IFE Chamber Research in HAPL

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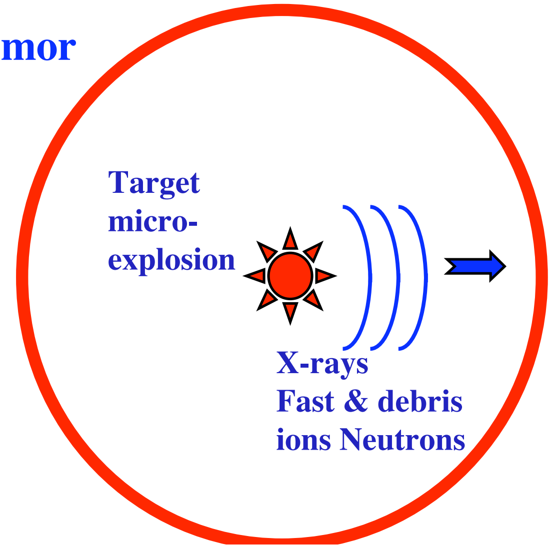
Outline

- Challenging to accommodate laser IFE ion threat with dry chamber wall
- Use of engineered armor for large chamber concept
- Magnetic intervention as advanced option to reduce or eliminate ion threat on chamber wall
- Scoping study of separate dump chamber with liquid wall
- Chamber considerations
- Summary

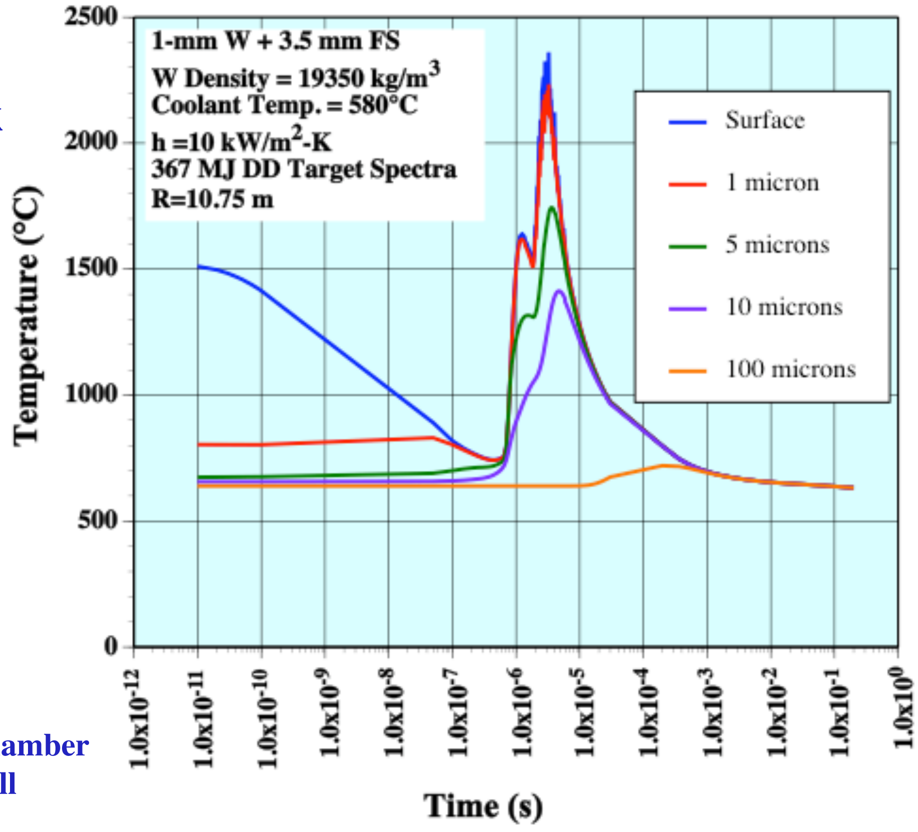
The HAPL Program Aims at Developing IFE Based on Lasers, Direct Drive Targets and Solid Wall Chambers

- **Challenging for dry wall armor to accommodate ion and photon threat spectra.**
- **For example, for baseline 350 MJ target (~24% of the energy is in ions and ~1% in photons), a large chamber (~10.75 m) is required to maintain W armor under a reasonable temperature.**
- **In addition, ion implantation (in particular He) can lead to exfoliation and premature armor failure (even for large chamber)**
- **Maintain large chamber as baseline and look at options to accommodate ion threat spectra on the armor.**
  - **Engineered armor**
  - **Magnetic intervention**


Target micro-explosion

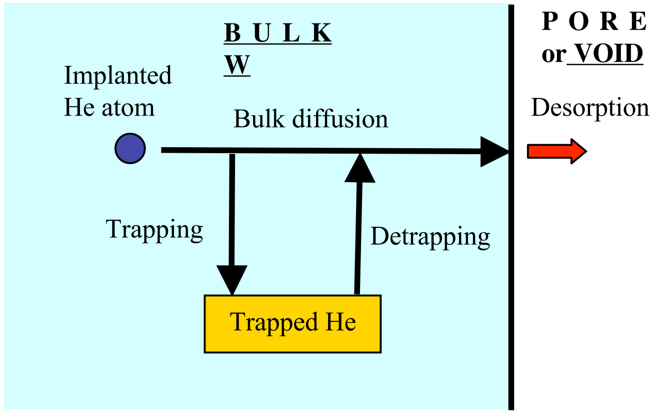
X-rays
Fast & debris ions Neutrons

Chamber wall



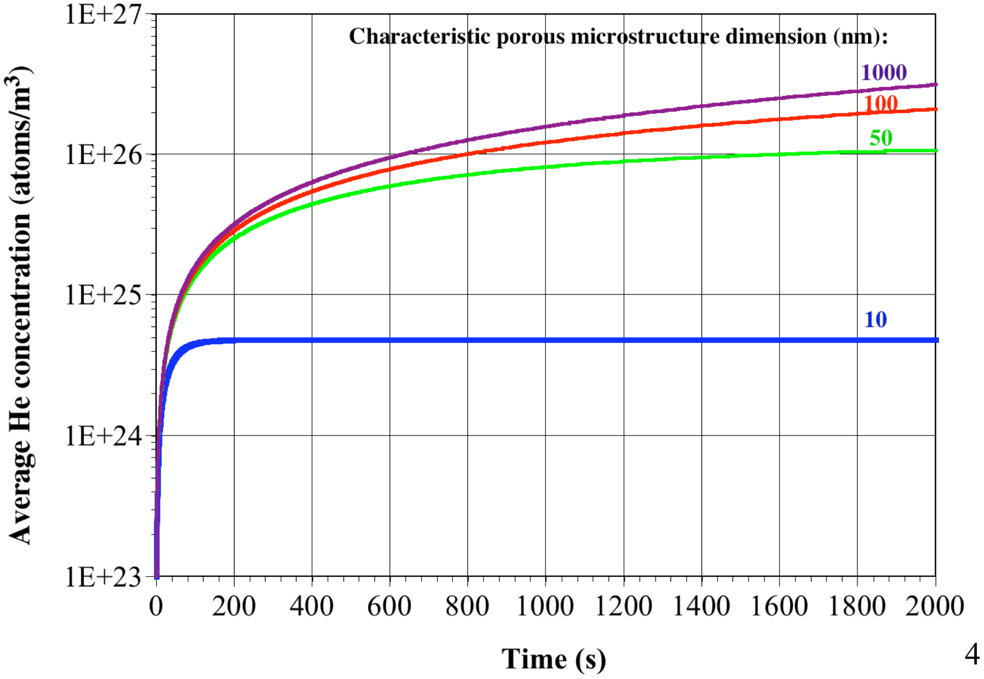
Use of Nano-Structured W Armor to Enhance He Release

- 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).



