Overview of IFE Chamber Wall Issues

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Outline

- **IFE chamber operating conditions**
  - **Comparison with MFE**
- **Dry Walls (major focus of presentation)**
  - **Design operating windows**
  - **Critical issues and required R&D**
  - **Synergy with MFE**
- **Thick Liquid Walls**
  - **Survey of US work**
- **Concluding Remarks**

Acknowledgements

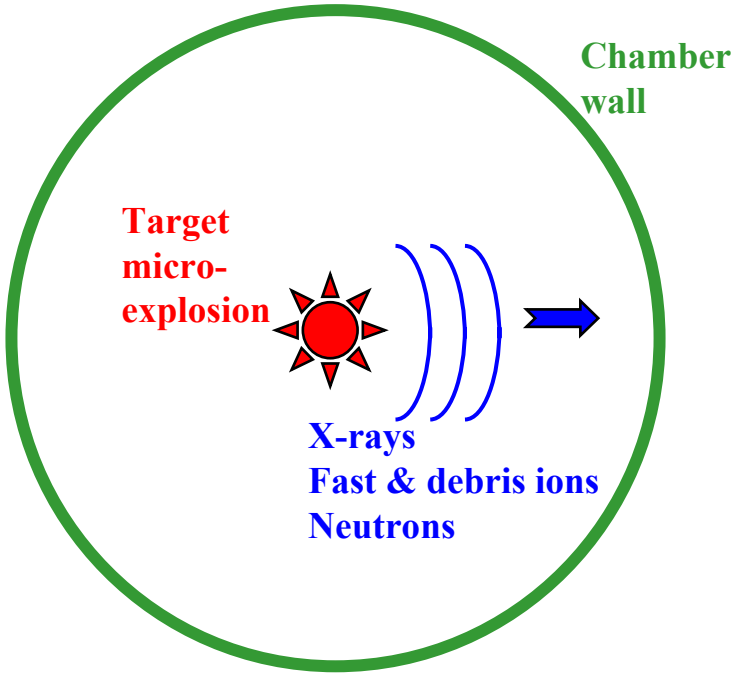
- **Bulk of slides are courtesy of Rene Raffray (UCSD)**

HAPL Program

- High Average Power Laser program
- Led by John Sethian (NRL)
- Archives at http://www-ferp.ucsd.edu/HAPL/
- KrF or DPSSL drivers
- Dry chamber wall – primary candidate is tungsten coating on a steel wall
- Strong Experimental Programs

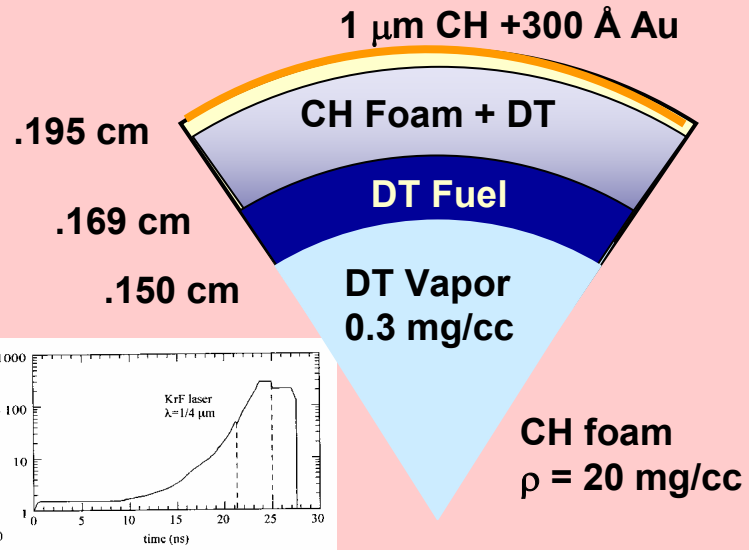
IFE Operating Conditions

- **Cyclic with repetition rate of ~1-10 Hz**
  - Target injection (direct drive or indirect drive)
  - Driver firing (laser or heavy ion beam)
  - Microexplosion
  - Large fluxes of photons, neutrons, fast ions, debris ions toward the wall
    - **possible attenuation by chamber gas**



Direct Drive

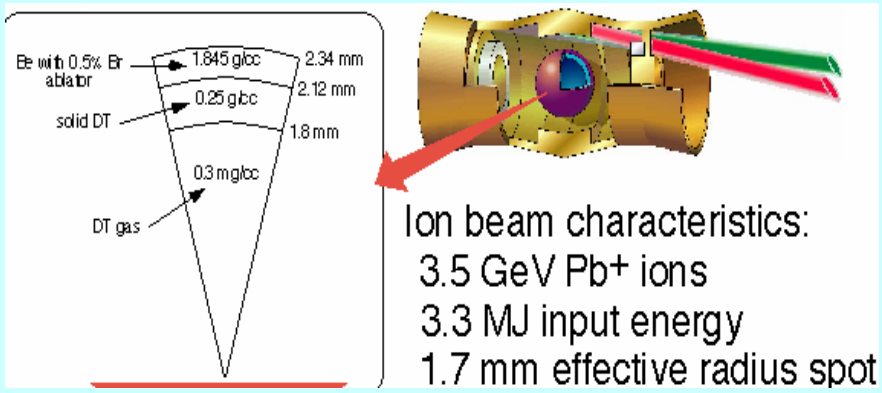
Example of Direct-Drive Target (NRL) (preferred option for coupling with laser driver)



Indirect Drive

Example of Indirect-Drive Target (LLNL/LBLL)

(preferred option for coupling with heavy ion beam driver)

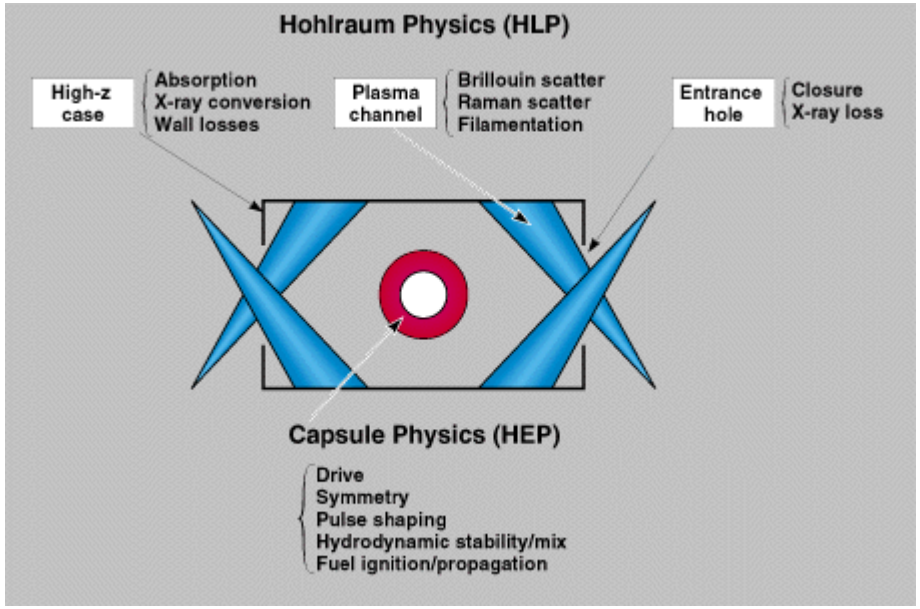


Ion beam characteristics:

3.5 GeV Pb^+ ions

3.3 MJ input energy

1.7 mm effective radius spot

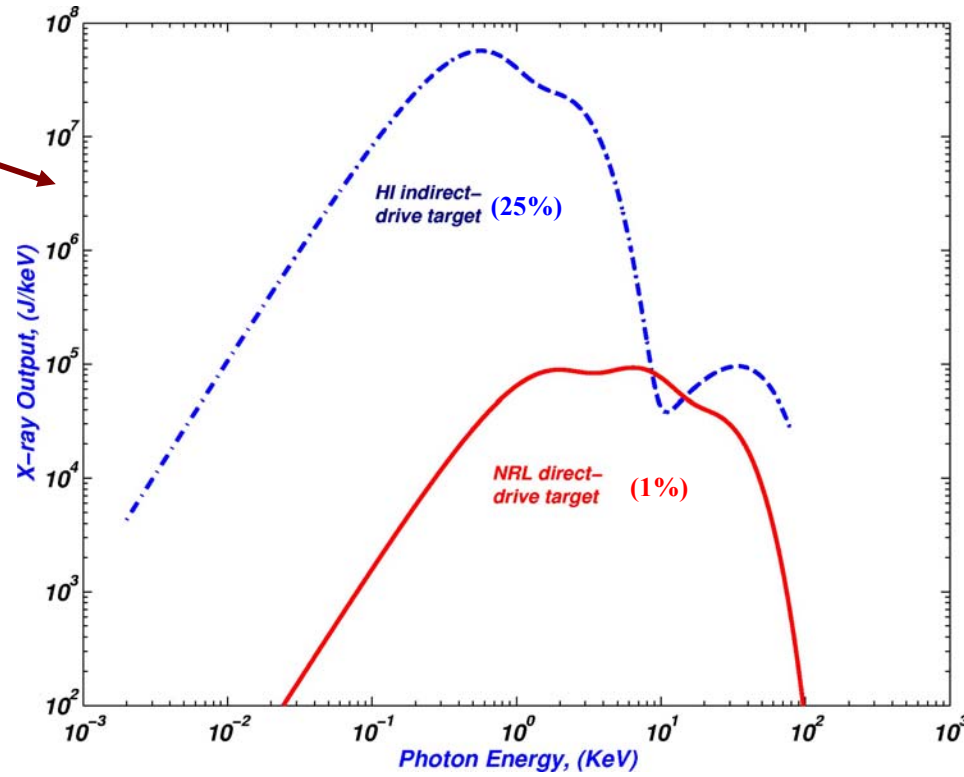


Energy Partitioning and Photon Spectra for Example Direct Drive and Indirect Drive Targets

