Modeling of Inertial Fusion Chamber

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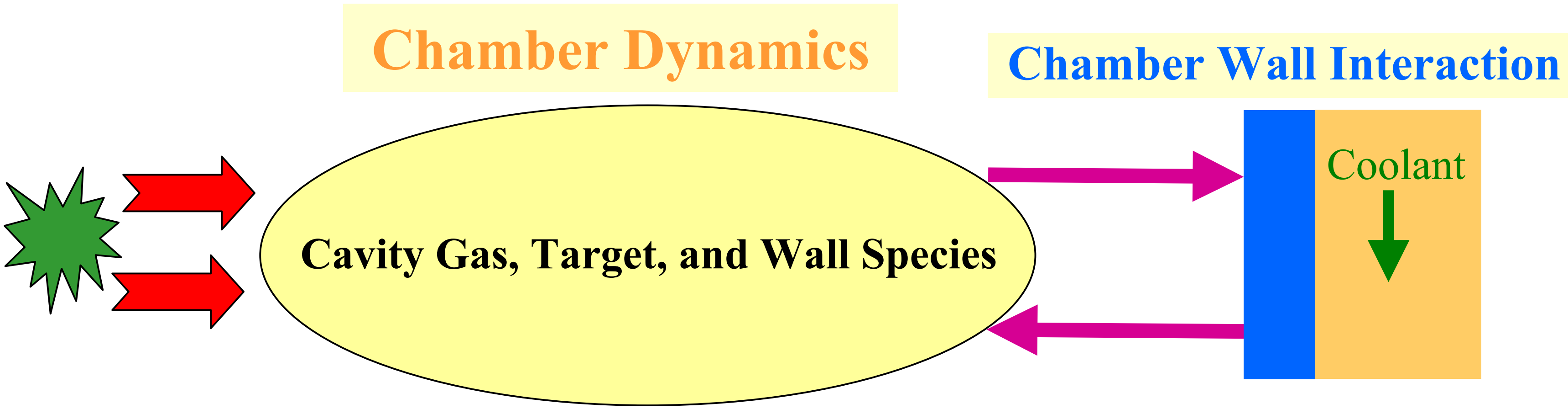
Why We Need Chamber Modeling

- **Key IFE chamber uncertainty is whether or not the chamber environment will return to a sufficiently quiescent and clean low-pressure state following a target explosion to allow a second shot to be initiated within 100–200 ms**
  - Target and driver requirement on chamber conditions prior to each shot

- **Chamber condition following a shot in an actual chamber geometry is not well understood**
  - Dependent on multiple processes and variables
  - A predictive capability in this area requires a combination of computer simulation of increasing sophistication together with simulation experiments to ensure that all relevant phenomena are taken into account and to benchmark the calculations

- **The proposed modeling effort includes:**
  - Scoping calculations to determine key processes to be included in the code
  - Development of main hydrodynamic code
  - Development of wall interaction module

Chamber Physics Modeling



Time of flight to wall:

X-rays	~20 ns
Neutrons	~100 ns
Alphas	~400 ns
Fast Ions	~1 µs
Slow 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

Timescale: ns to 100 ms

- Photon energy deposition
- Ion energy deposition
- Neutron & α energy deposition
- Conduction
- Melting
- Vaporization
- Sputtering
- Thermo-mechanics/ macroscopic erosion
- Radiation damage
- Blistering (from bubbles of implanted gas)
- Desorption or other degassing process

Timescale: ns to 100 ms

- **Convection & cooling**

Timescale: ms

Scoping Calculations Were First Performed to Assess Importance of Different Effects and Conditions

- **Chamber Gas**
  - At high temperature (> ~ 1 ev), radiation from ionized gas can be effective
  - In the lower temperature range (~ 5000K back to preshot conditions)
    - Conduction (neutrals and some electrons)
    - Convection
    - Radiation from neutrals
    - Other processes?
  - The temperature of the gas might not equilibrate with the wall temperature
    - May have implications for target injection

Effectiveness of Conduction Heat Transfer to Cool Chamber Gas to Preshot Conditions

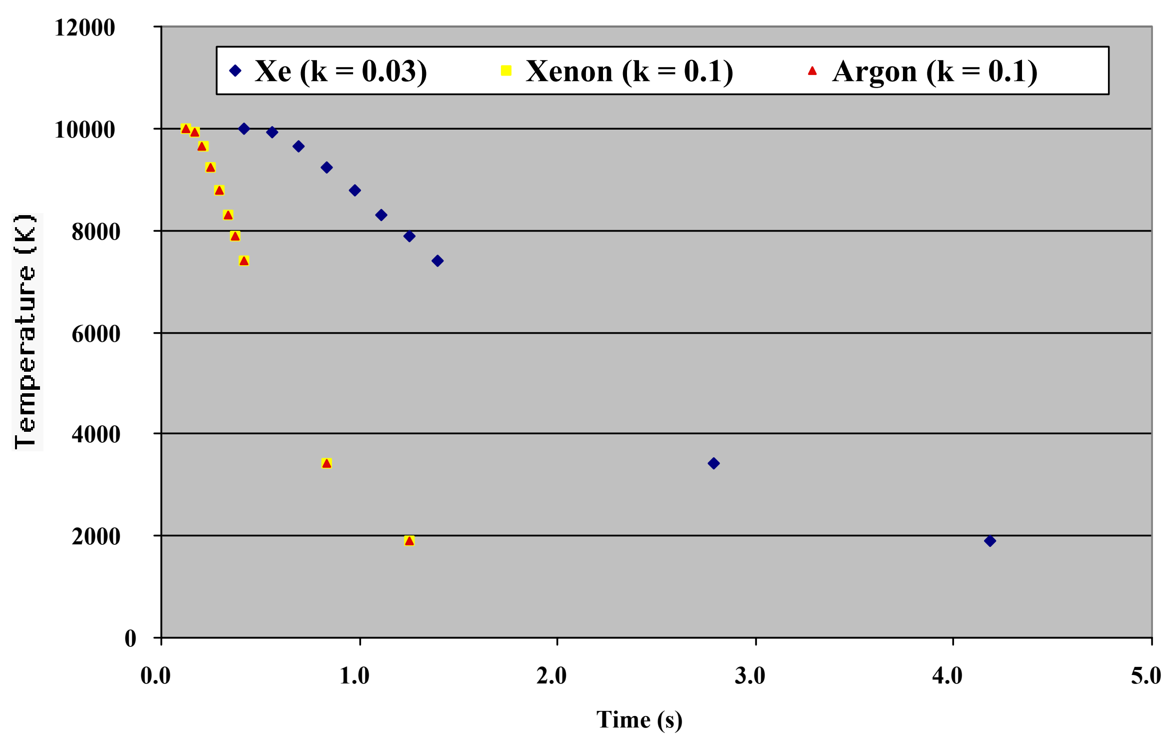
- Simple transient conduction equation for a sphere containing gas with an isothermal boundary condition(T_w)
  - k_{Xe} is poor (~0.015 W/m-K at 1000K, and ~0.043 W/m-K at 5000 K)
  - At higher temperature electron conductivity of ionized gas in chamber will help

