Chamber Physics:Target Output, Blast Propagation and First Wall Interactions

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ARIES Meeting
June 19-21, 2000
Madison, WI

In this Phase of ARIES, We will Consider Gas-Protected Dry-Wall Target Chambers

•Advantages

—Adaptable to chambers with many holes (direct-drive laser fusion for example).

—No vapors to condense on laser optics.

—Passive (no moving parts or jets).

—Allows high temperature wall (high thermal efficiency).

•Disadvantages

—High energy inventory in gas (radiative heat transfer slows when gas is still hot.)

—Target heating during injection.

•Issues

—Target Output

—Atomic physics and radiation transport in gas.

—Response of Wall to Blast

—Laser breakdown of gas.

—Impurity build-up and gas transmutation.

—Target Injection

—Gas Radioactivity

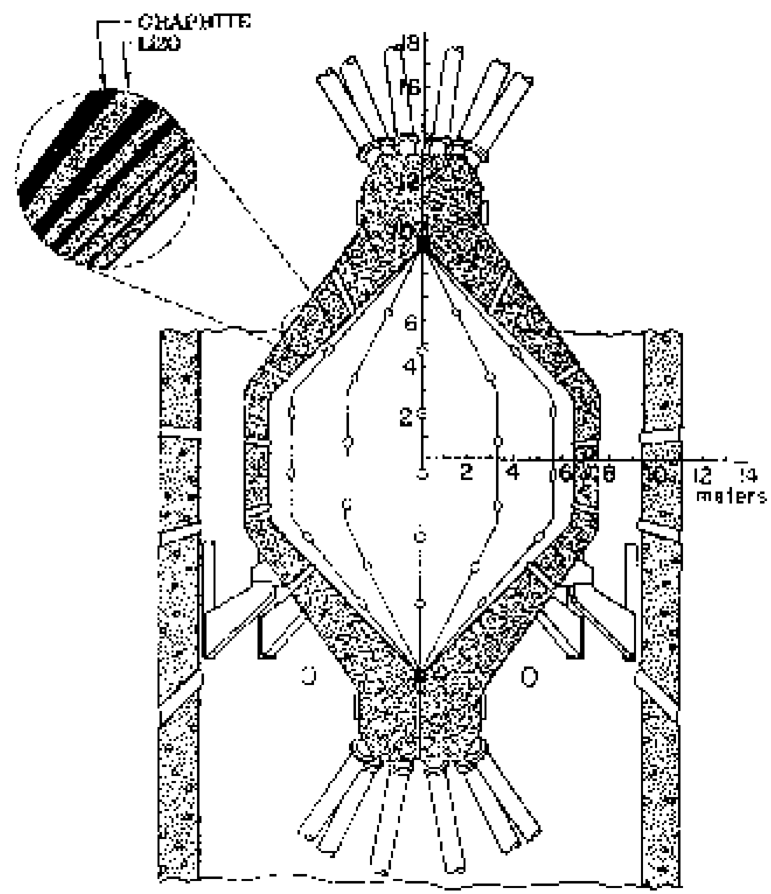
SOMBRERO is a Working Example of a Gas-Protected Dry-Wall Target Chamber

•In SOMBRERO, 0.5 Torr of Xe stops 1.6 MeV carbon ions (most of the non-neutronic target output) before they reach the chamber wall.

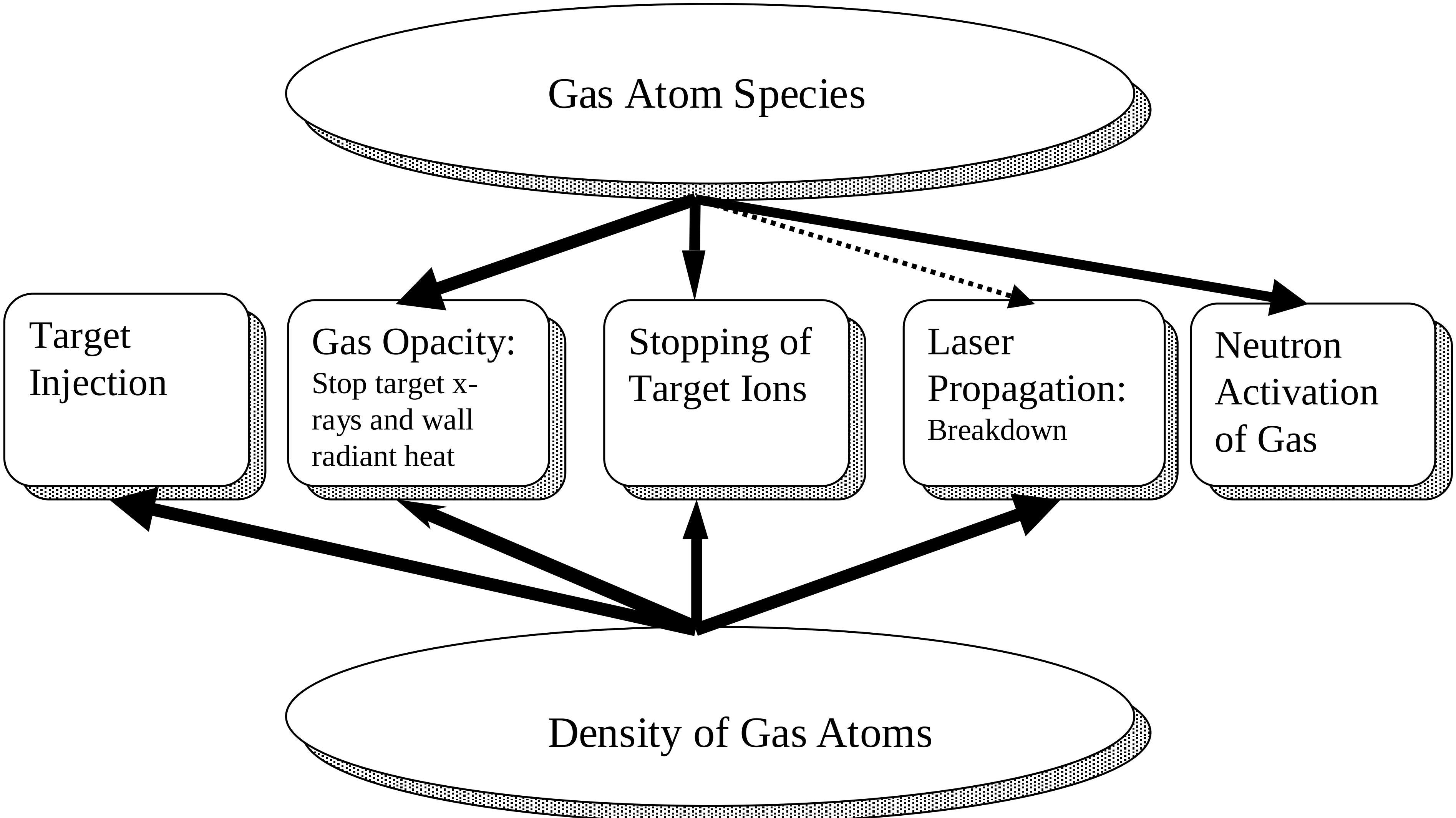
•The fireball radiation emission is slow enough that the graphite first wall stays below the sublimation limit. BUCKY predicts a peak surface temperature 2,155 C.

•The shock applied to the wall applies and impulse of 2.21 Pa-s and a peak pressure of 0.013 MPa.

•BUCKY simulations show that wall survival is sensitive to Xe opacity.



Variables Considered For Choosing the Cavity Gas Environment in SOMBRERO



Laser Propagation in Target Chamber Gases Limits Fill Gas Density

•Laser beams need to avoid laser breakdown of the fill gas and plasma instabilities that can lead to unsmooth beams or poor laser-target coupling.

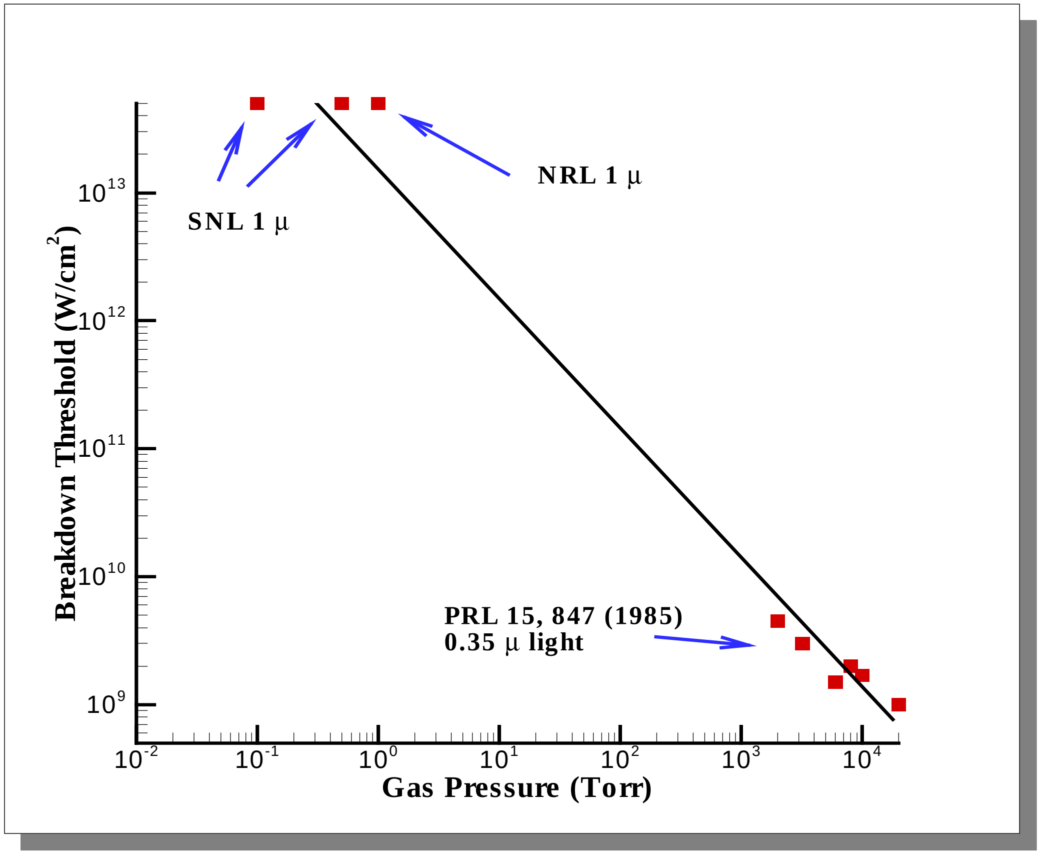
•SOMBRERO calls for 33 TW/cm^2 0.25 μ laser light on the surface of the target.

•The breakdown threshold is one way of measuring how well the laser traverses the gas.

•The breakdown threshold depends on laser wavelength, pulse shape, coherence, uniformity, focal length and gas conditions.

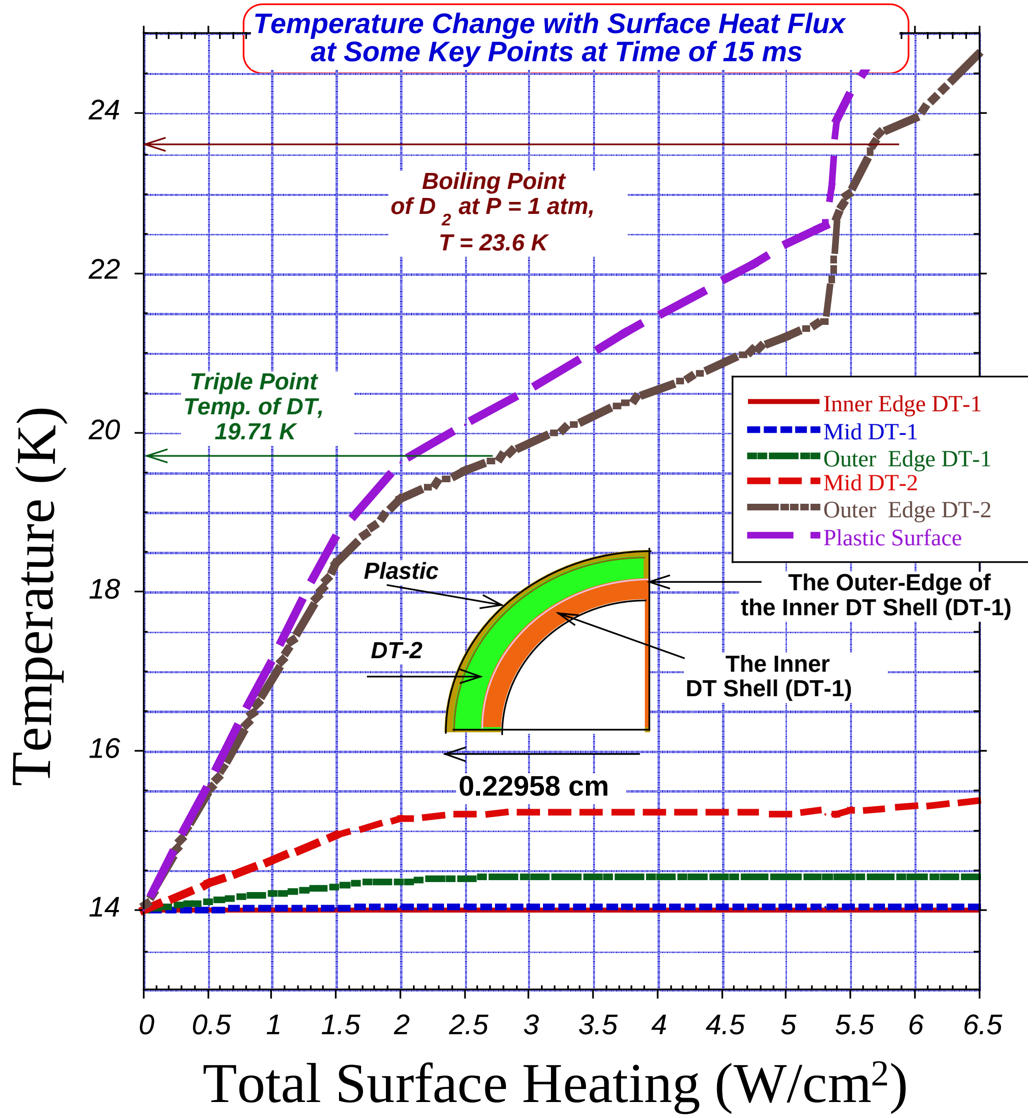
•Old data show that it is possible that KrF diver beams may traverse 1 Torr of Xenon; more experiments must confirm this.