Energy Partitions for Example Direct Drive and Indirect Drive Targets

	NRL Direct Drive Target (MJ)	HI Indirect Drive Target (MJ)
X-rays	2.14 (1%)	115 (25%)
Neutrons	109 (71%)	316 (69%)
Gammas	0.005 (0.003%)	0.36 (0.1%)
Burn Product Fast Ions	18.1 (12%)	8.43 (2%)
Debris Ions Kinetic Energy	24.9 (16%)	18.1 (4%)
Residual Thermal Energy	0.013	0.57
Total	154	458

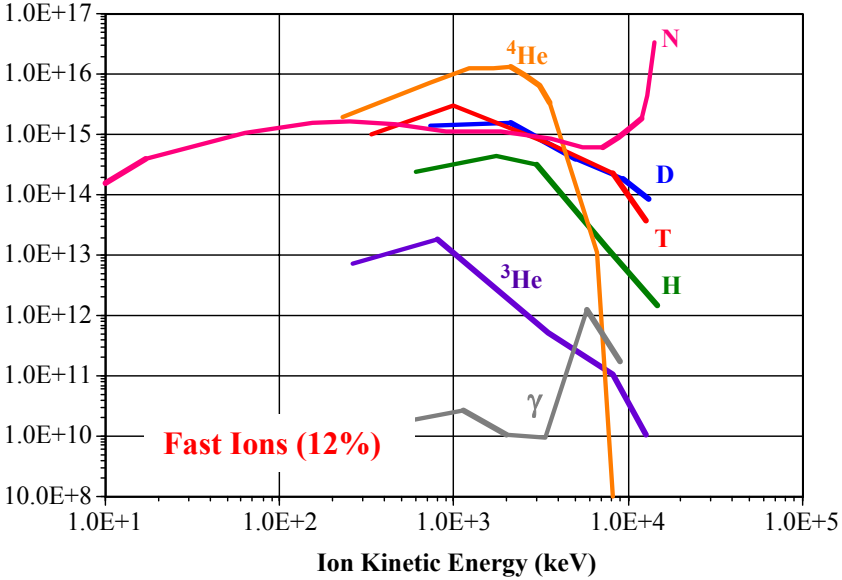
Photon Spectra for Example Direct Drive and Indirect Drive Targets



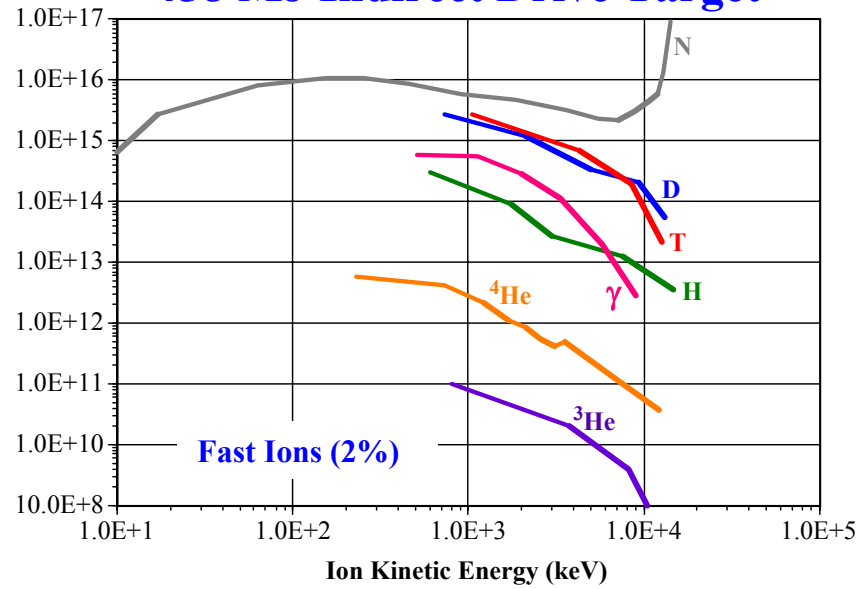
- Much higher X-ray energy for indirect drive target case (but with softer spectrum)
- More details on target spectra available on ARIES Web site: http://aries.ucsd.edu/ARIES/

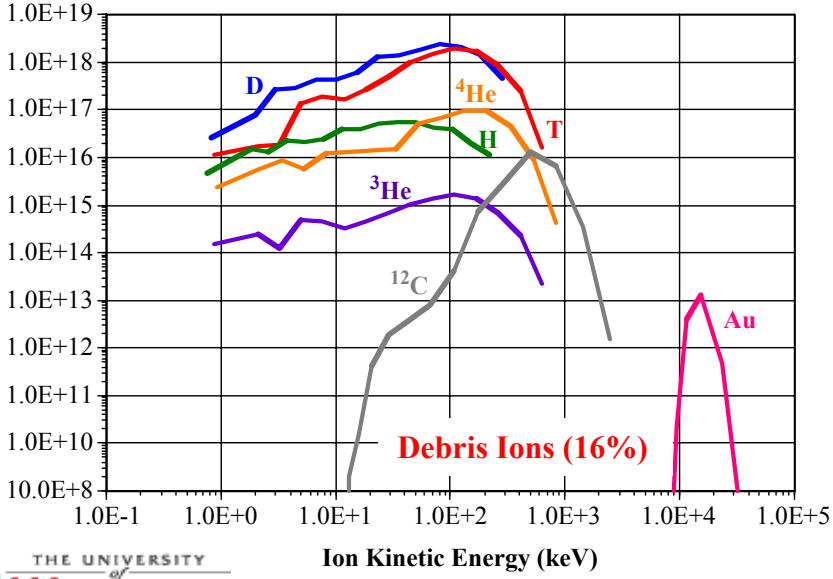
Example IFE Ion Spectra

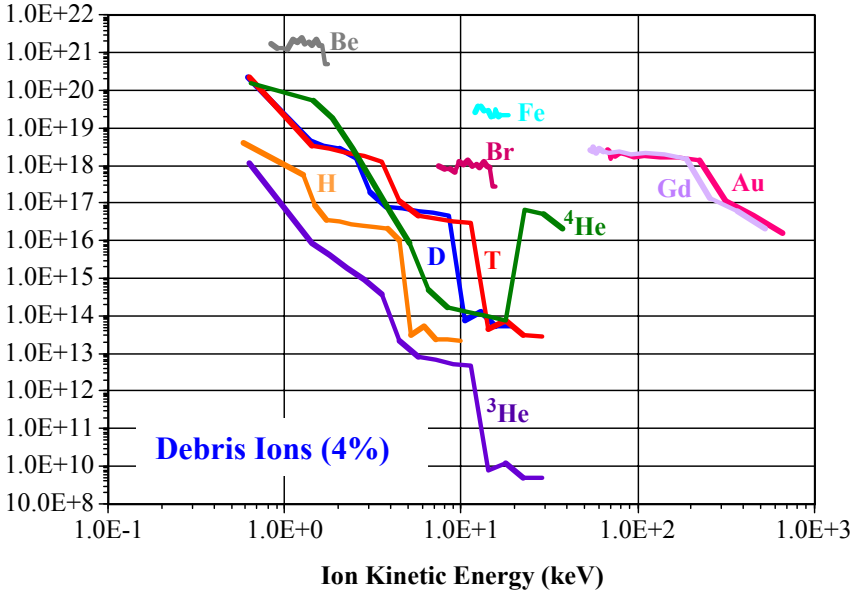
154 MJ NRL Direct Drive Target



458 MJ Indirect Drive Target







There are Similarities Between IFE and MFE Armor Operating Conditions e.g. ITER Divertor and 154 MJ NRL Direct Drive Target Spectra Case

- Although base operating conditions of IFE (cyclic) and MFE (steady state goal) are fundamentally different, there is an interesting commonality between IFE operating conditions and MFE off-normal operating conditions, in particular ELM's
  - Frequency, energy density and particle fluxes are within about one order of magnitude
- Assess performance of chamber dry wall option under these direct-drive target conditions

