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STREAMING AND SHIELDING ANALYSIS FOR THE NBI SYSTEM OF TDF

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ABSTRACT

Three-dimensional neutronics and photonics analysis has been performed for the neutral beam injection system of TDF. Using tungsten shield in the 0.35 m space available between the corner of the central cell solenoid and the duct wall provides adequate protection for the magnet. The peak radiation damage and nuclear heating in the magnet are well below the specified design limits. Acceptable heat loads were obtained in the cryopanels and superconductive shield. The radiation dose absorbed in the MACOR insulator of the ion source implies that it will last approximately 2.8 full power years.

INTRODUCTION

The Technology Demonstration Facility (TDF)[1] is a tandem mirror machine which provides a steady state neutron environment sufficient to test materials and integrated blanket concepts. Figure 1 is a cutaway view of the facility showing the major components of TDF. Most of the fusion neutrons are produced in the 8 m long central cell extending between the two high field choke coils. A neutron wall loading of $2\ \text{MW/m}^2$ is obtained in the central cell where blanket and material testing are performed. In addition to the two normal conductor choke coils, the central cell contains three super-

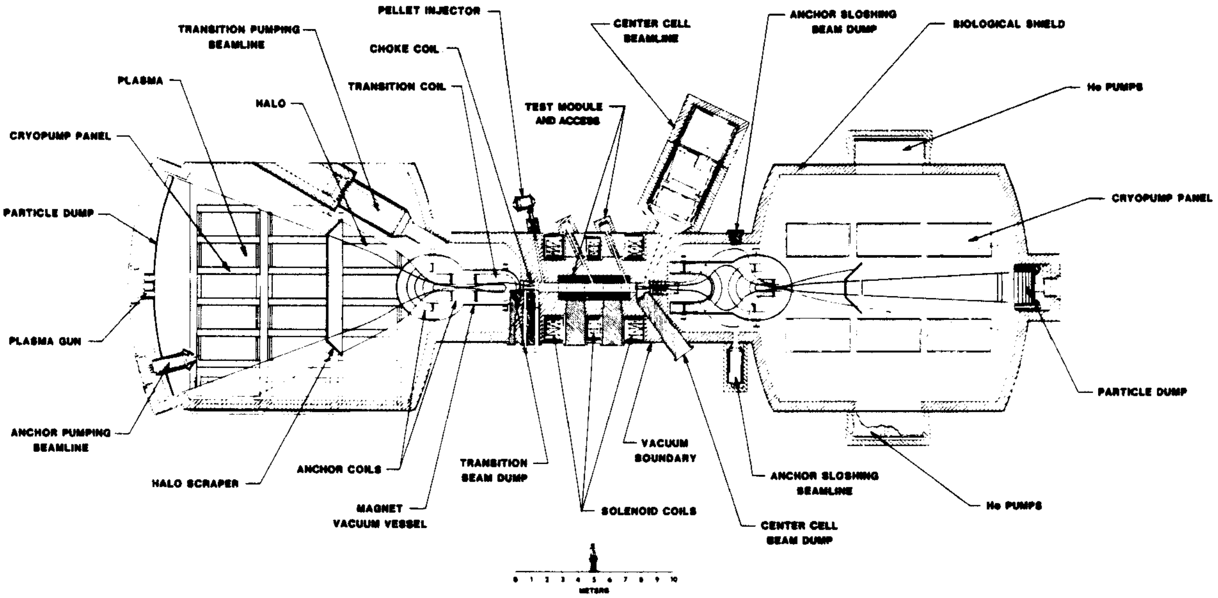

Fig. 1. A cutaway view of TDF.

conducting solenoid coils; one at the center of the machine (S0) and two at the ends of the central cell (S1).

Fusion reactors are required to accommodate a variety of penetrations. The purpose and size of these penetrations vary depending on the reactor type.[2-5] Proper shielding is required to protect the vital components in the penetration from excessive radiation damage caused by radiation streaming. In TDF, different penetrations are used for pumping, heating, fueling, and ion sloshing beams. Since the neutron source density in the anchor and end cells is about six orders of magnitude lower than that in the central cell, only radiation streaming into the central cell penetrations is analyzed. The central cell penetrations in TDF have different sizes and injection angles and must fit between the central cell magnets. Radiation streaming into these penetrations can lead to adverse radiation effects in the superconducting magnets. It is, therefore, essential to provide sufficient shielding between the duct wall and the magnets.

