Impact of Shield Material in the Design of a LAR Tokamak Reactor

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1. Introduction

LAR (Low Aspect Ratio) tokamak plasma has the potential of high β operation with high bootstrap current fractions. In the LAR tokamak reactor, the radial build of TF coil(TFC) and the shield play a key role in determining the size of a reactor since it has impact on the various reactor components.

An inboard shield requires improved performance with respect to neutron economy for enough tritium breeding and shielding capability to protect the superconducting TF coil; the fast neutron fluence to the superconductor, the peak nuclear heating in the winding pack, and the radiation dose absorbed by the insulator. In addition to tungsten carbide which has been considered as a shielding material in many reactor studies, metal hydrides such as zirconium hydride and titanium hydride [1,2] are reported to provide a good shielding performance.

Also, to find space for the radiation shielding of the superconducting TF coil inside the torus, high critical current density at high magnetic field strength is required for the TF coil conductor. Recent progress in the development of superconducting material [3], promising much higher engineering critical current density bigger than 10 kA/cm^2 for high magnetic fields, led us to investigate the possibility of employing the superconducting TF coil in the aspect ratios of 1.5 ~ 2.0.

In this work the impact of shield materials in the design of a superconducting LAR tokamak reactor concept is investigated.

2. Tokamak Reactor System Analysis Coupled with Neutron Transport Analysis

For neutronic optimization of the blanket and the shield, the quantities such as the tritium breeding ratio (TBR), nuclear heating, radiation damage to the TF coil have to be calculated and neutronic analysis need to be coupled in the system analysis. In most of the previous system studies, neutronic calculation and plasma analysis are performed separately, so blanket and shield size was determined independently from the reactor size. In this work, to account for the self-consistent determination of blanket and shield with the other components of a reactor system, we coupled the system analysis [4] with one-dimensional neutronic calculation to determine the reactor parameters in self-consistent manner. One-dimensional radiation transport code, ANISN [5] with 30 neutron group cross section library based on JENDL-3.2 [6] is used to calculate the neutronic response of the components, For the estimation of the local tritium breeding ratio (TBR), the JENDL dosimetry file is used.

In a system analysis, the main mathematical model to capture the physics and technologies are the plasma power balance equation which is represented as

$$P_{con} + P_{rad} = P_{OH} + P_{\alpha} + P_{CD} \qquad (1)$$

where the conduction (P_{con}) and radiation losses (P_{rad}) are balanced by α particle heating (P_{α}), auxiliary heating (P_{CD}) and ohmic heating (P_{OH}). These terms have a complex dependency on the plasma parameters. For the confinement scaling, the H-mode IPB98y2 scaling law [7,8] is used.

The plasma performance is limited through a beta limit, a plasma current limit imposed by a limitation on the safety factor q at the edge, and the plasma density limit. Appropriate models for plasma composition, non-inductive current drive, bootstrap current fraction, divertor heat load etc. are also needed to calculate plasma performance and for a detailed explanation of these physics constraints, we refer to Ref. [4].

There are various engineering constraints, such as the radial/vertical build, the startup and burn volt-second capability, critical current density in the superconducting coil, the maximum TF field, the stress limit, the ripple condition, the divertor heat load limit and the shield requirements..

3. Impact of Shield Materials in the Size of a LAR Tokamak Reactor

We consider the LAR tokamak reactor where the blanket and shield are installed inside the vacuum vessel surrounding the plasma. Central solenoid coil and the inboard blanket are discarded. Then the radial build of a reactor consists of toroidal field coils, vacuum vessel, shield, blanket and plasma. The vacuum vessel is 100 mm thick stainless steel type SS316LN which is the same material as the ITER vacuum vessel. The thickness of the scrape off layer (SOL) is assumed to be 0.1 m. The radial build of the other components should be determined by the physics and engineering constraints which they should satisfy.

