Thermofluid Magnetohydrodynamic Issues for Liquid Breeders

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Outline

- **The Big Issue: MHD Pressure Drop**
- **Other Thermofluid MHD Issues**
- **Liquid Breeder Concepts**
- **R&D on MHD Issues**
- **Conclusions**

Past References:

1. S. Malang, P. Leroy, G. P. Casini, R. F. Mattas and Yu. Strebkov, “Crucial issues on liquid metal blanket design,” *Fusion Engineering and Design*, 16, 95 (1991).
2. S. Malang, H.U. Borgstedt, E.H. Farnum, K. Natesan, I.V. Vitkovski, “Development of insulating coatings for liquid metal blankets,” *Fusion Engineering and Design,* 27, 570 (1995).
3. I.R. Kirillov, C. B. Reed, L. Barleon, K. Miyazaki, “Present understanding of MHD and heat transfer phenomena for liquid metal blankets, *Fusion Engineering and Design,* 27, 553 (1995).

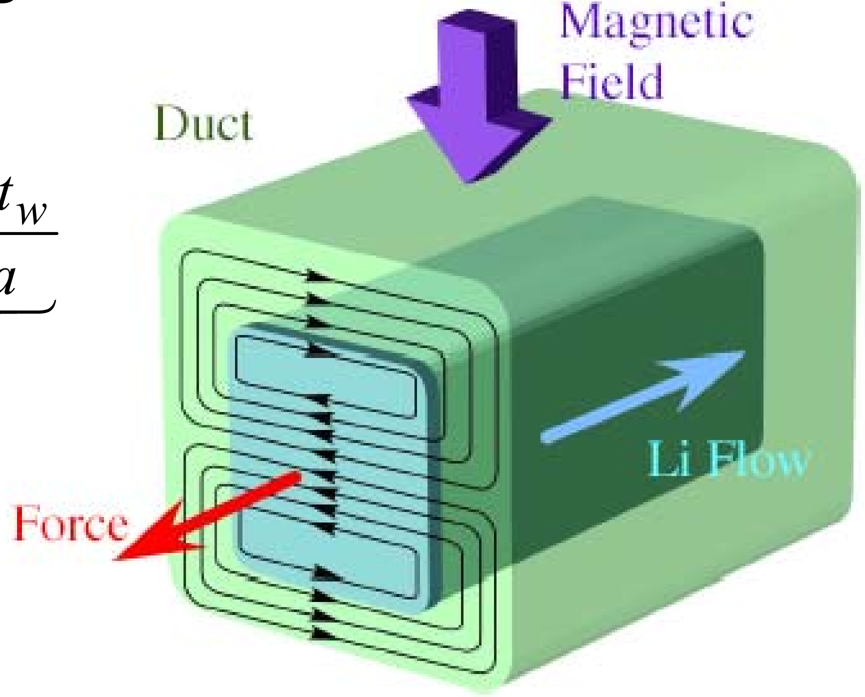
Main Thermofluid Issue for LM Blankets: MHD Pressure Drop

<u>Feasibility issue</u> - MHD retarding force is very high for electrically conducting ducts and complex geometry flow elements, especially long, high field, inboard flow channels

$$\Delta p_{MHD} = LJB \approx L\sigma VB^2 \underbrace{\frac{\sigma_w t_w}{\sigma a}}_{c}$$

$$\dot{m} = q'''La^2 \Big/ c_p \Delta T$$

$$S \approx Pa / t_w$$



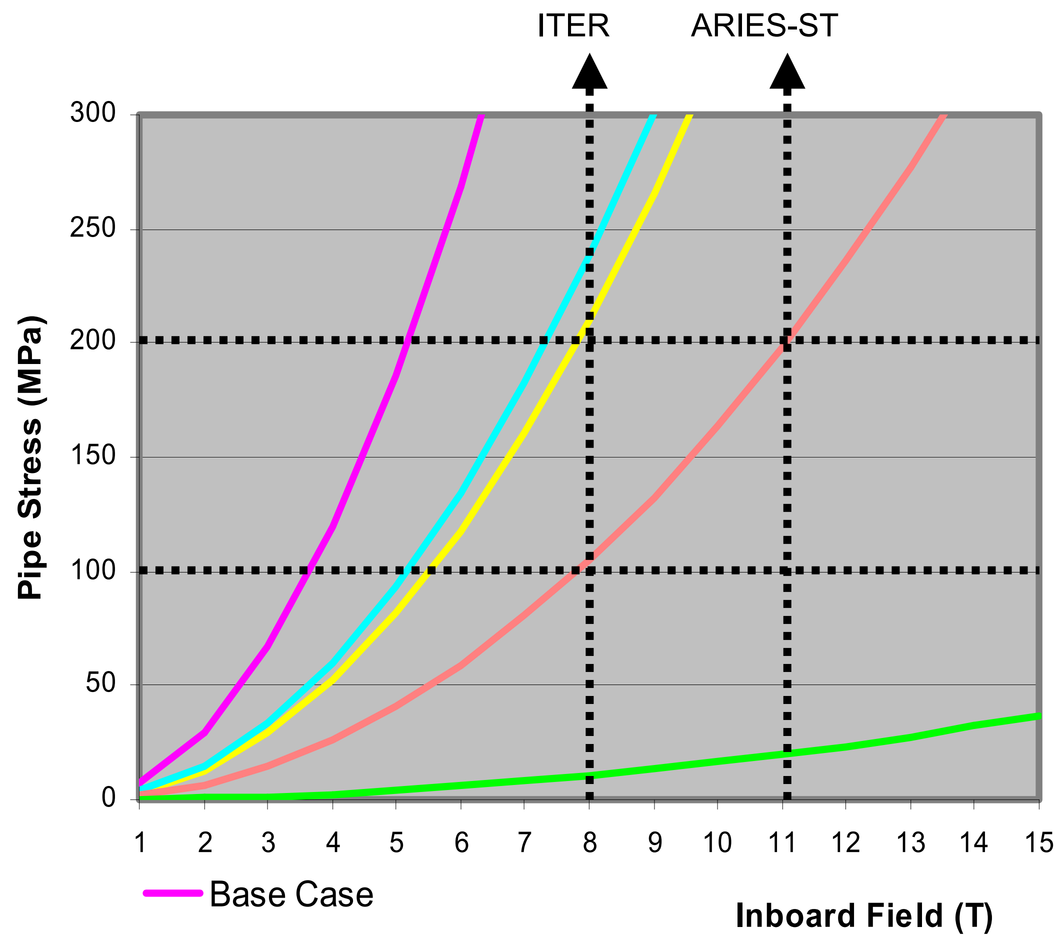
No stress window for inboard blanket operation at high wall load

$$S = \frac{(\mathrm{NWL})L^2B^2\sigma_w}{a\rho c_p \Delta T}$$

But NWL,*L*,*B*,*a* fixed by machine

U ~ 0.1-0.7 m/s

P_{max} ~ 5-10 MPa



Base Case

NWL = 2.2 MW/m2

DT = 300

DCLL flow conditions only

DCLL with FCI insulation

<u>Base Case</u>

NWL = 5 MW/m2

Pb-17Li alloy

RAFM steel

L = 8 m, a = 20 cm

ΔT = 150K

What can be done about MHD Pressure Drop?

$$\Delta P = cL\sigma_l VB^2$$

c represents a measure of relative conductance of induced current closure paths

- **Lower c**
  - Insulator coatings
  - Flow channel inserts

  } Break electrical coupling to thick load bearing channel walls

  - Elongated channels with anchor links or other design solutions

  } Force long current path
- **Lower V**
  - Heat transfer enhancement or dual/separate coolant to lower velocity required for first wall/breeder zone cooling
  - High temperature difference operation to lower mass flow
- **Lower B,L**
  - Outboard blanket only (ST)
- **Lower** σ (molten salt)

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Pressure drop effect on flow balance

- Changes in effectiveness in insulator can also have large effects on the flow balance between parallel channels.
- Velocity varies linearly with the pressure difference, so $v_1/v_2 = c_2/c_1$
- This is a significant issue for liquid metal blankets, even if the overall pressure drop is acceptable.

