Direct Measurement of Density Gradients Using Refraction Enhanced Radiography at the National Ignition Facility

HEDS seminar series

A. Do

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LLNL-PRES-843163

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Lawrence Livermore National Laboratory

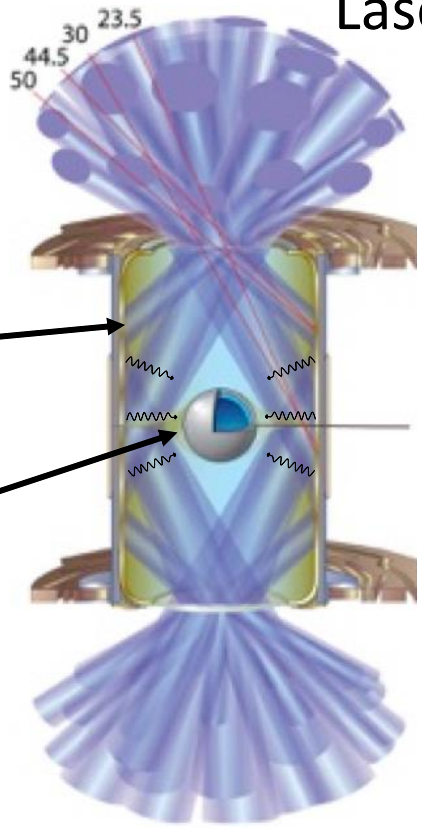
Acknowledgements

E. Dewald, O. Landen, C. Weber, D. Casey, D. Clark, S. Khan, A. McPhee, V. Smalyuk, S. Cheng, S. Nagel, K. Raman, N. Izumi, G. Hall, D. Bradley, T. Doeppner

Lawrence Livermore National Laboratory, USA

Understanding physics experiments at NIF requires very high quality x-ray imaging

Capsule implosion experiments for Inertial Confinement Fusion (ICF)



- Experiments at NIF typical scale are
  - Few 100s microns
  - Few picoseconds to nanoseconds

- Hostile environment for diagnostic (high temperature and density)

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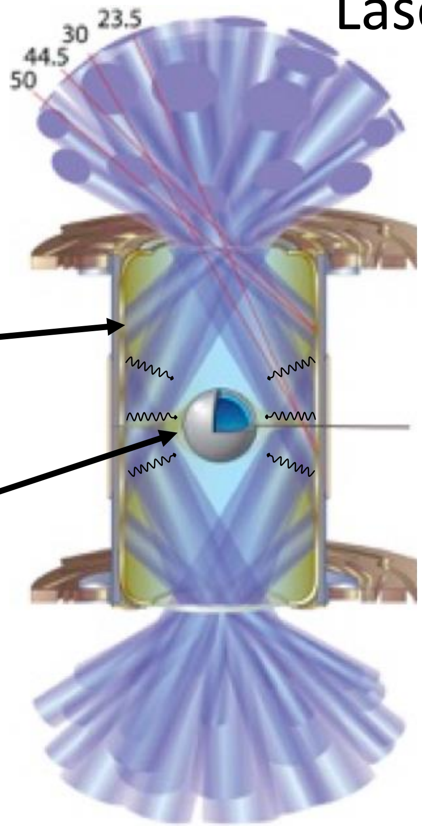
Laser Beams



Hohlraum

Capsule
~1 mm diameter

Laser Beams

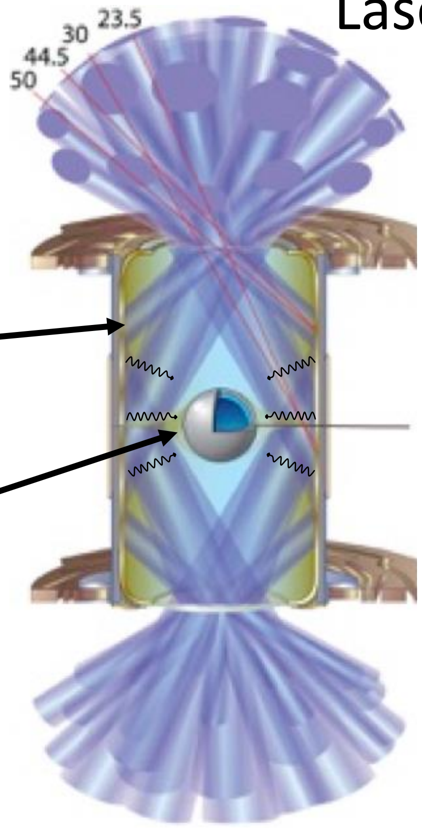
12/05/2022

3.15 MJ of fusion yield

Understanding physics experiments at NIF requires very high quality x-ray imaging

Capsule implosion experiments for Inertial Confinement Fusion (ICF)

Laser Beams



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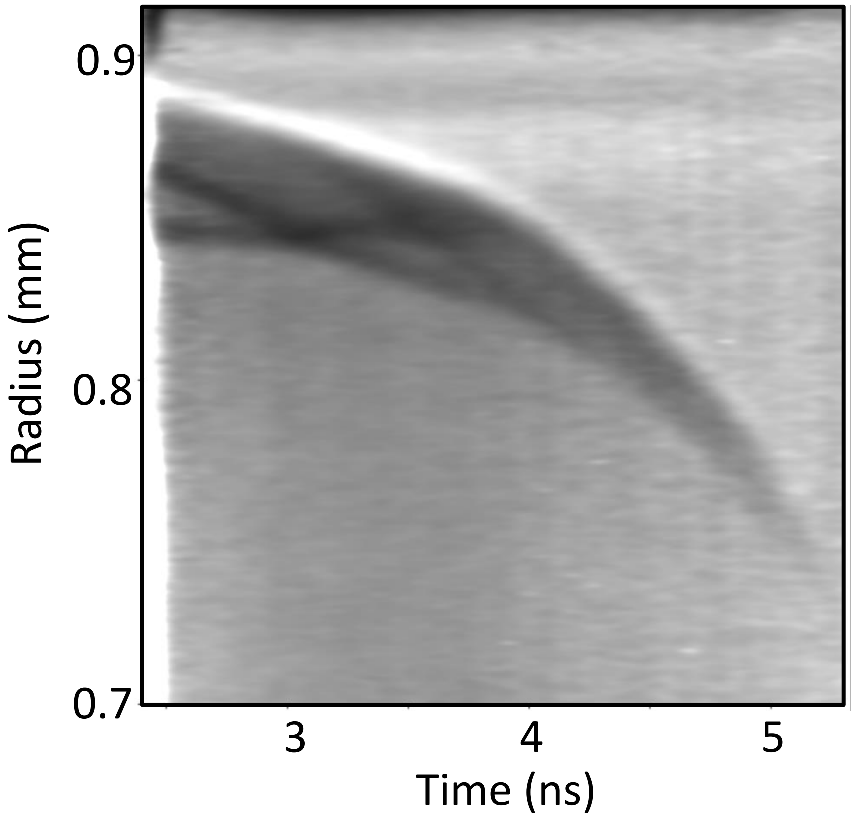
Summary

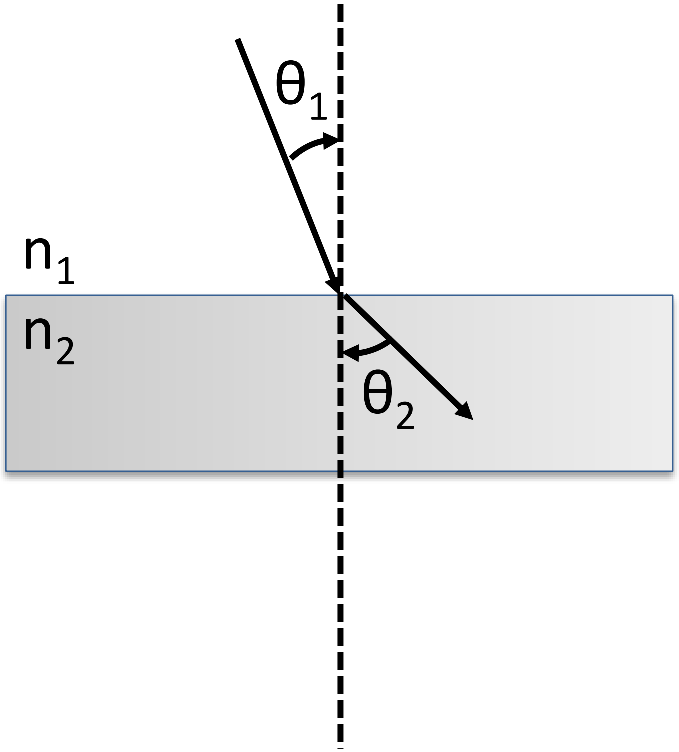
Refraction Enhanced Radiography (RER) is a useful tool for experiments at the National Ignition Facility

- High spatial (< 10 µm) and time resolution (<100 ps) 1D x-ray radiograph are required on NIF.
- RER has higher contrast than classic absorption experiments
- Used to retrieve density gradients and follow interfaces trajectory in capsule physics:
  - N+1 shock effect
  - Ice-ablator interface trajectory
- Thermal conductivity measurement in warm dense matter.
- Used to look at shock trajectory and timing inside a shocktube for hydrodynamic experiments.

RER data of capsule implosion



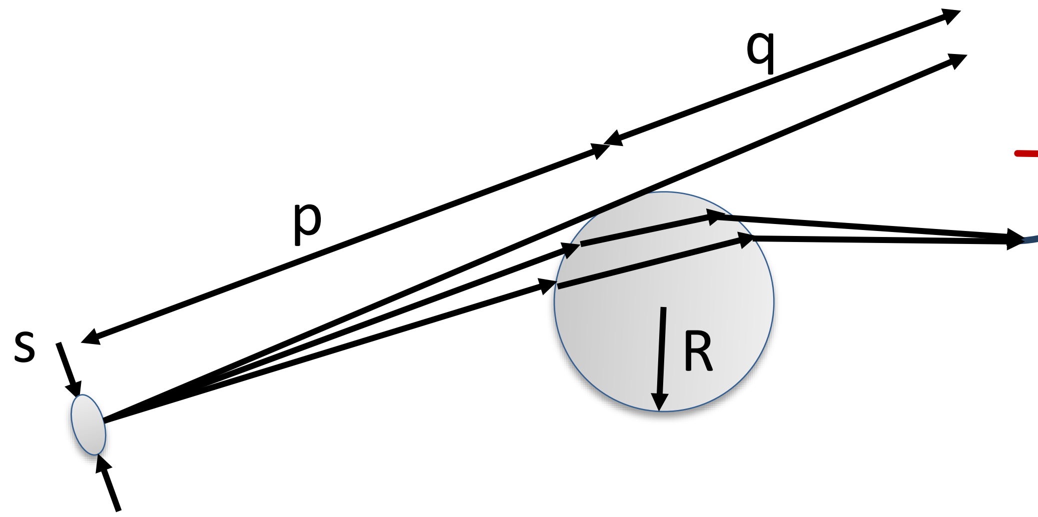
Refraction happens when light is passing from a medium to another one

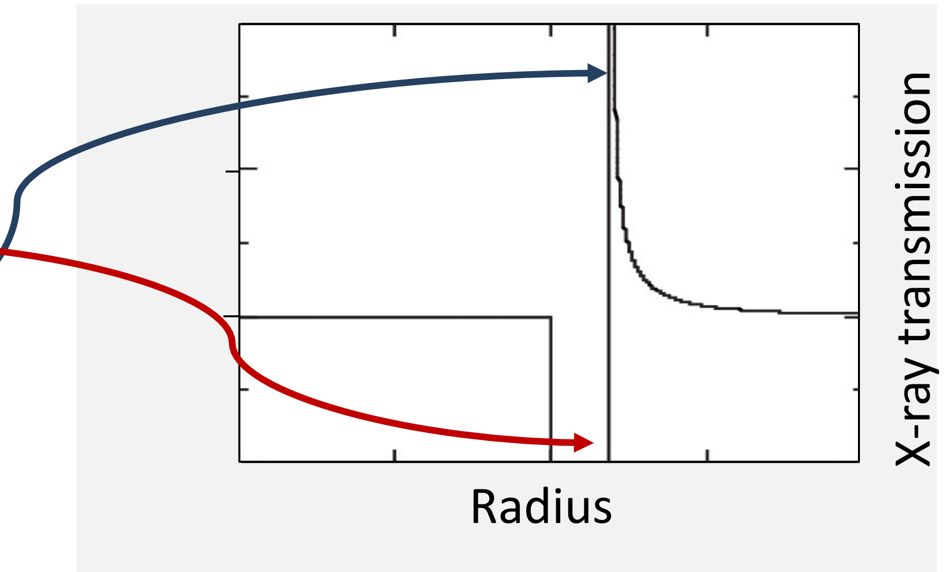


Snell's law

$$n_1 sin(\theta_1) = n_2 sin(\theta_2)$$

Refraction Enhanced Radiography (RER)* is a phase contrast imaging method that uses the difference in refractive index among materials





If $q >> p$, slit size s must satisfy:
s (µm) < $3[p\Delta n\,(R/2)^{1/2}]^{2/3}$

$$\Delta n = \frac{n_e}{2n_c}$$

*J. Koch, Journal of Applied Phys. 105, (2009).

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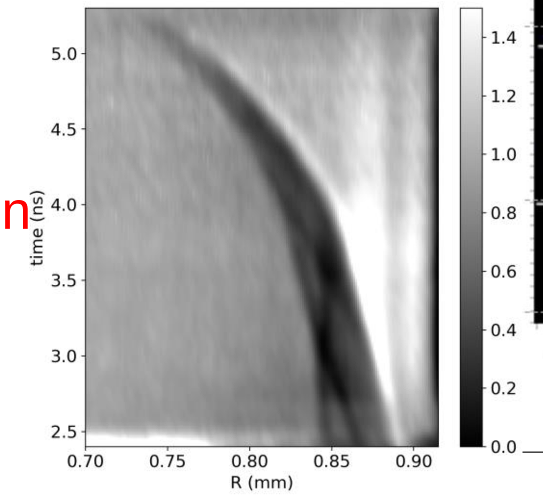
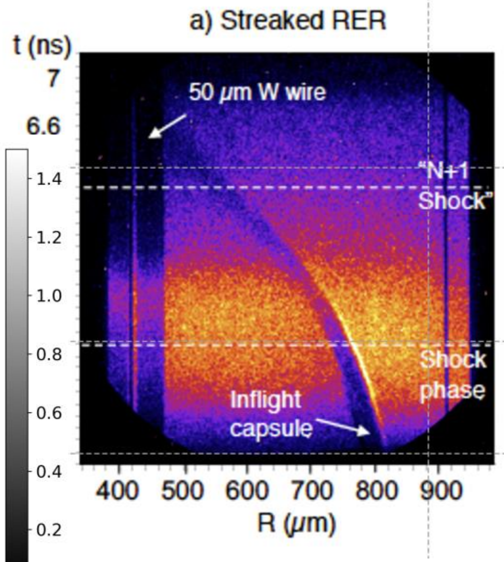
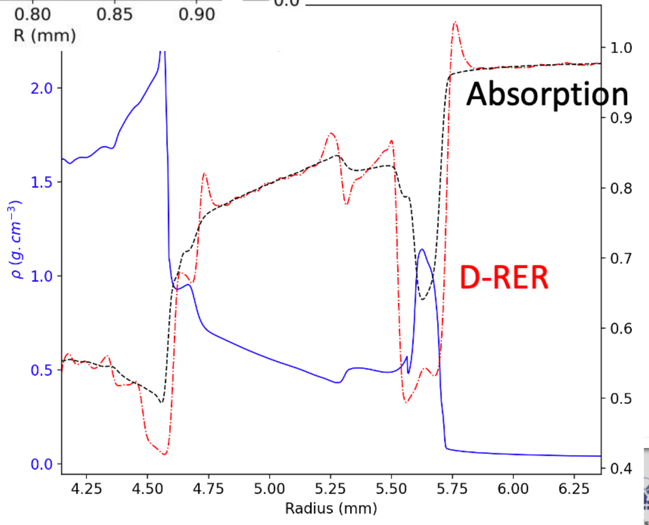
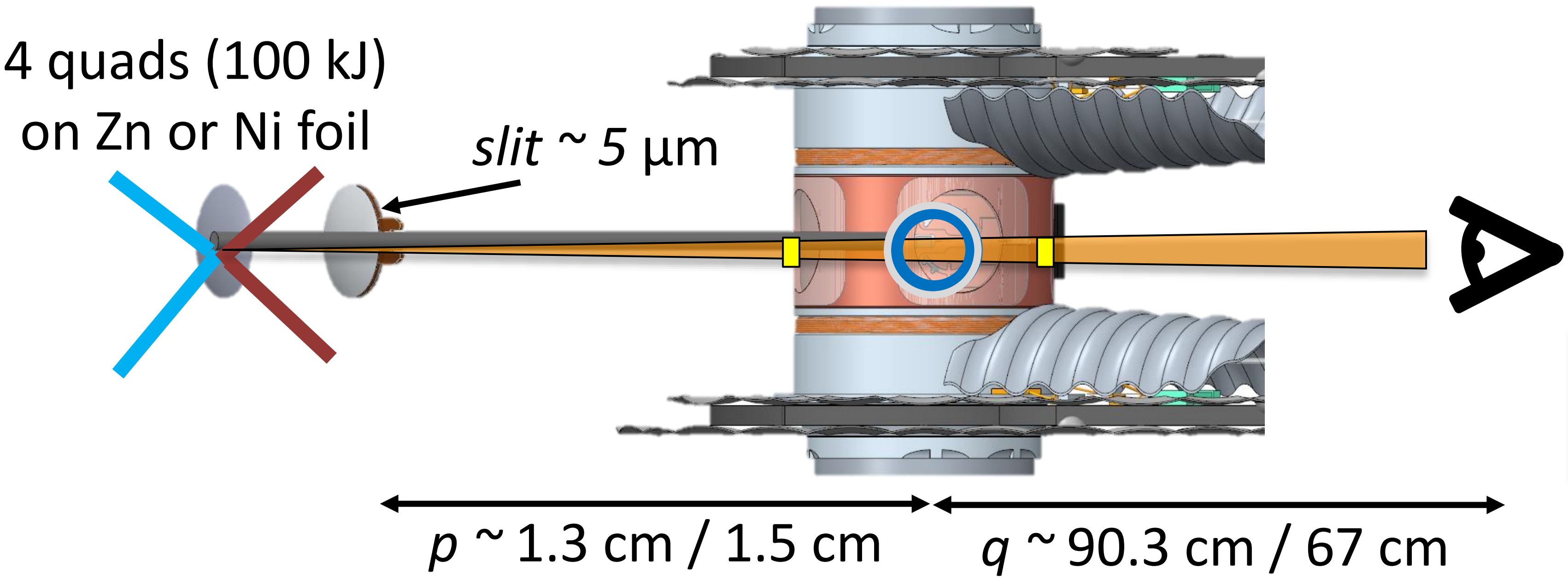






Refraction Enhanced Radiography for capsule implosion experimental set-up on NIF



Transmission function *T(x)*:

$T(x) = R(x)A(x)$

Refraction

Absorption

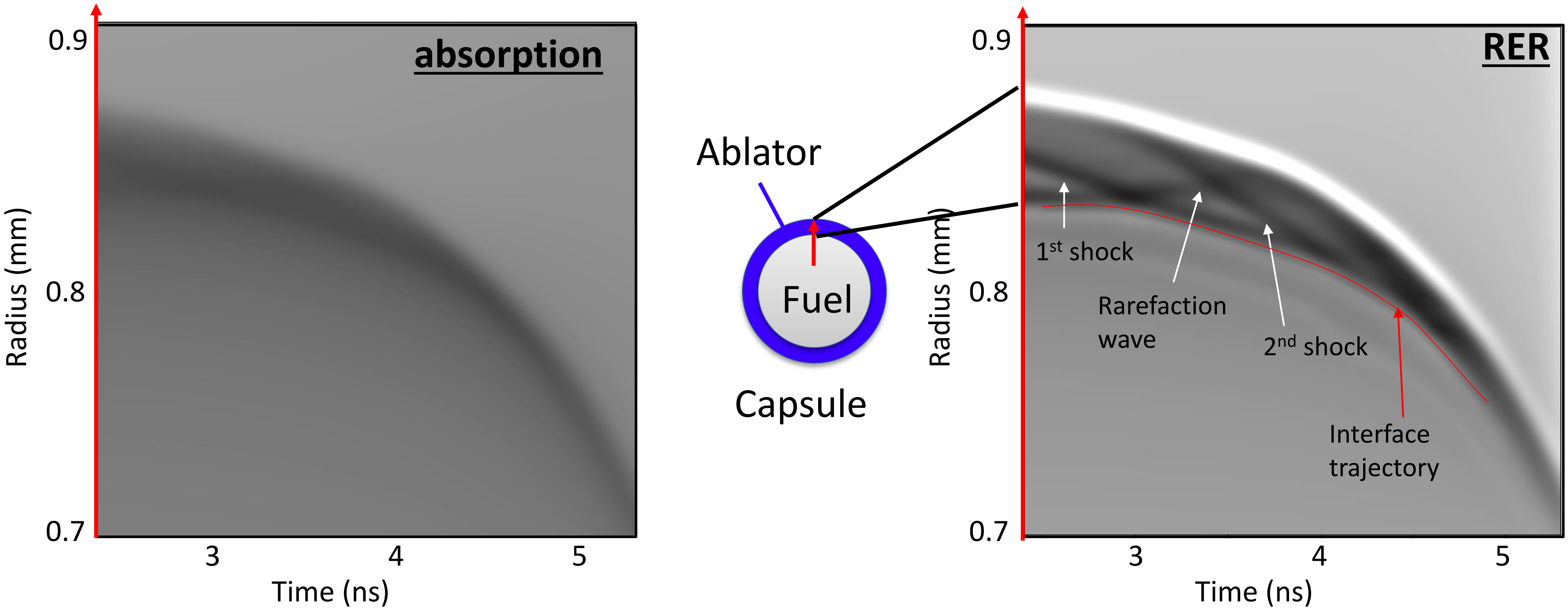
Resolution:

- Spatial: 5 µm
- Temporal: 25 ps
- ΔN_e: 10^{23} ~ 10^{24} cm^{-3}

E.L. Dewald, O.L. Landen, et al, High En. Dens. Phys. 36, 100795 (2020).

