Overview of US Chamber Technology

Mohamed Abdou

US-Japan Workshop on Blanket/Chamber

Tokyo, Japan - May 17, 2001

US Chamber Program SUB-ELEMENTS

1. APEX (started in 1998)

- Innovative (revolutionary) concepts, Advance underlying science(s)
- US multi-institutional, multidisciplinary team with voluntary international participation

2. Material System Thermomechanics Interactions

- Modelling and experiments for ceramic breeder/Be/structure thermomechanics interactions
- Framework: IEA collaboration; part of US strategy to gain access to the larger international program

3. JUPITER-II (started April 2001)

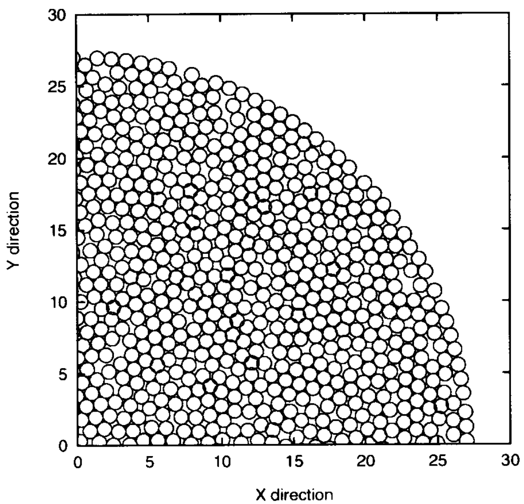
- Joint Japan-US collaboration on scientific and technical issues of common interest
- Japan matches US funds for use of unique US thermofluid and thermomechanics facilities

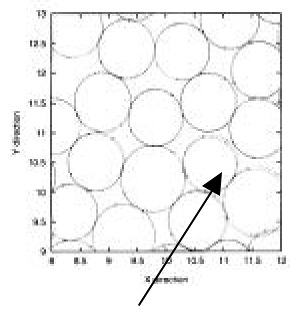
4. Neutronics (< 3%)

Material System Thermomechanics Interactions Studies at UCLA

Phenomenological and Numerical Modeling

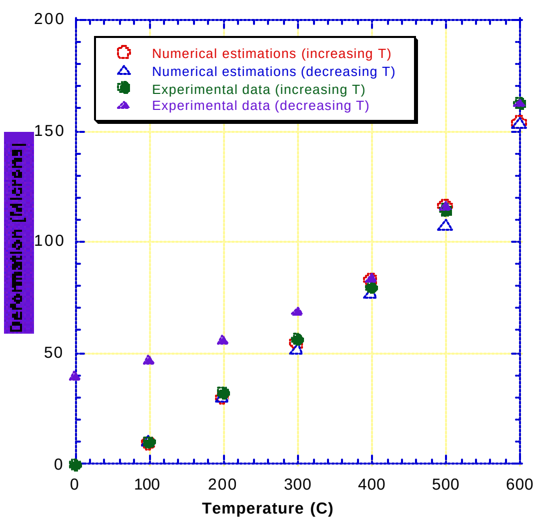
Packing characteristics of the bottom layer of packing (mean particle diameter = 1 mm total number of particles = 26,010)

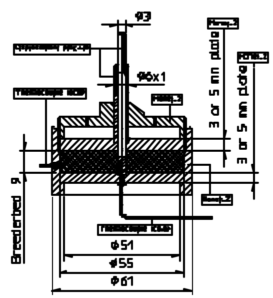




Particle relocation

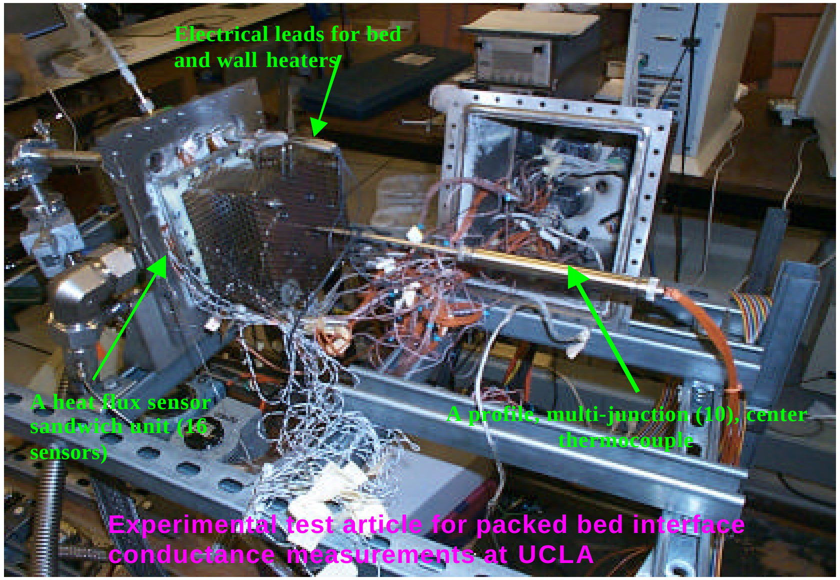
Experimental data is reasonably predicted by the numerical estimations based on fixed boundary conditions





Experimental test article

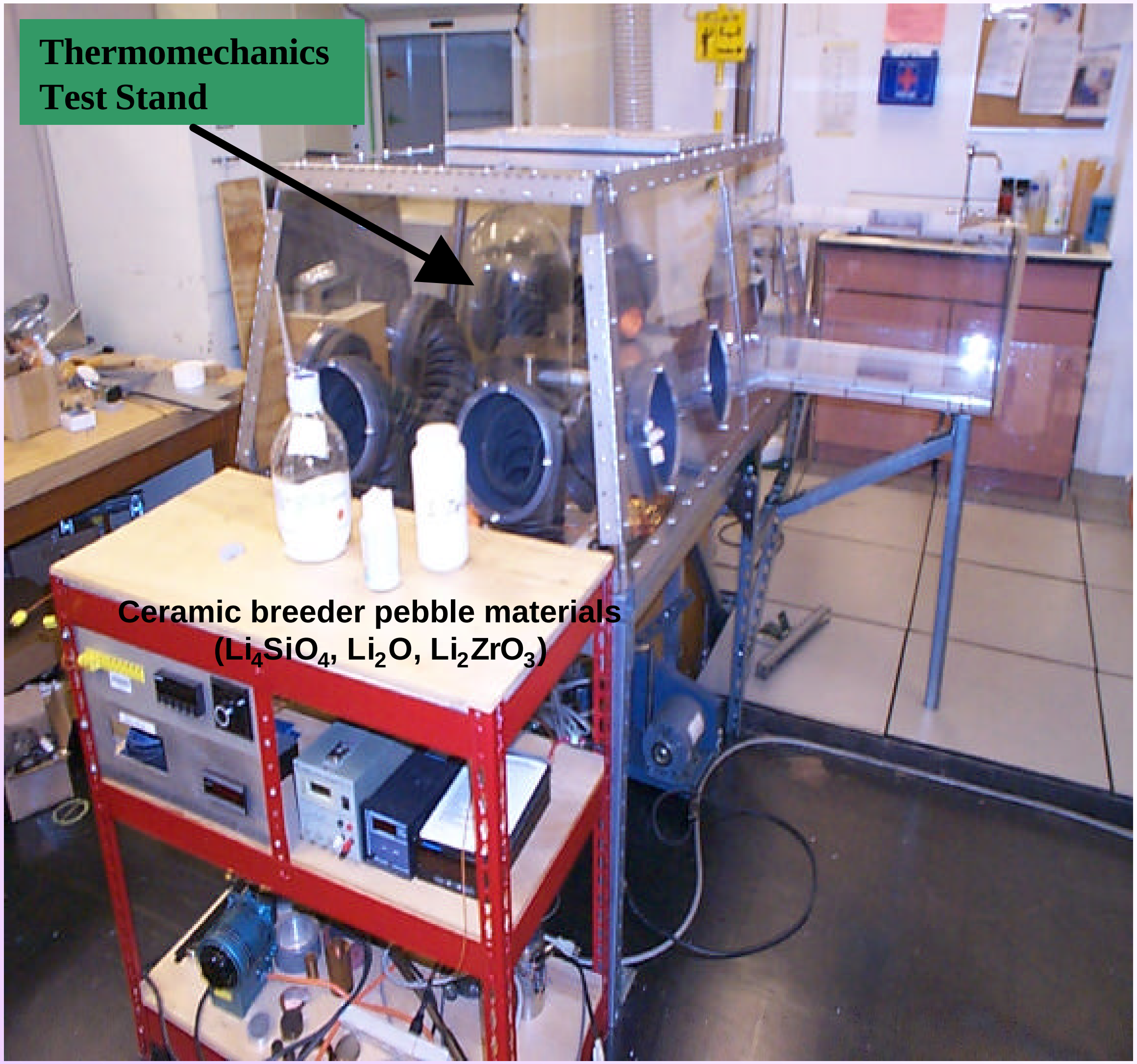
Small Scale Experiments

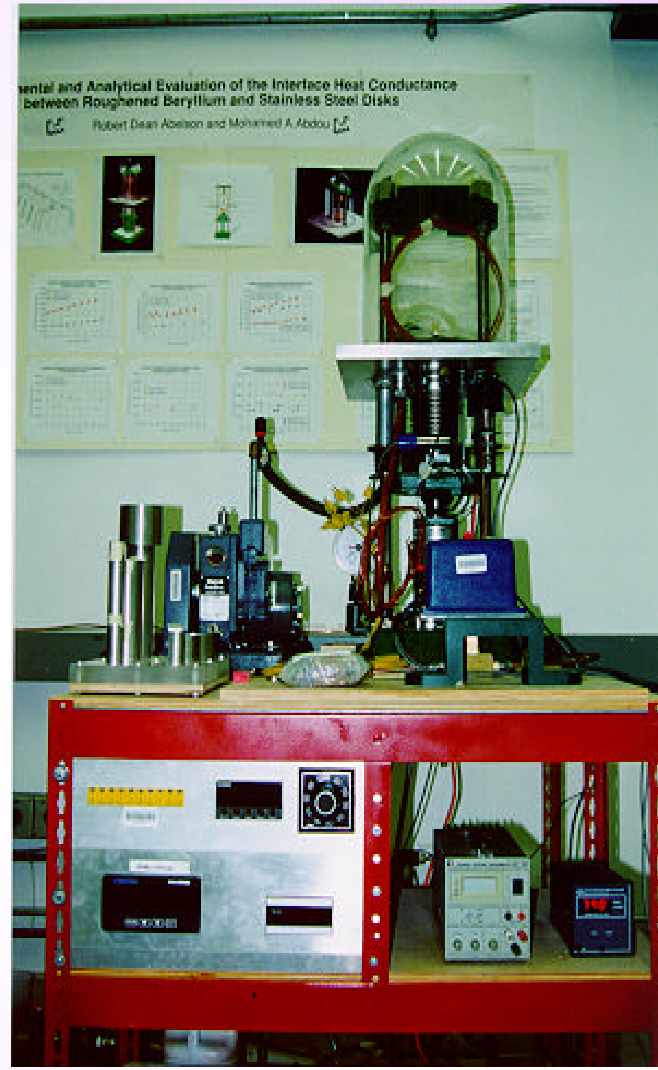


International Collaboration

JAERI scientists observing and discussing real-time experimental data in Japan

Beryllium Handling and Particulate Materials Thermomechanics Test Stand





Numerically, the non-linear elastic behavior of a particle bed is modeled as a collection of rigid particles interacting via Mindlin-Hertz type contact interactions

