Shielding and Breeding Considerations for ST-Based HTS-FNSF Design

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Overview

- Shielding and tritium breeding assessments for ST-FNSF represent key elements for achieving design engineering objectives.
- First phase of study focused on:
  - Adequate protection of electrically efficient high-temperature superconducting (HTS) magnet against radiation
  - Tritium self-sufficiency using outboard-only blanket as much as practically possible.
- Numerous shielding and cooling materials have been examined to select optimal IB shield that primarily protects IB magnet of 3 m major radius device.
- 3-D shielding and breeding model included details of IB shield, OB blanket, long-leg divertor configuration, five OB blanket/materials testing modules, and several H/CD ports.

HTS-FNSF Could Bridge Technical Capabilities from ITER to DEMO

- HTS-FNSF provides:
  - Operating behavior in fusion environment
  - High neutron fluence (~6 MWy/m^2)
  - HTS magnet that operates with high current/field and reduce cryogenic load
  - Modular configuration with vertical maintenance scheme
  - Long-legged/Super-X divertor to control peak heat load
  - Critical database for materials and integrated components using US power-plant relevant technologies:
    - Tritium breeding blanket with TBR ~ 1
    - High temperature DCLL blanket to efficiently generate electricity.
- Substantial pre-FNSF R&D program is pre-requisite for FNSF design, construction, and operation.

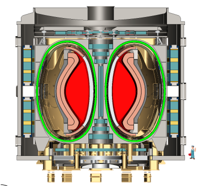
R= 3 m Configuration and Key Parameters

Major Radius	3	m
Minor Radius	1.5	m
Fusion Power	556	MW

Vertical Maintenance scheme

10 Sectors on Inboard (IB) side

20 Sectors on Outboard (OB) side

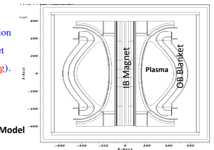


Plant Lifetime	~10.3	years	3.1 Full Power Years (FPY)
Availability	~30%		

Nuclear Analysis Performed with Sophisticated 3-D Neutronics Codes

- CAD coupled with MCNP using UW DAGMC code.
- Fully accurate presentation of entire torus.
- Neutron source model on R-Z grid, presenting fusion power density.
- No approximation or simplification involved in 3-D model.
- Evaluated:
  - Neutron wall loading distribution
  - Radiation damage at IB magnet
  - Tritium breeding ratio (ongoing).

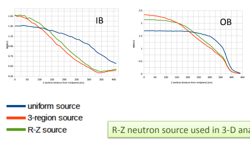
3-D Model

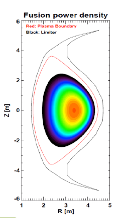


Neutron Wall Loading Distribution

Evaluated with 3 methods.

Average NWL	1.13 MW/m^2
Peak IB NWL	1.57 MW/m^2
Peak OB NWL	2.15 MW/m^2
Peak Div NWL	0.42 MW/m^2





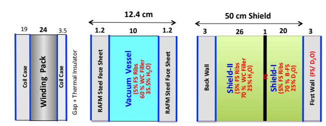
R-Z neutron source used in 3-D analysis

Radiation Limits

Overall TBR (for T self-sufficiency)	~ 1	
Damage to RAFM steel structure	20 < 50 > 65	dpa – GEN-I dpa – GEN-II dpa – ODS (NS)
Helium Production (for reweldability of FS)	1 ?	He appm
HTS Magnet (@ 20-40 K):		
Peak fast n fluence to HT superconductor (E_n > 0.1 MeV)	5 x 10^{18}	n/cm^2
Peak nuclear heating @ WP	5	mW/cm^3
Peak nuclear heating @ coil case	?	mW/cm^3
Peak dose to electrical insulator	5-10 x10^{10}	rads
Total nuclear heating in 10 TF coils	?	kW

Shielding Assessment

- Analysis focused on IB shield design.
- Main functions of IB shield:
  - Protect IB magnet for machine lifetime (3.1 FPY)
  - Enhance OB breeding by reflecting neutrons to OB
  - Generate low decay heat to control temperature response during accident ⇒ avoid using WC filler near FW.
- Assessed impact of candidate IB materials (ferritic steel, tungsten carbide, hydrides, water, borated water, and heavy water) on magnet shielding as well as reflecting neutrons to OB blanket to enhance TBR.
- Two-layer IB shield presents best option and satisfies design requirements:



Shielding Assessment (Cont.)

