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The $d(d,n)^3\text{He}$, $d(d,p)t$, $d(t,n)\alpha$, and $d(^3\text{He},p)\alpha$ fusion reactions have been measured by detection of the 2.5 MeV neutron, 3 MeV proton, 14 MeV neutron and 14.7 MeV proton emissions, respectively. These measurements provide information on the energy, density, and confinement properties of energetic ions in the tokamak plasma.

Introduction

During the last ten years, the fusion yield from tokamak experimental devices [1-7] has increased about one order of magnitude per year (Fig. 1). One reason for this growth is that heating schemes such as Neutral Beam Injection [8] and Ion Cyclotron Resonant Heating [9] have become available to create energetic ions within the plasma. Another reason is that as tokamaks have become larger, they are better able to confine energetic ions [10,11]. A consequence of the increasing reaction rates is a corresponding increase in plasma diagnostic information that is gained from the fusion reaction products.

One issue addressed by fusion reaction measurements is whether the reacting ions are part of a thermal distribution or of a non-thermal velocity "tail". Measurement of the energy spectrum of the fusion reaction products yields the relative energy of the reacting ions, while the magnitude of the emission is related also to the number density of the reactants.

In this manner, d-d fusion reactions during injection of energetic hydrogen neutrals into a deuterium plasma ($\text{H}^0 \rightarrow \text{D}^+$), during wave (ion cyclotron) heating of ^3He in a predominately deuterium plasma (^3He minority heating), and during ohmic heating (joule heating produced by the plasma current) have been identified as occurring in the bulk plasma. In contrast, measurements show that d-d reactions during D^0 neutral beam injection, during D minority ion cyclotron heating, and during lower hybrid wave heating are produced by energetic tail distributions.

Another issue addressed by fusion reaction measurements is the confinement properties of energetic ions as they slow down and burn up. The confinement can: a) be longer than the slowing-down time in which case the burnup is determined by the electron temperature of the plasma, b) be limited by the intersection of classical ion orbits with the walls in which case the burnup is determined by the plasma current, or c) be limited by anomalous processes (ion loss caused by a plasma instability or imperfect magnetic field topology) in which case the burnup is determined by the characteristics of the instability. In this paper, we illustrate the use of fusion reaction diagnostics by describing measurements of the energetic ion confinement in the Princeton Large Tokamak (PLT) and Poloidal Diverter Experiment (PDX), which currently are the largest producers of fusion reactions among tokamak devices. These studies rely on nuclear cross-section data primarily in the design and evaluation of detectors.

Fig. 1. The fusion yields (expressed as peak power produced) from various tokamaks: T-3 [1], ST [2], ATC [3], ORMAK [4], PLT¹ [5], PDX [6], and PLT² [7]. The TFTR power is the breakeven projection. Indicated in the insert is the fusion reaction and the form of the heating: OHMIC implies joule heating from the plasma current, NBI implies neutral beam heating, COMPR implies major radial plasma compression, and ICRF implies ion cyclotron resonant heating.

Fig. 2. Cross sections for the $d(d,n)^3\text{He}$, $d(^3\text{He},p)\alpha$, $d(d,p)t$, and $d(t,n)\alpha$ fusion reactions. The 1 MeV triton and 0.8 MeV ^3He ions are produced by the d-d reactions and slow down through the peaks of the dt and d- ^3He cross sections. The 0.05 MeV deuterons are produced by neutral beam injection. The 0.2 MeV ^3He ions are produced by ion cyclotron resonant heating.

Fusion Reactions in Tokamaks

The available energetic ions are able to cause several fusion reactions (Fig. 2). The $d(d,n)^3\text{He}$ and $d(d,p)t$ fusion reactions occur at their largest levels during high power (6 MW) neutral beam injection of 50 keV deuterons. After crossing the tokamak magnetic fields as neutral particles, the deuterons undergo charge exchange reactions with plasma ions and become 50 keV ions which are subject to the confinement characteristics of the tokamak. In a plasma with an electron temperature of 2 keV and an electron density of $3 \times 10^{13} \text{ cm}^{-3}$, a typical deuteron slows down through Coulomb collisions and joins the thermal ion population in about 30 msec. Since the deuterons are on a steep part of the cross section (Fig. 2), most d-d reactions occur before the deuterons lose much energy and the cross-section weighted slowing-down time is about 10 msec.

