FOIL DEPOSITION ALPHA COLLECTOR PROBE FOR TFTR'S D-T PHASE

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Foil Deposition Alpha Collector Probe for TFTR's D-T Phase

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Abstract

A new foil deposition alpha collector sample probe has been developed for TFTR's D-T phase. D-T fusion produced alpha particles escaping from the plasma are implanted in nickel foils located in a series of collimating ports on the detector. The nickel foils are removed from the tokamak after exposure to one or more plasma discharges and analyzed for helium content. This detector is intended to provide improved alpha particle energy resolution and pitch angle coverage over existing lost alpha detectors, and to provide an absolutely calibrated cross-check with these detectors. The ability to resolve between separate energy components of alpha particle loss is estimated to be ≈ 20%. A full 360° of pitch angle coverage is provided for by 8 channels having an acceptance range of ≈ 53° per channel. These detectors will be useful in characterizing classical and anomalous alpha losses and any collective alpha instabilities that may be excited during the D-T campaign of TFTR.

I. Introduction

TFTR's D-T phase now offers the first possibility of conducting a systematic study of alpha particle physics in a tokamak. A crucial aspect of alpha particle physics is the fraction of alphas lost to the first wall. In the design of ITER and future reactors it will be necessary to be able to predict the alpha particle losses to the first wall and divertor plates, since even a few percent loss may cause damage due to localized heating. Studies of alpha particle loss mechanisms could also prove invaluable in developing much needed methods of He ash removal and burn control.

The existing lost alpha scintillator detectors [1,2], which have been operating on TFTR for several years, are capable of detecting D-D fusion products as well as D-T alpha particles. Their choice of design has resulted in relatively good pitch angle resolution at the expense of gyroradius resolution, making it difficult to obtain an accurate energy distribution of detected particles. At best, it may be possible to resolve between the first orbit alpha loss component at 3.5 MeV and a second component of comparable loss strength occurring due to a different loss mechanism at work simultaneously at an energy at least 50% lower. The need for better energy resolution prompted the design of a new detector using a different detection method that could improve upon energy resolution and provide other advantages over the existing detectors.

The new lost alpha collector probe is based on the foil deposition technique originally proposed by Langley [3] and a similar method attempted on JET to determine the energy distribution of ^{3}He ions accelerated by ICRH [4,5]. As depicted schematically in Fig. 1, alpha particles can enter any one of a total of 16 collimating ports that are separated into two rows on the cylindrical probe head located at the bottom of the vessel. Each port only accepts particles within a particular range of pitch angles. At the back of each port is a stack of nickel foils into which the alpha particles implant and remain immobile as long as the foils remain below a critical temperature. Once the foils are exposed to the alpha flux of one or more discharges they are removed from the moveable probe and analyzed for He content. The sample analysis consists of melting the foils one at a time in a closed vacuum chamber, thus releasing the He, and measuring the partial pressure of He with a Residual Gas Analyzer (RGA). The alpha energy spectrum is deduced by measuring the depth distribution of He in the Ni foil stack.

II. Alpha Collector Probe

A. Design Considerations

The choice of nickel as the implantation foil was based on the immobile character of He in Ni at temperatures below ≈ 400° C. A 10 x 10 cm sheet of 1 μm Ni foil is folded to form 10 layers that are then wrapped around a cylindrical graphite spool that is inserted into the carbon-fiber-composite probe head.

Fig. 2 shows the depth distributions of alphas implanted at normal incidence in Ni at various energies [6]. The range of 3.52 MeV birth energy alpha particles in Ni is about 6 μm with a standard deviation, or straggling, of about 0.2 μm. Removing the first foil layer prior to analysis helps to limit tritium contamination and results in a lower energy limit of about 0.5 MeV. The collimating effect of the port results in most particles implanting into the foils at near normal incidence. For collimating ports of equal depth and diameter whose dimensions are much less than the gyroradius of an alpha, the depth distributions of Fig. 2 are broadened in the direction of reduced depth by ≈ 10% due to alphas implanting at less than normal incidence.

The choice of 1 μm Ni foils arranged in a stack, and collimating ports of equal depth and diameter should result in the ability to resolve between the first orbit alpha loss at 3.52 MeV, which should be implanted in the sixth and seventh layers of the foil stack, and other losses at energies below about 2.8 MeV, which would be implanted in the fifth and shallower layers. This results in an energy resolution of about 20%, a significant improvement over the ≈ 50% resolution of the scintillator detectors. Further improvement in the energy resolution may be possible by using thinner Ni foils and higher degrees of collimation. The use of 1/4 mm Ni foils and deeper collimating ports may allow energy resolutions as good as ≈ 5%.