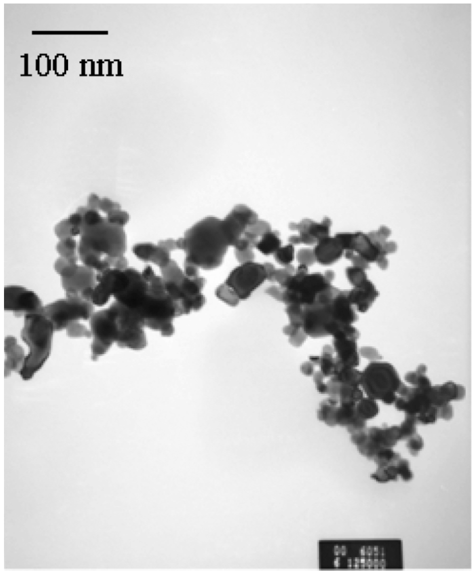
He concentration history in W under IFE Pulses

For comparison, atomic density of W = 6.22 x 10^{28} atoms/m^3

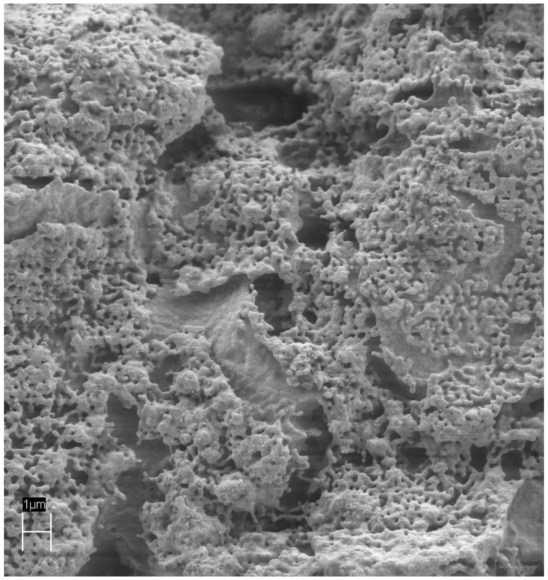


Program Underway to Develop and Test Nano-Structured W

- **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)**
- **Results could be applicable to accommodation of prompt alpha loss in MFE (if required, as in stellerator case)**



Nano-powder and nano-structured W from PPI



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Comparison of IFE and MFE Operating Conditions for ITER Divertor and NRL 154 MJ Direct Drive Target Spectra as Example Cases

- Although base operating conditions of IFE and MFE are fundamentally different, there is an interesting commonality between IFE operating conditions and MFE off-normal operating conditions, in particular ELM's
  - Frequency and energy density are within about one order of magnitude

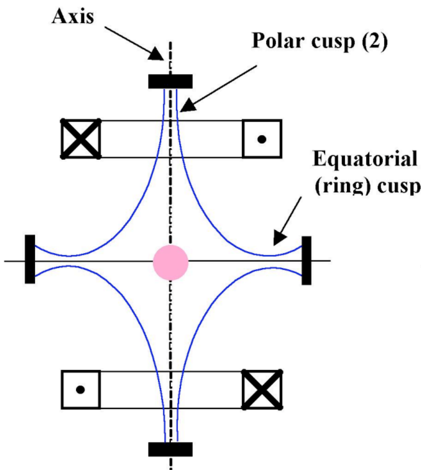
	ITER Type-I ELM's	ITER VDE's	ITER Disruption thermal quench	Typical IFE Operation (154 MJ DD NRL target)
Energy	10-12 MJ	~ 50 MJ/m^2	100-350 MJ	~ 0.1 MJ/m^2
Affected area	5-10 m^2†	A few m^2†	~10 m^2†	Chamber wall (R~5-10 m)
Location	Surface (near divertor strike points)	Surface/bulk	Surface (near divertor strike points)	bulk (~µm's)
Time	≥200 µs	~ 0.3 s	~ 1 ms	~ 1-3 µs
Max. Temperature	Melting/ sublimation	Melting/ sublimation	Melting/ sublimation	~ 2000-3000°C (for dry wall)
Frequency	Few Hz	~ 1 per 100 cycles	~ 1 per 10 cycles	~ 10 Hz
Base Temperature	≥ 500°C	~ 200°C	200-1000°C	~ >700°C
Particle fluxes	~10^{24} m^{-2}s^{-1}(peak under normal operation)			~10^{23} m^{-2}s^{-1}

† large uncertainties exist

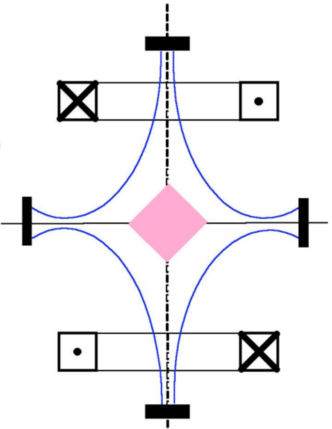
From A. R. Raffray, et al., Dynamic Chamber Armor Behavior in IFE and MFE, ISFNT-6, 2002

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

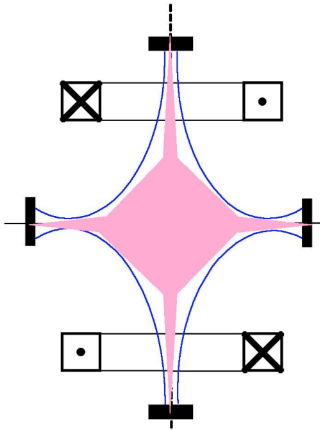
- **Utilization of a cusp field for such magnetic diversion has been experimentally demonstrated previously**
  - **1980 paper by R.E. Pechacek et al.,**
- **Following the micro-explosion, the ions would compress the field against the chamber wall, the latter conserving the flux. Because of this flux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



