Assessment of Carbon and Tungsten Dry Chamber Walls under IFE Energy Depositions

A. R. Raffray, M. S. Tillack, X. Wang, M. Zaghloul

University of California, San Diego

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Outline of Presentation

- **Thermal analysis**
  - **Consider C and W**
  - **Refined mesh for more accurate energy deposition calculations**
  - **Use material properties as a f(T), in particular k(T)**
  - **Inclusion of sublimation**
  - **Refined mesh for more accurate fiber analysis**
  - **Sensitivity analysis (total energy, ion energy deposition calculations)**
- **Lifetime issue**
  - **Identify possible erosion mechanisms**
  - **Assess relevance and order of magnitude for IFE application**
- **Concluding remarks**
  - **Status based on analysis**
  - **Remaining issues**

Lifetime is a Key Dry Chamber Wall Issue

- **Material Option (C, W, *SiC* ...)**
- **Material Configuration to Help Accommodate Energy Deposition**
- **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**

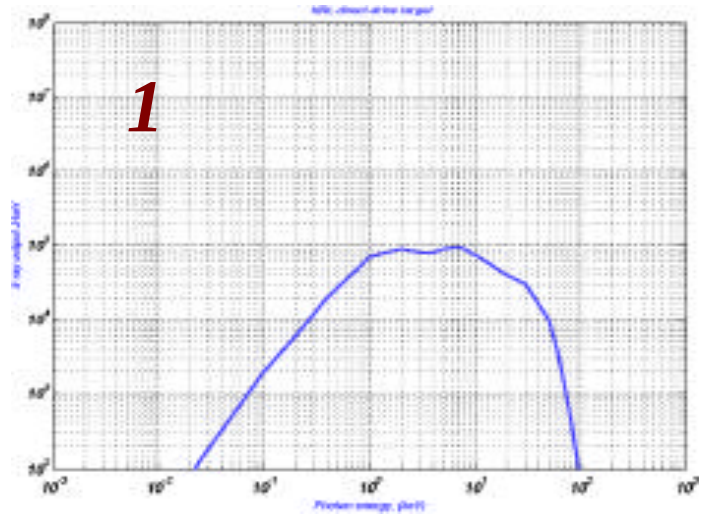
  Dry wall material configuration(s) which can accommodate energy deposition and provide required lifetime without any protective gas in chamber

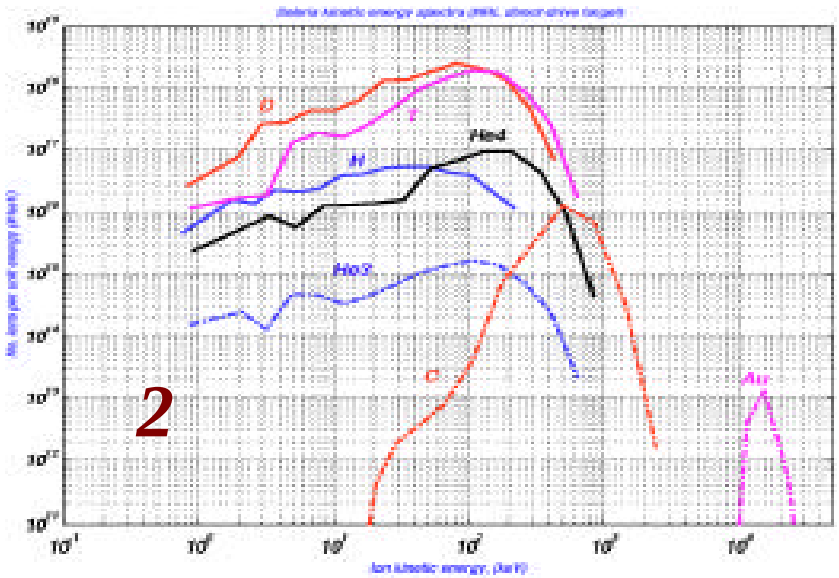
X-ray and Charged Particles Spectra

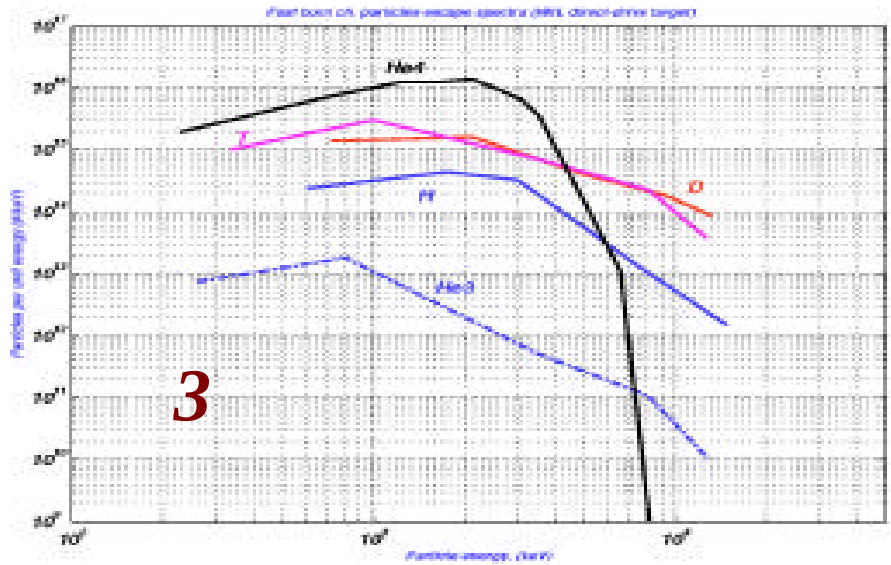
NRL Direct-Drive Target

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

(from J. Perkins, LLNL)







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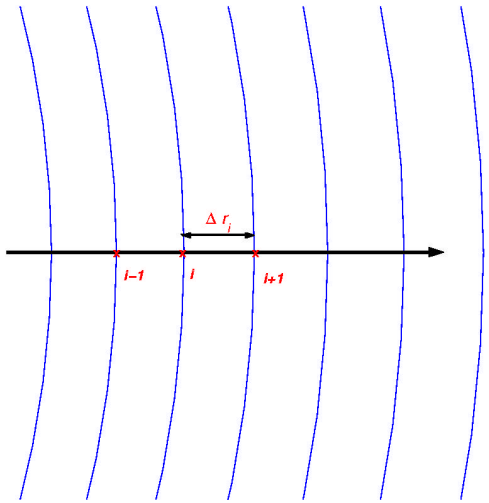
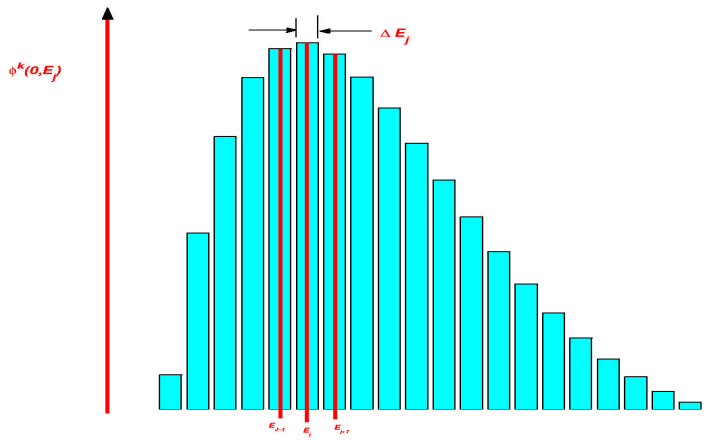
Energy Deposition Calculations

- **X-ray energy deposition through attenuation calculation**

- **Ion energy deposition dependent on energy level**
  - **Electronic stopping power + Nuclear stopping power**
  - **Model uses spectra to follow ions at each energy level though the material slab until all energy is deposited**



- **1-D radial geometry**
  - **Very fine mesh at wall surface**
  - **No protective gas**



$$E_j(r_i) = E_j(r_1) - \sum_{i=1}^{i} \frac{d\,E_j(x)}{d\,x}\Big|_i \;\Delta E_i$$