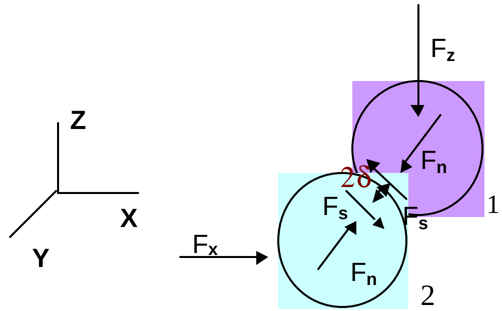
F_n = normal force

δ = the compliance between 1 and 2

F_s = shear force = κ $F_n \le \mu F_n$
(m: frictional coefficient)

F_z = force in z-direction or external imposed compressive force (packing structure dependent)

F_x = force in horizontal or x-direction (packing structure dependent)

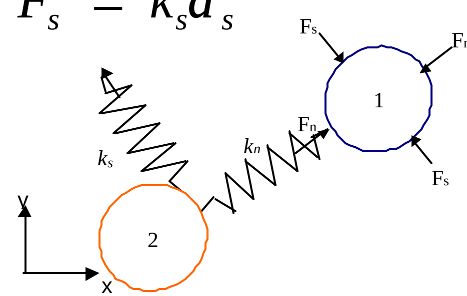


Forces at contact point include normal and tangential (shear) forces

Representation of the force-displacement relation at contact between two particles

$$F_n = k_n d_n$$

$$F_s = k_s d_s$$



Incremental displacement of the particle in the X-direction is derived, based on the net active force along the x-axis according to:

$$\Delta D_x = \frac{F_x}{k_t} = \frac{\sum_c F_{xc}}{k_n + k_s}$$

$$for, \frac{k_s}{k_n + k_s} \left| \sum_c F_{xc} \right| < k_f \sqrt{(\sum_c |F_{yc}|)^2 + (\sum_c |F_{zc}|)^2},$$

otherwise

$$\Delta D_x = \frac{F_x - k_f |F_t|}{k_n} = \frac{\sum_c F_{xc} \pm k_f \sqrt{(\sum_c |F_{yc}|)^2 + (\sum_c |F_{zc}|)^2}}{k_n}$$

Bed stiffness in the normal direction gives:

$$k_n = \frac{8E^* \sqrt{R d_f}}{7}$$

where d_f is the maximum value among all deformation at particle contact points.

Interface heat conductance studies of Non-Conforming Beryllium and SS316 Surfaces defined uncertainties involved in the ITER breeding blanket concept

Figure 3.41: Interface Conductance vs. Heat Flux, Vacuum and 760 torr He, Pc =10MPa, All Roughnesses, SaB Configuration

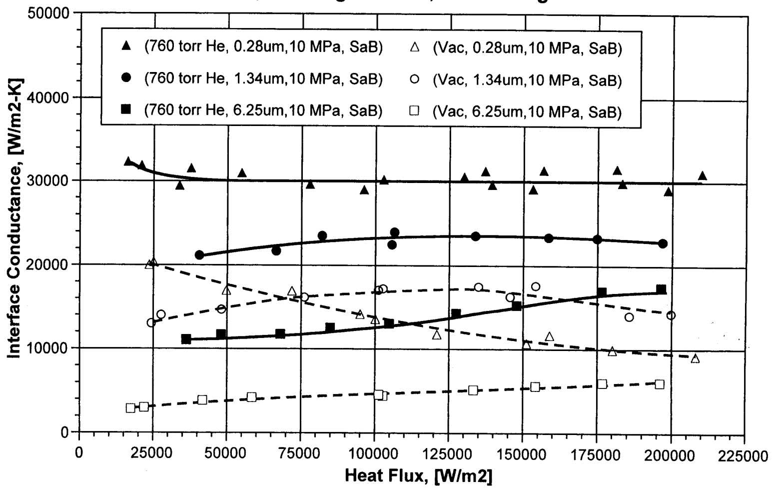
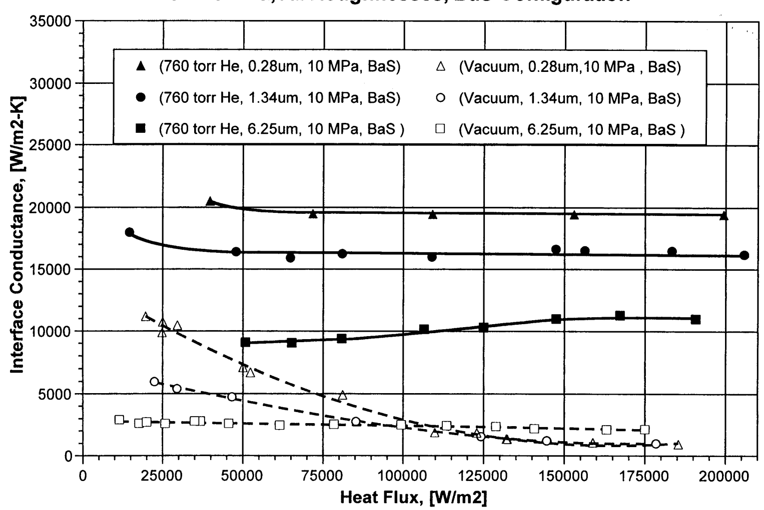


Figure 3.40: Interface Conductance vs. Heat Flux, Vacuum and 760 torr He, Pc = 10 MPa, All Roughnesses, BaS Configuration



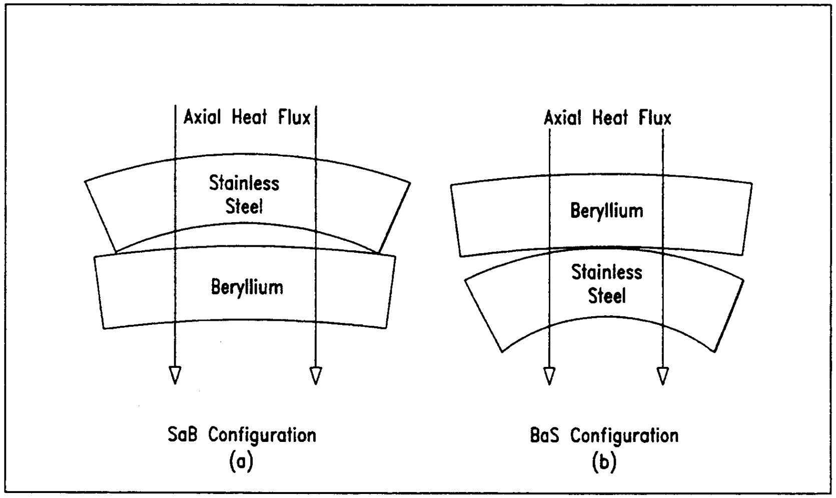


Figure 4.3: Two orientations of thermal deformation for the beryllium and stainless steel disks (profiles are highly exaggerated for clarity)

- **Interface heat conductance was a critical issue for the ITER breeding blanket concept where a sintered beryllium block was used as a means to control the temperature window of solid breeders.**
- **This work has been completed. A journal article for this work is published in Fusion Technology.**

APEX

APEX Web Site: www.fusion.ucla.edu/APEX

APEX Objectives

Identify and explore NOVEL, possibly revolutionary, concepts for the Chamber Technology that might:

1. In the near-term: enable plasma experiments to more fully achieve their scientific research potential

2. In the long-term: substantially improve the attractiveness of fusion as an energy source

3. Lower the cost and time for R&D

APEX is Organized as a Team

US Organizations (13 Universities and National Labs)

UCLA	ANL	PPPL	ORNL
LLNL	SNL	GA	UW
INEEL	U. Texas	LANL	UCSD / U. IL

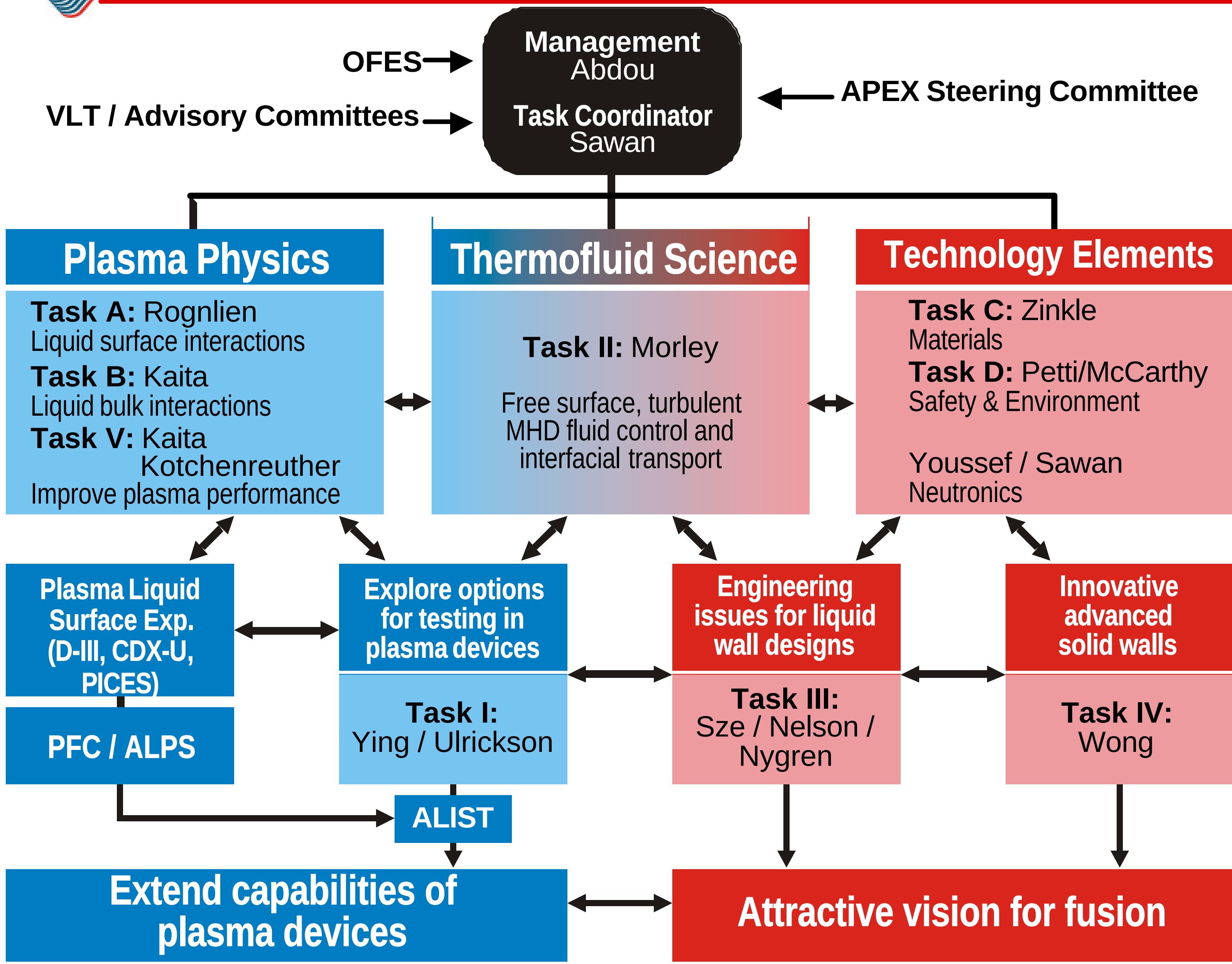
Important Contributions from International Organizations

