# Overview of US Power Plant Studies: A) Results from ARIES-IFE Study B) Plans For Compact Stellarator

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

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

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

## ARIES activities in FY03:

- **ARIES-IFE study was continued for another year (~50% of the effort):**
  - ✓ The ARIES-IFE study is now officially completed.
  - ✓ Work in FY03 was focused on thick-liquid wall concept (*i.e.*, HYLIFE)
  - ✓ Results from 2001 and 2002 research will appear in Journal of Fusion Science & Technology (pre-prints available on ARIES Web site).
- **ARIES compact stellarator (ARIES-CS) was started (~50% of effort)**
  - ✓ This is a three-years study
  - ✓ All of ARIES Team effort will be devoted to ARIES-CS in FY04.

# Selected Results from
# ARIES-IFE Studies
# (Laser-Driven Direct-Drive Systems)

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

**Objectives:**

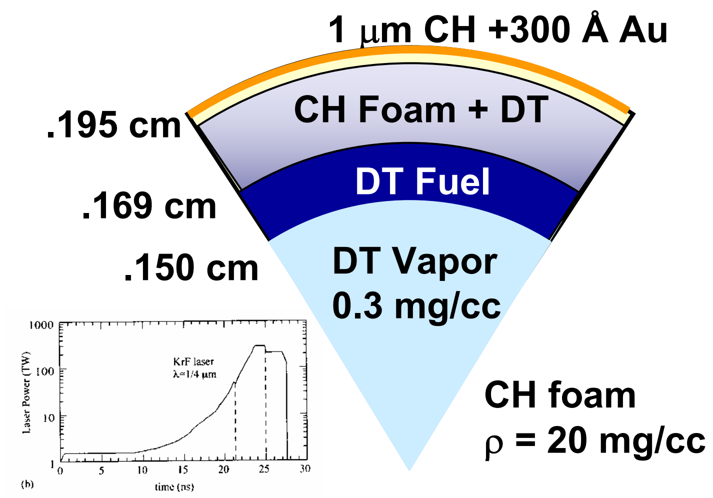
- Analyze & assess integrated and self-consistent IFE chamber concepts
- Understand trade-offs and identify design windows for promising concepts. *The research is **not** aimed at developing a point design.*

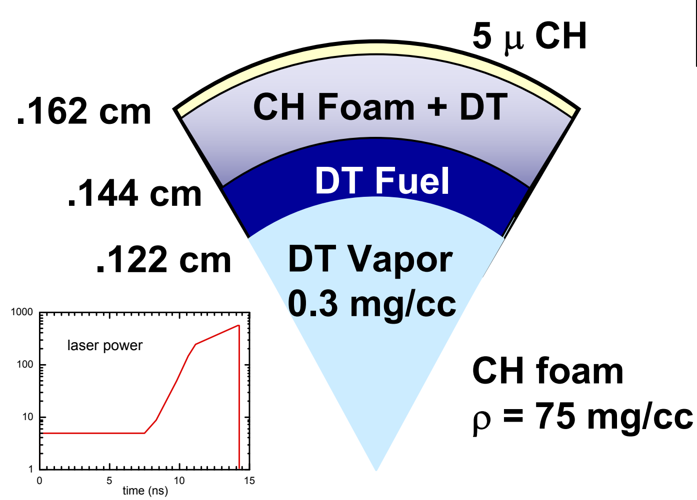
**Approach:**

- 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.

