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Preliminary calculations of expected signal levels of a thin Faraday foil lost alpha particle diagnostic for ITER

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Abstract

Thin Faraday collectors are being considered as a diagnostic of lost alpha particles on ITER. In an effort to evaluate the viability of this diagnostic, we are undertaking a series of calculations of the signal levels (A/cm2) for such devices. Preliminary results assuming a model high yield ITER plasma have been obtained for locations near the outer wall assuming a toroidally symmetric vacuum vessel. We find signal levels to be a strong function of foil location and orientation. Specifically the signal level will be optimized at a vertical location 0.5 m above the machine midplane and with the normal to the foil directed in the lower, radially outward, toroidally counterclockwise octant. A foil thus oriented at a radial distance of 15 cm from the vessel wall at a height of 0.583 m above the machine midplane will have an efficiency of 3.5 10^{-8} /cm^2 for alpha particles which undergo classic loss during the first ten revolutions around the torus during this model plasma. For the assumed d-t fusion power of this model plasma of 410 MW, this calculated efficiency will correspond to a measured current in the Faraday foil of 1.7 μA/cm^2.

Introduction

The International Thermonuclear Experimental Reactor (ITER) may offer the opportunity to investigate steady-state, self-heated or burning plasmas[1]. The confinement of the fusion product alpha particles from the d-t reactions in such plasmas is a necessary condition for this ignition. We have been investigating the use of thin Faraday foil collectors as a fast lost ion diagnostic for fusion plasmas by virtue of the capability of operation in relatively hostile thermal and radiation environments[2]. This concept has been proposed as a possible lost alpha diagnostic for ITER[3]. The present work thus examines this proposal by calculating the expected signal levels, to wit, the electric current generated by lost alpha particles which are stopped in a thin metallic foil located near the plasma boundary on ITER. The foil material is determined by the requirements of being able to withstand high temperatures an remain chemically inert in a hydrogen atmosphere. Nickel is the probably the best choice of material with a melting temperature of 1500 C. The foil thickness is determined by the range of fusion product alpha particles: the range of a 3.5 MeV alpha particle in Ni is 7 μm [4]. A very rough estimate of the current expected can be obtained from ITER's design and operating parameters. The present ITER design [5] calls for a surface area of 678 m^2 with 410 MW of d-t power corresponding to an alpha particle birth rate of 1.4 10^{20} s^{-1}. If all of these alpha particles were uniformly lost over the first wall, there would be a flux of 2.1 10^{13} alpha particles/cm^2 which would be a current of 6.8 μA/cm^2 in a Ni foil of thickness great than 7 μm. This very rough estimate of the current induced in the foil should be compared to the current induced by neutrons and hard gamma rays. The neutrons will induce a current primarily by the nuclear reaction $^{58}Ni(n,p)^{58}Co$. The fluence of the protons *out of* the foil will constitute a negative current. The magnitude of this current can be estimated given the fast neutron flux at the first wall of (again) 2.1 10^{13} neutrons/cm^2. The total cross section for this reaction at a neutron energy of 14 MeV is $\sigma = 0.8$ b $= 8.0\ 10^{-25}$ cm^2[6]. The number of reactions/(cm^2 - s) is then:

$$N_{reactions} = N_{targets} * N_{neutrons} * \sigma = 1.4\ 10^{9}$$

Where $N_{targets} = 8.3\ 10^{19}$ is the number of ^{58}Ni nuclei in, for example, a 10 μm thick Nickel foil with an area of 1 cm^2. This flux of neutrons will correspond to a negative current of 0.22 nA. The current induced by hard gamma rays would be due to photoemission and Compton scattering and will be roughly a factor of 10 smaller than the neutron induced current assuming a flux of hard gamma rays (up to about 10 MeV) comparable to that of the neutrons.

First Order Calculation

The very rough estimate of alpha particle flux described above can be improved upon through the use of an orbit tracing code in reverse time in which particles at an assumed detector location are tracked back through the plasma and the efficiency determined from the assumed spatial dependence of the source strength. The particle flux and hence the measured current is then the product of the efficiency and the total source strength. The code

ORBIT205 [7] was used to do this calculation. This code requires a model of the vessel inner wall, the magnetic equilibrium, the dependence of the source strength on the minor radius as well as the size, location and orientation of the detector. The current ITER design provided the poloidal cross section of the vessel[8]; for this calculation we assumed a toroidally symmetric vessel. By virtue of this assumption, the detector locations were necessarily within the plasma. In future calculations, a more realistic toroidally asymmetric vessel will be used and the detectors will be modeled in one of the large diagnostic ports, in the gaps between the blanket modules or in the immediate shadow of the adjustable poloidal limiters. The magnetic equilbria and source strength were taken from the recent review by Budny[9]. We have examined the efficiency dependence on the major radius, the height above the machine midplane and the orientation of the normal to the plane of the detector. In the calculations the orbits were integrated up to a maximum path length of 1000 m which typically corresponded to ten revolutions of the vessel. Hence the efficiencies correspond to a loss at the detector at some point during the first ten revolutions. The efficiency indicates a clear maximum in the lower, radially outward, toroidally counterclockwise octant. This direction at which the efficiency is maximized is, indeed, fortuitous as it allows the foil to be shielded from the direct flux of hard x-rays from the plasma and the gradual accumulation of in-vessel dust which might eventually alter the effective thickness of the foil. The vertical dependence of the efficiency is maximum at about 0.5 m above the machine midplane at radially inward distances of 10 and 15 cm from the vessel wall. The radial dependence decreases rapidly toward the vessel wall. As in the very rough estimate in the preceding section, we may use the calculated efficiency and the assumed total source strength to predict the measured current in the thin foil. For an efficiency of $3\ 10^{-8}$ /cm^2 (15 cm from the vessel wall at $z=+0.583$ m) and a source strength of $1.4\ 10^{20}$ /s (410 MW of d-t fusion power) there will be a current of 1.3 μA/cm^2. Again this is well above the sub-nanoAmpere currents induced by the flux of neutrons and gamma rays noted above. It should noted that in a prototype device installed in JET during their d-t1 experiment, the net electro-mechanical noise in the foils was at the few nA level[10].

Conclusion and future calculations

The above very simplistic calculations suggest the viability of a thin Faraday foil lost alpha particle diagnostic. A final evaluation must however be made on the basis of more realistic calculations in which a toroidally asymmetric vessel and magnetic field (to account for TF ripple) is assumed. We expect to carry out such calculations in the near future. We wish to acknowledge a number of very useful communications with George Viyakis, Chris Walker and Alan Costley of the ITER home team. This work is supported by U.S. Department of Energy Contracts DE-AC02-76CH03073, DE-FG03-95ER54303 and DE-FG02-04ER54775.

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