An Introduction to our Proposed Solutions to Address the Ion Threat to the Chamber Wall

Presented by

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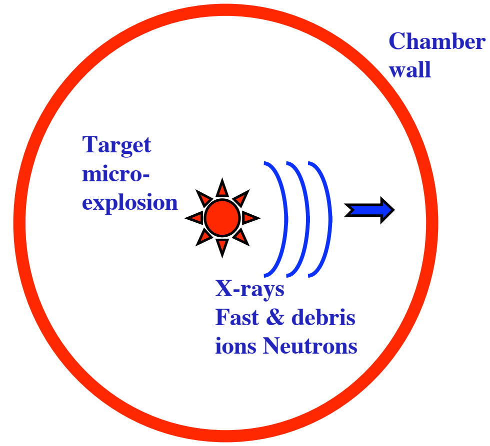
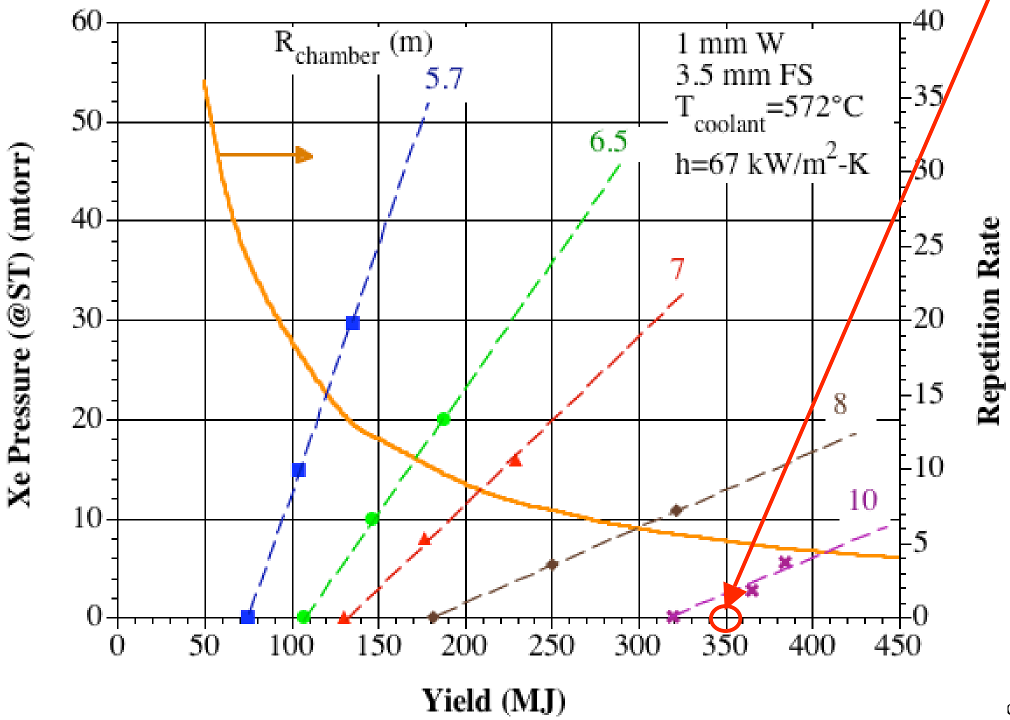
"The HAPL Program Aims at Developing IFE Based on Lasers, Direct Drive Targets and *Solid Wall Chambers*"

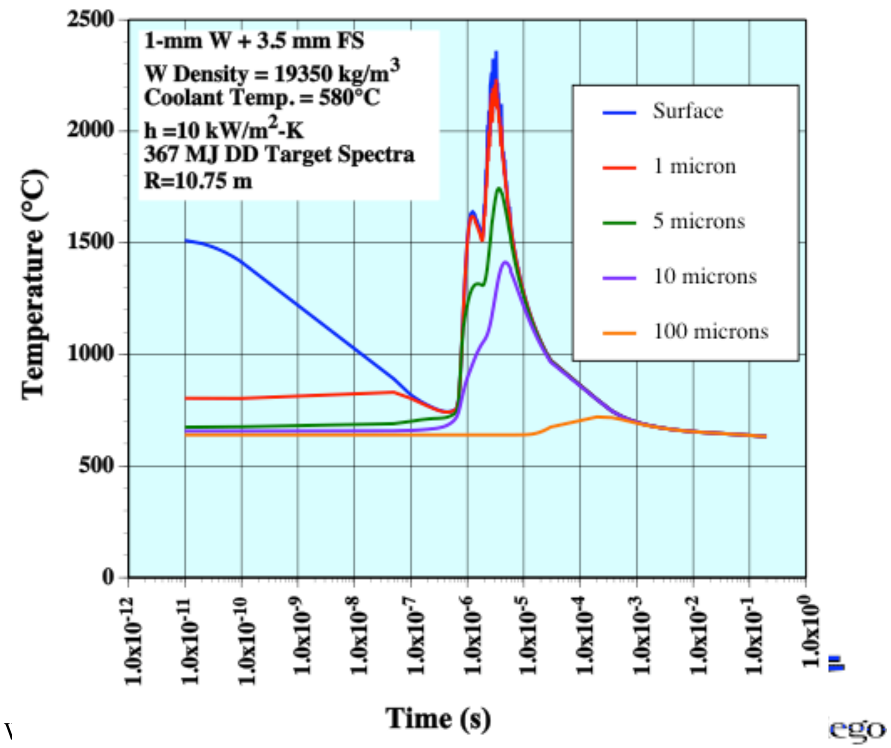
- Challenging for dry wall armor to accommodate photon and, in particular, ion threat spectra without protective gas (based on target injection & survival and laser propagation requirements).
- Thermo-mechanical constraints could be accommodated with large chamber.
- For example, for baseline 350 MJ target, a chamber of radius >10.75 m would maintain W armor <2400°C



Combination of P_{Xe} and $R_{chamber}$ Required to Maintain $T_{W,max}$<2400°C for Different Yield



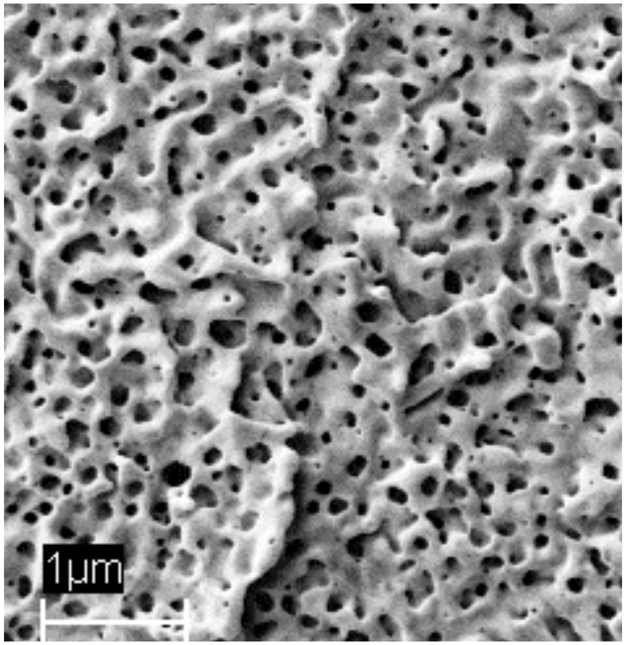
Temperature History at Different Depths in W Armor



Ion Implantation (in particular He) in Dry Chamber Wall is a Major Concern

- Can lead to exfoliation and premature failure of the armor (even for large chamber)
- Use of engineered armor
  - provide short pathway for implanted He to be released
  - microstructure could provide better accommodation of high thermal gradients
  - different possible concepts

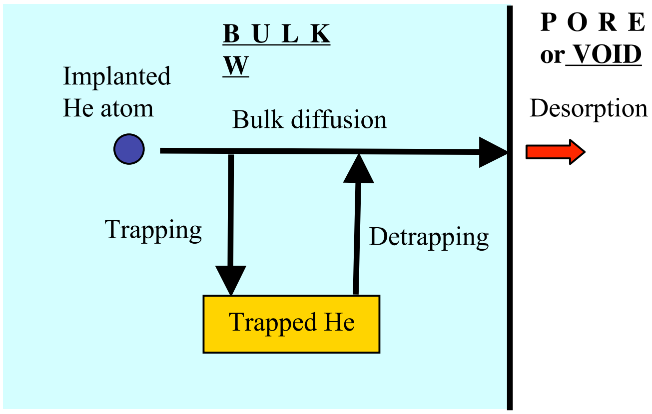
Example Case for $6x10^{22}$ He^{+}/m^{2}
40 kV, 60 mA Pulsed (1170±20°C baseline),
72 minute runtime on W armor
(UW IEC Facility)

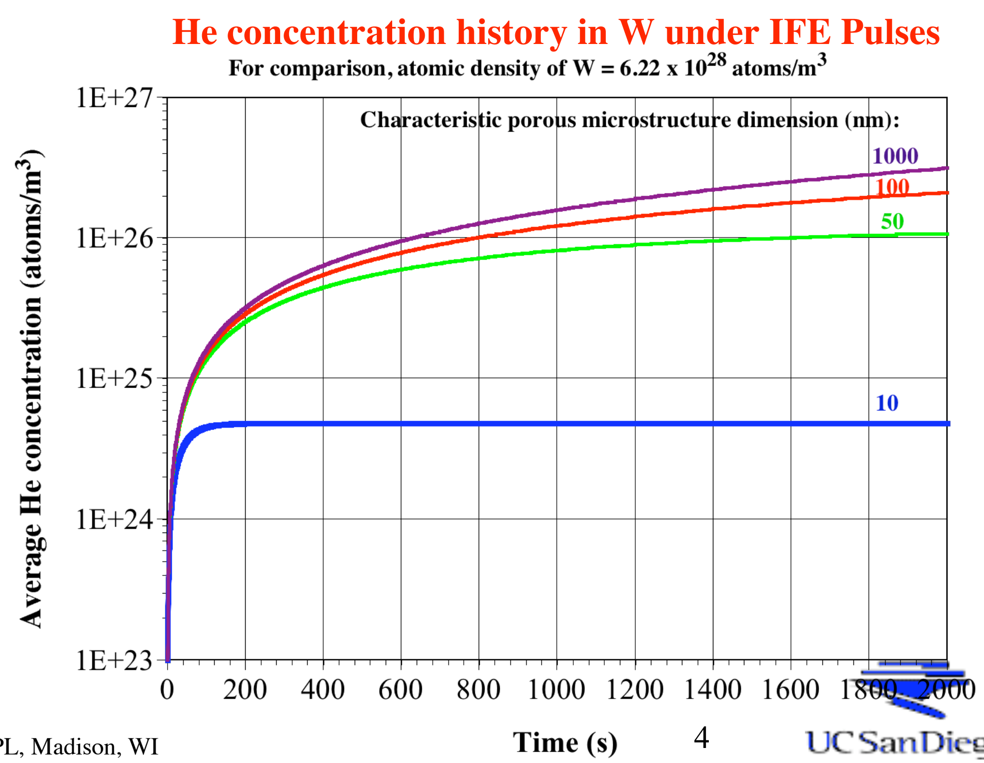


Other solutions
- Magnetic intervention to steer ions away from main chamber *(covered in next presentation)*
- Mobile C tiles: replacing or replenishing surface regularly