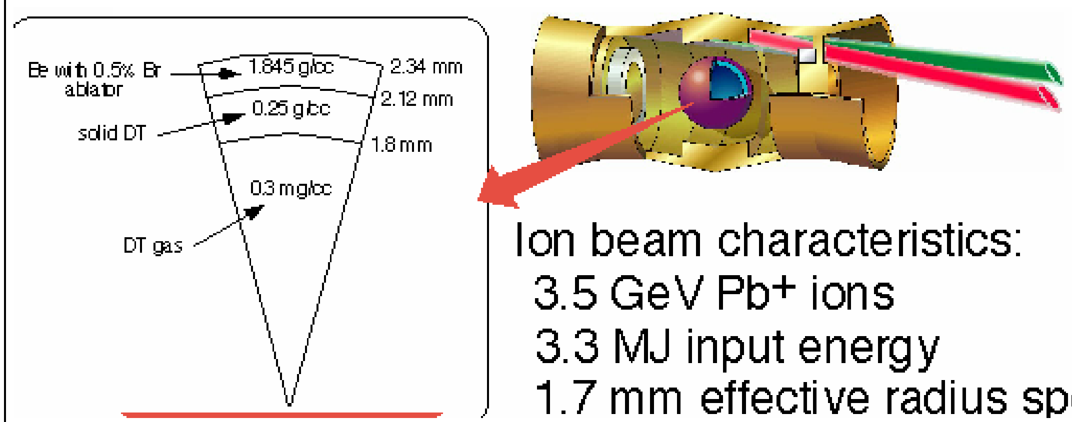
# Reference Direct and Indirect Target Designs

## NRL Advanced Direct-Drive Targets




## LLNL/LBNL HIF Target

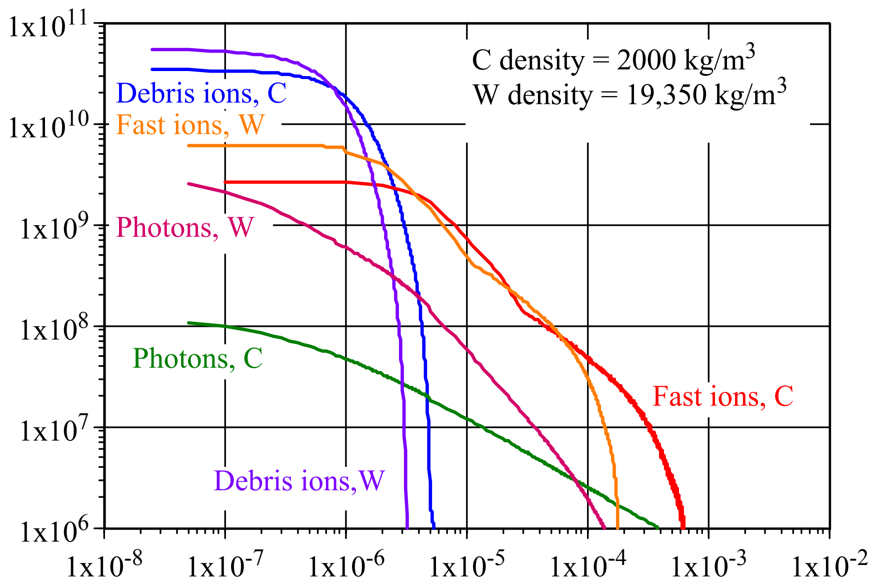



Ion beam characteristics:
3.5 GeV Pb+ ions
3.3 MJ input energy
1.7 mm effective radius spot

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

# 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)**



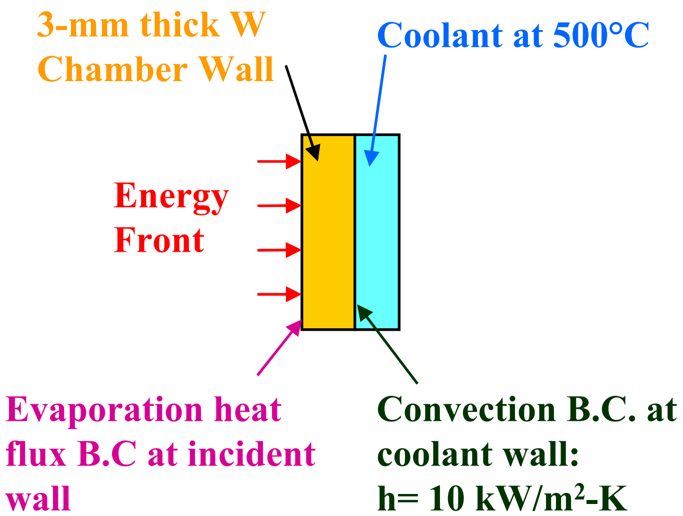

- ➢ Heat fluxes are much lower than predicted in previous studies:
- ✓ A much smaller portion of target yield is in X-rays.
- ✓ Time of flight of ions spread the temporal profile of energy flux on the wall over several μs.
- ➢ A cover gas may not be necessary for protecting the chamber wall

