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A TECHNIQUE FOR MEASURING THE LOSSES OF ALPHA PARTICLES TO THE WALL IN TFTR

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ABSTRACT

It is proposed to measure the losses of alpha particles to the wall in the Tokamak Fusion Test Reactor (TFTR) or any large deuterium-tritium (D-T) burning tokamak by a nuclear technique. For this purpose, a chamber containing a suitable fluid would be mounted near the wall of the tokamak. Alpha particles would enter the chamber through a thin window and cause nuclear reactions in the fluid. The material would then be transported through a tube to a remote, low-background location for measurement of the activity. The most favorable reaction suggested here is $^{10}B(\alpha,n)^{13}N$, although $^{14}N(\alpha,\gamma)^{18}F$ and others may be possible. The system, the sensitivity, the probe design, and the sources of error are described.

I. INTRODUCTION

H. Hendel and S. Seiler[1] have suggested that measurement of wall losses of alphas can be done by a scintillation technique in the Tokamak Fusion Test Reactor (TFTR). It is proposed here that a backup system for this measurement would consist of a measurement of the production of one or more radioactive isotopes produced by the alpha particle bombardment of selected materials at the wall of TFTR. Such a system appears to be easily implemented and capable of being calibrated. It is proposed to use the radioactive products resulting from the bombardment of samples behind a thin window, move these isotopes through long tubes to a remote counting room, and count them by conventional gamma ray counting techniques. This technique is particularly applicable to fairly energetic particles and, hence, is specific to the prompt alpha losses (i.e., the 3.5-MeV alpha particles lost by ripple trapping and banana diffusion).

II. DESCRIPTION OF THE IDEA

The problem of alpha losses has been described in detail elsewhere.[2-5] A measurement of the wall flux of energetic alpha particles is important for determining the plasma core heating due to alpha particles and for determining the effects of ripple and other error fields.

We propose a technique to measure the energetic alpha particles by one or two reactions that will show that the particles have hit the wall and produced certain isotopes. Although the reactions can be measured by scintillation techniques,[1] such techniques are subject to background problems. Scintillations can also be produced by gamma rays and X rays, as well as by neutron irradiation. The counting technique discussed here represents a backup system for this purpose to demonstrate that the scintillation rates are real. The counting is done between shots far from the tokamak, where the background is low and verification can be made that the counting rate is not due to noise.

Specifically, the requirements are the same as already described by Grisham et al.[6] In that case it was proposed to introduce a material into the plasma that would react with the contained alphas and then to collect the resulting isotopes on probes that would be extracted and counted. The experiment described here is specifically designed to look at the alpha losses, rather than at the contained alphas. Hence, the reactions will occur in samples in the wall.

The specific reactions proposed by Ref. 6 are:

$$^{10}\mathrm{B}(\alpha,\mathrm{n})^{13}\mathrm{N} \qquad Q = 1.06$$

$$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F} \qquad Q = 4.41$$

Here, the first reaction is preferred, and the second is given a lower priority due to the average lower cross section. Other reactions were mentioned but discounted in Ref. 6 due to the large negative Q values.

Both of the above reactions have a positive Q and, hence, a threshold of 0.0 MeV. Both reactions produce a radioactive gas that is a positron emitter. The first reaction gives a product with a 10-min half-life, and the second has a 1.83-h (or ~110-min) half-life. In both cases, the annihilation radiation (0.511-MeV) gammas would be counted.

III. ENERGY LOSS IN THE THIN WINDOW

One possibility is to use a material that can be contained behind a thin window in a probe inserted past the wall into TFTR. A thin Havar (Hamilton Precision Metals Co.)[a] or nickel window of ~1 μm thickness supported on a highly transparent mesh would be

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[a] Reference to any specific commercial product, process, or service by trademark, trade name, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. government or any agency thereof.

adequate to separate the vacuum system from the probe containment volume. For 3.5-MeV alphas normally incident on such a window, calculations[7] show that about 0.45 MeV would be lost in the window, leaving an alpha energy of ~3 MeV. Such an energy is adequate to produce reactions in the probe material. The isotopes (^{13}N and/or ^{18}F) evolved from the material would be contained behind the window. Although the probe would be operated at a pressure differential near 1 atm, the window should be capable of sustaining a pressure differential of 10 atm.