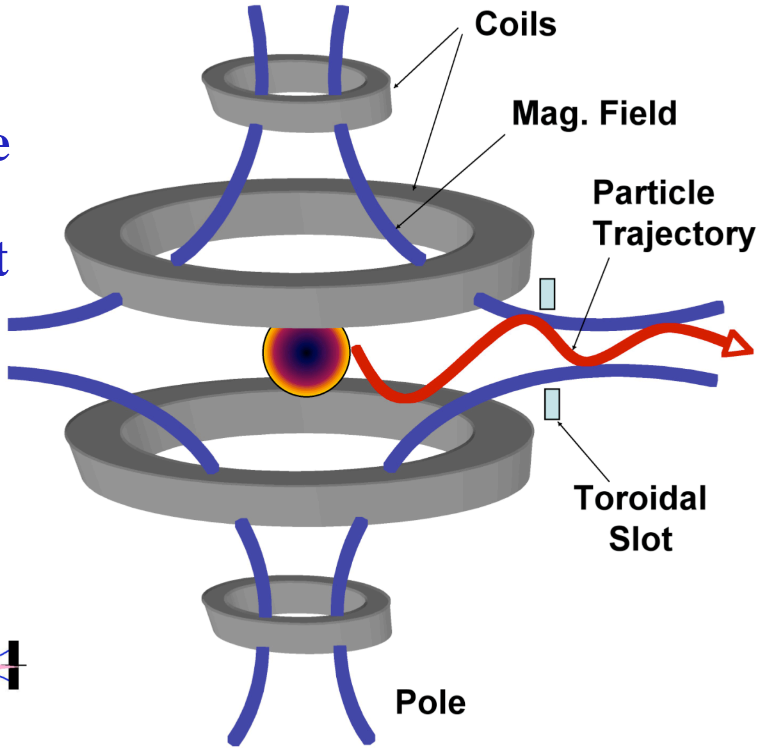
Plasma expansion initially spherical



Ion cloud deforms as it encounters cusp field



Ions leak out through the cusps

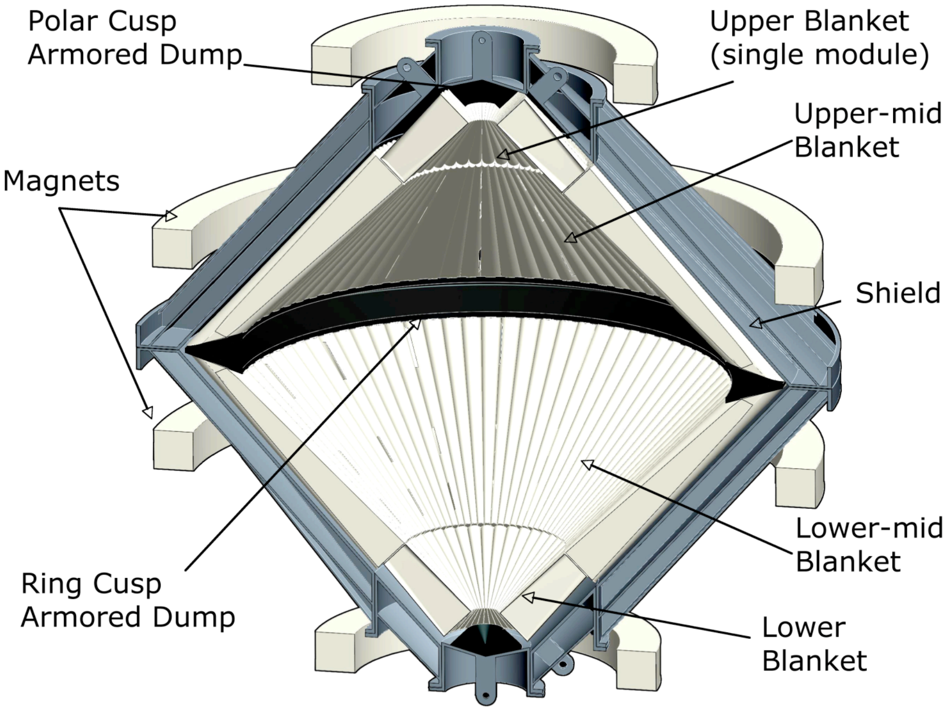


Biconical Chamber Well Suited to Simple Cusp Coil Geometry and Utilizing SiC_f/SiC for Resistive Dissipation

- SiC_f/SiC blanket with Pb-17Li or flibe as liquid breeder, coupled to Brayton cycle.
- Water-cooled steel shield is lifetime component and protects the coil.
- 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.

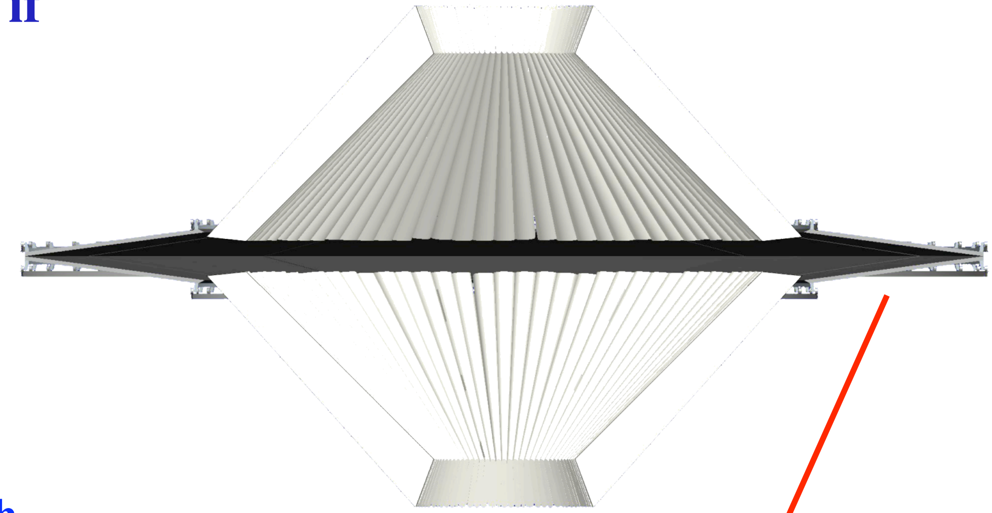
- Innovative carousel technique proposedfor maintenance.

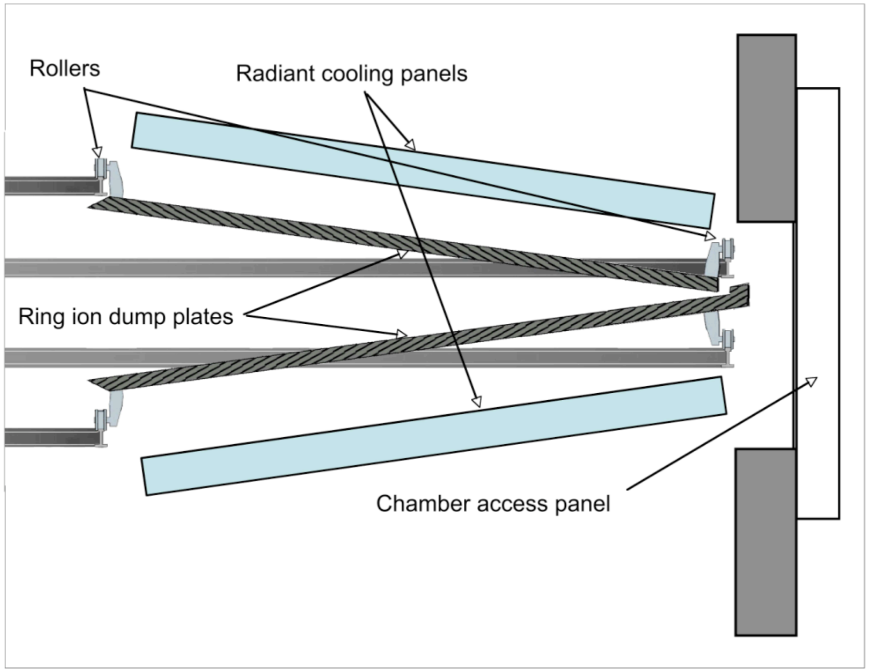
- However, ions still deposited on solid materials
  - He retention concern remains, although now transferred to an external location where they might be better accommodated.

- Also formidable challenge to accommodate high ion flux at the poles.

- This led to the consideration of liquid dumps .