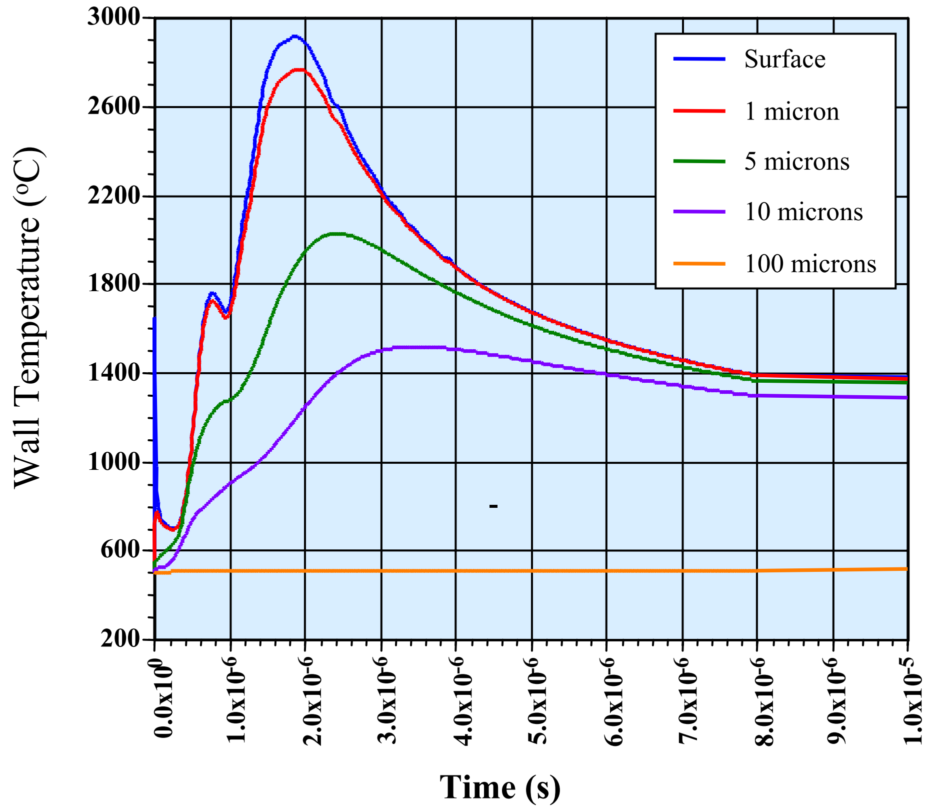
- ➢ Photon and ion energy deposition falls by 1-2 orders of magnitude within 0.1 mm of surface.

