Assessment of Dry Chamber Wall Configurations as Preliminary Step in Defining Key Processes for Chamber Clearing Code

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Chamber Clearing Modeling: Several Key Processes Dependent on Choice of Wall Configuration

Energy Source **Chamber Dynamics** **Chamber Wall Interaction**

Typical time of flight to wall:

X-rays (~20 ns)

Fusion neutrons (~100 ns)

Alphas (~400 ns)

Burn Products (~1 μs)

Debri Ions (~1-10 μs)

Photon transport & energy deposition

Ion transport & energy deposition

Heating & ionization

Radiation

Gas dynamics (shock, convective flow, large gradients, viscous dissipation)

Condensation

Conduction

Cavity clearing

Photon energy deposition

Ion energy deposition

Neutron + alpha energy deposition

Conduction

Melting

Vaporization

Sputtering

Thermo-mechanics/ macroscopic erosion

Radiation damage

Blistering (from bubbles of implanted gas)

Desorption or other degassing process

Convection & cooling

Outline of Presentation

- **Chamber Wall Options**
  - **Thermal and Lifetime Analysis for (from ARIES-IFE study):**
    - **C**
    - **W**
    - **Engineered surface (fibrous surface)**
  - **Summary of Erosion and Tritium Retention Issues**
    - **Must consider armor options (besides C)**
    - **Use of very thin armor on structural material to separate energy accommodation function from structural function**

- **Separate Functions as Required for More Effective Design**
  - **Separately-Cooled and Replaceable Chamber Wall Region**
    - **Effect on power cycle efficiency of operating first wall at lower temperature than blanket based on target injection and/or lifetime requirements**

Lifetime is a Key Dry Chamber Wall Issue

- **Armor Material Option (C, W, engineered surface) to Help Accommodate Energy Deposition**
  - **Armor material does not need to be the same as structural material**
  - **Actually, separating energy accommodation function from structural function is beneficial**
- **Protective Chamber Gas, e.g. Xe**
  - **Effect on target injection**
  - **Effect on laser**
  - **UW has performed detailed comparative studies for different materials and gas pressures (R. Peterson/D. Haynes)**

- **Goal:**

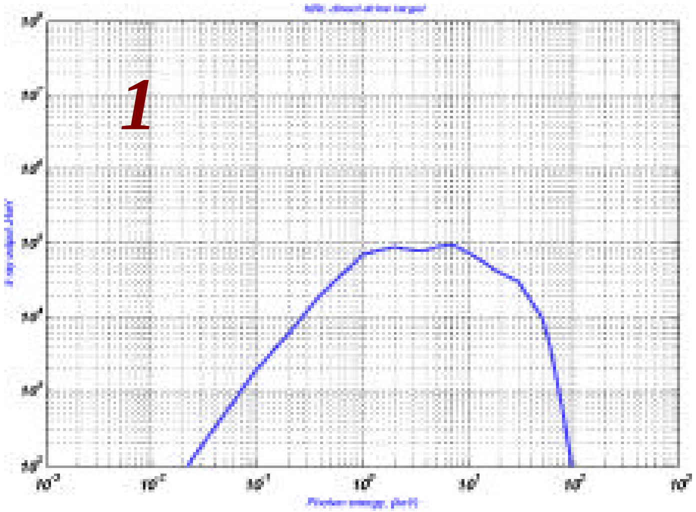
Dry wall material configuration(s) which can accommodate energy deposition and provide required lifetime without any protective gas in chamber

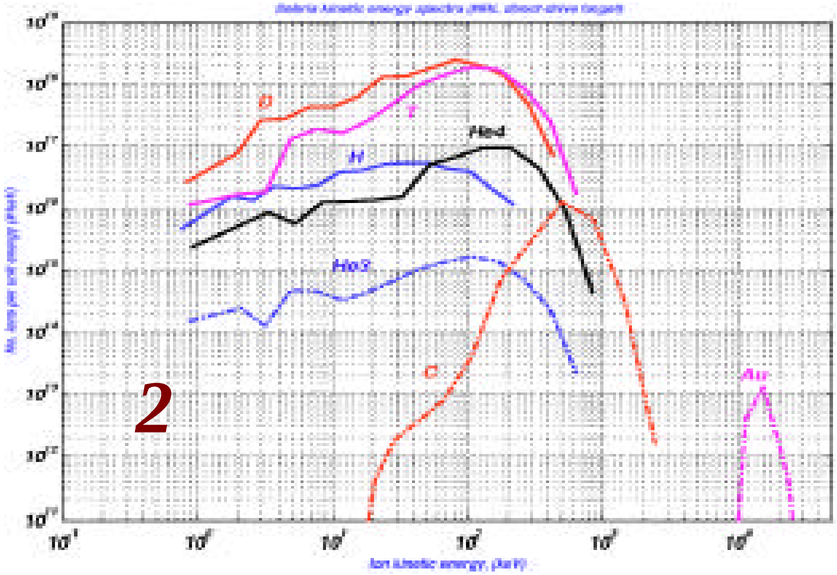
X-ray and Charged Particles Spectra

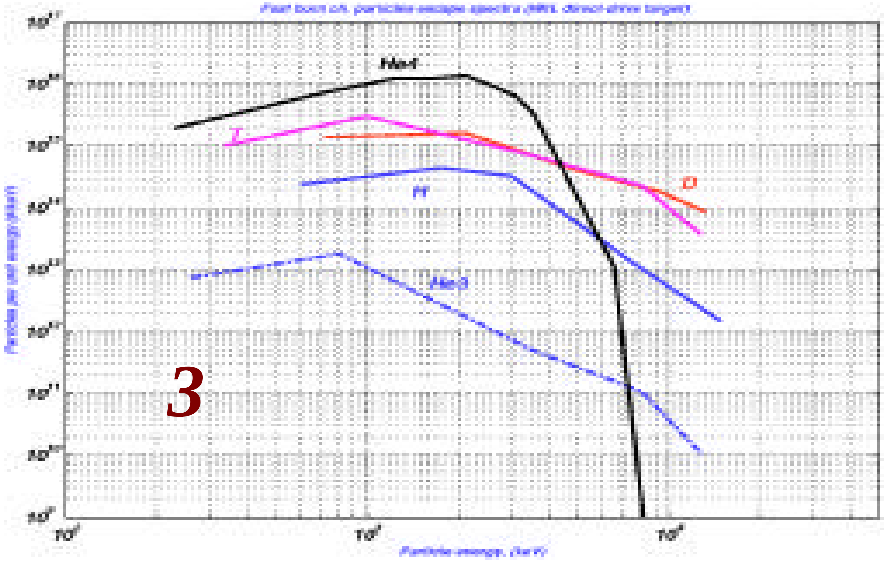
NRL Direct-Drive Target

1. X-ray (2.14 MJ)
2. Debris ions (24.9 MJ)
3. Fast burn ions (18.1 MJ)

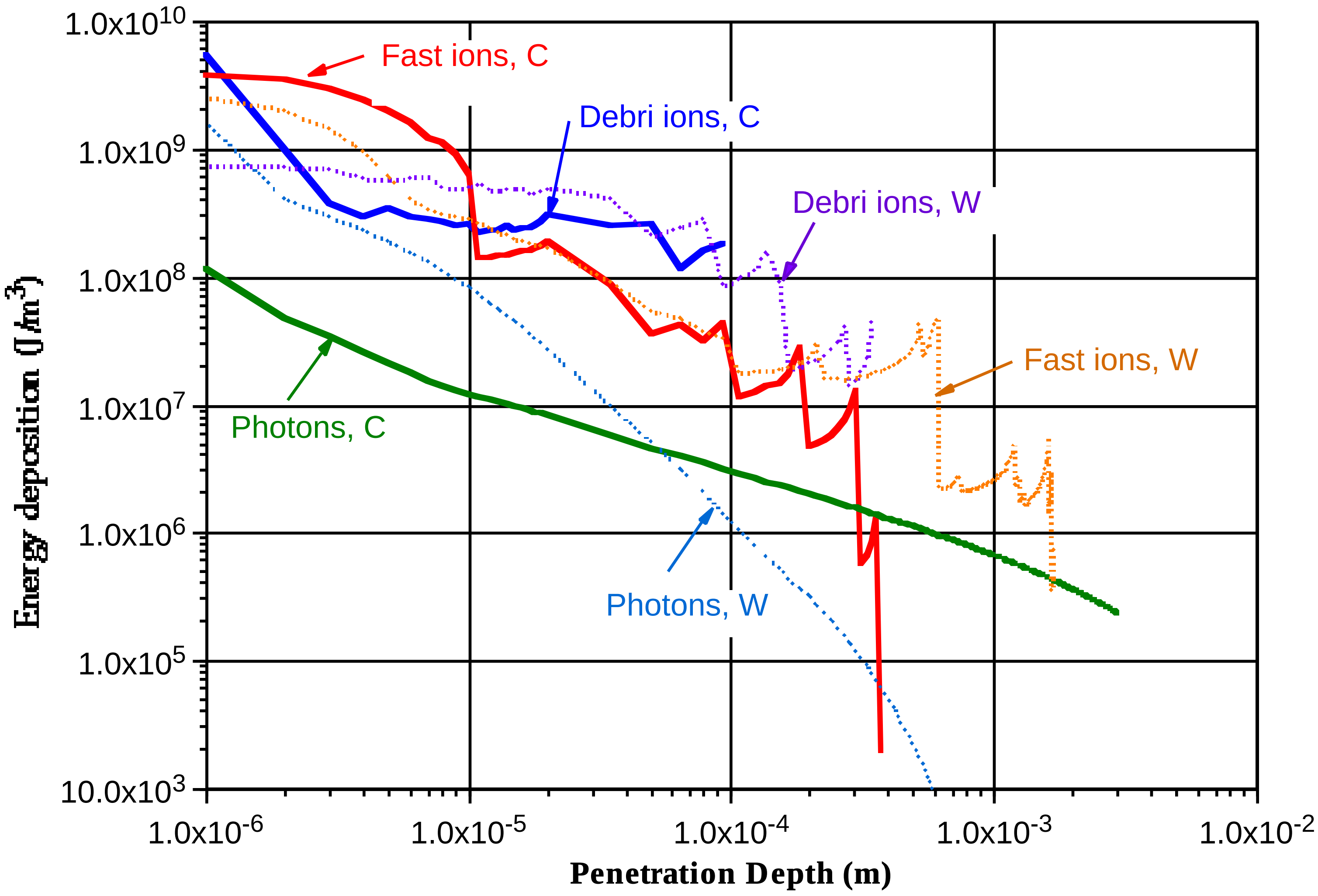
(from J. Perkins, LLNL)