Ion Energy Deposition Calculations

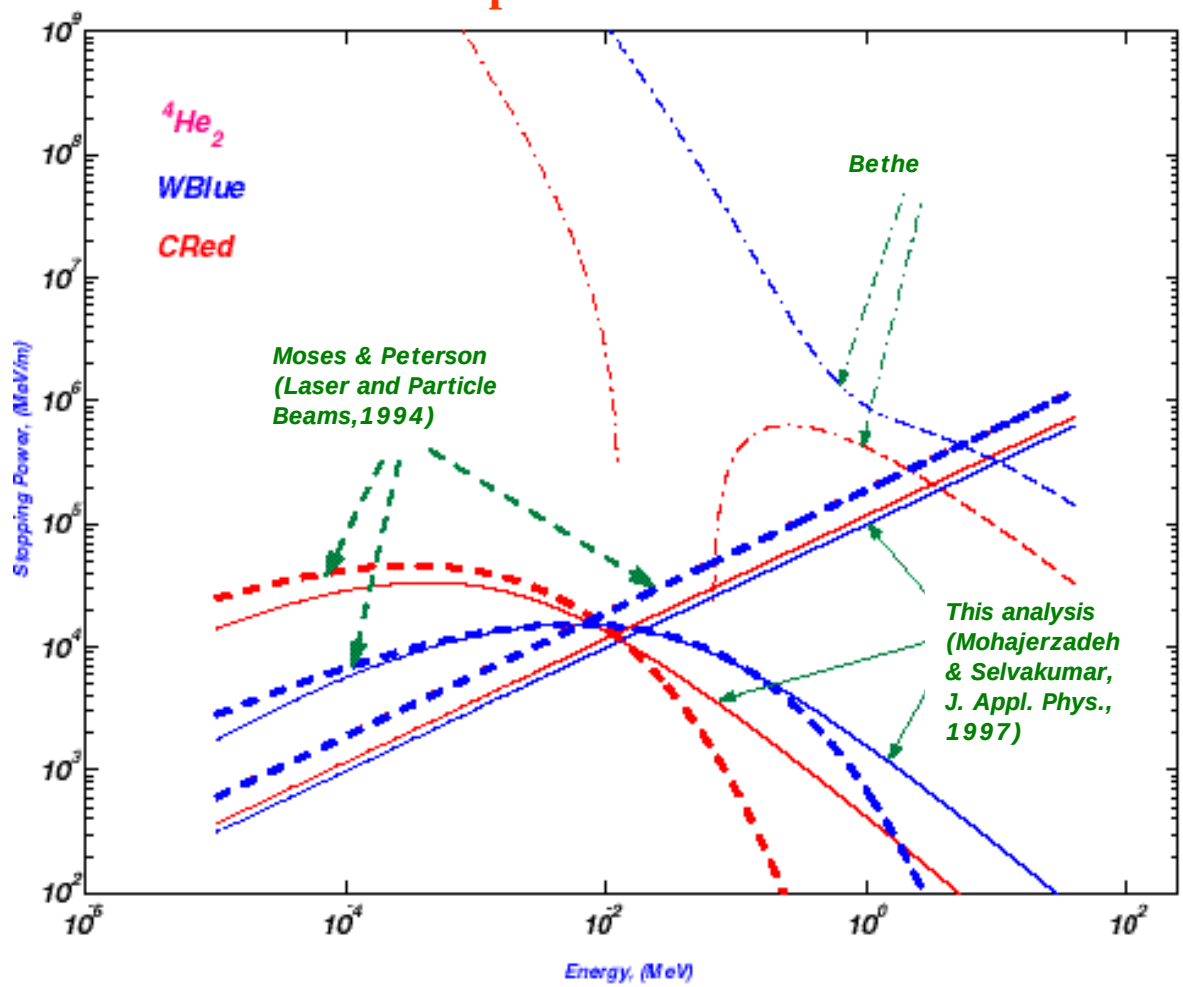
Electronic stopping power

- Bethe model for E >1 MeV/amu
- Lindhard model for E < 1 MeV/amu

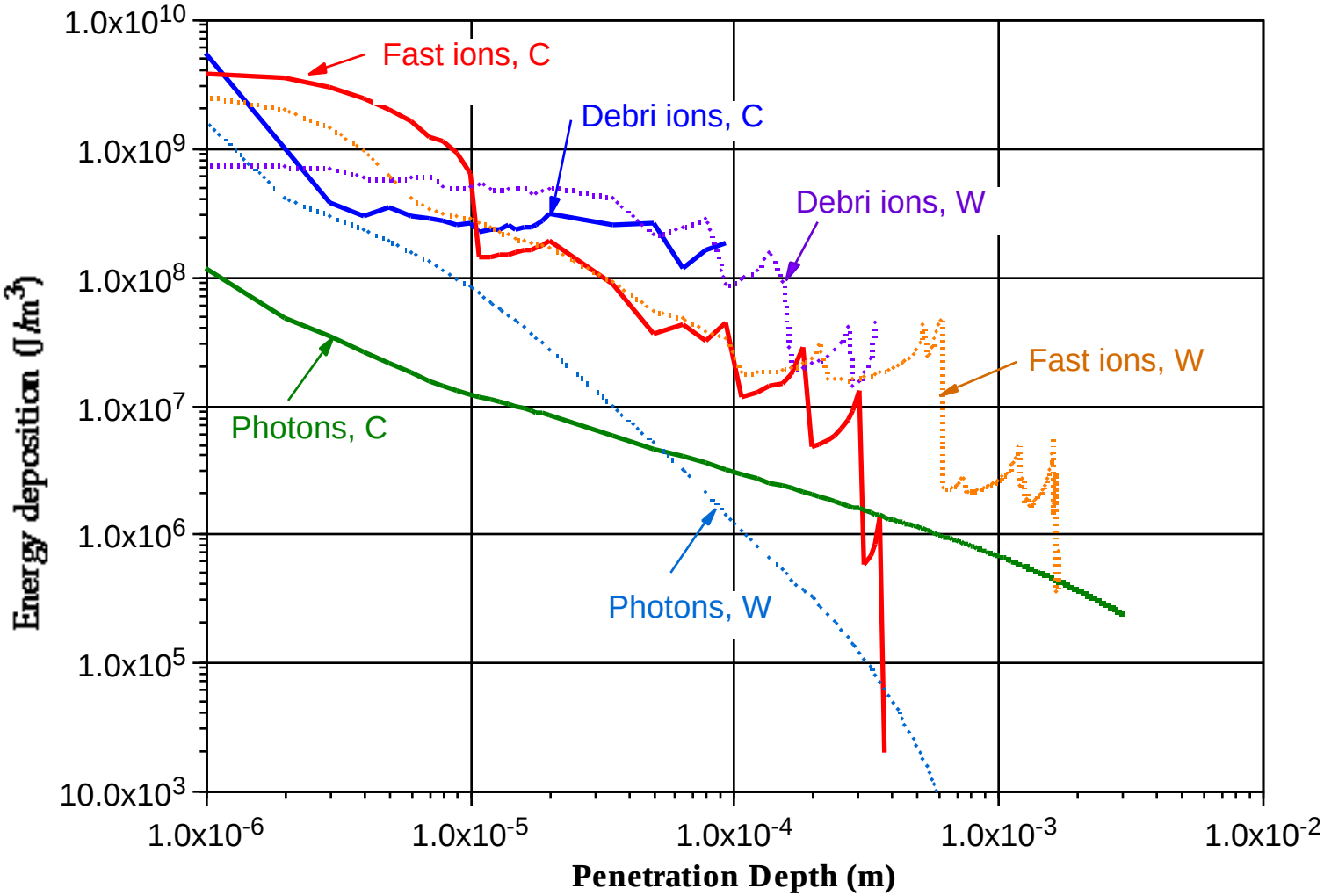
Nuclear stopping power

- Important at low energy (~keV/amu)

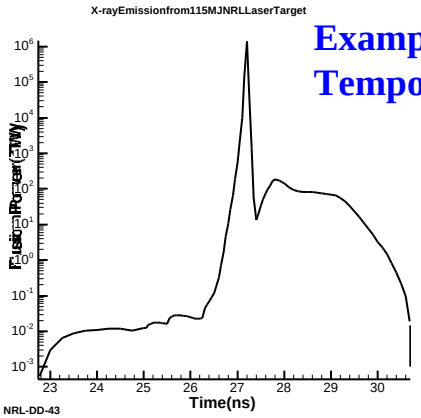
Example case for ^{4}He



Photon and Ion Attenuation in Carbon and Tungsten



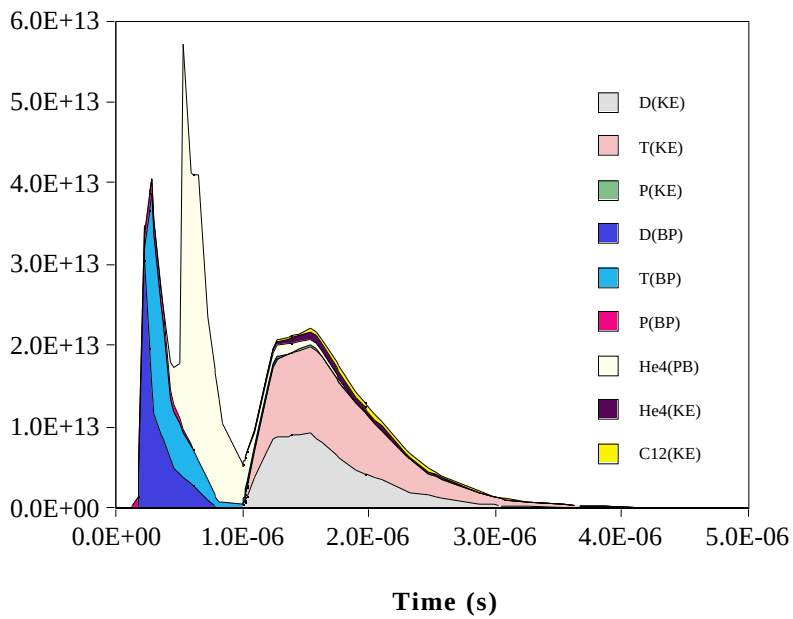
Temporal Distribution of Energy Distribution from Photons and Ions Taken into Account



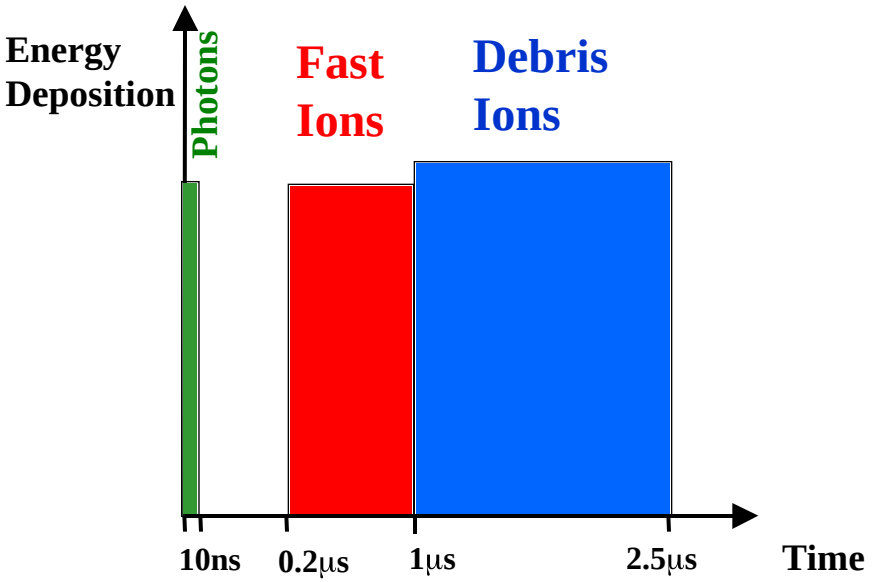
Example Photon Temporal Distribution

From R. Peterson and D. Haynes's presentation At ARIES meeting September 2000.

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, presented at the Dec. 2000 ARIES meeting**



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

Sublimation Can Be Estimated from the Vapor Pressure by Equating the Sublimating Flux to the Condensing Flux at Equilibrium

- From the kinetic theory of gases and using the Clausius-Clapeyron the condensing flux, G (kg/m^2-s) can be expressed as:

(equivalent to the sublimating flux at equilibrium)

$$G = \alpha P \sqrt{\frac{M}{2\pi RT}}$$

Where α= coefficient of evaporation, or accommodation coefficient (conservatively set to 1 in our calculations)

P = Vapor pressure (Pa) of material at temperature T(K)

M = Molecular weight of material

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

$$P = 10^{(A - \frac{B}{T})}$$

A and B are experimentally determined constants Consistent with several references, we use

For C: A = 14.8 and B = 40181

For W: A = 12.74 and B = 44485

- The evaporation heat flux, q_{ev}'' (W/m^2) can be estimated as:

$$q_{ev}'' = GH_{ev}$$

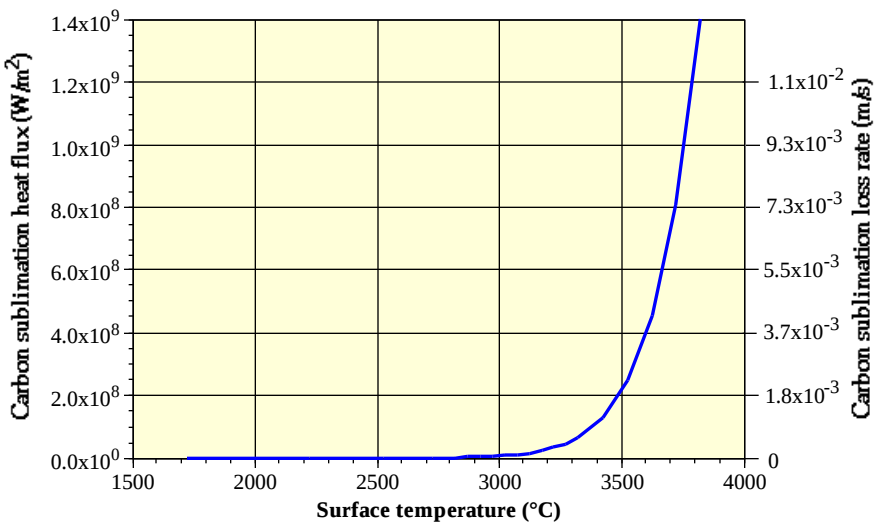
Where H_{ev} = Latent heat of evaporation (J/kg)