# Dry Wall Concepts

# Thermal Response of a W Flat Wall

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

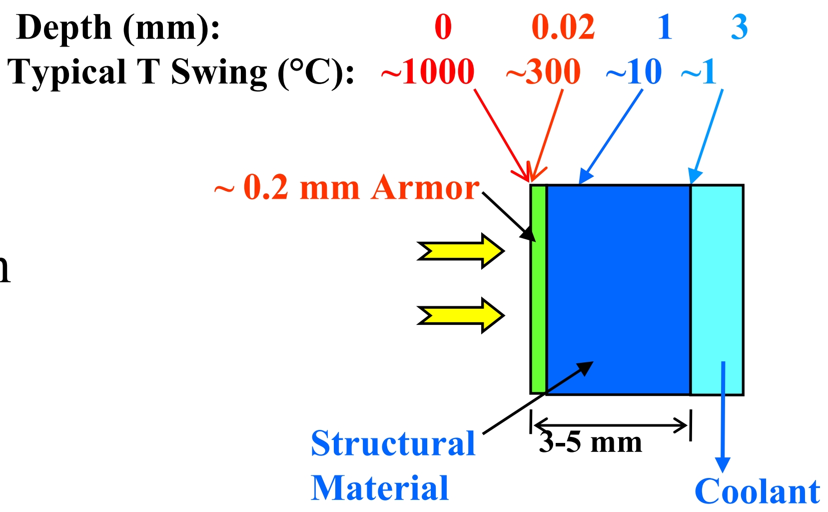



- Temperature variation mainly in thin (0.1-0.2 mm) region.
- Margin for design optimization (a conservative limit for tungsten is to avoid reaching the melting point at 3,410°C).
- Similar margin for C slab.

# 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
- **Blanket design can be adapted from MFE blankets**
- **Significant high-energy ion flux on the armor.**

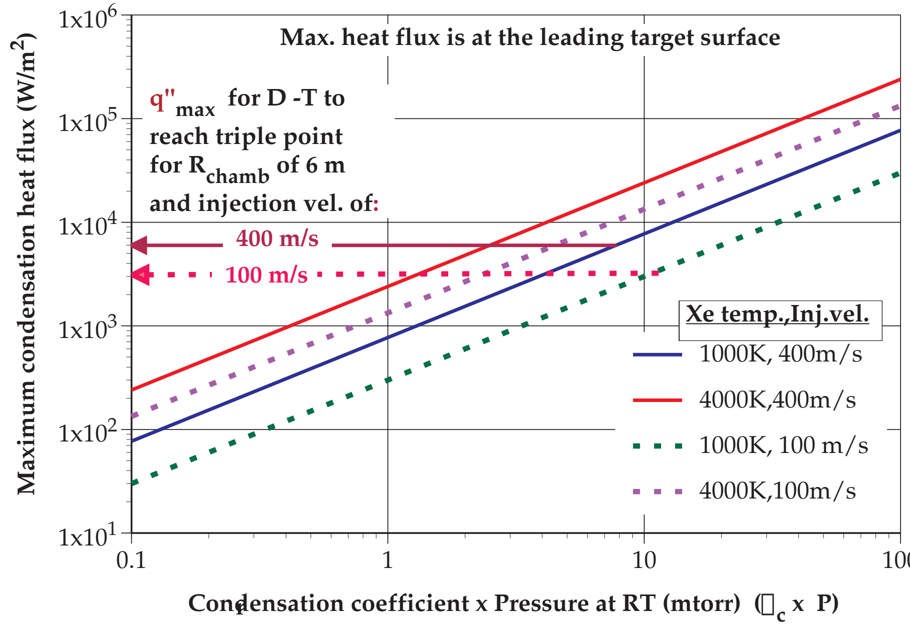
# IFE Armor Conditions are similar to those for MFE PFCs (ELM, VDE, Disruption)

