

**Fusion Science and Technology Research Program
at UCLA
(VLT Programs)**

Mohamed Abdou

Presented to VLT/PAC, December 4, 2000 at UCLA

Plasma and Fusion Science and Technology Research at UCLA

Research Funding

~ \$12 million/year

broadly funded by NSF, DOE, NASA, ONR, and USAFOR

Research Programs

- **UCLA Electric Tokamak: Dr. Robert Taylor, et al.**
 - Main purpose is to generate near unity beta plasma with greatly improved energy confinement at low magnetic field
- **Large Plasma Device (LAPD): Prof. W. Gekelman, Dr. J. Maggs, Prof. G. Morales**
 - Experimental and theoretical studies of fundamental processes related to naturally occurring plasmas (e.g. auroral ionosphere, solar corona), particle and heat transport, and structural formation in plasmas.
- **Computer Simulation of Plasmas: Profs. J. Dawson and W. Mori; Drs. V. Decyk and J. Lebouef**
 - High performance computing using particle in-cell codes to model plasmas (numerical Tokamak, advanced accelerators, inertial confinement, plasma space and astrophysics, semi-classical quantum models)
- **The MARS Laser Laboratory: Prof. C. Joshi, et al.**
 - (one terawatt CO₂ laser), exploring advanced concepts for ultra-high gradient acceleration of electrons using a collective acceleration scheme known as the Plasma Beat Wave Accelerator

Plasma and Fusion Science and Technology Research at UCLA (cont'd)

- **Fusion Science and Technology Research: Prof. M. Abdou, et al.**

- VLT Program: research aimed at advancing the underlying engineering sciences, understanding fundamental issues, and enhancing innovative concepts for Chamber Technology and Plasma-Material Interactions for IFE and MFE
- emphasis on laboratory experiments and phenomenological & numerical modelling

- **Materials: Prof. N. Ghoniem**

- VLT Program: fundamental understanding and advances of material science and applications: 1) laser effects on IFE final optics, 2) plastic & fracture instabilities, 3) design of fusion materials by computer simulation

- **Other Research Programs:**

- Particle Beam Physics Laboratory: Profs. Rosenzweig and Pellegrini
- The Millimeter-wave and Plasma Diagnostic Group: Drs. Peebles and Brower
- Space Simulation Group: Prof. Maha Ashour-Abdalla
- Simulation of Large-Scale Magnetospheric Electrodynamics: Prof. Coroniti, et al.
- Space Physics Group: Profs. Russell and Moldwin
- Space Weather Group: Prof. McPherron, et al.
- Plasma Physics of Magnetospheric Disturbances: Prof. Lyons, et al.
- Plasma Physics Laboratory: Prof. Wong, et al.
- Low Temperature Plasma Technology Laboratory: Prof. Frank Chen
- Laboratory for Computational Modelling and Energetic Processing of Materials: Prof. Ghoniem, et al.

Fusion Materials Research at UCLA

N.M. Ghoniem

Project

Objective

1

**Laser Effects On IFE
Final Optics**

- (1) Modeling microscopic laser damage;
- (2) Computer-Aided-Design of IFE optics;
- (3) Optimization of experiments at UCSD/GA for laser damage resistant materials.

2

**Plastic & Fracture
Instabilities**

- (1) Flow localization & fracture ;
- (2) Radiation hardening;
- (3) Helium effects on grain boundary fracture ;
- (4) Impurity segregation & effects on cracking;
- (5) Ductile-to-brittle-transition (DBTT).

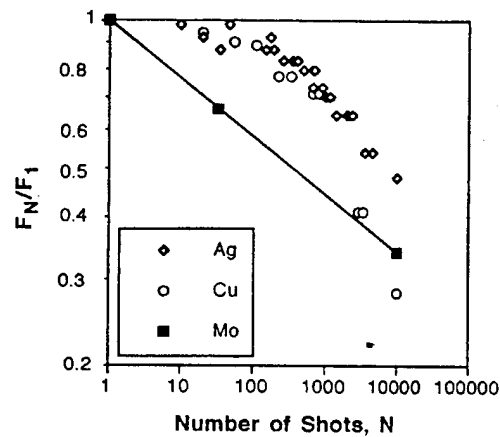
Pending

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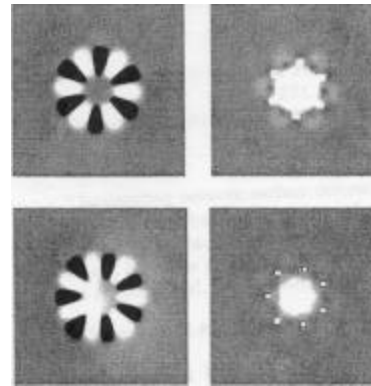
**Design of Fusion
Materials by Computer
Simulations (with UCSB)**

- (1) Multi-scale, multi-physics modeling of microstructure evolution;
- (2) Non-equilibrium phase stability;
- (3) Temperature & flux transient effects;
- (4) Computational design of fusion alloys.

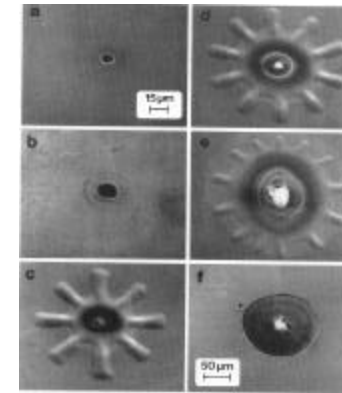
Laser Effects on IFE Final Optics



Laser-Induced Damage Threshold (LIDT) is a strong function of material & # of shots.

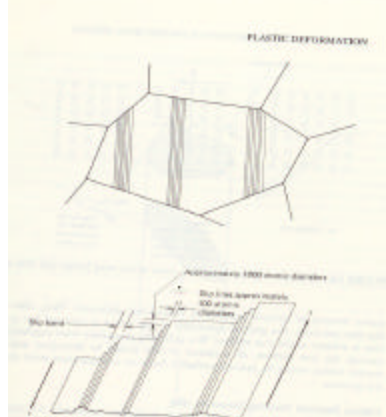


Computer Simulation



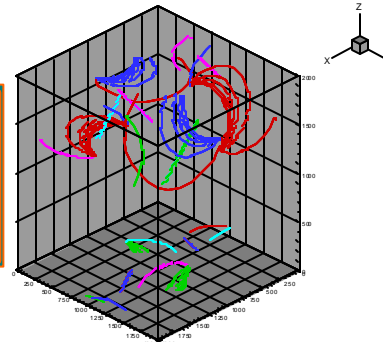
Experiment

Focused laser-induced surface deformation (Lauzeral, Walgraef & Ghoniem, *Phys. Rev. Lett.* 79, 14 (1997) 2706)

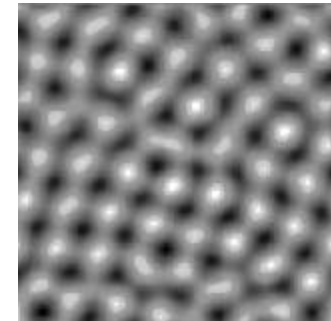


Mechanism

Plastic slip transmission to the surface.



Simulation



Uniform laser-induced surface deformation (Walgraef, Ghoniem & Lauzeral, *Phys. Rev. B*, 56, 23, (1997) 1536)

Fusion Science and Technology Research Program at UCLA

(M. Abdou, et al.)

Focus Area

Chamber Science and Technology for IFE and MFE

Objectives

- ◆ Advance the underlying engineering sciences
- ◆ Understand and Resolve Fundamental Issues
- ◆ Explore innovative concepts for: 1) improving performance of plasma devices, and 2) enhancing the attractiveness of fusion energy systems

Primary Scientific Disciplines

- ◆ Fluid Mechanics, MHD, Heat Transfer (Free Surface and Channel Flow)
- ◆ Particle and Radiation Transport
- ◆ Plasma-Material Interactions

Research Group

- ◆ Dedicated Faculty: M. Abdou
- ◆ Collaboration with other faculty renowned in their fields: Profs. Ghoniem, Dhir, Kim, Ho, Carmen, Gupta, Kelly
- ◆ Research Staff: N. Morley, A. Ying, M. Youssef, S. Smolentsev, H. Huang, S. Sharafat, T. Sketchley
- ◆ Students:
 - 10 Graduate Students: Mostly Ph.D. Thesis
 - 6 Undergraduate Students: attract through work study programs (many benefits)

Fusion Science and Technology Research Program at UCLA (cont'd)

Mode of Operation Emphasis

◆ **Emphasis on Science**

- Most of the research is Ph.D. thesis (also excellent mechanism for thorough “Peer Review”)
- Laboratory Experiments and Challenging Phenomenological and Computation Modelling

◆ **Publications in Scholarly Journals**

◆ **Collaboration with other US Institutions**

- UCLA Experiments in collaboration with PPPL, SNL, ORNL
- Formal collaboration with 12 Universities and national labs through APEX and other activities

◆ **International Collaboration**

- Long history of formal and informal collaboration
- JAERI and Japanese Universities have been sending one or two researchers each for a period of 1-2 years
- FZK, JAERI, and Canada have provided ceramic pebble bed materials and participated in experiments at UCLA
- **Most Recent:**
 - Very strong collaboration with renowned Professors from Japan on Free-Surface Phenomena
 - JUPITER II Collaboration on Thermofluids and Thermomechanics

◆ **Outreach to scientists outside of fusion**

- Faculty within UCLA
- Invite prominent scientists (e.g. Tien, Ho)
- Opportunities: e.g. CERN
- Faculty and researchers in Japanese Universities
- Technical sessions and papers in non-fusion societies

Fusion Science and Technology Research at UCLA

Key Research Areas: Thermofluids and Thermal-Mechanical Material Interactions

(Laboratory Experiments and Modelling)

1. IFE

A. **Chamber Clearing:** Vapor Dynamics and Condensation

Facility: ALICE

B. **Liquid Wall Issues:** Turbulent Liquid Jet Hydrodynamics

Facility: MeSOJet

C. **Liquid Film:** Rapid Heating and GILMM

2. Thermofluids (MFE focus with relevance to IFE)

A. free surface Hydrodynamics for high and low-conductivity fluids, including MHD

B. Free Surface and closed channel heat transfer, including MHD

Facilities: M-TOR and FliHy

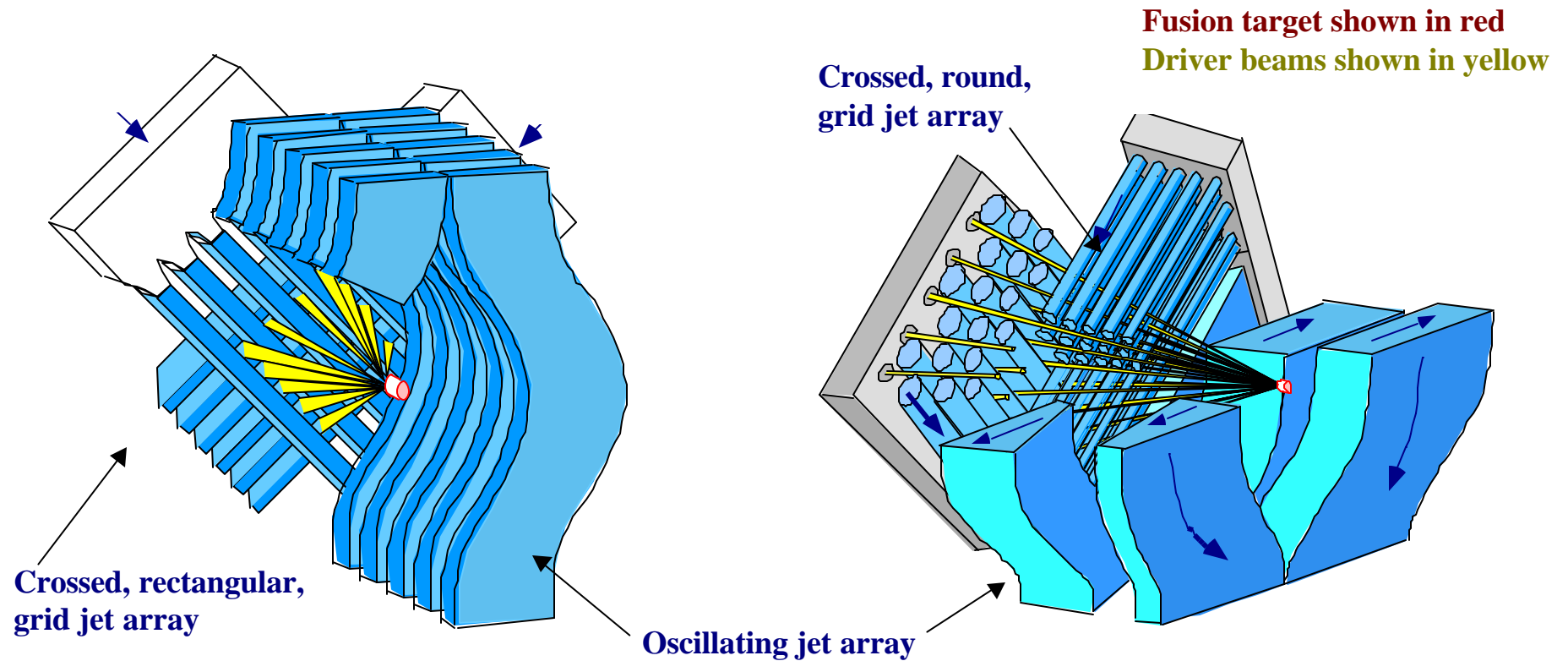
3. Non-Structural Material Science

A. Fundamental thermophysical properties for pebble beds

B. Material system thermomechanics interactions

Facilities: HiTec, UNICEX, Beryllium Handling Facility

Liquid Wall Issues for IFE Chambers



Jet Hydrodynamics and Heat Transfer Issues:

- How will the jets deform?
- How quickly will vapor condense?

