Overview of US Power Plant Studies

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Electronic copy: http://aries.ucsd.edu/najmabadi/TALKS

ARIES Web Site: http://aries.ucsd.edu/ARIES

Scope of
Current ARIES Research

ARIES Program charter was expanded in FY00 to include both IFE and MFE concepts

MFE activities in FY02 (~30% of total effort):

- **Systems-level examination of RFP** to assess impact of recent physics data on TITAN RFP (vintage 1988) embodiment.
  - ✓ RFP community provides physics input on a "voluntary" basis.
  - ✓ ARIES Team provides system and engineering support.
  - ✓ Project will be completed by the end of FY02.
- **Preparatory study on compact stellarators**
- **Update of ARIES System code**
  - ✓ Combined effort by PPPL/UCSD.
  - ✓ Project will be completed by the end of FY02.
- **Collaboration under IEA Cooperative Agreement**
  - ✓ A new Task (task 9) has been initiated under IEA cooperative agreement on the environmental, safety, and economics aspects of fusion power.

ARIES Program charter was expanded in FY00 to include both IFE and MFE concepts

IFE activities in FY02 (~ 70% of total effort):

- **Continuation of ARIES-IFE project**
  - ✓ **Scope:** Analyze & assess integrated and self-consistent IFE chamber concepts in order to understand trade-offs and identify design windows for promising concepts.
  - ✓ Project will be completed by the end of FY02.
  - ✓ Three classes of chamber options were considered in series in each case both direct-drive (lasers) and indirect-drive (Heavy-ion) targets:
    - Dry-wall chambers: Completed (some on-going work on heavy-ion beam transport)
    - Wetted-wall chambers: Analysis to be completed by March 2002.
    - Thick-liquid wall chambers: March-October 2002.

Selected Results from ARIES-IFE Studies

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

Objectives:

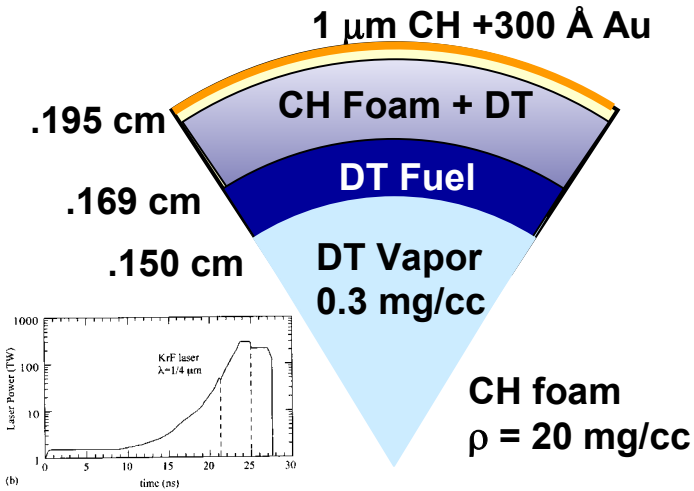
- Analyze & assess integrated and self-consistent IFE chamber concepts
- Understand trade-offs and identify design windows for promising concepts. *The research is **not** aimed at developing a point design.*

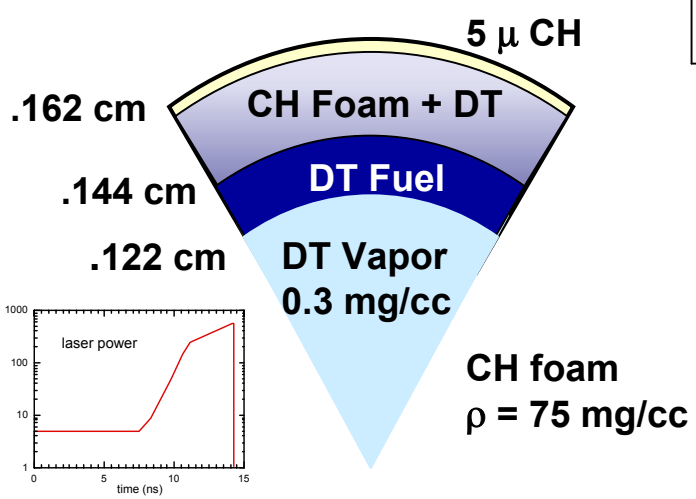
Approach:

- 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" (such as liquid films);
  - Thick liquid walls.
- We research these classes of chambers in series with the entire team focusing on each.

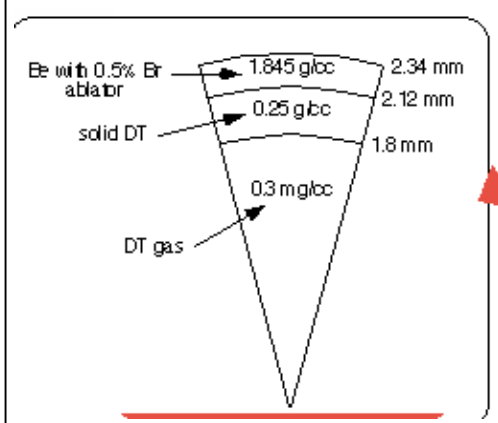
Reference Direct and Indirect Target Designs

