# Threat Spectra and Energy Partition for Au and Pd Coated Laser IFE Targets

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***•We are concerned with how ionization models and hydrodynamics models in target codes affect predictions of threats to IFE dry wall chambers.***
***•In this talk we will show how assumptions in the BUCKY target simulations change target output.***
***•We will conclude with recommended threat spectra.***

# OUTLINE

1. **Physics and Methods**
2. **Target Implosion Physics**
3. **Target Output Energy Partition**
4. **Target Ion Spectra**
5. **Target X-ray Spectra**
6. **Closing Comments**

# Radiative Properties depends crucially on the opacity of the chamber gas

The opacity depends on:

- detailed (and in the case of chamber Xe, highly complicated) atomic physics, and
- $Z^*$, the average charge state, and the population of the individual atomic levels.

$$\tau_\nu(\text{lines}) = \sum_{\text{lines}} \frac{\pi e^2}{mc^3} \bar{f} \hat{\varphi}_\nu N_l d$$

$$\tau_\nu(\text{free-free}) \propto \left\langle Z^2 \right\rangle / \nu^2$$

$$\tau_\nu(\text{bf, hydrogenic}) \propto \sum_{\text{ion}} \frac{1}{Z_{\text{ion}}^2} \sum_n \left(\frac{\nu_n}{\nu}\right)^3 N_{\text{ion},\,n} d$$

# For the simulation of target output and chamber blast waves, the simplifying approximation of LTE is NOT appropriate

- If collisional processes dominate the rate equations, then the calculation of opacities reduces to the calculation of the energy level structure and statistical weights of the various relevant ionization stages. (Saha-Boltzmann Equilibrium)
- For that to be the case, the electron density must satisfy

$$N_e \geq 7\times 10^{18} Z^7 n^{-17/2}\left(\frac{T}{E_n}\right)^{1/2} \text{ cm}^{-3}$$

- For propagation of blast waves in an IFE target chamber gas, the electron density is orders of magnitude too small to satisfy this relation, indeed, the coronal approximation is appropriate.

## IONMIX

- Takes as input ionization potentials of the ground states of all the ionization stages of an element.
- Assumes **hydrogenic** energy level structure for excited states and the cross-sections of collisional and radiative properties.
- Solves **CRE** equations to determine ionization balance and level populations.

STRENGTH: ZBar which interpolates appropriately between coronal and LTE values.

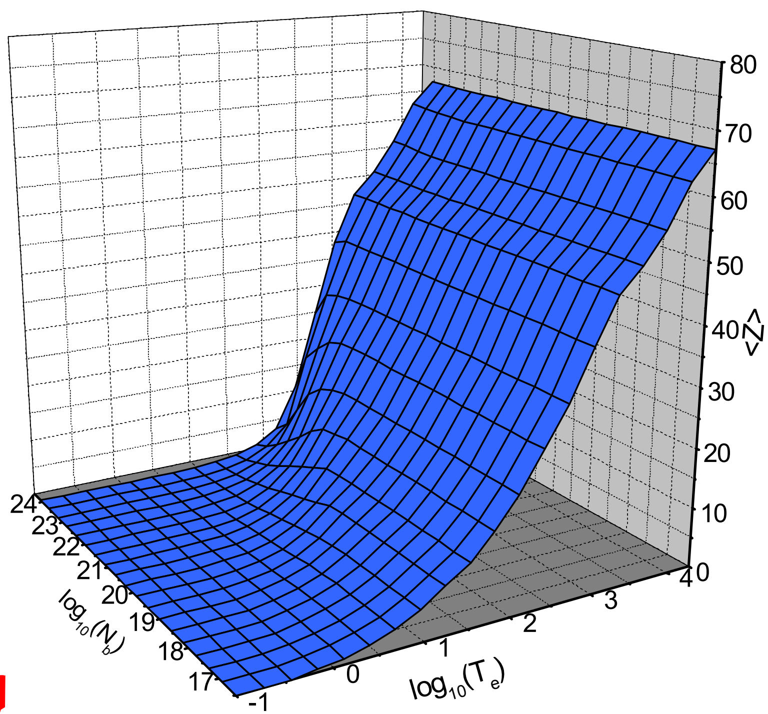
WEAKNESS: Simplified atomic physics.

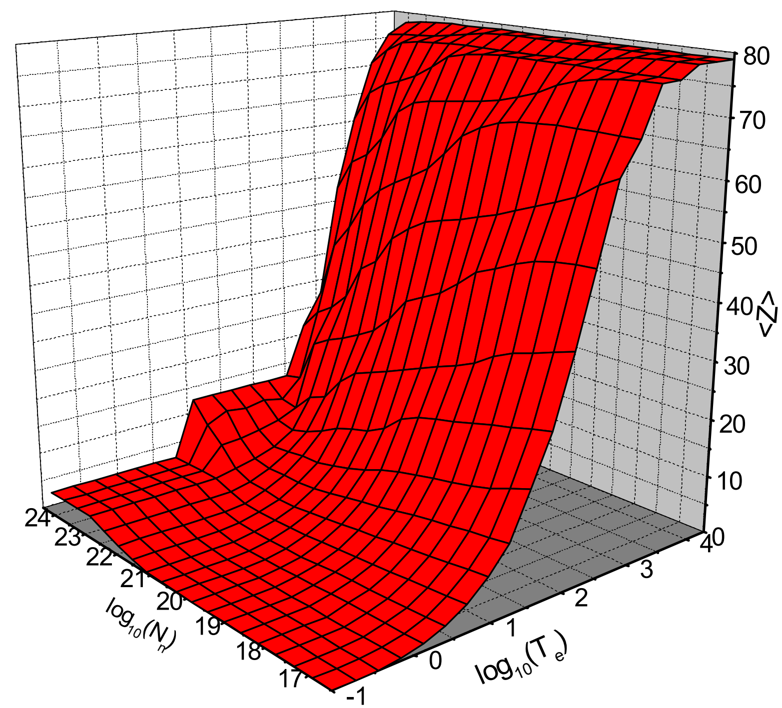
## EOSOPA (Z>18)

- Takes as input a list of configurations for each ionization stage.
- Generates **detailed multi-electron** atomic physics data (energy levels and dipole matrix elements) for all ionization stages by solving Hartree-Focke equations with relativistic corrections.
- Solves **LTE** (Saha) equations to determine ionization balance and UTA level populations.
- Linear Muffin Tin Orbital approximation to dense plasma effects

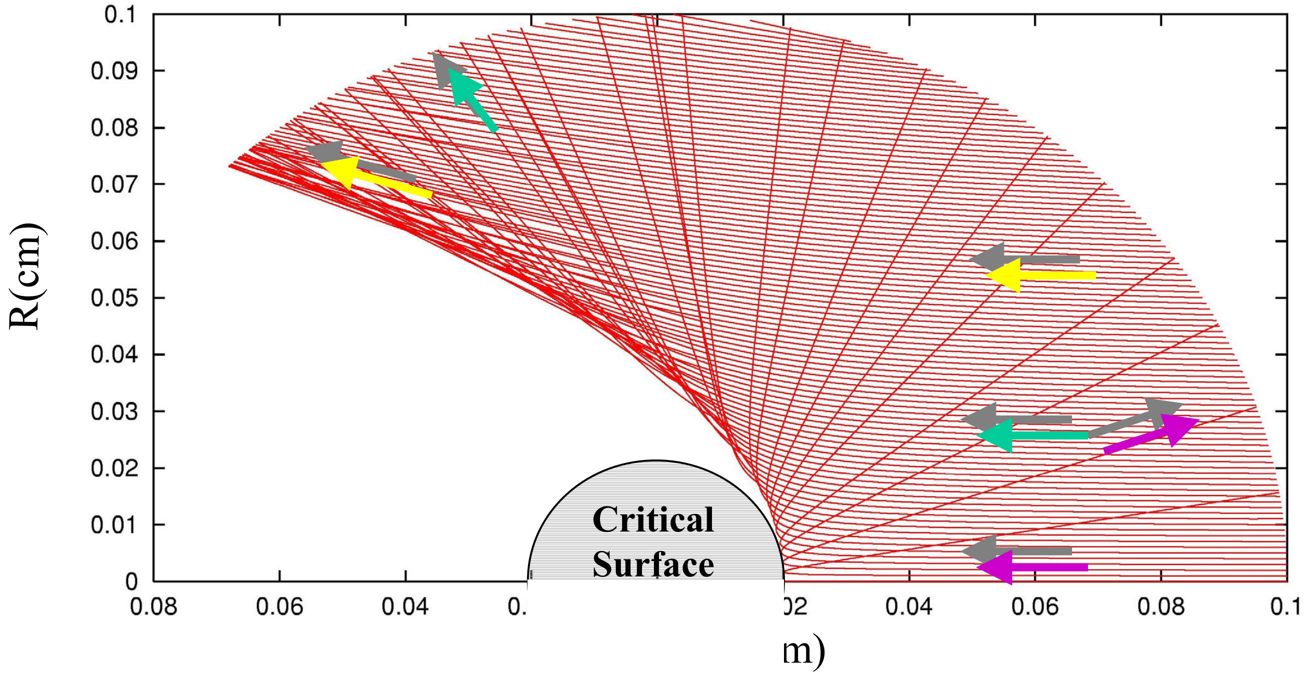
STRENGTH: Spectroscopic quality atomic physics.

WEAKNESS: No radiative rates taken into account. Strictly LTE.



# 2-D Laser Ray-Tracing Deposition Has Been Used to Calculate the Performance of High Yield Direct-Drive Targets




- **Laser Rays** are refracted by electron density profile.
- In the example, $n_e(r) = n_c(r_c/r)^{1.5}$ where $r_c$=0.02 cm.
- Rays are initially parallel, but are refracted or absorbed by electrons.

We are modeling the implosion, burn and explosion of High Yield Direct-Drive Targets.

1. We need to have the detailed plasma conditions at ignition time to predict evolution afterwards.
2. All codes constitute a unique set of physical assumptions and numerical approaches, so BUCKY represents another opinion for implosion and yield.

# ZOOMING Improves Laser Coupling to the Target

Zooming:

