ARIES-IFE Assessment of Operational Windows for IFE Power Plants

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ARIES Integrated IFE Chamber Analysis and Assessment Research Is An Exploration Study

Objectives:

- Analyze & assess integrated and self-consistent IFE chamber concepts
- Understand <u>trade-offs</u> and identify <u>design windows</u> for promising concepts. *The research is **not** aimed at developing a point design.*

Approach:

- Six classes of target were identified. Advanced target designs from NRL (laser-driven direct drive) and LLNL (Heavy-ion-driven indirect-drive) are used as references.
- To make progress, we divided the activity based on three classes of chambers:
  - Dry wall chambers;
  - Solid wall chambers protected with a “sacrificial zone” (e.g., liquid films);
  - Thick liquid walls.

ARIES-IFE study was completed in September 2003.

Outline

- Target Design
- Target emission spectra and energy and particle loads on the chamber wall
- Thermo-mechanical response of the chamber wall
- Target survival during injection
- Driver propagation and focusing in the chamber

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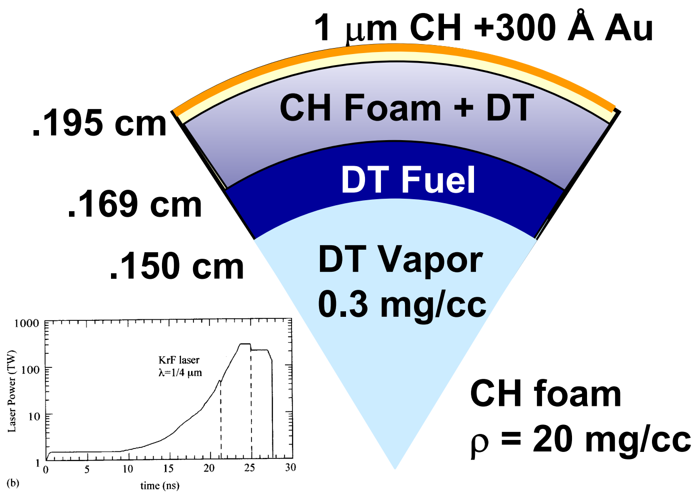
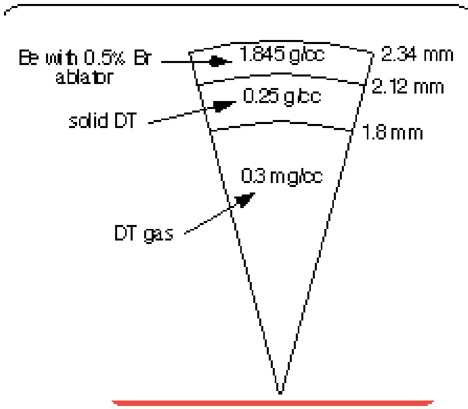
Operational Windows

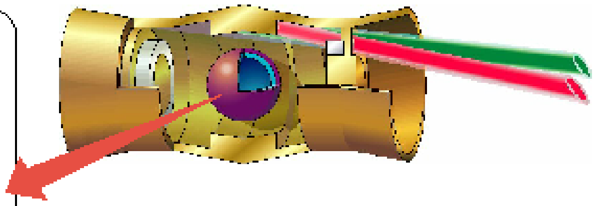
Reference Direct and Indirect Target Designs

NRL Advanced Direct-Drive Targets



LLNL/LBNL HIF Target

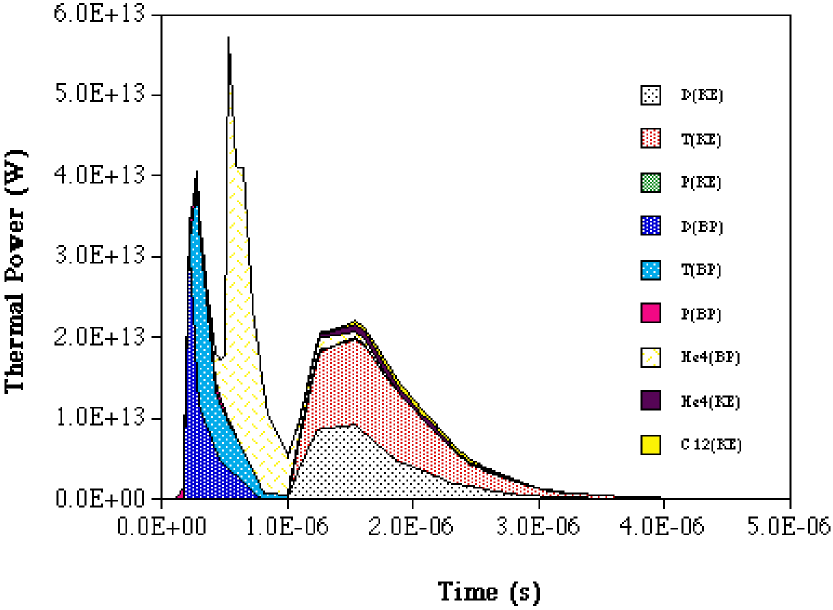




Ion beam characteristics:
- 3.5 GeV Pb+ ions
- 3.3 MJ input energy
- 1.7 mm effective radius spot