- FZK, Germany (Dr. S. Malang, Dr. L. Barleon)
- Japanese Universities
  - Profs. Kunugi (Kyoto), Satake (Toyama), Uchimoto (Tokyo), others
  - Joint Workshops on APEX/HPD

APEX Steering Committee includes Leaders from the Physics and Technology Community

M. Abdou (UCLA)	R. Kaita (PPPL)	K. McCarthy/D. Petti (INEEL)
N. Morley (UCLA)	B. Nelson (ORNL)	T. Rognlien (LLNL)
M. Sawan (UW)	D. Sze (ANL)	M. Ulrickson/R. Nygren (SNL)
C. Wong (GA)	A. Ying (UCLA)	S. Zinkle (ORNL)

APEX is organized as a partnership between plasma physics and all elements of science & technology



APEX has progressed along carefully planned and well documented phases

(Early 1998)

Preparation Phase

Attract Innovators →

• Understand Technological Limits

• Define Objectives/Criteria

→ APEX Website

→ FED Paper

(late 1998-99)

Idea Formulation Phase

VLT-PAC, Dec 98 →

Snowmass, Jul 99 →

• Many concepts proposed and analyzed

• Most promising concepts identified:

EVOLVE and Liquid Walls

→ Snowmass report

→ APEX Website

→ Journal publications

→ Interim Report, 600 p.

(Nov 1999- Present)

Concept Exploration Phase

VLT-PAC, Dec 00 →

Peer Review, Apr 01 →

• Model development

• Small scale experiments

• Critical Issue analysis

→ APEX Website

→ Journal publications

→ Special issue planned

R&D Requirements and POP Definition

Chamber Technology Goals Used in APEX to Calibrate New Ideas and Measure Progress

1. High Power Density Capability

   Average/Peak Neutron Wall Load ~ 7 / 10 MW/m^2

   Average/Peak Heat Flux ~ 1.4 / 2 MW/m^2

   (80% of the Alpha Power Radiated to First Wall to ease divertor loading)

2. High Power Conversion Efficiency (>40%)

3. High Availability (MTBF>43 MTTR)

4. Simpler Technological and Material Constraints

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* "APEX will explore concepts with lower power density capabilities if they provide significant improvement in power conversion efficiency or other major features."

Technological limits for "conventional concepts" have been documented in several papers; see for example APEX paper in Fusion Engineering & Design, vol. 54, pp 145-167 (1999)

APEX "Idea Formulation" Phase Identified Two Classes of Promising Concepts:

1. Liquid Walls 2. EVOLVE

- "Idea Formulation Phase": Many ideas proposed and screened based on analysis with "existing tools"
- Liquid Walls and EVOLVE (W alloy, vaporization of Li) were selected to proceed to the "Concept Exploration" Phase
- The "Concept Exploration" Phase involves extending modeling tools, small experiments, and analysis of key physics and engineering issues
- APEX remains open to new ideas

- Results of the "Idea Formulation" phase are fully documented on the website and in many journal publications
- An Interim Report (> 600 pages) fully documents all details:

"On the Exploration of Innovative Concepts for Fusion Chamber Technology", APEX Interim Report, UCLA-ENG-99-206 (November 1999).

The Framework for APEX Concept Exploration was guided by community deliberations that identified Chamber 5-Year Objectives

Liquid Walls:

1. Fundamental understanding of free surface fluid flow phenomena and plasma-liquid interactions verified by theory and experiments.

2. Operate flowing liquid walls in a major experimental physics device (e.g. NSTX)

3. Begin construction of an integrated Thermofluid Research Facility to simulate flowing liquid walls for both IFE and MFE.

4. Understand advantages & implications of using LW's in fusion energy systems.

Solid Walls:

5. Advance novel concepts that can extend the capabilities and attractiveness of solid walls.

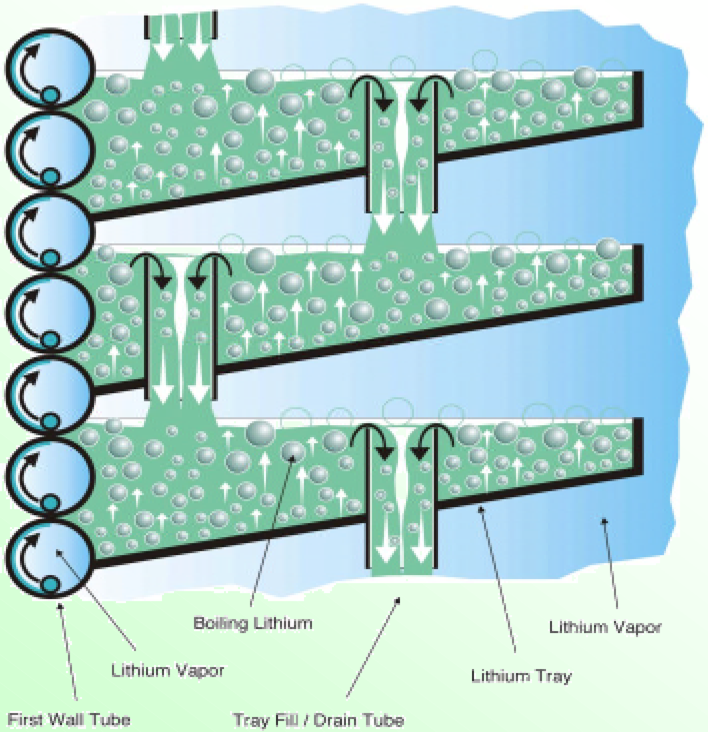
6. Contribute to international effort on key feasibility issues for evolutionary concepts in selected areas of unique expertise

Innovative concepts proposed by APEX can extend the capabilities and attractiveness of solid walls

•Structural material is key to extending capabilities of solid walls

- High-Temperature Refractory Alloys evaluated: W-alloy selected

•Helium cooling and Li boiling evaluated



EVOLVE

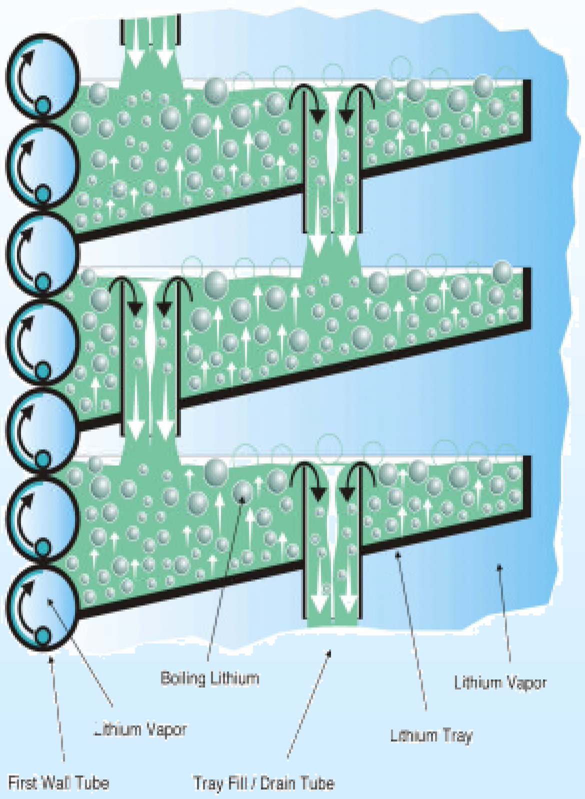
- Novel Concept based on use of high temperature refractory alloy (e.g. tungsten) with innovative heat transfer/transport scheme for vaporization of lithium
- Low pressure, small temperature variations greatly reduce primary and thermal stresses
- Low velocity, MHD insulator may not be required
- High Power Density, High Temperature (high efficiency) Capabilities

•SiC/SiC-LiPb limits are being evaluated

SiC may allow high temperature, but power density may be limited

Progress on Addressing Key Issues for Promising Advanced Solid Wall Concepts

EVOLVE



1. Material Issues

Assessment of Material Issues for high-temperature refractory alloys "operating temperature" range and areas of uncertainties

- Sparked great interest in the materials community
  (comprehensive Journal Paper by Zinkle, Ghoniem, Sharafat)
- R&D needs identified for the material program

2. Heat Transfer/Transport for 2-phase flow with MHD

- Experiments at Univ. of Wisconsin
- Modeling at UCLA, UW, FZK

3. Engineering Issues

- Analysis and Innovative Solutions
  (GA, FZK, UW, SNL, ORNL, ANL, UCLA)