    (assumed ~ 0.1 W/m-K for $n_e = n_o$ and 10, 000 K)
  - Argon better conducting gas

- T decreases from 5000K to 2000K in ~2 s for k_g = 0.03 W/m-K

- Even if k_g is increased to 0.1 W/m-K, it does not help much (~ 0.6 s)

Temperature History Based on Conduction from 50 mTorr Gas in a 5 m Chamber to a 1000K Wall



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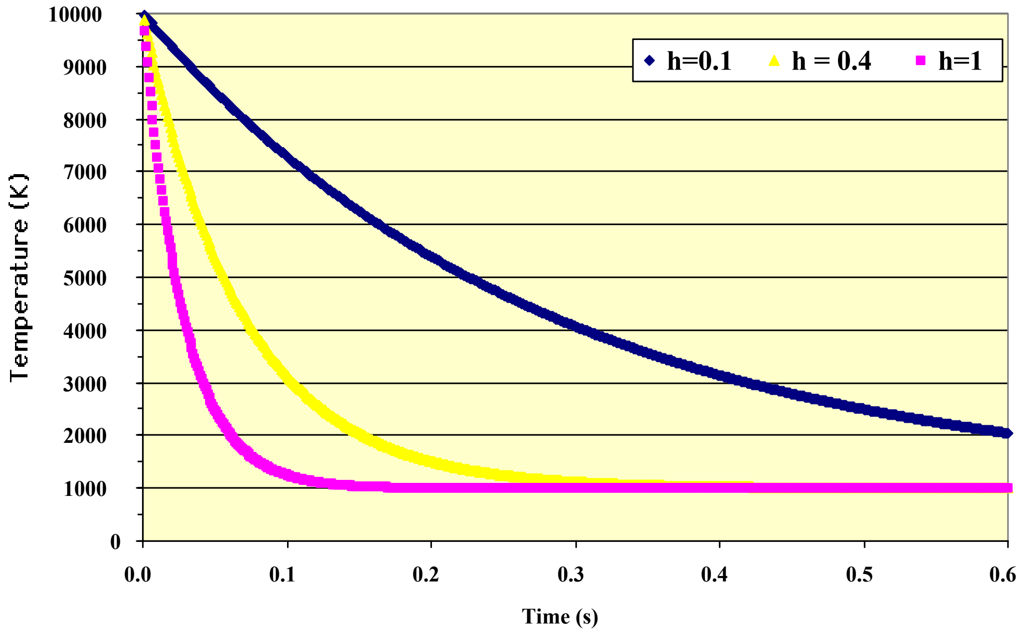
Effectiveness of Convection Heat Transfer to Cool Chamber Gas to Preshot Conditions

- Simple convection estimate based on flow on a flat surface with the fluid at uniform temperature
- Use Xe fluid properties
- Assume sonic velocity
  - c ~ 500 m/s
  - Re ~ 700 for L = 1 m
  - Nu ~ 13
  - h ~ 0.4 W/m^2-K
- Lower velocity would result in lower h but local eddies would help
  - Set h between 0.1 and 1 W/m^2-K representing an example range
- T decreases from 5000K to 2000K, in ~0.1 s for h = 0.4 W/m^2-K
- Increasing h to 1 W/m^2-K helps but any reduction in h rapidly worsens the situation (e.g. ~0.4 s for 0.1 W/m^2-K)

Temperature History Based on Convection from 50 mTorr Gas in a 5 m Chamber to a 1000K Wall



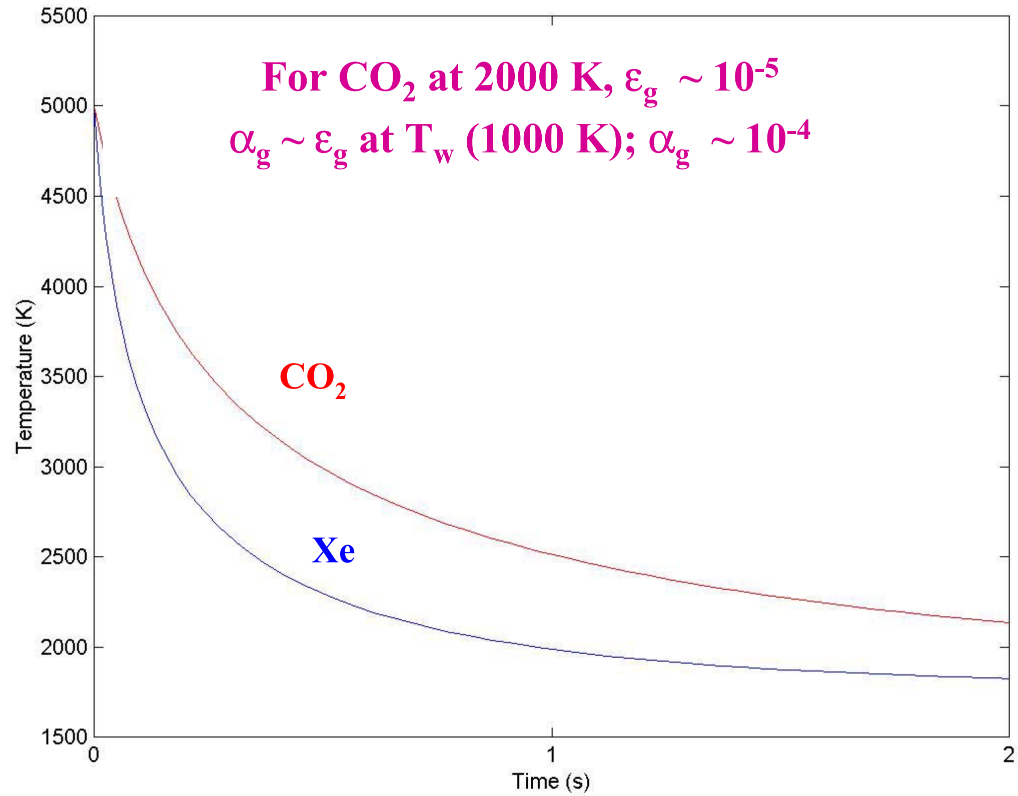
Effectiveness of Radiation Heat Transfer to Cool Chamber Gas from Mid-level Temperature (~5000K) to Preshot Conditions

