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"Burning Plasma" Diagnostics for the Physics of JET and ITER

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ABSTRACT

JET's recent experimental programme, with its high power and Trace Tritium Experimental (TTE) campaigns, has focused progressively more on producing plasmas of reactor relevance. Such a programme requires major progress in many detection techniques, in particular in the fields of "burning plasma diagnostics" "i.e." neutron, alpha particle, He ash, and Isotopic Composition measurements. In the last years it has emerged very clearly that the diagnostics for these quantities can also provide very useful information about crucial physical aspects of great reactor relevance.

First of all, several burning plasma diagnostics can improve significantly the ***diagnostic capability of the ion fluid***, which is traditionally measured only through its influence on impurities (for example via CXRS, Charge eXchange Recombination Spectroscopy). During TTE spatially resolved neutron measurements at JET were essential in obtaining the isotopic composition and the transport of the hydrogen isotopes, allowing a direct comparison between the measured transport coefficients and the neoclassical theory. The neutron emission profiles can give also crucial indications in assessing the merits of various heating schemes and their current drive capability. Neutron spectroscopy in its turn provides a clear and direct measurement of the temperature and the velocity distribution of the fuel ions. For example, the dependence of the toroidal velocity from the Ion Cyclotron Radio frequency Heating (ICRH) phasing was clearly seen during TTE. The requirements of accurate neutron measurements are also promoting considerable research in detector technology, in particular in the fields of compact spectrometers and solid state detectors.

Burning plasma diagnostics can also strongly contribute to the physics of ***energetic particles*** and their interaction with the main plasma. γ-ray spectroscopy is now an established method to determine the spatial localisation and to visualise the trajectories of the alpha particles and the fast deuterons. During TTE the slowing down of fusion born alphas was measured for the first time with this approach in various plasma configurations. A completely new method to detect the energetic particles, exploiting the line intensity ratio of Extreme UltraViolet (EUV) radiation emitted by suitable extrinsic impurities, is also being pursued. This approach, which could have also application in atmospheric physics, has the potential of providing information on the fast particles and their distribution function in an energy range, below 600keV, extremely interesting for the study of wave-particle interactions.

The operation of JET's "burning plasma" diagnostics can therefore provide essential data for the study of reactor relevant issues and for the design and integration of these measurements in ITER. These diagnostics tend also to promote significant research in various fields, ranging from atomic physics to detector technology, and are susceptible of creating interesting spin-offs.

1. INTRODUCTION

The recent emergence of a fast track approach to fusion has contributed to add emphasis to "burning plasma" issues in the Tokamak community. From an energetic point of view a plasma can be qualified as burning if at least two thirds of its power output is due to fusion reactions and at maximum one third to the power input [1]. This is a quite stringent definition and it will be an essential task of ITER to explore this regime of operation. On the other hand, from a diagnostic point of view, any plasma with a detectable amount of D-T fusion reactions qualifies as burning, in the sense that the main measuring techniques can be applied, tested and provide useful information once the fusion products reach a detectable level. Since the reactivity of D-T reactions is about two orders of magnitude higher than D-D reactions, in the temperature range of interest, a trace amount of tritium in a deuterium plasma is normally more than enough to give considerable scope for operating "burning plasma" diagnostics (see for example the Trace Tritium Experimental campaign TTE at JET in 2003 [2])

On the other hand, the introduction even of trace amount of tritium in high temperature plasmas presents some specific diagnostic challenges. First of all, contrary to the case of pure deuterium plasmas, ***the fuel mixture or isotopic composition***, "i.e." the relative percentage of D and T, must be carefully controlled. This is necessary for ranges of fuel mixtures that can vary from a few per cent of the minority species to a 50/50 mixture. The first case is typical of specific physics experiments aimed at studying the transport of various isotopes, like the Trace Tritium campaign at JET. Fuel compositions with n_T/n_D (where n_T is the particle density of tritium and n_D the particle density of deuterium) of the order of 50%, on the contrary, are meant to maximize the fusion output and therefore correspond to the regimes of the final reactor (JET DTE1 campaign).

Proper detection ***of the fusion products***, the 14MeV neutrons and the alpha particles, is of course of the highest relevance. In addition to being indispensable for regulatory and safety purposes, the fusion products are the final indicator of the reactor relevance of a plasma configuration. In the fusion reactor indeed the alphas are supposed to slow down mainly through collisions with the electrons and keep the plasma hot, while the neutrons are meant to deposit their energy into the blanket, where it would be extracted by the primary fluid to drive the turbines. They therefore constitute the ultimate indicators of the plasma performance.