Data compiled from work in the 1980's



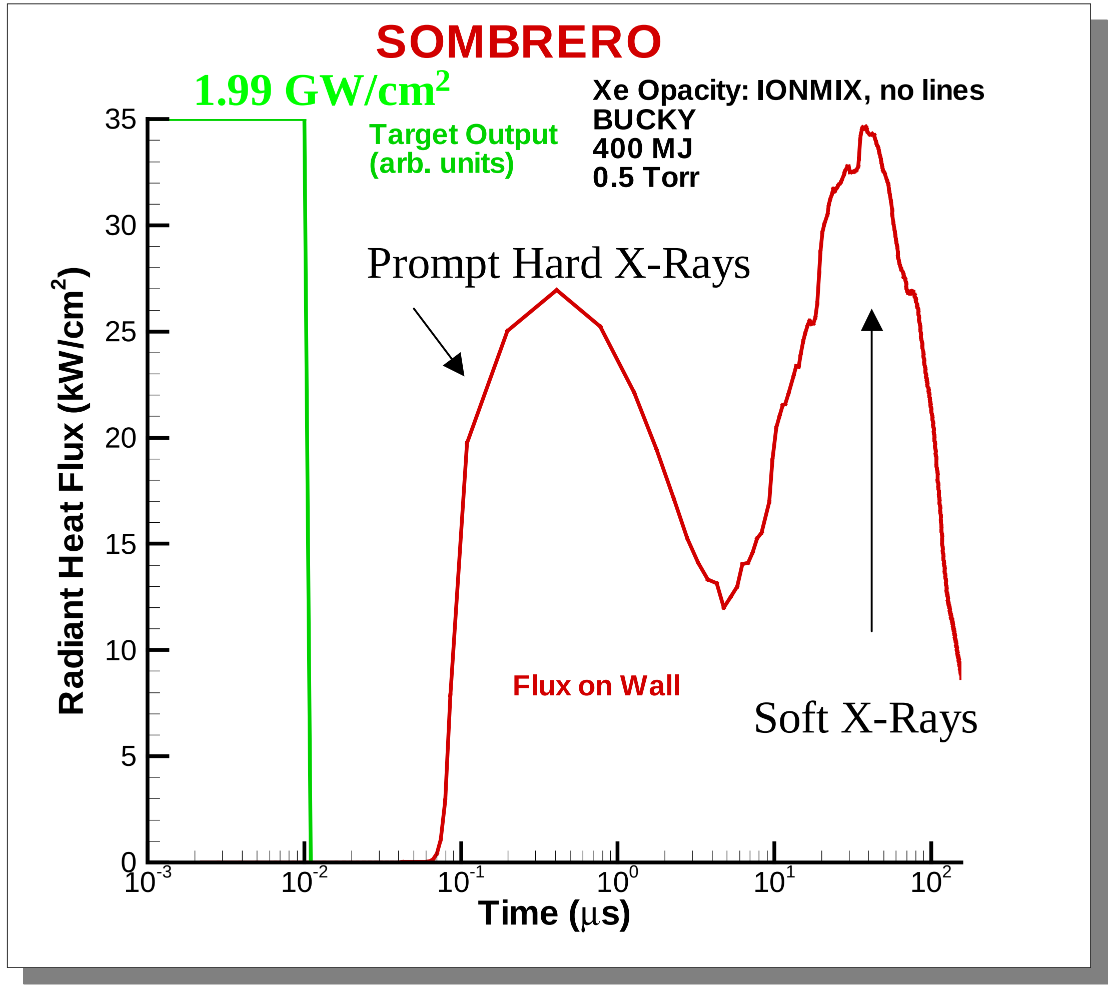
Target Chamber Gas Heats Target Through Friction and Radiation: Threat to Direct-Drive Cryogenic Fuel

- ANSYS calculations out to 15 ms.
- Perfect contact is assumed.
- Even at 1.0 W/cm^2, outer DT increases by 3 K to 17 K.
- Inner DT heats by less than 0.5 K, even at much higher heating.
- Protection strategies: Xe snowball, re-entry vehicle, target delivery tube, …



Xenon Gas in SOMBRERO Spreads Out the heat Transfer to the Wall of the Target Chamber

- 100 MJ of X-rays and Debris Ions are Released by the target over about 10 ns.
- Xenon Gas absorbs target x-rays and ions.
- Gas radiates energy to the wall over about 100 µs.
- Very sensitive to Xe opacities.



Chamber Physics Critical Issues Involve Target Output, Gas Behavior and First Wall Response

Target Output

Design,
Fabrication,
Output Simulations,
(Output Experiments)

X-rays,
Ion Debris,
Neutrons

Gas Behavior

Gas Opacities,
Radiation Transport,
Rad-Hydro Simulations

Thermal
Radiation,
Shock

Wall Response

Wall Properties,
Neutron Damage,
Near-Vapor Behavior,
Thermal Stresses

UW uses the BUCKY 1-D Radiation-Hydrodynamics Code to Simulate Target, Gas Behavior and Wall Response.

BUCKY is a Flexible 1-D Lagrangian Radiation-Hydrodynamics Code

- 1-D Lagrangian MHD (spherical, cylindrical or slab).
- Thermal conduction with diffusion.
- Applied electrical current with magnetic field and pressure calculation.
- Radiation transport with multi-group flux-limited diffusion, method of short characteristics, and variable Eddington.
- Non-LTE CRE line transport.
- Opacities and equations of state from EOSOPA or SESAME.
- Equilibrium electrical conductivities
- Thermonuclear burn (DT,DD,DHe^3) with in-flight reactions.
- Fusion product transport; time-dependent charged particle tracking, neutron energy deposition.
- Applied energy sources: time and energy dependent ions, electrons, and x-rays.
- Moderate energy density physics: melting, vaporization, and thermal conduction in solids and liquids.
- Benchmarking: x-ray burn-through and shock experiments on Nova and Omega, x-ray vaporization, RHEPP melting and vaporization, PBFA-II K_α emission, …
- Platforms: UNIX, PC, MAC

Inertial Fusion Target Output

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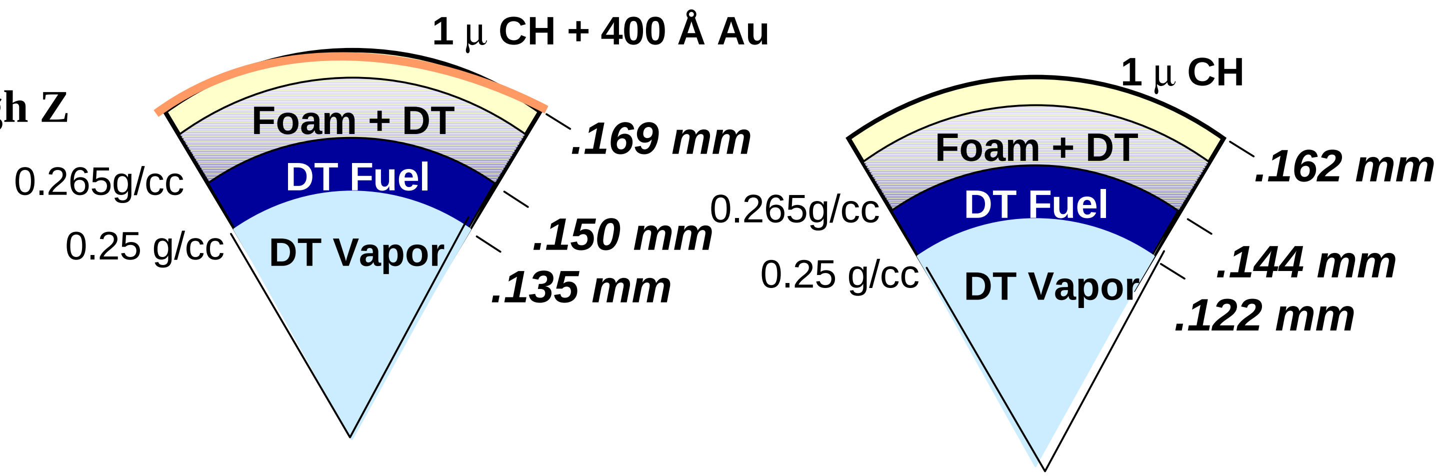
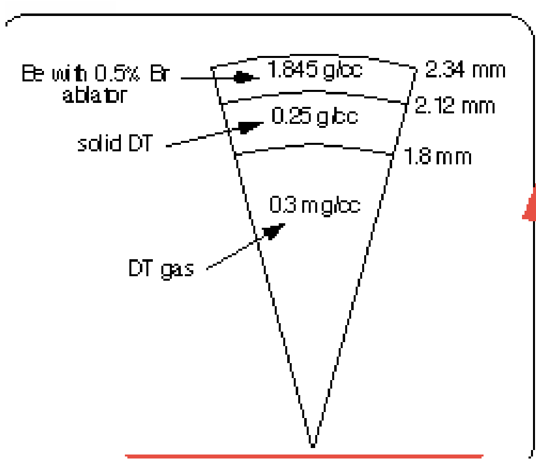
Direct and In-Direct Drive Targets Under Consideration Have Different Output

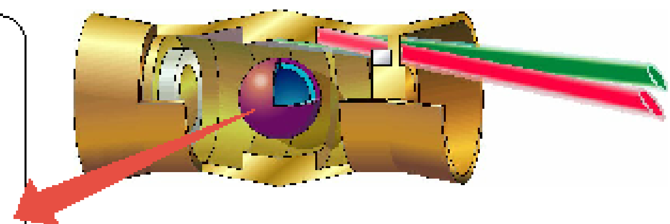
NRL Direct-drive Laser Targets May Contain High Z



Indirect-drive HIF and Z-pinch Targets Have High-Z Hohlraums

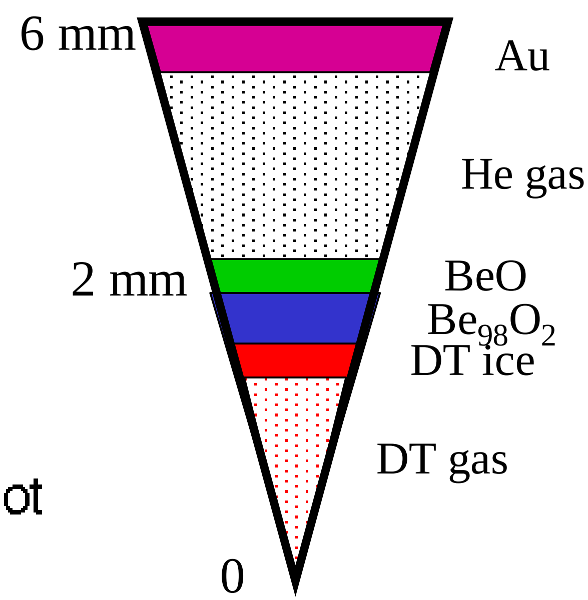
LLNL/LBNL HIF Target





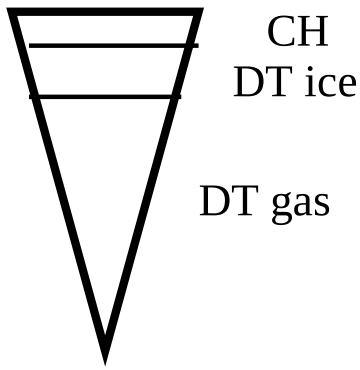
Ion beam characteristics:
- 3.5 GeV Pb+ ions
- 3.3 MJ input energy
- 1.7 mm effective radius spot

X-1 Target



Direct-Drive Target Output is Dominated by Neutrons and Energetic Ablator Ions

SOMBRERO Target



Debris Ions

94 keV D -	5.81 MJ
141 keV T -	8.72 MJ
138 keV H -	9.24 MJ
188 keV He -	4.49 MJ
1600 keV C -	55.24 MJ
Total -	83.24 MJ per shot

=15.68 J/cm^2 on SOMBRERO Wall

Neutrons

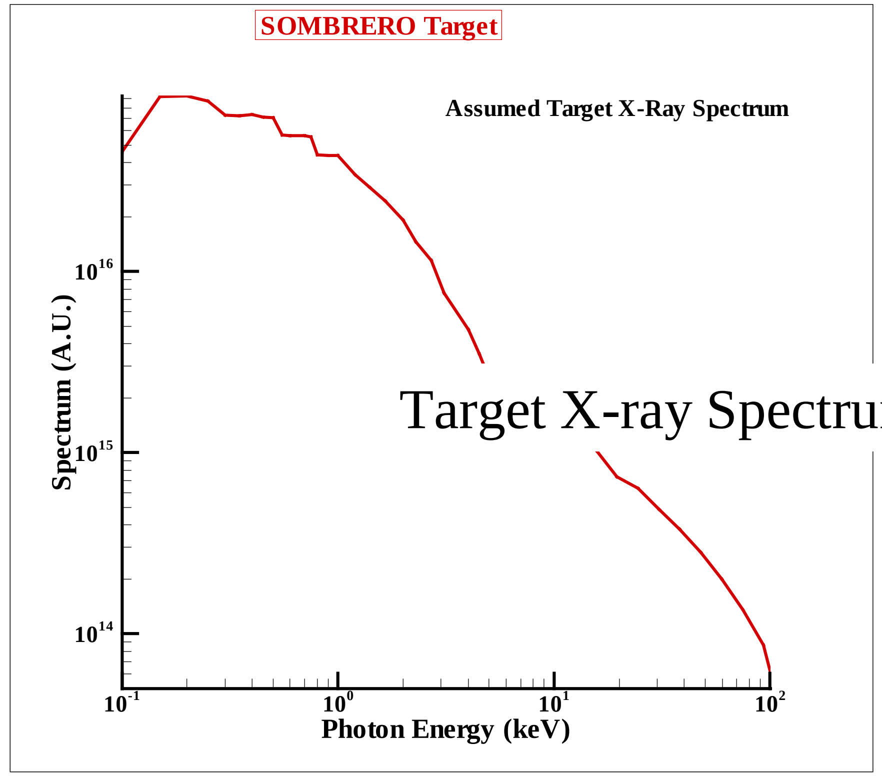
317 MJ per shot

=59.7 J/cm^2 on SOMBRERO Wall

X-Rays

22.41 MJ per shot

=4.22 J/cm^2 on SOMBRERO Wall

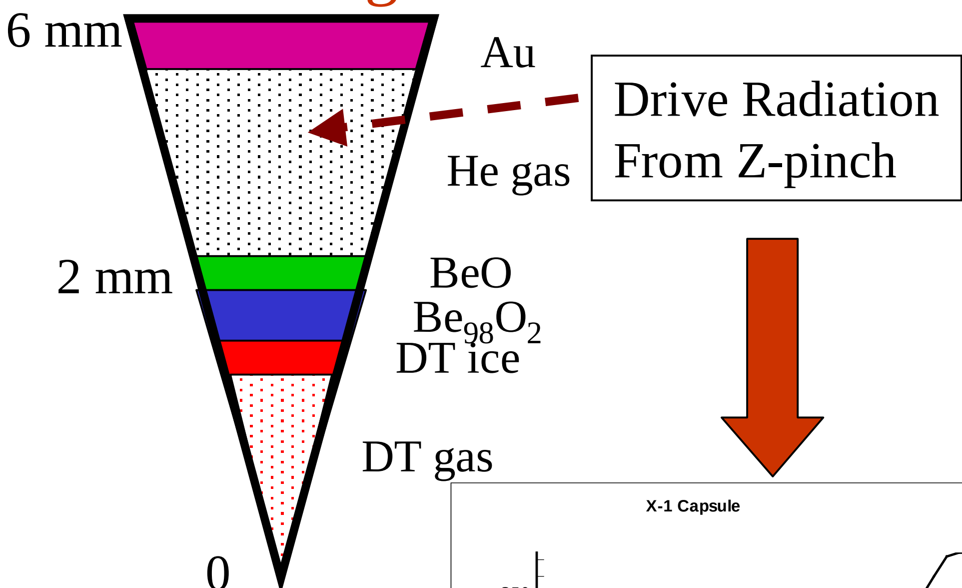


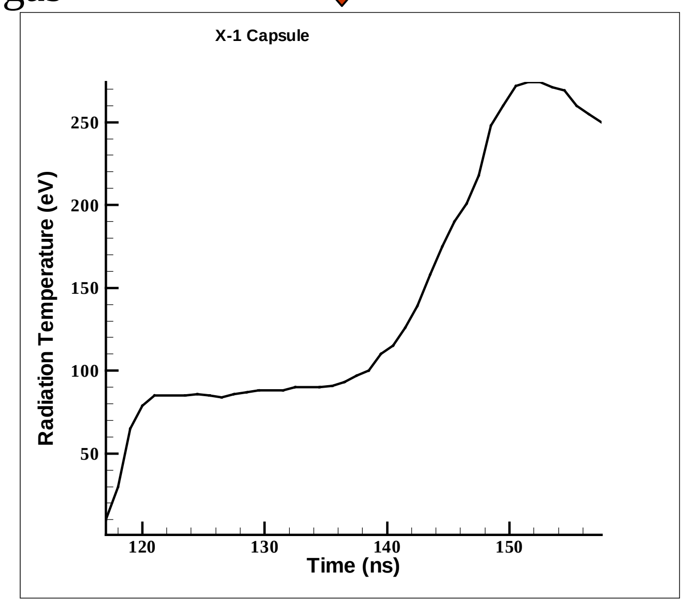
Target X-ray Spectrum

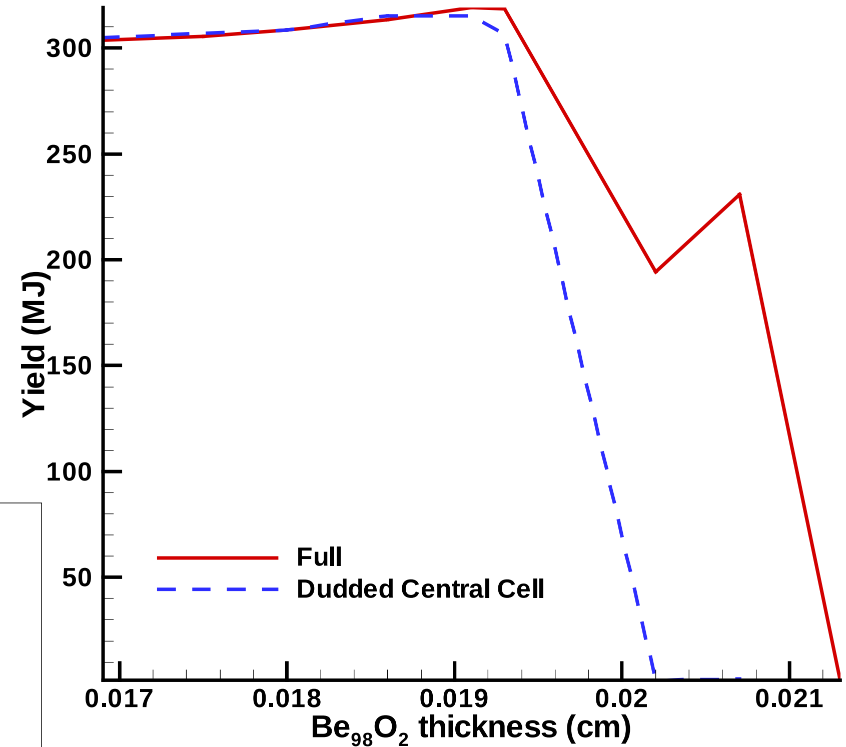
Z Experiments in Progress (6/15-6/21)