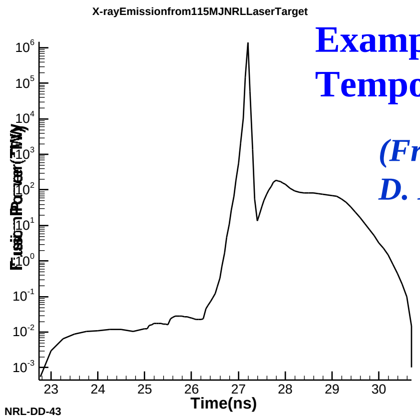




Photon and Ion Attenuations in Carbon and Tungsten



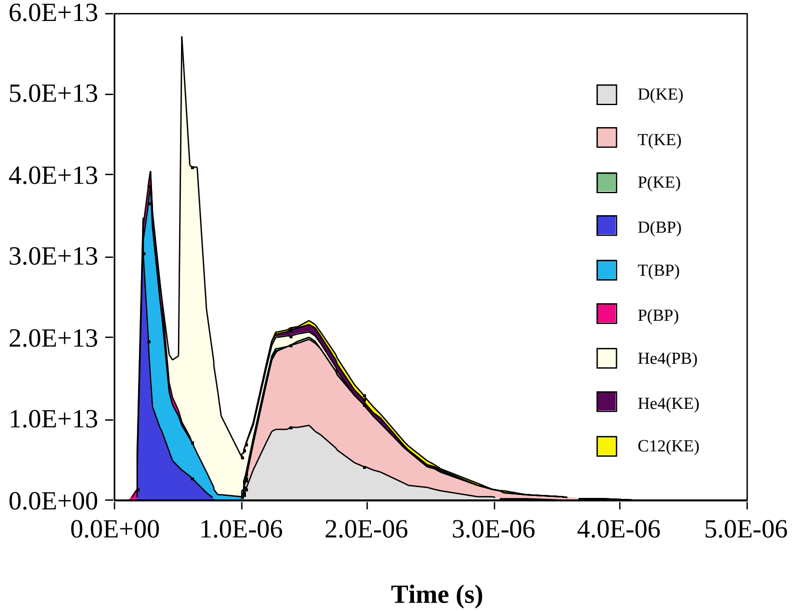
Temporal Distribution of Energy Distributions from Photons and Ions Taken into Account



Example Photon Temporal Distribution

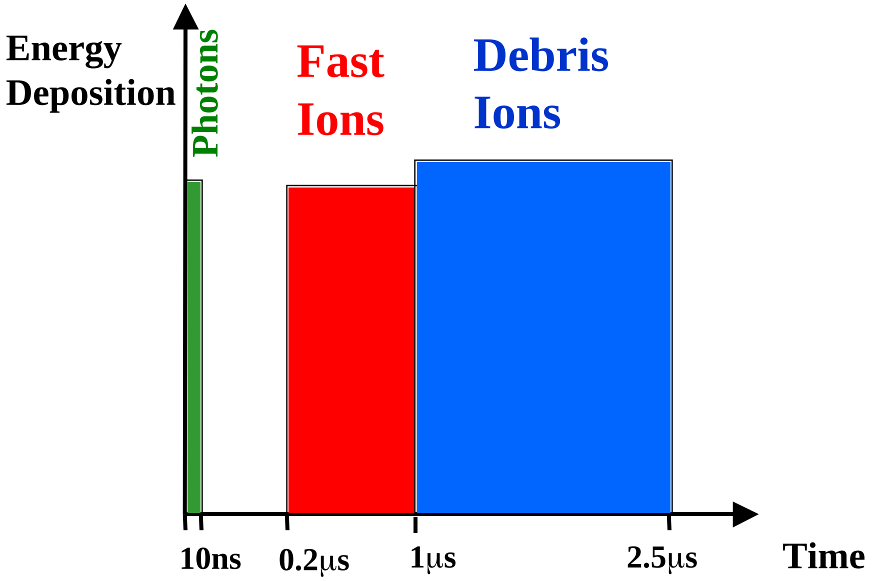
(From R. Peterson and D. Haynes)

Time-of-Flight Ion Power Spread



- **Dramatic decrease in the maximum surface temperature when including temporal distribution of energy deposition**
  - **e.g. T_{max} for carbon reduced from ~6000°C to ~1400°C for a case with constant k_{carbon} (400 W/m-K) and without protective gas**

    (from Dec. 2000 ARIES-IFE meeting)



Temporal Distribution for Ions Based on Given Spectrum and 6.5 m Chamber

Sublimation is a Temperature-Dependent Process Increasing Markedly at the Sublimation Point

Carbon

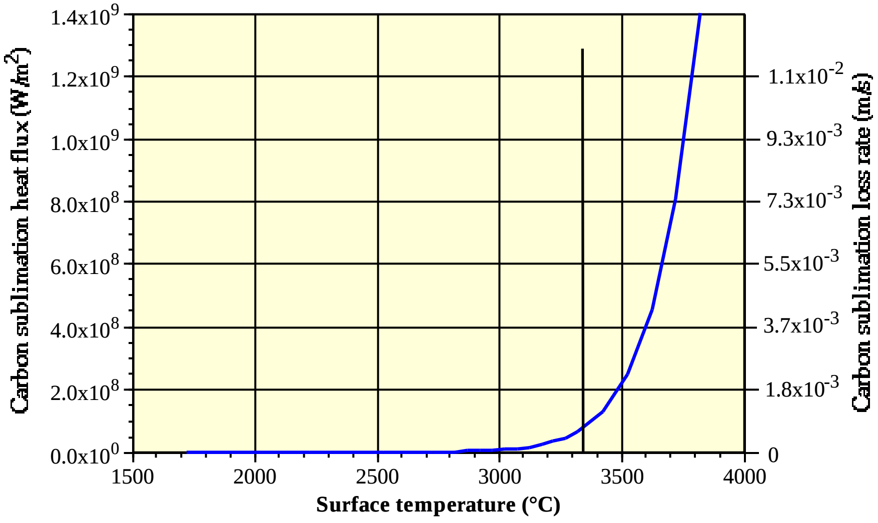
Latent heat of evaporation = 5.99 x10^7 J/kg