In the last years, particularly as the result of JET experiments, it has emerged quite clearly that the fusion products can also provide a wealth of information on the physics of reactor relevant plasmas. First of all they constitute extremely good indicators of the additional heating impact on the discharge. Moreover, they can help substantially in the characterization of ***the ion fluid***, which is very difficult to diagnose directly in high temperature plasmas. Indeed, the hydrogen isotopes in fusion plasmas are completely stripped and do not emit a detectable level of line radiation. Therefore the traditional techniques of spectroscopy are not viable except at the very edge were they are extensively used to determine local plasma parameters, like T_e, n_e and the influx of particles from the wall. Active spectroscopy, mainly CXRS, is extremely useful in providing information about the ion fluid but strictly speaking they detect the properties of the plasma impurities. Moreover, the electron fluid surrounding the ions determine the effective refractive index of the medium and therefore other traditional measuring techniques, like interferometry or reflectometry, can probe only the electrons. Also scattering of radiation, another classic tool of experimental physics, is also dominated by the electron contribution. On the other hand ***the neutrons***, being emitted by fusion reactions involving the hydrogen isotopes, are directly linked to the ion fluid and therefore are a direct indicator of the main plasma properties. ***The alpha particles***, and the energetic ions, in their turn, constitute an essential ingredient of reactor grade plasmas in themselves. For $Q=P_{fus}/P_{in}$ of 10 or higher, a regime already attainable in ITER, the pressure of the alphas is considered high enough to trigger many wave particle interactions and fast particle driven instabilities. All these physical phenomena must be studied and carefully kept under control, because they have the potential of reducing the confinement and degrading the plasma performance. Moreover, the alphas, even when properly confined, can induce another significant problem. Once thermalised, if they remain in the plasma, they can dilute the main fluid because they do not participate in the fusion reactions and have to be considered as impurities in this respect. The problem of getting rid of the so-called helium ash remains one of the main issues in the perspective of the reactor. To measure the level of He ash left in the plasma and to determine the fuel mixture, “i.e.” the amount of the various hydrogen isotopes, neutral particles generated by Charge Exchange are particularly helpful, since they can easily escape across the magnetic field.

As far as the structure of the paper is concerned, in the next section, the detection techniques for the neutrons finding application in fusion are briefly reviewed. Energetic particle detection is the subject of section 3. The most recent developments in “burning plasma” diagnostics for the investigation of the ion fluid properties and the fast particle physics are described in sections 4 and 5 respectively. Some further issues, that would be relevant to address in tritium operation, are summarised in the last section.

2. DIAGNOSTIC TECHNIQUES TO DETECT NEUTRONS AND THEIR APPLICABILITY TO FUSION

Since its discovery in 1932 by Chadwick, it was immediately realised that the neutron is a very elusive particle. Being neutral, it is not subject to electromagnetic forces and therefore it interacts with matter only through strong interactions, “i.e.” nuclear reactions, which in general give rise to charged particles. These charged particles deposit their energy in matter through coulomb interactions and are therefore much easier to detect. In general, the strong interactions are either elastic or non elastic. The former produce recoil nuclei, mainly protons in materials containing a high fraction of hydrogen. The inelastic nuclear reactions can involve a variety of nuclear particles in the final state, such as protons, alphas, gamma-rays or heavy fragments, in the case of fission reactions. These phenomena are summarised in figure 1. It should be mentioned that capture events of the type (n.γ) are also important interactions of the neutrons with matter but, since this conversion is not normally used for detection purposes, they are not particularly relevant n the context of the present paper. Moreover, it must be remembered that γ-rays will interact with matter mainly through Compton scattering, generating a shower of successively lower-energy photons and energetic electrons traversing the material. The electrons then dissipate their energy in much the same way as the heavier charged particles, through Coulomb interactions, but having a different mass, they normally produce a signal of a shape different from the one of the neutrons (see later).

2.1. NEUTRON COUNTING

The charged particles, produced by the neutrons interacting with the nuclei in the detector, can be measured exploiting the effects of Coulomb collisions in various materials. In the case of scintillators, the charged particles excite suitable molecules, which relax to the ground state emitting photons, which are normally detected with the help of PhotoMultiplier Tubes (PMT). A sensor of this type extensively used at JET is the NE213 liquid scintillator [3]. In NE213 (and some other scintillating materials) neutrons and gamma rays give rise to photon emissions with quite different time characteristics, thereby producing PMT output pulses of different shapes. This means that Pulse Shape Discrimination (PSD) techniques can be used to distinguish these two types of high energy radiation. Organic scintillators have been used at JET for a long time and they constitute the basic detectors of the neutron cameras [4], which consist of 19 lines of sight of which ten cover the horizontal and nine the vertical plasma cross section. With this configuration of the chords, the spatial resolution of the system in the centre is better than 10 cm. On each line of sight three different detectors are installed: 1) a NE213 liquid scintillator with PSD electronics for simultaneous recording of the 2.5MeV, 14 MeV neutron and γ-ray emission; 2) a BC418 plastic scintillator, quite insensitive to γ-rays with E_γ<10 MeV, for the measurement of 14MeV neutrons only; 3) a CsI(Tl) detector for measuring the hard X-ray and γ emission, in the energy range between 0.2 - 6MeV (the γ rays are induced by fast plasma ions interacting with C and Be impurities: see next section).

In semiconductor devices, the charged particles are converted into electron-hole pairs, which produce detectable currents. In the case of Si diodes, the most wide-spread approach used so far, there are several reactions taking place simultaneously (like $^{28}Si(n,p)^{28}Al$ and others producing alphas). Recently, Carbon Vapour Diamond (CVD) detectors have also been tested successfully for neutron counting. In this case the main conversion reaction is $^{12}C(n,\alpha)^{9}Be$. It is worth mentioning that this material is at least two orders of magnitude more robust to radiation damage than Si diodes and this is the main reason why it is being extensively tested at JET [5]. Since the manufacturing technology of carbon Vapour deposition is becoming increasingly cheaper, this approach looks very promising in the perspective of next step devices like ITER.