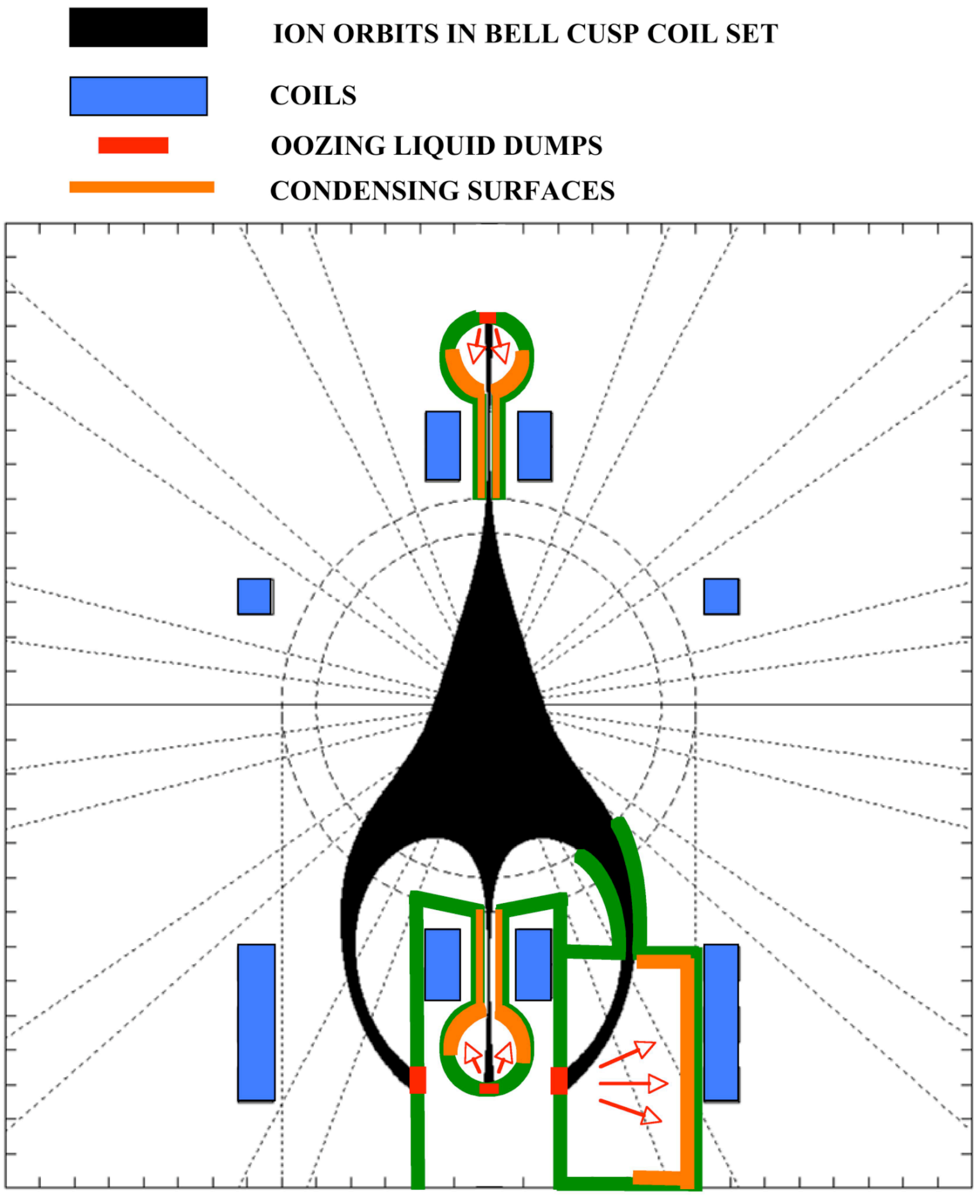
- Need more suitable geometry.





Bell or Tulip Cusp

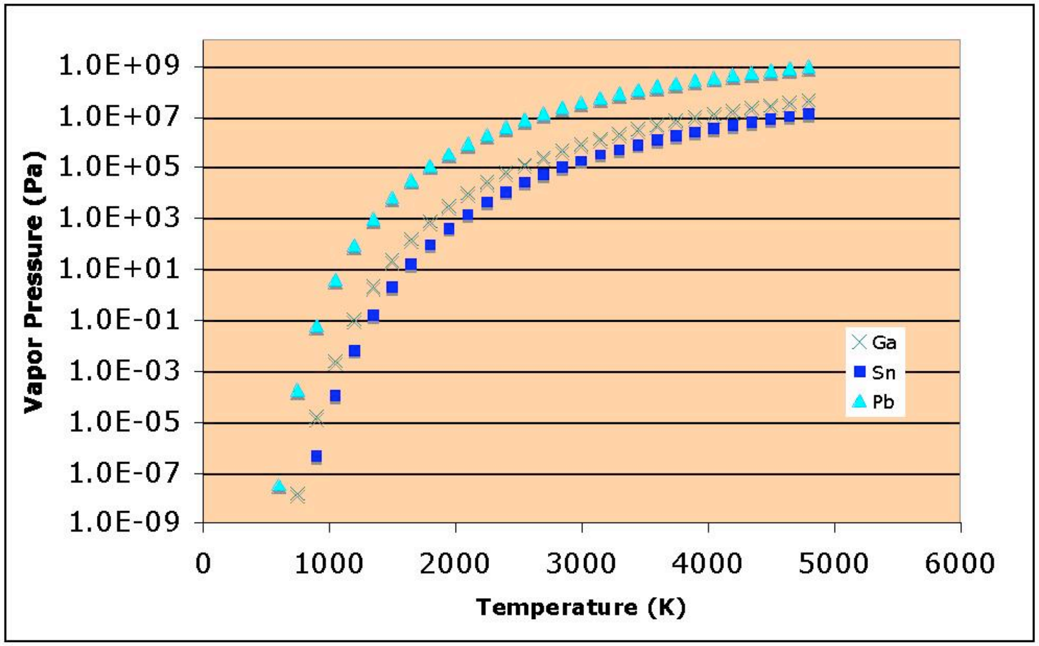
- Modification of simple cusp with 6 coils
  - Ions directed to a lower annular port and intersect the dump area at an angle with no line of sight to main chamber to minimize any contamination.
  - This configuration is particularly suited to a liquid dump concept, such as an oozing dumptarget (or liquid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

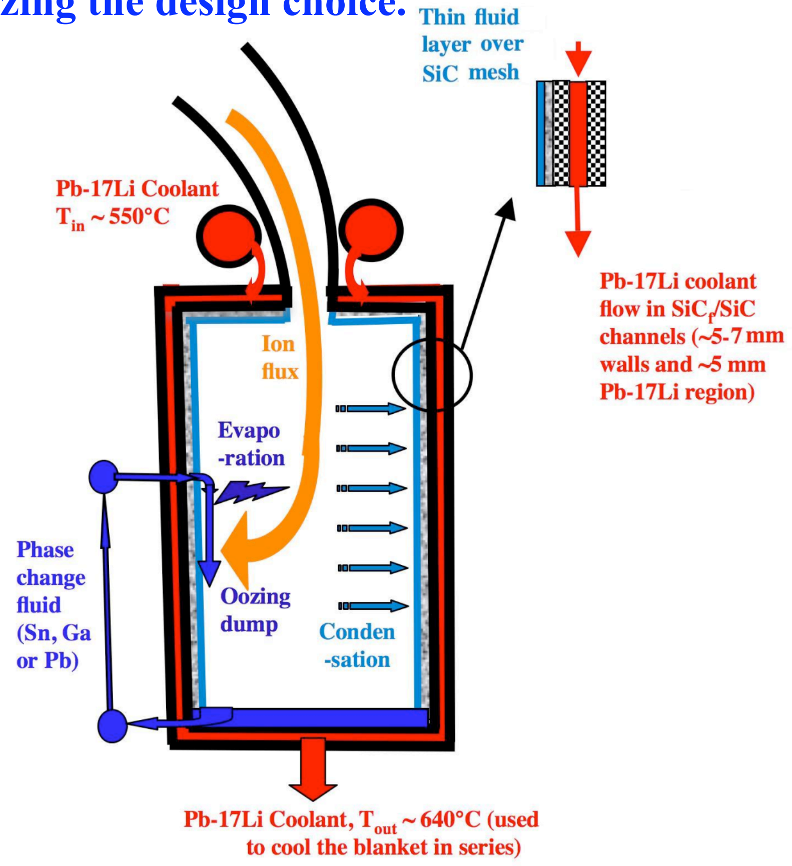


Evaporation/Condensation Studies for Bell Cusp

- **Three candidate fluids were considered for the dump chamber: Pb, Sn and Ga**
  - **Sn and Ga have high latent heats; Sn has the lowest vapor pressure, while Ga's low melting point would help for start-up and draining (without an additional heat source).**
  - **However, other factors including material compatibility would need to be considered in finalizing the design choice.**