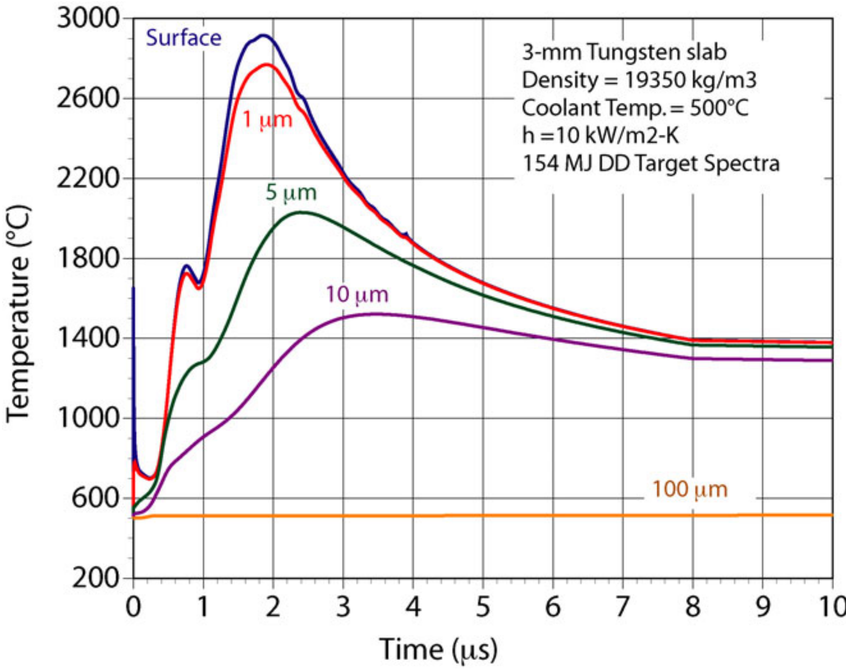
	Direct-Drive Target		Indirect-Drive Target	
	Energy (MJ)	% of yield	Energy (MJ)	% of yield
Driver Energy	1.3		3.3	
Total Yield	154		458	
Neutrons	109	71 %	316	69 %
Fast Ions	18.1	12 %	8.43	1.8 %
Debris Ions	24.9	16 %	18.1	4.0 %
X-rays	2.14	1.4 %	115	25 %

Time-of-Flight Ion Power Spread

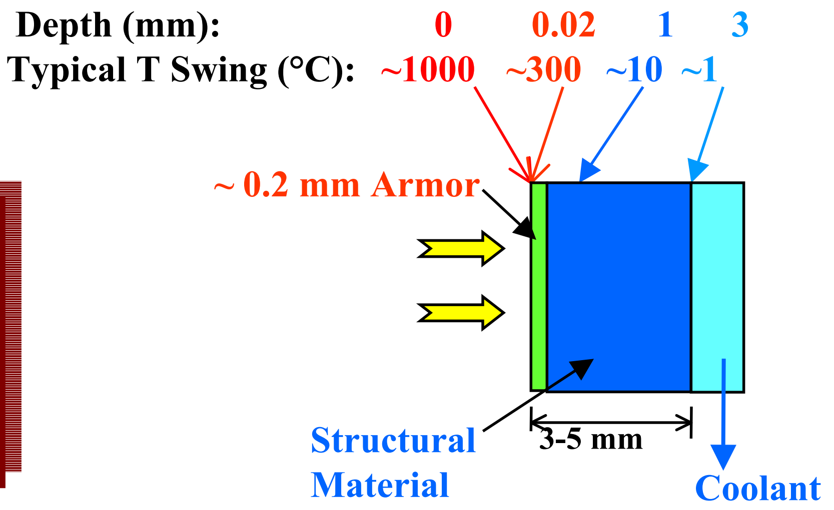


Dry-wall chamber can handle direct-drive target emissions

- Photon and ion energy deposition falls by 1-2 orders of magnitude within 0.1-0.2 mm of surface.
- Beyond the first 0.1-0.2 mm of the surface. First wall experiences a much more uniform q” and quasi steady-state temperature (heat fluxes similar to MFE).



- **Use an Armor**
  - ✓ **Armor optimized to handle particle & heat flux.**
  - ✓ **First wall is optimized for efficient heat removal.**



Depth (mm):	**0**	**0.02**	**1**	**3**
Typical T Swing (°C):	**~1000**	**~300**	**~10**	**~1**

- Critical Issue is the lifetime of the armor:
  - ✓ He retention and exfoliation
  - ✓ Cyclic Fatigue
  - ✓ De-bounding of the armor