There is a possibility that the window could break for unforeseen reasons. As discussed later, only a few cubic centimeters of liquid or gas are needed in the probe during a shot, and valves would be used to isolate the probe from the rest of the transfer system. For 3 cm^3 of the liquids considered here, a window rupture would cause a pressure rise of $<2 \times 10^{-3}$ torr. Since the liquids are all low atomic number materials, there should be no long-term deleterious effect from such an event. The probe would be mounted on a gate valve so that it can be withdrawn for window replacement.

IV. MATERIALS USED

It is proposed that material containing ^{10}B and/or ^{14}N could be easily contained behind such a window. Specifically, a number of liquids contain boron [e.g., boron hydrides such as B_5H_9, B_5H_{11}, and B_4H_{10}]. Also, there are some other materials (e.g., BF_3, NH_3, and N_2) which exist as cryogenic liquids or gases. If a liquid is not allowed, a number of solid materials are available. Boron, for example, would require special transfer techniques (discussed in the next section).

A number of other liquids are available. However, as the subsequent discussion will show, their use may present serious background problems. If the $^{10}B(\alpha,n)^{13}N$ reaction is used, a liquid containing nitrogen is not acceptable. If the reaction $^{14}N(\alpha,\gamma)^{18}F$ is used, then the liquid cannot contain fluorine or oxygen (water, for example).

Boron trichloride (BCl_3) is another possibility; however, its use presents a disadvantage because the mass fraction of ^{10}B is very low (~8%) compared to the boron hydrides. Also, several short-lived positron activities can be induced by neutron irradiation of chlorine that might present background problems.

The carboranes[8] are an interesting class of liquids that are not flammable but that still contain a high percentage of boron. These compounds are difficult to make in large quantities, and details about their physical properties are hard to find. The carbon in the compound has the potential of producing some background through the $^{12}C(p,\gamma)^{13}N$ reaction. However, calculations show that this background will not be a serious problem. (This situation is discussed in Sec. VIII.)

The boron hydrides mentioned above are flammable and poisonous but are apparently not corrosive. They represent the best possibility if the $^{10}B(\alpha,n)^{13}N$ reaction is used. Of the boron hydrides, B_5H_9 and B_5H_{11} appear to be the most stable and easiest to handle. Their boiling points are 58.4°C and 65°C – far above room temperature. B_5H_9 is spontaneously combustible in air, but a large quantity has been stockpiled by the U.S. Air Force. It has been used as a high energy fuel.

V. METHODS OF TRANSFER

Probes in TFTR will be used to expose materials to the plasma for surface physics studies.[9] A simpler probe than these is proposed for our samples. Unfortunately, the sample probes will not allow rapid transfer of the samples out of the TFTR vacuum chamber for analysis because they must go through a gate valve. Estimates are that such a transfer would require 20 min or more. In the case of the $^{10}B(\alpha,n)^{13}N$ reaction, the resulting isotope would have decayed by two half-lives before it could be counted. Liquids were suggested earlier just for this reason. A small sample of liquid behind a thin window could be easily transferred pneumatically to a remote location for counting. In the case of the

$^{14}N(\alpha,\gamma)^{18}F$ reaction, there is sufficient time to remove a solid object from the TFTR vacuum chamber and count it before all the activity is decayed. However, this does presume the use of the sample probe and a mechanism to transfer the sample from the probe to a *rabbit* system. Such a system is inherently more complicated and expensive than a simple pneumatic system to move a small sample of fluid in a tube.

The recommended practice with such a technique is to use a small sample in the probe for the irradiation, and then to transfer it by pulse displacement with an inert gas such as helium. The liquid would be blown off the wall by a high-velocity gas stream. Several small quantities of liquid would individually be sent after the irradiated sample and each removed the same way. These additional samples serve as carriers that should scavenge any radioisotopes adhering to the wall. All of the liquid would be collected for counting. Such a system should avoid the problem of a boundary layer of liquid adhering to the thin window. Such a layer might be expected to contain a large fraction of the radioactive isotope.