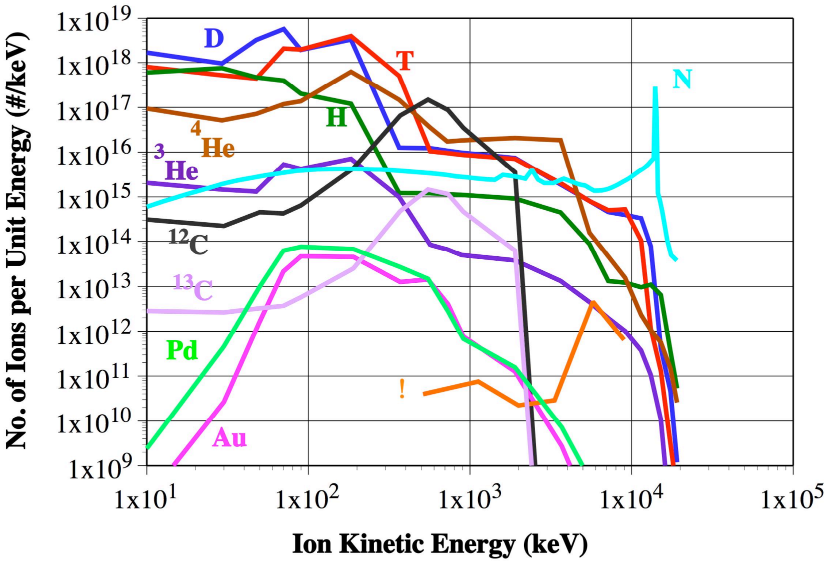
Fluid	Pb	Sn	Ga
Density (kg/m^3)	11300	6919	5904
h_{fg} (J/kg)	8.6×10^5	2.4×10^6	3.79×10^6
Base temp.	500°C	500°C	500°C
Cp (J/kg-K)	142	300	370
k (W/m-K)	16	35	41
Melting point (°C)	327.6	232	29.8
Boiling point (°C)	1740	2270	2204
Energy to evap. (J/m^3)	1.171×10^{10}	2.028×10^{10}	2.61×10^{10}



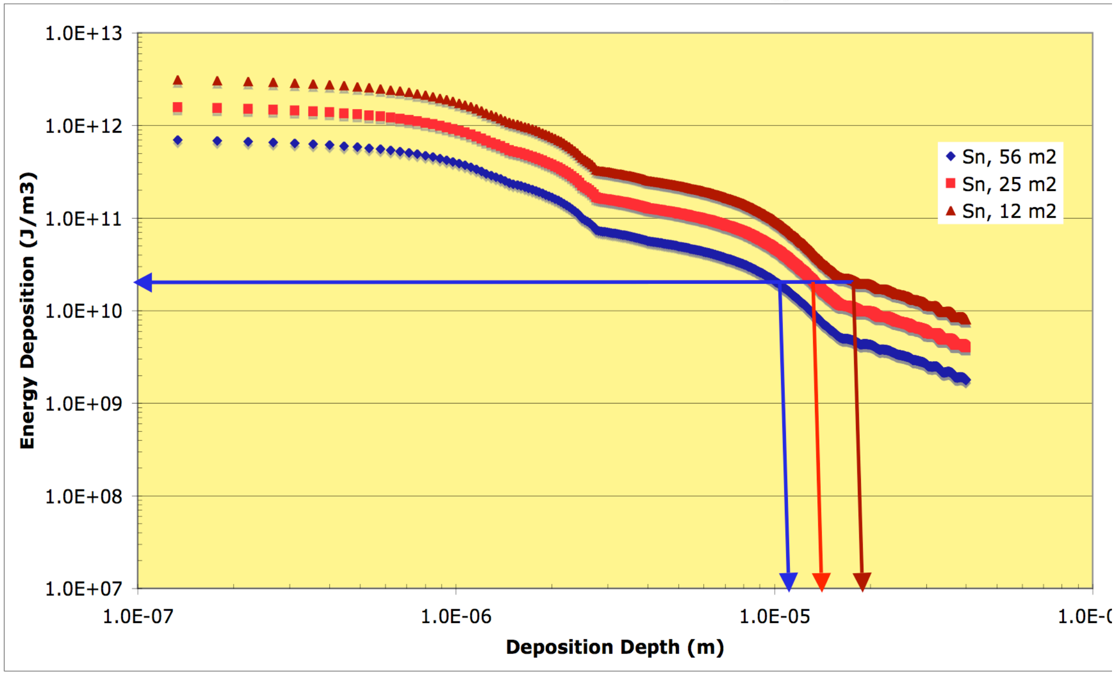


Estimating Evaporated Layer Thickness Based on Ion Energy Deposition for 350 MJ Spectra

- **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 and latent heat of evaporation.**

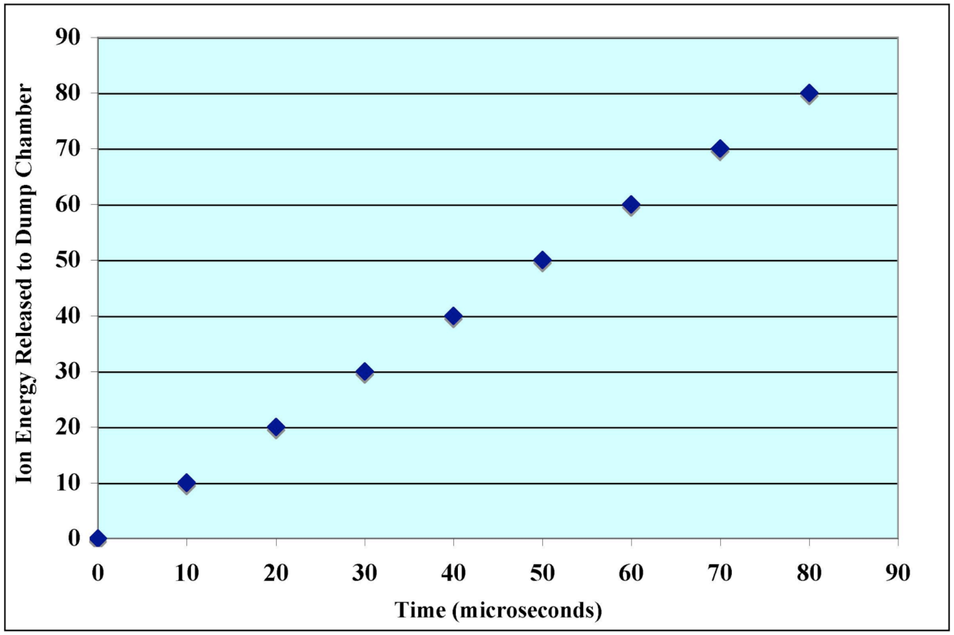


Dump area (m^2)	12	56
Thickness of evap. Sn (m)	1.83x10^{-5}	1.02x10^{-5}
Mass of evap. Sn layer (kg)	1.52	3.93
Thickness of evap. Pb (m)	3.05x10^{-5}	1.18x10^{-5}
Mass of evap. Pb layer (kg)	4.14	7.44
Thickness of evap. Ga (m)	1.58x10^{-5}	9.18x10^{-6}
Mass of evap. Ga layer (kg)	1.12	3.04