UW has been Studying Indirect-Drive Target Sensitivity to Fabrication Uncertainties for X-1

X-1 Target



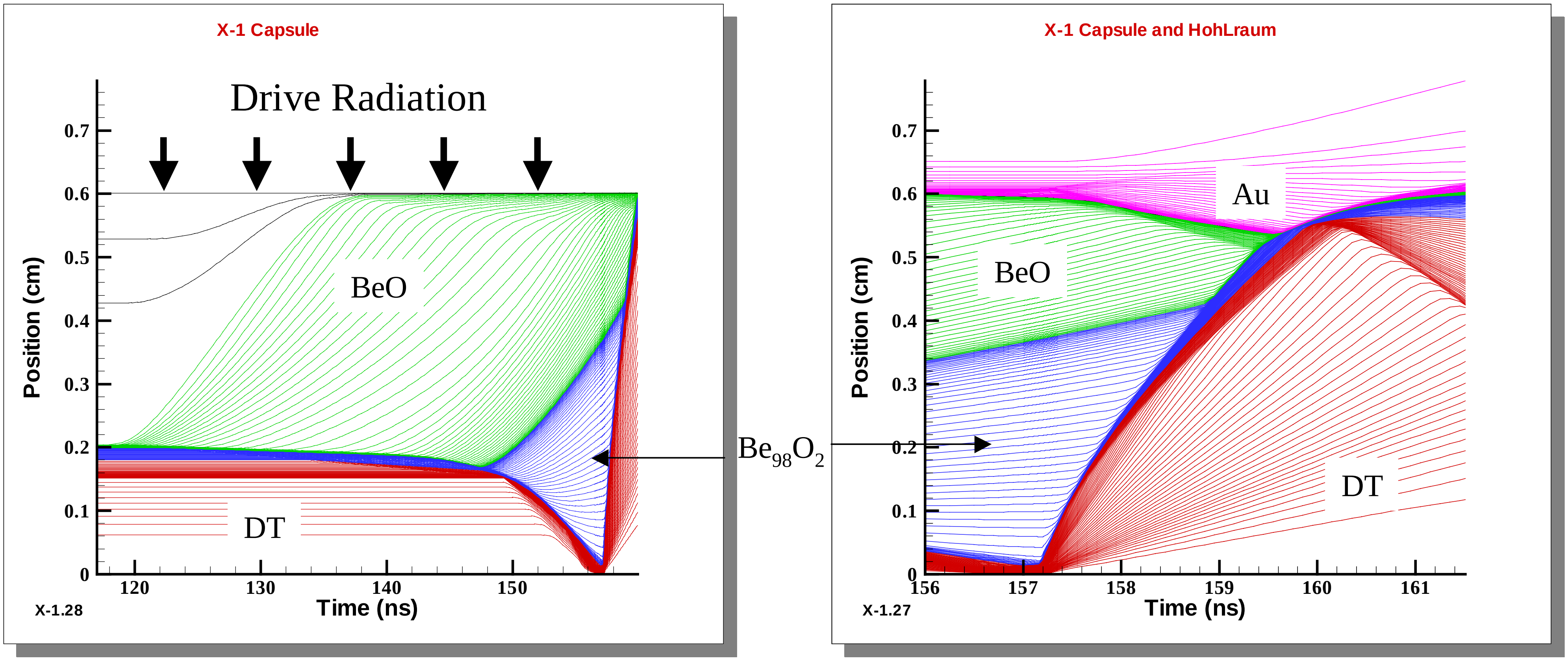




Indirect-Drive Target Output is Dominated by Neutrons and X-rays

<u>Implosion without hohlraum; radiation drive</u>
Used to design capsule and study sensitivity to variations in fabrication.
Run time, a few hours (HP C-180).

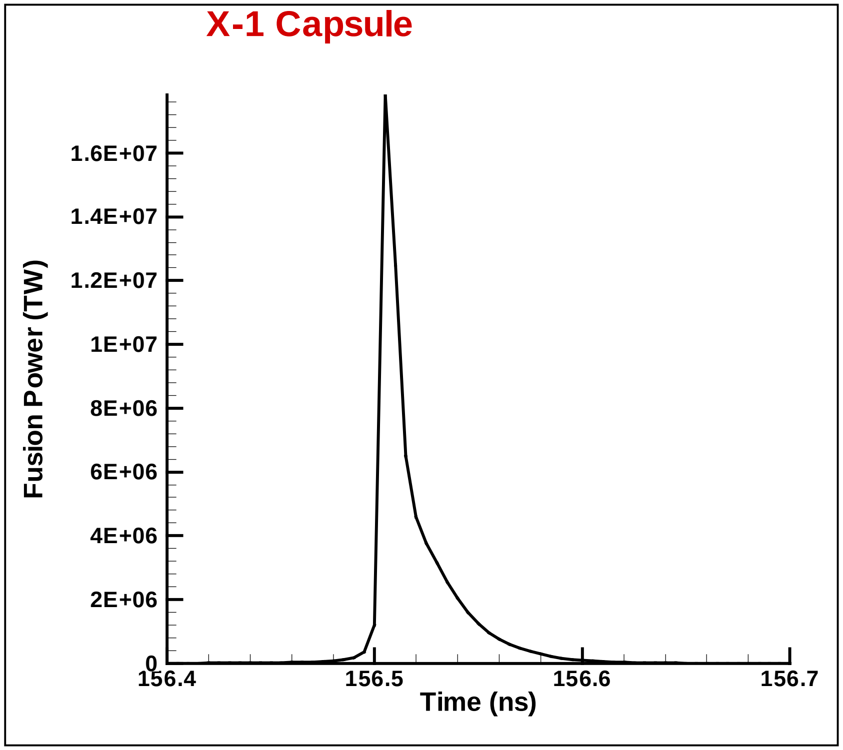
<u>Final implosion and burn with hohlraum; no drive</u>
Used to simulate x-ray and ion debris output
Run time, a few days (HP C-180).

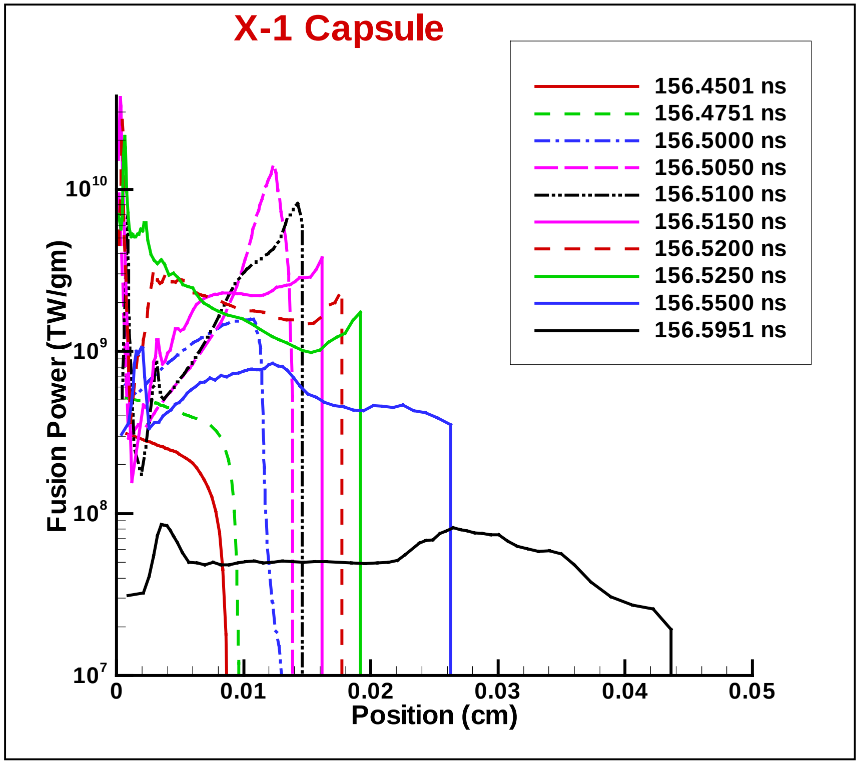


IFE Capsule Thermonuclear Burn Drives Target Radiative Disassembly and Neutronics

Fuel burns in a few 10's of ps, Power density is truly astronomical (10^{22} W/gm)

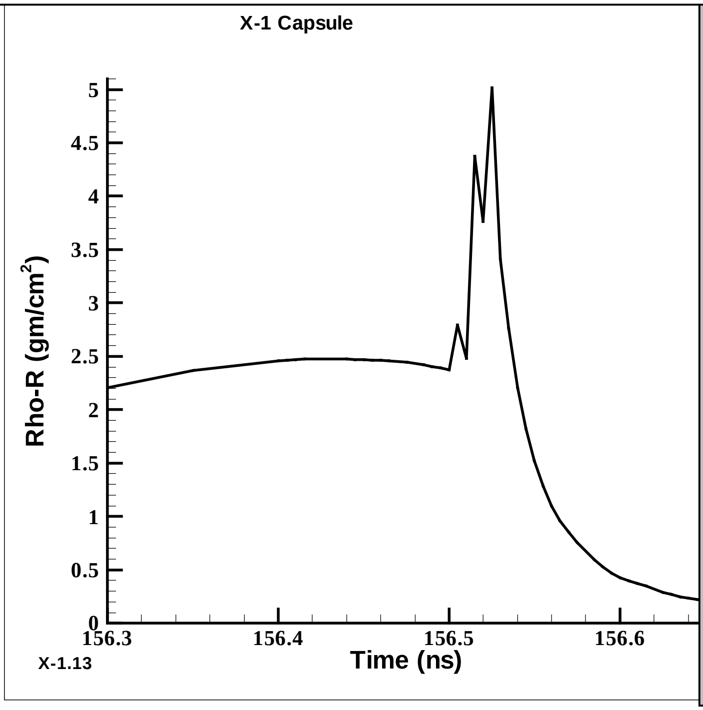
Burns propagates from central hot spot to rest of compressed fuel.

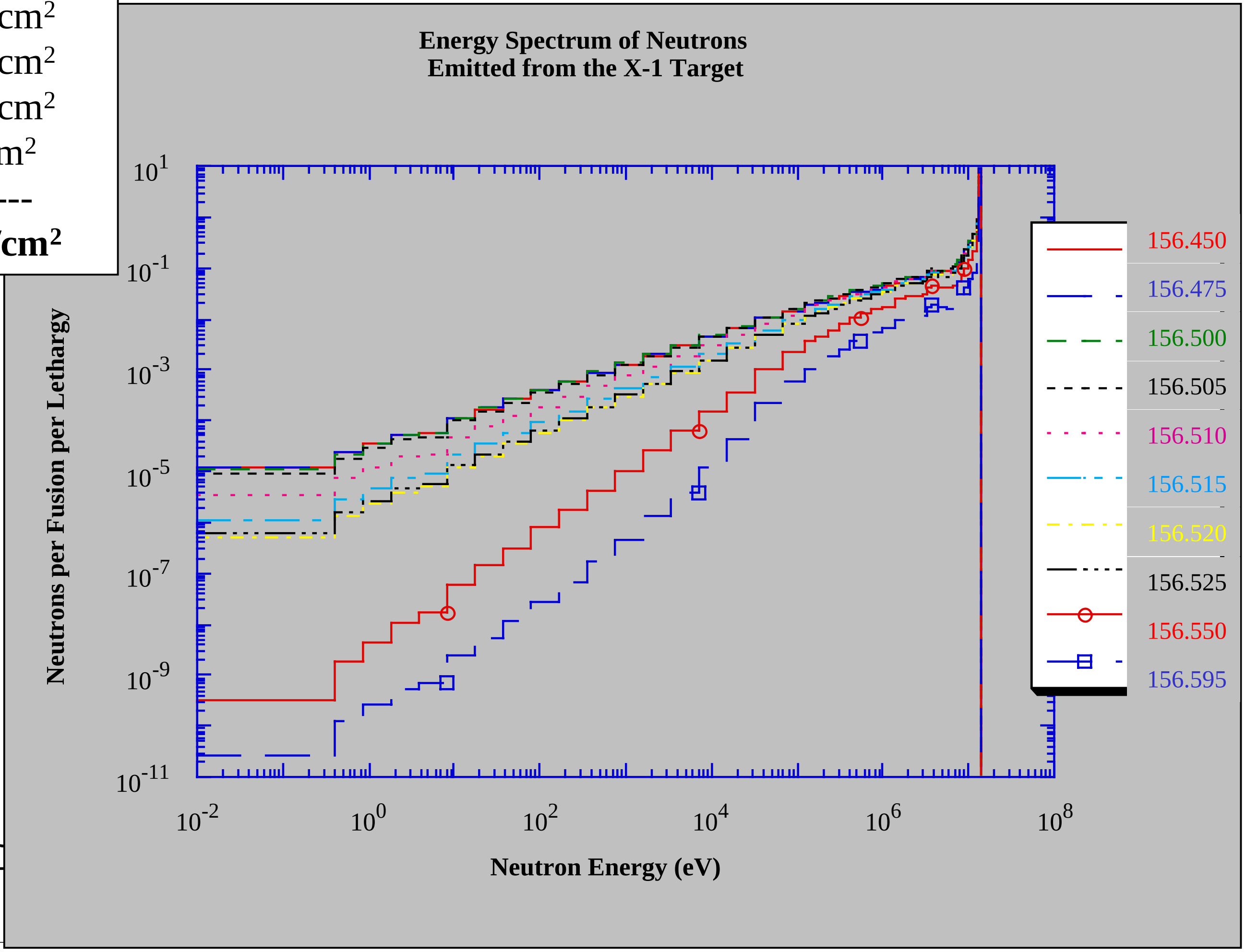




Fuel Density-Radius Product (ρR) is High Enough to Absorb Some Neutrons and Soften Spectrum

X-1 Energy Partition		Fluence on 650 cm Wall
Neutrons:	220 MJ (69.22%)	41.4 J/cm^2
Gammas:	0.95 MJ (.03%)	0.18 J/cm^2
X-rays:	61.3 MJ (19.3%)	11.5 J/cm^2
Ions:	28.6 MJ (9.0%)	5.4 J/cm^2
Endoergic:	7.8 MJ (2.45%)	-----------
Total:	**318 MJ**	**58.5 J/cm^2**