- **Xe is monoatomic and has poor radiation properties**
  - Complete radiation model quite complex
  - Simple engineering estimate for scoping calculations
  - No emissivity data found for Xe
  - Simple conservative estimate for Xe using CO_2 radiation data

  - T decreases from 5000K to 2000K, in ~1 s
    (would be worse for actual Xe radiation properties)

$$q_r'' = \sigma\, \varepsilon_w \left(\varepsilon_g T_g^4 - \alpha_g T_w^4\right)$$

Temperature History Based on Radiation from 50 mTorr Gas in a 5 m Chamber to a 1000K Wall



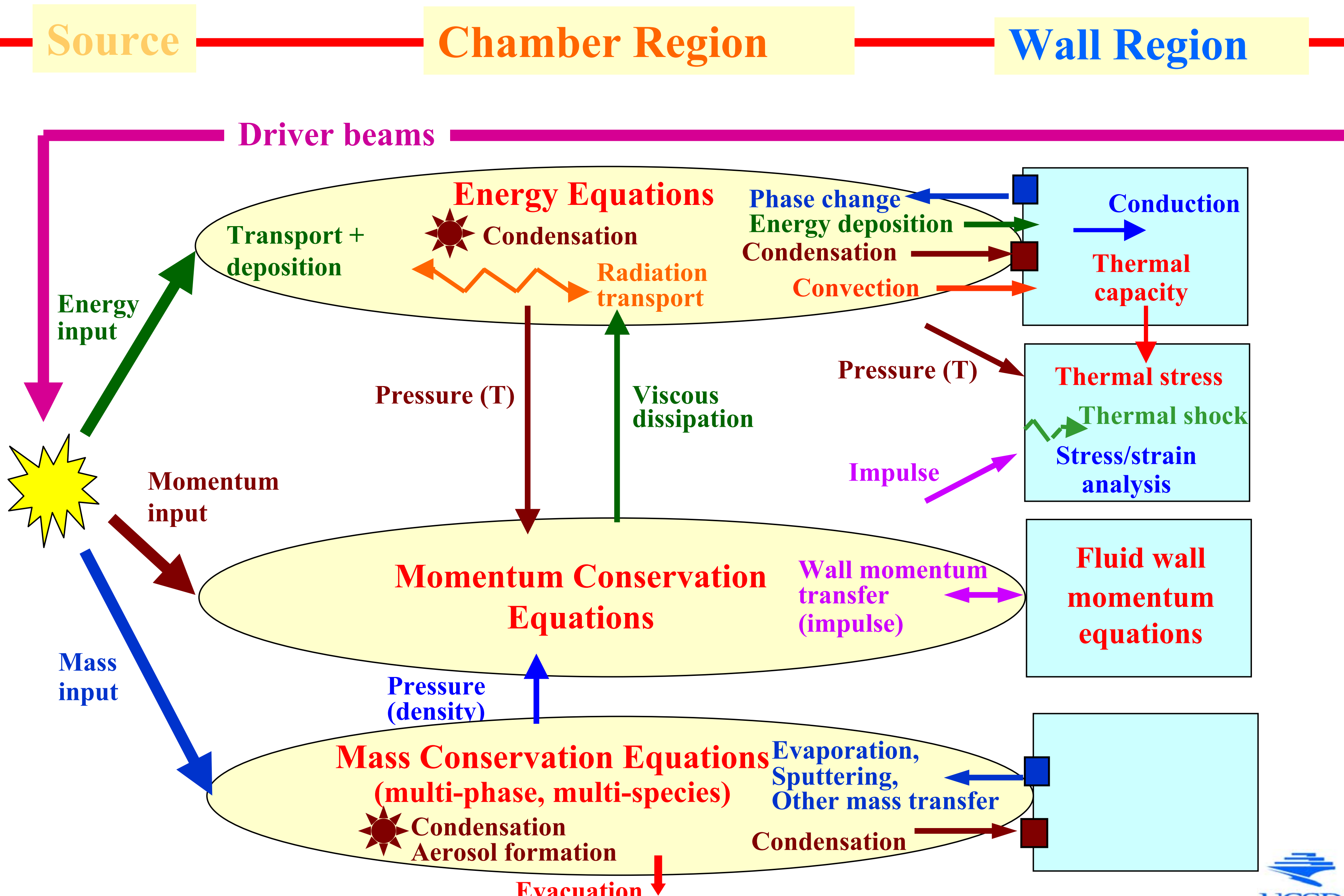
Effectiveness of Heat Transfer Processes to Cool Chamber Gas (Xe) to Preshot Conditions is Poor

Conservative estimate of Xe temperature (K) following heat transfer from 5000K

Time:	0.1 s	0.2 s	0.5s	~1 s
Conduction:				
k=0.03 W/m-K	4700	4500	3600	2700
k=0.1 W/m-K	3900	3200	2200	1500
Convection:				
h=0.1 W/m^2-K	3800	3000	1650	1200
h=0.4 W/m^2-K	1950	1220	~1000	
h=1 W/m^2-K	*1250*			
Xe Radiation:				
(assum. CO_2 ε and α)	3500	2850	2300	2200

- It seems that only possibility is convection with high velocity and small length scales (optimistic requiring enhancement mechanisms) and/or appreciable gas inventory change per shot (by pumping)
- Background plasma in the chamber might help in enhancing heat transfer (e.g. electron heat conduction, recombination)

Chamber Physics Modeling



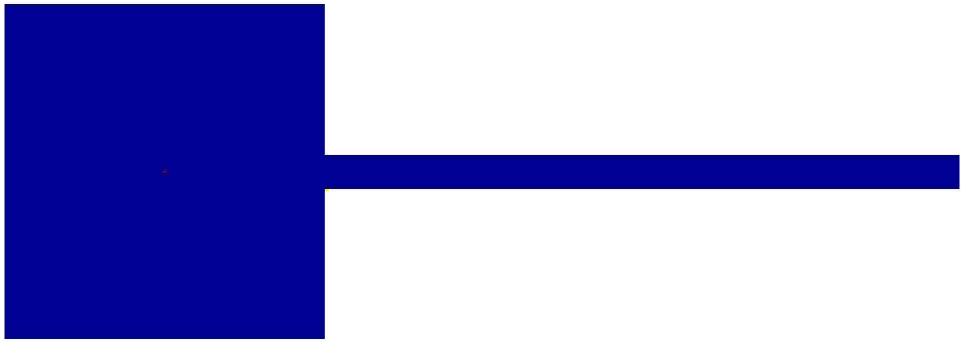
Numerical Modeling of IFE Chamber Gas Dynamics