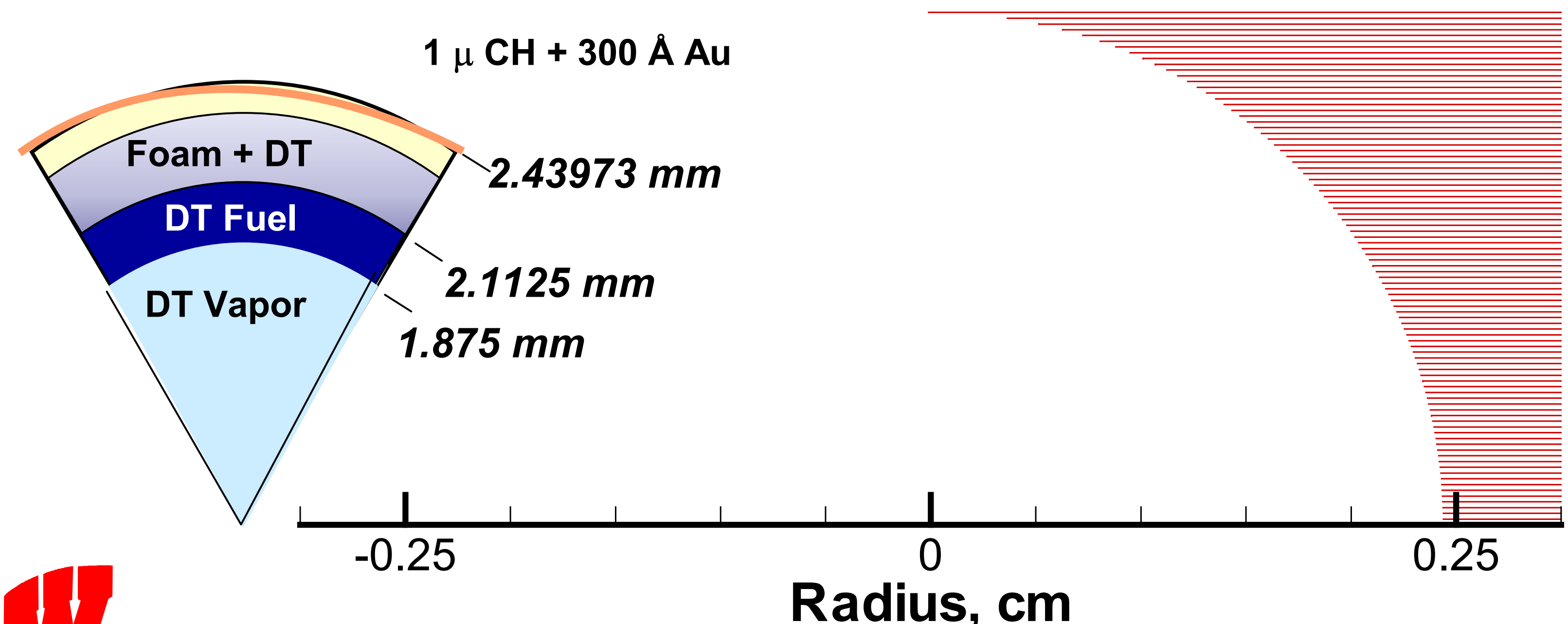
1: Time: 29.8 ns

2: Time: 32.1 ns

Time: 0.0 ns

Target radius: 0.244 cm

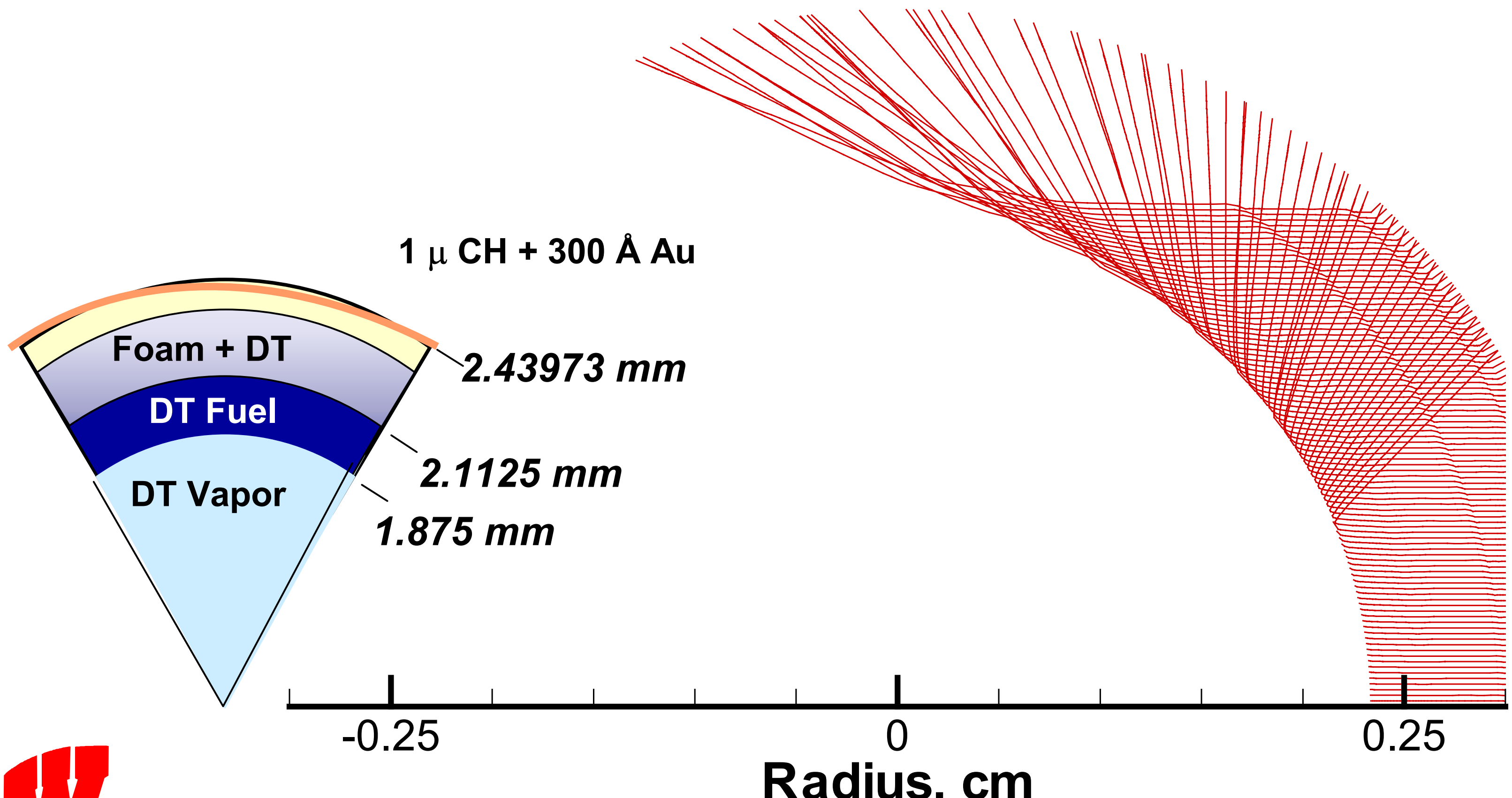
Critical radius: 0.244 cm



# <u>ZOOMING</u> Improves Laser Coupling to the Target

Zooming:
1: Time: 29.8 ns
2: Time: 32.1 ns

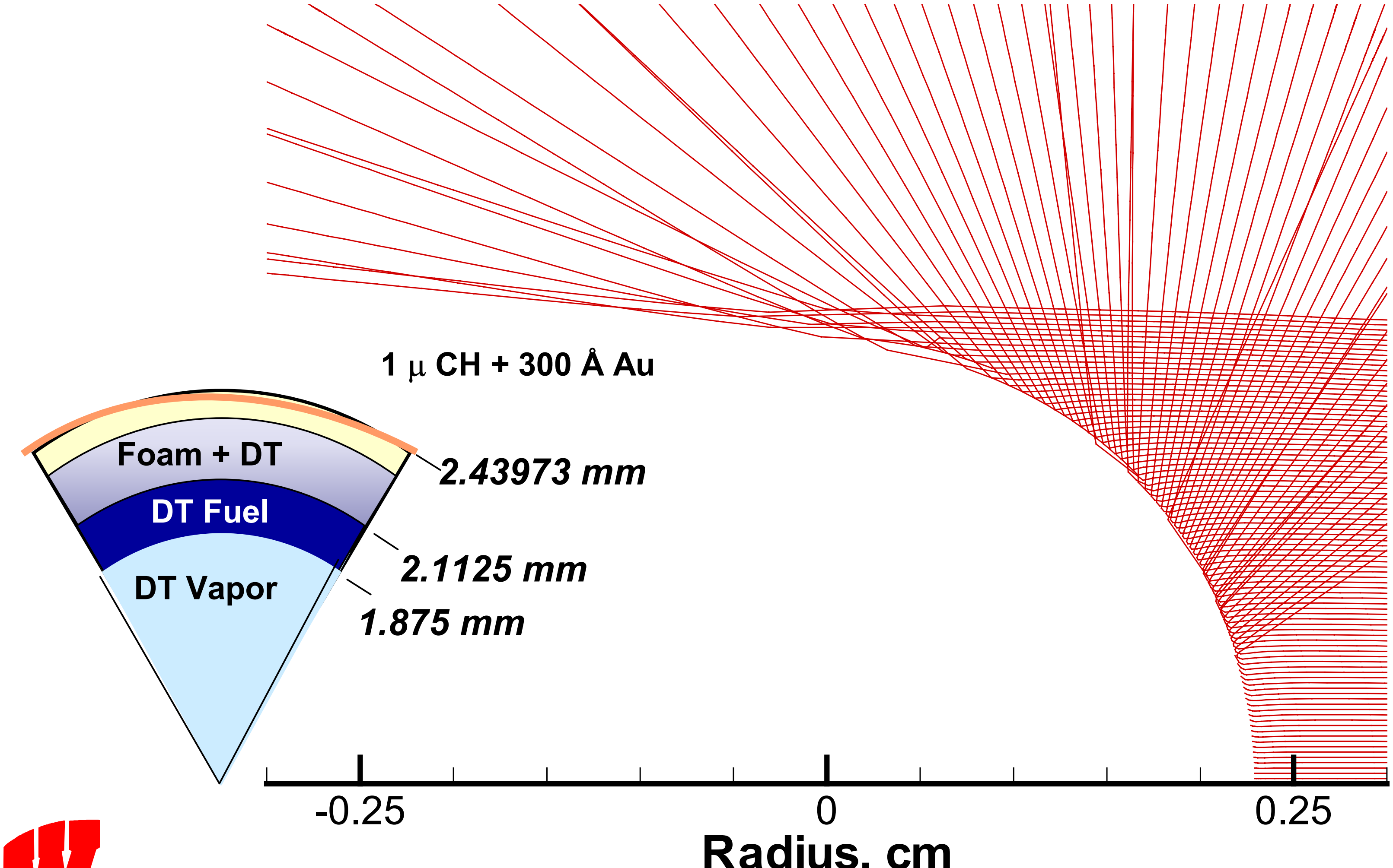
Time: 10.0 ns
Target radius: 0.344 cm
Critical radius: 0.233 cm



# ZOOMING Improves Laser Coupling to the Target

Zooming:
1: Time: 29.8 ns
2: Time: 32.1 ns

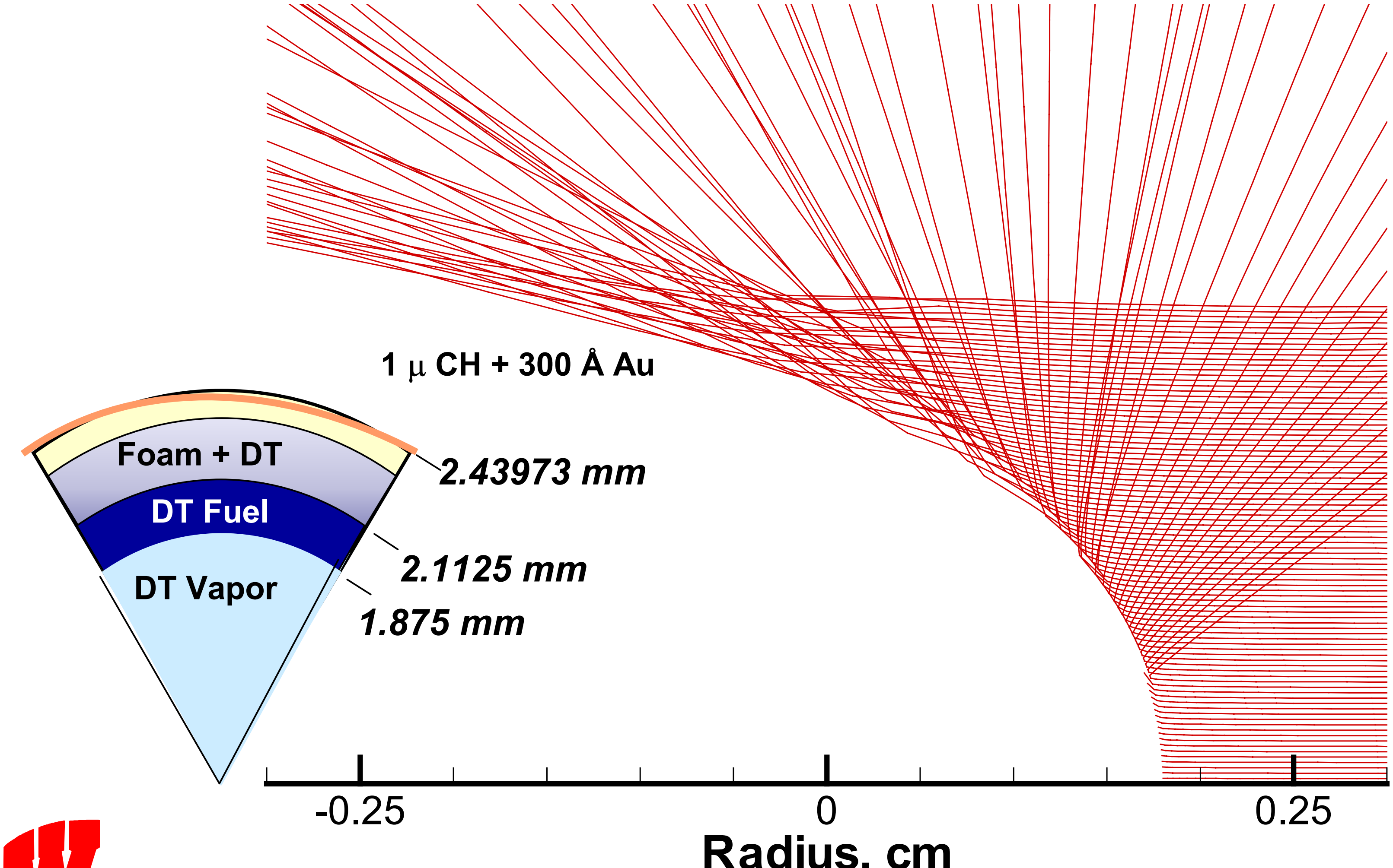
Time: 20.0 ns
Target radius: 0.527 cm
Critical radius: 0.228 cm