IFE Liquid Wall Research at UCLA

Turbulent Liquid Jet Hydrodynamics
(MeSO-Jet)

Liquid Film Hydrodynamics and Heat Transfer
(Popoff and GILMM)

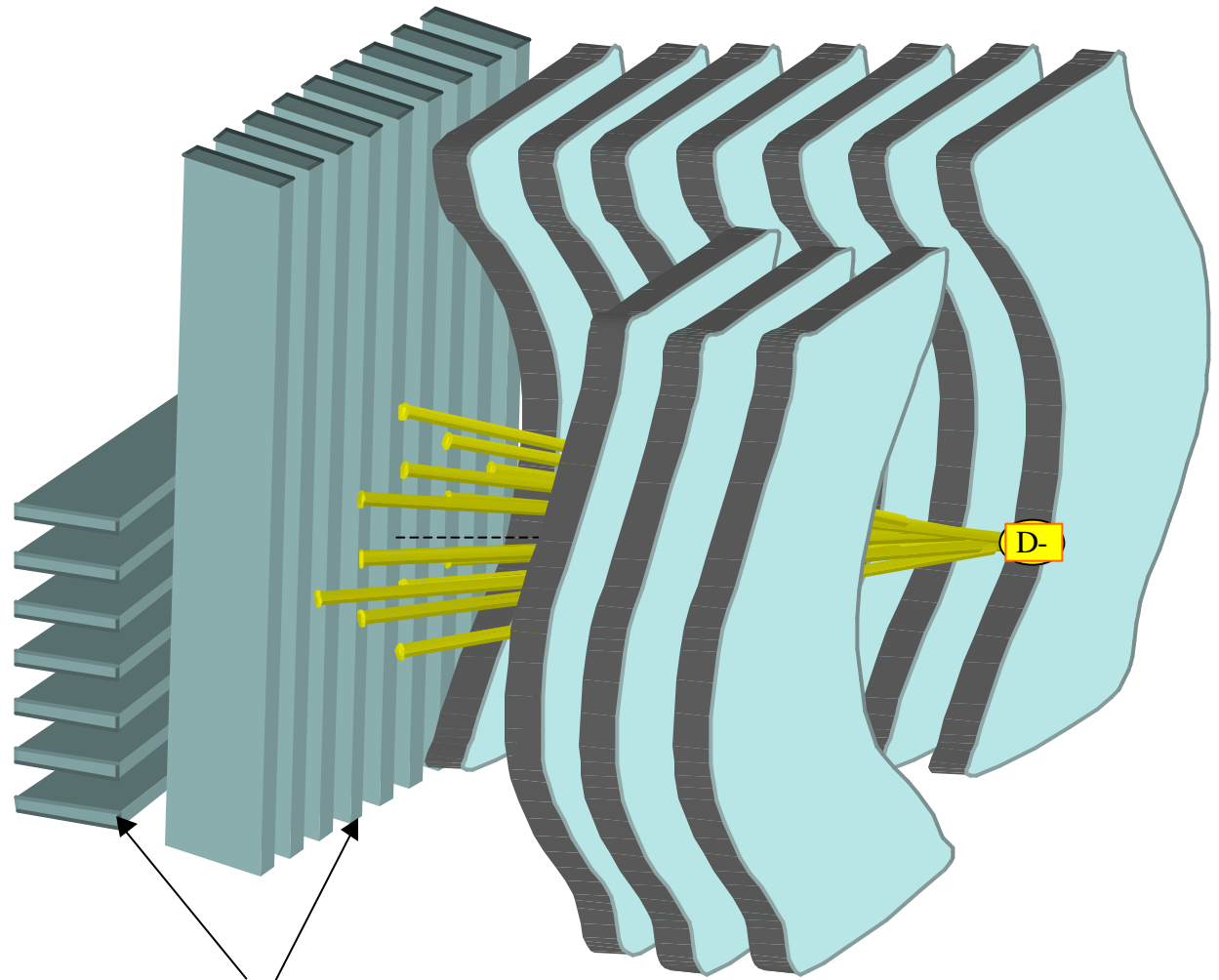
Vapor Hydrodynamics and Condensation
(ALICE)



Grid Jets Must Fit Close to Driver Beams

Jet hydrodynamics must be quantified:

- Surface rippling due to boundary layer relaxation and turbulence
- Gross deformation from surface tension effects, imperfect nozzle contraction, and gravity acceleration



Grid Jet Arrays

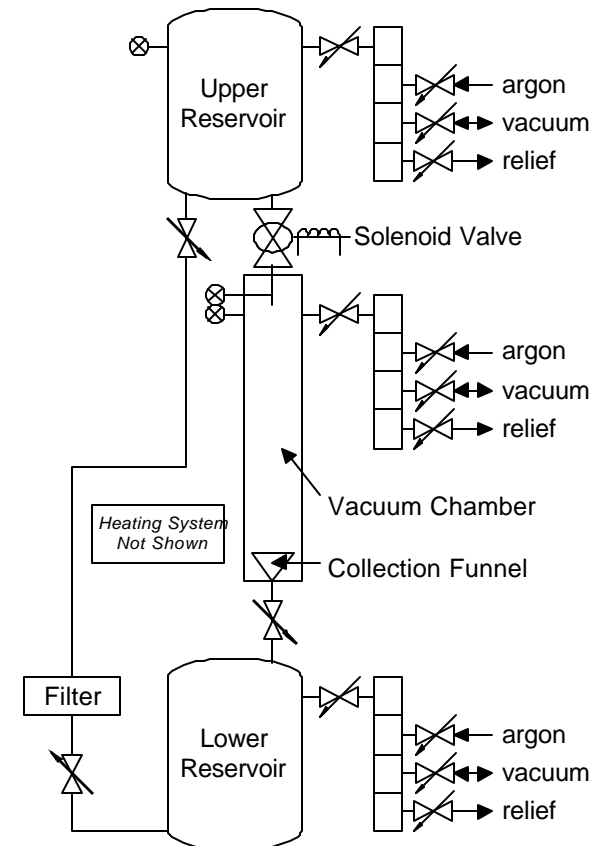
LM Turbulent Jet Studies at UCLA

Objectives:

- Produce high quality, high Re , We number, low nozzle contraction liquid jets for study
- Test combinations of upstream flow conditioning on jet surface quality, gross deformation and pressure drop

MeSO-Jet Facility

- Low melting point LM alloy used as working fluid (Low P_v , no flashing)
- Pressurized upper reservoir drives LM through nozzle assembly
- High-speed photography is the primary surface diagnostic. New optical surface slope method under consideration

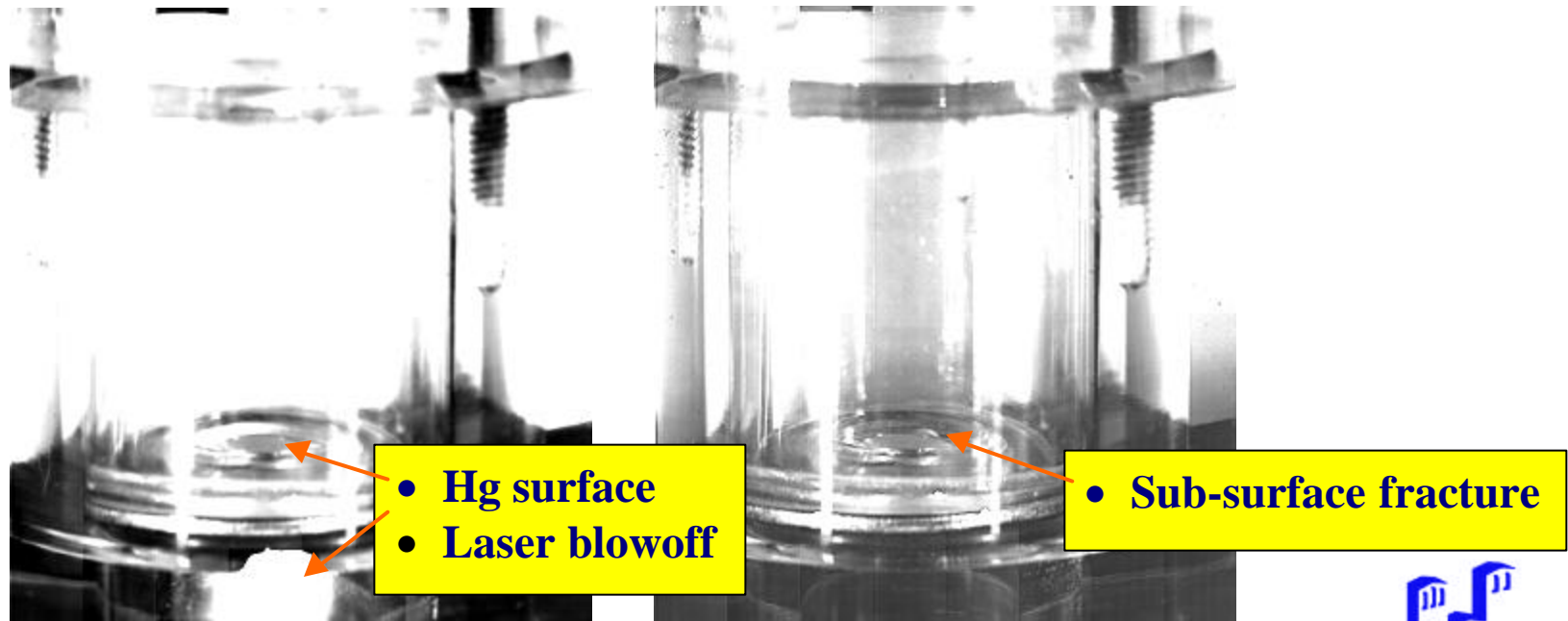


Liquid Fracture Strength Experiment

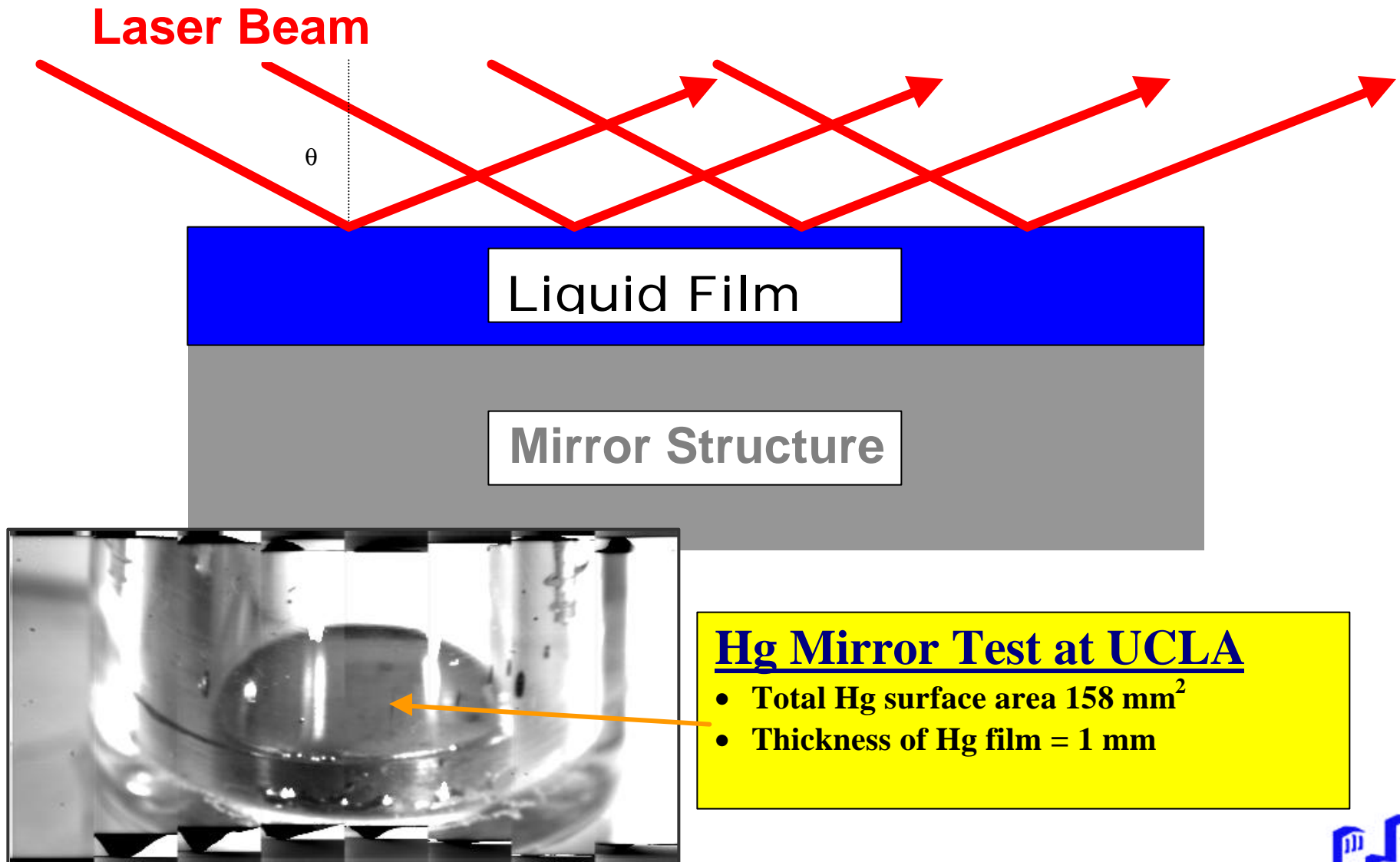
Goal: To measure fracture strength of various liquids subjected to fast tensile pulses from isochoric heating and ablation shocks

Initial results:

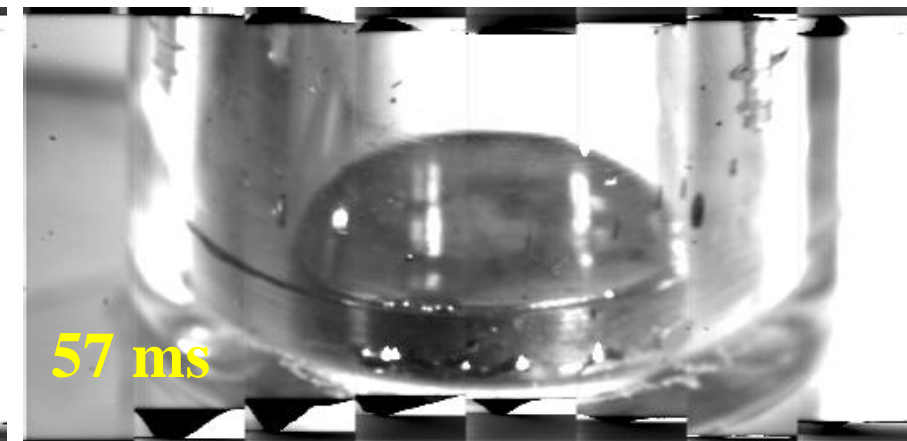
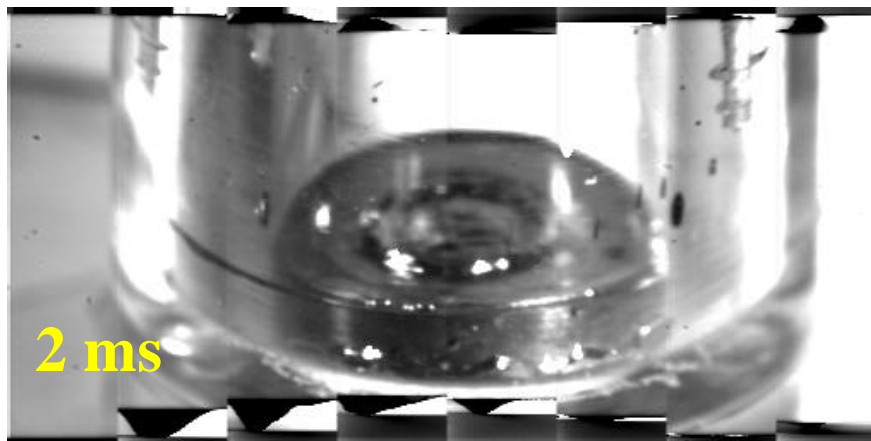
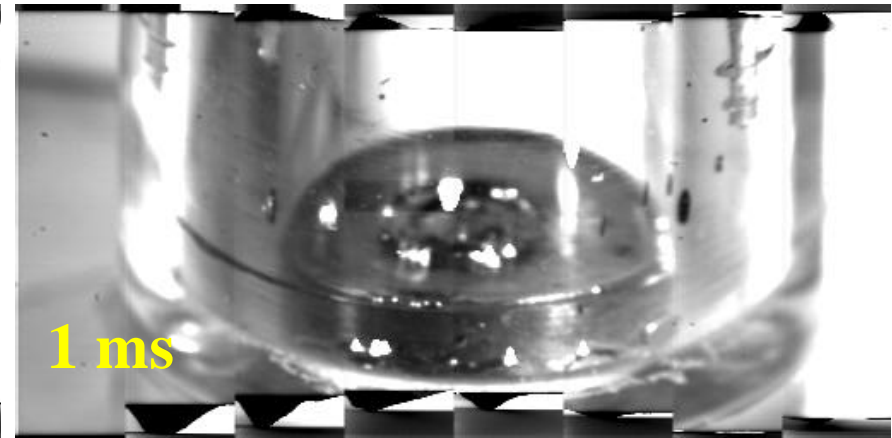
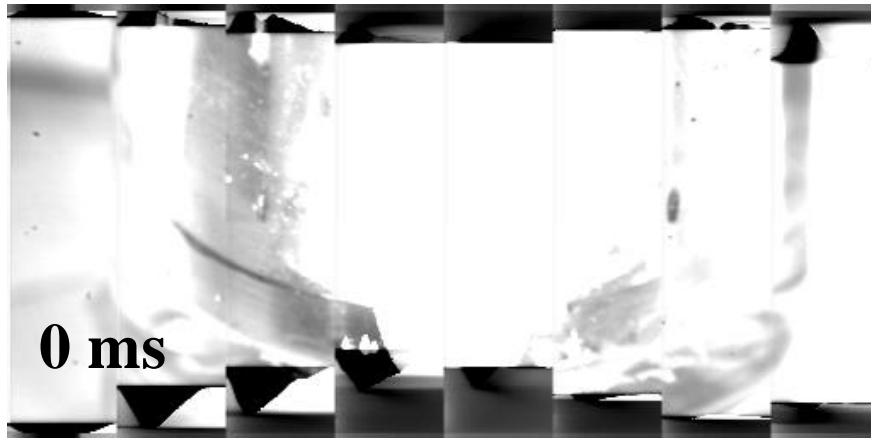
- Surface distention of >0.5 mm at approximately 3.5 ms after laser impact **indicates liquid fracture beneath the surface.**
- Some shots without camera showed small **Hg droplets** scattered around inside of test article



Grazing Incidence Liquid Metal Mirror



Hg Mirror After 3 ns, 1 J/cm² (ab) Pulse

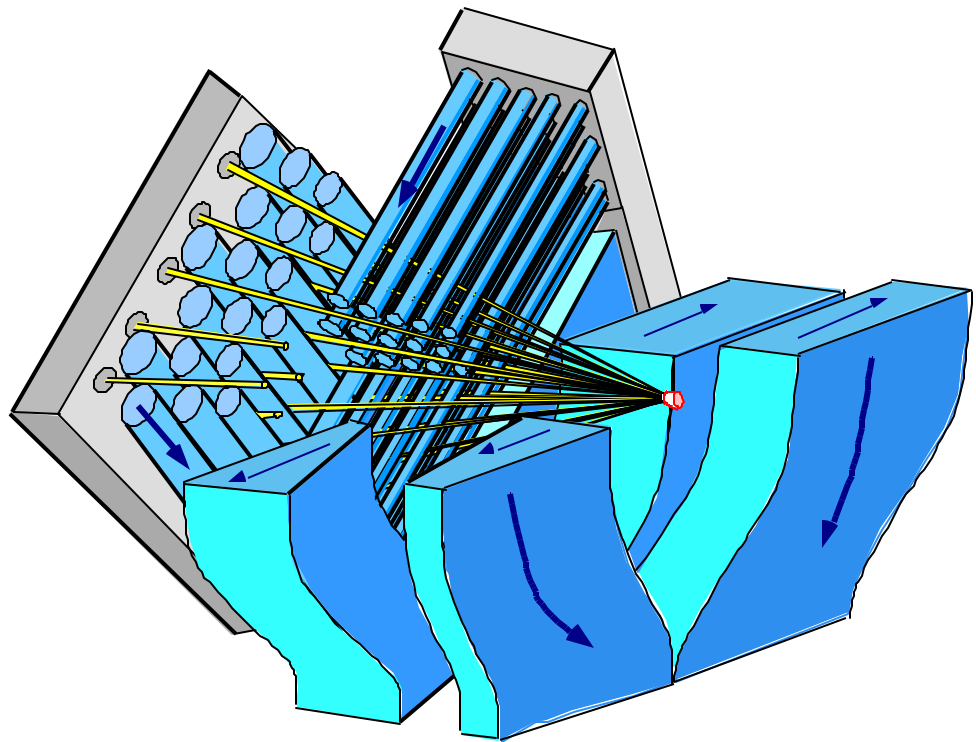


Large waves induced by laser, but no waves visible after 50 ms

Vapor Dynamics and Condensation Studies Help Assess IFE Liquid Chamber Clearing Issues

- ↪ IFE reactors reference explosion **frequency** is **5 Hz**
- ↪ **FLiBe** liquid wall: chamber protection, T breeding, heat recovery
- ↪ Fundamental issue for drivers efficiency is **chamber clearing**

In chamber designs involving liquid walls **condensation of vaporized material** is the time dominant process for beams path clearance recovery between each pulse

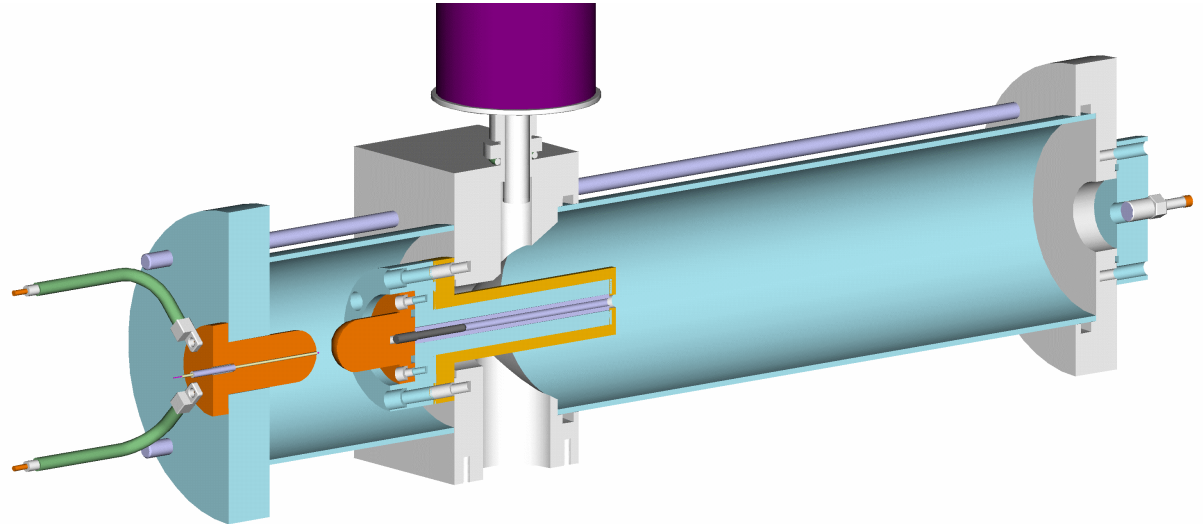


Vapor Dynamics and Condensation Study at UCLA

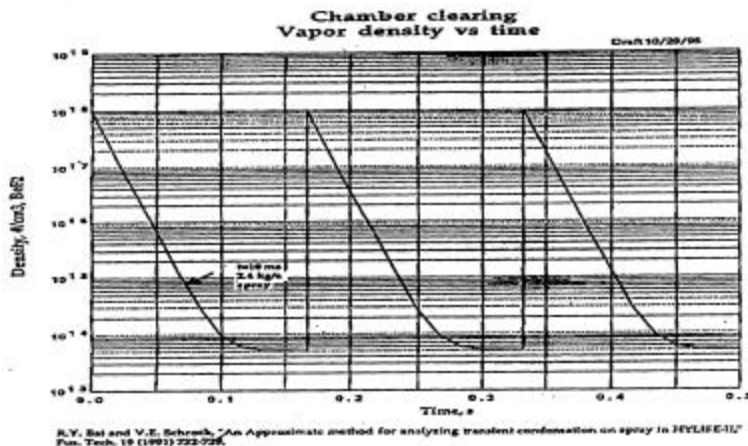
Experimental effort

A vaporized FLiBe jet is ejected from a **plasma source** into a condensation chamber.

Pressure relaxation history allows recovery of vapor clearing data



HYLIFE-II Result



Modeling

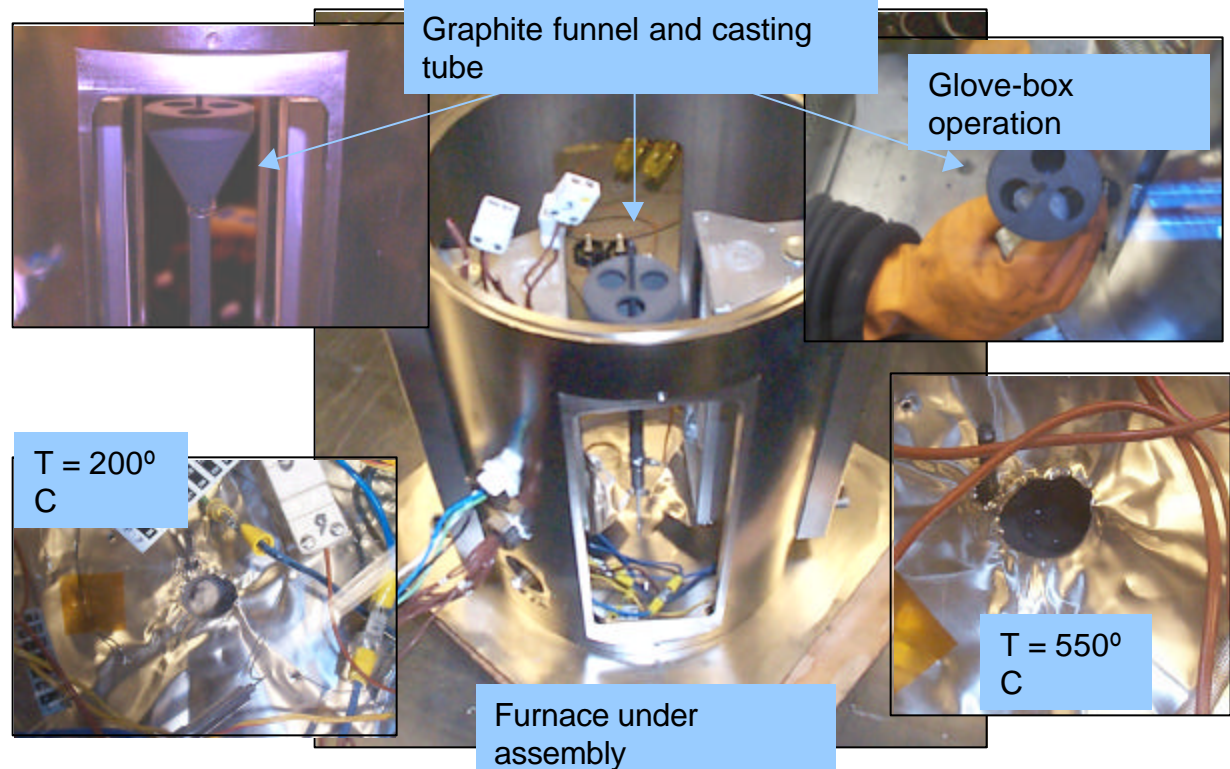
Time scale difference allows to use vapor generation and expansion (ms) as **initial conditions** for condensation process (ms)

ODIN code is used to evaluate **plasma parameters** inside the source and TSUNAMI to follow **jet expansion** and **vapor condensation**

Vapor Dynamics and Condensation Study Involves Many **Knowledge on:** Opportunities for Intradiscipline

- ↪ Pulse plasma generation, equation of state and dynamics
- ↪ Ablation, dissociation, ionization and chemical recombination
- ↪ vapor hydrodynamics, condensation, and liquid interaction
- ↪ Flibe handling and material interaction

- ◆ Molten salt FLiBe (33% BeF_2 + 66% LiF) is handled in a Be safe glove box
- ◆ Melting and recasting of FLiBe liners to be inserted in the plasma source accomplished
- ◆ A FLiBe flowing loop is under design for final form of condensation chamber



FLiBe Casting and Handling

Scientific Issues for Liquid Walls

- Effects of Liquid Walls on Core Plasma including:
 - Discharge evolution (startup, fueling, transport, beneficial effects of low recycling)
 - Plasma stability including beneficial effects of conducting shell and flow
- Edge Plasma-Liquid Surface Interactions
- Turbulence Modifications At and Near Free-Surfaces
- MHD Effects on Free-Surface Flow for Low- and High-Conductivity Fluids
- Hydrodynamic Control of Free-Surface Flow in Complex Geometries, including Penetrations, Submerged Walls, Inverted Surfaces, etc.

