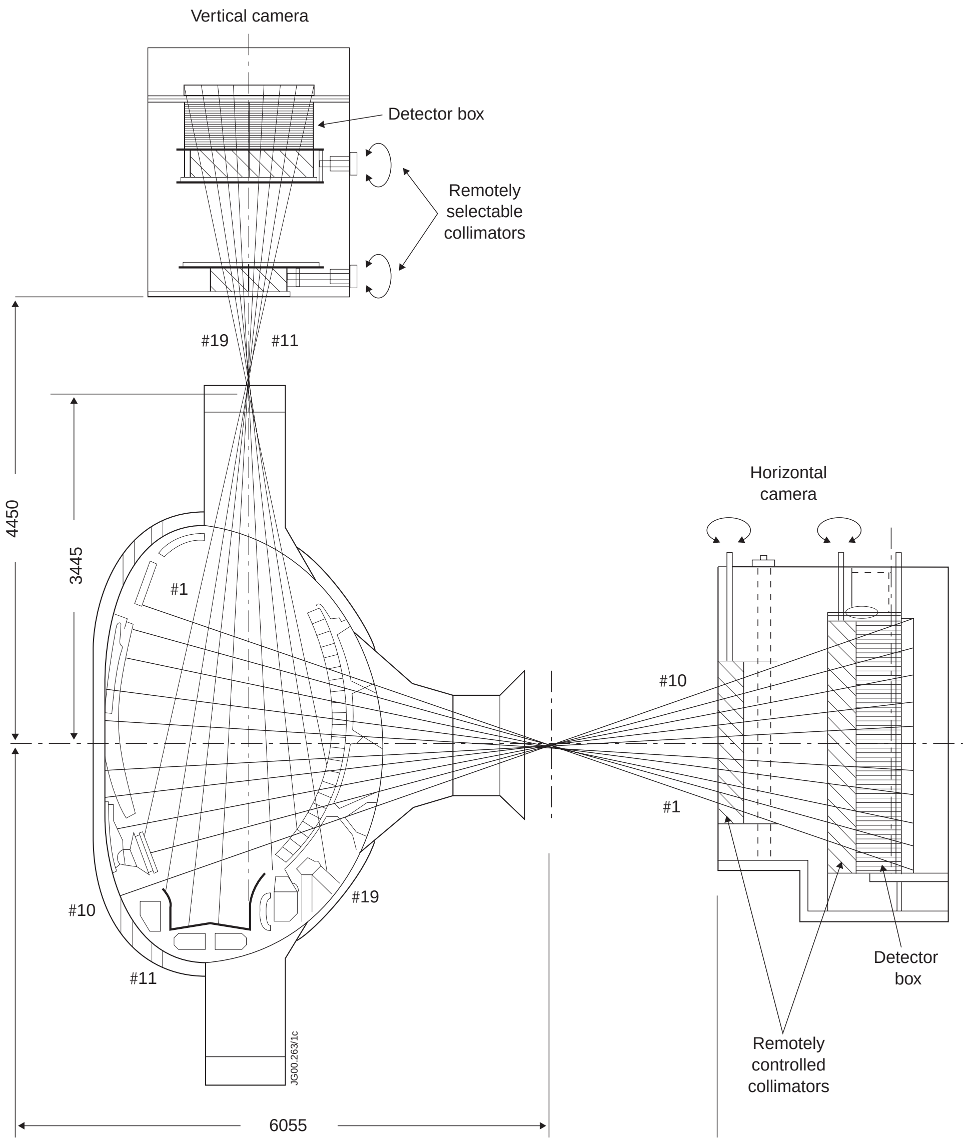

Figure 4: The topology of the neutron camera lines of sight.

