Neutronics Assessment of Blanket Options for the HAPL Laser Inertial Fusion Energy Chamber

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Background

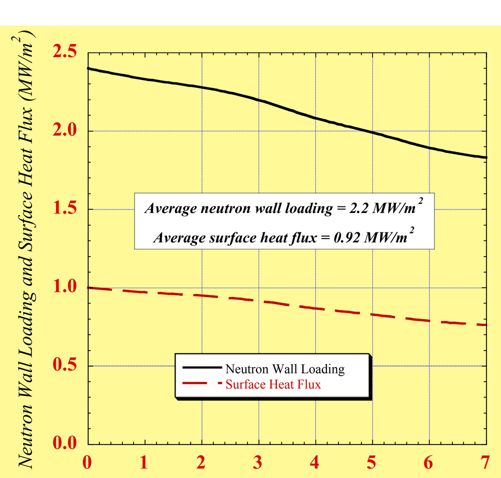
- High Average Power Laser (HAPL) program led by NRL develops IFE based on lasers, direct drive targets and dry wall
- Primary focus is development of W-armored ferritic steel FW that accommodates threat spectra from the fusion micro-explosion
- Only a thin region of armor (10-100 μm) experiences the highly cyclic x-ray and ion energy deposition transients
- FW structure behind armor as well as blanket will operate under quasi-steady-state thermal conditions, similar to MFE conditions
- It is possible to use blanket designs that are being developed for MFE and utilize information from large international MFE blanket R&D effort
- We carried out scoping studies of possible blanket designs that can be integrated with the FW protection scheme

Objectives

- Nuclear features compared for three candidate blanket designs in HAPL chamber:
  1. Self-cooled Li blanket
  2. He-cooled SB blanket with Be multiplier
  3. Dual-coolant LiPb blanket
- LAFS alloy F82H used as structural material
- He-cooled steel shield/VV used
- Common chamber parameters used in the neutronics analyses of the three blanket concepts

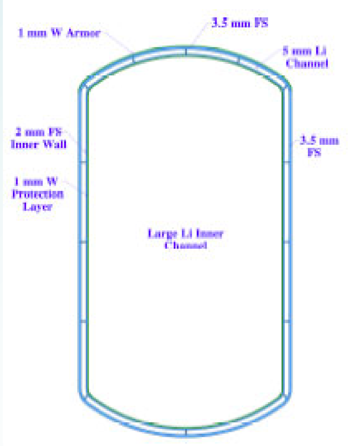
Common Basic Assumptions

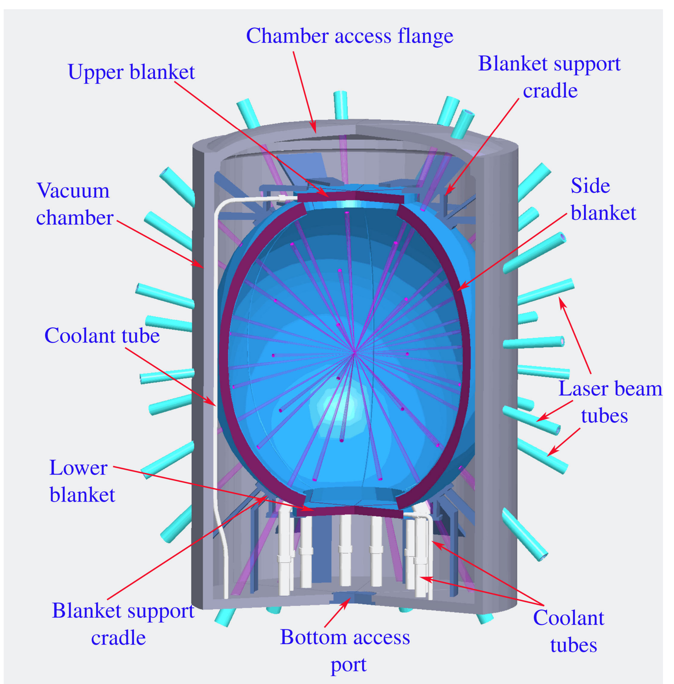
- 1 mm W armor on ferritic steel (F82H) FW
- Used target spectrum from LASNEX results (Perkins) for NRL direct-drive target
- 70.5% of target yield carried by neutrons with 12.4 MeV average energy
- 1.8 GW fusion power
- Chamber radius 6.5 m at mid-plane