Use of Nano-Structured W Armor to Enhance He Release

- **He atoms in a metal may occupy either substitutional or interstitial sites.**
- **As interstitials, they are very mobile, but they will be trapped at lattice vacancies, impurities and vacancy-impurity complexes.**
- **Results from UNC He implantation experiments on W indicate decrease of He retention as He implantation is spread over many cycles with associated temperature anneals.**
- **Modeling of these results and extrapolation to IFE case indicated possibility of He release with ~50 nm W nano-structure with interconnected porosity (UCLA, UCSD).**

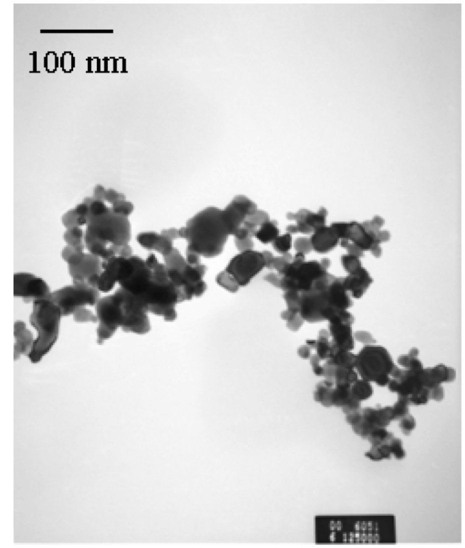




Program Underway to Develop & Test Nano-Structured W

- Develop and fabricate material by plasma spray of nano-particles (PPI)
- Characterize property data (PPI, ORNL)
- Test He retention/release under He ion irradiation (UNC, UW)
- Test thermomechanical behavior under laser-simulation of IFE conditions (UCSD) and under RHEPP He ion flux (SNL)

- Current plan
  - 30 samples (2.5 x 2.5 cm) with substrate except where indicated:
    - 10 for UCSD (Dragonfire)
    - 5 for property measurement at PPI
    - 5 for property measurement at ORNL
    - 10 extra (3 with substrate and 7 without)
  - 25 samples (1 cm x 1 cm) with substrate except where indicated:
    - 10 for UW (He implantation)
    - 5 for RHEPP (He ion experiment)
    - 10 extra (3 with substrate and 7 without)
  - Thickness of samples for measurement of properties ~ 2 mm.
  - Other samples will have a ~0.5 mm thick undercoat produced with micron-W feedstock powder and a ~0.05 mm topcoat produced with nano-W feedstock powder.
  - Property measurements
    - Thermal diffusivity, specific heat, density, and permeability.
    - Thermal expansion and mechanical properties if possible (might be difficult with this sample size)
    - Grain coarsening kinetics through exposure at high temperature ~2000°C)



Nano-powder and nano-structured W from PPI

Recent Results from UNC on He Retention Quite Encouraging*

100-500 keV He Implantation with Flash Heating to 2000°C for 5 s between Steps

Dose	SCW	Poly-W	nano-porous W w/HfC
10^{20}: 1 step	72%	99%	15%
10^{20}: 100 x (10^{18} implantation + anneal)	74%	84%	26%
10^{20}: 500 x (2×10^{17} implantation + anneal)		81%	15%

- **Samples implanted at 850°C at high dose of He and then heated to 2000°C for 10 s.**
  - Poly-W with 2 x 10^{21} He/m^2 showed blistering
  - Poly-W with 1 x 10^{22} He/m^2 showed exfoliation
  - Nano-cavity W with 5 x 10^{21} He/m^2 did not show surface blistering or exfoliation

*From 18th TOFE presentation: N. Parikh et al., "Study of Helium Retention in Nano-Cavity Tungsten Implanted with an IFE Threat Spectrum"

HAPL FY09 Milestone on this Effort

Milestone #3:

- **Investigate engineered nano-structured tungsten as a first wall material. Preliminary FY 08 experiments indicated a newly developed morphology for tungsten, based on deposition of nano size tungsten powder, could ameliorate retention of helium. In FY 09 we will examine this material for helium retention (using IEC device at Wisconsin), thermal management (using Dragonfire Laser Facility at UCSD) and ion damage (using RHEPP facility at SNL). Support experiments with modeling.**

Magnetic Intervention Dump Concepts

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Outline

- Magnetic intervention as advanced option to reduce or eliminate ion threat on chamber wall
  - Magnetic intervention configurations
- Scoping study of separate dump chamber with liquid wall
- Chamber considerations
- Summary

Magnetic Intervention: Utilizing a Magnetic Field to Guide the Ions to Specific Locations Outside the Main Chamber

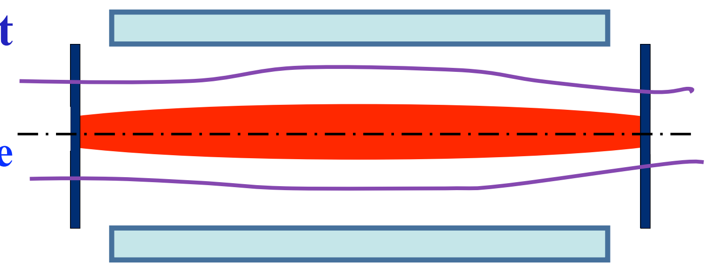
Number of coils, their locations and the coil currents can be designed so as to produce a number of different magnetic field configurations.

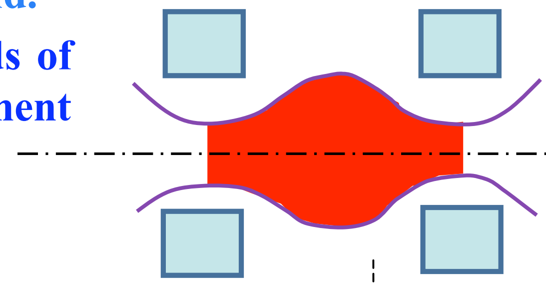
(1) Straight solenoid, where the magnetic field constrains the ions in the radial direction, but not in the axial direction.
- **Issues include MHD stability and the physically massive ion dumps that would be needed at each end.**

(2) Magnetic mirrors, where the field is higher at the ends of the solenoid reflecting the ions and forming a confinement system for particles.
- **Also subject to MHD instability that destroys the radial confinement.**
- **A confinement system for particles is also not the goal here.**

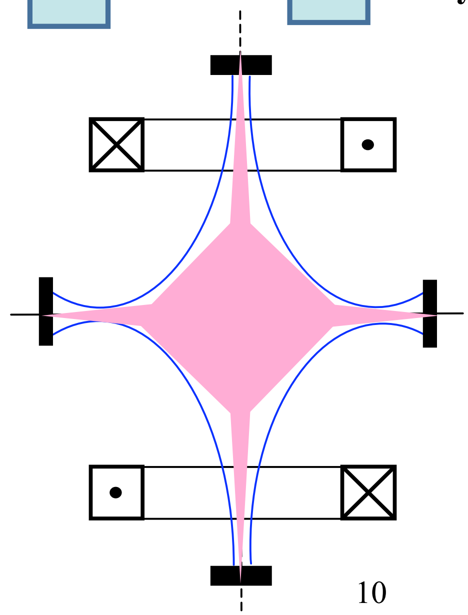
(3) The cusp, which is a poor, leaky confinement system, acting to channel the ions through well-defined holes or cusps.
- **Ions may then be deposited on dumps outside the chamber.**
- **In contrast to the mirror machine, the curvature of the field lines promotes MHD stability.**
- **Most promising configuration.**