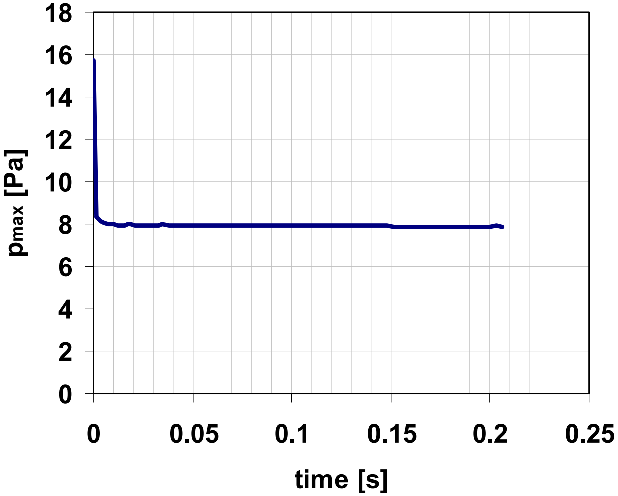
- **Build Navier-Stokes solver for compressible viscous flow**
  - **Second order Godunov algorithm.**
  - **Riemann solver used as a form of upwinding.**
  - **Progressive approach**
    - **1-D --> 2-D**
    - **inviscid --> viscous flow**
    - **rectangular geometry --> 2-D and 3-D arbitrary geometry (to be done)**
    - **grid splitting into sub-domains for multi-geometry modeling**

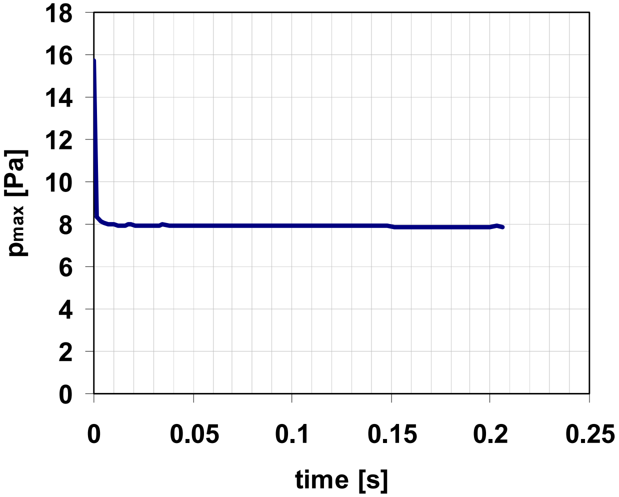
- **Perform code verification**
  - **1-D and 2-D acoustic wave propagation**
  - **Conservation laws**

Example Case to Illustrate Code Capability: Square Chamber Cavity With a Rectangular Beam Channel – Centered Initial Disturbance

- **Inviscid flow**
- **Initial pressure and density disturbance centered, zero velocity field**
- **Reflective wall boundary conditions**
- **Ambient Xe (T = 800K, ρ = 1.3028 10^{-4} kg/m^3, p = 7.857 Pa)**







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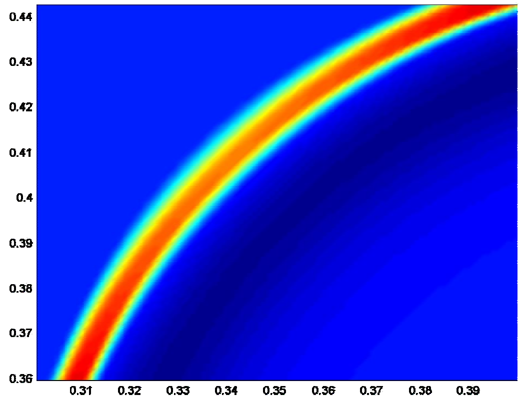
Comparison Between Viscous and Inviscid Flow for Example Xe Case

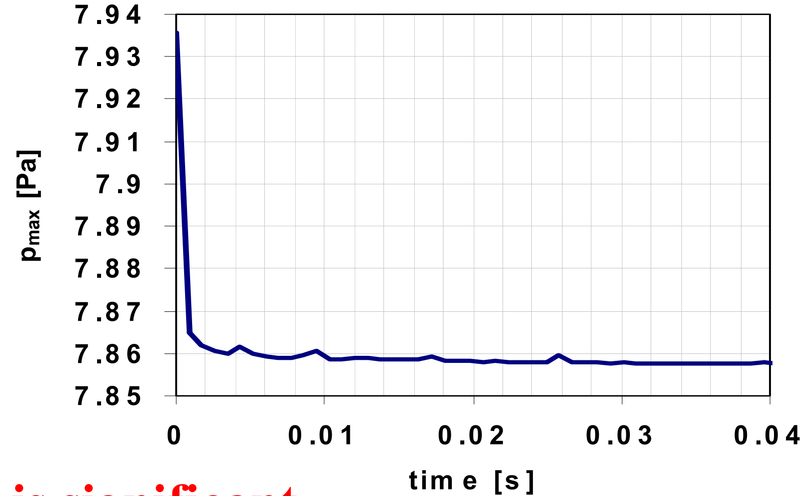
Inviscid

$v_{max} = 0.0975$ m/s

$p_{max} = 7.86$ Pa

$\rho_{max} = 1.3032\ 10^{-4}$ kg/m^3





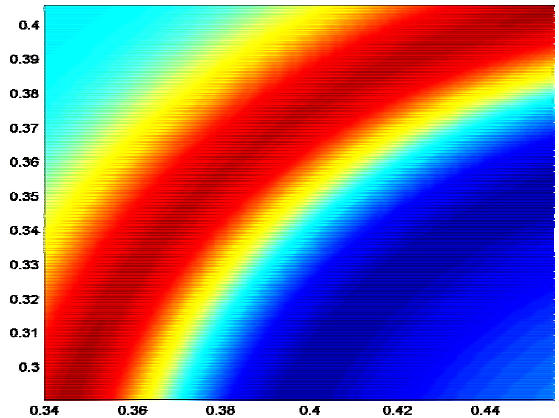
The effect of viscosity is significant.