The collimating ports are cylindrical holes drilled into the probe head, a cylindrical shell whose wall thickness determines the depth of the ports. In the initial design of this probe the collimating ports have been given an equal diameter and depth of 1/4" (0.635 cm) which is much less than the alpha birth energy gyroradius of about 5 cm. The pitch angle acceptance range, as determined by the range of pitch angles that are capable of striking the center of the back of the port, is about 53°. A spacing of 45° between ports allows complete pitch angle coverage whereas the scintillator detectors are limited to about 45° to 85° in pitch angle.

B. Preliminary Results and Discussion

Three D-T exposures of the alpha collector probe have been completed. All three exposures were performed in 2.45 m plasmas with the probe tip inserted 1.9 cm inside the RF limiter radius of 99 cm. The first set of foils were exposed to two identical D-T discharges conducted at a plasma current of 0.6 MA and a neutral beam power of 5 MW using one co-going (in relation to the plasma current) tritium beam and one counter-going deuterium beam. This exposure resulted in the unexpected melting of the Ni foils in most of the collimating ports. It is suspected that neutral beam ion loss was responsible for the overheating of the foils.

To reduce the neutral beam ion loss in order to avoid heat damage to the foils, the second exposure was conducted at an increased plasma current of 1.8 MA and used only co-going beams still at a power of 5 MW with one tritium and one deuterium beam. The effect of the higher plasma current is to reduce the banana width of trapped beam ions allowing more of them to be confined. The use of co-going beams also reduces beam ion loss since the beam particles are ionized on the co-going leg of their banana orbits and move in closer to the center of the plasma on the subsequent counter-going leg allowing more of them to be confined. These two modifications resulted in virtually no overheating of the foils with the exception of two ports which were facing directly into the magnetic field and presumably were exposed to excessive thermal plasma flux.

For the third exposure the plasma current was lowered to 1.0 MA and the neutral beam power was increased to 10 MW using two deuterium and two tritium beams. Again, only co-going beams were used to reduce the beam ion loss. Although these foils have not been removed from the probe, the foils in four outboard facing (i.e. away from the center line of the torus) and four inboard facing ports are visible through windows in the probe chamber when the probe is fully retracted. No overheating of the foils in these ports is evident.

The foils from the first two exposures have been removed from the probe head. Although, due to overheating, the first exposure will not provide useful data in terms of a depth profile of He, the resulting heating pattern has provided useful information. The fact that the heat damage occurred in ports oriented nearly perpendicular to the toroidal direction implies that the damage was caused by high energy ions. This is because a large gyroradius is necessary to avoid collimation at these large pitch angles. The maximum alpha heat flux to the foil stack in the collimating port oriented 75° outboard of the toroidal direction for this exposure as predicted by the orbit following code ORBIT [7] is ≈ 300 mW/cm^2. The heat flux necessary to melt the Ni foils is > 100 W/cm^2. Thus the expected alpha heating is nearly three orders of magnitude too small to cause any melting. The peak D-T neutron rate for these shots of 6 x 10^{16} n/sec corresponds to a maximum alpha power of 34 KW. The larger NBI power of 5 MW, combined with the possibility of higher relative NBI ion loss to the probe due to their nonisotropic velocity distribution may account for the overheating of the foils.

NBI ions were not taken into consideration in the design of the collimating ports. Their relatively large gyroradius of about 1.6 cm for 100 KeV tritons allows a large fraction of them to reach the foils without being separated out by collimation. Fig. 3 shows the fraction of ions that can reach the 75° foils without being separated out versus the collimating port depth. This plot was generated by a code that tracked ions backwards in time from an evenly spaced grid originating on the foil. A port width of 1/4" and a flat pitch angle distribution were assumed and the gyrophases of the particles were incremented from -90° to 90°, 0° being the bottom of a gyro-orbit. The maximum transmission is calculated for particles hitting the foil at the pitch angle corresponding to the orientation of the port. It can be seen from Fig. 3 that the original design depth of 1/4" (0.635 cm) did little to discriminate between alphas and the smaller gyroradius NBI tritons. By increasing the port depth the collimator is much more effective in discriminating between the two ion species.