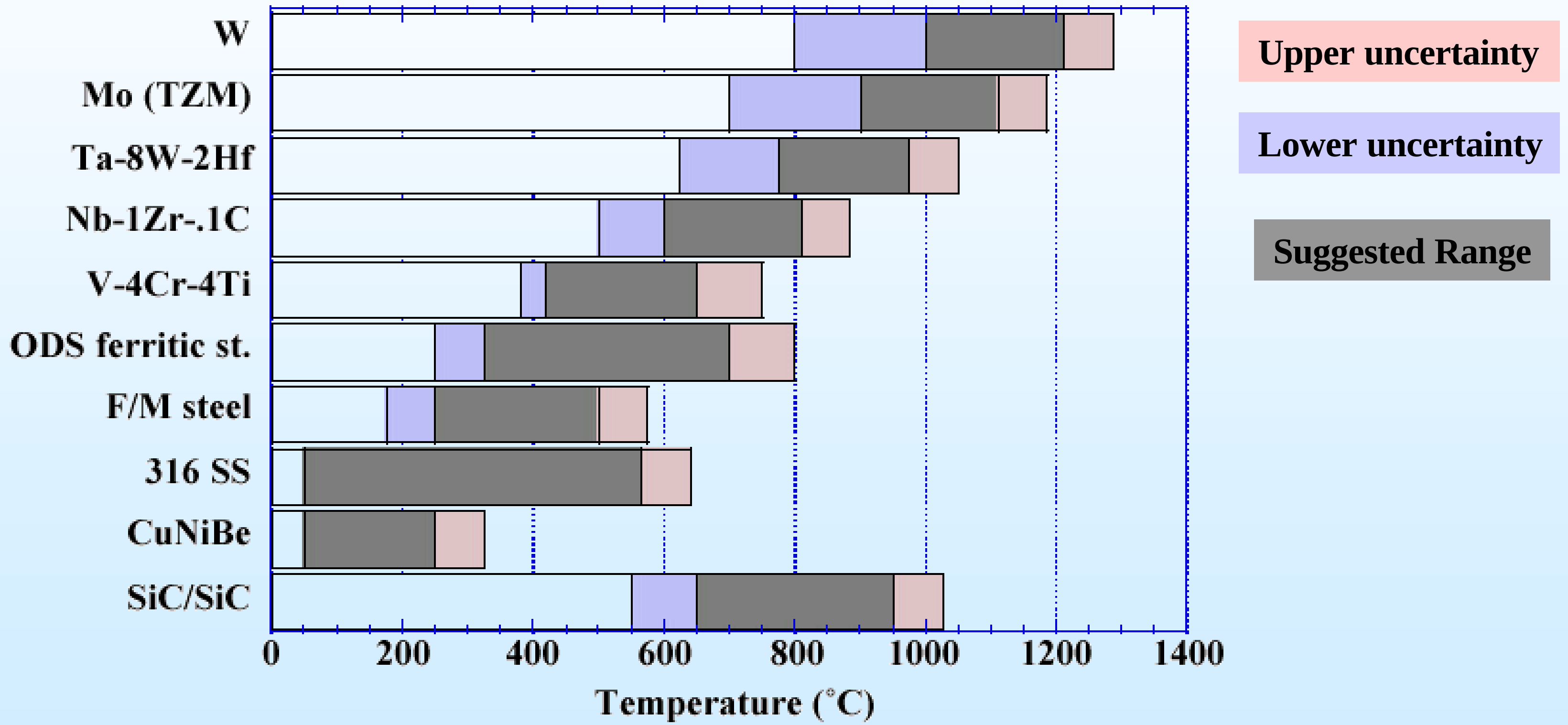
4. Safety & Environmental

- Decay Heat and Waste Disposal (INEEL)

5. Reliability

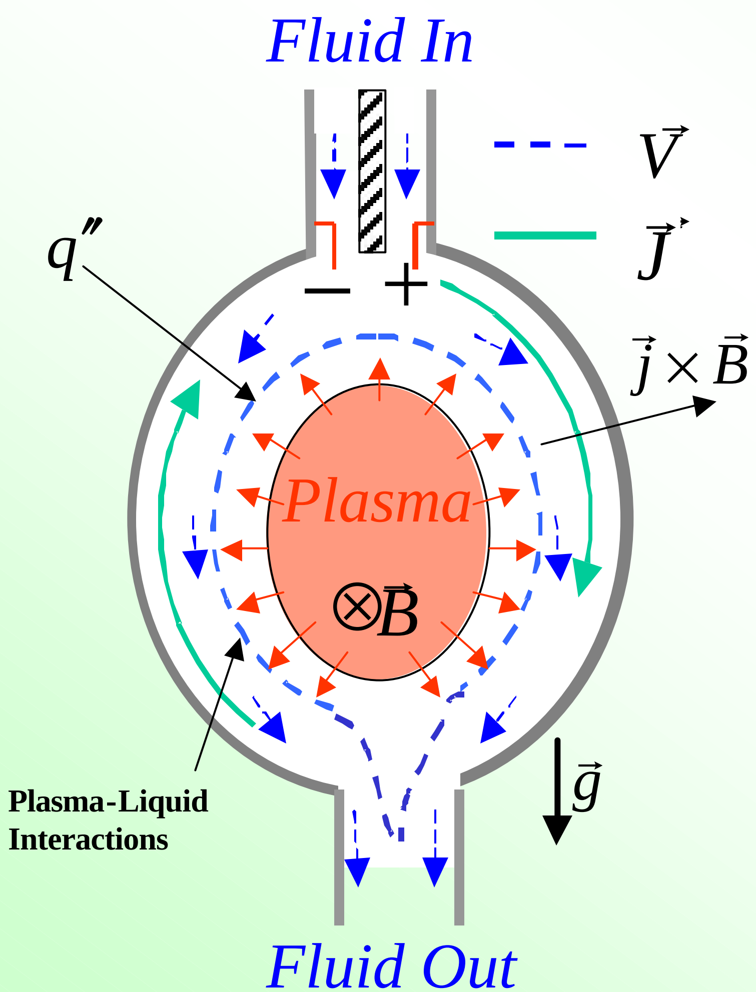
- Leak Tolerance (Majumdar/ANL)
- Reliability is a critical issue for fusion; discussed often, but very difficult to address

Our EVOLVE Concept stimulated considerable interest in the material community to investigate high-temperature refractory alloys (e.g. W)



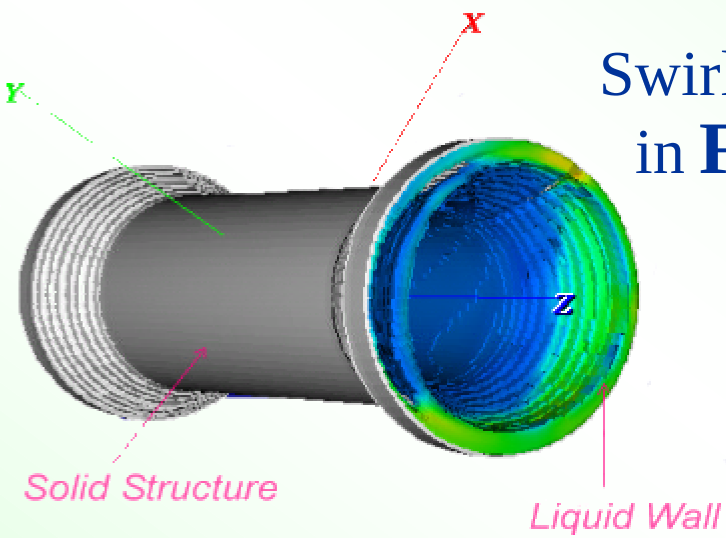
Operating Temperature Windows (based on radiation damage and thermal creep)

"Liquid Walls" Emerged as one of the Two Most Promising Classes of Concepts to proceed to "Concept Exploration"



- **The Liquid Wall idea is "Concept Rich"**
  - a) Working fluid: Liquid Metal, low conductivity fluid
  - b) Liquid Thickness
    - thin to remove surface heat flux
    - thick to also attenuate the neutrons
  - c) Type of restraining force/flow control
    - passive flow control (centrifugal force)
    - active flow control (applied current)
- **We identified many common and many widely different merits and issues for these concepts**

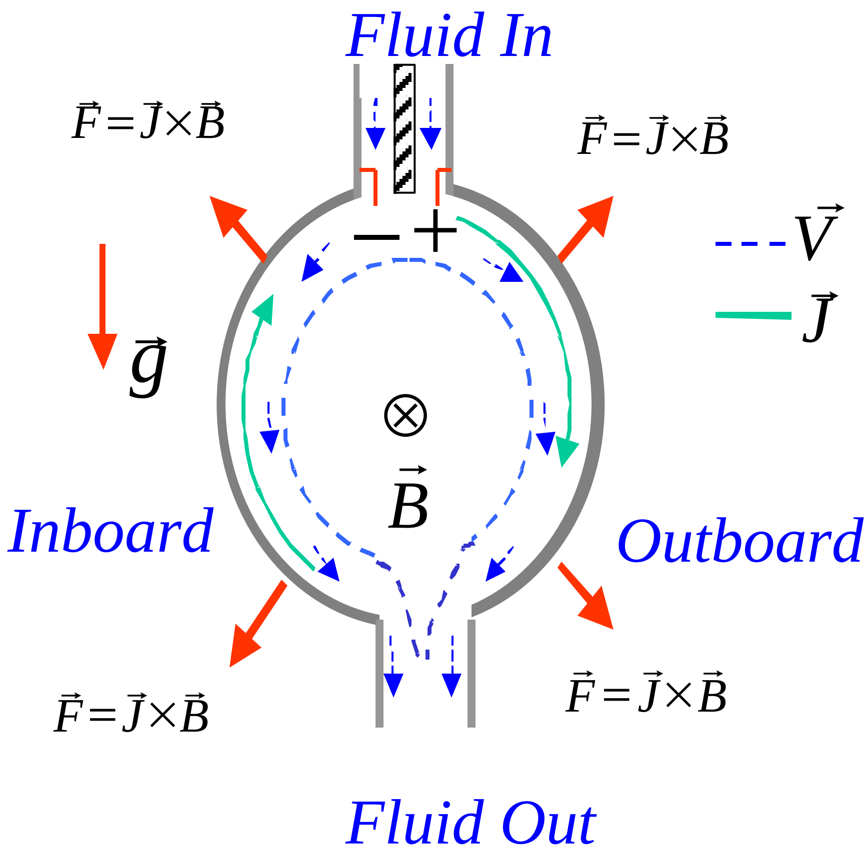
Swirl Flow in **FRC**



ELECTROMAGNETIC FLOW CONTROL: electric current is applied to provide adhesion of the liquid and its acceleration

Electromagnetically Restrained LM Wall (R.Woolley)

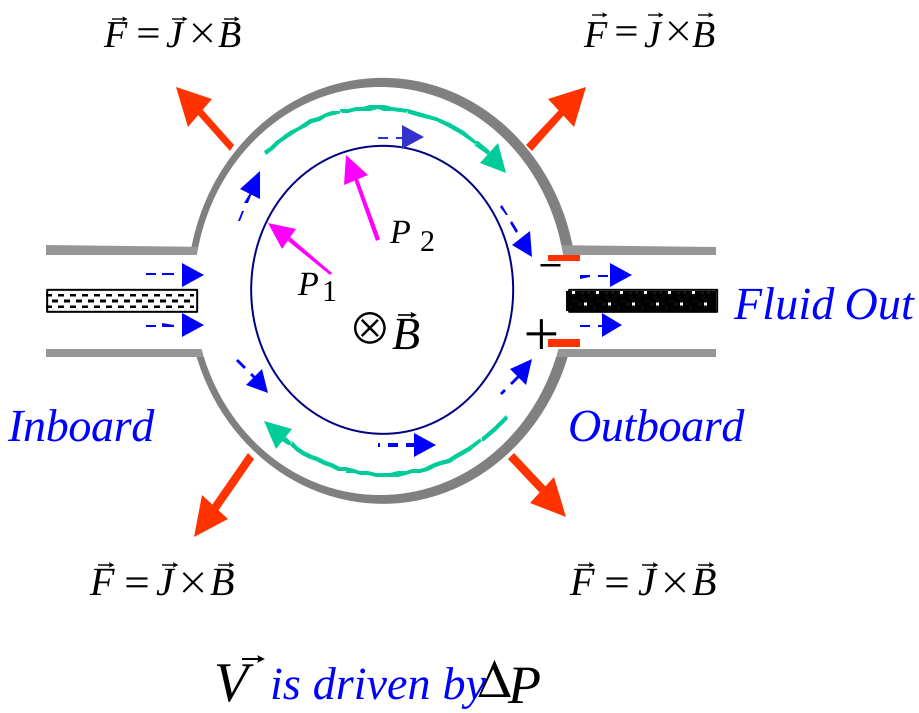
- Adhesion to the wall by $\vec{F} = \vec{J} \times \vec{B}$



