Scoping Neutronics Analysis in Support of FDF Design Evolution

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Objectives

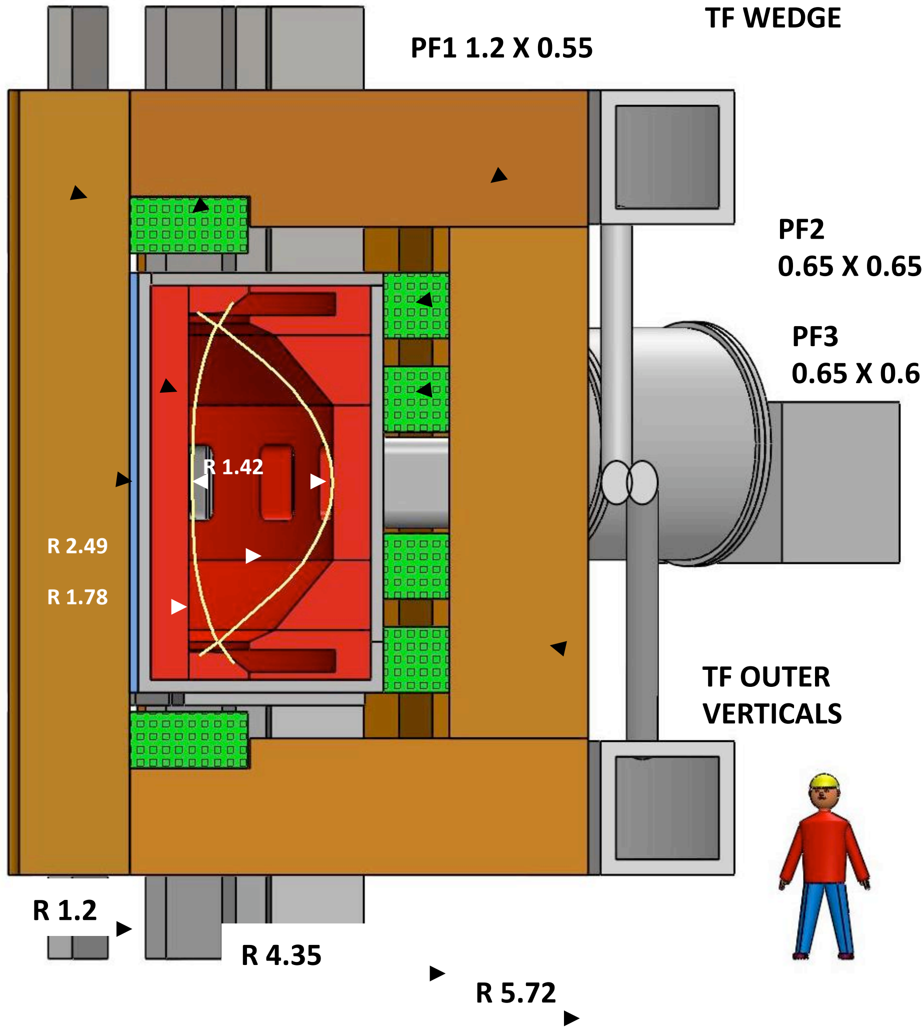
- Scoping analysis is required to guide the evolution of the FDF conceptual design and ensure that shielding and breeding requirements are satisfied

- Toroidal cylindrical 1-D calculations performed in this stage for IB and OB regions with detailed 3-D DAG-MCNP calculations performed after conversion on a conceptual design

Assumptions

- Assumed FDF parameters
  - R= 2.49 m, a= 0.71 m, A= 3.5
- Inboard shield/blanket is 50 cm thick
- Outboard blanket is 70 cm thick
- Normal Cu magnet used
- VV is placed between shield/blanket and magnet
- Assumed peak inboard fluence of 4 MWy/m^2, peak outboard fluence of 6 MWy/m^2 and average reactor fluence of 4 MWy/m^2. Results scale linearly with fluence