A new probe design has been completed which has doubled the depth of the collimating ports to 1/2" (1.27 cm) while leaving the diameter at 1/4". As can be seen in Fig. 3 this has the effect of nearly eliminating the ability of NBI ions to reach the foils in this 75° outboard facing port while only reducing the maximum transmission of alpha particles by about a factor of 2. This combined with a reduced pitch angle acceptance range of also ≈ a factor of 2 results in reducing the alpha flux by only about a factor of 4 for the 75° port when compared to the original design. This new probe head is expected to be used in all future exposures and should allow the use of the alpha collector in discharges with low plasma current and/or counter-going beams.

III. Sample Analysis

A. Apparatus and Method

The sample analysis vacuum chamber located at the University of Toronto's Istitute for Aerospace Studies is shown in Fig. 4. The system is pumped down and baked at ≈ 150° C resulting in a base pressure of ≈ 10^{-9} torr. This bake is conducted at sufficiently low temperature to ensure that the implanted He remains immobile in the Ni. As the analysis is carried out in a closed system, the titanium sublimator and the liquid nitrogen cold finger are used to remove gasses other than He, maintaining vacuum ≈ 10^{-8} torr.

Each of ten tantalum foil strips is folded in half to form a pocket which holds a piece of Ni foil corresponding to a specific collimating port and layer depth. Attached to one side of each tantalum holder is an electrical lead that penetrates the vacuum vessel through a vacuum sealed electrical feedthrough. The other side of each holder is grounded to the vessel. One at a time, a current of ≈ 25 A is passed through each tantalum holder, resistively heating it to > 1700° C as measured with tne optical pyrometer viewing the holders through a vacuum window. The Ni, with a melting point of 1453° C, quickly melts, releasing the implanted He to the closed vacuum system. The ^{4}He signal of the RGA is then recorded by an interfaced PC. Between each foil analysis the valve is opened to allow the pumps to remove the He in the system from the previous sample. The RGA output is calibrated before and after the analysis by introducing He into the system at a known rate using a calibrated He leak.

B. Absolute Calibration

For use as a check of the absolute calibration of the sample analysis, calibration samples have been prepared at McMaster University using a Van de Graff accelerator. A monoenergetic beam of He ions accelerated to 2.5 MeV was implanted into a stack of 1 μm Ni foils to a total integrated fluence of 1.0 (± 0.2) x 10^{12} ions. This sample was then analyzed using the method described above. As can be seen from Fig. 2, 2.5 MeV He ions have a predicted penetration distance of ≈ 4.1 μm placing them mainly in the fifth foil of the stack. Due to straggling, a significant portion of the He is also to be expected in the fourth foil. The sample analysis resulted in a total release from all the foils of 1.16 x 10^{12} He atoms giving reasonable agreement with what was implanted. The measured distribution indicated that ≈ 1% of the He atoms were retained by layer 3, ≈ 57% by layer 4, ≈ 42% by layer 5, and less than the minimum sensitivity of the analysis of ≈ 3 x 10^9 atoms by the remaining layers. Fig. 2 implies that a larger fraction of the He should have been concentrated in layer 5 than 4. However, a small shift of a few percent towards lower depth in the peak of the depth distribution could easily account for the disparity. Additional calibration samples implanted at varying fluences and energies will be analyzed prior to analyzing samples exposed in TFTR.

IV. Conclusion

A new foil deposition alpha collector probe is currently being evaluated during TFTR's D-T phase to measure alpha particle losses to the first wall. Design choices have made improvements in energy resolution and pitch angle coverage over existing scintillator detectors possible. Since there are no optics nor electronics that can experience interference or degradation from high neutron fluxes, the foil deposition technique may prove more survivable than other detection methods in ITER and future D-T reactors.

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Figure Captions

Figure 1: Conceptual diagram of alpha collector probe head. Alpha particles enter collimating ports and implant into stack of ten 1 mm nickel foils.

Figure 2: Depth distribution of He ions implanting into Ni at various energies (Trim-89).

Figure 3: Maximum transmission fraction for particles hitting the foil stack at the pitch angle corresponding to the ports orientation versus port depth plotted for birth energy alphas and NBI tritons. Averaged over gyrophase (-p/2 to p/2) and foil surface for 75° port with a diameter of 1/4".

Figure 4: Schematic of sample analysis apparatus. Ni foils are melted in a small volume vacuum chamber one at a time in resistively heated tantalum holders. Released He is measured using RGA to obtain depth distribution of implanted alphas in Ni.