RER uses refraction to measure density gradients with higher contrast than classic absorption

Simulation for an "HDC" drive



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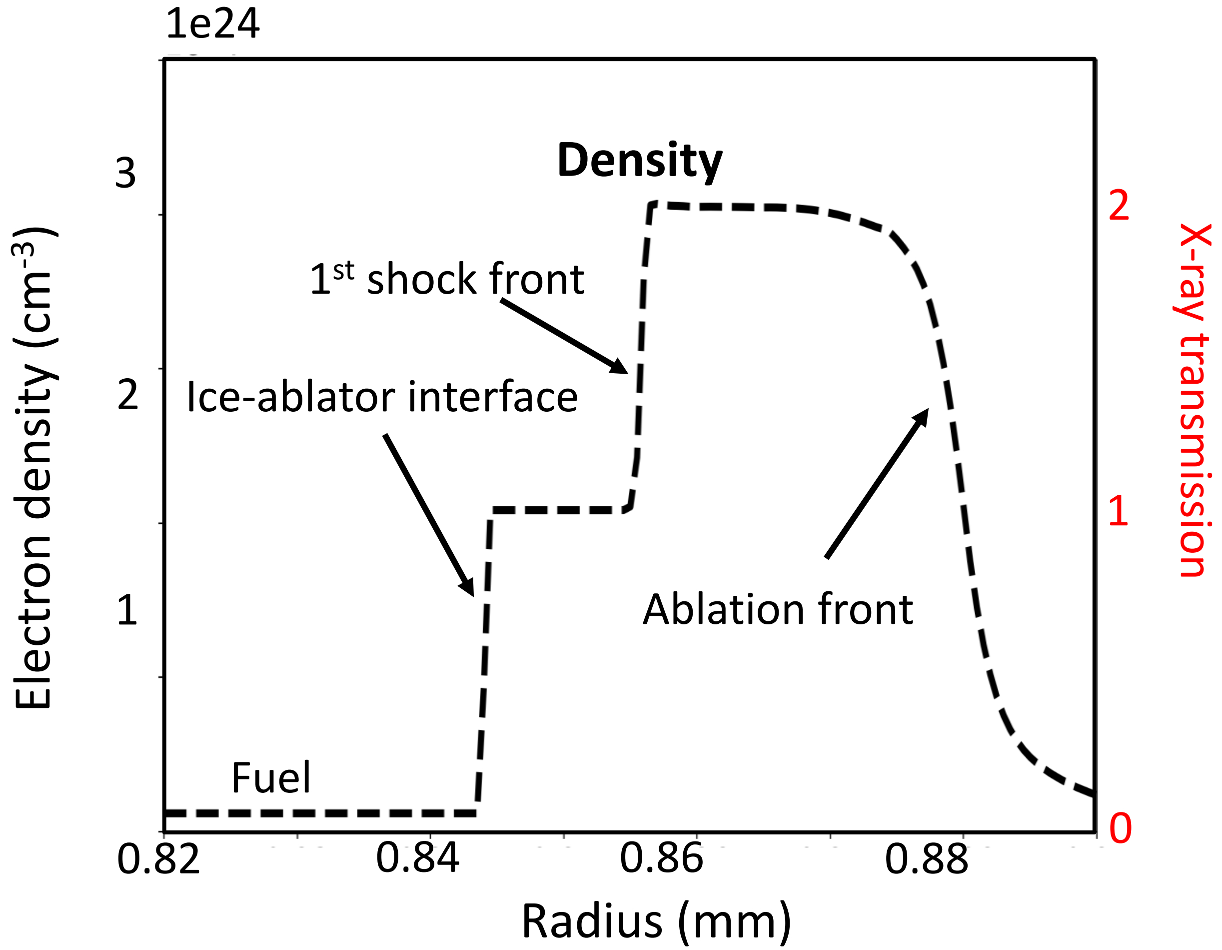
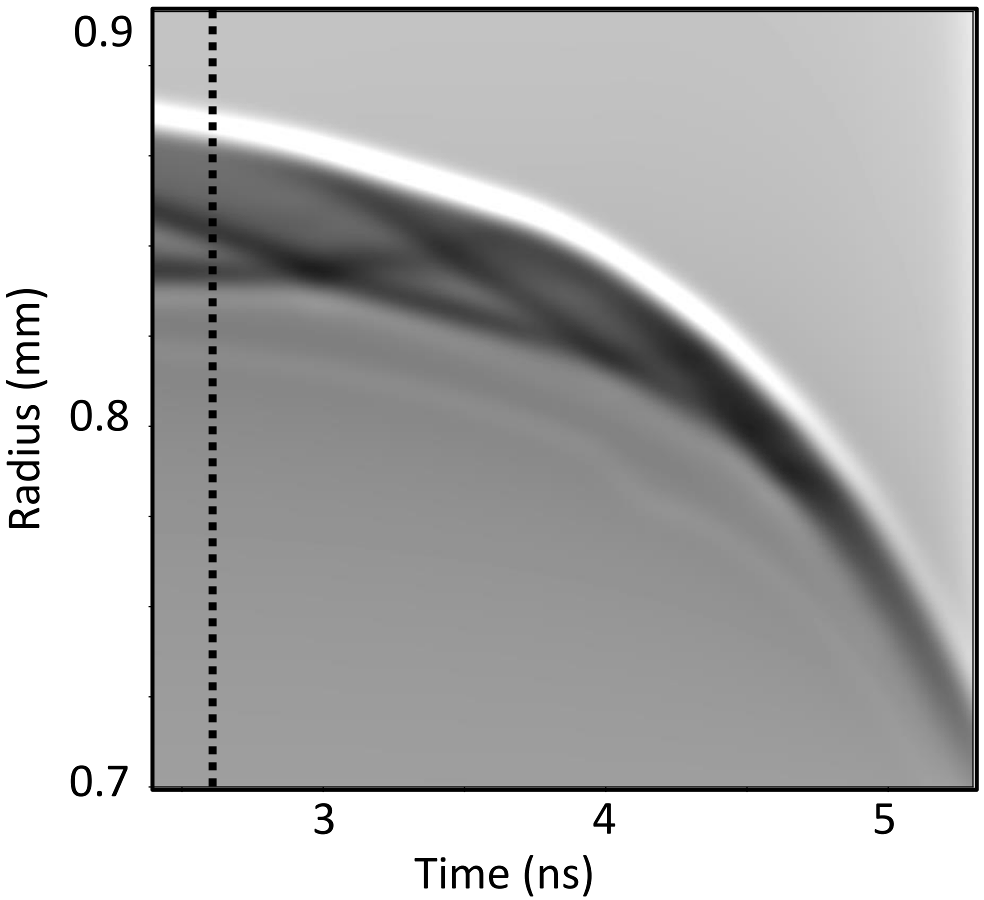


Simulation for an "HDC" drive



*J. Koch, JAP 105 2009, E. Dewald, HEDP 36, 2020

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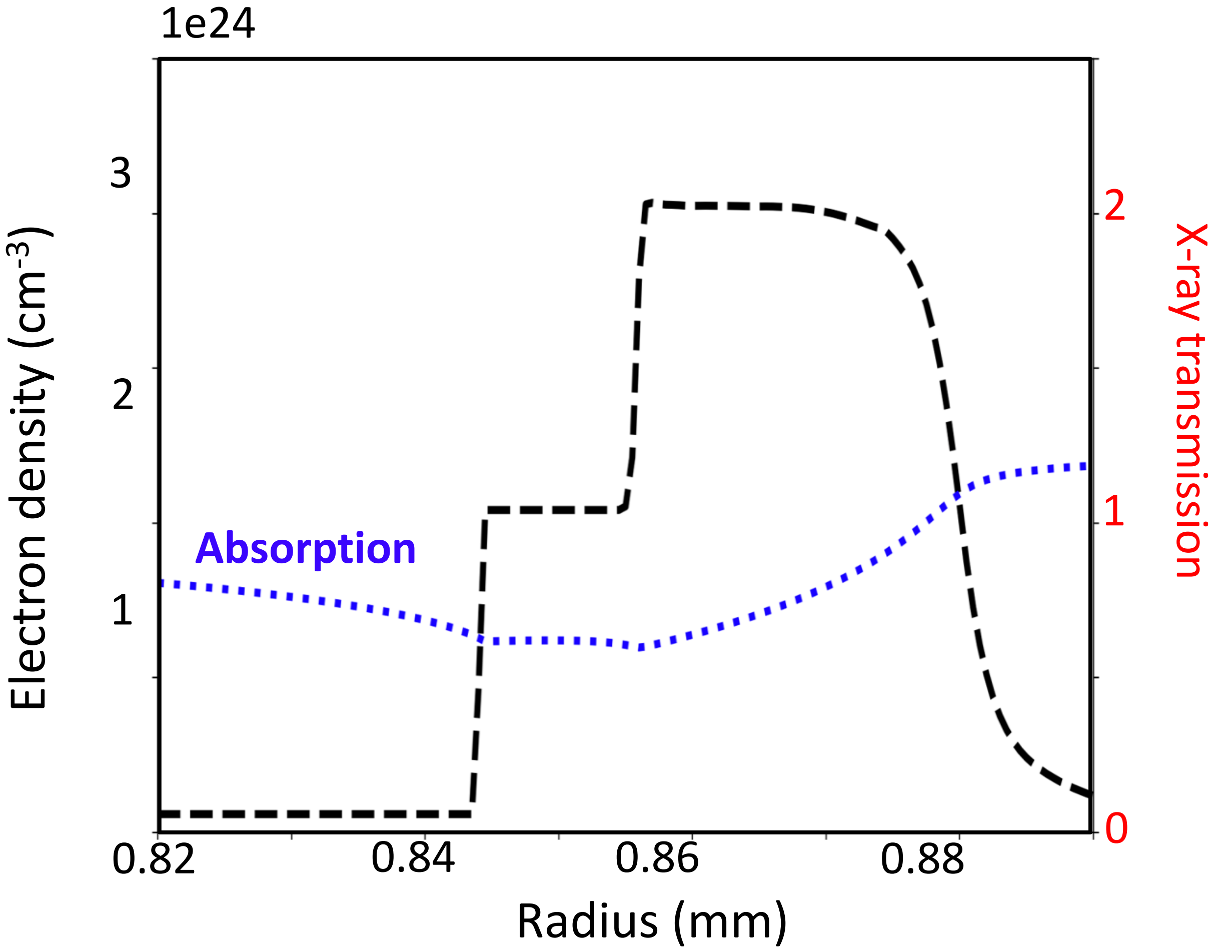

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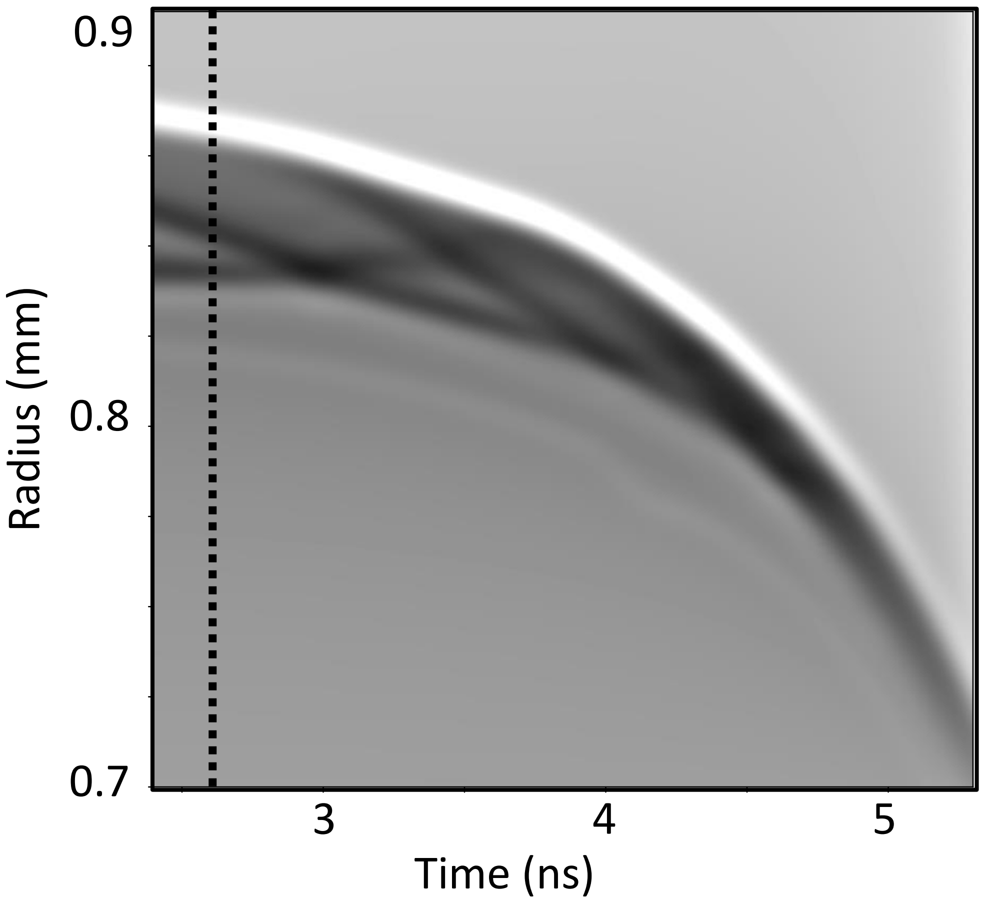

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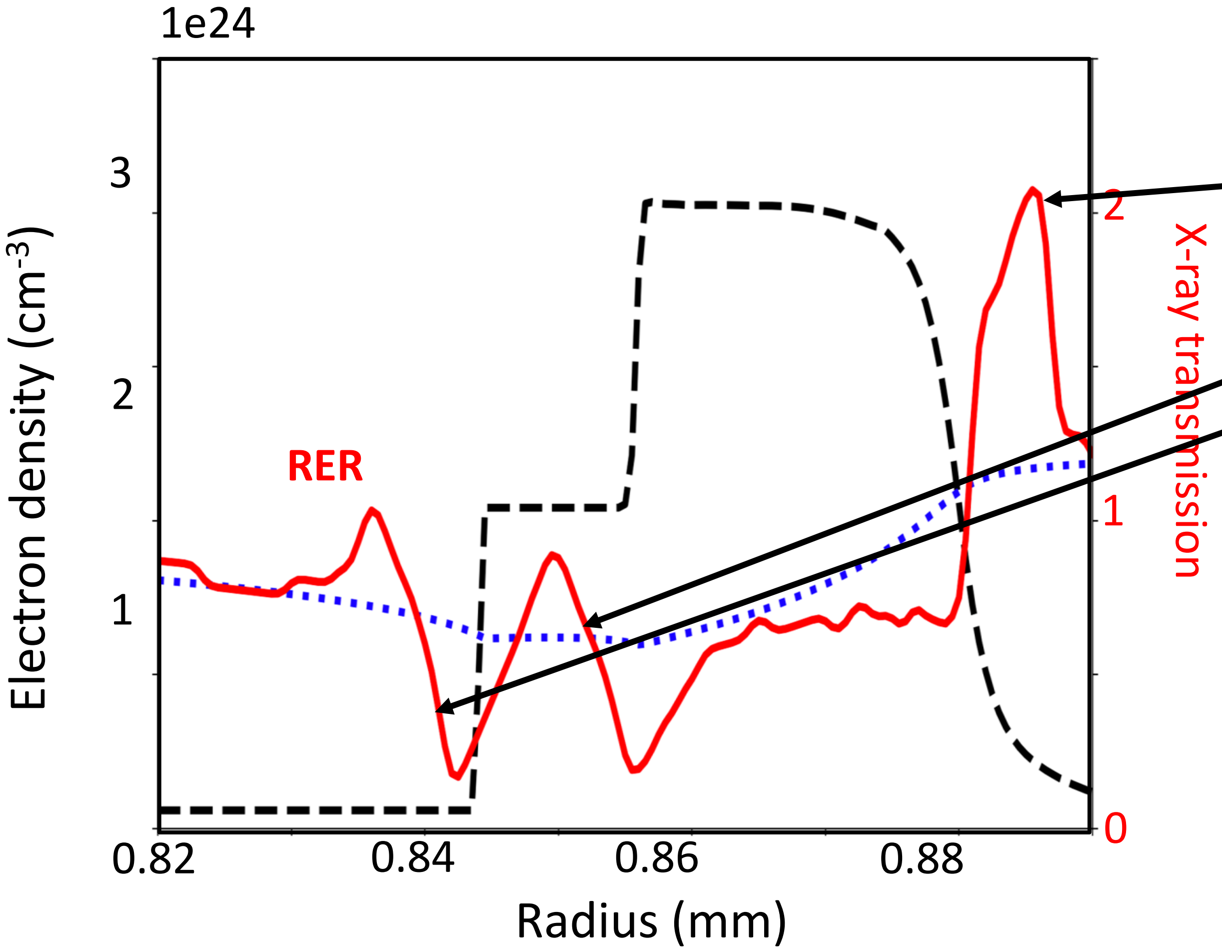

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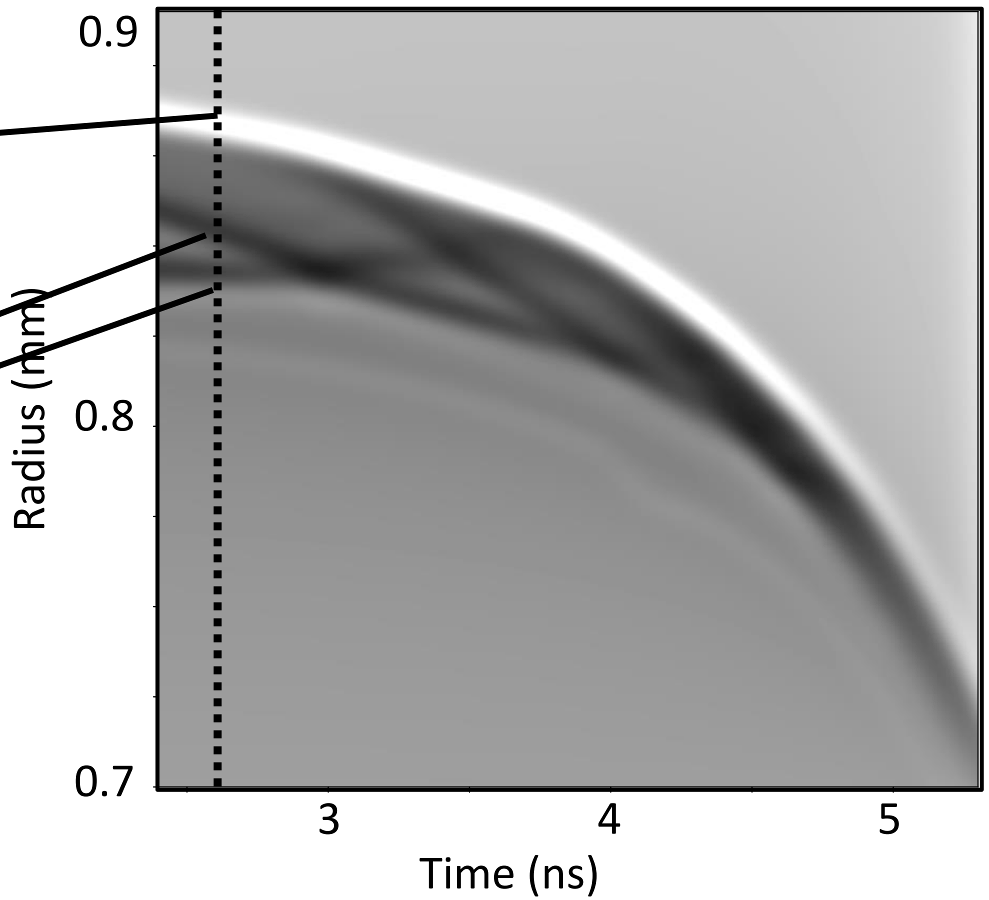
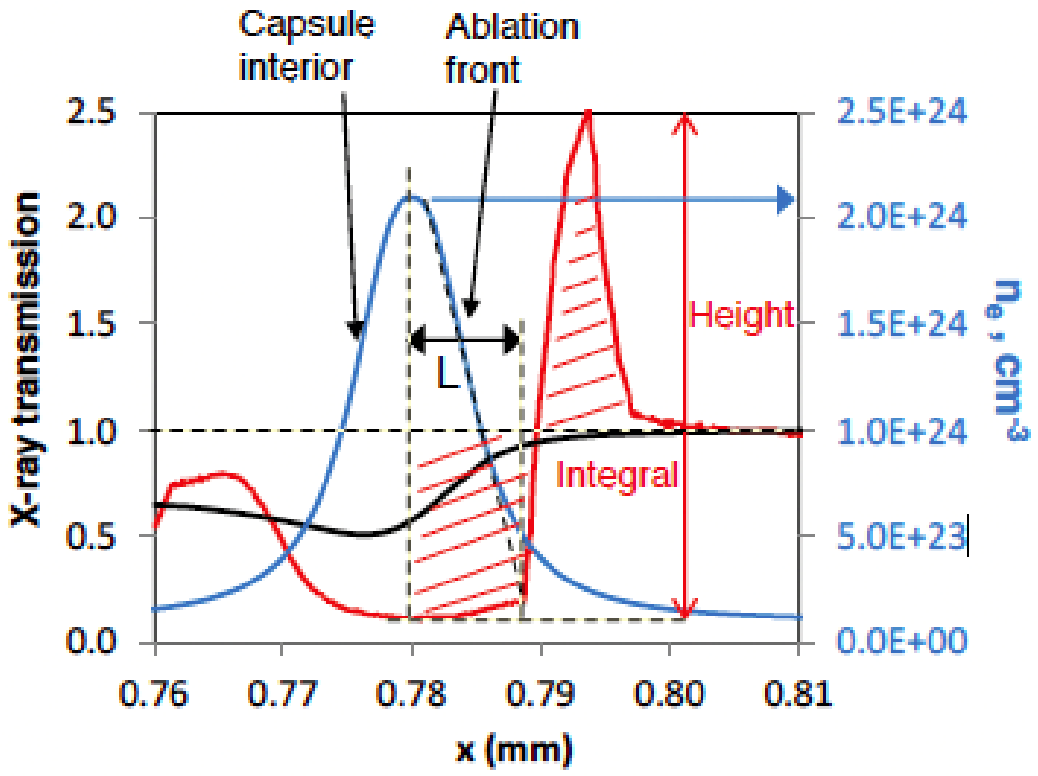
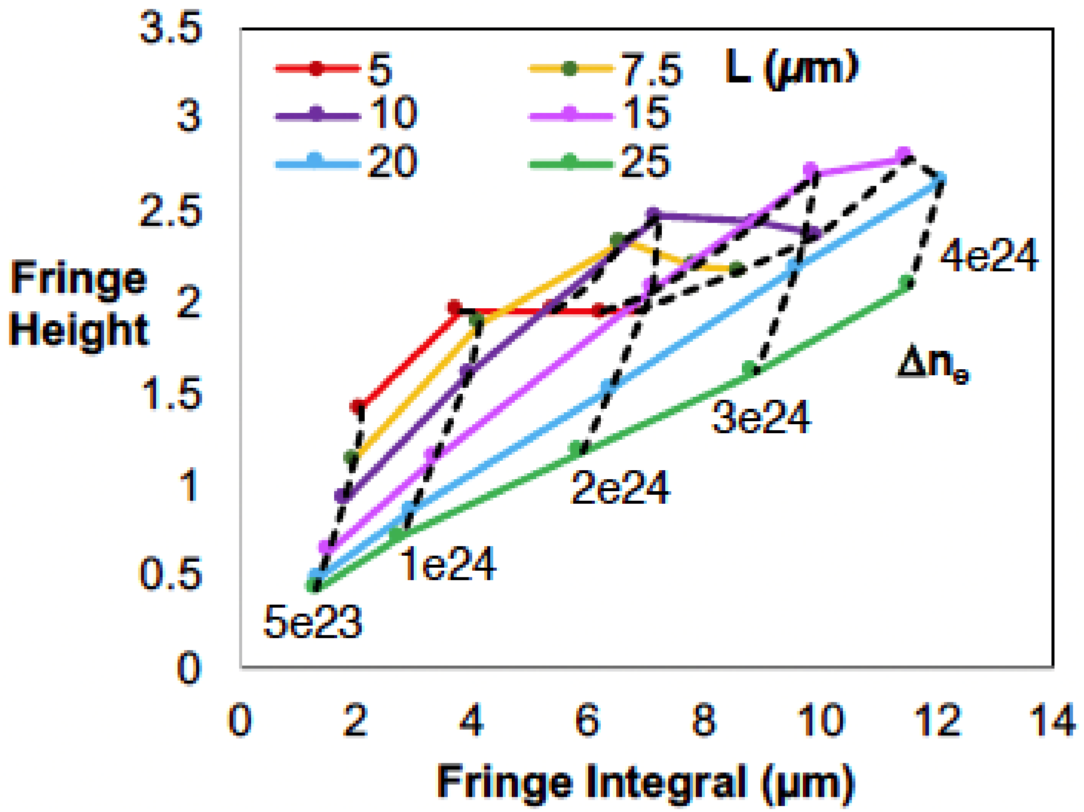


*J. Koch, JAP 105 2009, E. Dewald, HEDP 36, 2020

The density gradient can be inferred from the RER data

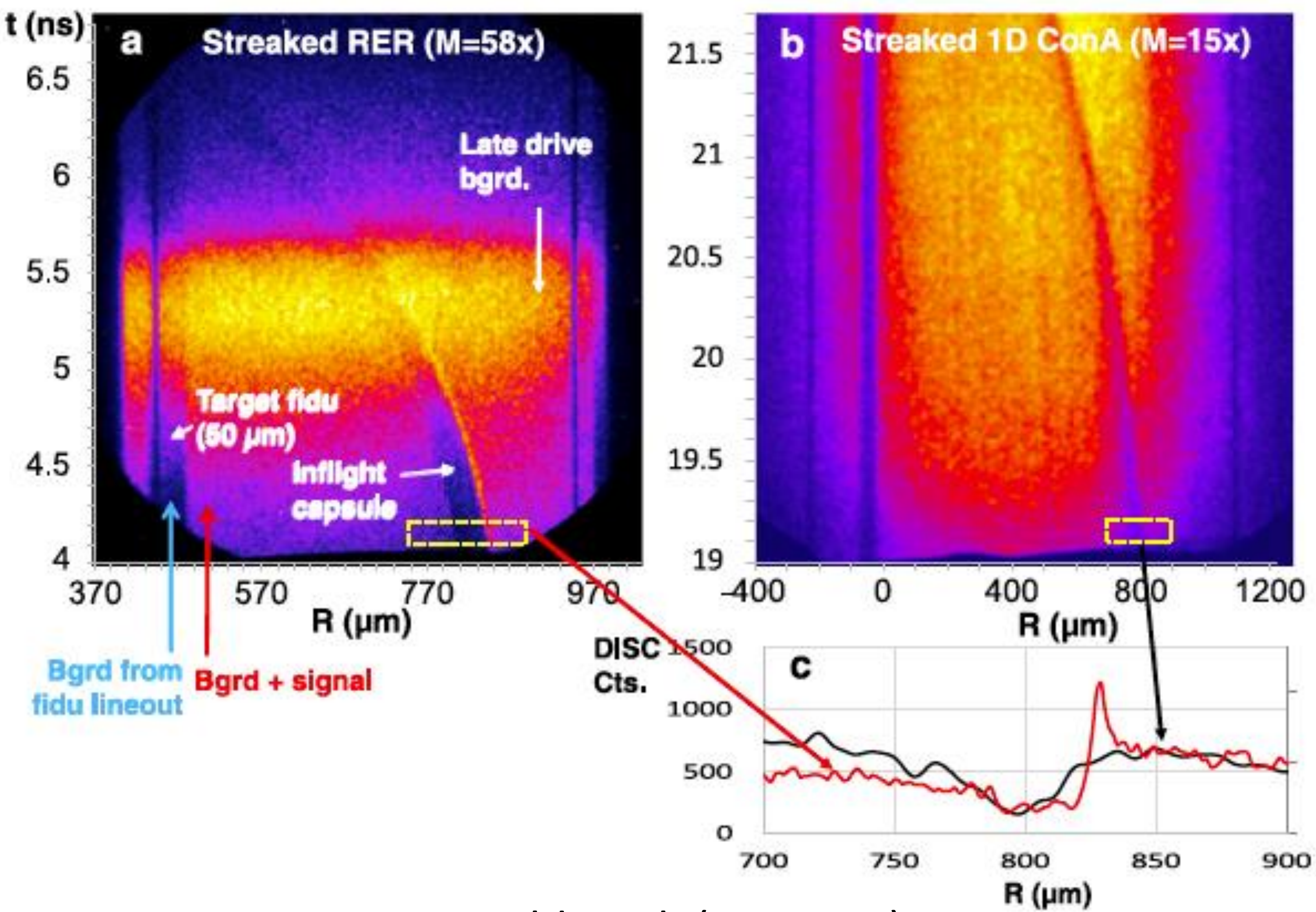




fringe height and integral are nearly orthogonal to density features:
integral ~ density, while height ~ density scale length

