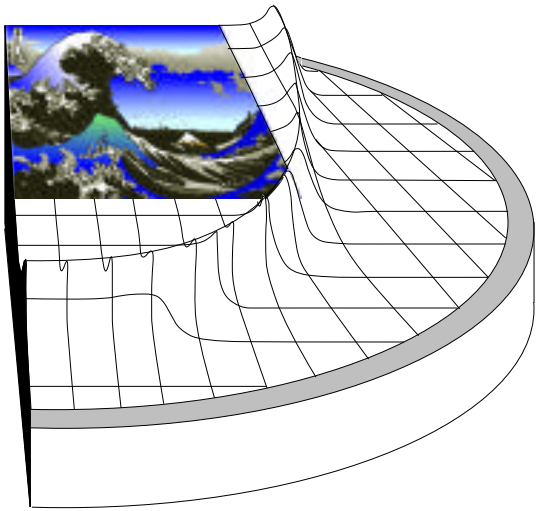
Inertial Fusion Technology (IT): The Science Basis for IFE Chambers and Targets



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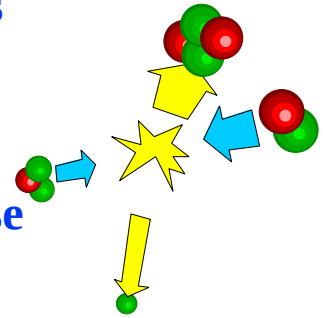
University of California, Berkeley

Snowmass Fusion Summer Study

July 8, 2002

- **Defining IFE chamber and target functional requirements**
  -target gain, repetition rate, reliability and safety
- **Chamber science**
  -phenomena scaling
  -prediction, control and optimization of chamber response
  -target fabrication and injection
- **Examples of recent progress**



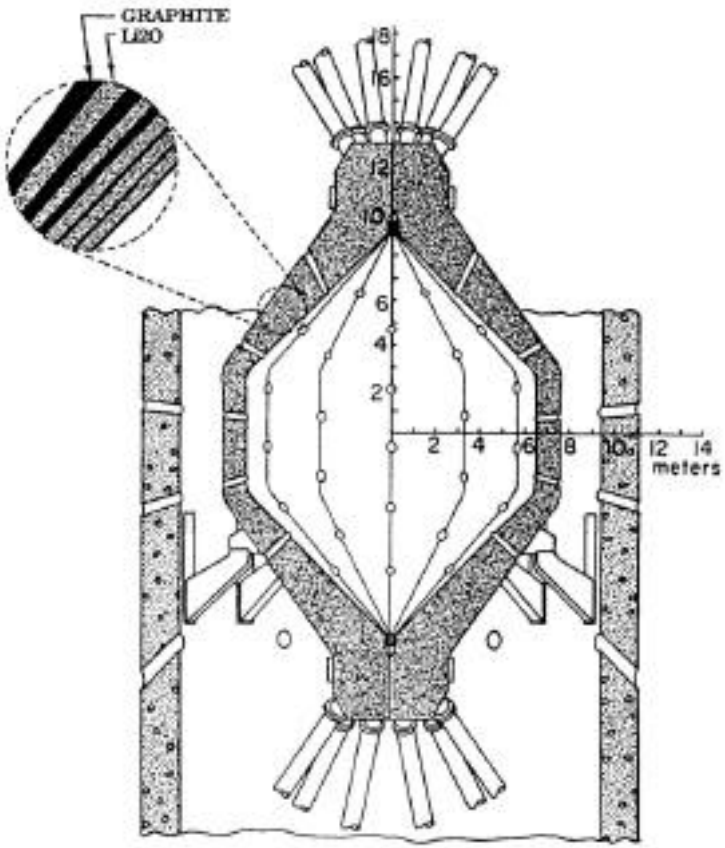
IFE target chambers must meet four requirements defined at the 1999 Snowmass Summer Study

- **Regenerate chamber conditions for target injection, driver beam propagation, and ignition at sufficiently high rates**
- **Protect chamber structures for several to many years or allow easy replacement of inexpensive modular components**
- **Extract fusion energy in high-temperature coolant, regenerate tritium**
- **Reduce radioactive waste generation, inventory, and possible release fractions low enough to meet no-public-evacuation standards.**

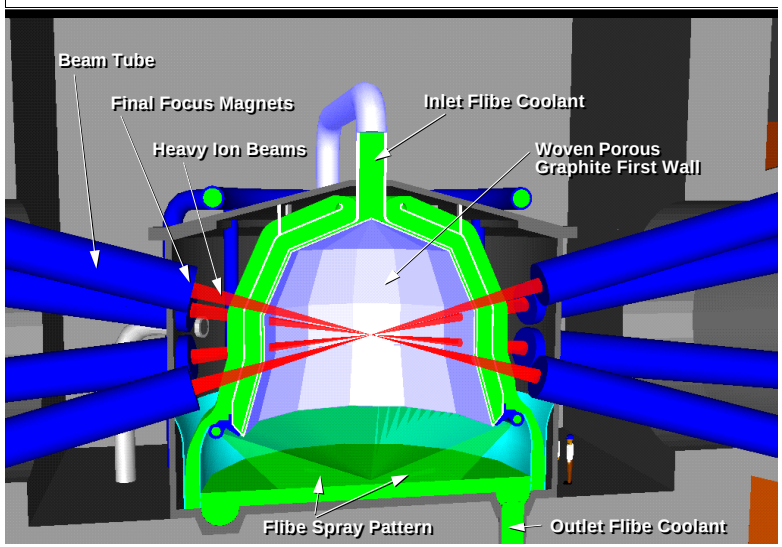
Chamber will be 9-15% of total capital cost
Design, not chamber cost, is the most important issue