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

Carbon

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

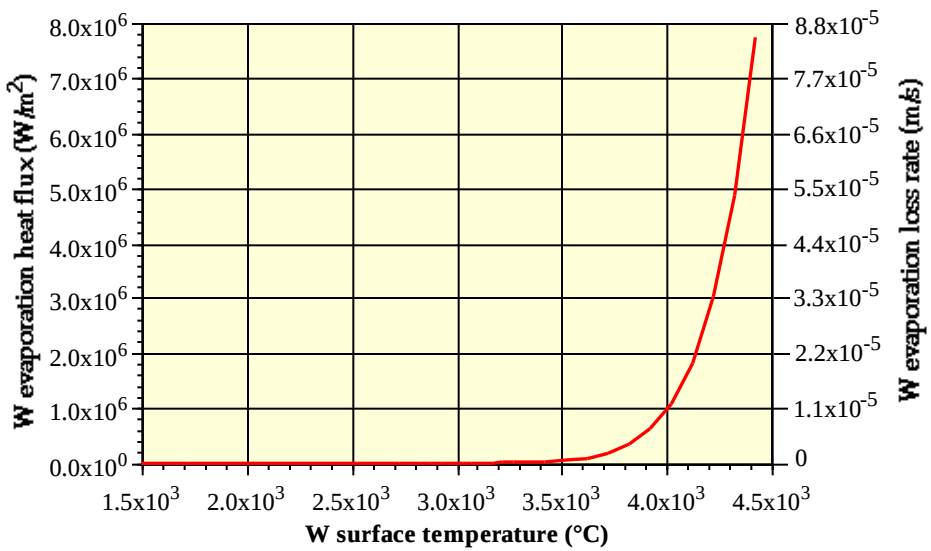
Sublimation point ~ 3367 °C



Tungsten

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

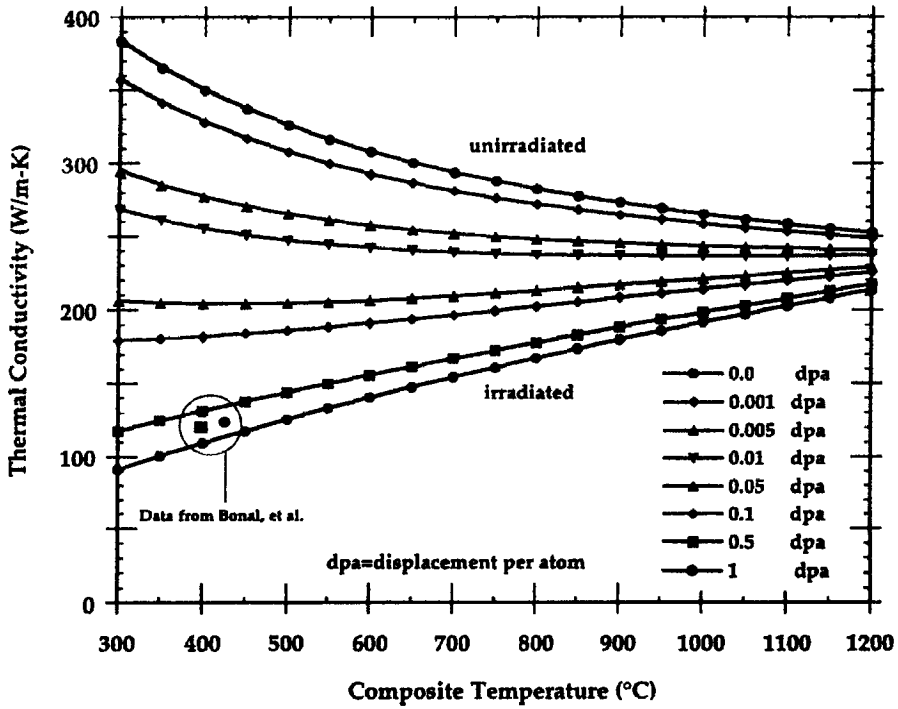
Melting point ~ 3410 °C



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)

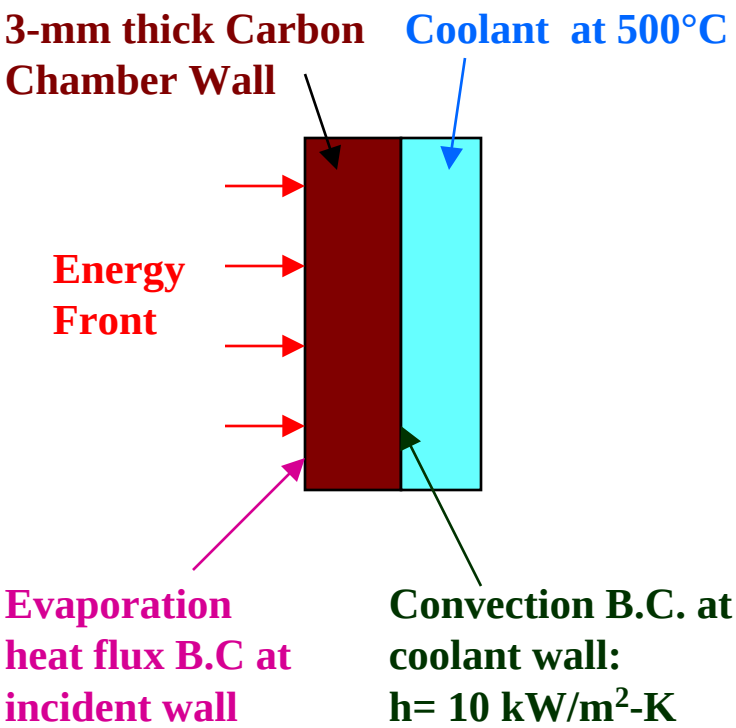


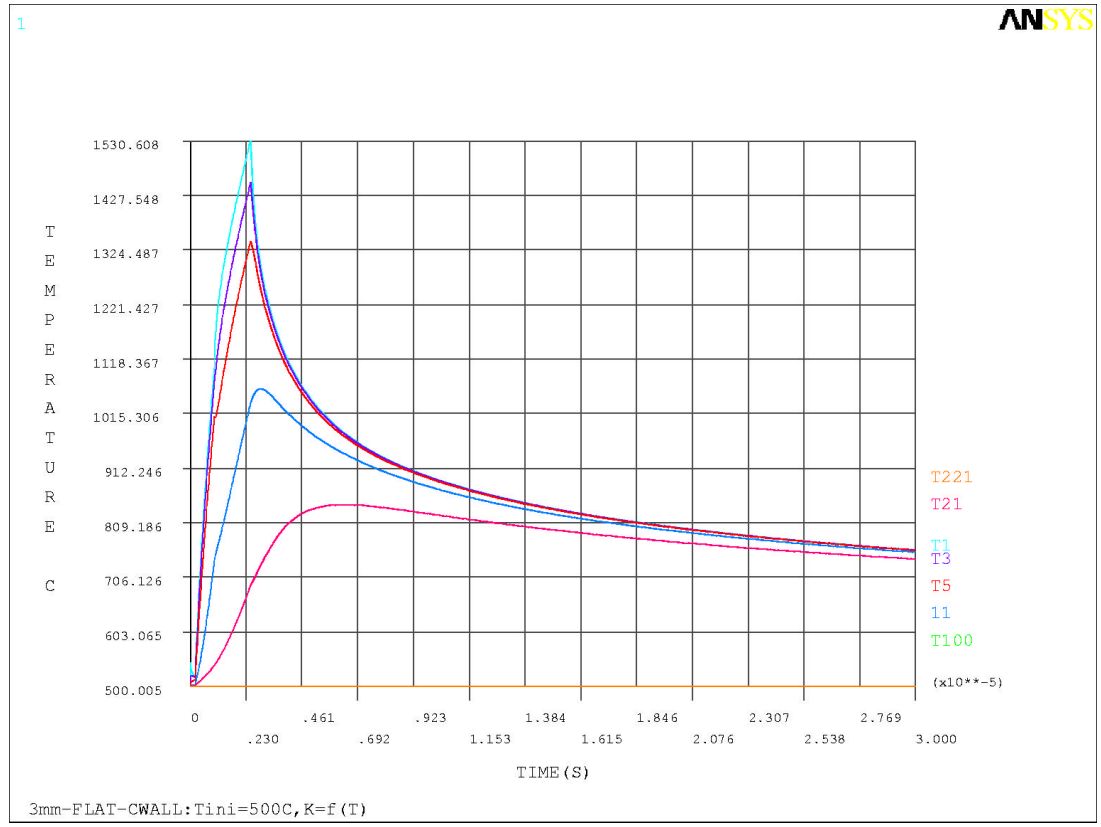
Calculated thermal conductivity of neutron irradiated MKC-1PH CFC

(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 = 3×10^{-13} m (availability=0.85)**





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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}

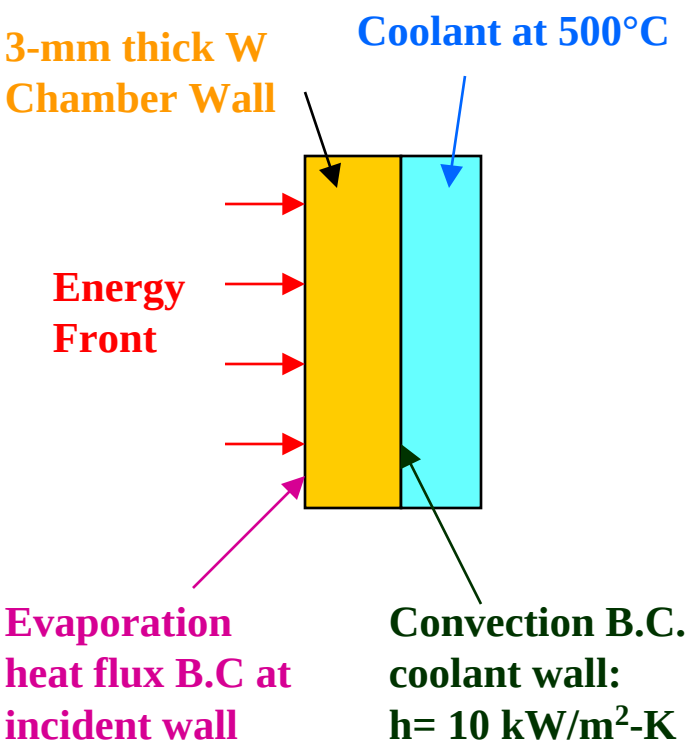
* Shot frequency = 6; Plant availability = 0.85

