JUPITER-II

Thermofluids and Thermomechanics Tasks and Facilities

Led by UCLA in collaboration with SNL, ORNL, PPPL, ANL

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Thermofluid Task Objectives

(JUPITER-II)

1. Understand Underlying Science and Phenomena for Flibe (and other low conductivity, high Prandtl No. liquid) Flow and Heat Transfer through:

    a. Conducting Experiments Using Flibe Simulants
    b. Modeling and Analysis of fundamental phenomena

2. Compare Experimental and Modeling Results to Provide Guidance and Database for Flibe Designs and Next Generation Stage of Larger Flibe Experiments.

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

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Why is Research on Flibe of Common Interest to the US and Japan?

USA

- For MFE: Important to identify a low-conductivity fluid for both Free Surface and Closed Channel as an alternative to liquid metals. Flibe is an EXAMPLE candidate.

- For IFE: Flibe is the Primary Liquid Wall Fluid.

JAPAN

- Japanese universities MFE designs are based on Flibe.

Also of common interest

- Better scientific understanding of fluid flow hydrodynamics, turbulence, MHD, and heat transfer by contrasting the behavior of low-conductivity, high-Pr to high-conductivity, low-Pr fluids.

JUPITER-II Thermofluids

Key Thermofluid Issues for Flibe

1. Narrow Temperature Window
   - Need innovative Heat Transfer Enhancement Techniques
   - (Also APEX is exploring jointly with the material program high temperature materials for use with flibe)

2. MHD may affect heat transfer in low-conductivity fluids
   - Need experiments in magnetic field

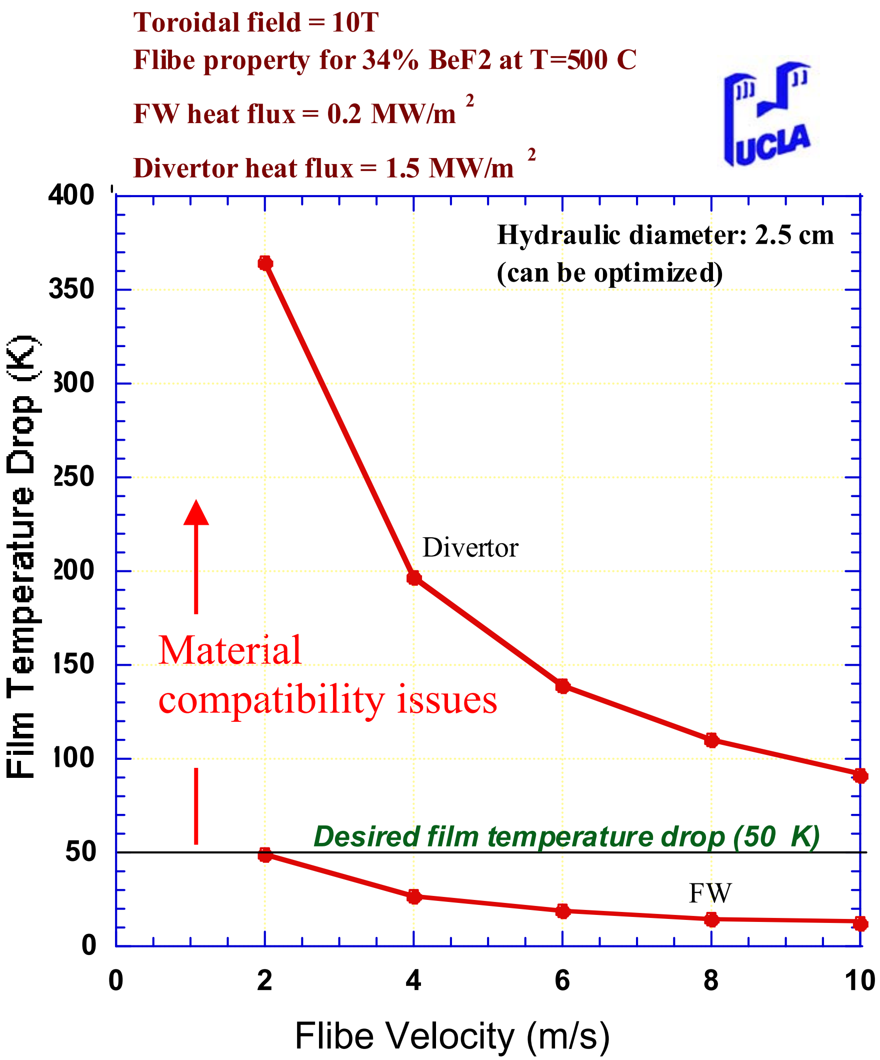
Approach

- Joint experiments on FliHy Facility at UCLA using flibe simulant (water/KOH) with and without magnets

- Joint effort on “challenging” modelling

Heat Transfer Enhancement for FFHR-2 and LW High Heat Flux Application is critical

- Inlet temperature for Flibe must be > 500°C
- Maximum operating temperature of FFHR structural material is estimated at < 600°C.
- Maximum operating temperature for LW plasma compatibility is estimated at < 600°C (possibly < 500°C)
- Film temperature rise must be < 50°C to keep operating window open



Toroidal field = 10T
Flibe property for 34% BeF2 at T=500 C
FW heat flux = 0.2 MW/m^2
Divertor heat flux = 1.5 MW/m^2

Hydraulic diameter: 2.5 cm
(can be optimized)

Material compatibility issues

Desired film temperature drop (50 K)

MHD Affects Heat Transfer for Low Electrically-Conducting and High Prandtl Number Fluids

- ❑ *Only a limited amount of data exist on the effects of MHD on heat transfer in a closed channel for high Prandtl fluids*
- ❑ *No data available on the effect of MHD on turbulent characteristics and heat transfer of high Prandtl fluids for free surface flows*
- ❑ *Therefore, data and models for both free surface and closed channels should be of interest to the US and Japan.*

Available data shows that the decrease in the heat transfer at a Hartmann wall due to modification of turbulent eddies by the magnetic field is correlated as:

$Nu/Nu_o = 1-1.2\ N$

where N is the interaction parameter (based on the hydraulic diameter of the closed duct).