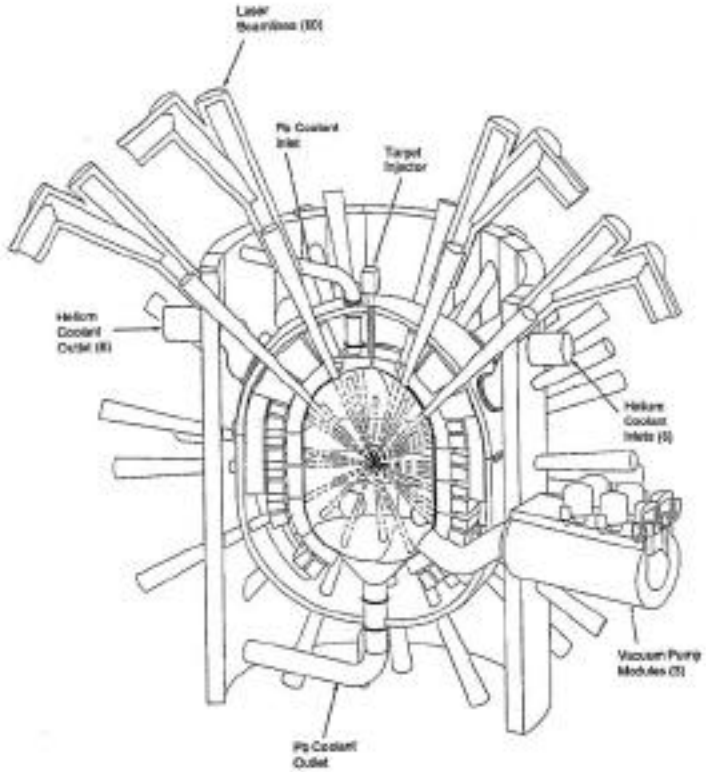
Sombrero is an example Dry Wall chamber

- **Example: Sombrero Conceptual Design**
  - **Direct drive targets**
  - **Carbon-carbon first wall and flow structures**
  - **Xenon gas controls x-ray and debris damage to first wall**



Osiris/Prometheus are examples of Wetted Walls





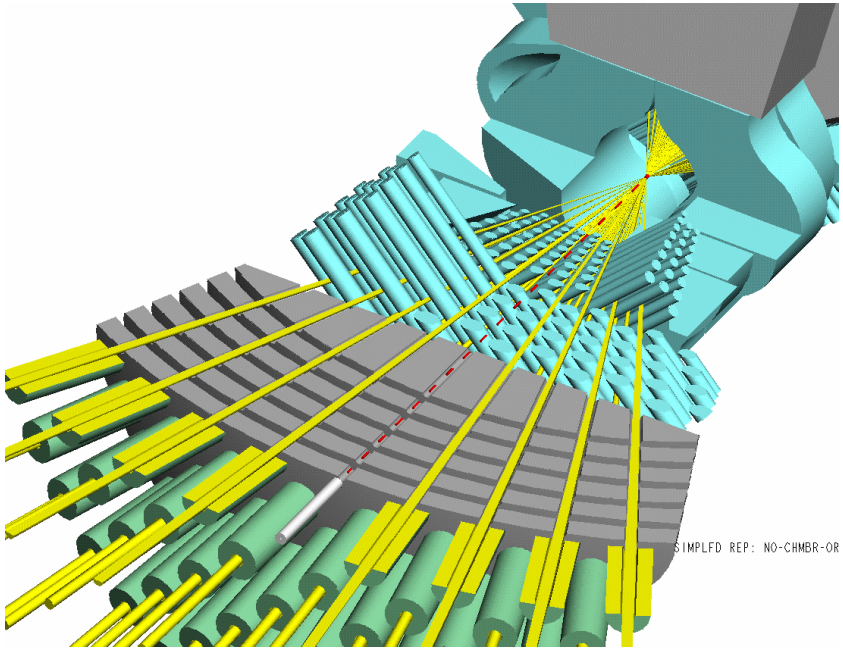
HI indirect drive: Osiris

Laser direct drive: Prometheus

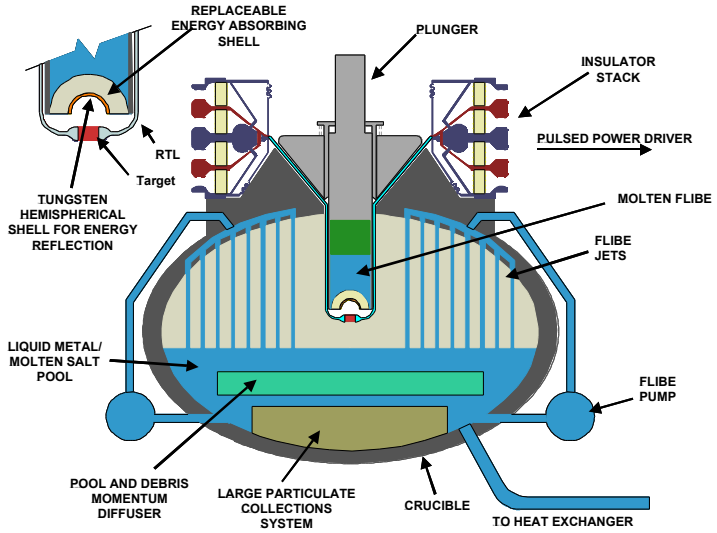
- **Renewable liquid provides neutron shielding for structural components**
- **Fabrics or thin tubes guide liquid flow and control liquid geometry, are designed for easy replacement**
- **Thin liquid films or sheets shield x-ray ablation of flow guiding structures**

HYLIFE/Z are examples of Thick Liquids

- **Thick liquid jets shield chamber structures—fluid mechanics questions replace materials questions**
- **No blanket replacement required, increases availability**



HYLIFE (Heavy Ions)



ZFE (Z-Pinch)

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/ion/neutron emission/deposition (~100 ns)
- **Microsecond IFE Phenomena (IT-1)**
  - Surface x-ray response (~1 μs)
  - Vapor/gas venting and equilibration (~100 μs)
  - Isochoric-heating pressure relaxation in liquid/structures (~30 μs)
- **Millisecond IFE Phenomena (IT-2/4)**
  - Liquid shock propagation and pocket regeneration (~50 ms)
  - Structure thermal response and equilibration (~100 ms)
  - Debris condensation/gas cooling (~100 ms)
  - Target injection (~50 ms)
- **Quasi-steady IFE Phenomena (IT-3/4)**
  - Structure response to startup heating (~1 to 10^4 s)
  - Chemistry-tritium control/target fabrication/safety (10^3-10^9 s)
  - Corrosion/erosion/radiation damage of chamber structures (10^8 sec)
  - Target fabrication (10^5 sec)

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

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, venting, impulse	Debris condensation	—
Hohlraum (if used)	X-ray and debris emission			—
Driver energy transport paths	Beam transport and focusing			Debris accumulation
Pocket Void/Vent Paths	—			—
External Condensing Region	—			—
Target-facing Surface Layers	X-ray deposition	Ablation/impulse	Liq. hydraulics/ solid thermal mechanics	Activation, neutron damage (solids), safety
Blanket (liquid/solid)	Neutron and gamma deposition	Neutron heating relaxation		
Final focus elements		—	—	Damage rate
Chamber structures		—	—	Safety, tritium, activation, corrosion
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 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 ab 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				—
Extern				—
Targe		pulse	Liq. hydraulics/ solid thermal mechanics	Activation, neutron damage (solids), safety
Blank		ating 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 <u>repetition rate</u>**
  - > **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				—
Target-facing Surface			ulics/	Activation, neutron damage (solids), safety
Blanket (liquid/solid)			rmal ics	
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**