A major penetration in the central cell of TDF is the neutral beam injector (NBI) duct which is characterized by a large size. The duct opening at the first wall is 0.3 by 0.6 m. There are four such penetrations at each end of the central cell. In this work, a detailed streaming and shielding analysis for the NBI system is presented. Other central cell penetrations include pellet fueling and test specimen tube penetrations. These are small in size (approximately 7.5 cm in diameter) and have less severe streaming problems than the NBI ducts. Using a simple neutronics calculation, it was estimated that a minimum shielding thickness of 0.15 m is needed between these penetrations and the magnets. Hence, these penetrations can be accommodated in the central cell without causing any serious radiation streaming problem for the superconducting magnets.

RADIATION STREAMING INTO THE NBI DUCT

Evaluation of the radiation flow into the ducts requires an accurate knowledge of the neutron source and the geometrical configuration of the shield, as well as the size of the ducts. The MCNP[6] continuous energy coupled neutron-gamma Monte Carlo code was used to model the reactor geometry. The neutron source was sampled from the neutron linear source density distribution along the machine axis. The source density was normalized to a central cell neutron wall loading of 2 MW/m^2 at a radius of 0.25 m. A trapping surface was located at the entrance surface to the NBI duct. At this surface all particles entering the duct were counted according to energy and angle bins. Cross section data based on ENDF/B-V evaluation were used in the calculation.

The energy spectra of neutrons and gamma photons streaming into the NBI duct are shown in Fig. 2. The pronounced peak at 14.1 MeV in the neutron energy spectrum is due to the uncollided source neutrons streaming directly into the duct. This amounts to 44% of the streaming neutrons. A total of 3.08 x 10^{17} neutrons stream per second into the duct with an average energy of 6.91 MeV. A total of 5.63 x 10^{16} gamma photons averaging 1.44 MeV in energy stream per second into the duct. The angular distribution of neutrons and gamma photons are given in Fig. 3. The angle θ is measured from the normal to the duct entrance surface. It is clear that the angular distribution peaks at normal incidence. The injection angle (angle between duct and plasma centerlines) is 65°, implying that $\cos\theta = 0.9$. Therefore, a large fraction of streaming radiation will go directly towards the ion source at the end of the duct. In general, shielding requirements for the ion source are more severe for larger injection angles. These results were stored to serve as source distributions in later modeling of the NBI duct itself.

SHIELDING OF CENTRAL CELL SOLENOIDS AGAINST RADIATION STREAMING INTO THE NBI DUCT

Figure 4 shows the geometrical model used for modeling the NBI system of TDF. The model

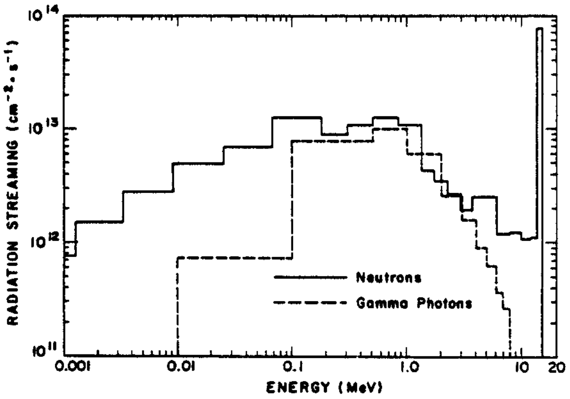

Fig. 2. Energy spectra of neutrons and gamma photons streaming into NBI duct.

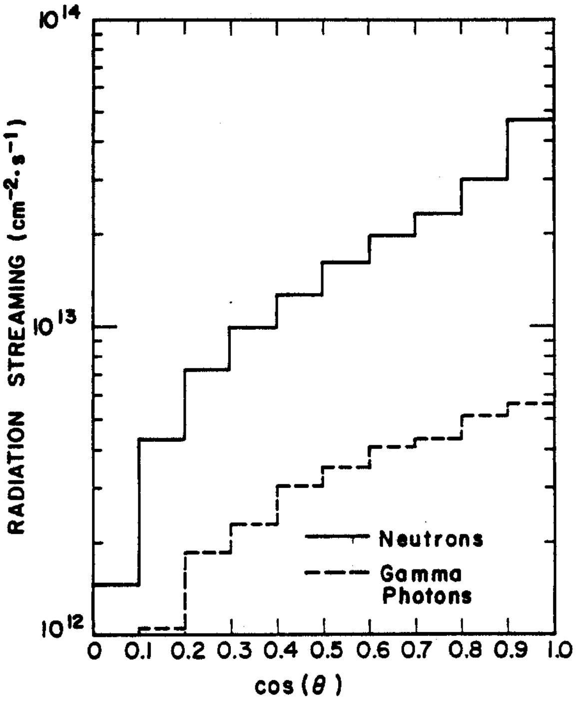

Fig. 3. Angular distribution of neutrons and gamma photons streaming into NBI duct.