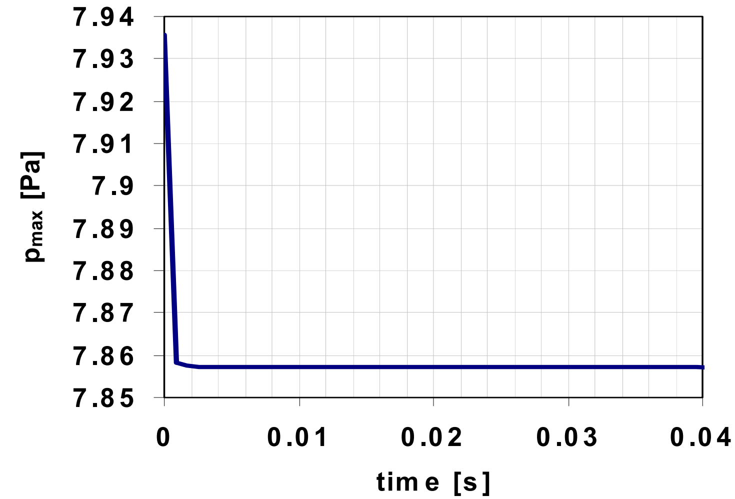
Viscous

$v_{max} = 0.0078$ m/s

$p_{max} = 7.8573$ Pa

$\rho_{max} = 1.3035\ 10^{-4}$ kg/m^3

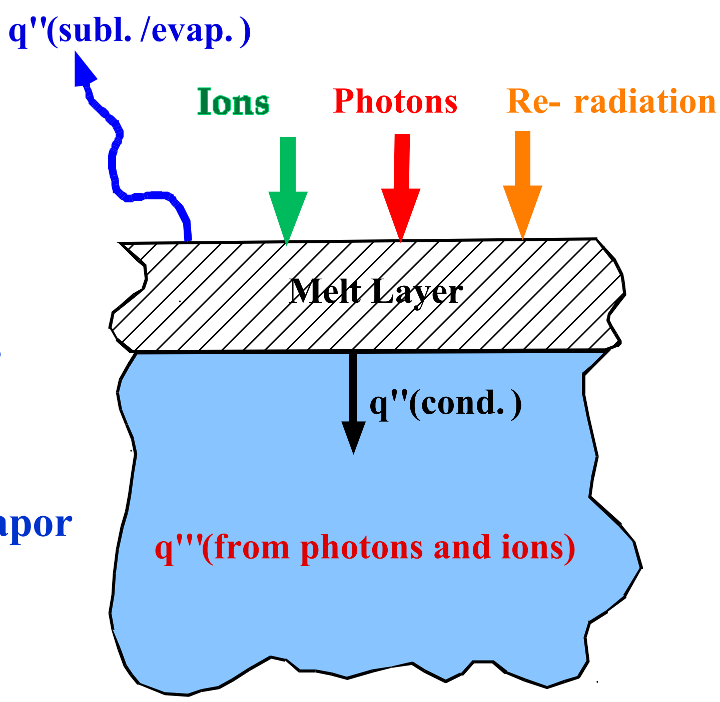




Wall Interaction Module Development

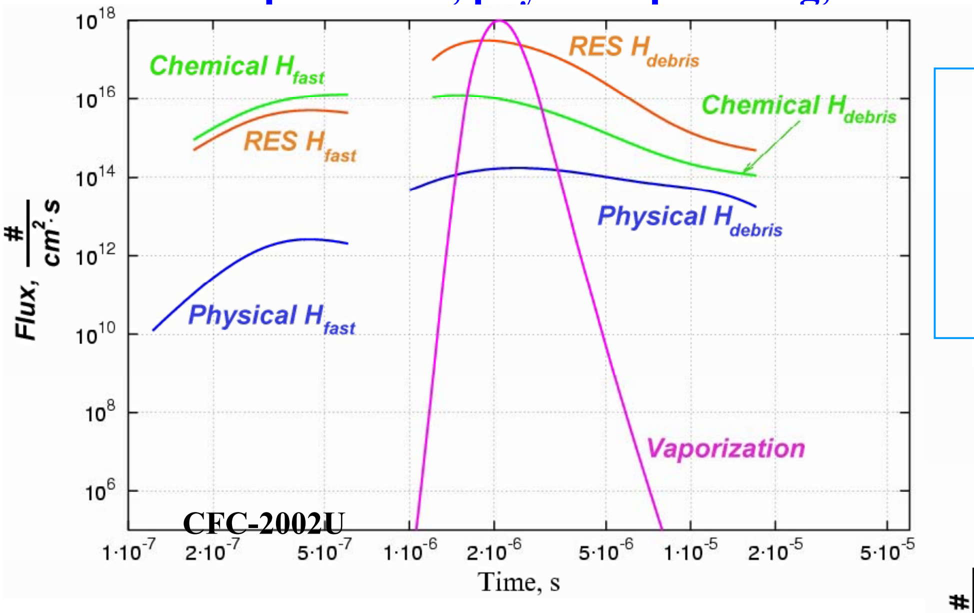
- **Ion and photon energy deposition calculations based on spectra**
  - **Photon attenuation based on total photon attenuation coefficient in material**
  - **Use of SRIM tabulated data for ion stopping power as a function of energy**
- **Transient Thermal Model**
  - **1-D geometry with temperature-dependent properties**
  - **Melting included by step increase in enthalpy at MP**
  - **Evaporation included based on equilibrium data as a function of surface temperature and corresponding vapor pressure**
    - **For C, sublimation based on latest recommendation from Philipps**
- **Model calibrated and example cases run**
- **To be linked to gas dynamic code**

Example IFE Chamber Wall Configuration Under Energy Deposition



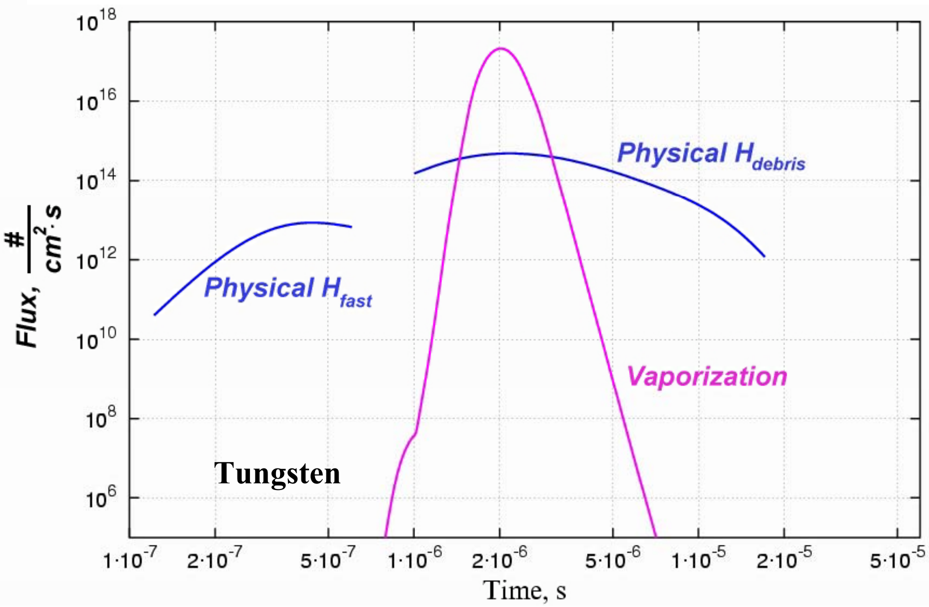
Other Erosion Processes to be Added (ANL)

- **Scoping analysis performed**
  - **Vaporization, physical sputtering, chemical sputtering, radiation enhanced sublimation**