Aerosol Generation and Transport is the Key Issue for Thin-Liquid Wall Concepts

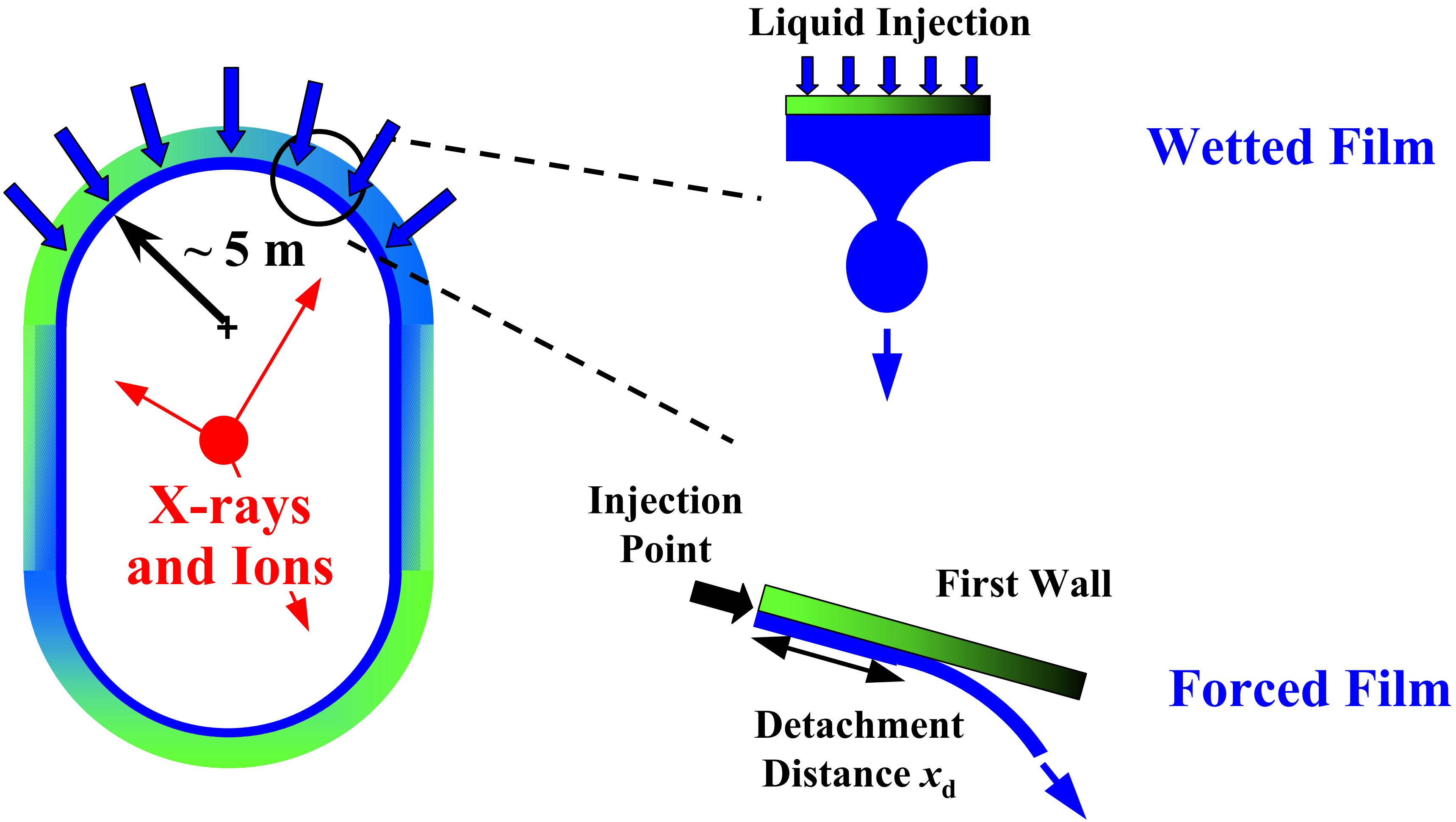
A renewable thin-liquid protection resolve several issues:

- It can handle a much higher heat fluxes compared to solid surfaces;
- It will eliminate damage to the armor/first wall due to high-energy ions.

A renewable thin-liquid protection, however, introduces its own critical issues:

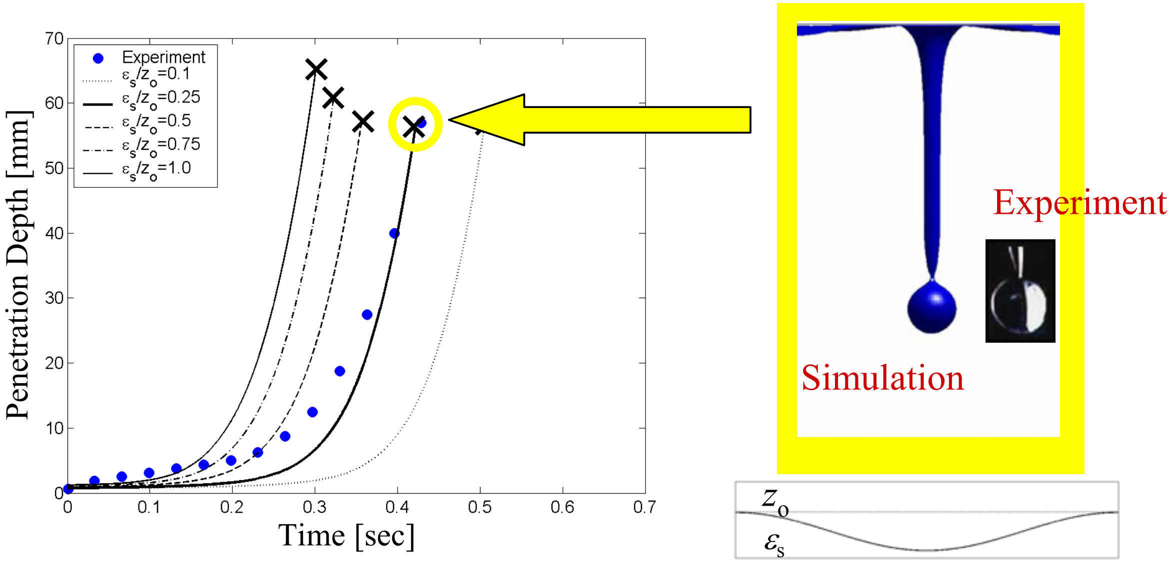
- Fluid-dynamics aspects (establishment and maintenance of the film)
  - ✓ "Wetted wall:" Low-speed normal injection through a porous surface
  - ✓ "Forced film:" High-speed tangential injection along a solid surface
- Chamber clearing (recondensation of evaporated liquid)
  - ✓ "Source term:" both vapor and liquid (e.g., explosive boiling) are ejected
  - ✓ Super-saturated state of the chamber leads to aerosol generation
  - ✓ Target injection and laser beam propagation lead to sever constraints on the acceptable amount and size of aerosol in the chamber.