Self-Cooled Li Blanket Design

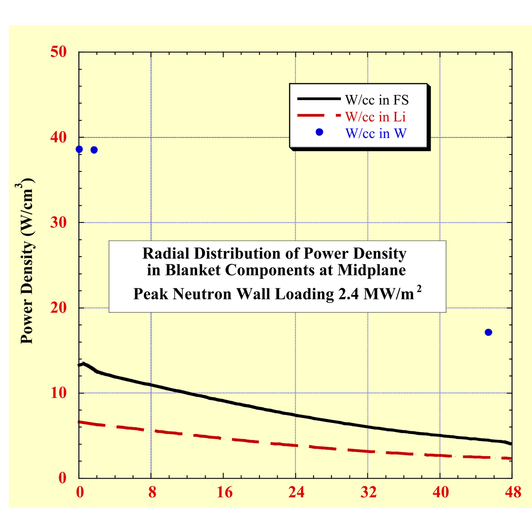
- This concept has similarities with that used in ARIES-AT
- There are 12 side blanket modules, each subtending 30° of circumference and each module is made of 13 sub-modules
- The sub-modules consist of two concentric rectangular tubes separated by a constant gap
- The blanket module containing the ports has a constant width special sub-module in the center, which contains the ports
- Lithium enters the sub-module at bottom and flows at a high velocity in gap between the tubes to cool FW, then makes a 180° turn and travels back at a very low velocity through the large central channel





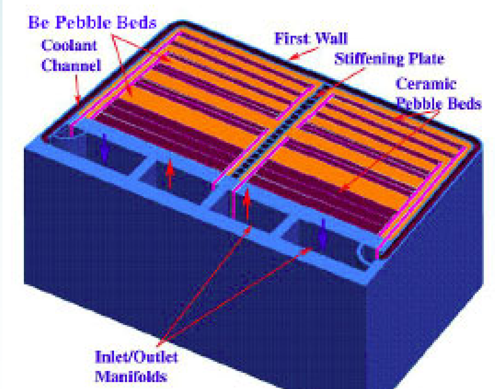
- Overall TBR >1.1 can be achieved with small Li content in top/bottom blanket (20%) and no breeder in VV. There is no need to enrich Li in Li-6
- VV can be lifetime component with minimum blanket thickness of 47 cm on the side and 30 cm in top/bottom
- Blanket lifetime expected to be ~10 FPY
- The He-cooled VV should be at least 50 cm thick to allow rewelding at its back
- Differential swelling at the interface between W armor and FS FW needs to be assessed. At interface, W dpa is lower than FS dpa by a factor of 3 and W He production is lower by a factor of 38. Nuclear heating in W is higher by a factor of 3