After being properly slowed down, neutrons can induce fission reactions in materials like ^{235}U. This effect is exploited, for example, in JET three pairs of fission chambers [6]. They consist of ^{235}U and ^{238}U fission ionisation chambers, with a polyethylene moderator and contained in lead shielded assemblies. They cover a flux range of about ten orders of magnitude with a quite flat efficiency in the energy region relevant for measurements of 2.45 and 14MeV neutrons.

2.2. NEUTRON SPECTROMETRY

In addition to simply counting the amount of emitted neutrons, a wealth of information can be derived by determining also their energy spectra. Neutron spectrometry is one of the most effective methods to diagnose the ion fluid but it requires very sophisticated and complex instrumentation. The three basic approaches to determine the energy spectra of fast neutrons are reported in figure 2.

In the first solution, which is the one most widely used so far, the neutrons coming from the plasma are collimated on a target where they generate recoil protons. Since in head-on collisions the neutrons transfer practically all their energy to the protons, these can in turn be analysed in momentum with a magnetic field and directed onto a linear scintillator array. The proton position histogram is recorded and used to deduce the spectrum of the original neutrons. In the second approach, the neutrons are subjected to two scattering processes, in a first scintillator, which also plays the role of the scatterer, and in a second series of scintillators located on the equal time of flight sphere. The energy of the neutrons is determined by the time of flight between the two detectors as given by the measured time difference between the scintillator pulses generated by recoil protons in detector 1 and detector 2, respectively. A new spectrometer of this type, TOFOR [7], is being installed on JET to measure the spectra of the 2.45MeV neutrons. In the third approach (Fig.2c), a single piece of scintillator plays the role of both converter (scatterer) and detector, increasing the compactness of the device. In this case, the recoil proton can have any energy in the range $0 < Ep < En$ (wher Ep is the nergy of the rcoil proton and En the energy of the original neutron) and extracting neutron energy spectra from such data requires careful prior calibration of the detector and the use of sophisticated unfolding and analysis methods. The use of NE213 liquid scintillators in this application has made significant progress over the last years, employing accelerator-based calibration and data analysis techniques such as Bayesian estimation and maximum entropy regularisation [3]. This approach is presently the subject of intense research.

Up to now, the most successful method to perform neutron spectroscopy in JET has been the proton recoil approach. The diagnostic implementation of this technique is the so-called Magnetic Proton Recoil (MPR) spectrometer, a unique JET diagnostic [8]. Neutrons emitted from the plasma are collimated on a CH_2 target, where elastic collisions on the hydrogen nuclei give rise to recoil protons, which in the selected forward direction have practically the same energy as the incident neutrons. The recoil protons in their turn are momentum analysed in a suitably shaped magnetic field and imaged on a 37-element scintillator array (hodoscope). The information in these time resolved proton position histograms is then used to deduce the spectra of the neutrons emitted by the plasma. During the TTE campaign in 2003, the diagnostic was upgraded to provide the absolute total yield rate. This absolute calibration is based on first principle calculations that take into account all the relevant physical and geometrical characteristics of the diagnostic, from the neutron collimator to the proton detection array. As a result, during TTE the MPR provided for the first time an absolute measurement of the total 14MeV neutron yield, using a profile correction factor derived from the neutron cameras. The MPR estimate was successfully compared with the measurements of the other neutron systems [9], in particular the activation samples (the reference measurement of the total neutron yield since the beginning of JET operations). The exploitation of synergies between different neutron diagnostics is an important new line of development in neutron detection research and could be of great relevance for ITER.

3. DIAGNOSTIC TECHNIQUES TO DETECT ALPHA AND ENERGETIC PARTICLES

The alpha and energetic ions are very difficult to detect in a Tokamak environment even if they are charged particles. This is due to the fact that in general their properties have to be determined while they are still in the plasma and cannot be assessed after they have escaped like the neutrons. Nowadays the most effective way to detect the alphas in JET consists of measuring the γ-ray radiation emitted by nuclear reactions following collisions between impurities and the alphas themselves [10, 11]. The most effective reaction exploited so far is the $^{9}Be(\alpha,n\ \gamma)^{12}C$ between the alphas and the Be intrinsic impurity. The γ line at 4.44MeV emitted by the reaction allows the identification of the particles with energy in excess of about 2MeV. The other most important energetic particles, the deuterons and the ^{3}He accelerated by the radio-frequencies, are detected measuring the γ-rays generated by the reactions $^{12}C(d,p\gamma)^{13}C$ (main emitting line at 3.1 MeV) and the $^{12}C(^{3}He,p\gamma)^{14}N$ (emitting several lines: 2.31MeV, 5.1MeV and others). At JET the most used sensors for the γ-rays are the solid state detectors of the CsI(Tl) or NaI(Tl) type. The high energy photons create electron hole pairs in the conduction band of the crystal. The electrons migrate to the sites occupied by the activator impurity Tl, whose de-excitation generates photons of the right wavelength for detection. Even if γ-ray spectroscopy has been very successful in the last years, the energy of the particles, which can be detected with this approach, must be in excess of 1MeV. This makes the technique an excellent approach to study the first slowing down of the alphas and the effects of the various heating schemes on fast ions. On the other hand the range of energy more interesting from the point of view of fluid effects due to wave particle interactions is estimate to be below 600keV. To attack this weakness of JET diagnostic capability, another more recent approach consists of exploiting the sensitivity of certain atomic transitions to the presence of fast particles in the plasma. Fluorine like configurations of extrinsic impurities like Krypton present levels preferentially populated by collisions with energetic particles. The line ratio between the emission of transition involving these levels and others populated by electron collisions provides a quantity proportional to the plasma fast particle content as shown in figure 3.