	ITER Type-I ELM's	ITER VDE's	ITER Disruption thermal quench	Typical IFE Operation
Energy	10-12 MJ	~ 50 MJ/m^2	100-350 MJ	150-400 MJ
Affected area	5-10 m^2†	A few m^2†	~10 m^2†	Chamber wall (R~5-10 m)
Location	Surface (near divertor strike points)	Surface/bulk	Surface (near divertor strike points)	bulk (~µm's)
Time	≥200 µs	~ 0.3 s	~ 1 ms	~ 1-3 µs
Max. Temperature	Melting/ sublimation	Melting/ sublimation	Melting/ sublimation	~ 2000-3000°C (for dry wall)
Frequency	Few Hz	~ 1 per 100 cycles	~ 1 per 10 cycles	~ 10 Hz
Base Temperature	≥ 500°C	~ 200°C	200-1000°C	~ >700°C
Particle fluxes	~10^{24} m^{-2}s^{-1}(peak under normal			~10^{23} m^{-2}s^{-1}

† large uncertainties exist

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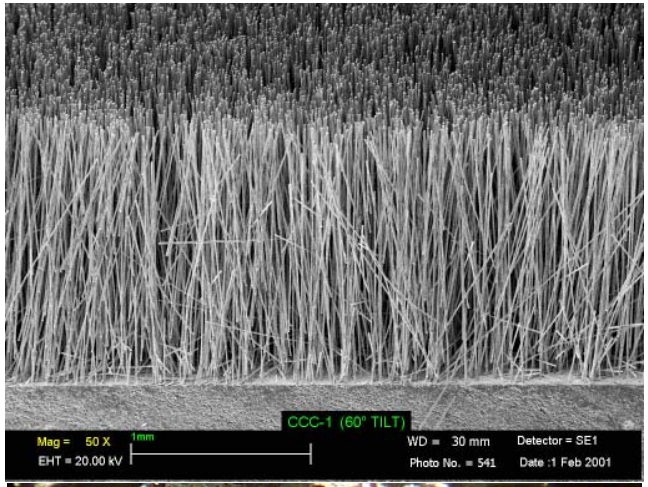
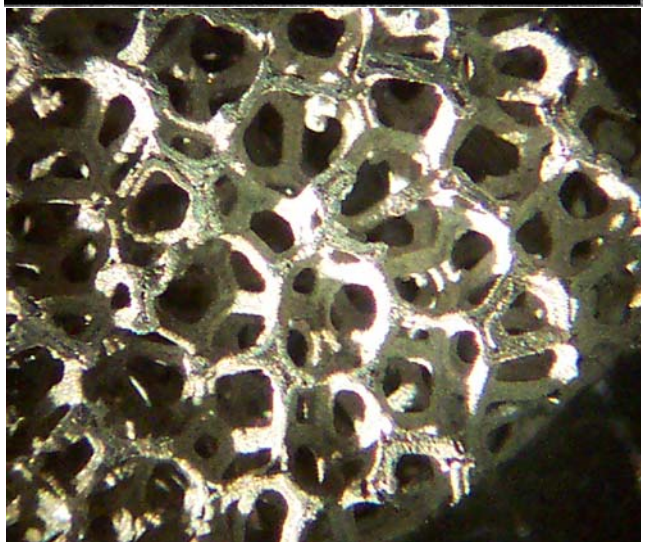
Candidate Dry Chamber Armor Materials Must Have High Temperature Capability and Good Thermal Properties for Accommodating Energy Deposition and Providing Required Lifetime

- **Carbon and refractory metals (e.g. tungsten) considered**
  - **Reasonably high thermal conductivity at high temperature (~100-200 W/m-K)**
  - **Sublimation temperature of carbon ~ 3370°C**
  - **Melting point of tungsten ~3410°C**
- **In addition, possibility of an engineered surface to provide better accommodation of high energy deposition is considered**
  - **e.g. ESLI carbon fiber carpet showed good performance under ion beam testing at SNL (~5 J/cm^2 with no visible damage)**
- **Example analysis results for C and W armor for NRL 154 MJ direct drive target**

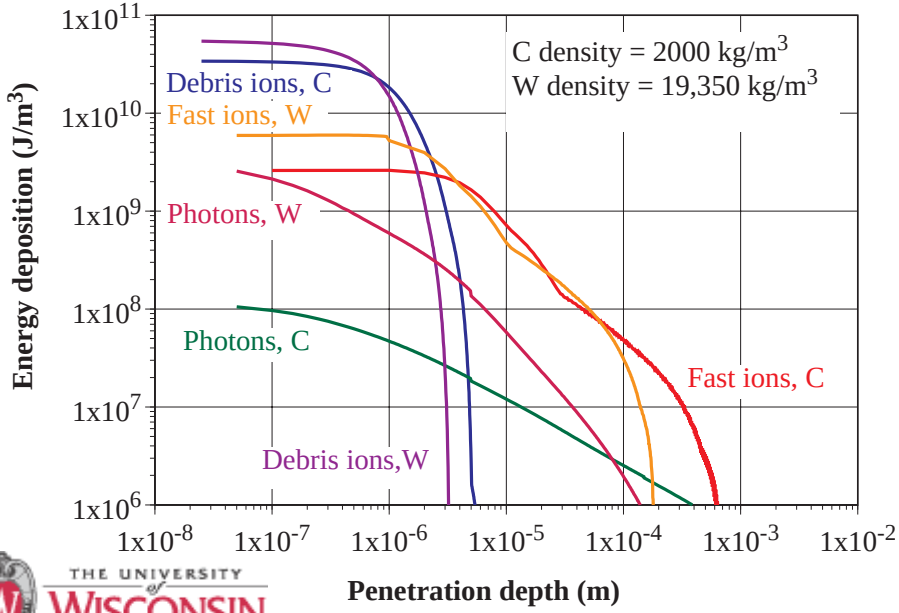




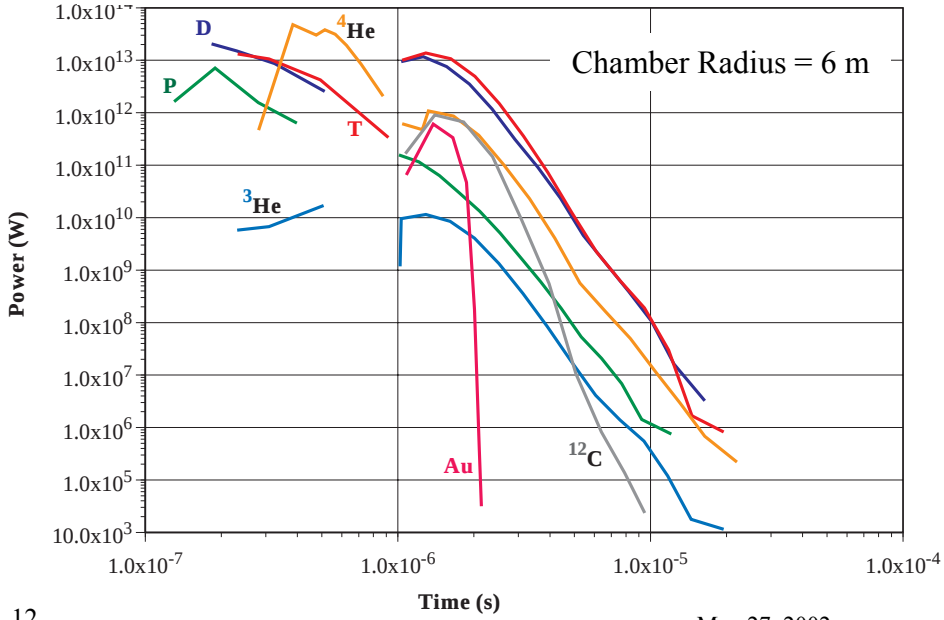
Characteristics of the Target Spectra Strongly Impact Chamber Wall Thermo-Mechanical Response

- **Penetration range in armor dependent on ion energy level**
  - **Debris ions (~20-400 kev) deposit most of their energies within μm's**
  - **Fast ions (~1-14 Mev) within 10's μm**
- **Important to consider time of flight effects (spreading energy deposition over time)**
  - **Photons in sub ns**
  - **Fast ions between ~0.2-0.8 μs**
  - **Debris ions between ~ 1-3 μs**
  - **Much lower maximum temperature than for instantaneous energy deposition case**