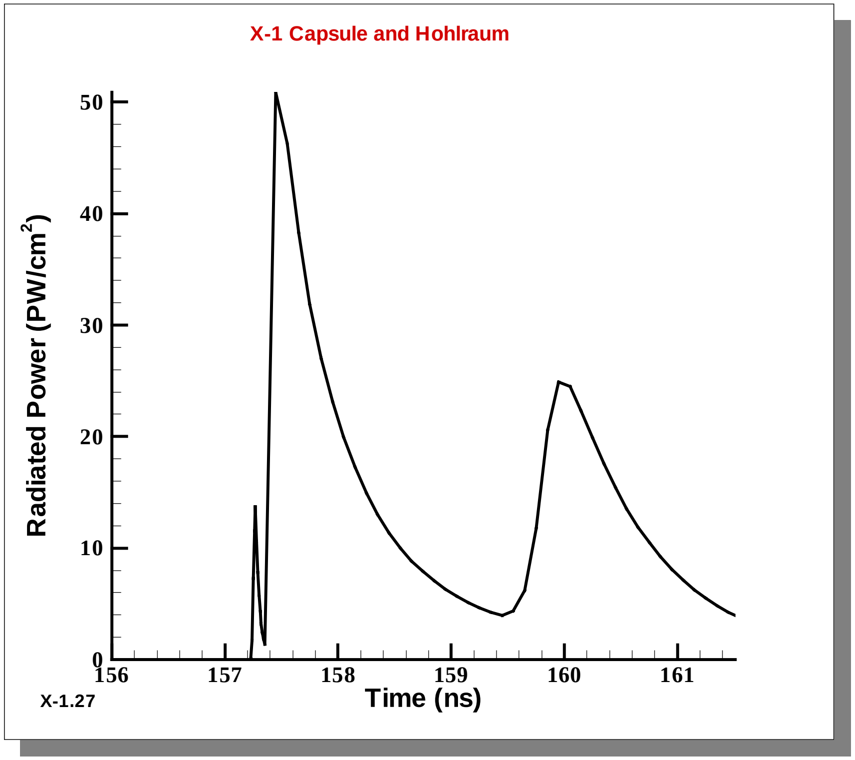


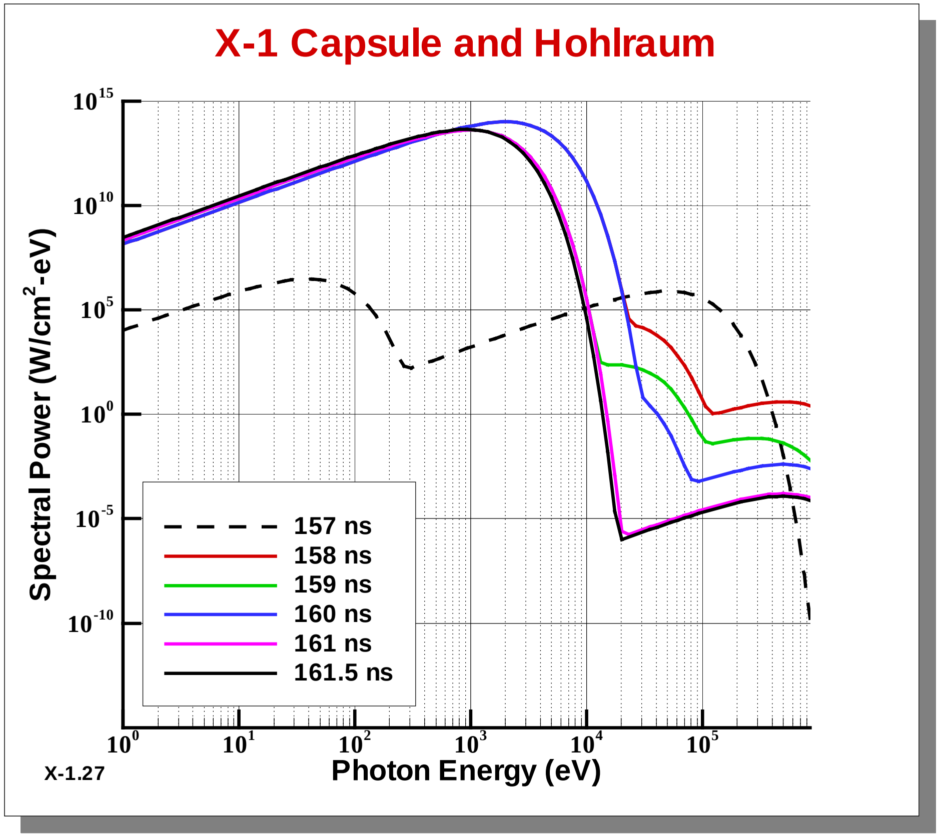
X-ray Emission from Indirect Drive (X-1) Targets is Largely Due to Collisions Between Expanding Shells

Output X-rays are released in two pulses over about 5 ns.

Output X-ray Spectrum: Sum of 3 Blackbody spectra

157 ns: 14 eV, 177 keV	160 ns: 709 eV, 4 keV, 177 keV
158 ns: 709 eV, 6 keV, 177 keV	161 ns: 354 eV, 6 keV, 177 keV
159 ns: 354 eV, 6 keV, 100 keV	161.5 ns 325 eV 6 keV, 177 keV





Blast Propagation

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The opacity of the chamber gas is an important input into reactor designs such as SOMBRERO

- In SOMBRERO, 0.5 Torr of Xe stops 1.6 MeV carbon ions (most of the non-neutronic target output) before they reach the chamber wall.
- The fireball radiation emission is slow enough that the graphite first wall stays below the sublimation limit. BUCKY predicts a peak surface temperature 2,155 C.
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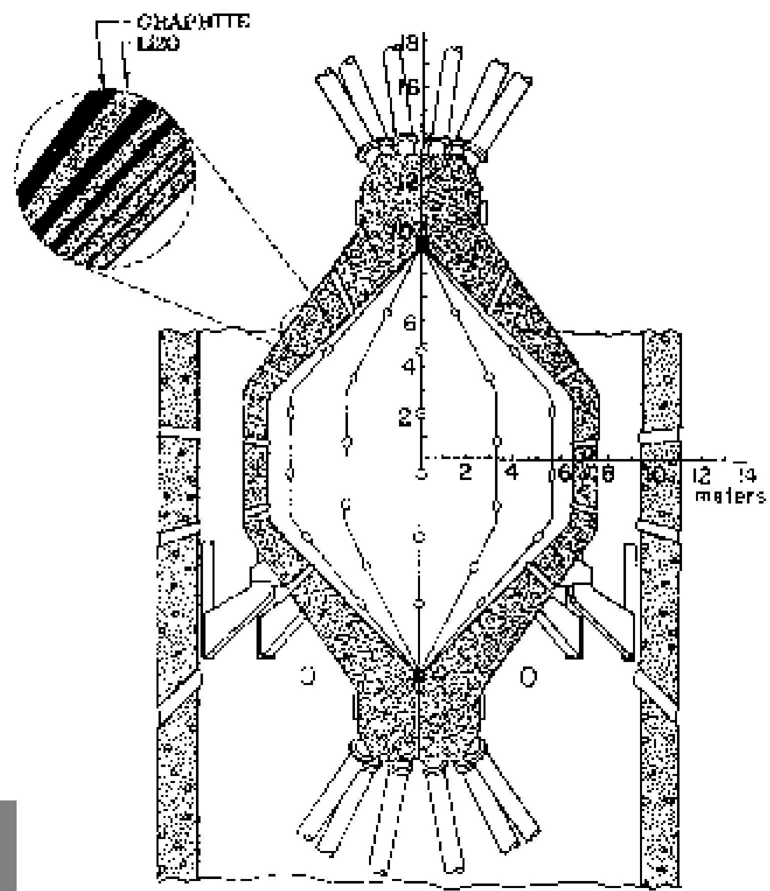
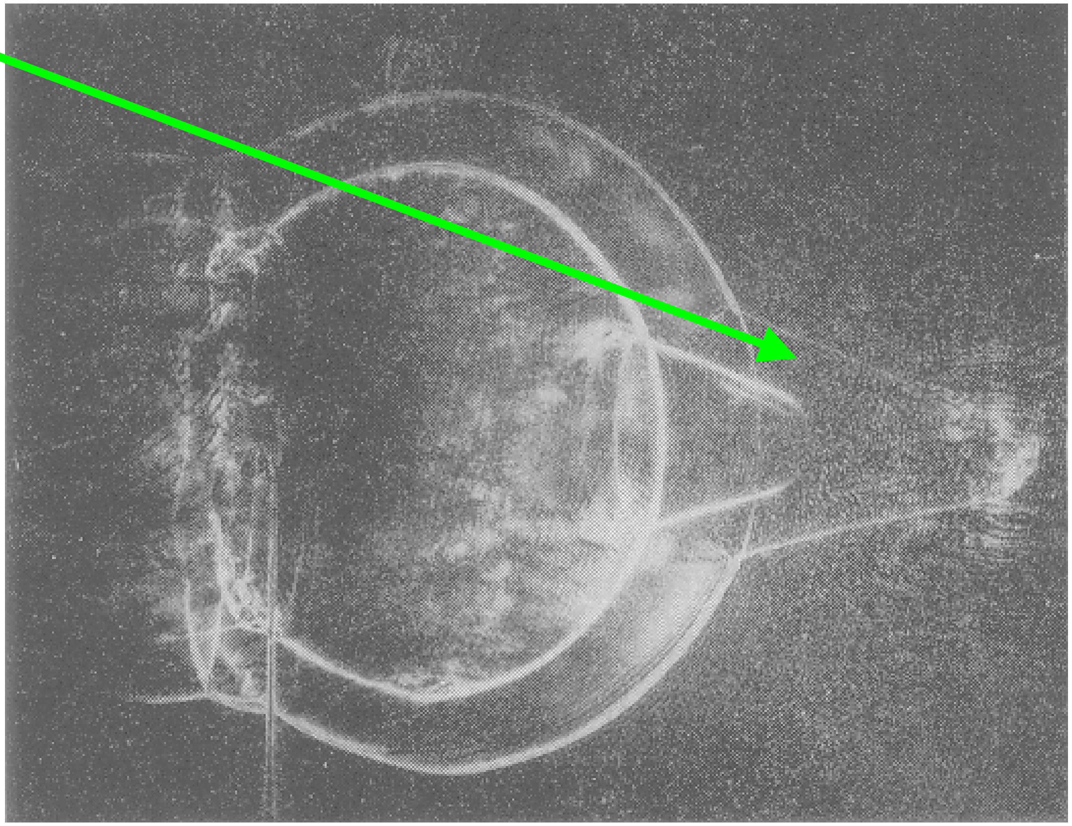


- BUCKY simulations show that wall survival is sensitive to Xe opacity.

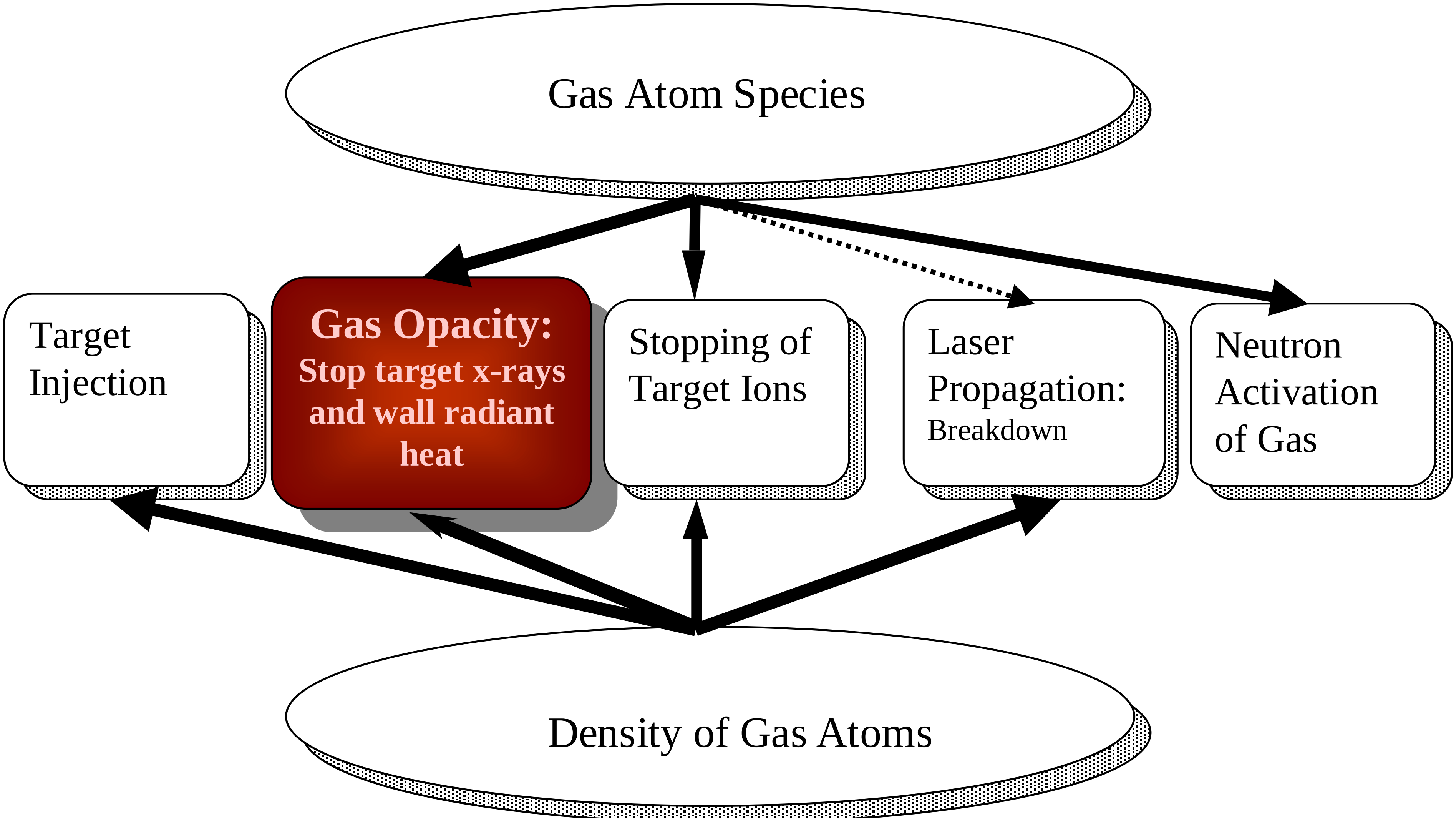
In experiments at NRL, the propagation of blast waves was shown to depend on the opacity.

- 1988 NRL Laser Generated Fireball Experiments Show Propagation in Laser Path Ahead of Main Fireball.
- Dark-field Shadowgrams at 71 and 146 ns.
- Reduced Opacity in Laser Path due to Laser Heating.



J.A. Stamper, et al., *Phys. Fluids* **31,** 3353 (1988).

Variables Considered For Choosing the Cavity Gas Environment in SOMBRERO



Though Direct-Drive Target Output is Dominated by Neutrons and Energetic Ablator Ions, the Target x-ray Emission must be Buffered.

Debris Ions

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138 keV H -	9.24 MJ
188 keV He -	4.49 MJ
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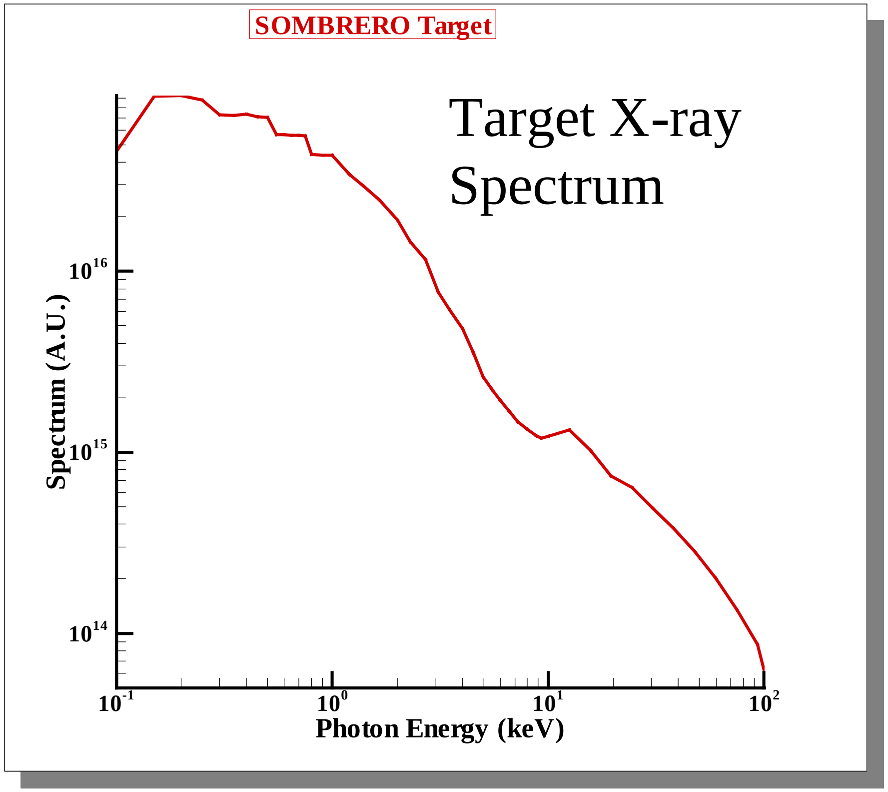
X-Rays

