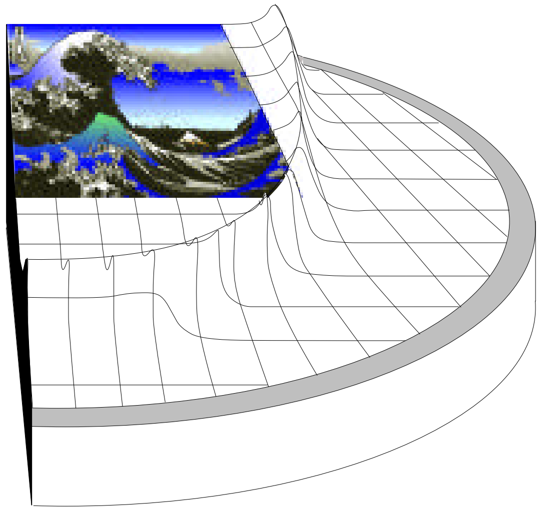
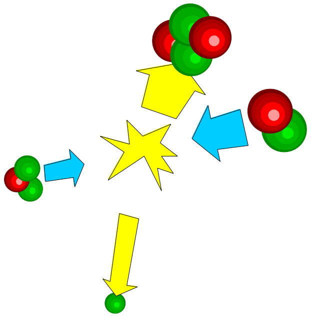
Introduction to Liquid-Wall Chamber Configurations and Phenomena

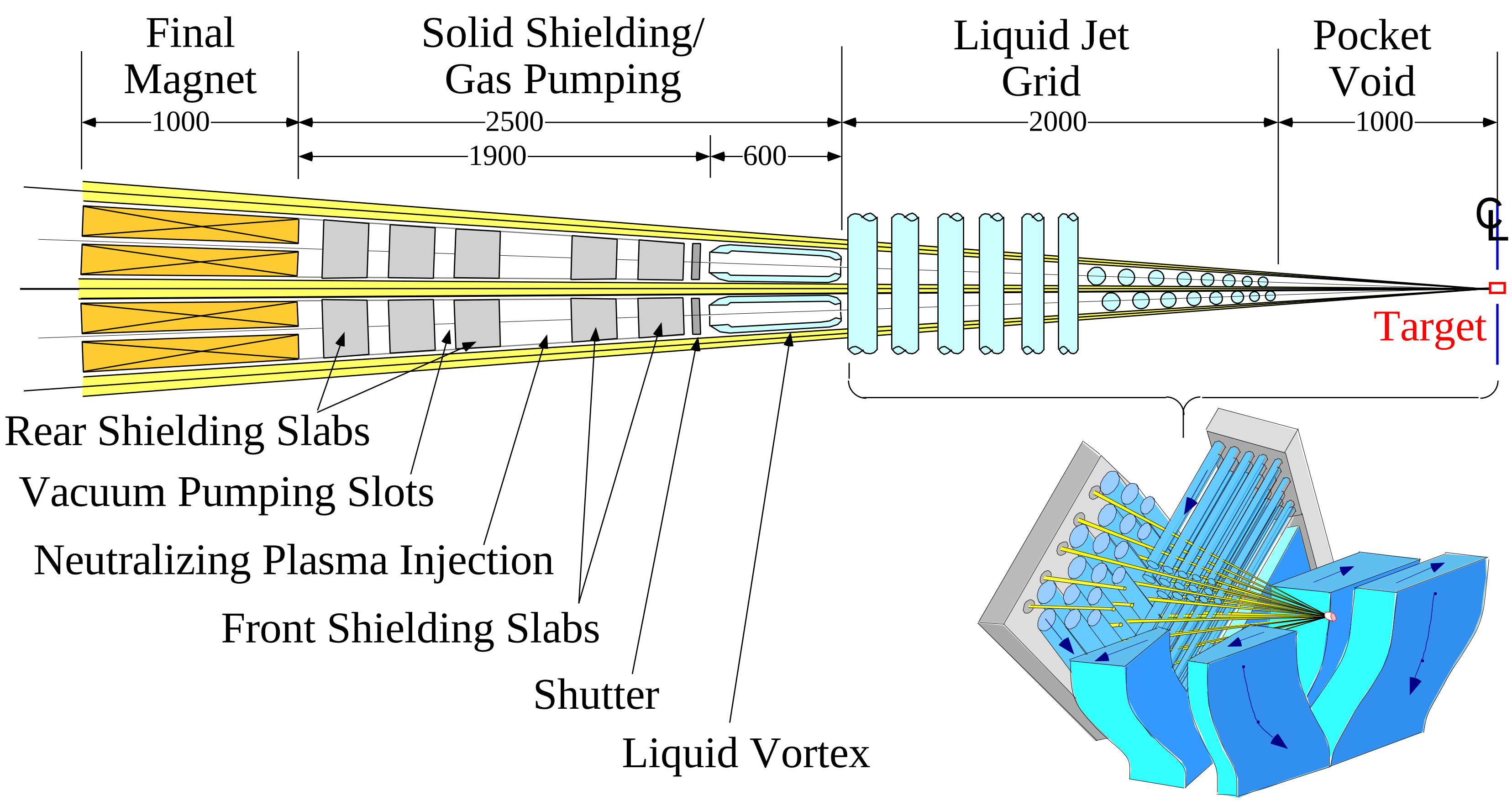


Per F. Peterson
Department of Nuclear Engineering
University of California, Berkeley