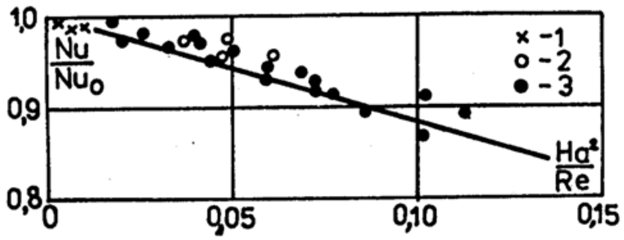


Fig. 6.8 Dependence of the total heat transfer intensity in the flow of an electrolyte in a transverse field on parameter Ha^2/Re at the values of Ha: 1 -- 3.7 (Ref. 6.6); 2 -- 18; 3 -- 31 (Ref. 6.3).

Main Areas of Collaborative Scientific Interest

Turbulent Hydrodynamics 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**

High Prandtl Number heat transfer at 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**

Sub-areas of Interest for Collaborative Efforts

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**

Unique thermo-fluid capabilities at UCLA will contribute greatly to a successful collaboration

Laboratory Thermofluid Facilities

- Multiple flow loops
- Multiple magnets and high current power supplies (from PPPL and MIT)
- High bay space and high load crane

Special materials handling capabilities (Be, Flibe)

- Glovebox and enclosure facilities
- Approval for large scale Be handling (PISCES and Solid Thermomechanics experiments)
- Flibe qualification underway for vaporization/condensation experiments for IFE

UCLA Capabilities (Continued)

Thermofluid Instrumentation

- Laser Doppler velocimetry
- Micrometer & ultrasonic flow depth probes
- Bubble/dye flow visualization and fast digital photography
- Holographic temperature profiling

Computational Tools

- DNS/LES/MHD codes
- Free Surface Codes
- Parallel computing clusters and data visualization laboratory

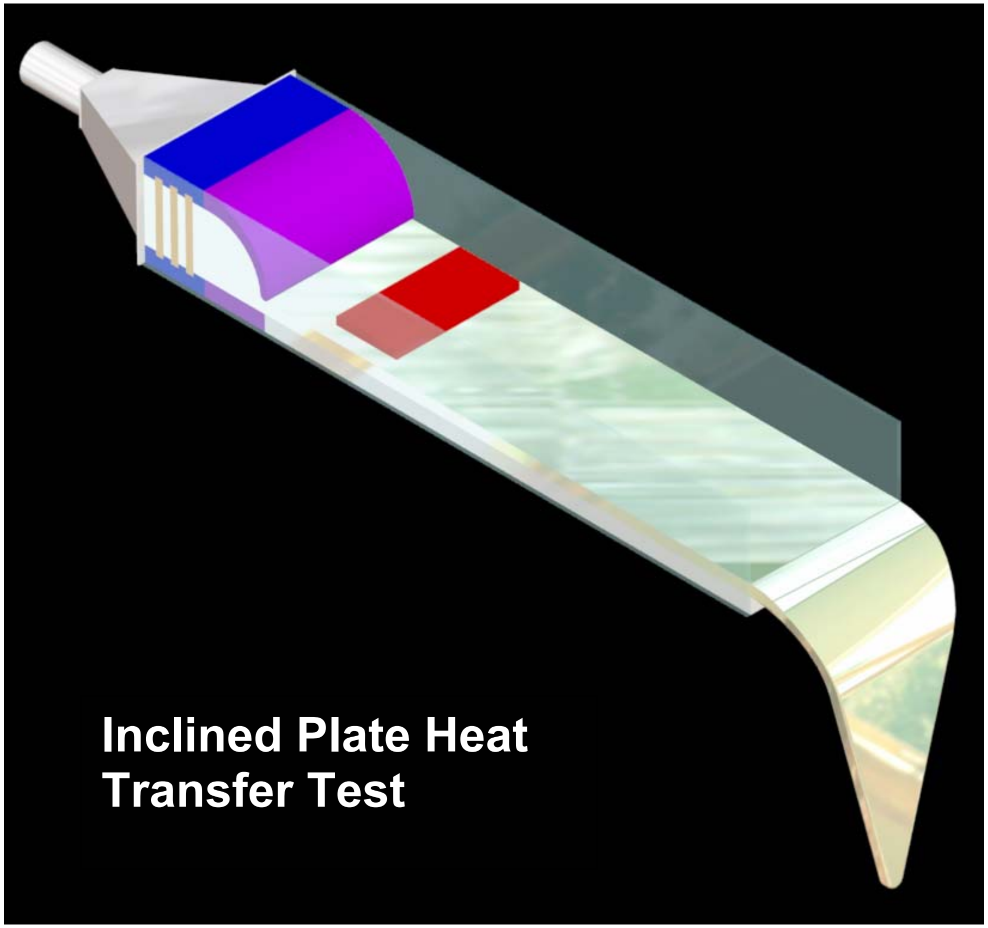
Interested UCLA faculty with worldwide reputations