IFE Technology research is now underway in all areas of chamber/target technology

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, venting, impulse	Debris condensation	—
Hohlraum (if used)	X-ray and debris emission			—
Driver energy transport paths	Beam transport and focusing			Debris accumulation
Pocket Void/Vent Paths	—			—
External Condensing Region	—			—
Target-facing Surface Layers	X-ray deposition	Ablation/impulse	Liq. hydraulics/ solid thermal mechanics	Activation, neutron damage (solids), safety
Blanket (liquid/solid)	Neutron and	Neutron heating laxation		
Final focus elem		—	—	Damage rate
Chamber structu		—	—	Safety, tritium, activation, corrosion
Coolant recirc./h loop		—	—	
Accelerator/laser systems	Driver physics	—	Driver rep. rate and reliability	
Target injection	—	—	Accel./heating	—
Target fabrication	—	—	—	Safety/reliability
Balance of plant	—	—	—	Safety/reliability

This talk provides selected examples of research in the highlighted areas

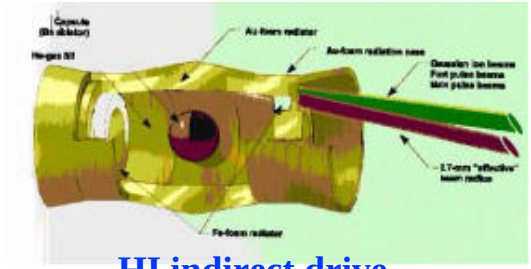
IFE has a sequence from fast to slow phenomena

- **Fast phenomena provide initial conditions for slower phenomena**
- **The current IFE chamber science program covers all areas of chamber phenomena**
  - **By time scale: nanosecond/microsecond/millisecond/quasi-steady**
  - **By region: driver/final focus/pocket/condensers/balance of plant**

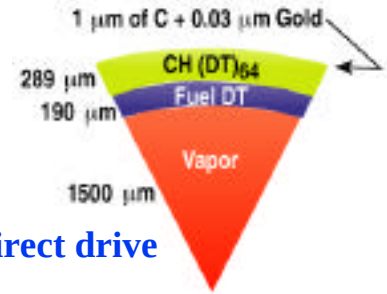
First-principles chamber modeling appears possible

Nanosecond phenomena govern driver energy transport, target gain, and chamber initial conditions

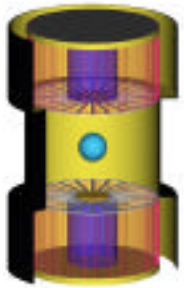
- **Driver energy transport phenomena**
  - Is the most important interface issue between drivers and chambers
  - IREs (and IBX) will provide primary experimental test capability
- **Target x-ray/debris/neutron emission**
  - The most important questions are:
    - » partitioning of target energy between x-rays, debris ions, and neutrons
    - » effective x-ray black body temperature(s)/ion energy spectra
  - NNSA target design codes can model
- **Neutron shielding/energy deposition**
  - 3-D codes (e.g. TART) can model



HI indirect drive



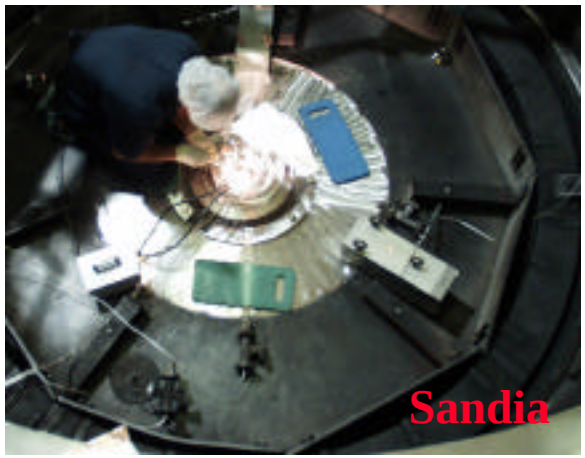
Laser direct drive



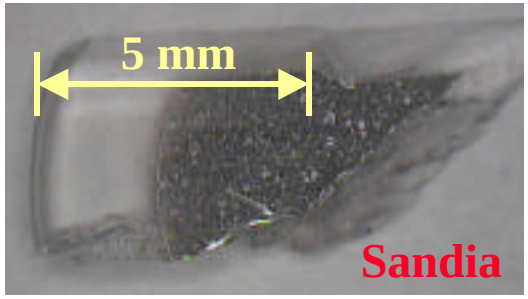
Z-pinch indirect drive

Current facilities are reaching prototypical energy fluences for microsecond first-wall response phenomena

- **Experiments**
  - Z is currently the highest energy cold x-ray source available
  - RHEPP provides pulsed ions
  - Bench top lasers provide short-pulse laser energy
  - Reproduce 3-D gas dynamics/radiation transport/reradiation/structure impulse history
- **Numerical modeling**
  - Equations of state must include melt, vaporization, dissociation, ionization
  - Radiation transport is important first 10's of microseconds
  - Existing codes (2-D w/ TSUNAMI, 1-D w/ BUCKY)



Inserting wire array in Z

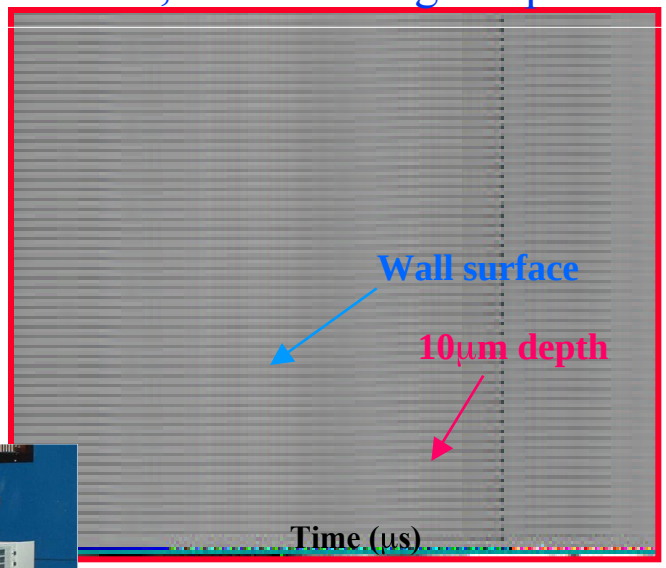


LiF at 41 J/cm^2 shows 3-4 μm ablation step (2.8 μm predicted)

