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NEW APPROACHES TO CONFINED ALPHA DIAGNOSTICS

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ABSTRACT

Three new approaches to obtain information on the confined fast alphas in International Thermonuclear Experimental Reactor (ITER) are proposed. The first technique measures the energetic charge exchange (CX) neutrals that result from the alpha collision-induced knock-on fuel ion tails undergoing electron capture on the MeV D neutral beams planned for heating and current drive. The second technique measures the energetic knock-on neutron tail due to alphas using the lengths of the proton recoil tracks produced by neutron collisions in nuclear emulsions. The range of the 14 to 20 MeV recoil protons increases by ~140 microns per MeV. The third approach would measure the CX helium neutrals resulting from confined alphas capturing two electrons in the ablation cloud surrounding a dense gas jet that has been proposed for disruption mitigation in ITER.

I. INTRODUCTION

In magnetic confinement fusion experiments, achieving ignition requires that the 3.5 MeV α particles from deuterium-tritium (DT) reactions deposit a large fraction of their energy in the reacting plasma before they are lost. The α's must be confined for a time scale longer than their classical slowing-down time (~1 s). Instabilities such as fishbones or TAE modes can lead to rapid α losses, while large sawteeth are observed to redistribute α's and may make ignition more difficult. Burning plasma experiments are planned as an important next step in fusion research, and would significantly benefit from the development of new ideas for alpha particle diagnostics.

This paper proposes three new approaches to diagnosing confined alpha particles in large tokamaks such as International Thermonuclear Experimental Reactor (ITER). The first two ideas measure the energetic knock-on tails resulting from alpha particle-fuel ion collisions [1]. Under plasma conditions near those needed for fusion ignition, the alpha-induced tails on both the deuterium and tritium ion distributions are larger than the Maxwellian thermal ion populations at ion energies above ~250 keV, where they are $\sim 10^{-3}$ of the total ion population.

II. KNOCK-ON MEASUREMENTS USING ITER MeV NEUTRAL BEAMS

ITER plans tangential injection of 1 MeV deuterium neutral beams for plasma heating and current drive. The presence of the 1 MeV beams can serve as a charge exchange target to allow measurements of the knock-on fuel ion tails [2]. Since the charge exchange cross section is only large for relative velocities $< 2\times10^8$ cm/s, the charge exchange signals will be largest for knock-on ions traveling at similar energies and at small angles with respect to the beam direction. Charge exchange neutrals with energies above the beam energy of 1 MeV must be measured to avoid the injected beam ions and the energetic tails on the fuel ion distributions induced by the beam as a result of elastic scattering collisions. Figure 1 shows the charge exchange cross-section for 1.1 MeV deuterium ions as a function of the observation angle with respect to the injected neutral beam direction.

For an analyzer outside the toroidal field coils on ITER, the minimum viewing angle appears to be close to 45 degrees, leading to low signal levels. Estimates of the knock-on signal levels for a conventional high energy particle analyzer, similar to the Ioffe analyzers used on JET and TFTR, yield ~10 counts/s at 45 degrees. Smaller observation angles would require installing the charge exchange neutral detector inside an ITER port box and the toroidal field coils. The charge exchange neutrals could be ionized using a stripping foil. It should be possible to design an analyzer that would utilize the ITER toroidal field to momentum analyze the ions exiting the stripping foil, and direct them to detectors that could be shielded from the direct flux of neutrons and gamma-rays. Knock-on signal levels as large as $10^5/\mathrm{s}$ may be possible at observation angles of the order of 10 degrees.

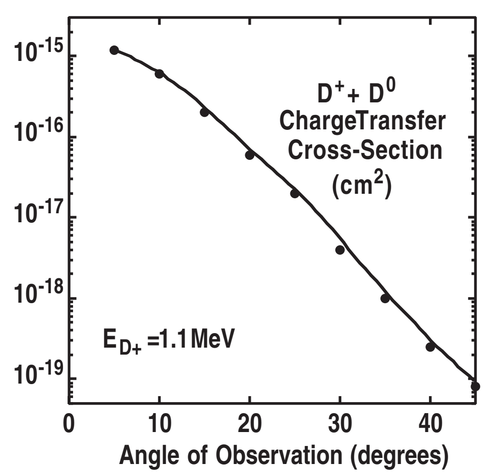

FIG. 1. The cross-section for 1.1 MeV D ions in the α knock-on tail capturing an electron from the 1 MeV heating beam falls rapidly with the angle of observation with respect to the beam direction.

III. MEASUREMENTS OF THE KNOCK-ON NEUTRON TAIL

Fusion reactions between the knock-on tail ions and the background plasma can produce DT neutrons with energies significantly above 14 MeV as a result of the excess kinetic energy of the reacting ions in the center-of-mass frame. For energetic deuterium incident on thermal tritium, $E_N = 14.1\text{ MeV} + 0.56E_o + 0.51\ [E_o(17.6\text{ MeV} + 0.6E_o)]^{1/2} \cos\phi$ where ø is the CM–frame angle of emission of the neutron with respect to the energetic deuterium ion direction.