Ions collected on end dumps





Ion plasma confined radially by field, axially by mirrors



Ions leak out through the cusps

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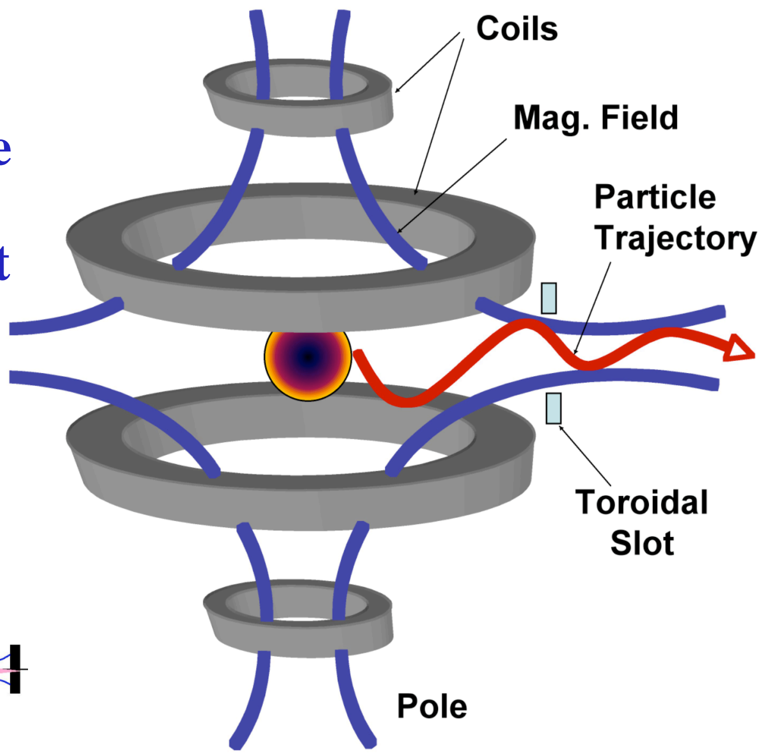
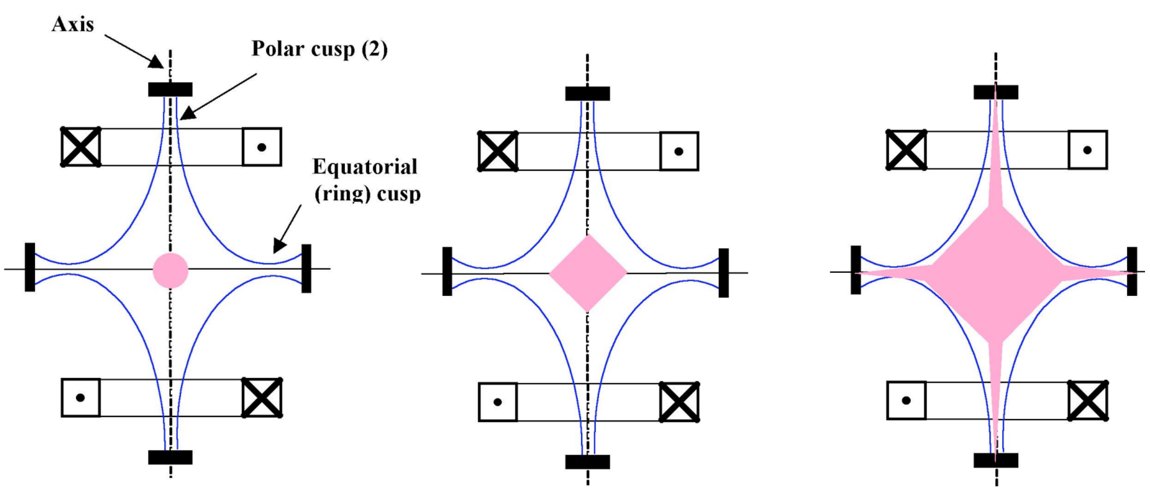
Utilizing a Cusp Field to Create a Magnetic Bottle Preventing the Ions from Reaching the Wall and Guiding them to Specific Locations at the Equator and Poles

- **Utilization of a cusp field for such magnetic diversion has been experimentally demonstrated previously.**
  - **1980 paper by R.E. Pechacek et al.,**
- **Following the micro-explosion, the ions would compress the field against the chamber wall, the latter conserving the flux. Because of this flux conservation, the energetic ions would never get to the wall.**





Plasma expansion initially spherical

Ion cloud deforms as it encounters cusp field

Ions leak out through the cusps

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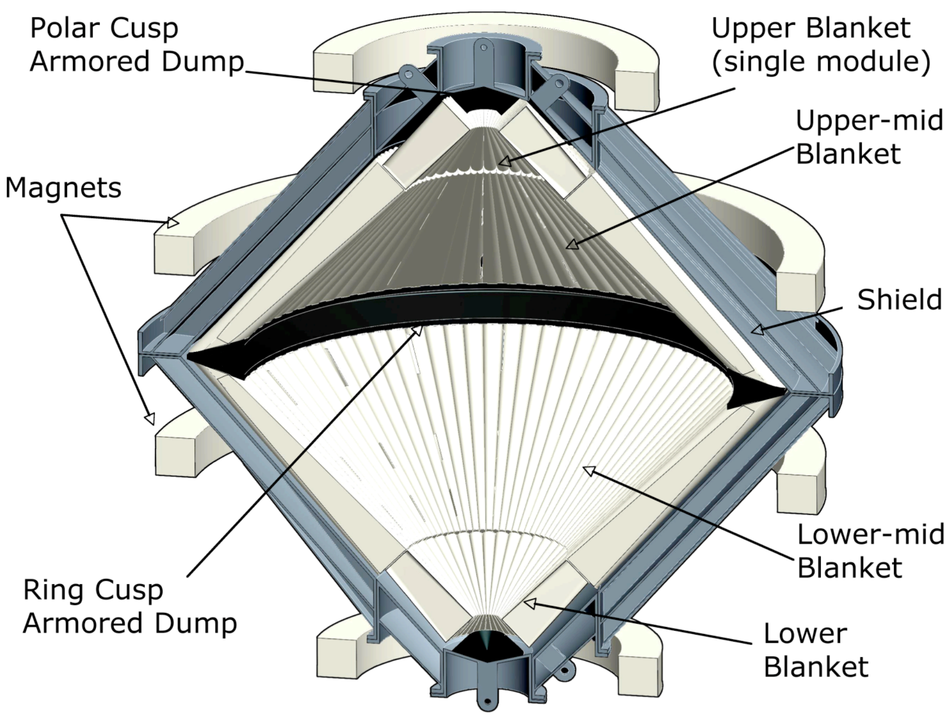
Biconical Chamber Well Suited to Simple Cusp Coil Geometry and Utilizing SiC_f/SiC for Resistive Dissipation

- SiC_f/SiC blanket with Pb-17Li or flibe as liquid breeder (tight assembly of submodules), coupled to Brayton cycle.
- Water-cooled steel shield is lifetime component and protects the coil (can also be locally placed around coils).
- Although resistive dissipation of > 50% of the ion energy seemed possible, there were concerns about the high voltages generated between the blanket modules.
- Armored ion dumps schematically shown inside chamber, but preferably placed outside for easier maintenance access.

Example Chamber Parameters

Target yield	367 MJ
Neutron/ion/photon energy partition	0.75/0.24/0.01
Rep rate	5 Hz
Fusion power	1.84 GW
Total thermal power	~2.1 GW
Cone height/radius	6/6 m
Peak/avg. neutron wall load	6.1/4.3 MW/m^2
Peak/avg. photon heat flux on first wall	0.11/0.08 MW/m^2



Dimensions that Satisfy All Design Requirements for the Blanket Options

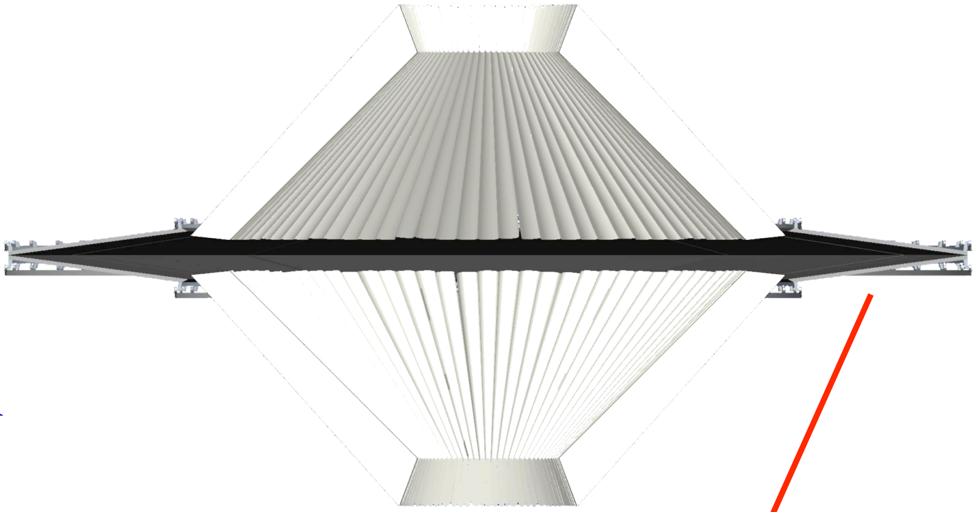
- **Tritium self-sufficiency (calculated TBR = 1.1)**
- **Shield, magnets, VV are lifetime components; VV is reweldable**
- **Operational personnel accessibility outside bio-shield**

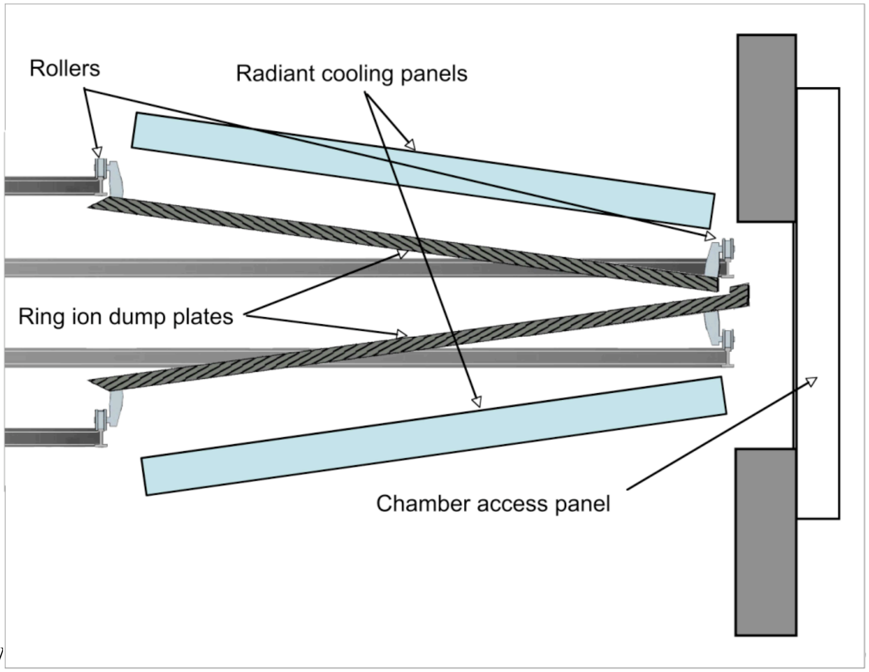
	Flibe Blanket	Pb-17Li Blanket
Blanket Thickness (cm)	100-150	80-120
Lithium Enrichment	7.5% ^{6}Li	10% ^{6}Li
Magnet Shield Thickness (cm)	25	45
Vacuum Vessel Thickness (cm)	10	10
Bio-shield Thickness (cm)	190	220