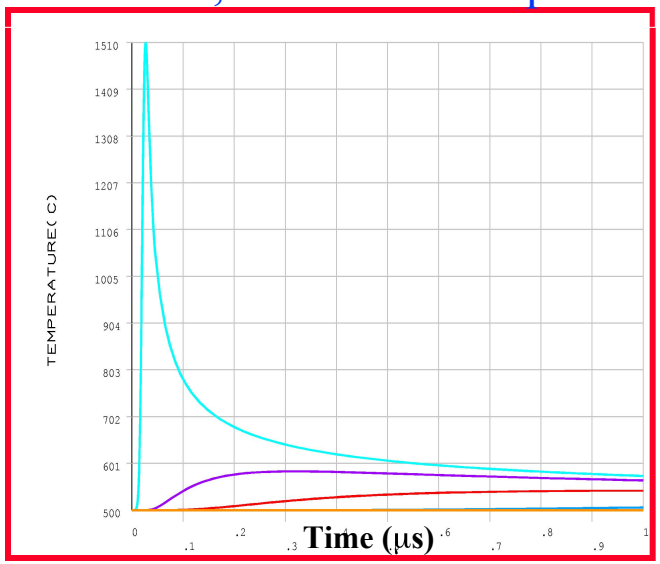
Microsecond/Quasi-steady (many pulse) Phenomena (IT1)

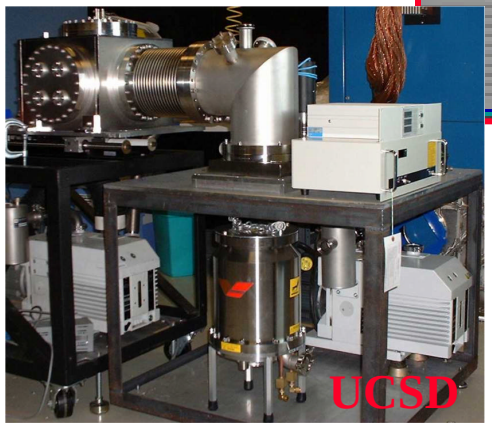
Lasers can replicate pulsed dry-wall surface temperature transients, permitting study of thermal stress effects

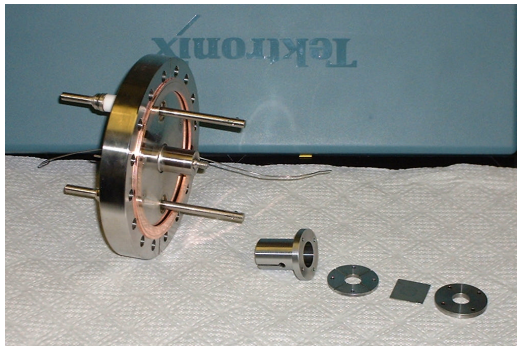
NRL Target, x-ray only
1 J/cm^2, 10 ns rectangular pulse

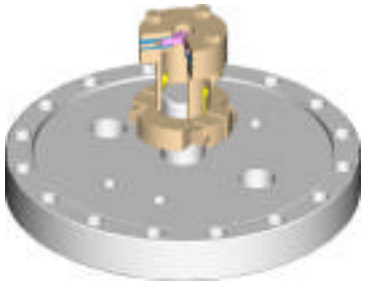


Laser
0.24 J/cm^2 ,10 ns Gaussian pulse



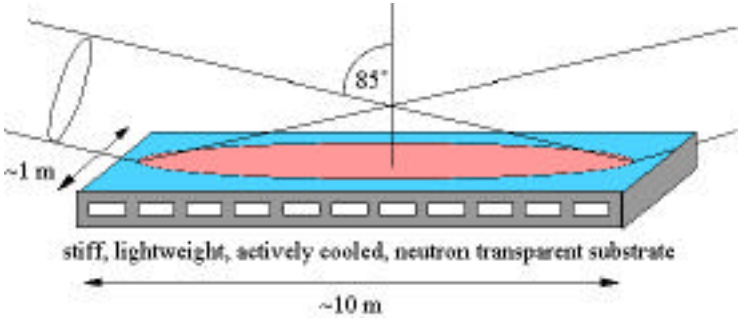




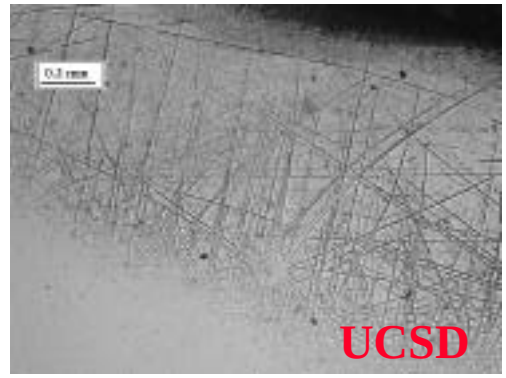


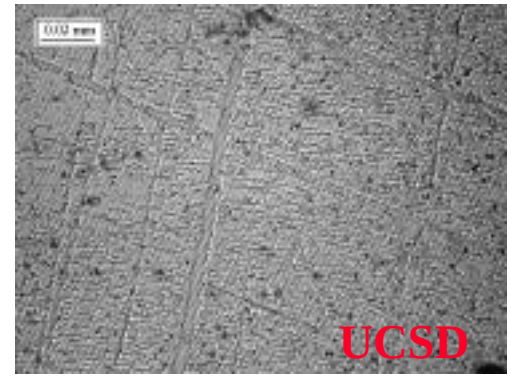
Microsecond/Quasi-steady (many pulse) Phenomena (IT1)

