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ROLE OF FUSION PRODUCT MEASUREMENTS IN PHYSICS UNDERSTANDING OF A BURNING PLASMA

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ABSTRACT

The roles of fusion products in diagnosing plasmas are quite diversified and rich in scientific content. From the early days to the new frontier of burning plasmas, the study of fusion products has allowed a deeper understanding of the physics found in these plasmas, spanning all configurations, in both magnetic and inertial confinement. In many early experiments, the measurement of plasma performance was based almost entirely on neutron yield measurements. Since then, the capability to measure fusion products has grown tremendously, and many new measuring techniques have been successfully tested and used in experiments. The first role is based on single-particle diagnosis, which can yield important information on performance, confinement, source and current profiles, plasma fluctuations, effects of ripples, MHD mode structure, *etc*. The second role, which has expanded tremendously in the last few years, includes the diagnosis of collective effects, which can yield additional information on instabilities, heating, and many others. This scientific capability is enhanced by the large number of fusion products (neutrons, charged particles, gammas) generated by the primary or secondary fusion processes such as the commonly studied, D+D, D+T and D+^{3}He reactions. This paper will review the applications of fusion product measurements used in the scientific study of plasma confinement and stability, and will describe the prospects and opportunities offered in burning plasma experiments such as ITER.

1. INTRODUCTION

The worldwide research effort in developing nuclear fusion as a viable source of energy has generated many exciting discoveries over the years. That excitement and everlasting hope for success could be, arguably, partly attributed to the fact that in virtually all magnetically confined fusion plasma experiments a sizable (but not yet sufficient) number of fusion events could be witnessed and measured. In early experiments, when deuterium was used as a fuel, production of fusion yields were in excess of 10^{10} events/sec- a staggering number by itself- while remaining well short of the $>\sim10^{20}$ events/sec required for a sustainable burning plasma reactor. While the measurement of fusion yields by nuclear detection (*e.g.*, total neutron production) has always played a fundamental role in measuring the plasma performance, the field has grown into developing numerous techniques based on fusion products as a way to diagnostic many key plasma parameters.

The achievement of a sustained, fusion reactor will require two significant steps to be fulfilled for which fusion products (FP) diagnosis can be key in their optimization and realization. First, sufficient plasma densities and temperatures have to be achieved in order to produce a sufficient number of fusion reactions. Second, in order to enable a self-heated plasma, the charged fusion products (*e.g.*, alpha particles) must be confined long enough to deposit their energy back to the plasma. These conditions thus require a careful analysis and diagnosis of production, transport, stability and heating of fast ions in the plasma, together with a proper monitoring of first wall components to avoid any short term material deterioration (*e.g.*, first wall damage).

This paper aims at reviewing and illustrating some key roles of diagnostic measurements based on fusion products detection.

2. FUSION REACTIONS

It is first important and interesting to review the basic and advanced fusion reactions relevant to magnetically confined plasmas. The steady progress in magnetic confinement experiments has allowed the study of fusion products from a number of reactions including:

$$D + D \rightarrow {}^{3}\text{He (0.8 MeV)} + n \text{ (2.45 MeV)}$$
$$D + D \rightarrow T \text{ (1 MeV)} + p \text{ (3 MeV)}$$
$$D + T \rightarrow \alpha \text{ (3.5 MeV)} + n \text{ (14.1 MeV)}$$
$$T + T \rightarrow \alpha + 2n \text{ (total of 11.3 MeV)}$$

These basic reactions have been observed, and verified experimentally in many experimental devices. However, with new and planned experiments, conditions are now approaching burning plasma conditions for which the following aneutronic reactions are also becoming of interest.

$$D + {}^{3}\text{He} \rightarrow \alpha \text{ (3.6 MeV)} + p \text{ (14.7 MeV)}$$
$$p + {}^{11}\text{B} \rightarrow 3a \text{ (total of 8.7 MeV)}$$

Interestingly enough, the conditions found in a burning plasma experiment could approach the fusion conditions found in stars and help in verifying experimentally many of the conjectured reactions expected in stellar cores.

2.1. STUDY OF CONFINEMENT PROPERTIES FOR FUSION PRODUCTION OPTIMIZATION

Fusion product measurements made on early tokamaks and other confinement devices were based on the detection of the 2.45 MeV neutron. They showed the key importance of making accurate measurements in fusion performance, in part in trying to elucidate the reasons for the observed anomalous transport of heat and particles. At the same time, initial measurements were performed to determine the fusion yield of the D+^{3}He reaction, an aneutronic reaction, based on the direct collection of the 14.7 MeV proton product [1].