- **Although Pb-17Li blanket is thinner, its weight is still larger than the flibe blanket**
- **Local magnet shield is a factor of ~2 heavier with Pb-17Li blanket resulting in more support requirements**
- **~0.3 m thicker bio-shield is required with Pb-17Li blanket**

Radiatively-Cooled Duck Bill Dump with Solid Armor

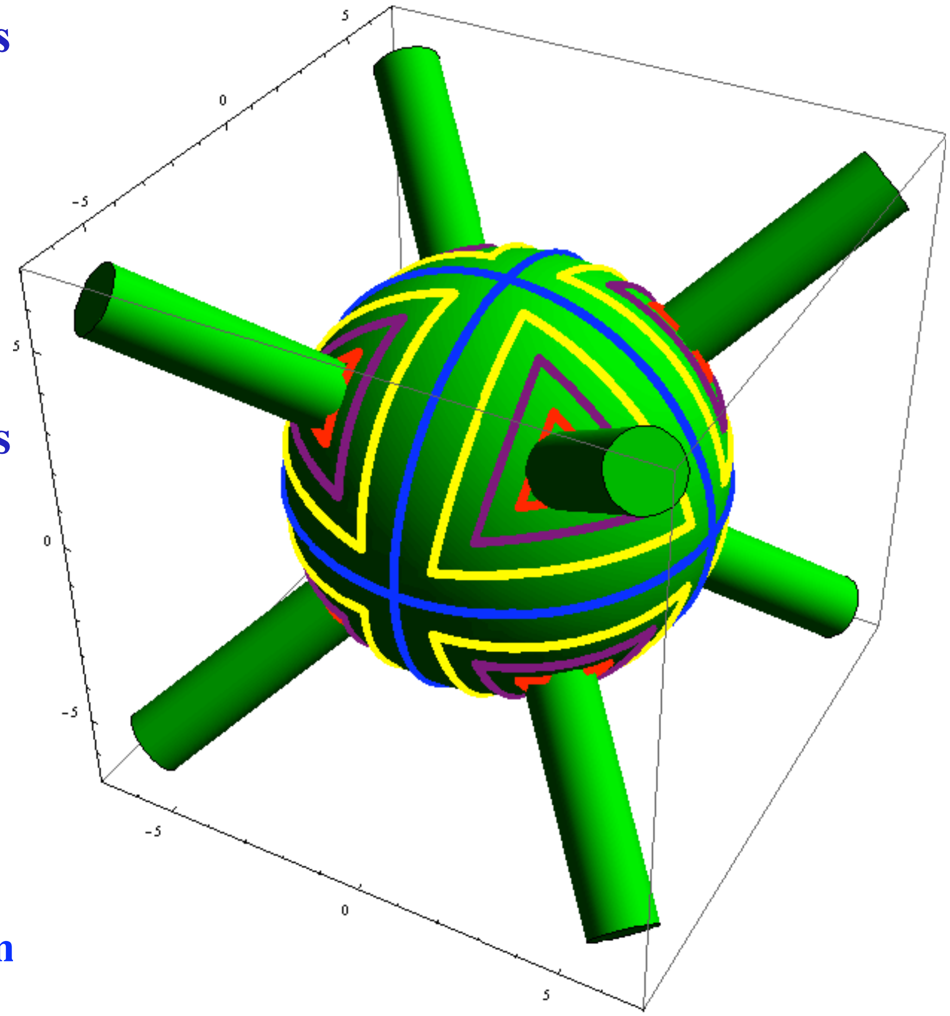
- Thermal analysis indicated feasibility if ion footprint large enough.
- Innovative carousel technique proposed for maintenance.
- However, ions still deposited on solid materials.
  - He retention concern remains, although now transferred to an external location where they might be better accommodated.
- Also formidable challenge to accommodate high ion flux at the poles.
- This led to the consideration of liquid dumps.
- Need more suitable geometry.





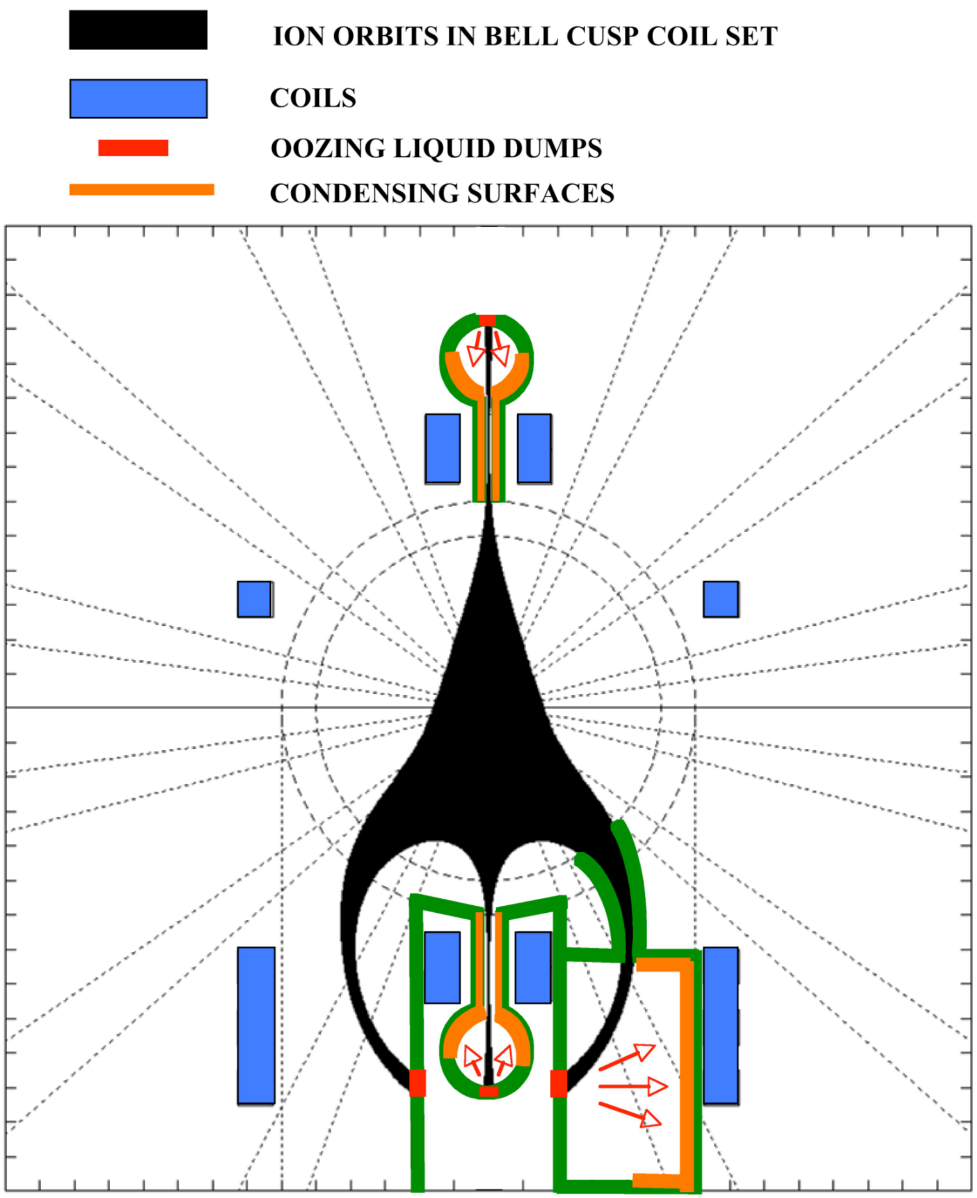
Octagonal Cusp

- The octagonal cusp converts isotropic expansion of target into eight identical beams
- The main chamber still utilizes a dry wall to satisfy target and laser requirements.
- The ion fluxes through the 8 ports are attenuated by a protective fluid (e.g. Pb), possibly in the form of a mist.
- The evaporated and ionized Pb then condenses on the cooled dump chamber walls with minimal impact on the main chamber environment.
- For a dump chamber length of ~10 m, the required Pb mist density ~0.001 ρ_{liquid} (~ Pb P_{vapor} at 1750 K).
- Concerns with this configuration included:
  - Lack of axial symmetry making it difficult to channel all ions through the 8 ports
  - Line of sight path of evaporated fluid to the main chamber
  - Difficulty of maintaining a mist in the dump chambers.



Bell or Tulip Cusp

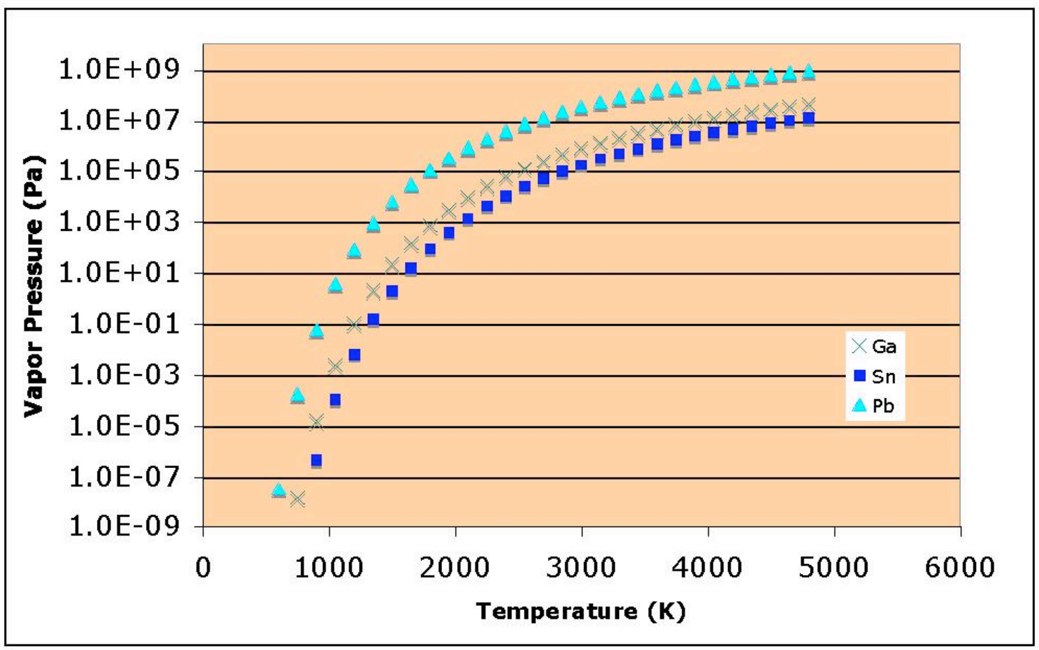
- Modification of simple cusp with 6 coils
  - Ions directed to a lower annular port and intersect the dump area at an angle with no line of sight to main chamber to minimize any contamination.
  - This configuration is particularly suited to a liquid dump concept, such as an oozing dumptarget (or liquid wall)
  - Evaporation and ionization of fluid, followed by condensation on cooled dump chamber walls.