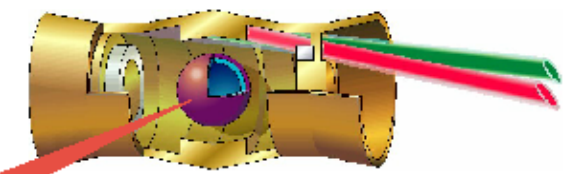
NRL Advanced Direct-Drive Targets





LLNL/LBNL HIF Target



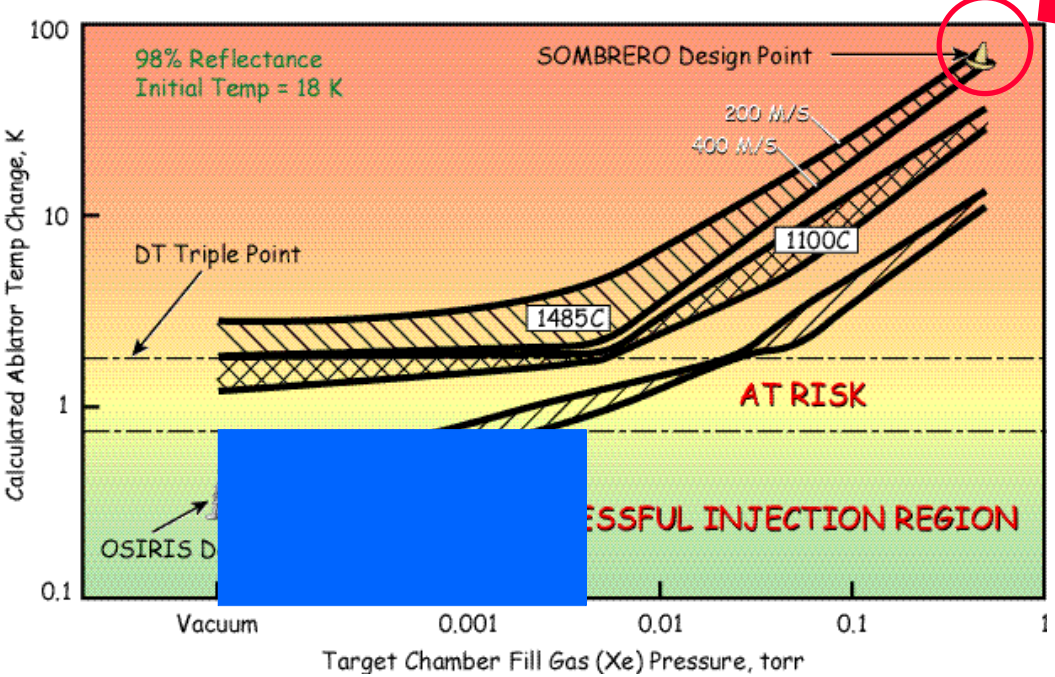


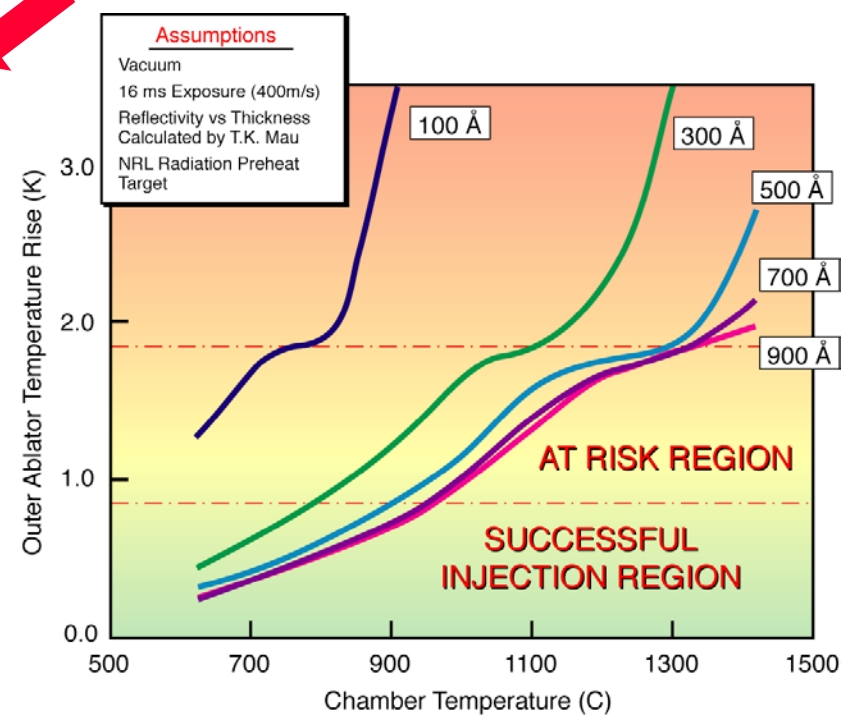
Ion beam characteristics:
- 3.5 GeV Pb^+ ions
- 3.3 MJ input energy
- 1.7 mm effective radius spot

- NRL Direct Drive Target Gain Calculations (1-D) have been corroborated by LLNL and UW.

Target injection Design Window Naturally Leads to Certain Research Directions

- Analysis of design window for successful injection of direct and indirect drive targets in a gas-filled chamber (e.g., Xe) is completed.
  - ✓ No major constraints for <u>indirect-drive</u> targets (Indirect-drive target is well insulated by hohlraum materials)
  - ✓ Narrow design window for <u>direct-drive</u> targets:



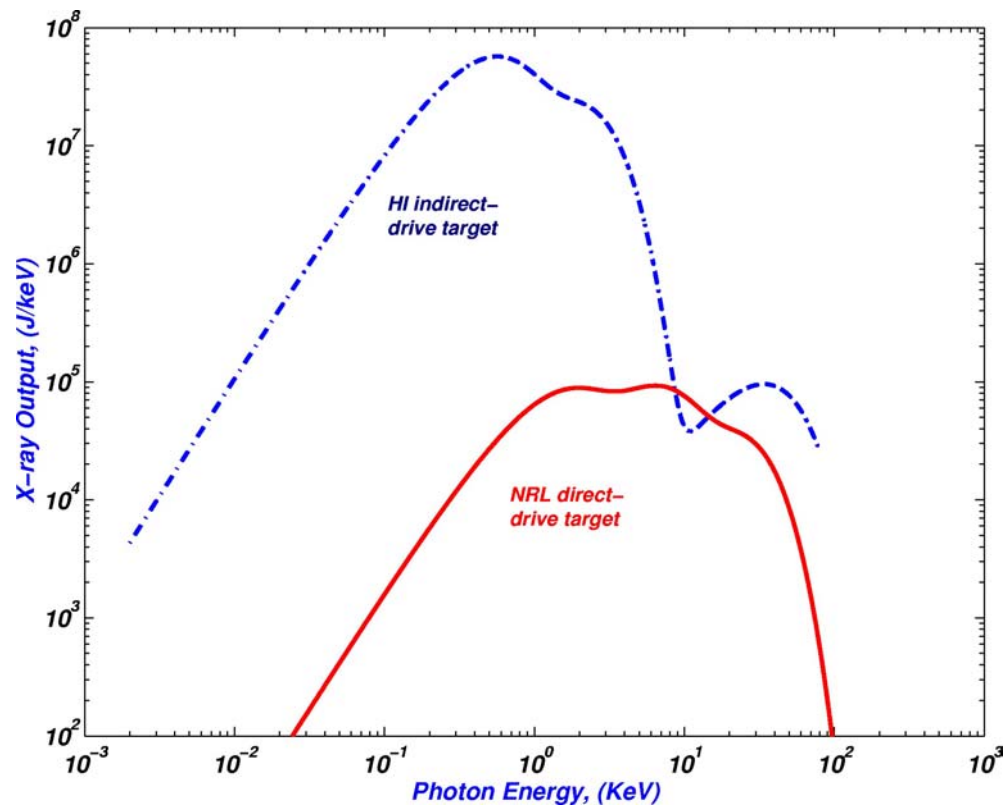


$\Rightarrow$ (Pressure < ~50 mTorr, Wall temperature < ~700°C).