Fig. 1

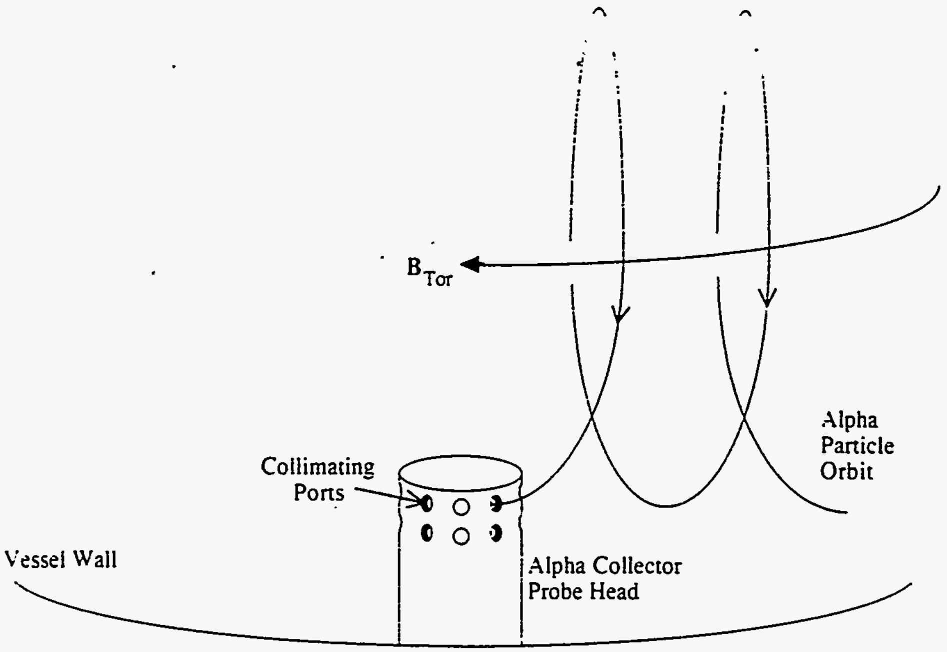

B_{Tor}
Alpha Particle Orbit
Collimating Ports
Vessel Wall
Alpha Collector Probe Head