IAEA TCM Meeting
Vienna, Austria
May 20-24, 2001

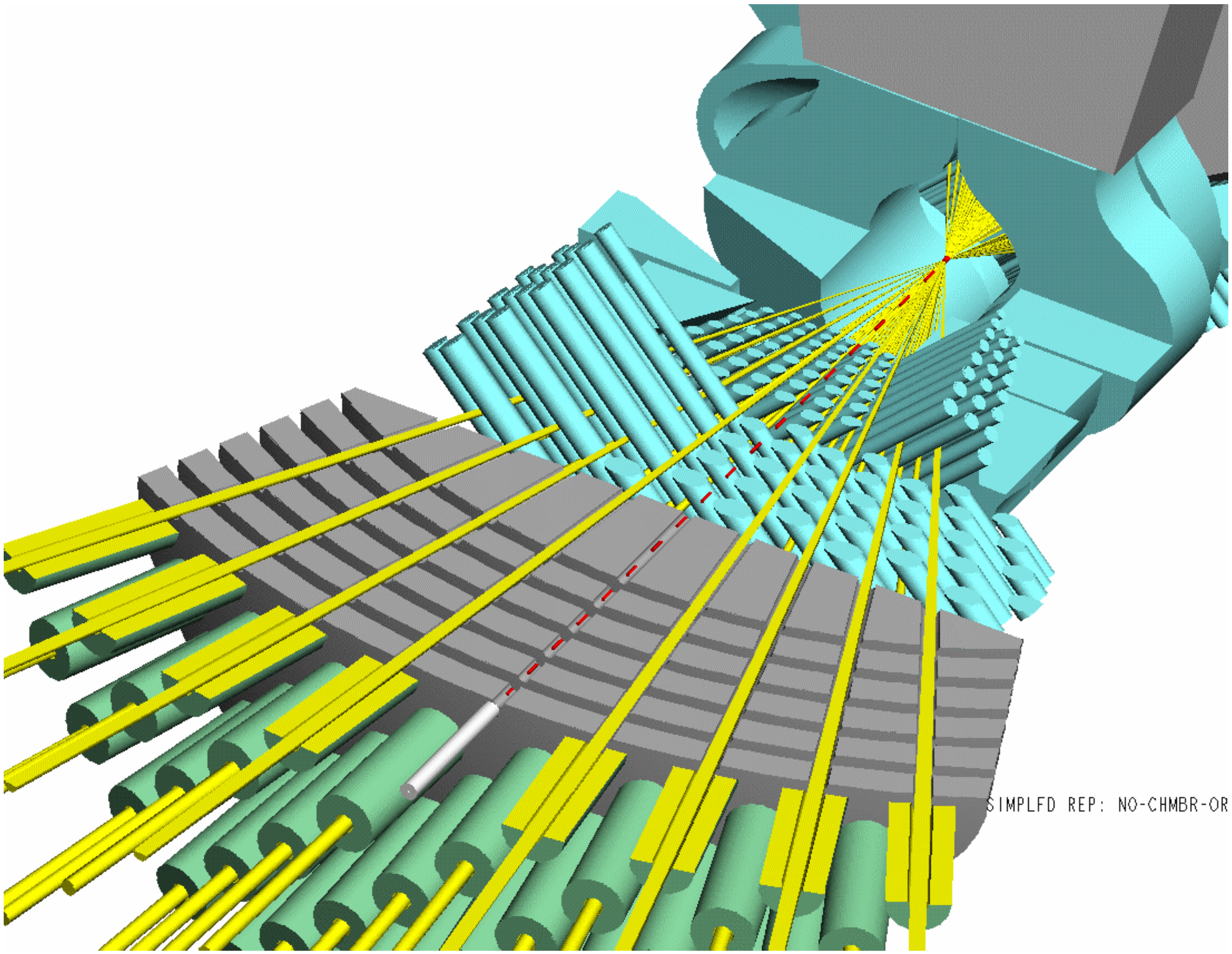


The key heavy-ion thick-liquid chamber phenomena include liquid hydraulics and vapor condensation



Schematic Liquid Jet Geometry

Cut-away view shows beam and target injection paths for a 160-beam example thick-liquid chamber



IFE phenomena span an extremely wide range of scales

- **Time: 10^{-8} sec — 10^{9} sec**
  - **Target drive — chamber life time**
- **Length: 10^{-6} m — 10^{3} m**
  - **X-ray ablation layers — driver dimensions**
- **Temperature: 10 K — 10^{7} K**
  - **Cryogenic targets — post-ignition target debris**
- **Pressure: 10^{12} Pa — 10^{-1} Pa**
  - **X-ray ablation layers — pre-shot beam-line vacuum**
- **Matter states**
  - **Solid — liquid — vapor — ionized plasma**