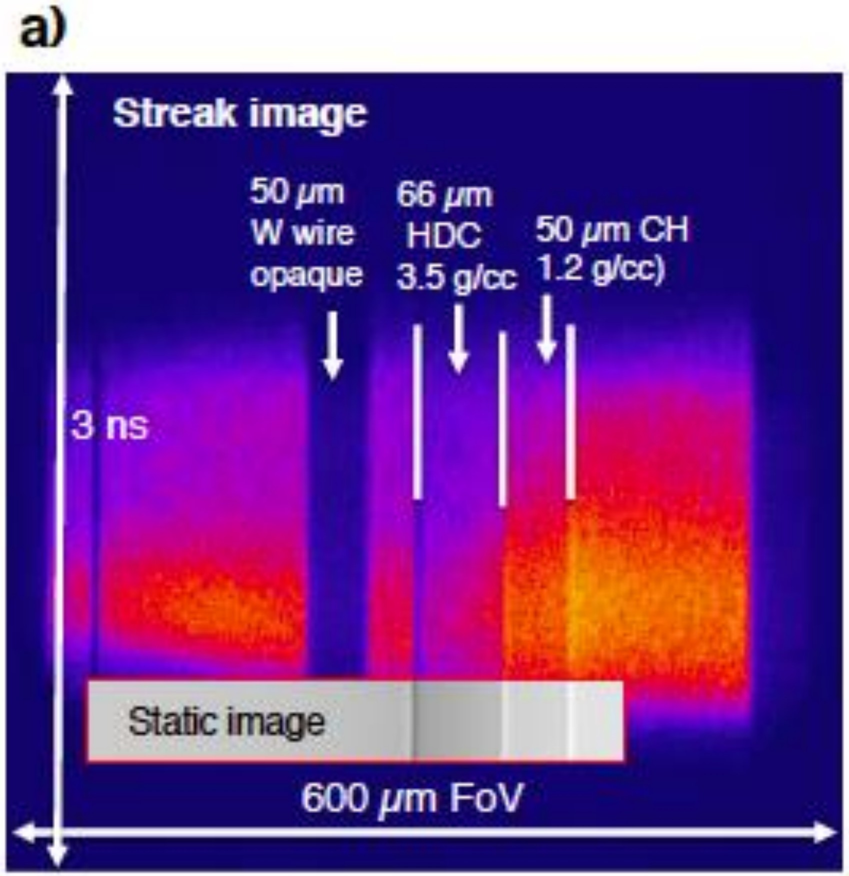
Dewald et al. (HEDP 2020)

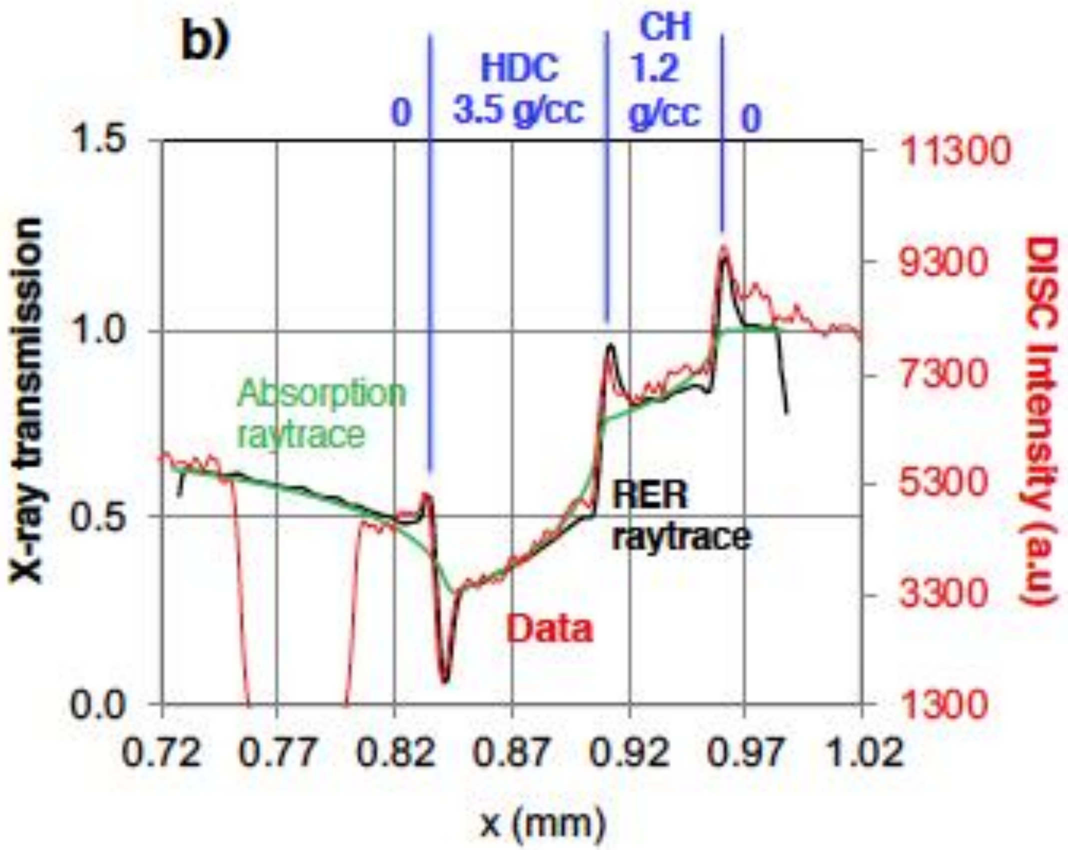
Enhanced contrast was demonstrated on the first RER of a capsule implosion



Dewald et al. (RSI 2018)

Contrast and density sensitivity has been demonstrated on a static capsule shot





Dewald et al. (RSI 2018)

Outline – RER experiments at the National Ignition Facility

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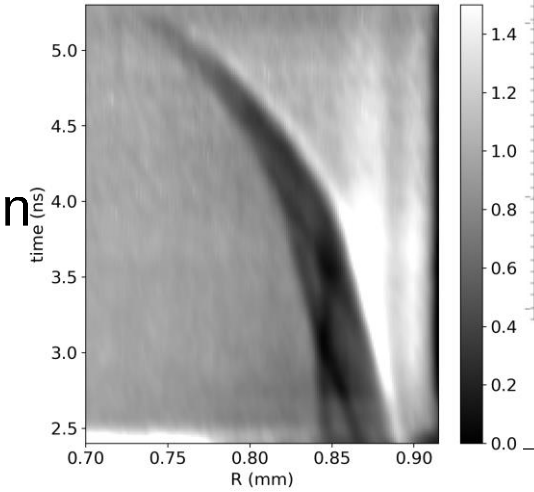
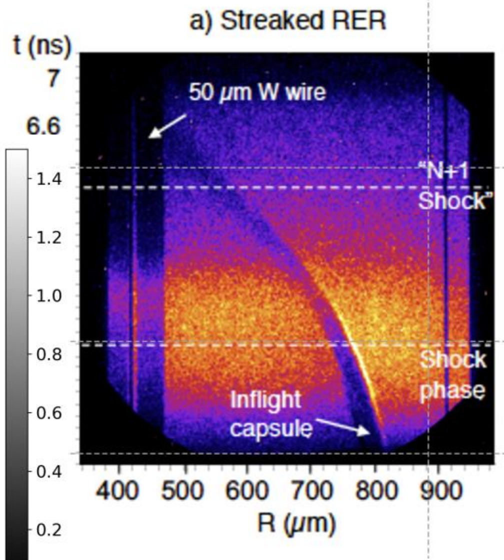
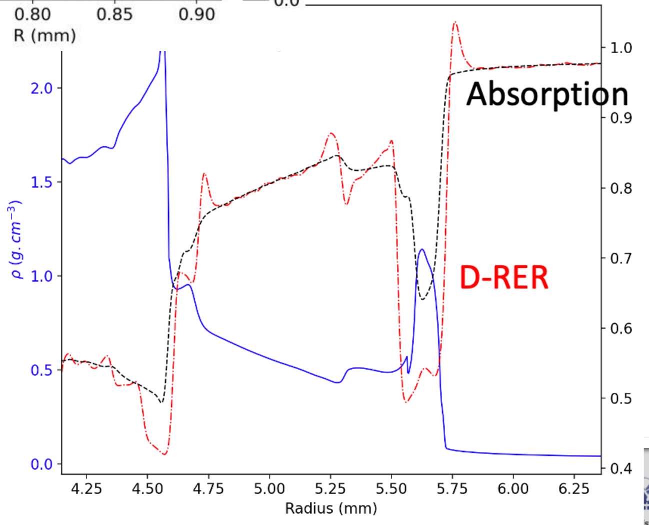
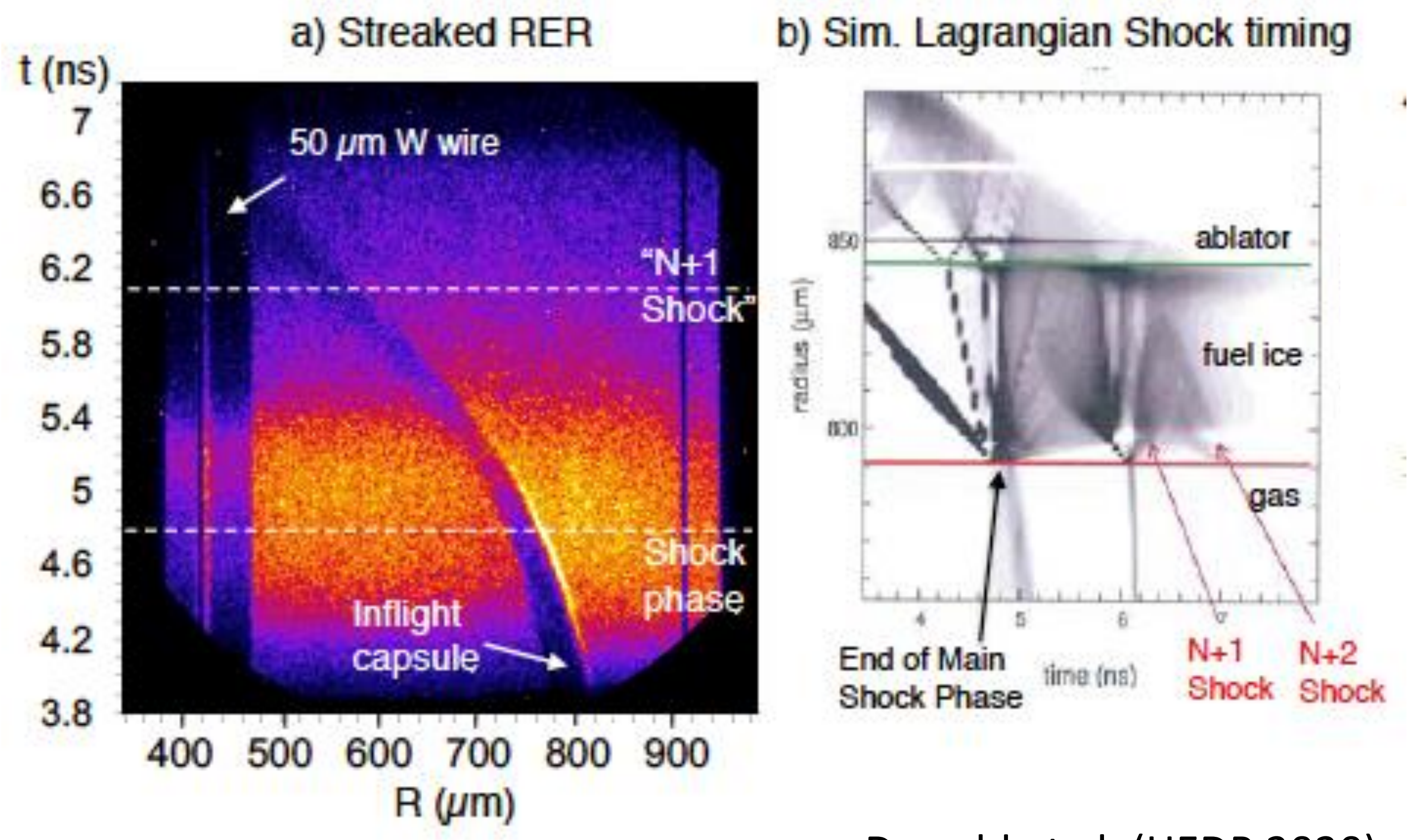
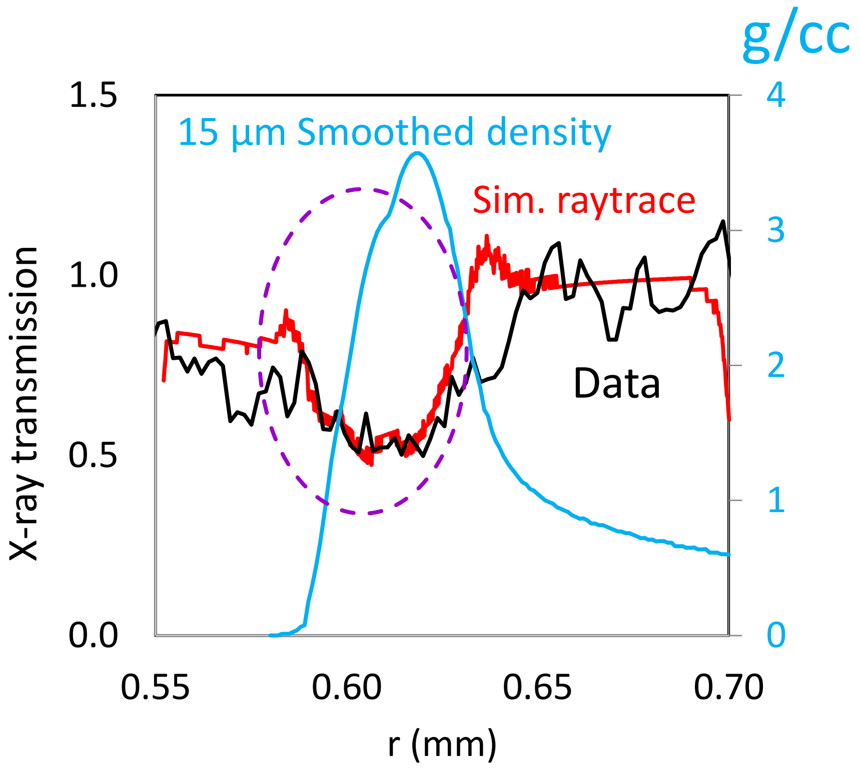






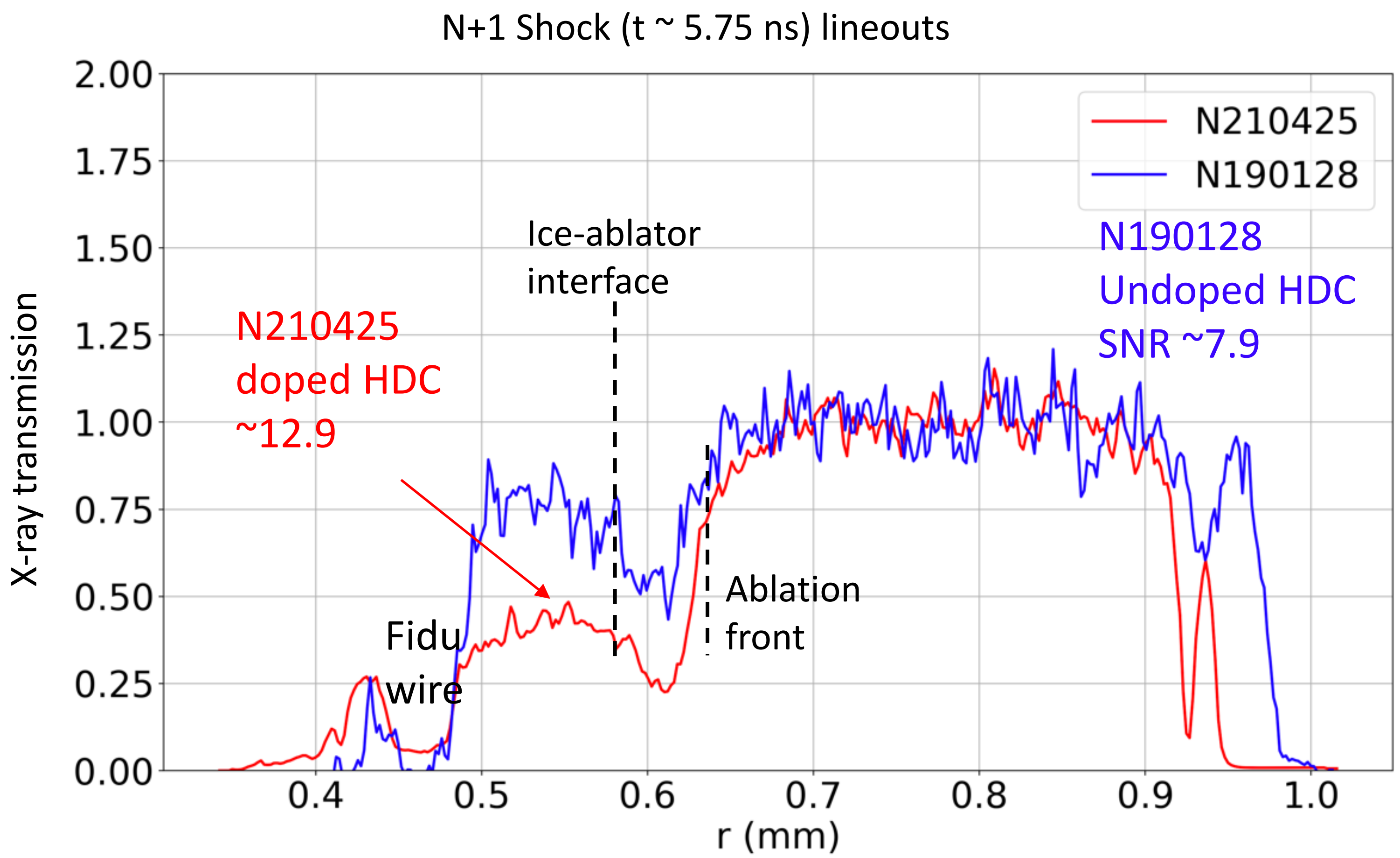
N+1 experiments showed trace of mix at the ice-ablator interface with low SNR





Dewald et al. (HEDP 2020)

Using a Ni tube backlighter the signal-to-noise ratio has been improved by ~75%



Increasing signal-to-noise ratio is crucial because at these time, the ice-ablator velocity goes over 100 µm/ns which requires ~25 ps or less gating time.

Backlighter development is currently ongoing to improve the photon fluence to further increase SNR

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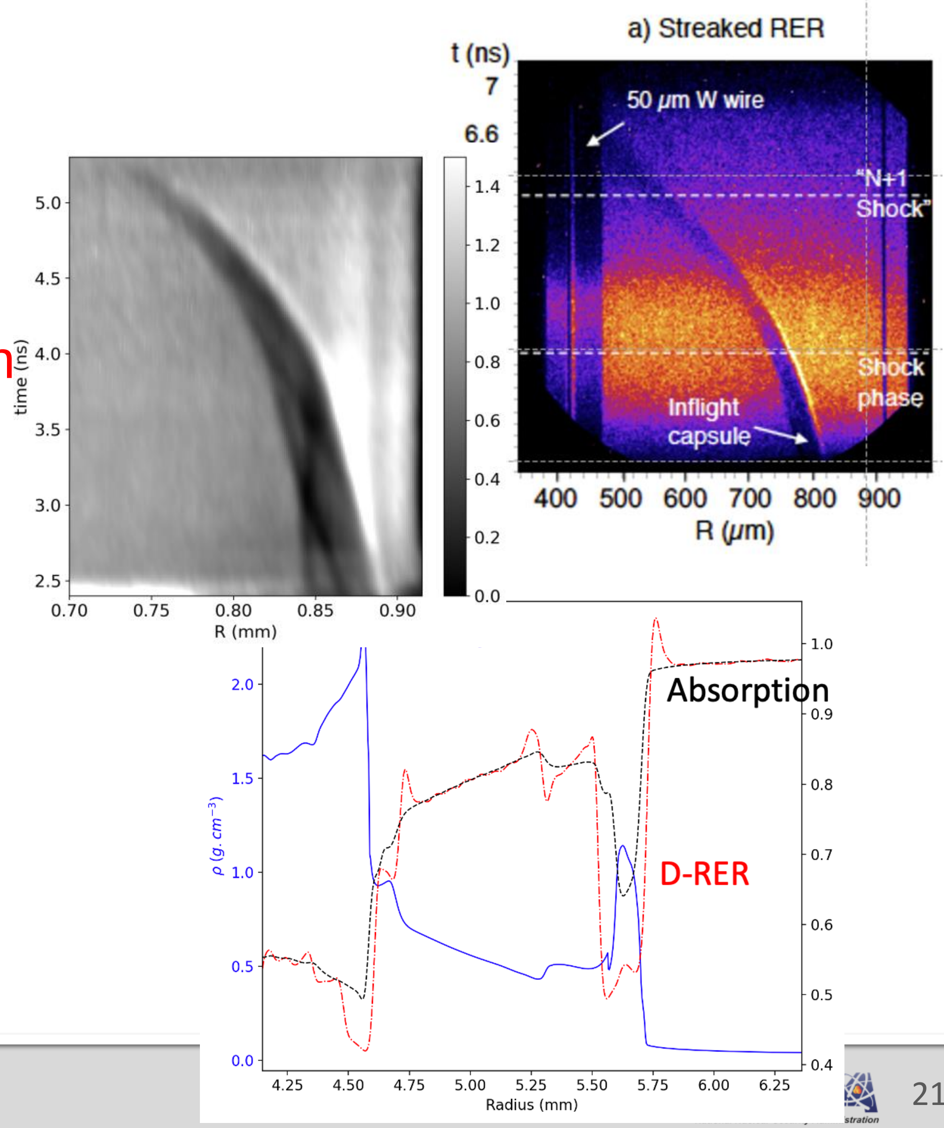
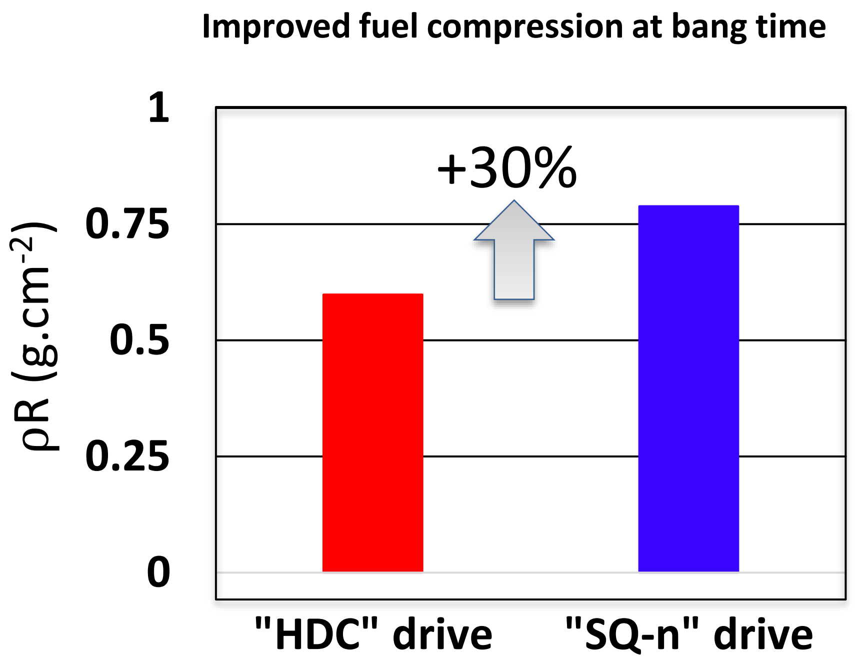
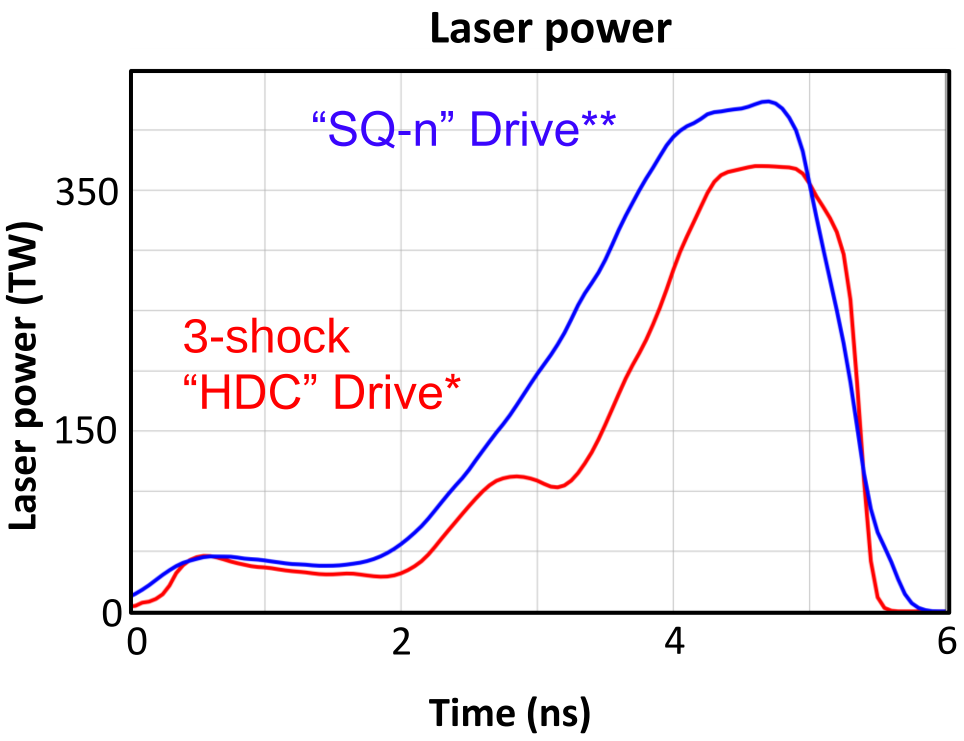


Achieving high compression and areal density (ρR) is key for high gain in Inertial Confinement Fusion (ICF).