Later on, the fusion yield measurements, coupled to increasingly detailed determination of basic parameters such as electron density and temperature, enabled the study of the ion dynamics. An example of this application can be found from the Alcator C-Mod tokamak where the ion temperature is determined from the measurement of the total neutron yield. In this particular case the information is also used to study the effects of the formation of an internal transport barrier on the main ion dynamics [2]. In many other applications or experiments, the inverse process has been applied. Modeling of the transport mechanisms, and derived profiles are constrained by the total measured neutron production (and/or profile).

One of the key measurements in diagnosing conditions necessary for optimal fusion production resides in the ability to resolve the source profile. This is usually accomplished by fielding many neutron detectors arranged in a fanning or parallel array. Examples of such systems have been fielded on TFTR [4], JET [7] and JT-60U [8]. They usually require considerable amount of shielding and an elaborate calibration process. Common results obtained from source profile measurements indicate a peaked emission centered and symmetric about the magnetic axis, as one would expect from simple confinement following flux surfaces. This would also imply a relatively isotropic and symmetric distribution of ions. Shown in Fig. 1 is an example of source profile measurements done on TFTR [4] in deuterium only plasma, in which the 2.45 MeV and 14.1 MeV neutrons were resolved. Source profile and subsequent energetic ion confinement can thus be inferred using the shape and magnitude of the emission.

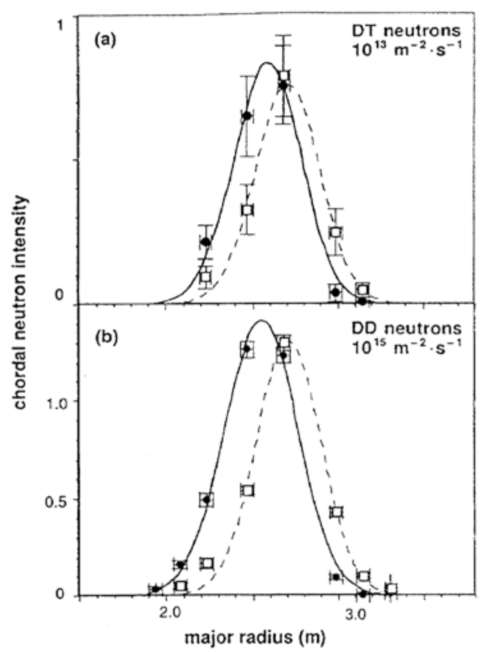

Fig. 1. Neutron profiles of (a) DT and (b) DD for two plasmas with different major radii on TFTR (in deuterium fill only). Solid line/circles are for plasma major radius of 2.45 m and dashed line/squares for 2.57 m plasma major radius. [Reprinted J.D. Strachan *et al.*, *Nucl. Fusion* **36**, 1189 (1996).]

In experiments where confinement and performance are sufficiently high, such as JET, TFTR and JT-60U, for example, measuring burnup as a tool to study energetic particle confinement have been quite illuminating. Burnup is defined as the fusion reaction in which a product of a primary reaction (*e.g.*, T, or ^{3}He from the DD reaction) becomes a reactant in the secondary reaction (*e.g.*, DT or D^{3}He). Initial measurements on TFTR using neutron activation techniques (from the 14.7 MeV neutrons) have shown a less than classical confinement of energetic ions [3]. However, later measurement using the TFTR neutron collimator [4] and activation measurements done at JET [5] and JT-60U [6] have shown much closer agreement with classical confinement.

However, an increasing number of deviations from centered and poloidally symmetric profiles have been observed, notably on JET, which are more readily resolvable given the 2-D tomographic capability of that system. In some instances, discharges with non-monotonic current profiles, such as current holes [9] showed a shift of the emission to the low field side, as illustrated in Fig. 2. Others, including rf heating schemes with tritium indicated a shift to the high field side [9]. Other techniques, based on the 2-D gamma ray detection following a secondary fusion reaction of high energy deuterium or alpha particles also showed unusual 2-D emission profiles which may be attributed to the generation, confinement (orbits) of these high energy particles [10]. These observations would support the need for the fielding of a 2-D tomographic system, even with partial coverage, in ITER, enabling increasing ability to optimize the main ion heating, stability and alpha heating in advanced scenarios, for example.