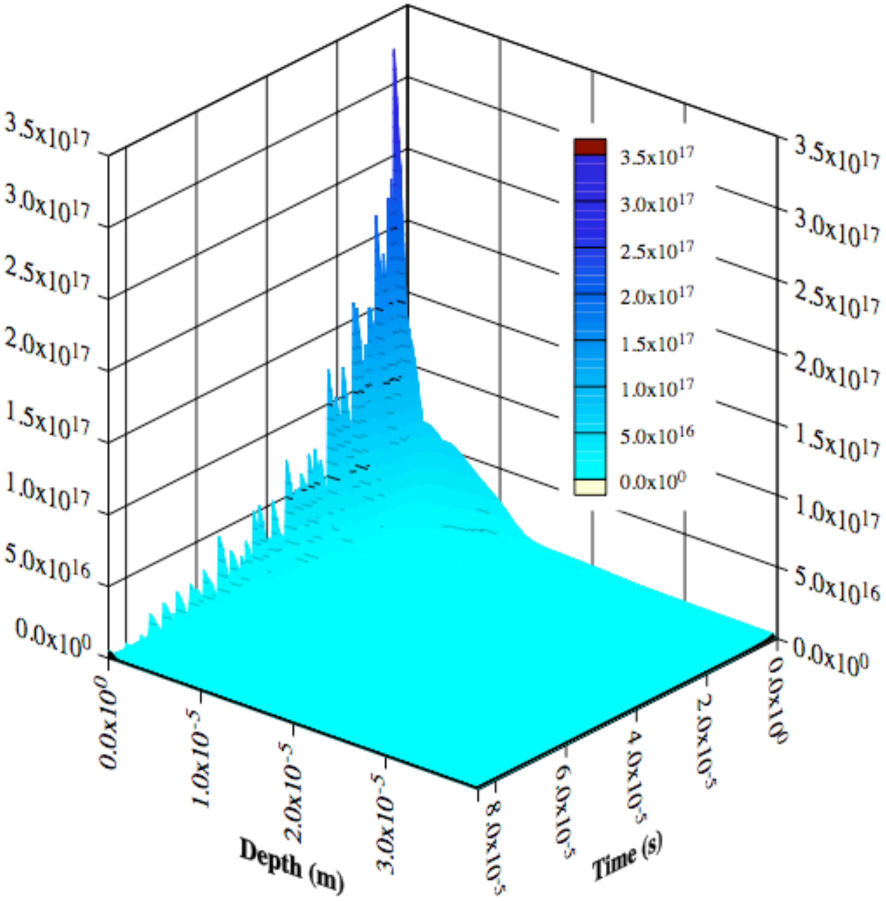


Evaporation Study Based on Transient Ion Energy Deposition and Thermal Behavior of Ion Dump

- **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**



Ion Energy Release to Dump Chamber Based on Physics Modeling



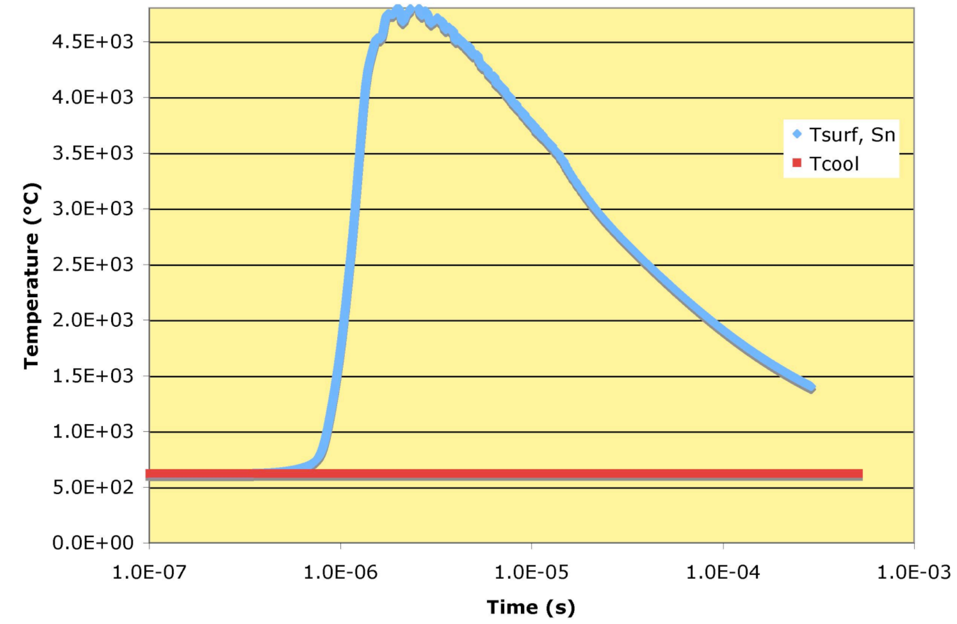
Example Spatial and Temporal Distribution of Volumetric Heat Generation (W/m^3) in Sn Ion Dump

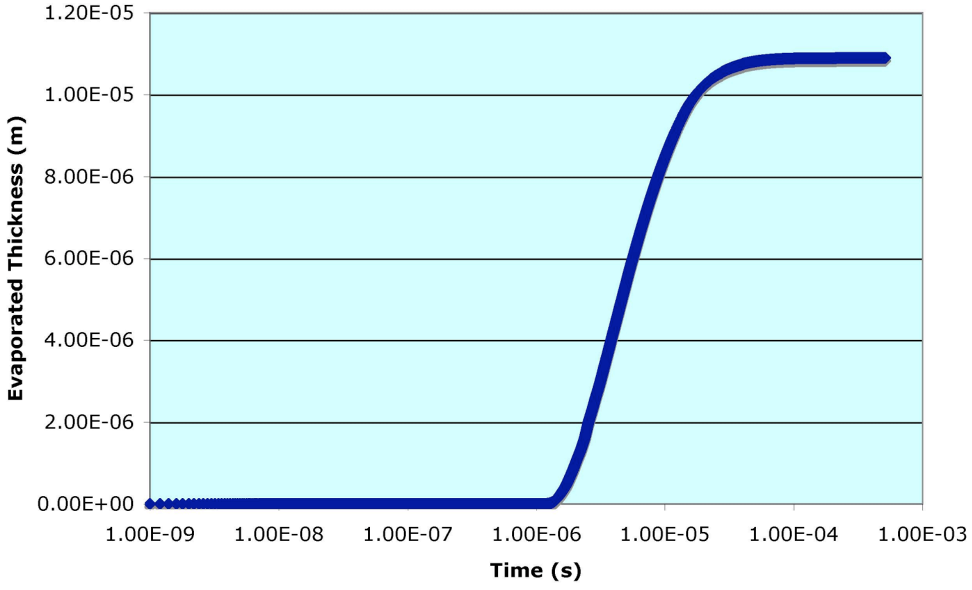
Evaporated Thickess Estimate Based on RACLETTE-IFE Transient Analysis

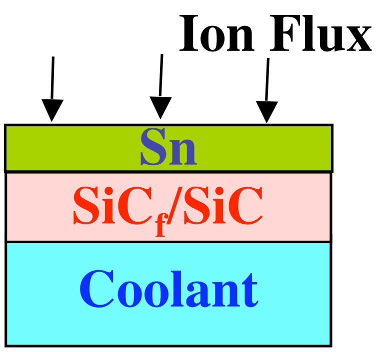
- Example results for Sn and an assumed 56 m^2 dump area

- 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).