Two Methods for Establishment of Thin-Liquid Walls Have Been Proposed



A Thin-Liquid Protected Film can be Established and Maintained

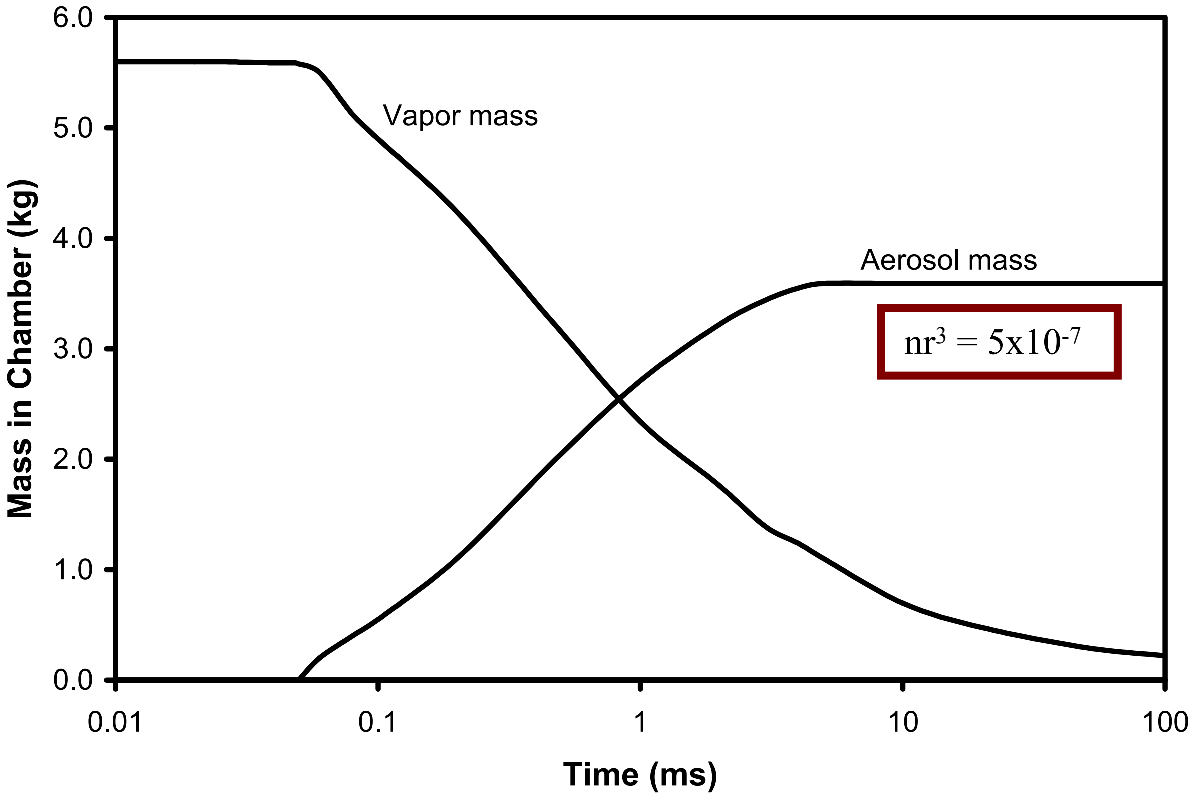
- ➢ Developed general non-dimensional charts for film stability
- ➢ Model predictions are closely matched with experimental data.



- ➢ Radial injection scheme appear to be feasible and does not impose major constraints. Attractiveness of this concept depends on:
  - ✓ Details on the chamber and power plant design
  - ✓ Impact of the required pumping power on the recirculating power & overall economics
- ➢ For the forced-flow scheme, behavior of the film near major obstacles is a major concern

Most of Ablated Material Would Be in The Form of Aerosol

- FLiBe aerosol and vapor mass history in a 6.5-m radius chamber (ablated thickness of 5.5 mm)
- Only homogeneous nucleation and growth from the vapor phase.

