Overview of the HAPL IFE Dry Wall Chamber Studies in the US

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Outline

- **Summary of IFE Technology Effort in US**
- **HAPL Program Overview**
- **HAPL Dry Wall Chamber Effort**
- **Conclusions**

IFE Chamber Studies in US

- **ARIES-IFE study concluded a couple of years ago**
  - focused on evolving parameter design space
  - laser and heavy ion drivers
  - direct and indirect-drive targets
  - dry wall, wetted wall and thick liquid wall chambers
  - results reported at several conferences and most recently in special issue of Fusion Science & Technology (November 2004)

- **In recent years, IFE technology funding has decreased and finally been zeroed out from DOE OFES budget**
  - Serious impact on heavy ion, indirect-drive target, thick liquid wall chamber studies (HYLIFE)

- **Only IFE technology funding is through Congress add-ons and funded through DP branch of DOE**
  - HAPL study (multi-year, multi-institution effort led by NRL)
  - Z-pinch study (starting last year, led by SNL)

The Path to develop Laser Fusion Energy
(courtesy of John Sethian)

Phase I:
Basic fusion science & technology
1999- 2005

HAPL
Krypton fluoride laser
Diode pumped solid state laser
Target fabrication & injection
Final optics
Chambers materials/design

Target design & Physics
2D/3D simulations
1-30 kJ laser-target expts

Phase II
Validate science & technology
2006 - 2014

Full Scale Components
Power plant laser beamline
Target fab/injection facility
Power Plant design

Ignition Physics Validation
MJ target implosions (NIF)
Calibrated 3D simulations

Phase III
Engineering Test Facility
operating ~ 2020

- ***Full size laser: 2.4 MJ, 60 laser lines***
- ***Optimize targets for high yield***
- ***Develop materials and components.***
- ***~ 300-700 MW net electricity***

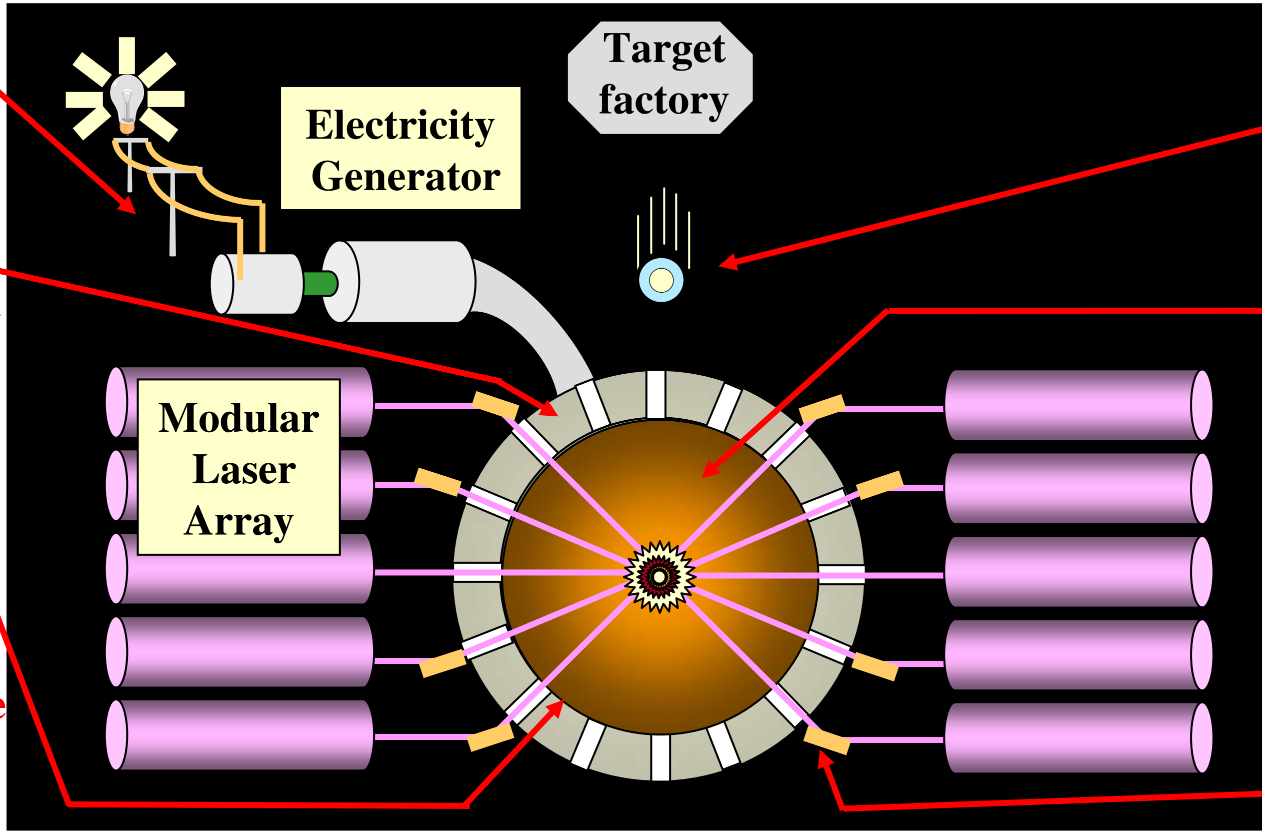
The HAPL Program Aims at Developing a New Energy Source: IFE Based on Lasers, Direct Drive Targets and Solid Wall Chambers

(Major chamber interfacing systems/components)

System (including power cycle)

Blanket (make the most of MFE design and R&D info)

Dry wall chamber (armor must accommodate ion+photon threat and provide required lifetime)



Target injection, (survival and tracking)

Chamber conditions (physics)

Final optics (+ mirror steering)

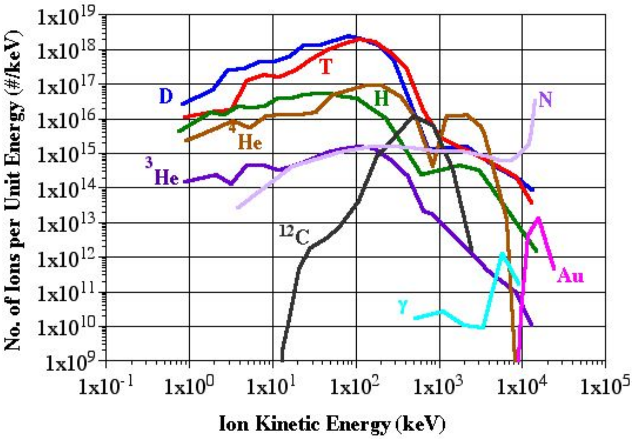
- **Modular, separable parts: lowers cost of development AND improvements**
- **Conceptually simple: spherical targets, passive chambers**
- **Builds on significant progress in US Inertial Confinement Fusion Program**

HAPL

Chamber Physics Needs to be Understood

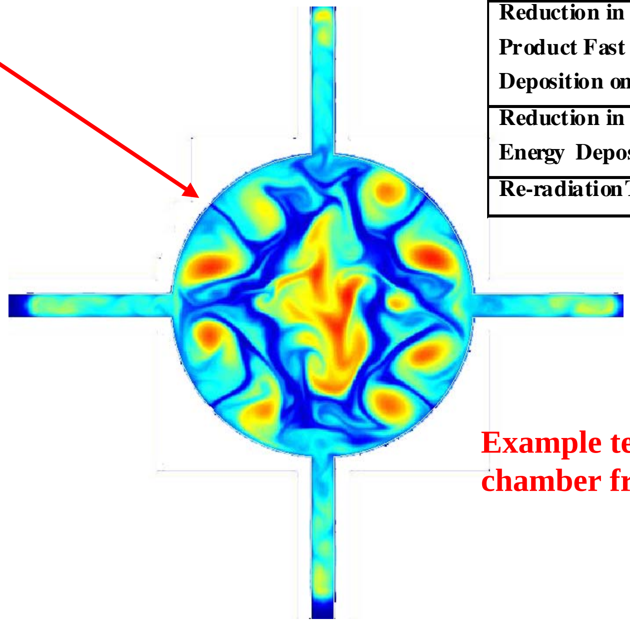
Ion and Photon Threat Spectra and Chamber Conditions Prior to Each Shot Must Be Well Characterized (UW)

