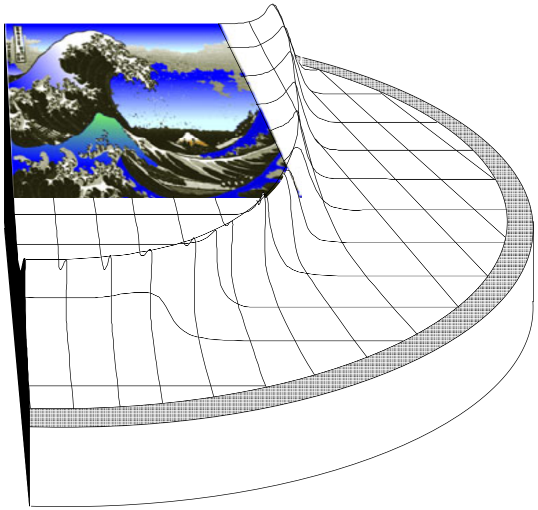
Dynamics of Liquid-Protected Fusion Chambers



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Outline: Thick liquids can replace fusion materials questions with fluid mechanics questions

- The scaling basis for understanding and predicting thick-liquid IFE chamber performance
- Recent progress
  - RPD 2002
  - Chamber gas dynamics
  - Molten salt vapor pressure
    - Liquid disruptions
- Vortex flows and vortex chambers
- Power conversion for fusion chambers

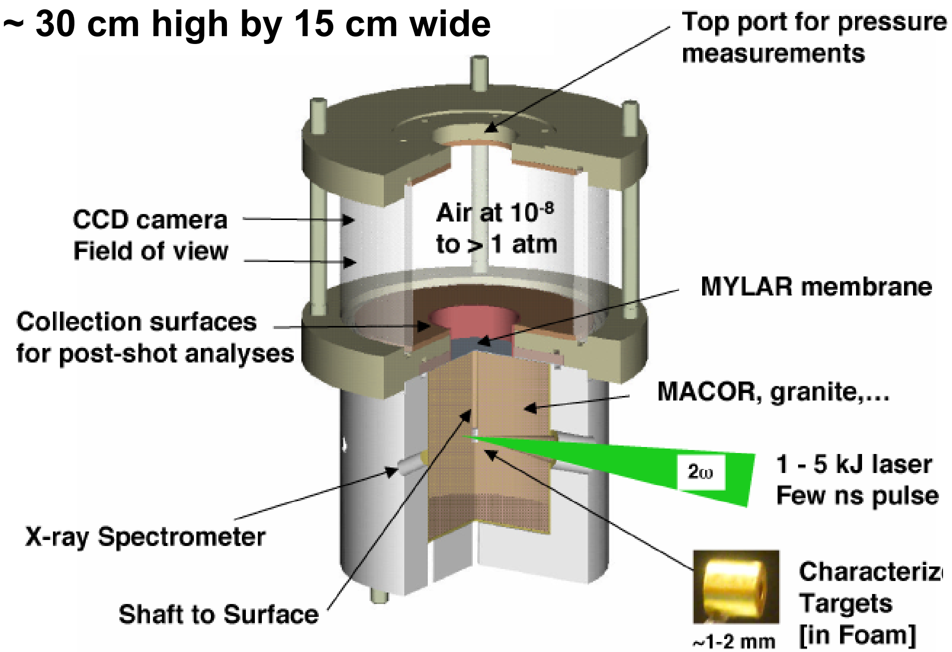
IFE system phenomena cluster into distinct time scales

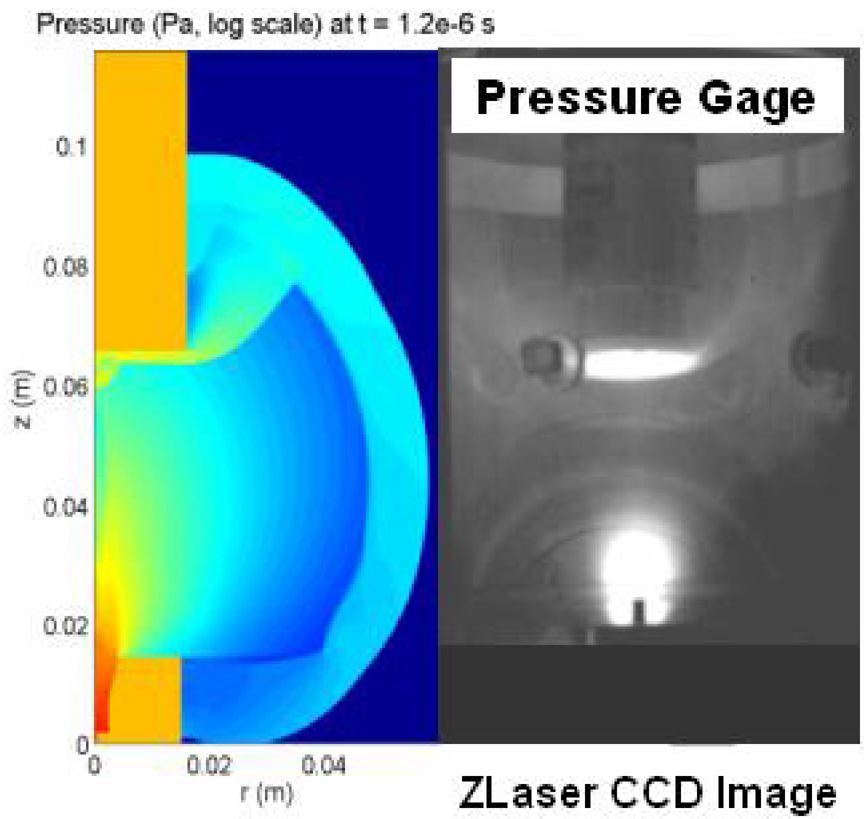
- Nanosecond IFE Phenomena
  - Driver energy deposition and capsule drive (~30 ns)
  - Target x-ray/debris/neutron emission/deposition (~100 ns)
- Microsecond IFE Phenomena
  - X-ray ablation and impulse loading (~1 μs)
  - Debris venting and impulse loading (~100 μs)
  - Isochoric-heating pressure relaxation in liquid (~30 μs)
- Millisecond IFE Phenomena
  - Liquid shock propagation and momentum redistribution (~50 ms)
  - Pocket regeneration and droplet clearing (~100 ms)
  - Debris condensation on droplet sprays (~100 ms)
- Quasi-steady IFE Phenomena
  - Structure response to startup heating (~1 to 10^4 s)
  - Chemistry-tritium control/target fabrication/safety (10^3-10^9 s)
  - Corrosion/erosion of chamber structures (10^8 sec)