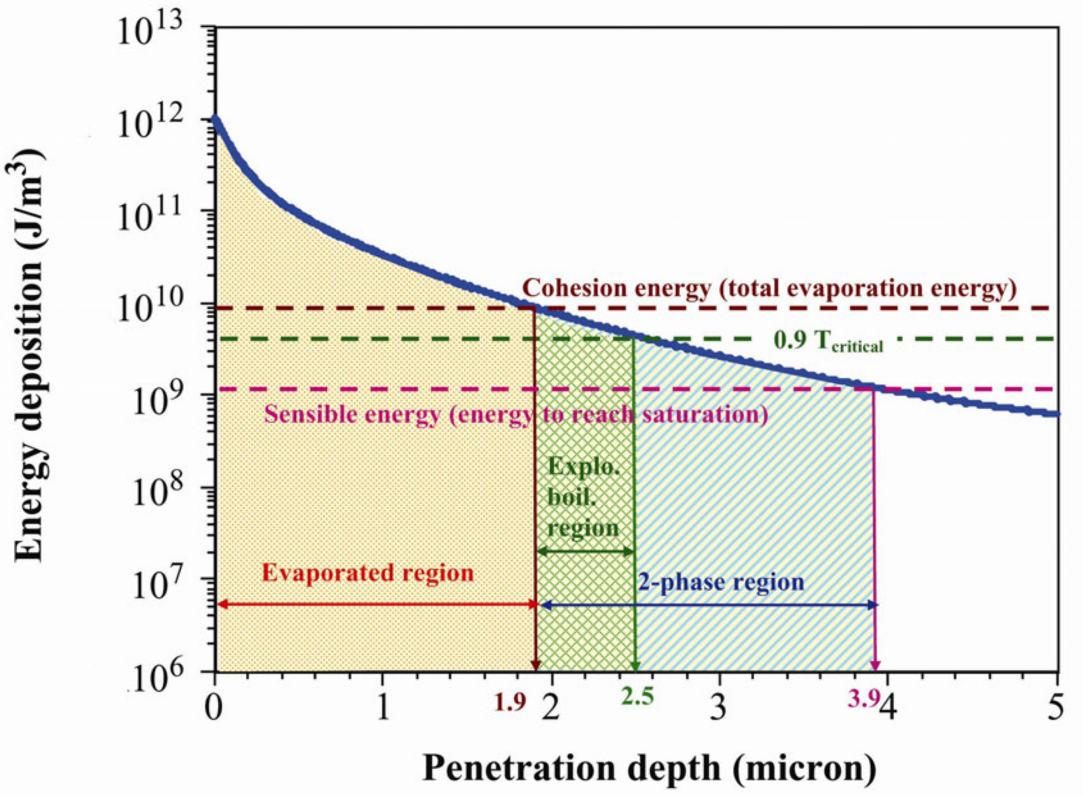


- Most of ablated material remains in the chamber in aerosol form;

- Similar analysis for a 3-m chamber radius leads to 1.8 kg aerosol mass but higher $nr^3 = 8 \times 10^{-6}$

There Are Many Mechanism of Aerosol Generation in an IFE Chamber

- Homogeneous nucleation and growth from the vapor phase
  - ✓ Supersaturated vapor
  - ✓ Ion seeded vapor
- Phase decomposition from the liquid phase
  - ✓ Thermally driven phase explosion
  - ✓ Pressure driven fracture
- Hydrodynamic droplet formation (May be critical in Thick-liquid Wall concepts")



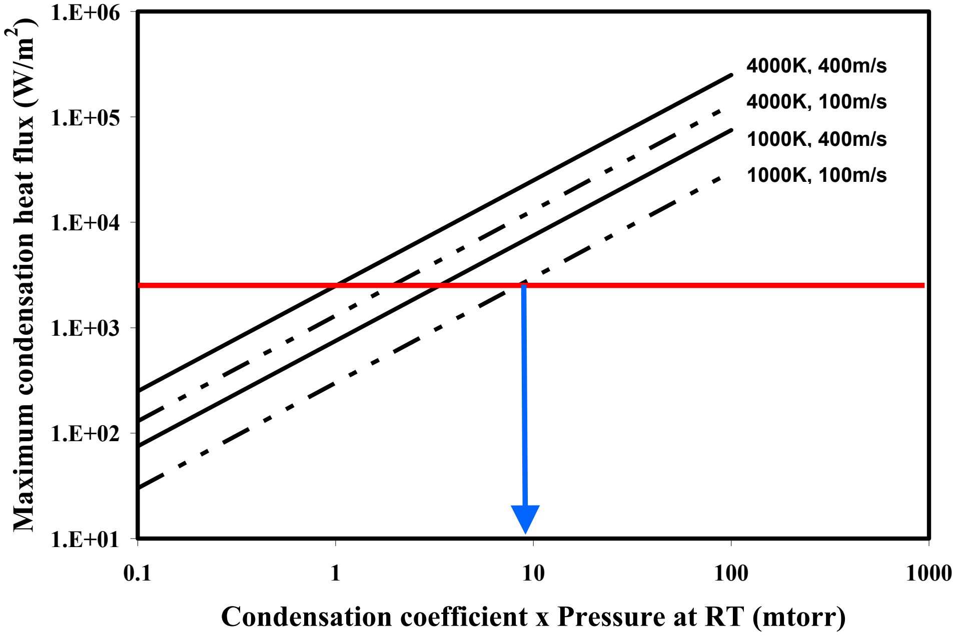
Aerosol Generation and Transport is also the Key Issue for Thick-Liquid Wall Concepts

- Studies of structural materials choices and limits
  - ✓ If a 300 series SS is required as a near-term base line for the design, then Ti-modified 316SS (PCA) should be used. Chamber vessel would not be a life-time components.
  - ✓ However, it was strongly recommended to consider alternate structural material candidates (ferritic steels and SiC/SiC composites) offering the possibility of higher operating temperature & performance. In this case, chamber vessel may be a life-time component.

- Aerosol concerns (similar to thin liquids) were highlighted.
  - ✓ Hydrodynamic droplet formation is a key issue. Flow conditioning and careful nozzle design are needed to control the hydrodynamic source.

Target injection Design Window Naturally Leads to Certain Research Directions

- Direct-drive targets (initial T=18K) are heated during their travel in the chamber by:
- Friction with the chamber gas (mainly through condensation heat flux) requiring
  - ✓ Lower gas pressure
  - ✓ Slower injection velocity
- Radiation heat flux from hot first wall, requiring
  - ✓ Lower equilibrium temperature
  - ✓ Faster injection velocity
- Addition of a thin (~70μm) foam improves the thermal response considerably.