- Attenuation of ion and photon spectra seen by wall by using a protective chamber gas
- Dynamics of chamber gas (including fusion micro-explosion products) need to be understood to ascertain chamber conditions prior to each shot (UCSD model)
  - Multi-dimensional
  - Heat transfer mechanisms (including radiation)
  - Turbulence effects
  - Laser lines and effect on final optics
  - Impact target injection and survival



Chamber Gas Ion and Photon Attenuation for Chamber with R=6.5 m (from BUCKY)

Gas Density (mTorr at 300K)	10	20
Reduction in Initial Photon Intensity on the Wall	9%	16%
Reduction in Initial Burn Product Fast Ions Energy Deposition on the Wall	1%	2%
Reduction in Initial Debris Ions Energy Deposition on the Wall	29%	48%
Re-radiation Time Scale (μs)	300-700	300-700

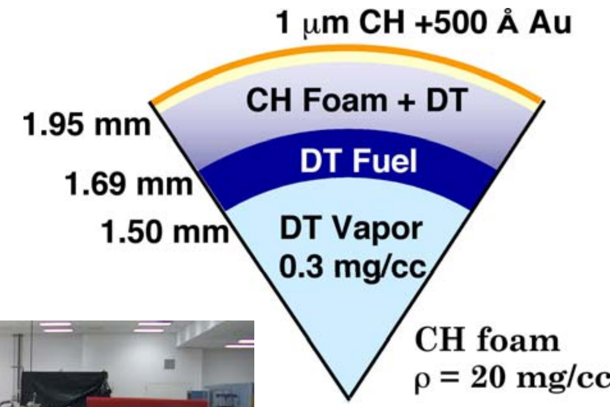


Example temperature distribution in chamber from SPARTAN analysis

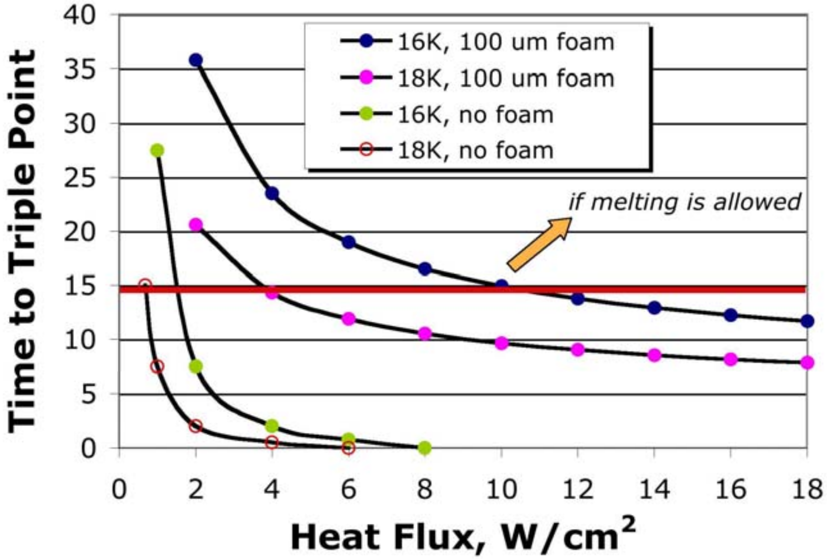
Must Ensure Successful Injection & Tracking and Survival of Target (GA/UCSD/LLE)

- **Target injection & tracking**
  - Gas gun or electromagnetic injection
  - ±5 mm target injection accuracy, ~2 μm target/laser accuracy
  - mirror steering synchronized with target tracking

GA target injection facility

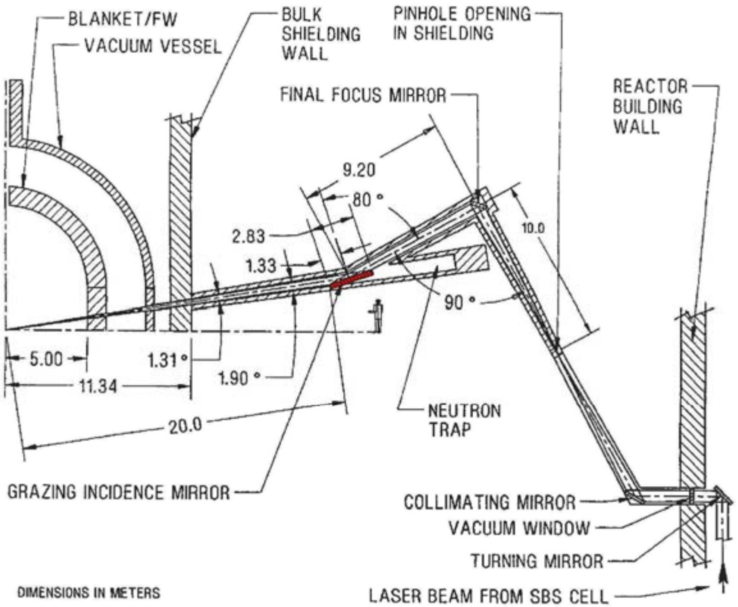


- **Target survival**
  - Must accommodate heat transfer from background gas and wall radiation and meet target integrity requirements based on target physics
  - Possibility of designing more thermally robust target



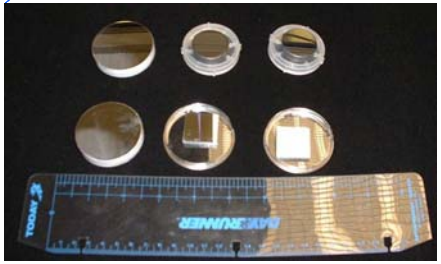
Long Term Survival & Optical Fidelity Required of Final Optics

- **We are developing damage-resistant final optics based on grazing-incidence metal mirrors and testing them (effort coordinated by UCSD; LLNL)**



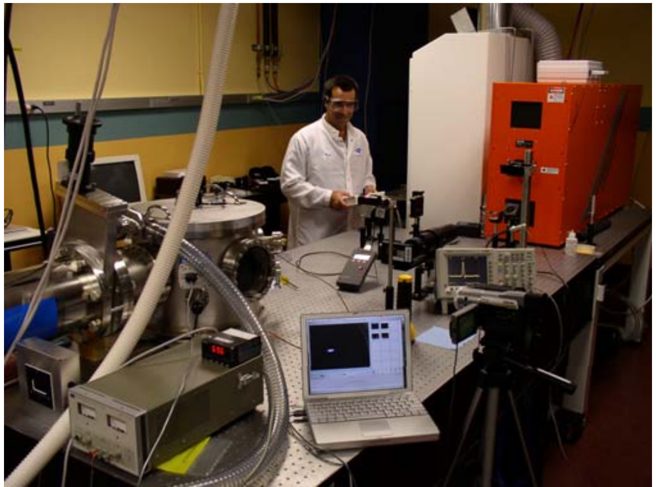
Material choices:

- Monolithic Al (>99.999% purity)
- Electroplating
- Thin film deposition on stiff, lightweight, radiation-resistant substrate (e.g. SiC)
- Surface finishing
- Advanced Al alloys



Mirror requirements:

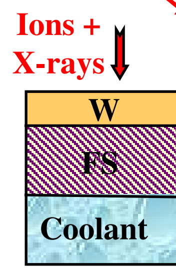
- 5 J/cm^2
- 2 yrs, 3x10^8 shots
- 1% spatial non-uniformity
- 20 μm aiming
- 1% beam balance

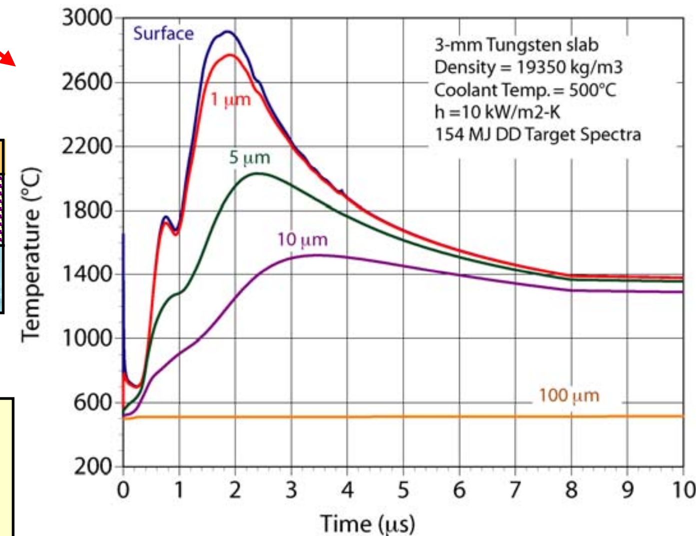


UCSD Laser Lab

Credible Armor/First Wall Configuration to Accommodate the Threat Spectra and Provide the Required Lifetime

- **Separation of function: armor for threat accommodation; FW for structural function**
  - Front runner configuration: thin W armor (~ 1 mm) on FS



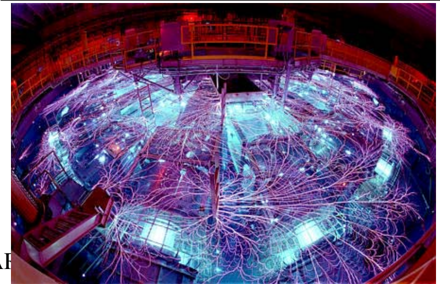


- **Exposure experiments + modeling to determine response of candidate material configuration to IFE ion and photon threats**
  - High temperature, repetitive pulses
  - Thermo-mechanical response
  - Lifetime

RHEPP (SANDIA) [repetitive ions]

DRAGONFIRE (UCSD Laser Lab) [mimic x-rays & ions]

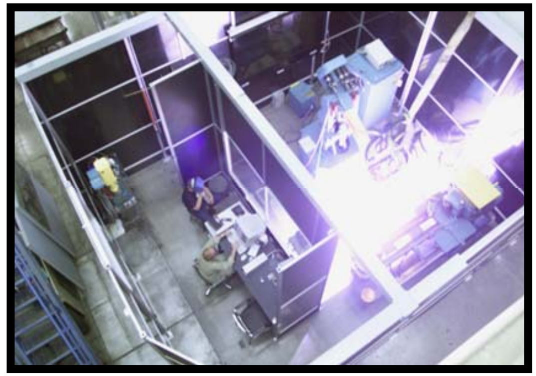
Z (SANDIA) [Single shot x-rays]

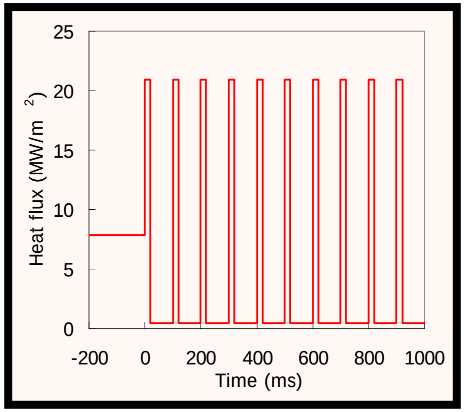


ZAPPER -LLNL [rep-rate x-rays]

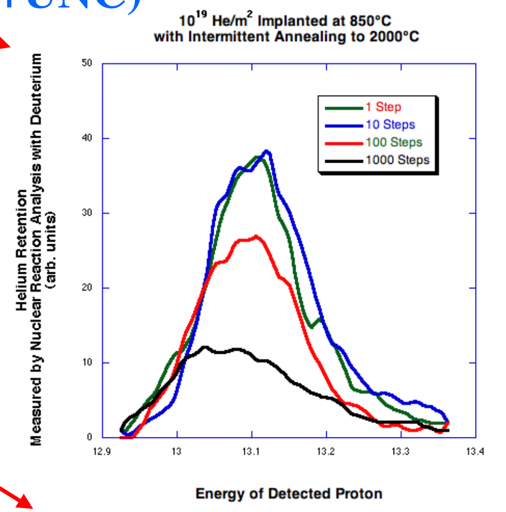
Assessment of Potential Causes of Armor Failure and Consideration Advanced "Engineered" Material for Potentially Superior Performance

- **W/FS bond development (ORNL)**
  - Testing in infrared facility (ORNL)
  - Modeling (T cycles, fatigue) (UW)



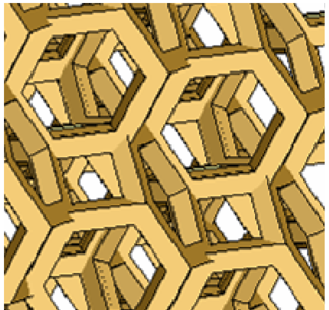


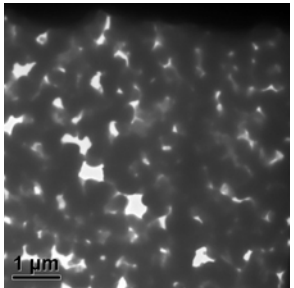
- **He retention**
  - He implantation/anneal cycle experiment + modeling (ORNL+UNC)
  - He + D implantation in IEC facility (UW)



- **Development of engineered (porous) W armor for longer lifetime (UCLA/Ultramet, PPI/UCSD)**
  - Stress relief
  - Enhanced release of implanted He ions (microstructure dimension smaller than He migration distance)

W foam (Ultramet/UCLA)



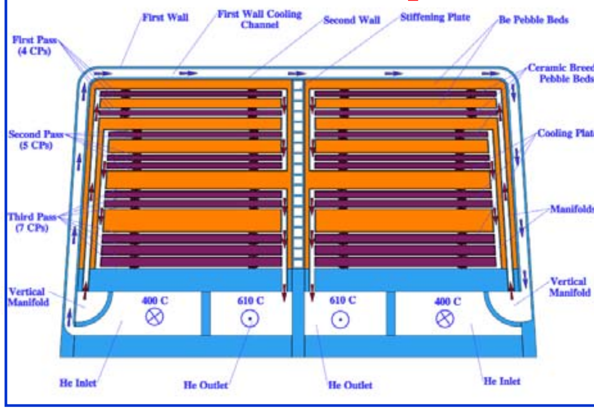


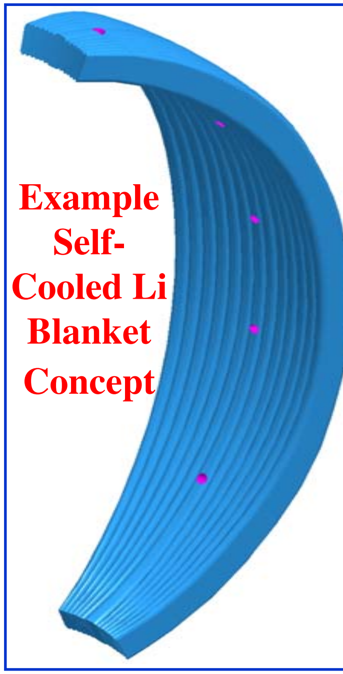
Vacuum Plasma Spray Porous W (PPI/UCSD)