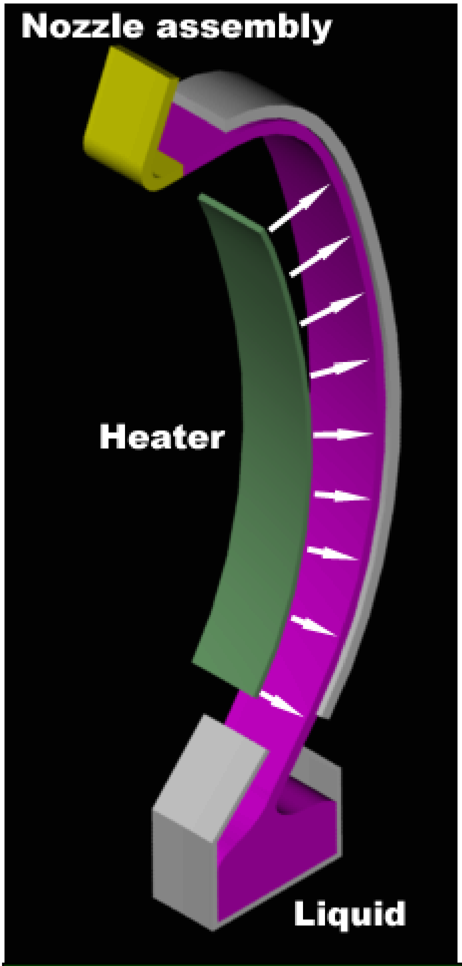
- Vijay Dhir: Fluid heat transfer
- John Kim: DNS and MHD
- Robert Kelly: Free surface flow
- Nasr Ghoniem: Fusion materials

UCLA Fusion Science and Technology Group experience

- Magnet design and construction
- Thermofluid/MHD experimentation
- MHD/free surface modeling

Fli-Hy Example Test Sections


Inclined Plate Heat Transfer Test

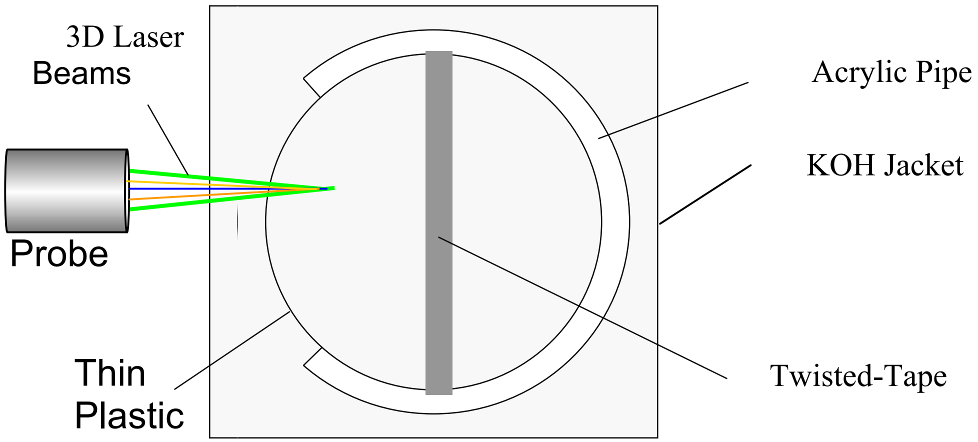


Curved Plate Heat Transfer Test

JUPITER-2 Collaboration:

Complex pipe shape effects on turbulence and heat transfer

- Purpose: Pipe flow experiments with complex inner wall surface like fins are performed to develop an understanding of high heat flux removal applied for the High-Pr. fluid system.



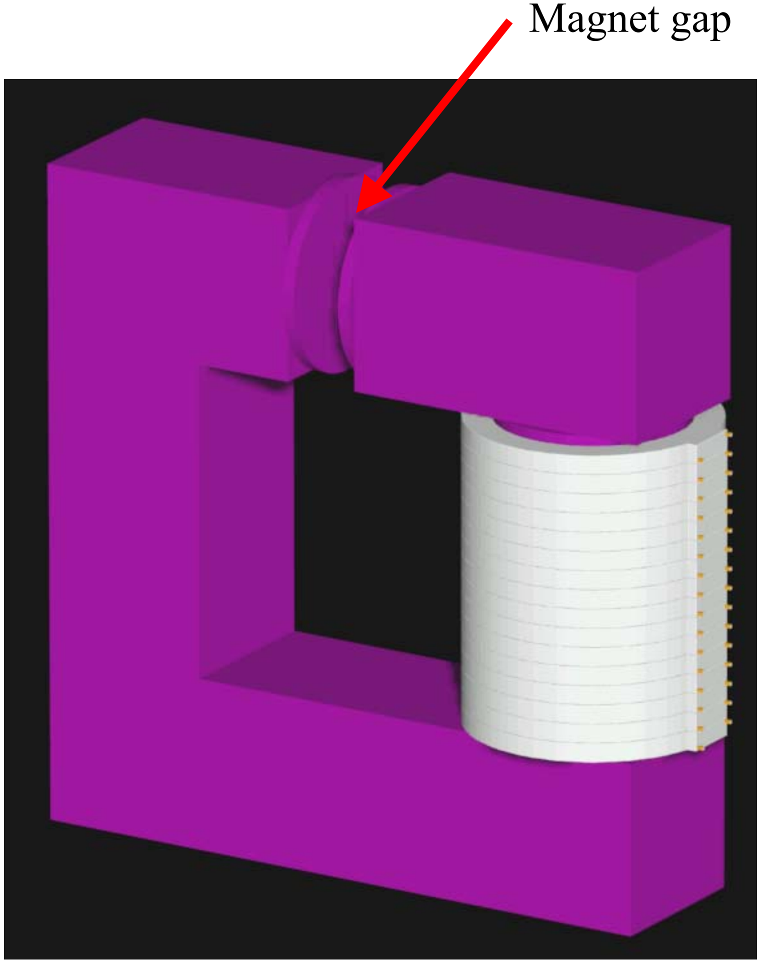
- Diagnostics: Pipe and free surface test section on improved FLI-HY with transparent structure and windows, and with functions of inclination or rotatory movement and magnetic field, 3D LDV and hot-film anemometers