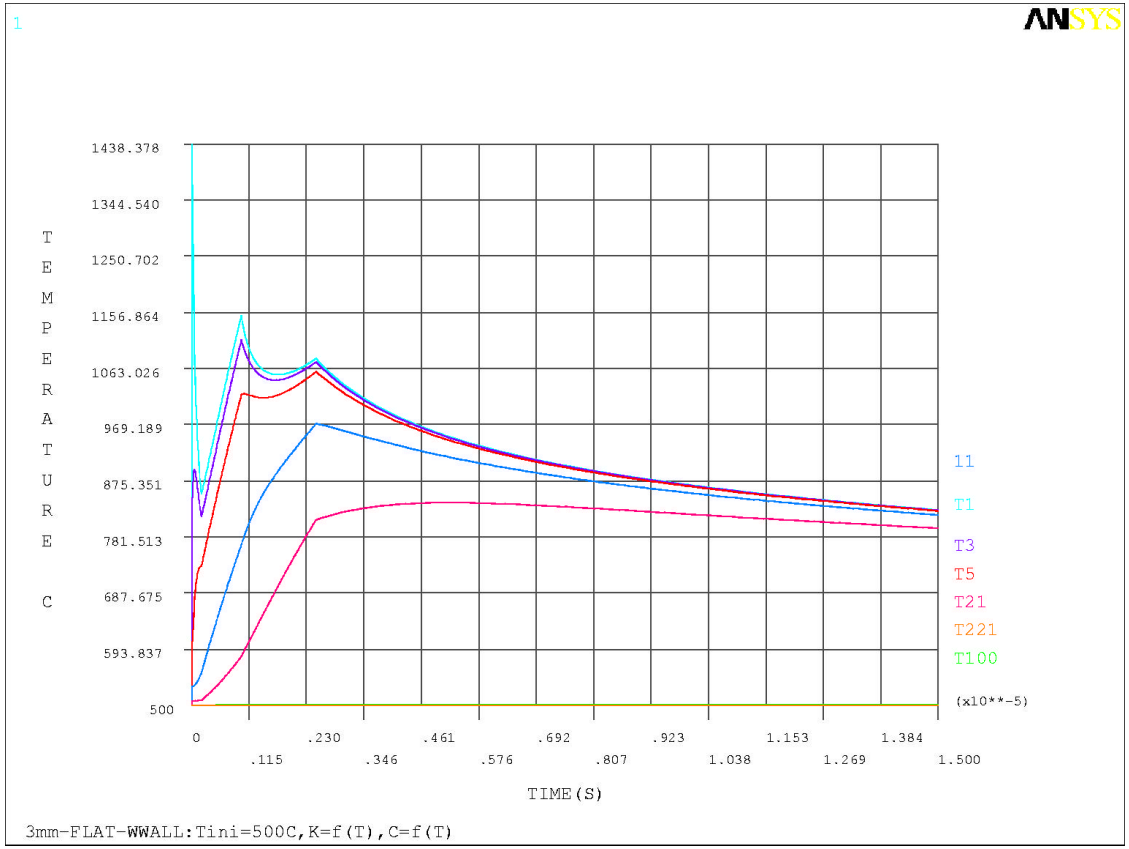
- Encouraging results: sublimation only takes off when energy deposition is increased by a factor of 2-3
- Margin for setting coolant temperature and chamber wall radius, and accounting for uncertainties

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**





W compared to C:

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

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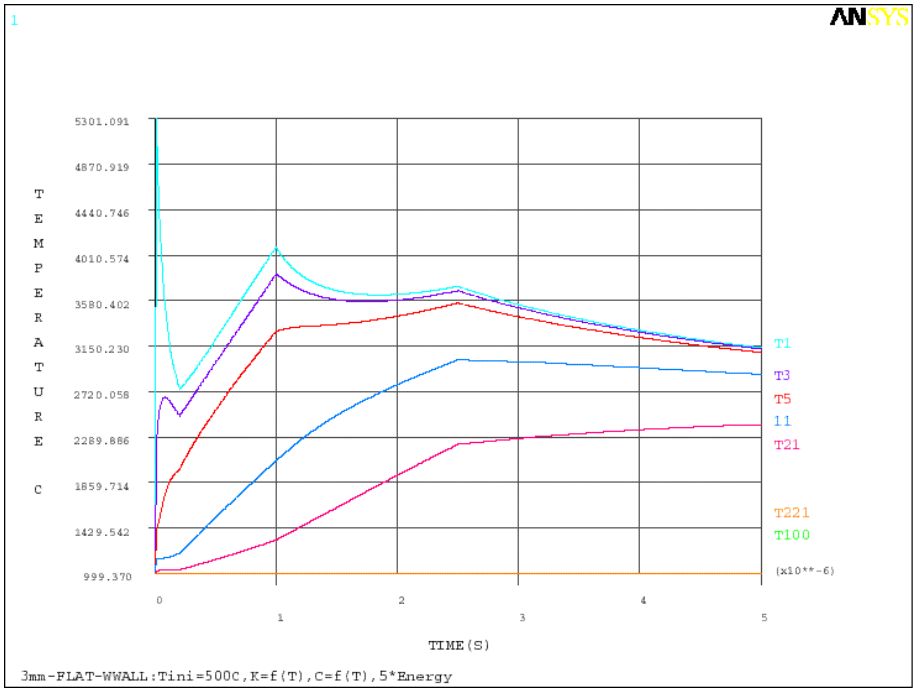
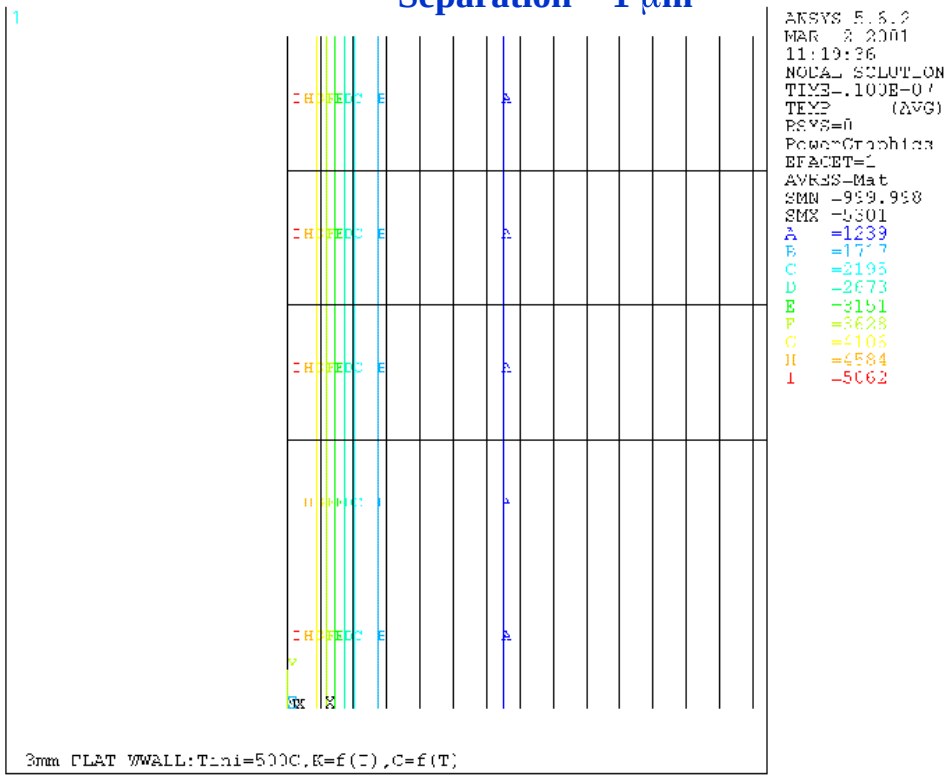
Example Temperature History for Tungsten Flat Wall Under 5 x Energy Deposition from NRL Direct-Drive Spectra

- **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



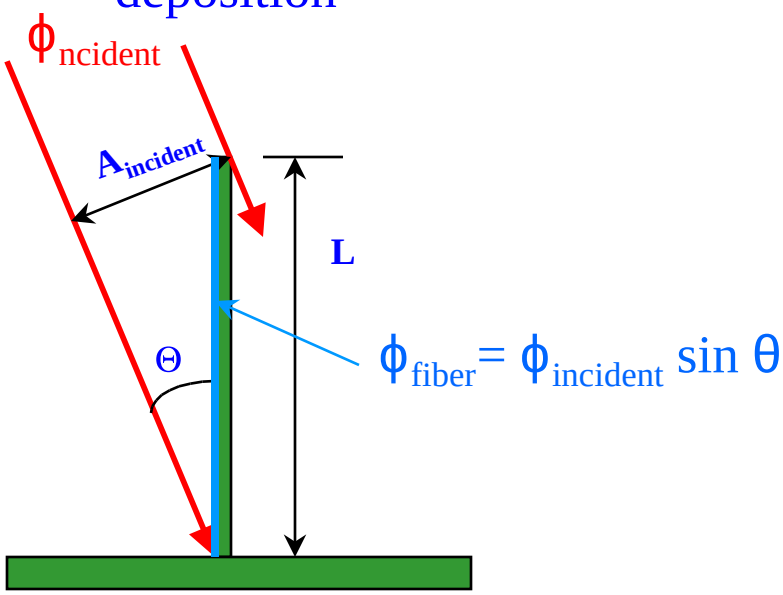
Summary of Thermal Results for Tungsten Flat Wall

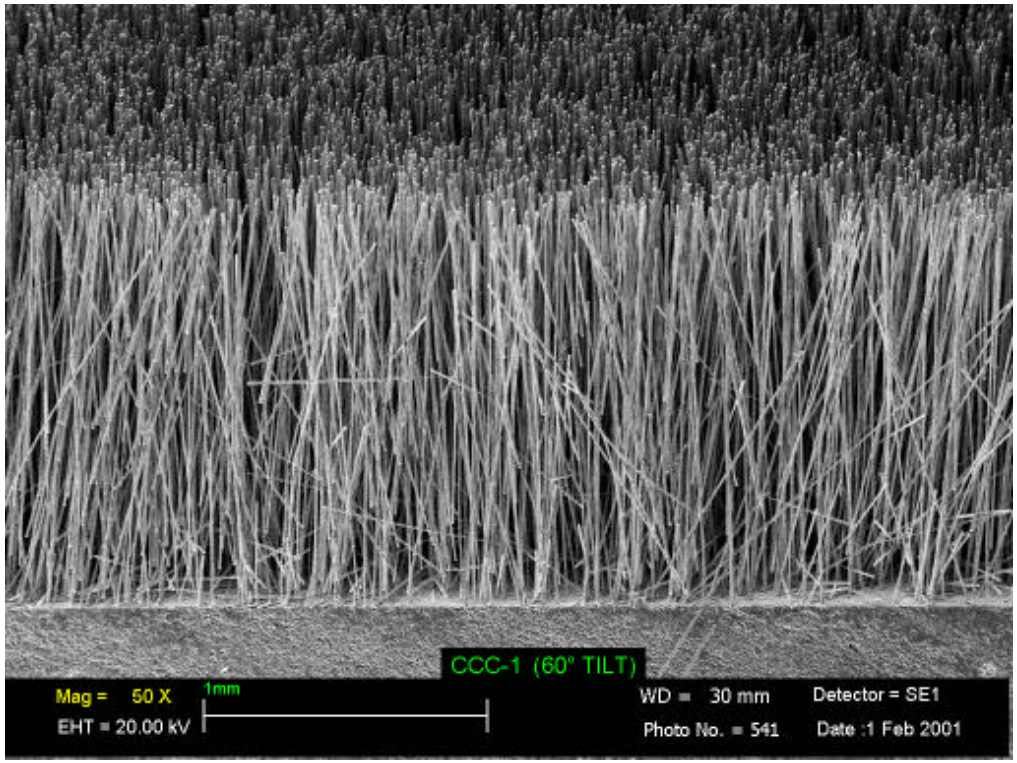
Coolant Temp. (°C)	Energy Deposition Multiplier	Maximum Temp. (°C)
500	1	1438
800	1	1710
1000	1	1972
500	2	2390
500	3	3207
500	5	5300