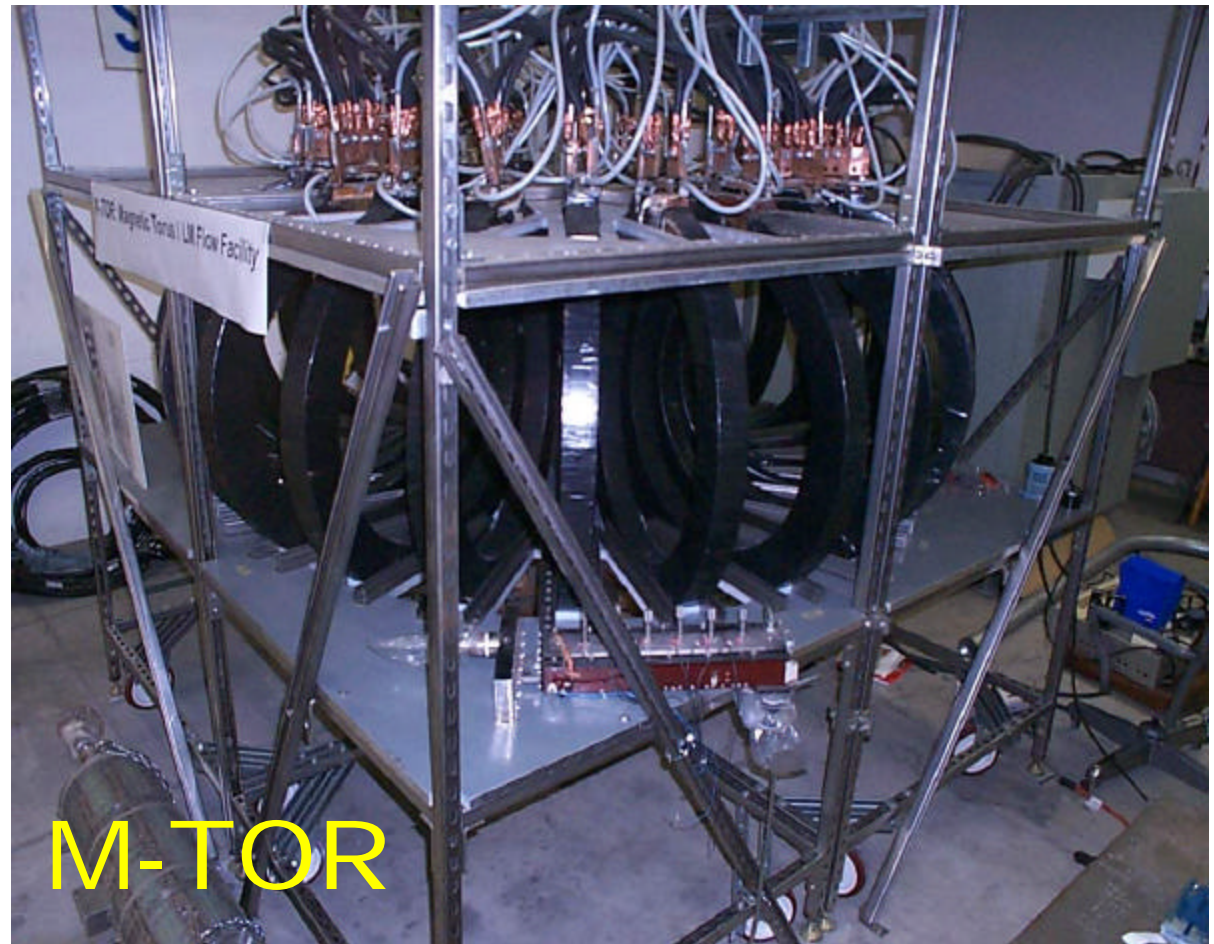
Exploration of Fundamental MHD Issues in Free Surface LM Flows

Magnetic Torus / LM Flowloop

Designed in
collaboration with
PPPL and ORNL

Recycled Equipment:

- Magnets from TARA mirror experiment at MIT
- Power supplies for PPPL and LLNL
- LM Pump from Russia



M-TOR Facility Objectives

- **Study toroidal field and gradient effects on drag.** Free surface flows are very sensitive to drag from toroidal field $1/R$ gradient, and surface-normal fields
- **3-component field effects on drag and stability.** Complex stability issues arise with field gradients, 3-component magnetic fields, and applied electric currents
- **Effect of applied electric currents**, including: Magnetic Propulsion and other active electromagnetic restraint and electromagnetic pumping ideas
- **Geometric Effects**, including axisymmetry, expanding contracting flow areas, inverted flows, penetrations
- **NSTX Environment simulation** for module testing. Including time varying field effects

M-TOR Staged Implementation

Stage 1

- 24 coil torus, 1800 A per coil, ~600 kW ($B_T \sim 0.6$ T)
- Surface normal fields built with permanent magnets ($B_P \sim 0.1$ T)
- 15 liter Ga-In-Sn liquid metal flowloop with max flowrate ~3 l/s
- Applied electric currents > 1000 A possible.

Status

- Toroidal field magnets assembled and tested
- 1 L flowloop used for diagnostic testing and initial MHD experiments
- Awaiting cooling water and 15 L Ga-In-Sn for full stage 1 operation

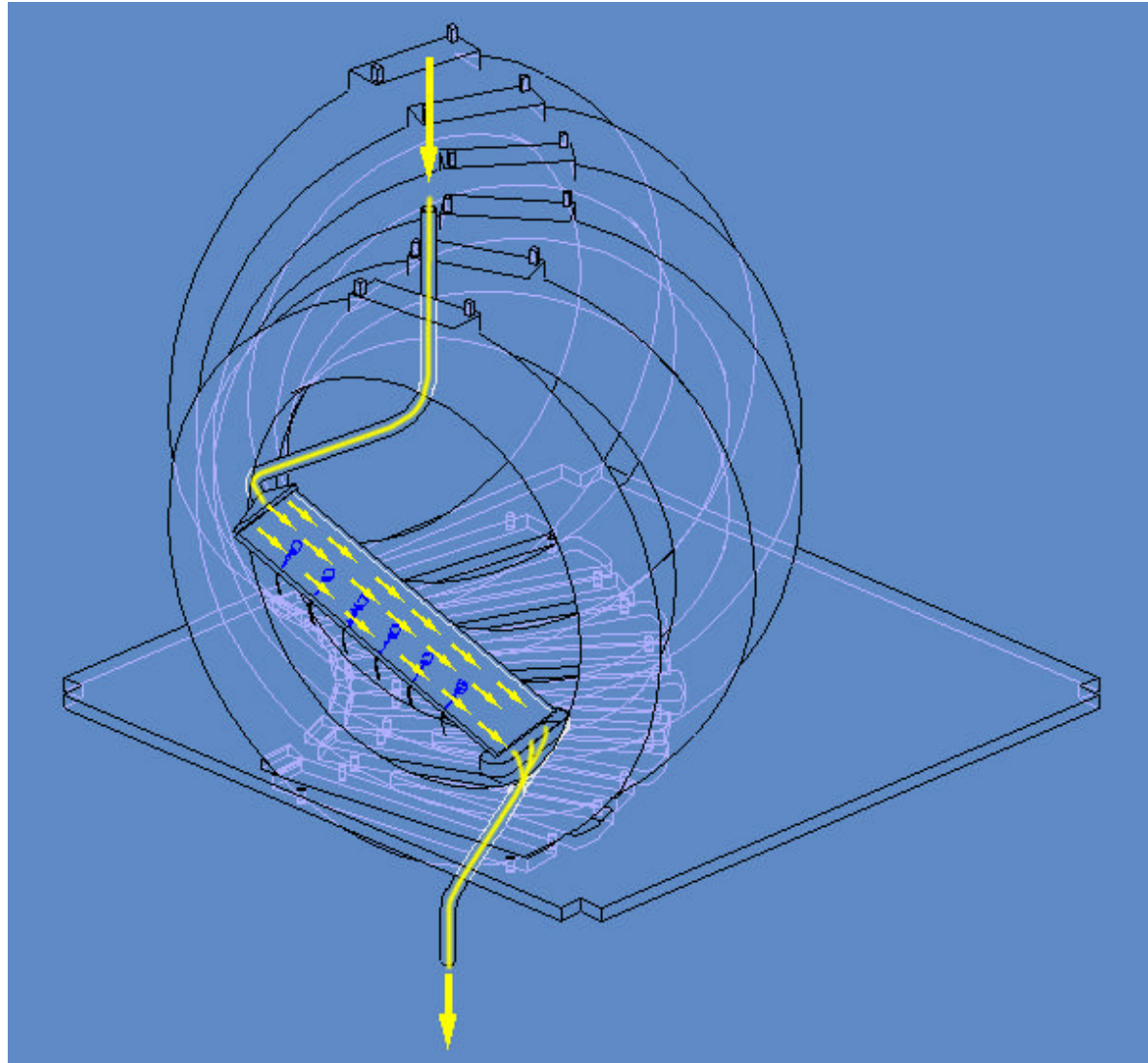
Later Stages

- Toroidal field magnets run at full current, 3664 A/coil ($B_T \sim 1.2$ T)
- Flow loop upgrade to Li or Na alloy at ~25 l/s for large test sections
- Polodial field generation with pulsed conductors (simulate OH, vertical fields and plasma current)

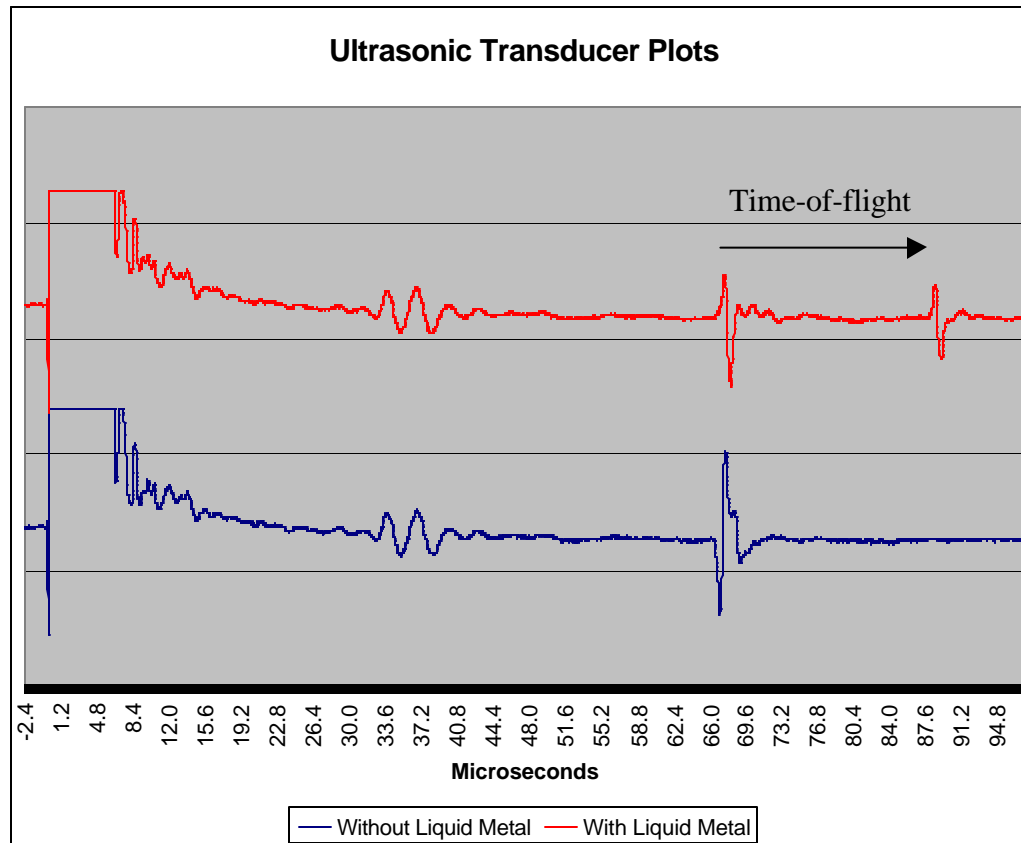
First LM-MHD Experiments in M-TOR

Effects to Study

- Explore effect of elongation of flow along B field on Hartmann drag
- Explore effect of finite surface-normal fields on drag and stability
- Explore MP and other EMP/R ideas
- Explore diverging flow area effect
- Explore effect of conducting penetrations

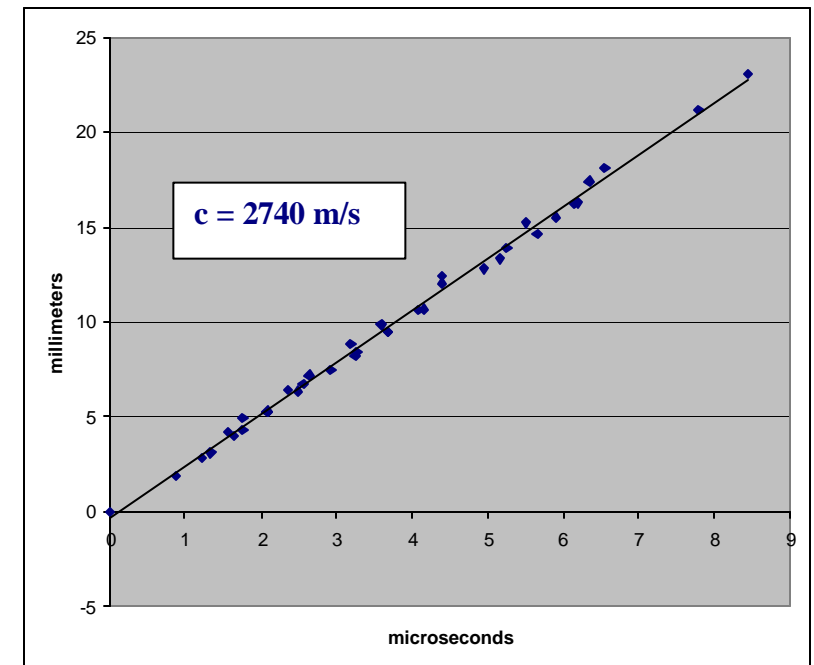


Ultrasonic Measurement of LM Thickness



Ultrasonic time-of-flight (TOF) is converted into layer thickness (h) via the sound speed (c),

$$h = c \times \text{TOF}$$



Sound speed is measured using stagnant films and sensitive micrometers to measure height. For room temperature Ga-In-Sn, $c = 2740 \text{ m/s}$

FliHy

Flibe hydrodynamic Simulation Facility

Facility Role:

Flexible flibe simulant loop for a variety of hydrodynamic, magnetohydrodynamic, and heat transfer experiments.