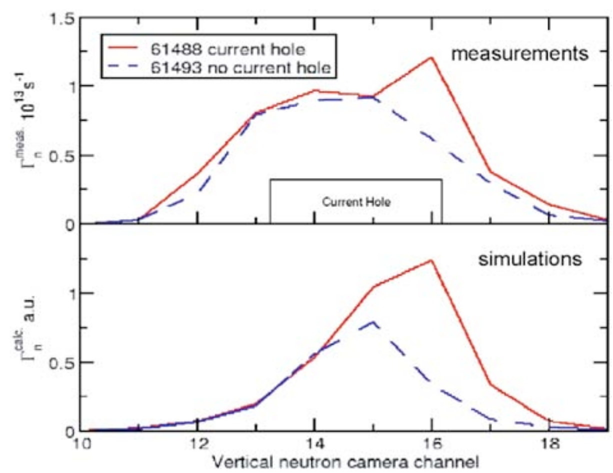

Fig. 2. Comparison of 14 MeV neutron profile for on-axis tritium beams (measurements – top box, simulation – bottom box) as measured on JET. An outward displacement of the neutron emission profile is clearly detectable with plasma with current hole (continuous line) (current hole shown in the inset – top box). Channel 15 corresponds to the magnetic axis. [Reprinted from A. Murari *et al.*, *Nucl. Fusion* **45**, S195 (2005).]

In addition, much information can also be gathered by measuring the energy spectrum of the produced neutrons. Finite temperature of the main ions (D, T, *etc.*) would manifest itself by a broadening of the neutron energy spectrum around the center-of-mass birth energy (2.45 MeV in D-D and 14.1 MeV in D-T). Furthermore, the presence of a separate energetic ion population (neutral beam ions, RF tail ions) would bring indicative wings to the spectrum. The full spectrum is dependent of the viewing angle of the detectors with respect to the plasma, in accordance with the pitch angle dependence of the fast ion population and the angular dependence of the fusion cross-section [11]. This information, usually unfolded by modeling, can be important in understanding the role of the different heating mechanisms and of transport on various classes of ions.

2.2. STUDY OF CONFINEMENT PROPERTIES FOR ALPHA HEATING OPTIMIZATION

In seeking to reach conditions where burning plasmas can be sustained, it is important to study and characterize the confinement of energetic ions, such as the alpha particles produced in the DT reaction. However, since the production of a sufficient population of alpha particles (*e.g.*, in DT) is limited to TFTR and JET, it has long been realized that the 3 MeV proton and the 1 MeV triton, produced in one of the DD fusion branches, should possess very similar single particle behavior, since both gyroradius and slowing down time are very similar to the 3.5 MeV α. Collective effects, the effects of the fusion products as a sufficiently large population, can only be studied when they (or equivalent energetic ions) are in sufficient number to affect the plasma stability and/or confinement.

In the attempt to understand their behavior, new techniques were developed to study directly the confinement of charged fusion products (CFPs) (including energetic ions such as beam and RF tail ions) primarily through the measurement of particle flux to the first wall. The most comprehensive system has been fielded on TFTR using poloidally and toroidally displaced probes, fixed to the first wall, plus a radially scannable probe from the outer midplane [12,13]. With this system, the escaping flux is resolved in time, energy and pitch angle (angle sustained by the particle along the local magnetic field), allowing a full mapping of the particle orbits in physical and phase space. This technique has also been extended to other facilities.

In plasma conditions where the single particle confinement of energetic ions (*e.g.*, first-orbit) is partial, where passing particles are normally confined but not necessarily for all trapped particles, the diagnosis of escaping (*e.g.*, lost) flux can be extremely powerful to identify and quantify anomalous loss or diffusive mechanisms. The first group of diffusion or loss processes include deviations from non-asymmetric conditions which are externally imposed, such as the TF ripple, error fields or possibly resonant magnetic perturbations [more recently used for edge localized mode (ELM) control]. The potency of ripple diffusion, either through stochastic ripple diffusion or trapping has been long established and verified experimentally [14], see for example Fig. 3. The second group includes non-axisymmetric effects internally produced such as MHD activity [such as neoclassical tearing mode (NTM), fishbones, sawteeth, and others]. This group also includes Alfvén eigenmode activity, a category of modes which has the critical particularity of being driven by energetic ions which in turn can lead in their expulsion or loss. Such activity is a good example of collective effects. In presence of MHD activity the CFPs (and other energetic particles) which possess very high velocities (and short transit times), usually sample a “frozen” perturbed magnetic equilibrium and experience additional transport, especially when the mode is particularly strong and perturbations large compared to the particle's gyroradius or orbit shift.