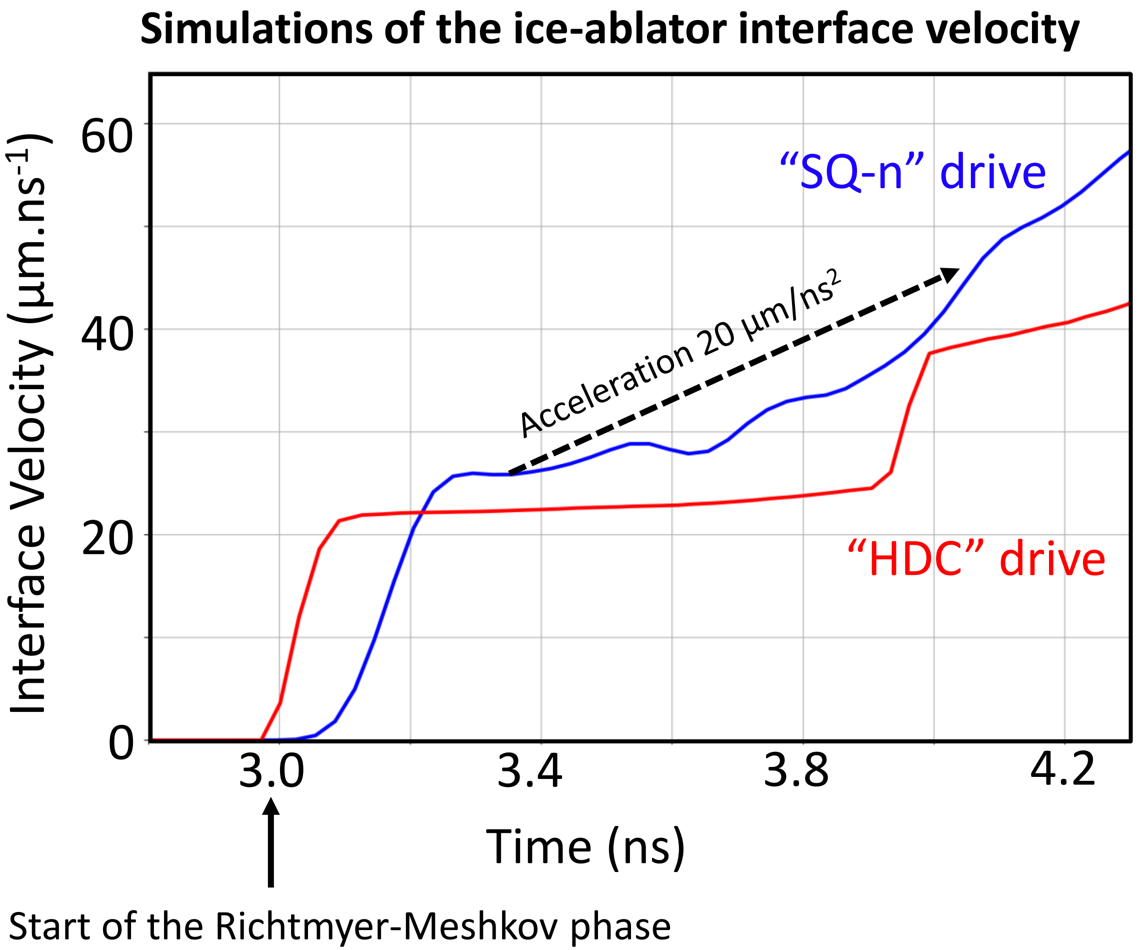
- A new ICF drive, “SQ-n”, has been developed based on improved stability throughout the implosion.
- The key feature is the early time acceleration of the ice-ablator interface, predicted to improve stability by ~10x.
- Measurement showed that we have improved fuel areal density (ρR) by 20%-30%.



Gentle acceleration of the ice-ablator interface is one of the key feature of the SQ-n campaign to improve capsule implosion compression



Gentle ramp is designed to reduce interface growth

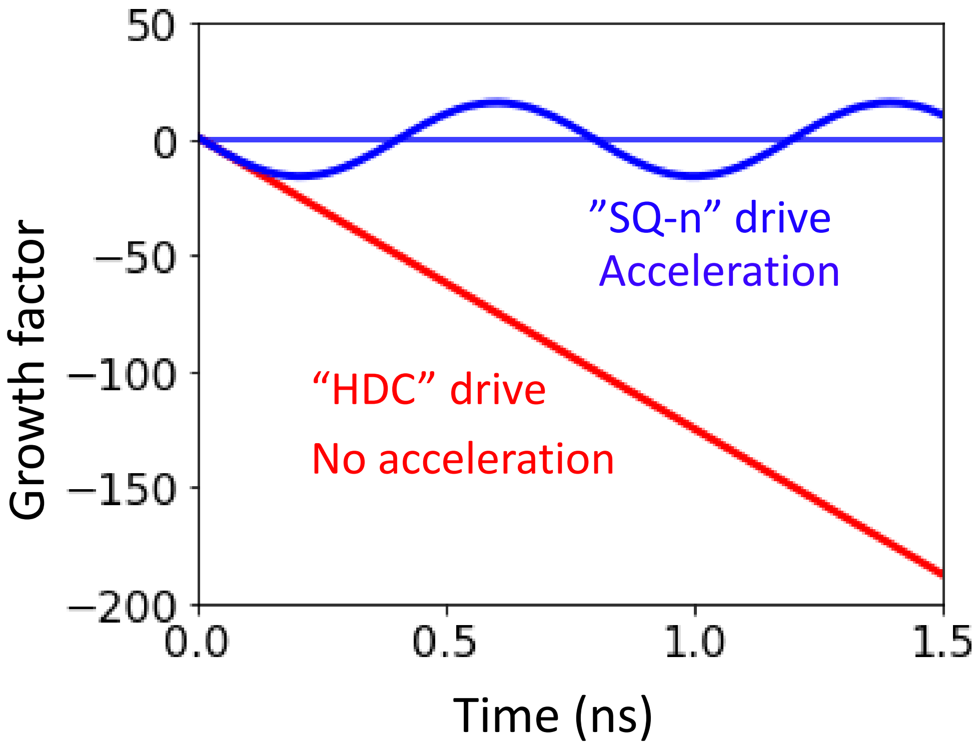


*L. Berzak Hopkins et al., Phys. Rev. Letter, 2015

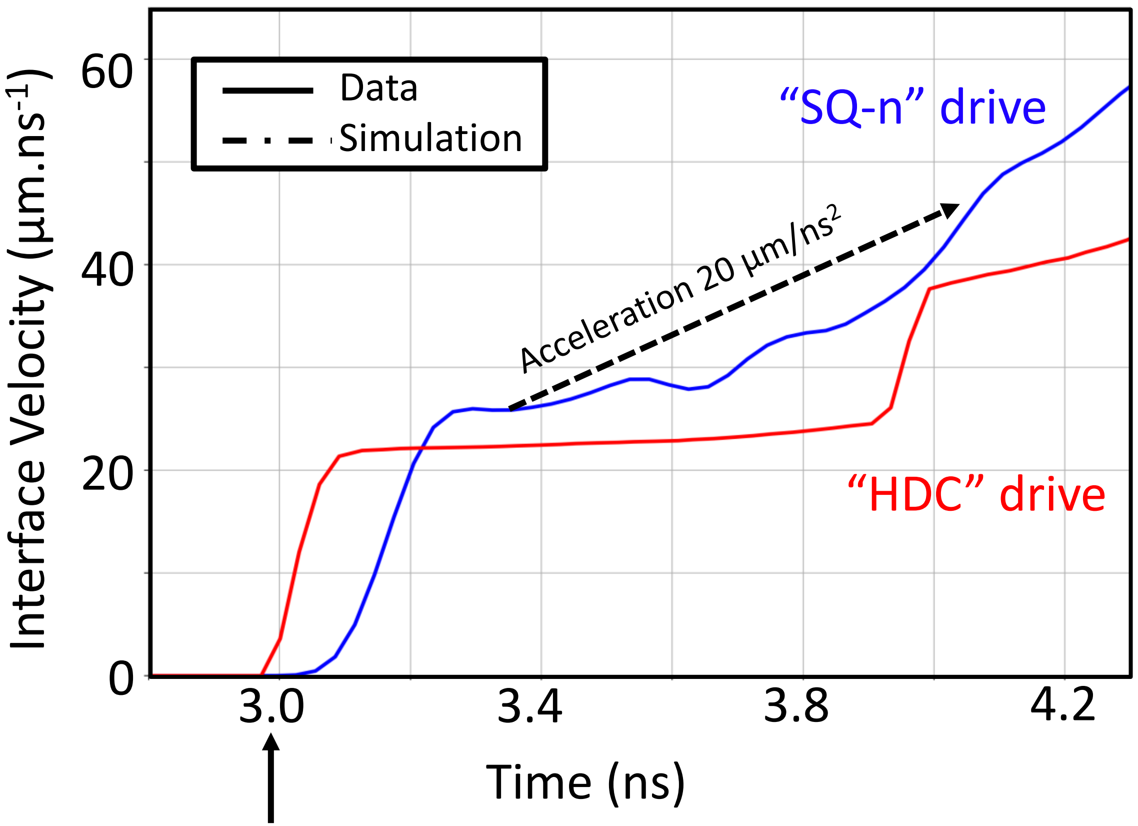
**D. Clark et al., Phys. Plasmas, 29 2022,
**C. Weber, Phys. Rev. Letter, 2022 (submitted)

Interface mix is predicted to be reduced by an order of magnitude with interface acceleration during Richtmyer-Meshkov phase

Growth factor for 1 µm wavelength perturbation



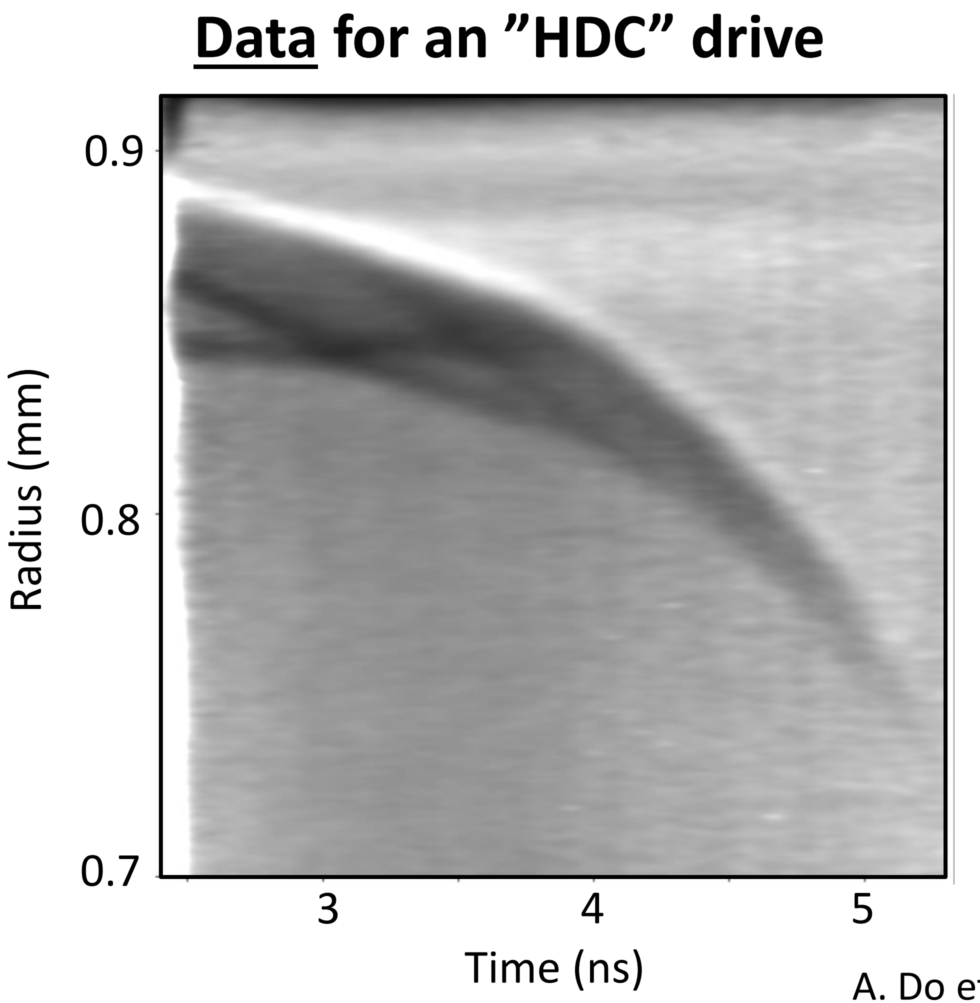
Simulations of the ice-ablator interface velocity

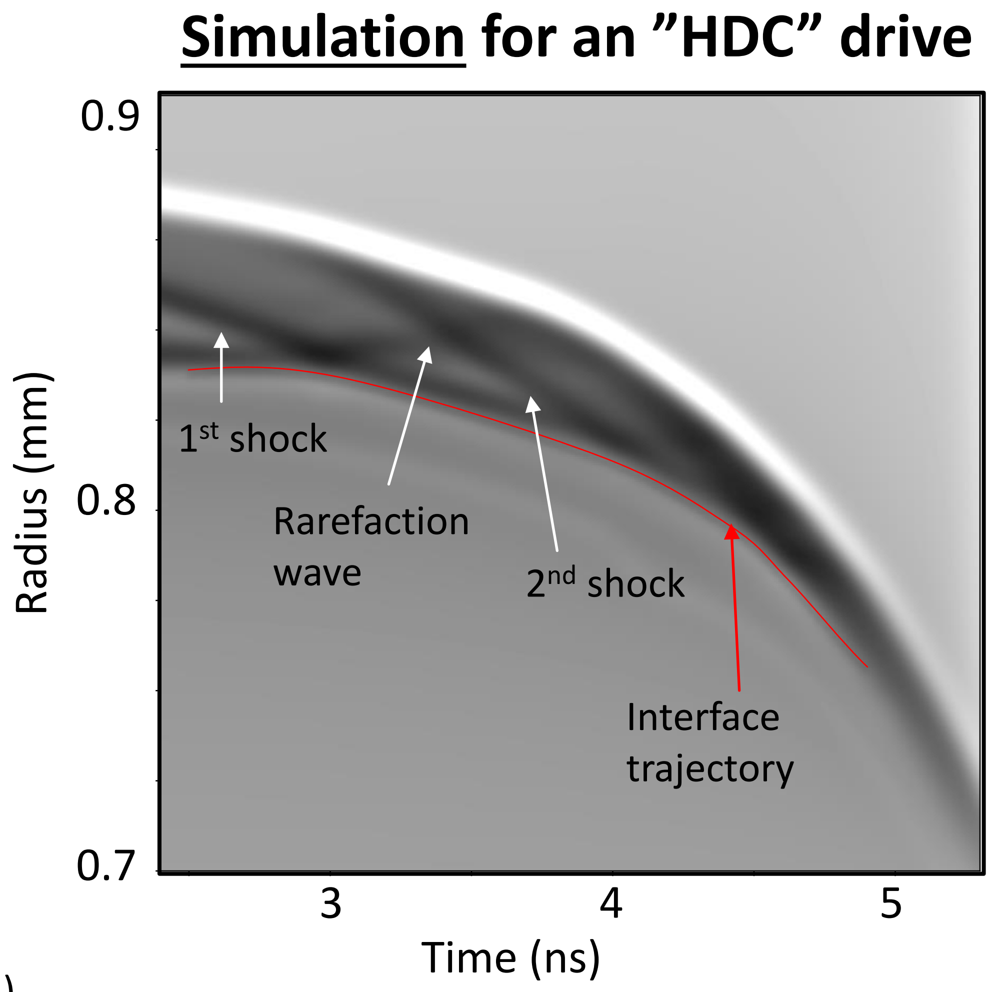


Richtmyer-Meshkov phase

C. Weber

RER sensitivity to gradients allows to image interface trajectories and shocks propagation in the ablator not visible with classic radiography

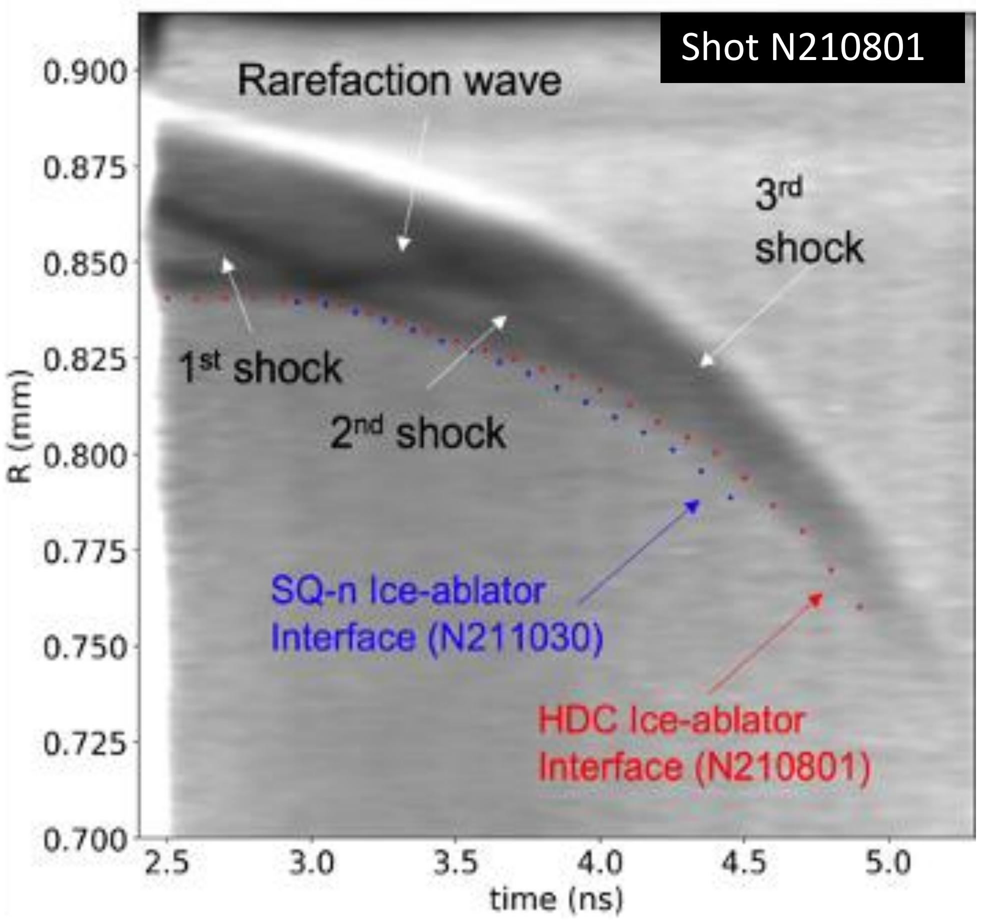




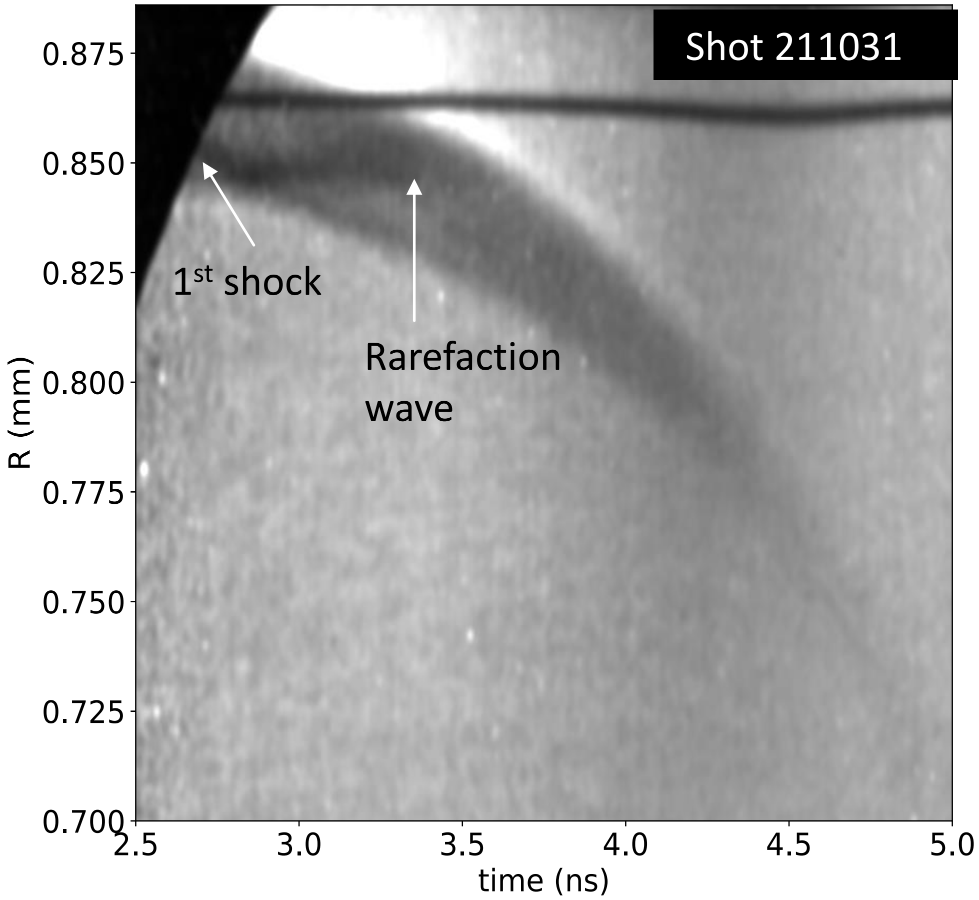
A. Do et al. PRL (2022)