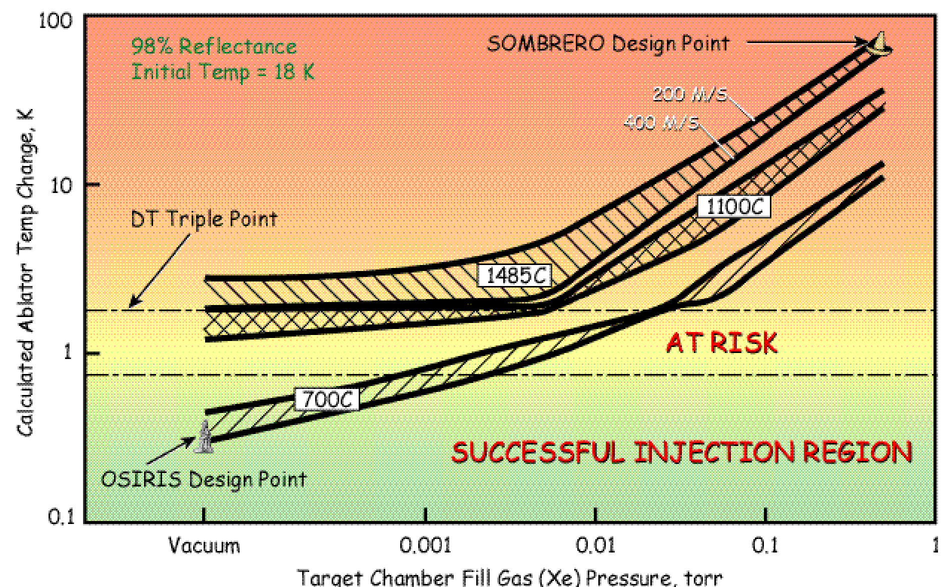
| | ITER Type -I ELM's | ITER VDE's | ITER Disruptions | Typical IFE Operation (direct-drive NRL target) |
|---|---|---|---|---|
| Energy | <1 MJ/m$^2$ | ~ 50 MJ/m$^2$ | ~ 10 MJ/m$^2$ | ~ 0.1 MJ /m$^2$ |
| Location | Surface near div. strike points | surface | surface | bulk (~µm's) |
| Time | 100-1000 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.**

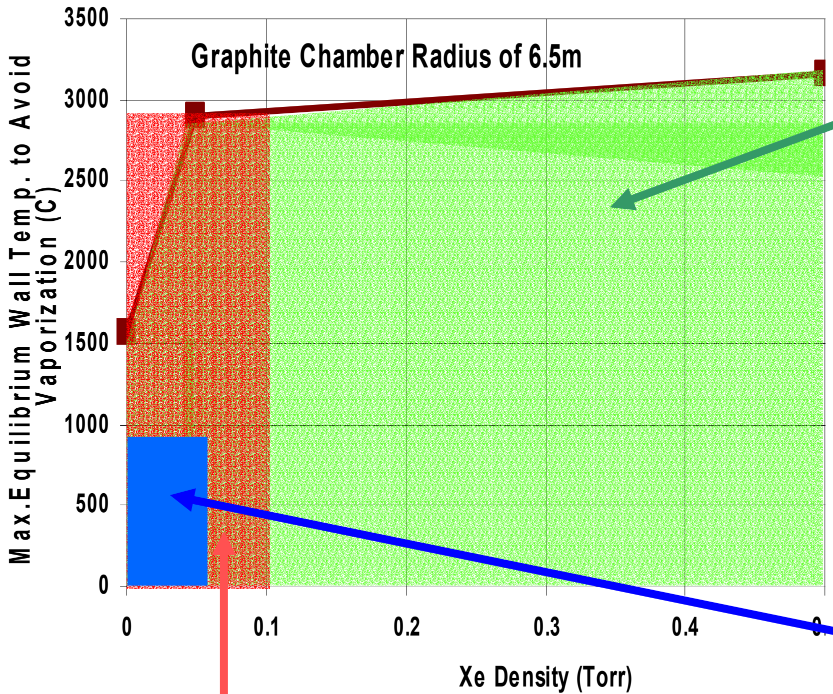
# Target injection Design Window Naturally Leads to Certain Research Directions

- 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.