Principal focus for IFE Technology R&D...

Validation of the gas dynamics code TSUNAMI through LLNL's Condensation Debris Experiment

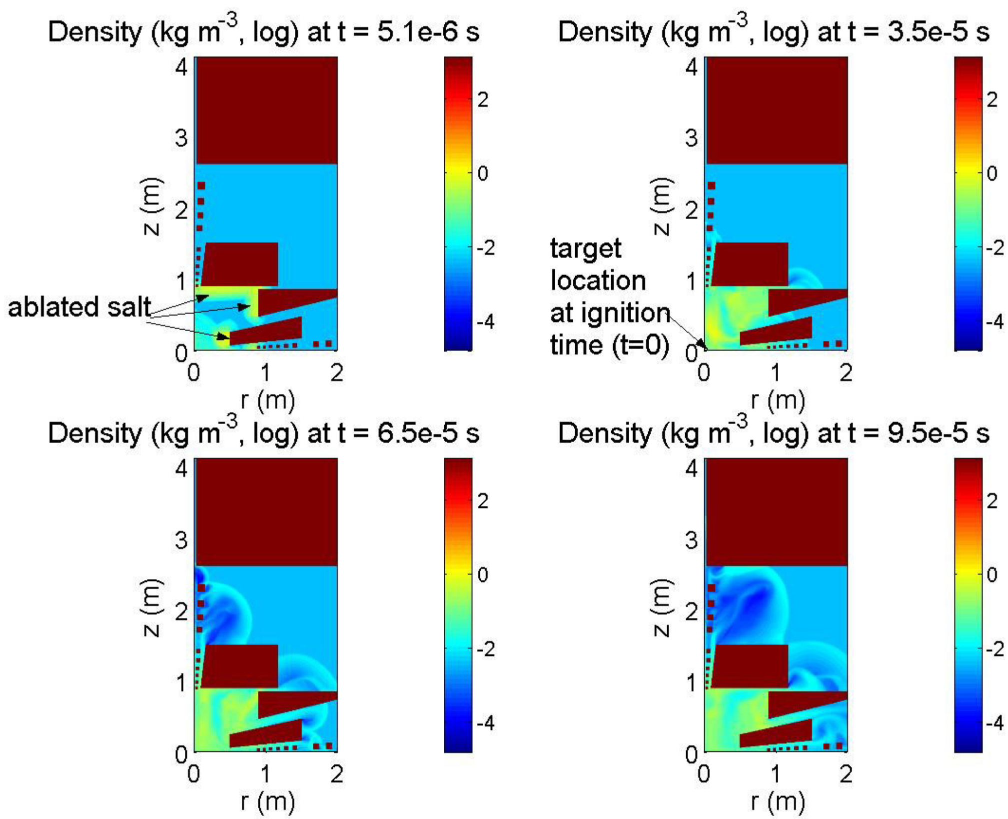
~ 30 cm high by 15 cm wide





Experimental and numerical results are in good qualitative and quantitative agreement

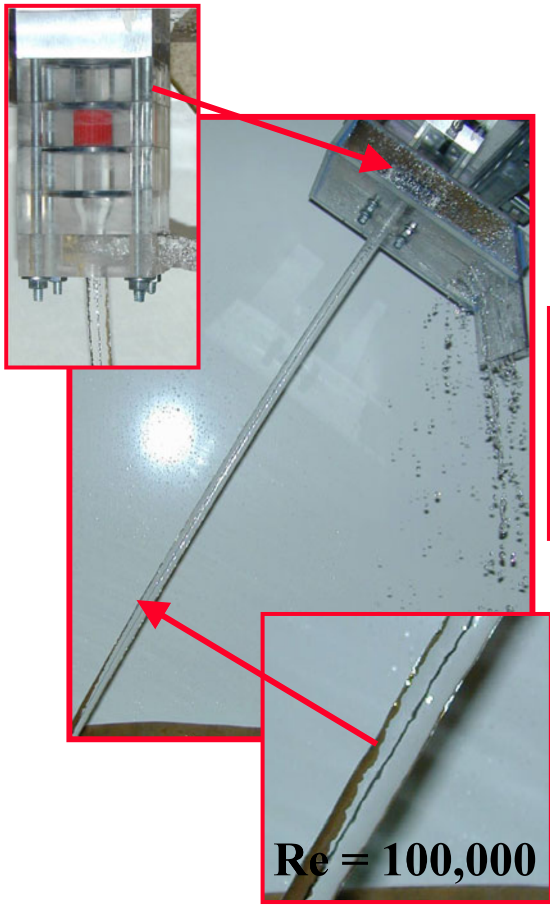
Gas dynamics studies address key design issues and support novel beam lines and thick-liquid chambers