is an idealization and adaptation of the actual NBI system design. The duct opens from a size of 0.3 by 0.6 m at the first wall to a size of 0.7 by 1.18 m at a distance of 3.2 m from the plasma centerline. A 1 cm thick stainless steel duct lining was modeled in the calculation. Only the corner of the central cell solenoid S1, which has the largest radiation effects from streaming particles, was modeled. The magnet winding pack consists of 2 vol% NbTi, 23.88 vol% Cu, 54.12 vol% 304 SS, 10 vol% liquid helium, and 10 vol% polyimide insulation. The magnet case, cryostat, and vacuum vessel surrounding the winding pack have a total effective stainless steel thickness of 0.125 m which was modeled in the calculation. Only 0.35 m space is available for shielding between the vacuum vessel at the magnet corner and the duct wall. The low activation steel Fe-1422 (14 wt% Mn, 2 wt% Cr, 2 wt% Ni, and 82 wt% Fe) was used in the shield. The shield consists of 56 vol% Fe-1422, 26 vol% B_4C, 14 vol% Pb, and 4 vol% H_2O. The option of replacing Fe-1422 by tungsten in the shield zone at the magnet corner was considered to provide adequate magnet protection.

The NBI system model used in the three-dimensional Monte Carlo calculation employs neutron and gamma surface sources at the duct opening with energy spectra and angular distributions obtained from the previous streaming calculation. An angular source biasing technique was used to get statistically adequate

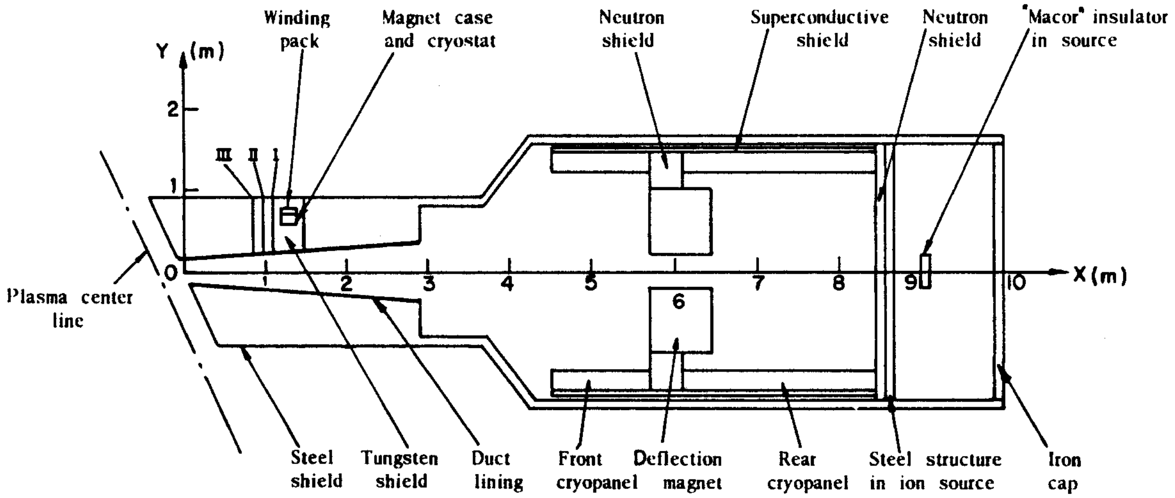

Fig. 4. Geometrical model of NBI system for MCNP calculation.

estimates for the quantities of interest. MCNP runs of 50,000 histories were carried out, resulting in statistical uncertainties less than 20%.

The shielding requirements for the central cell superconducting magnet S1 are determined by a number of radiation limits. A 20% increase in the electrical resistivity of the copper stabilizer, resulting from irradiation, is allowed. This corresponds to 1.1×10^{-4} displacements per atom (dpa) which should not be exceeded before the first magnet anneal. Annealing at room temperature results in only 80-85% recovery of the radiation induced defects.[7] Hence, annealing frequency should increase as one approaches the end of life of the machine. Based on machine availability requirements, a minimum period of one full power year (FPY) should be maintained between magnet anneals. For an estimated reactor lifetime of 5.4 FPYs, this implies that the first magnet anneal should occur after at least 2 FPYs. Therefore, the dpa rate in Cu should not exceed 5.5×10^{-5} dpa/FPY.