- 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**
  - Fiber diameter ~ diffusion characteristic length for 1 μs
  - Increase incident surface area per unit cell seeing energy deposition

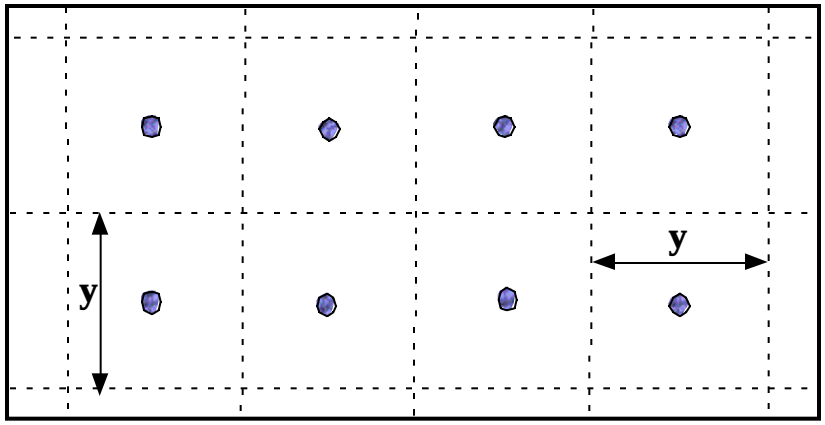




ESLI Fiber-Infiltrated Substrate

Large fiber L/d ratio ~100

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

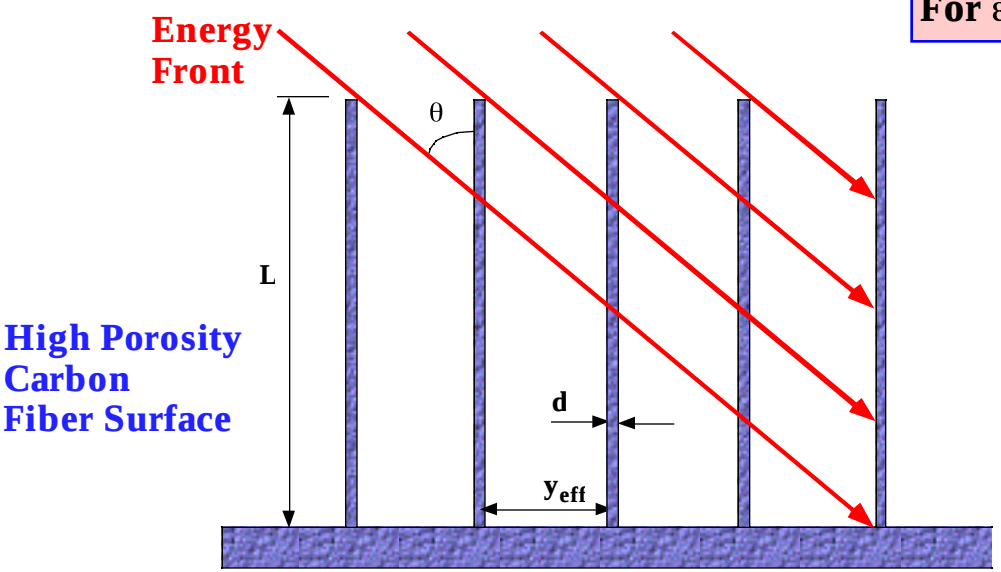
where $n=y/d$

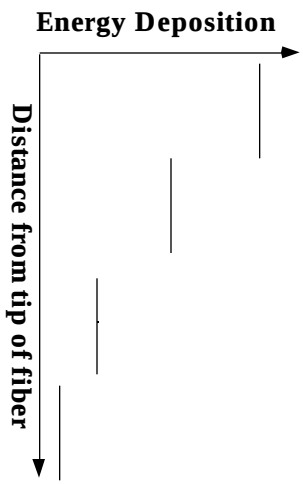
$y_{eff} = yP_1+2yP_2+3yP_3...+nyP_n$

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

For ε**=0.9 and d=10**μ**m, y=28**μ**m,** y_{eff} **= 54**μ**m**

For ε**=0.8 and d=10**μ**m, y=19.8**μ**m,** y_{eff} **= 29.6**μ**m**

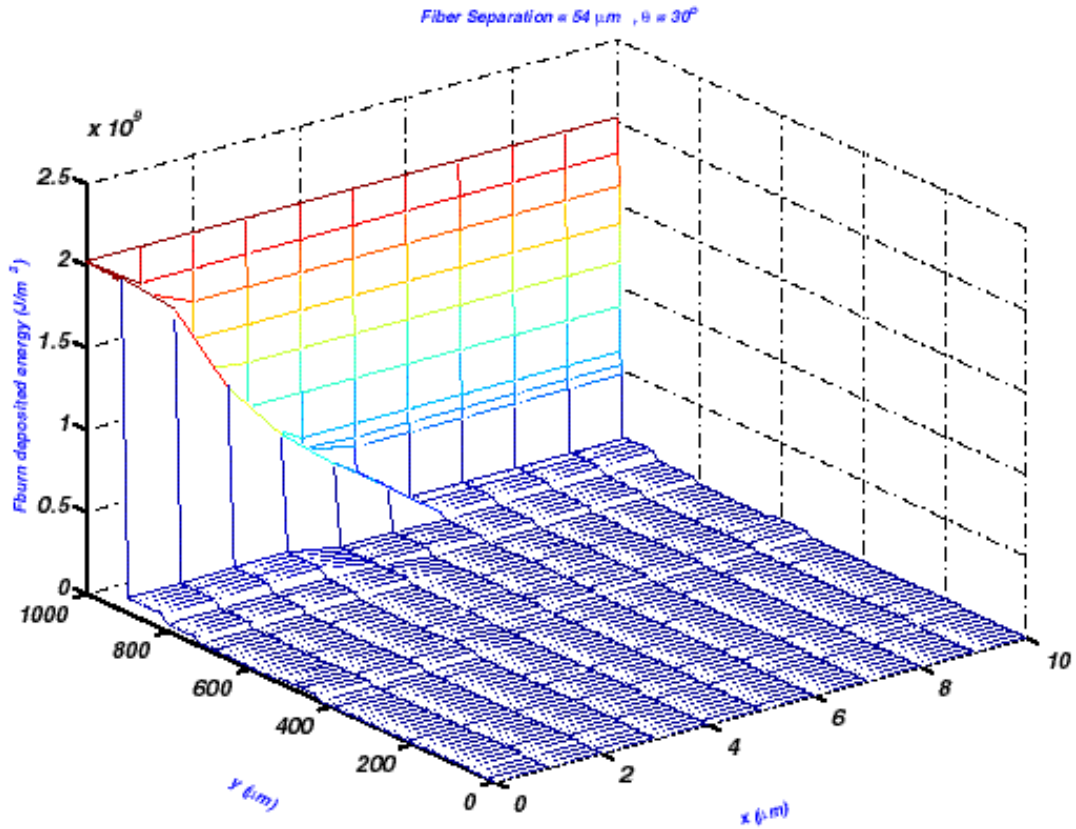




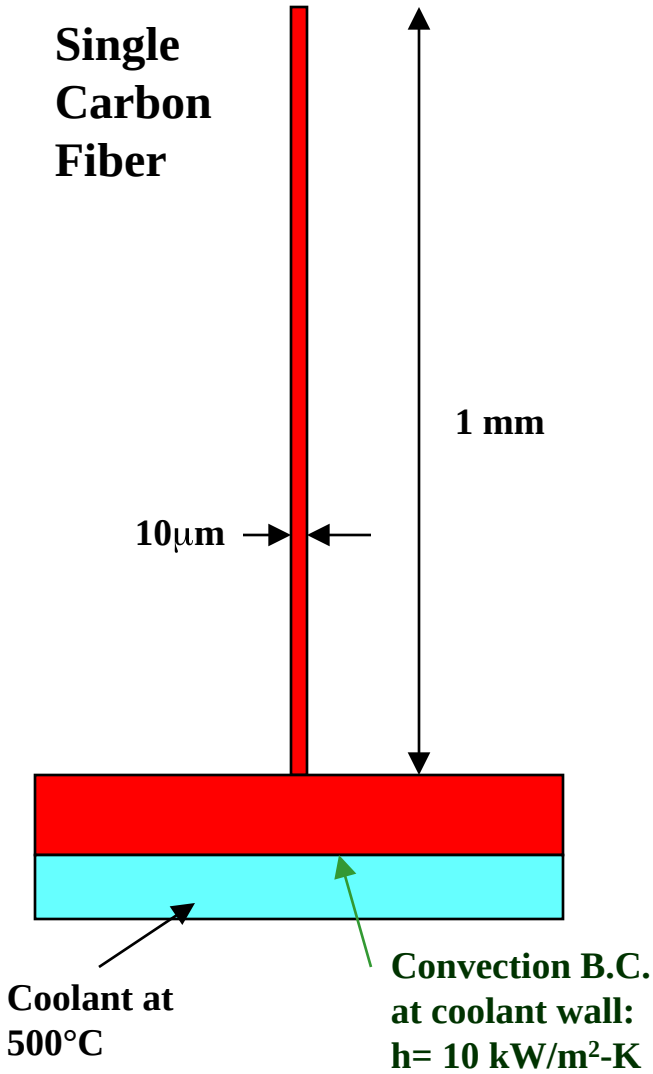
Photon+Ion Energy Deposition In Fiber

Example case

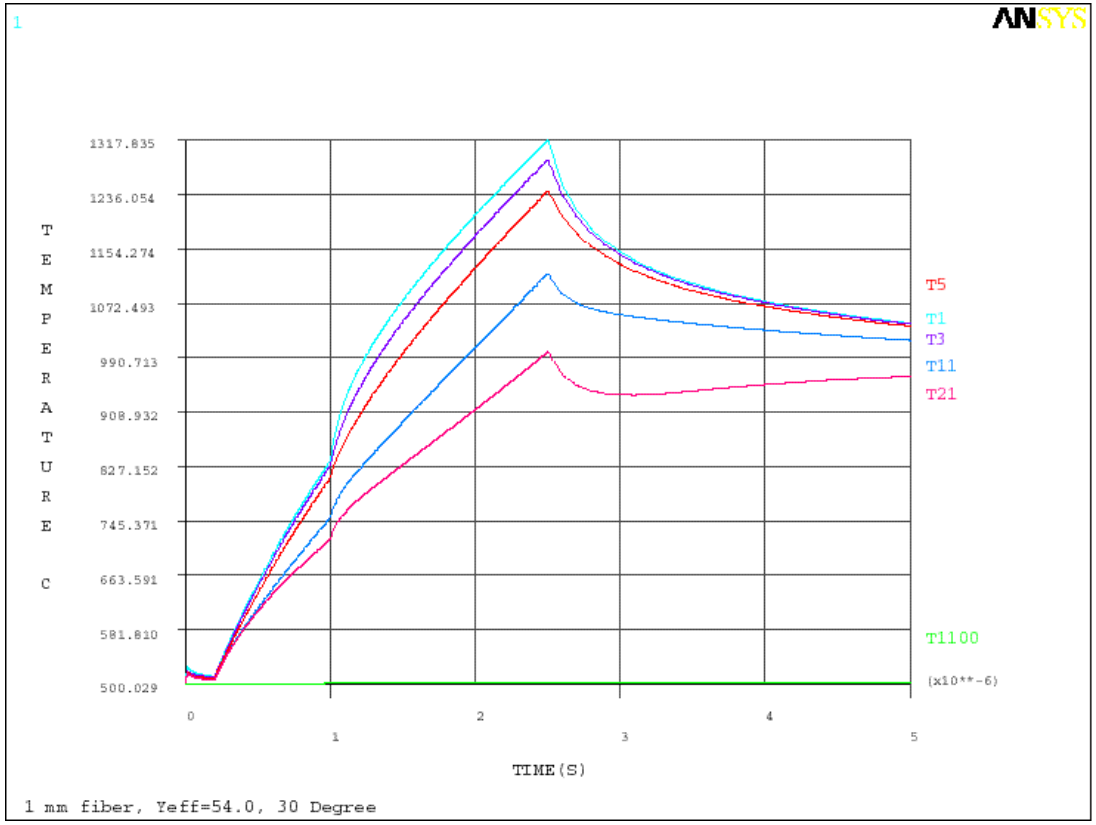
- **Incidence angle = 30°**
- **Porosity = 0.9**
- **Fiber Length = 1 mm**