- **Beam and target propagation sets stringent requirements for the background gas density and the cleanliness of the beam tubes**
- **Thick-liquid structure response mostly determined by gas dynamics**

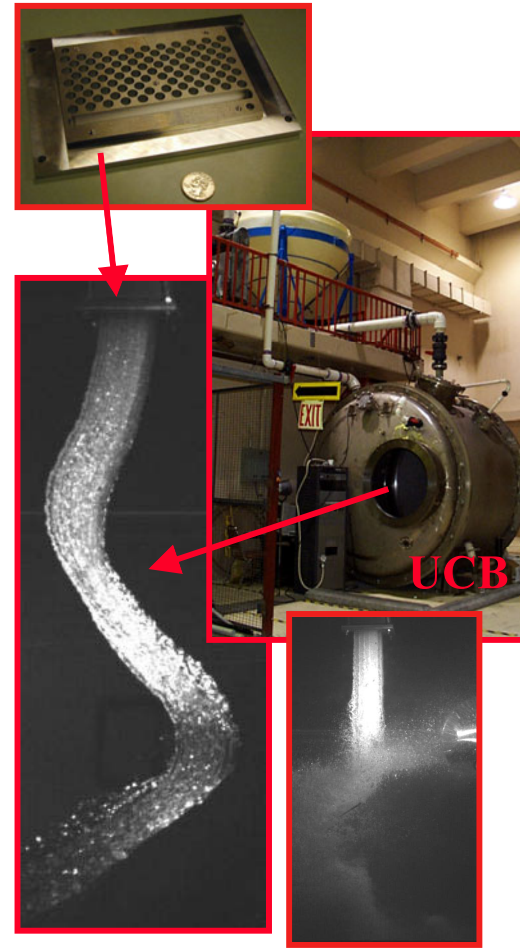
The TSUNAMI code has been tailored to model ablation and venting phenomena in thick-liquid chambers

Scaled water experiments are demonstrating the capability to form the jets used in RPD-2002



High-Re Cylindrical Jets

Vortex Layers for Beam Tubes

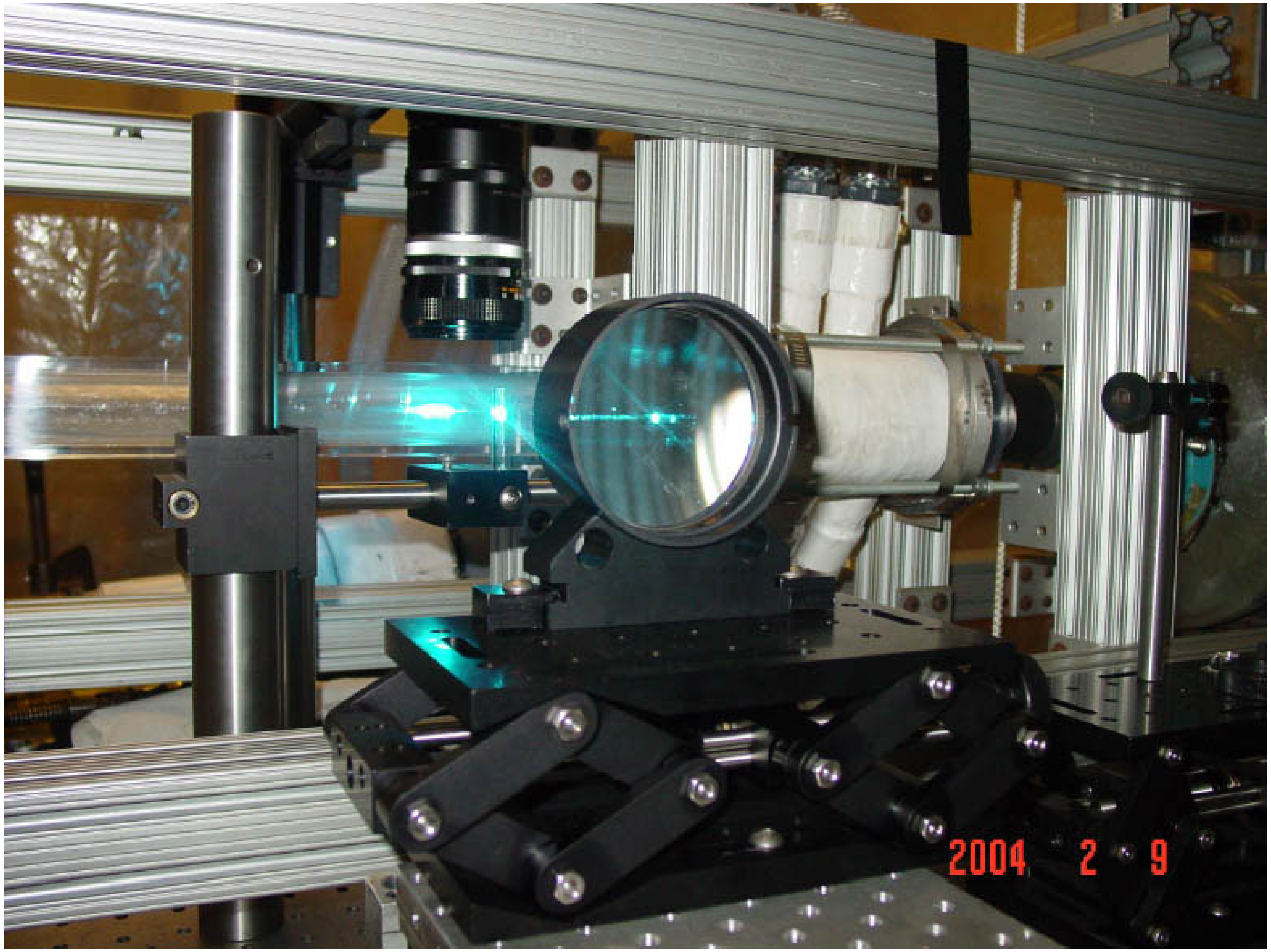


Oscillating Voided Liquid Slabs

Penreco® Drakesol® 260 AT light mineral oil allows molten salt scaled experiments with low distortion