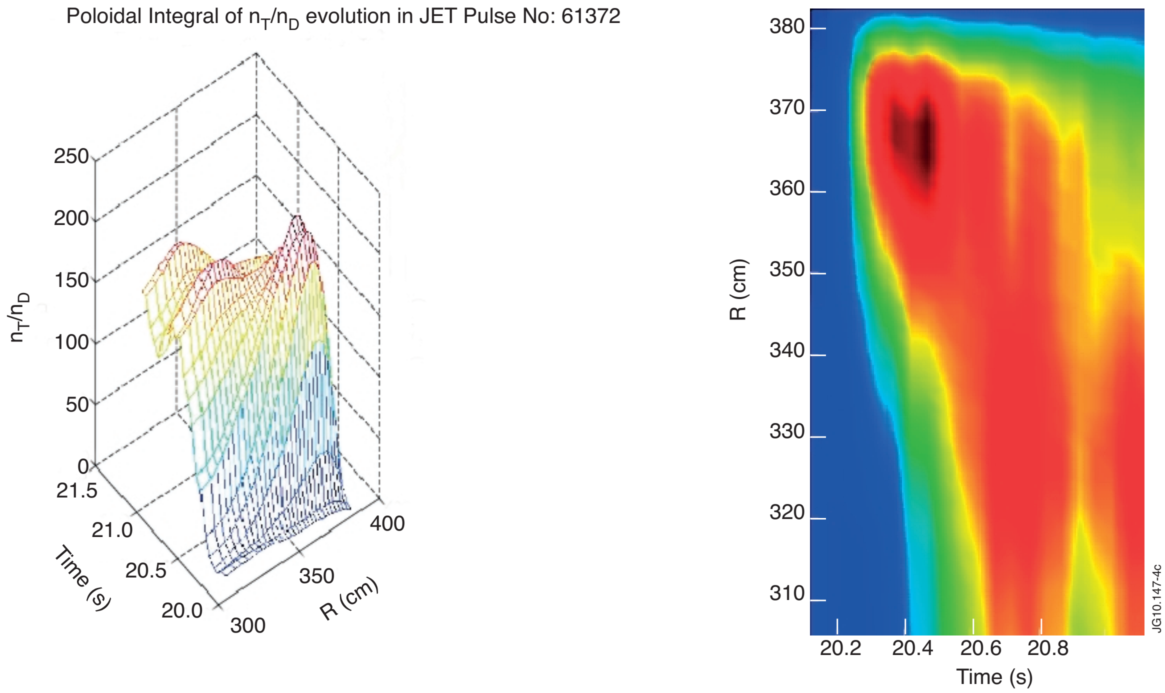

Figure 5: Time evolution of the tritium content after gas puffing in an experiment of the 2003 Trace Tritium campaign in JET.

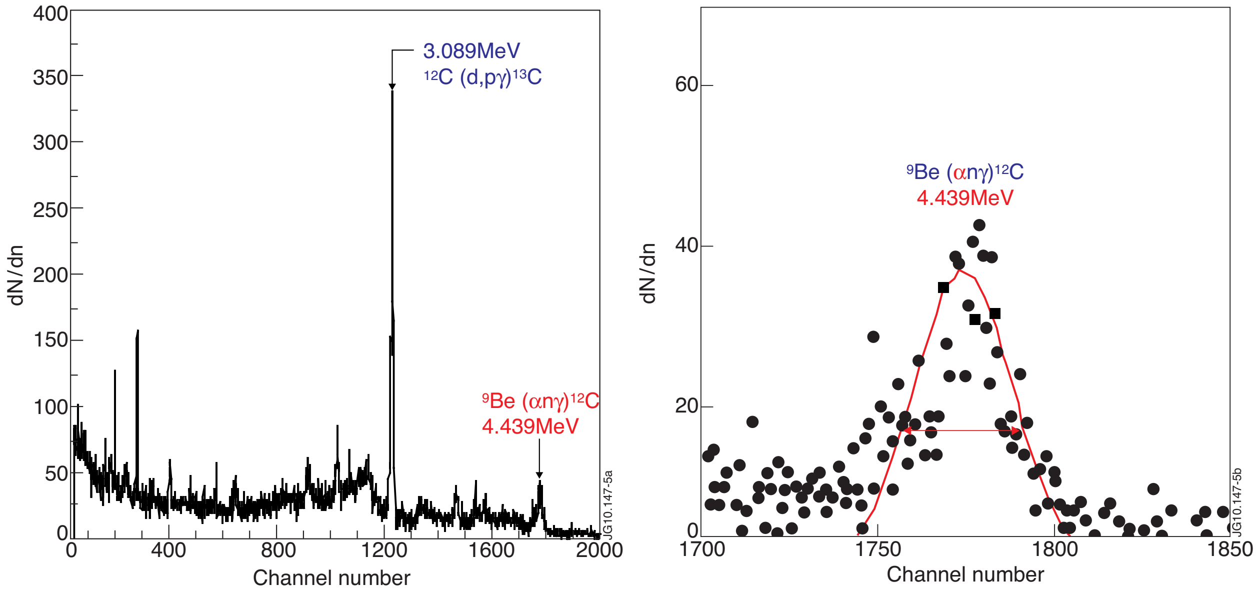

Figure 6: Top: the spectrum measured with a HPGe detector, showing various emitted lines with unprecedented energy resolution. Bottom: the doppler broadening of th 4.439MeV line, corresponding to a temperature of about 200keV