Pulsed laser experiments are studying damage thresholds for laser final optics

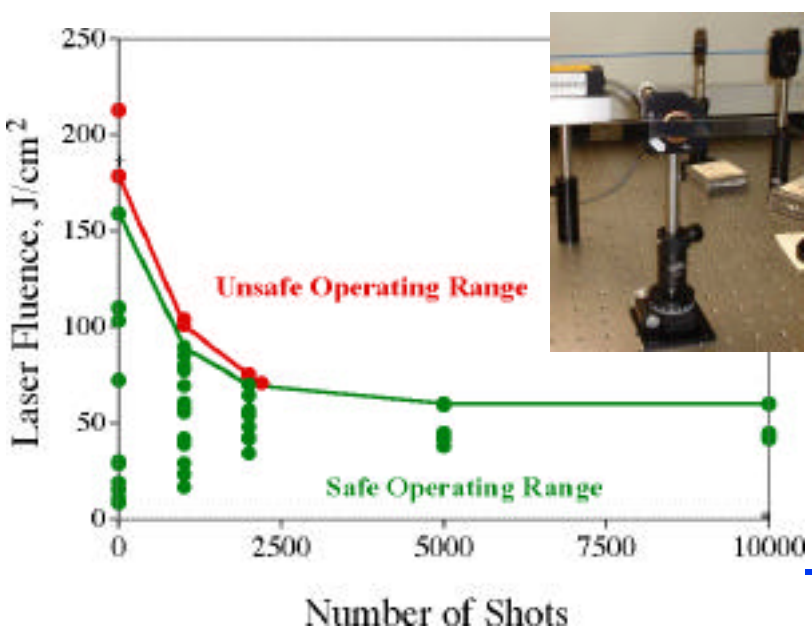


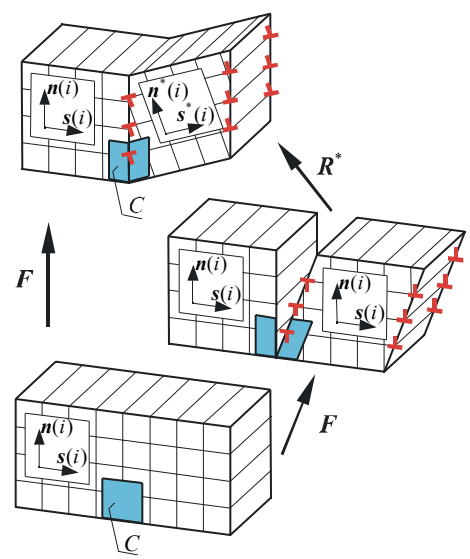
Grazing incidence metal mirrors provide one option for laser final optics



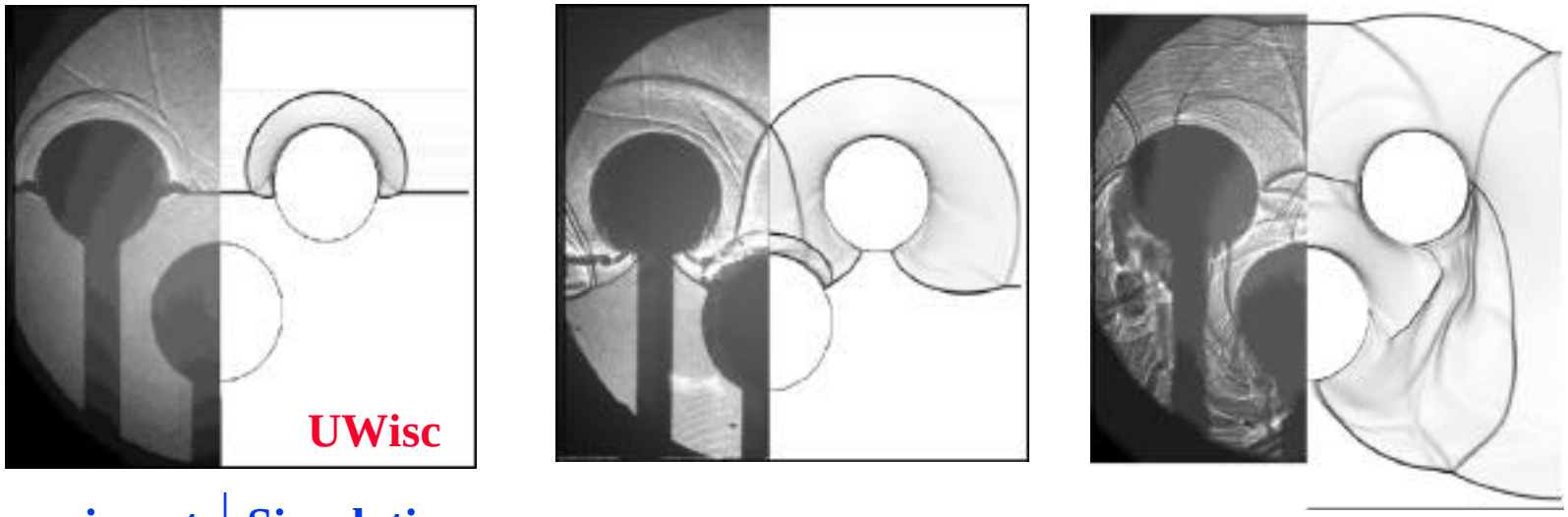


Experiments identify fundamental damage mechanisms for aluminum





Multi-dimensional venting gas dynamics are being reproduced in shock-tube experiments



Experiment | **Simulation**

Experiments and calculations for shock interaction with a cylinder array

For liquid-protected chambers, fluids are incompressible over millisecond time scales

Mass and momentum conservation

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

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:

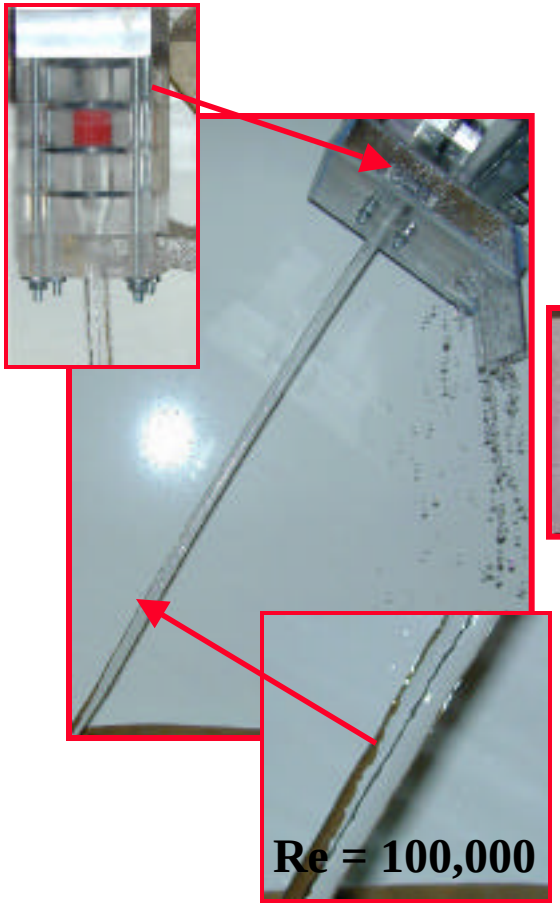
$$^*\ \mathbf{v}^* = 0 \qquad \mathrm{St}\frac{\partial \mathbf{v}^*}{\partial t^*} + \mathbf{v}^*\quad {}^*\mathbf{v}^* = -\quad {}^*p^* + \frac{1}{\mathrm{Re}}\quad {}^{*2}\mathbf{v}^* + \frac{1}{\mathrm{Fr}}\frac{\mathbf{g}}{g}$$