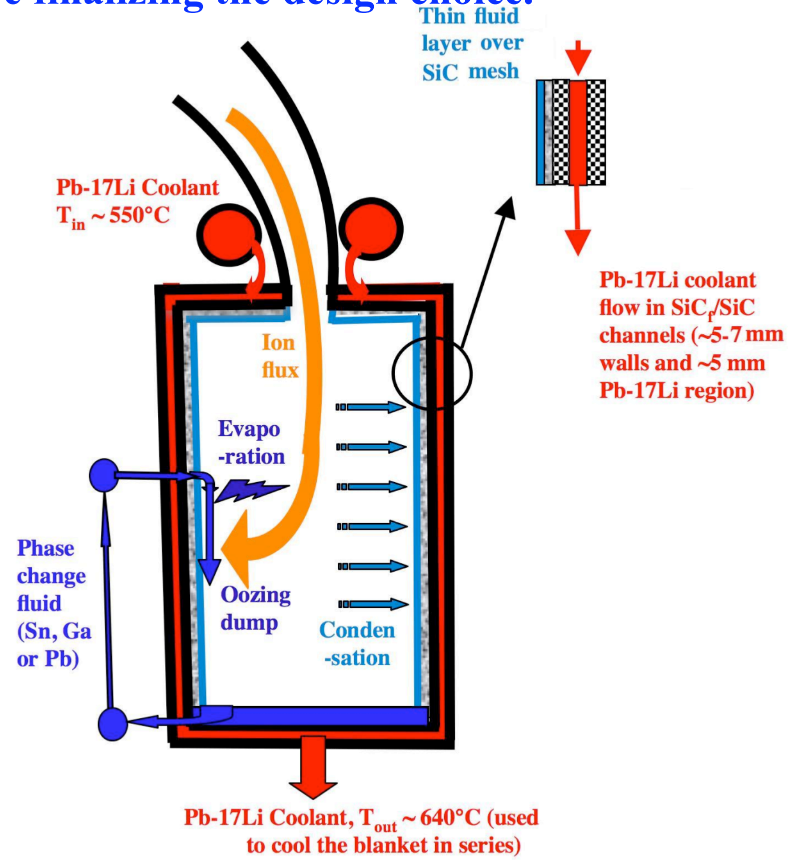


Evaporation/Condensation Studies for Bell Cusp

- **Three candidate fluids were considered for the dump chamber: Pb, Sn and Ga**
  - **Sn and Ga have high latent heats; Sn is attractive because of its low vapor pressure, while Ga's low melting point would help to start up the dump chamber without having to heat and melt the liquid first.**
  - **However, other factors including material compatibility would need to be considered before finalizing the design choice.**

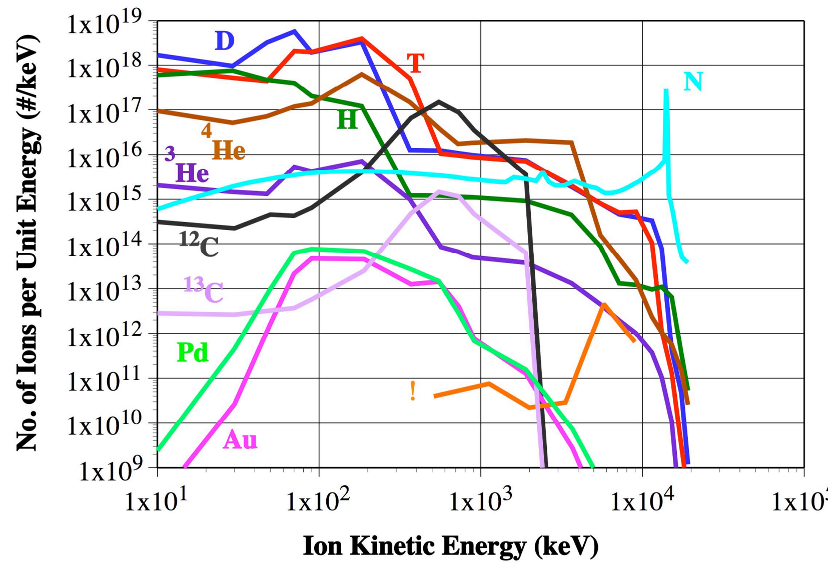
Fluid	Pb	Sn	Ga
Density (kg/m^3)	11300	6919	5904
h_{fg} (J/kg)	8.6×10^5	2.4×10^6	3.79×10^6
Base temp.	500°C	500°C	500°C
Cp (J/kg-K)	142	300	370
k (W/m-K)	16	35	41
Melting point (°C)	327.6	232	29.8
Boiling point (°C)	1740	2270	2204
Energy to evap. (J/m^3)	1.171×10^{10}	2.028×10^{10}	2.61×10^{10}



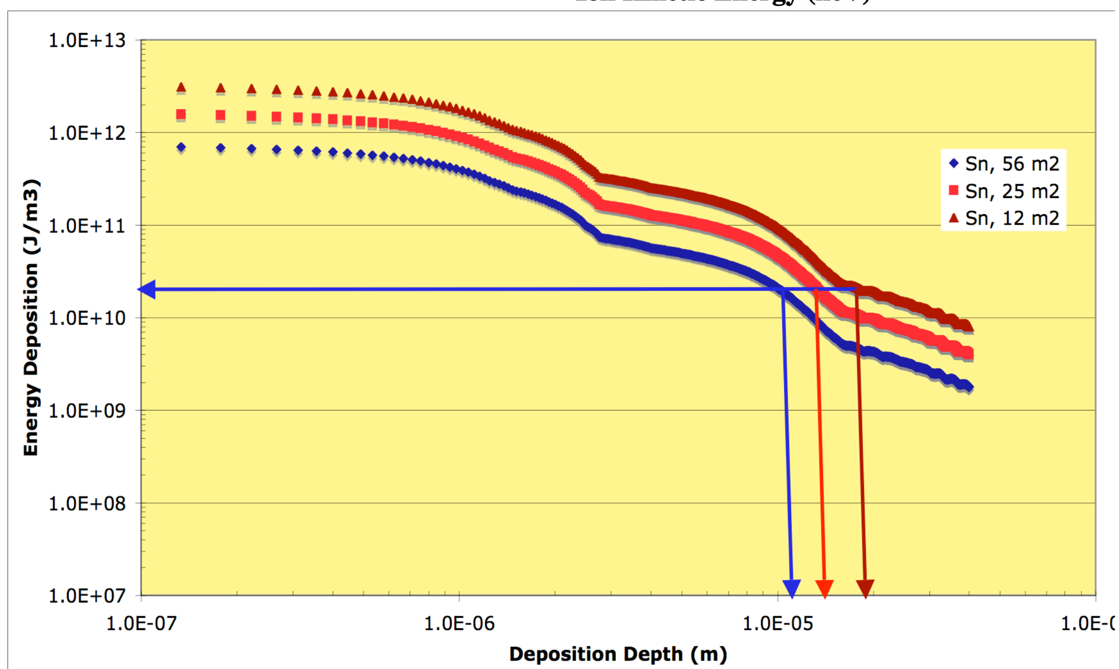


Estimating Evaporated Layer Thickness Based on Ion Energy Deposition for 350 MJ Spectra

- **97% of ion energy in bell cusp dump chamber ~ 84 MJ**
- **Ion energy deposition calculated based on SRIM attenuation data**
- **Evaporated thickness estimated from energy required to raise liquid to the boiling point (from 500°C to BP + latent heat of evaporation).**

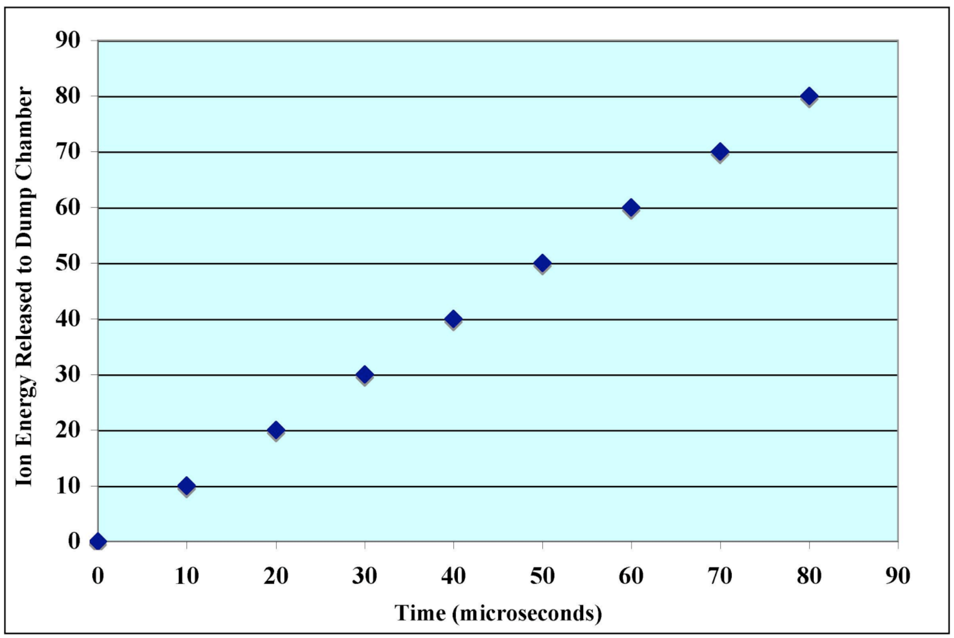


Dump area (m^2)	12	56
Thickness of evap. Sn (m)	1.83×10^{-5}	1.02×10^{-5}
Mass of evap. Sn layer (kg)	1.52	3.93
Thickness of evap. Pb (m)	3.05×10^{-5}	1.18×10^{-5}
Mass of evap. Pb layer (kg)	4.14	7.44
Thickness of evap. Ga (m)	1.58×10^{-5}	9.18×10^{-6}
Mass of evap. Ga layer (kg)	1.12	3.04