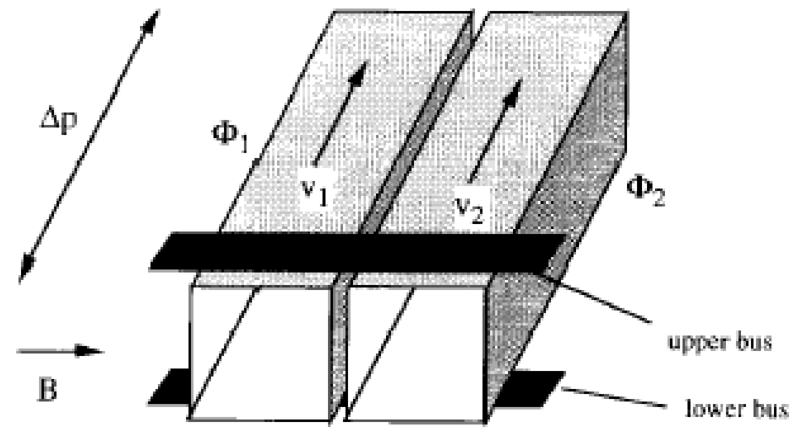
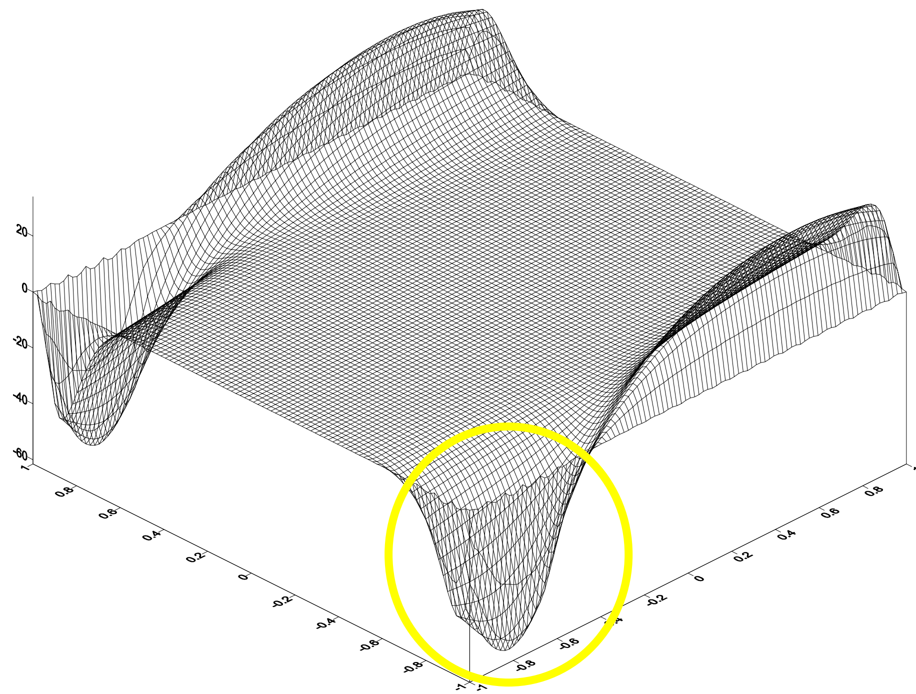


Fig. 7. Locally coupled ducts.

- It is desirable to choose and insulation scenario where small changes in insulation do not produce large changes in pressure drop.
- Another possible mitigation technique is to force some degree of flow balancing by electrically connecting the channels in clever ways

MHD velocity profiles and effect on heat transfer

- The velocity itself is modified by the MHD forces it creates via JxB force
- Typical fully velocity profiles in ducts with conducting walls include the potential for very large velocity jets near or in shear layers that form parallel to the magnetic field.
- In channels with insulator coatings these reversed flow regions can also spring up near local cracks.
- The impact that these velocity profiles have on the thermal performance can be strong.
- Reversed or stagnant flow can lead to hot spots, especially for self cooled designs where the LM flow must cool the heated walls.



Reversed flow region due to cracks in insulator coatings – fully developed velocity profile

Other Thermofluid MHD phenomena affecting heat transfer, corrosion, and tritium transport

- **Natural convection and degree of MHD damping**
  - MHD can act to suppress natural convection, but
  - **Concepts with large thermal gradients and slow liquid breeder velocity will likely be affected by natural convection phenomena**
- **Turbulence damping**
  - Turbulence is damped by magnetic field in conducting channels
  - Turbulence may persist in modified form even for strong magnetic fields in insulated channels
  - **Turbulent heat transfer may be affected/reduced in low conductivity liquid breeders (molten salts)**
- **Electrolysis**
  - **High speed (1-10m/s) molten salt may generate voltages sufficient to decompose**

What are the world blanket concepts utilizing liquid breeders?

- **Self-cooled Lithium with Vanadium alloy structure and integral electro-insulating barrier**
  - Russia, US, Japan have designs and current research
  - **Russia leading this concept for testing in ITER**
  - Example: ARIES-RS, BCSS
- **Separately-cooled Lithium / Helium with reduced activation ferritic-martensitic (RAFM) steel structure**
  - Korea working on design, concept is new
  - **Korea leading this concept for testing in ITER**
- **Self-cooled lead-lithium alloy with SiC_f/SiC structure**
  - EU and US have advanced designs
  - No ITER testing planned
  - Examples: ARIES-AT, EU Tauro concept
- **Separately-cooled lead-lithium / helium with RAFM steel structure**
  - EU mainline blanket design, evolved from water-cooled lead-lithium design
  - **EU leading this concept for testing in ITER**
  - Example: EU-HCLL

Are there others?