Magnetic propulsion scheme (L.Zakharov)

Adhesion to the wall by $\vec{F} = \vec{J} \times \vec{B}$

Utilization of 1/R variation of $\vec{B}$ ***to drive the liquid from the inboard to outboard***



Motivation for Liquid Wall Research

What may be realized if we can develop good liquid walls:

- Improvements in Plasma Stability and Confinement
  Enable high ß, stable physics regimes if liquid metals are used
- High Power Density Capability
- Increased Potential for Disruption Survivability
- Reduced Volume of Radioactive Waste
- Reduced Radiation Damage in Structural Materials
  -Makes difficult structural materials problems more tractable
- Potential for Higher Availability
  -Increased lifetime and reduced failure rates
  -Faster maintenance

No single LW concept may simultaneously realize all these benefits, but realizing even a subset will be remarkable progress for fusion

Scientific Issues for Liquid Walls

1. Thermofluid Issues

- Interfacial Transport and Turbulence Modifications at Free-Surface
- Hydrodynamic Control of Free-Surface Flow in Complex Geometries, including Penetrations, Submerged Walls, Inverted Surfaces, etc
- MHD Effects on Free-Surface Flow for Low- and High-Conductivity Fluids

2. Bulk Plasma-Liquid Interactions

Effects of Liquid Wall on Core Plasma including:

- Discharge Evolution (startup, fueling, transport, beneficial effects of low recycling
- Plasma stability including beneficial effects of conducting shell and flow

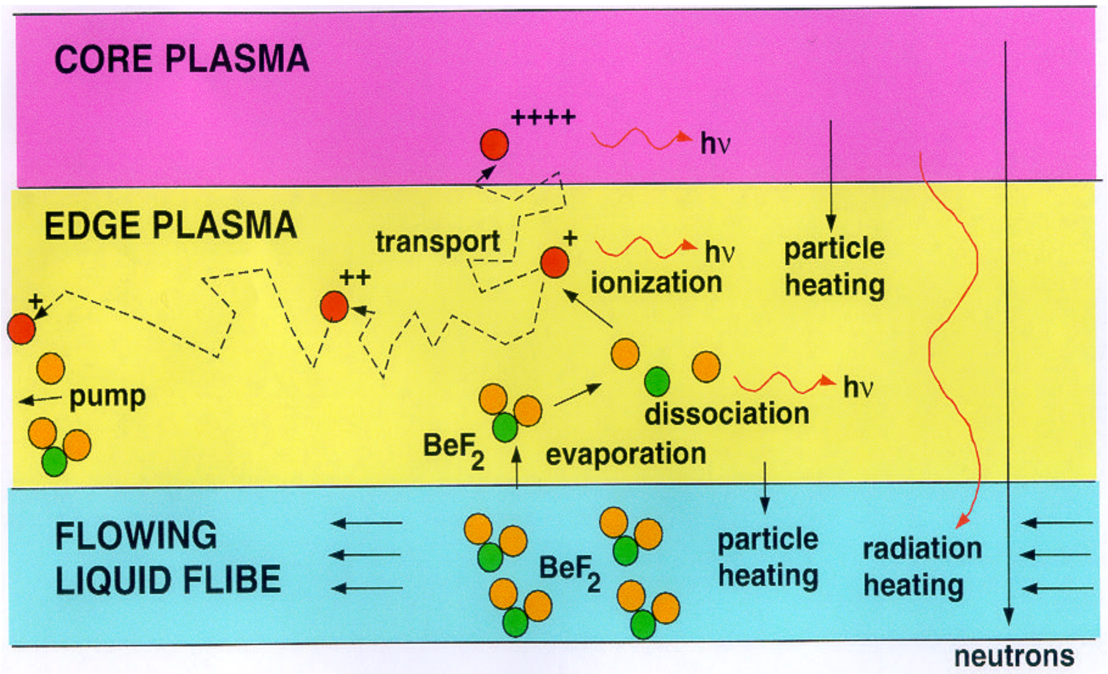
3. Plasma-Liquid Surface Interactions

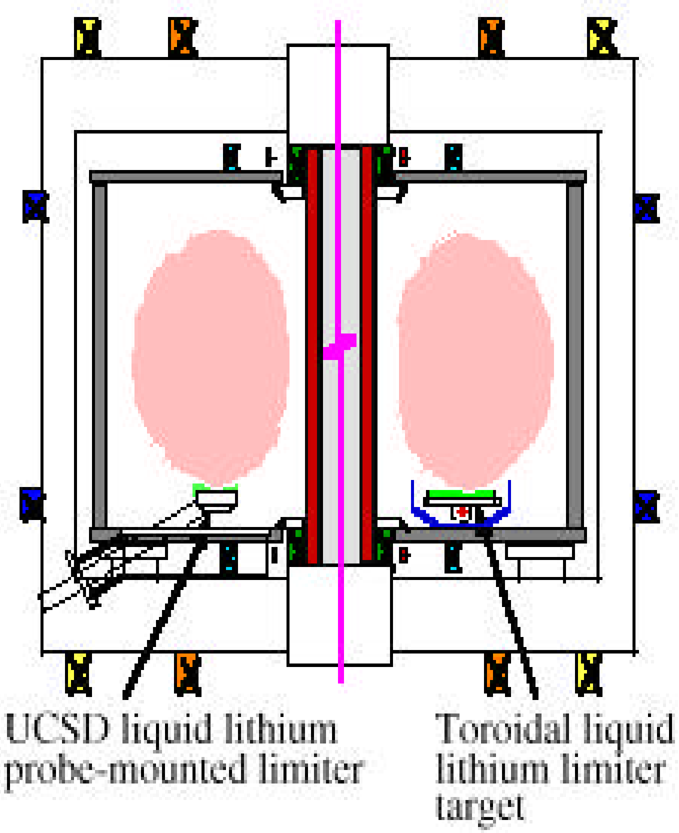
- Limits on operating temperature for liquid surface

Plasma-Liquid Surface Interactions

- Multi-faceted plasma-edge modeling validation with data from experiments
- Experiments in plasma devices (CDX-U, DIII-D and PISCES)

Processes modeled for impurity shielding of core



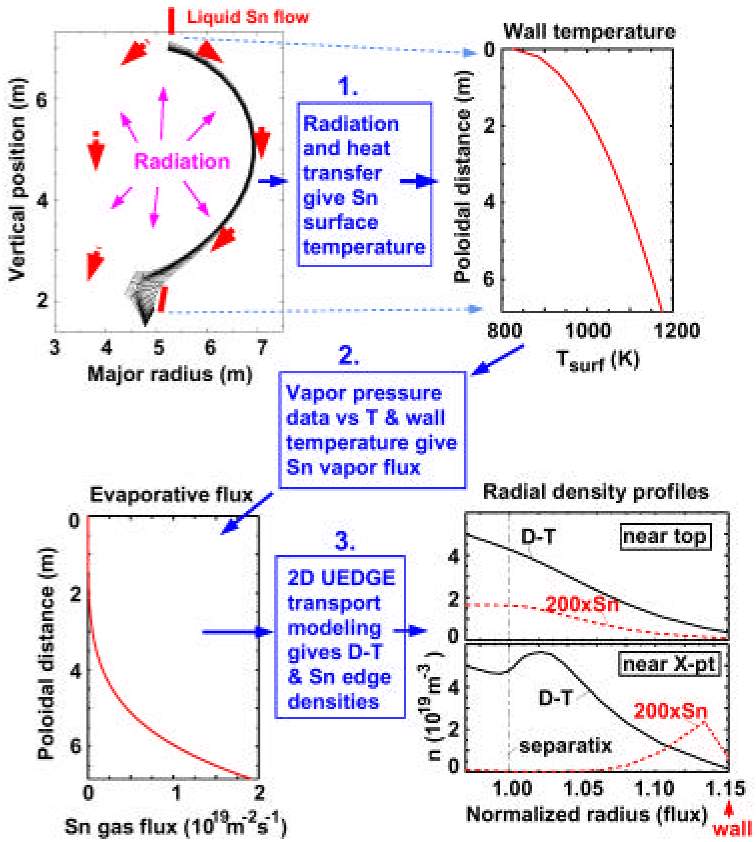


Liquid lithium limiter in CDX-U

Validated Plasma Edge Models were extended to predict the Physics Limits on LW Surface Temperature

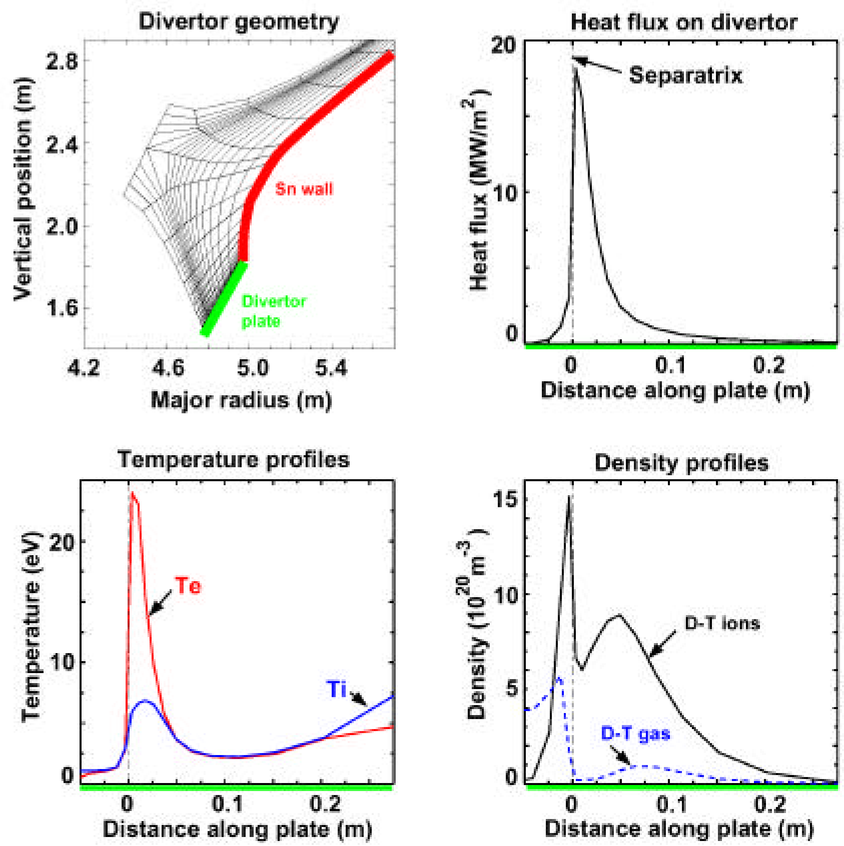
A systematic set of steps predicts the core impurity level from liquid walls