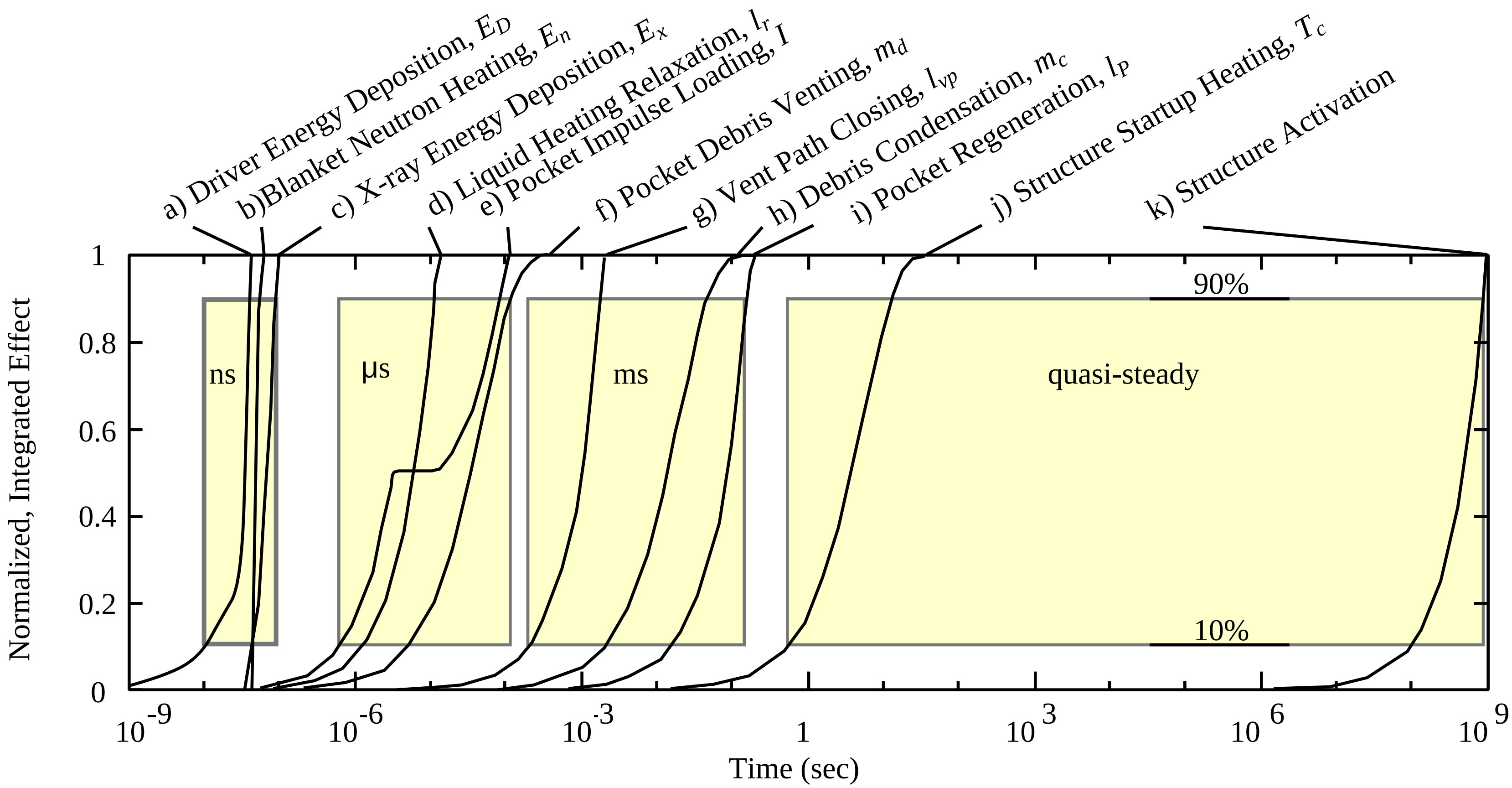
Few topics share these scale extremes: Astrophysics, reactor safety analysis, global climate modeling… Complexity makes appropriate scaling methods essential

IFE system phenomena cluster into distinct time scales

Principal focus for IFE Technology R&D...

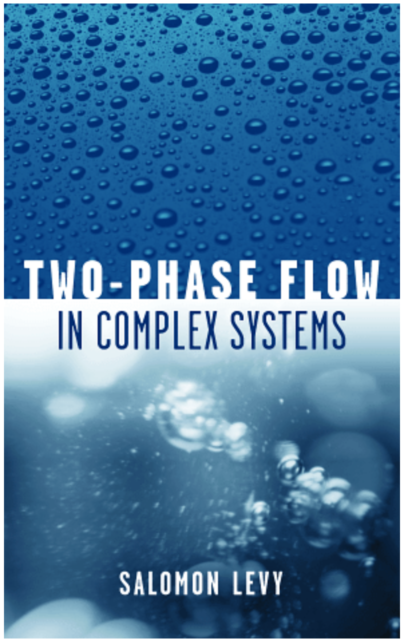
- **Nanosecond IFE Phenomena**
  - **Driver energy deposition and capsule drive (~30 ns)**
  - **Target x-ray/debris/neutron emission/deposition (~100 ns)**
- **Microsecond IFE Phenomena**
  - **X-ray ablation and impulse loading (~1 μs)**
  - **Debris venting and impulse loading (~100 μs)**
  - **Isochoric-heating 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)**

IFE chamber time histories show that major subgroups of phenomena are decoupled in time



IFE has intriguing complexity characteristics

- **Strong phenomena decoupling occurs in both time and space**
  - **Spatial decoupling boundaries**
    - » **small or unidirectional mass and energy fluxes**
    - » **large time scale differences—slow side sees integral effect of fast**
  - **Temporal decoupling boundaries**
    - » **large time scale differences —slower phenomena sees integral effect of fast**
  - **Inside these boundaries, phenomena interactions must be considered**
    - » **integral experiments must preserve key phenomena at reduced length/energy**



S. Levy, 1999

All IFE scientific topics can be identified and characterized by time scale and spatial location

<table>
<tr><th rowspan="2">Spatial Volume</th><th colspan="4">Time Scale (Phenomena Duration)</th></tr>
<tr><th>Nanosecond
(Target Gain)</th><th>Microsecond</th><th>Millisecond
(Rep. Rate)</th><th>Quasi-Steady
(Safety/Reliab.)</th></tr>
<tr><td>Capsule</td><td>Neutron/ion/ x-ray emission</td><td rowspan="5">Target debris expansion/ interaction with ablation debris, venting, impulse</td><td rowspan="5">Debris condensation</td><td>—</td></tr>
<tr><td>Hohlraum (if used)</td><td>X-ray and debris emission</td><td>—</td></tr>
<tr><td>Driver energy transport paths</td><td>Beam transport and focusing</td><td>Debris accumulation</td></tr>
<tr><td>Pocket Void/Vent Paths</td><td>—</td><td>—</td></tr>
<tr><td>External Condensing Region</td><td>—</td><td>—</td></tr>
<tr><td>Target-facing Surface Layers</td><td>X-ray deposition</td><td>Ablation/impulse</td><td rowspan="2">Liq. hydraulics/ solid thermal mechanics</td><td rowspan="2">Activation, neutron damage (solids), safety</td></tr>
<tr><td>Blanket (liquid/solid)</td><td rowspan="3">Neutron and gamma deposition</td><td>Neutron heating relaxation</td></tr>
<tr><td>Final focus elements</td><td>—</td><td>—</td><td>Damage rate</td></tr>
<tr><td>Chamber structures</td><td>—</td><td>—</td><td rowspan="2">Safety, tritium, activation, corrosion</td></tr>
<tr><td>Coolant recirc./heat recovery loop</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>Accelerator/laser systems</td><td>Driver physics</td><td>—</td><td colspan="2">Driver rep. rate and reliability</td></tr>
<tr><td>Target injection</td><td>—</td><td>—</td><td>Accel./heating</td><td>—</td></tr>
<tr><td>Target fabrication</td><td>—</td><td>—</td><td>—</td><td>Safety/reliability</td></tr>
<tr><td>Balance of plant</td><td>—</td><td>—</td><td>—</td><td>Safety/reliability</td></tr>
</table>