Above ~15.5 MeV, neutrons resulting from α knock-on collision effects begin to demonstrate over the thermonuclear neutron production at $T_i \sim 20$ keV [1]. The size of the energetic neutron tail is linearly proportional to the α population at the spatial location where the neutrons are generated. Measurements of the energetic neutron energy spectrum can be unfolded to obtain information on the α energy spectrum. The knock-on neutron tail is very small, with only $\sim 10^{-3}$ of the total DT neutrons above 15.5 MeV for a tokamak under plasma conditions near those needed for fusion ignition.

Using the previous equation, the 1 MeV neutral beams in ITER will result in beam-target neutrons with energies up to ~17 MeV for small ø, making the α knock-on tail signals significantly more difficult. Fortunately, the ITER beams are all oriented to inject in the same toroidal direction in order to maximize the plasma current drive. By observing neutrons emitted in the opposite toroidal direction (ø > 90 degrees), the beam-target neutrons will be downshifted in energy and it should be possible to avoid a large background signal due to the beam-target neutrons. Since pitch-angle scattering is approximately three times slower than the energy slowing-down time scale, by time the injected beam ions pitch angle scatter into the observation sight line, they should have lost much of their energy and no longer present a problem. Similarly, passive measurements of the knock-on fuel ion tails using charge exchange techniques [3] should still be possible by observing the charge-exchange neutrals emitted in the opposite toroidal direction from the beam injection.

Measurements of the knock-on neutron tail will require a detector capable of measuring the small energetic tail in the presence of the much larger flux of lower energy DT neutrons from thermonuclear, beam-target and beam-beam reactions in ITER. The detector must also discriminate against a comparable flux of energetic gamma-rays that result from n,γ reactions in the structures surrounding the tokamak. Previous studies examined a number of neutron spectroscopy techniques for knock-on tail measurements [1,3], including pulse height spectroscopy using scintillators or diamond detectors, time-of-flight spectrometers, and threshold activation detectors.

In experiments on JET, a magnetic proton recoil (MPR) spectrometer was used to successfully obtain the first experimental observations of the knock-on neutron tail [4]. Despite the much larger neutron production expected in ITER, diagnostic access limitations may not allow an MPR to be installed where the incident neutron flux is large enough to allow measurements of the knock-on tail with sufficient statistical accuracy to obtain information on alpha particle physics in ITER. Similarly, the low neutron detection efficiency of gel bubble detectors [5] may make it very difficult to obtain accurate information on the behavior of the alphas. S. Trusillo [6] has proposed to develop a high efficiency flowing bubble chamber neutron detector, but this is a difficult development project and success is not guaranteed.

IV. PROTON RECOIL TRACKS IN NUCLEAR EMULSIONS

This paper discusses a new approach [6], using proton tracks in nuclear emulsions, that should allow accurate measurements of the knock-on neutron tail. A small fraction of the incident neutrons elastically scatter on the hydrogen atoms in the emulsion. The energy of the resulting recoil proton is $E_p = E_n \cos^2 \vartheta$ where ϑ is the scattering angle of the recoil proton with respect to the direction of the incident neutron.

As a result of their interactions with the silver halide grains in the emulsion, the recoil protons will create visible tracks in the developed emulsion. The longest tracks will reflect the energies of the protons that result from nearly head-on collisions, where almost all of the neutron energy is transferred to the protons. Figure 2 shows the calculated range of the recoil protons in the 12 to 20 MeV energy range of interest. The range of the 16 MeV protons due to alpha knock-on neutrons will be ~1.3 mm, and will increase by ~140 microns/MeV. By measuring the length of the longest tracks in the emulsion using a microscope, one can determine the energy spectrum of the incident neutrons. The variation in the range due to energy straggling will be ~1.1% or less at these proton energies. For neutrons in this energy range, the neutron energy resolution that is possible using emulsions is "as good as that of any other known detector" (R. Stephen White, 1959) [7].

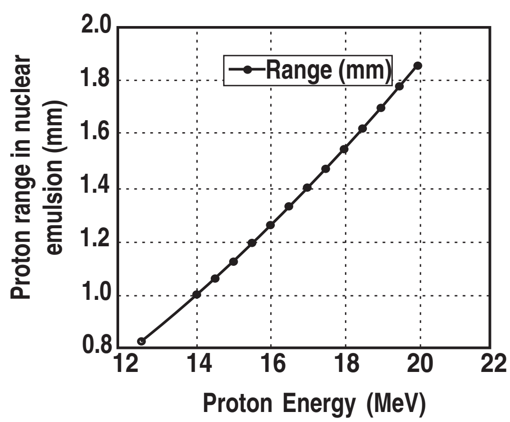

FIG. 2. Calculated range of recoil protons in a nuclear emulsion.