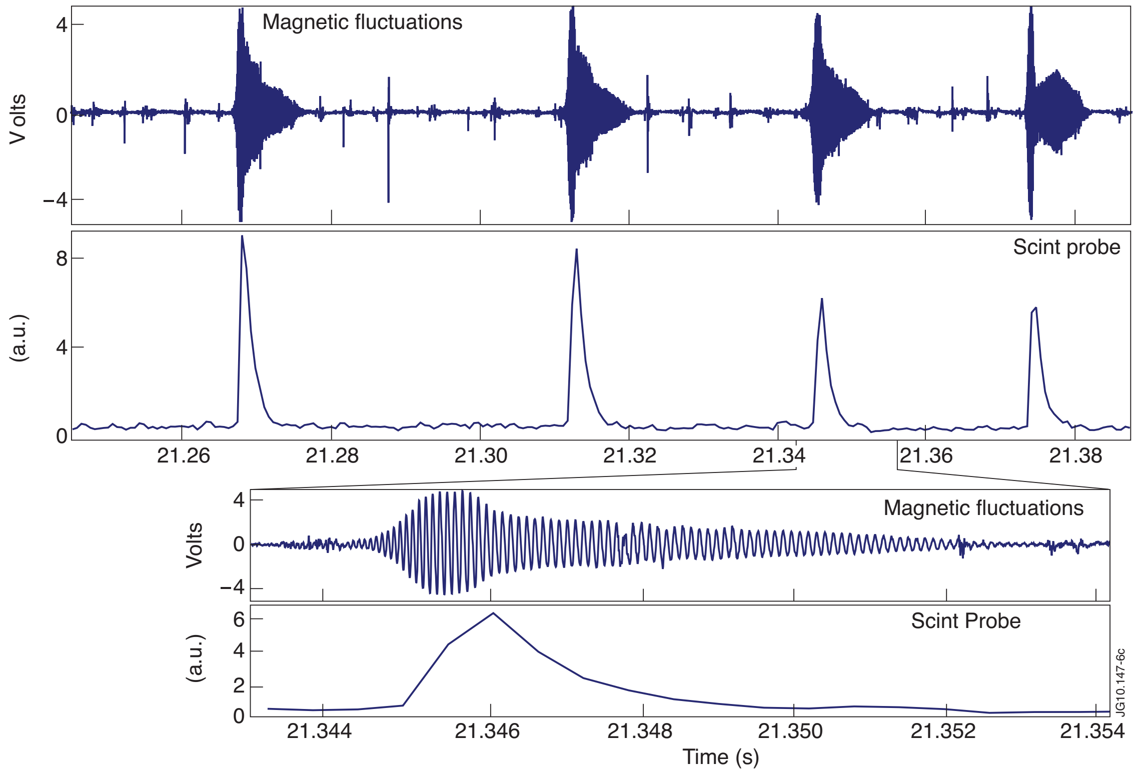

Figure 7: Magnetic fluctuation time trace with four fishbones, together with one of the photomultiplier signals of the scintillator diagnostic. Below expanded view for a single fishbone. After the maximum is reached, the fast ion loss signal is limited by the finite decay time of the scintillator material.