Nanosecond phenomena control scientific viability

Spatial Volume	Time Scale (Phenomena Duration)			
	Nanosecond **(Target Gain)**	Microsecond	Millisecond **(Rep. Rate)**	Quasi-Steady **(Safety/Reliab.)**
Capsule	Neutron/ion/ x-ray emission	Target debris expansion/ interaction with abl… ven…	Debris condensation	—
Hohlraum (if used)	X-ray and debris emission			—
Driver energy transport paths	Beam transport and focusing			
Pocket Void/Vent Paths	—			
External Condensing Region	—			
Target-facing Surface Layers	X-ray deposition	Abl…		
Blanket (liquid/solid)	Neutron and gamma deposition	Ne…		
Final focus elements				
Chamber structures				
Coolant recirc./heat recovery loop	—			
Accelerator/laser systems	Driver physics	—	Driver rep. rate and reliability	
Target injection	—	—	Accel./heating	—
Target fabrication	—	—	—	Safety/reliability
Balance of plant	—	—	—	Safety/reliability

Nanosecond phenomena:

- **Target gain**
  > **Must be understood to judge the scientific viability of IFE**
- **Target output**
  > **Must be understood to predict chamber response**

Millisecond phenomena control repetition rate

Spatial Volume	**Time Scale (Phenomena Duration)**			
	Nanosecond **(Target Gain)**	Microsecond	Millisecond **(Rep. Rate)**	Quasi-Steady **(Safety/Reliab.)**
Capsule	Neutron/ion/ x-ray emission	Target debris expansion/ interaction with ablation debris, ...pulse	Debris condensation	—
Hohlraum (if used)	X-ray and debris			—
Drive...				Debris accumulation
Pocke...				—
Exter...				—
Targe...		...pulse	Liq. hydraulics/ solid thermal mechanics	Activation, neutron damage (solids), safety
Blank...		...ting ...n		
Final ...			—	Damage rate
Cham...			—	Safety, tritium, activation, corrosion
Coola... loop			—	
Accelerator/laser systems	Driver physics	—	Driver rep. rate and reliability	
Target injection	—	—	Accel./heating	—
Target fabrication	—	—	—	Safety/reliability
Balance of plant	—	—	—	Safety/reliability

Millisecond phenomena:

- **Control the repetition rate**
  - > **Must be understood to judge the engineering viability of IFE**
- **Initial conditions**
  - > **Created by nanosecond and microsecond phenomena**

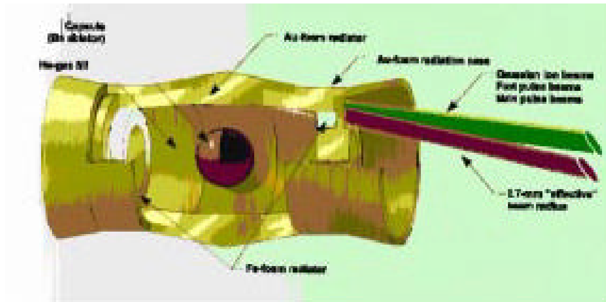
Quasi-steady phenomena control safety and reliability

Spatial Volume	Time Scale (Phenomena Duration)			
	Nanosecond **(Target Gain)**	Microsecond	Millisecond **(Rep. Rate)**	Quasi-Steady **(Safety/Reliab.)**
Capsule	Neutron/ion/ x-ray emission	Target debris expansion/ interaction with ablation debris	Debris condensation	—
Hohlraum (if used)	X-ray and debris			—
Driver energy transpo				Debris accumulation
Pocket Void/Vent Pat				—
External Condensing I				—
Target-facing Surface			ulics/ rmal ics	Activation, neutron damage (solids), safety
Blanket (liquid/solid)				
Final focus elements				Damage rate
Chamber structures				Safety, tritium, activation, corrosion
Coolant recirc./heat re loop				
Accelerator/laser systems	Driver physics		Driver rep. rate and reliability	
Target injection	—	—	Accel./heating	—
Target fabrication	—	—	—	Safety/reliability
Balance of plant	—	—	—	Safety/reliability

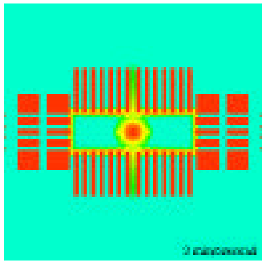
Quasi-steady phenomena:

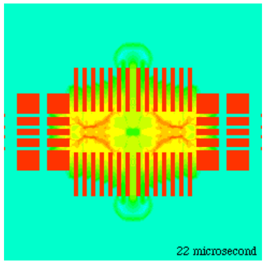
- **Control safety**
  - > **Must be understood to judge the engineering viability of IFE and of experimental facilities**
- **Control reliability**
  - > **Must be understood to judge the attractiveness of IFE**

Nanosecond/Microsecond Phenomena Overview



- **Nanosecond Phenomena:**
  - **Driver final transport**
    - » **Coordinated with HI-VNL researchers**
  - **Target x-ray/debris/neutron emission**
    - » **1-D Lasnex calculations have given better understanding of target output**
  - **Neutron shielding/energy deposition**
    - » **3-D TART calculations have been performed**
- **Microsecond Phenomena**
  - **Upcoming Z experiments will study x-ray ablation with prototypical chamber coolants**
  - **Extensive 1-D (Bucky) and 2-D (Tsunami) calculations have been done**





Scaling for millisecond liquid hydraulics preserves the liquid trajectory and surface configuration

Mass and momentum conservation (incompressible flow)

$$\mathbf{v} = 0 \qquad \rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \quad \mathbf{v}\right) = - \quad p + \mu \quad {}^2\mathbf{v} + \rho\mathbf{g}$$