The facility serves the experimental research needs for exploring low conductivity, Pr fluids for a) liquid walls in MFE, b) liquid walls for IFE, and c) open and closed channel flows for JUPITER-II.

Support

UCLA effort is supported by SNL, ORNL, PPPL, and Japan

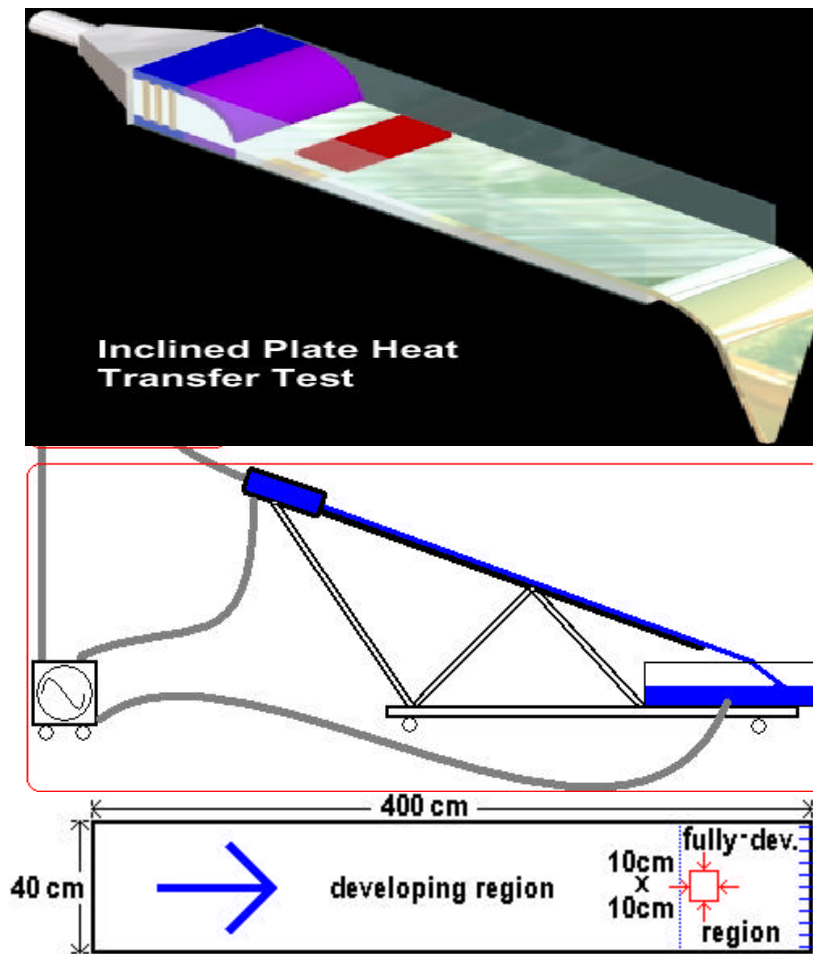
Status

- Technical requirements and specifications agreed to by the community through APEX and JUPITER-II
- Extensive design reviews completed
- Construction has just begun

FLIHY Facility Objectives

- Study **surface heat transfer** for wavy and inclined open channel flows
- Examine flow motion dynamics around curved channel and **penetrations**
- Allow for upgrades through modular design. For example, add magnet module and vary fluid conductivity to explore MHD
- Effects on low-conductivity fluids (Part of JUPITER-II collaboration with Japan)

FliHy Facility: First Experiment



- Inclined planar channel: investigate heat transfer at surface and basic hydrodynamics of open channel flow over inclined plate.
- Uses dye visualization, infrared camera, ultrasound, and turbine flow meter.
- Applicable to MFE & IFE

Concurrent Experiment: Curved Channel with Penetration

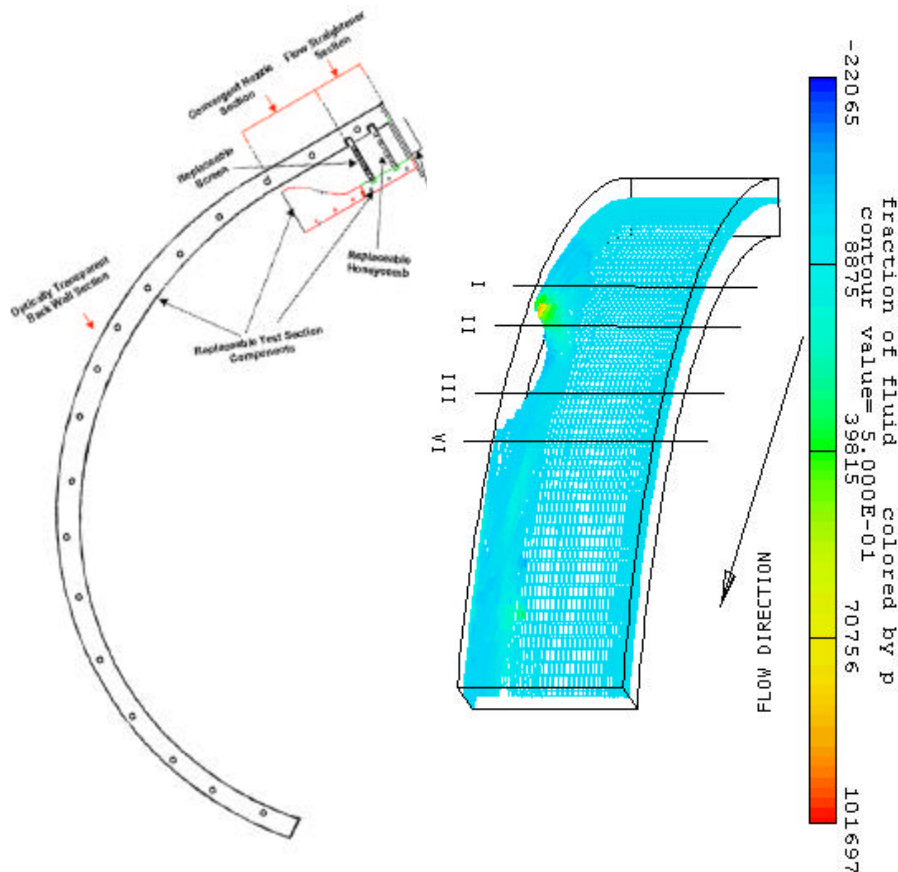


Figure: Curved channel with penetration

- Investigates options to insure full fluid coverage around various types of penetrations
- Analytical and experimental approach will be used to determine effective approaches to flow around penetrations based on CLIFF requirements.

FREE SURFACE MODELING FOR FUSION LED BY UCLA IN COLLABORATION WITH JAPAN AND SBIR

- $Ha/Re > (Ha/Re)_{cr} \rightarrow$ flow laminarization;
- Strong MHD interaction

Liquid Metal modeling

$\sigma \sim 10^6 \text{ 1/Ohm} \cdot \text{m}$

1.5-D, 2-D, 2.5-D UCLA MHD models and codes

Flow3D modified (UCLA)

3-D MHD modeling by HyPerComp in collaboration with UCLA
DOE-SBIR Phase I, II ?

- $Ha/Re < (Ha/Re)_{cr} \rightarrow$ turbulence;
- Weak MHD interaction

Low-conductivity fluid modeling (Flibe)

$\sigma \sim 10^2 \text{ 1/Ohm} \cdot \text{m}$

Direct Numerical Simulation (Japan) in collaboration with UCLA

RANS modeling ("K-e" model, RST model) at UCLA

Flow3D (UCLA)

LIQUID METAL MODELING AT UCLA

- **1.5-D, 2-D and 2.5-d MHD models and computer codes have been developed on the basis of the Navier-Stokes-Maxwell equations;**
- **Commercial CFD software, Flow3D, have been modified to include MHD effects (Flow3D-M).**

$$\frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \nabla) \vec{V} = -\frac{1}{\rho} \nabla p + \nu \Delta \vec{V} + \underbrace{\frac{1}{\rho} \vec{j} \times \vec{B}}_{MHD \text{ force}};$$

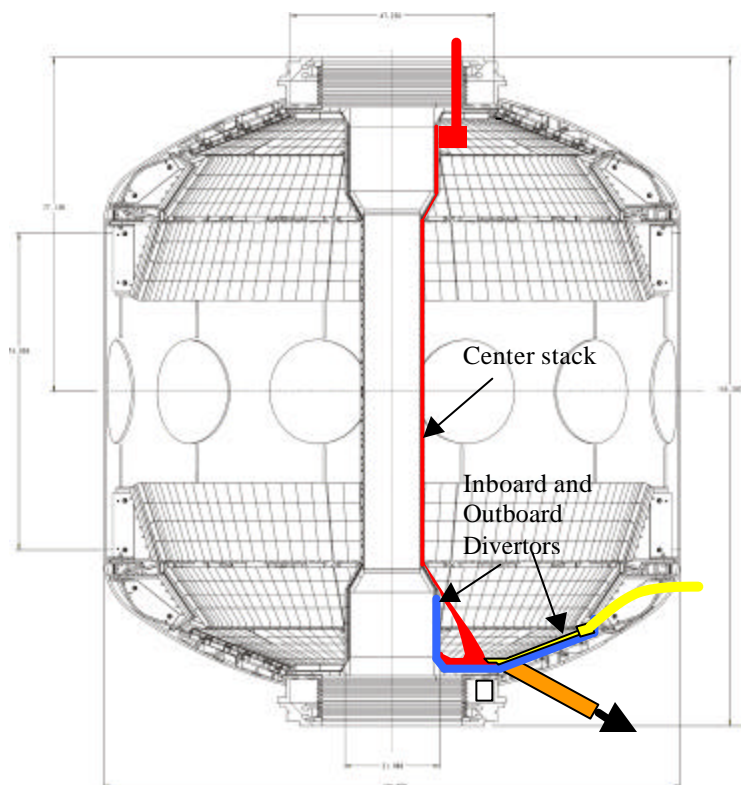
$$\nabla \cdot \vec{V} = 0; \quad \nabla \cdot \vec{j} = 0;$$

$$\vec{j} = \frac{1}{\mu_0} \nabla \times \vec{B};$$

$$\frac{\partial \vec{B}}{\partial t} = \frac{1}{\sigma \mu_0} \nabla \times \vec{B} + \nabla \times (\vec{V} \times \vec{B}).$$

LIQUID METAL MODELING AT UCLA

Free surface Li flows in NSTX

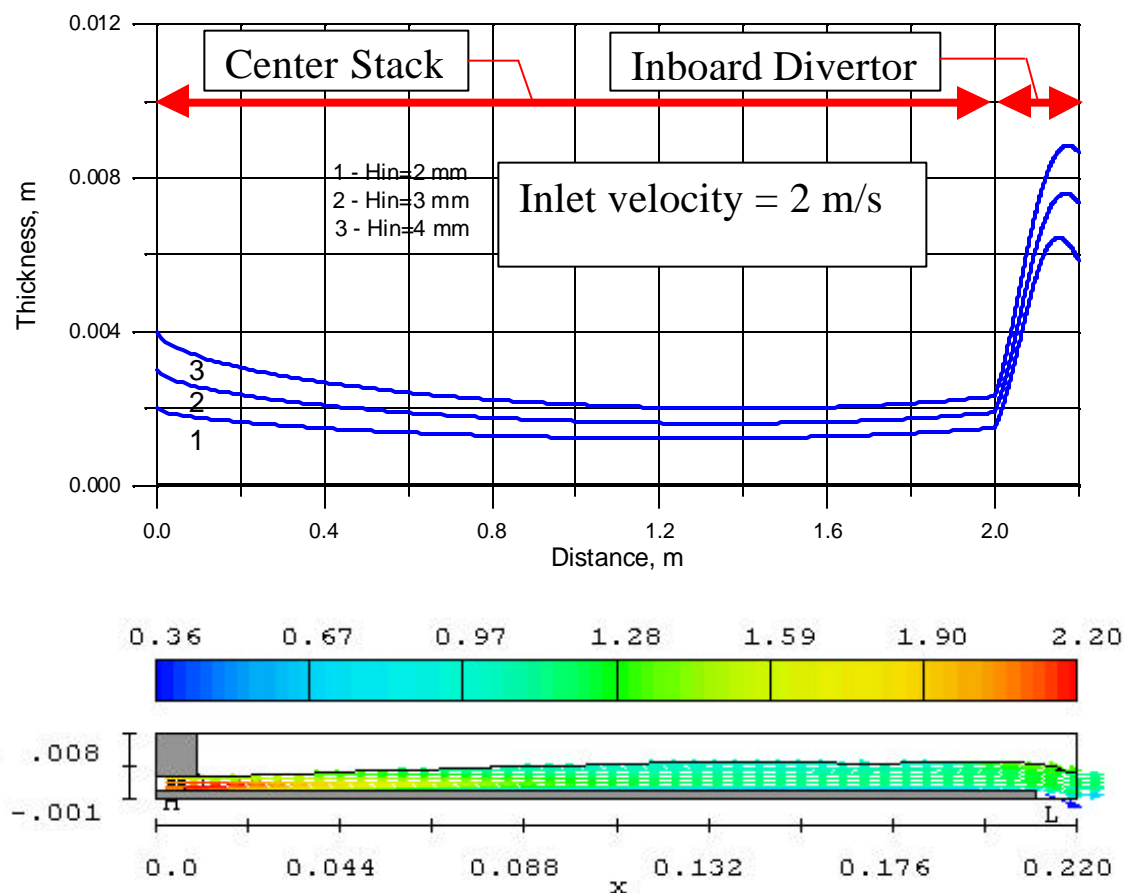


MHD and Heat Transfer Conclusions:

- Stable Li film flow can be established over the Center Stack;
- The Center Stack projected heat load can be removed by a 4 mm film ejected at 2 m/s.