An acceptable core Sn level is obtained for ARIES case:



Global edge plasma/neutral transport modeling used to aid divertor design

- Designing divertor-region hardware is a critical element
- Validated 2D UEDGE predicts divertor plasma conditions



Flowing LM Walls may Improve Plasma Stability and Confinement

SNOWMASS

Several possible mechanisms identified at Snowmass…

Presence of conductor close to plasma boundary (Kotschenreuther) - Case considered 4 cm lithium with a SOL 20% of minor radius

- Plasma Elongation $\kappa > 3$ possible – with $\beta > 20\%$
- Ballooning modes stabilized
- VDE growth rates reduced, stabilized with existing technology
- Size of plasma devices and power plants can be substantially reduced

High Poloidal Flow Velocity (Kotschenreuther)

- LM transit time < resistive wall time, about ½ s, poloidal flux does not penetrate
- Hollow current profiles possible with large bootstrap fraction (reduced recirculating power) and $E \times B$ shearing rates (transport barriers)

Hydrogen Gettering at Plasma Edge (Zakharov)

- Low edge density gives flatter temperature profiles, reduces anomalous energy transport
- Flattened or hollow current density reduces ballooning modes and allowing high β

APEX Plasma-Liquid Interaction Tasks are Utilizing and Extending State-Of-The-Art Codes with Comparisons to the Latest Data, and Exploring Exciting Possibilities Identified in Snowmass

- **Dynamic modeling of plasma equilibria uses the Tokamak Simulation Code (TSC), a PPPL code validated with NSTX data. For example, TSC simulations of NSTX equilibria were used to estimate the magnitude of forces due to eddy currents on the liquid surface test module for NSTX**

- **Physicists are contributing exciting ideas for liquid walls**
  - Electromagnetically Restrained Blanket (Woolley)
  - Soaker Hose (Kotschenreuther)
  - Magnetic Propulsion (Zakharov)

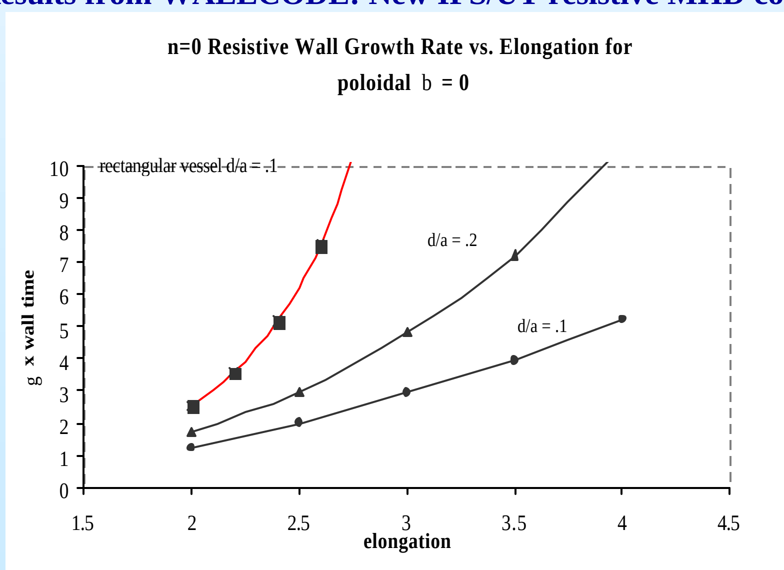
- **Studies of Innovative Wall Concepts are providing insight into nature and control of plasma instabilities**
  - Stabilization schemes for resistive wall modes and neoclassical tearing modes are of broad interest to the fusion community
  - A new resistive MHD Code (WALLCODE) has been developed by IFS/UT to explore the stabilizing properties of various conducting wall geometries

- **Initial Results: Liquid metals can be used as conducting walls that offer a means for stabilizing plasma MHD modes**

Utilization of Liquid Metals for a Conducting Shell May Allow Higher Power Density Tokamak Plasma

- **Initial results from new WALLCODE resistive MHD code: Stable highly elongated plasmas possible with appropriately <u>shaped conducting shell</u>**
- **Liquid metals may be used for the <u>conducting shell</u>**
- **Implications for fusion:**
  - High power density plasma (plus power extraction capability)
  - Overcome physics-engineering conflicting requirements that reactor designers have struggled with for decades

Results from WALLCODE: New IFS/UT resistive MHD code



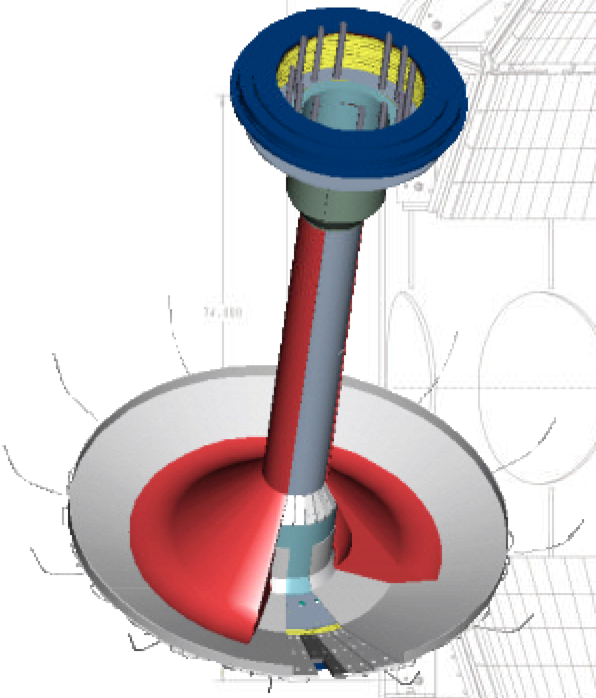
* Instability growth rate depends on conformity of wall to plasma

Beta Limits for high elongation
(example of initial results)

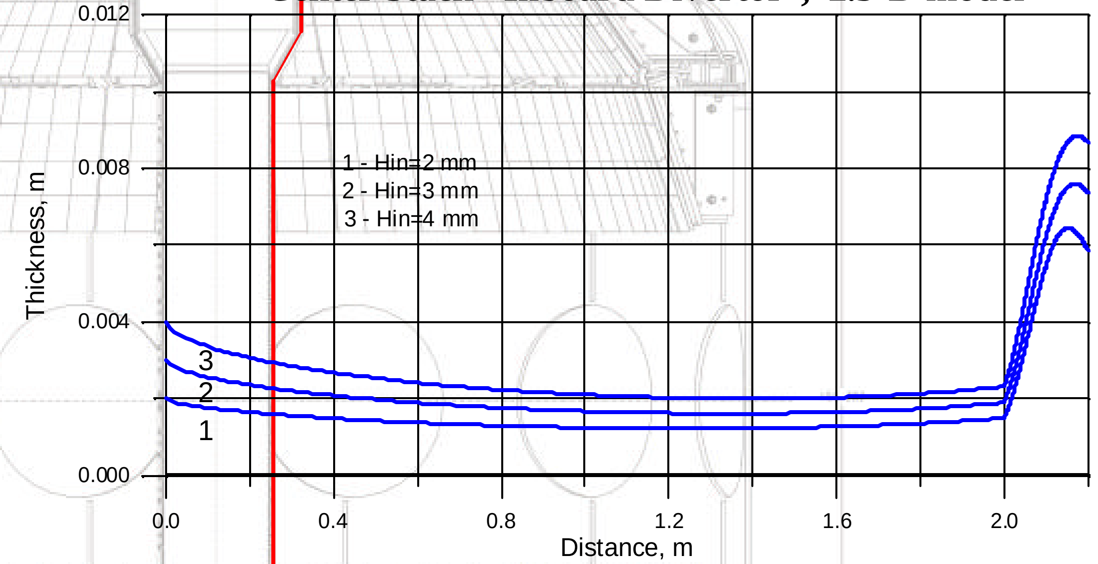
k	d	D	b*
2	.7	0	4.3%
3	.78	0	11.5%
4	.9	.1	14%
5	1.28	.5	22%

D o **indentation/minor radius**

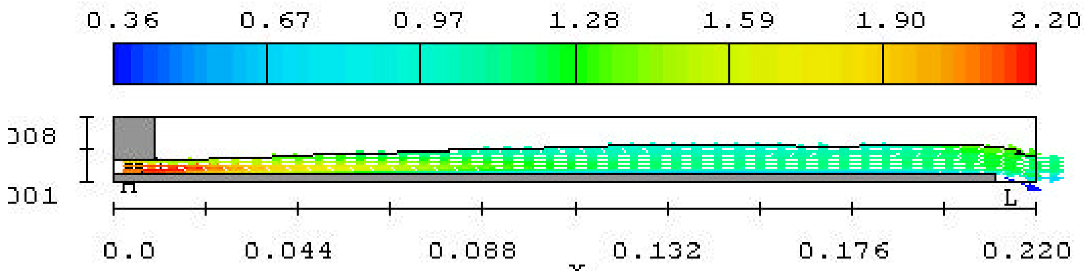
Simulations of Flowing Lithium in NSTX using Newly Developed MHD Free Surface Tools



"Center Stack +Inboard Divertor", 2.5-D model



"Inboard Divertor", Flow3D-M



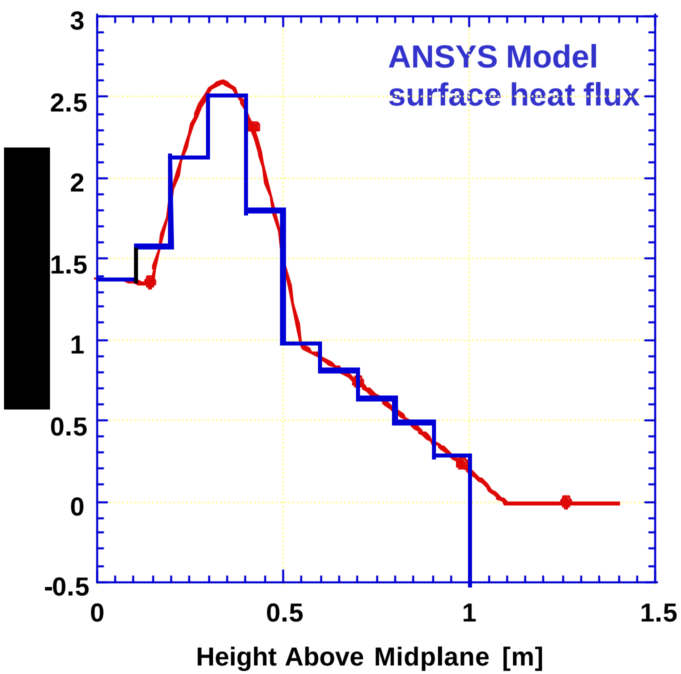
- **Flow3D code was extended to include MHD effects (Flow3D-M)**
- **New 2.5-D model and computer code were developed to calculate MHD free surface flows in a multi-component magnetic field**