Calculations show that a high-velocity (~22-m/s) liquid stream of boron hydride would have a very thin boundary layer (~10 μm). There would be high turbulence inside the flowing liquid, and in the boundary layer the velocity would go from zero velocity on the wall to the stream velocity at 10 μm. Hence, no appreciable loss of the radioactive isotope would be expected due to a stationary boundary layer. The decision to use either pulse displacement or turbulent flow to remove the isotope would be determined by further studies.

About 1 cm^3 or less of the liquid would be in the probe head. All the liquid would be collected in a NaI(Tl) well counter, where the activity could be determined. The well counter, plus additional crystals, could be used to ensure near-4π counting geometry. By using a very thick NaI(Tl) crystal with a well, a photopeak efficiency of ~80% can be achieved for 511-keV gamma rays.

A liquid transfer system has been previously suggested for neutron measurements in a tokamak.[10] In that case, the reaction products from various threshold reactions were transferred from a point near the vacuum wall to a counting chamber exterior to the tokamak by a suitable fluid (e.g., CCl_4 or H_2O). By choosing a suitable set of isotopes, the ratio of D-D to D-T neutrons could be determined.

Another possibility is transfer of a gas. However, calculations suggest that moving small samples of gaseous materials through very long tubes may not be practical; most of the gas will be adsorbed on the wall of a long tube and not reach the end, even if the tube is heated, evacuated to very high vacuum, and the gas collected cryogenically. However, a layer of boron or other appropriate material could be exposed to the alpha particle flux coming through the thin window. The gas produced by the reactions (^{13}N and/or ^{18}F) would be evolved by heating the material. The gas could be transported through a short heated tube (~30 cm) to a cryogenically cooled *rabbit* collector. After the gas is adsorbed on the *rabbit*, a gate valve could be closed and the *rabbit* transferred to a remote location for counting. Such a system, while possible, seems much more complicated than a liquid transfer system.

A continuous gas-flow system has been used on a TRIGA reactor.[11] The $^{9}Be(n,\alpha)^{6}He$ reaction was used, and the ^{6}He was carried out of the reactor by a fast helium gas stream. The decay of ^{6}He was counted in an external, shielded room. The system could be used as a continuous monitor of the power level. Such a system does not seem to be applicable to the TFTR because of its low efficiency and the pulsed nature of TFTR, but the concept deserves further investigation, particularly if only gases can be used such as BF_3, N_2, or NH_3.

Another possible system is a slurry transport system. A material such as powdered boron could be carried in and out quickly to and from the probe by a carrier liquid. The practicality and advisability of such a system would have to be determined by further studies.

There is a possibility of designing a solid-body transfer system, without a gate valve behind the thin window, incorporating a slug of boron. This possibility presents many design challenges but should not be discounted at this time.

VI. ESTIMATES OF PRODUCTION RATES AND COUNTING RATES

The cross section for the $^{10}B(\alpha,n)^{13}N$ reaction was measured by Gibbons and Macklin,[12] Shire et al.,[13] and Van der Zwan and Geiger.[14] At 3.0 MeV, the cross section is about 11 mb. According to Fig. 5 of Ref. 5, almost all of the particles incident on the target arrive with angles of incidence within 25° of normal. Hence, the energy loss in the foil varies from 0.45 MeV for normal incidence to 0.50 MeV for the maximum angle. A calculation has been made of the yield of radioactive atoms by assuming a 3.0-MeV particle energy entering the liquid. A numerical integration has been made using the measured cross sections and the known energy loss rate (stopping power) in the material.[7,15] The yield Y (radioactive atoms per incident particle) is given by

$$Y(E_\alpha) = \frac{n_t}{\rho} \int_0^{E_\alpha} \frac{\sigma(E)}{dE/\rho dx}\, dE \ , \tag{1}$$

where $\sigma(E)$ is the cross section as a function of energy E, $dE/\rho dx$ is the energy-dependent stopping power (energy loss per mg/cm^2 of material traversed), n_t is the number density of target atoms (^{10}B), and ρ is the mass density of the target material. We assume the use of B_5H_9 with a density of 0.66 mg/cm^2, so that the material is 81% ^{10}B by weight.[a] The energy loss is calculated from Ref. 7, with an effective atomic number of 2.4 suitable for

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[a] A large quantity of 98% pure ^{10}B is available at Oak Ridge National Laboratory.

such a compound (i.e., an equivalent material intermediate between helium and lithium). The calculated yield is then 4.45×10^{-8} atoms per incident alpha.