The $d(^3\text{He},p)\alpha$ fusion reactions occur at their largest levels during application of strong (MW) ICRF heating to a predominately deuterium plasma containing about 10% ^3He ions. When the frequency of the radio waves (25 MHz) equals the frequency of ^3He cyclotron motion at the plasma center, the ^3He ions are accelerated by the waves. Simultaneously, the ions lose energy through collisions with the background plasma. The result is a distribution function that is continuous up to 0.2 - 0.4 MeV energies. Again the cross-section weighted slowing-down time is about 10 msec.

$D-^3\text{He}$ fusion reactions are also produced by the 0.8 MeV ^3He ion created by the $d(d,n)^3\text{He}$ fusion reaction. In this case, the ^3He ion is born near the plasma center and slows down through the maximum of the d- ^3He cross section in a cross-section weighted slowing-down time of about 20 msec. Similarly, $d(t,n)\alpha$ fusion reactions are produced by the 1 MeV triton created in the $d(d,p)t$ fusion reaction. In this case, the 1 MeV triton is born at an energy well above the peak of the d-t cross section (Fig. 2) and the slowing down duration to the peak can be as long as 200 msec.

Fig. 3. Poloidal cross section of the tokamak indicating the torus major radius R, the orientation of the toroidal magnetic field, the toroidal plasma current and the poloidal magnetic field induced by the plasma current. Indicated are the poloidal projection of particle orbits for a 0.04 MeV deuteron, a 15 MeV proton, and a 1 MeV triton (or 3 MeV proton or 3 MeV alpha). Each particle was born with $v\text{-toroidal}/v = 0.6$ into a plasma with a 22 k Gauss toroidal magnetic field and a 400 kA plasma current.

Measurement of the emission levels, time evolution, spectra, and spatial origin of the fusion reaction products yield information on the confinement of 0.05 MeVd, 0.2 MeV ^3He , 0.8 MeV ^3He , and 1 MeV t plasma ions. These confinement properties are important in evaluating magnetic confinement schemes, auxiliary heating effectiveness, and processes which might influence the 3 MeV alphas in an ignited device.

Confinement Theory

Since the tokamak is a closed magnetic field system in the form of a torus, ions experience vertical curvature and grad B drifts as they travel along the curved magnetic field lines. Ions are prevented from drifting out of the machine by the poloidal magnetic field produced by the toroidal plasma current (Fig. 3). This field makes the net field (and particle orbits) helical. Thus, ions spend time both above and below the horizontal midplane so that the vertical drift causes displacement towards the plasma edge half the time and displacement towards the plasma center the other half; the net radial displacement in a full orbit is zero. Since the vertical drifts depend upon particle energy, more plasma current is required to confine more energetic ions. The energetic ions can exist at any pitch angle (direction of the particle velocity with respect to the magnetic field) and orbits for a particular pitch angle (ratio of $v\text{-toroidal}/v$) are shown in Fig. 3. For a specific device with a fixed maximum magnetic field and plasma current, some ions (such as 0.05 MeV d and 0.2 MeV ^3He ions in PLT) will be confined for all pitch angles, more energetic ions will be confined for some pitch angles and will intersect the plasma walls for other pitch angles (0.8 MeV ^3He and 1 MeV t ions are on such partially confined orbits in PLT), and still more energetic ions will leave the plasma for all pitch angles (15 MeV protons in PLT are all on unconfined orbits).

Fig. 4. Time evolution of the d-d fusion reaction rate measured by the 2.5 MeV neutron emission as detected by an array of moderated BF_3 proportional counters. The neutron emission increases five orders of magnitude when the 50 keV deuterium neutral beams (4 MW) are applied and decreases exponentially when the beams are turned off. The 15 MeV proton emission is caused by the burnup of the 0.8 MeV ^3He fusion product and is detected by a surface barrier detector located at the plasma edge.

Unconfined Orbits

All of the 15 MeV protons and many of the 3 MeV protons leave the plasma on classical orbits which intersect the walls (Fig. 3). These escaping particles are detected using surface barrier detectors located outside the plasma so that energy and time resolution of the $d(d,p)t$ and $d(^3\text{He},p)\alpha$ reactions can be made. Spectral measurements of the 3 MeV protons [12] show negligible energy losses prior to detection, indicating that detected particles escape the plasma.