# ZOOMING Improves Laser Coupling to the Target

Zooming:
1: Time: 29.8 ns
2: Time: 32.1 ns

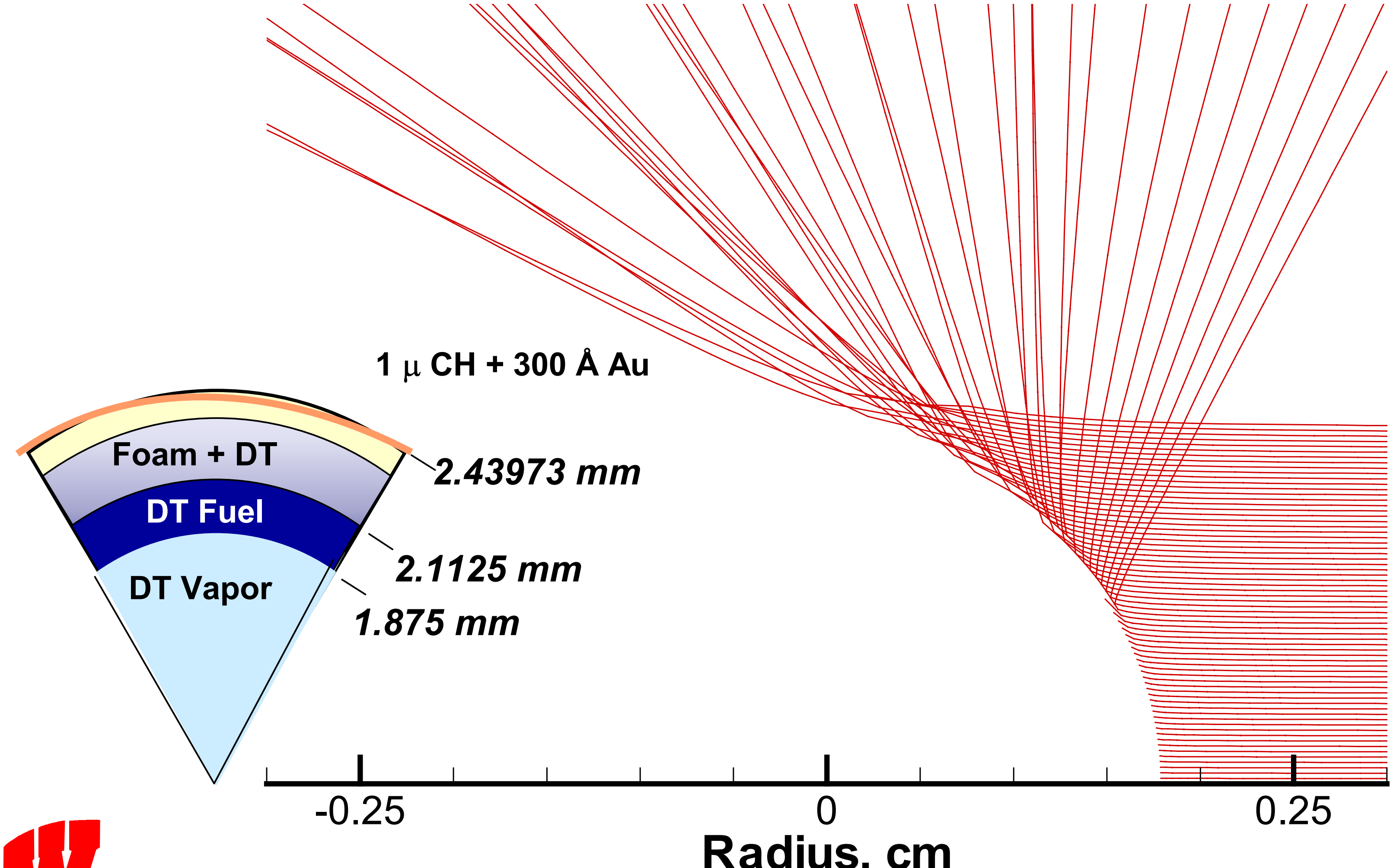
Time: 29.7 ns
Target radius: 0.834 cm
Critical radius: 0.180 cm



# ZOOMING Improves Laser Coupling to the Target

Zooming:
1: Time: 29.8 ns
2: Time: 32.1 ns

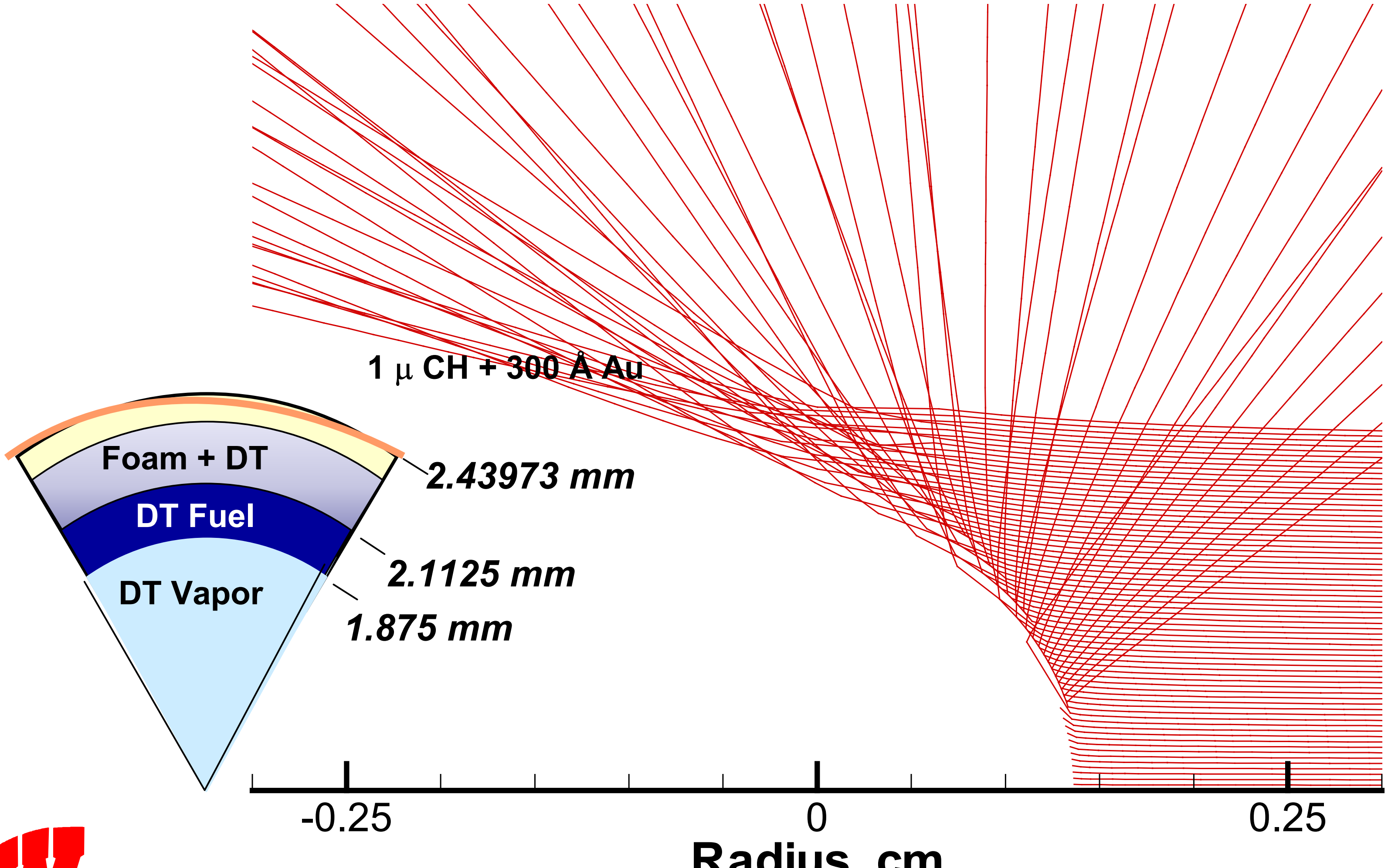
Time: 29.9 ns
Target radius: 0.843 cm
Critical radius: 0.179 cm



# ZOOMING Improves Laser Coupling to the Target

Zooming:
1: Time: 29.8 ns
2: Time: 32.1 ns

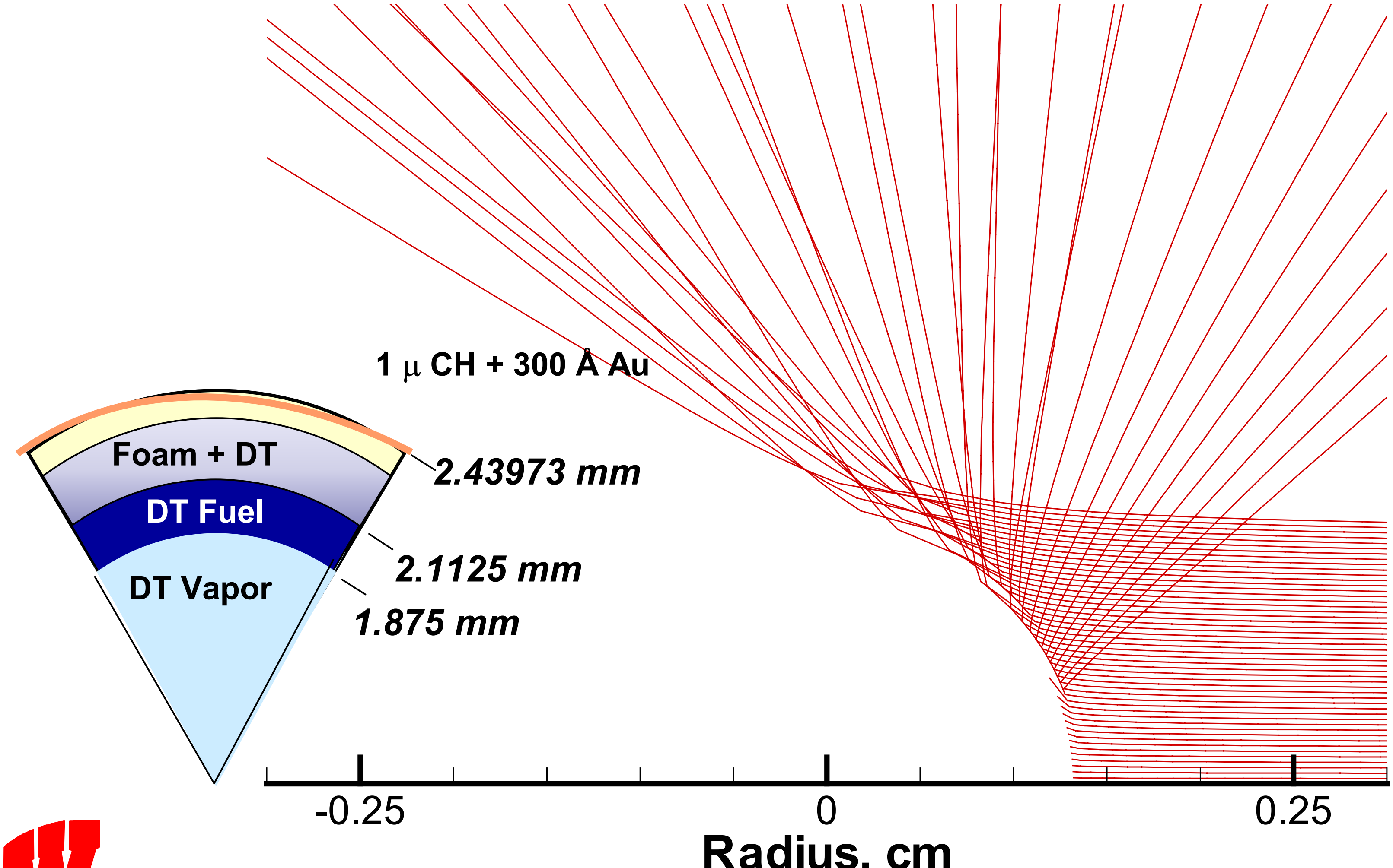
Time: 32.0 ns
Target radius: 0.952 cm
Critical radius: 0.132 cm