- **Dual-coolant lead-lithium / helium with RAFM steel structure and SiC composite flow channel inserts**
  - US and EU have designs and current research
  - **US leading this concept for testing in ITER**
  - Example: ARIES-ST, EU-DCLL, US-TBM Reference (Wong)
- **Self-cooled molten salt (Flibe or Flinabe) with RAFM steel structure and Be neutron multiplier**
  - US and Japan have designs and current research
  - No ITER testing currently planned
  - Example: Japan FFHR, US-TBM Reference (Wong), US IFE
- **Dual-coolant molten salt (Flibe or Flinabe) molten salt / helium with RAFM steel structure and Be neutron multiplier**
  - Only US has designs and current research
  - No ITER testing currently planned
  - Example: US-TBM Reference (Wong)

Liquid Lithium Breeder

- **Configuration:**
  - Self-cooled
  - Vanadium alloy structure
- **Reference Designs:**
  - Blanket Comparison and Selection Study
  - Tokamak Power Systems Study
  - ARIES-RS

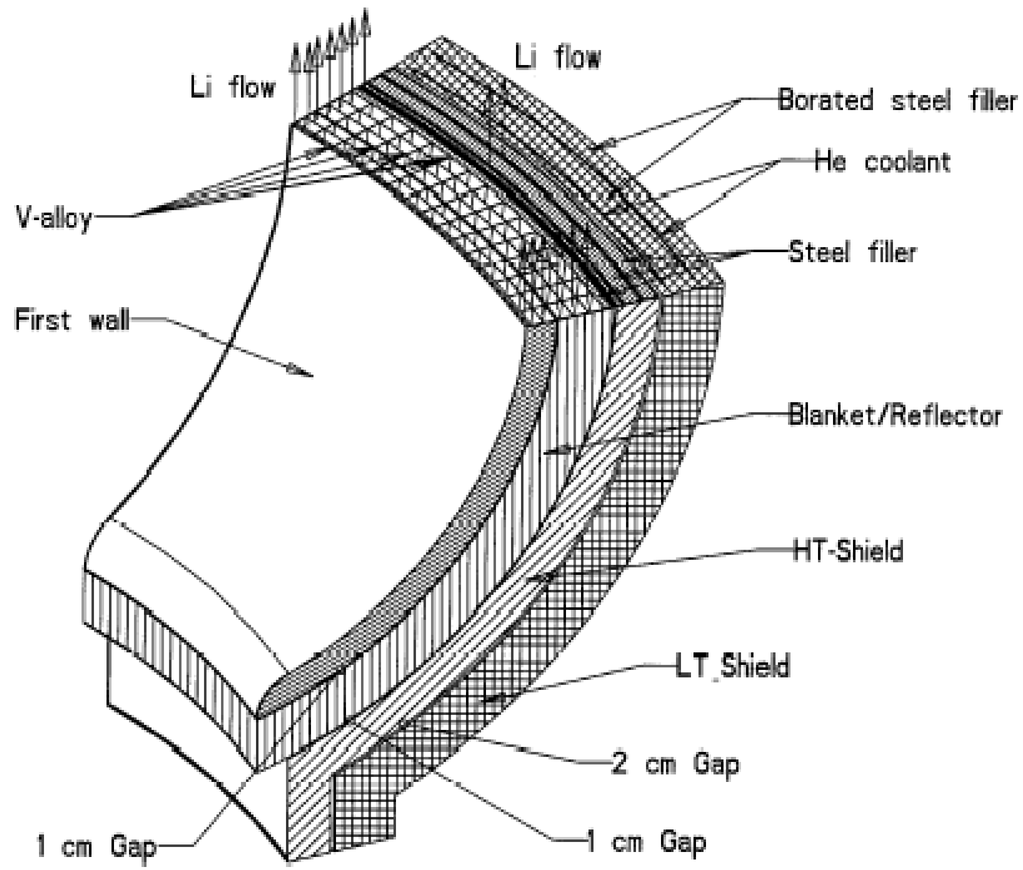


Fig. 3. Outboard blanket and shield.

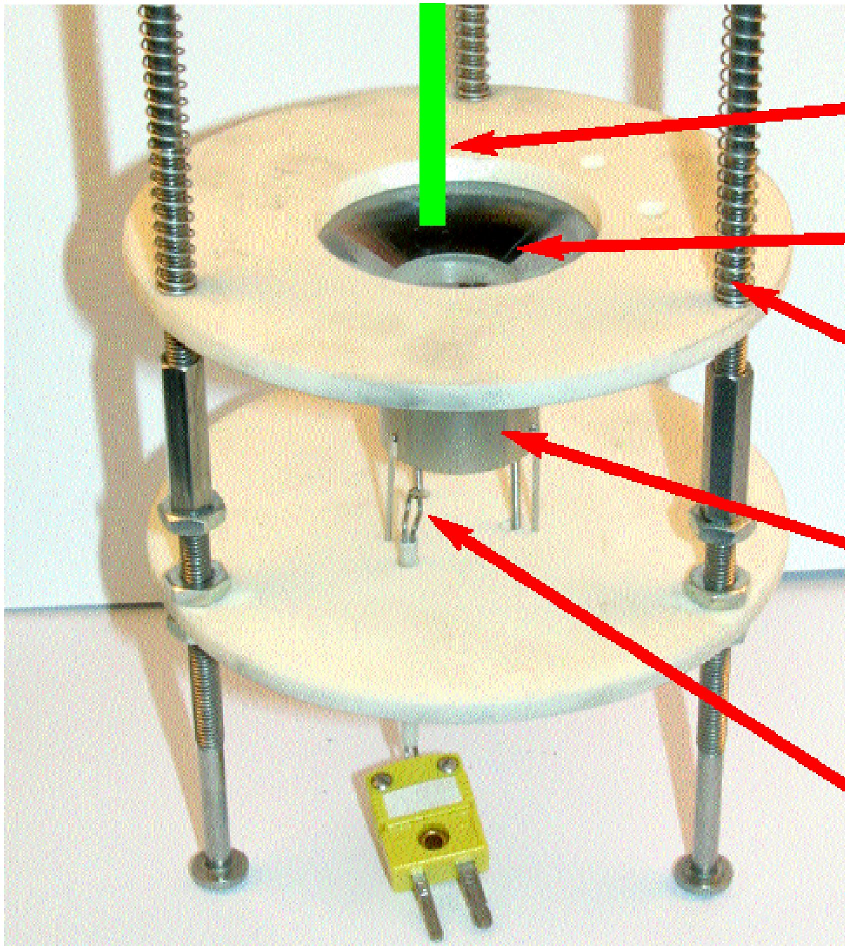
Insulator coating main focus in US, Russia, Japan for Li/V

- **Ideal coatings are the ideal solution, research on-going**
- **Tolerable crack fraction (assuming Li wetting) appears to be quite low, well below that achievable with real coatings**
  - How well does the lithium penetrate small cracks and electrically contact the pressure bearing wall as a function of time?
  - What is the crack fraction, size, distribution as a function of time?
  - Can self-healing work?
- **US materials people pessimistic about self-healing, suggestion has been made to move to multi-layer insulating barriers – alternating layers of insulator and metallic protection layer**
  - Metal layer seals underlying insulator so insulator cracks have no effect.
  - Thickness of metal layer will govern pressure drop

(See Thursday Morning, Bruce Pint, *Recent Progress Addressing Compatibility Issues Relevant to Fusion Environments*)