FDF Dimensions for Reference



TF CENTER POST

BLANKET 0.5 THK

OHMIC HEATING
COIL

PF1 1.2 X 0.55

TF WEDGE

PF2
0.65 X 0.65

PF3
0.65 X 0.65

7.15

TF OUTER
VERTICALS

R 1.2

R 4.35

R 5.72

Nuclear Parameters Determined and Design Limits

- IB and OB TBR
- Peak VV He production (for both FS and SS316 options)
  - Limit for reweldability is 1 He appm
- Peak fast neutron (E>0.1 MeV) fluence in magnet
  - Limit for superconducting magnets is 10^{19} n/cm^2
  - Limit for ceramic insulator is 10^{22} n/cm^2
- Peak absorbed dose in organic insulator
  - Limit for organic insulator is 10^{10} Rads

IB Options Considered

1) He-cooled FS shield
2) He-cooled FS shield with WC filler
3) Water-cooled SS shield
4) Water-cooled SS shield with WC filler
5) He-cooled FS shield with 6 cm Be behind FW
6) He-cooled FS shield with WC filler and 6 cm Be behind FW
7) DCLL IB blanket
8) 25 cm DCLL blanket followed by He-cooled FS shield with WC filler

Variations of options 2 and 8 were considered with B4C replacing WC filler

*Detailed layered radial build and material composition provided by S. Malang

Impact of IB Design

IB Design Option	1	2	2a	3	4	5	6	7	8	8a
	He/FS	He/FS/ WC	He/FS/ B4C	H2O/SS	H2O/SS/ WC	He/FS/ Be	He/FS/ WC/Be	DCLL	DCLL/ He/FS/ WC	DCLL/ He/FS/ B4C
IB TBR	0	0	0	0	0	0	0	0.37	0.25	0.22
OB TBR	1.00	0.90	0.73	0.75	0.57	1.03	0.97	0.94	0.93	0.90
Total TBR	1.00	0.90	0.73	0.75	0.57	1.03	0.97	1.31	1.18	1.12
Peak He appm in SS VV	27.2	0.57	1.04	0.77	0.15	16.6	0.80	18.9	2.1	1.7
Peak He appm in FS VV	0.34	0.09	0.59	0.15	0.05	0.42	0.14	1.5	0.41	1.2
Peak fast neutron fluence in magnet (n/cm^2)	5.1×10^{21}	9.4×10^{19}	3.1×10^{20}	7.6×10^{19}	1.2×10^{19}	2.0×10^{21}	8.8×10^{19}	4.5×10^{21}	2.9×10^{20}	2.7×10^{20}
Peak organic insulator dose in magnet (Rads)	4.1×10^{12}	8.4×10^{10}	2.2×10^{11}	9.5×10^{10}	1.3×10^{10}	2.3×10^{12}	1.2×10^{11}	3.6×10^{12}	4.1×10^{11}	3.3×10^{11}

Findings

- Without IB breeding, TBR is marginally OK (close to 1.0) only if He/FS shield is used with modest enhancement (3%) obtained if 6 cm Be is added behind FW
- Using WC, B_4C, or H_2O in IB shield, while improving IB shielding, has a devastating effect on TBR
- Worst IB shielding occurs if He/FS shield or DCLL blanket are used in all of IB space
- Using WC filler in He/FS shield improves shielding by two orders of magnitude with similar effect resulting from replacing He/FS shield by H_2O/SS shield
- Shielding improvement resulting from using WC filler in H_2O/SS shield is smaller
- Minimal effect on shielding performance results from using 6 cm Be behind IB FW
- B_4C is good at attenuating low energy neutrons compared to high and intermediate energy neutrons in WC resulting in lower TBR and higher VV He. Slight improvement in a few parameters when placed behind DCLL (option 8a)
- Best shielding performance results from using H_2O/SS/WC shield but TBR is only 0.57
- There is no problem with FS VV rewelding for most of the options
- Rewelding is an issue for SS VV for all options that yield reasonable TBR
- All options yield acceptable fluence for ceramic insulator but not for organic insulator
- Option 8 where an IB DCLL blanket is used followed by He/FS/WC appears to be the best compromise between breeding and shielding requirements