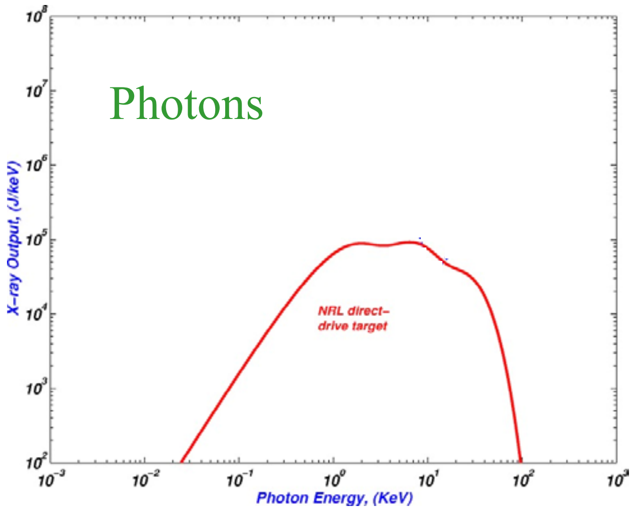
Plots illustrating relative importance of erosion mechanisms for C and W for 154 MJ NRL DD target spectra

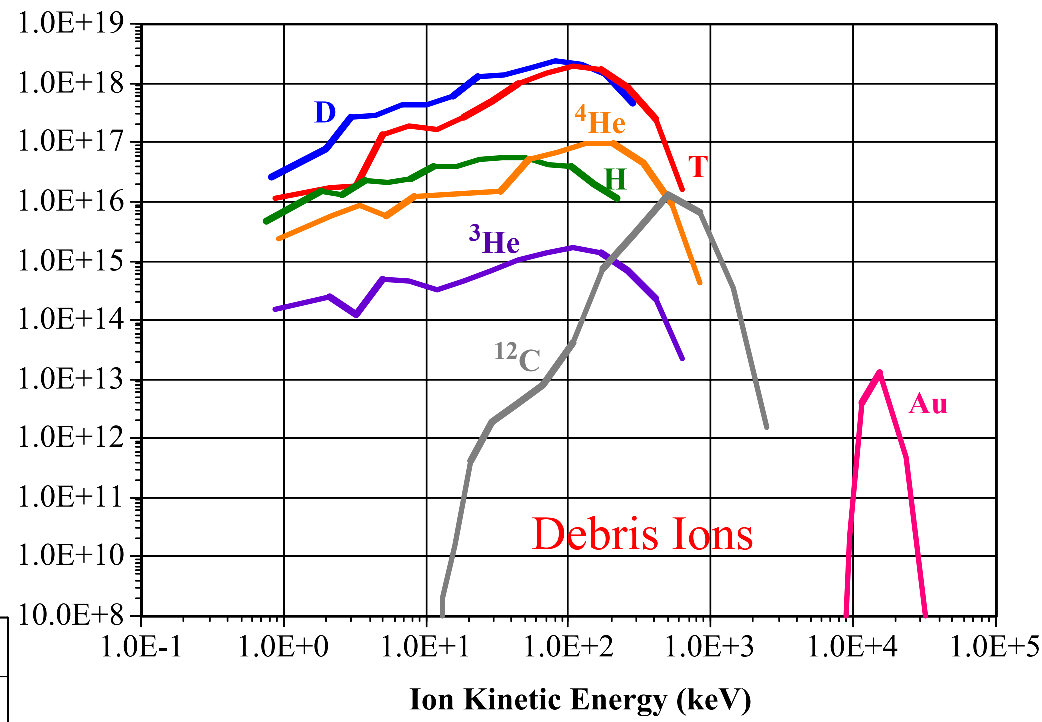
Chamber radius = 6.5 m.

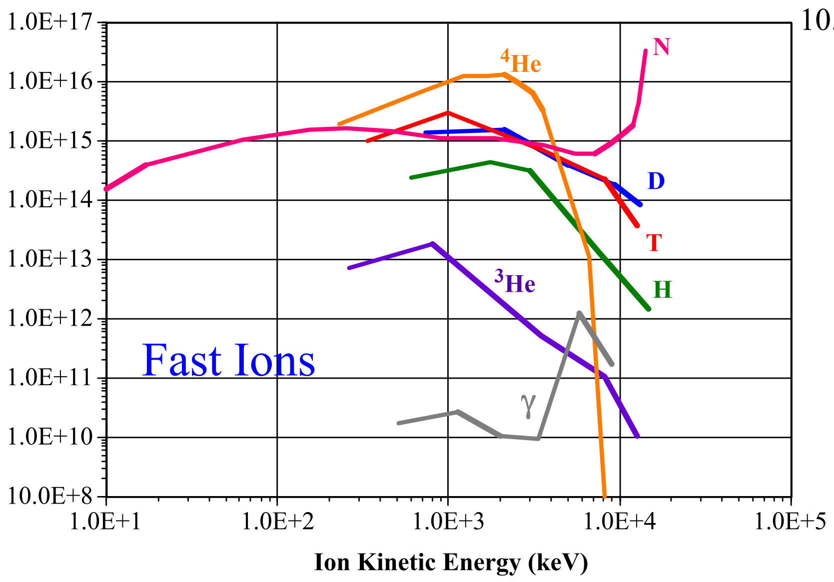


- **These results indicate need to include RES and chemical sputtering for C (both increase with temperature)**
- **Physical sputtering relatively less important for both C and W for minimally attenuated ions (does not vary with temperature and peaks at ion energies of ~ 1keV)**