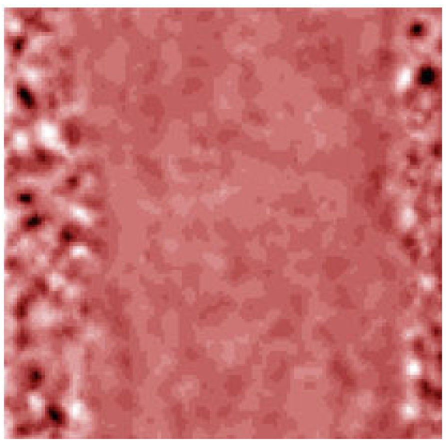
			Flibe at 600°C	Flibe at 900°C
Adjustable Parameters	Oil Temperature		110°C	165°C
	Length-Scale	L_s/L_p	0.40	0.39
	Velocity-Scale	U_s/U_p	0.63	0.62
	Δ T-Scale	$\Delta T_s/\Delta T_p$	0.36	0.40
Reynolds Number		Re_s/Re_p	1	1
Froude Number		Fr_s/Fr_p	1	1
Weber Number		We_s/We_p	0.63	0.72
Prandtl Number		Pr_s/Pr_p	1	1
Rayleigh Number		Ra_s/Ra_p	1	1
β ΔT		$\beta\Delta T_s/\beta\Delta T_p$	1	1
Nusselt Number		Nu_s/Nu_p	1	1
Pumping Power		Qp_s/Qp_p	0.015	0.015
Heating Power		Qh_s/Qh_p	0.012	0.013

UCB is now doing detailed experimental measurements of turbulence and surface topology in vortex tubes

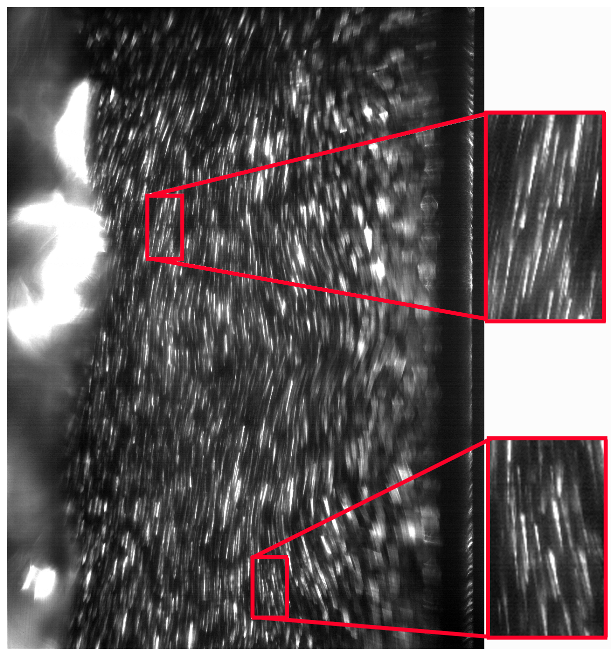


Particle image velocimetry is providing detailed velocity and turbulence information

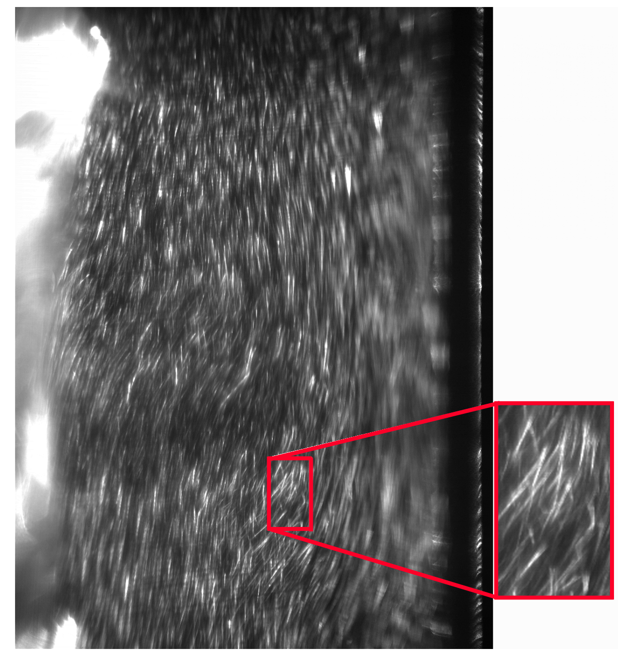
- Ar CW laser allows visualization of micron particles
- Water has been replaced by Mineral Oil for improved visualization
- Evidence for intense turbulence at small length scales