The Blanket and Beyond: Strategy for Blanket Development and Integrated System Studies Study (UCSD/UW/LLNL)

- **Blanket strategy aims at making the most of MFE design and R&D info in developing an attractive IFE blanket concept**
  1. **Scoping study of blanket concepts coupled to selected power cycle(s) to the point where we can intelligently evaluate them and select most attractive one(s).**
  2. **Detailed design analysis of selected concept(s) closely integrated with our system studies and with design of interfacing components**

Example Ceramic Breeder Blanket Concept

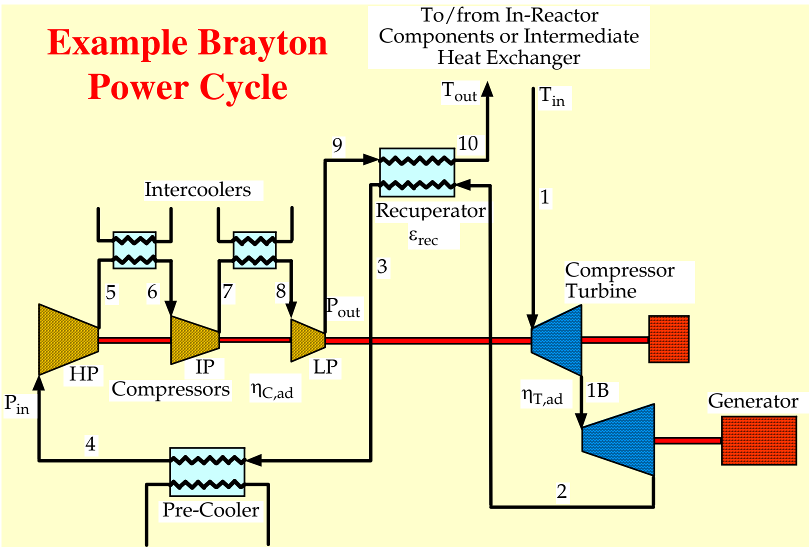




Example Self-Cooled Li Blanket Concept

- **System Studies Comprise a Multi-Step Approach:**
  1. **Develop tools and constraints and perform initial and scoping analysis of parameter space that accommodates material and design constraints.**
  2. **Complete integrated system code for laser IFE that includes performance scaling, constraints, cost for all major parts of the power plant (targets, drivers, chambers, power plant facilities, etc.)**
  3. **Perform full trade-off studies to help develop an integrated HAPL power plant conceptual design**

Example Brayton Power Cycle



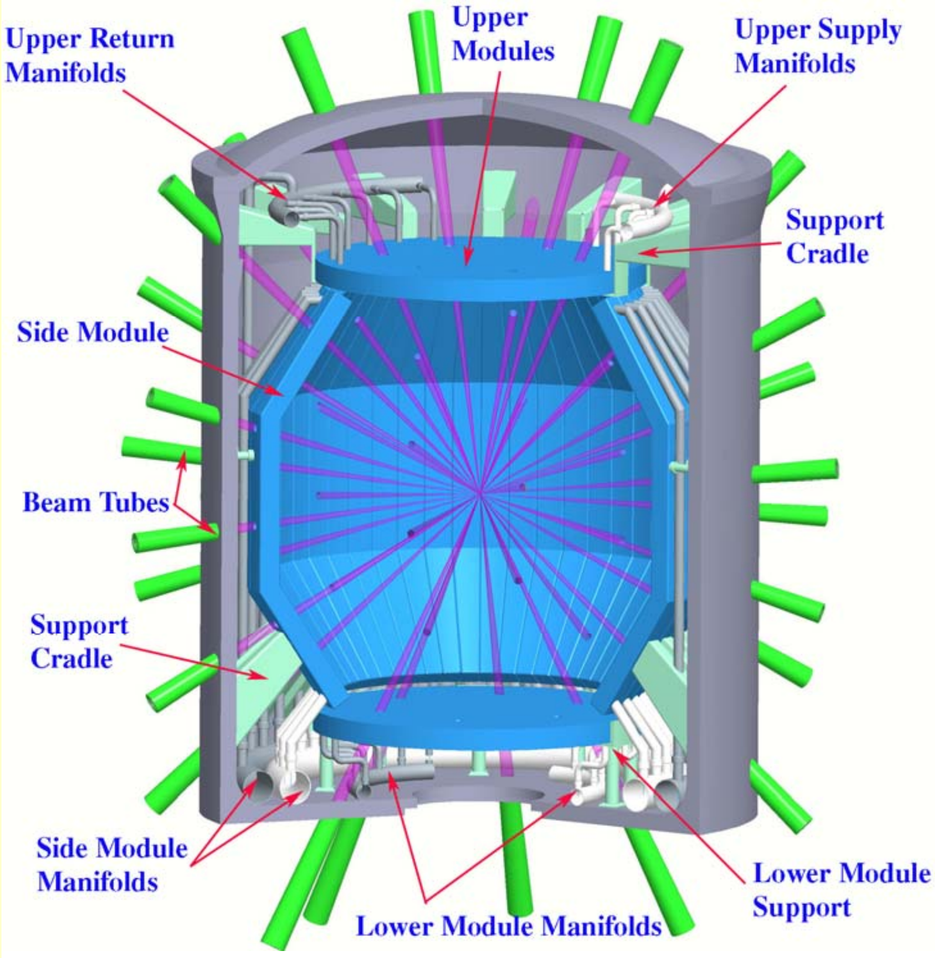
Interfaces Among the Different Components Very Important in Developing an Integrated View of an HAPL Power Plant

- **Phase I effort focused on basic science and technology of different components**

- **Effort has started to evolve a consistent integrated concept for an HAPL power plant based on the initial results available for the various components.**

  - **Concept will evolve as R&D and analysis progress.**
  - **Help highlight interface issues that need to be addressed**
  - **Help build credible case to go to Phase II.**

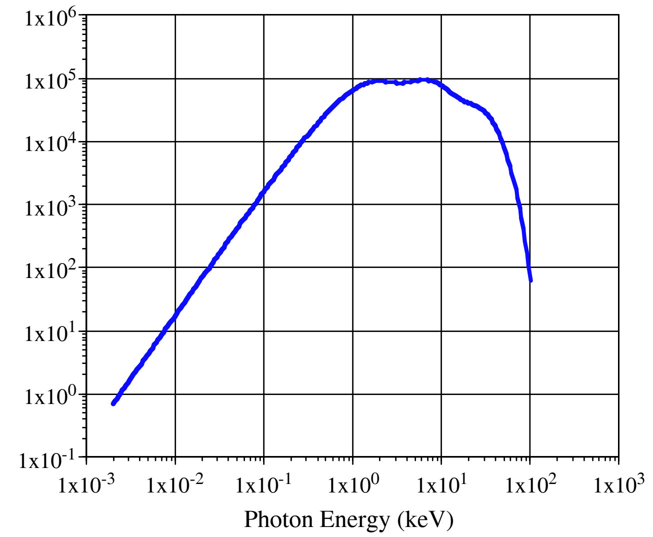
Initial Effort on Evolving In-Vessel Machine Layout