# ZOOMING Improves Laser Coupling to the Target

Zoomimg:
1: Time: 29.8 ns
2: Time: 32.1 ns

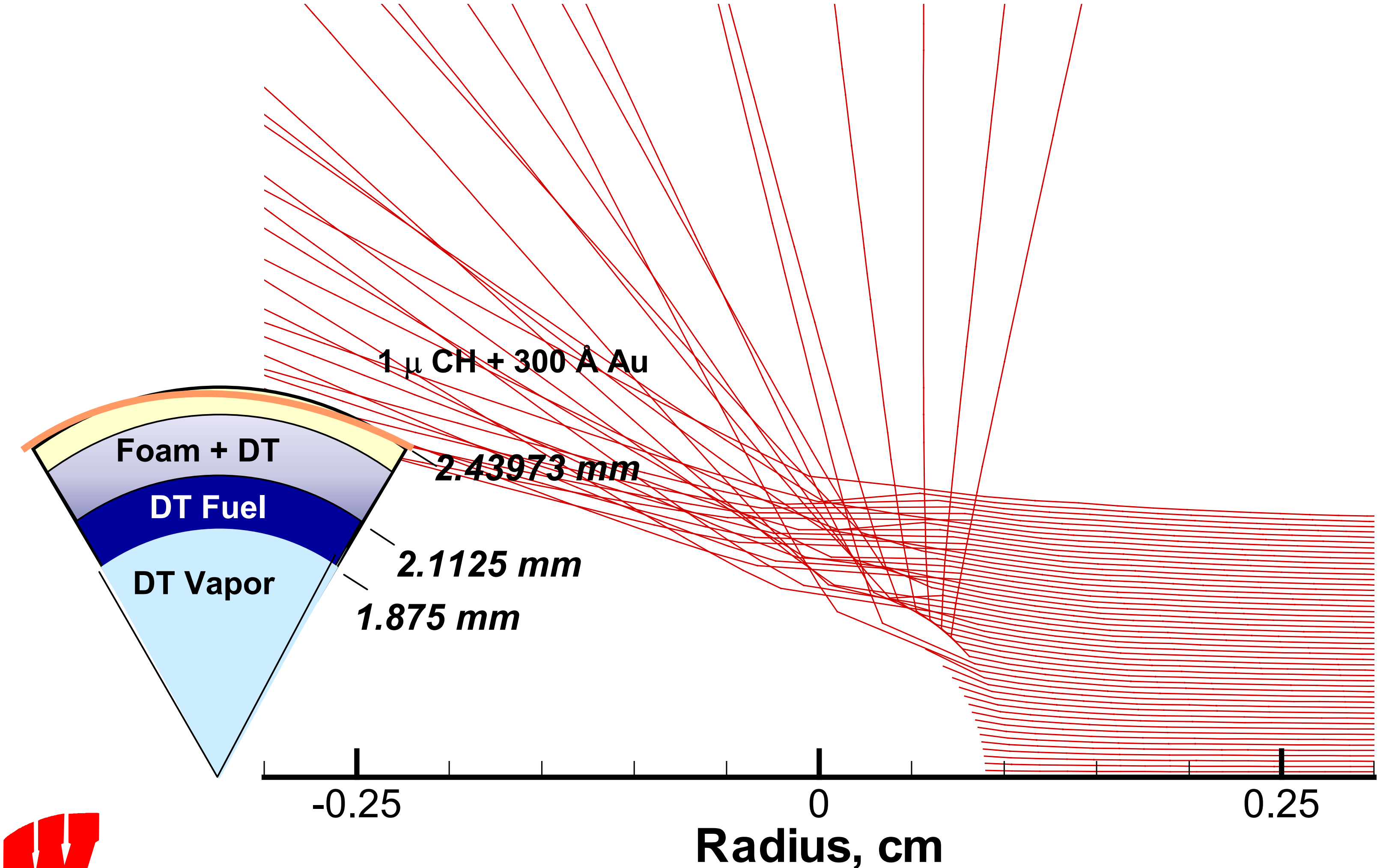
Time: 32.2 ns
Target radius: 0.965 cm
Critical radius: 0.131 cm



# ZOOMING Improves Laser Coupling to the Target

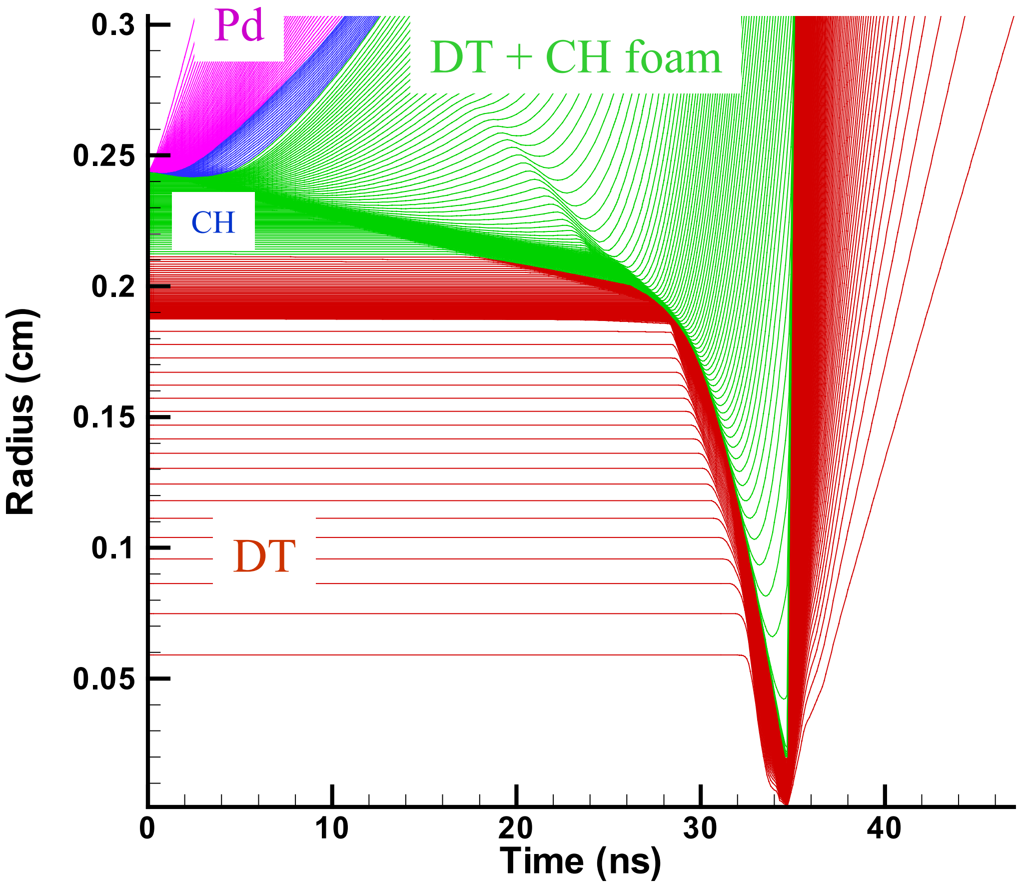
Zooming:
1: Time: 29.8 ns
2: Time: 32.1 ns

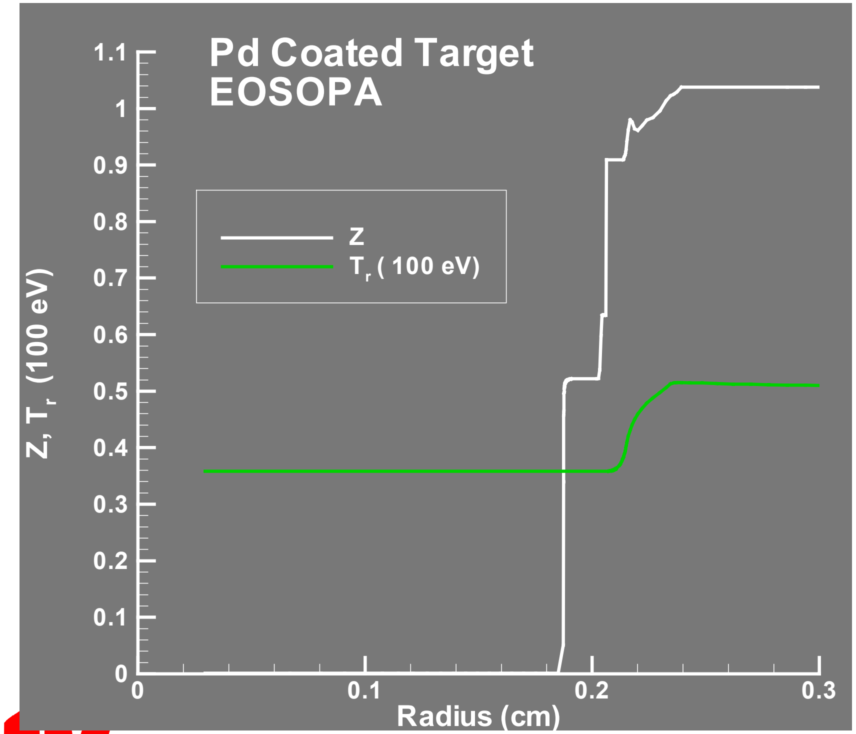
Time: 34.0 ns
Target radius: 1.086 cm
Critical radius: 0.078 cm



# We Have Achieved Ignition for the NRL High Yield Direct-Drive Radiation-Smoothed Laser Target

- Yield = 354 MJ
- Laser Energy = 2.9 MJ
- Deposited Laser Energy = 2.33 MJ
- Net Gain = 122
- Capsule Gain = 152
- EOSOPA used for Pd