Layer vorticity structure



200 μs exposure time



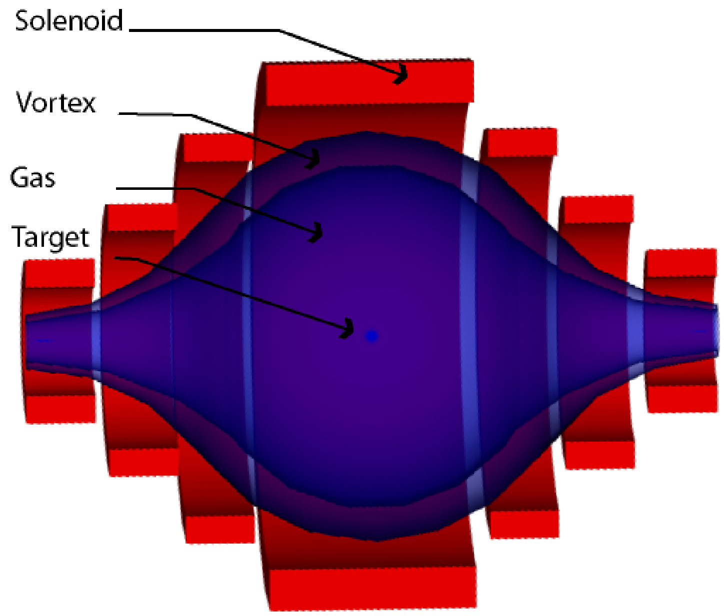
1000 μs exposure time

If surface-renewal frequency is 1 kHz, 2MW/m^2 is possible with a surface temperature 50°C greater than bulk temperature

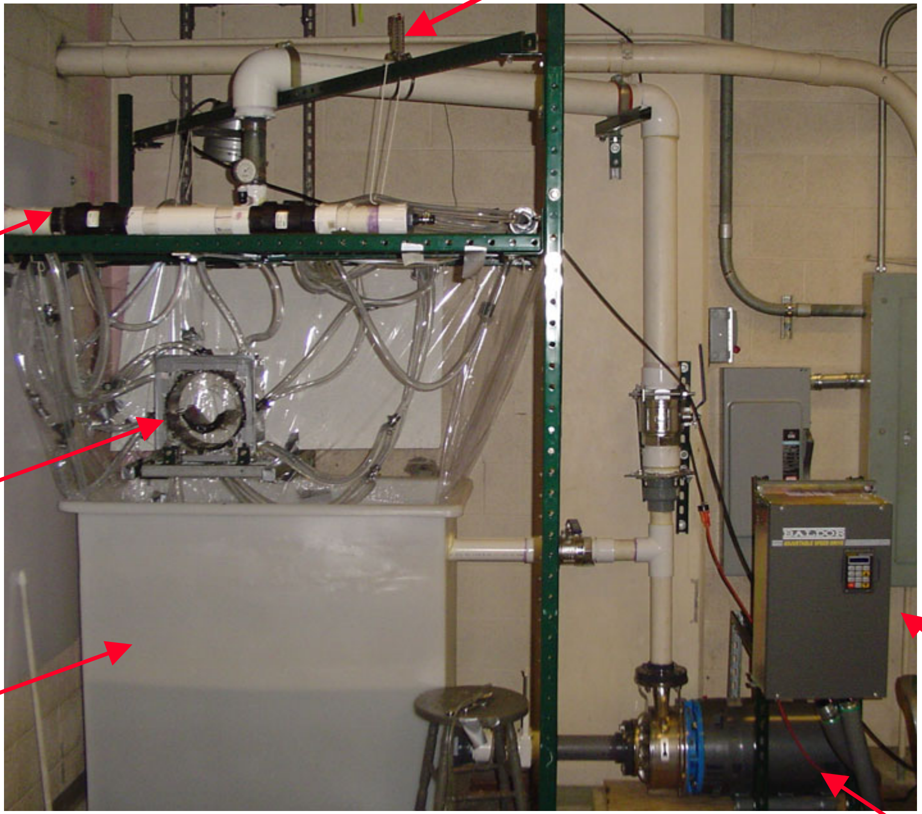
U.C. Berkeley

Modular solenoid HIF chamber could potentially use a large-scale vortex flow

- **Issues:**
  - **Using injection and suction to maintain vortex flow on substrate with non-uniform radius**
  - **Response of liquid layer to x-ray ablation (surface waves, substrate stresses, droplet ejection)**
  - **Effects of turbulent surface renewal on surface temperature and condensation**



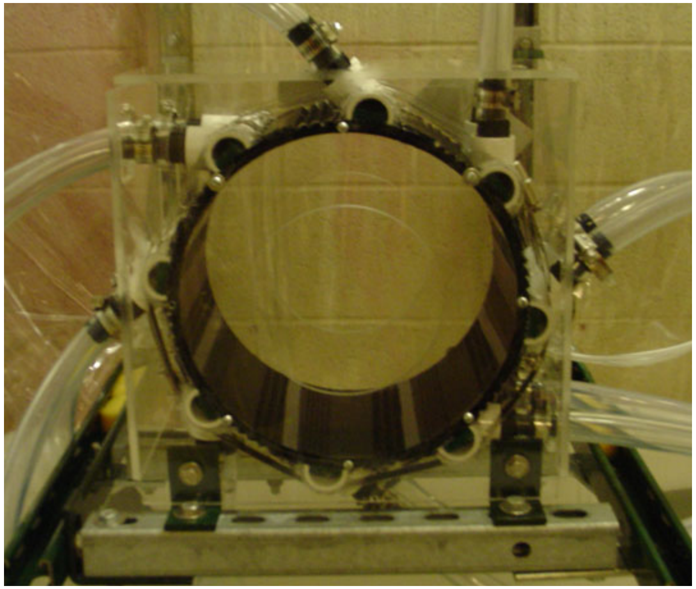
A large variable recirculation flow loop was constructed