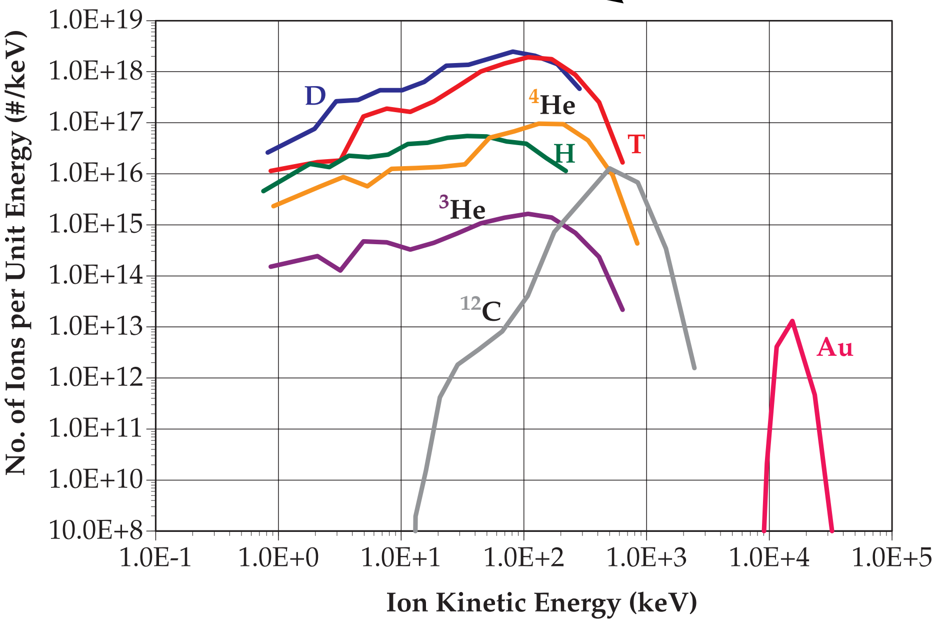


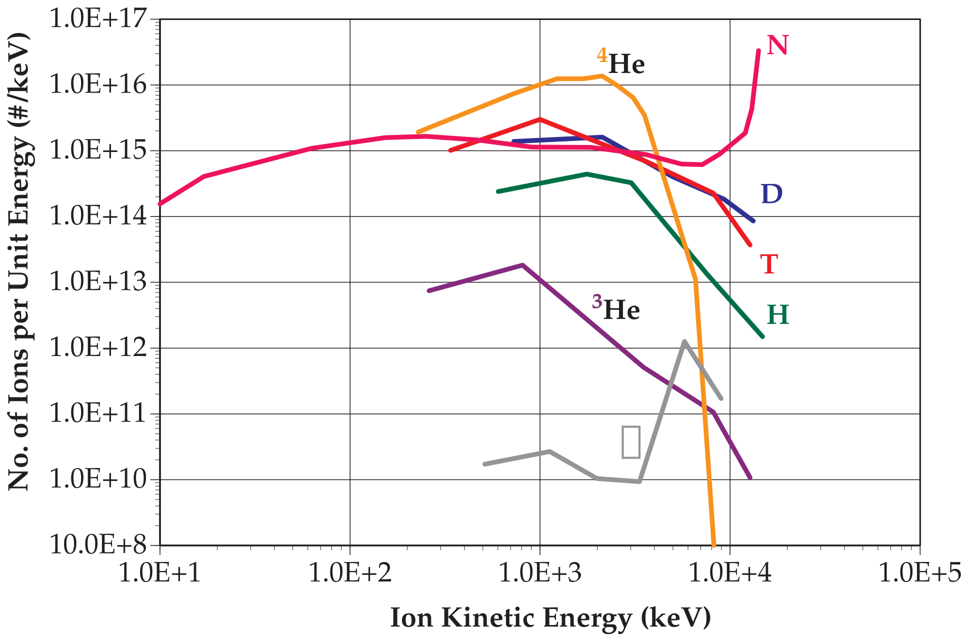
Example Integration Analysis of Chamber Armor/FW/Blanket (including Interface with Target Survival)