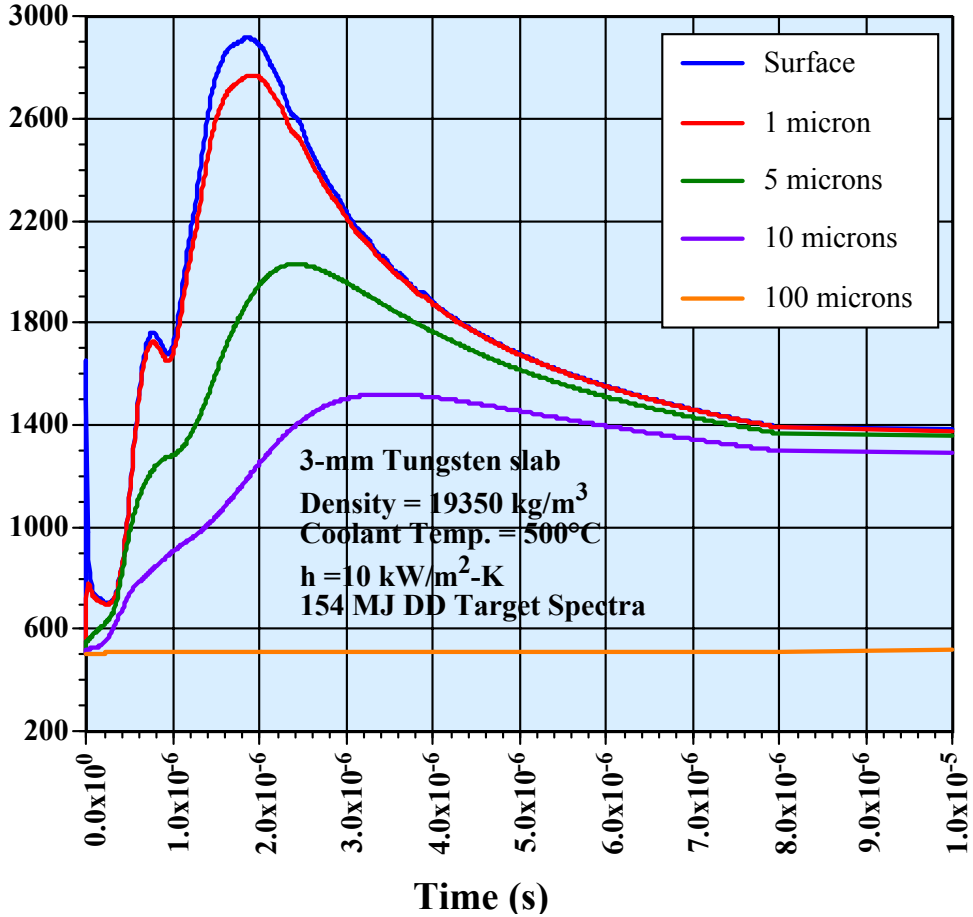
Energy Deposition as a Function of Penetration Depth for 154 MJ NRL DD Target

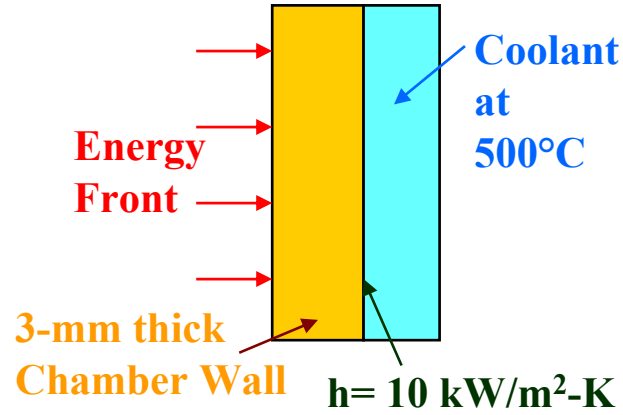


Ion Power Deposition as a Function of Time for 154 MJ NRL DD Target



Temperature History of C and W Armor Subject to 154MJ Direct Drive Target Spectra with No Protective Gas





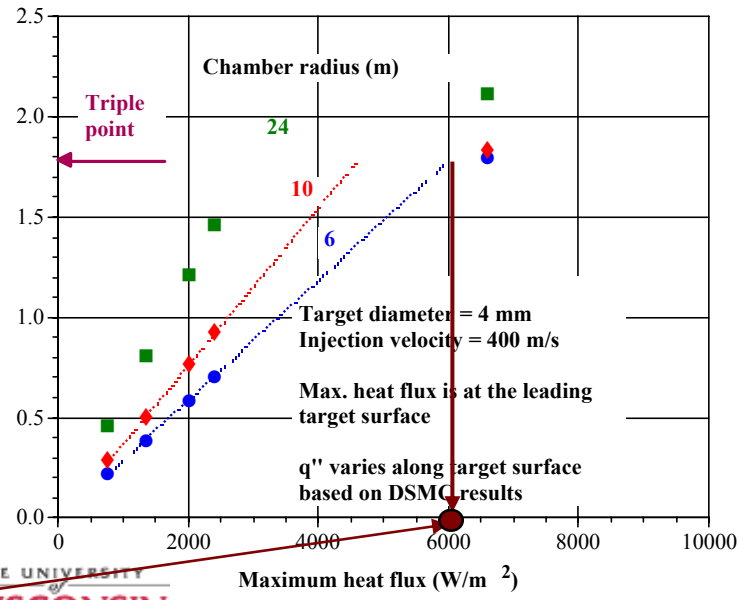
- For a case without protective gas:
  - Tungsten T_{max} < 3000°C (MP=3410°C)
  - Some margin for adjustment of parameters such as target yield, R_{chambe}, $T_{coolant}$, P_{gas}
  - Similar results for C (T_{max} < 2000°C)
- All the action takes place within <100μm
  - Separate functions: high energy accommodation in thin armor, structural function in chamber wall behind
  - Focus IFE effort on armor; can use MFE blanket

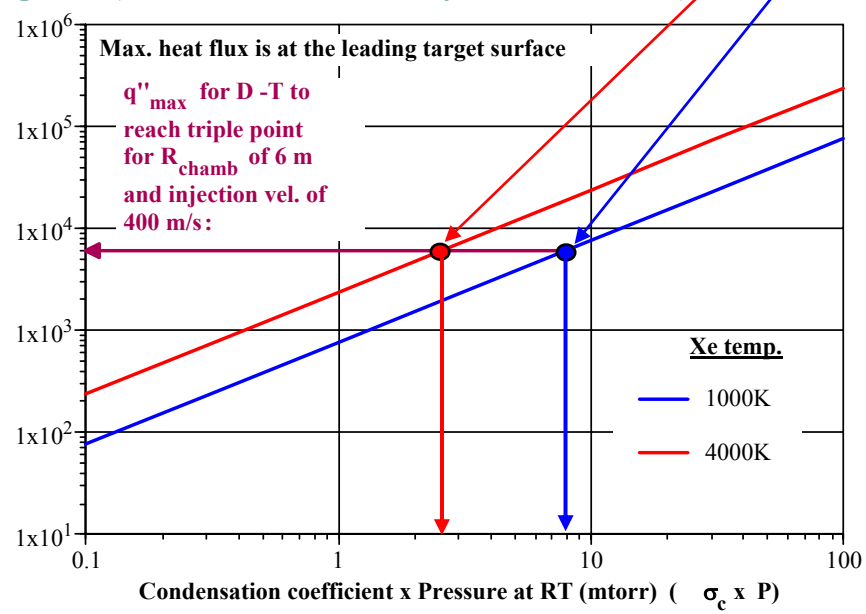
Target Injection Requirements Impose Constraints on Pre-Shot Chamber Gas Conditions

- Total q''_{max} on injected target is limited to avoid D-T reaching triple point and possibly causing local micro-explosion instability

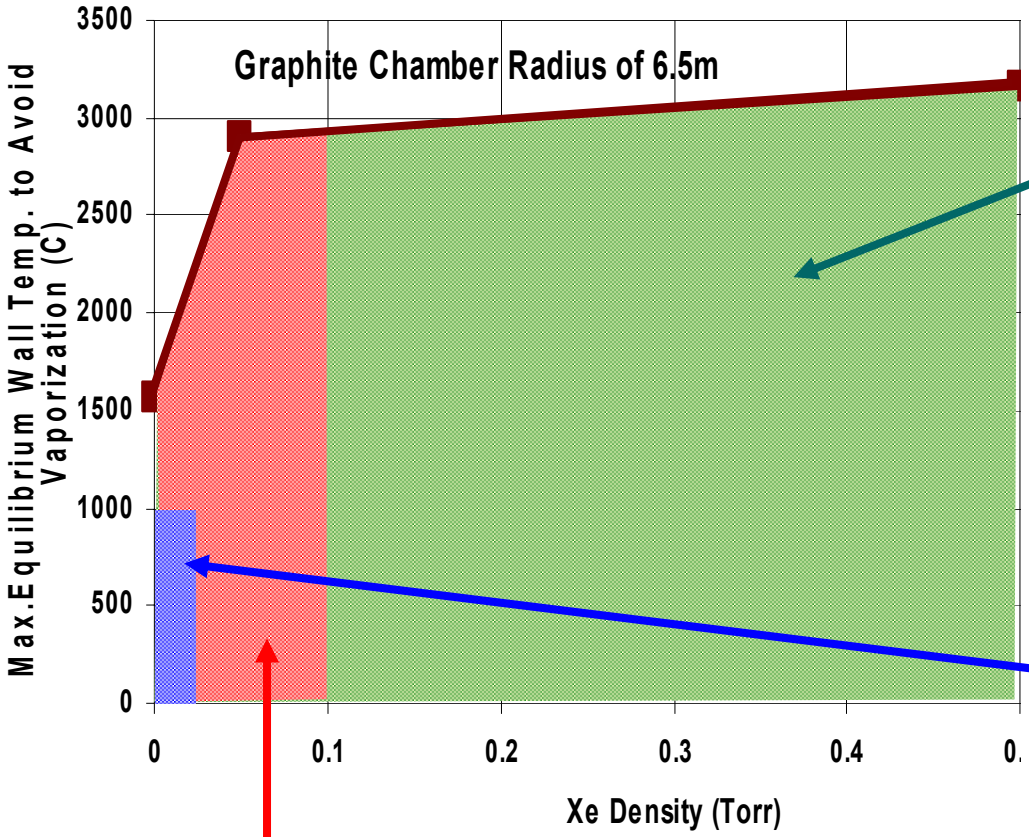
- For a direct drive target injected at 400 m/s in a 6 m chamber, q''_{max} <~6000 W/m^2
  - Max. q''_{rad} from the wall = 6000 W/m^2 for T_{wall} = 545 K
  - Example combinations of T_{Xe} and Px_e resulting in a max. $q''_{condens.}$ = 6000 W/m^2
    - T_{gas}=1000 K and P_{Xe} = 8 mtorr
    - T_{Xe} = 4000 K and P_{Xe} = 2.5 mtorr
  - Narrow design window for direct drive target
  - Need more thermally robust target