Ion Flux

Sn

SiC_f/SiC

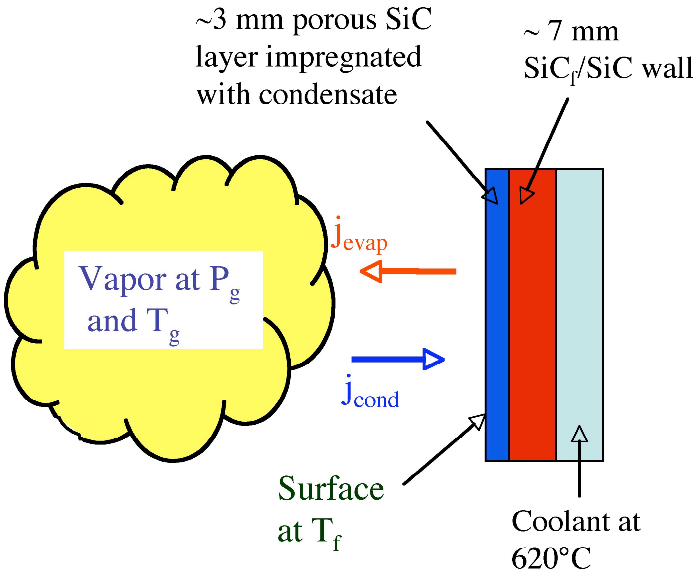
Coolant

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 ions and atoms as they cool down and condense would require quite a complex model, beyond the scope of the present study.**
- **For the scoping analysis presented here, 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)



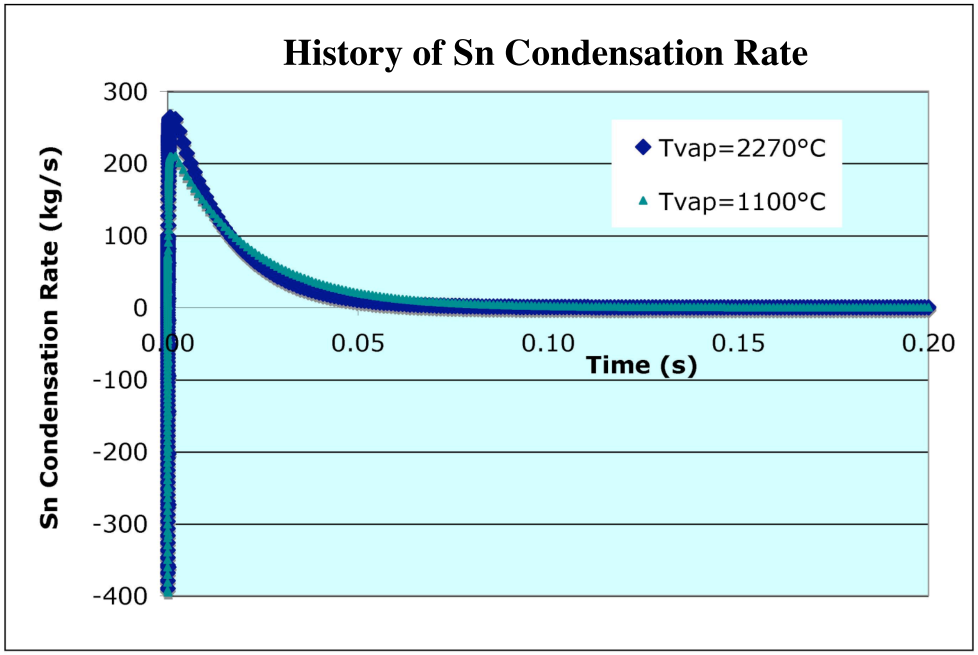
Scoping Analysis of Condensation

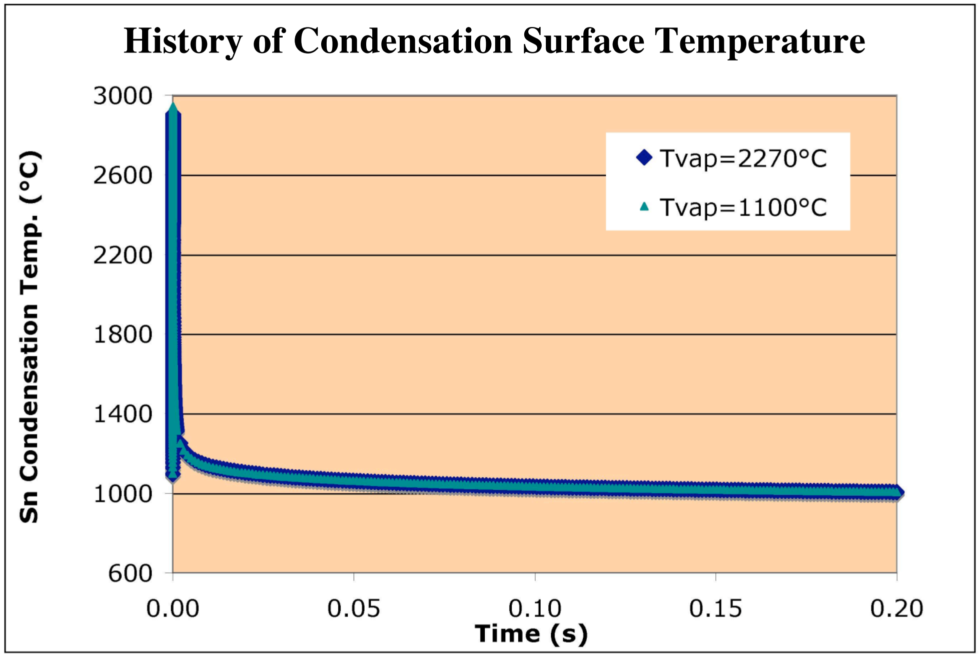
- During the condensing process, it is the final condensation at lower vapor temperature which takes longer, as the initial cooling down and condensation at high vapor pressure and temperature is fast.

- The condensation analysis conservatively focuses on end-of-condensation process, with example T_{vapor} of 2270°C and 1100°C.
  - mass of 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 to cool ionized vapor to assumed T_{vapor} assumed to occur over initial 80 µs (avg. heat flux ~1.8×10^9 W/m^2).