For the conductor of the TF coil, a high temperature super-conducting material, Bi2212 is assumed. SC filament operation current density is assumed to be 0.8 times the critical current density. The number of the TF coils is 16. The design stress of structure material for the TF coil case is assumed to be 800 MPa

The inboard shield plays the role of radiation shield for the TFCs. Metal hydrides and borohydrides as advanced shielding materials showed[2] superior neutron shielding capability compared to the conventional materials due to their high density of hydrogen. A mixture of tungsten and either titanium or zirconium hydride gives improved performance with respect to activation parameters of importance to waste management. A shield composed of tungsten carbide showed the best neutron shielding performance but it was shown that poor performance with respect to activation parameters. We investigate the impact of various shield materials on the design of LAR tokamak reactor.

The tritium production is mainly made by outboard blankets consisting of the He-cooled lithium lead (LiPb) as tritium breeding and neutron multiplying material, and the reduced activation ferritic steel as structural material.

The coupled system analysis code is used to find the minimum LAR tokamak reactor size, i.e., the major radius R_0 with the aspect ratio in the range of 1.5 to 2.0. We assume the maximum plasma performance with $q_a = q_{a,min}$, $\beta_N = \beta_{N,max}$, $H = 1.2$, and n/n_G =1.2. Figures 1 and 2 show the major radius R_0 as the magnetic field at magnetic axis B_T varies for the aspect ratio of 1.5 and 2.0. The minimum radius which satisfies all the physical and engineering requirements increases with B_T. A required inboard shield thickness is mainly determined by the requirement on the protection of the TF coil against insulator dose. For given fusion power, larger B_T is necessary for small R_0 and small auxiliary heating power The shielding capability is the best for WC and mixture such as W-TiH$_2$ and WC-Pb also shows good shielding performance. Thus with a fusion power bigger than 3,000 MW in the LAR reactor with a superconducting TF coil, a major radius bigger than 4.0 m is required for the reference case with the aspect ratio of 1.5. With larger aspect ratio of 2.0 the major radius can be reduced to be less than 4.0m, but 50% more auxiliary heating power is required as shown in Fig.2.

4. Conclusion

For self-consistent calculation of the physical and engineering constraints which relate the various components of a tokamak reactor, the system analysis code was coupled with the one dimensional radiation transport code, ANISN. It aws shown that with the use of advanced technology in the shield and superconducting TF coil, a compact superconducting LAR reactor with aspect ratio of less than 2 is a viable power plant.

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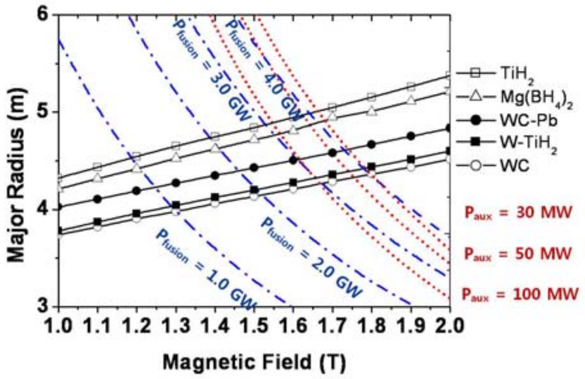

FIG. 1. Minimum major radius and plasma performance as a function of B_T when $A = 1.5$.

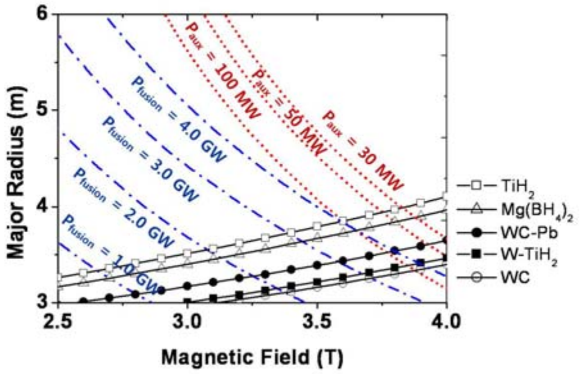

FIG. 2. Minimum major radius and plasma performance as a function of B_T when $A = 2.0$.