The reaction rate R is given by

$$R = YF/l \quad , \tag{2}$$

where F is the incident flux, and the path length in the material is l. From Hively and Miley,[5] F is typically $10^{12}\,\text{cm}^{-2}\,\text{s}^{-1}$, and l is calculated to be 1.2×10^{-3} cm (1.8 mg/cm^2). The total number of atoms N produced in a target of volume V for an irradiation time of t seconds is given by

$$N = RVt \quad . \tag{3}$$

For this case, with $V = 10^{-3}$ cm^3 ($1 \times 1 \times 10^{-3}$ cm) and an irradiation time of 1 s, $N = 3.7 \times 10^4$ atoms. Transferring this material to a remote detector in a time that is short compared to the half-life would result in a count rate of 43 s^{-1}. Counting statistics of less than 1% error can be obtained in less than 4 min. It should be emphasized that this calculation is approximate and needs to be accurately computed and verified by a measurement.

The cross section for the ^{14}N(α,n)^{18}F reaction has been measured by two groups.[16,17] The cross section is very small (<0.1 μb), except at certain resonances. Fowler et al.[18] have calculated the cross section in regimes of interest to astrophysics. The integrated cross section is certainly lower than for the ^{10}B(α,n)^{13}N reaction. It is difficult to make reasonable estimates of the counting rates that can be expected on the basis of these cross sections, so it is proposed that experiments be carried out to measure the yield from an alpha beam irradiating such a target.

It should be noted that this technique is probably less sensitive than the technique of Hendel and Seiler,[1] who estimate that a flux of alphas much greater than

5×10^7 cm^{-2} s^{-1} is required to be above the background induced by neutrons and gammas. The technique presented here would require greater than 10^{10} cm^{-2} s^{-1} to achieve good statistics for boron hydride, but the background should be negligible.

Another passive technique has been proposed recently by Muller et al.[19] Alpha particles at the plasma edge charge exchange while passing through foils and exit as neutrals. At some distance from TFTR, they are reconverted to ions and are counted. The sensitivity of this technique is estimated at 10^{-6} per square centimeter of foil area.

VII. PROBE DESIGN

Figure 1 is a schematic of a possible probe head design with the salient features needed for this experiment. A thin window on one side faces the incident alpha flux. A highly transparent (80%–90%) thin metal grid would help support the window. Such a grid would only slightly decrease (~10%) the acceptance solid angle of the incident alpha particles. A shutter can cover the window for background checks. The shutter needs to be thick enough to stop 3.5-MeV alphas and 14.7-MeV protons. Tubes would lead the liquid in and out of the irradiation volume. Rotation about the probe axis would allow irradiation for the two possible field directions and would also allow another background check (i.e., if the probe were faced away from the incident alpha direction, no activity should be induced in the sample material). Radial motion would be required to investigate the radial flux dependence, as well as to remove the probe when not in use.

Baffles would be used to avoid direct contact of the plasma with the thin window, while still allowing the energetic alpha particles with large orbits to reach the thin window. Careful design of the baffles would be required to avoid unnecessarily restricting the acceptance solid angle of the incident alpha particles, while still allowing window protection from plasma bombardment. Calculations presented in Ref. 5 show that in TFTR almost all of the alpha particles will be incident on the foil within a critical angle, α_c, to the foil normal (where $\alpha_c \simeq 20°-25°$ for reasonable locations), with the peak flux near the critical angle. Very few particles are incident tangential to the foil (normal to the tokamak wall). Hence, the baffle design should incorporate this information. As will be discussed, these baffles should also be designed to prevent 14.7-MeV protons from striking the window, if possible. Since the magnetic rigidity of the alpha particles is $\sim 27 \times 10^4$ gauss-cm, the typical gyroradius in a 30-kG field is 9 cm (or 5.1 cm in a 52-kG field). This means that the probe could be located behind a protective limiter and still intercept the alpha orbits. The side of the probe facing the plasma could have a considerable amount of additional material (e.g., stainless steel or carbon) mounted on it for its own protection. In principle, it could also be actively cooled.