Refraction Enhanced Radiography (RER)* uses refraction to measure density gradients with higher contrast than classic absorption

HDC design

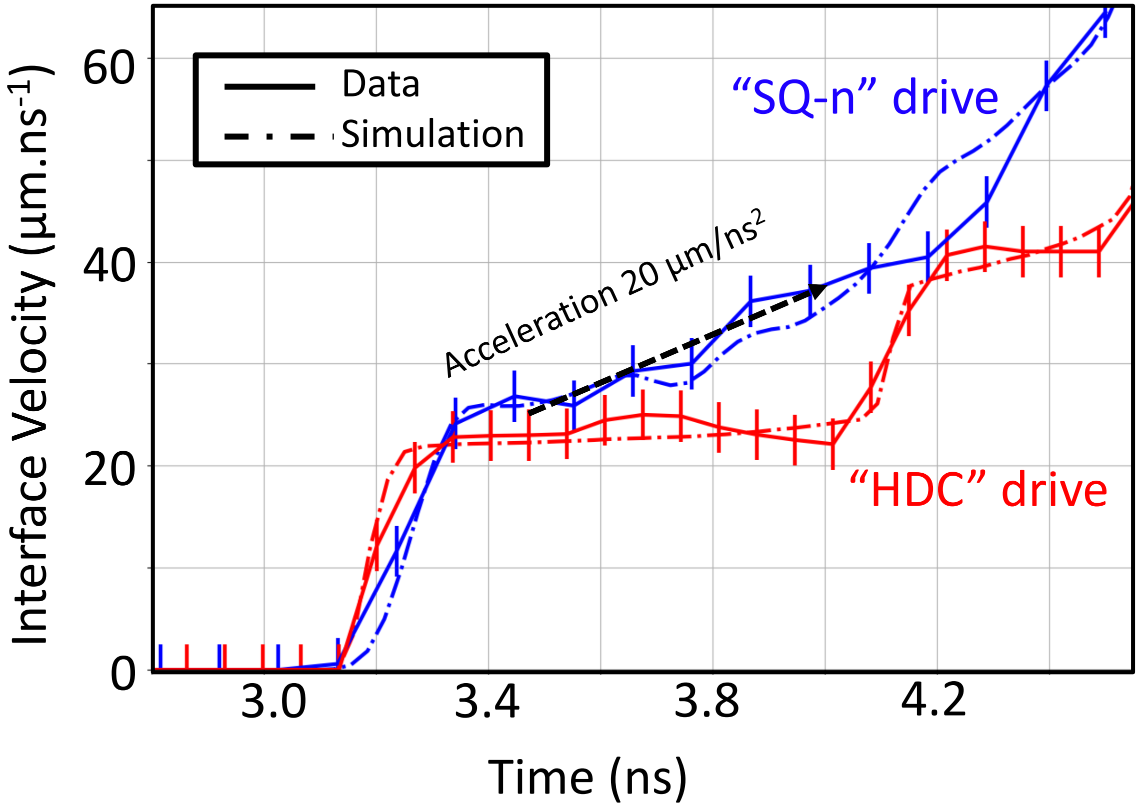


SQ-n design



A. Do et al. PRL (2022)

The new “SQ-n” drive replaces 2nd shock with smooth acceleration



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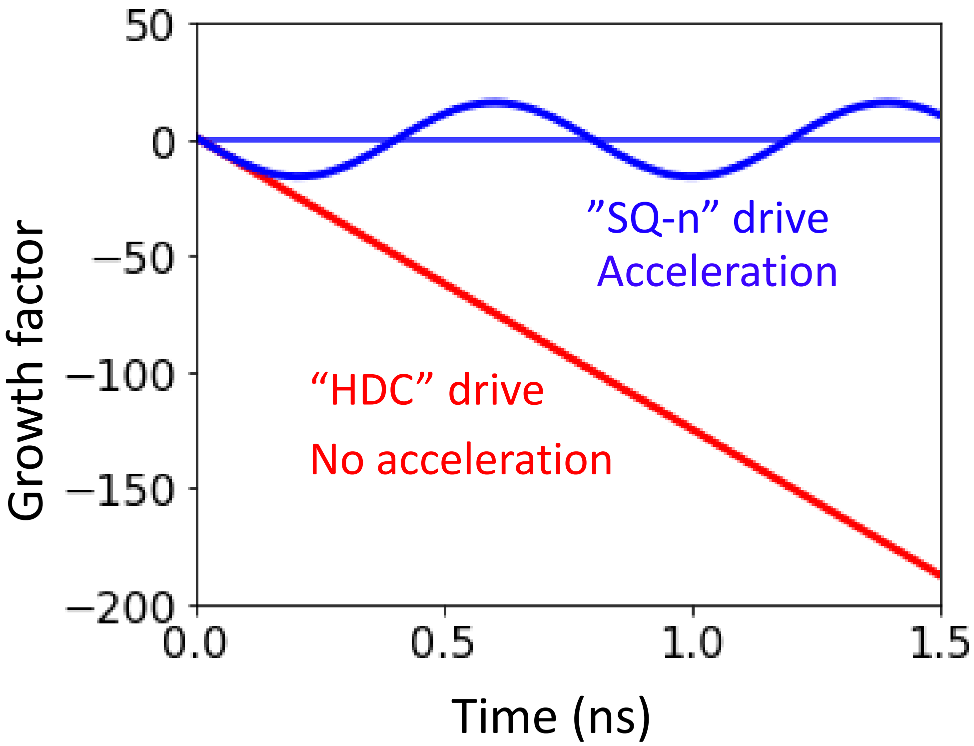

Ice-ablator interface acceleration of 20 μm/ns^2 is predicted to increase the stability by factor 10

A. Do et al. PRL (2022)

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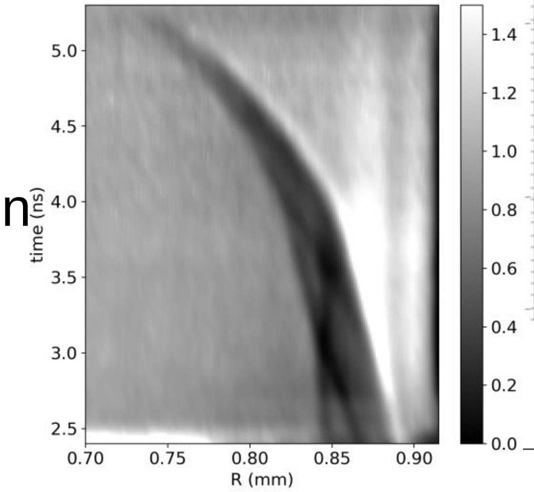
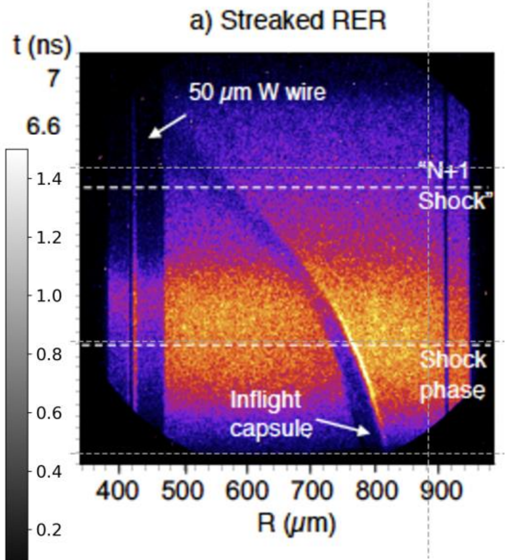
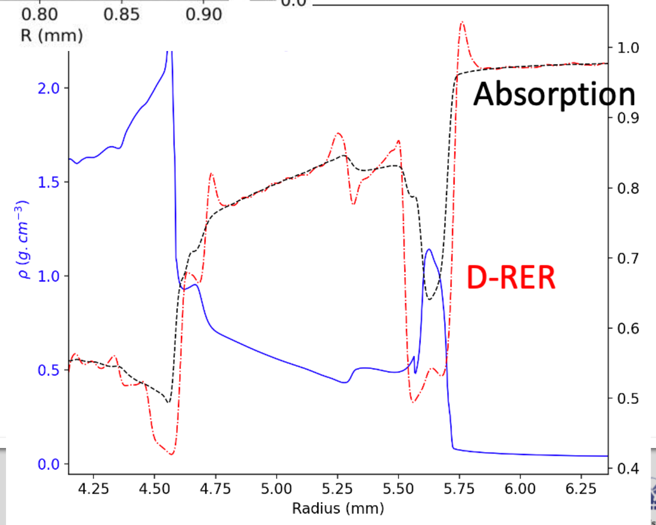
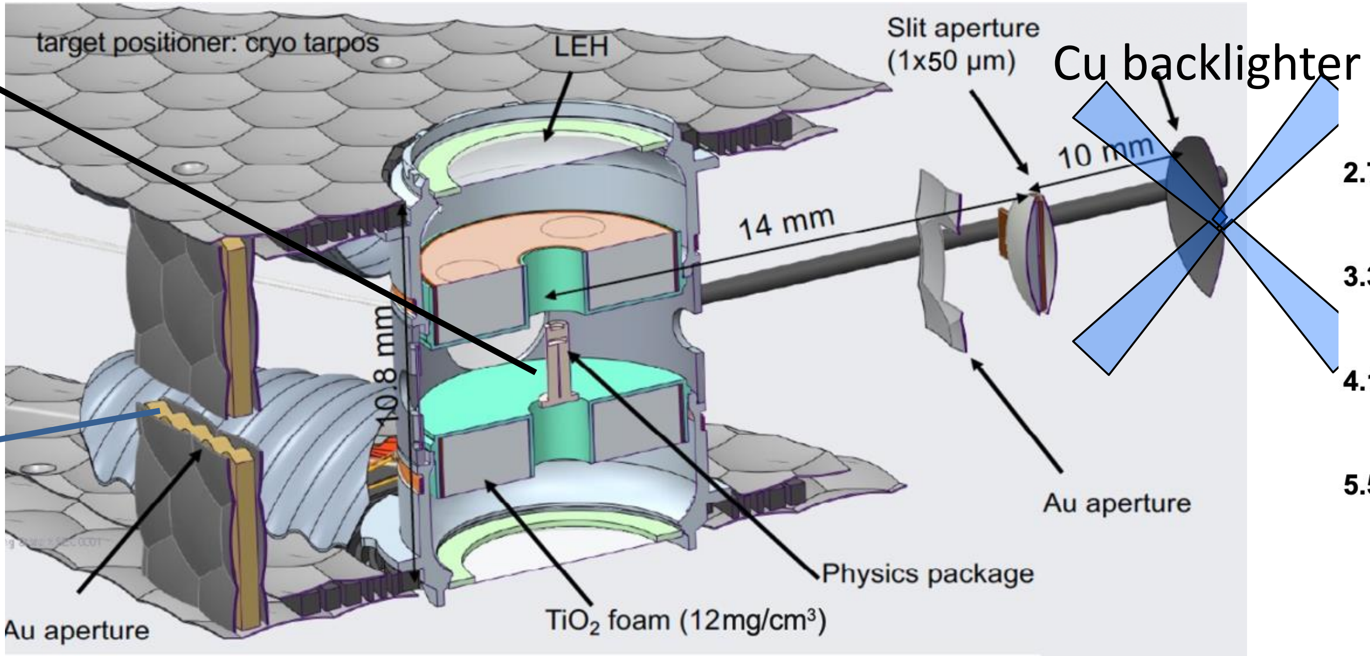


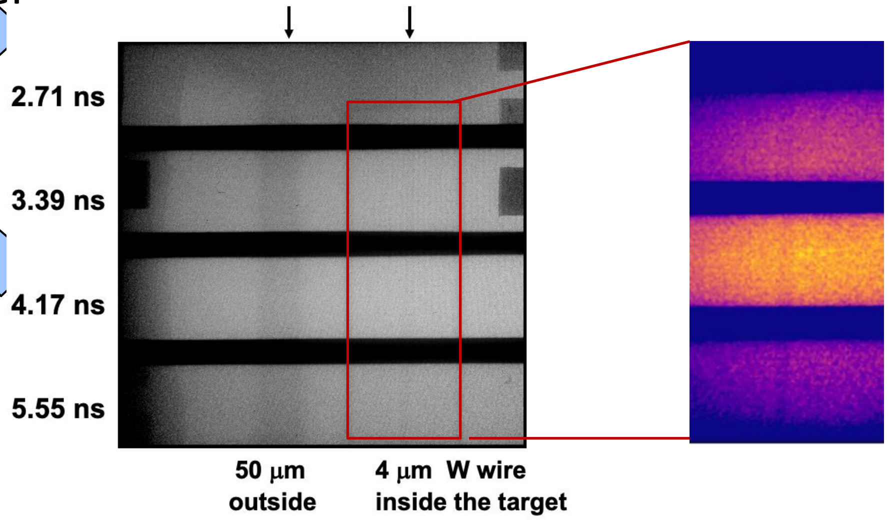




Measurement of Mutual Diffusion and thermal conductivity across differentially heated material interfaces

Imaging towards 90-78





- We use Ti K-shell x-ray emission (~ 5 keV) to isochorically heat a cylindrical physics package at the center of a Universal TMP

T. Doeppner, C. Allen, M. Oliver, C. Spindloe, D. Gericke, M. Schoelmerich, L. Divol, O. Landen, G. Kemp, Y. Ping, J. Delora-Ellefson, J. Kroll, M. Biener, A. Haid, N. Masters, B. Ferguson, D. Kalantar, R. Zacharias

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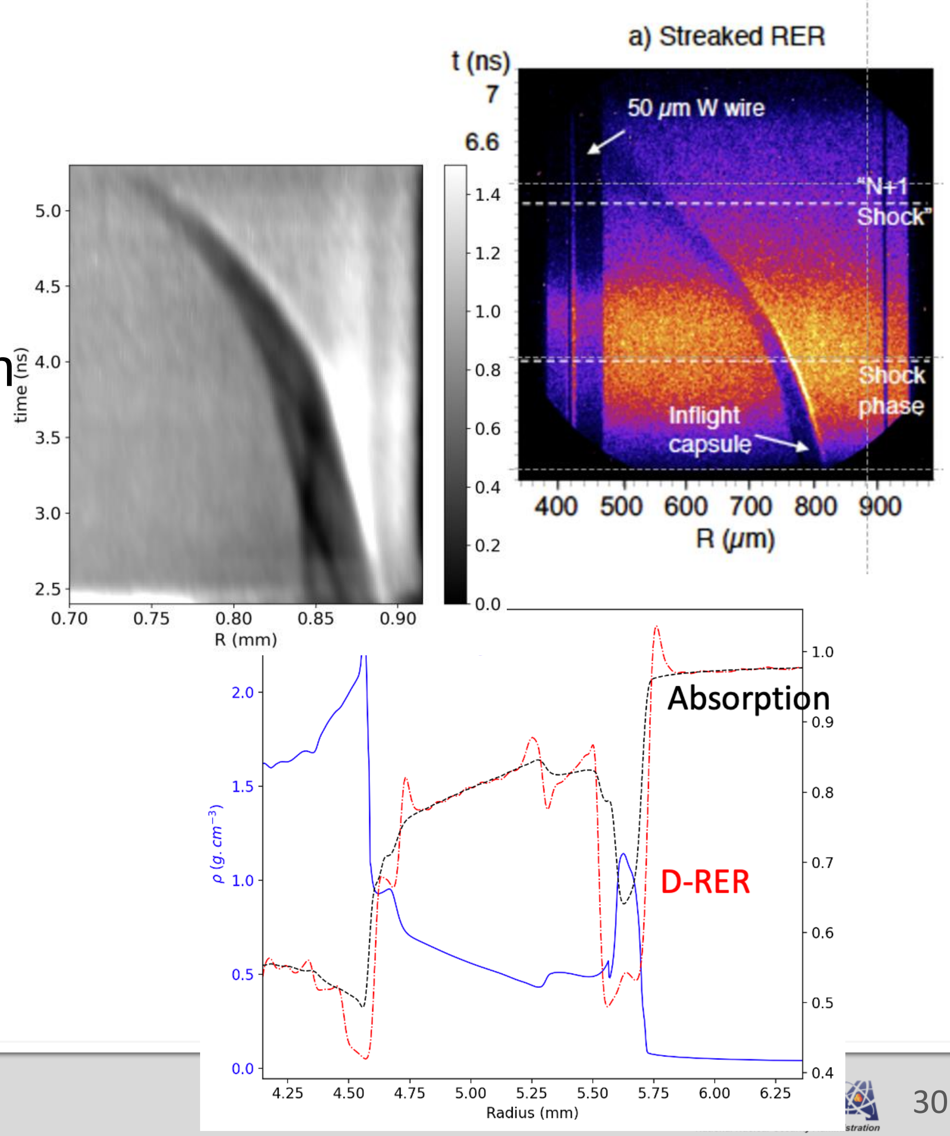


Study of hydrodynamic instabilities

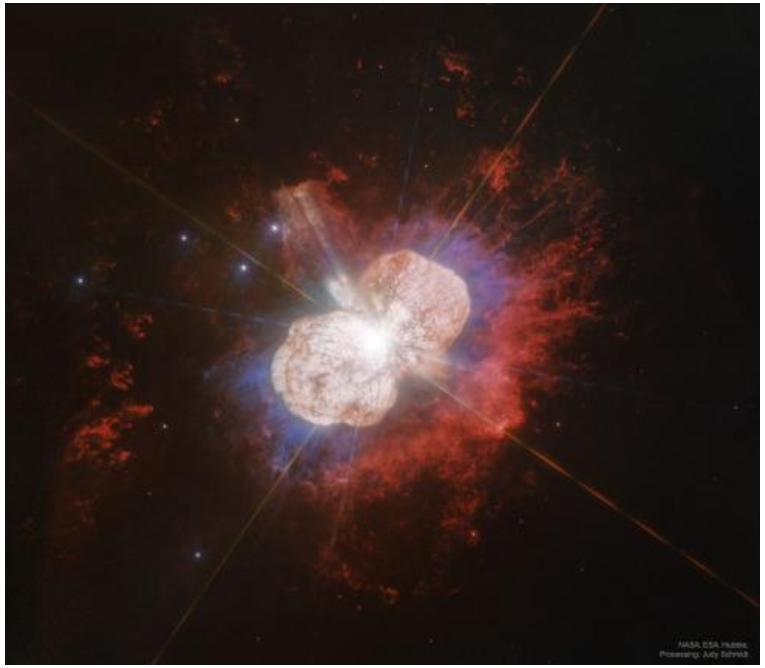
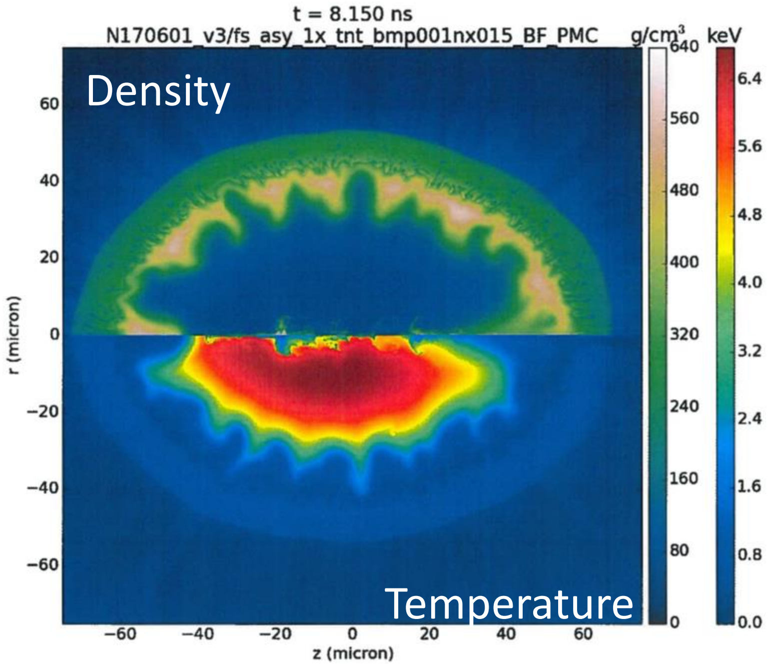
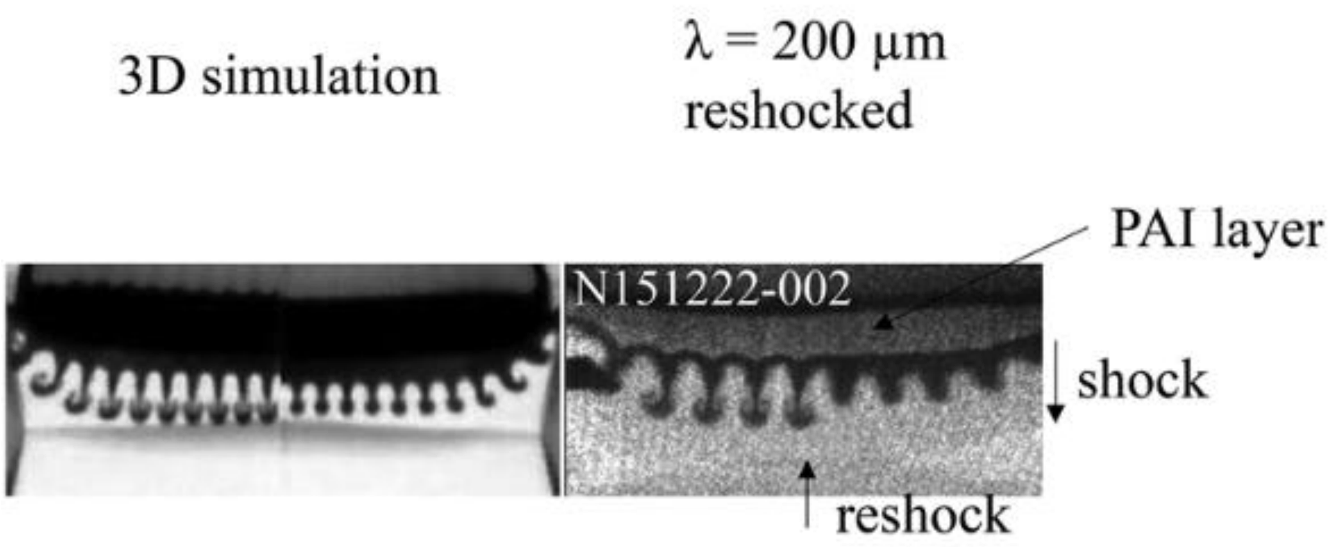