This innovative technique, based on atomic physics and requiring accurate measurements in the far and extreme ultraviolet parts of the spectrum, is still in its infancy but significant progress has recently been made. The necessary quantum mechanical cross sections were calculated with the R matrix method for Krypton and therefore the interpretation of some preliminary experiments is advancing quite rapidly. In particular good indications were already obtained, in detecting fast deuterons injected with JET neutral beams. For Krypton a clear dependence of the I_{31}/I_{21} ratio from the neutral beam power (80keV deuterons for a total power of 8MW) was clearly detected as shown in figure 4. The observed trend of the intensity ratio with the neutral beam power is very encouraging and therefore more specific experiments are planned for the following campaigns.

4. “BURNING PLASMA” DIAGNOSTICS FOR THE CHARACTERIZATION OF THE ION FLUID

The neutron emission can provide essential information about the effects of the heating systems on the ion fluid. The location of the maximum absorption of T second harmonic RF heating was clearly identified during TTE [10] with the neutron cameras. The effects of the magnetic topology on the deposition profile of the neutral beam were also investigated again with the same diagnostic. Particular attention was devoted to discharges with a current hole, a region in the core of the plasma with no or negligible toroidal current. In such configurations, the neutron emission is clearly displaced outwards with regard to the same discharge with a monotonic q profile. This is shown in figure 5 for the 14 MeV neutrons in two discharges where T was inserted with neutral beam blips. The line integrals of the neutron cameras were inverted with the help of tomography using the Minimum Fisher Information as regularisation method [12]. These results confirm the reduced confinement of fast particles in configurations with a current hole, as already determined for the thermal born alphas using γ-ray spectroscopy [11].

During TTE, the neutron cameras were the most important tools to perform particle transport studies, the main objective of the entire campaign [2]. The main rationale behind these experiments was the intrinsic ambiguous nature of particle transport in Tokamak plasmas. At steady state indeed it is not possible to deduce a unique value for the transport coefficients D and V, the diffusion coefficient and the pinch velocity, from the usual diagnostic information available. On the other hand, since the presence of tritium into the discharge is emphasised by its high fusion cross section, even a trace amount of T can very easily be detected. This is therefore an ideal tool for particle transport studies, since the transport of T can easily be followed in dynamic conditions measuring the 14MeV neutron emission. Moreover, injection of a trace amount (of the order of 1%) of a hydrogen isotope is certainly not perturbative in JET plasmas. One approach to the data analysis consists of simulating the various lines of sight (for the 14MeV neutrons) using different profiles for the transport coefficients, until a good agreement is found with the experimental measurements. This one dimensional technique was very successful and has allowed to prove for example that the particle transport coefficients come very close to the neoclassical level in the region of ITBs [2]. A different more prototypical method consists of calculating the ratio of the 2.45 and 14MeV emission. In this way the fuel ratio can be deduced directly without relying on the simulation of the absolute measurements [13]. Moreover, in the case of simple T gas puffing, the approach is very robust to errors or inaccuracies in the power deposition profiles of the neutral beam. This is due to the fact that the D-D and D-T reactivities have very similar trends with temperature in the energy range of interest and therefore the errors cancel out when taking the ratio. In JET this method was implemented using tomographic reconstructions of both the 2.45 and the 14MeV emissivities. The ratio of the two tomographic reconstructions was then calculated to obtain the desired 2D spatial distribution of the n_T/n_D ratio. The results, see figure 6, allow to determine the radial evolution of the tritium density in two dimensions and could therefore be of great interest to study more advanced phenomena. In full D-T operation it is considered practically impossible to perform measurements of the 2.45MeV neutrons, due to the excessive numebr of D-T ones. To determine tha isotopic composition inn such consitions different techniques have to be considered. Plasma ions can escape the plasma after charge exchange recombination with neutrals, injected with the neutral beams for example. Neutral particle analysis is indeed being developed at JET for this purpose but the results during TTE were not particulalry positive, mainly due to excessive neutron background noise. Various solutions to improve the hardwar are therefore under consideratiion ad will probably be implemented in the near future.

Neutron spectrometry proved already in the nineties a great potential in determining the kinetic parameters of the fuel ion populations, such as temperature and relative fraction of thermal and supra-thermal components. These quantities were routinely measured with the MPR during the DTE1 campaign in 1997 [8] and this remains today the unique diagnostic capable of giving a direct experimental estimate of the thermal yield and it is therefore essential in the calculation of Q_{therm}. (defined as $P_{out\ thermal}$ /P_{input}). During TTE the emphasis was more on the physical studies and in particular the assessment of collective states of the fuel ions, such as toroidal rotation. The effects of different phasing of the ICRH on the toroidal velocity of the fast ion components was clearly detected as shown in figure 7 [14]. This result emphasises the potential of the MPR and of neutron spectroscopy in general to provide useful information on the ion fluid and the physics of the various additional heating schemes.