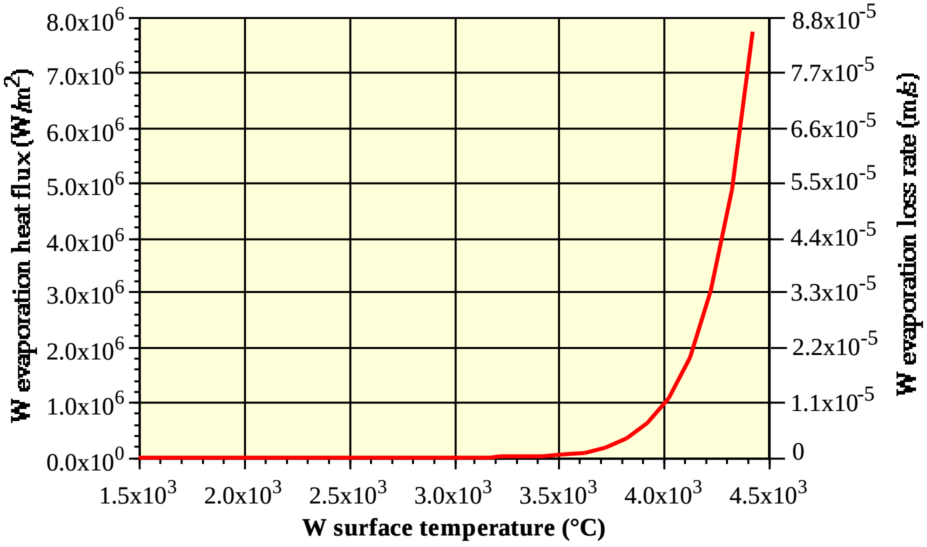
Sublimation point ~ 3367 °C

Tungsten

Latent heat of evaporation = 4.8 x10^6 J/kg

Melting point ~ 3410 °C

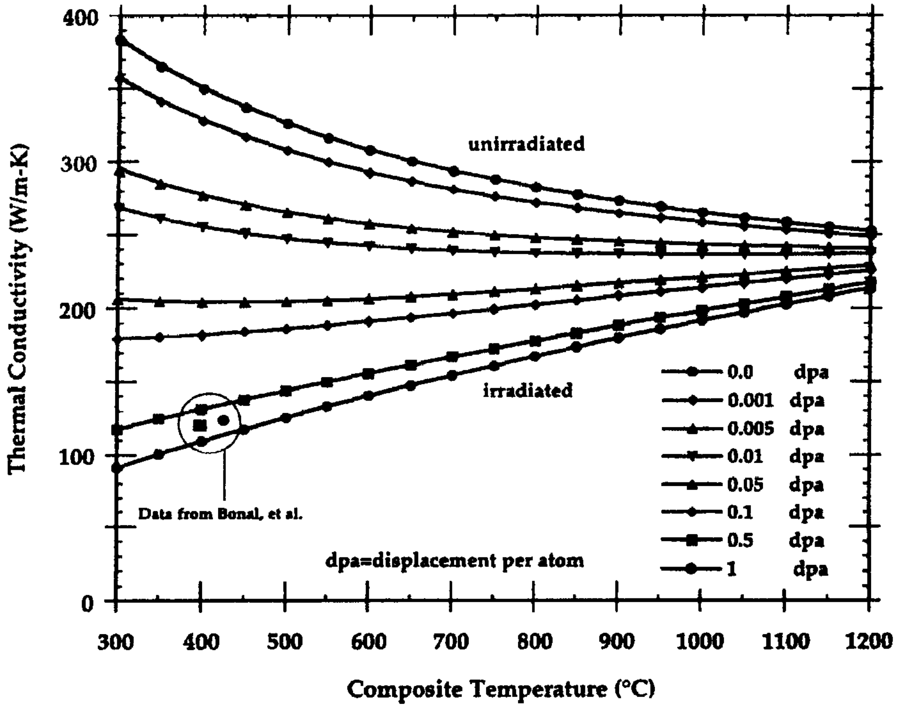




Use evaporation heat flux as a f(T) as surface boundary conditions to include evaporation/sublimation effect in ANSYS calculations

Consider Temperature-Dependent Properties for Carbon and Tungsten

- C thermal conductivity as a function of temperature for 1 dpa case (see figure)
- C specific heat = 1900 J/kg-K
- W thermal conductivity and specific heat as a function of temperature from ITER material handbook (see ARIES web site)

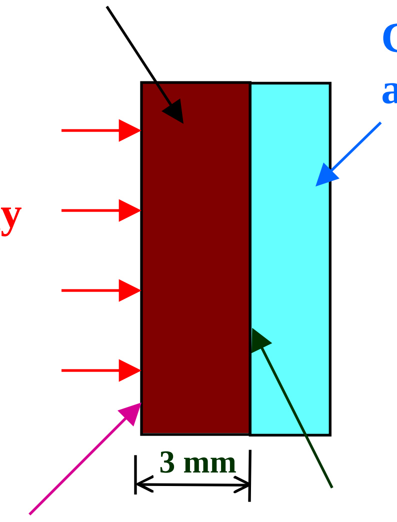


Calculated thermal conductivity of neutron irradiated MKC-1PH CFC

(L. L. Snead, T. D. Burchell, Carbon Extended Abstracts, 774-775, 1995)

Example Temperature History for Carbon Flat Wall Under Energy Deposition from NRL Direct-Drive Spectra

- **Coolant temperature = 500°C**
- **Chamber radius = 6.5 m**
- **Maximum temperature = 1530 °C**
- **Sublimation loss per year = 3x10^{-13} m (availability = 0.85)**



C Chamber Wall

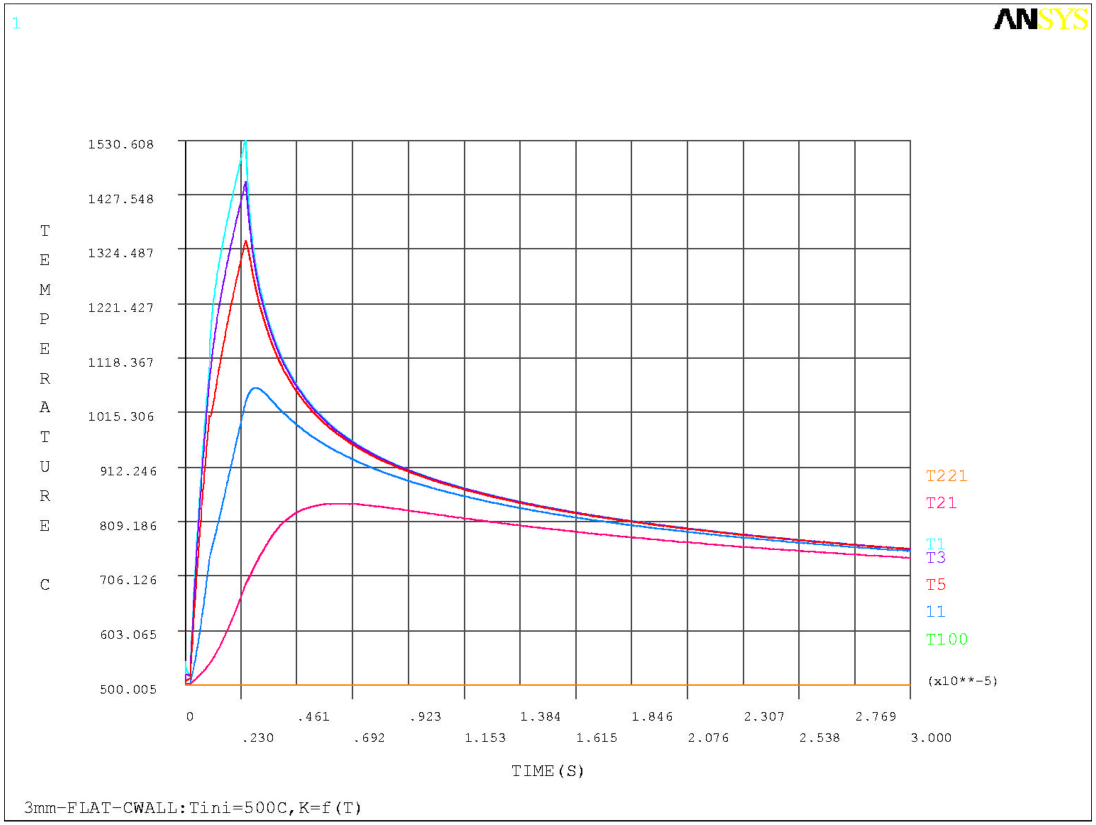
Coolant at 500°C

Energy Front

3 mm

Evaporation heat flux B.C at incident wall

Convection B.C. at coolant wall: h= 10 kW/m^2-K



Summary of Thermal and Sublimation Loss Results for Carbon Flat Wall

Coolant Temp. (°C)	Energy Deposition Multiplier	Maximum Temp. (°C)	Sublimation Loss per Shot (m)	Sublimation Loss per Year (m)*
500	1	1530	1.75×10^{-21}	3.31×10^{-13}
800	1	1787	1.19×10^{-18}	2.25×10^{-10}
1000	1	1972	5.3×10^{-17}	1.0×10^{-8}
500	2	2474	6.96×10^{-14}	1.32×10^{-5}
500	3	3429	4.09×10^{-10}	7.73×10^{-2}

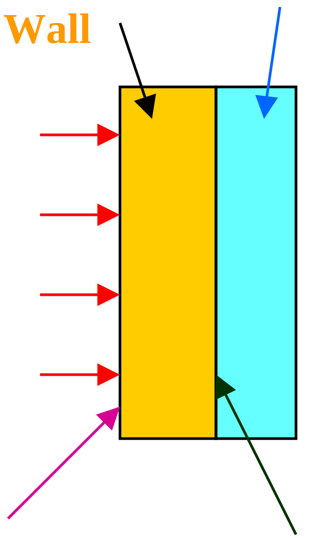
* Shot frequency = 6; Plant availability = 0.85

- Encouraging results: sublimation only takes off when energy deposition is increased by a factor of 2-3
- Margin for setting coolant temperature and chamber wall radius, and accounting for uncertainties

Example Temperature History for Tungsten Flat Wall Under Energy Deposition from NRL Direct-Drive Spectra