Development of high field magnet options

- *Design using iron gives up to 2 T field, large working volume and easily accessible test area*
- *High current air core solenoid design has potential for higher fields with existing power capabilities*

Status:

- **Design of small, low cost 4T, air core coil underway in collaboration with PPPL**



2 T Tara coils/iron core concept

Need for Coupled Modeling Effort

Explanation:

Fusion designs require practical computational models that must utilize input data from more elaborate theory and experiments. (* Note that theory implies Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS).)

Collaboration:

1. Enhance LES and DNS numerical techniques to:
    - understand near-wall and near-surface turbulence structures in magnetic fields
    - help clarify experimental observations
    - provide input data for practical computational models needed for fusion component design
2. Develop practical computational models using input from experiments, LES and DNS.

Joint Effort by Many Interested Scientists

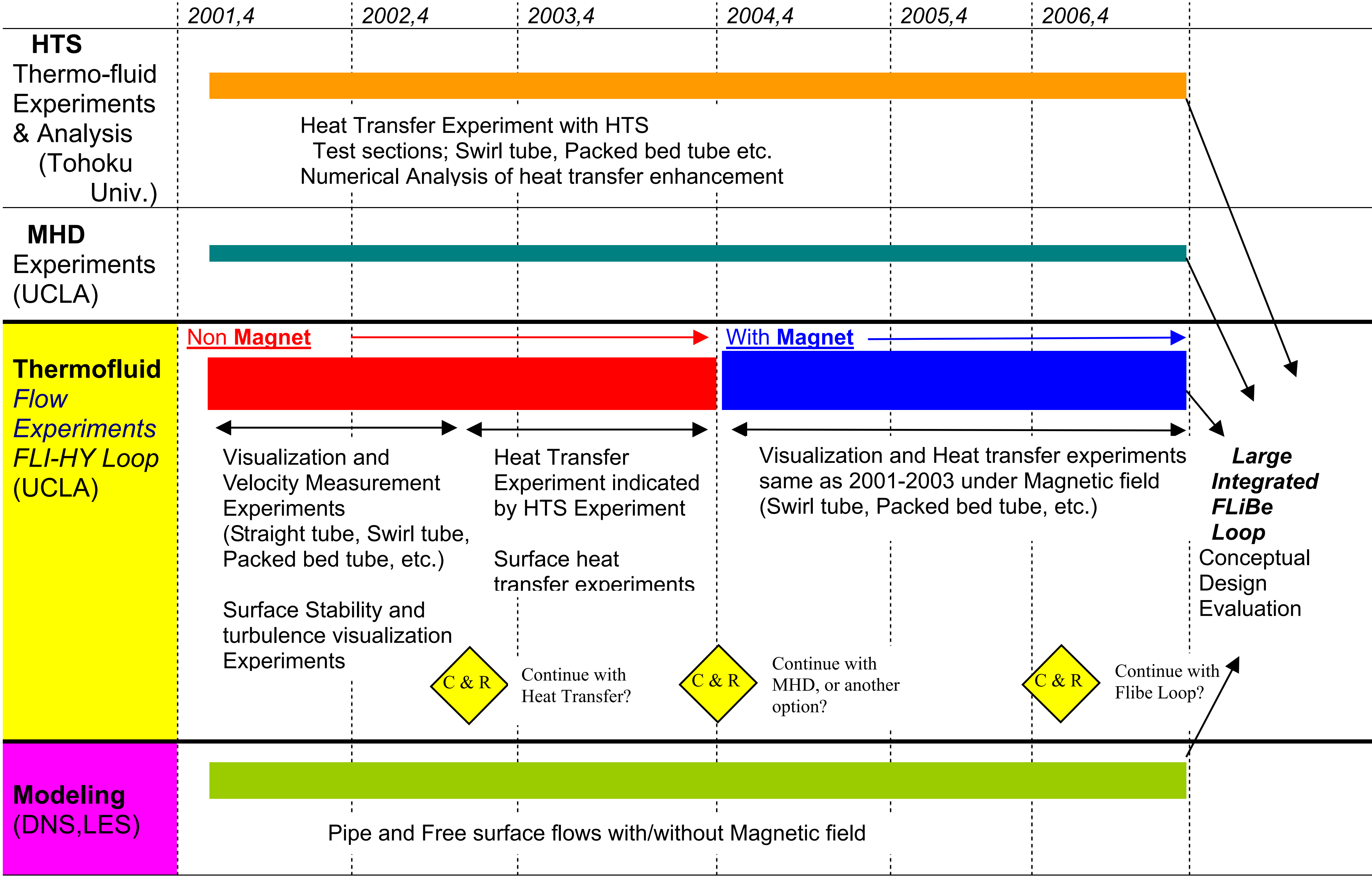
Contributions USA:

N. Morley, M. Abdou, V. Dhir, J. Kim, R. Kelley, N. Ghoniem, A. Ying, S. Smolentsev, T. Sketchley, B. Freeze, M. Dagher (UCLA)
M. Ulrickson, R. Nygren (SNL)
D-K Sze (ANL), B. Nelson (ORNL), R. Wolley (PPPL)

Contributions Japan:

S. TODA, H. HASHIZUME, K. YUKI, S. CHIBA (Tohoku U.)
K. AMAGAI (Gumma U.), T. TERAI (U. of Tokyo)
M. TAKAHASHI (Tokyo Institute of Technology)
S. SATAKE (Toyama U.)
A. SAGARA (NIFS)
T. KUNUGI (Kyoto U.)
H. HORIIKE (Osaka U.)
Y. AOYAMA (Ehime U.)
A. SHIMIZU, T. YOKOMINE, E. HOASHI (Kyshu U.)

TASK 1-1-B Thermo-fluid Experiments and Modeling Schedule for 6 years



2001,4 | 2002,4 | 2003,4 | 2004,4 | 2005,4 | 2006,4

HTS
Thermo-fluid
Experiments
& Analysis
(Tohoku
Univ.)

Heat Transfer Experiment with HTS
Test sections; Swirl tube, Packed bed tube etc.
Numerical Analysis of heat transfer enhancement

MHD
Experiments
(UCLA)

Thermofluid
Flow
Experiments
FLI-HY Loop
(UCLA)

Non **Magnet**

With **Magnet**

Visualization and Velocity Measurement Experiments (Straight tube, Swirl tube, Packed bed tube, etc.)

Surface Stability and turbulence visualization Experiments

Heat Transfer Experiment indicated by HTS Experiment

Surface heat transfer experiments

Visualization and Heat transfer experiments same as 2001-2003 under Magnetic field (Swirl tube, Packed bed tube, etc.)

Large Integrated FLiBe Loop
Conceptual
Design
Evaluation

C & R

Continue with Heat Transfer?

C & R

Continue with MHD, or another option?

C & R

Continue with Flibe Loop?

Modeling
(DNS,LES)

Pipe and Free surface flows with/without Magnetic field

JUPITER-II Material Thermomechanics Interactions Task

Background

- For the past several years, UCLA has conducted, with modest funding, a successful research program on measurements and modelling of:
    1. fundamental thermophysical properties of pebble beds (ceramic breeders and beryllium)
    2. interface thermal conductance and thermomechanics interactions between pebble beds and structural materials

- This modest investment by the US was intentional in the post-restructuring strategy to ensure continued access to research results from the much larger Japanese and European Programs.

- This strategy proved prudent and has paid off.
    - The success of the UCLA experiments and modelling attracted JAERI and FZK to send expensive materials (Li_2O, Li_4SiO_4) to UCLA and to have the US a partner in IEA activities

    - Japanese Universities proposed as part of JUPITER-II that UCLA conduct experiments and modelling on the thermomechanics interactions of pebble beds with silicon carbide.

        -Although SiC is strong as a structural material for fusion, key fundamental data is lacking. Fabrication and joining techniques are in very early stage. It is very expensive to make useful pieces (e.g. with holes for coolant channels)

        -Japan will provide the: 1) SiC needed for the experiments, 2) funding to support the experiments

JUPITER-II

Thermal-Mechanical Interactions for the SiC/SiC-Pebble Bed Breeder / Be / He System

Primary Objectives

1. Investigate the ability to achieve and maintain an acceptable temperature profile in the SiC / He /Ceramic Breeder / Be material system

   - Key: Measure interface thermal resistance at the SiC / Ceramic pebble bed breeder and at the SiC / Be interfaces (under different conditions: different SiC composites, pebble size(s), porosity, helium purge pressure and temperature, etc.)

   - Obtain data and develop innovative techniques for predicting and controlling the temperature response in the material system (especially at interafaces).

   - Determine the temperature window (min. and max.) in which SiC will have to operate based on the material system thermal constraints.

Primary Objectives (Cont'd)

2. Investigate thermal-mechanical interactions

e.g.:

- effect of mismatch in thermal coefficient of expansion between SiC-pebble bed breeder and SiC-beryllium or the pebble bed integrity and mechanical deformation in SiC / SiC (compaction or breaking SB pebbles?, micro-cracks in SiC?)

- Can high pressure helium coolant be flown directly into a ceramic pebble bed in order to raise the operating temperature of SiC / SiC?
  (Stability issues: variation in pebble bed fraction → higher local temperature → larger pebble deformation → even smaller void fraction → ??)