X-ray and Ion Spectra from Reference Direct and Indirect-Drive Targets Are Computed

	NRL Direct Drive Target (MJ)	HI Indirect Drive Target (MJ)
X-rays	2.14 (1%)	115 (25%)
Neutrons	109 (71%)	316 (69%)
Gammas	0.0046 (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

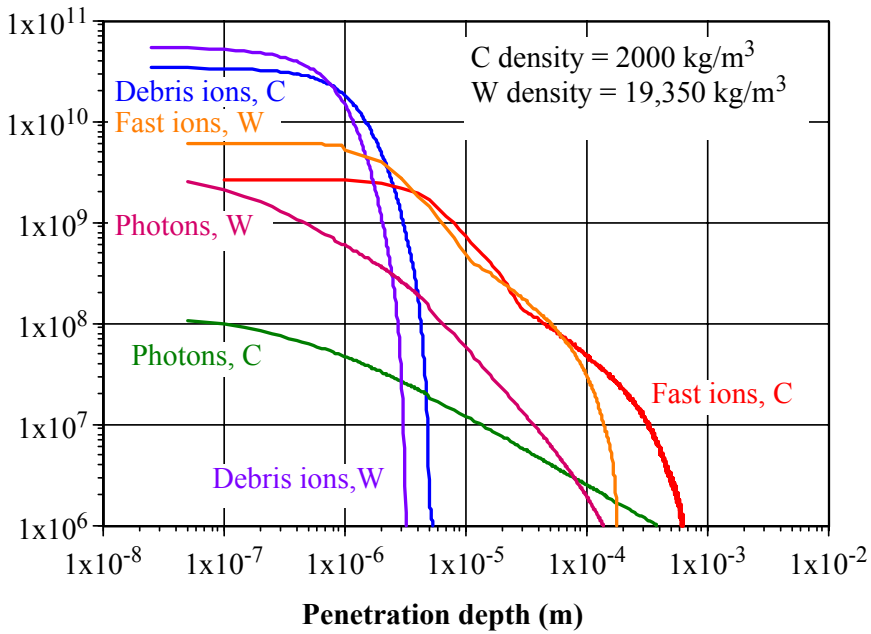
- Little energy in the X-ray channel for NRL direct-drive target



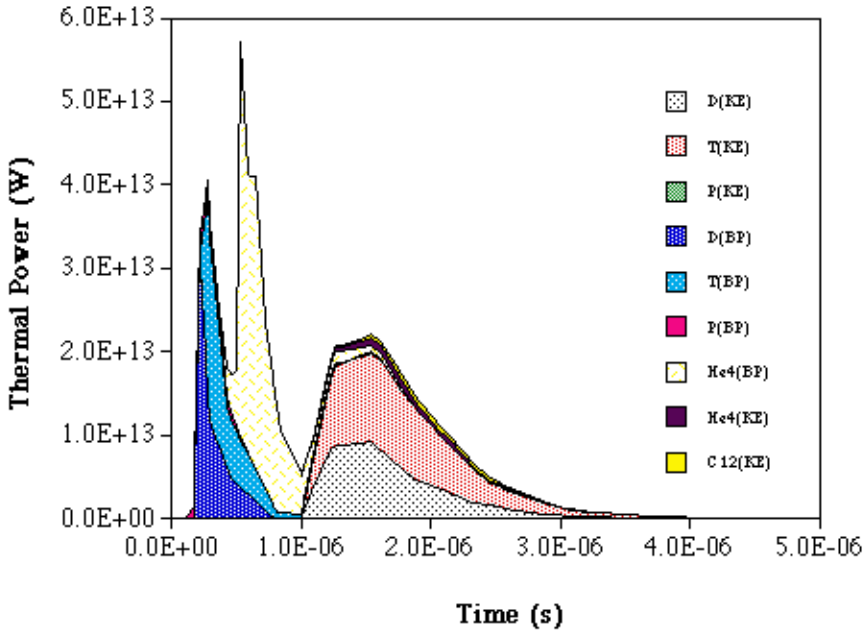
- Detailed target spectrum available on ARIES Web site http://aries.ucsd.edu/ARIES/

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

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



Ion power on chamber wall (6.5-m radius chamber in vacuum)