“in-situ” coating test

measure resistance of coating in contact with Li



All contained in large Ar glove box to minimize reaction

Additional plexiglass containment to capture Li vapor

high vapor pressure above 400°C could limit experiment

Multiple Layer Coatings

- Corrosion of this liner is an important potential issue.
- The thin metallic coating could even be a free standing liner, as long as it was supported everywhere so as not to balloon out in unsupported regions by the large liquid pressure.
- Russian research in this area going on for several years having difficulty achieving dense metallic layers on top of AIN insulator coatings by spraying technique
- Considering separate metallic liners or baked on foils

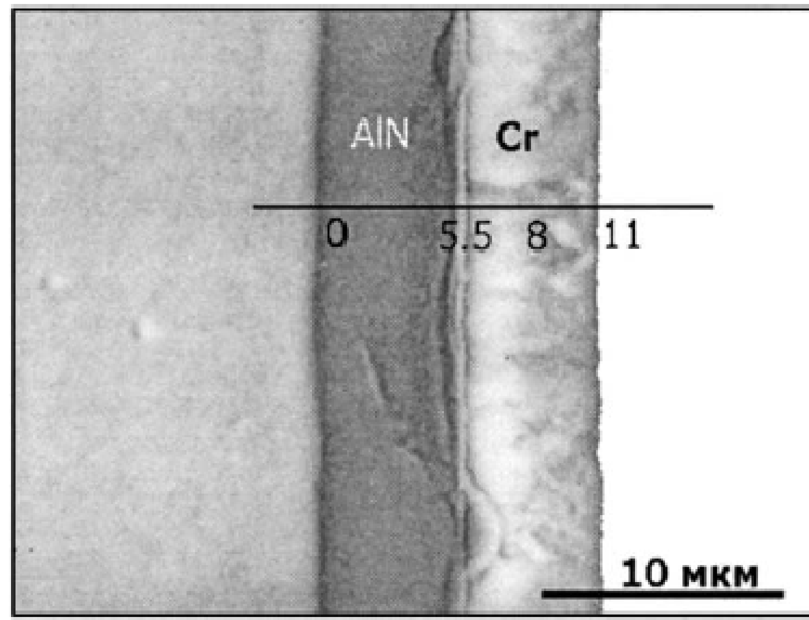


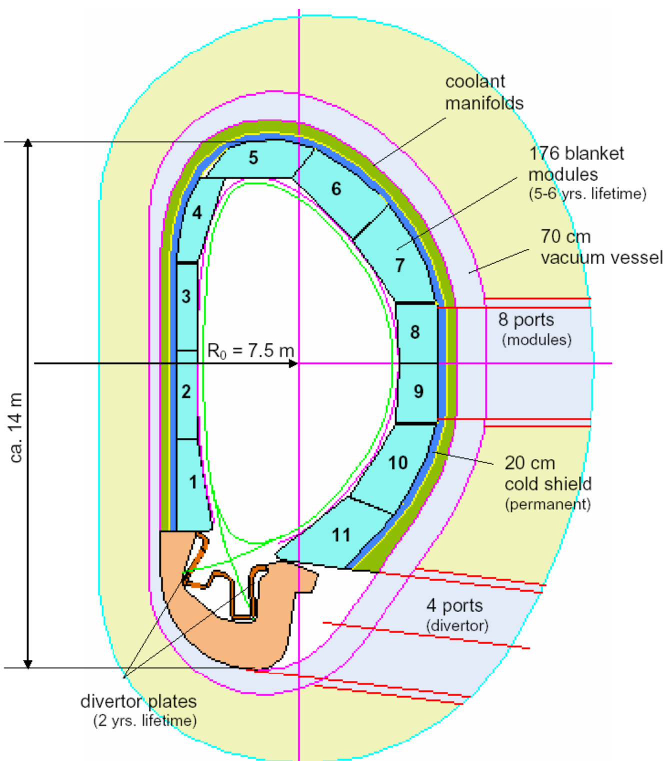
Fig. 2. AlN+Cr coating on VCrTi, $h_{AlN} = 5.5$ μm, $h_{Cr} = 5.5$ μm, $h_{Cr2O3} = 3$ μm (sample No. 7.1).

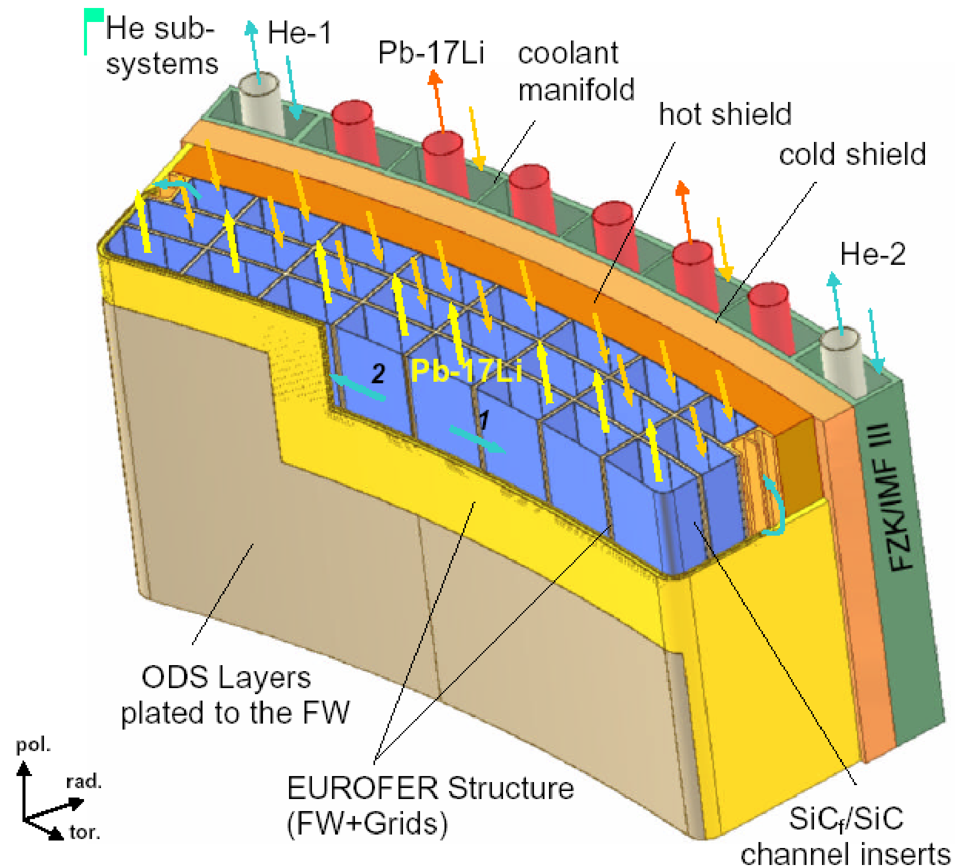
Vitkovkski et al. FED, v. 61-62 (2002)

EU Advanced Dual Coolant DEMO Blanket (FED, 61-62, 2002 or FZKA 6780)

Features:

- **Inboard/Outboard poloidally segmented blanket modules, each with two-pass poloidal Pb-Li flow**