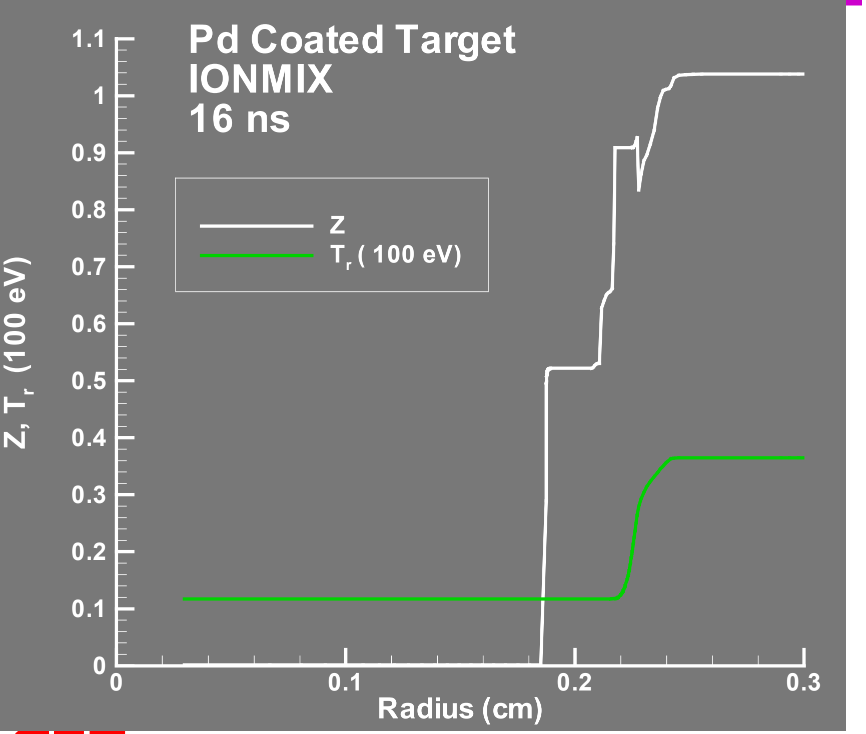


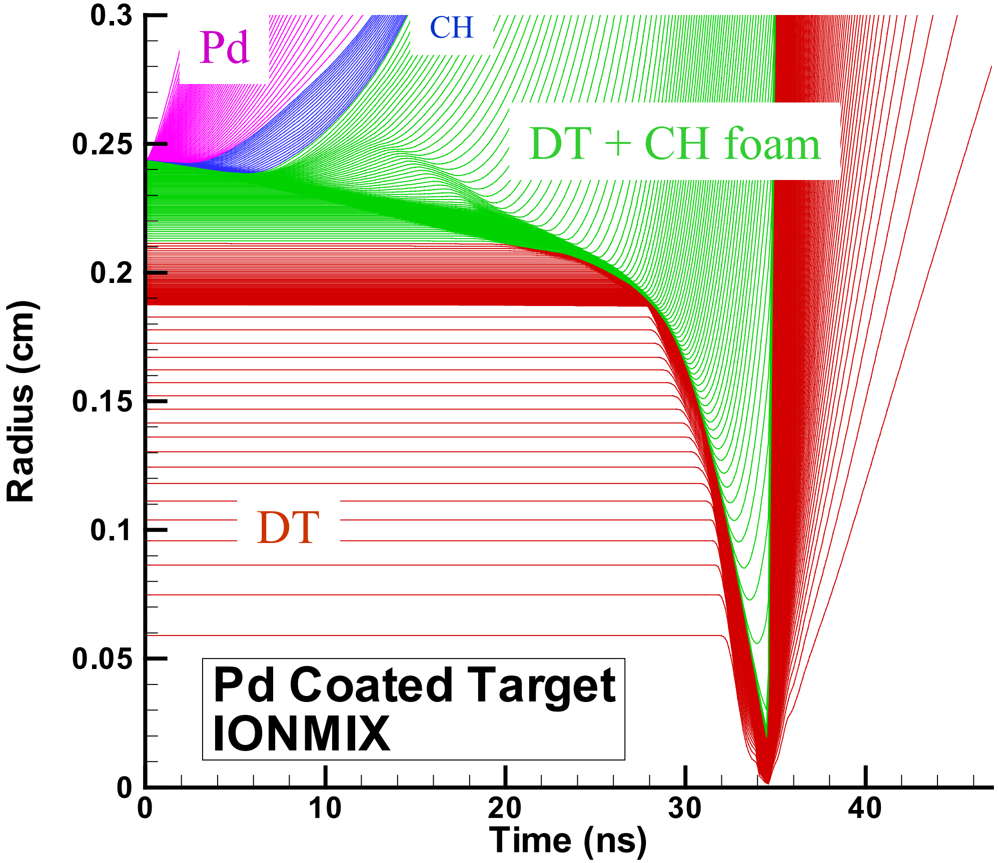




- Radiation from the Pd is absorbed in the ablator.
- There is an ionization edge at 22 ns at 0.24 cm.
- The radiation is absorbed at this edge.
- Small differences in the physics can lead to asymmetries.

# The IONMIX and EOSOPA Based Pd opacities give the same Yield but Differences in Implosion

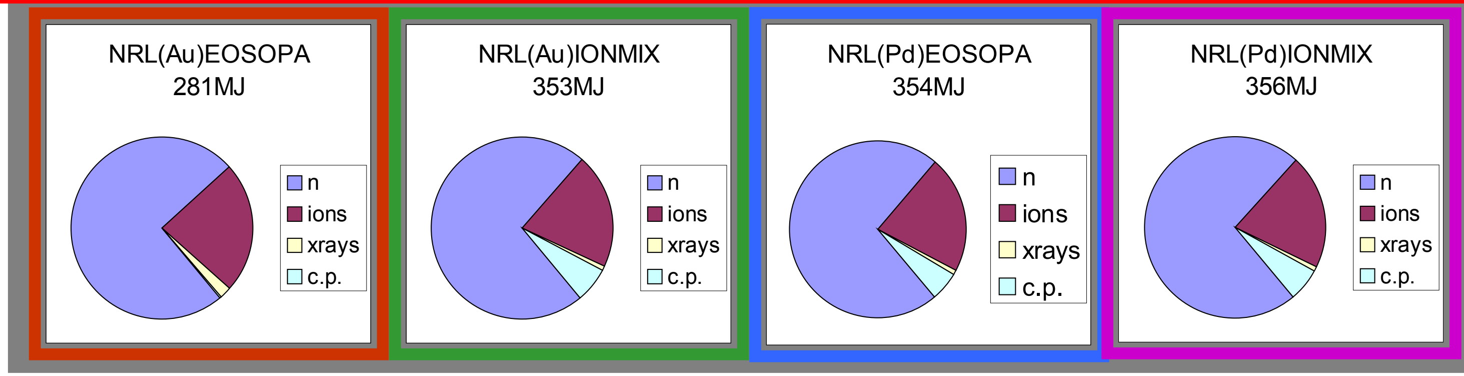
- Yield = 356 MJ
- Laser Energy = 2.9 MJ
- Deposited Laser Energy = 2.33 MJ
- Net Gain = 123
- Capsule Gain = 153
- IONMIX used for Pd




- There is an ionization edge at 16 ns at 0.24 cm.
- The radiation is absorbed at this position, leading to a radiation driven shock that is different from the EOSOPA calculation.
- These differences are not reflected in the yield.

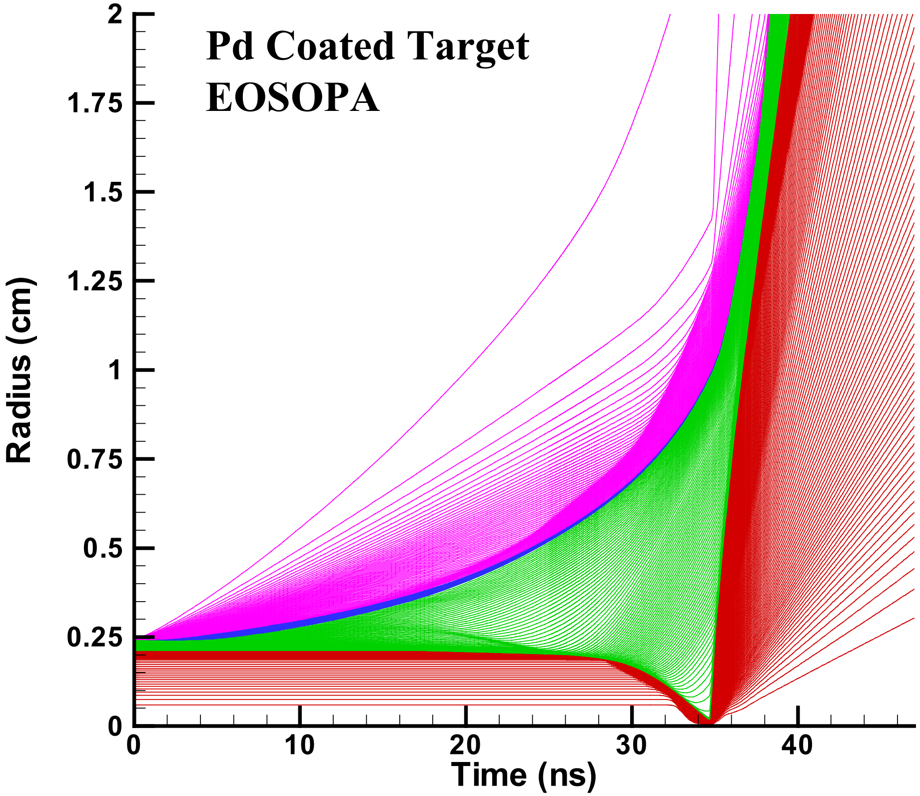
# Energy Partition for Au and Pd-Coated Laser IFE Targets

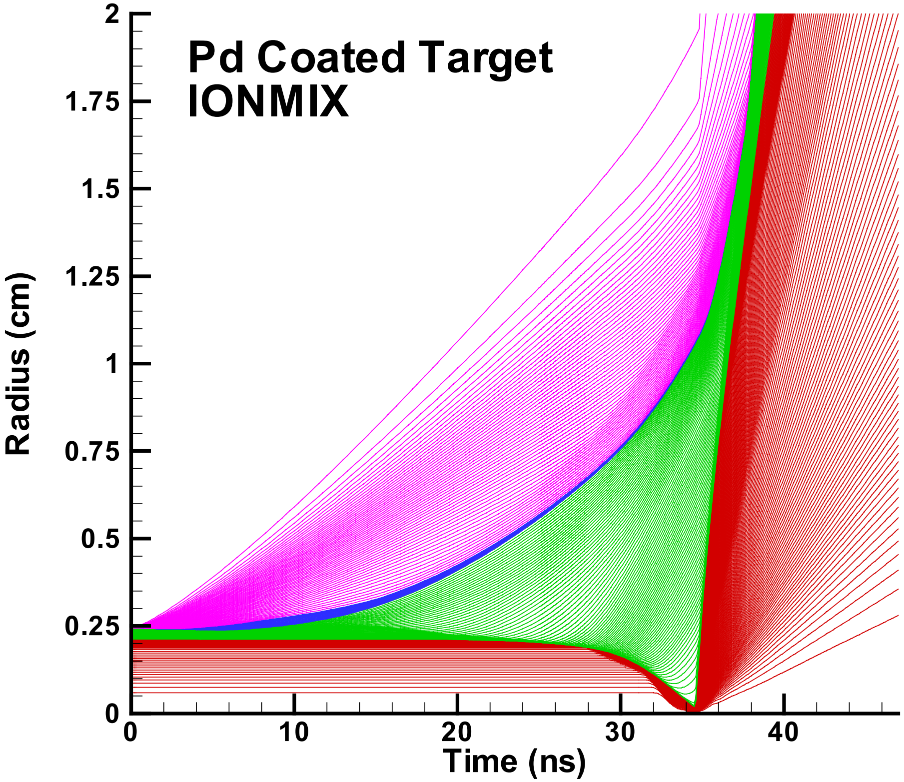



| | Au EOSOPA | Au IONMIX | Pd EOSOPA | Pd IONMIX |
|---|---|---|---|---|
| **Yield (MJ)** | 281.1 (99.0 %) | 353.1 (99.2 %) | 353.7 (99.2 %) | 355.7 (99.2 %) |
| **Neutron (MJ)** | 209.6 (73.8 %) | 257.0 (72.2 %) | 256.7 (72.0 %) | 260.1 (72.5 %) |
| **X-ray (MJ)** | 4.94 (1.74 %) | 2.66 (0.75 %) | 2.68 (0.75 %) | 2.71 (0.76 %) |
| **Target Debris (MJ)** | 68.4 (24.8 %) | 74.6 (21.0 %) | 78.1 (21.9 %) | 68.4 (19.1 %) |
| **Charged Fusion Product (MJ)** | 1.08 (0.38 %) | 21.7 (6.1%) | 19.1 (5.4 %) | 20.9 (5.8 %) |