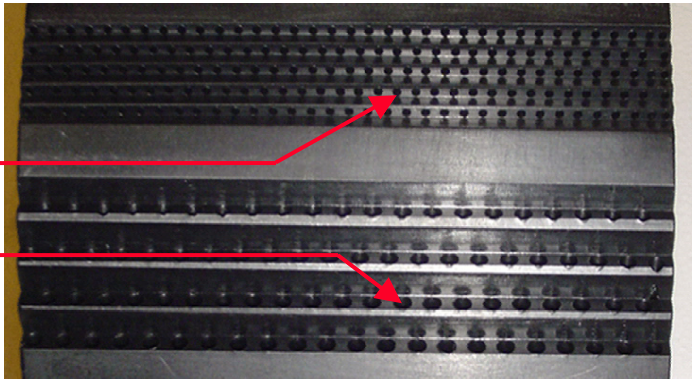


- Pump is rated for 500-gpm at 300-ft of head
- Thanks to the frequency controller, the flow rate can be accurately varied between 0 and ~4000-gpm

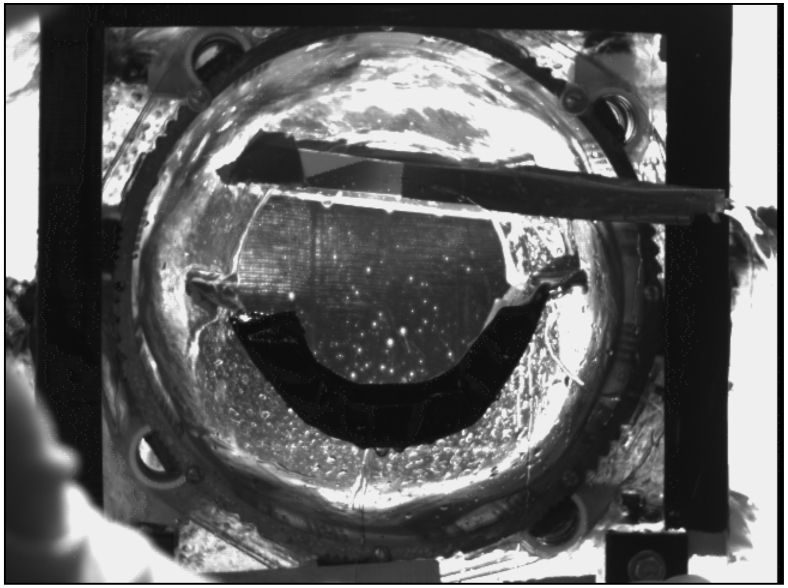
An improved device was constructed, based on the previous experiment

- A test device was fabricated from a segment of cylindrical pipe (25.4-cm diameter, 14-cm wide)
- Injection and suction holes were fabricated with precision
- Eight pressurized plenums provided blowing flow
- Perforations between injection plenums provided suction
  - $A_{suction} = 2A_{injection}$
- End walls produced modest non-ideality

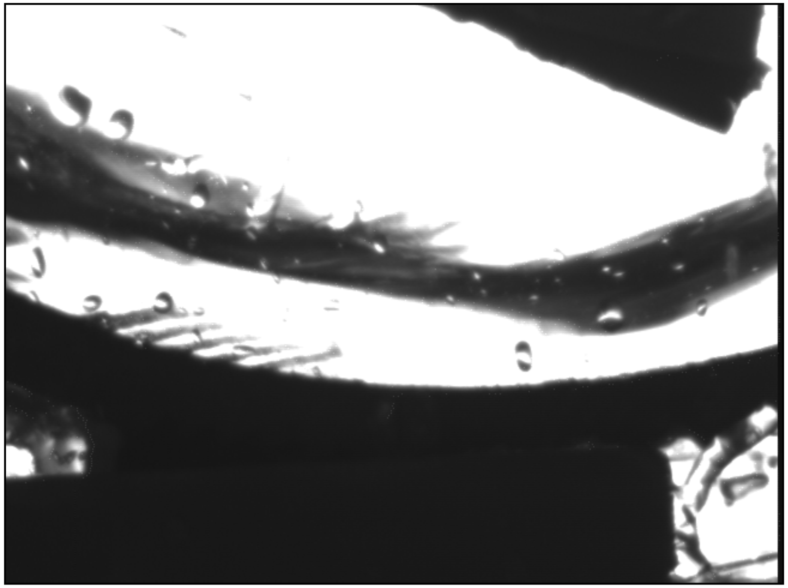




Different layer thicknesses have been obtained with Froude number as low as 3



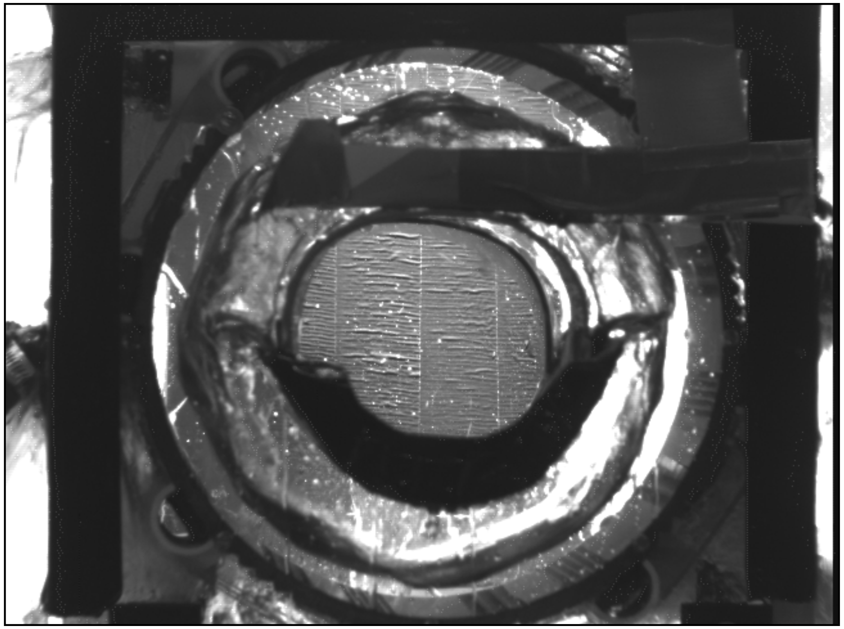
- $\delta/R = 5\%$
- $Fr = U^2/gR = 13.6$
- $Re = UR/\nu = 5 \cdot 10^5$