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GENERAL ATOMICS

Impact of IB Design on Cu Conductor Radiation damage

IB Design Option	**1** **He/FS**	**2** **He/FS/WC**	**3** **H2O/SS**	**4** **H2O/SS/WC**	**5** **He/FS/Be**	**6** **He/FS/WC/Be**	**7** **DCLL**	**8** **DCLL/He/FS/WC**
Peak Cu magnet damage (dpa)	**1.25**	**0.03**	**0.04**	**0.008**	**0.85**	**0.07**	**2.0**	**0.15**
Resistivity increase due to displacement damage (nΩm)	1.2	1.14	1.18	0.66	1.2	1.2	1.2	1.2
Resistivity increase due to solute transmutation (nΩm)	0.36	0.009	0.01	0.002	0.24	0.02	0.57	0.04
Total resistivity increase (nΩm)	1.56	1.15	1.18	0.66	1.44	1.22	1.77	1.24
% increase in OFHC Cu resistivity	**9.8%**	**7.2%**	**7.4%**	**4.1%**	**9.0%**	**7.6%**	**11.1%**	**7.8%**

Comments on Cu Magnet Damage

- Radiation levels up to 2 dpa could result in the Cu conductor
- Significant effect on physical and mechanical properties might occur
- The issue was addressed in FIRE though with much lower fluence
- Issues identified that need to be resolved include low temperature embrittlement, thermal creep at high temperatures, fracture toughness, and fatigue crack growth rate

  [M. Sawan, H. Khater, S. Zinkle, “Nuclear Features of the Fusion Idnition Research Experiment (FIRE),”” Fusion Engineering & Design, vol. 63, pp. 547-557 (2002)]
- Resistivity increase is dominated by that from displacement damage
- % increase in resistivity at end-of-life is modest (<11%) and not sensitive to shield option choice for RT operation and should not be a concern for any of the shield options. If magnets are operated at LN temperature (80K) with ~ 2 nΩ-m unirradiated resistivity, up to 90% increase in resistivity could occur

Further IB Design Assessment

- Preferred option divides the 50 cm IB blanket/shield space equally between blanket and He-cooled FS shield with 70% WC filler
- Design analyzed further by adding 8.5 cm OH coil made of 75% Cu, 10% spinel ($MgAl_2O_4$) ceramic insulator, and 15% H_2O placed in front of the IB leg of TF coil
- Assumed VV and OH coil are replaced at 1/3 the machine lifetime (@ 2 MWy/m^2 peak OB fluence) while the TF magnet is lifetime component
- Another option with water replacing He cooling in shield was considered
- Two breeding blanket concepts considered (DCLL, HCCB)
- Estimated required additional shielding to allow using organic insulators

Blanket Options Considered

Two blanket concepts were considered:

- ➢ Dual Coolant Lead Lithium (DCLL) blanket
  - FS structure/He/PbLi (90% Li-6)/SiC FCI
  - Radial build provided by S. Malang
- ➢ Helium Cooled Ceramic Breeder (HCCB) blanket
  - FS structure/He/Li_4SiO_4 (80% Li-6)/Be
  - Radial build provided by C. Wong

Impact of IB Design

IB Design Option	He-cooled shield		Water-cooled shield	
	DCLL	HCCB	DCLL	HCCB
IB TBR	0.25	0.23	0.23	0.22
OB TBR	0.93	0.83	0.92	0.83
Total TBR	1.18	1.06	1.15	1.05
Peak He appm in SS VV	1.68	0.80	0.31	0.29
Peak He appm in FS VV	0.10	0.15	0.07	0.11
Peak fast neutron fluence in OH coil (n/cm^2)	$1.9x10^{20}$	$1.2x10^{20}$	$4.7x10^{19}$	$4.4x10^{19}$
Peak organic insulator dose in OH coil (Rads)	$2.1x10^{11}$	$1.1x10^{11}$	$4.6x10^{10}$	$4.4x10^{10}$
Peak fast neutron fluence in TF coil (n/cm^2)	$7.3x10^{19}$	$6.2x10^{19}$	$2.9x10^{19}$	$3.3x10^{19}$
Peak organic insulator dose in TF coil (Rads)	$2.2x10^{11}$	$1.2x10^{11}$	$4.8x10^{10}$	$4.8x10^{10}$
Shield e-fold for organic insulator dose (cm)	7.6 cm	7.6 cm	5.5 cm	6.3 cm
Added shield for using organic insulator in OH coil	~23 cm	~19 cm	~8 cm	~10 cm
Added shield for using organic insulator in TF coil	~23 cm	~19 cm	~8 cm	~10 cm