Mechanical strength tests of irradiated magnet insulators have shown that polyimides are 5 to 10 times more radiation resistant than comparably prepared epoxies.[8] The polyimide insulator retains more than 80% of its compressive strength up to a dose of 5×10^9 rads. This represents the limit on the radiation dose that should not be exceeded at the end of the machine's life. Irradiation of the superconducting material (NbTi) results in degradation of the critical current density. In this work, we require the peak neutron fluence (E > 0.1 MeV) to not exceed 3×10^{22} n/m^2 which corresponds to a 10% decrease in the critical current density.[9] The peak magnet heat load resulting from neutron and gamma heating should not exceed 0.06 mW/cm^3. This requirement was established to ensure that the nuclear heat load on the magnet does not cause excessively high cryogenic plant costs and powers.

Since in this calculation, only radiation effects in the magnet resulting from streaming into the NBI duct are considered, the extra contributions from the bulk shield must be accounted for. Based on detailed one-dimensional neutronics analysis, a bulk shield consisting of a 0.8 m thick zone made of 85 vol% Fe-1422 and 15 vol% H_2O followed by a 0.1 m thick B_4C shield was designed for TDF.[1] The bulk shield contributions to the radiation effects in the central cell solenoids are given in Table I. These values must be added to the beam duct streaming contributions to determine the peak radiation effects.

TABLE I

Bulk Shield Contributions to the

Radiation Effects in Central Cell Coils

Peak dpa rate in Cu stabilizer, dpa/FPY	7.6×10^{-6}
Peak dose in electrical insulator after 5.4 FPYs, rads	1.3×10^{8}
Peak magnet heat load, mW/cm^3	0.01
Peak neutron fluence (E > 0.1 MeV) after 5.4 FPYs, n/m^2	1.4×10^{21}

The MCNP results for the peak radiation effects in the S1 coil resulting from radiation streaming into the NBI duct are given in Table II. The results are given for the case when 56 vol% Fe-1422 is used in the shield and for the options in which Fe-1422 is replaced by tungsten along the duct at the magnet corner. In options I, II, and III, the tungsten shield lengths are 0.4, 0.5, and 0.6 m, respectively. The extra tungsten shield is added to the side close to the first wall as shown in Fig. 4 because most of the streaming neutrons will impinge on that part of the shield. Only option III will meet all design criteria and, hence, it is adopted in shielding the magnets against radiation streaming.

Adding the bulk shield contributions, it is clear that all design limits are met with substantial margin. The peak dpa rate in Cu is 1.6×10^{-5} dpa/FPY implying that no magnet annealing will be needed during the whole life of the machine. The peak radiation dose in the insulator at the end of life of the machine is 2.13×10^{8} rads. Hence, the less expensive (about a factor of five cheaper) epoxy can replace the polyimide. Further cost reduction might be achieved by slightly reducing the tungsten shield length at the magnet corner.

RADIATION EFFECTS IN VITAL COMPONENTS IN THE NBI SYSTEM

Radiation streaming into the NBI duct can cause adverse radiation effects in the vital components of the system. The geometrical model used in the calculations included the different critical components in the NBI system. Aluminum cryopanels are used to pump the tritium and deuterium gas. The 0.25 m thick cryopanels were

TABLE II

Peak Radiation Effects in Magnets from Radiation Streaming into the NBI Duct

	Fe-1422 Shield	W Shield		
		Opt. I	Opt. II	Opt. III
Peak dpa rate in Cu stabilizer, dpa/FPY	3.84×10^{-4}	1.1×10^{-4}	5.8×10^{-5}	8.4×10^{-6}
Peak dose in polyimide after 5.4 FPYs, rads	3.56×10^{9}	9.5×10^{8}	5.7×10^{8}	8.26×10^{7}
Peak magnet heat load, mW/cm^3	0.1	0.052	0.041	0.025
Peak neutron fluence ($E > 0.1$ MeV) in s/c after 5.4 FPYs, n/m^2	4.16×10^{22}	1.13×10^{22}	6×10^{21}	8.7×10^{20}

modeled as shown in Fig. 4. The heat deposition in the cryopanels has an impact on both the capital and operating cost of the system. The limit on the cryopanel heat load was set to be 10 mW/cm^3. The average heat loads in the front and rear cryopanels were found to be 0.96 and 0.027 mW/cm^3, respectively, which are well below the design limit.

Proper operation of the neutral beam lines requires that the area between the ion source and the deflection magnet is free of external magnetic fields. A superconductive shield is used for this purpose. This 0.05 m thick magnetic shield was modeled as shown in Fig. 4. The results for the superconductive shield are given in Table III. The results for dpa rate and heat load exceed the limits set for the central cell magnets. However, because of its small volume, the superconductive shield can be annealed more frequently. Furthermore, the total nuclear heating is small and does not require an excessive refrigeration system.