NSTX flow modeling:

Upper - “Center Stack +Inboard Divertor”, 2.5-D model;
Lower – “Inboard Divertor”, Flow3D-M



Liquid Metal modeling in SBIR Phase I, II

Modeling of Free-Surface Liquid Flows for Heat Removal in Fusion Energy Systems

DOE-SBIR Phase I

Grant Number 03-00ER83018

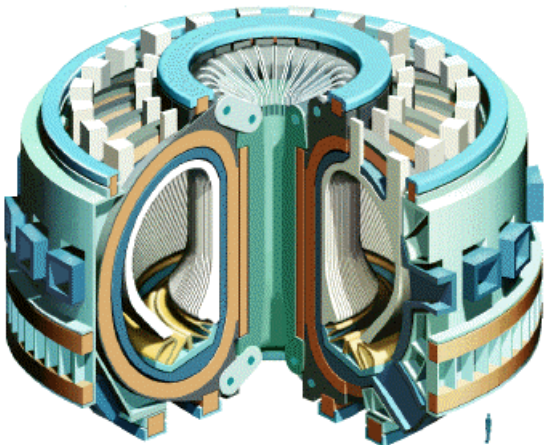
Period of performance Sept. '00 - March '01

Team

Ramakanth Munipalli, Vijaya Shankar
HyPerComp, Inc.

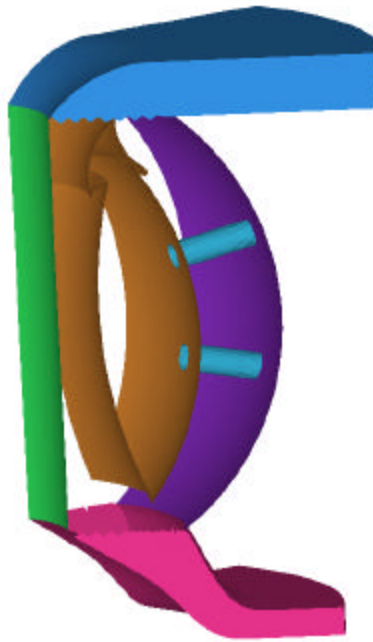
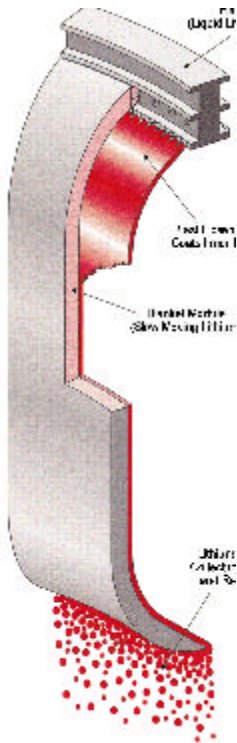
Ali Hadid
(Consultant)

*in collaboration with
Prof. M.A. Abdou and the APEX group at UCLA*

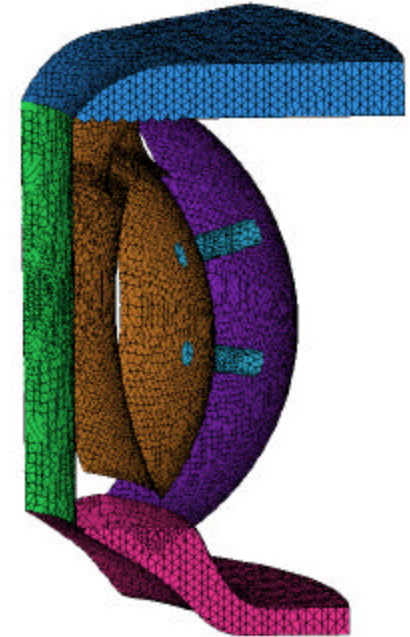


Liquid Metal modeling in SBIR Phase I, II

- Develop engineering predictive capabilities in support of APEX design that include liquid metal flow with a free surface under intense heat and magnetic fluxes in complex geometry
- Provide computational analysis tools for design applications to fusion technology development



3-D modeling

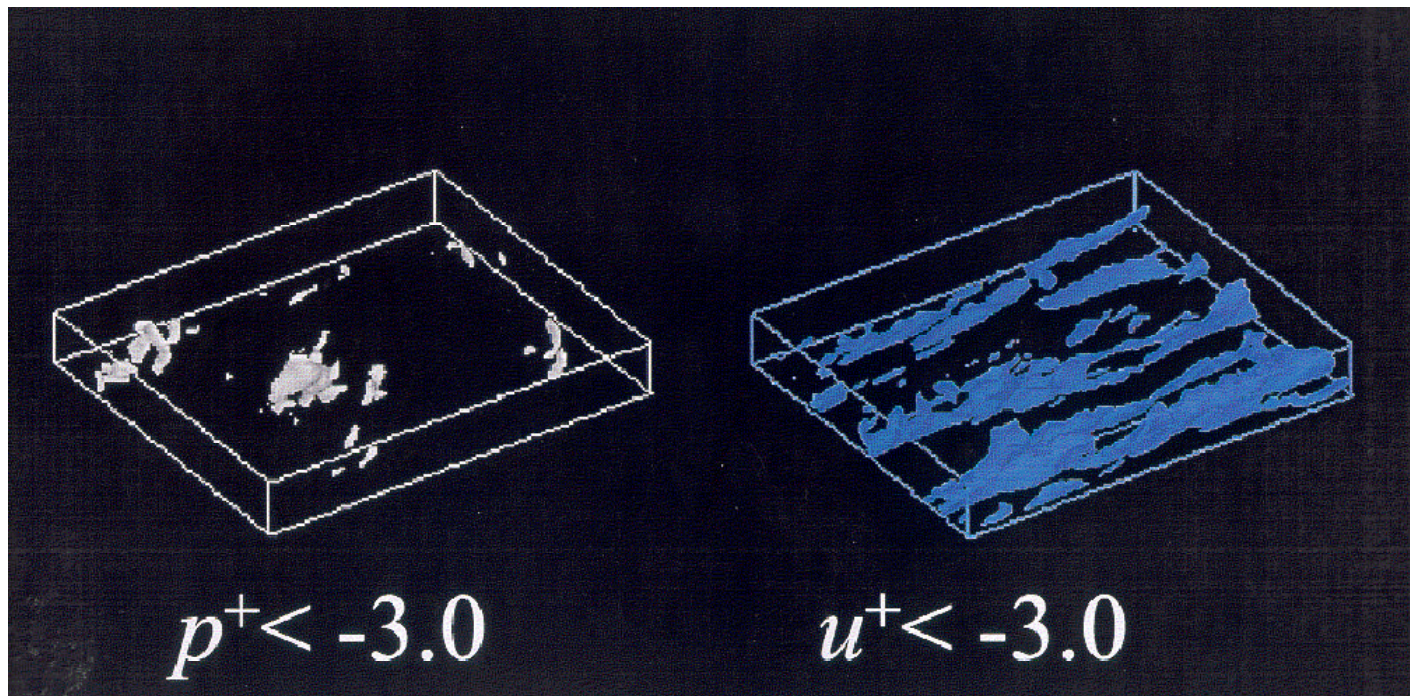


LOW-CONDUCTIVITY FLUID MODELING

DNS of free surface flows in the presence of magnetic field

Japanese collaborators: Prof. S.Satake (Toyama University), Prof. T.Kunugi (Kyoto University)

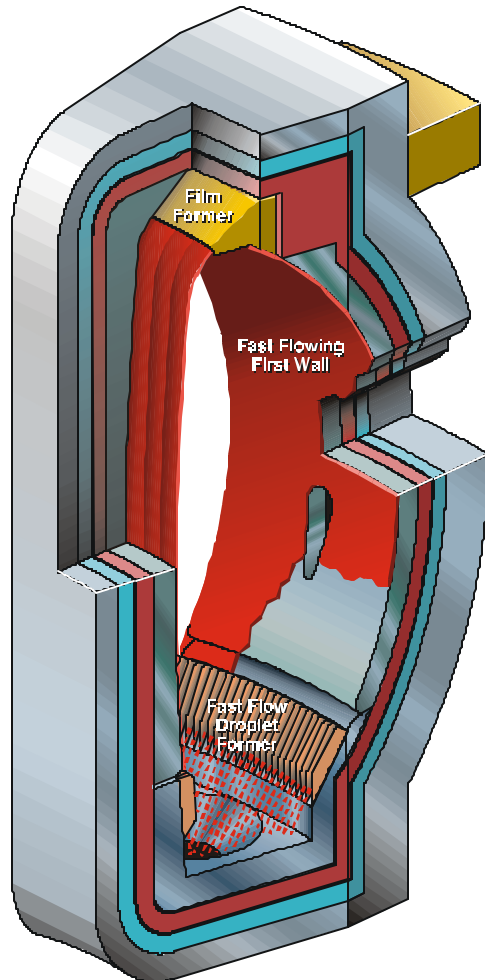
Turbulent structures: $Ha=20$, streamwise magnetic flux



LOW-CONDUCTIVITY FLUID MODELING BASED ON RANS EQUATIONS: “K-e” model

CLIFF Configuration

1/16 Sector - 3D Cutaway



Turbulence model

$$\frac{\partial K}{\partial t} + \langle v_j \rangle \frac{\partial K}{\partial x_j} = \underbrace{v_t \left(\frac{\partial v_i}{\partial x_j} \right)^2}_{\text{Production}} + \underbrace{\frac{\partial}{\partial x_j} \left[\left(v + \frac{v_t}{\sigma_K} \right) \frac{\partial K}{\partial x_j} \right]}_{\text{Diffusion}} - \underbrace{\epsilon - \epsilon_{em}}_{\text{Dissipation}};$$

$$\frac{\partial \epsilon}{\partial t} + \langle v_j \rangle \frac{\partial \epsilon}{\partial x_j} = C_1 \frac{\epsilon}{K} v_t \left(\frac{\partial v_i}{\partial x_j} \right)^2 + \frac{\partial}{\partial x_j} \left[\left(v + \frac{v_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] - C_2 \frac{\epsilon}{K} \epsilon - \frac{\epsilon}{K} \epsilon_{em}.$$

Joule dissipation term:

$$\epsilon_{em} = D_I + D_{II} =$$

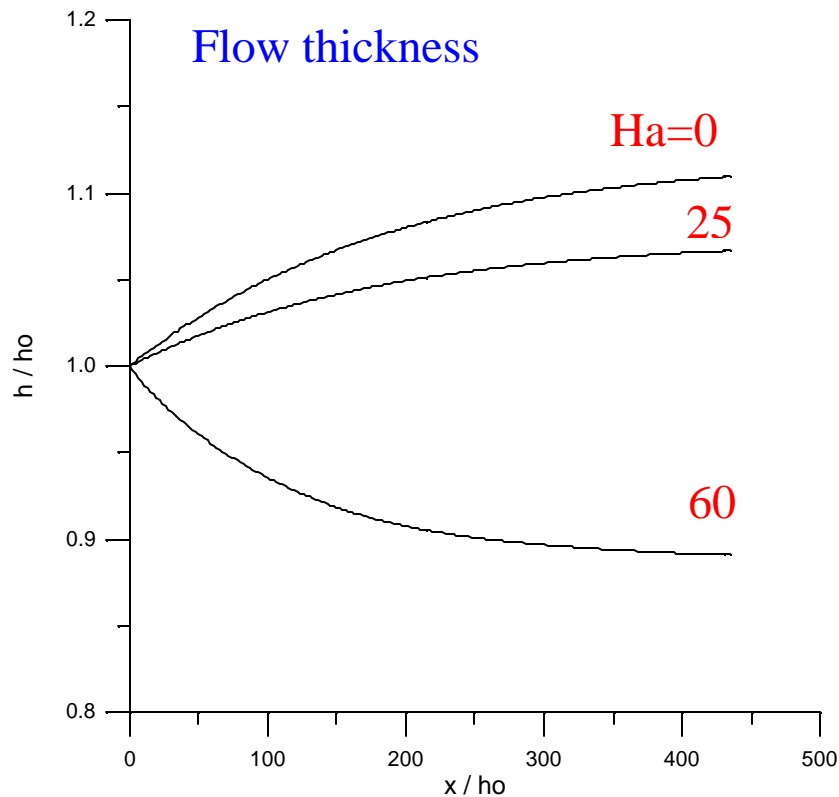
$$\begin{aligned} &= \frac{\sigma}{\rho} [2(B_{01}^2 + B_{02}^2 + B_{03}^2)K - B_{01}^2 \langle v_1'^2 \rangle - B_{02}^2 \langle v_2'^2 \rangle - B_{03}^2 \langle v_3'^2 \rangle - \\ &\quad - 2B_{01}B_{03} \langle v_1' v_3' \rangle - 2B_{01}B_{02} \langle v_1' v_2' \rangle - 2B_{02}B_{03} \langle v_2' v_3' \rangle - \\ &\quad - B_{01} \left(\left\langle \frac{\partial \phi'}{\partial x_2} v_3' \right\rangle - \left\langle \frac{\partial \phi'}{\partial x_3} v_2' \right\rangle \right) - B_{02} \left(\left\langle \frac{\partial \phi'}{\partial x_3} v_1' \right\rangle - \left\langle \frac{\partial \phi'}{\partial x_1} v_3' \right\rangle \right) - B_{03} \left(\left\langle \frac{\partial \phi'}{\partial x_1} v_2' \right\rangle - \left\langle \frac{\partial \phi'}{\partial x_2} v_1' \right\rangle \right)] . \end{aligned}$$

$\underbrace{\hspace{15em}}_{D_I}$ $\underbrace{\hspace{15em}}_{D_{II}}$

$$\epsilon_{em} = C_3 \frac{s}{\gamma} B_0^2 K \quad (\text{K-equation}), \quad C_4 \frac{s}{\gamma} B_0^2 K \quad (\text{e-equation})$$

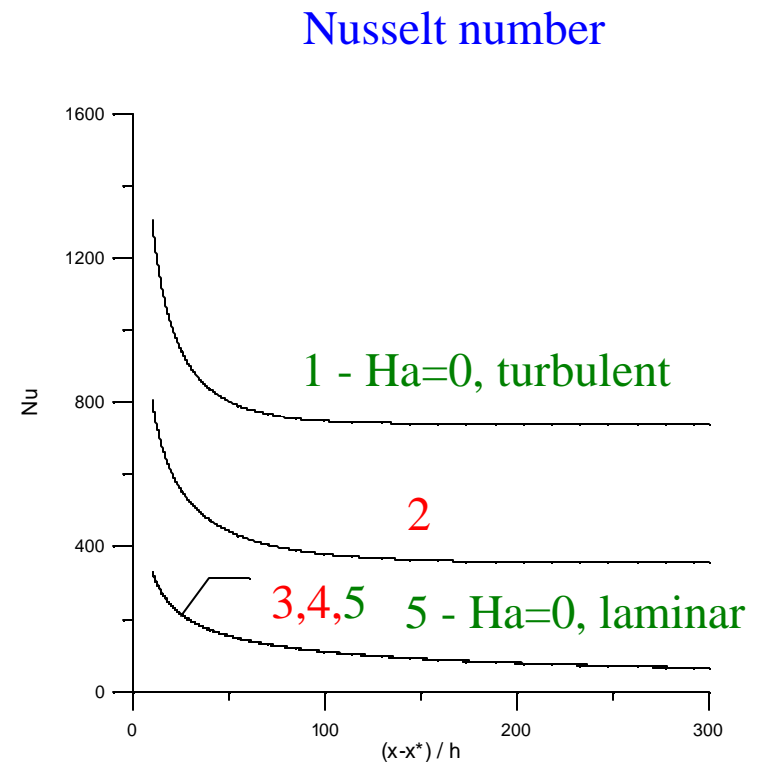
LOW-CONDUCTIVITY FLUID MODELING BASED ON RANS EQUATIONS: “K-e” model

Application to free surface flows



Spanwise magnetic field: $Re=30\ 250$; $Fr=44\ 350$; $\alpha=45$

Turbulence reduction by a magnetic field results in a smaller flow thickness



Turbulence reduction is accompanied by the heat transfer degradation.