For a D-T burning plasma depositing 1 MW/m^2 on the probe, calculations show that a 1-cm-thick stainless steel protective layer on the probe should undergo an average temperature rise of ~24°C. Internal heating by neutron and gamma irradiation of the probe body containing the liquid should cause a temperature rise of less than 2°C.

As mentioned before, the probe would be designed to be extracted through a gate valve to replace windows in the event of a rupture. Such a rupture should not cause any long-term harmful effects. Since the fluid system would be equipped with valves that are closed during the TFTR plasma shot, a rupture would allow the TFTR vessel pressure to rise somewhat ($1-2 \times 10^{-3}$ torr) but would not represent a serious vacuum accident. The foils being considered are commonly used under intense particle bombardment in various laboratories and can withstand heat fluxes of several hundred watts per square centimeter, steady state. In fact, the liquid or gas behind the window represents a heat sink that would allow the foil to withstand a larger heat load. Calculations of the scrape-off layer for TFTR[20] predict that the e-folding length λ of the energy deposition profile will be between 0.4 and 2.5 cm. For an incident flux of 10 MW/m^2 on the limiter and $\lambda = 1.5$ cm (3 cm behind the limiter), the heat load would be only 130 W/cm^2, which would be largely absorbed by the baffles.

VIII. SOURCES OF ERROR

The probe considered here would be in a strong neutron and possibly large gamma flux inside TFTR. Hence, there is a strong possibility of competing reactions occurring that could produce radioisotopes that could represent background in the detector. In addition, the alphas coming through the window might cause additional reactions in other materials in the probe, which could produce background.

A survey has been made that shows the possible radioisotopes from the elements in the proposed liquids from (n,α), (n,p), etc. reactions. Most of these are of short half-life, very long half-life, or decay by some other channel than a positron decay. Hence, they do not represent a serious source of background. For example, the ^{19}F(n,p)^{19}O reaction results in a radioactive product with a beta (negatron) decay and a half-life of 29 s. This should not represent a serious source of background. If the probe material contains oxygen, the ^{17}O(n,α) reaction will produce ^{14}C, which has a beta decay with a 5770-y half-life. A number of other elements will also yield ^{14}C by (α,p), (n,γ), (n,p), and (n,α) reactions. None of these appear to produce a serious background. The ^{19}F(n,α)^{16}N reaction produces an isotope with a beta decay and a 7.34-s half-life. There are a number of other possibilities that do not appear to be of concern, but since the actual probe sample material is not yet determined, the possibility of some background reactions causing difficulty cannot yet be ruled out.

Several reactions are potentially very troublesome and were alluded to in Sec. IV. Specifically, they are given in Table I. The third reaction in Table I has an observed threshold of 10.7 MeV. All these reactions have large negative Q values, and the first and third require very high gamma ray energies. Hence, these are only possible under strong runaway conditions. The second and fourth reactions, however, can be induced by the strong 14.1-MeV neutron flux present at the wall of TFTR simultaneous with the alpha flux. The neutron flux is expected to be as high as 1×10^{13} cm^{-2} s^{-1} during these times[21] and, hence, has a strong possibility of inducing these reactions. The cross sections[22] in Table I are large, and calculations show that these reactions will produce more activity in the liquid than will the alpha flux if fluorine or nitrogen is present in the liquid, because a much larger volume of liquid will be in the probe region ($\sim 1\ \mathrm{cm}^3$) compared to that available to alpha bombardment ($\sim 10^{-3}\ \mathrm{cm}^3$). If the $^{10}\mathrm{B}(\alpha,\mathrm{n})^{13}\mathrm{N}$ reaction is chosen, then the sample material must be chosen so that no nitrogen is in the liquid. If the $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}$ reaction is chosen, then the sample material must be chosen so that it contains no fluorine.