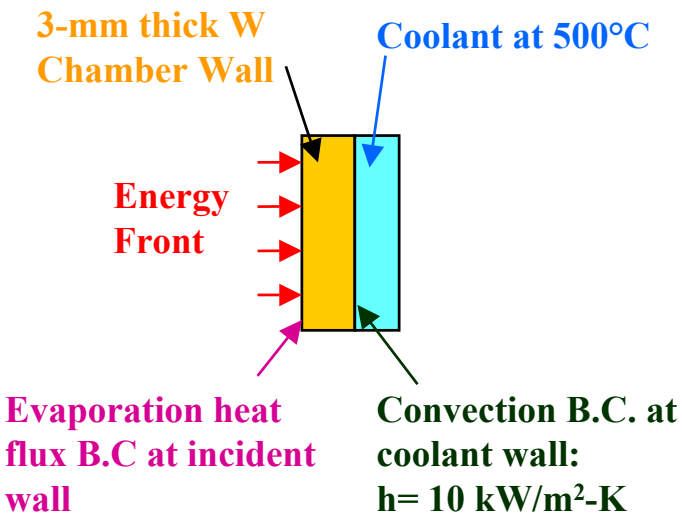


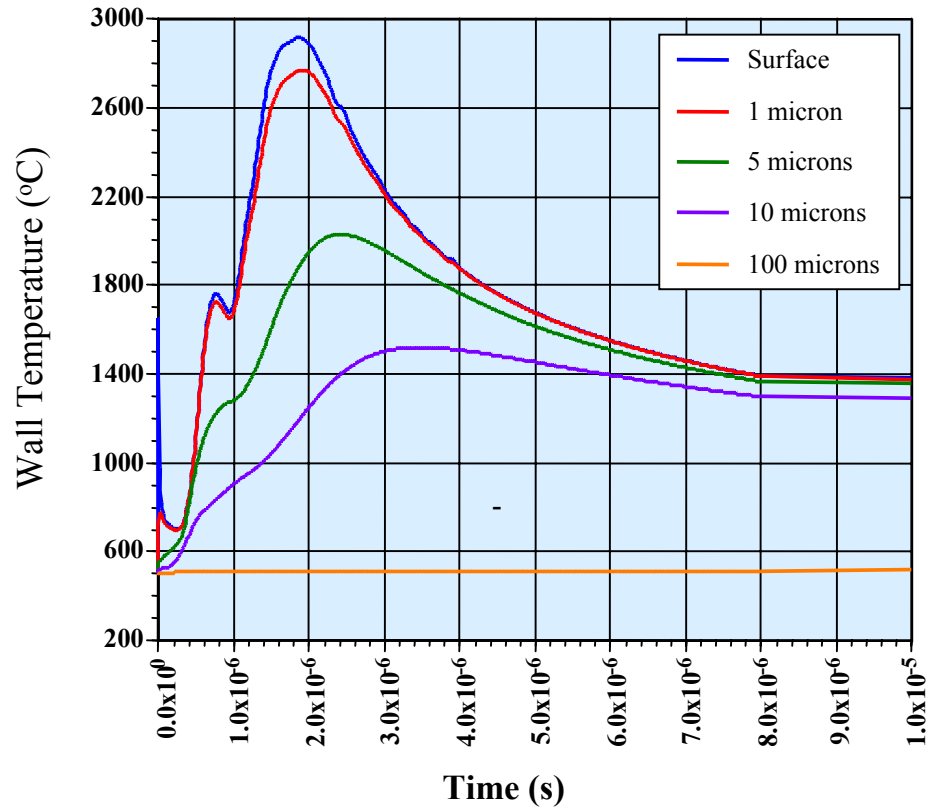
- Photon and ion energy deposition falls by 1-2 orders of magnitude within 0.1 mm of surface
- Most of heat flux due to fusion fuel and fusion products (for direct-drive).

- Time of flight of ions spread the temporal profile of energy flux on the wall over several μs (resulting heat fluxes are much lower than predicted previously).

Is Gas Necessary to Product Solid Walls (for NRL Direct-Drive Targets)? NO

- Thermal response of a W flat wall to NRL direct-drive target (6.5-m chamber with no gas protection):

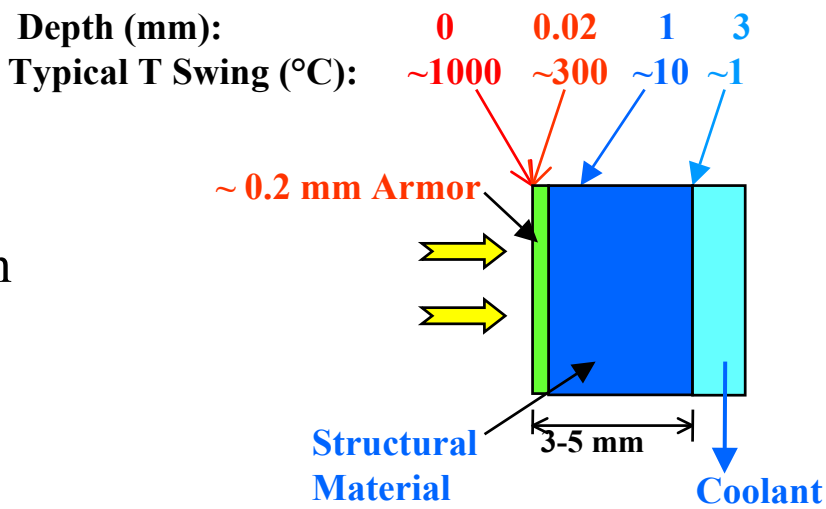




- Temperature variation mainly in thin (0.1-0.2 mm) region.
- Margin for design optimization (a conservative limit for tungsten is to avoid reaching the melting point at 3,410°C).
- Similar margin for C slab.

All the Action Takes Place within 0.1-0.2 mm of Surface -- Use an Armor

- 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).

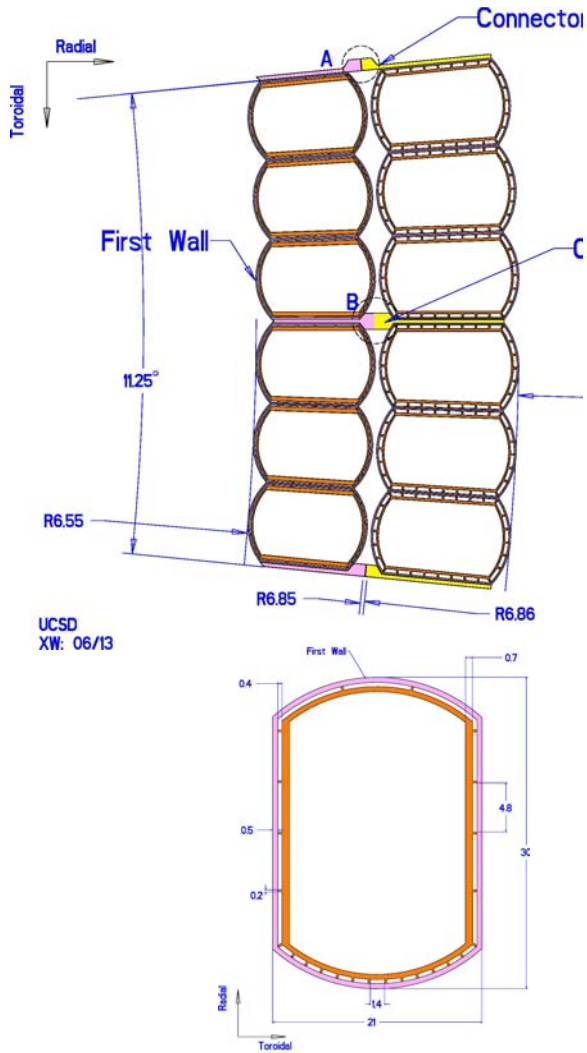


- **Use an Armor**
  - ✓ **Armor optimized to handle particle and heat flux.**
  - ✓ **First wall is optimized for efficient heat removal.**
- Most of neutrons deposited in the back where blanket and coolant temperature will be at quasi steady state due to thermal capacity effect
- **Focus IFE effort on armor design and material issues**
- **Blanket design can be adapted from MFE blankets**