5. "BURNING PLASMA" DIAGNOSTICS FOR FAST PARTICLE PHYSICS

The developments of γ-ray spectroscopy allowed to determine the slowing down and confinement of the thermal born D-T alphas during the TTE campaign [10, 11]. The technique is now routinely used in RF heated discharges to determine the power deposition and the spatial distribution of the accelerated particles. A significant recent development is the ability to discriminate the various ion species, like D, alphas and ^{3}He ions, in the same discharges. The visualisation of the fast particle trajectories, obtained with tomographic inversions and confirmed by various simulations as indicated in figure 8, renders this method a very interesting diagnostic tools also for benchmarking theoretical and computational models. In particular the effects on the fast ions of the various heating schemes and/or the magnetic topology can clearly be identified.

A refinement of the data analysis consists of trying to determine the radial dependence of the confinement time of the fast particles. This can be achieved by measuring the γ-ray decay time for each line of sight of JET cameras during notches in the ICRH heating ("i.e." short intervals in which the additional heating is switched off or strongly reduced). From that it is possible to derive an estimate of the slowing down time and therefore obtain indications on the confinement of the energetic ions in the various radial regions of parts of the plasma column. An example of such an approach is reported in figure 9 where the decay time of the 3.1MeV line of the $^{12}C(d,p\gamma)^{13}C$ reaction is plotted versus the channel number. In figure 9 the dashed lines are the results of very preliminary calculations obtained assuming classical slowing down of the particles. Moreover, average values for the temperatures were used and therefore the effects due to the actual orbits are not properly modelled. In any case, even if the data analysis is still at a preliminary level, these preliminary results indicate that these measurements should allow investigation of the alpha particle confinement dependence from the radial position.

A different and complementary approach to detect the as and the fast ions consists of determining their interactions with the Magneto-Hydro-Dynamic (MHD) modes. The use of the so-called MHD spectroscopy technique [15] has been demonstrated on the JET tokamak as a diagnostic tool to add information on various properties of the bulk and supra-thermal plasma components [16]. This approach relies on the excitation of collective modes, either by fasts ions (passive diagnostic) or by in-vessel antennas (active diagnostic). Alfvén Eigenmodes (AEs) [17] are the collective modes best suited for this diagnostic use for the bulk plasma and the fast ion populations, since these modes are weakly damped and their frequency range is free of incoherent fluctuations. Information on the bulk plasma can be extracted from the measurement of the AE frequency and mode numbers. By comparing the calculated AE spectrum with that actively driven by antennas for low-n modes, the reconstruction of the core q-profile and of the edge density profile can be improved [18]. Similarly, by analysing the fast ion driven AlfvÈn Cascades [19] in advanced scenarios, the time evolution of the minimum in the non-monotonic q-profile can be inferred. The plasma toroidal rotation at the mode radial location can be determined by the Doppler shift in the frequency of fast-ion driven AEs [20]. Finally, the plasma effective mass, hence the DT concentration, can be inferred from the frequency of antenna-driven AEs in plasmas with similar equilibrium (density, current) profiles.The AE stability limits, and their onset/disappearance as the plasma evolves, provide information on the energy and spatial distribution of the fast ion population. The presence of unstable AEs at different radial locations provides lower limits in the local energy of the fast ions and allows inferring the fast ion pressure gradient. Moreover, when the onset/disappearance of AEs at different radial locations can be correlated to other plasma instabilities such as sawteeth or error field modes, information on the radial redistribution of the fast ions can also be obtained. Finally, the details of the AE spectrum in the nonlinear stage can be used to gain insights into the fast particle velocity space diffusion. Both active and passive MHD spectroscopy could be used in future burning plasma experiments, such as ITER. Whereas the previous JET results using the active diagnostic technique have been obtained for low-n (n = 1,2) AEs, in ITER the most relevant range of n’s is predicted to be around n = 5-10. Hence, to test the possibility of exciting and detecting AEs with such intermediate mode numbers using small in-vessel antennas, and their possible application as an active diagnostic tool, a new set of dedicated AE antennas has been designed and is being installed on JET [21,22].