It will not be possible to produce $^{13}\mathrm{N}$ and $^{18}\mathrm{F}$ from (n,α) reactions in the sample material because the required targets ($^{16}\mathrm{F}$ and $^{21}\mathrm{Na}$) are radioactive and not naturally occurring. Calculations suggest that (n,α) reactions in the walls of the target chamber (mostly made of iron, cobalt, and nickel) would not produce a sufficient intensity of energetic alphas to cause substantive additional (α,n) or (α,γ) reactions in the sample material. The intensity of this source should be 10^5 to 10^6 times smaller than the alpha flux through the window.

There are still other sources of background. Some D(D,p)T reactions will be occurring in the plasma. The 3-MeV protons produced in this reaction can impinge on the target and can cause other reactions. Furthermore, the $\mathrm{D(D,n)^3He}$ reaction will produce $^3\mathrm{He}$, which can further react with deuterium $[\mathrm{D(^3He,p)^4He}]$ to produce 14.7-MeV protons. There are a number of reactions with energetic protons that must be avoided. If the liquid contains carbon or oxygen, then the following reactions might produce a serious background problem: $^{16}\mathrm{O}(\mathrm{p},\alpha)^{13}\mathrm{N}$, $^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}$, $^{13}\mathrm{C}(\mathrm{p,n})^{13}\mathrm{N}$, $^{18}\mathrm{O}(\mathrm{p,n})^{18}\mathrm{F}$, and $^{17}\mathrm{O}(\mathrm{p},\gamma)^{18}\mathrm{F}$. Based on the available cross sections,[23] the $^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}$ reaction will not produce significant background. However, the $^{16}\mathrm{O}(\mathrm{p},\alpha)^{13}\mathrm{N}$ reaction is particularly troublesome. In the strong neutron environment, the knock-on protons in water or other hydrogen-containing substance can produce appreciable $^{13}\mathrm{N}$ activity, as well as the direct proton bombardment.

Hence, oxides and water cannot be used. The reactions with ^{17}O and ^{18}O do not appear to be significant because of their small percentages in normal oxygen, but this should be verified by further studies. It is possible to discriminate against the 14.7-MeV protons with baffles; however, the 3-MeV proton and 3.5-MeV alpha have the same magnetic rigidity (gauss-cm) within 7%, so that baffles could not reasonably be used to discriminate against the 3-MeV proton.

The $^{10}B(p,\alpha)^{7}Be$ reaction will not cause difficulty because the ^{7}Be isotope decays with a very long half-life (53.7 d) by internal conversion with a gamma ray of 478 keV. Hence, it can be easily distinguished from the 511-keV gamma. The $^{10}B(p,\gamma)^{11}C$ reaction might be of concern because the ^{11}C decays with a 20.4-min half-life by positron emission. This could cause significant background due to the similarity of half-lives. However, the measured cross section[24] at 3 MeV is 3.8 μb, so that for a flux of protons equal to the alpha flux, the production of ^{11}C would be about 3000 times lower than the production of ^{13}N by alphas. The $^{10}B(p,n)^{10}C$ reaction also produces a positron emitter with a half-life of 19.1 s. However, the Q value is -4.07 MeV, so that it is energetically forbidden. There would naturally be a small fraction of ^{11}B in the target. The $^{11}B(p,n)^{11}C$ reaction has a threshold of ~3 MeV, so that it would not contribute background from the 3-MeV protons. However, knock-on protons from the neutron irradiation may contribute. Calculations suggest that this source of background will be small because of the small percentage of ^{11}B. In any case, the flux of protons is much lower than the alphas. so that the proton-induced activity is much lower from all these reactions.

In the same way, it can be shown that the energetic proton reactions will not cause background problems if the $^{14}N(\alpha,\gamma)^{18}F$ reaction is used. The reactions in Table II are all possible, and all have positron decays. The first two reactions in Table II have very short half-lives, and the first is energetically forbidden. The cross section for the second reaction is very small. The last two are energetically forbidden for 3-MeV protons.