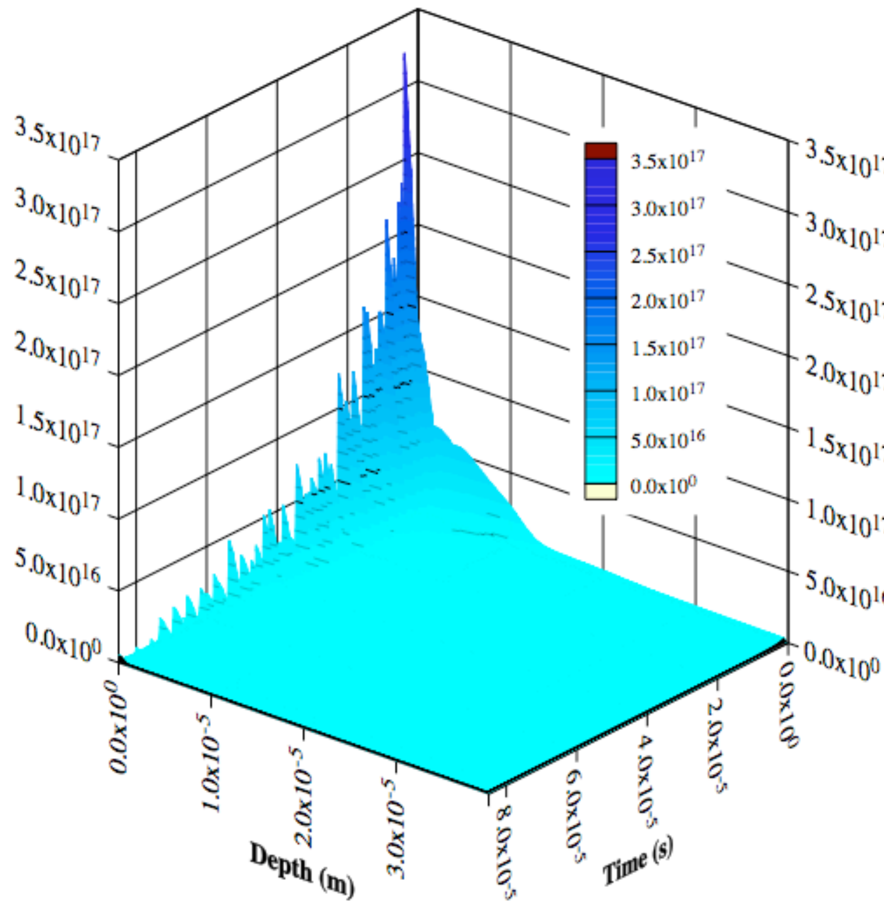


Evaporation Study Based on Transient Ion Energy Deposition and Thermal Behavior of Ion Dump

- **Volumetric heat generation estimated from ion attenuation and time of flight analysis for 350 MJ ion spectra**
- **Ion leakage time scale based on physics modeling for ion energy release to dump chamber (from D. Rose)**



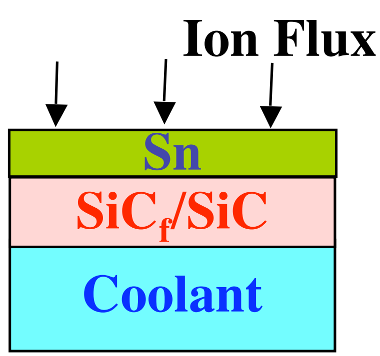
Ion Energy Release to Dump Chamber Based on Physics Modeling

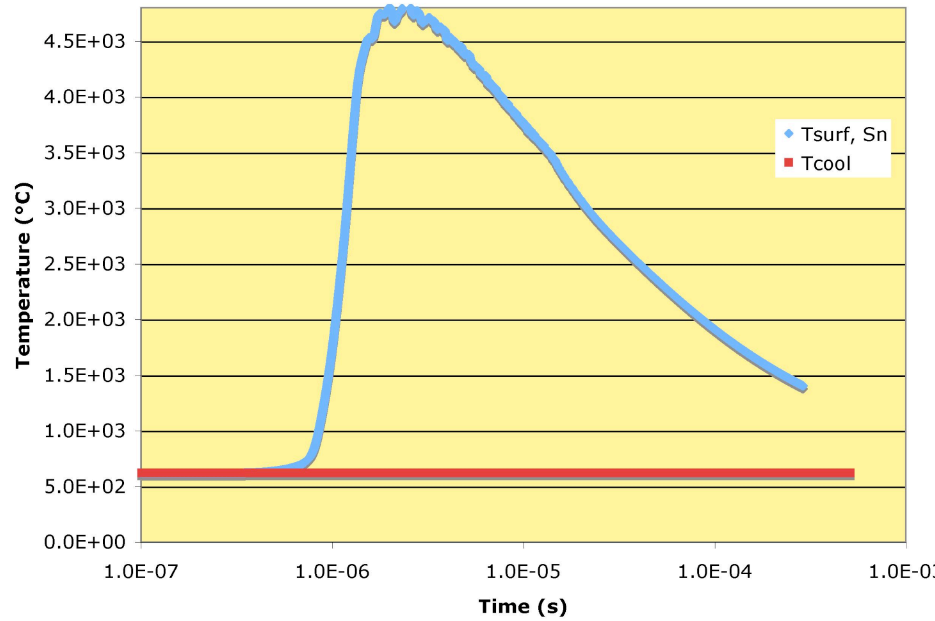


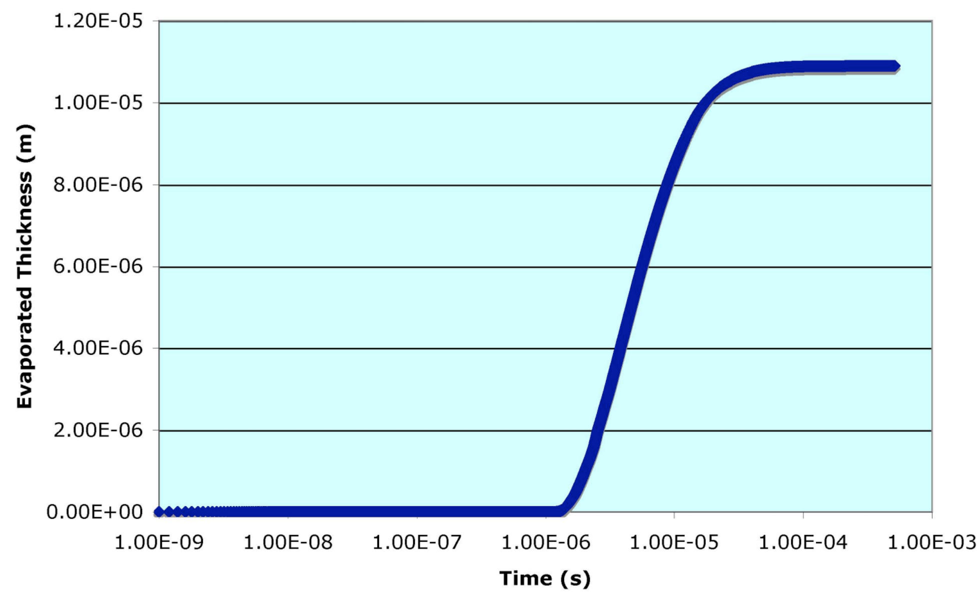
Example Spatial and Temporal Distribution of Volumetric Heat Generation (W/m^3) in Sn Ion Dump

Evaporated Thickness Estimate Based on RACLETTE-IFE Transient Analysis

- **Example results for Sn and a 56 m^2 dump area**
- **The temperature within about 12 µm of the surface is actually higher than the surface temperature due to the ion energy deposition spatial profile and it is possible that a larger thickness of Sn would be ejected in the chamber.**
- **Maximum evaporation from the surface is ~ 12 µm (similar to the previous estimate).**



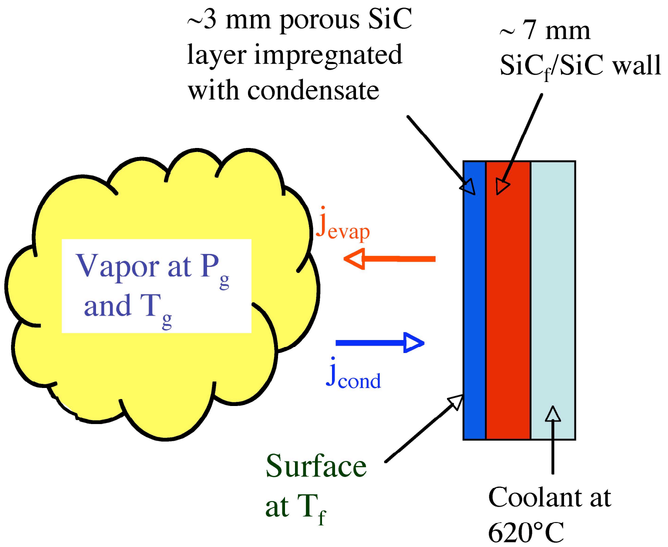




Condensation Study

- **Following evaporation, energy is carried to the dump chamber walls in two ways:**
  - **radiation (ultra-violet and soft x-rays on the timescale of the ion energy deposition, ~80 µs)**
  - **condensation.**
- **Accurate simulation of the behavior of the ions (including the influence of the magnetic field and recombination to the neutral state) and atoms as they move in the chamber, cool down and condense would require quite a complex model, beyond the scope of the present study.**
- **For the scoping analysis presented here and to obtain a rough understanding of the condensation process and of the time scale involved, a simple model was developed, separating the radiation and condensation processes.**
- **The condensation process was modeled by coupling a rate equation to the transient conduction equation for the condensation surface:**

$$j_{net} = \left(\frac{M}{R2\pi}\right)^{0.5}\left[\Gamma\sigma_c \frac{P_g}{T_g^{0.5}} - \sigma_e \frac{P_f}{T_f^{0.5}}\right]$$



j_{net} = net condensation flux (j_{cond}-j_{evap}) (kg/m^2-s)