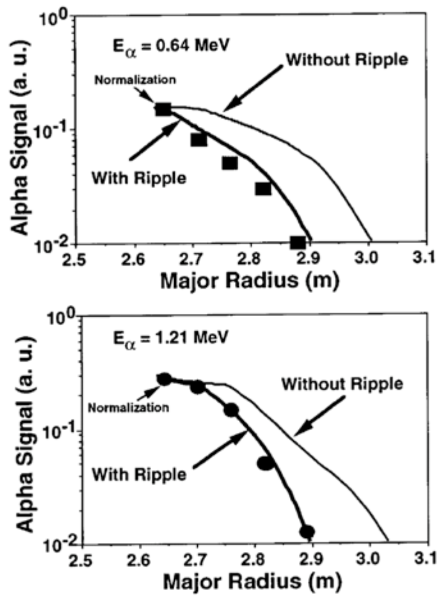

Fig. 3. Measurements of DT α populations as a function of major radius and energy in TFTR. The PCX measured radial profiles (left) agree well with modeling which includes stochastic ripple diffusion. The PCX measured alpha spectrum (right) shows a classic thermalization of alpha particles in the core of MHD quiescent discharges. [Reprinted from S.S. Medley *et al.*, *Nucl. Fusion* **38**, 1283 (1998).

A third category of perturbations, micro-turbulence, also internal in nature, has the potential for increased transport, in a process similar to the anomalous transport observed for thermal ions. However, experiments done on TFTR [15] has shown that this mechanism be largely inoperative for CFPs, an indication that large gyroradii particles (*i.e.*, CFPs) may be unaffected through averaging of micro-turbulence over a gyroradius and gyroperiod.

Similar measurements of fast ion loss to the first wall will be more difficult in burning plasma experiments. The current profile and plasma size will prevent any first-orbit losses to the first wall of particles originating from the plasma core. To the first order, this means that any CFP transport mechanism acting on energetic particles will not be immediately visible on the first-wall. Since energetic particles drift away from a magnetic flux surface primarily in the toroidal direction, they will approach the outer wall surface very gradually (toroidal drift » poloidal drift » radial drift). They are likely to impact a leading edge (if present) located on the outer wall, urging the need for a complete IR camera coverage of the outer wall surface of a burning plasma experiment. Any direct detection and identification of lost particles will consequently be quite arduous, since the sensor would be required to be located very near the surface. In addition, broad trenches would be required to be cut in the blankets to allow escaping particle flux to reach the sensor. Similar arrangements were made necessary on TFTR as shown in Ref. [14]. The direct detection of ripple trapped losses has the opposite problem that the drifts are predominantly vertical and that for all purposes, a sensor would shadow itself (when including shielding and casing).

On the other hand, the measurement of confined CFP populations serves more than to validate, complement or replace loss measurements as described above. The primary goal of such measurement will reside in its ability to diagnose the temporal, spatial and phase space distribution of CFPs (*e.g.*, alphas) and their role in self-heating (deposit their full energy back to the plasma). The spatial and phase space (velocity distribution) information is important in understanding the drive mechanism of Alfvén eigenmode activity and in turn, how such activity affects the energetic ions themselves. Monitoring of the slowed down alpha particle population (also known as helium ash) is also a critical aspect in preventing large accumulation in the core, which would dilute the fuel and affect burning conditions.

A variety of techniques have been proposed and tested. They include spectroscopic techniques, such as alpha-CHERS [16]. A second category is based on scattering techniques, which at small angles, uses laser probing [17] or at large angles, microwaves [18]. Other techniques are based on nuclear detection of fuel ion fusion accelerated in the knock-on process [19]. Another category includes neutral particle detection [20], using neutral beams or pellet injection as a source of neutrals. An example of its application on TFTR is shown in Fig. 3. In this case, lithium pellets were injected neutralizing alpha particles which were then detected outside the torus. Energy and spatial distributions were obtained showing classical confinement, with TF ripple effects taken in account.