The ^{3}He and triton particles themselves will have sufficient energy to penetrate the window; however, no reactions have been found that have such a low threshold that these particles can cause the reaction. Hence, no additional background would result from them.

In summary, by avoiding certain materials in the fluid, backgrounds should be negligible. For the $^{10}B(\alpha,n)^{13}N$ reaction, the boron hydrides will produce negligible background. For the $^{14}N(\alpha,\gamma)^{18}F$ reaction, NH_3 and N_2 will produce negligible background.

IX. FURTHER WORK

It is suggested that the feasibility of using the two above-mentioned reactions would be determined by tests at Oak Ridge National Laboratory (ORNL) on the small Van de Graaff accelerator in the Physics Division. Further measurements with 3.5-MeV alphas could be conducted on the Engineering Physics Division D-T neutron generator that is equipped for associated particle measurements of neutron flux. These tests would also involve developing a liquid sample probe with a thin window. The practical energy threshold for detection of alpha particles should be determined at the Van de Graaff. Because the technique integrates over the TFTR burn pulse, consideration should be given to developing a fast shutter that could be used to make temporal measurements of the flux at various times during the burn pulse.

A probe of this general design could be built and inserted for survival tests into an existing tokamak, such as the Impurity Study Experiment (ISX-B) or the Princeton Large Torus (PLT). If further calculations support a reasonable counting rate, such a probe could be used to try to measure the proton loss rate to the wall from the $D(D,p)^3He$ reaction, using some appropriate reaction. Further *in situ* tests on TFTR could be performed prior to the actual D-T experiments.

A remeasurement of the $^{14}N(\alpha,\gamma)^{18}F$ reactions would be advisable in the energy range up to 3 MeV at the Van de Graaff.

Hively[2] has calculated that the alpha losses are highest in certain poloidal and toroidal locations. For example, ripple losses are enhanced near the outboard wall of the tokamak between the toroidal field (TF) coils at poloidal angles near 30° from the midplane. Axisymmetric losses are enhanced over the entire outboard wall but are peaked at poloidal angles of ~60° from the midplane. A further study would have to be made of the best locations for such probes. In an actual experiment, several probes at different poloidal locations would be desirable to map the alpha flux loss.

The possible background contributions from various nuclear reactions mentioned, but neglected, in this report need further investigation, as does the applicability of the suggested fluids. Further consideration of other materials (e.g., carboranes) and the advisability of their use in the TFTR environment should be made.

X. SUMMARY AND CONCLUSIONS

This proposal describes a technique for measuring the alpha particle losses to the walls in TFTR. The technique uses a small cell containing a suitable fluid in which an appropriate nuclear reaction will be induced by the alpha particle flux. Based on our present knowledge, the $^{10}B(\alpha,n)^{13}N$ reaction is the most promising candidate, but others may be possible. The fluid would be transported to a remote location for counting the induced activity. The average alpha particle flux over the D-T burn period would be determined. Multiple targets would allow a mapping of the losses to the wall – poloidally and toroidally.

This technique would give neither the energy distribution of the particles nor a measurement of the alpha particle density in the center of the discharge. It would be most sensitive to the most energetic alphas (i.e., the prompt losses).

At this time, a total of ~10 D-T shots is being considered; therefore, a very simple, inexpensive, and reliable system is needed to measure the losses. Very complicated schemes may not give useful information for the limited number of shots available. The scheme suggested here is simple, reliable, and inexpensive.