Free surface pressure boundary condition with impulse load *I*

$$p - p_v = \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \qquad \text{where} \qquad p_{v,ave} = \frac{IU}{L} = \frac{U}{L}\int_0^{L/U} p_v\, dt$$

Nondimensionalize with appropriate scaling parameters:

$$\mathbf{v}^* = \mathbf{v}/U \qquad {}^* = L \qquad p^* = p/\rho U^2 \qquad t^* = f\,t \qquad r^* = r/L \qquad p_v^* = \frac{p_v L}{IU}$$

Giving governing equations:

$$ {}^* \quad \mathbf{v}^* = 0 \qquad \mathrm{St}\frac{\partial \mathbf{v}^*}{\partial t^*} + \mathbf{v}^* \quad {}^* \mathbf{v}^* = - \quad {}^* p^* + \frac{1}{\mathrm{Re}} \quad {}^{*2} \mathbf{v}^* + \frac{1}{\mathrm{Fr}}\frac{\mathbf{g}}{g}$$

$$p^* - I^* p_v^* = \frac{1}{\mathrm{We}}\left(\frac{1}{r_1^*} + \frac{1}{r_2^*}\right)$$

A scaled system behaves identically if initial conditions and St, Re, Fr, I*, and We are matched...

Major IFE simplification:
No EOS, No energy equation
No MHD

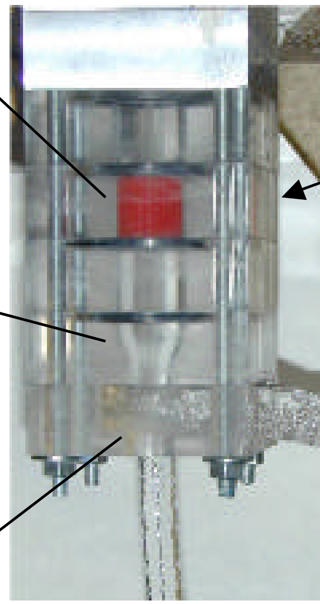
Recent experiments show that cylindrical jets can be sufficiently smooth for beam-line protection

Flow Conditioning

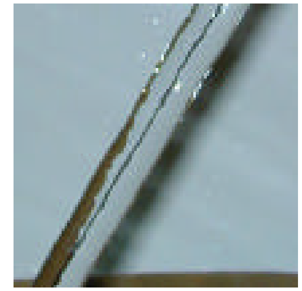
honeycomb

screen/nozzle

cutter blade

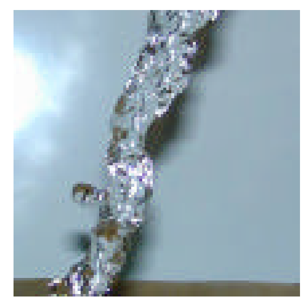


Jet with 1.5 : 1.0 nozzle contraction ratio



Re = 100,000

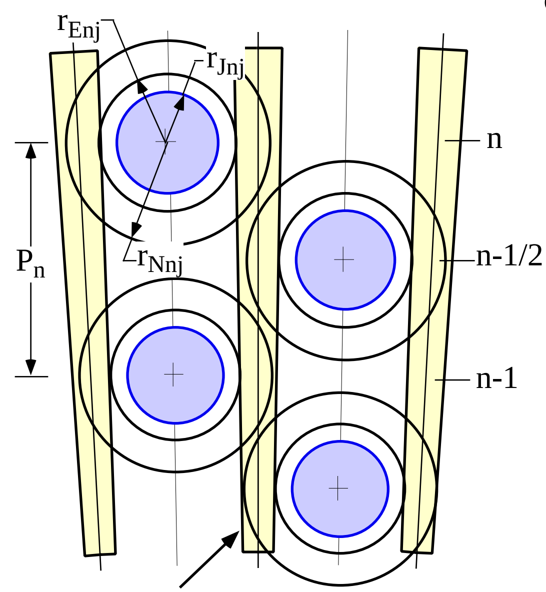
Re = 186,000



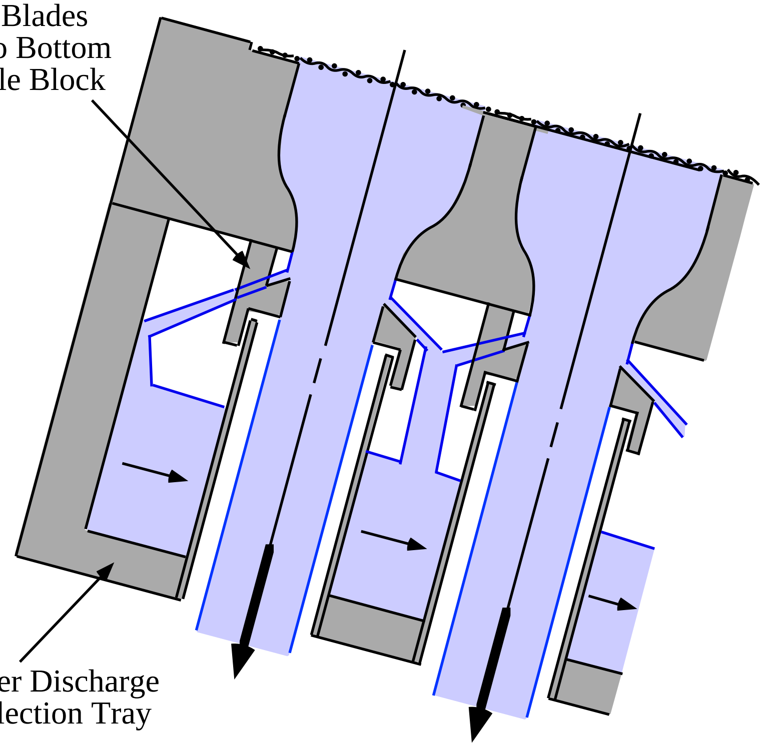
Re = 70,000 (no conditioning)

Cylindrical jets can be arrayed for beam-line shielding

- **Staggered geometry reduces collimation of liquid droplets and slugs down beam lines**
- **Pitch to diameter ratio $P_n/2r_{Jn}$ will be between 1.6 and 2.5**