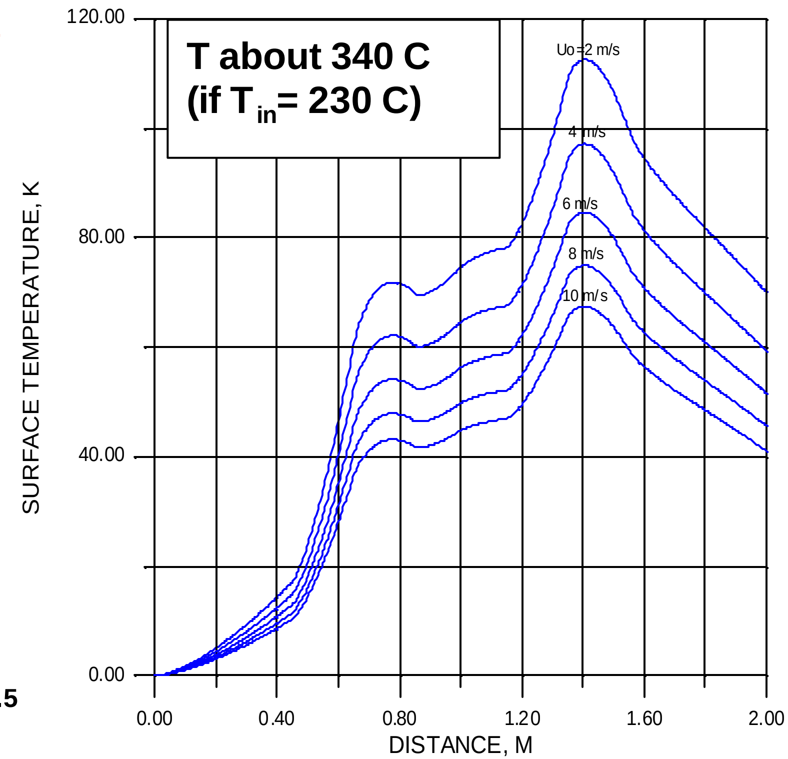
Stable Li film flow can be established over the center stack

NSTX: Heat flux can be removed with flowing lithium along the center stack with acceptable surface temperature (even with 4-mm film at 2m/s)

Results of Heat Transfer Calculations for NSTX Center Stack Flowing Lithium Film

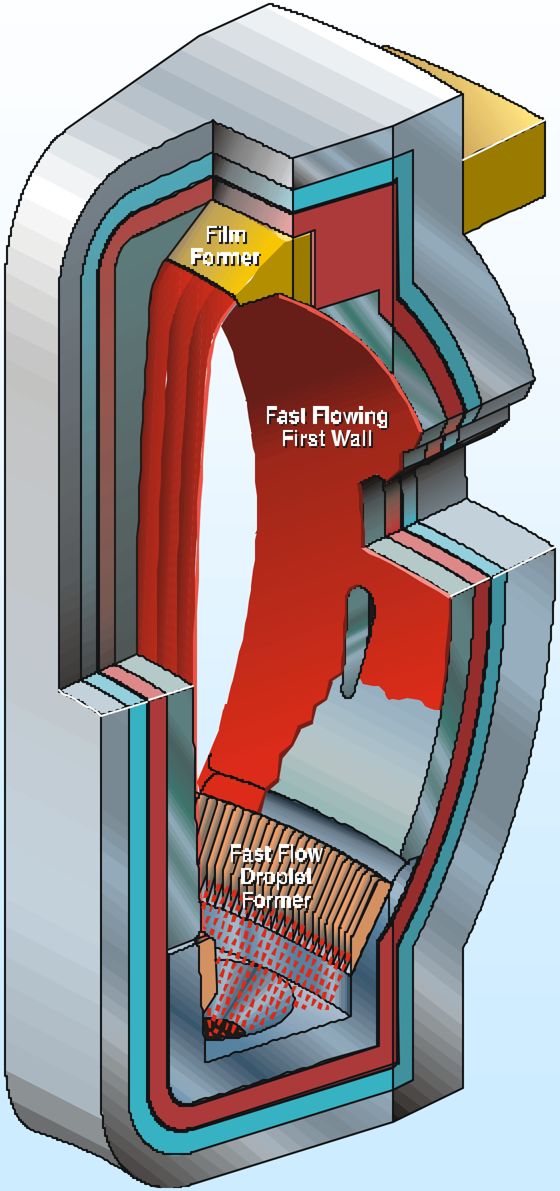
Projected NSTX_center stack_heat flux profile (total power = 10 MW)



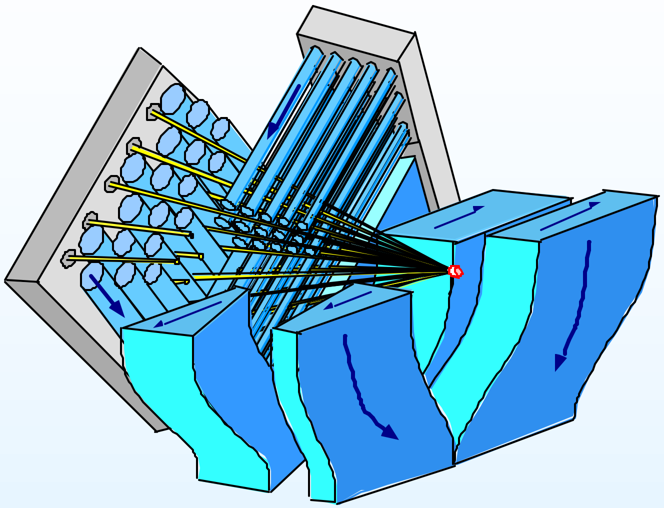


- **Lithium surface temperature increases as flow proceeds downstream as a function of lithium inlet velocity**
- **Two local temperature peaks are related to local maximums in the heat flux profile**

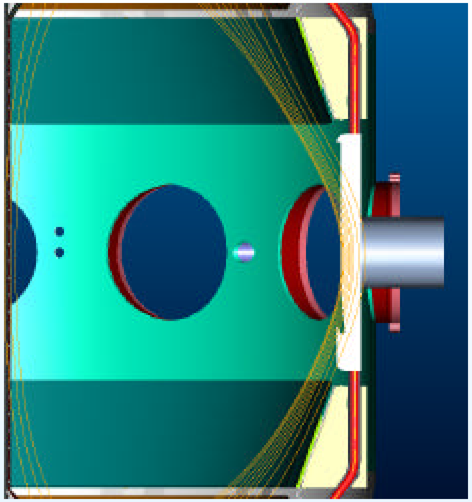
Liquid Wall Science is being Advanced in Several MFE & IFE Research Programs



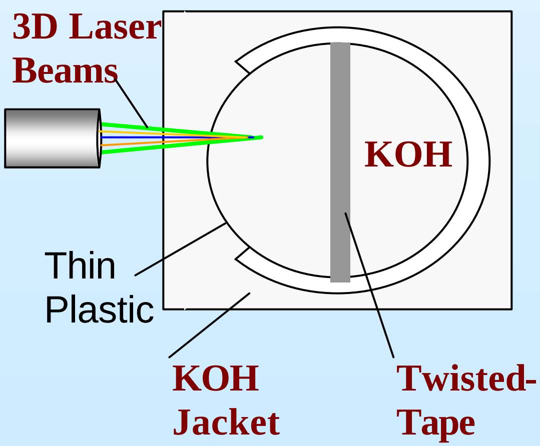
APEX CLiFF



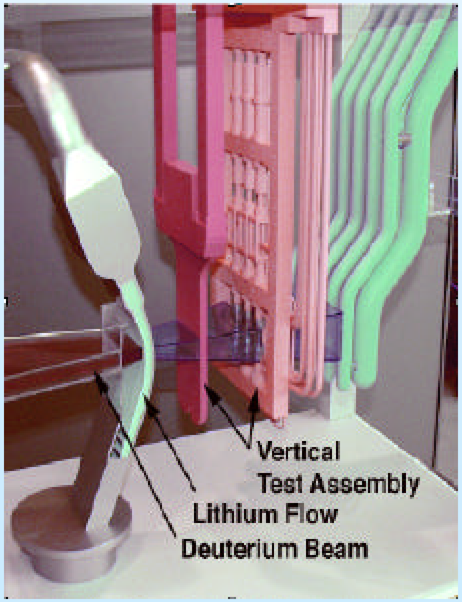
HYLIFE-II



NSTX Li module



JUPITER-II



IFMIF

JUPITER-II

Started: April 2001

JUPITER-II: Introduction/Overview

- **JUPITER is an acronym for Japan-US Collaborative Program for Materials Irradiation, Theory, and Experimental Research**

- **JUPITER-II is a new phase of US-Japan (DOE-Monbusho) collaboration**

  Collaboration began in July 1987 as Annex I to DOE-Monbusho Exchange of Letters of Cooperation in Fusion Research and Development

  JUPITER-II has just begun (April 2001) for a period of 6 years

- **JUPITER-II is broader in scope than previous phases of collaboration**

  JUPITER focused on irradiation effects in structural materials

  JUPITER-II will address issues of structural and non-structural materials and their interactions for a broad spectrum of thermal, chemical, magnetic, and irradiation environmental conditions

JUPITER-II Thermofluid Task Objectives

1. Understand underlying Science and Phenomena for low conductivity, high Prandtl liquid flow and heat transfer through:
   - **a. Conducting experiments using Flibe simulant**
   - **b. Modeling and analysis of fundamental phenomena**

2. Compare experimental and modeling results to provide guidance and database for designs and next generation stage of larger experiments

3. Identify and assess new innovative techniques for enhancement of heat transfer (a major feasibility issue for Flibe designs)