Image Credit: NASA, ESA, HST

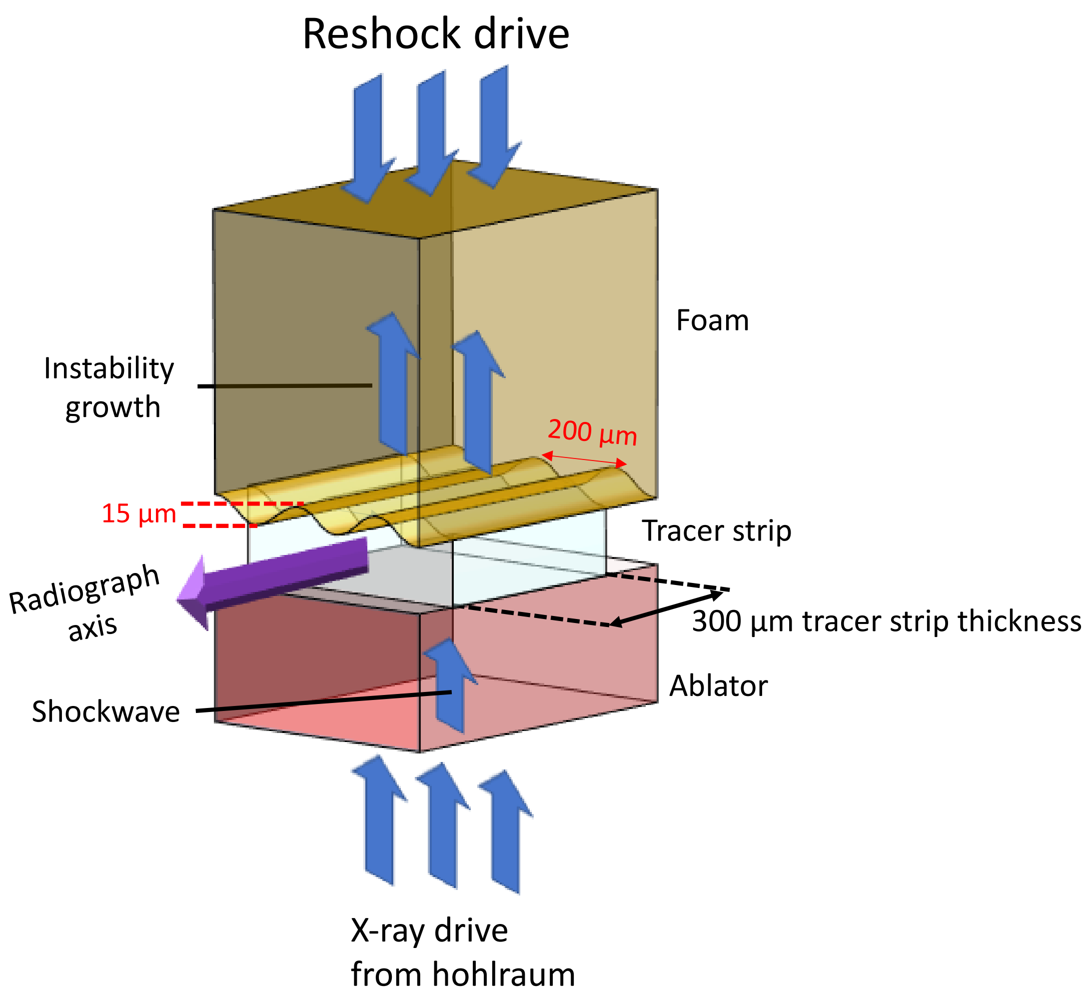


D. Clark

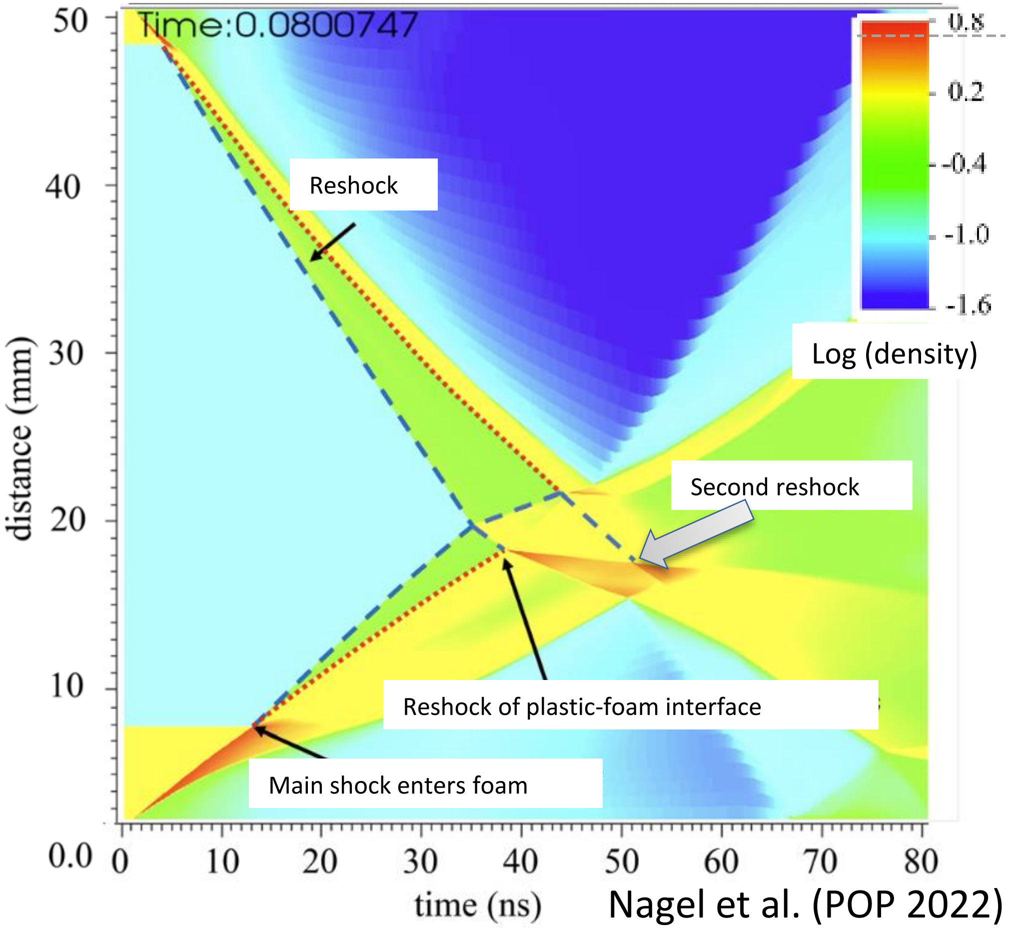
High Resolution Turbulence experiments looks to study the onset of the turbulent regime with high resolution 2D x-ray radiography



Nagel et al. (POP 2022)



A second light reflected reshock has been observed in the data and is predicted by the simulation



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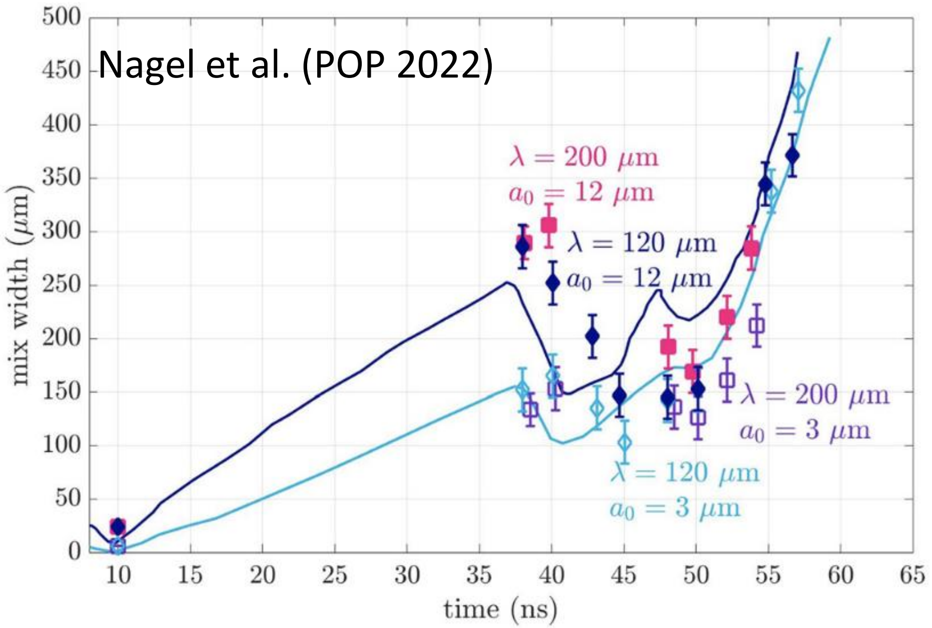
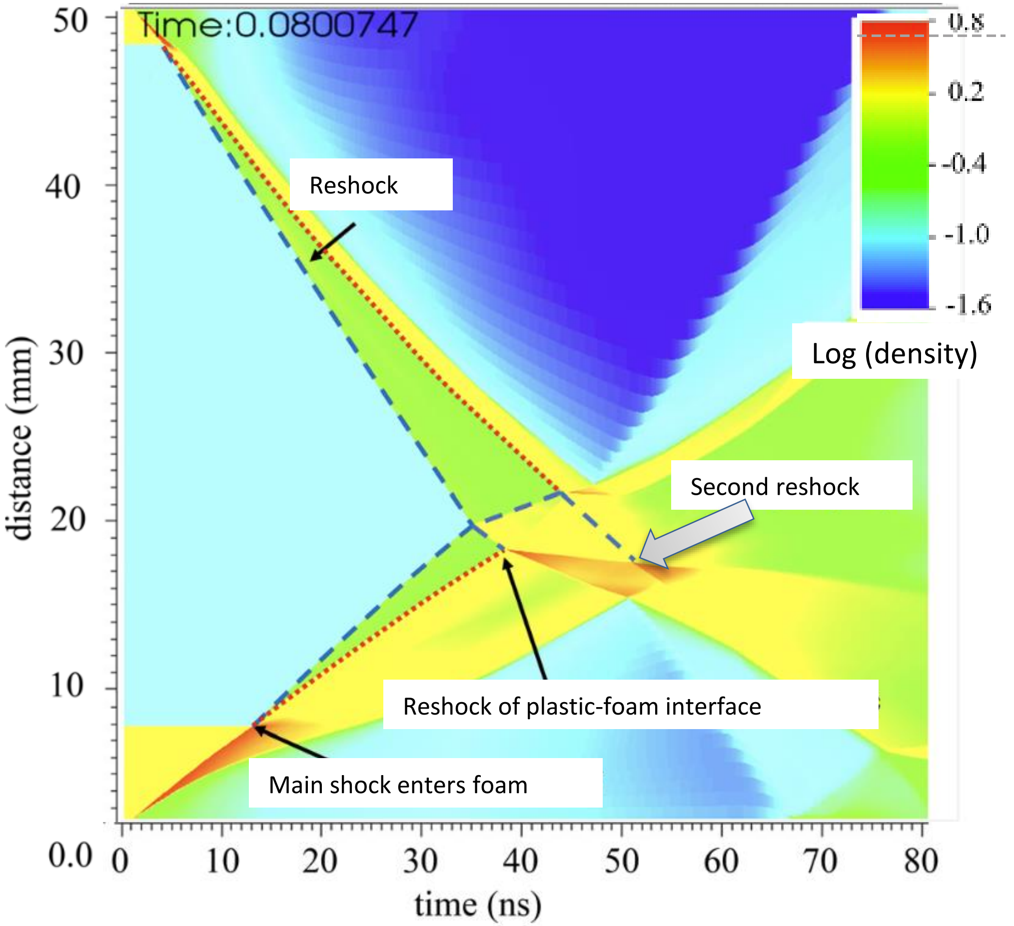


Required measurements:

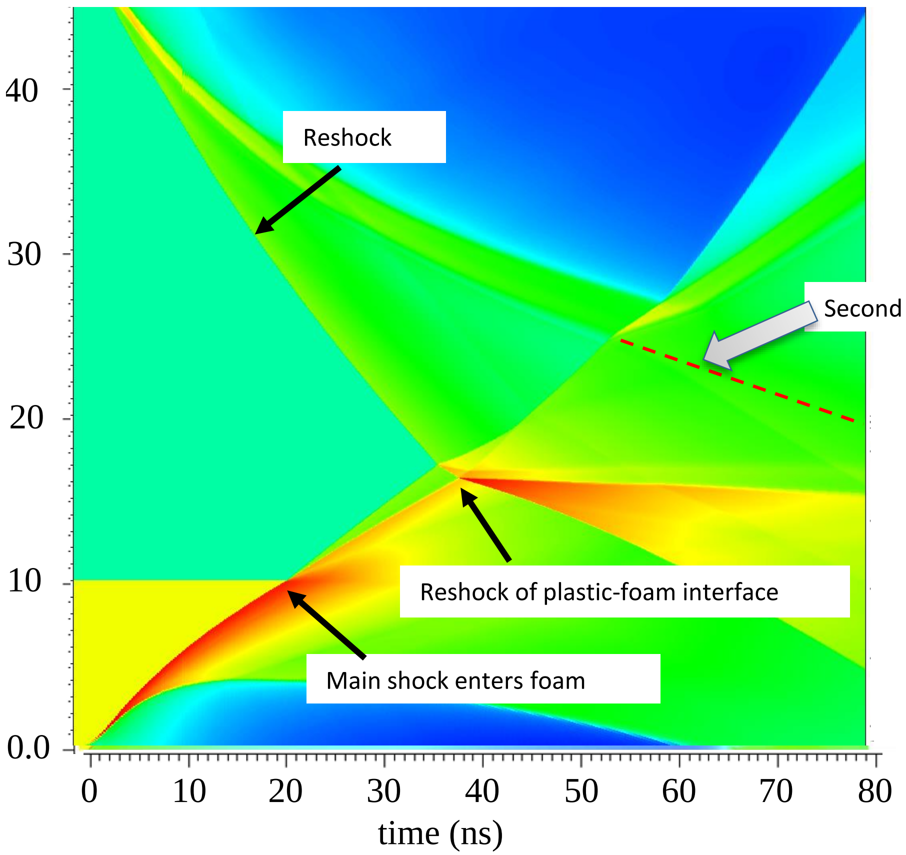
- 2^{nd} shock timing and position
- 2^{nd} shock trajectory

Second shock density gradient in the CRF foam is ~0.1 g/cc

A new drive and shocktube design has been developed to delay this 2nd reshock at a later time



New design with delayed 2nd reshock



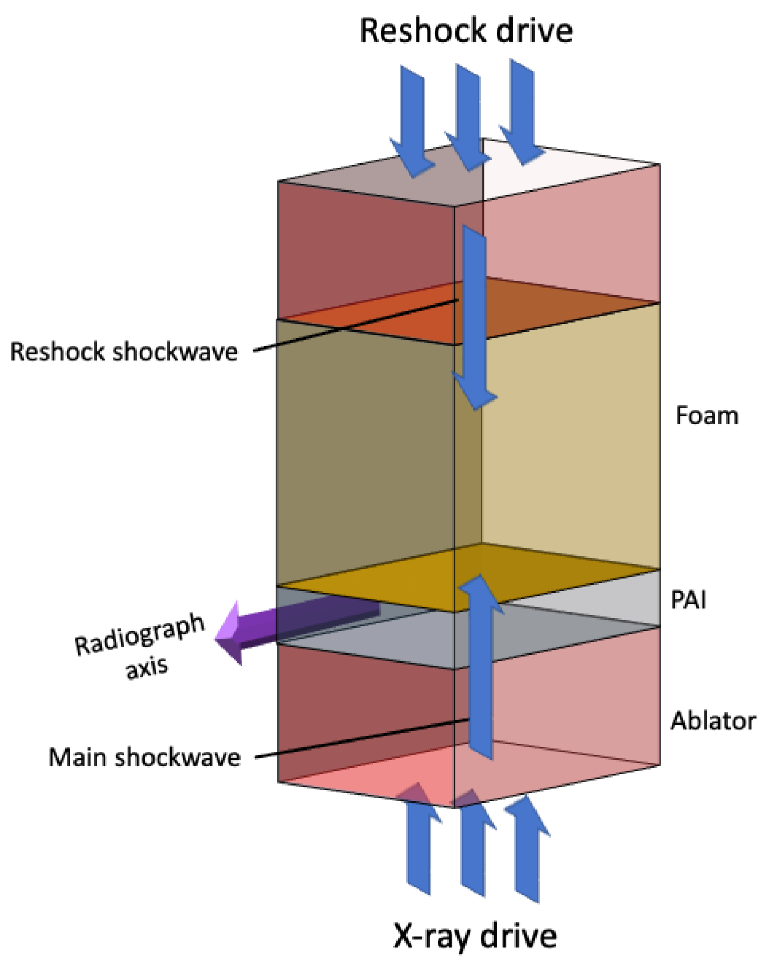
Density gradient throughout the target and wall effect induces phase shift from diffraction and refraction

Source size limitation from RER:

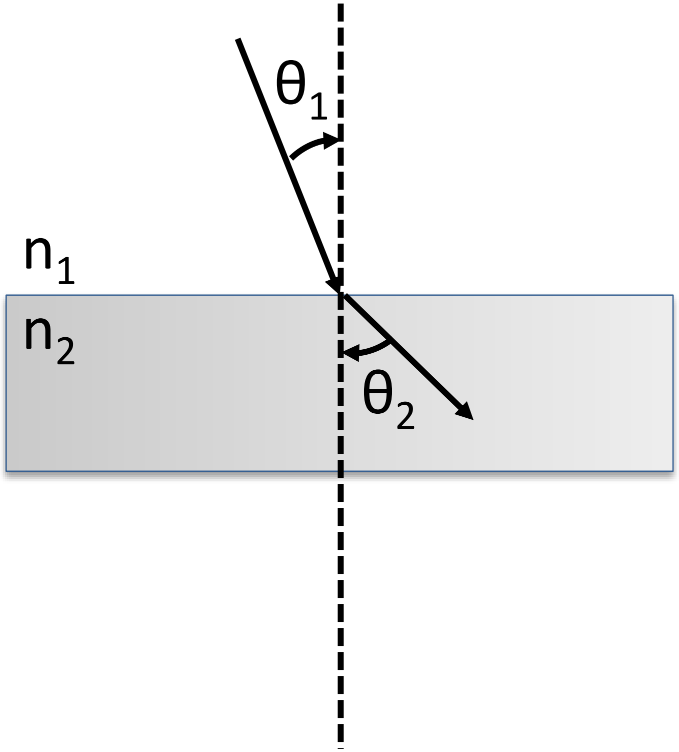
$$s\ (\mu m) < 3[p\Delta n\ (R/2)^{1/2}]^{2/3}$$

↓

Δn is multiple orders of magnitude lower than capsule implosion RER



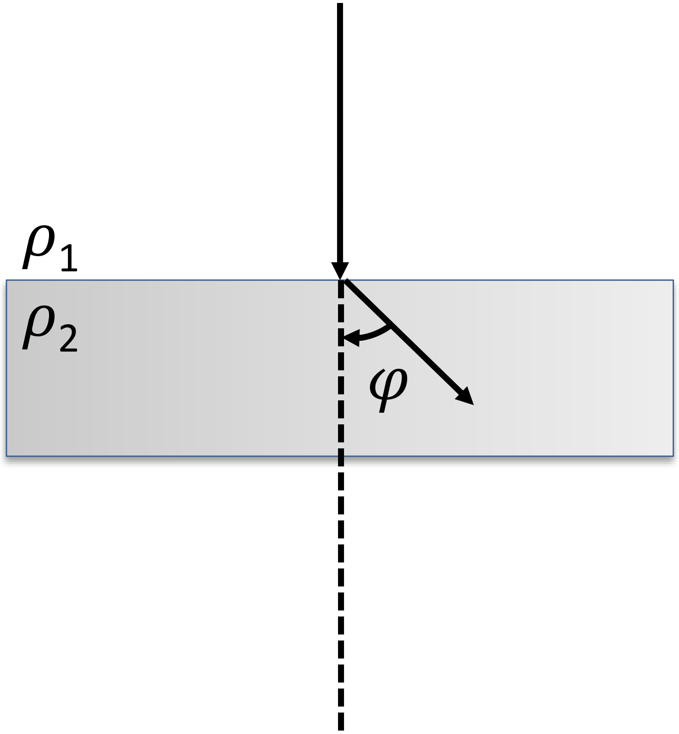
Refraction happens when light is passing from a medium to another one



Snell's law

$$n_1 sin(\theta_1) = n_2 sin(\theta_2)$$

Diffraction happens when light is passing through a density gradient



<u>Phase shift</u>

$$\varphi = k * 2 * thickness * \delta$$

<u>Complex refraction index</u>

$$n = 1 - \delta + i\beta$$

$$k = \frac{2\pi}{\lambda}$$

Density gradient throughout the target and wall effect induces phase shift from diffraction and refraction

Source size limitation from REI:

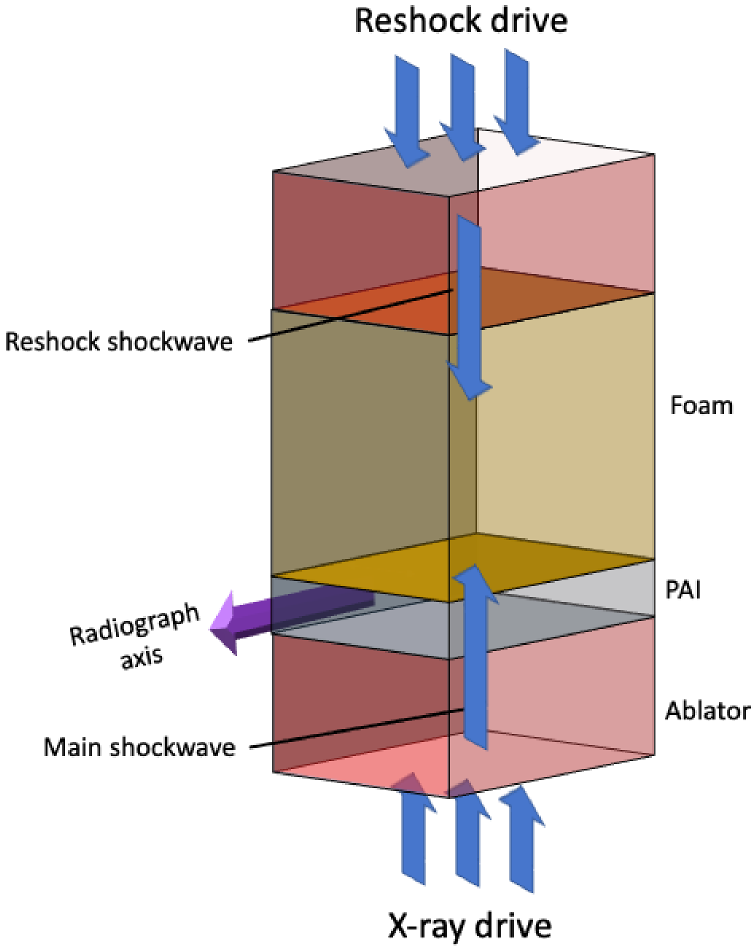
s (µm) < ~~$3[p\Delta n\,(R/2)^{1/2}]^{2/3}$~~ + p $\Delta\phi$

Phase shift $\varphi = k * 2 * thickness * \delta$

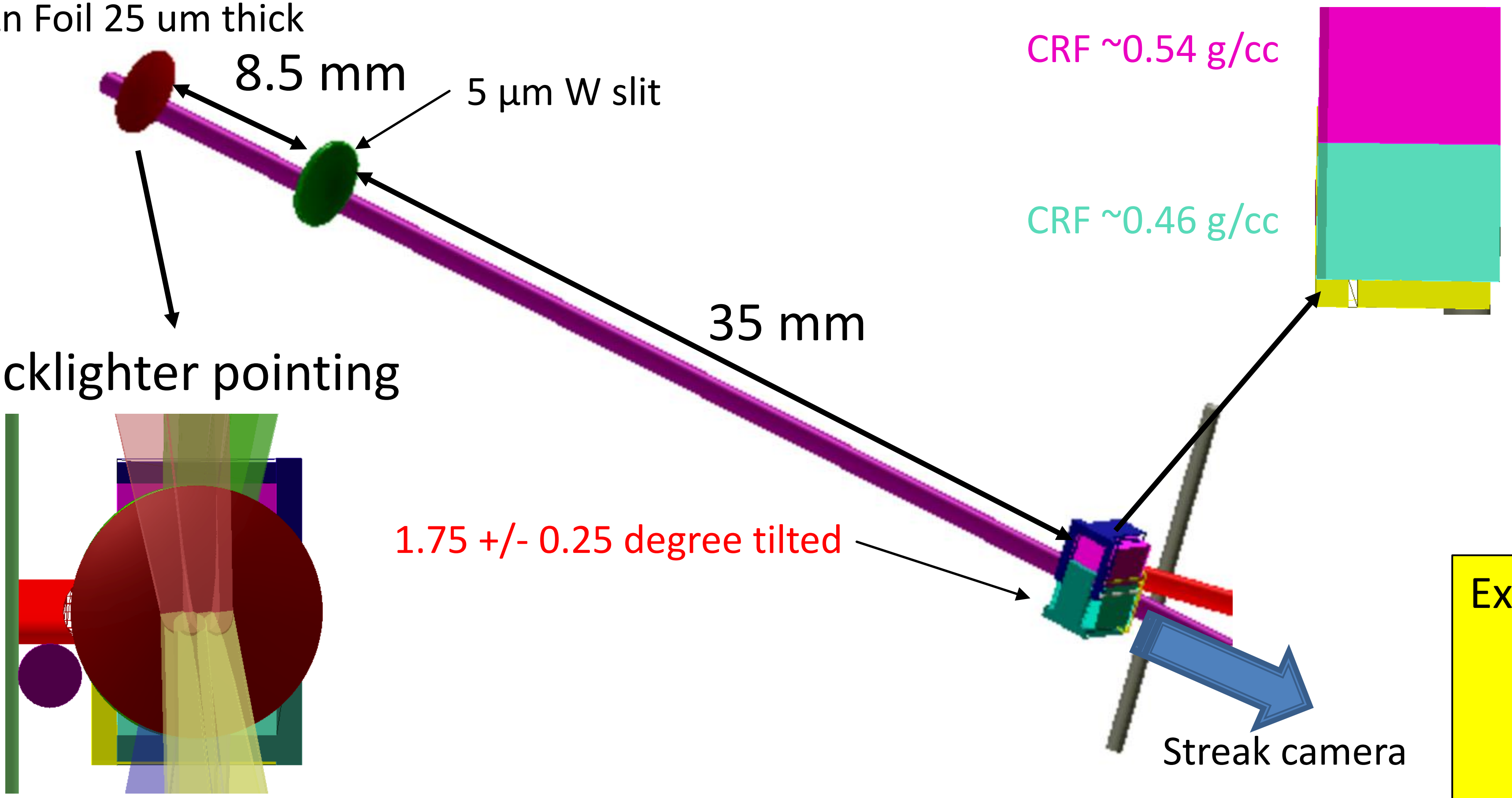
$$with\ \delta = \frac{N_e r_0 \lambda}{2\pi}$$