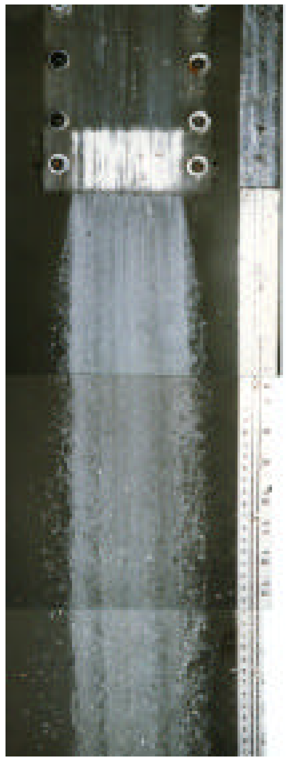


Staggered Jet Array Cross Sections

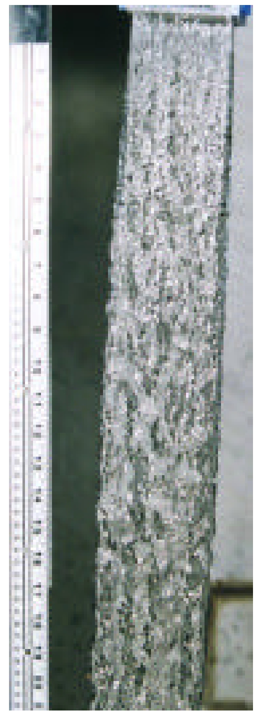


Nozzle Cross Section

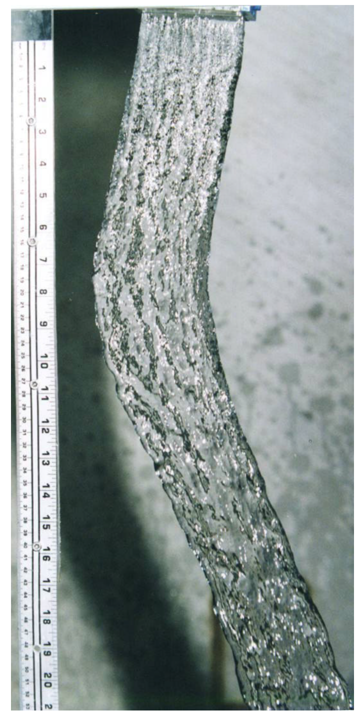
Single-jet experiments provide jet geometries for constructing integrated pockets



Bad:
Breaks up



Stationary



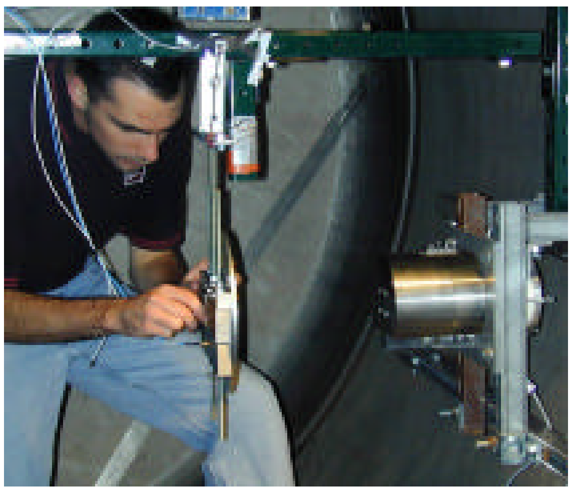
Oscillating

Better: No Droplets

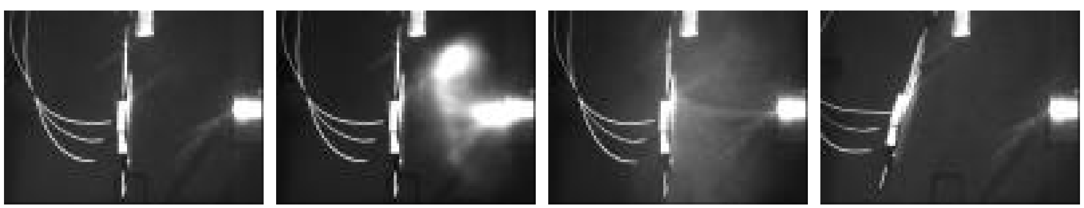
UCB Stationary Jets (1.6 cm x 8.0 cm,
view from flat side, Re = 160,000, We = 29,000)

Vacuum Hydraulics Experiment (VHEX) studies IFE jet disruption and regeneration

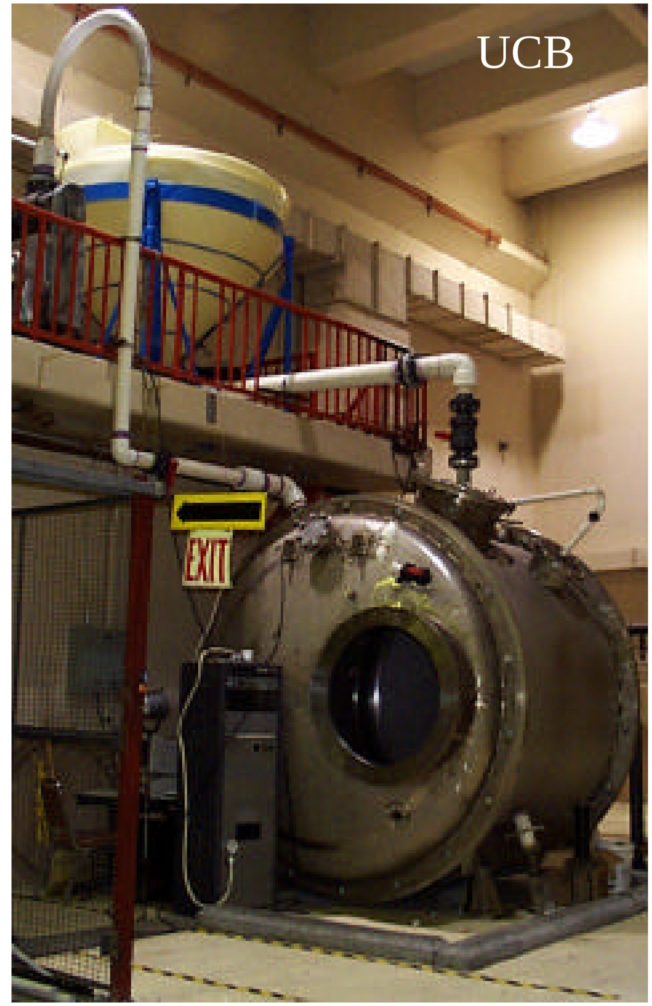
- Create hydrodynamically similar single jets and several jet arrays
- Transient flow into large vacuum vessel—water simulates flibe