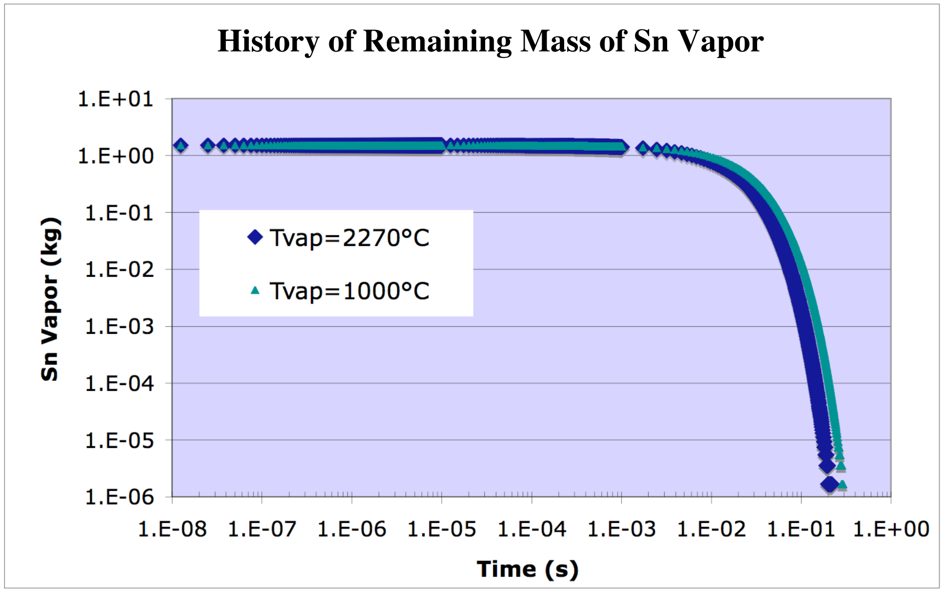
- This would yield conservative results and an upper bound of the time scale required for condensation.

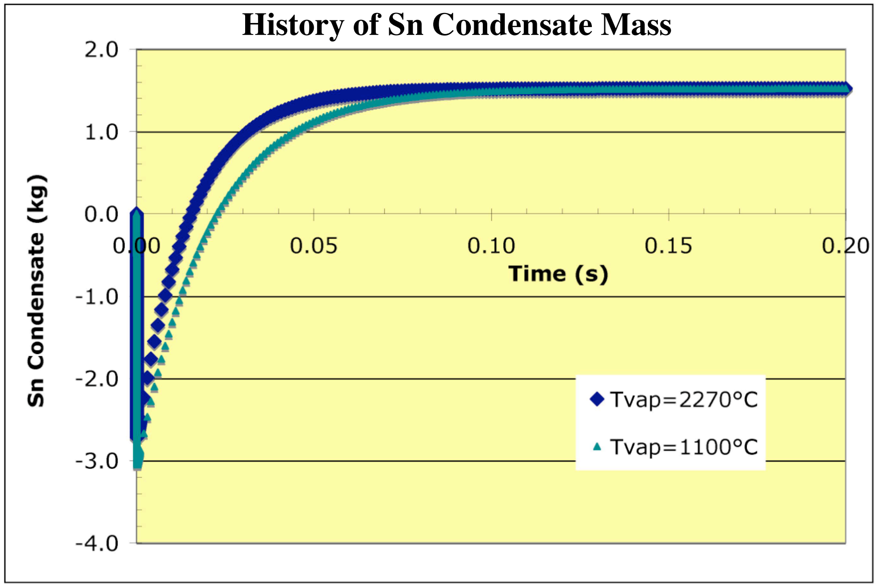


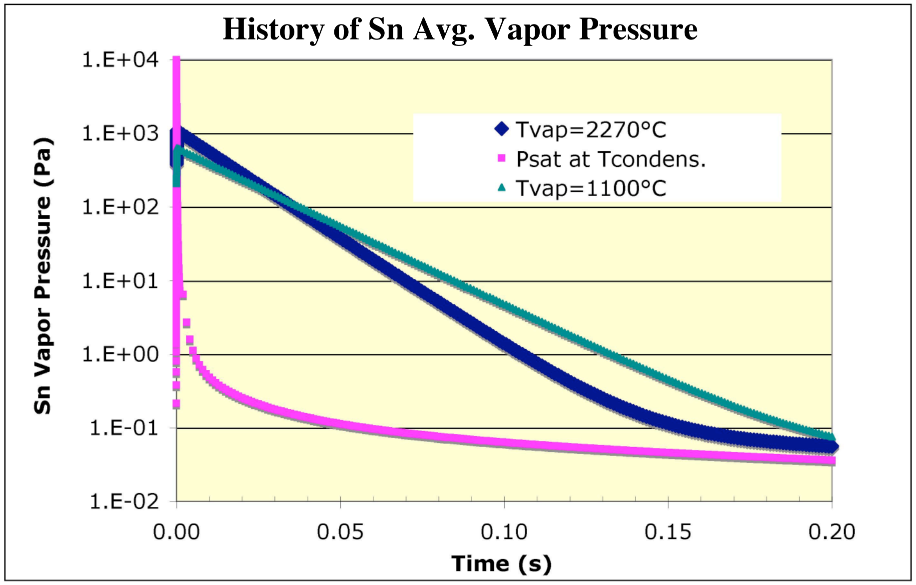


Results of Condensation Scoping Analysis

- 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 R&D.







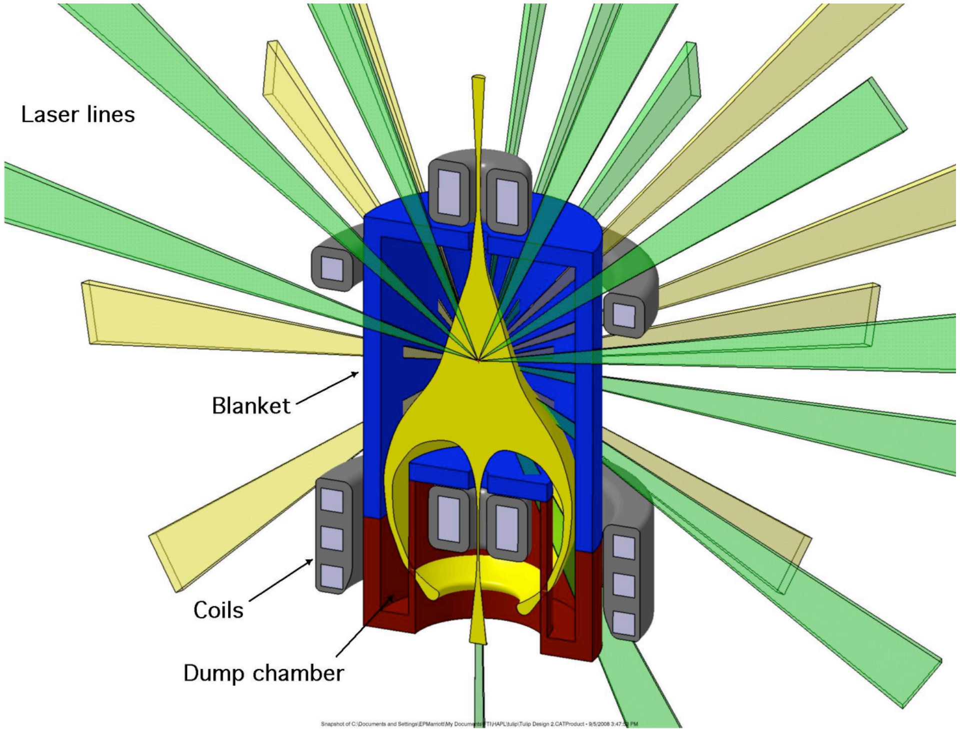
Overall Chamber and Reactor Concept with Bell Cusp Configuration

- **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.**



Summary

- **A key issue for an IFE dry wall is the survival of the armor under the ion threat spectra.**

- **The possibility of steering the ions away from the chamber to specially-designed dump ports using magnetic intervention has been assessed.**

- **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 is a plus for start-up.**
  - **However, other factors including material compatibility would need to be 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.**

- **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.**

Additional Slide

Integrated Chamber Core and Reactor for Bell Cusp Configuration