N_e the electron density, r_0 the electron radius and λ the wavelength

=> s (µm) $\lesssim$ 11 µm



Experimental demonstration of RER density sensitivity will be shot on 12/29 this year

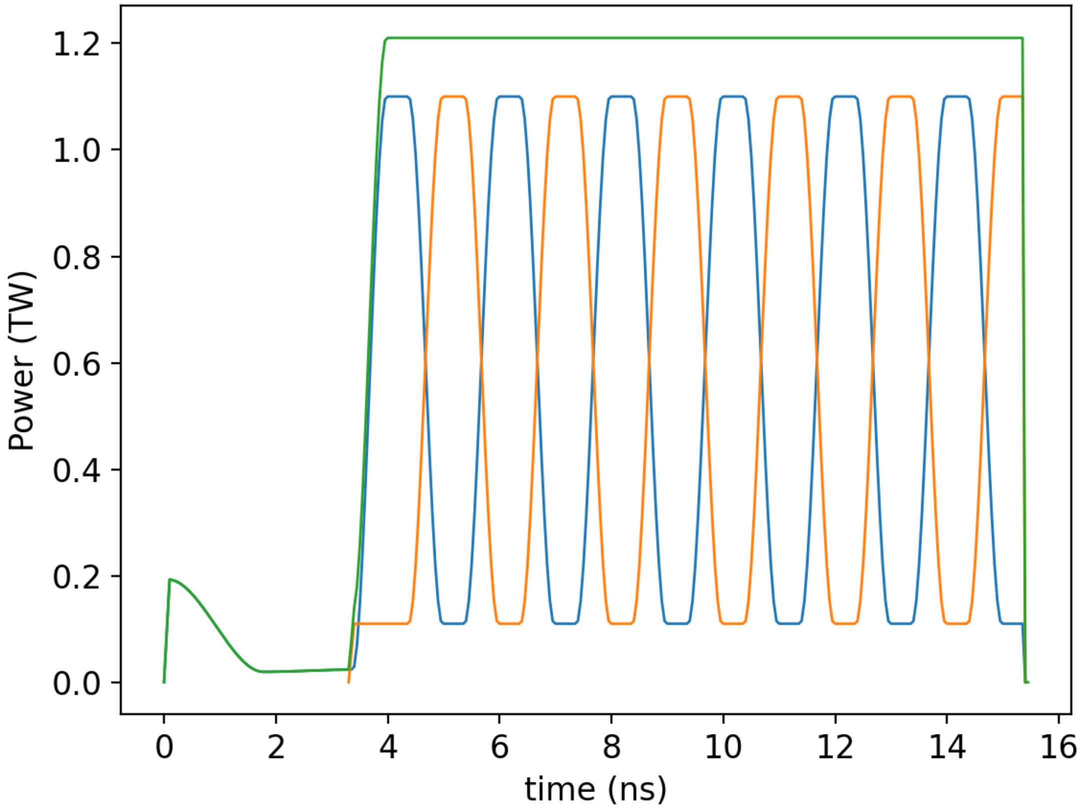


Experimental determination of:

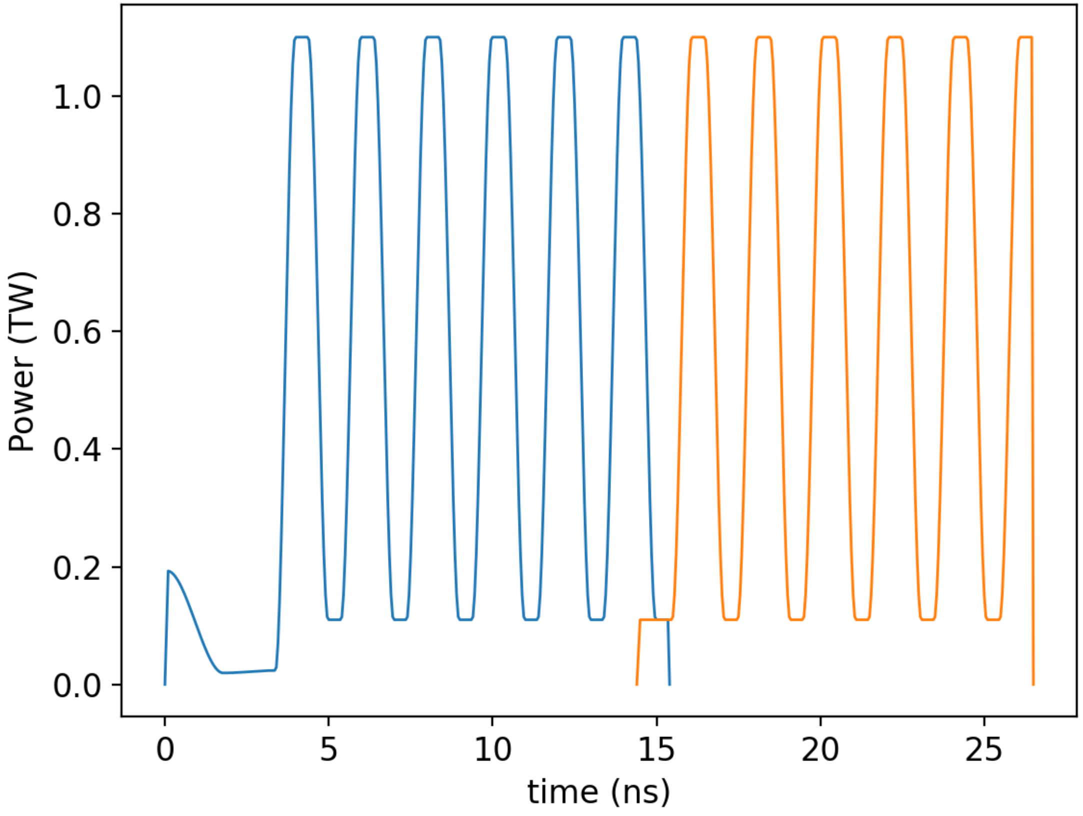
- Slit closure
- Resolution
- Density sensitivity
- Photon flux

Laser pulse design allow a longer time window

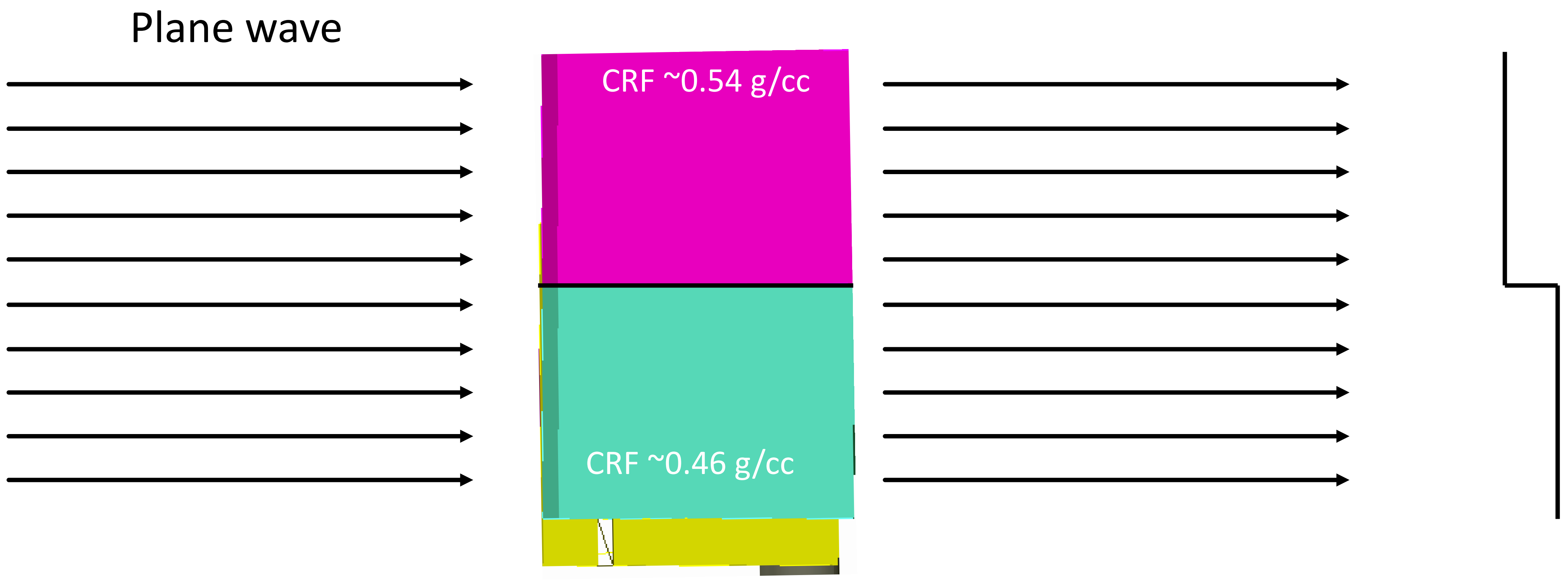
Continuous ~12 ns 2 waves



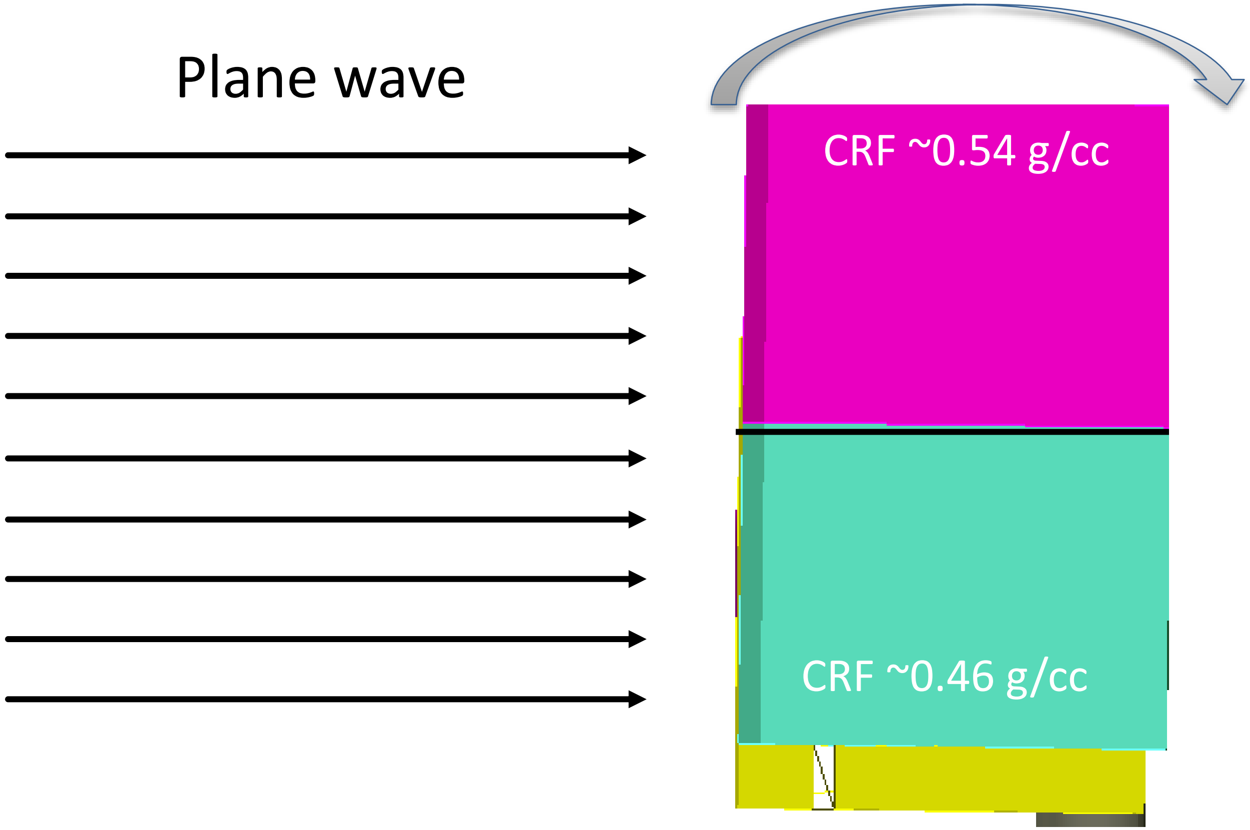
Chirped ~22 ns 2 waves



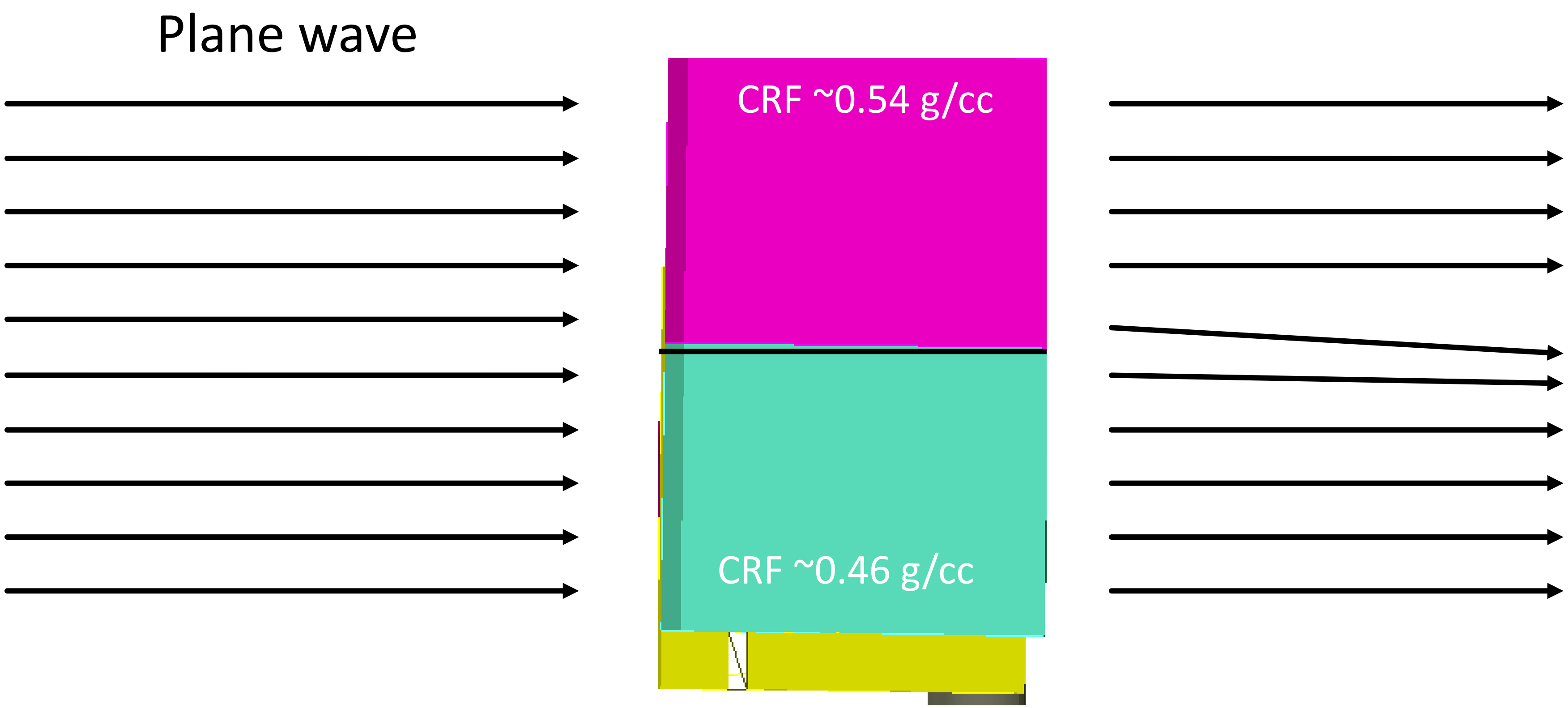
Wave propagation simulation of Refraction enhanced imaging

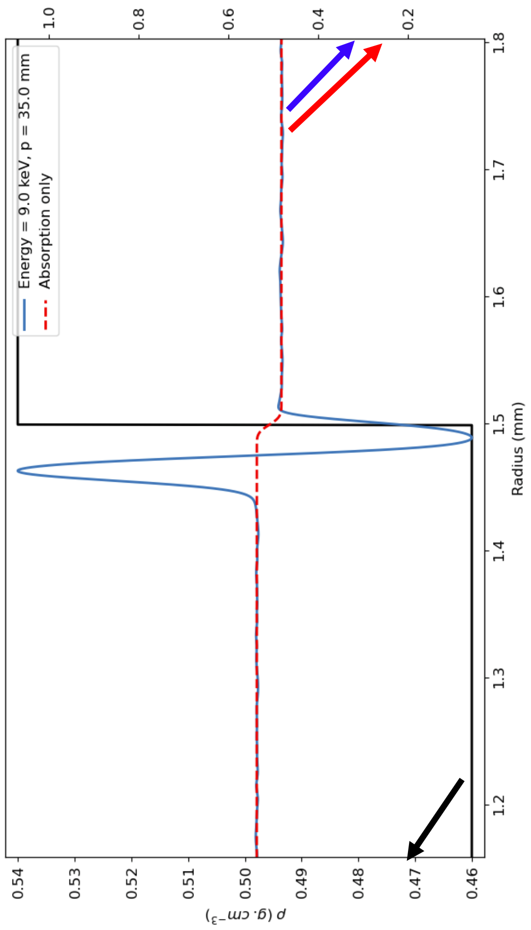


Wave propagation simulation of Refraction enhanced imaging



Wave propagation simulation of Refraction enhanced imaging

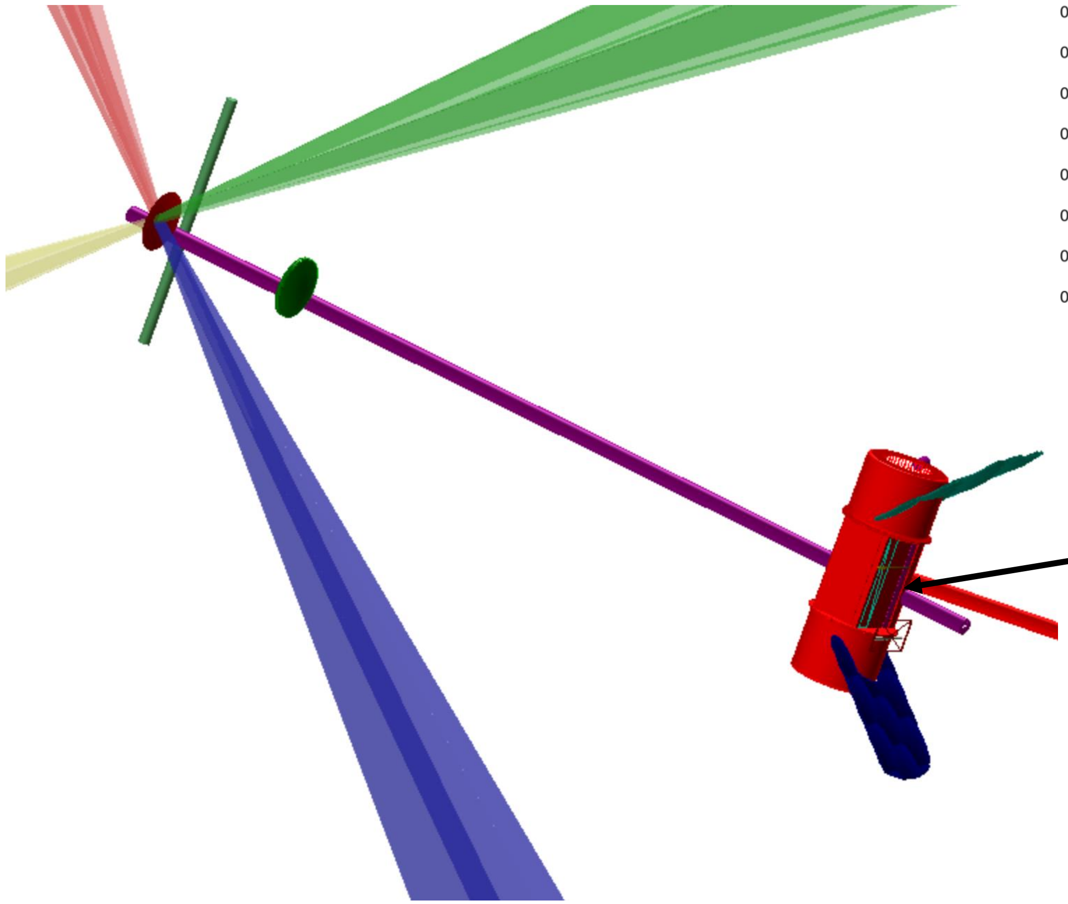


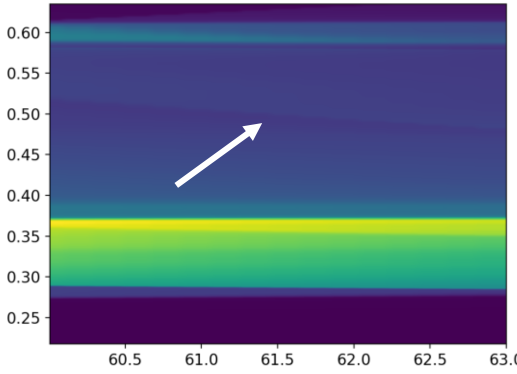


Tilting the target allows refraction to happen

Planned first measurement of shock physics inside a shocktube with a reshock drive with PAI and CRF foam using RER