22.41 MJ deposited in 1ns



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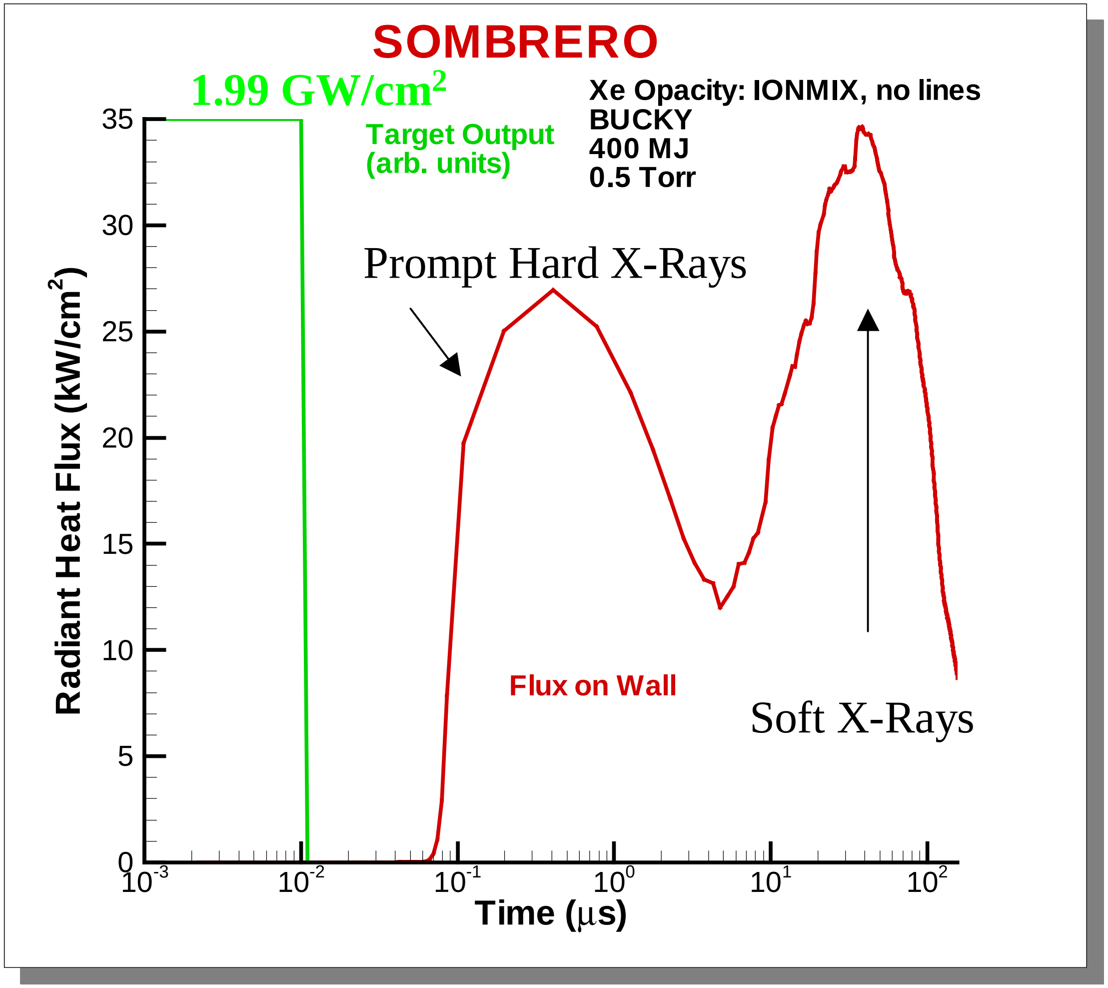
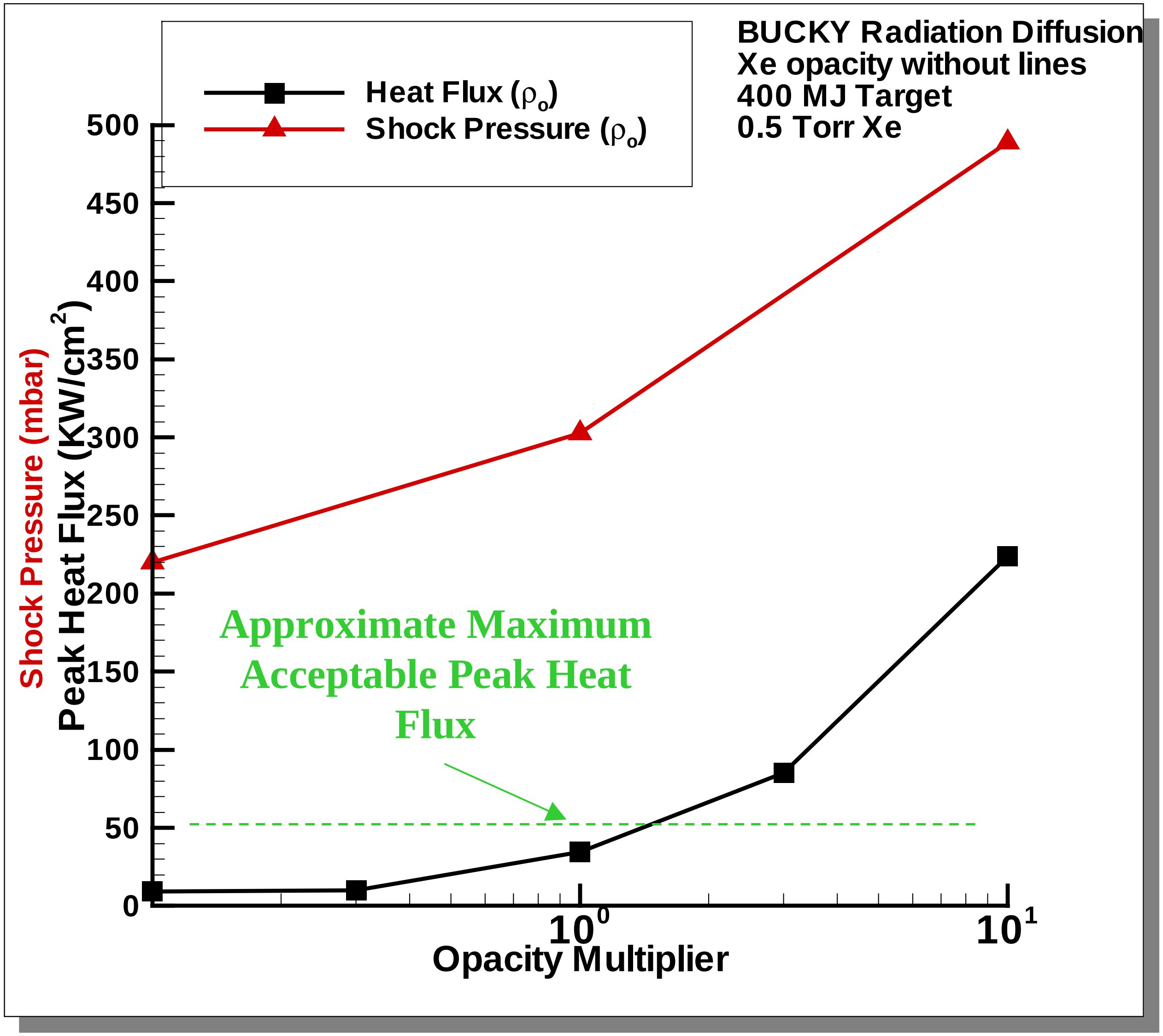


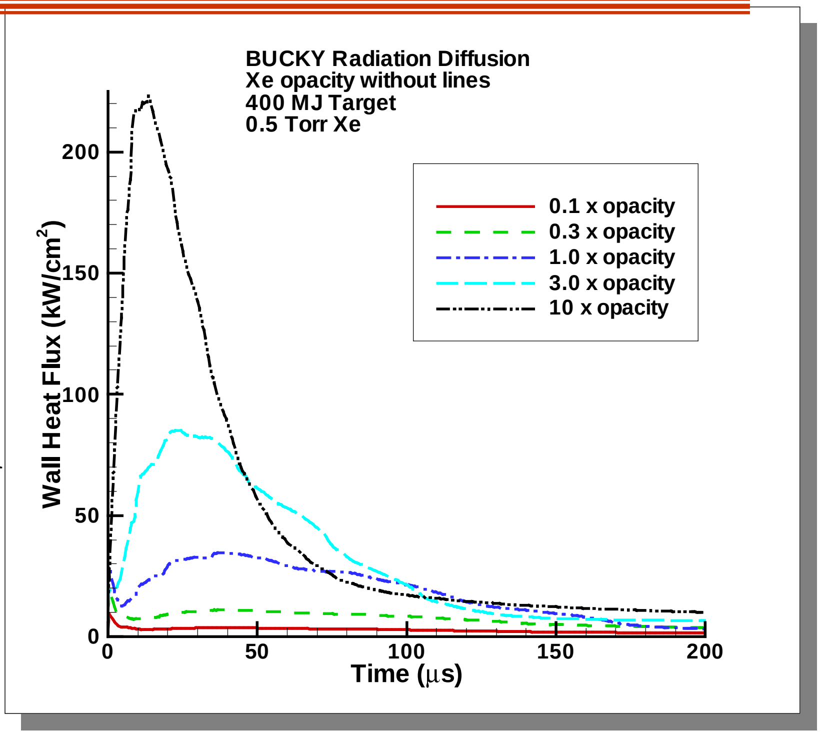
Wall Thermal and Mechanical Loading is Sensitive to Gas Opacity



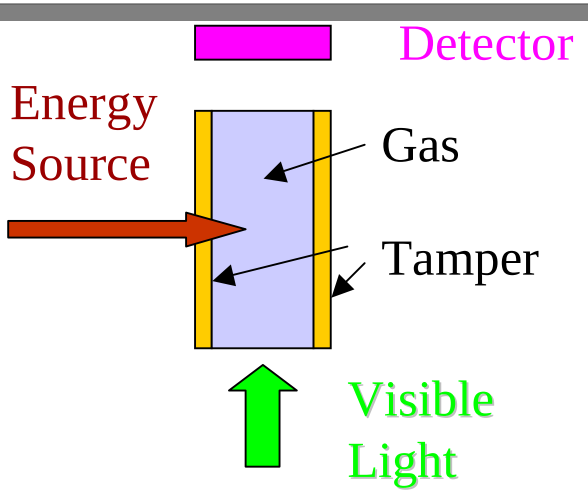
Atomic Physics and Opacity Effects Dictate Fireball Behavior: Experiment and/or Benchmarking are Needed

ISSUE: Gas opacity dominates fireball dynamics. Fireball dynamics determines survival of first wall.

PROBLEM: For SOMBRERO Xenon (Z=54) has a very complicated atomic structure, leading to a great many lines that cannot be modeled with any reasonable group structure in a radiation hydrodynamics calculation.

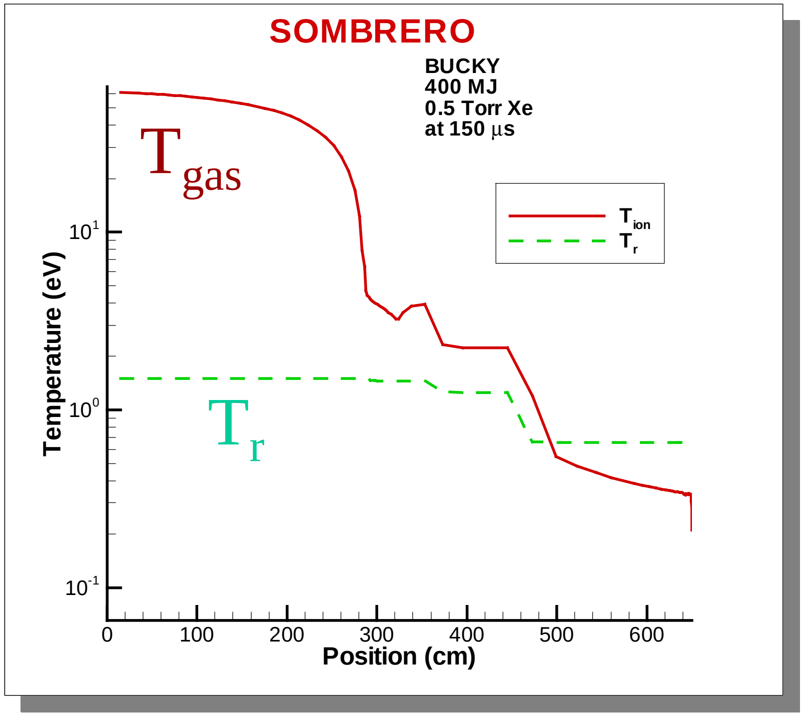


Experimental Validation: The opacity needs to be measured at about 1 Torr and 100 eV.



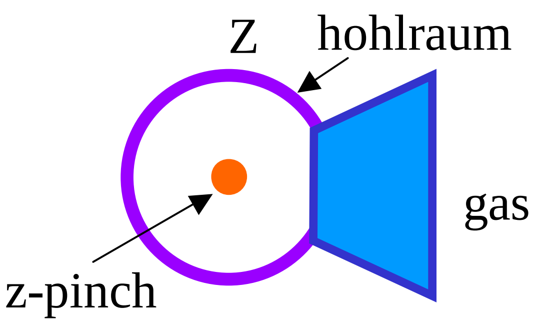
Radiation Transport in Gas Protected Target Chambers

Issue: Radiation Transport in SOMBRERO fireballs is far out of equilibrium and flux-limited radiation diffusion must be validated. $T_r \neq T_e$ table lookup methods exist, or an Average Atom model could be implemented.



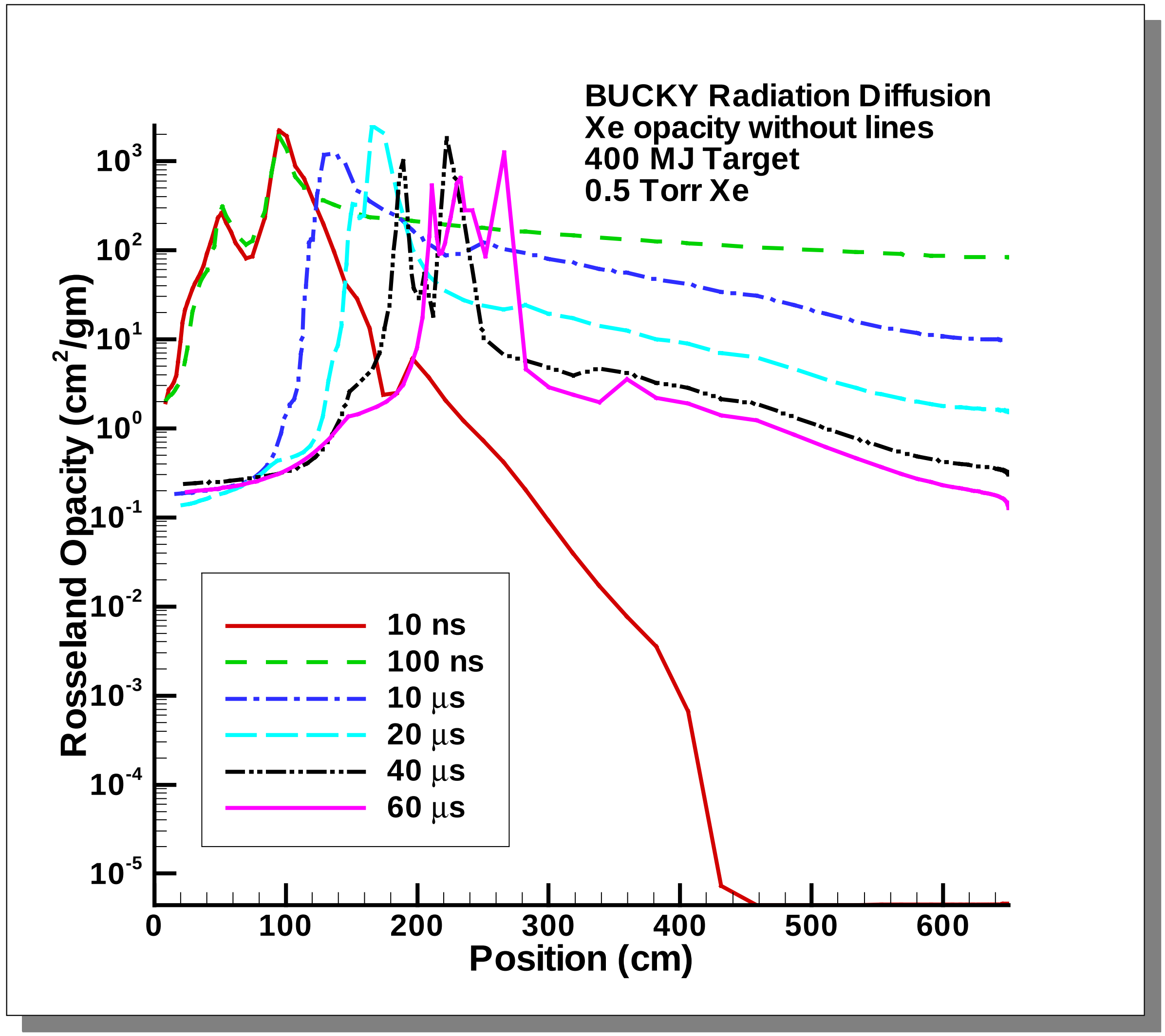
Status: Radiation-hydro codes (BUCKY, RAGE, Lasnex) can model radiation-dominated-blasts.