- No major constraint for indirect drive targets (well insulated by hohlraum)





Example Design Window for Direct-Drive Dry-Wall Chambers



Thermal design window

- ✓ Detailed target emissions
- ✓ Transport in the chamber including time-of-flight spreading
- ✓ Transient thermal analysis of chamber wall
- ✓ No gas is necessary

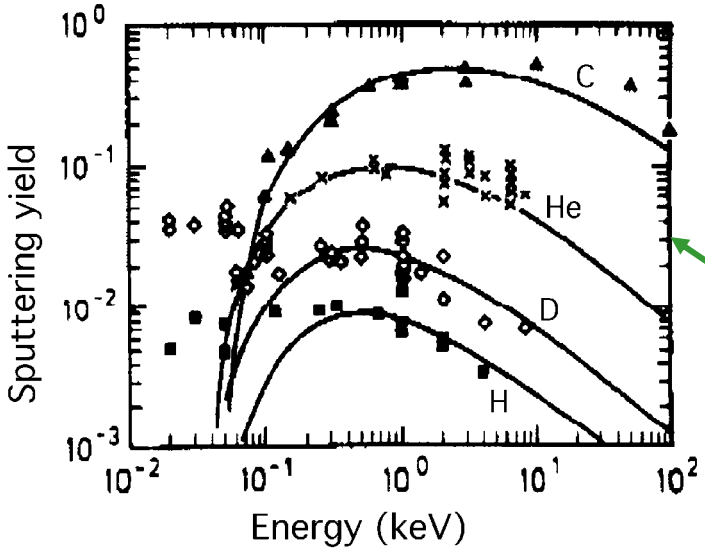
Target injection design window

- ✓ Heating of target by radiation, friction and condensation
- ✓ Constraints:
  - Limited rise in temperature
  - Acceptable stresses in DT ice
- ✓ Need more thermally robust target

Laser propagation design window(?)

- ✓ Experiments on NIKE

In addition to Vaporization, Other Erosion Processes are of Concern in Particular for Carbon



Chemical Sputtering

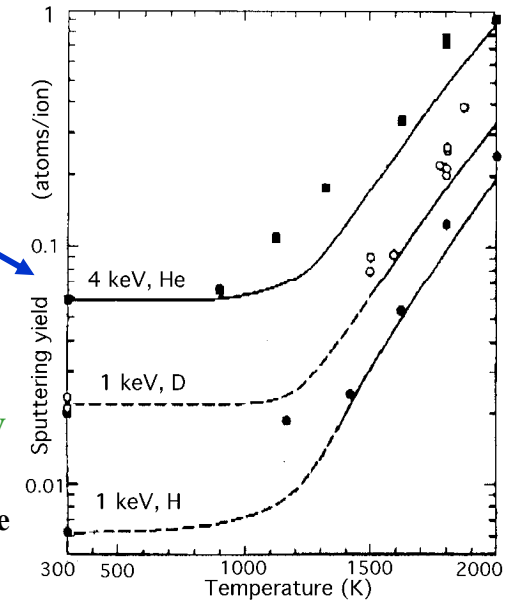
Radiation Enhanced Sublimation

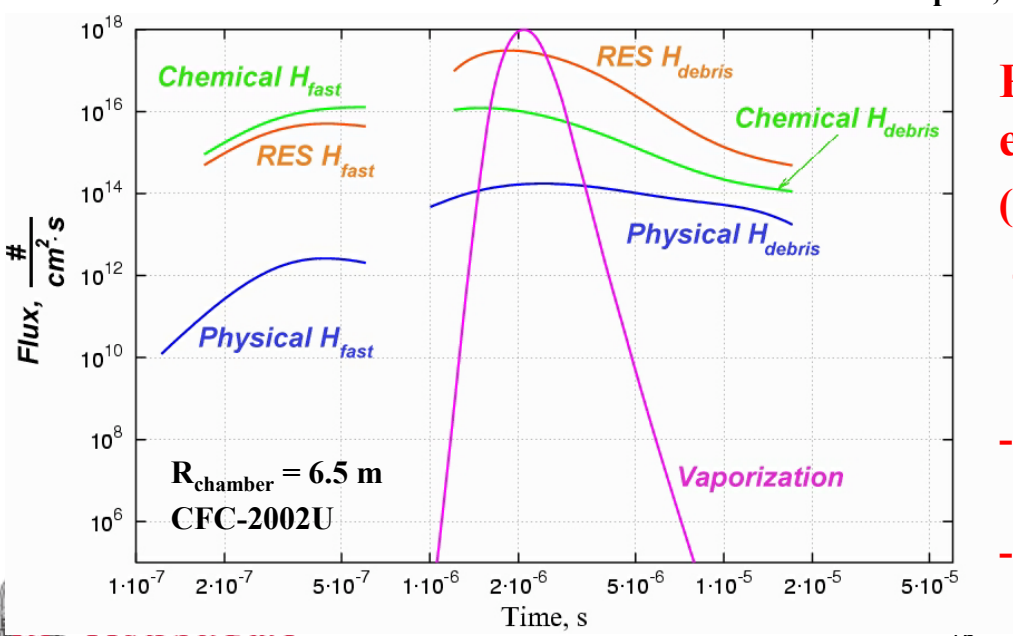
- **Increases with temperature**

Physical sputtering

- **Not temperature-dependent**
- **Peaks with ion energies of ~1kev**

(from J. Roth, et al., "Erosion of Graphite due to Particle Impact," Nuclear Fusion, 1991)





Plots illustrating relative importance of C erosion mechanisms for example IFE case (154 MJ NRL DD target,HEIGHTS code, ANL)

- **RES and chemical sputtering lower than sublimation for this case but quite significant also**
- **Physical sputtering is less important than other mechanisms**
- **Increased erosion with debris ions as compared to fast ions**

Tritium Inventory in Carbon is a Major Concern

- **Operation experience in today's tokamaks strongly indicates that both MFE and IFE devices with carbon armor will accumulate tritium by co-deposition with the eroded carbon in relatively cold areas (e.g. R. Causey's ISFNT-6 presentation)**
  - **H/C ratio of up to 1**
  - **Temperature lower than ~800 K**

- **Source of carbon in IFE**
  - **From armor C dry wall (even one molecular layer lost per shot results in cm's of C lost per year)**
  - **From target (but much smaller amount)**

- **Redeposition area in IFE**
  - **C armor at high temperature (~2000°C)**
  - **However, penetration lines for driver and target injection would be much colder**

- **If C is to be used, techniques must be developed for removal of co-deposited T**
  - **Baking, mechanical, local discharges…**

Major Issues for Dry Wall Armor Include:

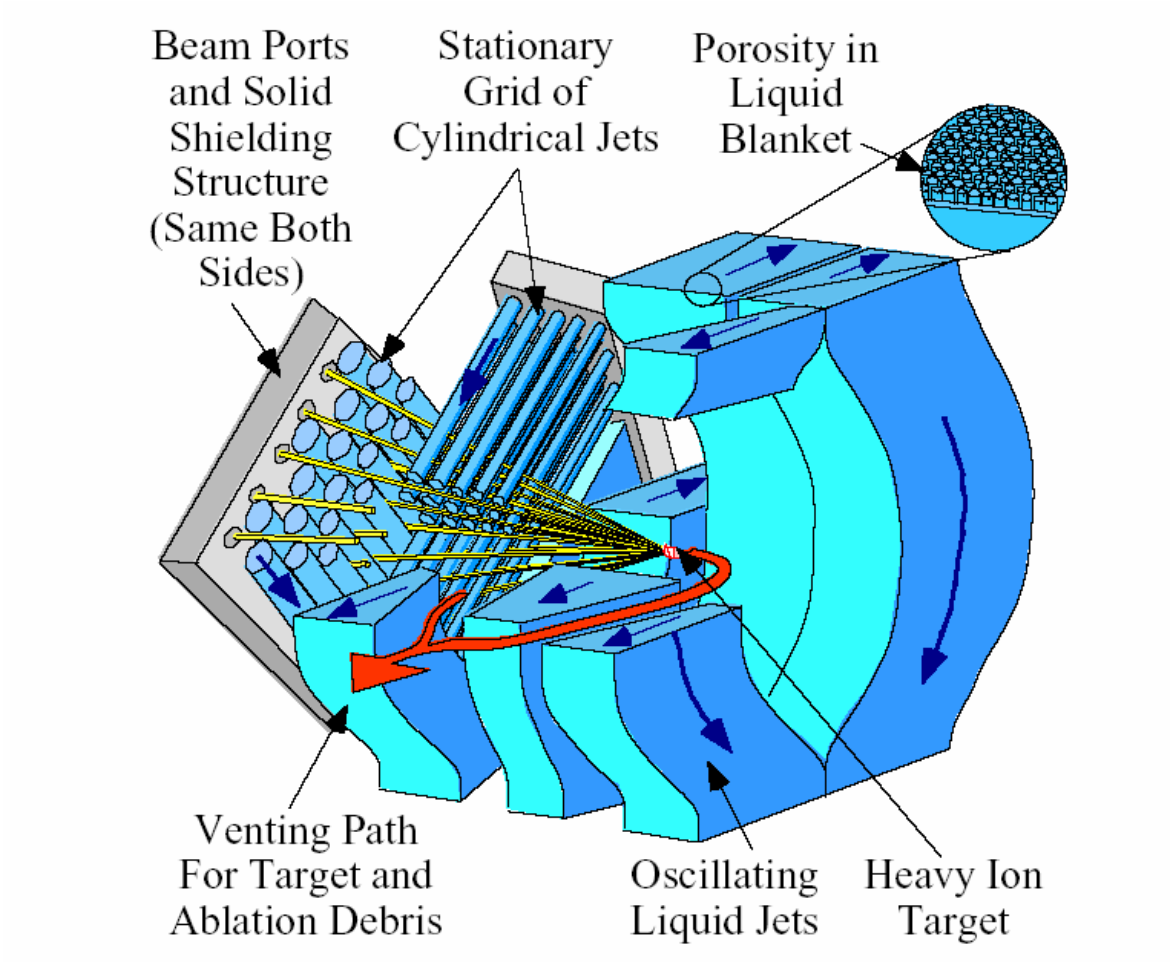
	MFE	IFE
Carbon		
• Erosion	✓	✓
- Microscopic erosion (RES, Chemical and Physical Sputtering)		
- Macroscopic Erosion (Brittle fracture)		
• Tritium inventory	✓	✓
- Co-deposition		
Refractory metal (e.g. Tungsten)		
• Melt layer stability and splashing	✓	✓
• Material behavior at higher temperature	✓	✓
- e.g. roughening due to local stress relief (possible ratcheting effect)		
- Possible relief by allowing melting? - quality of resolidified material		
Carbon and Tungsten		
• He implantation leading to failure (1 to 1 ratio in ~100 days for 1 μm implantation depth)		✓
- In particular for W (poor diffusion of He)		
- Need high temperature or very fine porous structure		
• Fabrication/bonding (integrity of bond during operation)	✓	✓
Search for alternate armor material and configurations	✓	✓
In-situ repair to minimize downtime for repair		
• Cannot guarantee lifetime	✓	✓

Commonality of Key Armor Issues for IFE and MFE Allows for Substantial R&D Synergy

Liquid Walls

- Liquid Walls protect chamber materials from neutrons, x-rays, and ions
- They must permit target injection and driver propogation
- Goal is to reduce chamber size and prolong chamber lifetime (ultimately reducing cost of electricity)
- HYLIFE-II uses a lattice of stationary sheets
- Alternative is to oscillate jets or use vortex tubes

HYLIFE-II Geometry



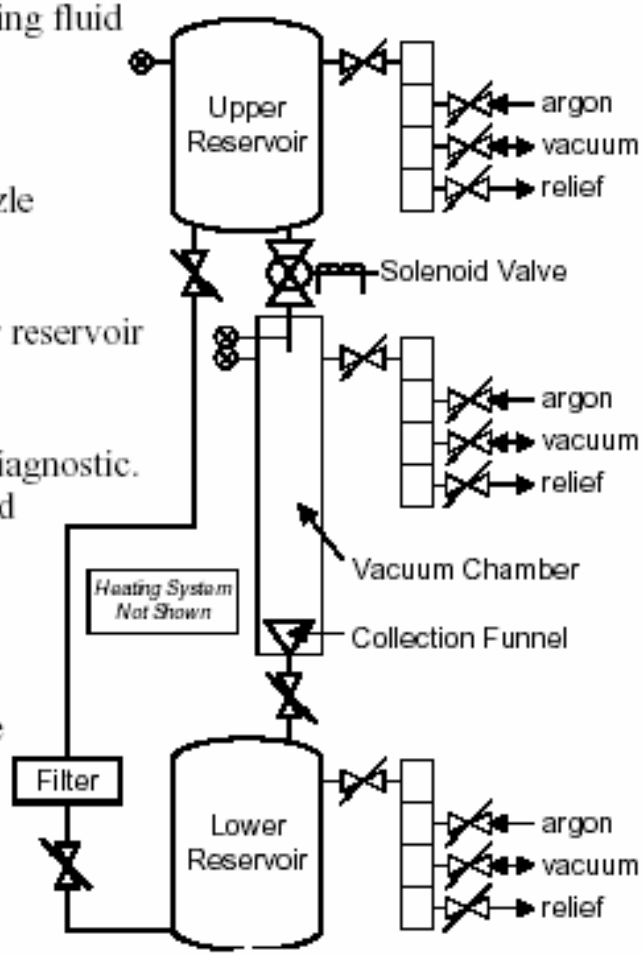
http://www.nuc.berkeley.edu/thyd/papers/Thick_Liquid_Design_FT.pdf

Liquid Wall Issues

- Effect of initial conditions (nozzle geometry, flow conditioner, re, We) on liquid wall behavior
- Surface Ripple
- Breakup
- Reformulation after shot