2 - $Ha=25$, spanwise magnetic field

3 - $Ha=60$, spanwise magnetic field

4 - $Ha=25$, wall-normal magnetic field

RELATED APPLICATIONS of NEAR SURFACE TURBULENCE MODIFICATION and MHD EFFECTS

- Melt and solid microstructure control in metallic casting and crystal growth
- Turbulent drag reduction and MHD ship propulsion
- Oceanography and atmospheric processes
- Droplet formation and fuel mixing for internal combustion and jet engines

Non-Structural Materials Science

Material System Thermomechanics Interactions

Mission: Advance the **engineering science knowledge base** necessary for understanding the thermomechanical performance and material interactions, and possibly **extending technology limits**, of ceramic breeders and beryllium material systems.

Objectives:

Perform laboratory experiments and modelling for:

- a) fundamental thermal-physical-mechanical properties for packed beds
- b) material system thermomechanics interactions and deformations

□ **This research is conducted as part of international collaboration (IEA, JUIPTER-II)**

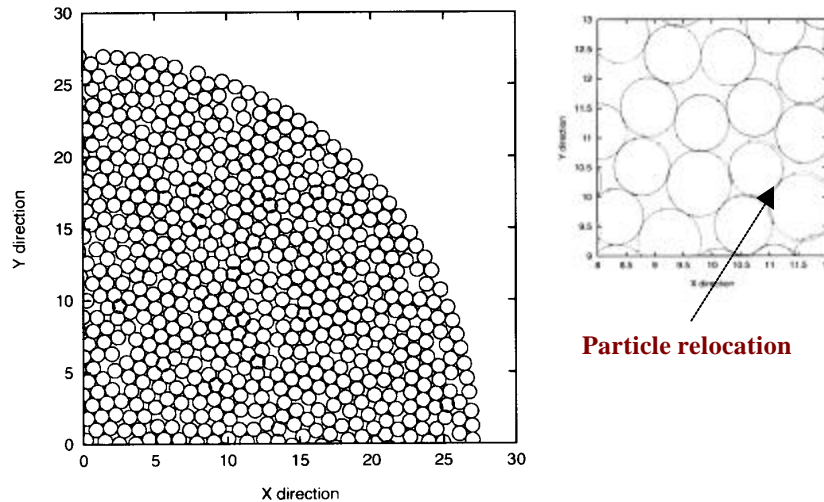
- It is part of US strategy to participate in selected areas of R&D to contribute and gain access to data from the larger international community (EU and JA)

□ **Excellent area of research for University**

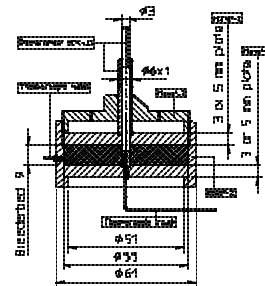
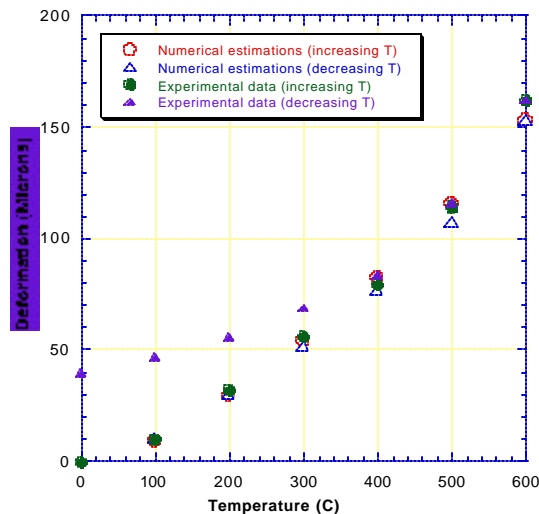
Material System Thermomechanics Interactions Studies at UCLA

❑ Phenomenological and Numerical Modeling

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

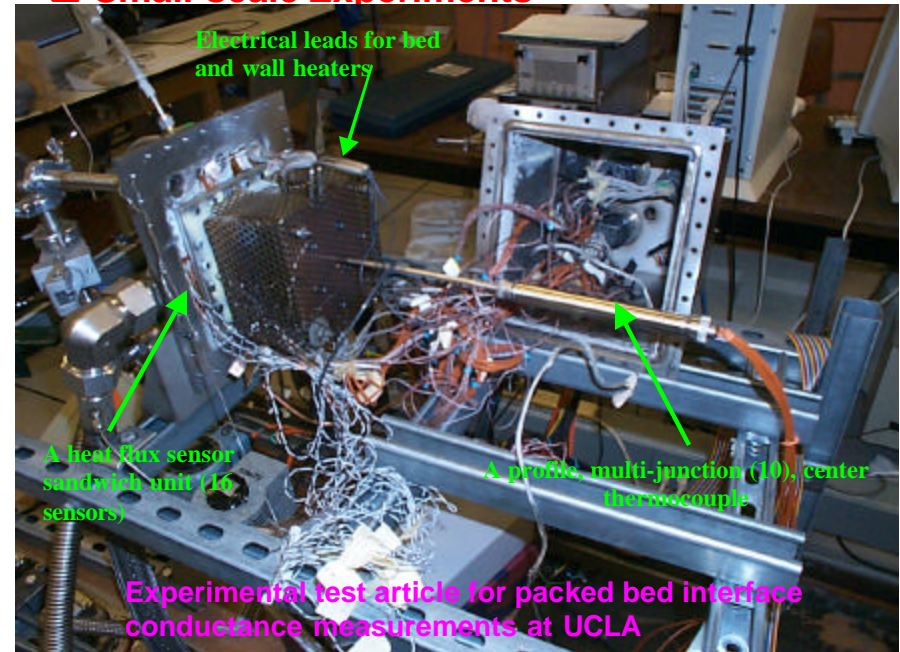


Experimental data is reasonably predicted by the numerical estimations based on fixed boundary conditions



Experimental test article

❑ Small-scale Experiments

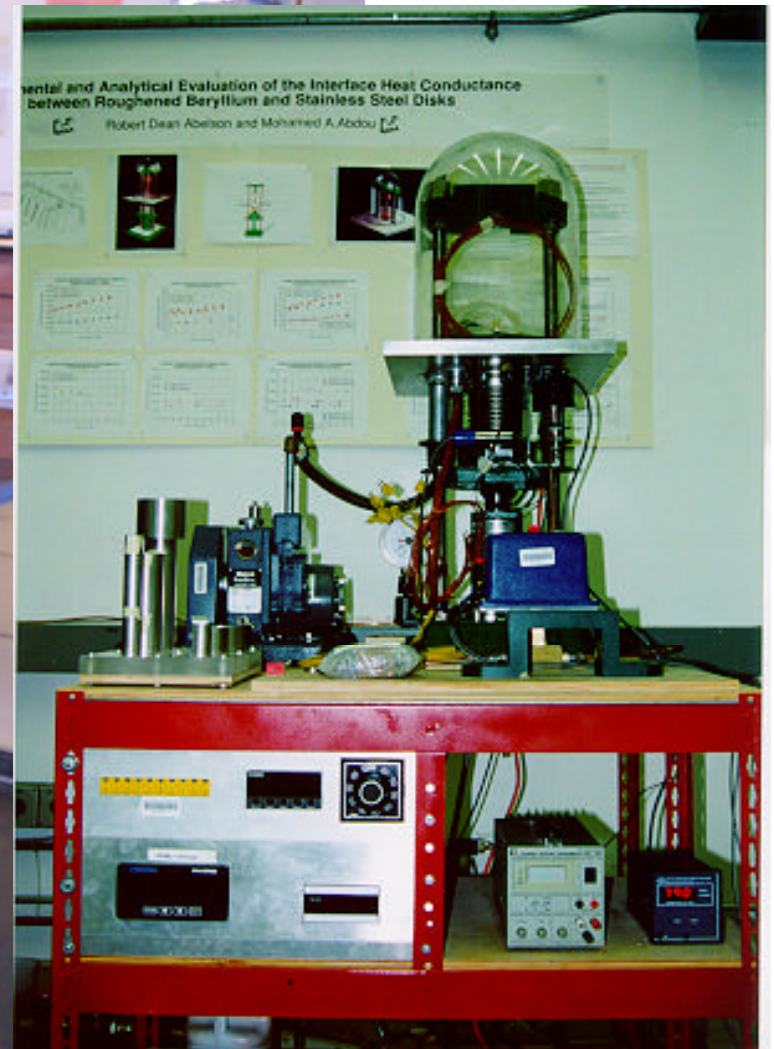
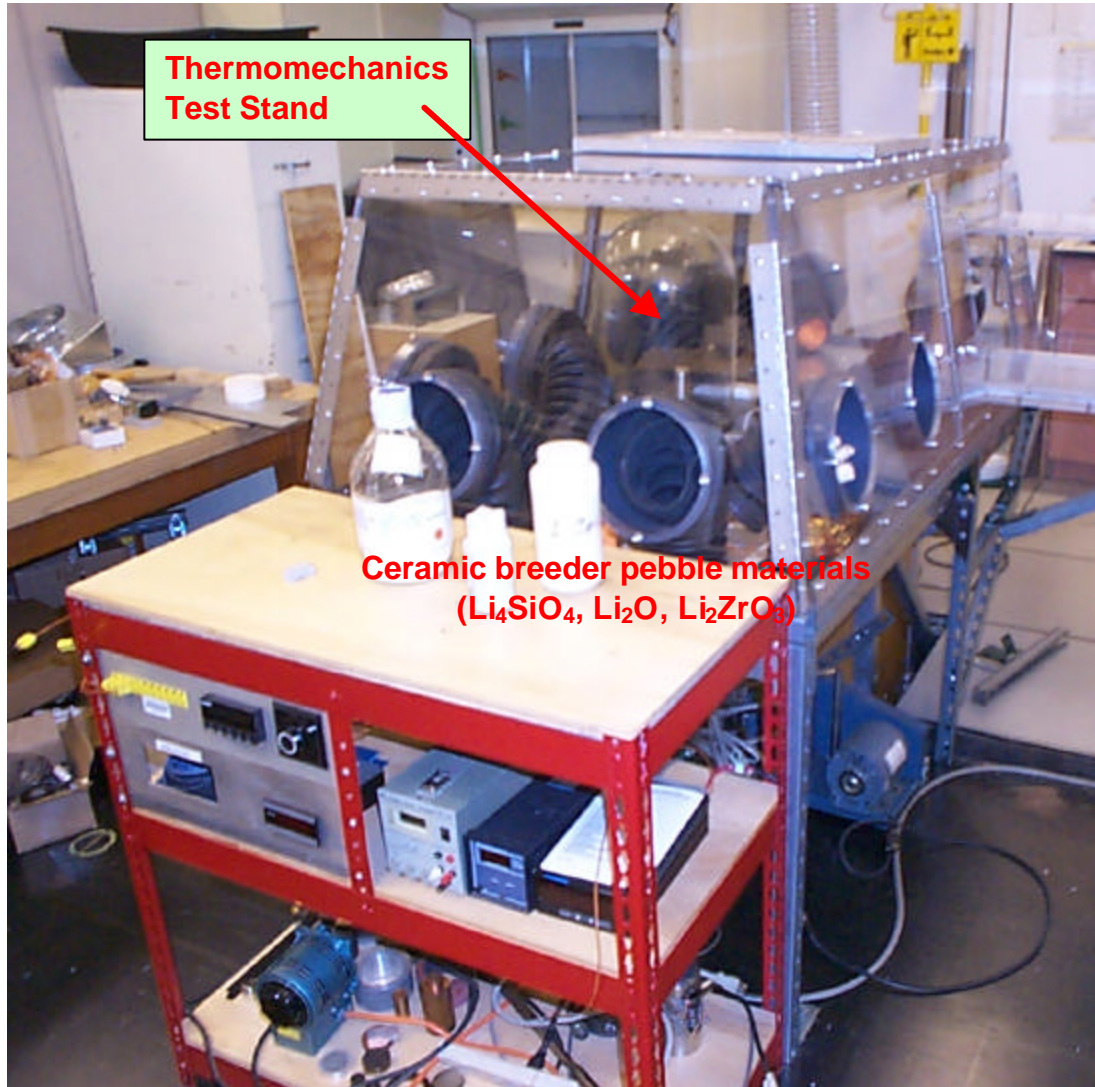