3. Provide fundamental scientific and engineering input to the design of irradiation experiments

- material temperature range – material form
- basic material property changes without irradiation

Other Possible Objectives (see next page)

Other Possible Objectives

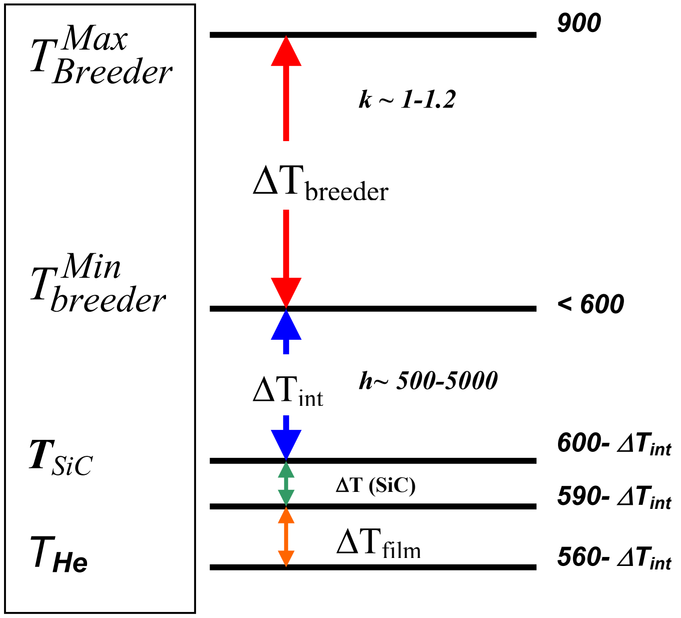
- To provide data on short-term temperature effects on chemical compatibility
- Determine cyclic effects
- Test effectiveness of hermitic seals developed in other tasks and measure helium leak rates as a function of temperature history and oxygen vapor pressure

Thermal Interface Conductance is Critical for SiC/SiC

1) to maintain SiC temperature above the limit for radiation-induced conductivity degradation (i.e. above 600 °C)
2) to keep He coolant temperature high for a high efficiency (> 600 °C)

- **Maximum breeder temperature must be < 900 °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

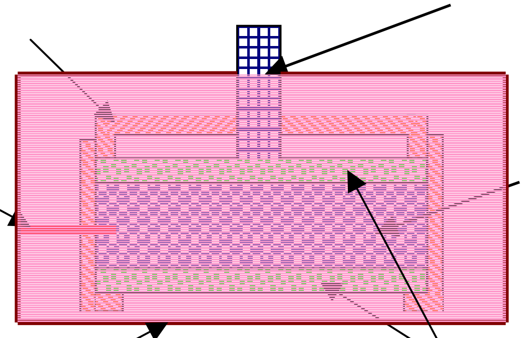


Conclusion

- ***Attaining high interface thermal conductance is essential for practical utilization of SiC***
- ***Note that similar conclusions are obtained when a maximum beryllium temperature (~ 600-700 °C) is imposed***

Test Configuration 2 (2001-2002)
Thermal Mechanical Deformation Tests

- At elevated temperatures, internal stresses can develop due to the mismatch in the thermal expansion coefficient between pebble bed and SiC/SiC and may break the particles or produce micro-cracks in SiC/SiC.