# Pd-Coating on Direct-Drive Laser Target is Puffed up by Laser Then Shocked Off by Target Explosion

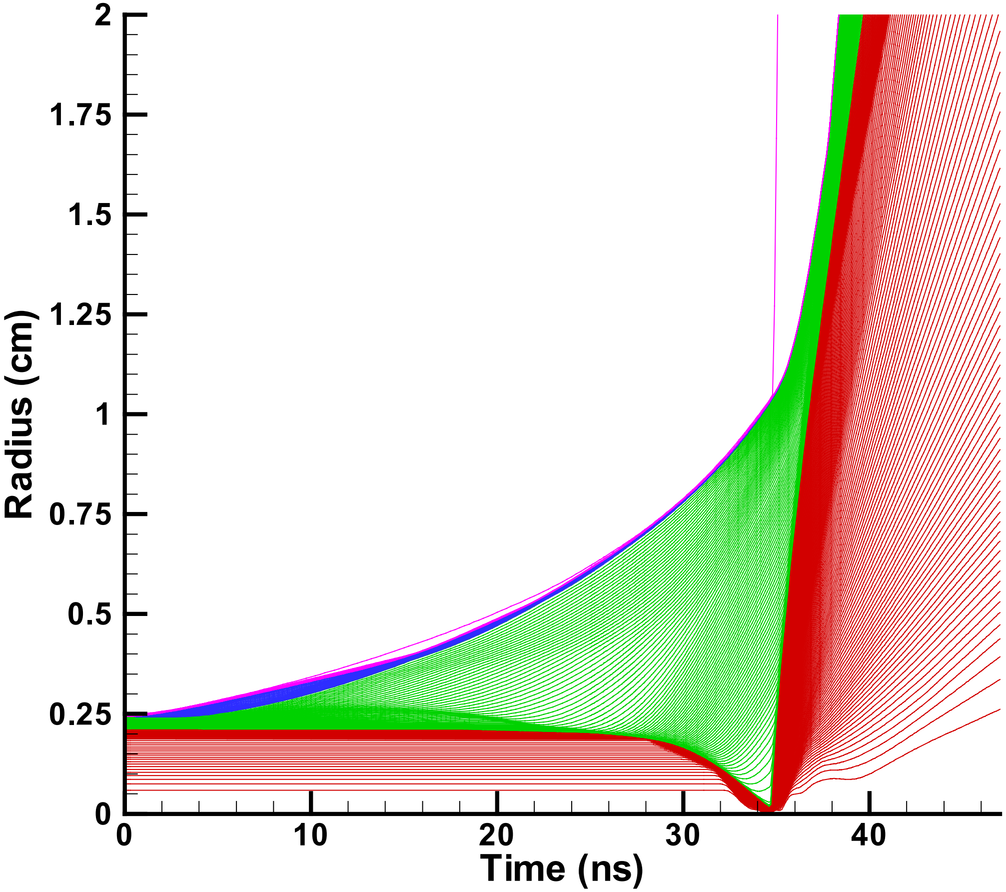
- BUCKY model has 56 zones of Pd.
- Laser Heating of Pd blows it off of target
- EOSOPA opacity leads to more radiative cooling and slow expansion.
- Shock after ignition time causes rapid blow off.



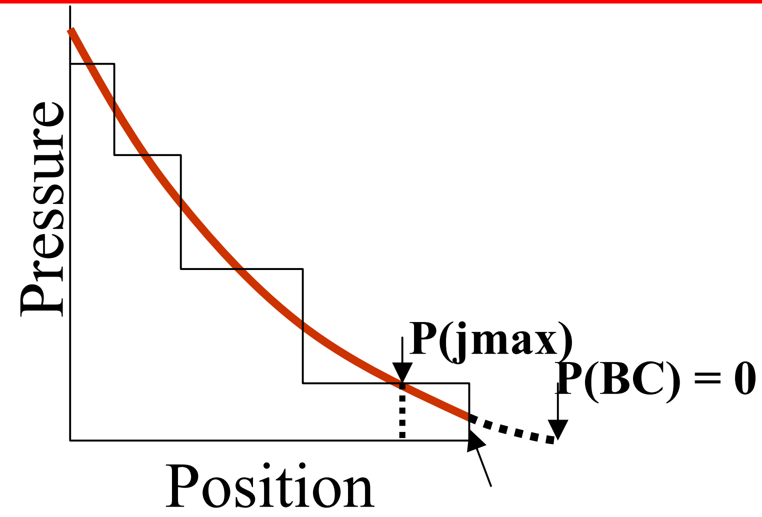



# Disassembly of the Target is Driven by Energy Released in the Burning Core But Care is Taken in Collisional Limit

IONMIX Au




Addressing weakness in pressure boundary conditions in Lagrangian (BUCKY) code




<u>We have reasons to doubt predictions of very high debris ion velocities</u>

- Hydrodynamic approximation may not be valid because collisional mean-free-path is larger than Lagrangain zones in gold.
- Zel'dovich and Raizer: Rarefaction velocity should not be greater than $[2/(\gamma-1)]c_s$.
- Quasi-neutrality is probably violated in Au/Pd shells.

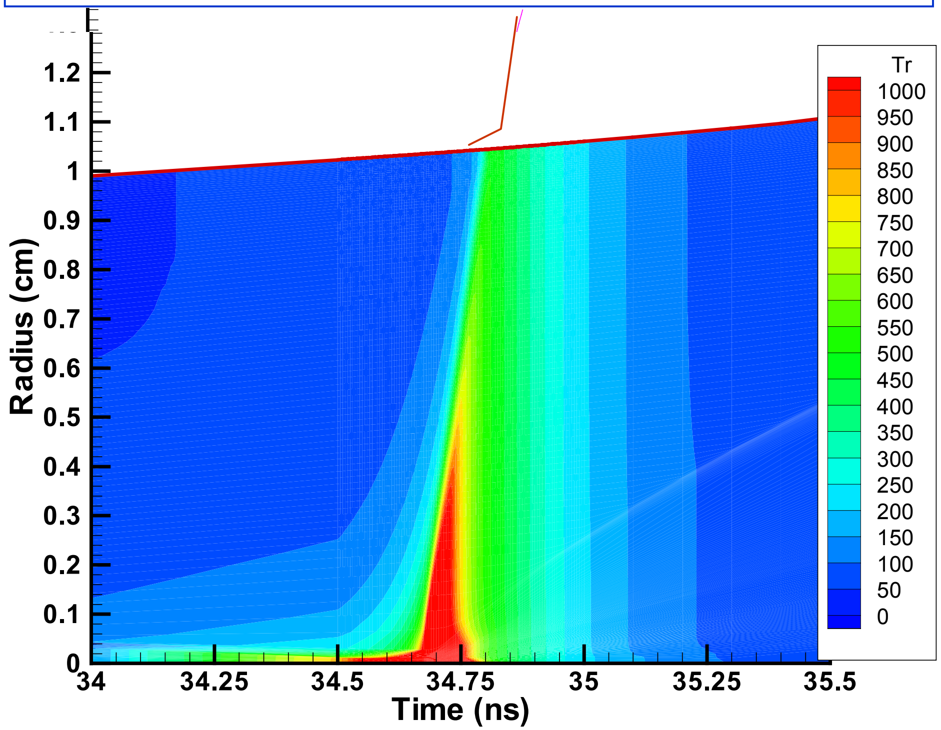
# Radiation Flows Quickly from Burning Fuel Through Ablator, Plastic, and Gold and Heats Electrons

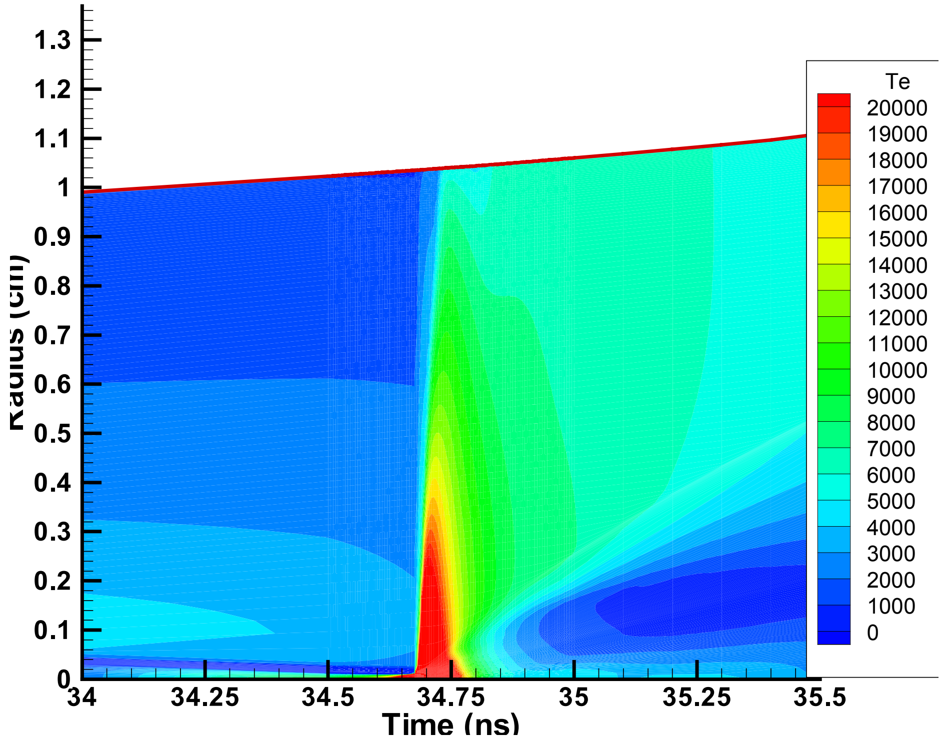
**Radiation "Temperature" ($(E_{rad}/137)^{1/4}$ (eV))**