Fig. 2

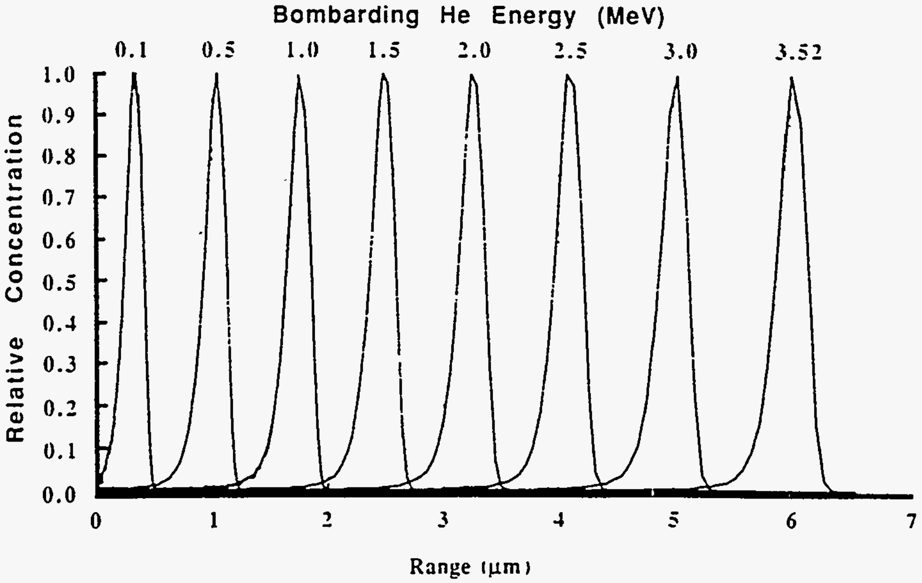
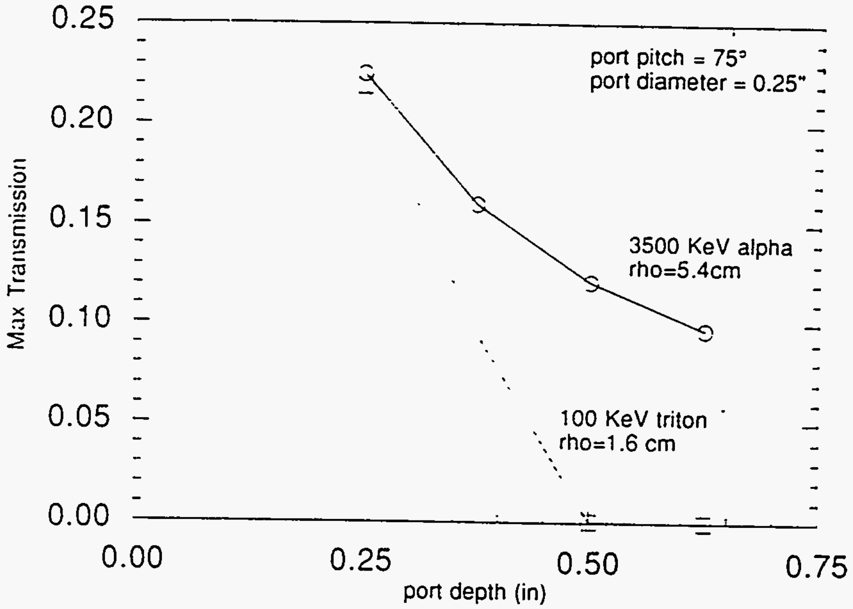
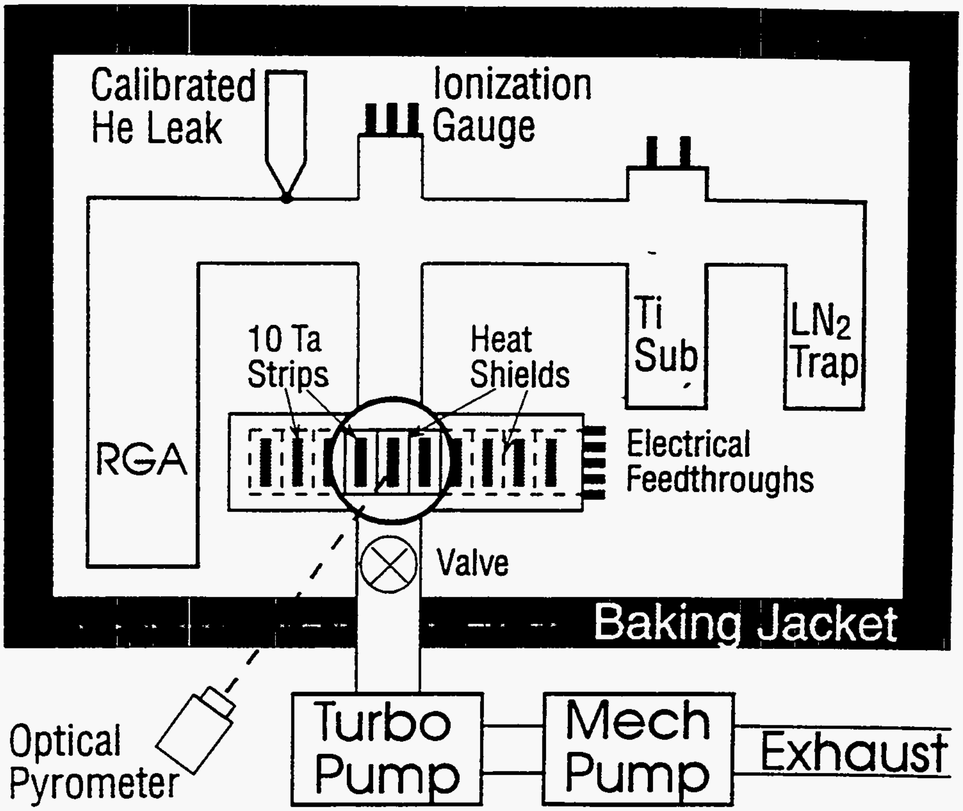

Bombarding He Energy (MeV)
0.1
0.5
1.0
1.5
2.0
2.5
3.0
3.52
Relative Concentration
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
7
Range (μm)

Fig. 3



0.25
0.20
0.15
0.10
0.05
0.00
Max Transmission
0.00
0.25
0.50
0.75
port depth (in)
port pitch = 75°
port diameter = 0.25"
3500 KeV alpha
rho=5.4cm
100 KeV triton
rho=1.6 cm

Fig. 4



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