Use of an Armor Allows Adaptation of Efficient MFE Blankets for IFE Applications

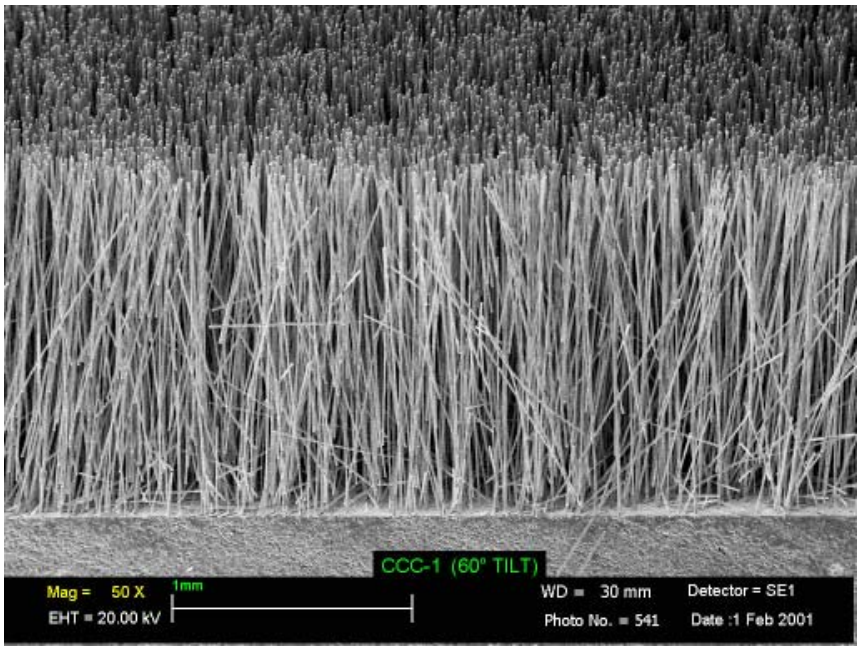
- As an example, we considered a variation of ARIES-AT blanket as shown:
- Simple, low pressure design with SiC structure and LiPb coolant and breeder.
- Innovative design leads to high LiPb outlet temperature (~1100°C) while keeping SiC structure temperature below 1000°C leading to a high thermal efficiency of ~ 55%.
- Plausible manufacturing technique.
- Very low afterheat.
- Class C waste by a wide margin.

Outboard blanket & first wall



Candidate Dry Chamber Armor Materials

- **Carbon (and CFC composites)**
  - ✓ Key tritium retention issue (in particular co-deposition)
  - ✓ Erosion
  - ✓ Oxidation, Safety
- **Tungsten & Other Refractories**
  - ✓ Fabrication/bonding and integrity
- ✓ **"Engineered Surfaces"**
  - ✓ An example is a C fibrous carpet.



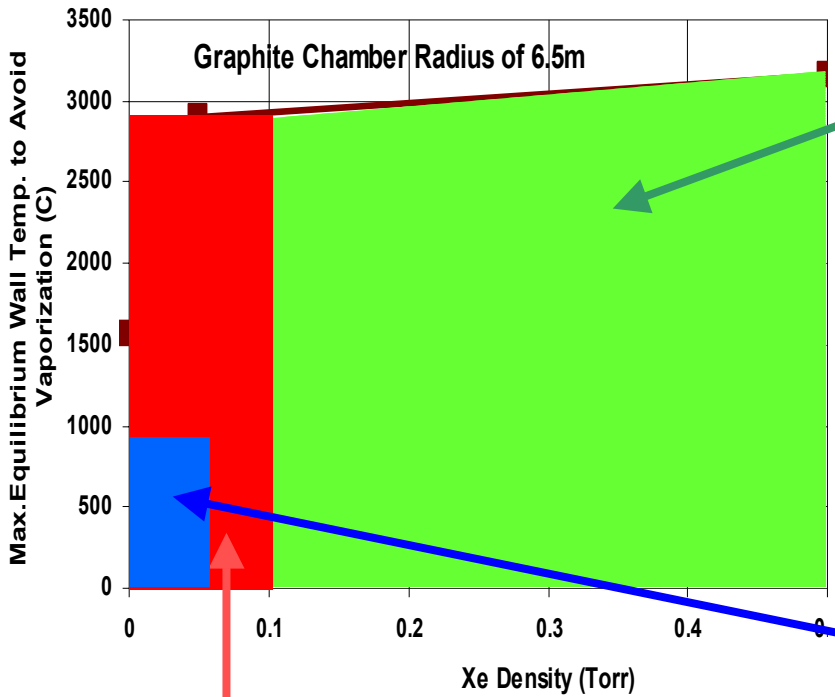
- **Others?**
- **Lifetime is the key issue for the armor**
  - ✓ Even erosion of one atomic layer per shot results in ~ cm erosion per year
  - ✓ Need to better understand molecular surface processes
  - ✓ Need to evolve in-situ repair process

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

- **We should make the most of existing R&D in MFE area (and other areas) since conditions can be similar (ELM's vs IFE)**