Constraint or floating

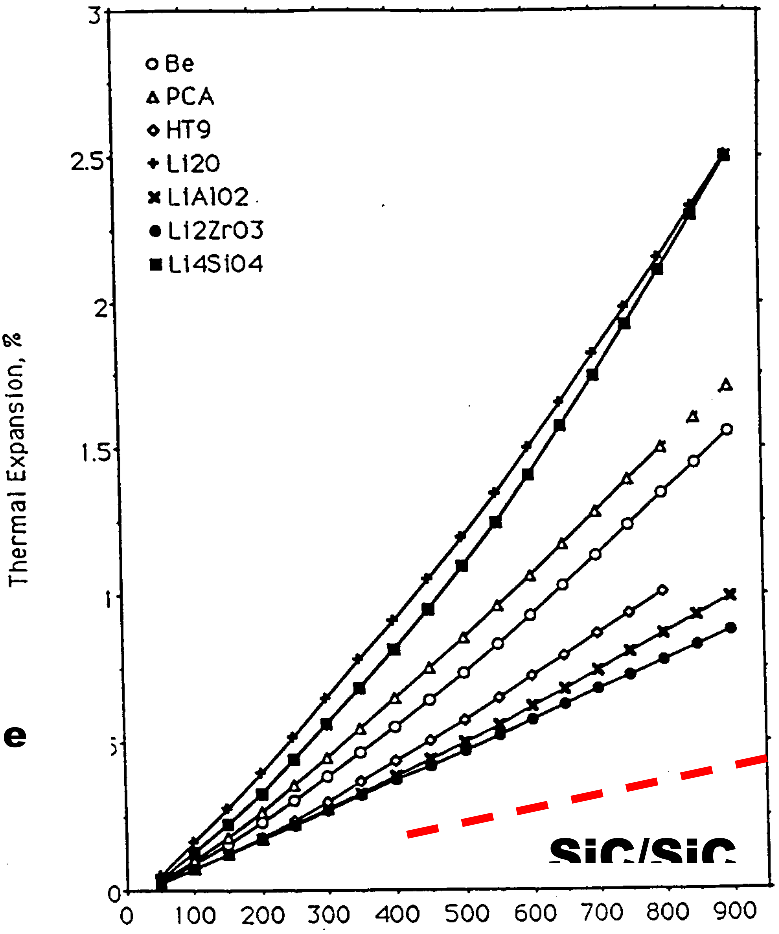
Force and displacement transducers

TC

Ceramic or beryllium pebble

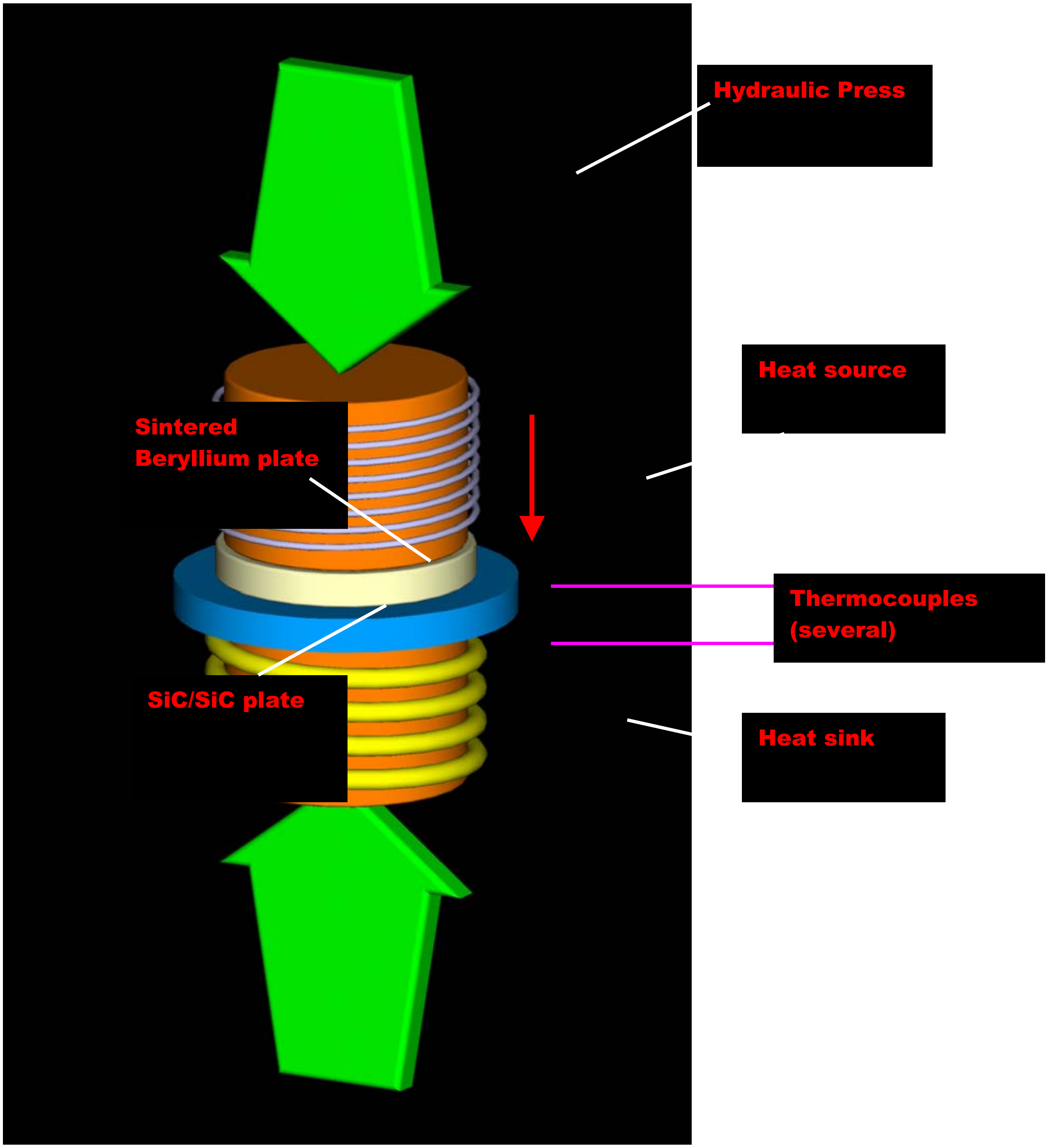
SiC/SiC plate

Furnace



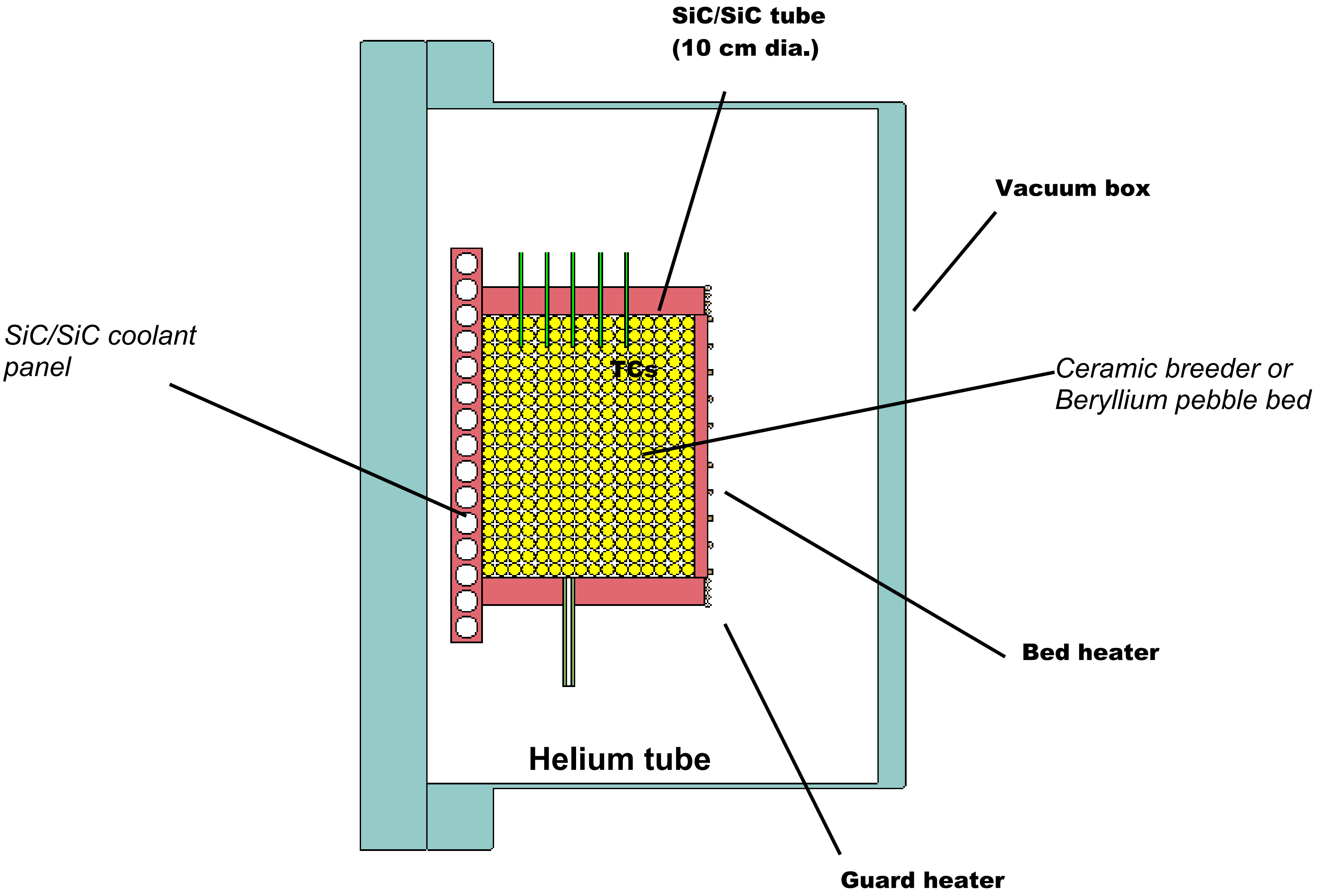