By varying the silver halide content and grain sizes, emulsions can be purchased that should discriminate against the large background flux of gamma rays and x-rays present on tokamaks. The electrons that result from the gamma and x-ray interactions do not have a large enough dE/dx to produce tracks in these emulsions.

The emulsions would be placed in a vertical plane with one edge facing the tokamak. Since the mean free path for DT neutrons in nuclear emulsions is several cm, the recoil proton tracks of interest will occur throughout the plane of each emulsion. After exposure to the ITER neutron flux, the emulsions would be removed and developed, resulting in a permanent record of the recoil proton tracks. The width of the proton recoil tracks will be as small as 0.6 to 0.8 microns in the nuclear emulsions sold by Ilford Imaging in the UK. There should be no problem distinguishing a 16 MeV recoil proton from a 15.5 MeV proton, due to the 70–micron difference in their ranges.

For a 140 cm long, 2.5 cm diameter neutron collimator similar to that planned in the ITER RNC, the plasma neutron flux is incident within approximately one degree of the collimator axis. By measuring the recoil proton tracks with angles of less than 10.5 degrees with respect to the neutron collimator axis, we will measure recoil protons with energies ≥0.97 of the incident neutron energy and achieve the required 0.5 MeV energy resolution at 16 MeV. The tracks would be viewed under a microscope. Pattern recognition software should allow computer analysis of the track length and direction with respect to the incident axis.

Time-resolved knock-on measurements using nuclear emulsions would be very difficult. Translating the emulsions into and out of a collimated neutron flux would take at least a few seconds. But any approach to α diagnostics that is based on observing the knock-on tails is fundamentally limited by the slowing-down time for the energetic fuel ions, which is of the order of a second under ITER-like plasma conditions.

Proton recoil tracks in nuclear emulsions were used to determine the direction of the incident DD neutrons and hence the neutron emission profiles in the PLT tokamak [8]. After exposure to an integrated neutron fluence of $\sim 2\times10^{8}\ \mathrm{n/cm^{2}}$, PLT observed 30 to 50 long (top 5% in length) tracks using a 20 micron thick emulsion 2.5 cm by 5 cm. The longest tracks were ~60 microns long (the range of a 2.5 MeV proton in the emulsion) and ~5 microns in width. A few very long tracks due to the 14 MeV neutrons from burnup of the 1 MeV DD tritons were also observed.

The knock-on signal levels expected in ITER will depend on the number and thickness of nuclear emulsions employed. The number of long tracks in a thin emulsion increases as the square of the emulsion thickness; since both the probability of creating a recoil proton and the probability that the longest tracks will remain in the emulsion increase linearly with the emulsion thickness. Nuclear emulsions are available from Ilford Imaging with a thickness between 10 and 1200 microns. The expected neutron flux in a 25 mm diameter and 140 cm long, collimator [similar to the collimators planned for the ITER Radial Neutron Camera (RNC)] viewing a plasma producing 500 MW of fusion power is $\leq 2.6\times10^{9}\ \mathrm{n/cm^{2}/s}$. A single 300 micron thick emulsion 25 mm high by 70 mm deep would result in ~30 knock-on tracks/second. A stack of ~80 such emulsions filling the 25 mm diameter collimator aperture would result in a total of ~2000 knock-on signal events/second. This is ~100 to 1000 times larger than the number of knock-on events that one could expect to measure using a magnetic proton recoil spectrometer or gel bubble detectors installed behind this size aperture.

Knock-on measurements may also be possible using a neutron spectrometer based on multiple layers of crossed scintillation fibers, similar to the system that proposed by T. Elevant, for ion temperature measurements on ITER [9]. We will investigate whether the direction and length of the recoil proton tracks can be determined by imaging the light signals generated in the crossed fiber arrays, avoiding the need to analyze a large number of tracks in nuclear emulsions.

V. ALPHA DIAGNOSTICS USING JET CHARGE EXCHANGE

Pellet charge exchange (PCX) measurements of alpha particle behavior in TFTR were very successful, and PCX remains the only proven diagnostic of energetic confined alphas. The large plasma radius in ITER will likely limit PCX measurements to $r/a > 0.5$, since it will be extremely difficult to inject an impurity pellet that will penetrate into the plasma core of high electron temperature discharges.

Massive gas injection has been proposed for disruption mitigation in ITER [10]. The initial experiments on DIII-D appeared to show that the neutrals may have penetrated into the plasma core. If this results hold up under further testing, it may be possible to replace the impurity pellet in PCX with a massive gas jet. The Jet charge exchange (JCX) approach would measure the CX helium neutrals resulting from confined alphas capturing two electrons in the ablation cloud surrounding a dense gas jet.

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