Key issue for tungsten is to avoid reaching the melting point = 3410°C

- **Coolant temperature = 500°C**
- **Chamber radius = 6.5 m**
- **Maximum temperature = 1438 °C**



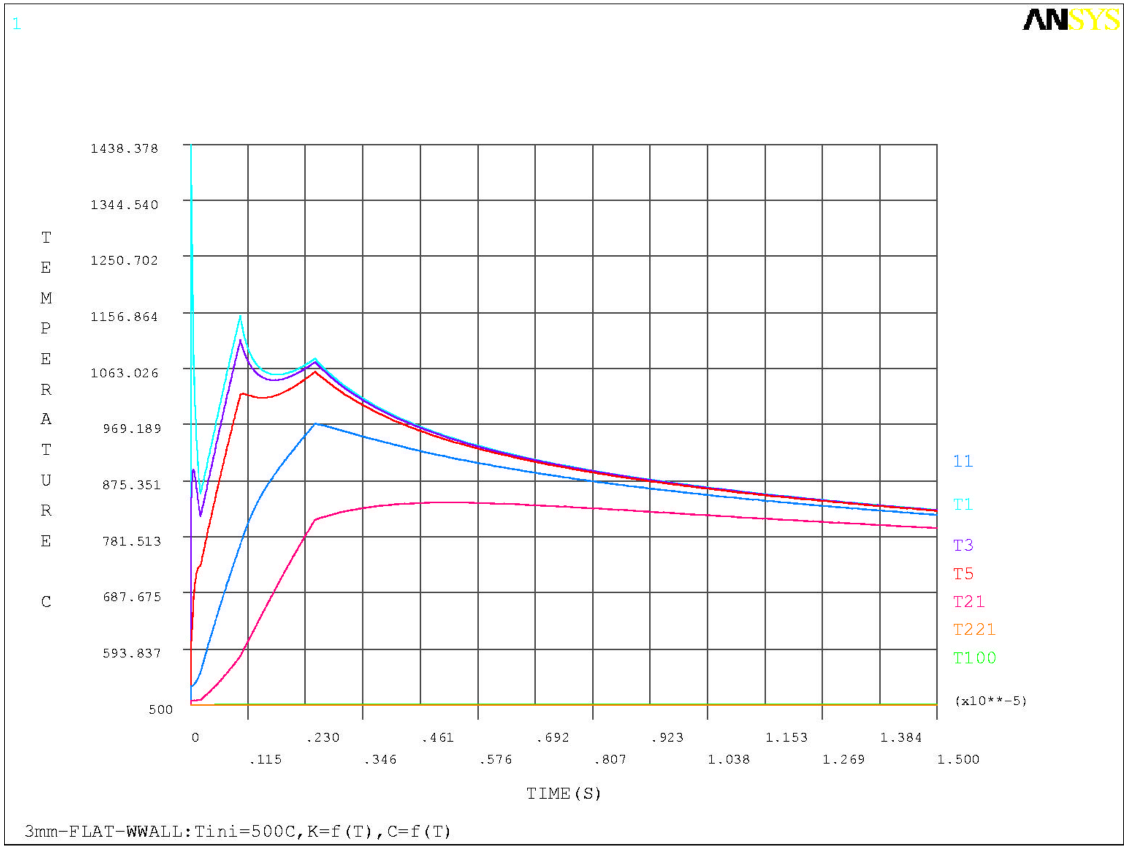
3-mm thick W Chamber Wall

Coolant at 500°C

Energy Front

Evaporation heat flux B.C at incident wall

Convection B.C. at coolant wall: h= 10 kW/m^2-K

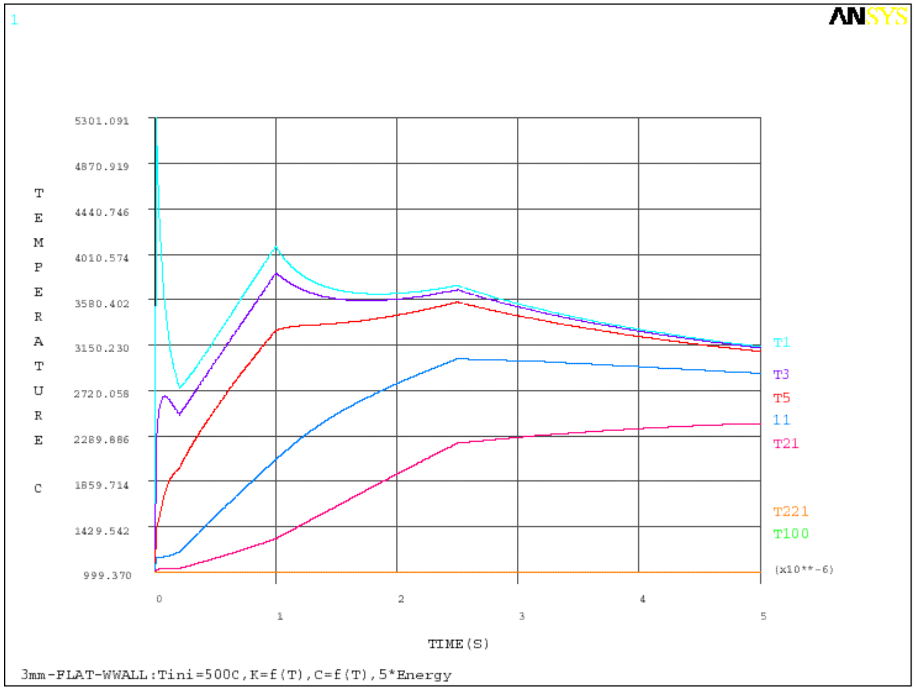


W compared to C:

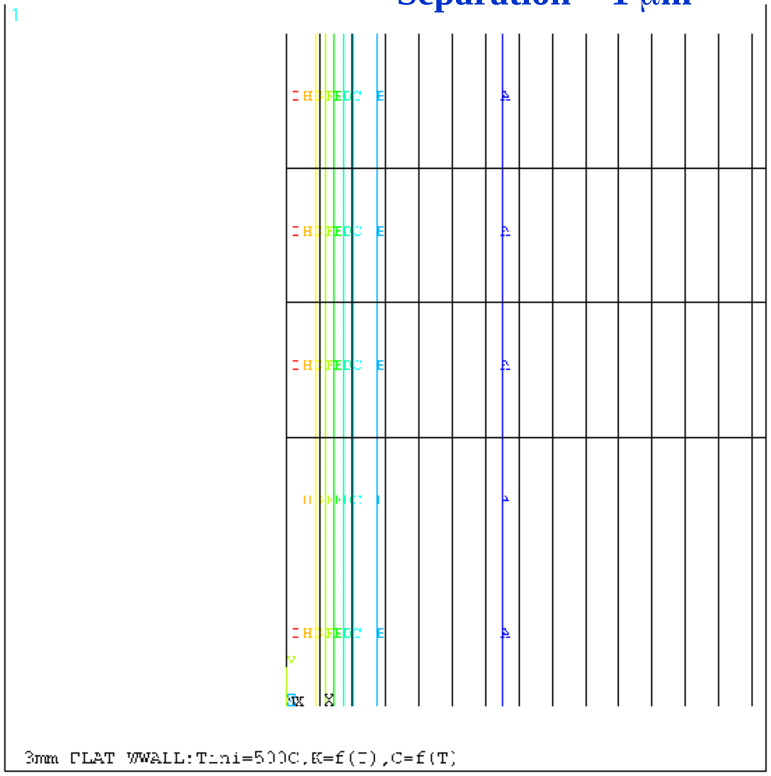
- **Much shallower energy deposition from photons**
- **Somewhat deeper energy deposition from ions**

Example Temperature History for Tungsten Flat Wall Under 5 x Energy Deposition from NRL Direct-Drive Spectra

- **Illustrate melting process from W; melting point = 3410°C**
- **Include phase change in ANSYS by increasing enthalpy at melting point to account for latent heat of fusion (= 220 kJ/kg for W)**
- **Melt layer thickness ~ 1.2 µm**



Separation = 1 µm



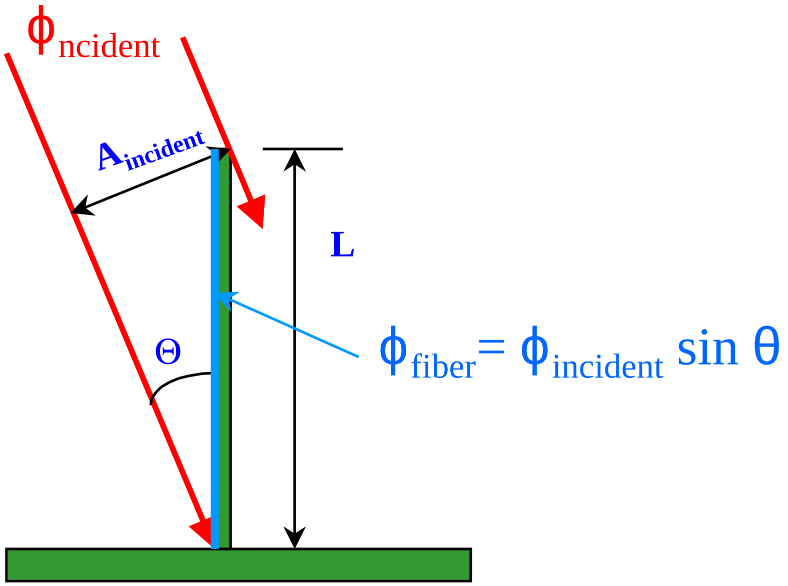
Summary of Thermal Results for Tungsten Flat Wall