M = molecular weight (kg/kmol)

R = Universal gas constant (J/kmol-K)

P_g, T_g = vapor pressure (Pa) and temperature (K)

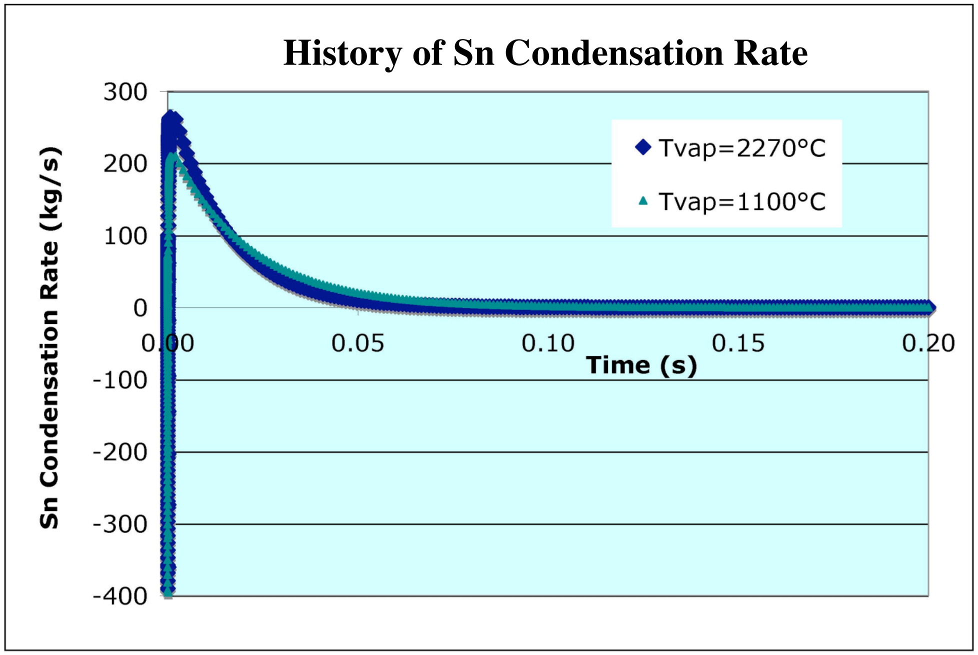
P_f, T_f = saturation pressure (Pa) and temperature (K) of film

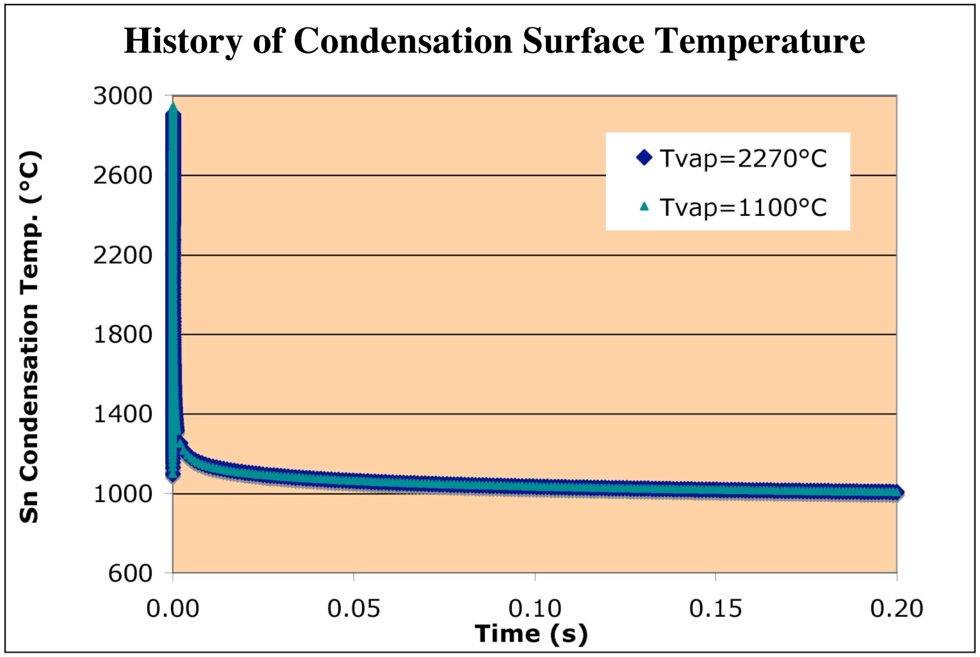
σ_c, σ_e = condensation and evaporation coefficients (assumed as unity)

Γ = correction factor for vapor velocity towards film (conservatively assumed as unity)

Scoping Analysis of Condensation (Sn as example)

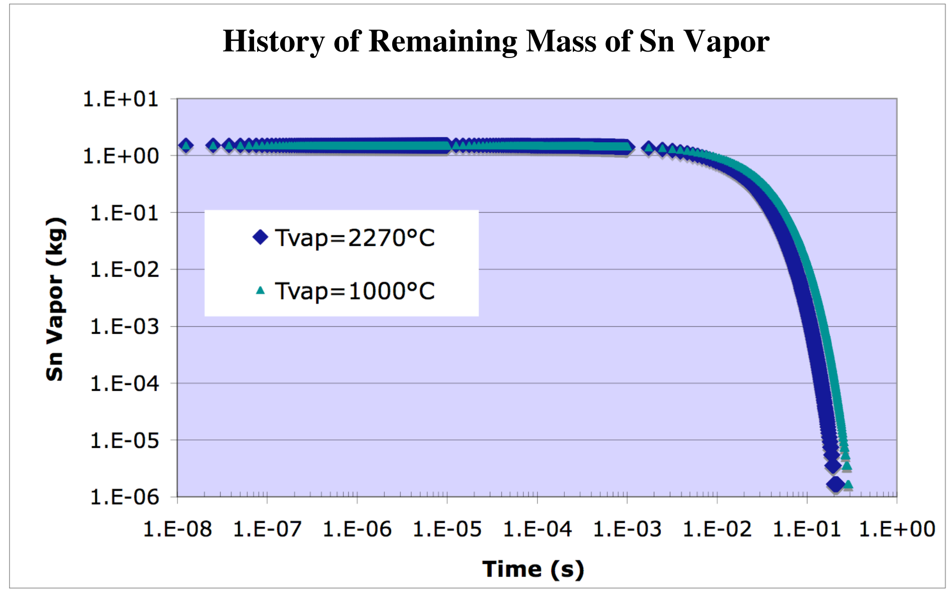
- During the condensing process, it is the final condensation at lower vapor temperature and pressure which takes longer, as the initial cooling down and condensation at high vapor pressure and temperature is fast.
- The condensation analysis conservatively focuses on this end-of-condensation process scenarios with example vapor temperatures corresponding to 2270°C and at 1100°C.
  - mass of of evaporated fluid from previous evaporation analysis = 1.52 kg for Sn
  - line-of sight cond. area = ~276 m^2
  - dump chamber vol. = 552 m^3
  - mass of vapor and pressure in the chamber adjusted continuously as vapor condenses.
- Radiation from ionized vapor included by assuming that energy to cool ionized vapor to assumed vapor temperature is radiated over initial 80 µs (avg. heat flux ~1.8×10^9 W/m^2).
- This would yield conservative results and an upper bound of the time scale required for condensation.