Observations

- Both shield options with DCLL blanket yield reasonable TBR with slightly higher margin with He cooling
- Lower TBR obtained with HCCB blanket
- Using HCCB blanket in place of DCLL blanket results is slightly better shielding performance (due to large steel content and Be moderator) with He-cooled shield but comparable effects with water-cooled shield (that compensates for less steel and moderator in DCLL blanket)
- Rewelding VV is not an issue for all options if FS is used
- Using water-cooled shield allows rewelding for VV even if it is made of 316SS
- Replacing He by water in the shield reduces radiation parameters in VV, OH, and TF coils by factors of ~1.5-5
- All options yield acceptable fluence for ceramic insulator in both OH and TF
- Absorbed dose in organic insulator exceeds limit in both OH and TF coils
- Despite the added 8.5 cm shielding by the OH coil, end-of-life dose in TF coil is similar to that in OH coil which has 1/3 the lifetime
- In order to allow using organic insulators in OH and TF coils, shield thickness should be increased by ~8-23 cm depending on design option

OB VV and Magnet Parameters are not Sensitive to IB Shield Choice

	DCLL	HCCB
Peak He appm in SS VV	1.7	0.4
Peak He appm in FS VV	0.1	0.1
Peak fast neutron fluence in magnet (n/cm^2)	1.8x10^{21}	1.3x10^{20}
Peak organic insulator dose in magnet (Rads)	1.3x10^{12}	1.9x10^{11}
Added He-cooled shield to use organic insulators	~37 cm	~23 cm
Added H_2O-cooled shield to use organic insulators	~27 cm	~19 cm

- Both blankets provide adequate shielding for the VV if it is made of FS. If SS VV is used ~5 cm shield should be added between blanket and VV in case of DCLL blanket
- With the 70 cm OB blanket, the HCCB blanket provides significantly better shielding for the TF coil than the DCLL blanket
- Magnet is well shielded by either blanket if ceramic insulator is used. If organic insulator is used, we need to add ~19-37 cm shield in front of magnet depending on blanket and shield used

Generated tables with e-fold distances (cm) for attenuation in different materials to be used by designers for quick assessment of design changes

	Fast neutron flux	FS He production	Organic insulator dose
HCCB blanket (facing plasma)	11.5	9.1	11.7
DCLL blanket (facing plasma)	18.8	12.7	16.6
WC/He shield (behind HCCB)	9.4	6.2	7.6
WC/He shield (behind DCLL)	7.0	6.2	7.6
WC/H2O shield (behind HCCB)	6.7	5.9	6.3
WC/H2O shield (behind DCLL)	5.0	5.7	5.5

Recommendations

- If ceramic insulator is used in both OH and TF coils, the radial build can be left as is
  - 50 cm IB with blanket used in front half and shield used in back half
  - 70 cm OB all blanket
  - With both blankets (DCLL, HCCB) and either shield designs (He or water-cooled) magnets and FS VV are well shielded
- If organic insulator is used in OH and TF coils, additional shield is required
  - For water-cooled WC shield, adding ~10 cm to IB radial build and ~30 cm to OB radial build will work with both blanket options
  - For He-cooled WC shield, adding ~25 cm to IB and ~40 cm to OB will allow using both blanket options
  - For 80 cm OB radial build to work with organic insulator need 45 cm DCLL, 35 cm H_2O/WC shield; or 50 cm HCCB, 30 cm H_2O/WC but with reduced TBR
  - If we prefer using He/WC shield we can use organic insulators with 60 cm all shield in IB and 80 cm OB radial build (35 cm DCLL+45 cm shield or 45 cm HCCB+35 cm shield)
  - Thicker blanket at top and bottom of OB helps TBR
  - With this added shielding we can use superconducting magnets
- TBR is acceptable with DCLL but marginally OK with HCCB