- Direct-drive target injection imposes the toughest constraint on chamber gas pressure.
- Impact of aerosol is unknown
- No constraint for indirect-drive targets

Studies of Ion Transport Modes Indicate Several Options are Feasible

Transport Mode	**Ballistic Transport** *chamber holes ~ 5 cm radius* *most studied*		**Pinch Transport** *chamber holes ~ 0.5 cm radius* *higher risk, higher payoff*	
Chamber Concept	**Vacuum-ballistic** *vacuum*	**Neutralized-ballistic** *plasma generators*	**Preformed channel** **("assisted pinch")** *laser + z-discharge*	**Self-pinched** *only gas*
Dry-wall *~6 meters to wall*	**Not considered now: requires ~500 or more beams**	ARIES-IFE (2002) **Possible option: but tighter constraints on vacuum and beam emittance**	ARIES-IFE (2001) **OPTION: uses 1-10 Torr** ***2 beams***	ARIES-IFE (2001) **OPTION: uses 1-100 mTorr** **~2-100 beams**
Wetted-wall *~ 4-5 meters to wall*	HIBALL (1981) **Not considered: needs ≤ 0.1 mTorr**	OSIRIS-HIB (1992) ARIES-IFE (2002) **Possible option: but tighter constraints on vacuum and beam emittance**	ARIES-IFE (2001) **OPTION: uses 1-10 Torr** ***2 beams***	PROMETHEUS-H (1992) ARIES-IFE (2001) **OPTION: uses 1-100 mTorr** ***~2-100 beams***
Thick-liquid wall *~ 3 meters to wall*	**Not considered: needs ≤ 0.1 mTorr**	HYLIFE II (1992-now) ARIES-IFE (2002) **Main-line approach: uses pre-formed plasma and 1 mTorr for 3 m** ***~50-200 beams***	ARIES-IFE (2002) **OPTION: uses 1-10 Torr** ***2 beams***	ARIES-IFE (2002) **OPTION: uses 1-100 mTorr** ***~2-100 beams***
		$nr^3 \leq 10^{-9}$ (aerosol) or ~ 1 mTorr (gas)	$nr^3 \leq 10^{-6}$ (aerosol) or ~ 1 Torr (gas)	$nr^3 \leq 10^{-7}$ (aerosol) ~ 100 mTorr (gas)

Summary

Dry wall chambers

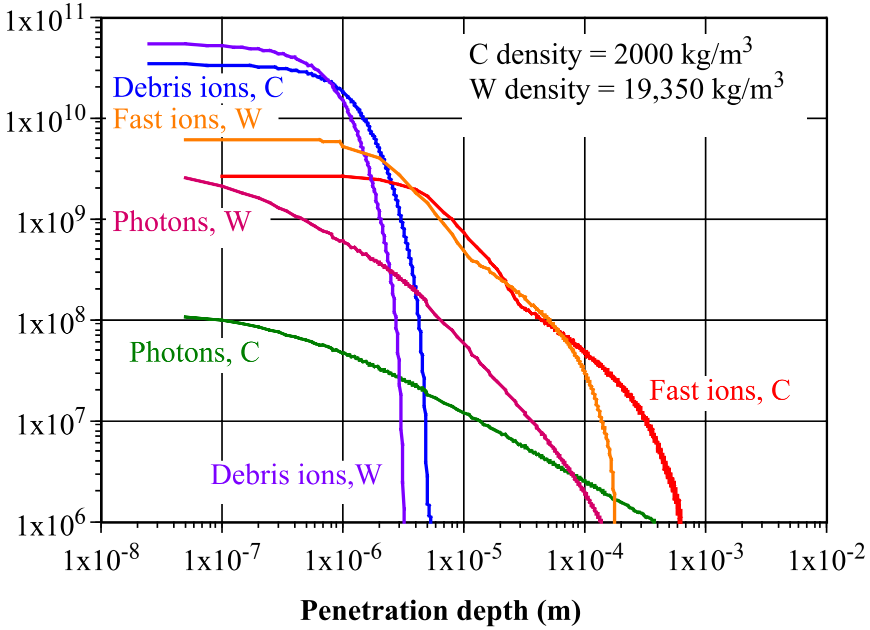
- ➢ Laser and direct-drive targets:
  - ✓Sever constraint on chamber gas pressure (from target injection).
  - ✓Wall can survive without any gas protection
  - ✓The major issue is the lifetime of the armor
- ➢ Laser or heavy-ions and indirect-drive targets:
  - ✓Required protection gas pressure may be too high for laser and/or heavy-ion propagation
  - ✓Recycling of hohlraum material is a major issue.

Wetted-wall and Thick-liquid wall chambers

- ➢ Heavy-ion and indirect-drive targets:
  - ✓Requires assisted pinch propagation
  - ✓Aerosol generation and transport is a major issue.

Extra Slides

Details of Target Spectra Has A Strong Impact on the Thermal Response of the Wall



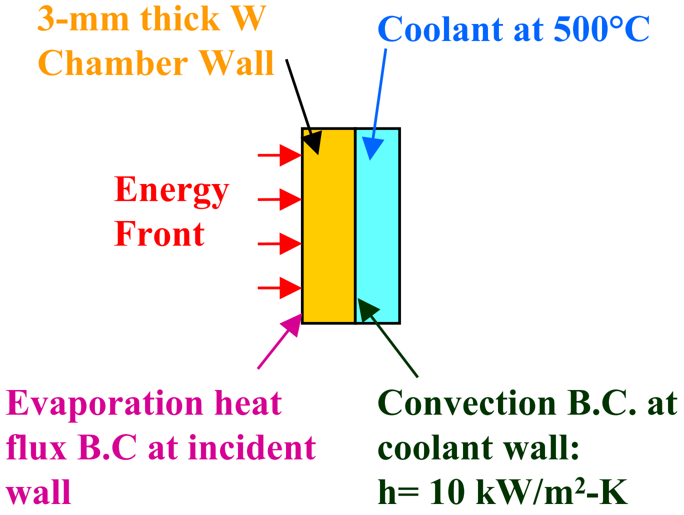
Energy Deposition (J/m²) in C and W Slabs (NRL 154MJ Direct Drive Target)

- ➢ Heat fluxes are much lower than predicted in previous studies:
  - ✓ A much smaller portion of target yield is in X-rays.
  - ✓ Time of flight of ions spread the temporal profile of energy flux on the wall over several μs.
- ➢ A cover gas may not be necessary for protecting the chamber wall

- ➢ Photon and ion energy deposition falls by 1-2 orders of magnitude within 0.1 mm of surface.