3. APPLICATIONS TO ITER

In ITER, a series of diagnostics are proposed for the measurements of fusion products. The selection of measurements and associated techniques corresponds to carefully studied requirements for control and physics understanding, coupled to severe space and environmental (*e.g.*, radiation) constraints [21,22]. The techniques proposed and their role is summarized in Table 1.

Table 1
Roles of Fusion Products Measurements, their Corresponding Measurement and Proposed Techniques for ITER [21,22].

Role	Parameter Measured	Proposed Technique
Fusion power	Neutron yield	Fission chambers (external and internal)
Alpha source profile	Neutron emission profile	Radial and vertical neutron cameras
Ion temperature	Neutron emission profile and spectrum	Radial and vertical neutron cameras, spectrometers
Isotopic ratio (n_D/n_T)	2.45 and 14.1 MeV neutron flux, energy spectrum	Neutron spectrometer
Loss of alpha particles	Heat flux to first wall	Infra-red cameras
Confinement of energetic particles (incl. alphas)	Energetic ion distribution function	Collective Thomson scattering
	Energy resolved Gamma emission profiles	Gamma cameras and spectrometer
	Ion knock-on tail (through neutron emission)	High energy neutron spectrometer

4. SUMMARY

With their ability to diagnose key features of burning plasmas, and because of their inherent compatibility with the environment (although some techniques are not), fusion product measurements are a fundamental part of the diagnostic set required for the optimization and viability of magnetically confined fusion reactors. Overall, measurements based on neutron and gamma emission are crucial in understanding and diagnosing conditions leading to optimal fusion production. When these measurements include profile and energy distribution, one can infer and optimize the composition, distribution and population of thermal and energetic ions.

Measurements based on the detection of confined charged fusion products (CFPs) are critical in diagnosing their important role in self-heating (through alpha particles for example). In addition to profile and energy distributions a key element of information is their phase space distribution, which influences the stability of the plasma and their sensitivity to loss mechanisms, either internally or externally driven. In addition, the detection techniques are sufficiently broad to include also the study of the confinement of the energetic fuel ions, which contribute significantly in the expected fusion production.

Finally, it is expected that the conditions expected on a DEMO reactor will require a reduced set of diagnostics, including fusion product measurements, while taking additional duties related to burn control. This set of diagnostics will require a dedicated vetting process on burning plasma experiments such as ITER.

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REFERENCES

1. W. W. Heidbrink, *Nucl. Fusion* **24**, 636 (1984).
2. C. L. Fiore *et al.*, *Phys. Plasmas* **8**, 2023 (2001).
3. C. W. Barnes *et al.*, *Nucl. Fusion* **38**, 597 (1998).
4. J. D. Strachan *et al.*, *Nucl. Fusion* **36**, 1189 (1996).
5. S. Conroy *et al.*, *Nucl. Fusion* **28**, 2127 (1988).
6. T. Nishitani *et al.*, *Plasma Phys. Contr. Fusion* **38**, 355 (1996).
7. J. M. Adams *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **239**, 277 (1993).
8. M. Ishikawa *et al.*, *Rev. Sci. Instrum.* **77**, 10E706 (2006).
9. A. Murari *et al.*, *Nucl. Fusion* **45**, S195 (2005).
10. V. G. Kiptily *et al.*, *Nucl. Fusion* **45**, L21 (2005).
11. W. Heidbrink, *Rev. Sci. Instrum.* **56**, 1098 (1985).
12. S. J. Zweben *et al.*, *Nucl. Fusion* **35**, 893 (1995).
13. R. L. Boivin *et al.*, *Nucl. Fusion* **33**, 449 (1993).
14. S.J. Zweben *et al.*, *Nucl. Fusion* **35**, 1445 (1995).
15. S. J. Zweben *et al.*, *Nucl. Fusion* **31**, 2219 (1991).
16. G. McKee *et al.*, *Phys. Rev. Lett.* **75**, 649 (1995).
17. T. Kondoh *et al.*, *Rev. Sci. Instrum.* **77**, 10E505 (2006).
18. S. B. Korsholm *et al.*, *Rev. Sci. Instrum.* 77, 10E514 (2006).
19. R. K. Fisher *et al.*, *Nucl. Fusion* **34**, 1291 (1994).
20. S. S. Medley *et al.*, *Nucl. Fusion* **38**, 1283 (1998).
21. M. Sasao *et al.*, Plasma Phys. Contr. Fusion **46**, S107 (2004).
22. A. V. Krasilnikov *et al.*, Nucl. Fusion **45**, 1503 (2005).