**Not a real temperature because Radiation Spectrum is far from equilibrium**

**Electron Temperature (eV)**

**BUCKY assumes Maxwellian electron velocity distribution so this is a "real" temperature.**

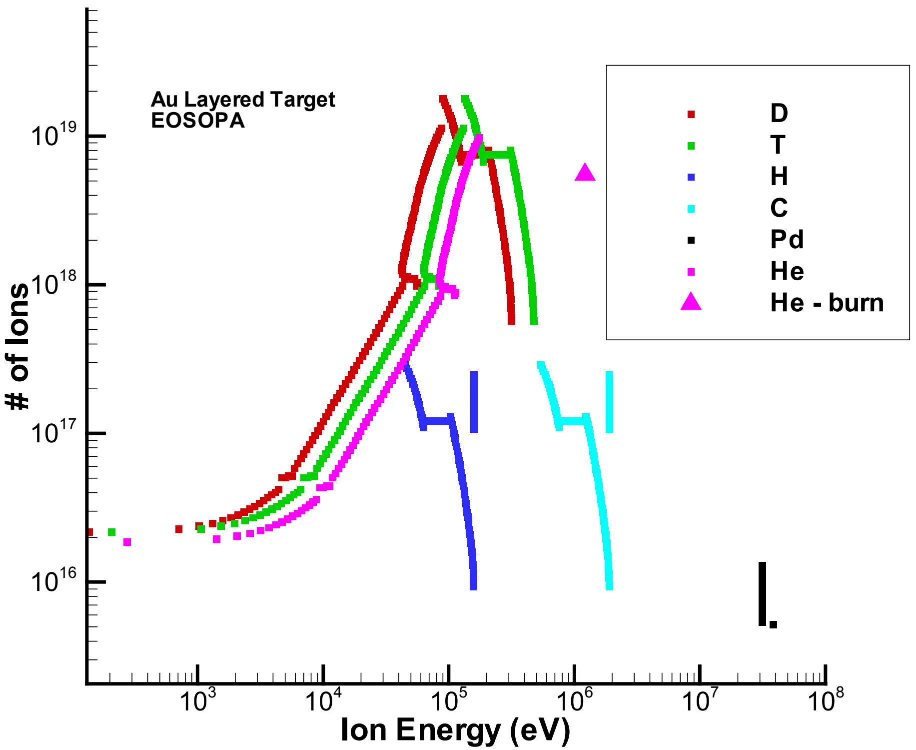


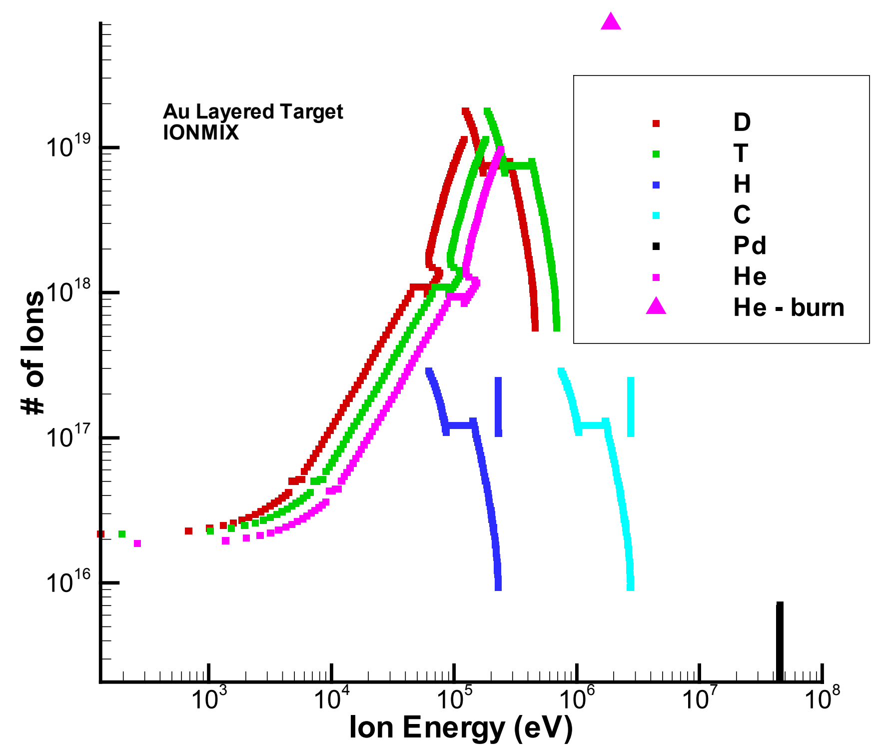




IONMIX Au 270 Zones

# Debris Ion Spectrum from Au-Coated Direct-Drive Laser Target

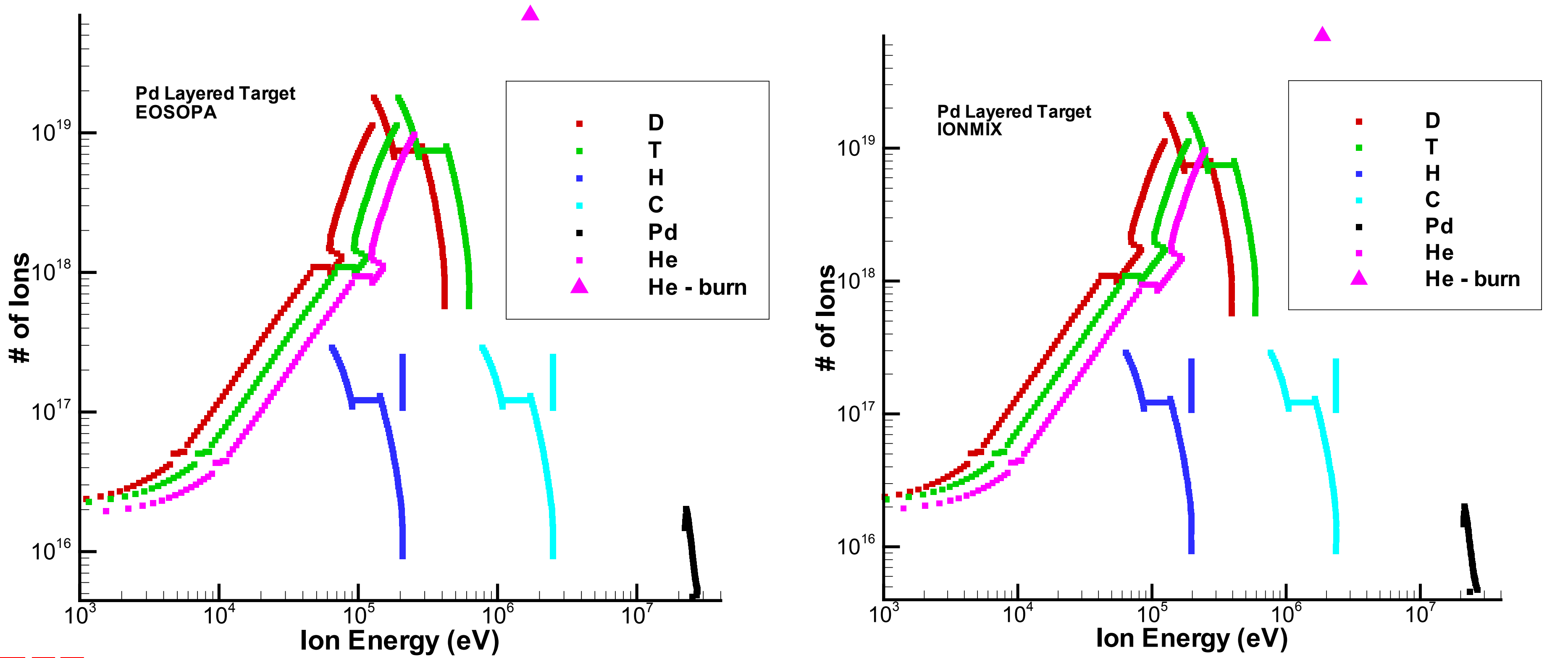
- BUCKY assumes all electrons and ions move a the speed of the hydrodynamic zones where they reside.
- Ion energies = $mv^2/2$.
- Z&R: velocities are limited to a few times the sound speed.
- Escaped Fusion Products Included. BUCKY uses Brysk model for fusion product deposition, what about Corman or Li and Petrasso?



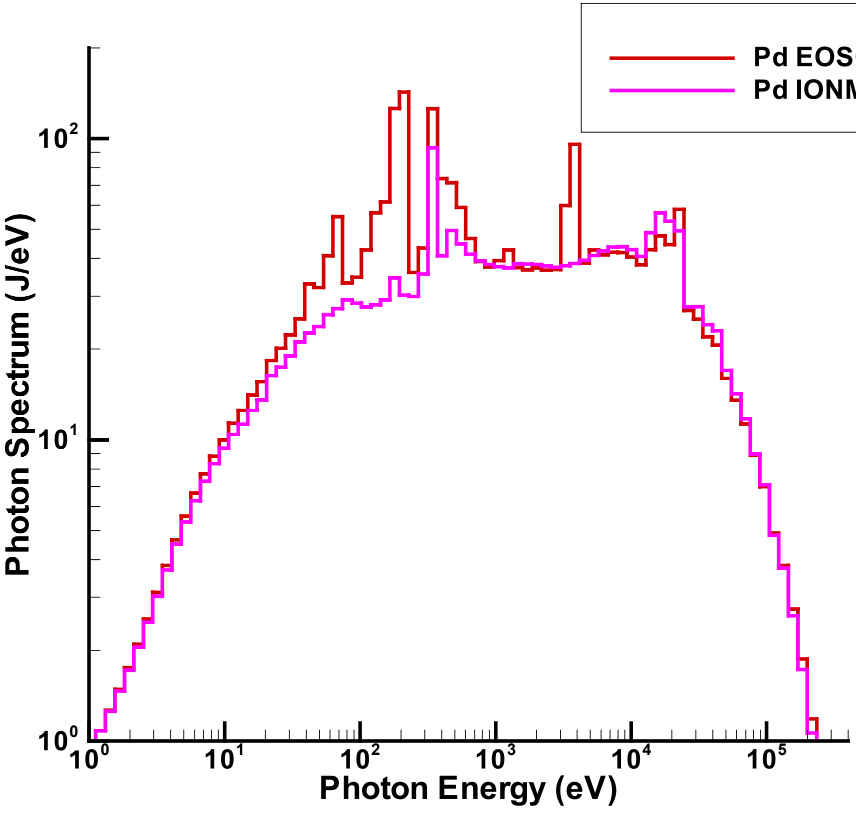
# Debris Ion Spectrum from Pd-Coated Direct-Drive Laser Target

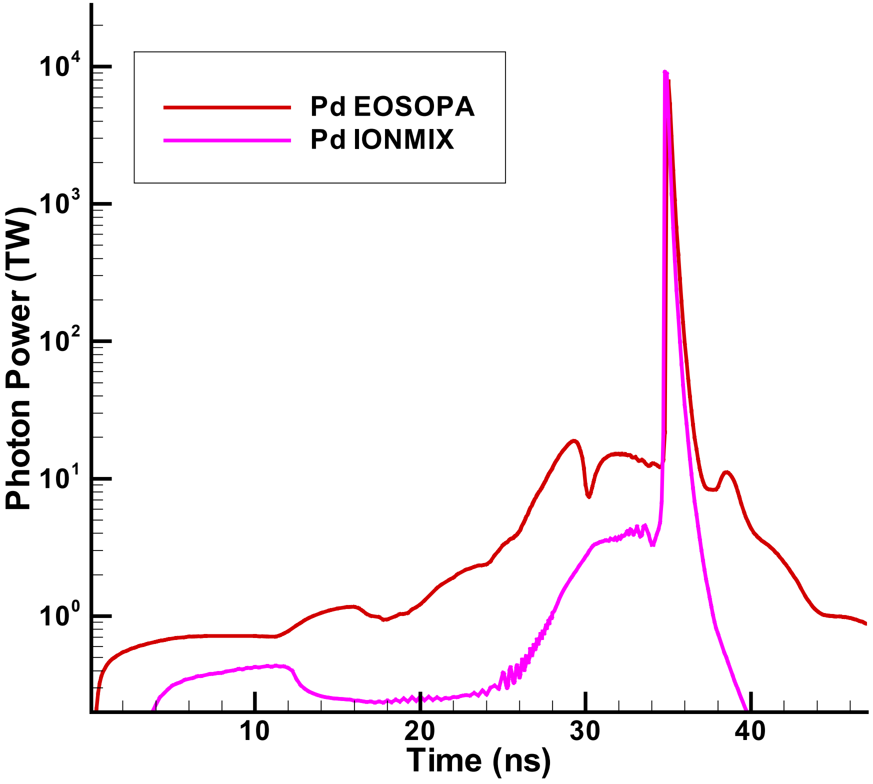
- Pd ions at 10 MeV
- Au ions were at 30 – 40 MeV.
- About 20 MJ in Fusion Produced He. Same for Au IONMIX calculation.
- Very little difference between IONMIX and EOSOPA Pd opacity calculations



# X-ray Spectrum and Power for Pd-Coated Target Is Somewhat Sensitive Ionization Model

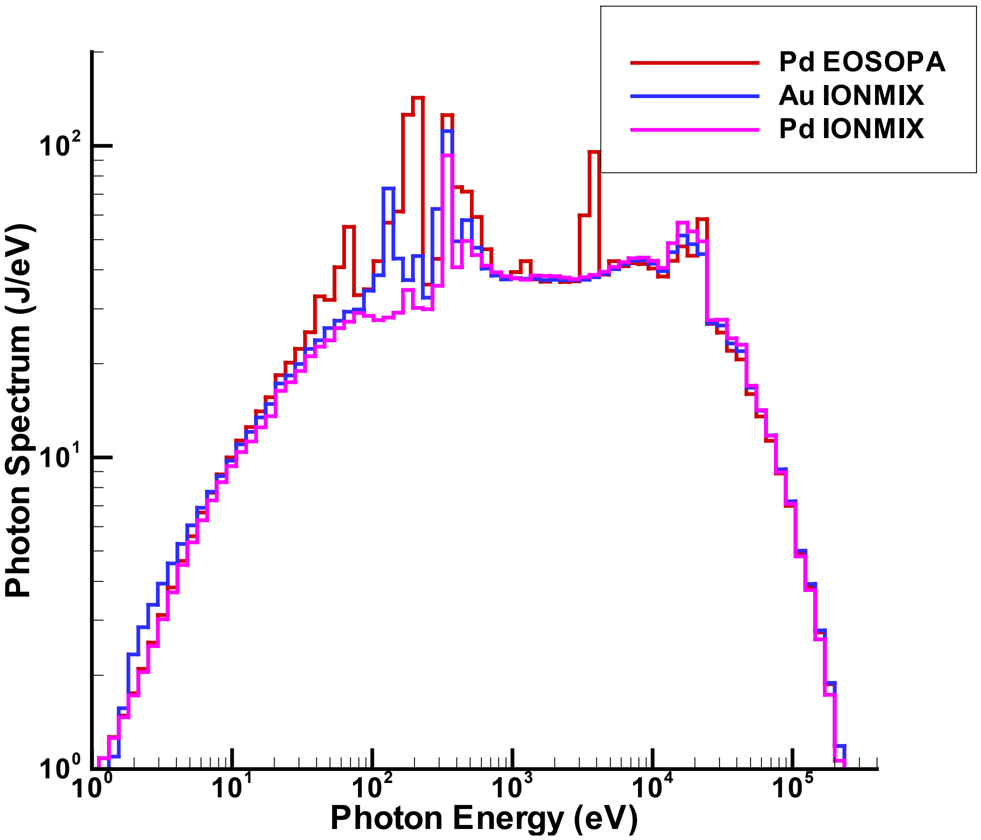
- Continuum part of spectrum is unchanged by choice of Pd opacity model; line emission is changed
- EOSOPA leads to more radiation from target before and after main burst.