Key features of Dual Coolant Lead-Lithium DCLL Concepts

- **Cool FW and ferritic steel structure with separate coolant – He (also used for preheating)**
- **Breeding zone is self-cooled Pb-17Li moving at a slow velocity – no separate neutron multiplier needed**
- **Use flow channel inserts (FCIs), wherever possible to:**
  - Provide electrical insulation to reduce MHD pressure drop
  - Provide thermal insulation to decouple PbLi bulk flow temperature (~800 C max) from ferritic steel wall temperature (~500 C max)
  - Serve as corrosion barrier

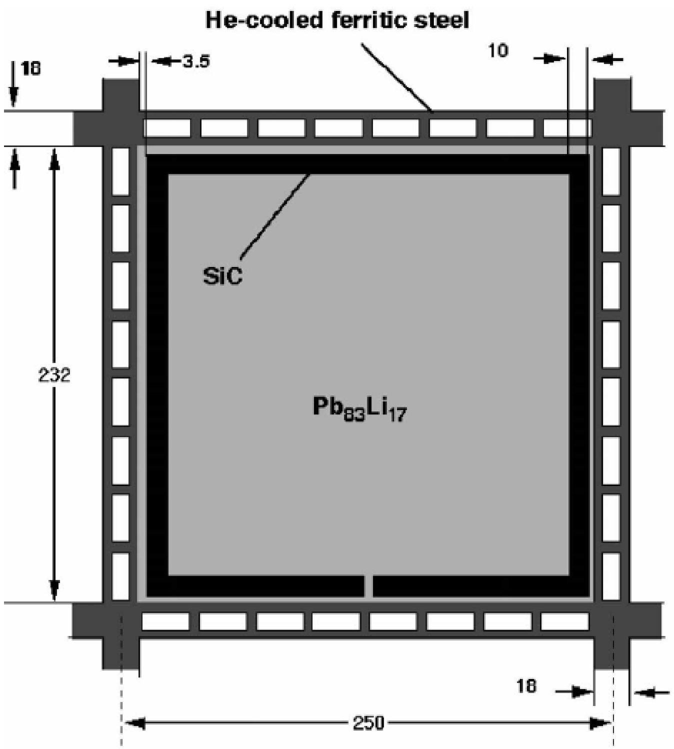
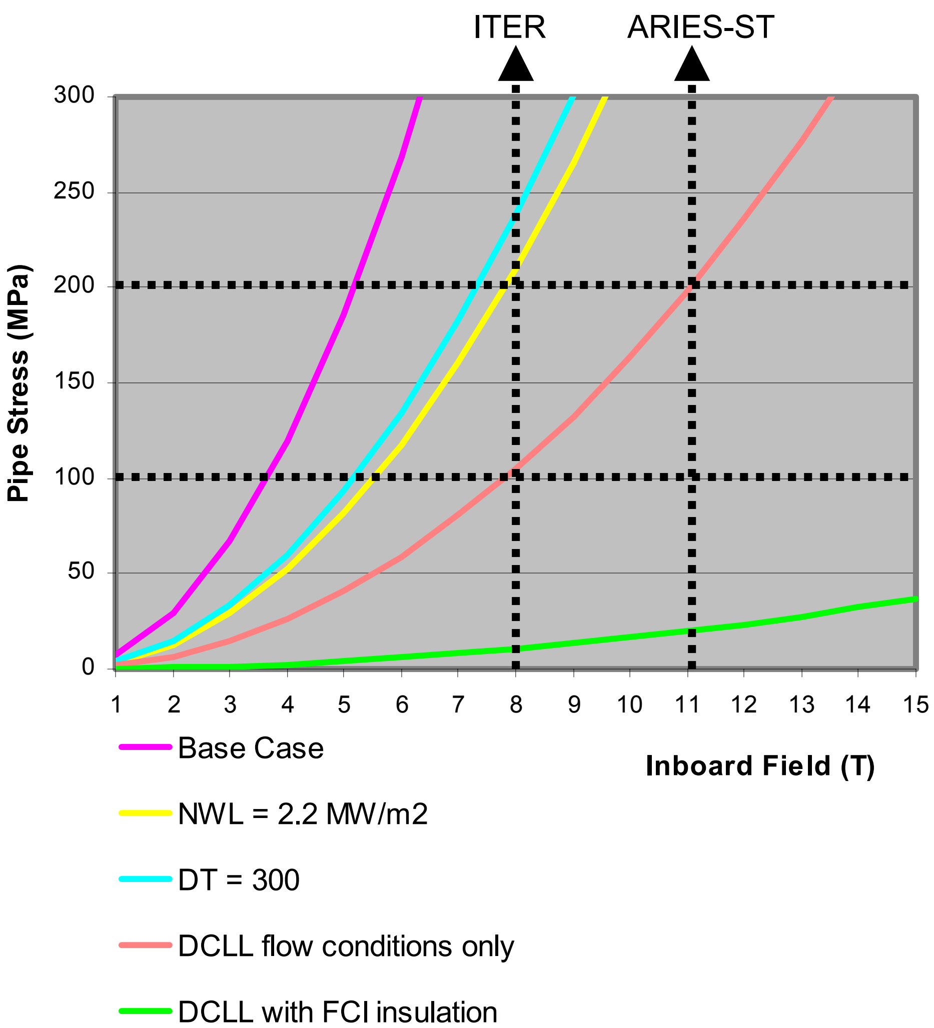


Fig. 8. Cross section of the breeder region unit cell.

Aspects of DCLL design that help in MHD pressure drop

- **Low velocity** due to elimination of the need for FW cooling reduces MHD pressure drop
- **Higher outlet temperature** due to FCI thermal insulation and separate structure cooling allows large coolant delta T in breeder zone, resulting in lower mass flowrate requirements and thus lower velocity.
- **Electrical insulation** provided by insert gives effective wall conductance ratio, c ~ 10^{-3} to 10^{-2}