- **Fiber diameter = 10 μm**
- **Unit cell dimension = 28 μm**
- **Effective fiber separation = 54 μm**



Example Thermal Analysis for Fiber Case



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



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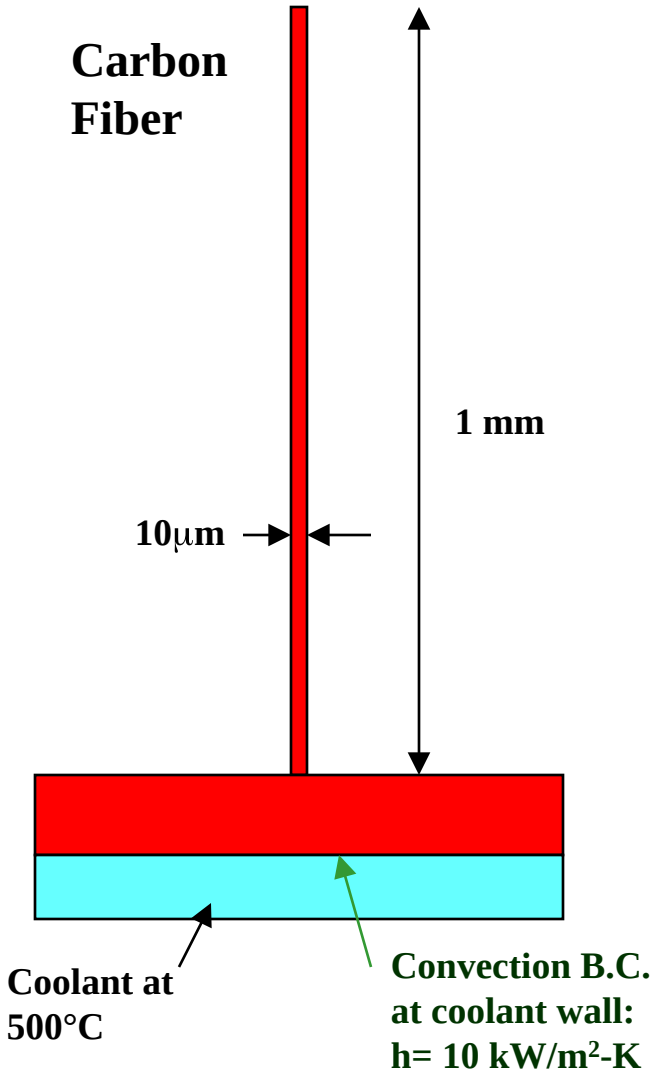
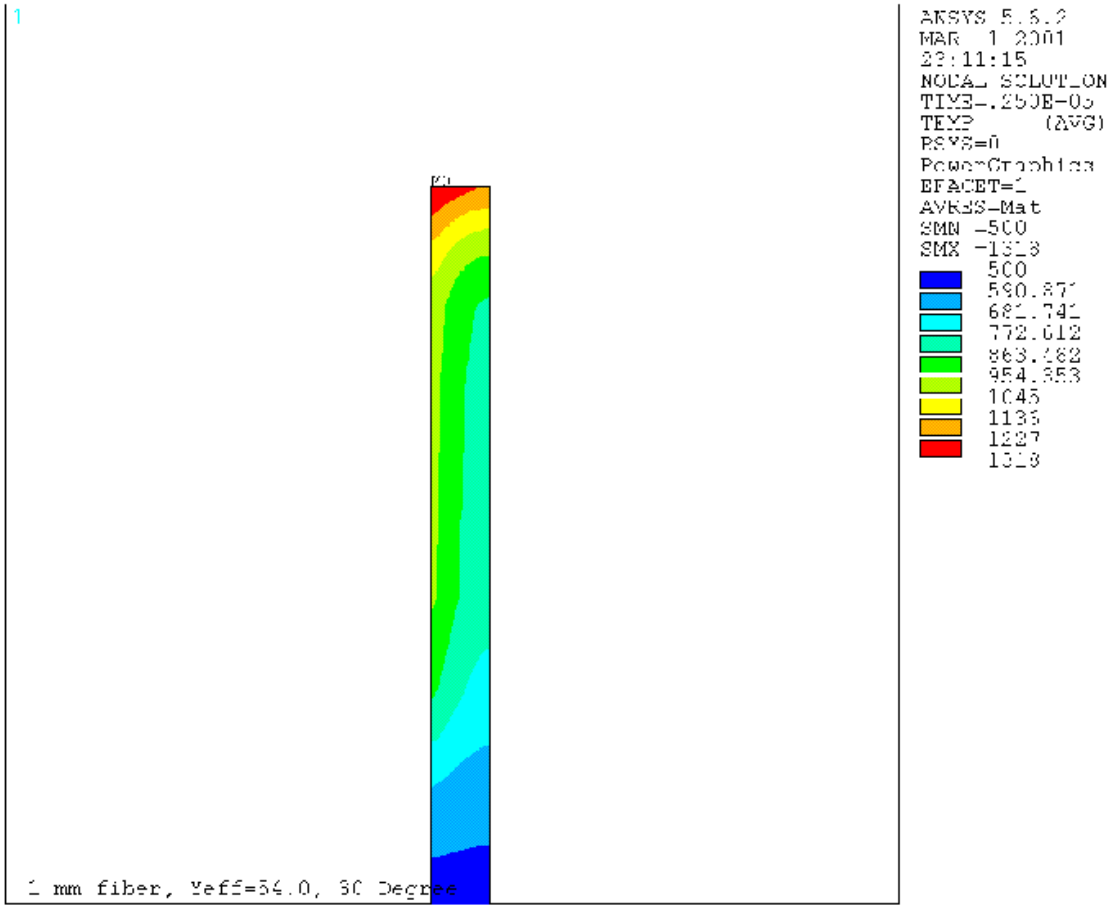
Temperature Contour of Example Fiber Case at 2.5 μs

- **Incidence angle = 30°**
- **Porosity = 0.9; Effective fiber separation = 54 μm**





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

Sensitivity Analysis for Ion Energy Deposition Calculations

Comparison with NIST Data for He ion (ASTAR database)

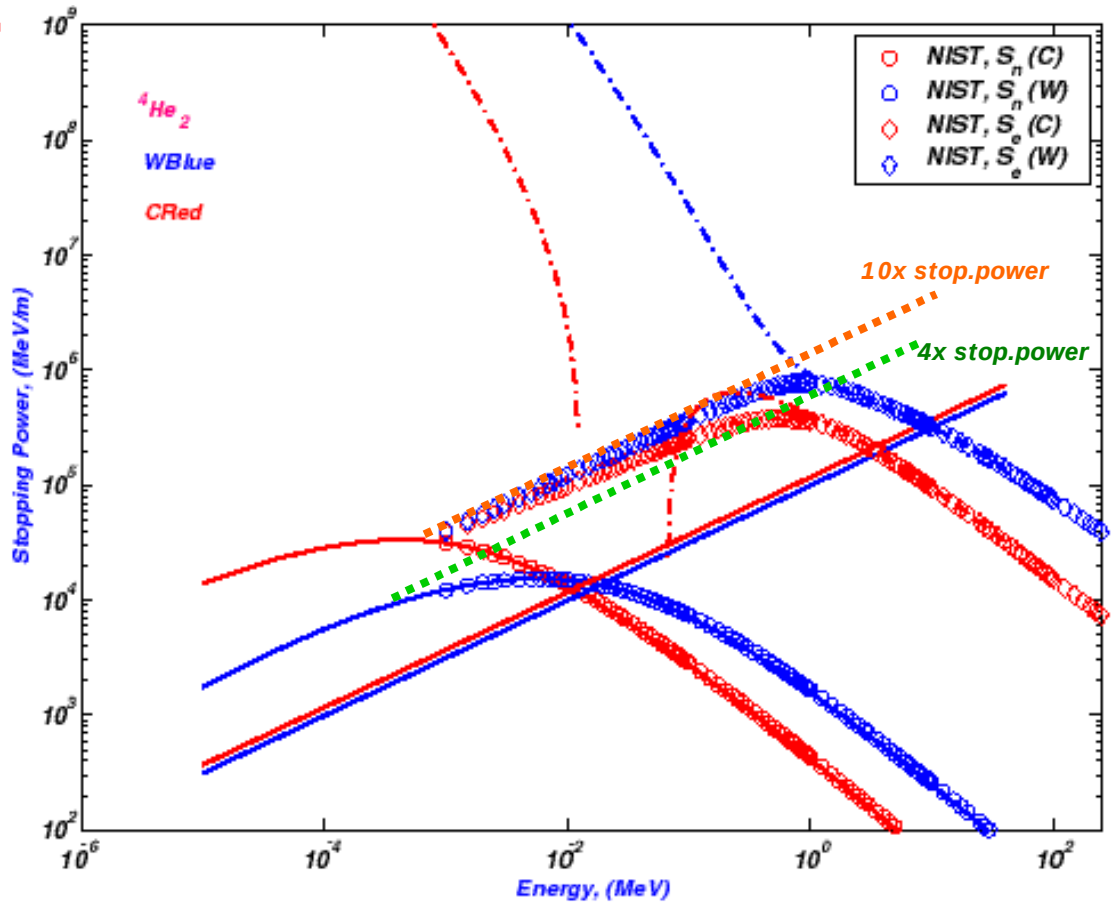
Electronic stopping power

- Our values from the Bethe model for E >1 MeV/amu are similar to NIST's values
- Our values from Lindhard model for E < 1MeV/amu are lower than the semi-empirical values of NIST (by a factor of up to ~10)