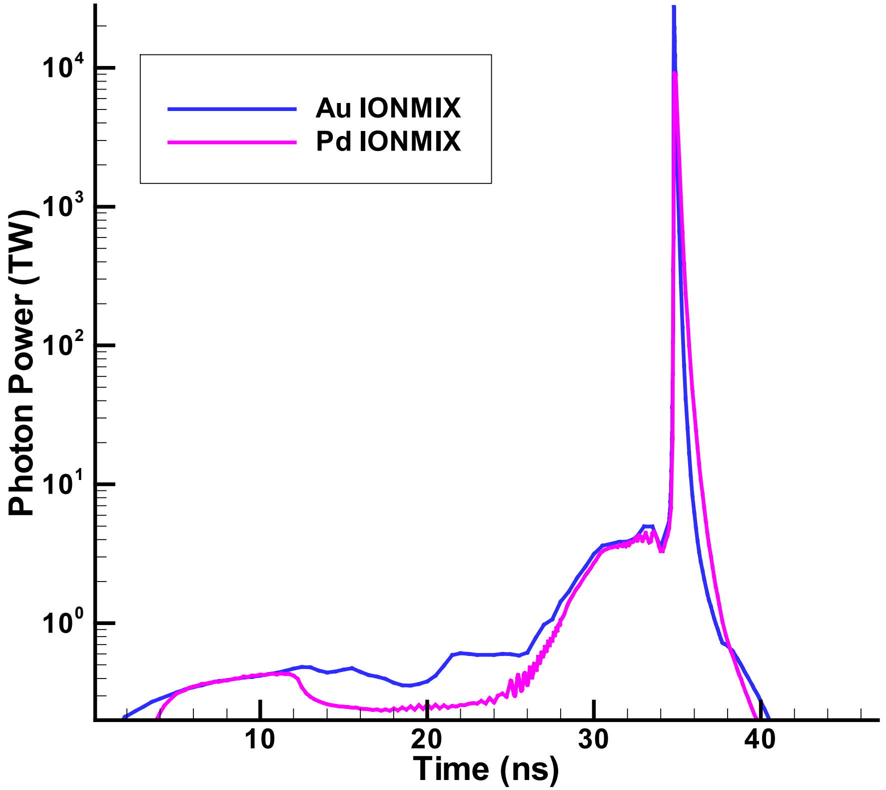


# X-ray Spectrum and Power Predictions for Au-Coated Target Using IONMIX is Similar to Both Pd-Coated Target

- Only difference between Au and Pd target x-ray emission with IONMIX is used is in Line Emission
- Radiative power is very similar.



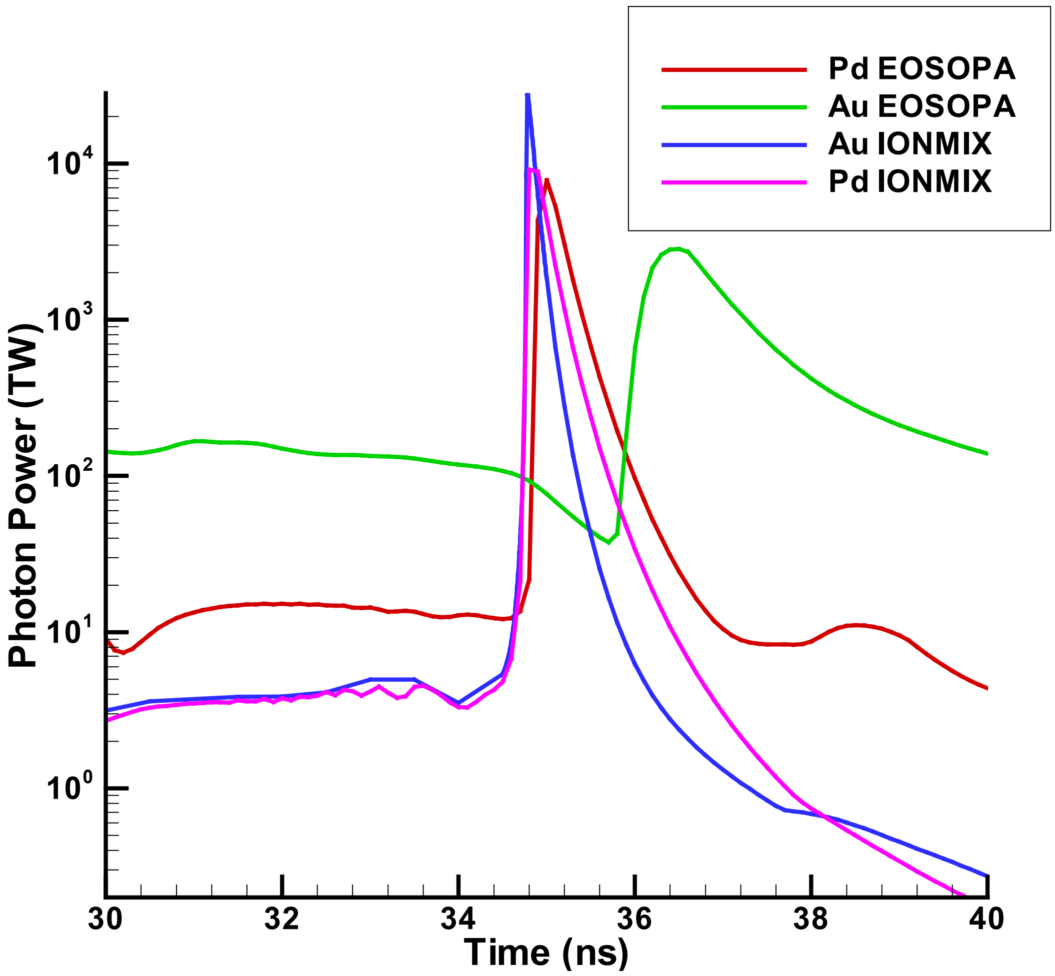



# X-ray Radiation from Target is in a Very Narrow Spike

**Pulse Width (FWHM)**

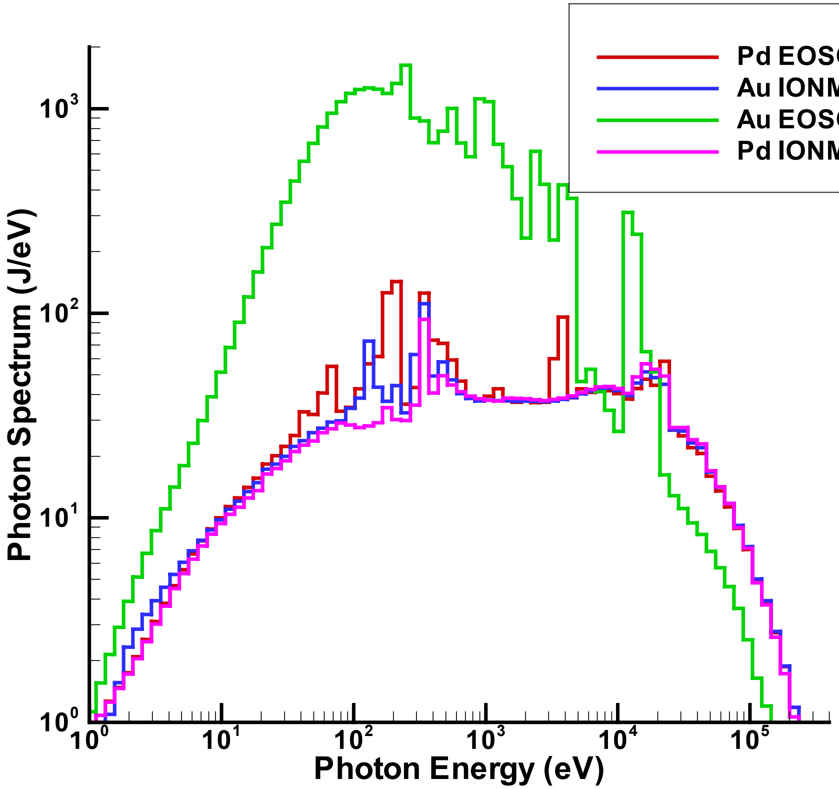
- Pd EOSOPA: ~200 ps
- Au EOSOPA: ~1.5 ns
- Au IONMIX: ~100 ps
- Pd IONMIX: ~150 ps

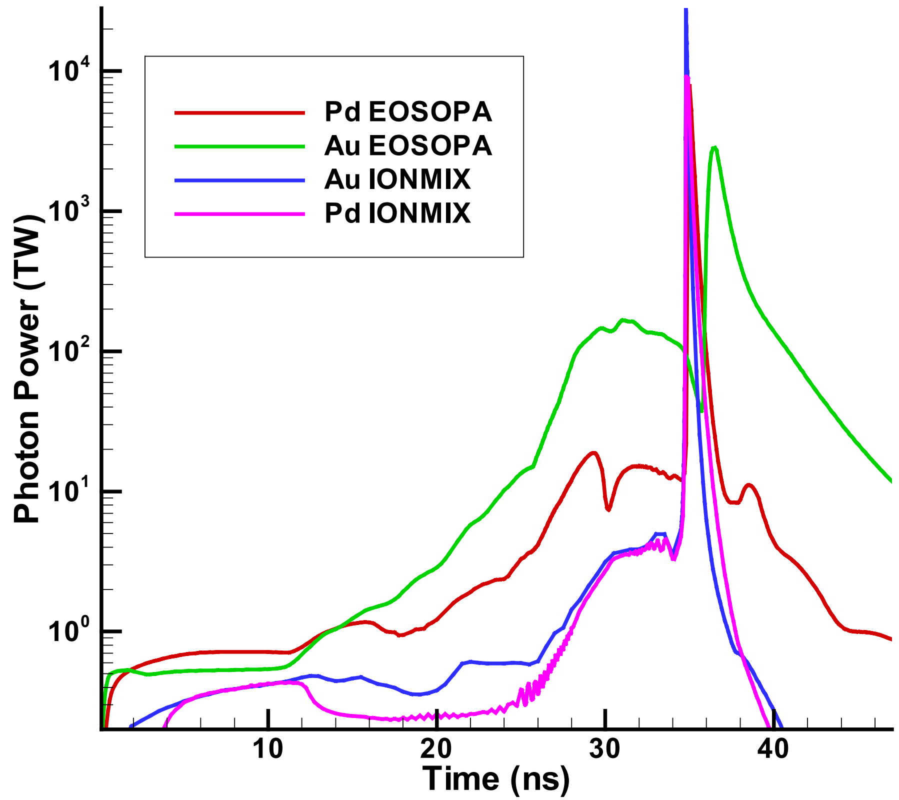
- X-ray Pulse-width varies from Au to Pd and IONMIX to EOSOPA.
- All pulse-widths are small compared to thermal diffusion times in chamber walls.



# X-ray Emission for Au-Coated Target Using EOSOPA is Different from All other Calculations

- Au EOSOPA opacity table has been validated through burn through experiments on Nova
- Au EOSOPA emission is much stronger in sub-3 keV spectral region.
- High energy part of continuum is reduced due to lower yield.



# Conclusions

- **Atomic physics and ionization play roles in Laser IFE target x-ray output. The effect of model choice is reduced for Pd compared to Au.**
- **EOSOPA opacities predict greater radiative losses during implosion.**
- **In Pd target, model choice for Pd opacity affects details of radiation-driven shock in ablator, but the yield and ignition time is unchanged.**
- **Very high energy debris ions are due to numerical problems in Lagrangian hydrodynamics and are not physical.**
- **Radiation validation experiments are required for relevant plasma conditions and need to be considered when discussing IRE plans..**