Test Configuration 3

Effect of SiC/SiC Surface Characteristics on Interface Thermal Conductance



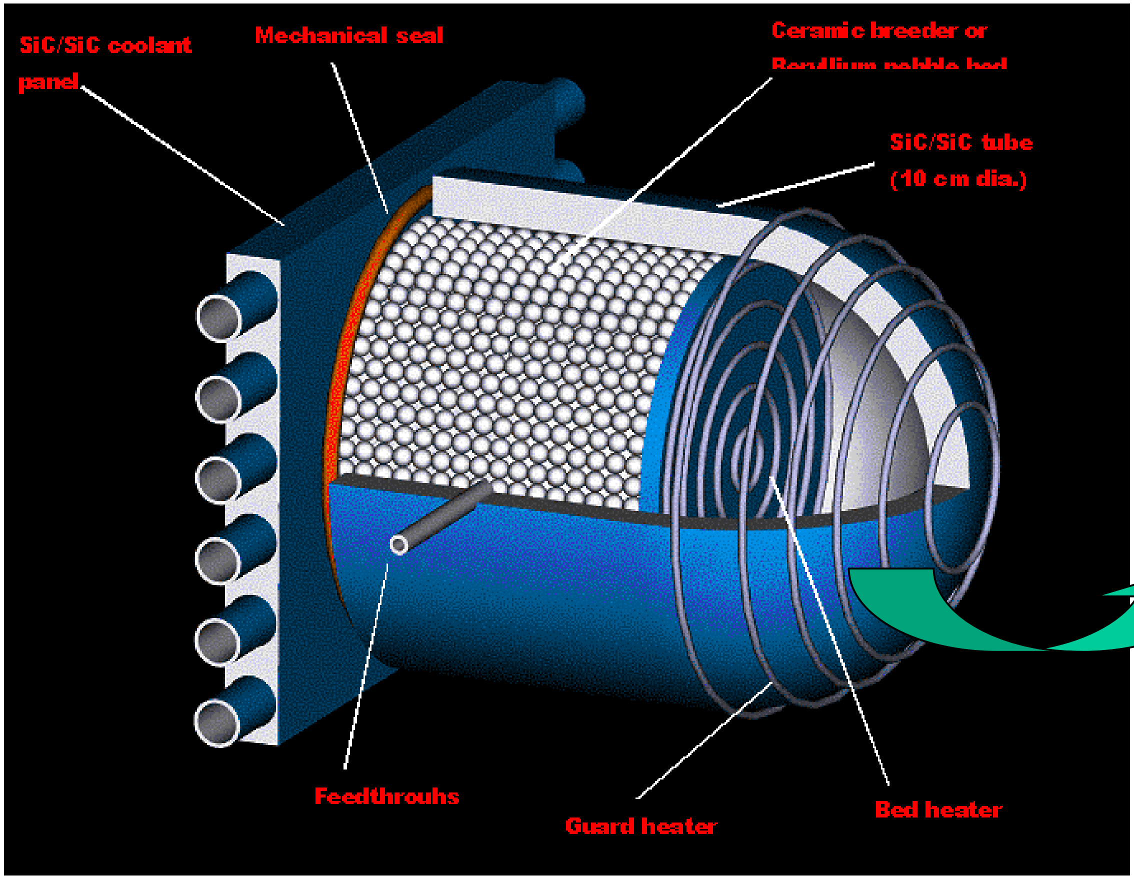
Test Configuration 4 (schematic view)

Helium-Cooled SiC/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.**