Example Cases Run for 154 MJ NRL Direct Drive Target Spectra



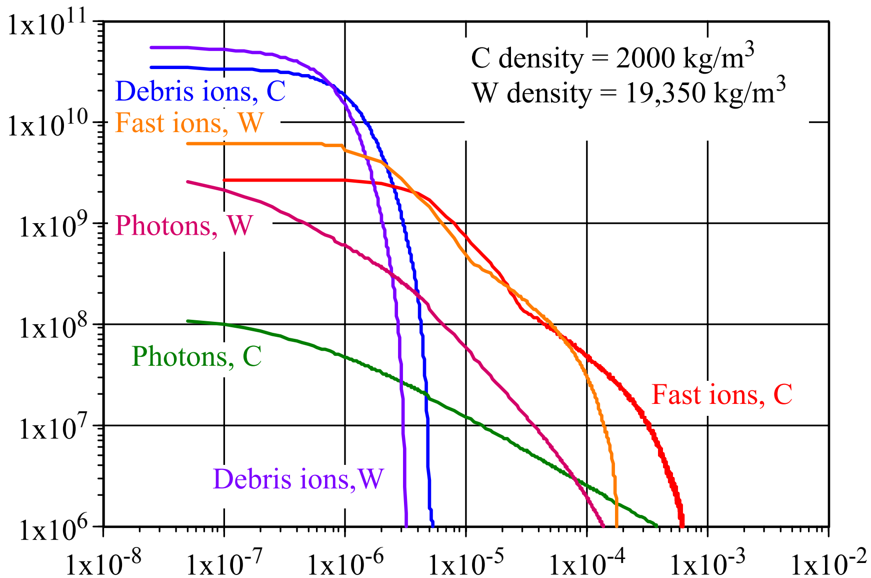




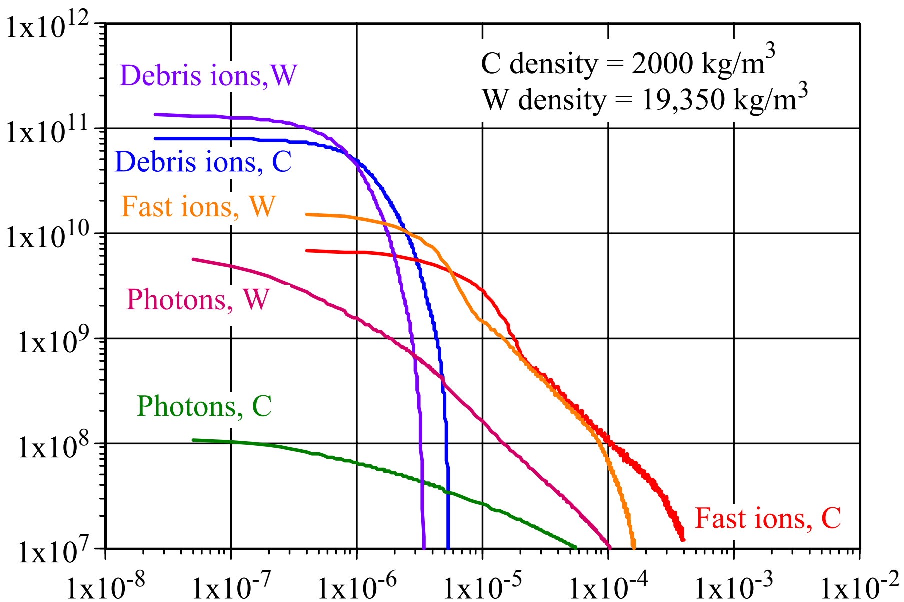
Spatial Profile of Volumetric Energy Deposition in C and W for Direct Drive Target Spectra