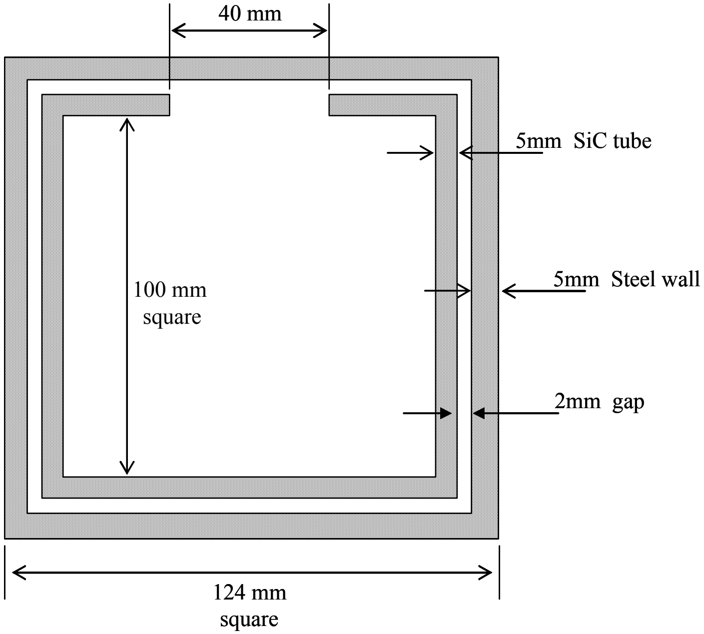


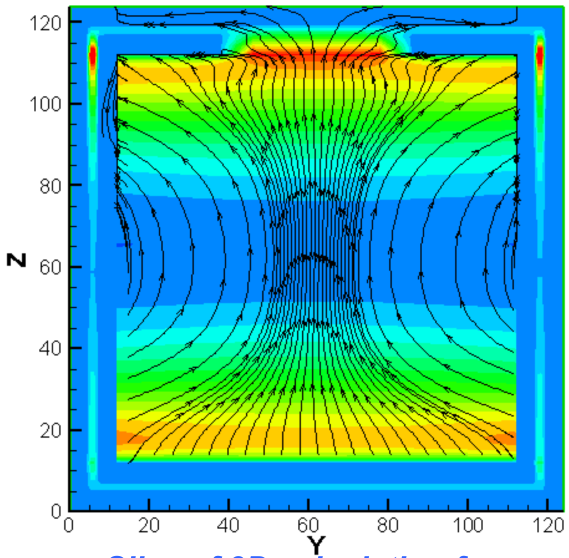
Flow Channel Insert properties and failures critically affect thermofluid MHD performance

- Electrical and thermal conductivity of the SiC/SiC perpendicular to the wall should be as low as possible to reduce pressure drop and to avoid velocity profiles with side-layer jets and excess heat transfer to the He-cooled structure.
- The inserts have to be compatible with Pb-17Li at temperatures up to ~800 °C
- Liquid metal must not "soak" into pores of the composite in order to avoid increased electrical conductivity and high tritium retention. In general, dense SiC layers are required on all surfaces of the inserts.
- There are minimum primary stresses in the inserts. However, secondary stresses caused by temperature gradients must not endanger the integrity of irradiated FCIs.
- The insert shapes must be fabricable and affordable

MHD analysis of imperfect FCIs and geometric complexities

- ❑ **Primary issue for blanket application and ITER testing is the MHD pressure and flow distribution for complex geometry flow elements:**
  - SiC FCI overlap regions (stovepiping)
  - Defects in FCIs
  - Flow balancing sections
  - Turns in poloidal plane
  - Toroidal to poloidal turns
  - Radial to toroidal manifolds
  - Contractions/expansions in poloidal plane
  - Coaxial Pb-Li supply/return lines
- ❑ **R&D and utilization on 3D HIMAG in US and Inertialess code in EU is continuing**
- ❑ **Experimental validation will be required for many flow elements – the need will be determined this year.**





Slice of 3D calculation from HIMAG showing current

SiC FCI effect on pressure drop

- **A low σ *perpendicular* to the wall is desired to keep overall pressure drop low**

dp/dx~.015MPa/m

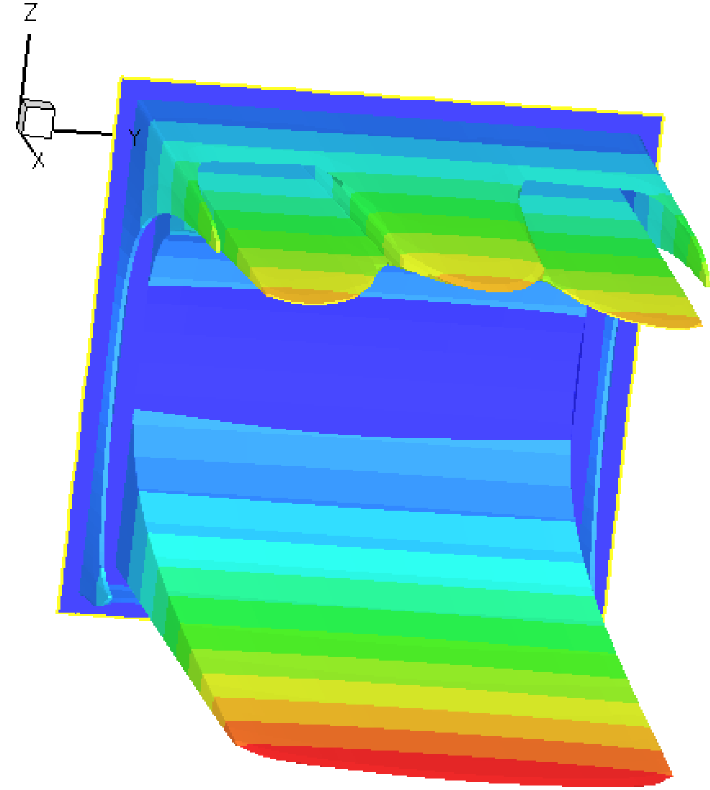
For ITER testing conditions:

- Flow domain: 16 cm x 16 cm
- FCI (SiC/SiC$_f$): 5 mm
- RAFM steel wall: 5 mm
- Magnetic field: 5 T
- Pressure equalization slot: 8 mm
- Liquid: Pb-17Li

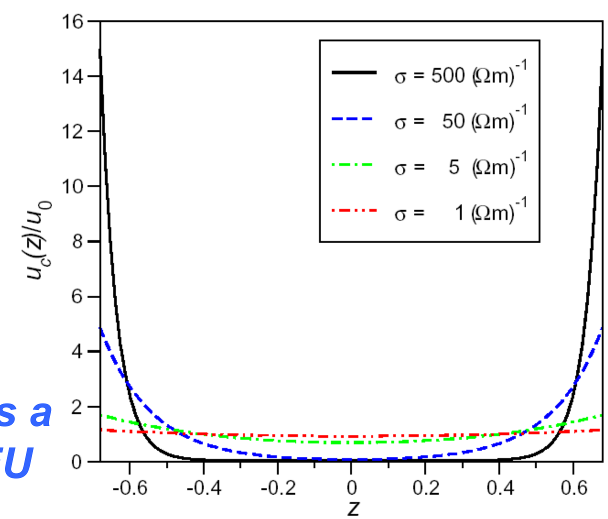
	Relative pressure drop
Insulated walls	10^{-3}
FCI (with σ_{SiC}=10 S/m)	10^{-2}
FCI (with σ_{SiC}= 200 S/m)	10^{-1}
Bare wall	1

Strong velocity jets should be expected for DCLL at present estimates for SiC conductivity

- Velocity profile shows strong jets with σ_{SiC}= 500 S/m
- Velocity jets seen even in “stagnant” Pb-17Li layer between insert and walls
- σ_{SiC}~ 5 S/m needed to eliminate large velocity jets