Needs: High energy density (enough to heat Xe to ~ 100 eV) experiments on Z are being designed which would simulate radiation dominated blasts. Need a sample large enough to be optically thick.



In SOMBRERO Radiation Flow is Governed by Emission, NOT Transport

- Highest opacity at the edge of the fireball is the barrier to radiation transport.
- In this barrier, $\sigma_{Ross}\rho \approx 10^{-3}$ 1/cm, or the radiation mean-free-path is 1000 cm.
- Therefore, radiation flow to the wall is limited by emission.

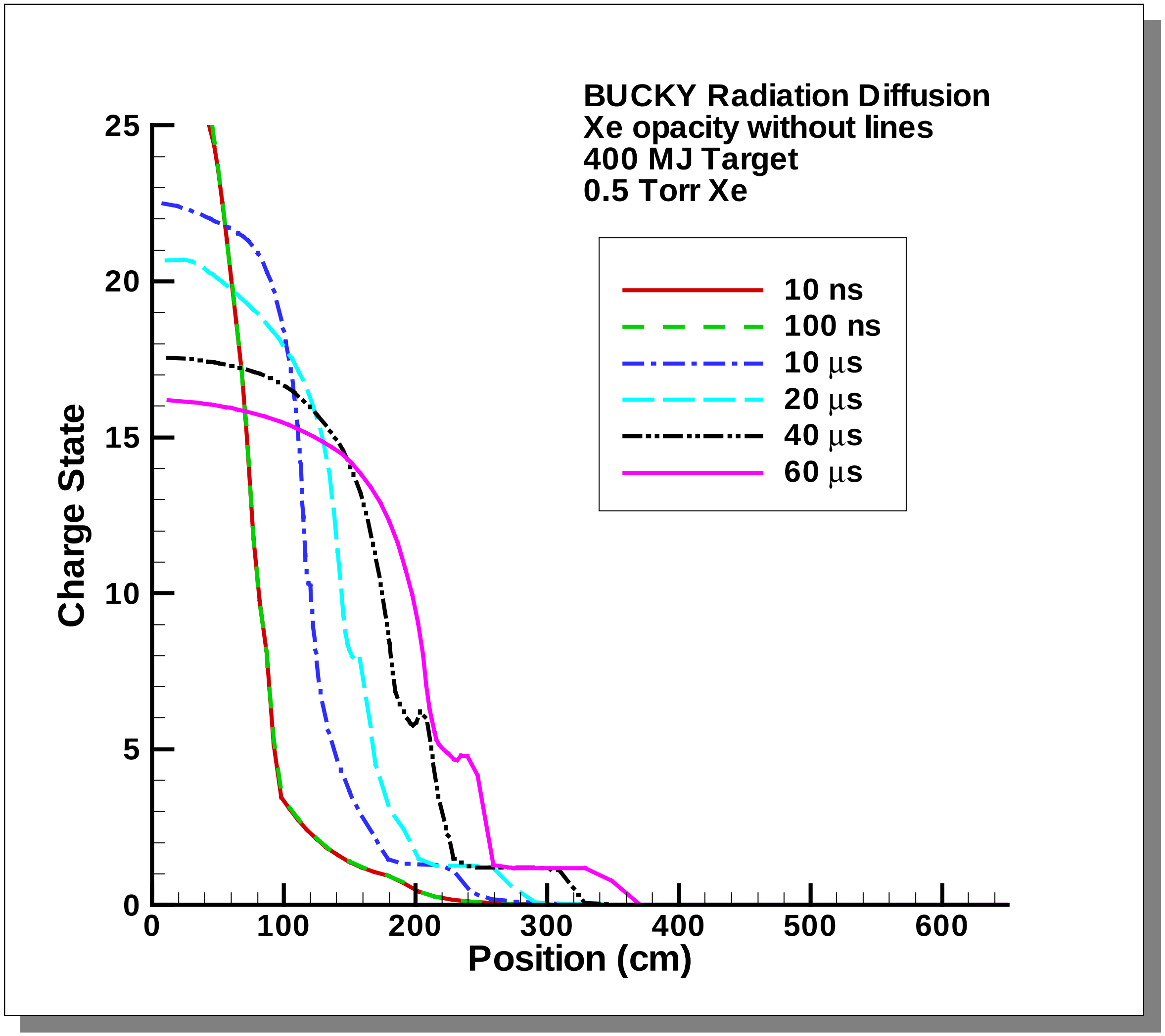


Details of Gas Atomic Physics Is Important to Opacity

•Opacity is strongly affected by charge state of gas.

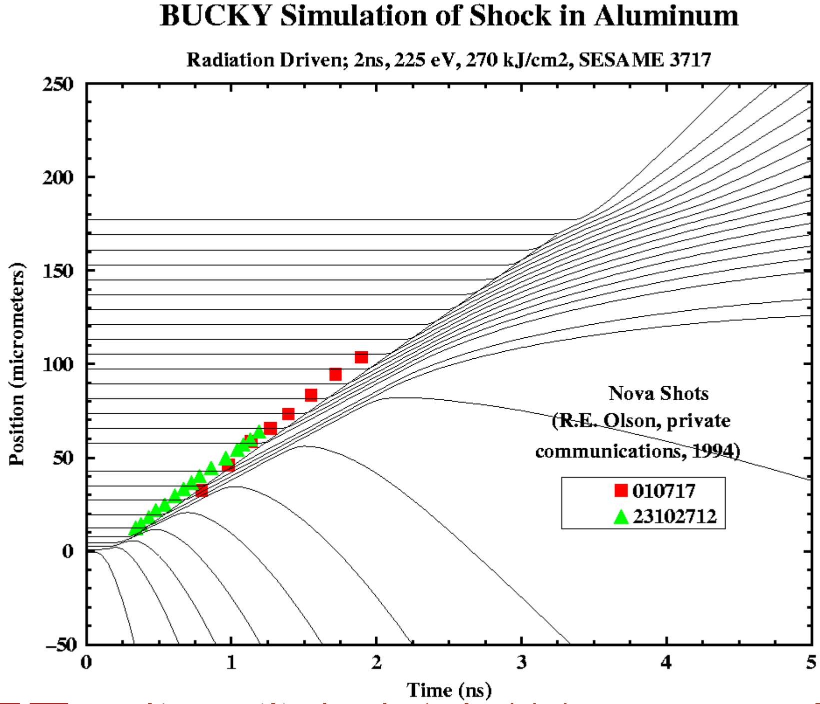
•Charge state profile is highly structured; high near target and low near wall.

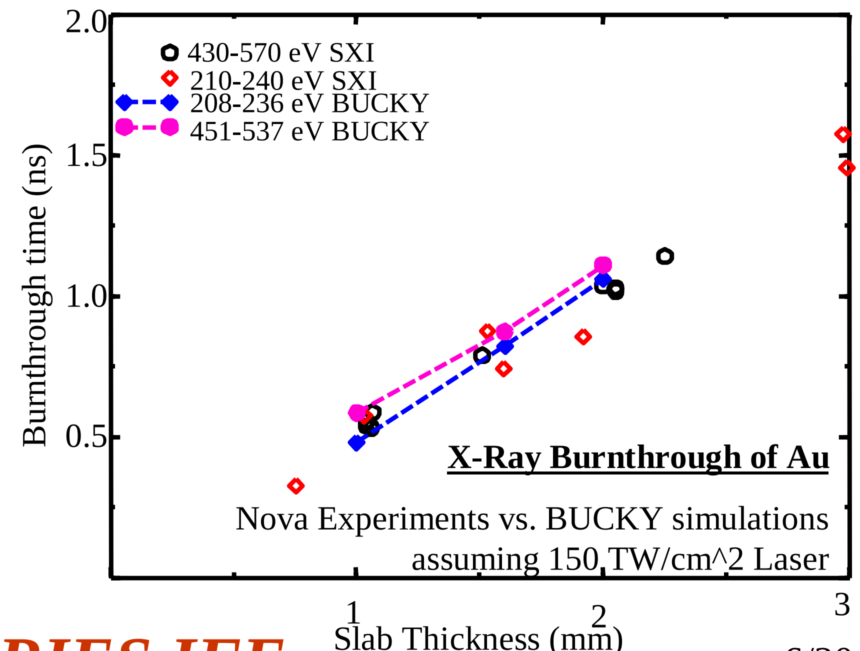
•Calculation based on equilibrium model; is it right?



In light of the importance of chamber gas opacity to the first wall, we plan to revisit the calculation of the Xe opacity using a more sophisticated code, EOSOPC

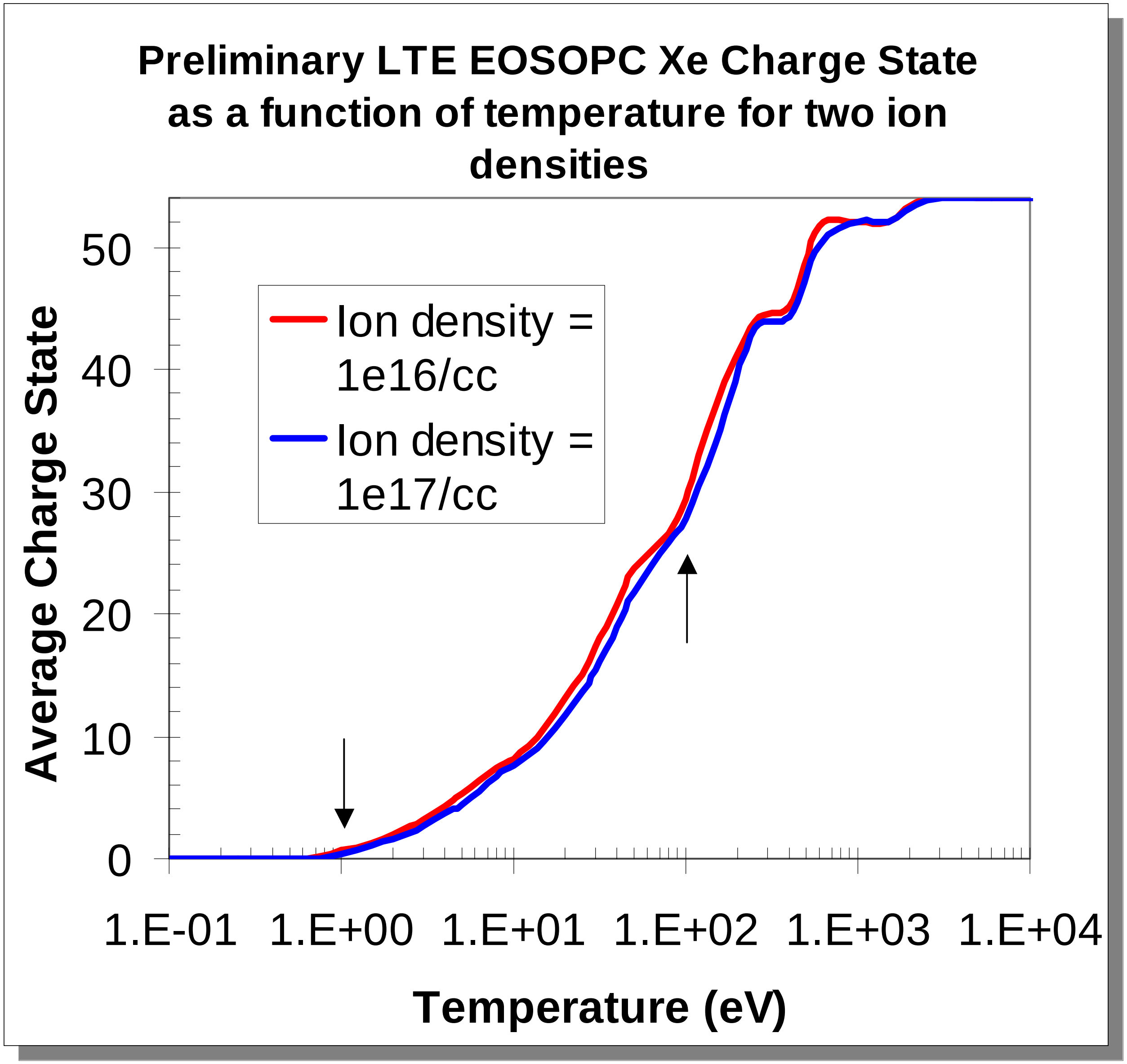
- EOSOPC represents an improvement over IONMIX:
  - Atomic Physics: multi-electron wavefunctions (UTA)
  - Degeneracy lowering: Hummer-Mihalas formalism is implemented
  - Additional effects in EOS: (partial degeneracy, modified Debye-Hückel interaction)
  - Results from EOSOPC have been benchmarked against burnthrough experiments, and compared with other major opacity codes, such as STA.



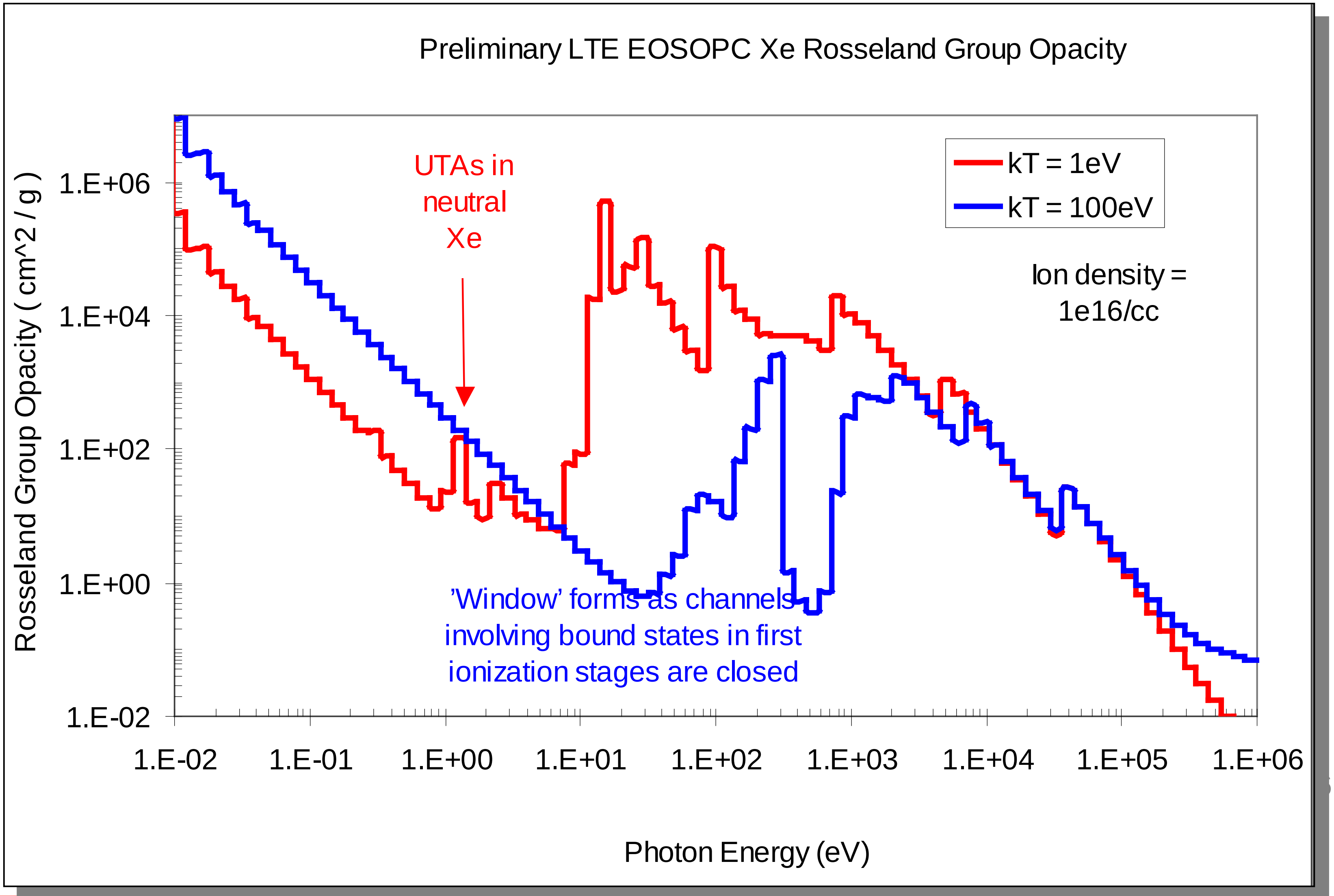


Preliminary LTE EOSOPC calculations for the Xe opacity have been performed, but need further study and benchmarking.