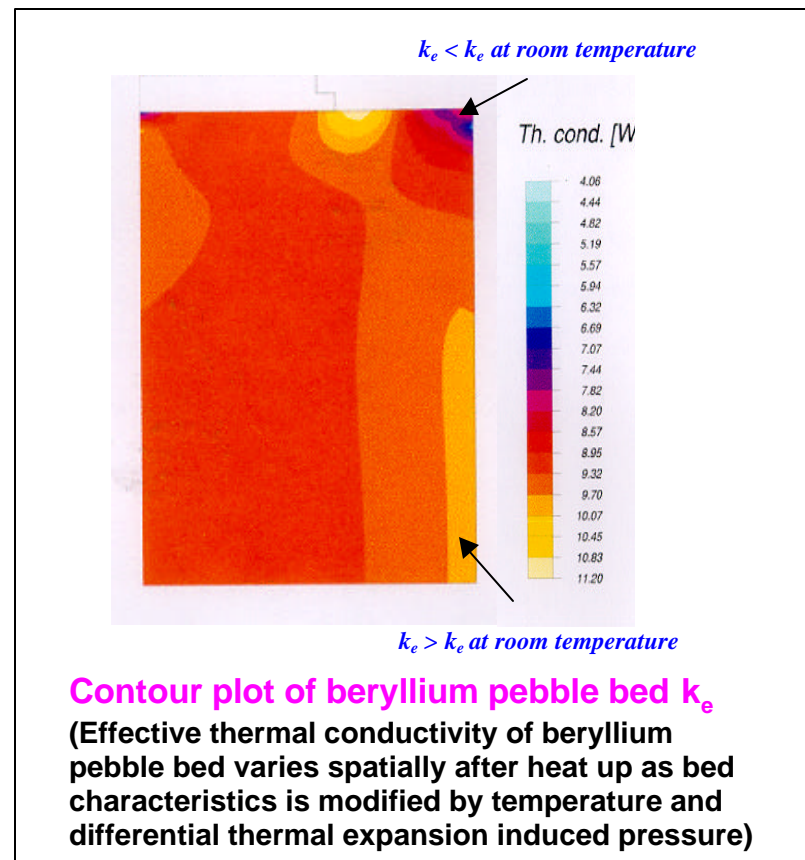
❑ International Collaboration



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

$$= \frac{4}{3} E^* \sqrt{R} d^3$$

$$\frac{1}{E^*} = \frac{1-n_1^2}{E_1} + \frac{1-n_2^2}{E_2}$$

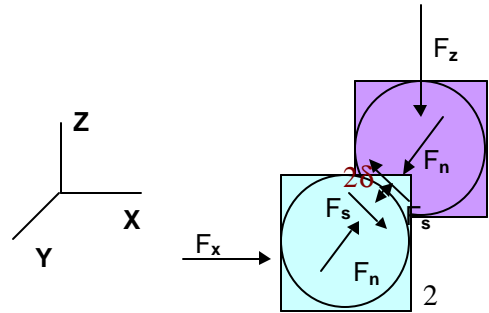
δ = the compliance between 1 and 2

F_s = shear force = κF_n
 $\leq \mu F_n$

(μ 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)

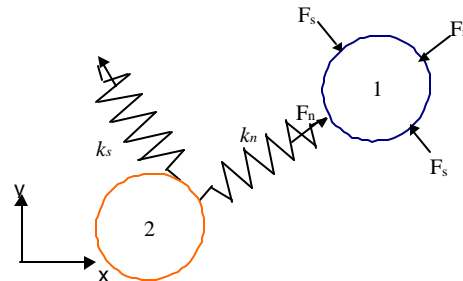


Forces at contact point include normal and tangential (shear) forces

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:

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

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

otherwise

$$\Delta D_x = \frac{F_x - k_f |F_t|}{k_n}$$

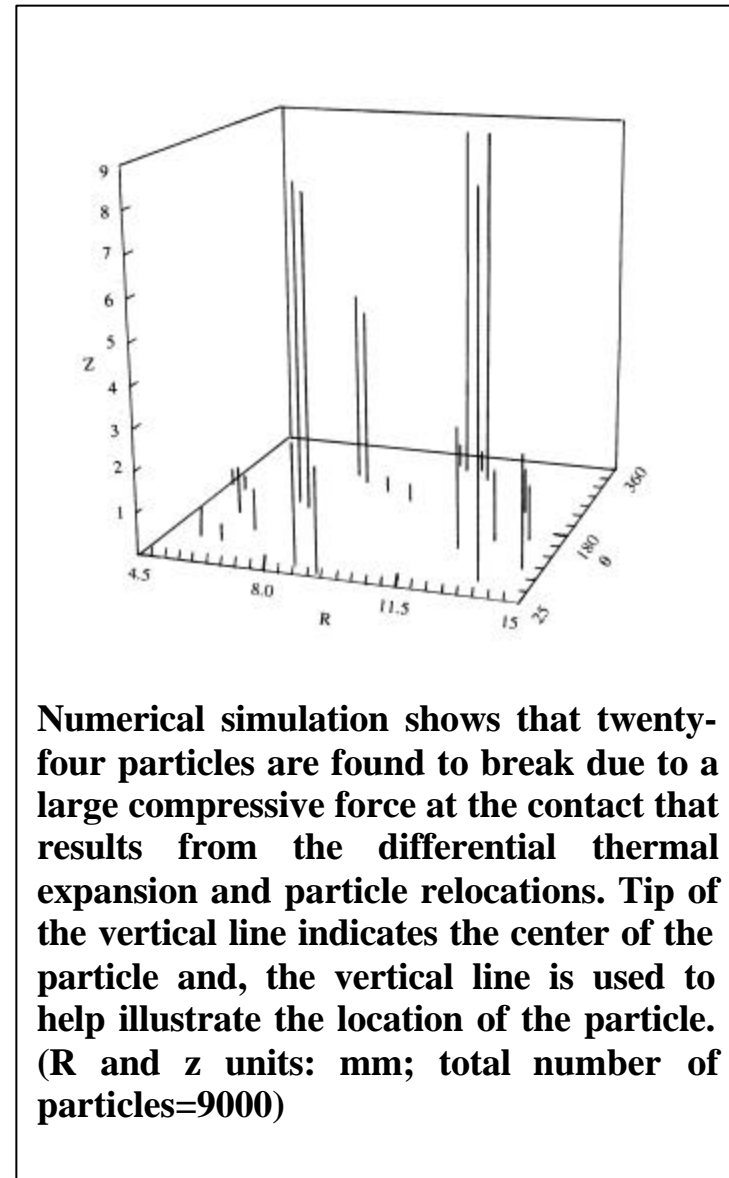
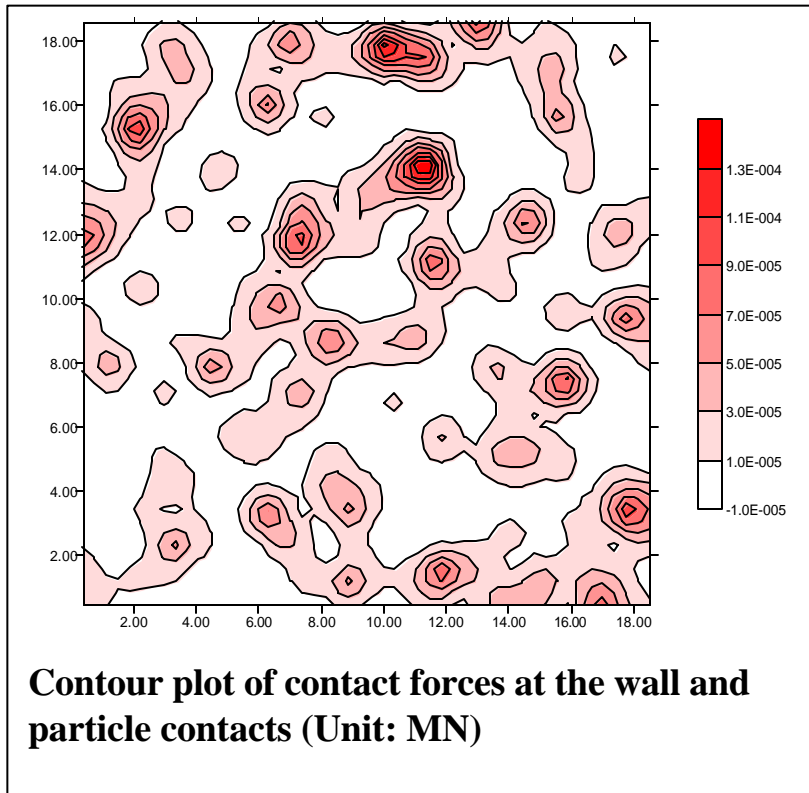
$$\frac{\sum F_{xc} \pm k_f \sqrt{\left(\sum \frac{|F_{yc}|}{c}\right)^2 + \left(\sum \frac{|F_{zc}|}{c}\right)^2}}{k_n}$$

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.

Discrete numerical simulation provides insights to the microscopic properties (contact pressure, particle relocation, etc.) affecting the thermomechanical performance



Interface Heat Conductance between **Non-Conforming** Beryllium and SS316 Surfaces Subjected to **Non-Uniform Thermal Deformation**

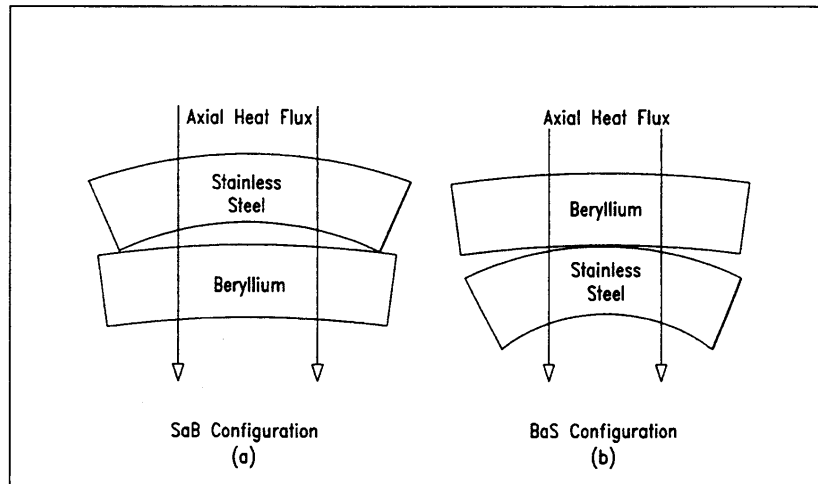


Figure 4.3: Two orientations of thermal deformation for the beryllium and stainless steel disks (profiles are highly exaggerated for clarity)

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

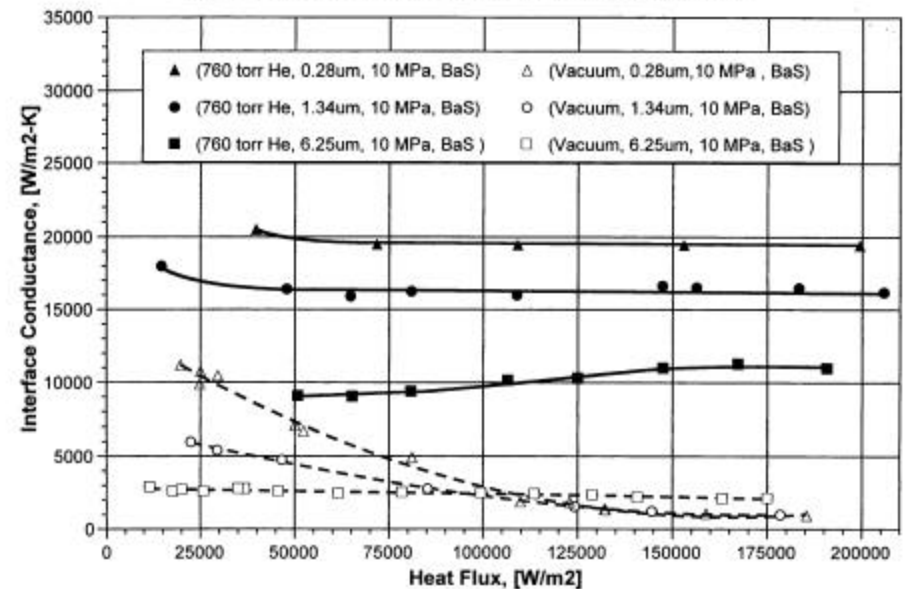


Figure 3.41: Interface Conductance vs. Heat Flux, Vacuum and 760 torr He, $P_c = 10$ MPa, All Roughnesses, SaB Configuration

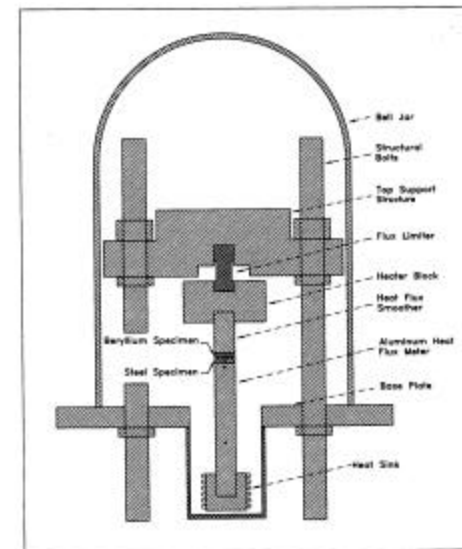
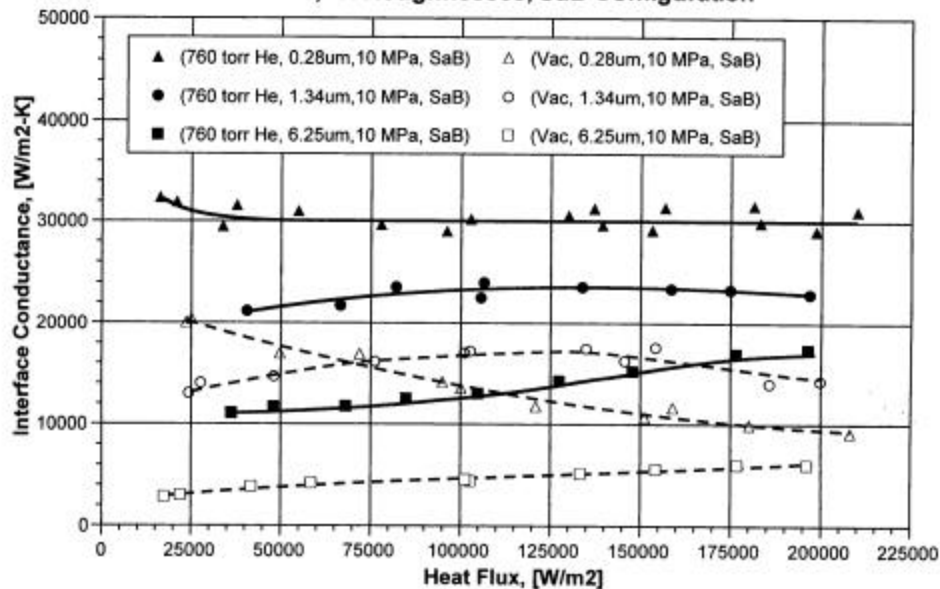


Figure C.2: ICE Test Article Design for 1 inch Diameter Specimens