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

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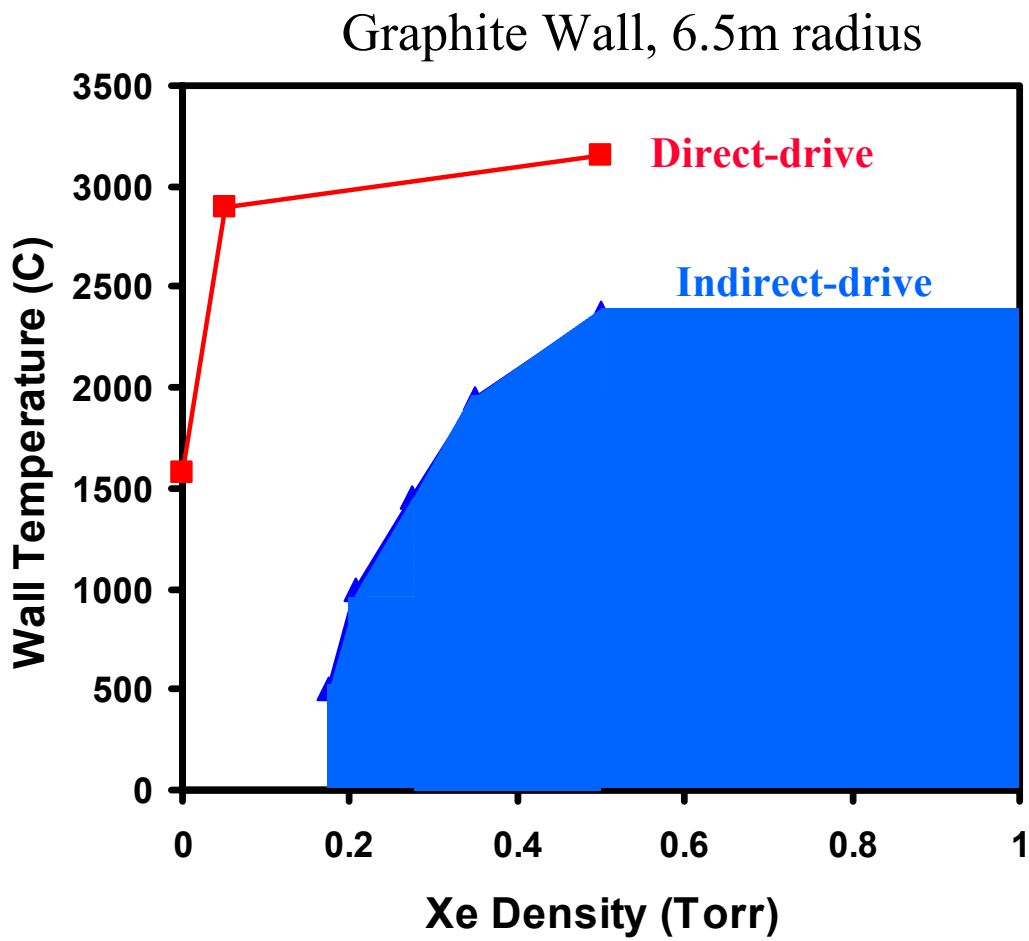
	ITER Type-I ELM's	ITER VDE's	ITER Disruptions	Typical IFE Operation (direct-drive NRL target)
Energy	<1 MJ/m^2	~ 50 MJ/m^2	~ 10 MJ/m^2	~ 0.1 MJ /m^2
Location	Surface near div. strike points	surface	surface	bulk (~μm's)
Time	100-1000 μs	~ 0.3 s	~ 1 ms	~ 1-3 μs
Max. Temperature	melting/ sublimation points	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 Window for Indirect-Drive Dry-Wall Chambers

- Gas pressures of ≥ 0.1-0.2 torr is needed (due to large power in X-ray channel). Similar results for W
- No major constraint from injection/tracking.
- Operation at high gas pressure may be needed to stop all of the debris ions and recycle the target material.
- Heavy-ion stand-off issues:
  - ✓ Pressure too high for neutralized ballistic transport (mainline of heavy-ion program).
  - ✓ ARIES program funded research in neutralized ballistic transport with plasma generator and pinch transport (self or pre-formed pinch) in FY02.



Beam Transport Option for Heavy-Ion Driver

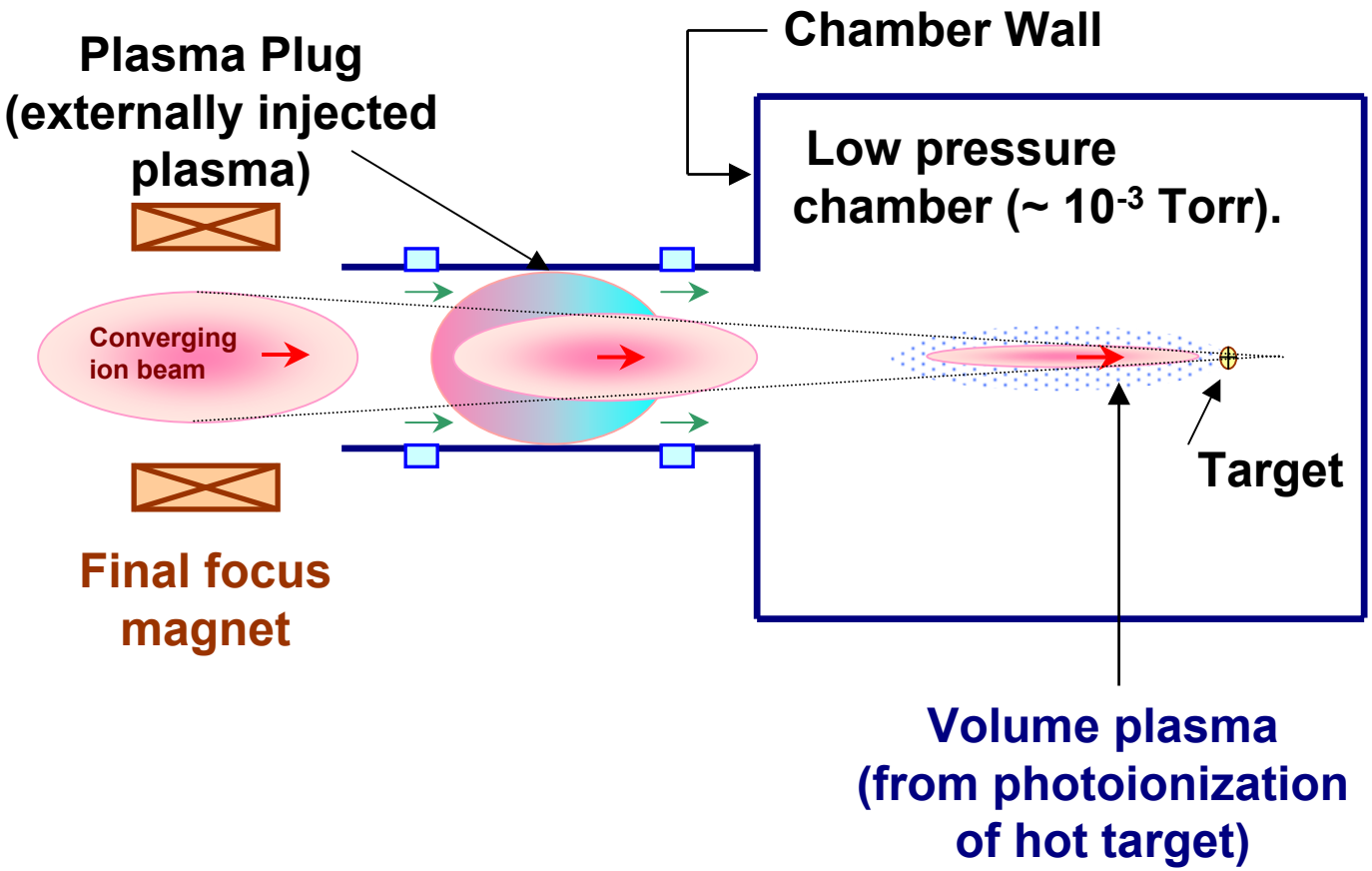
Transport Mode / Chamber Concept	Ballistic Transport *chamber holes ~5 cm radius* *most studied*		Pinch Transport *chamber holes ~0.5 cm radius* *higher risk, higher payoff*	
	Vacuum-ballistic *vacuum*	**Neutralized-ballistic** *plasma generators*	**Preformed channel** ("assisted pinch") *laser + z-discharge*	**Self-pinched** *only gas*
Dry-wall *~6 meters to wall*	Not considered now: Requires ~500 or more beams	Not considered: insufficient neutral-ization for 6 meters	Option: uses 1-10 Torr *2 beams*	Option: uses 1-100 mTorr ~2-100 beams
Wetted-wall *~4-5 meters to wall*	HIBALL (1981) Not considered: Needs ≤ 0.1 mTorr leads to ⇦	OSIRIS-HIB (1992) Possible option: but tighter constraints on vacuum and beam emittance	Option: uses 1-10 Torr *2 beams*	PROMETHEUS-H (1992) Option: uses 1-100 mTorr ~2-100 beams
Thick-liquid wall *~3 meters to wall*	Not considered: Needs ≤ 0.1 mTorr leads to ⇧	HYLIFE II (1992-now) Main-line approach: uses pre-formed plasma and 1 mTorr for 3 meters *~50-200 beams*	Option: uses 1-10 Torr *2 beams*	Option: uses 1-100 mTorr ~2-100 beams