- The average charge state is a good figure of merit to compare between EOS codes, and is an important factor in the opacity.
- NEEDED: Benchmarking (NRL?) of EOSOPC results.



The dependence of the opacity on ionization balance is illustrated for plasma conditions relevant to dry wall IFE reactors.



Chamber Gas Opacity is a Critical Issue

- Chamber gas opacity is a crucial input which helps to determine first wall response.

- A more sophisticated suite of EOS / Opacity code is being used to re-investigate the effects of Xe opacity on chamber dynamics.

- **Though EOSOPC has been benchmarked against burnthrough data for Al and Au, Validation and Benchmarking of Code is still needed, especially for these non-equilibrium, highly non-isotropic conditions!!**

Wall Response in Gas-Protected IFE Chambers

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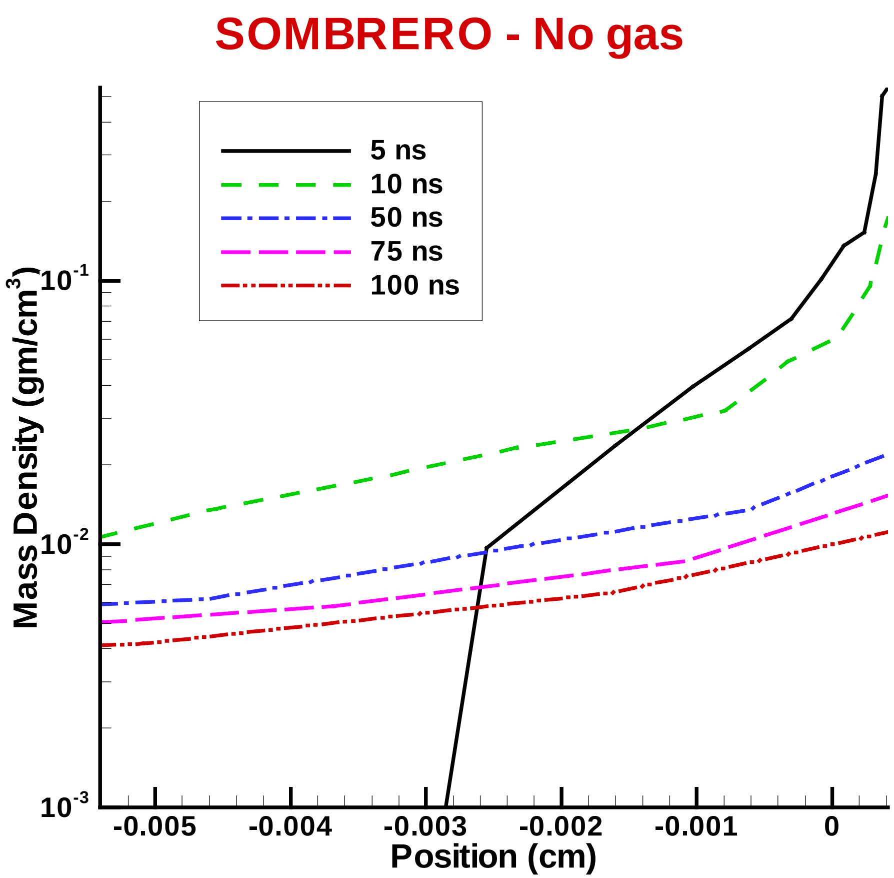
Chamber Gas is Effective in Preventing Thermal Damage to Walls.

•BUCKY simulations of wall response with and without gas protection.
•Importance of thermal properties of graphite.
•Minor design modifications can correct for surprises in thermal properties and/or opacities.
•Need for experiments on “low” fluence vaporization.

Vaporization of a 650 cm Radius Graphite Wall is Un-Avoidable without Gas-Protection

BUCKY Simulation: SOMBRERO target output, no gas, 650 cm radius graphite wall

- X-rays reach surface first (t=0 is arrival time of first x-rays).
- 4.22 J/cm^2 of x-rays vaporize part of wall, forming a self-shielding layer.
- Ions stop in vapor, heating it.
- No additional vaporization seen from re-radiation.
- Need to look at low temperature C opacity in more detail.



Without Gas-Protection, Wall Surface Gets Very Hot

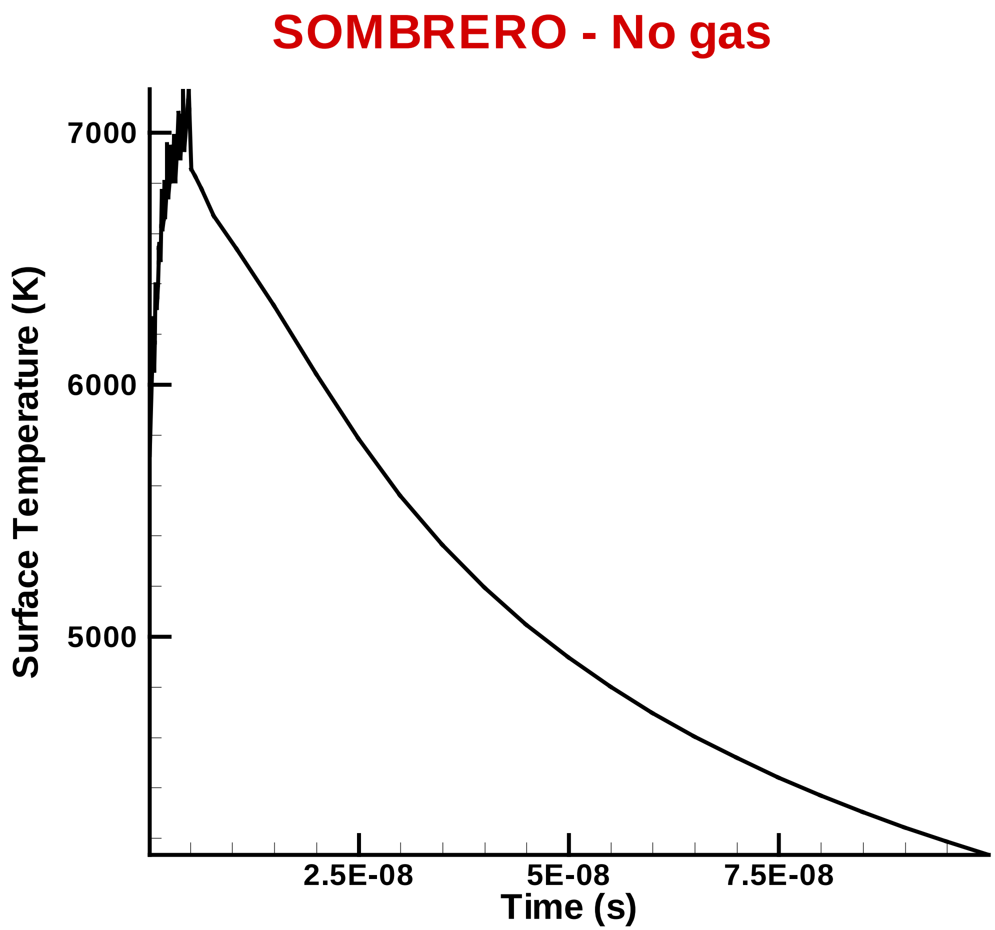
BUCKY Simulation: SOMBRERO target output, no gas, 650 cm radius graphite wall

Mass Ablation Rate:

$$\frac{dm}{dt} = \frac{2}{3} P_{sat} A_{wall} \left(\frac{\mu}{RT} \right)^{1/2}$$

$$P_{sat} = \exp\left(\frac{\Delta H_{vap}}{kT_{vap}} \left(1 - \frac{T_{vap}}{T} \right) \right)$$

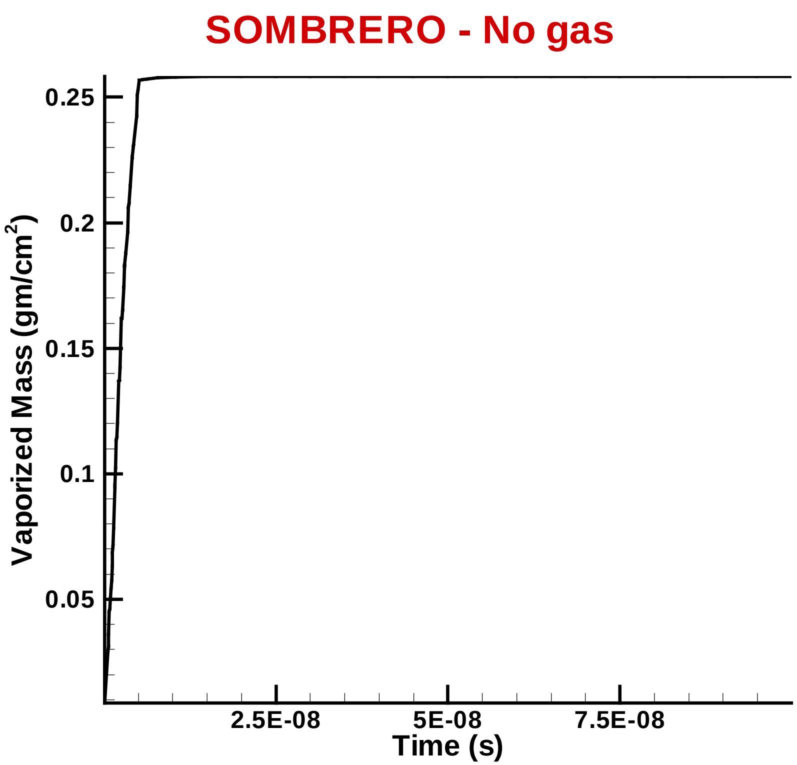
dm/dt will be high at 7000 K, and there will be substantial evaporation.



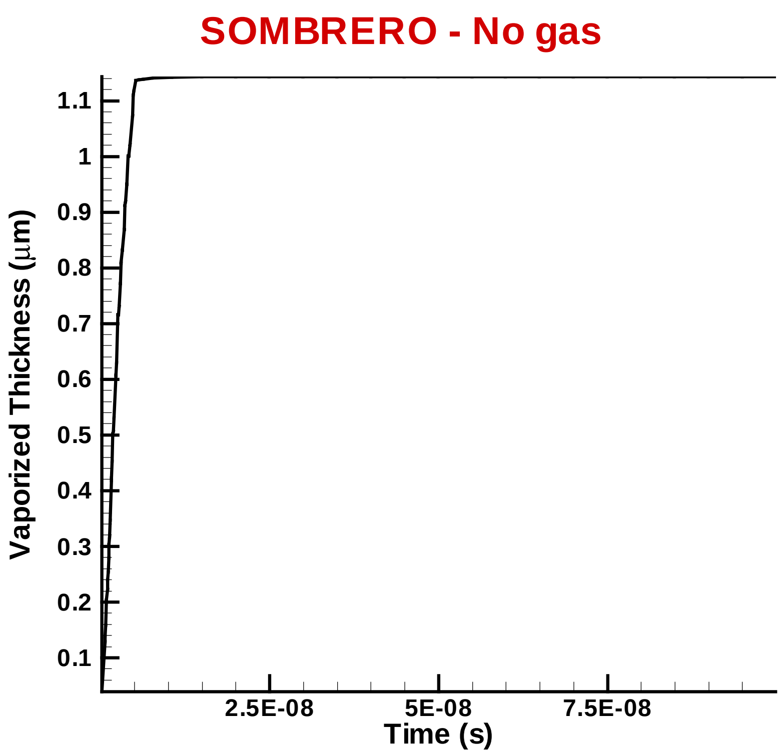
Without Gas-Protection, There is Significant Vaporization of SOMBRERO Wall

BUCKY Simulation: SOMBRERO target output, no gas, 650 cm radius graphite wall

Vaporize 0.25 gm/cm^2 of Wall = 1.3 metric tons per shot

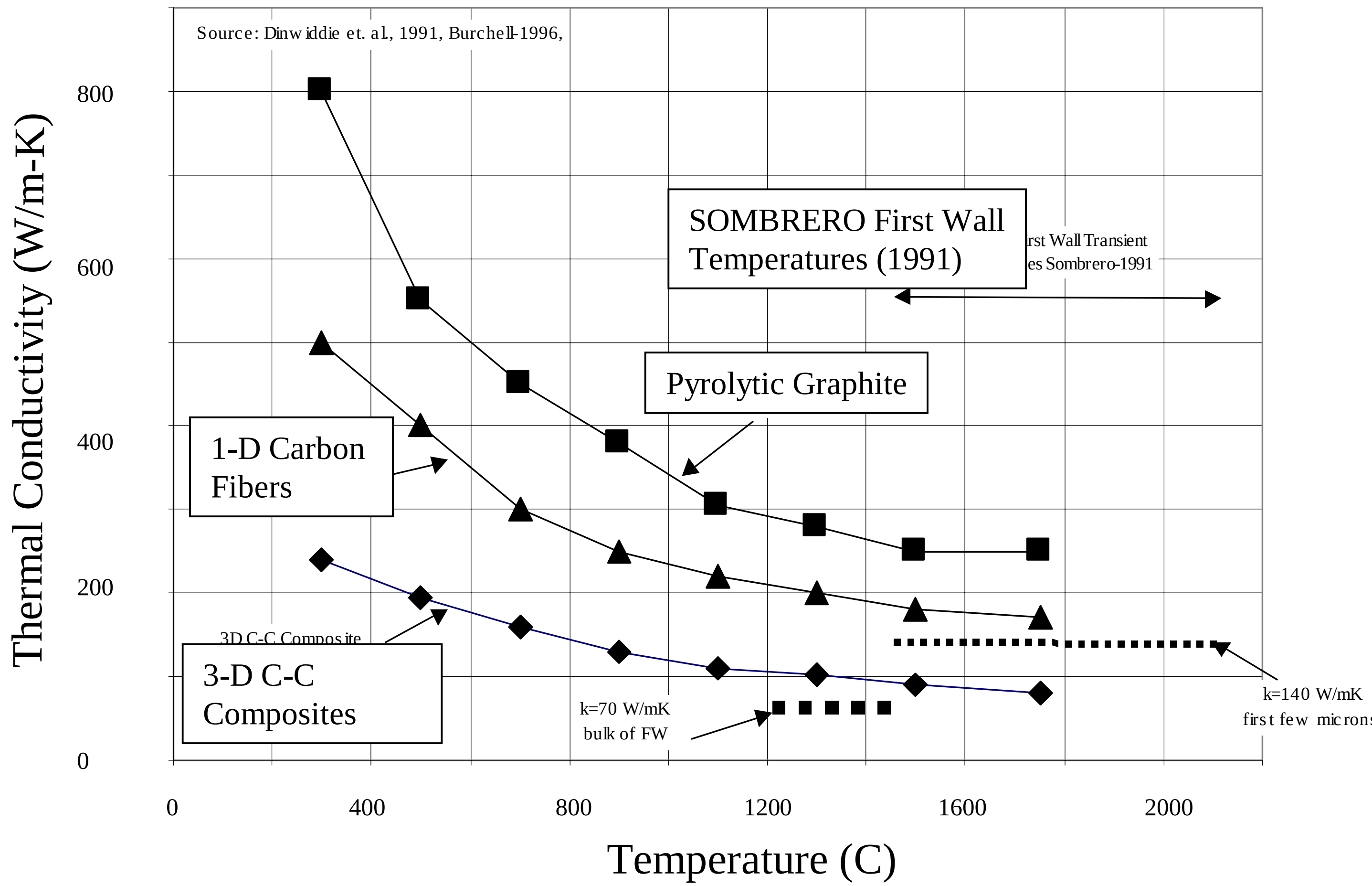


Vaporize 1.1 µm of Wall per shot = 63 cm per day (5.8×10^5 shots per day)