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

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

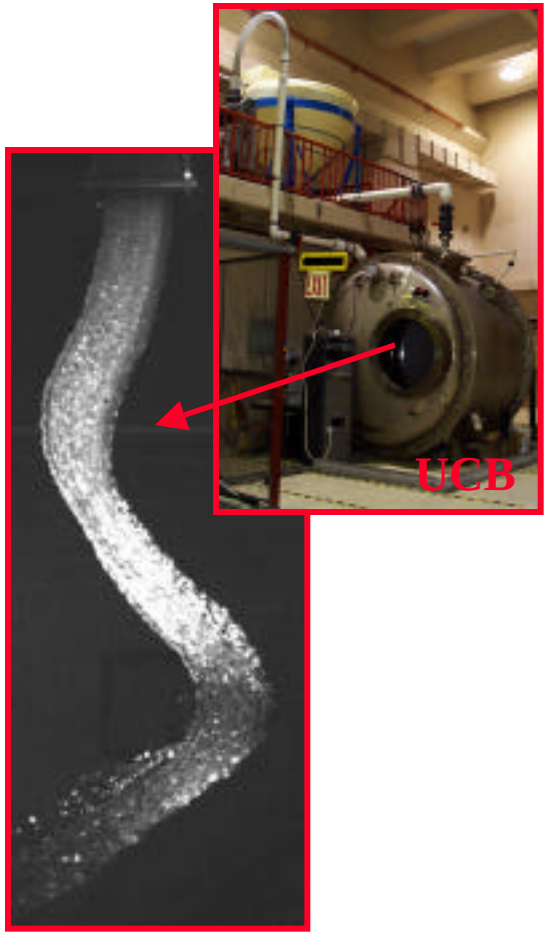
Major simplifications:
No EOS, No energy equation
No MHD

Scaled water experiments are demonstrating the capability to form many classes of liquid jets



High-Re
Cylindrical Jets

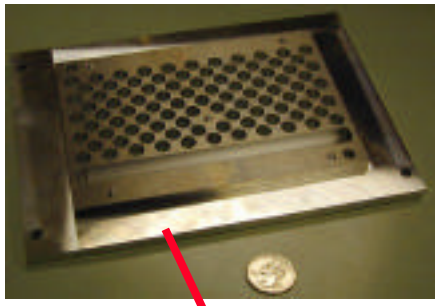
Vortex Layers for
Beam Tubes



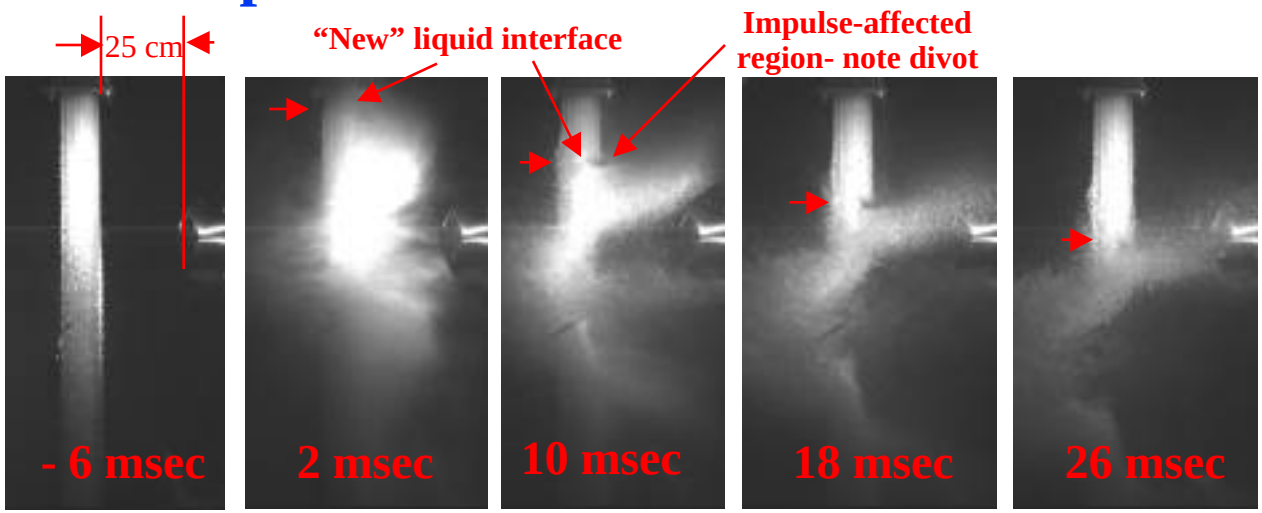
Oscillating Voided
Liquid Slabs

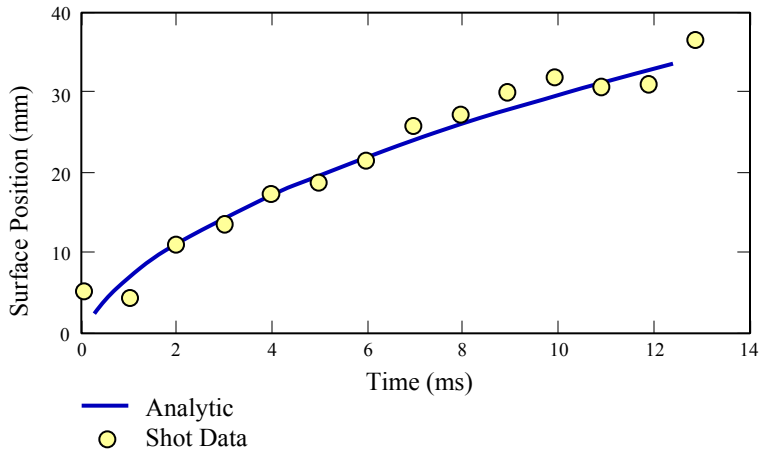
Millisecond Phenomena (IT2)