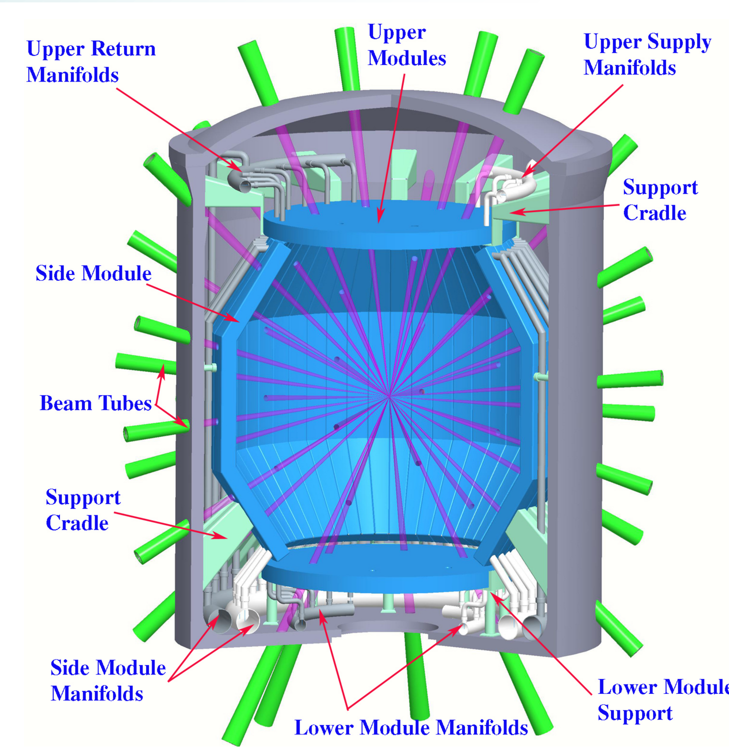
Nuclear Heating Distribution



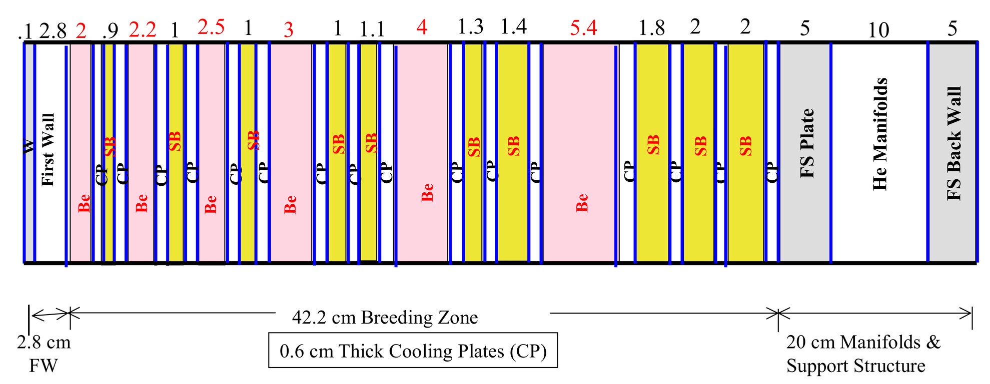
Solid Breeder Blanket Design

- This solid breeder blanket design has been mainly developed in Europe at FZK and has been considered for several designs including the EU-Demo and ARIES-CS
- The structure is ferritic steel and the blanket is entirely cooled with He gas
- The He gas, after cooling the FW, enters the breeding region which has plates of Be and solid breeder interspersed, and cools them before exiting the blanket and going to the heat exchanger





Radial Build of SB Blanket



- Radial build of ARIES-CS SB blanket used
- 65 cm total blanket thickness
- Li_4SiO_4 breeder and RAFS F82H structure
- 1 mm W armor used in front of FW
- Uniform Li enrichment (60% Li-6) used