(They are lower than the NIST proton results (PSTAR) by a factor of up to ~5)

Nuclear stopping power

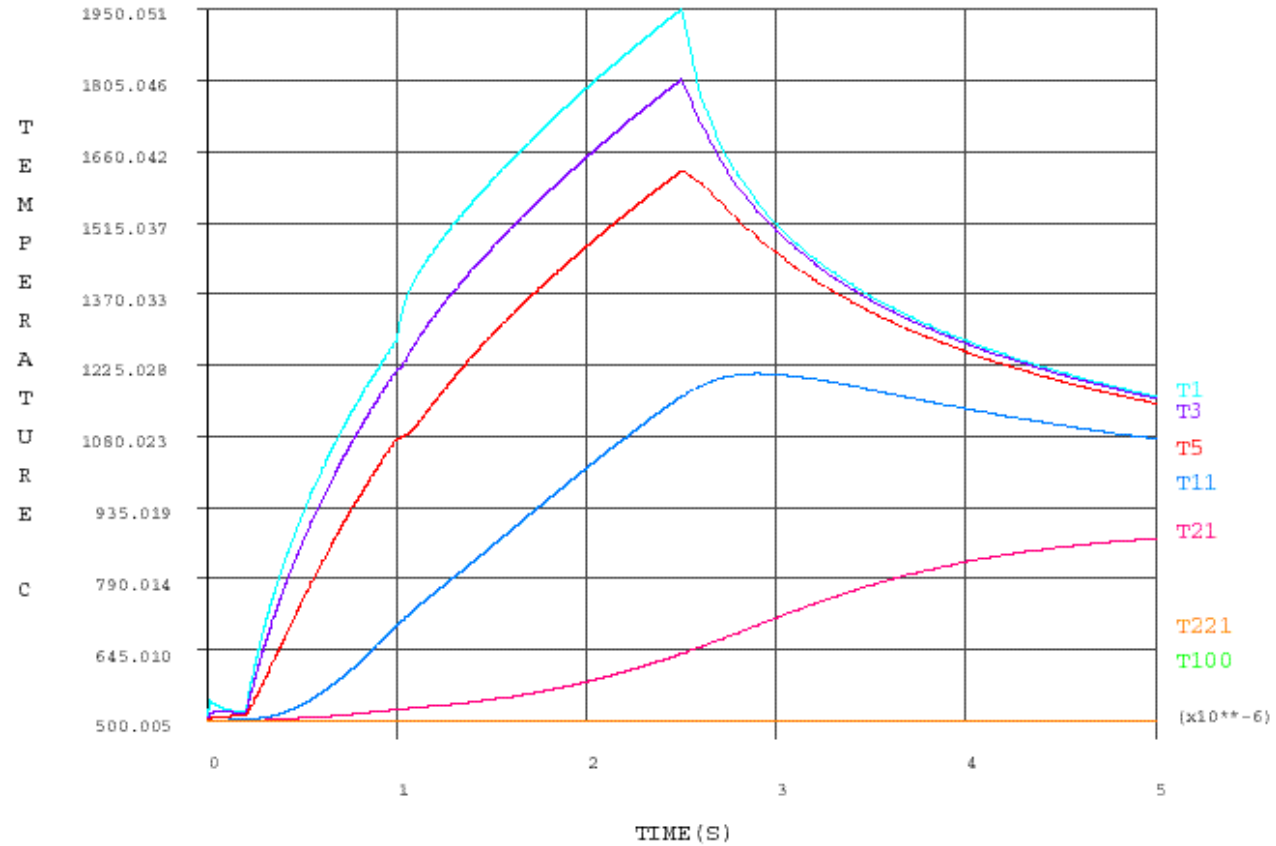
- Our values are the same as NIST's values



- **Perform a sensitivity analysis by conservatively multiplying the stopping power from Lindhard model by a factor of up to 10 and compare the resulting maximum temperature and sublimation to the previous results**

Maximum Temperature History for Carbon Flat Wall for a case with 4 x Stopping Power of Lindhard Model

- **The increase in stopping power results in higher ion energy deposition close to the surface and higher temperature**



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Thermal and Sublimation Analysis Results for Carbon Cases with Artificially Higher Stopping Power in Lindhard Model

Coolant Temp. (°C)	Stopping Power 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}
500	4	1950	2.25×10^{-17}	4.26×10^{-9}
500	10	3097	2.5×10^{-11}	4.7×10^{-3}

* Shot frequency = 6; Plant availability = 0.85

- The increase in stopping power results in higher ion energy deposition close to the surface and higher temperature
- However, even with a conservative factor of 10 increase in stopping power, the resulting temperature and sublimation loss are probably acceptable (although very marginal)
- We have to be vigilant with the design analysis of the dry wall but it appears that a design window is available based on sublimation loss (in particular when considering engineered surface)

Chamber Wall Erosion Lifetime for Dry Wall Concepts Potentially Dependent on a Number of Phenomena

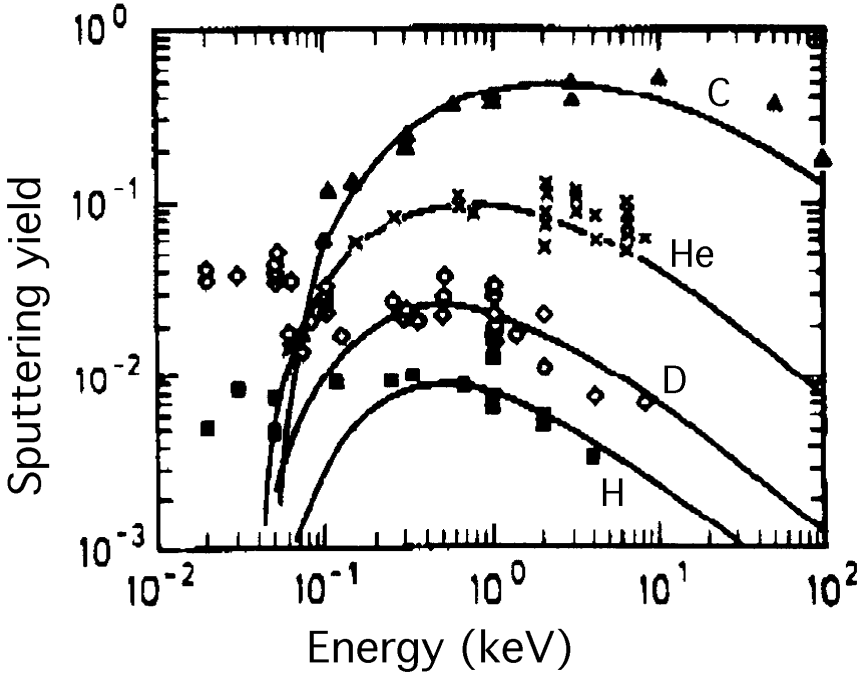
- **Main mass transfer mechanisms for carbon (in addition to sublimation)**
  - Physical Sputtering
  - Chemical Sputtering
  - Radiation Enhanced Sublimation (RES)
  - Other (including macroscopic erosion due to thermo-mechanical effects under highly pulsed, irradiated conditions)
  - Condensation/redeposition

- **Key parameters**
  - Ion energy
  - Ion flux
  - Temperature
  - Angle of incidence
  - Surface characteristics (e.g. contaminants/dopants, smoothness..)

- **Need to assess importance of different mass transfer mechanisms for IFE chamber conditions**

Physical Sputtering Peaks at a Certain Ion Energy Level and is Independent of Temperature

- **Sputtering yield peaks at ~1 keV and decreases with increasing ion energy level**
  - **Could be important for debris ions but not for fast ions**
- **High carbon self-sputtering yield**
  - **Small factor for IFE**
- **Sputtering yield peaks at an angle of incidence of ~80°**
  - **IFE case closer to normal incidence (0°)**



Dependence of the physical sputtering yield of graphite on energy for H, D, He and C ions at normal incidence

(from J. Roth, et al., "Erosion of Graphite due to Particle Impact," Nuclear Fusion, 1991)

Chemical Sputtering Depends Strongly on Temperature and to a Lesser Extent on Ion Energy Level

- **Chemical sputtering is linked with formation of volatile molecules such as CO, CO_2 and/or C_xH_y**

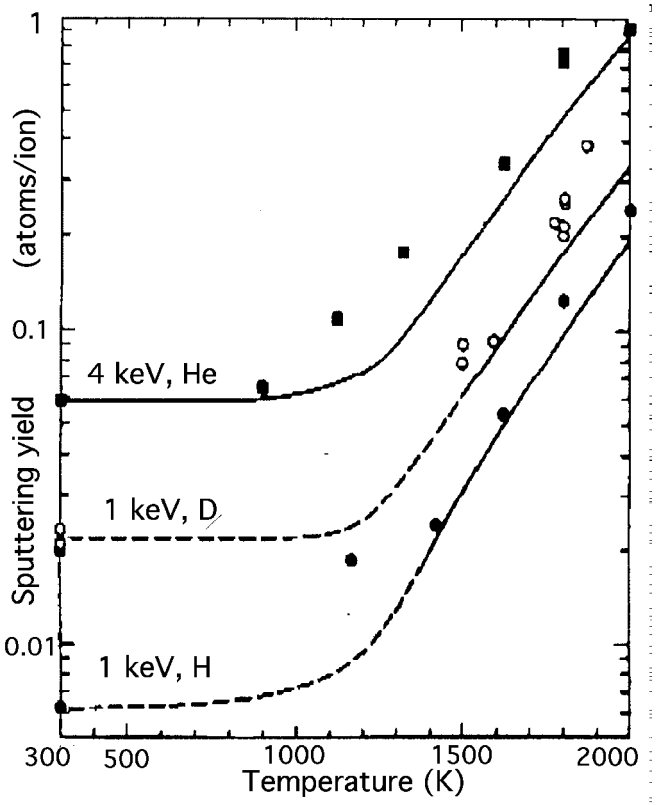
- **Chemical sputtering yield peaks at ion energy level of ~0.5 keV and temperature of ~800K**