6. FUTURE PROSPECTS

Notwithstanding its importance in the reactor perspective, the experience in “burning plasma” operation is quite limited in the community. In the history of magnetic fusion only four campaigns with tritium were ever performed (three at JET and one at TFTR) and nowadays JET is the only device left with tritium handling capability. This relative lack of experiments is reflected in the weakness of various diagnostic solutions, which are not completely mature for ITER yet. Moreover, in the last years and in particular as a consequence of the TTE campaign, it has become more evident that tritium operation can help clarifying interesting physical issues even in experiments with reduced neutron fluxes. Additional tritium operation could provide very useful additional knowledge of reactor relevance in at least three major directions: a) physical issue b) diagnostic techniques and c) technology. With regard to the physics some recent plasma scenarios should be qualified for ITER in D-T operation, as was the case of the Elmy H mode in DTE1. Not only the hybrid and the advanced scenarios, but also high triangularity ITER like shapes with type III ELMs could be tested and their isotopic dependence studied before exporting them to ITER. Some new aspects of confinement scaling, like for example the more favourable β_N dependence emerged recently from a more sophisticated analysis of the international data base [23, 24], would require confirmation in D-T. Even in the field of additional heating, tritium operation could provide further interesting information. Second harmonic heating of tritium, one of the main additional heating schemes in ITER, could be studied in JET in 100 % tritium discharges. Switching to the issue of diagnostics, several concepts would require more investigation before being completely validated for ITER. Completely consolidated techniques are still lacking for important parameters like the He ash and the fuel mixture. An advanced technique, fast wave reflectometry, is indeed being considered to complement JET present diagnostic capability in this direction. γ-ray and XUV spectroscopy would require further work to identify the best solution for ITER to measure the slowing down alpha particles. Another advanced diagnostic, collective scattering, would also require validation before final implementation in ITER. With regard to the neutrons, even if a series of techniques and methods are quite well established, the absolute calibration remains an issue for ITER. The neutrons, in particularly the 14MeV ones due to D-T reactions, constitute also the main motivation behind various technological developments. The effects on cables, fibre optics and detectors, like bolometers and pressure gauges, are still under investigation to guarantee solution of enough life time in the high fluences of next generation machines.

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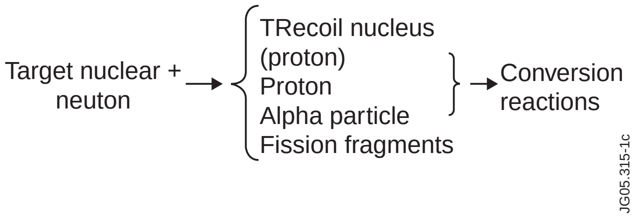

Figure 1: The charged particles produced by interactions between neutrons and nuclei. The strong forces can be either elastic or inelastic.

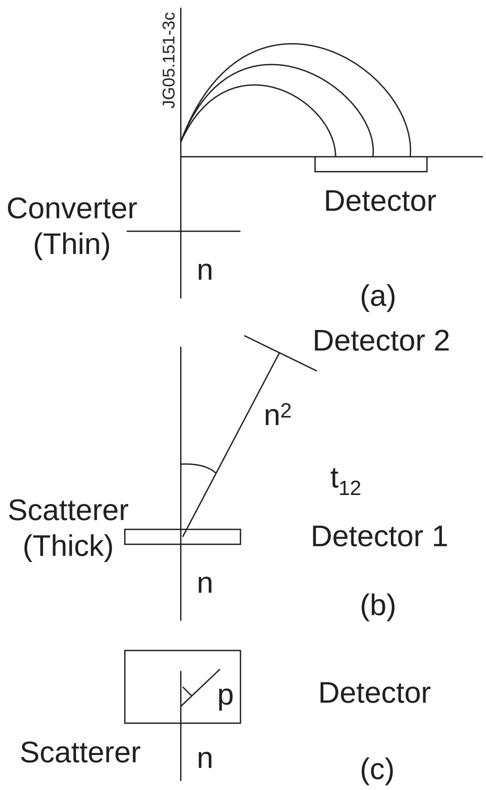

Figure 2: Different approaches to neutron spectrometry

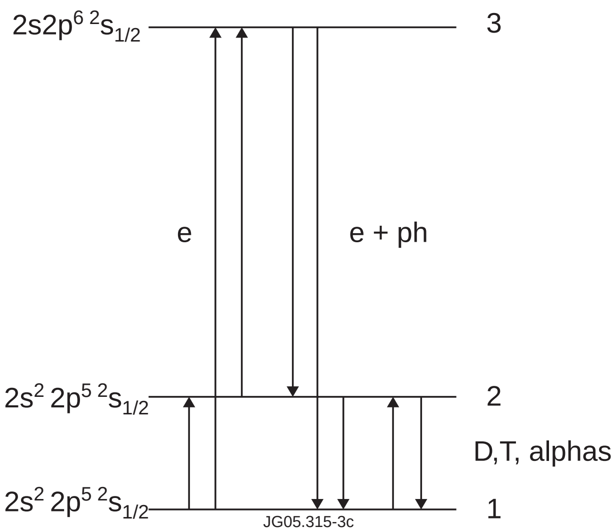

Figure 3: Line ratio method to detect the presence of fast particles, with energies of hundreds of keV, in the plasma. The 2-1 transition is the one most sensitive to the presence of energetic particles.