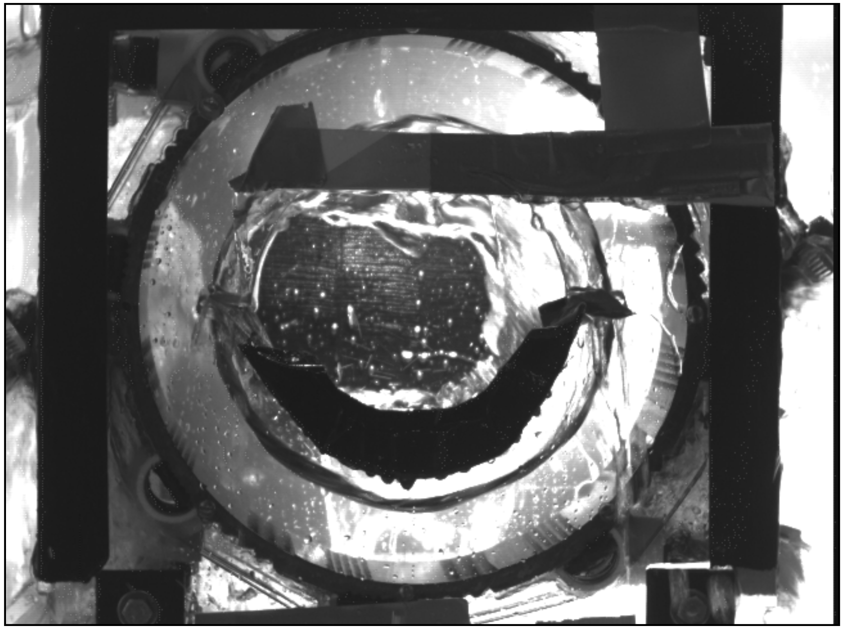
- the layer is inhomogeneous, due to sharp angle of injection

hexagon shape layer

Different layer thicknesses have been obtained with Froude number as low as 3, cont



- $\delta/R = 20\%$
- $Fr = 3.6$
- $Re = 3\cdot10^5$ (~20% of prototype)



- $\delta/R = 28\%$
- $Fr = 3.7$
- $Re = 3\cdot10^5$ (~20% of prototype)

Based on the previous experiment a new modular nozzle will be developed

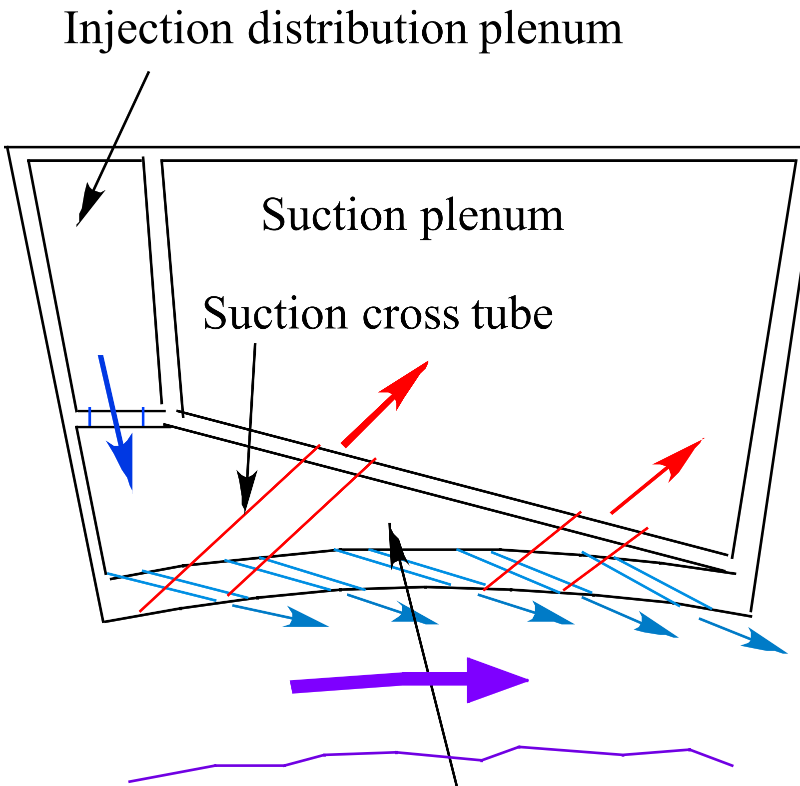
- **the new modular nozzle will have 8 to 12 interchangeable modules**