Coolant Temp. (°C)	Energy Deposition Multiplier	Maximum Temp. (°C)
500	1	1438
800	1	1710
1000	1	1972
500	2	2390
500	3	3207
500	5	5300

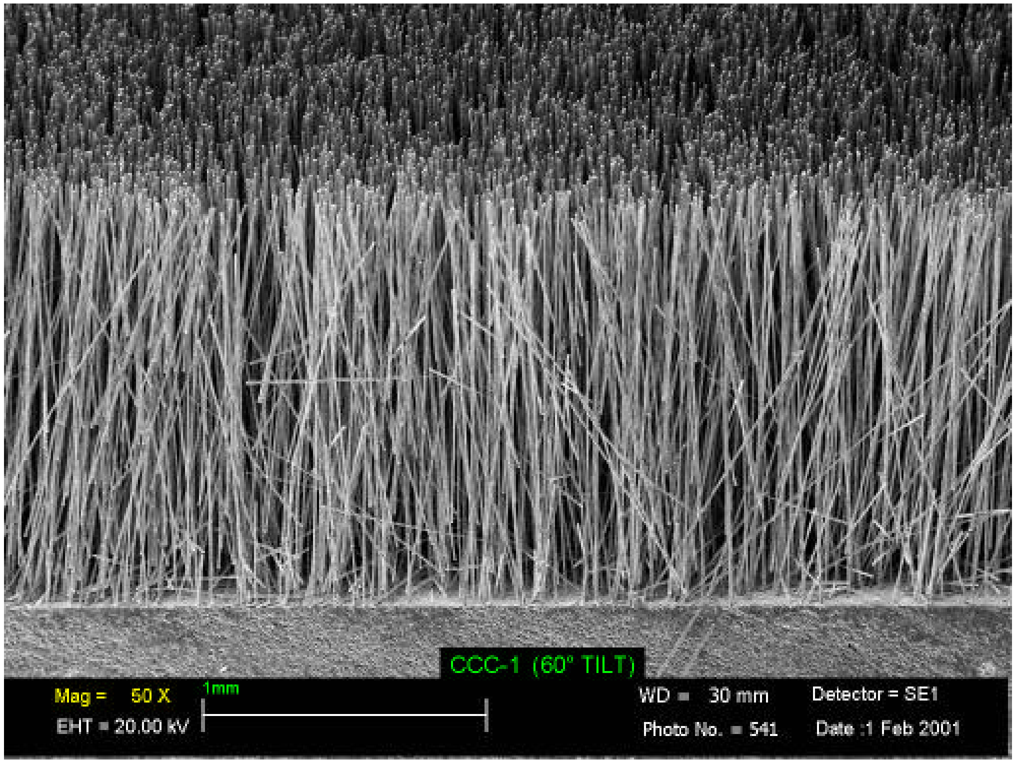
- **Encouraging results: melting point (3410°C) is not reached even when energy deposition is increased by a factor of 3**
- **Some margin for setting coolant temperature and chamber wall radius, and accounting for uncertainties**

Consider Engineered Surface Configuration for Improved Thermal Performance

- **Porous Media**
  - Carbon considered as example but could also be coated with W
  - Fiber diameter ~ diffusion characteristic length for 1 μs
  - Increase incident surface area per unit cell seeing energy deposition



$$\phi_{fiber} = \phi_{incident} \sin\theta$$

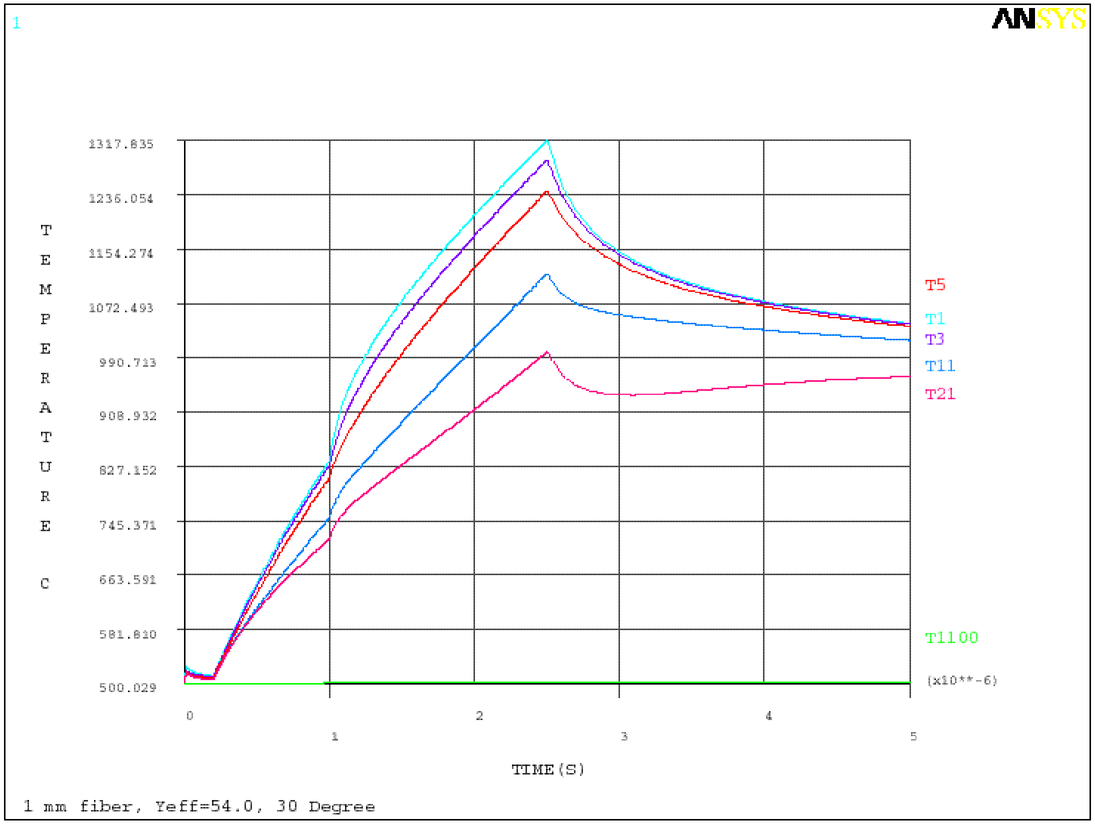


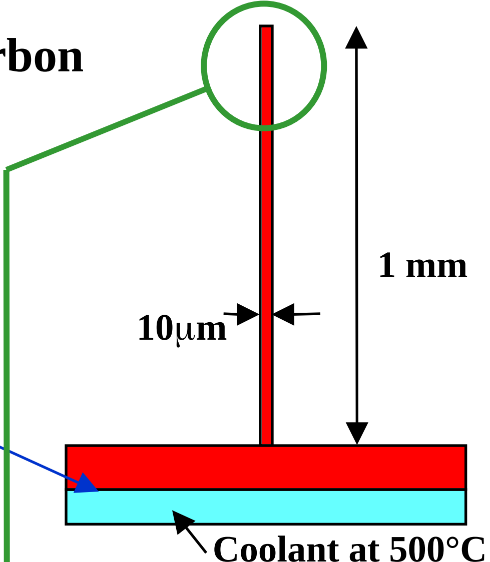
ESLI Fiber-Infiltrated Substrate

Large fiber L/d ratio ~100

Example Thermal Analysis for Fiber Case

- **Incidence angle = 30°**
- **Porosity = 0.9**
- **Effective fiber separation = 54 μm**
- **Sublimation effect not included**

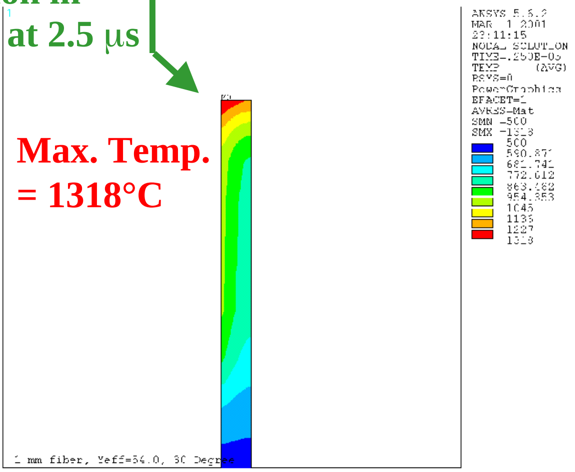




Single Carbon Fiber

Convection B.C. at coolant wall: h= 10 kW/m^2-K

Temperature Distribution in Fiber Tip at 2.5 μs



Max. Temp. = 1318°C

Summary of Thermal Results for Carbon Fibrous Wall

Coolant temperature = 500 °C
Energy deposition multiplier = 1

Porosity	Fiber Effective Separation (μm)	Incidence Angle (°)	Maximum Temp. (°C)
0.8	29.6	5	654
0.8	29.6	30	1317
0.8	29.6	45	1624
0.9	54	30	1318
C flat wall as comparison:			1530