Slice of 3D calculation from HIMAG showing velocity jets

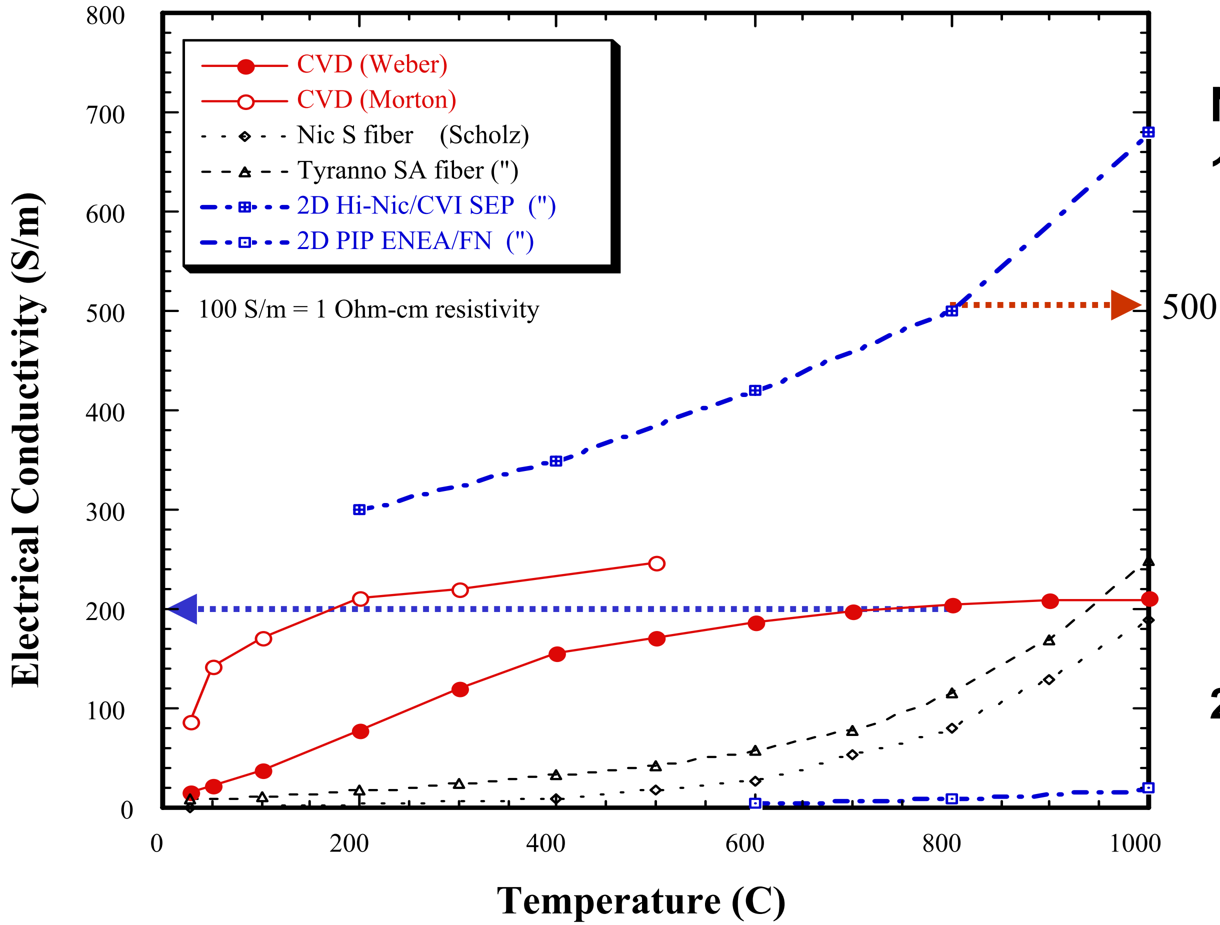


Side layer formation as a function of σ_{SiC} from EU

Achievable electrical conductivity in SiC composites

- Electrical conductivity (along fiber) is strongly influenced by carbon interlayer between SiC fiber and matrix used to add pliancy, blunt crack propagation, and provide strength and radiation resistance in the otherwise brittle composite.
- PROPOSED ASSUMPTION: An interlayer is needed, so the most probable case scenario for a 2D weave composite with fibers parallel to the SiC/Pb-17Li interface is to assume:
  - parallel (to the fibers and the interface) conductivity dominated by the interlayer to be 500 $\Omega^{-1}m^{-1}$ (likely this can be reduced)
  - perpendicular conductivity dominated by dense SiC matrix to be 200 $\Omega^{-1}m^{-1}$ (currently being measured by J. Youngblood PNNL)
- Further reduction of σ_{perp} (to ~10) can be accomplished by using amorphous SiC matrix and introducing small scale porosity in the matrix (like via the polymer infiltration and pyrolysis PIP technique) however this adversely affects the strength of the composite by reducing the area bonded to fibers.
- REMAINING QUESTION: is there a technique for reducing the SiC matrix conductivity in such a way that irradiation resistance and strength are not significantly affected.

Composite, fiber, and monolithic SiC conductivity data



Electrical conductivity of several SiC-based materials. Red is monolithic CVD-SiC, black is bare fibers, and blue is 2D SiC/SiC composite parallel to the fabric layers.

Notes:

1. At high temperatures the monolithic, dense, SiC conductivity becomes intrinsic (mostly independent of impurities that cause variations at low temperatures)

2. Composite measurements are along the fiber direction, not perpendicular to it

What experiments needed to determine Pb-Li SiC compatibility?

Compatibility of Pb-17Li with SiC has not yet been established based on existing data – this is the primary feasibility issue for the whole DC concept with PbLi

1. **More definitive capsule experiments required to show first level of compatibility (not all experts believe this is necessary/productive)**
   - More prototypic SiC sealed composite should be used
   - Exposure time long enough to overcome any incubation period for wetting
   - Careful post-examination of both SiC crucible for evidence of attack and PbLi melt for accurate Silicon concentration
2. **As an intermediate step suitable models should be developed and the basic material properties (most important diffusivity and saturation concentration as functions of temperature) should be obtained from the literature when available, and from dedicated experiments as necessary.**
3. **Final quantification of the allowable interface temperature will require experiments in a loop with relevant temperature gradients, typical materials, and realistic flow conditions.**

Data on Pb-Li compatibility with SiC from FZK shows some evidence of attack

(Kleykamp, JNM, v. 321, p. 170, 2003)

- **Capsule experiments at FZK with limited volume of Pb-17Li in contact with monolithic sintered SiC (sintered with small amounts of B and Al) for 672 hours showed:**
  - Silicon concentration in the PbLi of 0.017 mass% (eqv. to 1.7 μm loss from the crucible) for 600 C exposure
  - Silicon concentration of 0.035 mass% for 800 C exposure
  - Silicon concentration of 0.05% and roughened crucible wall with SiC granuale in the PbLi melt for 1000 C exposure
  - Very strong gradient of near wall and core Silicon concentration in PbLi , indicating low Si diffusivity.
- **However, there is some dissent about the applicability of any conclusions from this work**
  - The conclusion are drawn from Si concentration measurements in the Pb-17Li which may not be accurate at such low levels with microprobes
  - The material with added sintering aids is not very prototypic. Sintering aids may have influenced attack, and small SiC particles may have affected microprobe measurements.