  to study the influence of the injection and suction angles

  the injection will be homogeneously distributed over the circumference

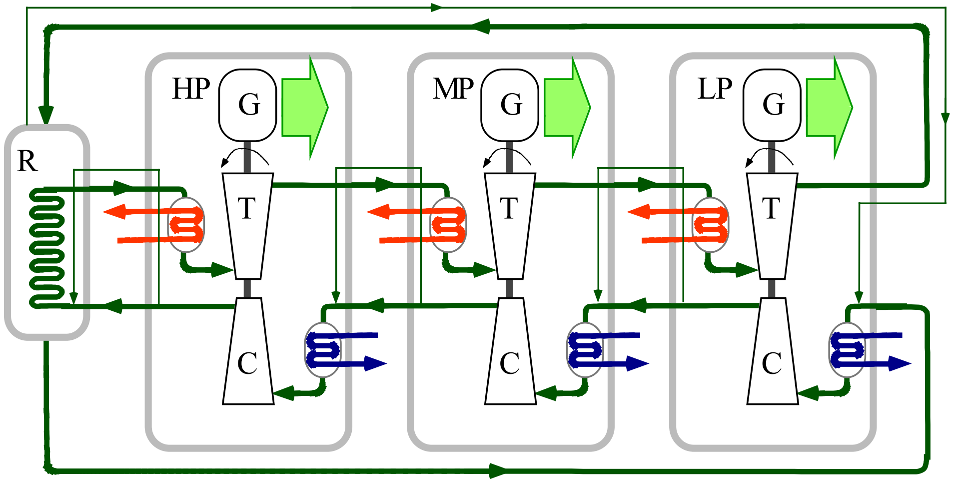
- **the modules will be built with rapid prototyping**

- **D-shape complex geometries (tokamak like) will also be investigated**

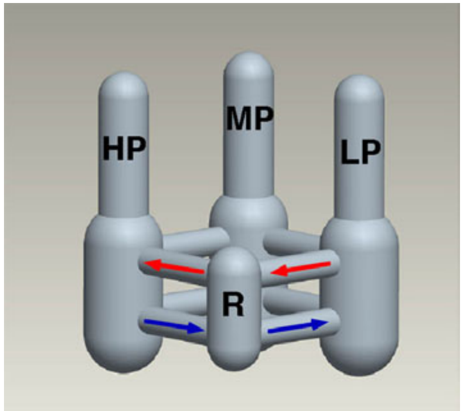


UCB has completed a pre-conceptual design study for a MCGC power conversion system

- Pre-conceptual design allows comparison of "molten coolant gas cycle (MCGC)" versus gas-cooled reactor power conversion
  - Based on GT-MHR PCU design
  - Includes detailed calculations for MS-to-He heat exchangers
- Results for high-temperature design
  - 2400 MW(t)
  - 900°C turbine inlet temp.
  - 54% thermal efficiency
  - 1300 MW(e)
- Power density comparison
  - GT-MHR: 230 kW(e)/m^3
  - MCGC: 360 kW(e)/m^3
  - Additional MCGC savings expected due to non-nuclear grade turbine building



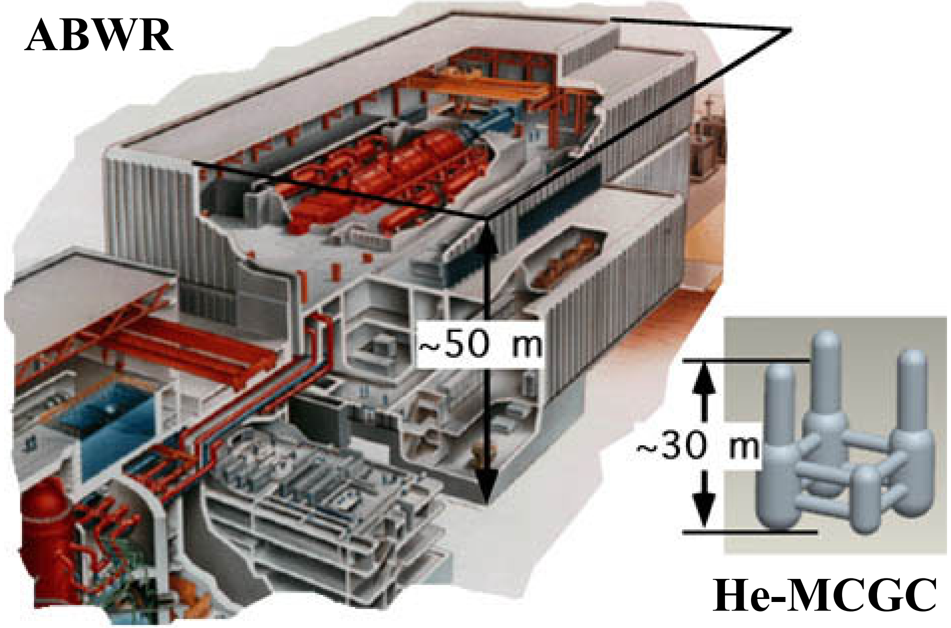
Components fit in four pressure vessels



Physical arrangement based on the GT-MHR PCU (vessels are ~ 30 m high)

H. Zhao and P.F. Peterson, "A Reference 2400 MW(t) Power Conversion System Point Design for Molten-Salt Cooled Fission and Fusion Energy Systems," Report UCBTH-03-002 (Rev. B), Jan. 10, 2004.

A scaled comparison of the 1380 MWe ABWR turbine building and ~1300 MWe MCGC equipment



The MCGC can likely achieve a substantial reduction of the turbine building volume

- **MCGC turbine building must also contain crane, turbine lay-down space, compressed gas storage, and cooling water circulation equipment**
- **MCGC requires ~1100 MWt of cooling water capacity, compared to 2800 MWt for ABWR**

Conclusions

- Substantial progress has been made in understanding thick-liquid IFE chamber response
- Vortex flows are interesting and have substantial promise
  - Potential for very high surface heat fluxes
  - Issues:
    - » droplet ejection from surface
    - » effects of ablation impulse loading
    - » control of flow for complex geometries
- The Next Generation Nuclear Plant will advance and demonstrate key fusion chamber technologies
  - advanced materials
  - molten salt heat transfer fluids
    - » materials compatibility
    - » target debris recovery
  - helium Brayton cycle power conversion
  - tritium safety and management