- Initial results indicate that for shallow angle of incidence the fiber configuration perform better than a flat plate and would provide more margin
- Statistical treatment of incidence angle and fiber separation would give a better understanding

Outline of Presentation

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  - **Thermal and Lifetime Analysis for (from ARIES-IFE study):**
    - **C**
    - **W**
    - **Engineered surface (fibrous surface)**
  - **Summary of Erosion and Tritium Retention Issues**
    - **Must consider armor options (besides C)**
    - **Use of very thin armor on structural material to separate energy accommodation function from structural function**

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1. Several Erosion Mechanisms Must Be Considered for the Armor

2. Tritium Co-Deposition is a Major Concern for Carbon Because of Cold Surfaces (Penetration Lines)

	Carbon	**Tungsten**
Erosion:		
Melting	No	Yes (MP = 3410°C)
Sublimation/ evaporation	Yes (SP ~3367°C)	Yes
Physical Sputtering	Yes (peaks at ~ 1 keV)	Yes, high threshold energy
Chemical Sputtering	Yes (peaks at ~ 0.5 keV and 800 K))	No
Radiation Enhanced Sublimation	Yes (increases dramatically with T, peaks at ~ 1 keV)	No
Macroscopic (Brittle) Erosion	Yes (thermal stress + vapor formation)	No
Splashing Erosion	No	Yes (melt layer)
Tritium Retention:		
Co-deposition	Yes (with cold surfaces with H/C ratio of up to 1)	No

From the ARIES Tritium Town Meeting (March 6–7, 2001, Livermore (IFE/MFE Discussion Session):
(http://joy.ucsd.edu/MEETINGS/0103-ARIES-TTM/)

- **Carbon erosion could lead to tritium co-deposition, raising both tritium inventory and lifetime issues for IFE with a carbon wall. Redeposition/co-deposition requires cold surfaces which would exist in the beam penetration lines and pumping ducts.**

(For H/C=1, 60 g T per 1μm C for R=6.5 m)

- **Macroscopic erosion might be a more important lifetime issue than sputtering and sublimation for IFE operating conditions for high energy ions (>>1 keV)**

- **Overall, the required R&D effort for IFE armor material should not be underestimated**

- **Must Consider Alternate Options for Armor (e.g. W)**

Conditions Assumed for ITER ELM's, VDE's and Disruptions Compared to Conditions Associated with a Typical Direct Drive Target IFE (latest NRL target)

	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	~ 6 s^{-1}
Base Temperature	200-1000°C	~ 100°C	~ 100°C	~ >500°C

From ARIES TTM:

- **Overall, the required R&D effort for IFE armor material should not be underestimated**

However:

- **We should make the most of existing R&D in MFE area (and other areas) since conditions can be similar within ~1-1.5 order of magnitude (ELM's vs IFE)**

Separate Near-Surface Energy Deposition and Erosion Accommodation From Wall Structural Function

Possibility of Using a Very Thin Armor (~10-100 μm) on the Structural Material (e.g W on SiC$_f$/SiC)

- Most issues linked with armor itself and not affecting integrity and lifetime of structural material
- Behavior of thin armor under transients
  - **Aim to use high temperature transients to alleviate thermo-mechanics and tritium issues in thin layer (e.g . Implanted tritium within the thin armor layer could diffuse out to the high temperature, high diffusivity surface region and escape)**
- Lifetime
  - **Possibility of repairing armor in-situ?**
- Fabrication to minimize any thermal expansion discrepancy
  - **Possibility of gradually transitioning from one material to other (e.g. CVD in porous layer or gradual deposition)**
  - **ASDEX (Garching, Germany) researchers have some experience on W deposition on C**
  - **Contacted H. Bolt to set up an information meeting on July 16 and a visit to Plansee (Austrian manufacturer) to discuss their experience from MFE and its possible application to IFE**

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    - **W**
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    - **Must consider armor options (besides C)**
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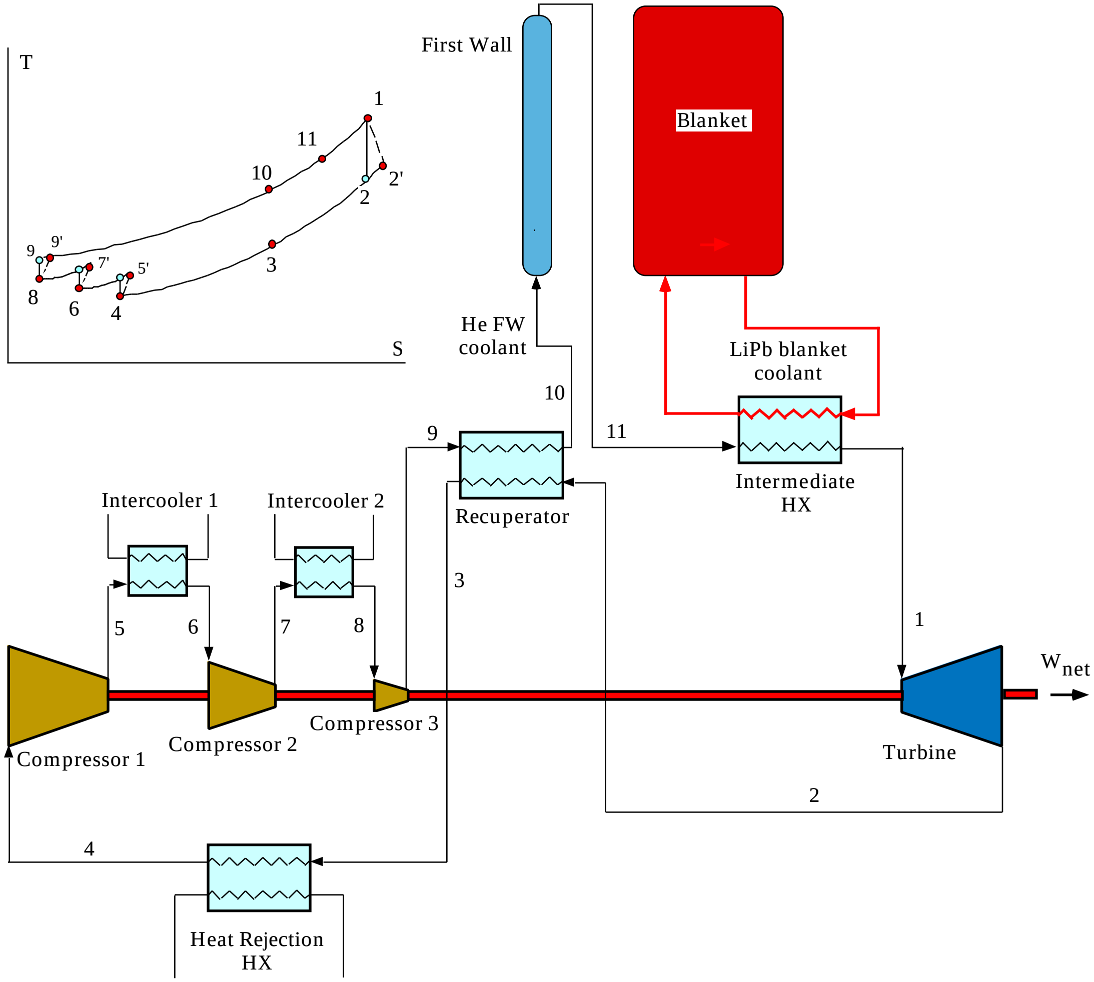
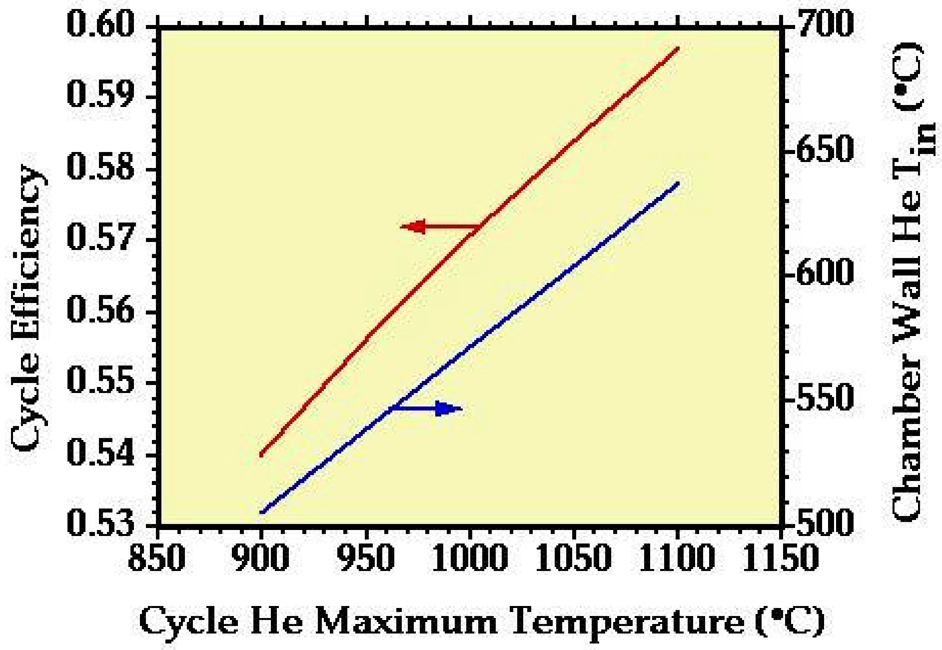
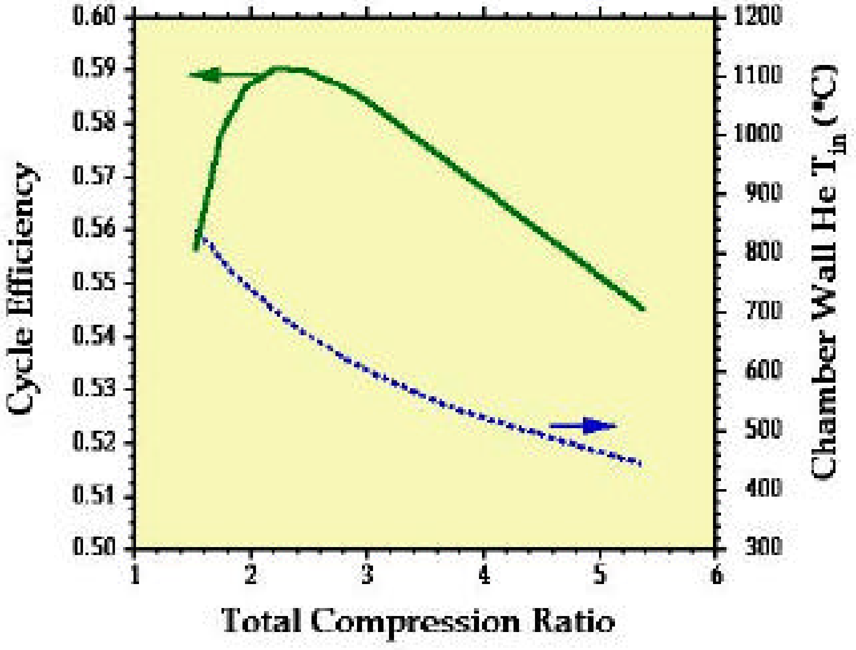
Use ARIES-AT Brayton Cycle as Example to Illustrate Effect on Overall Cycle Efficiency of Running a Low Temperature Chamber Wall and a High Temperature Blanket