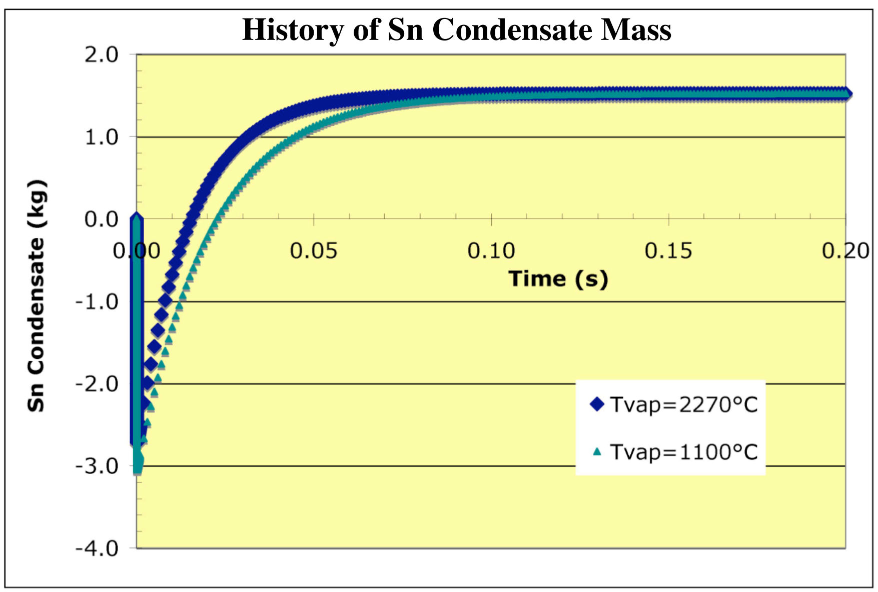


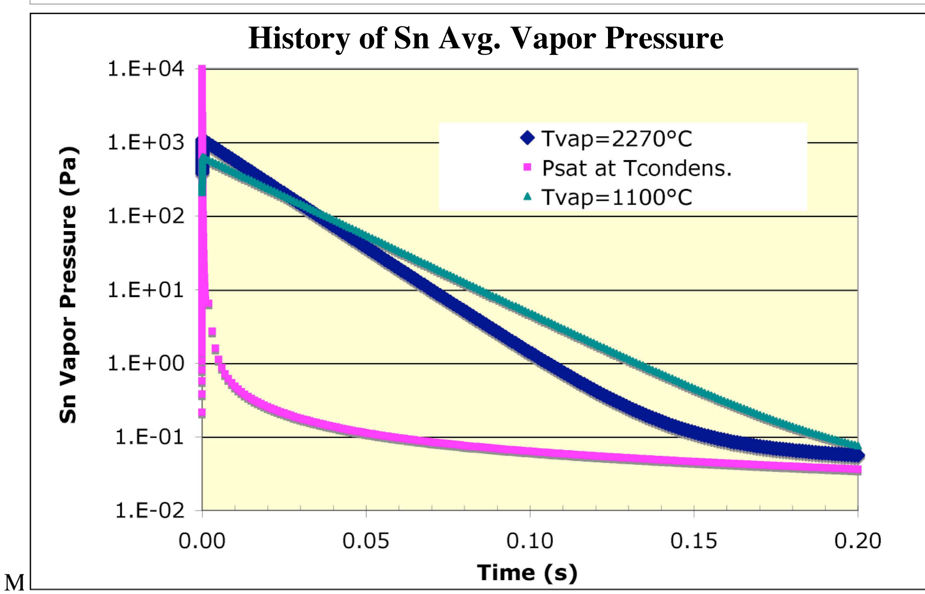


Results of Condensation Scoping Analysis

- Condensation is quite fast even for the case with a vapor temperature of 1100°C.
- Avg. pressure of the vapor in the chamber decreases to 0.076 Pa after 0.2 s (Sn P_{vap} at 1010°C ~0.04 Pa).
- The effective vapor velocity for the higher condensation rates ~120 m/s.
- Similar results for Pb and Ga
  - Pb avg. vapor pressure decreases to ~970 Pa after 0.2 s (Pb P_{vap} at 1075°C ~850 Pa).
  - Ga avg. vapor pressure decreases to ~0.54 Pa after 0.2 s (Ga P_{vap} at 1002°C ~ 0.49 Pa).
- Results encouraging but needs to be confirmed by more detailed studies.







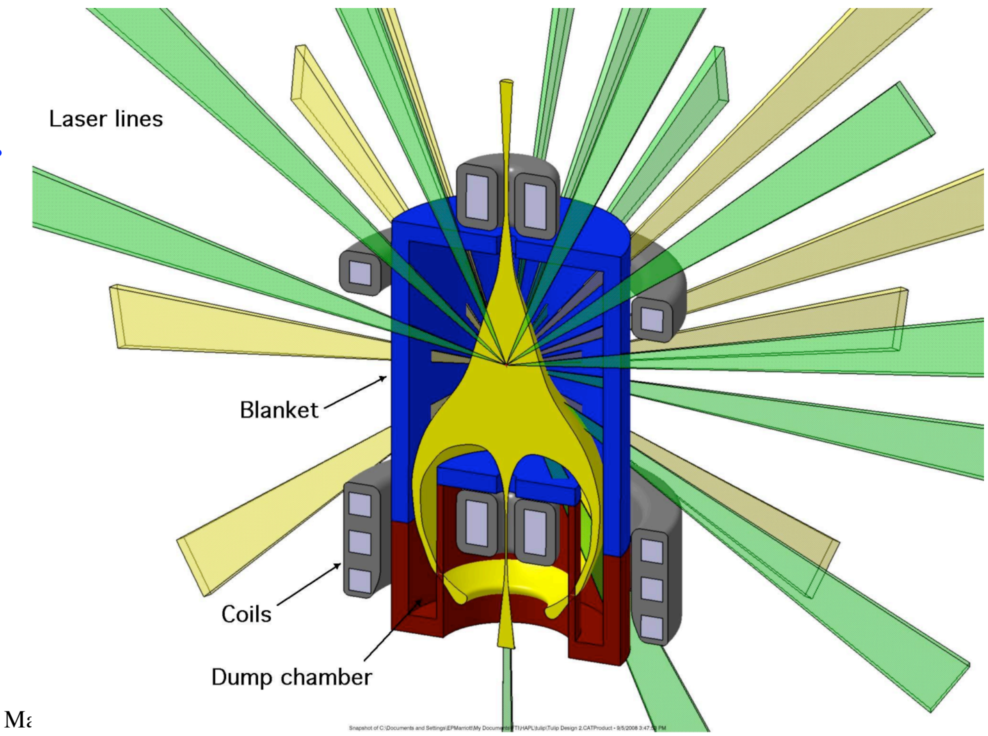
Overall Chamber and Reactor Concept with Bell Cusp Configuration

- **Two laser lines intersect the dump chamber region.**
  - Vapor pressure prior to each shot should be low enough not to impact the laser propagation.

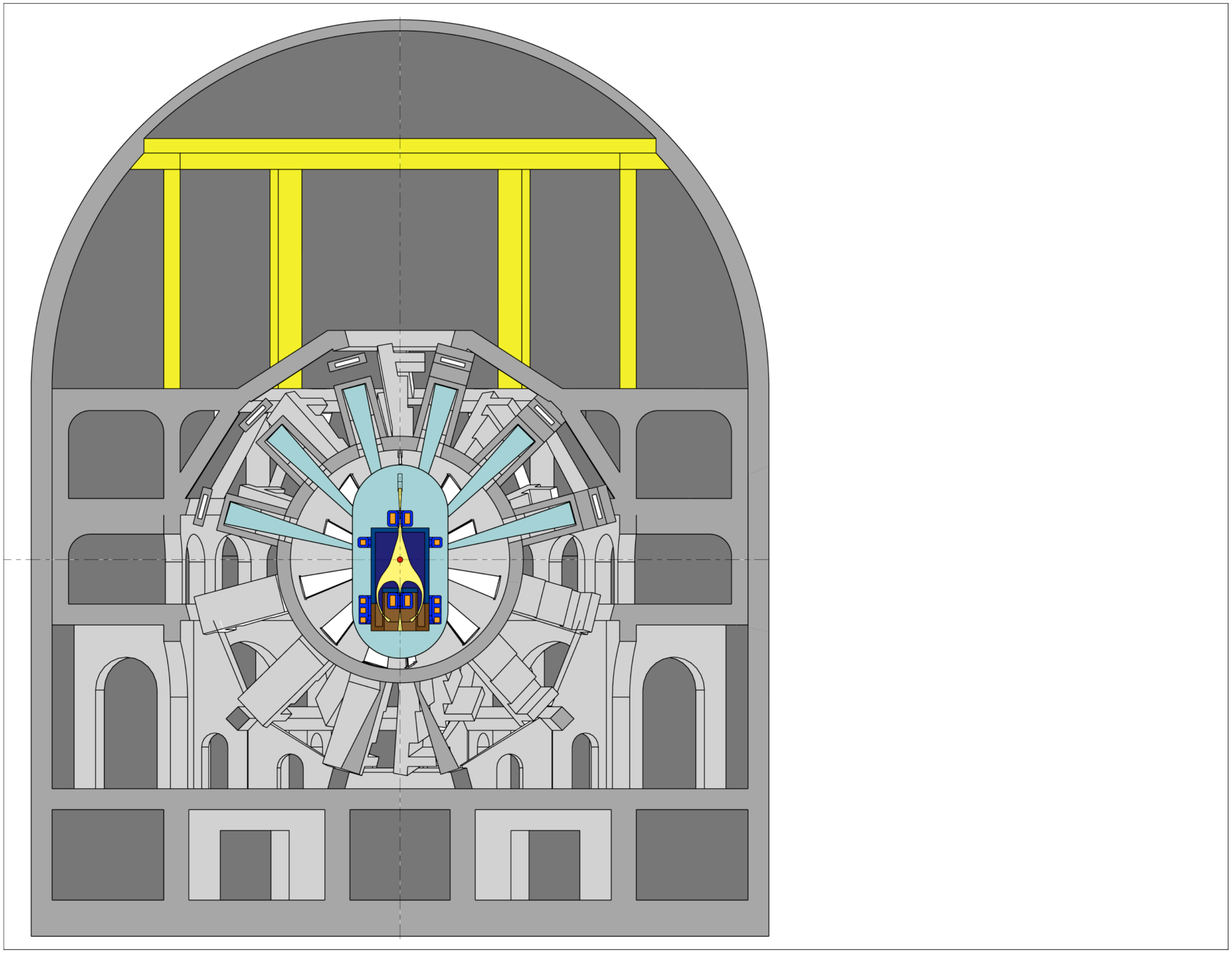
- **The closest FW region to the center of the chamber is 4.5 m with a corresponding neutron wall load of 5.4 MW/m^2.**

- **Both blanket concepts previously considered for the biconical chamber could be utilized in this configuration**
  - TBR >1.1 (with 7.5-10% ^{6}Li and including loss of coverage due to ports and cusp openings).

- **Other nuclear requirements also accommodated.**
  - a combined blanket/shield thickness of 1.25 m.
  - a vacuum vessel thickness of 10 cm.
  - FS shield and VV are lifetime components with peak end-of-life radiation damage <<200 dpa.
  - VV is reweldable with peak end-of-life He production <1 He appm.
  - Magnets are lifetime components with peak fast neutron (E>0.1 MeV) fluence <10^{19} n/cm^2 and peak insulator dose <10^{10} Rads.



Integrated Chamber Core and Reactor for Bell Cusp Configuration



Summary (I)

- **Different magnetic configurations were considered leading to a bell cusp configuration providing the possibility of accommodating the ion flux on a liquid dump target in a separate chamber with no line of sight to the main chamber.**

- **Different fluids were assessed, including Pb, Sn and Ga as part of an evaporation and condensation scoping study.**
  - **Both Sn and Ga have high latent heats; Sn is attractive because of its low vapor pressure, while Ga's low melting point would help to start up the dump chamber without having to heat and melt the liquid first.**
  - **Other factors including material compatibility would need to be also considered before finalizing the design choice.**
  - **Condensation was found to be fast for all 3 fluids (Sn, Ga and Pb).**
  - **However, the results are based on a simple, albeit conservative, model and would need to be confirmed through more detailed R&D.**

- **Preliminary chamber layout consideration indicated the possibility of blanket coverage meeting the key nuclear requirements.**

Summary (II)

- **Although this initial assessment is encouraging, a more detailed study is required to obtain a better picture, including looking in more detail at:**
  - **Liquid wall configuration in the dump chamber and mass transfer processes**
  - **Material compatibility under operating conditions**
  - **Design of the small polar condensation chambers**
  - **Better assessment of possible contamination of main chamber through dump and laser ports**