Chemical detonations are reproducing liquid disruption phenomena



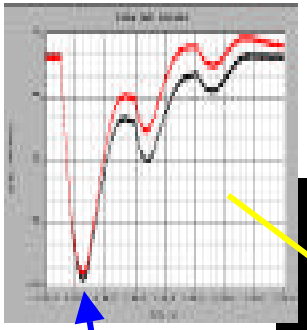
96-jet nozzle assembly in operation



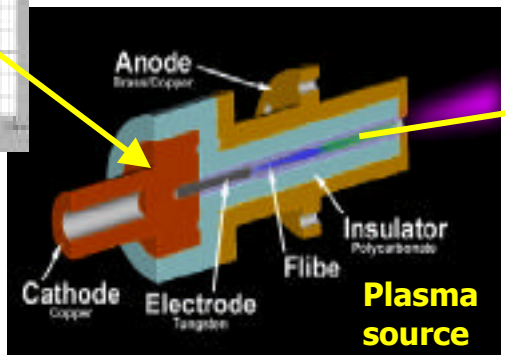


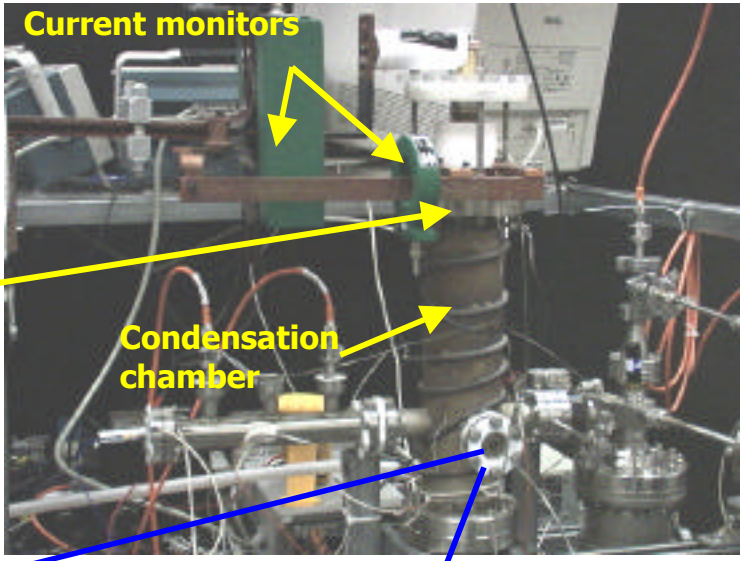
Incompressible theory accurately predicts shock propagation

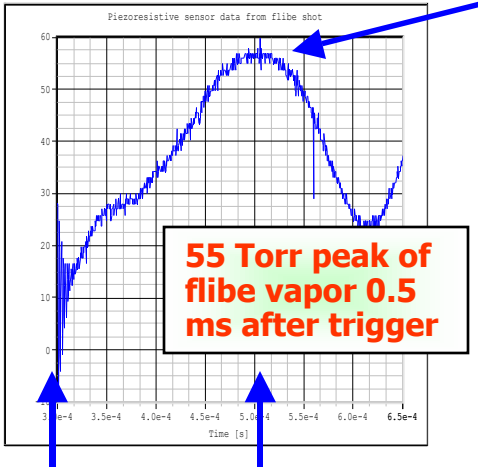
Condensation of ablation debris is being studied with pulsed power and prototypical first-wall materials