- **Min. He Temp. in cycle (heat sink) = 35°C**
- **3-stage compression with 2 inter-coolers**
- **Turbine efficiency = 0.93**
- **Compressor efficiency = 0.88**
- **Recuperator effect. = 0.96**
- **Cycle He fractional ΔP = 0.03**
- **Intermediate Heat Exchanger ΔT(Pb-17Li/He) ~ 50°C**



Chamber Wall He Temperature Dictated by Maximum Cycle He Temperature and Compression Ratio





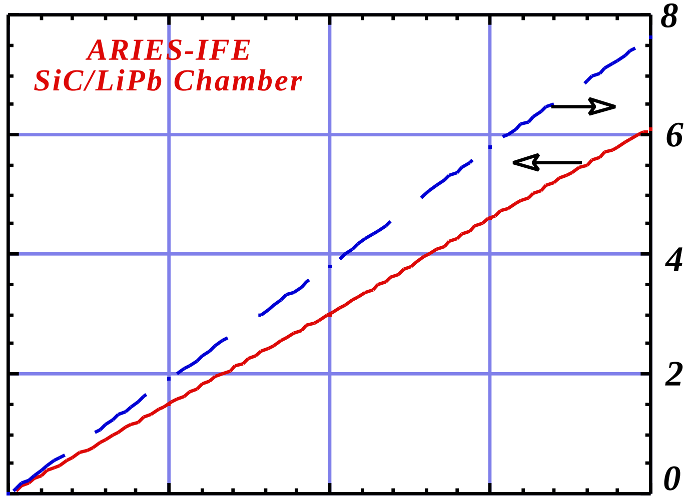
Total Thermal Power in Chamber Wall Region

- SiC/LiPb chamber
- NRL target: 161 MJ yield, 6 Hz
- 4 m FW radius; Γ ~ 3.4 MW/m^2
- Peak heating is 15 W/cm^3 and varies as (4/R)^2 with FW radius
- ~800 MW total nuclear heating in FW/B/S

- Fraction of output energy:
  - X-rays + ions + gamma = 29%
  - Neutrons = 71%
- Assume:
  - multiplication factor of 1.1
  - ~ 4% nuclear heating in FW