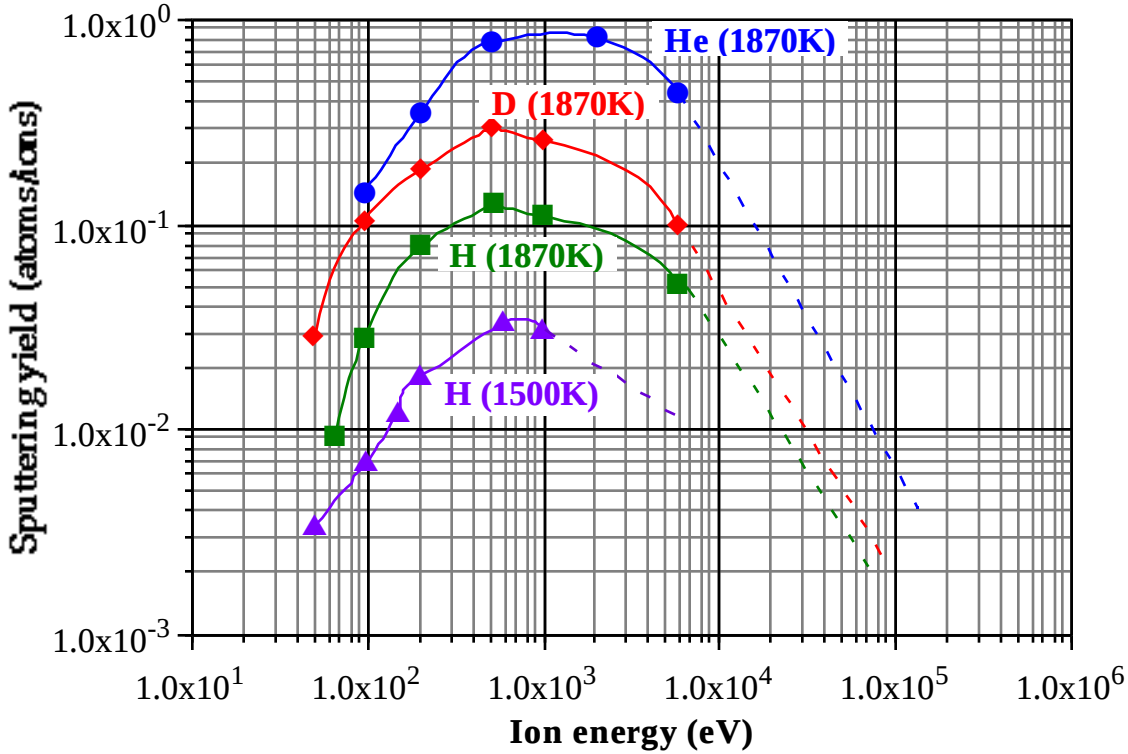
  - **Should not be a major factor for IFE**

Radiation Enhanced Sublimation Observed in Carbon-Based Materials

Hypothesis

- Vacancy-interstitial pairs created by nuclear collisions
- Diffusing interstitials reach the surface and sublimate thermally with low binding energy



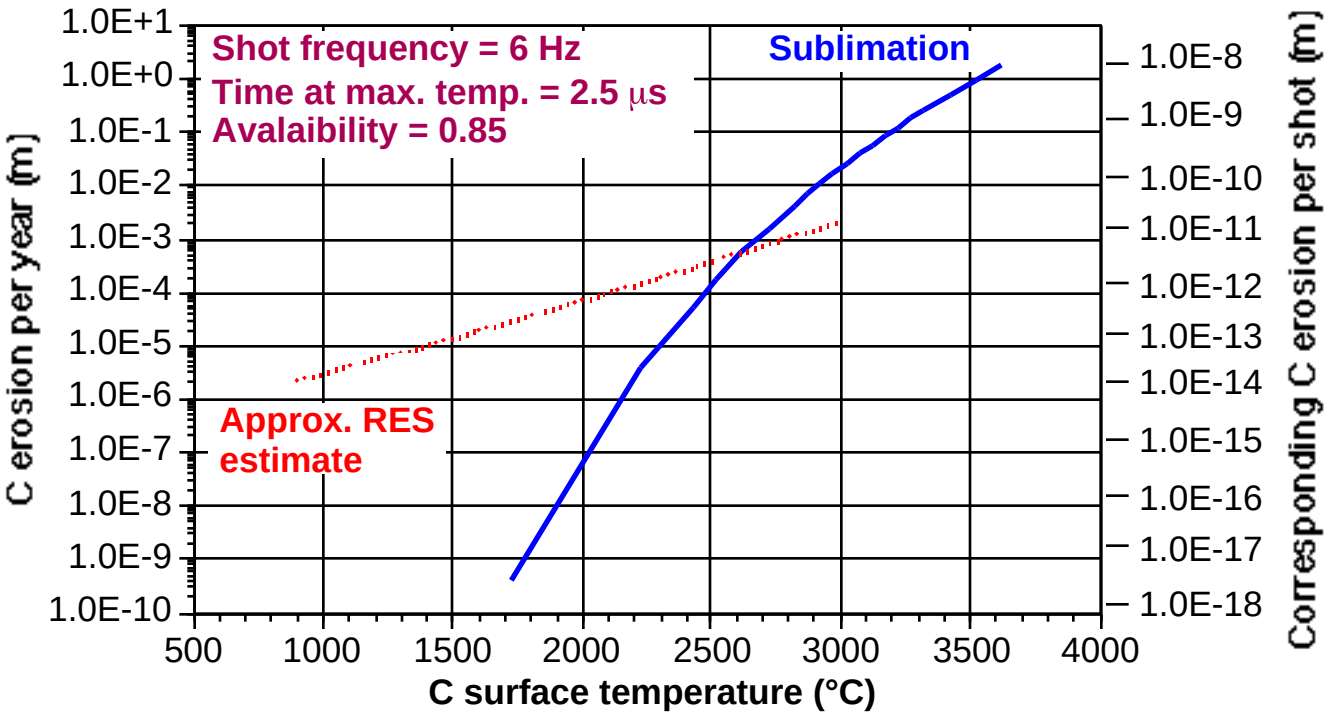


- Process increases dramatically with temperature
- Peaks with ion energies of ~1 keV

(from J. Roth, et al., "Erosion of Graphite due to Particle Impact," Nuclear Fusion, 1991)

Rough Estimate of Radiation Enhanced Sublimation as Compared to Regular Sublimation

- Use extrapolation from sputtering yield vs ion energy results to estimate RES for carbon under IFE conditions (NRLdirect-drive spectra) for 1870 K
- Use extrapolation from RES sputtering yield vs temperature data to estimate effect of temperature



- Results indicate that for this case regular sublimation is more important than RES above ~ 2600°C
- Also, for our case with higher ion energies (>> 1 keV) it is possible that deeper penetration leaves longer diffusive paths for interstitial C and higher probabilities of recombination with vacancies

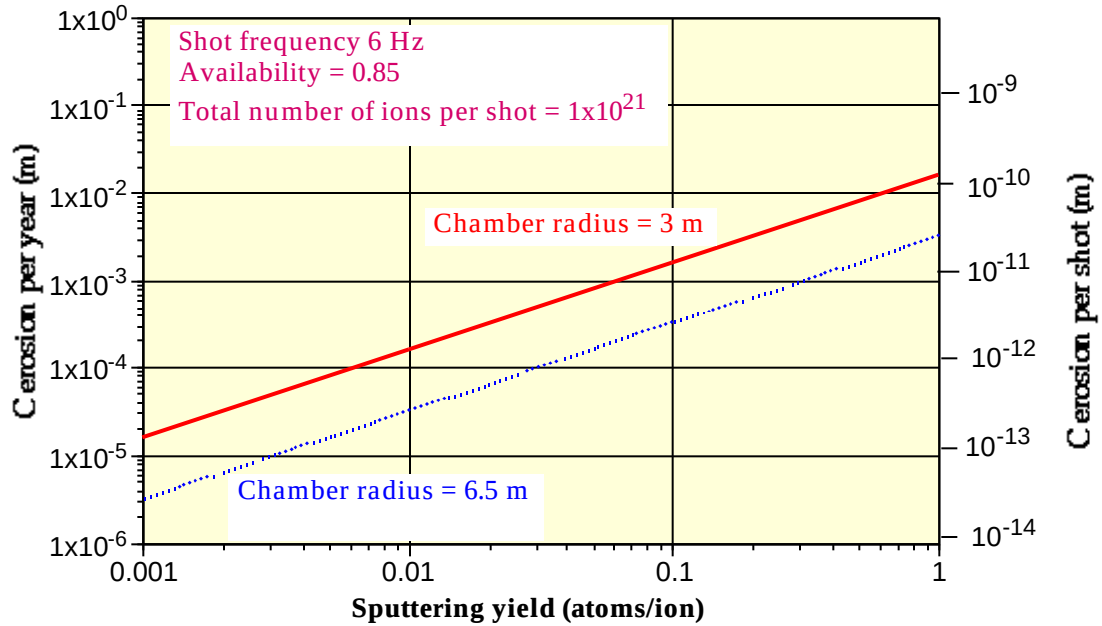
A. R. Raffray, et al., Assessment of Carbon and Tungsten Dry Chamber Walls under IFE Energy Depositions

UCSD

Carbon Dry Wall Lifetime as a Function of Sputtering Yield

- **A reasonable lifetime limit should be a few mm per year(?), less than 10^{-10} m a shot**

- **Depending on the chamber radius, an overall average sputtering yield of 1 could be accommodated, much larger than what is expected**
  - **e.g., RES estimate for C under IFE conditions (NRLdirect-drive spectra) for 1870 K corresponds to an average sputtering yield of 0.05**



- **It would be prudent to have measures for (infrequent) in-situ coating of chamber wall to guard against unforeseen local losses**

Conclusions: Cautious Optimism for IFE Dry Chamber Wall Without Protective Gas

- **Analysis results indicate that a design window exists for flat wall for reasonable chamber radius**
  - **Fine mesh provides more accurate results for energy deposition and thermal analyses**
  - **Sensitivity studies indicate that substantially higher heat deposition (2-3 times) could be accommodated for both C and W armor**
  - **However, uncertainty in ion energy deposition calculations could reduce this margin**
  - **Fiber surface would provide additional margins depending on angle of incidence (in particular for shallow angle of incidence)**

- **No data is available for C sputtering and RES under high energy ion fluxes and high temperature. However, based on existing data and extrapolation:**
  - **It appears that carbon sputtering would not be a problem since it peaks at energy ~ 1 keV, lower than most IFE ions**
  - **RES would be lower than regular sublimation for NRL-type direct drive spectra**
  - **Also, it is speculated that higher energy ions will create interstitial C and vacancies deeper in the C material. Longer diffusive path for the interstitial to reach the surface provides more chance for recombination with vacancies and lower RES**
  - **This needs to be confirmed through R&D and analysis**

Conclusions: Cautious Optimism for IFE Dry Wall, but Important Issues Remain

- **Must separate thin armor region from structural backbone**
  - **Most issues linked with armor itself**
  - **Possibility of repairing armor (in-situ)**
- **Still many unknowns**
  - **How to understand and apply properties and parameters derived for equilibrium conditions for highly-pulsed, irradiated IFE conditions (thin region (~10's of μm) of C (or W...) which gets to high temperature (~2000 °C) in a highly cyclic manner, ~6 s^{-1})**
  - **Erosion**
    - Sublimation- and sputtering-based, but also
    - Macroscopic erosion (thermo-mechanical + irradiation effects on armor under IFE operating conditions)
  - **Tritium inventory in carbon armor under high-temperature cyclic operation**
    - It is thought that any implanted tritium within the thin armor layer would diffuse out to the high temperature, high diffusivity surface region and escape
    - Importance of irradiation trapping?
    - Co-deposition should not be a problem at high temperature but colder surfaces (e.g. in penetration lines) could be a problem
  - **Prudent to have more than one option in case C is unacceptable (e.g. W)**
- **Important not to underestimate issues and effort to resolve them**
  - **Development of material configuration and resolution of these issues will take resources and time**