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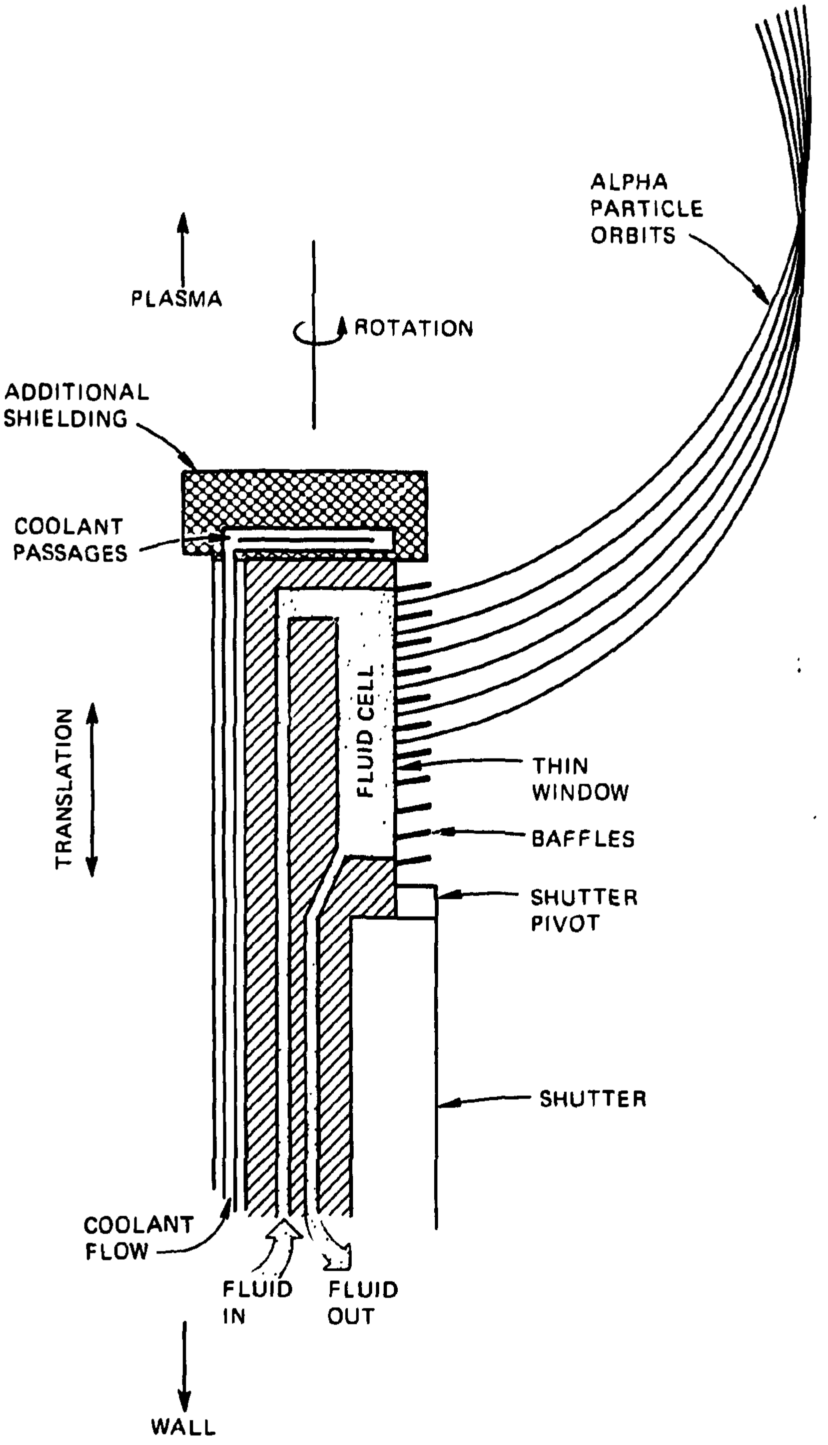

Fig. 1. Schematic of proposed probe head.

Table I. Potentially troublesome reactions

Reaction	Q value (MeV)	σ(14.1 MeV) (mb)
$^{19}F(\gamma,n)^{18}F$	−10.43	
$^{19}F(n,2n)^{18}F$	−10.43	47.4
$^{14}N(\gamma,n)^{13}N$	−10.55	
$^{14}N(n,2n)^{13}N$	−10.55	6.1

Table II. Energetic proton reactions

Reaction	Half-life	Q
$^{14}N(p,n)^{14}O$	7.1 s	−5.91
$^{14}N(p,\gamma)^{15}O$	124.0 s	7.347
$^{14}N(p,D)^{13}N$	10.0 min	−10.545
$^{14}N(p,\alpha)^{11}C$	20.3 min	−2.916

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