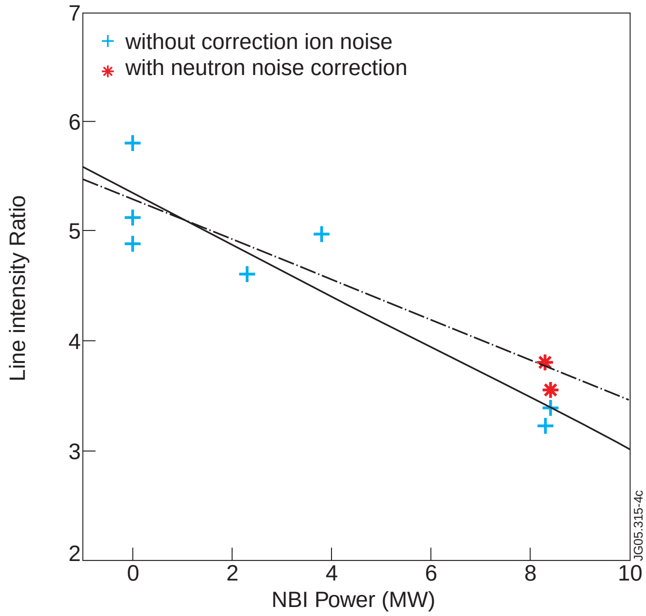

Figure 4: Line ratio dependence from the neutral deuterium beam power. The lines measured are the ones specified in figure 3 for Krypton.

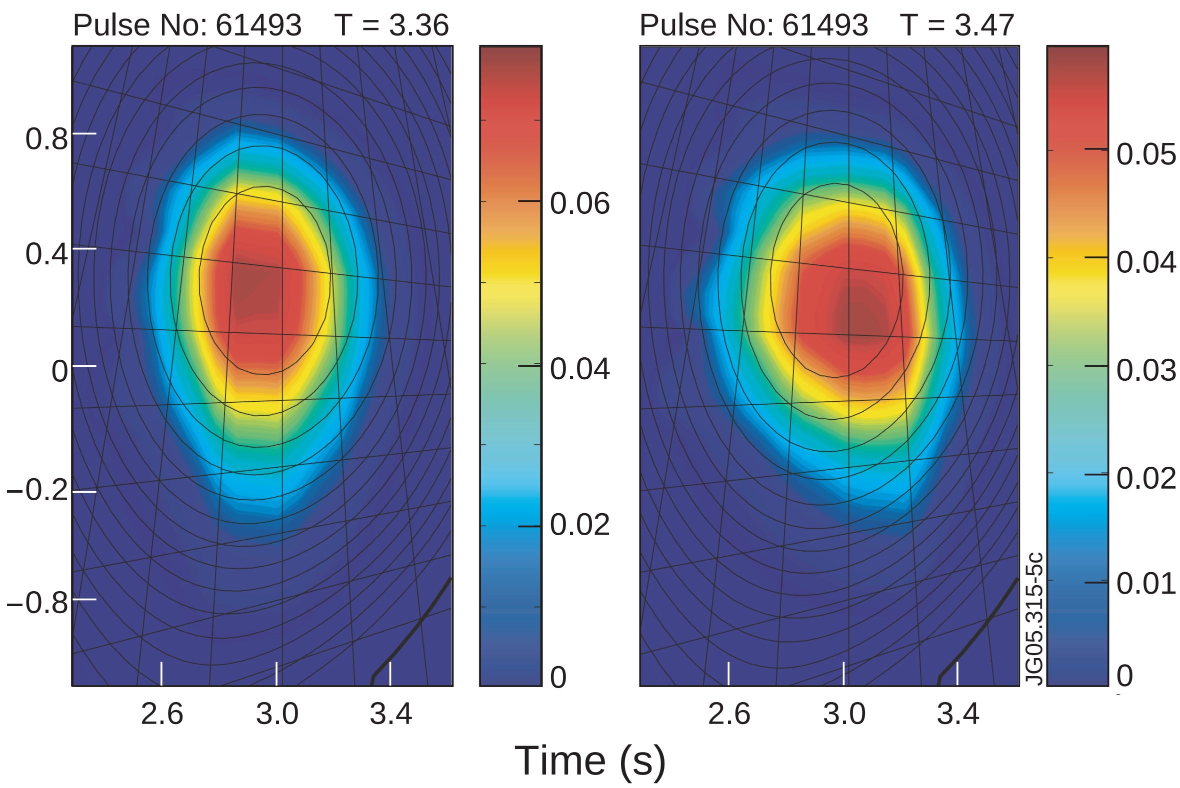

Figure 5: 14 MeV neutron emission for a discharge with a monotonic q profile (left) and one similar but with a current hole (right).