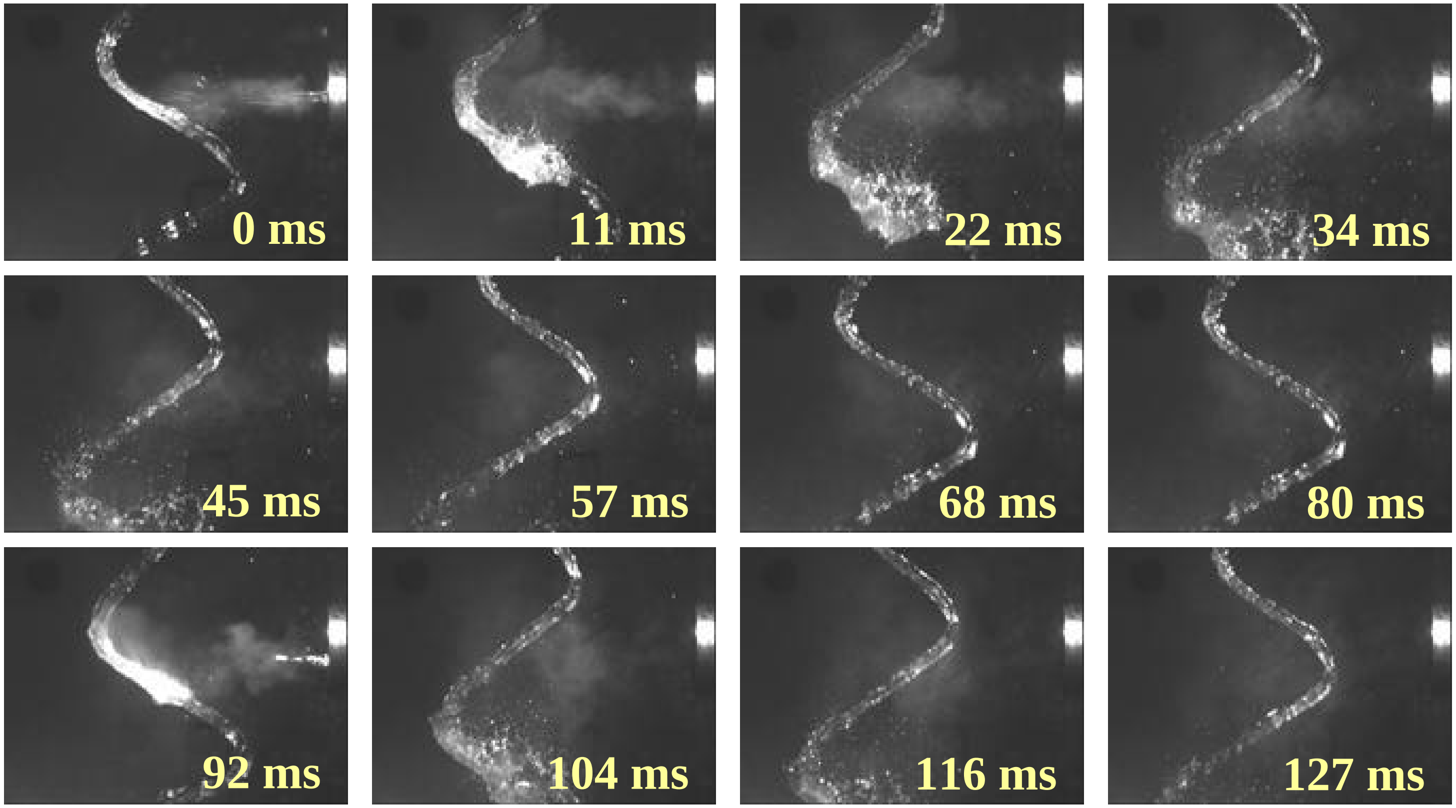
Impulse load calibration underway



t = 0 | t = 0.8 ms (muzzle flash) | t = 1.6 ms (plume has hit) | t = 32 ms (peak deflection)