# 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

# Wetted-Wall Concepts

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

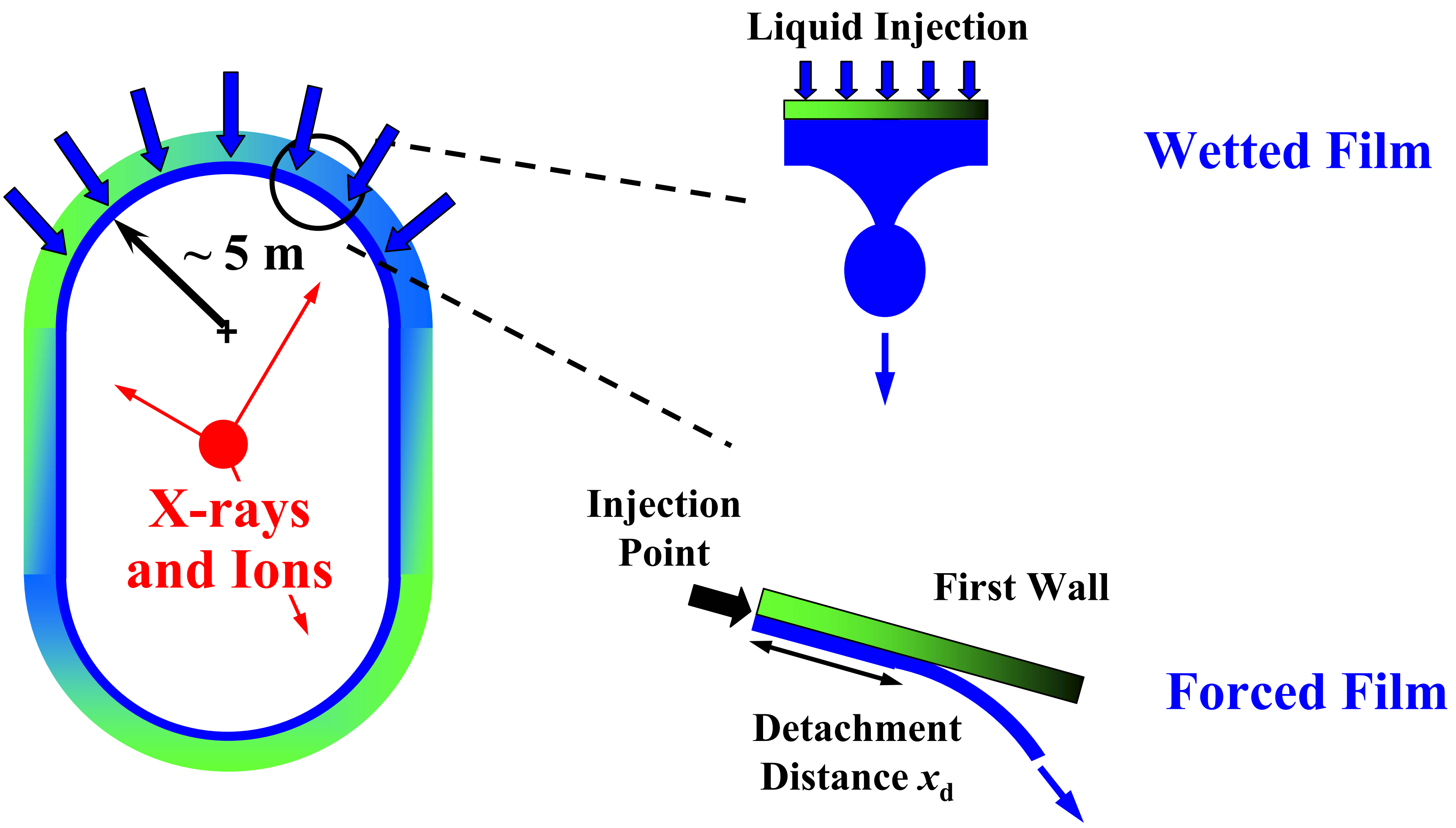
A renewable thin-liquid protection resolve several issues:

- 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



# We Have Developed Design Widows for Establishment and Stability of the Protective Film

"Wetted-wall" concept:

- Developed general non-dimensional charts for film stability over a wide variety of candidate coolants and operating conditions.
- Model predictions are closely matched with experimental data.
- It will eliminate damage to the armor/first wall due to high-energy ions.