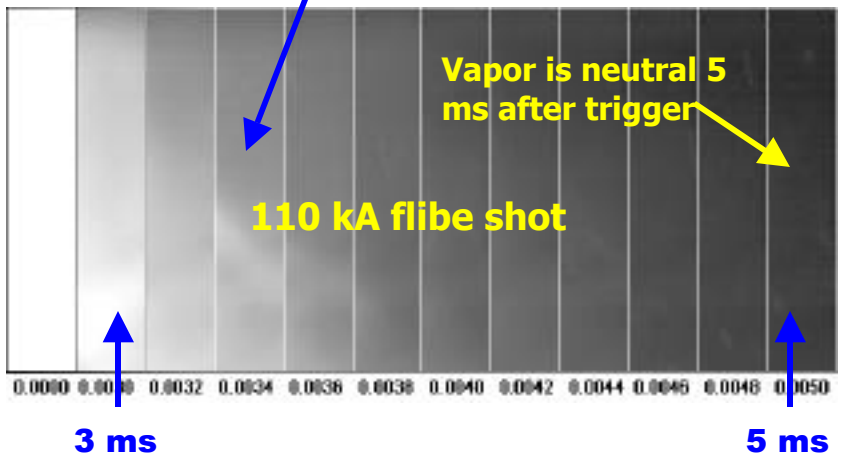


Peak current at 30 μs

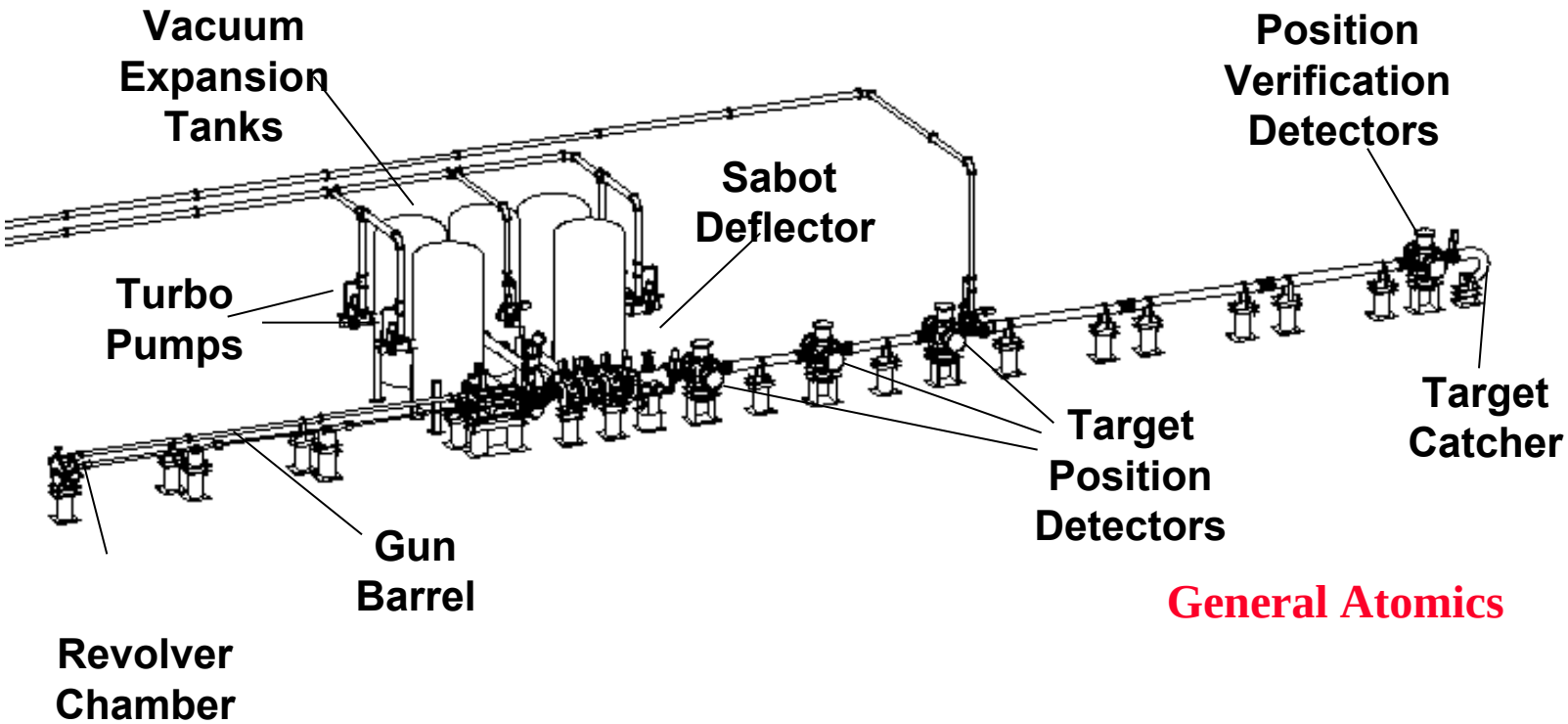








IFE target injection environments will be accurately reproduced and studied in experiments

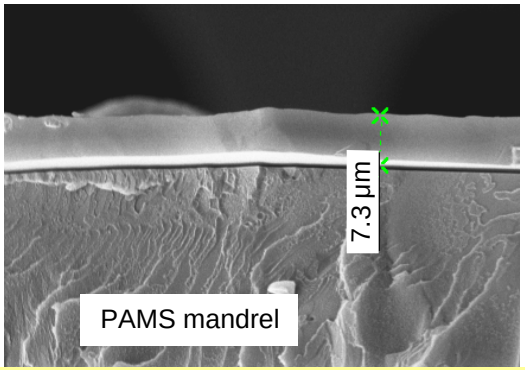


General Atomics

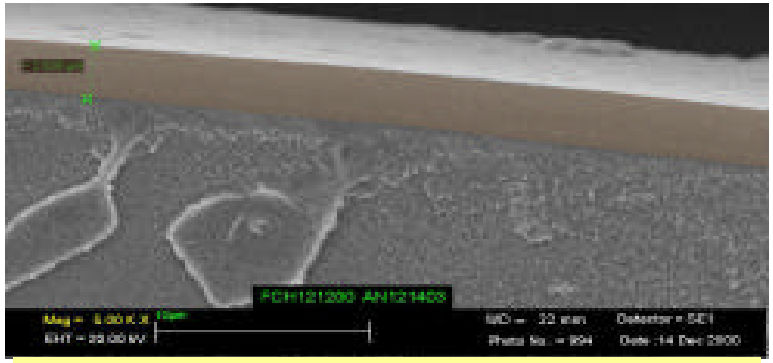
Phased procurement approach - beginning with component verification testing → single-shot w/ tracking at one detector → then full single-axis tracking with timing

Fluidized beds are being adapted from current few-capsule production to mass production

Fluidized beds



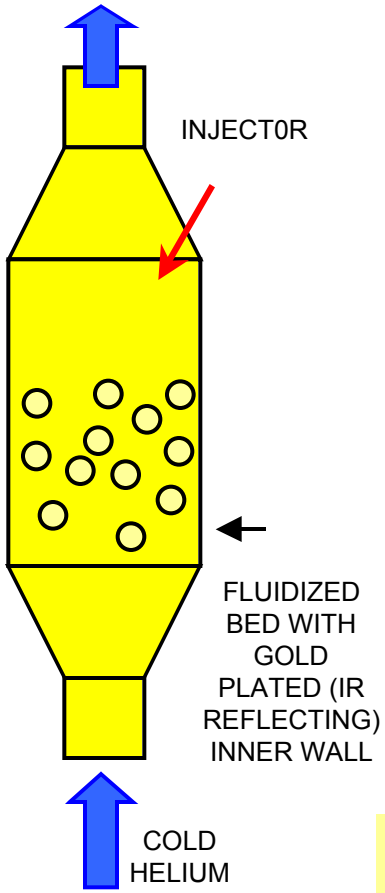
~ 7 micron thick PAA coating



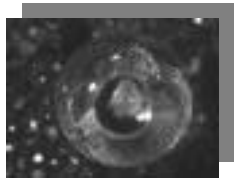
Coating

Mandrel

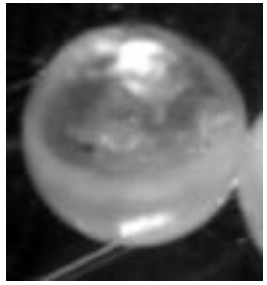
~ 3 micron thick GDP coating on PAMS



Cryo Fluidized Bed



Filled thru hole and sealed



Before

After

Layering demo with neopentyl alcohol in fluidized bed

LANL/GA

System integration models are identifying optimal designs for the IRE's, ETF's, and Demo plants

- **Example: Engineering Test Facilities**
  - **Single-shot chamber**
    - » **Explore target/driver physics to yields approaching prototypical (all nanosecond phenomena)**
  - **Repetition-capable chamber**
    - » **Complete integration of all phenomena**
      - **(Nanosecond, microsecond, millisecond, quasi-steady)**
    - » **Reduced chamber geometric scale/target yield/power**
      - **Scaled chamber ~40% of prototypical dimensions (6% volume)**
        - **e.g. preserve Froude number (gravity vs. inertia)**
      - **Target yield/rep. rate ~10%/130% of prototypical**
      - **Balance of plant uses optimized scaling**
        - **Tritium recovery/chemistry control - full height, reduced area**
        - **Power conversion - geometrically scaled**
      - **Structure activation/neutron damage - use accelerated time scaling**
      - **Electrical power output ~ 150 MWe**

Conclusions

- **IFE chamber phenomena are readily characterized by time scale and spatial region**
- **Fast phenomena tend to look like initial conditions to slower phenomena**
  - **In separate effects experiments, initial conditions can often be replicated with small distortion (e.g. x-ray response using Z)**
  - **The potential exists for a fundamental predictive capability for chamber response**
- **Target fabrication and injection are readily studied at full scale**

Conclusions (con't)

- **Snowmass 2002 will cover chamber/target science and design issues**
  - **Tuesday (7/9) 2 hours: Chamber/target science**
    - » **Current and future experiments/codes**
  - **Thursday (7/11) 7 hours: Technology/Driver crosscut issues**
    - » **Viability and integration issues-current status, IRE/ETF design requirements**