Start with spectra from NRL 154 MJ direct-drive target

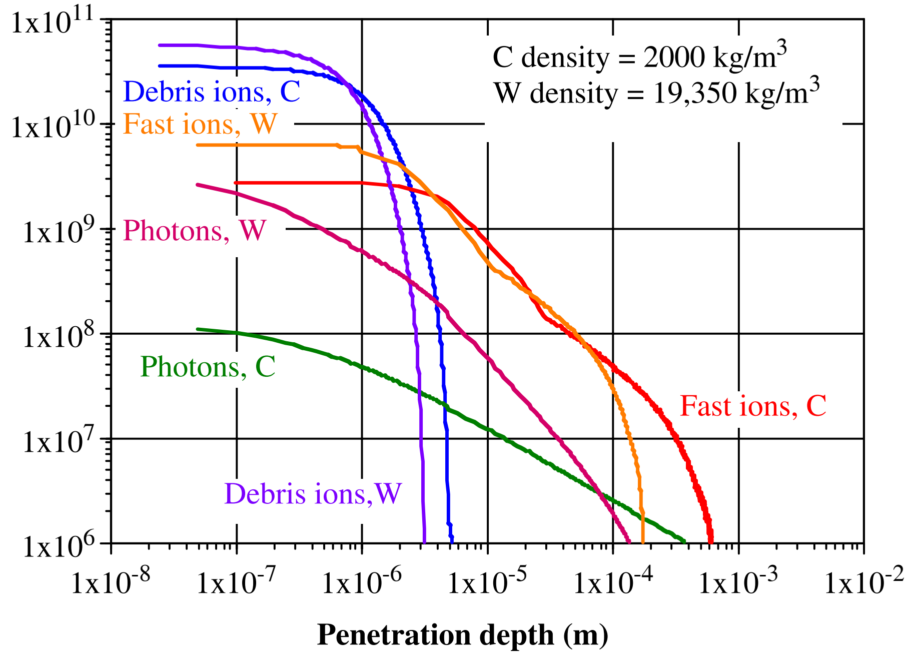
- Photon
- Fast ions
- Debris ions

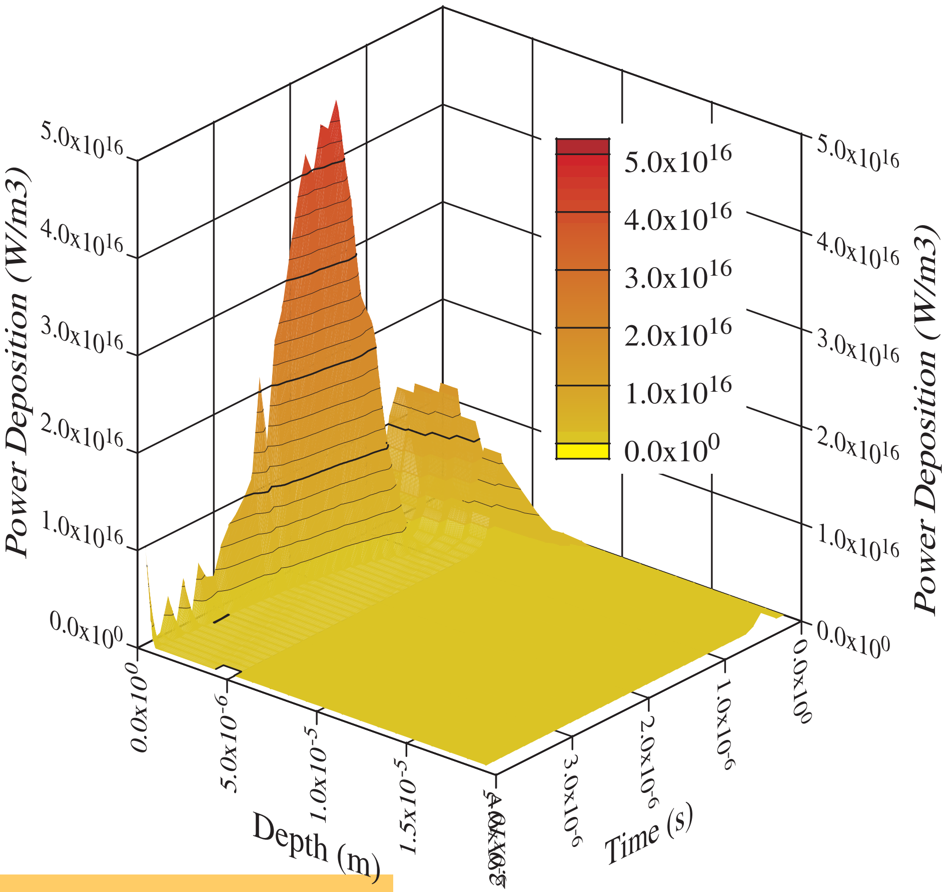




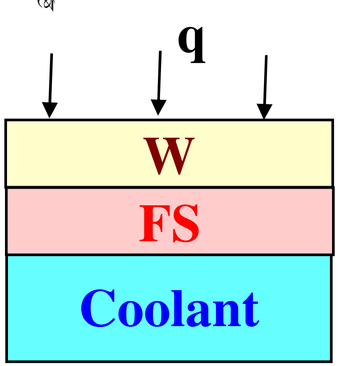


Calculate Energy Deposition in Armor Based on Spectra and Time of Flight Effect



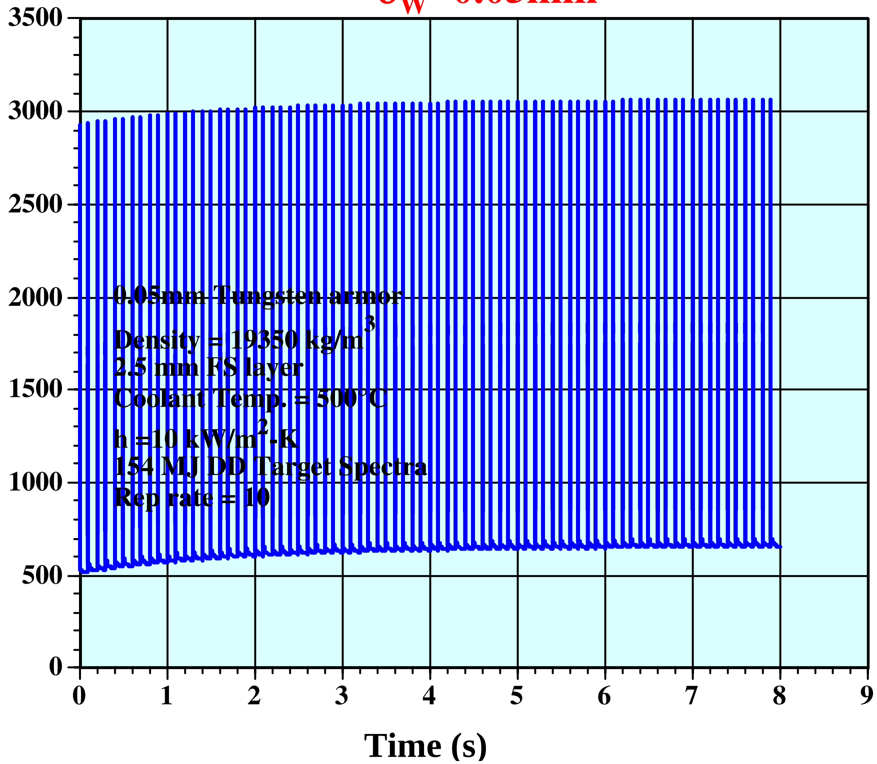


- **Use results of photon and ion energy deposition analysis as input in RACLETTE-IFE code to calculate cyclic armor thermal response**

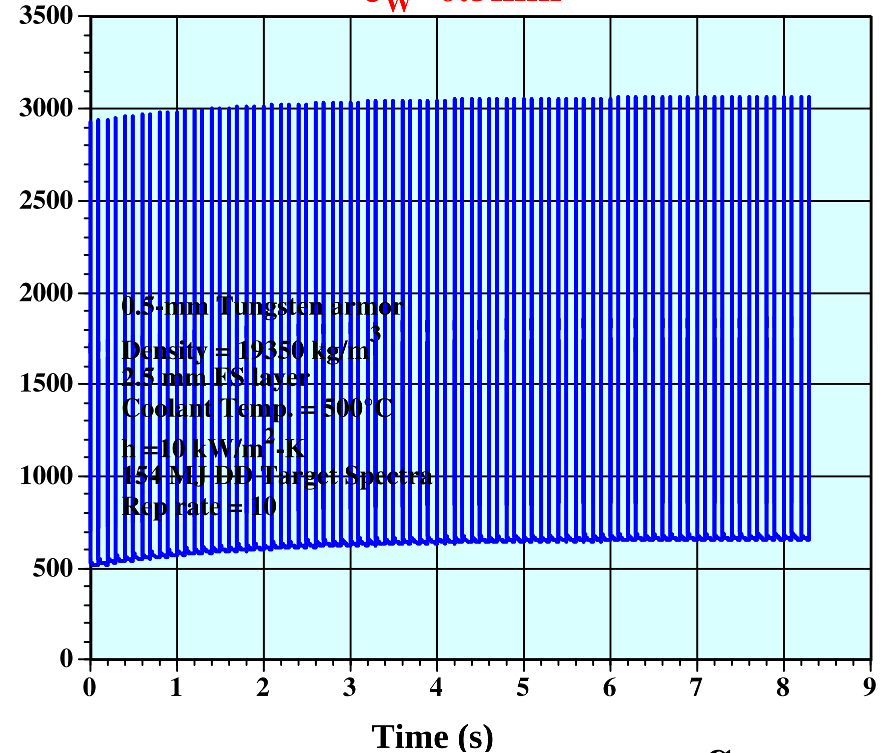


Example Results Comparing W Temperature Histories for Armor Thicknesses of 0.05 mm and 0.5 mm, respectively