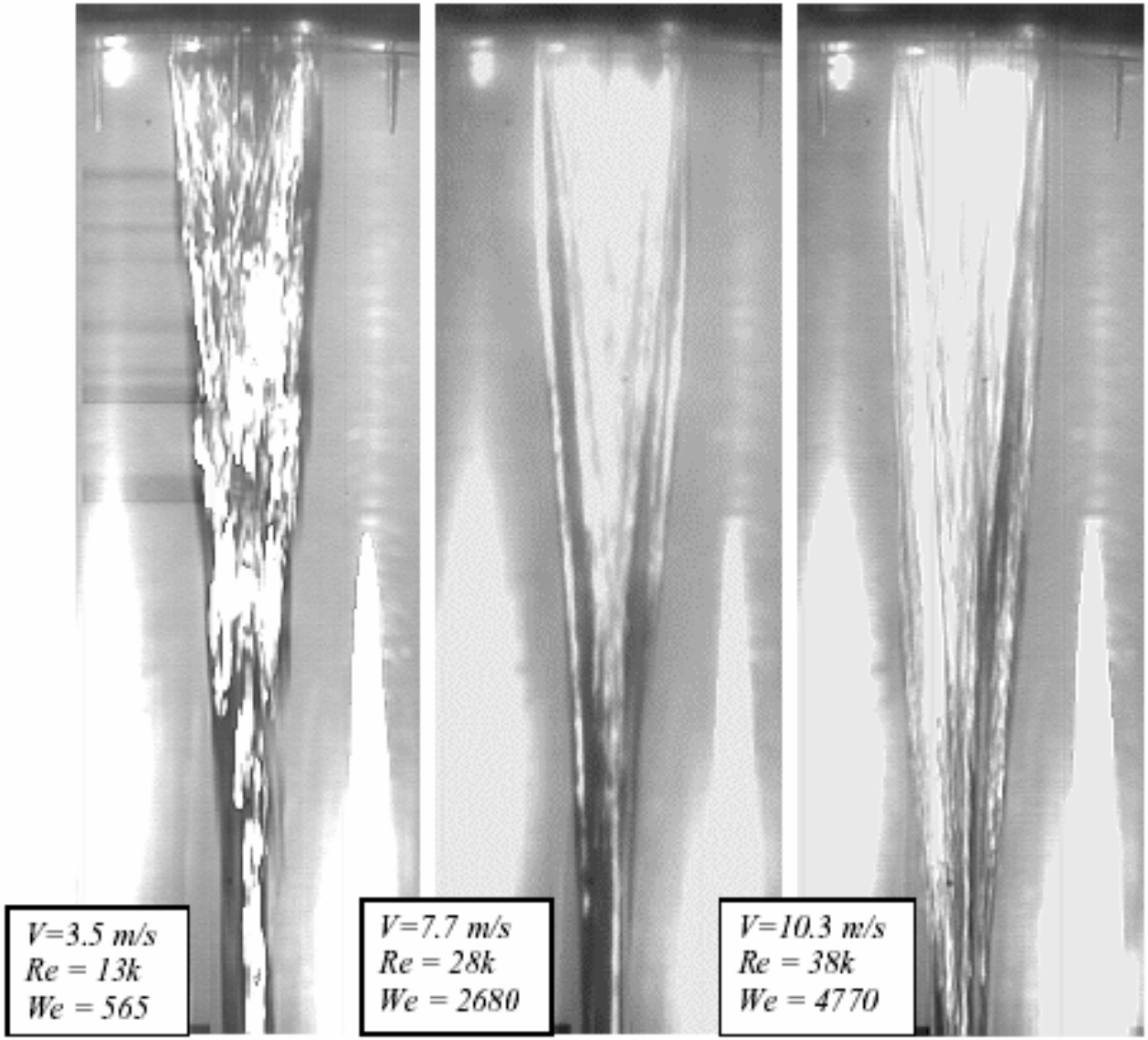
Liquid Metal Jet Facility at UCLA

- Low melting point liquid metal alloy is used as the working fluid
  - Low vapor pressure (no flashing)
  - Small reservoir size and flowrates
- Pressurized upper reservoir drives LM flow through nozzle assembly into vacuum chamber
- Solenoid valve automatically shuts off flow before upper reservoir is exhausted
- High-speed photography is the primary surface quality diagnostic. Transparent vacuum chamber allows flexible lighting and camera position/focus
- Temperature of major elements is actively controlled
- Pressure is measured on back side of nozzle to determine liquid flow rate



http://www.fusion.ucla.edu/IFE/

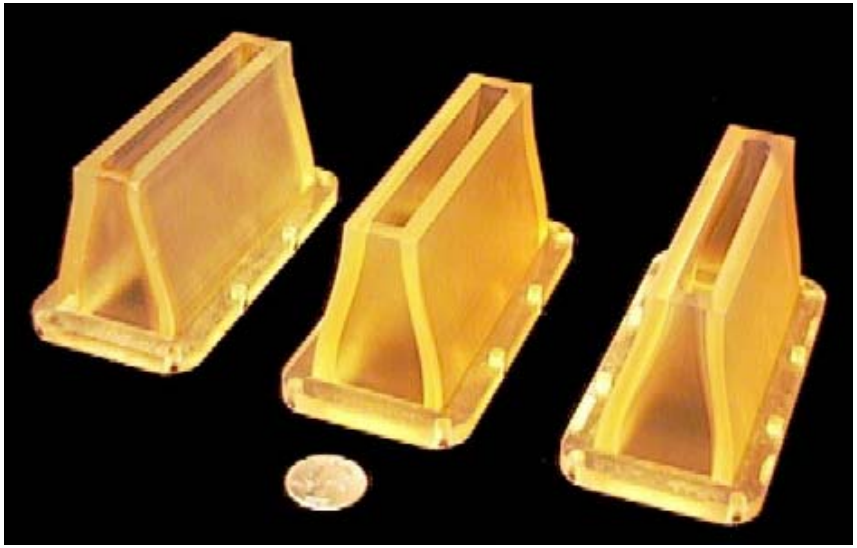
Results from Nozzle 1

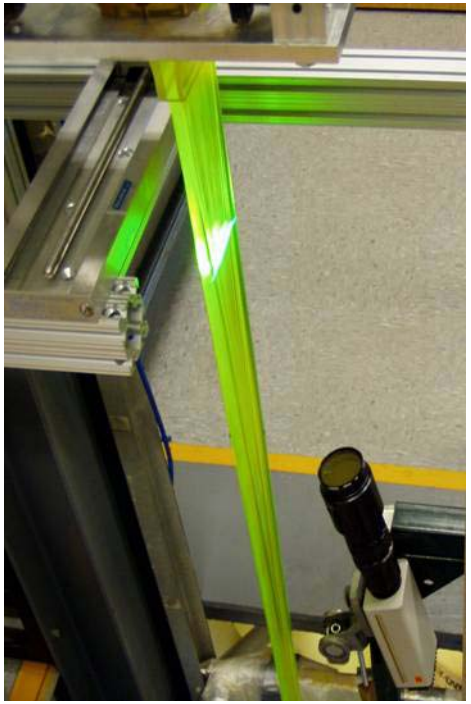


- Non-parallel stream-lines at nozzle exit cause rapid contraction of rectangular cross section jet
- Largest surface waves come from rounding of corner regions due to surface tension

Georgia Tech – Thick Wall

- Protect wall from all threats
- Free-standing, oscillating or steady
- FLiBe
- Re up to 150,000

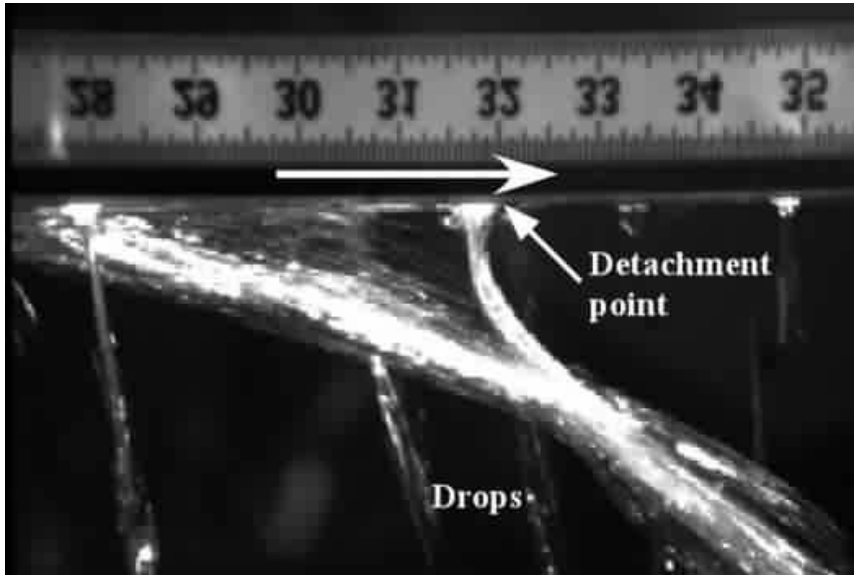


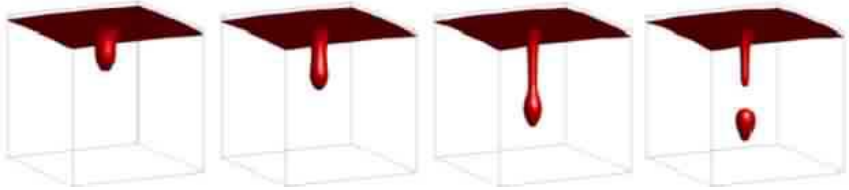


http://www.me.gatech.edu/minami.yoda/FLOIDLab/protection/protection.htm

Georgia Tech - Thin Wall

- Protect wall from x-rays and ions
- Attached to walls
- Pushed through porous wall or injected tangentially





http://www.me.gatech.edu/minami.yoda/FLOIDLab/protection/protection.htm

Millisecond Phenomena (IT2)