30% of total power in chamber wall region

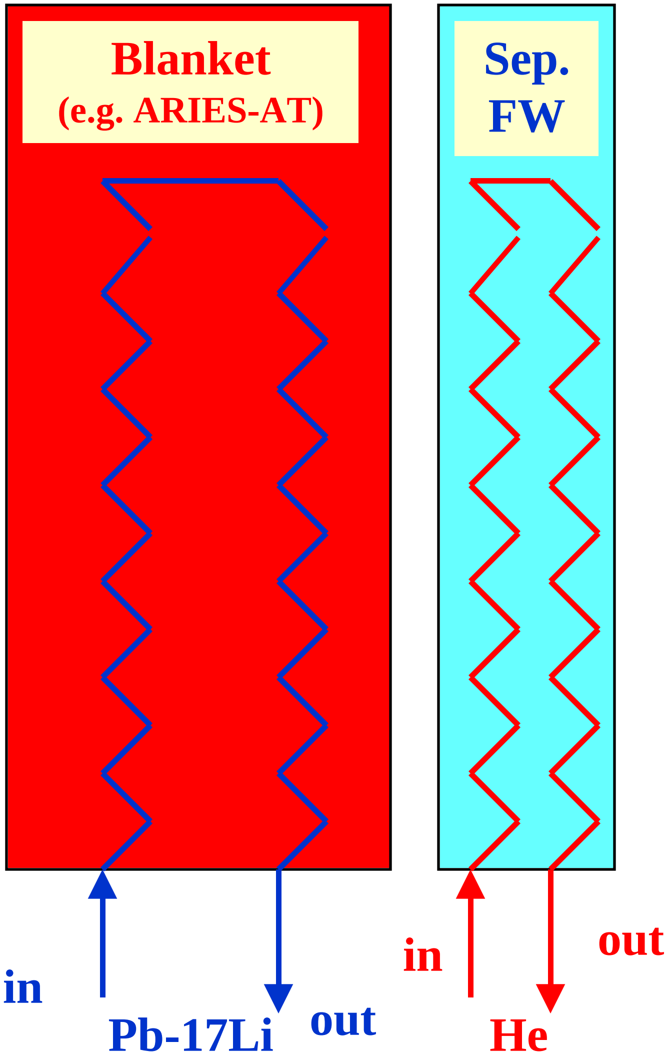
Nuclear Heating in First Wall

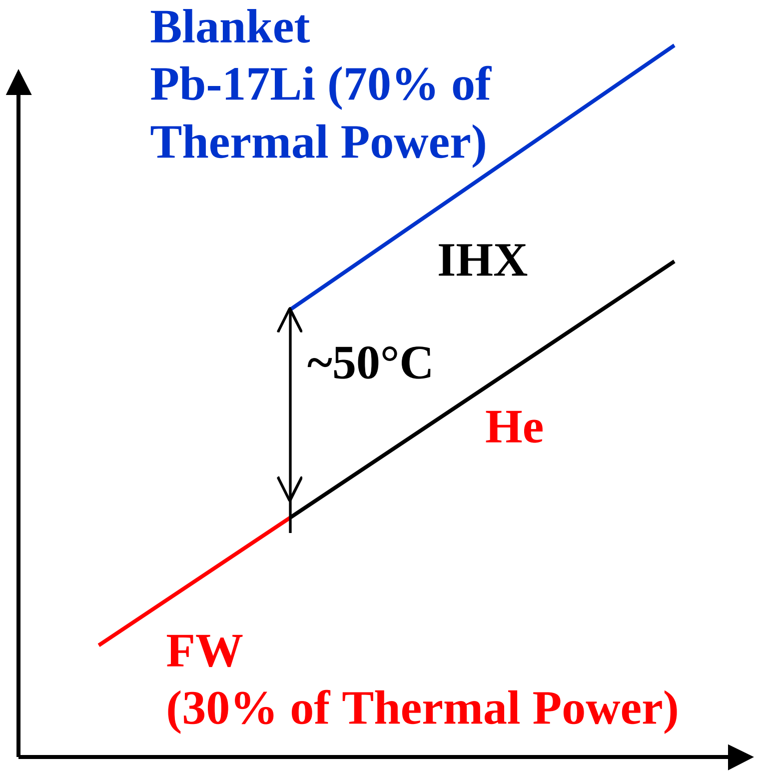


From Laila El-Guebaly

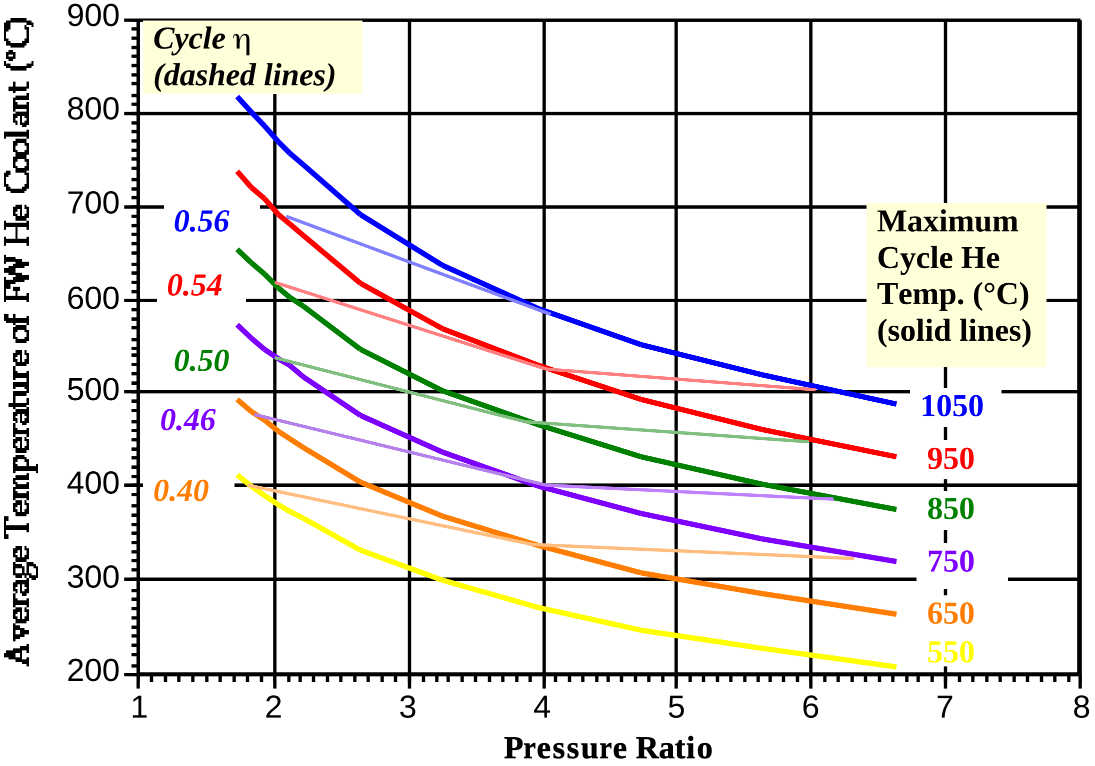
Fusion Technology Institute
University of Wisconsin - Madison

ARIES-ST Power Parameters





The Chamber Wall Temperature can be Maintained < 900 K to Reduce Radiation to the Target while Maintaining an Acceptable Cycle Efficiency



Example Case:

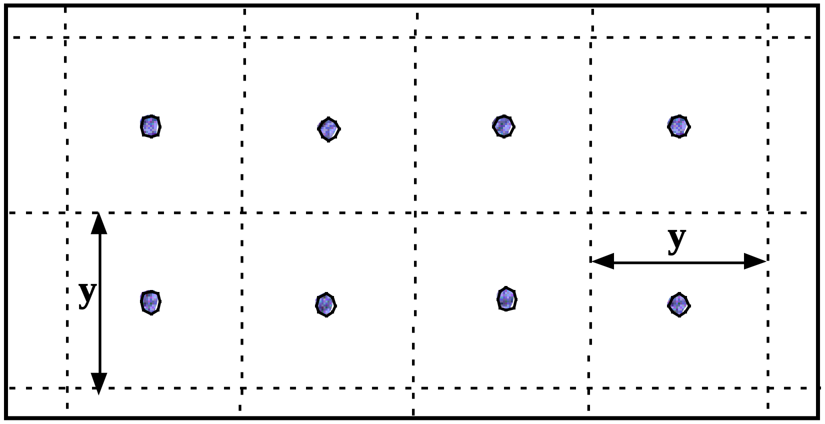
- For a ΔT_{FW} of ~100-150°C and compression ratio of 4.5, the avg. surface T_{wall} at target injection can be lowered to ~600°C while maintaining a cycle efficiency of 50%

Concluding Remarks

- **Chamber Wall Options**
  - Erosion lifetime estimates very encouraging for both W and C without protective chamber gas
  - Several mechanisms need to be better defined for IFE operating conditions, in particular for C
  - Tritium co-deposition is a major concern for C and it is essential to consider alternate options
  - Use of a thin armor region beneficial to separate the accommodation of energy deposition and high loading transients from the structural function
  - W is an attractive armor candidate (if melting can be avoided), which should be further investigated, including assessing fabrication methods and the possibility of in-situ repair
- **Some Key Material Issues on Thermo-Mechanical Behavior, Erosion, Tritium and Fabrication Must Be Further Addressed**
  - Overall, the required R&D effort for IFE armor material should not be underestimated
  - We should make the most of existing R&D in MFE area (and other areas)
- **Separately Cooled Chamber Wall Region**
  - Based on a Brayton cycle example, the chamber wall temperature can be maintained < 900 K to reduce radiation to the target (or if required by lifetime consideration)while maintaining an acceptable cycle efficiency
- **Impact on Chamber Clearing Code**
  - Must prioritize erosion mechanisms for C: which ones to include and when?
  - Must include key processes for W (melting, evaporation and condensation)

Extra Back-Up Slides

Modeling Porous Fiber Configuration



Probability for energy front to contact fiber:

over first unit cell, $P_1 = d/y$

over second unit cell, $P_2 = (1-P_1)\, d/(y-d)$

over third unit cell, $P_3 = (1-P_1-P_2)\, d/(y-2d)$, etc...

up to $P_n=(1-P_1-P_2-...P_{n-1})\, d/(y-(n-1)d)$

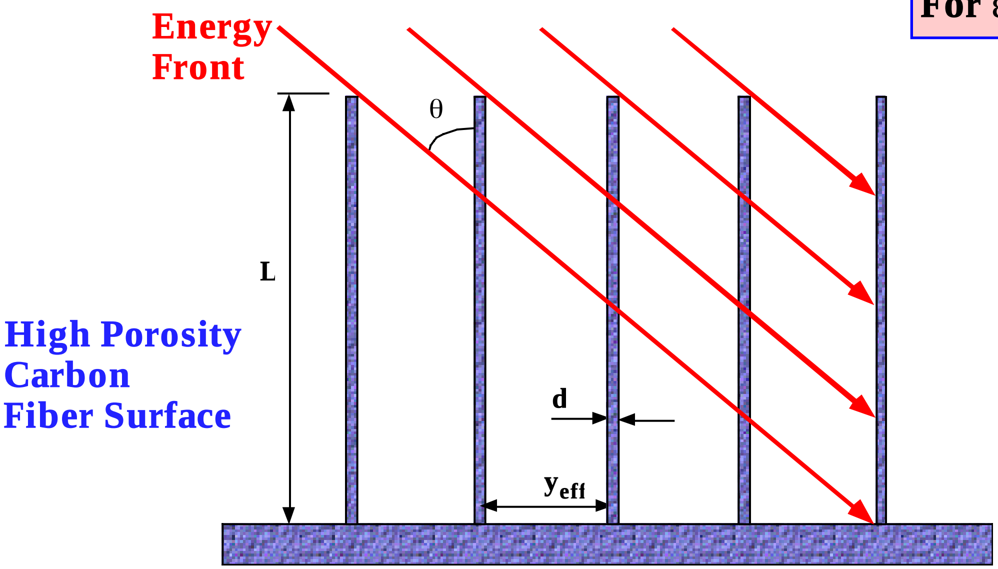
where $n=y/d$

$$y_{eff} = yP_1+2yP_2+3yP_3...+nyP_n$$

Fiber Density, $(1-\varepsilon) = \pi d^2/4y^2$

For $\varepsilon=0.9$ and $d=10\mu m$, $y=28\mu m$, $y_{eff} = 54\mu m$

For $\varepsilon=0.8$ and $d=10\mu m$, $y=19.8\mu m$, $y_{eff} = 29.6\mu m$



Photon+Ion Energy Deposition In Fiber

Example case

- **Incidence angle = 30°**
- **Porosity = 0.9**
- **Fiber Length = 1 mm**
- **Fiber diameter = 10 μm**
- **Unit cell dimension = 28 μm**
- **Effective fiber separation = 54 μm**