Material composition in radial layers includes module sides

FW: 40.7% FS, 59.3% He

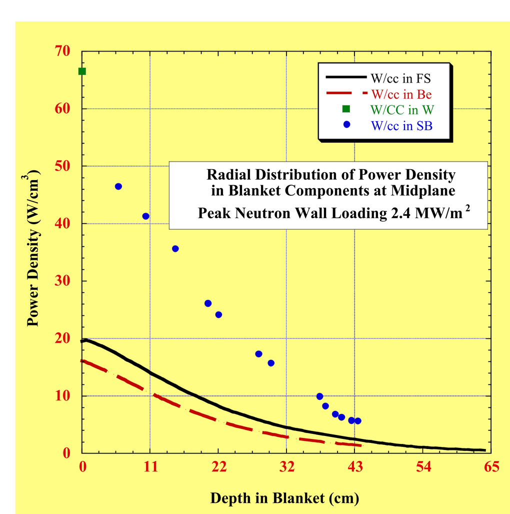
Be zone: 53% Be, 6% FS, 41% He

SB zone: 51% SB, 2.5% Be, 6% FS, 40.5% He

CP zone: 52% FS, 2.5 Be, 45.5% He

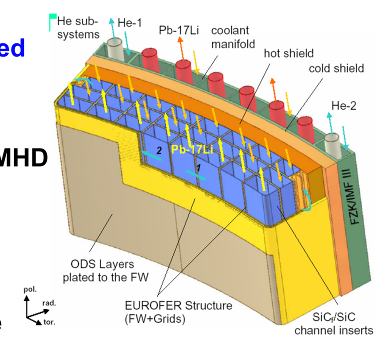
Nuclear Heating

- Nuclear heating calculated in radial zones of blanket and used in thermal hydraulics analysis



KEY FEATURES OF DUAL COOLANT LITHIUM-LEAD CONCEPT (DCLL)

- **Helium cools the ferritic steel FW and structure and is used for FW/blanket preheating and possible tritium control**
- **Breeding $Li_{17}Pb_{83}$ is circulating at low speed**
- **No separate neutron multiplier needed**
- **Use flow channel inserts (FCI) to:**
  - **Provide electrical insulation to reduce MHD pressure drop in MFE systems**
  - **Provide thermal insulation to decouple LiPb bulk flow temperature from wall temperature**
  - **Provide additional corrosion resistance since only stagnant LiPb is in contact with the ferritic steel structural walls**

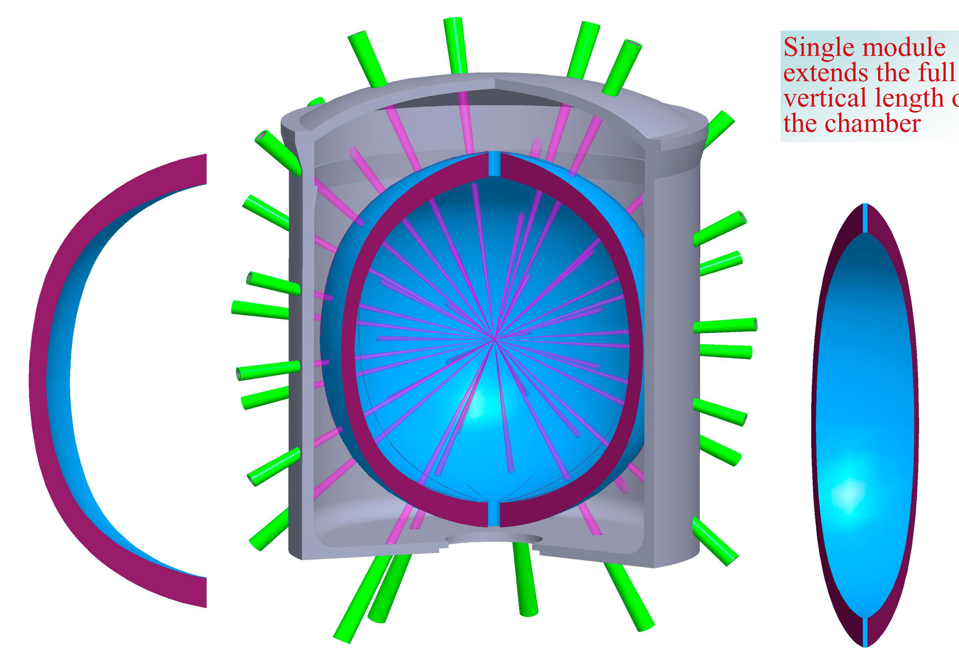


DCLL concept used in several MFE designs (EU Demo, US Demo, ARIES-ST, ARIES-CS) and will be tested in ITER TBM