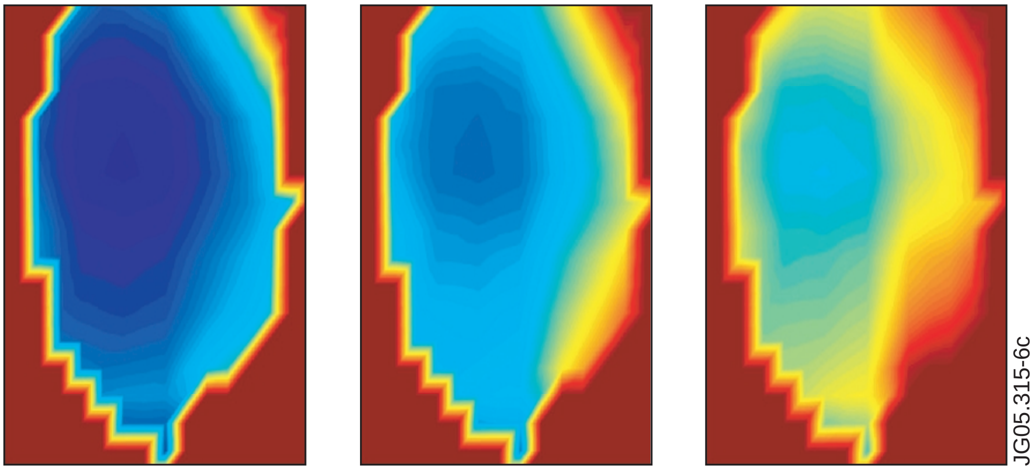

Figure 6: Time evolution of 2D fuel mixture spatial distribution obtained with the ratio method using tomographic reconstructions of the neutron camera signals. The progressive diffusion of the tritium inside the plasma is clearly detected and visualised.

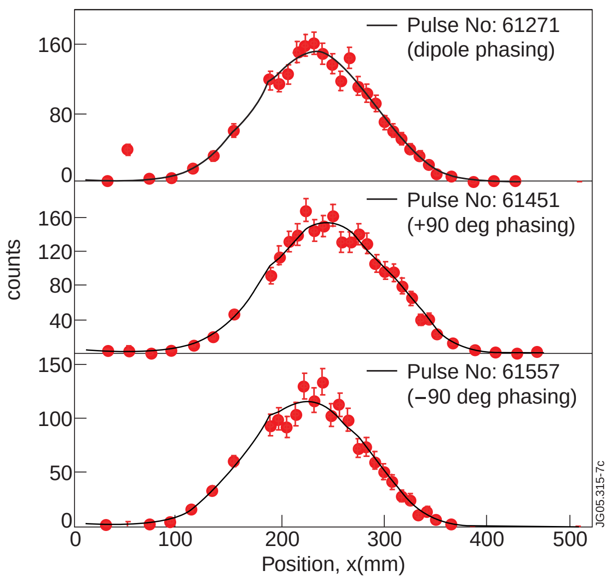

Figure 7: Dependence of the toroidal velocity of the fast ion population from the phasing (+ 90 degrees –90 degrees) of the ICRH power.

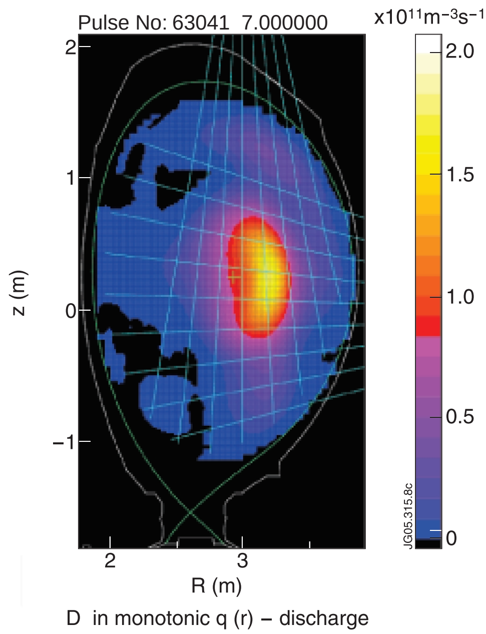

Figure 8: Comparison of the γ-ray emission topology and the simulation of fast particle trajectories for various ion species.

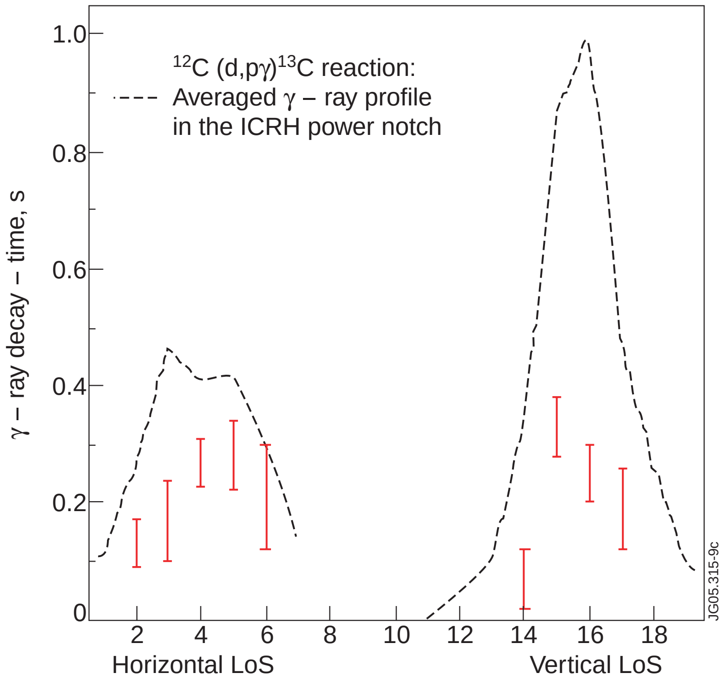

Figure 9: Relaxation time profiles of 3.1 MeV γ-rays during an ICRH notch. The fast particles detected are the fast deuterons. The centre of the plasma corresponds to channels 4 and 16 approximately. The blue dotted line represents the result expected in the case of classical slowing down of the fat deuterons. The red points are the experimental measurements with their error bars.