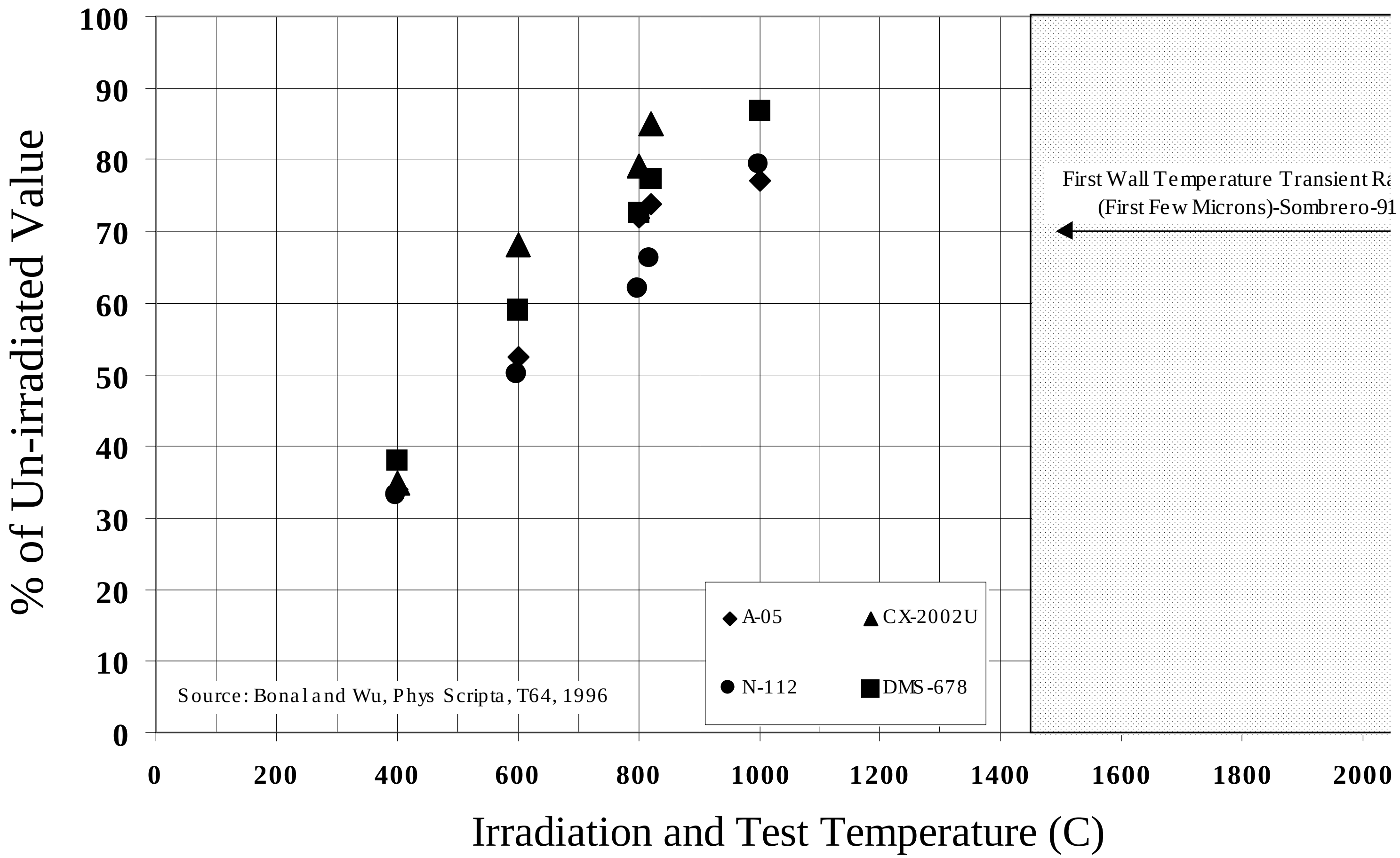
The Thermal Conductivity of Pyrolytic Graphite, Carbon Fibers and C-C Composites Drops with Increasing Temperature

•SOMBRERO design assumes a 70 W/m-K bulk thermal conductivity and a surface value of 115.



Neutron Irradiated Thermal Conductivity of Graphite at ≈ 1-2 dpa Approaches Un-irradiated Thermal Values at High Temperatures

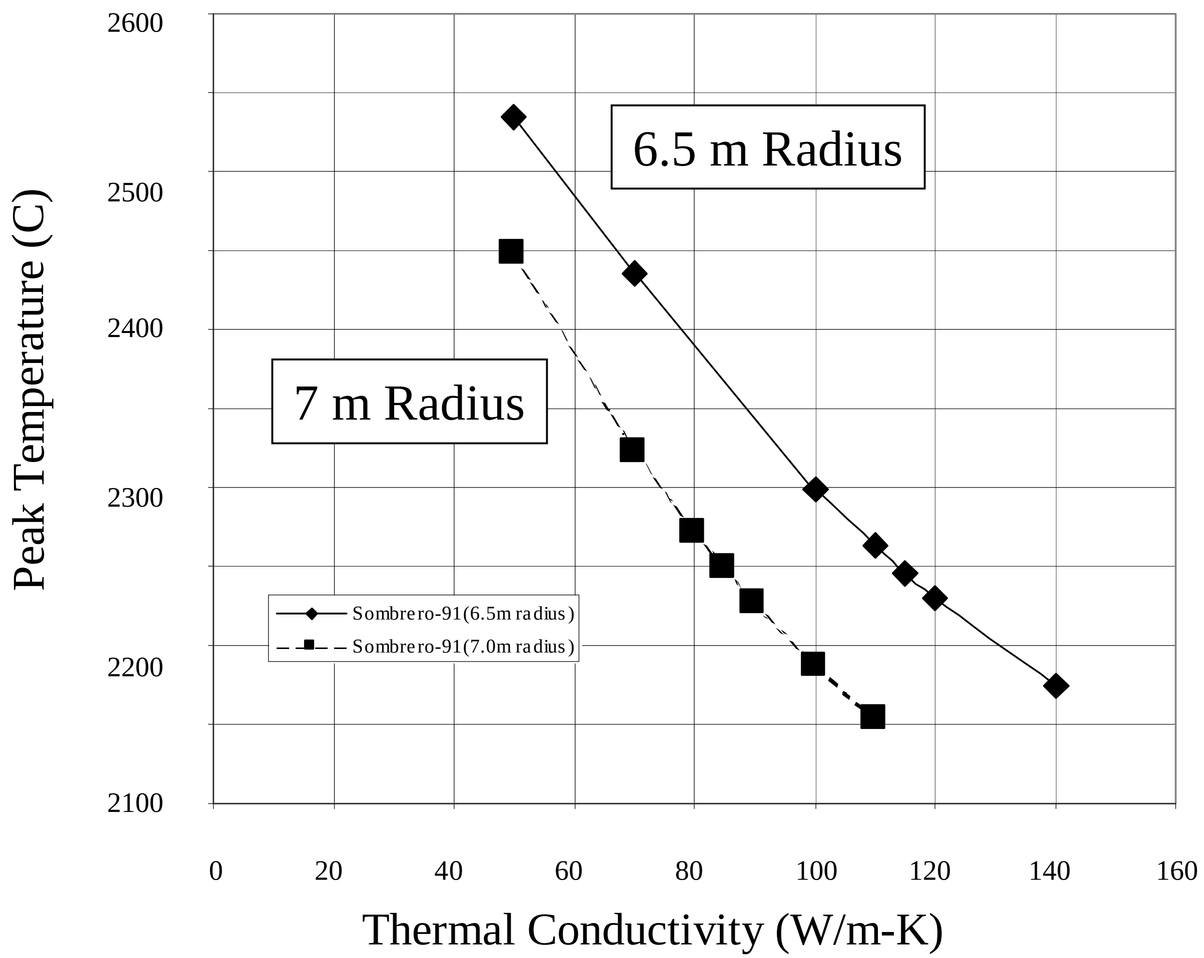
- At SOMBRERO wall surface temperatures, radiation damage has only a small effect on thermal conductivity of graphite.



The Peak First Wall Temperatures in SOMBRERO Depend on the Thermal Conductivity of the First Few Microns

BUCKY Simulation: SOMBRERO target output, 1.8×10^{16} cm^{-3} Xe, 650 cm radius graphite wall

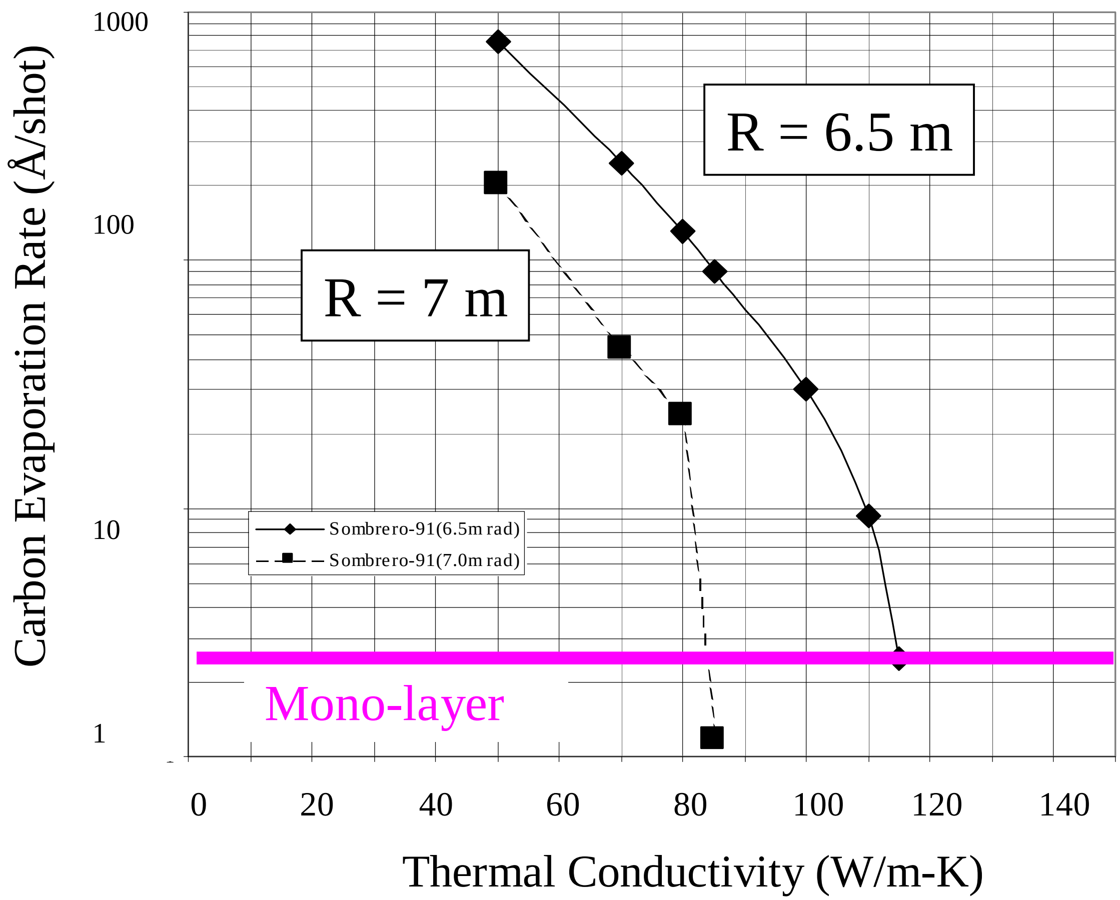
- **BUCKY** simulations of first wall temperatures show a peak temperature of 2260 C for a 6.5 m radius chamber and a conductivity of 115 W/m-K.
- Peak temperature can be controlled with minor changes to the wall radius.
- IONMIX Xe opacities, need to use EOSOPA opacities.



Once the Evaporation is Below a Few Å Per Shot There is Essentially No Erosion of the C-C First Wall

BUCKY Simulation: SOMBRERO target output, 1.8×10^{16} cm^{-3} Xe, 650 cm radius graphite wall

- Experiments with many shots would be required to confirm low evaporation behavior.
- Molecular dynamics simulations of solid would be quite useful.
- IONMIX Xe opacities, need to use EOSOPA opacities.



Ion Beam Melting and Onset Vaporization Experiments Have Been Done on RHEPP at SNL

•RHEPP Ions on Silicon.

•Laser Reflectivity Measures Melt-Duration

•**BUCKY** Simulations.

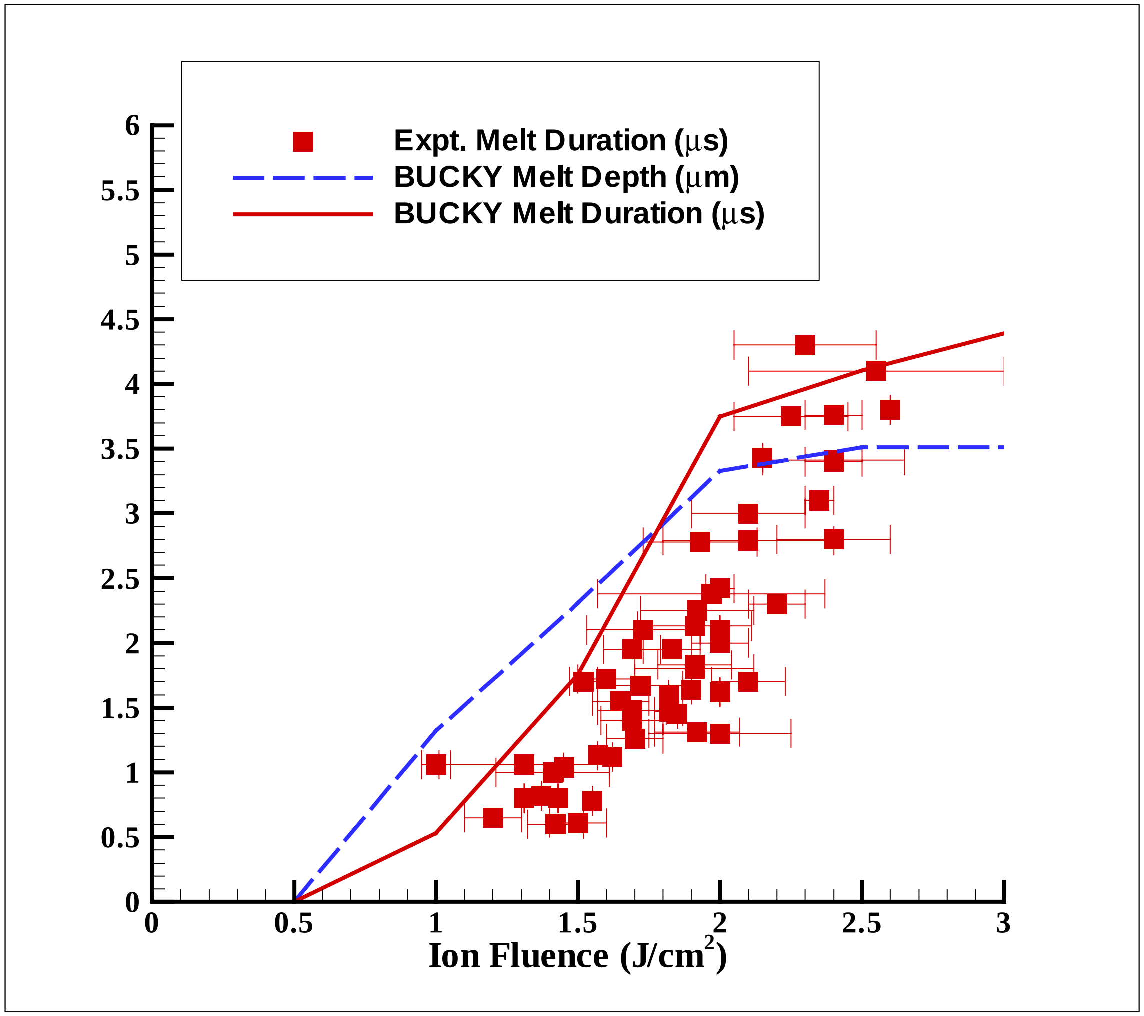
•IFE Direct Drive Target Relevant Ions:

➢657 keV Protons

➢1318 keV N^{2+}

➢ 665 keV N^{+}

•Vaporization Begins around 2 J/cm².



Chamber Physics Critical Issues Involve Target Output, Gas Behavior and First Wall Response

Target Output

Design, Fabrication, Output Simulations, (Output Experiments)

X-rays, Ion Debris, Neutrons

Target Design: NRL
Fabrication: GA
Output Simulations: UW, NRL, LLNL
(Z-experiments UW-SNL)

Gas Behavior

Gas Opacities, Radiation Transport, Rad-Hydro Simulations,

Thermal Radiation, Shock

Xe, Kr Opacities: UW,NRL
Transport Models: UW
Blast Simulations: UW

Wall Response

Wall Properties, Neutron Damage, Near-Vapor Behavior, Thermal Stresses

Thermal Properties: UCSD, UW, ANL
First Wall Simulations: UW,UCSD
Thermal Stresses: UCSD,UW