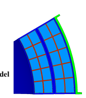
- Fast neutron fluence to HTS drives IB shield design.
- Combination of WC and H_2O represents superior shielding option as it helps reduce both fluence and magnet heating.
- Avoid:
  - Using B-H_2O **and** hydrides (having less shielding performance compared to WC/H_2O)
  - Straight radial assembly gaps.
- 3-D analysis confirmed radiation damage at IB magnet are below limits:

Peak fast n fluence to HTS (E_n > 0.1 MeV)	4.3 x 10^{18}	n/cm^2
Peak nuclear heating @ winding pack	1.7	mW/cm^3
Peak nuclear heating @ coil case	4.8	mW/cm^3
Peak dose to electrical insulator	4 x10^9	rads
Total nuclear heating in IB magnet	8.7	kW

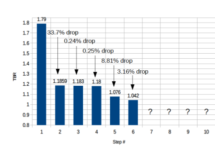
Blanket Design and Breeding Potential

- Dual-cooled LiPb blanket (DCLL) – preferred US blanket concept for DEMO and power plants.
- 1 m thick OB blanket divided into two segments (to accommodate vertical stabilizing shells)
- He-cooled structural ring (SR) supports 20 OB blanket sectors.
- Several ports penetrate VV, SR, and blanket.
- During operation, 4 tritium breeding modules (TBM) and one Materials Testing Module (MTM) develop more advanced blanket/materials technologies for GEN-II, III, and IV DCLL blanket systems.
- To accurately estimate the overall TBR, 3-D model included details of blanket internals and externals:
  - 2 cm wide assembly gaps between toroidal sectors
  - Internals of two OB DCLL blanket segments modeled in great details, including: FW, side, top/bottom, and back walls, cooling channels, SiC Flow Channel Inserts (FCI).
  - 2 cm thick W vertical stabilizing shell between OB blanket segments.
  - Ports (4 TBMs, 1 MTM, NNBIs).

3-D Blanket Model



Impact of Blanket Internals on TBR Evaluated in Steps (ongoing study)



Steps:

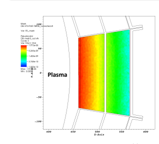
1. 1-D infinite Cylinder: 100% LiPb breeder with 90% enriched Li
2. $Li_{17}Pb_{83}$ confined to OB blanket region and blanket behind divertor
3. 2 cm assembly gap between blanket modules
4. FS structure and FCI added to homogeneous mixture of blanket at top/bottom ends and behind divertor only
5. Materials assigned to 4 cm thick OB FW
6. Materials assigned to side, bottom/top, and back walls of blanket

To be added:

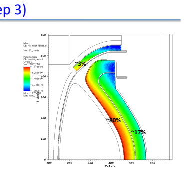
7. IB and OB cooling channels
8. SiC FCI
9. W Stabilizing shell
10. Penetrations.

Mapping of Tritium Production

(Step 3)



Horizontal cross section at OB midplane (one sector out of 20)



Vertical cross section through blanket regions

Inner segment of OB blanket provides most of breeding

Final Remarks

- Steps 7-10 will reduce TBR below unity.
- High aspect ratio STs (A ≥2) result in less OB blanket coverage and lower TBR.
- Options to enhance breeding include:
  - Adding thin breeding blanket on IB side (replacing 20 cm thick D_2O-cooled shield)
  - Move to lower aspect ratio (< 2) to increase TBR geometrically.
- Impact of adding thin IB blanket on magnet damage will be examined.