DCLL Configuration in HAPL Chamber

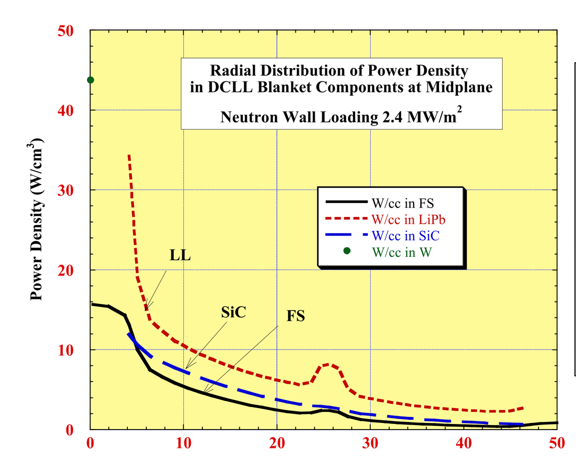
- Blanket designed to cover the entire vertical length of the chamber
- LiPb is admitted at bottom of blanket module, travels vertically upwards in a large channel behind FW, then makes a U turn at top, and travels down exiting the module on bottom. He coolant connections are also made on the bottom
- Toroidal channels are difficult to implement on the module extremities where it comes to a point. At those locations, at a distance of 2m from the ends, the cooling switches to vertical channels
- A horizontal manifold located near the FW feeds the vertical channels, which in turn exhaust into collector manifolds located at the sides of the module

Example Layout of Chamber with LiPb Blanket



Nuclear Heating

Radial variation of nuclear heating (W/cm³) determined in the components of the DCLL blanket



- Power density in W armor 43.8 W/cm³
- Peak power density in FS structure 15.6 W/cm³
- Peak power density in LiPb 34.2 W/cm³
- Peak power density in SiC FCI 11.9 W/cm³

Comparison between Nuclear Performance of Li, SB, and LiPb Blankets in HAPL

	Li Blanket	*SB Blanket*	*DCLL Blanket*
Overall TBR	1.12	1.17	1.17
Blanket thickness (cm)	47	65	52
Total Thermal power (MW)	2103 (12% He)	2302 (100% He)	2096 (40% He)
Power density in FW structure (W/cm³)	13	20	16
Peak FS damage rate (dpa/FPY)	19	20	26
Peak EOL (40 FPY) dpa in VV	170	19	58
Blanket lifetime (FPY)	10	10	7
Required VV thickness (cm)	50	30	30
Thermal Efficiency	*~45%*	*~30-35%*	*~40-45%*

Summary of Nuclear Performance Differences between Candidate Blankets

- The three blankets have comparable TBR values >1.1 ensuring tritium self-sufficiency. There are design flexibilities to allow adjusting the TBR if needed
- Thicker SB blanket with significant amount of Be required for tritium breeding (due to low breeding capability of SB and large amount of structure needed for the cooling plates between the many layers of SB and Be)
- While no lithium enrichment is required for the Li blanket, the SB and DCLL blankets require Li enrichment
- The large amount of Be in SB blanket yields ~10% more thermal power but this is offset by the much lower thermal efficiency
- Power density in FW of SB blanket is 20-40% higher than for the other blanket designs adding a burden on the FW cooling
- While all of thermal power is carried by He in the case of SB blanket, only 12%, and 40% is carried by He in cases of Li and DCLL blankets with rest carried by breeder
- While FW radiation damage is similar for Li and SB, it is about 30% higher for the DCLL blanket which is reflected in shorter blanket lifetime
- Thicker VV is required with Li blanket (due to poor shielding capability of Li) to allow rewelding at back of VV
- VV is a lifetime component in three cases
- Based on the neutronics results, the Li blanket seems to be the preferred option. However, other considerations (material compatibility, safety, tritium retention/control, thermal efficiency, complexity, fabrication, weight, cost, development risk and R&D cost, …) should be accounted for in the blanket selection