ARIES-funded research shows that neutralized ballistic transport is feasible for 6-m chambers

ARIES has funded research on pinch transport

Slide from D. Welch (MRC) presentation at Jan. 2002 ARIES Meeting

Neutralized Ballistic Transport



Slide from D. Welch (MRC) presentation at Jan. 2002 ARIES Meeting

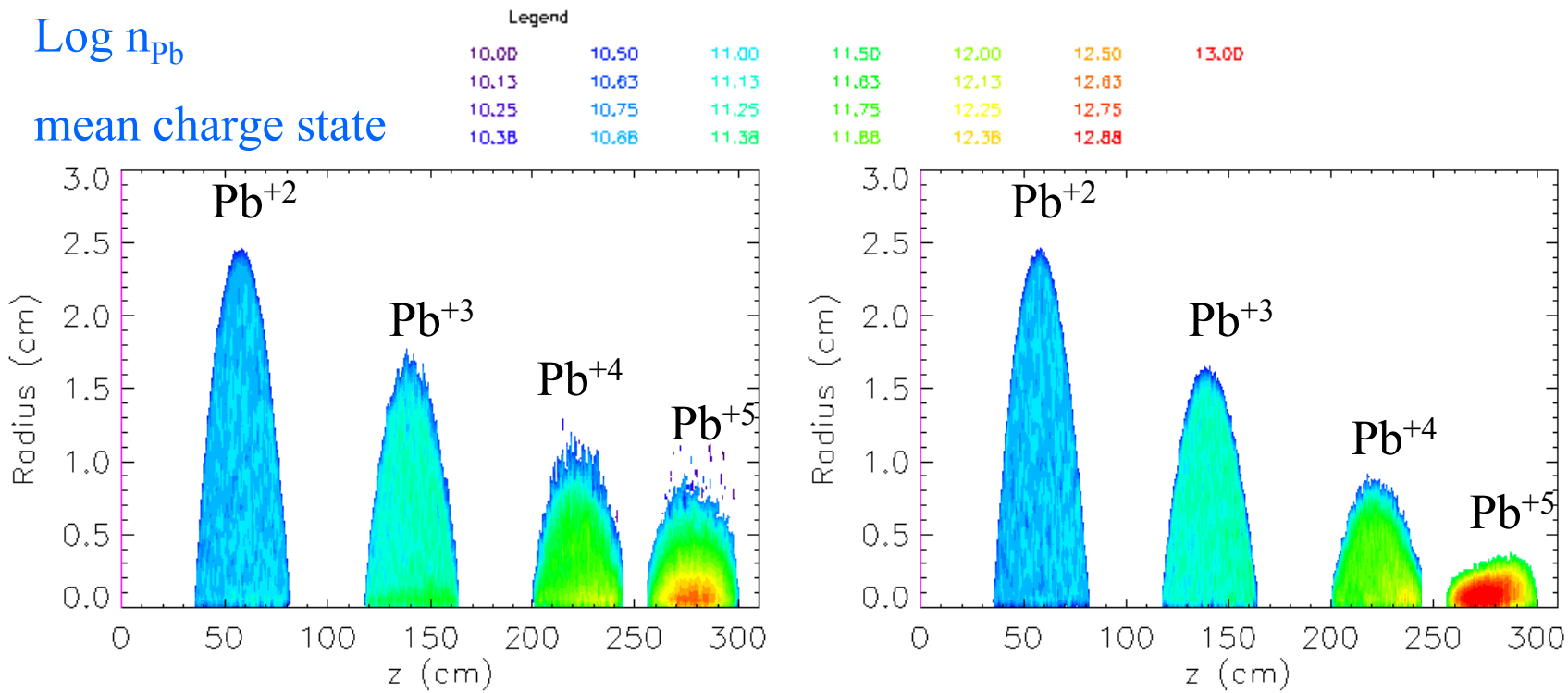
Plasma neutralization crucial to good spot

Stripped ions deflected by un-neutralized charge at beam edge*

Plasma provides > 99% neutralization, focus at 265 cm

Log n_{Pb}

mean charge state



No Plasma

Plasma

*D. A. Callahan, Fusion Eng. Design **32-33**, 441 (1996)