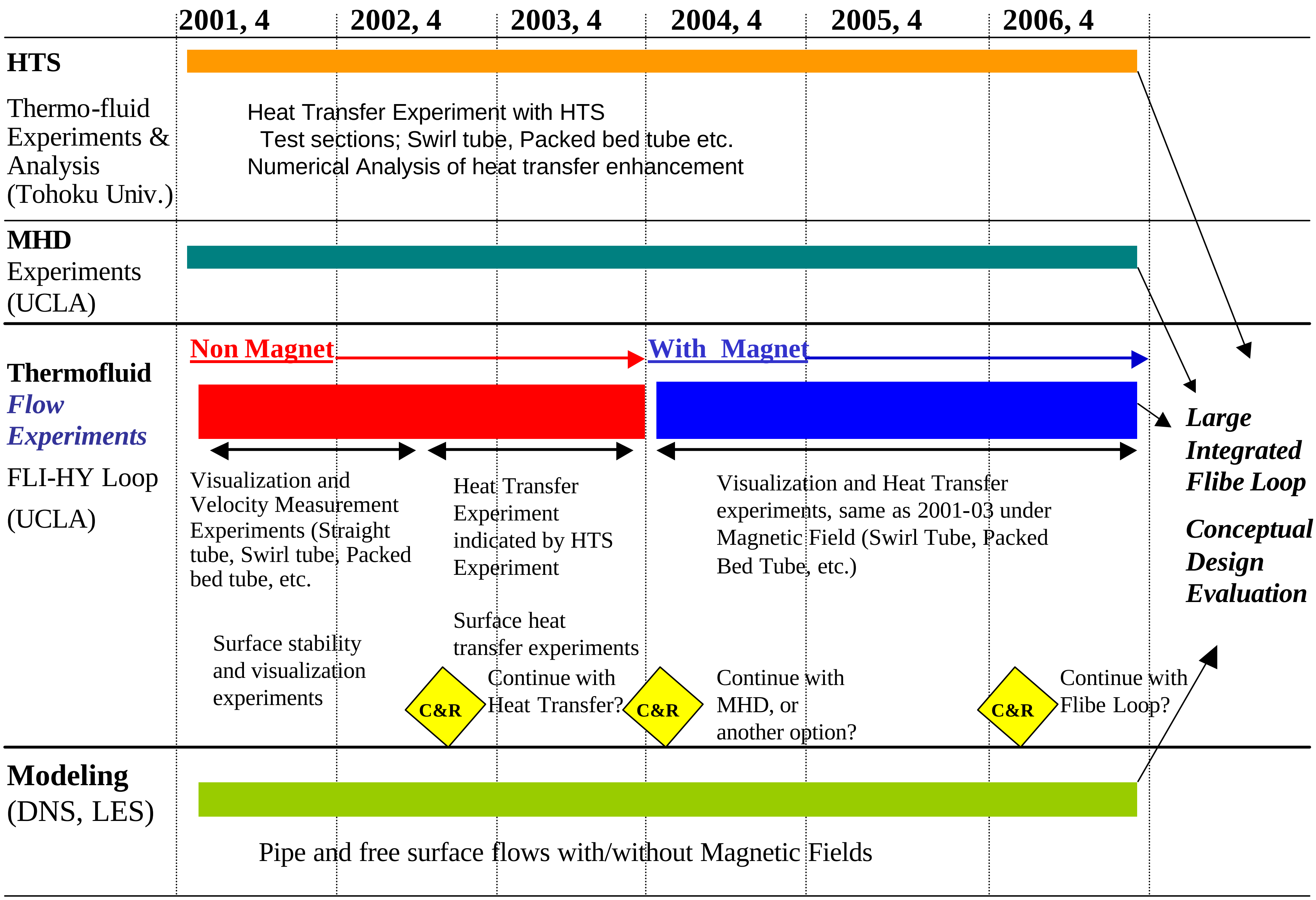
Main Areas of Collaborative Scientific Interest between JUPITER and APEX

Turbulent Hydrodynamics and heat transfer near solid walls and at liquid/vacuum interfaces of Flibe simulants flowing in closed channels and swirl pipes, and on flat and curved plates, with and without MHD effects

Identification of instrumental and experimental techniques: Radiant heating, laser and ultrasonic surface topology reconstruction, infra-red temperature measurements, laser Doppler and particle image velocimetry, others.

Development and benchmarking of new modeling techniques: MHD turbulence interactions and turbulence wall and free surface interactions in k-e, DNS, LES

TASK 1-1-B Thermofluid Experiments and Modeling Schedule for 6 years



JUPITER-II

Thermomechanics for SiC/SiC/He with Be and ceramic breeders

- Extends the present thermomechanics modeling and experiments to SiC/SiC, helium-cooled systems with ceramic breeders and beryllium
- Objectives/Scope: experiments and models for:
  - *Thermomechanic interactions of SiC/SiC with Be and ceramic breeders*
  - *Short-term temperature effects on chemical compatibility*
  - *Thermomechanical performance at elevated temperatures (>800 C at interfaces)*
  - *Provide important scientific and engineering input to*

    a) the design of irradiation experiments, b) reactor studies
- Although SiC is a strong candidate structural material for fusion:
  - *Key fundamental data is lacking. Interface thermal conductance is a feasibility issue to keep SiC above the minimum temperature for radiation induced thermal conductivity degradation*
    - *Also, fabrication and joining techniques are in early stages*
    - *Japan will provide the SiC needed for the experiments from their R&D program (in addition to funds*)
- Collaborative efforts between (UCLA, ORNL) and (Kyoto Univ, Univ of Yamanashi, JAERI)

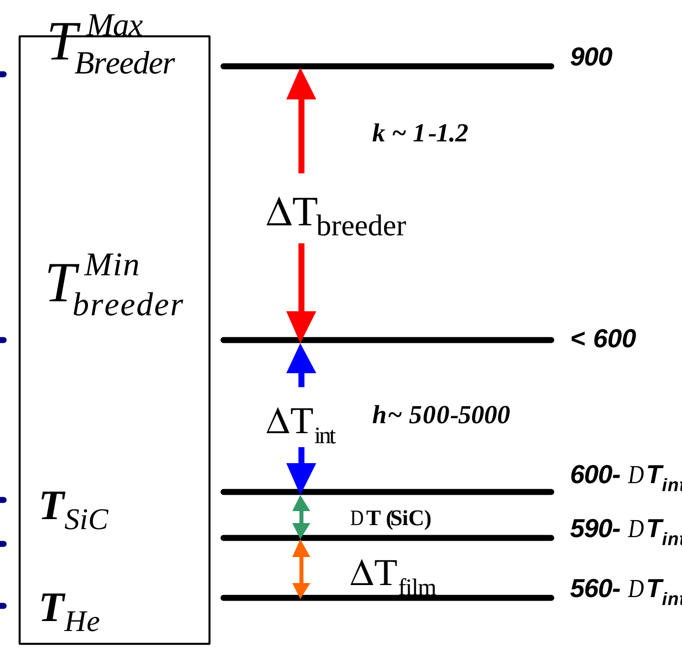
Thermal Interface Conductance is Critical for SiC/SiC He-cooled SB System

1) to maintain SiC temperature above the limit for radiation-induced conductivity degradation (i.e. above 600^{o}C)

2) to keep He coolant temperature high for a high efficiency (> 600^{o}C)

- Maximum breeder temperature must be < 900 ^{o}C
- Thermal conductivity of ceramic breeder bed is low ~ 1-1.2 W/mK
- δ_{SB} must be large enough for TBR (taken 1 cm here)
- Interface thermal conductance is highly uncertain and function of many parameters

h_{int} =5000	h_{int} =500
900	900
600	600
570	300
560	290
530	260



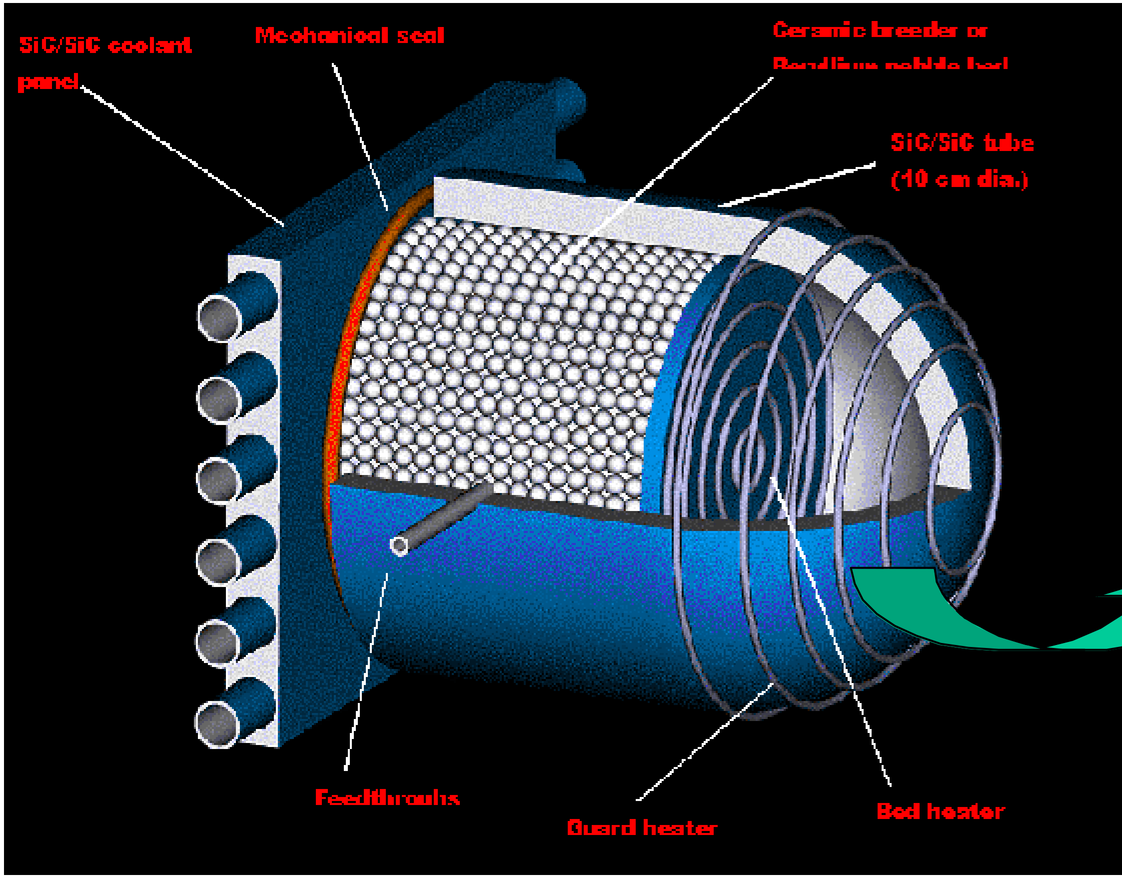
Conclusion

ttaining high interface thermal conductance is essential for practical utilization of SiC

Potential Shaping Techniques Were Identified for SiC to Fabricate

JUPITER-II Solid Breeder/SiC Material System Test Articles

JUPITER-II Collaboration between UCLA and University of Kyoto



JUPITER tests will also be very useful in:

- **Integrating a number of technical disciplines and technical issues**
- **Providing boundary conditions for SiC based on Be/Ceramic Breeder consideration (and vice versa)**
- **Providing an opportunity for scientists and engineers in the material and blanket communities to work together**