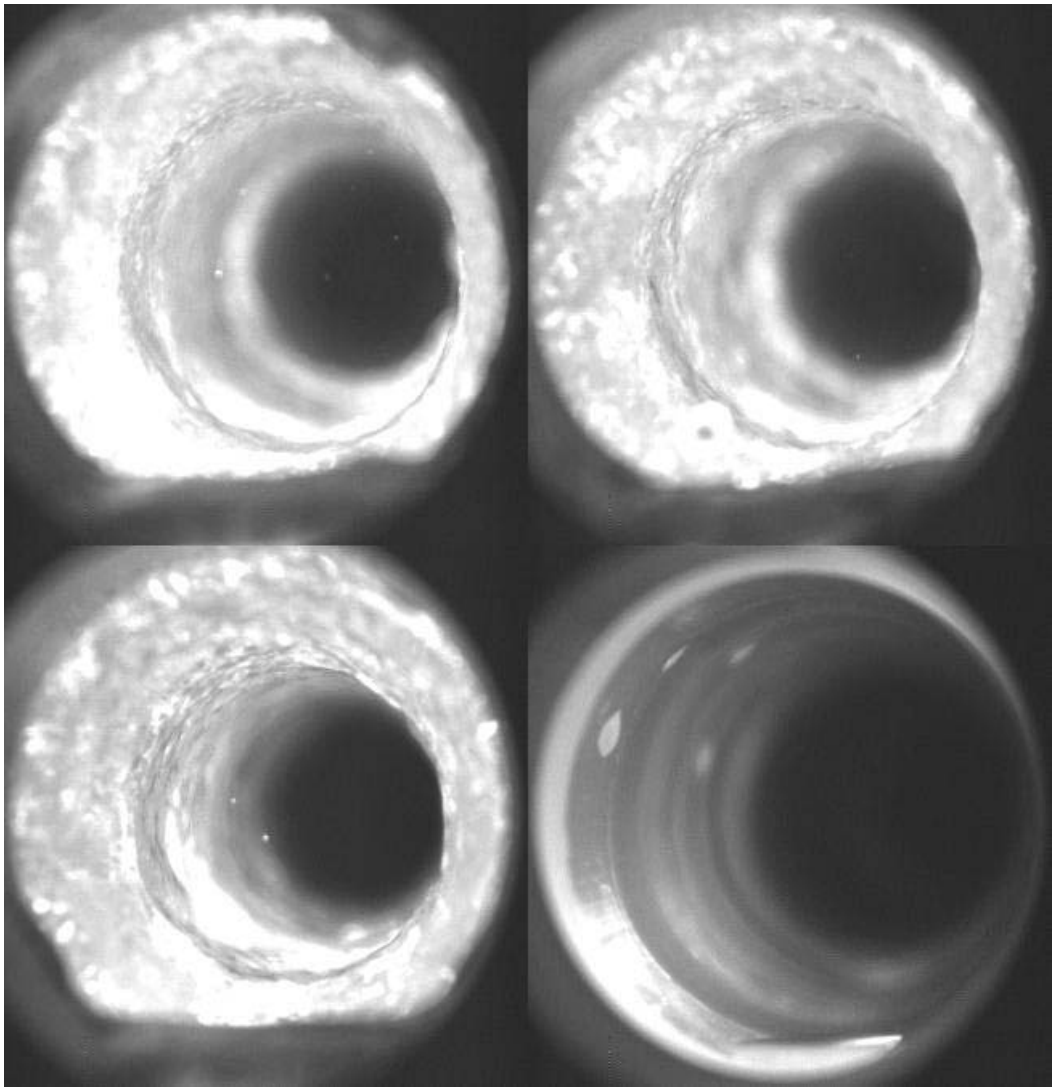
Scaled water experiments are demonstrating the capability to form many classes of liquid jets

High-Re Cylindrical Jets

Vortex Layers for Beam Tubes

Oscillating Voided Liquid Slabs

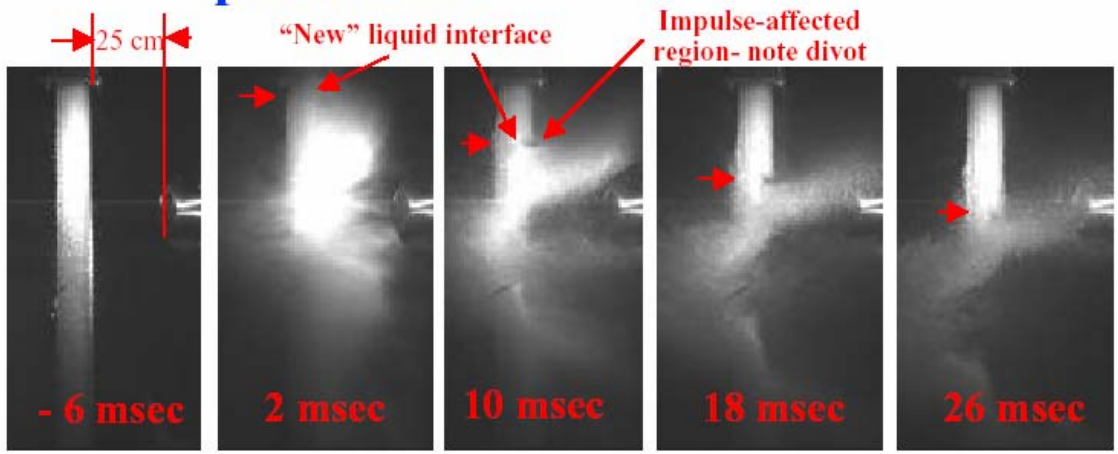
Vortex Flows

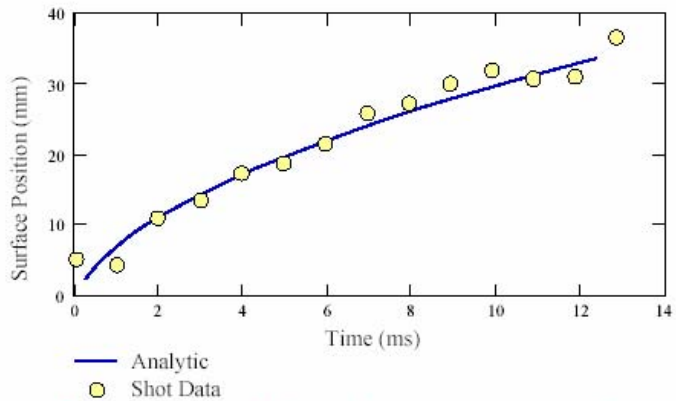


Millisecond Phenomena (IT2)

Chemical detonations are reproducing liquid disruption phenomena

96-jet nozzle assembly in operation

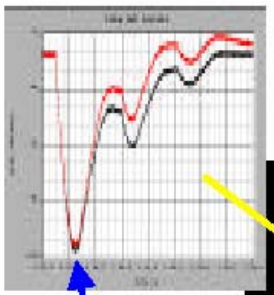




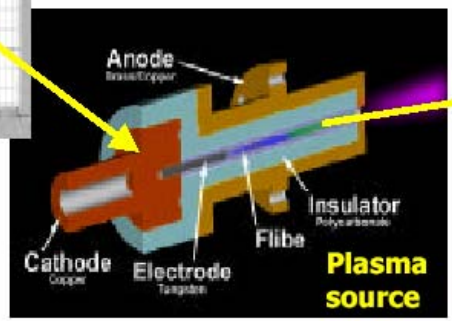
Incompressible theory accurately predicts shock propagation

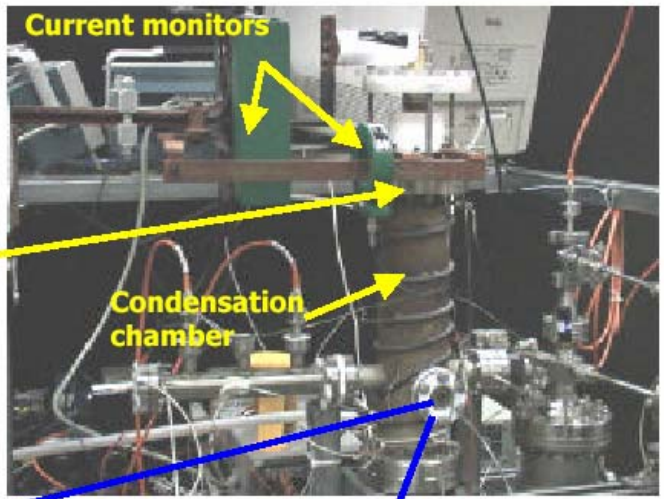
Millisecond Phenomena (IT2)

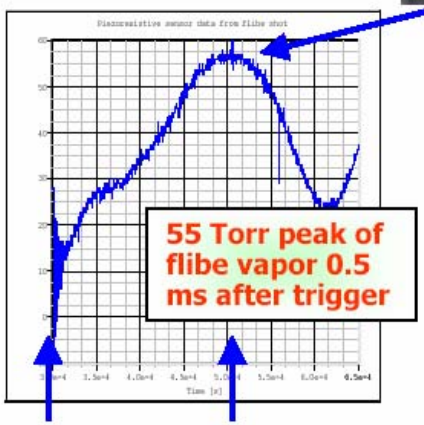
Condensation of ablation debris is being studied with pulsed power and prototypical first-wall materials

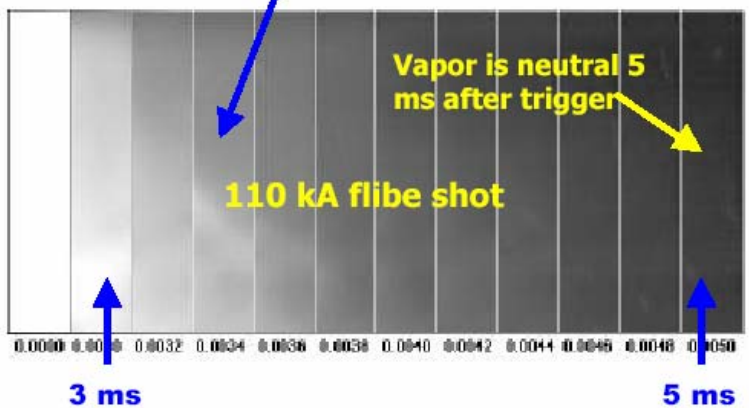


Peak current at 30 μs









Concluding Remarks

- **Very challenging conditions for chamber wall armor in IFE**

- **Different armor materials and configurations are being developed**
  - **Dry wall option**
  - **Liquid wall options**
  - **Similarity between MFE and IFE materials**

- **Some key issues remain and are being addressed by ongoing R&D effort**
  - **Many common issues between MFE and IFE chamber armor**

- **Very beneficial to:**
  - **develop and pursue healthy interaction between IFE and MFE communities**
  - **make the most of synergy between MFE and IFE chamber armor R&D**