Data on Pb-Li compatibility with SiC from CEA and ORNL indicates no attack

- **Capsule experiments at CEA with limited volume of Pb-17Li in a TZM crucible in contact with Cerasep N3-1 SiC/SiC composite for 3000 hours at 800C show:**
  - No variation in the initial concentration of Si at 12 ppm in the Pb-17Li
  - Some adhesion of the Pb-17Li to the SiC but no measurable change in sample dimension (within 10's of microns) or surface morphology changes seen in SEM micrographs.
  - Rotating disk samples had similar results on as received surfaces, and some penetration into pores on machined surfaces

  (Deloffre et al., RT-SCCME 586, 2001; and Deloffre et al., EFDA TW2-TTMA-001, 2003)
- **Capsule experiments at ORNL with limited volume of Pb-17Li in contact with monolithic CVD SiC surfaces for 1000 hours show:**
  - No visual evidence of attack or wetting on monolithic SiC at 800 C
  - Limited wetting (cleaned up with no SiC mass loss) at >1100 C
  - No measurement of melt Si concentration

  (Pint, ICFRM-11)

UCLA

Thermal stress effects on SiC composite flow channel inserts

- EU analysis with temperature difference ~180k has calculated values below limits (tension, compression, vonMises)

Shape Fabrication of SiC composites

- Basic shape fabrication appears feasible (90 degree corners might be difficult, but this is not a necessary feature)
- More complex shapes will require some development
- Joining technique not required, insert overlap (stove-piping) should be acceptable
- Cost of CVI composites will be high (quote on a small insert from Ultramet was ~10k), but alternate technique like PIP, with less expensive, low conductivity fibers might be significantly less.

Need for DCLL Testing in ITER as part of the Test Blanket Program

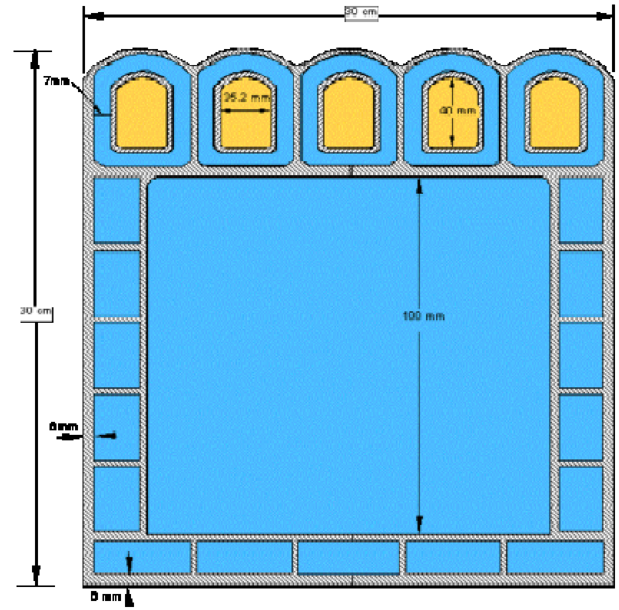
- While ITER itself is limited in total burn time and accumulated fluence, it will provide a very challenging test environment for blanket modules that have had no other significant integrated testing.
- Specifically for thermofluid MHD of the DCLL blanket concept, the rather strong steady toroidal field (~5 T) with prototypic gradients in the large magnetic volume provides in itself a unique environment for MHD testing.
- The H and D phases will not have significant nuclear heating or radiation damage, but will have magnetic fields including transient effects and likely even disruptions. Such conditions are ideal for MHD testing of the flow system in the high magnetic field conditions and for electromagnetic testing of the TBM structure.
- Failures in FCI in ITER will not result in catastrophic over-pressurization, flow stoppage or overheating for properly designed tests. Such failures can be explored in ITER.

DCLL Test Phases in ITER

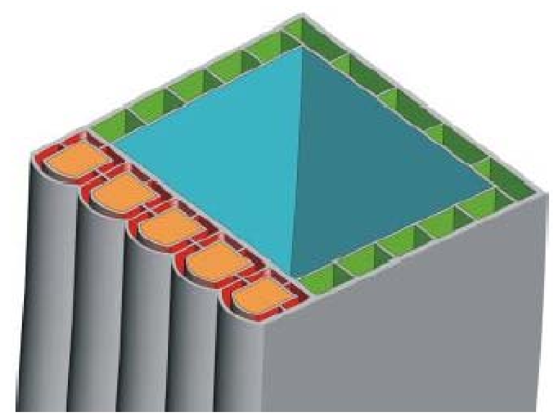
- Specific electromagnetic structure and MHD TBMs will be used that are specially designed to simulate MHD effects at higher fields (via larger flow channels and/or slower velocities) with special precautions to avoid under any scenario the spilling of the Pb-17Li while gaining experience in how the TBMs are likely to react to various plasma transient plasma events.
- During the Low Duty DT phase the TBM will begin to see integrated effects due to nuclear heating. More integrated TBMs will be required at this point, designed to address many issues.
- The response and reliability of thermally loaded SiC inserts and their effects on pressure drop and thermal field will be a key issue for thermofluid MHD, especially after many thermal cycles and as some radiation damage begins to acrue. By the end of the High Duty DT phase it may be possible to reach 1-2 dpa in the inserts and judge their performance as both MHD and thermal insulators in a real fusion system.

Molten-Salt Breeder

- **Configuration:**
  - Various mixtures of Fl-Li-Be and Fl-Li-Na-Be
  - Self-cooled, Separately-Cooled
  - Ferritic-Steel or Advanced Ferritic Steel structure
- **Reference Designs:**
  - Blanket Comparison and Selection Study (separately-cooled)
  - Japan FFHR
  - APEX task III and IV designs
- **Main Thermofluid Issues:**
  - MHD effects on turbulent heat transfer from heated structure
  - Overall temperature window, need for heat transfer enhancement
  - **Being addressed in J2 program**, but other work or ITER testing planned.



Midplane cross section of an outboard module.


Midplane cutaway of outboard module showing the channels progressing toward the lower extremity.

Summary of MHD issues

- MHD Pressure drop is a serious concern for inboard LM blankets in high field, high power density reactors
- Even moderate, non-uniform MHD pressure drops can seriously affect flow balance between parallel channels.
- MHD velocities profiles can exhibit strong jets next to regions of stagnation and even reversed flow – effects on blanket thermal performance must be evaluated for each concept
- Large temperature gradients can drive natural convection flows that MHD effects do not damp – can swamp forced flow velocity in slow moving breeder zone regions, especially for molten salts.
- Turbulence modification and suppression by MHD forces and joule dissipation will likely affect performance of molten salt blankets

Conclusions on thermofluid MHD R&D

- Insulator coatings are sensitive to flaws and may not have sufficient self healing in a non-isothermal systems.
  - measurement of coating performance while in contact with Li is required to characterize coating performance
  - multi-layers coating development may be necessary to overcome coating flaw sensitivity
- SiC flow channel inserts in PbLi dual coolant systems have an interesting combination of effects that reduce pressure drop as compared to self-cooled LM systems
  - Sensitivity to flaws must be carefully examined
  - Flow in complex geometry flow elements are likely to dominate pressure drop and experimental validation must be carefully planned
  - Flow balancing technique must be analyzed and tested in more detail.
  - Compatibility and performance of FCI is a critical development issue
- Effective DCLL testing in ITER is possible and desirable
  - MHD testing in D and H phases can address first MHD and electromagnetic structure test. Integrated testing in Low and High Duty Cycle phases needed for integrated FCI performance
  - Synergism with EU PbLi and RAFM program, more LM volume allowable in ITER than for Li – can serve as generic MHD test bed.