Slide from D. Welch (MRC) presentation at Jan. 2002 ARIES Meeting

Conclusions

- Photo ionization plasma assists main pulse transport - but not available for foot pulse
- Without local plasma at chamber, beam transport efficiency is < 50% within 2 mm for "foot" pulse
- Electron neutralization from plasma improves efficiency to 85% - plasma plug greatly improves foot pulse transport
- Lower chamber pressure should help beam transport for both foot and main pulses given plasma at chamber wall
- 6-m NBT transport with good vacuum looks feasible for dry wall chamber design
- System code: "Alpha" factor for neutralization roughly 1 in vacuum, increases with increasing pressure and propagation distance

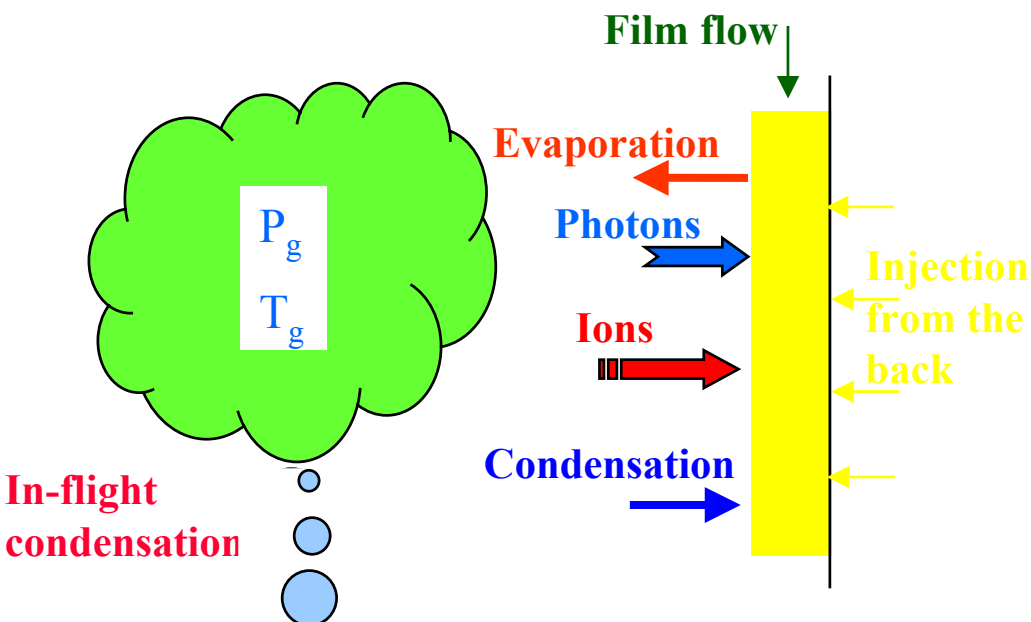
Major Issues for Wetted Wall Chambers

Wall protection:

- Armor film loss:
  - ✓ Energy deposition by photon/ion
  - ✓ Evaporation
- Armor film re-establishment:
  - ✓ Recondensation
  - ✓ Coverage: hot spots, film flow instability, geometry effects
  - ✓ Fresh injection: supply method (method, location)

Chamber clearing requirements:

- ✓ Vapor pressure and temperature
- ✓ Aerosol concentration and size
- ✓ Condensation trap in pumping line



Key processes:

- Condensation
- Aerosol formation and behavior
- Film dynamics

Analysis & Experiments of Liquid Film Dynamics Are On-going

- Re-establishment of the Thin Liquid Film Is the Key Requirement.
  - ✓ Recondensation
  - ✓ Fresh injection: supply method (method, location)
  - ✓ Coverage: hot spots, film flow instability, geometry effects.
- 2-D & 3-D Simulations of liquid lead injection normal to the chamber first wall using an immersed-boundary method.

  Objectives:
  - ✓ Onset of the first droplet formation
  - ✓ Whether the film "drips" before the next fusion event

  Parameters
  - ✓ Lead film thicknesses of 0.1 - 0.5 mm; Injection velocities of 0.01 - 1 cm/s;
  - ✓ Inverted surfaces inclined from 0 to 45° with respect to the horizontal
- Experiments on high-speed water films on downward-facing surfaces, representing liquid injection tangential to the first wall
  - ✓ Objective: Reattachment of liquid films around cylindrical penetrations typical of beam and injection port.

ARIES Research Plans for FY03-FY05

We would like to continue ARIES IFE research

- ARIES-IFE has been technically successful. It is an excellent example of , IFE and MFE researchers together and large synergy between MFE
- Focus of ARIES IFE activities will be critical issues for heavy-ion inertial fusion as highlighted by ARIES-IFE research.
  - ✓ Beam propagation studies for chambers at relatively high pressure:
    - Channel-assisted Pinch (pressures between 1 to 20 torr)
    - Self-pinch (1 to 100 mTorr)
    - Balastic Neutralized Transport (1 to 100 mTorr)
  - ✓ Integrated engineering of final HI optics and chamber interface:
  - ✓ Detailed studies of aerosol generation and transport to explore thin-liquid wall chamber concepts.
  - ✓ Detailed studies of selected system for thick liquid wall concepts.

We would like to initiate a three-year study of compact stellarators as power plants

- Initiation of NCSX and QSX experiments in US; PE experiments in Japan (LHD) and Germany (W7X);
- Review committees have asked for assessment of compact stellarator option as a power plant; Similar interest has been expressed by national stellarator program.
- Such a study will advance physics and technology of compact stellarator concept and addresses concept attractiveness issues that are best addressed in the context of power plant studies.
- NCSX and QSX plasma/coil configurations are optimized for most flexibility for scientific investigations. Optimum plasma/coil configuration for a power plant may be different. Identification of such optimum configuration will help compact stellarator research program.

ARIES-Compact Stellarator Program is a Three-year Study

FY03: Development of Plasma/coil Configuration Optimization Tool

1. Develop physics requirements and modules (power balance, stability, α confinement, divertor, *etc.)*
2. Develop engineering requirements and constraints.
3. Explore attractive coil topologies.

FY04: Exploration of Configuration Design Space

1. Physics: β, aspect ratio, number of periods, rotational transform, sheer, *etc.*
2. Engineering: configurationally optimization, management of space between plasma and coils.
3. Choose one configuration for detailed design.

FY05: Detailed system design and optimization