δ_W=0.05mm

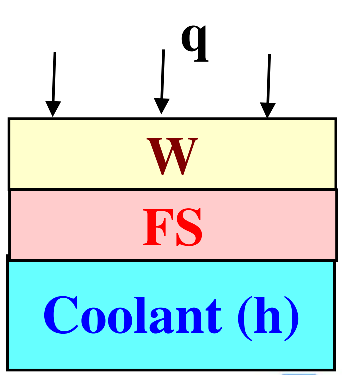


δ_W=0.5mm

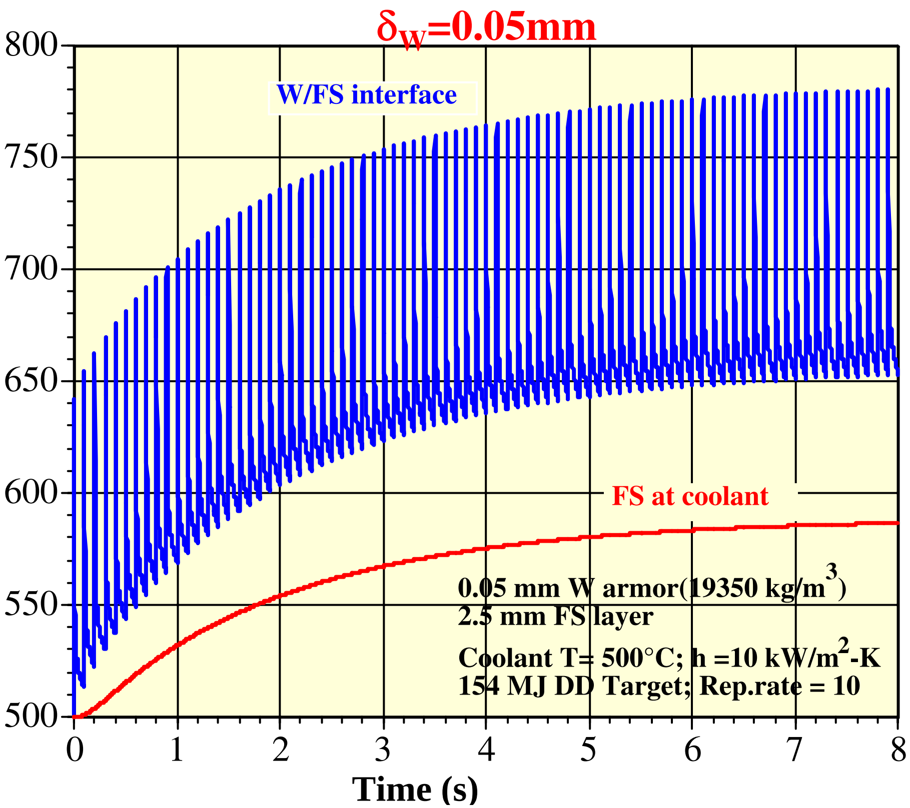


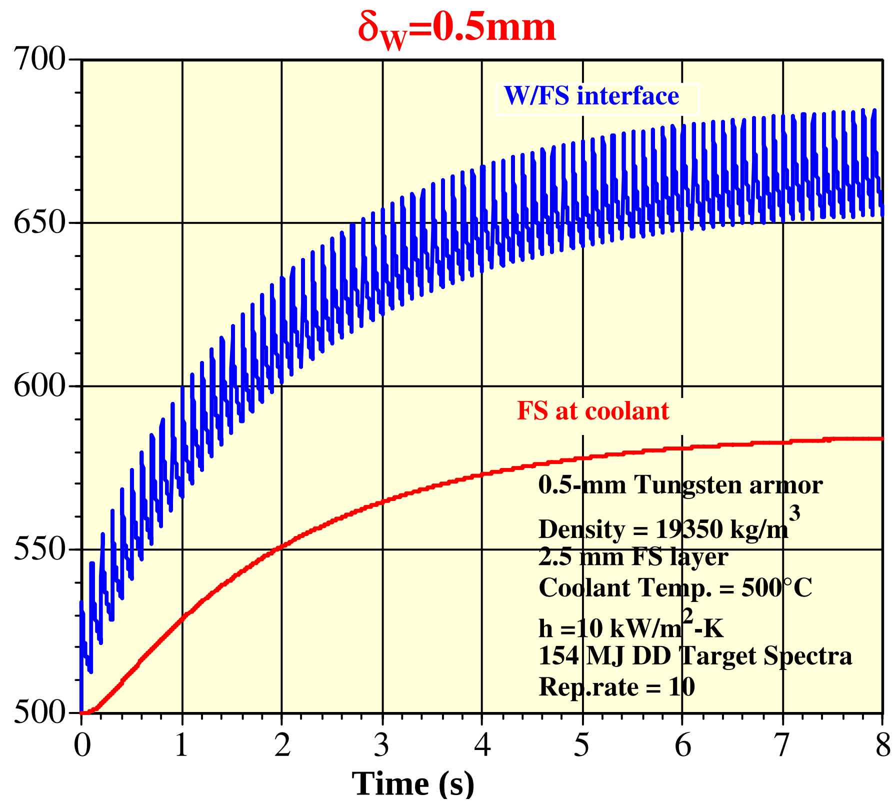
154 MJ yield
No gas
Rep Rate =10
$R_{chamber}$ = 6.5 m
δ_{FS} = 2.5mm
$T_{coolant}$= 500°C

- Not much difference in maximum W temperature and in number of cycles to ramp up to the maximum temperature level



Example Results Comparing FS Temperature Histories for W Armor Thicknesses of 0.05 mm and 0.5 mm, Respectively

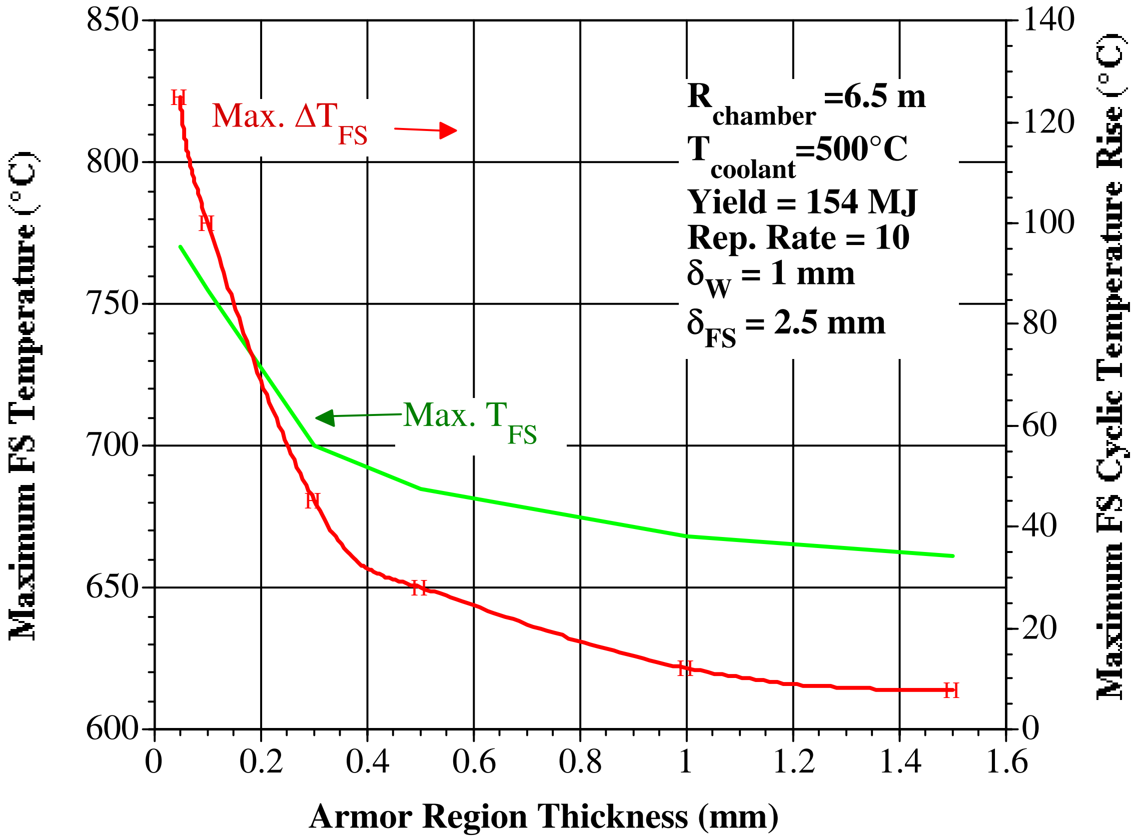




154 MJ yield
No gas
Rep Rate =10
$R_{chamber}$ = 6.5 m
δ_{FS} = 2.5mm
$T_{coolant}$= 500°C

- **Substantial differences in max. T_{FS} and cyclic ΔT_{FS} at FS/W interface depending on δ_W**
- **Can adjust T_{max} by varying $T_{coolant}$ and $h_{coolant}$**
- **Design for separate function and operating regime:**
  - **armor function under cyclic temperature conditions**
  - **structural material, coolant and blanket operation designed for quasi steady-state**