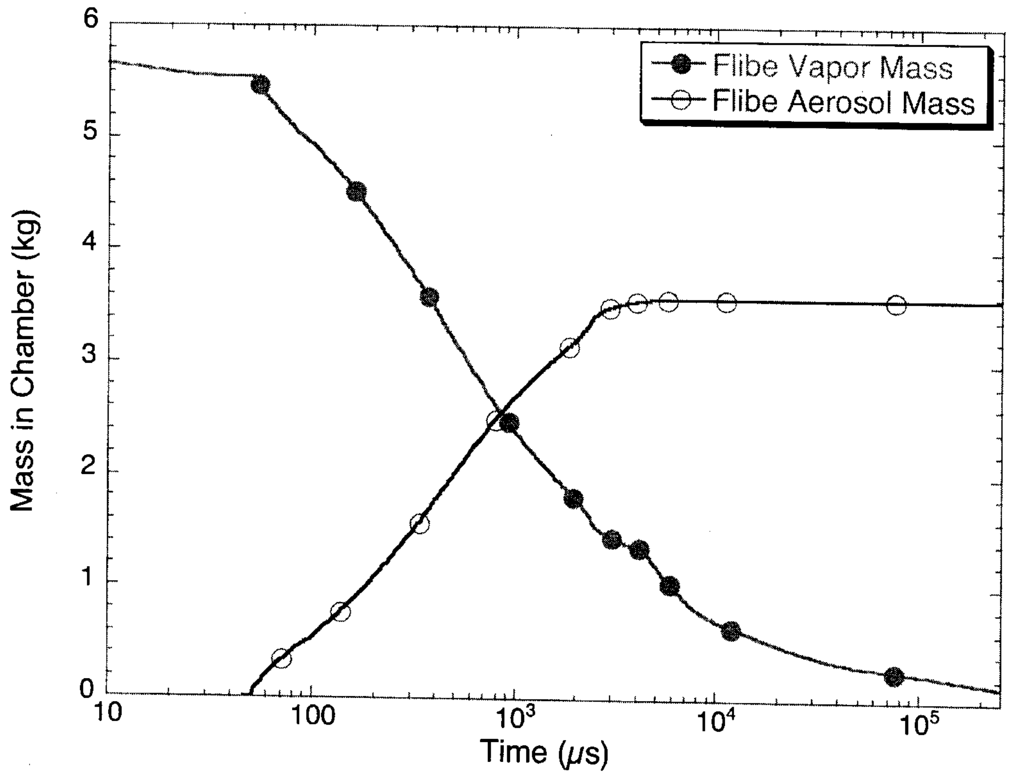
"Forced-flow" concept:

- Developed non-dimensional design widows for longitudinal spacing of injection/coolant/removal slots to maintain attached protective film;
- A wetting first wall surface requires fewer injection slots than non-wetting surface – Wetting surfaces are more desirable.

- Details are given in Prof. Abdel-Khalik's Presentation.

# Most of Ablated Material Would Be in The Form of Aerosol

- FLiBe aerosol and vapor mass history in a 6.5-m radius following a target explosion (ablated thickness of 5.5 mm)
- Most of ablated material remains in the chamber in aerosol form;
- Only homogeneous nucleation and growth from the vapor phase.



# 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")

- Details are given in Dr. Tillack's Presentation.

# ARIES Research Plans for FY03-FY05

# We Have Initiated a Three-Years Study of Compact Stellarators as Power Plants

- Initiation of NCSX and QSX experiments in US; Successful operation of LHD in Japan and construction of W7X in Germany;
- 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 Was Proposed as a Three-year Study