Thermal Response of a W Flat Wall

- NRL direct-drive target in 6.5-m chamber with no gas protection:



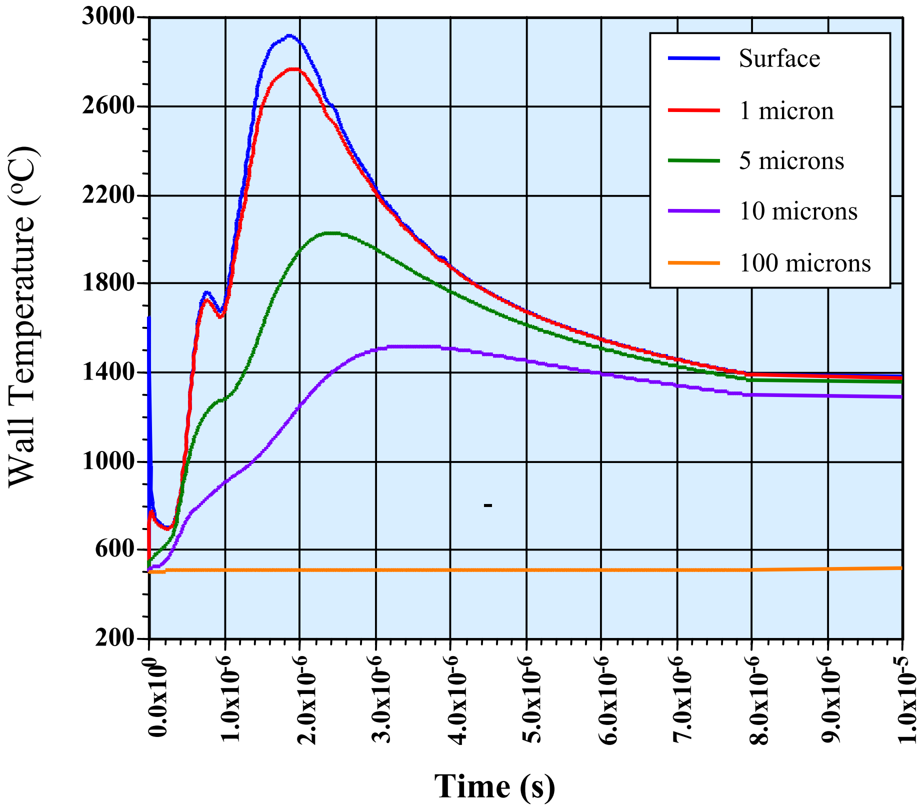
3-mm thick W Chamber Wall

Coolant at 500°C

Energy Front

Evaporation heat flux B.C at incident wall

Convection B.C. at coolant wall: h= 10 kW/m²-K



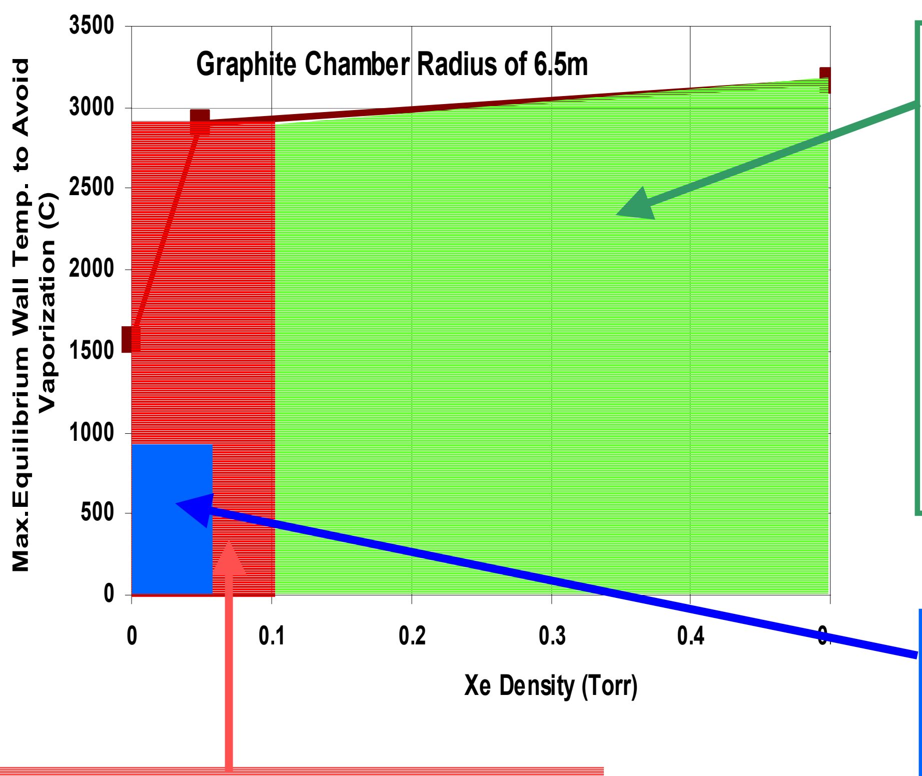
- Temperature variation mainly in thin (0.1-0.2 mm) region.
- Margin for design optimization (a conservative limit for tungsten is to avoid reaching the melting point at 3,410°C).
- Similar margin for C slab.