Maximum T_W, T_{FS}, ΔT_{FS} as a Function of Armor Thickness for Example Parameters



- **Maximum W temperature is virtually constant over range of armor thicknesses, ~ 3050°C**

- **Must be integrated with chamber system modeling for consistent overall blanket and armor design parameters**
- **For given IFE conditions and chamber parameters, set maximum possible δ_W (to minimize cyclic ΔT_{FS} and FS T_{max} and provide lifetime margin) that would accommodate:**
  - **maximum allowable T_W**
  - **fabrication**

Procedure for Example Parametric Armor Analysis

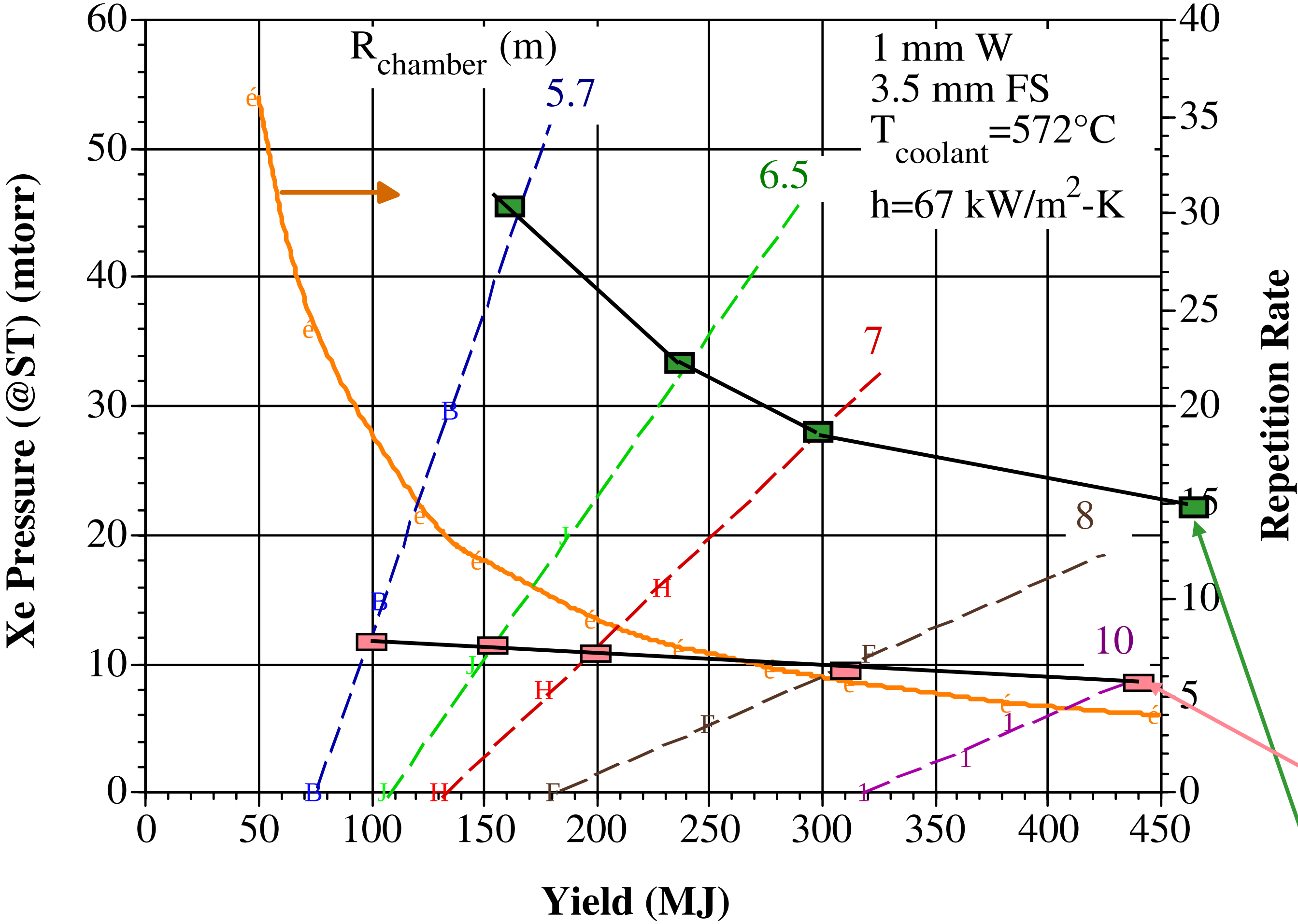
- **Utilize consistent parameters from steady state parametric study of example blanket/FW/power cycle configuration (FS/Li/Brayton Cycle)**
  - Maximum coolant temperature in FW ~ 572°C

- **1-mm W armor over 3.5-mm FS assumed for analysis**
  - maintain cyclic ΔT_{FS} <~20° C for example cases
  - also applicable for higher energy density cases as increasing the W thickness in the range of ~1 mm has only a ~10°C effect on the max. T_W
  - could be regarded as a mid-life or end of life scenario also

- **For given fusion power from blanket analysis, calculate combination of yield, chamber radius and protective gas density which would maintain assumed maximum W armor temperature limit**
  - Not clear which chamber gas (if any) to use; Xe assumed for example case
  - Gas attenuation estimated from BUCKY results with different chamber gas density
  - Reduction in photon/burn ion/debris ion of 9%/1%/29% for 10mtorr Xe and R=6.5 m
  - Reduction of 16%/2%/48% for 20mtorr Xe and R=6.5 m
  - Conservative assumption: shift ion energy spectrum correspondingly
  - Heat in gas reradiated to surface over time 300-700 μs

Example Results of Armor Parametric Analysis Illustrating Combination of Xe Chamber Pressure, Yield and Chamber Size to Maintain W Armor Within 2400°C for a Fusion Power of 1800 MW

Required P_{Xe} as a Function of Yield to Maintain $T_{W,max}$<2400°C for 1800 MW Fusion Power and Different $R_{chamber}$



- **W temperature limit of 2400°C assumed for illustration purposes**
- **Actual limit based results of ongoing experimental and modeling armor R&D effort**

Example target survival constraints based on allowable q'' (including 0.25 W/cm² radiation from wall) to reach DT triple point for assumed 16 K, 400 m/s target and 4000 K Xe in chamber:

- **Baseline target**
- **Insulated target (with 100µm 10% dense foam)**

- **Other requirements such as pumping need to be considered when setting chamber gas and pressure**

Conclusions

- **The HAPL Program Aims at Developing a New Energy Source: IFE Based on Lasers, Direct Drive Targets and Solid Wall Chambers**

- **The Path to Develop Laser Fusion Energy Envisions 3 Phases**
  - Basic fusion science & technology
  - Validate science & technology
  - Engineering test facility

- **HAPL Phase I Effort Proceeding Well**
  - R&D on specific components focused on solving major issues
  - Interfaces and requirements among components/systems
  - Integrated view to develop consistent parameters for the core of a laser IFE power plant