Cartridges can provide required impulse loading



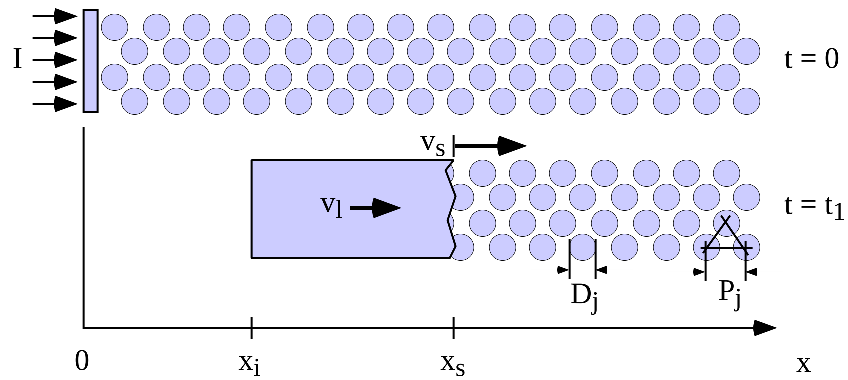
Single-jet disruption at 10.3 Hz

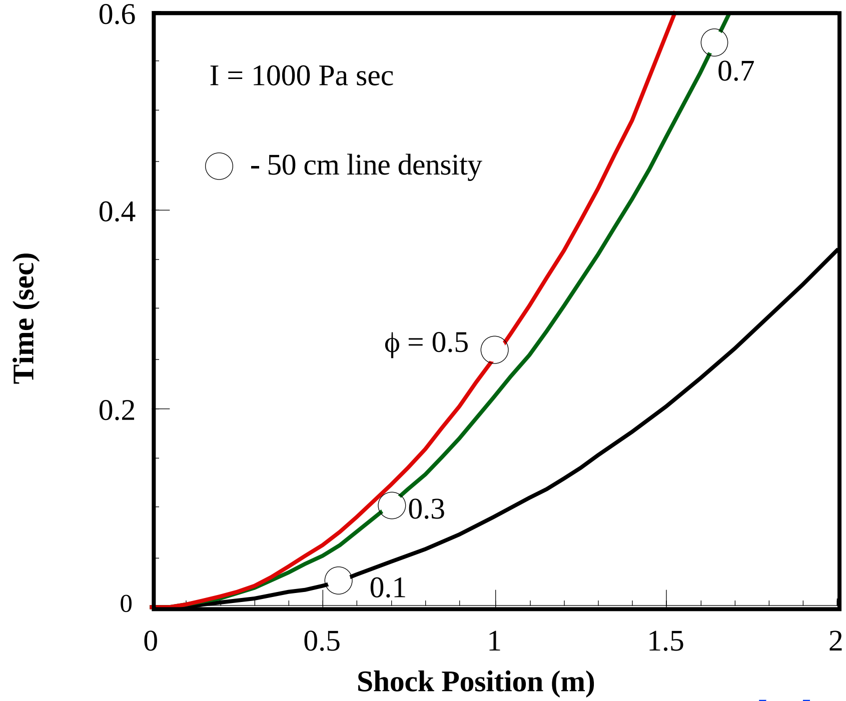
Models predict that porous liquid will strongly mitigate shocks

- **Impulse from x-ray ablation and pocket pressurization generates shock**
- **Simple "snowplow" model gives shock transit time as function of liquid void fraction ϕ :**

$$t = \frac{\phi(1-\phi)\rho x_s^2}{2I}$$

- **Shocks require > 100 ms to arrive at outside of porous pocket liquid**
- **Caveat: pocket openings may collimate high-velocity liquid**

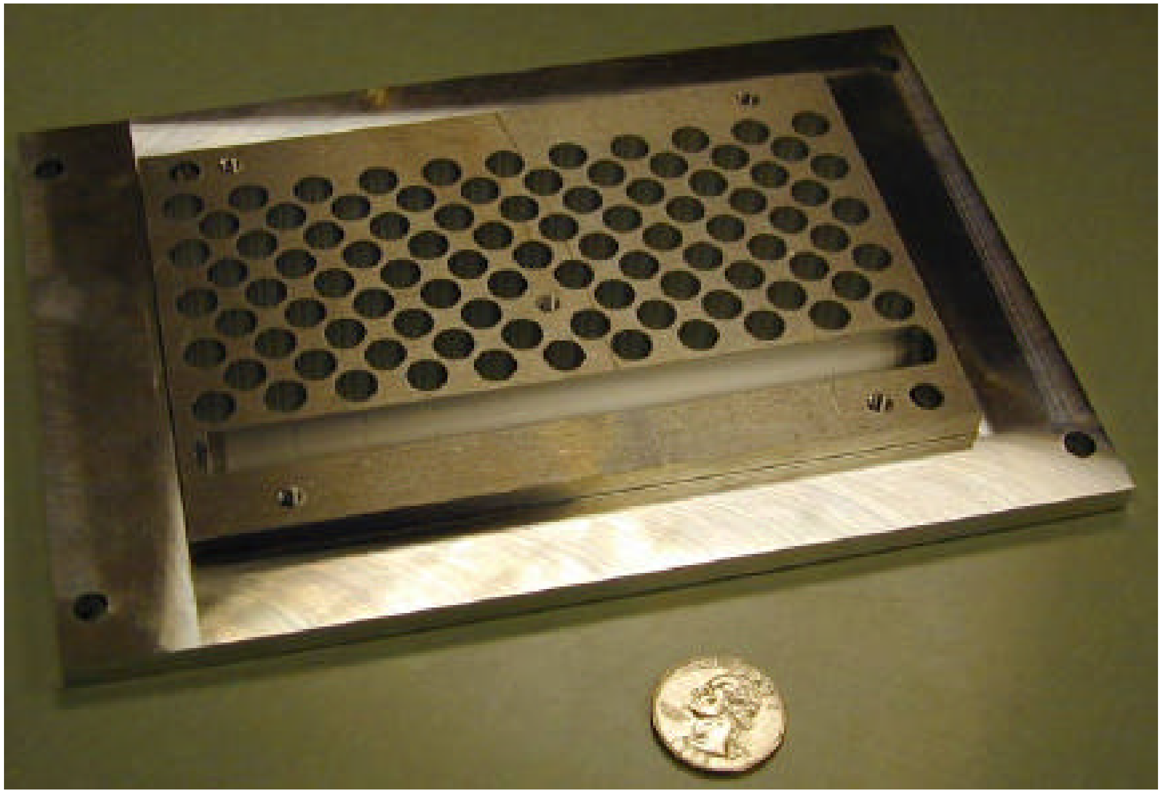




UC Berkeley

Multiple jet experiments will start soon

- **Numerically controlled machining allows precision fabrication of multiple nozzles**



96-nozzle system uses sheet jet and multiple cylindrical jets

Future directions

- **Build further our understanding of multiple jet interactions**
  - **Colliding jets (G. Tech. experiments, UCLA CFD)**
  - **Shock transport through multiple jet arrays (UCB experiments)**
  - **Clearing between crossed jet arrays (UCB experiments)**
  - **Effect of debris on droplets, films and jets (UCLA experiments)**

- **Continued exploration of fundamental fracture and recombination phenomena (EOS/modeling/design data)**
  - **Z experiments on flibe ablation**
  - **Laser fracture experiments to measure liquid strength (UCLA, UCSD)**
  - **Flibe electrathermal plasma source (UCLA)**