- **Tabulated data from SRIM for ion stopping power used as input**

Energy Deposition as a Function of Penetration Depth for 154 MJ NRL DD Target

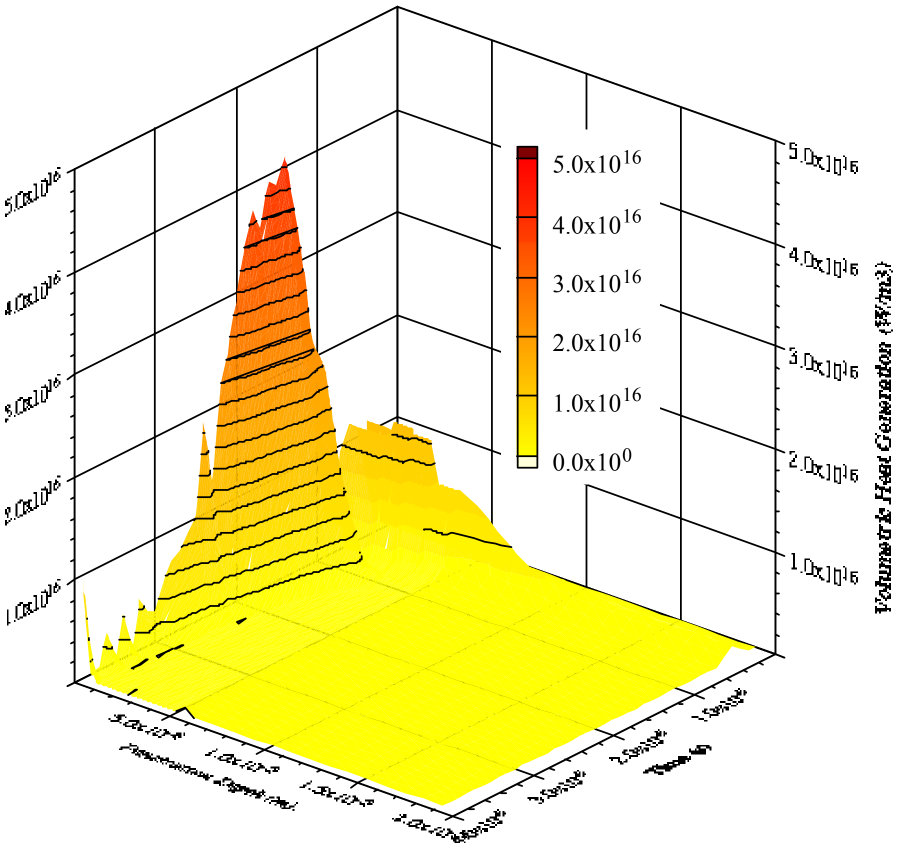


Energy Deposition as a Function of Penetration Depth for 401 MJ NRL DD Target

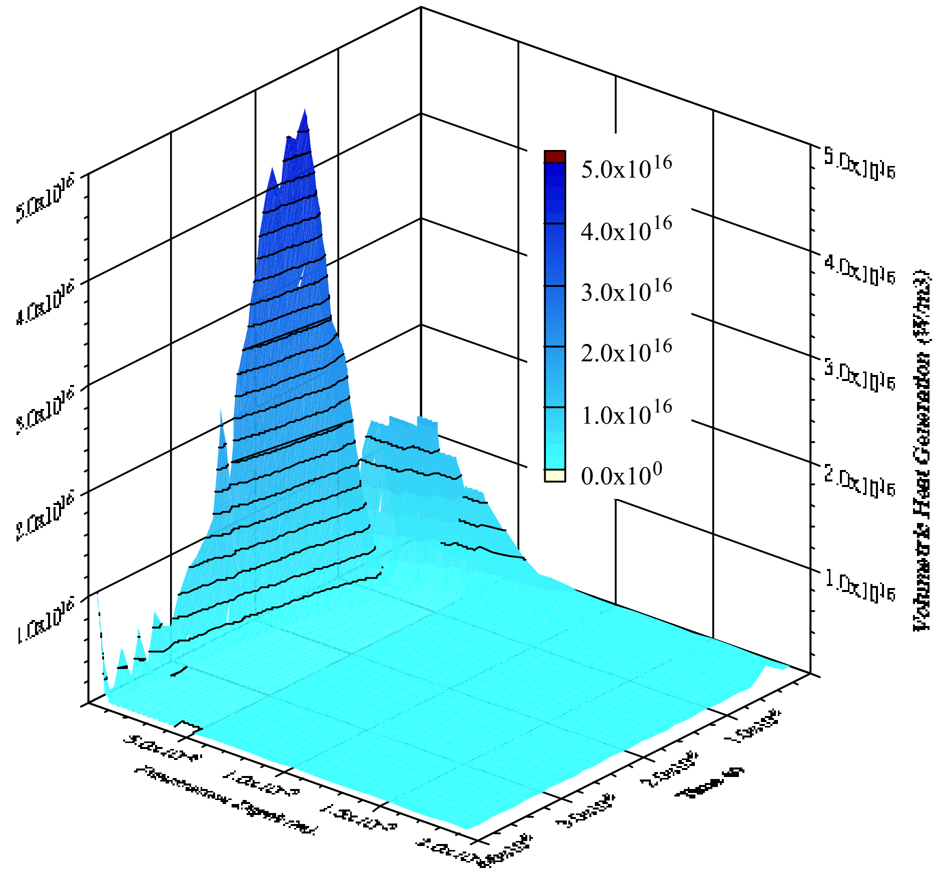


Spatial and Temporal Heat Generation Profiles in C and W for 154MJ Direct Drive Target Spectra

Temporal and Spatial Profile of Ion Power Deposition in C Armor from 154 MJ DD Target Spectrum

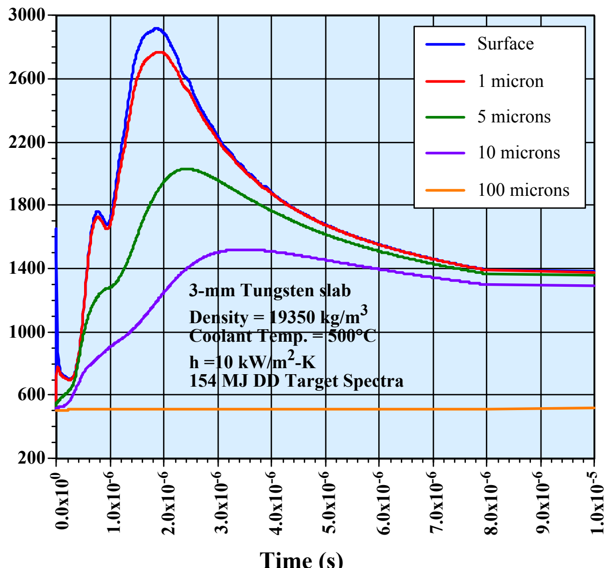


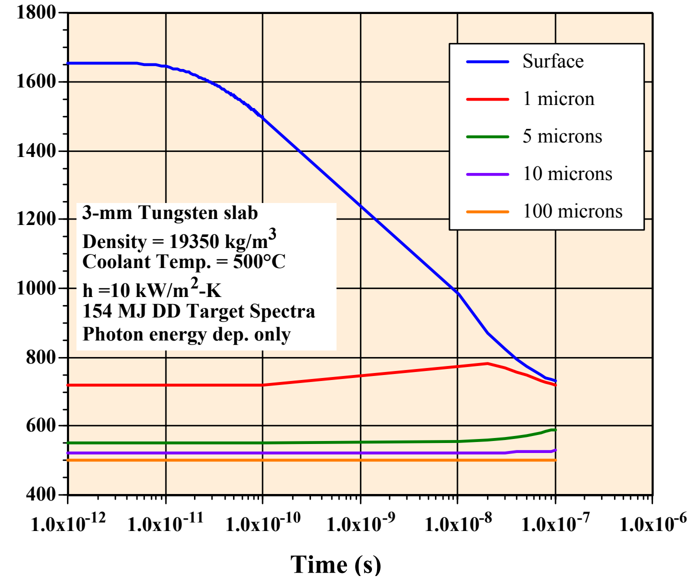
Temporal and Spatial Profile of Ion Power Deposition in W Armor from 154 MJ DD Target Spectrum

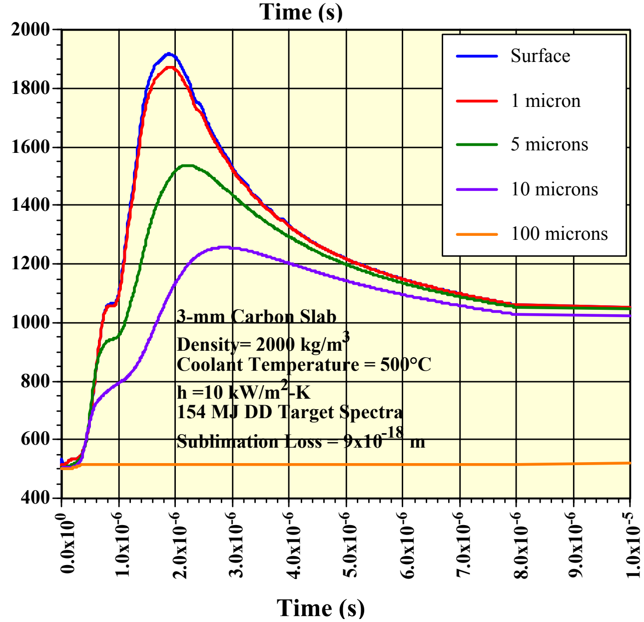


- **Assumption of estimating time from center of chamber at t = 0 is reasonable based on discussion with J. Perkins and J. Latkowski**

Temperature History of C and W Armor Subject to 154MJ Direct Drive Target Spectra with No Protective Gas







- **Initial photon temperature peak is dependent on photon spread time (sub-ns)**
- **For a case without protective gas and with a 500°C wall temperature:**
  - **C T_{max} < 2000°C**
  - **W T_{max} < 3000°C**
  - **Some margin for adjustment of parameters such as target yield, chamber size, coolant temperature and gas pressure**

Future Effort Will Focus on Model Improvement and on Exercising the Code (1)

- **Exercise code:**
  - Investigate effectiveness of convection for cooling the chamber gas
  - Assess effect of penetrations on the chamber gas behavior including interaction with mirrors
  - Investigate armor mass transfer from one part of the chamber to another including to mirror
  - Assess different buffer gas instead of Xe
  - Assess chamber clearing (exhaust) to identify range of desirable base pressures
  - Assess experimental tests that can be performed in simulation experiments

- **Improve Code**
  - Extend the capability of the code (full inclusion of multi-species capability)
  - Implement adaptive mesh routines for cases with high transient gradients and start implementation if necessary
  - Implement aerosol formation and transport models (INEEL)
  - Implement more sophisticated mass transport models in wall interaction module (ANL)

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