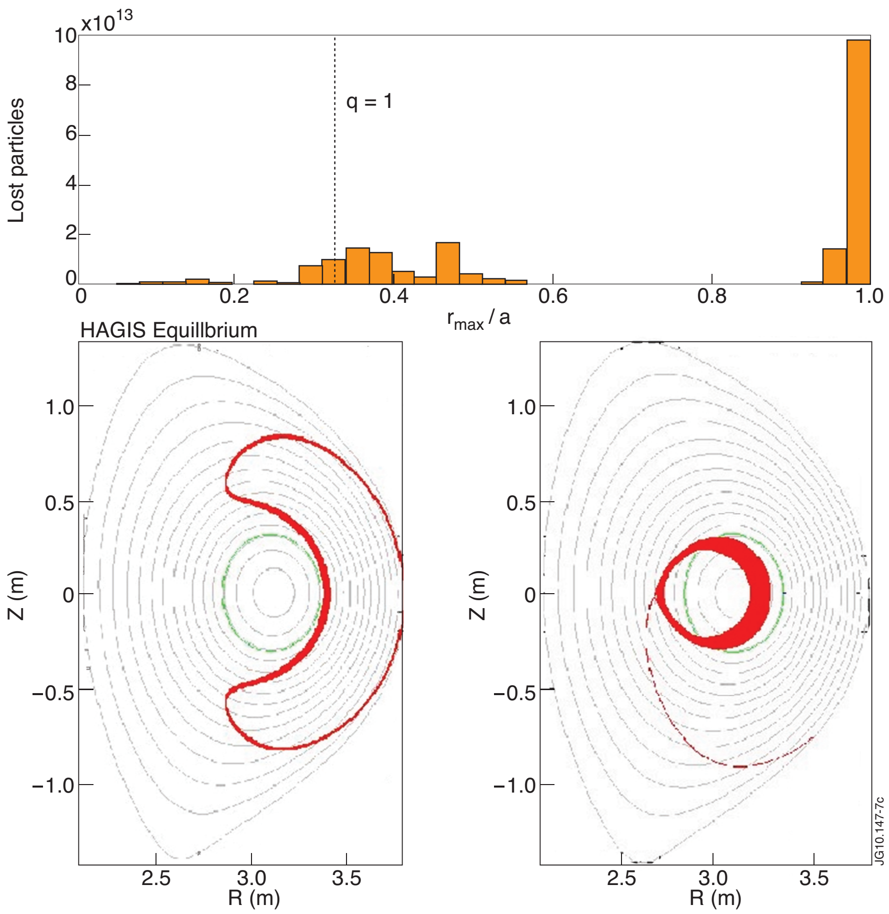

Figure 8: Top: radial origin of the fast particle losses as predicted by the code HAGIS. Middle and bottom: the two types of orbits giving rise to the two peaks in the HAGIS simulations.

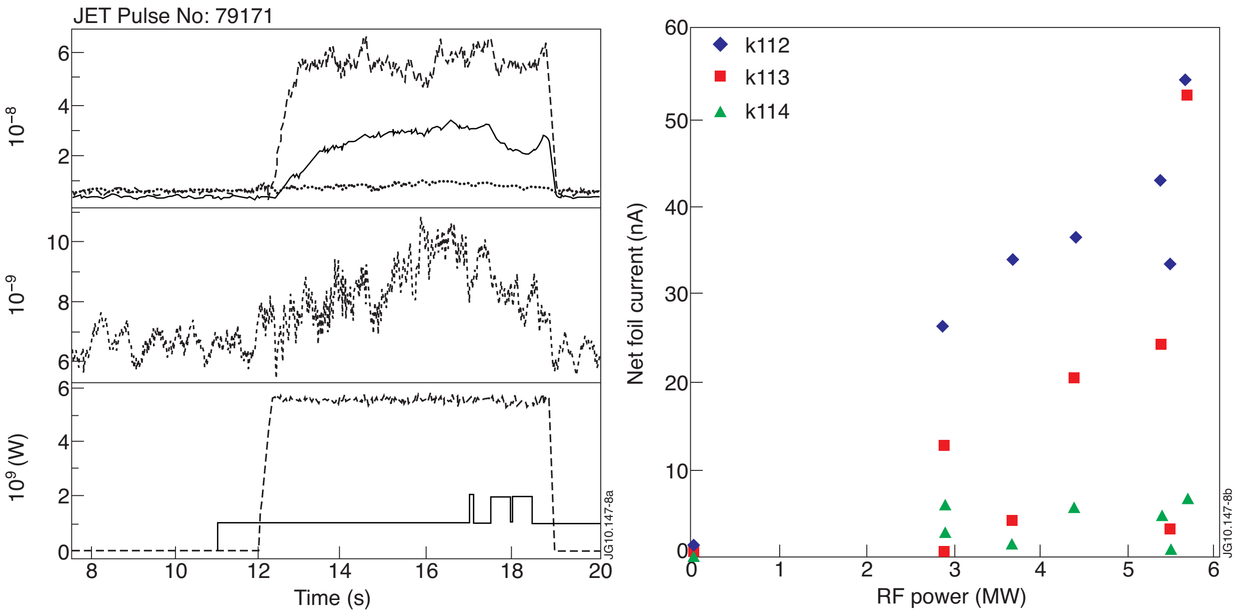

Figure 9: Left: the signals collected by three of the foils of a Faraday cup. The red curve is the measurement of the foil which collects ions in the energy range between 2.3 and 3.7MeV, the blue curve corresponds to the foil collecting ions in the energy range between 4.2 and 5.9MeV, the pink curve corresponds to a foil which can be reached by ions with energy between 6.3 and 7.2MeV. Second plot form the top: a detail of the current generated by the foil corresponding to ions with with energy between 6.3 and 7.2MeV. Third plot form the top: the time evolution of the additional heating power. Right plot. The trend with the RF power of the same foils as in the left plot.