**FY03: Assessment of systems options**

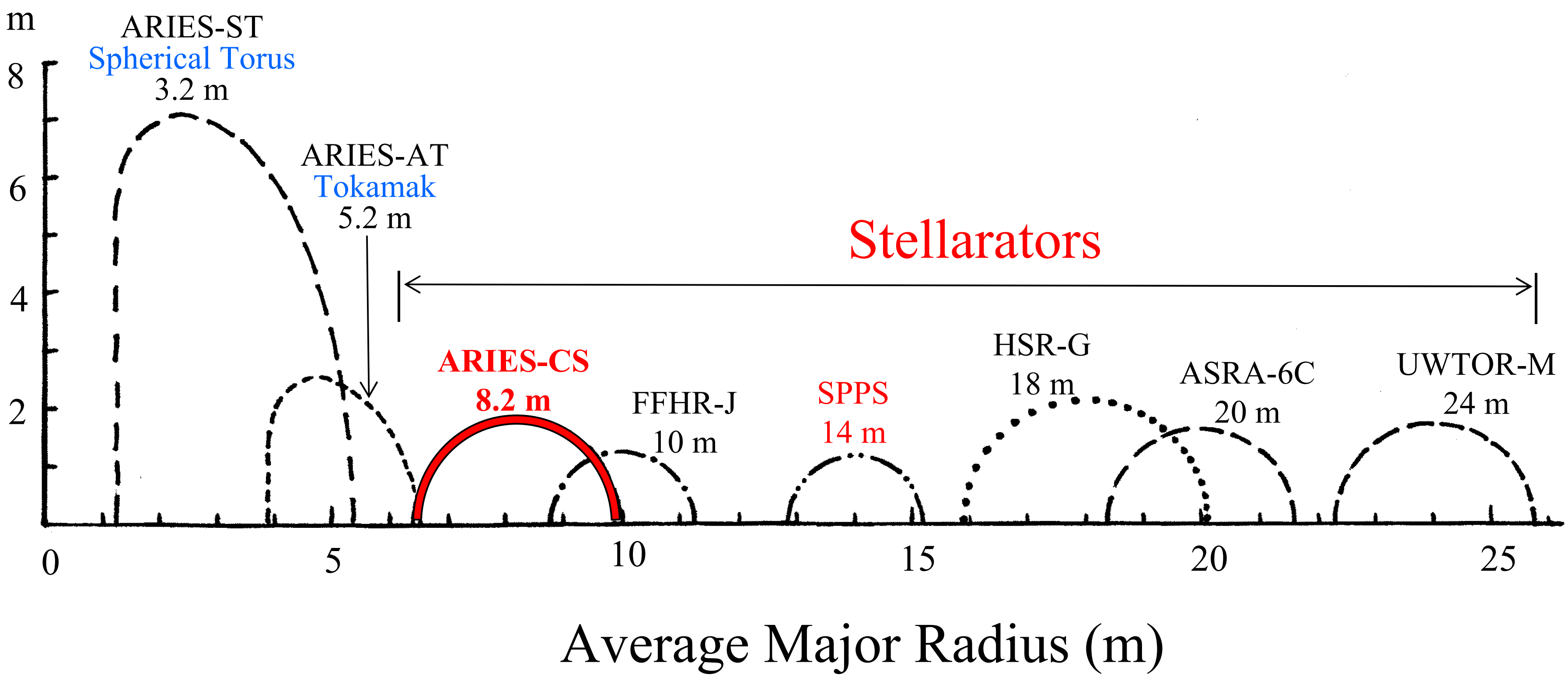
1. Develop physics requirements and modules (power balance, stability, α confinement, divertor, *etc.)*
2. Develop engineering requirements and constraints.
3. Explore attractive coil topologies.

**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**

# Comparison of Power Plant Sizes



# Status of ARIES-CS Study

- Because only half of ARIES effort was devoted to ARIES-CS in FY03 and reduction in funding in FY04, the study will probably stretch into FY 06.
- We have developed two candidate configuration for a self-consistent evaluation (Details in Dr. Mau's Presentation).
- Our initial engineering assessment has highlighted maintenance as a key driver for blanket selection. (Details in Dr. Raffray's Presentation).
- An ARIES Town-Meeting with Stellarator physicist is planned for Dec. 5-6 in PPPL.
- We should explore possibilities of collaborations in the helical systems in this workshop.