TABLE III

Results for the Superconductive Shield

Average heat load, mW/cm^3	0.47
Neutron fluence ($E > 0.1$ MeV) after 5.4 FPYs, n/m^2	1.76×10^{22}
Dose in polyimide after 5.4 FPYs, rads	2.57×10^{9}
Dpa rate in Cu, dpa/FPY	2.1×10^{-4}

The radiation problem of greatest concern in the ion source is the effect on the insulating electrode support structure. Because of its fabricability, MACOR machinable glass-ceramic is an attractive candidate insulation material. The structure of MACOR consists of a set of mica crystals embedded in a glass matrix. Since both glass and mica may undergo radiolysis, an enhanced damage rate in MACOR is possible. The MACOR used in the ion source is concealed from direct line of sight of source neutrons by a 0.1 m thick steel structure. Preliminary results showed that the ion source structure is not adequate to protect the MACOR from excessive radiation effects. An extra 0.1 m thick tungsten shield, with holes allowing for the beams to go through, is used in front of the steel structure.

For simplicity, only the MACOR insulator, steel structure, and tungsten shield were used to model the ion source. The 0.75 m thick deflection magnet, which provides further shielding for the ion source, was included in the model. Not included in the model are the thin neutralizer tubes which will have a very small effect on radiation damage to the ion source insulator.

An experimental study of radiation effects in MACOR indicated slight damage by 14 MeV neutrons at a fluence of 10^{22} n/m^2, which was estimated to correspond to a dose of 6 x 10^8 rads.[10] Our calculations show that the dose rate in MACOR is 2.17 x 10^8 rad/FPY implying that the ion source insulators will last 2.77 FPYs as far as radiation is concerned.

SUMMARY

A detailed three-dimensional neutronics and photonics calculation has been performed to analyze radiation streaming and shielding in the neutral beam injection system of TDF. Adequate shielding is required to shield the superconducting solenoids against radiation streaming into the NBI duct. Because of the limited space available between the magnet and duct wall, the option of using the more effective tungsten shield was considered. This results in peak radiation effects in the magnet which are well below the design limits. The radiation damage and nuclear heating of the various components in the NBI system were calculated. Acceptable heat loads were obtained in the cyropanels and superconductive magnetic shield. Because of the low radiation dose limit for MACOR, an additional 0.1 m thick tungsten shield in front of the ion source steel structure was required to increase the life of the ion source to 2.77 FPYs. We conclude from this study that the NBI penetration shield design for TDF will provide adequate protection for the superconducting magnets and other vital components in the system.

REFERENCES

1. "A Tandem Mirror Technology Demonstration Facility," UCID-19328, Lawrence Livermore National Laboratory (1983).

2. J. JUNG and M.A. ABDOU, "Radiation Shielding of Major Penetrations in Tokamak Reactors," *Nucl. Technol., 41,* 71 (1978).

3. M.M. RAGHEB, A.C. KLEIN, and C.W. MAYNARD, "Neutronics Shielding Analysis of the Last Mirror-Beam Duct System for a Laser Fusion Power Reactor," *Nucl. Technol./Fusion, 1,* 99 (1981).

4. R.A. LILLIE et al., "Neutron and Gamma-Ray Streaming Calculations for the Engineering Test Facility Neutral Beam Injectors," *Nucl. Technol./Fusion, 2,* 325 (1982).

5. L.A. EL-GUEBALY and C.W. MAYNARD, "End Plug Radiation Streaming in a TMR Neutral Beam Port," *Trans. Am. Nucl. Soc., 42,* 612 (1982).

6. "MCNP - A General Monte Carlo Code for Neutron and Photon Transport," LA-7396-M, Los Alamos National Laboratory (1981).

7. B.S. BROWN et al., "Low-Temperature Fast-Neutron Radiation Damage Studies in Superconducting Materials," *J. Nucl. Mat., 52,* 215 (1974).

8. R.R. COLTMAN and C.E. KLABUNDE, "Mechanical Strength of Low-Temperature-Irradiated Polyimides: A Five-to-Tenfold Improvement in Dose-Resistance over Epoxies," *J. Nucl. Mat., 103 & 104,* 717 (1981).

9. M. SÖLL, "Influence of Radiation Damage to the Maximum Attainable Magnetic Field for Toroidal Fusion Magnet Systems," *J. Nucl. Mat., 72,* 168 (1978).

10. J.D. FOWLER et al., "14 MeV Neutron Irradiation Effects in MACOR Glass-Ceramic," *J. Nucl. Mat., 103 & 104,* 755 (1981).