IFE Armor Conditions are similar to those for MFE PFCs (ELM, VDE, Disruption)

	ITER Type-I ELM's	ITER VDE's	ITER Disruptions	Typical IFE Operation (direct-drive NRL target)
Energy	<1 MJ/m^2	~ 50 MJ/m^2	~ 10 MJ/m^2	~ 0.1 MJ /m^2
Location	Surface near div. strike points	surface	surface	bulk (~µm's)
Time	100-1000 µs	~ 0.3 s	~ 1 ms	~ 1-3 µs
Max. Temperature	melting/ sublimation points	melting/ sublimation points	melting/ sublimation points	~ 1500-2000 °C (for dry wall)
Frequency	Few Hz	~ 1 per 100 cycles	~ 1 per 10 cycles	~ 10 Hz
Base Temperature	200-1000 °C	~ 100 °C	~ 100 °C	~ >500 °C

- **There is a considerable synergy between MFE plasma facing components and IFE chamber armor.**

Design Windows 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

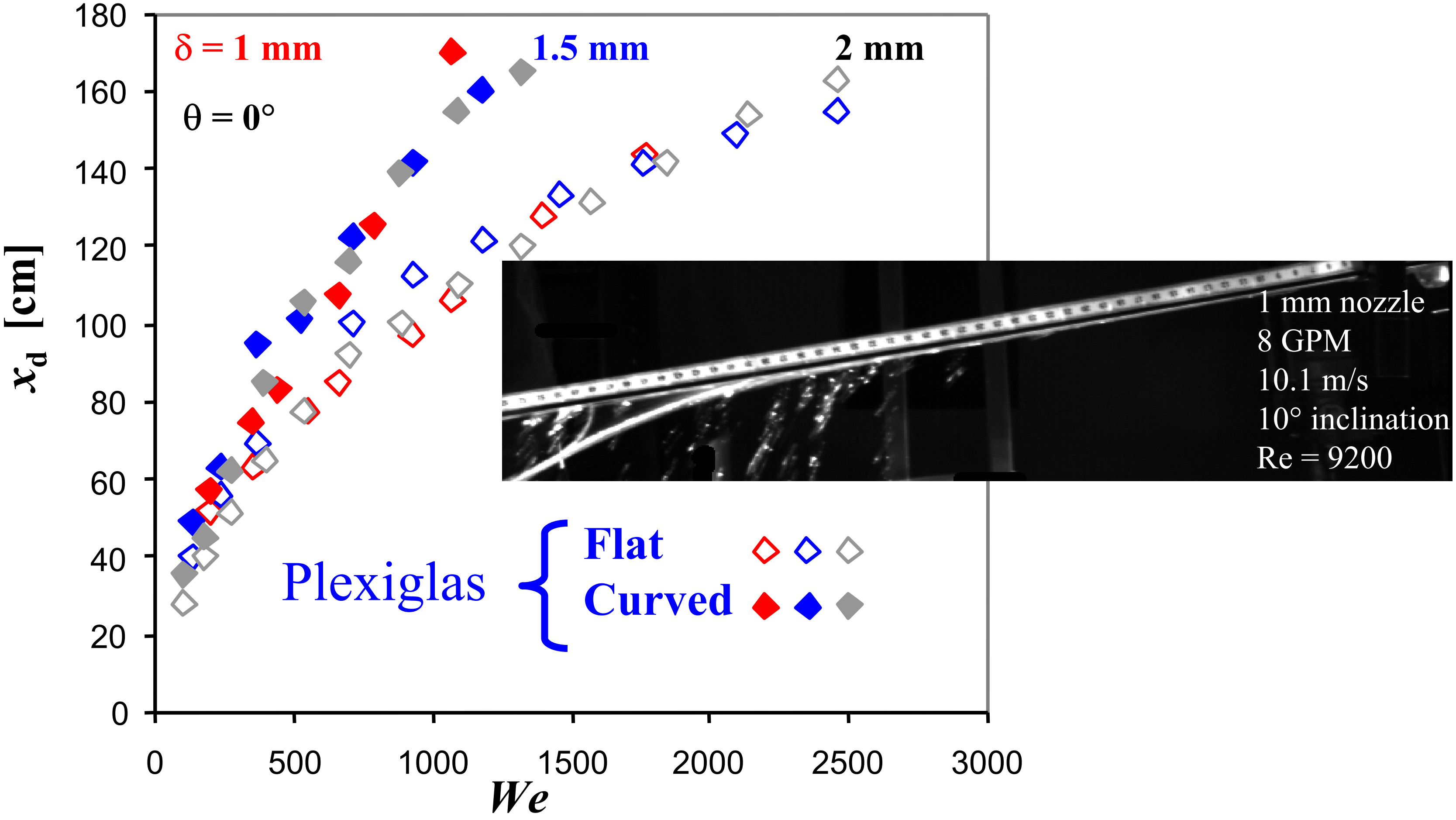
- ✓ Heating of target by radiation and friction
- ✓ Constraints:
  - Limited rise in temperature
  - Acceptable stresses in DT ice

Laser propagation design window(?)

- ✓ Experiments on NIKE

We Have Developed Design Widows for The Forced-Wall Concepts

- ➢ Developed non-dimensional design widows for longitudinal spacing of injection/coolant/removal slots to maintain attached protective film;



Selected Results from ARIES-IFE Study :

<u>Wetted Wall Concepts</u>

Selected Results from ARIES-IFE Study :

Thick Liquid Wall Concepts