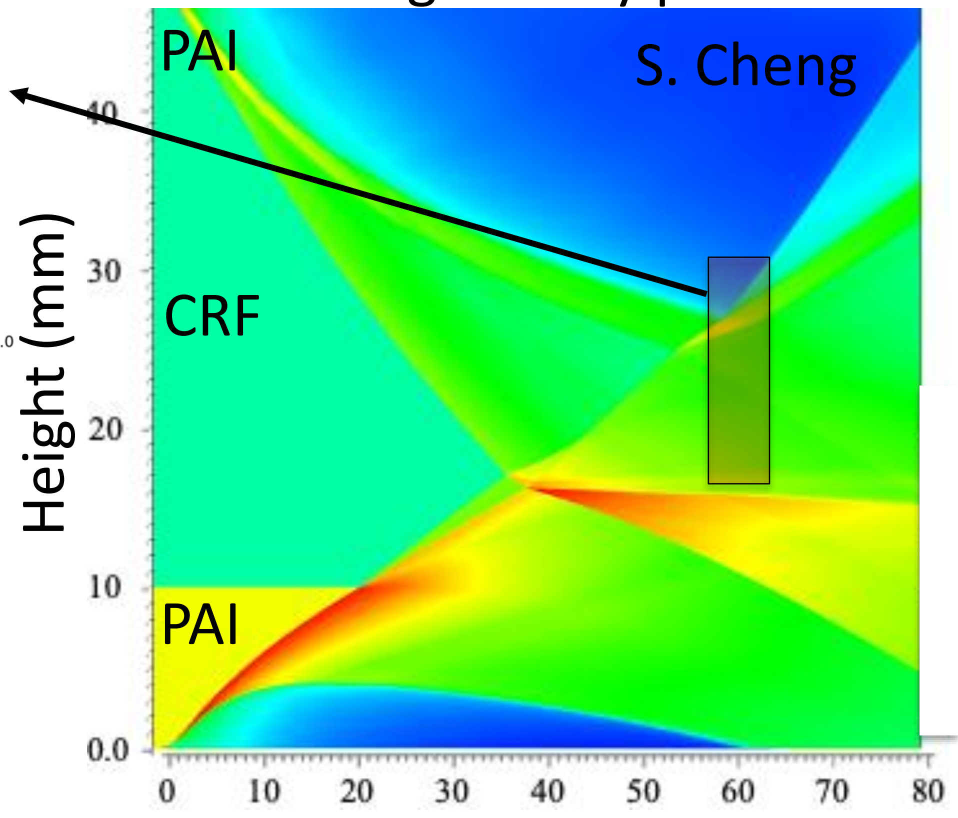
Design for 04/2023



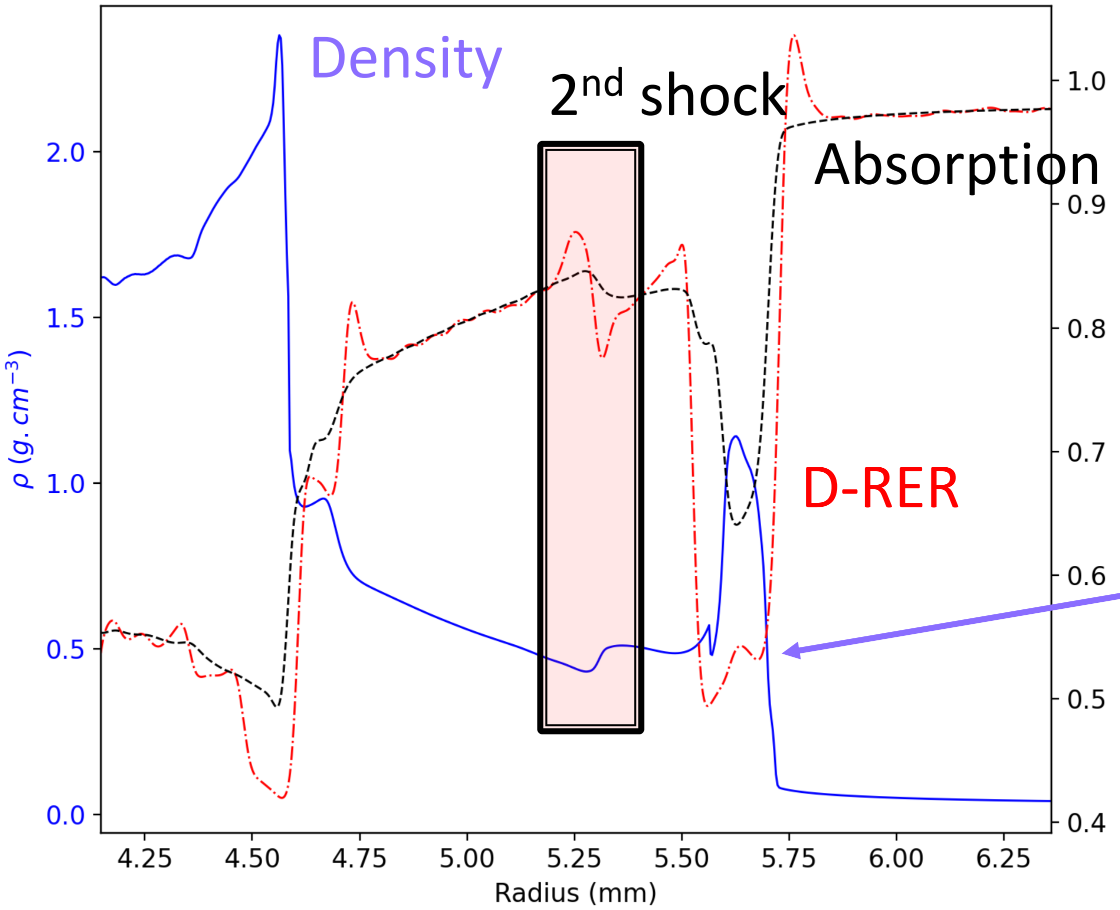


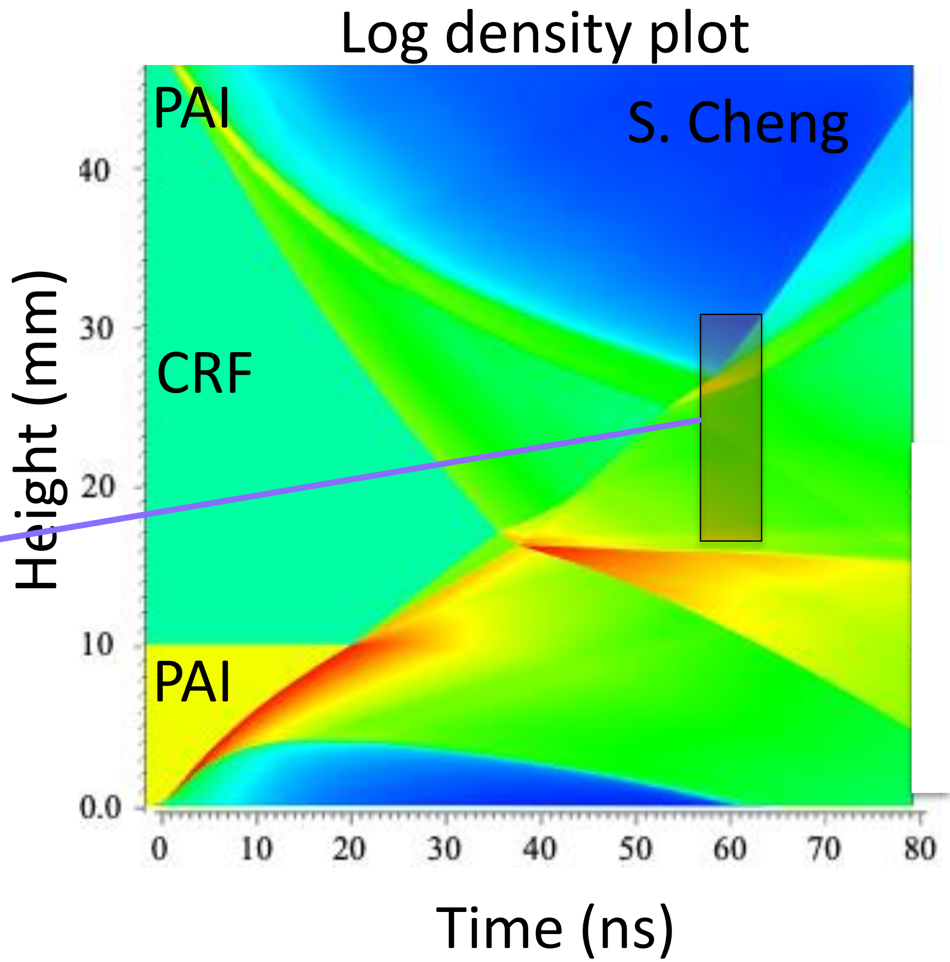
No ripples

Log density plot



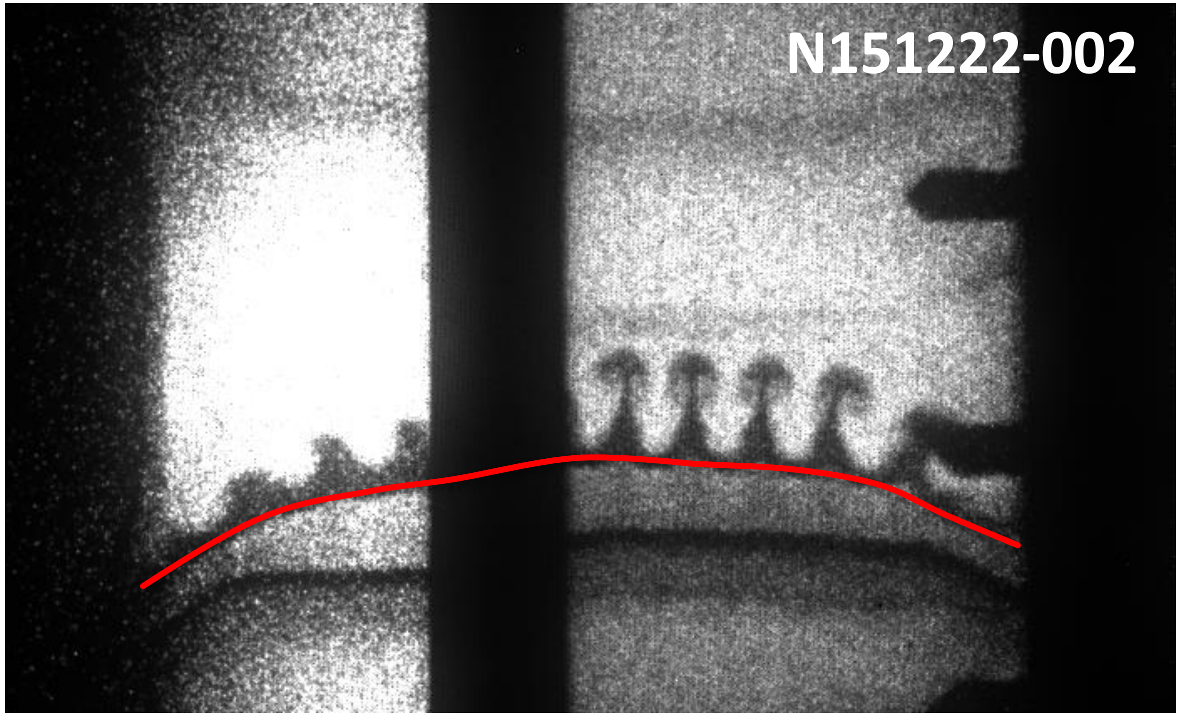
Simulations shows later time higher contrast of the 2nd reshock from RER

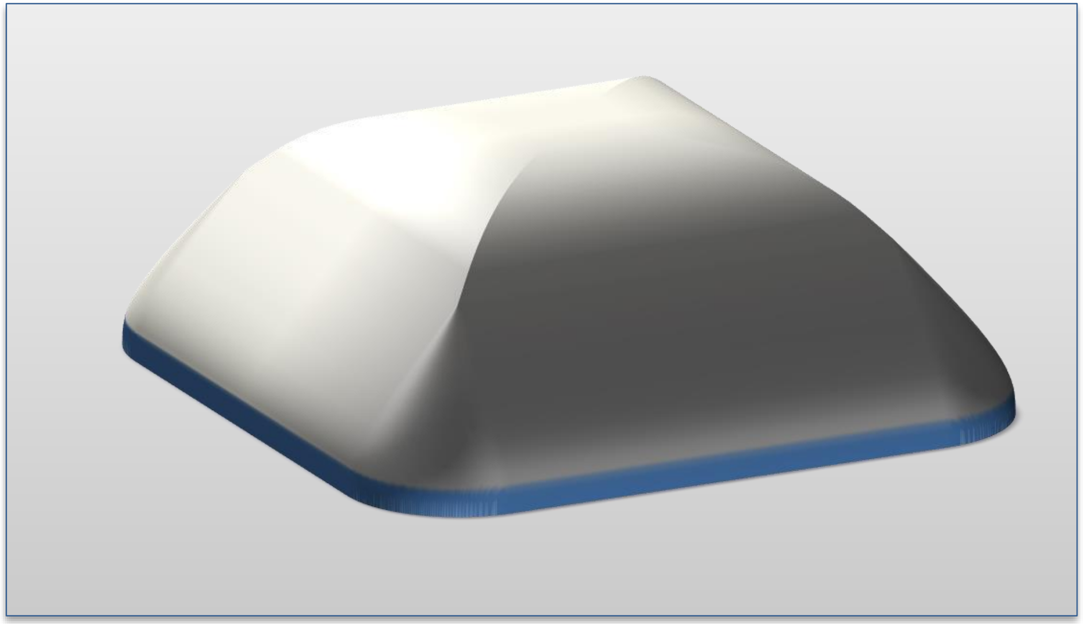




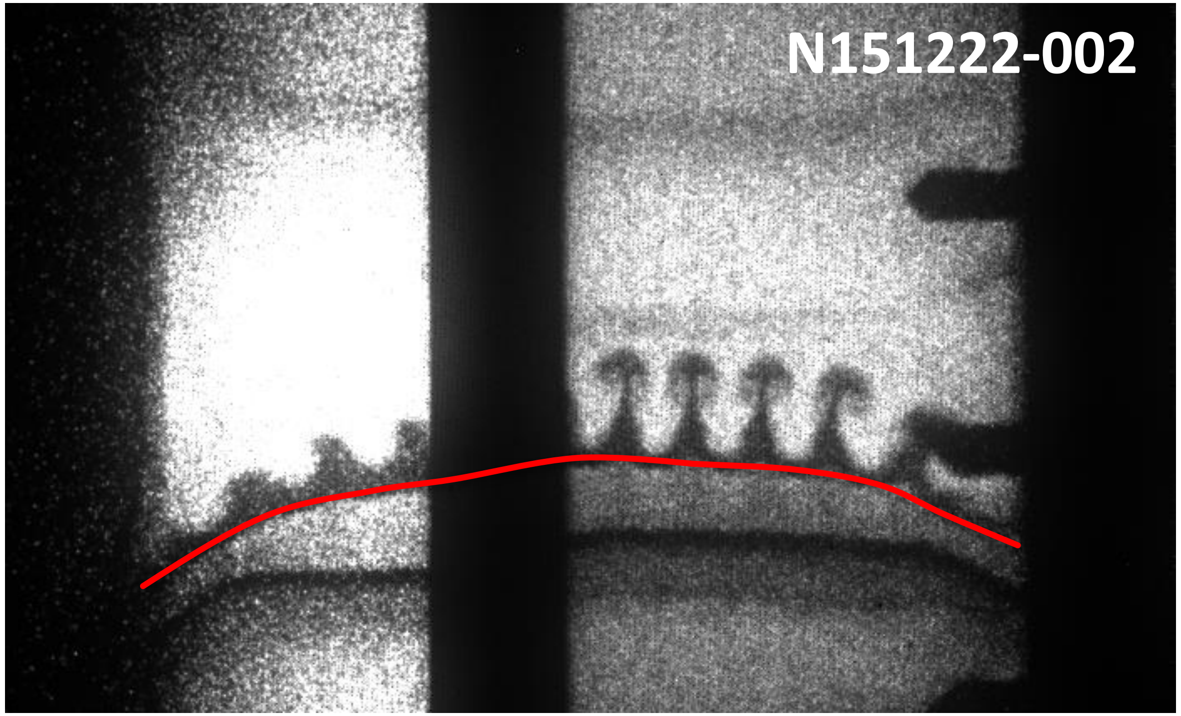
Gentle density gradients allows diffraction to occur

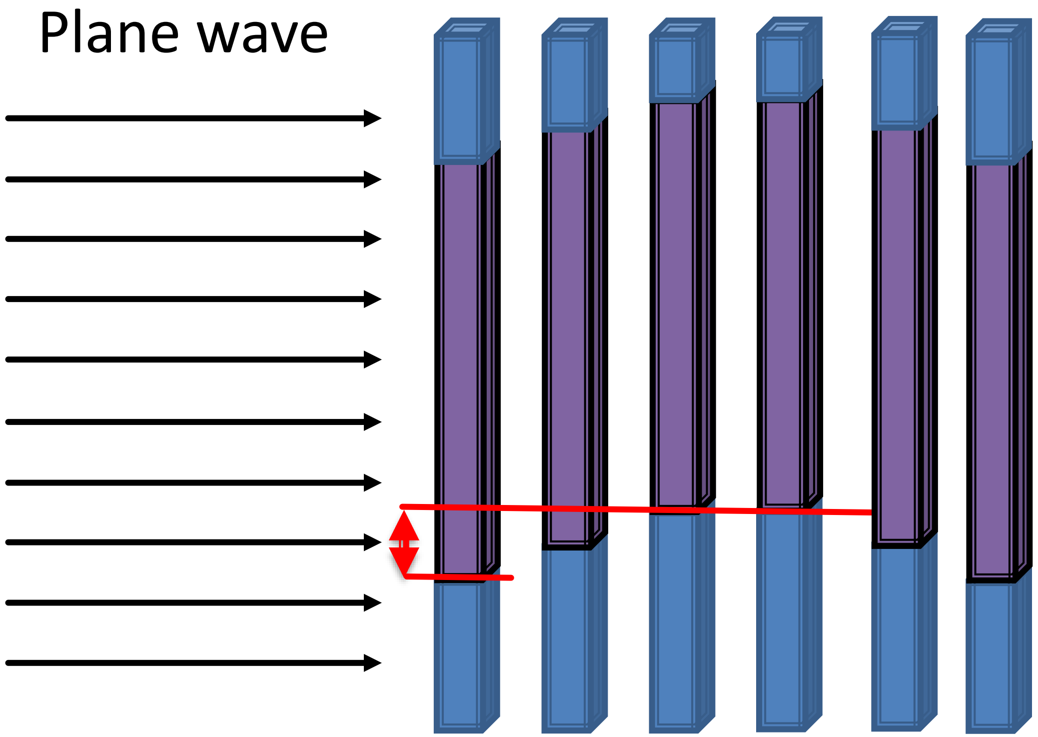
Hydrodynamic simulations and data suggest wall effect to curve the plastic-foam interface in 2 directions which exacerbate the refraction



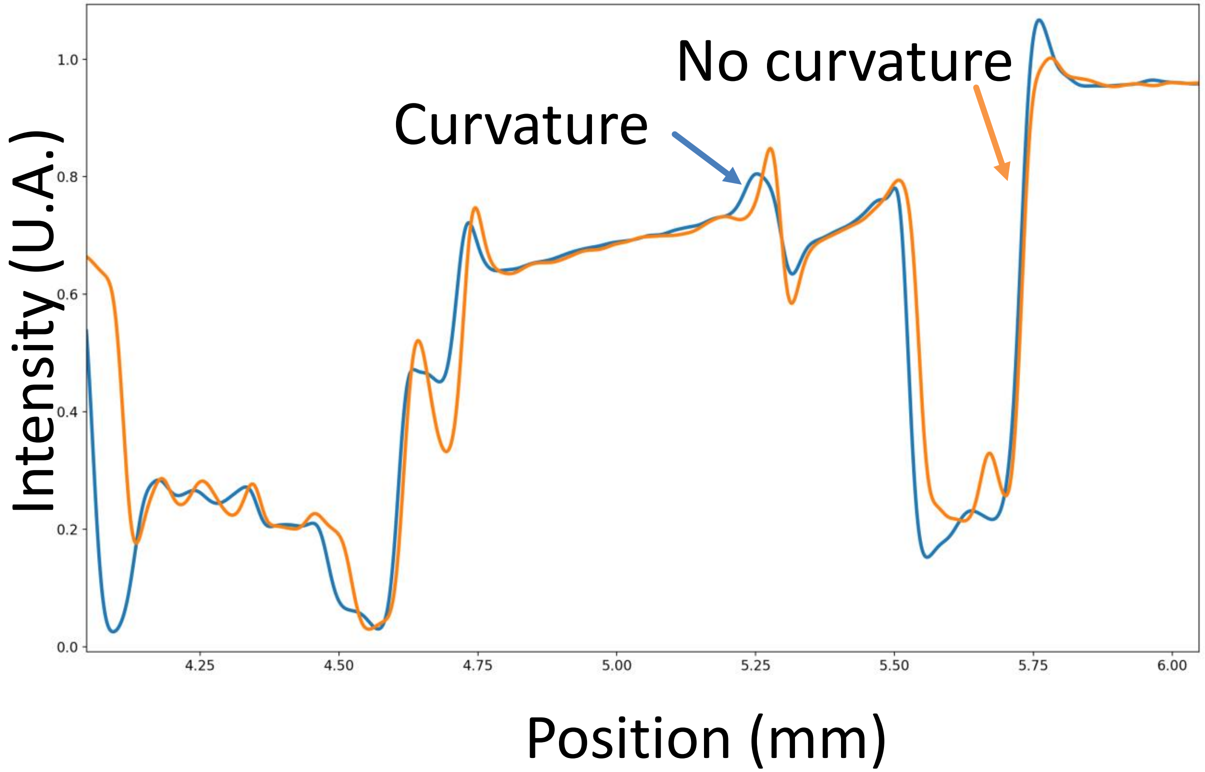


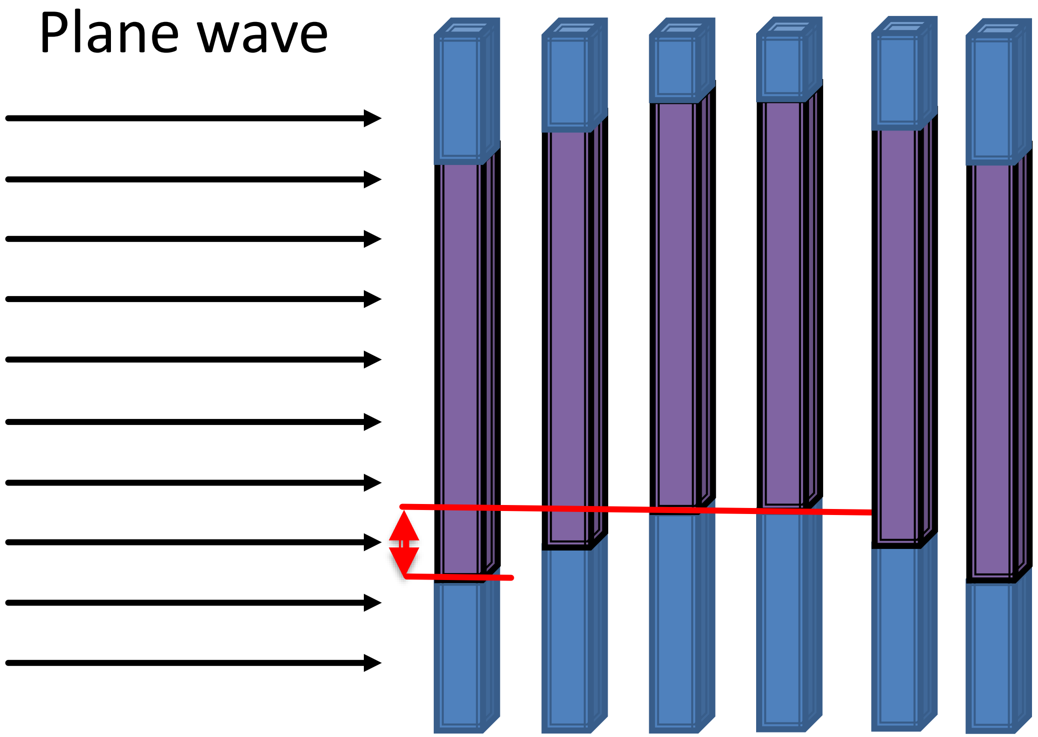
Hydrodynamic simulations and data suggest wall effect to curve the plastic-foam interface in 2 directions which exacerbate the refraction





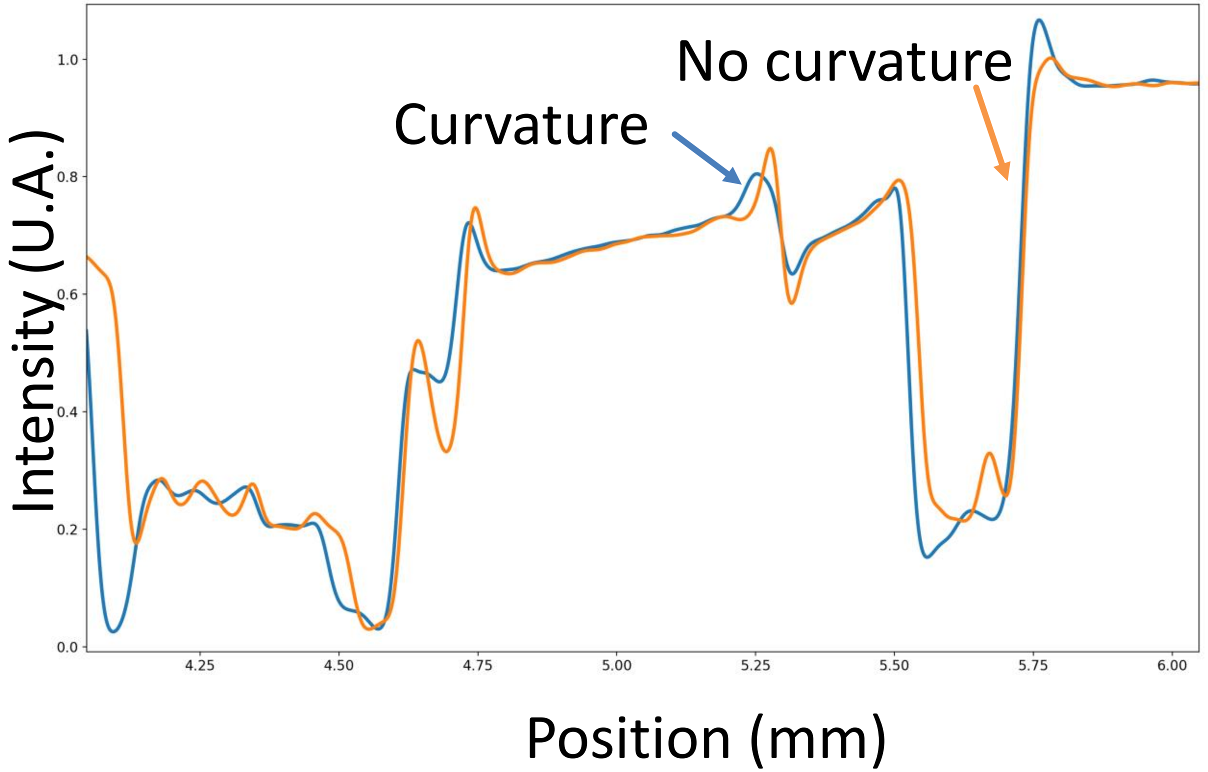
Hydrodynamic simulations and data suggest wall effect to curve the plastic-foam interface in 2 directions which exacerbate the refraction

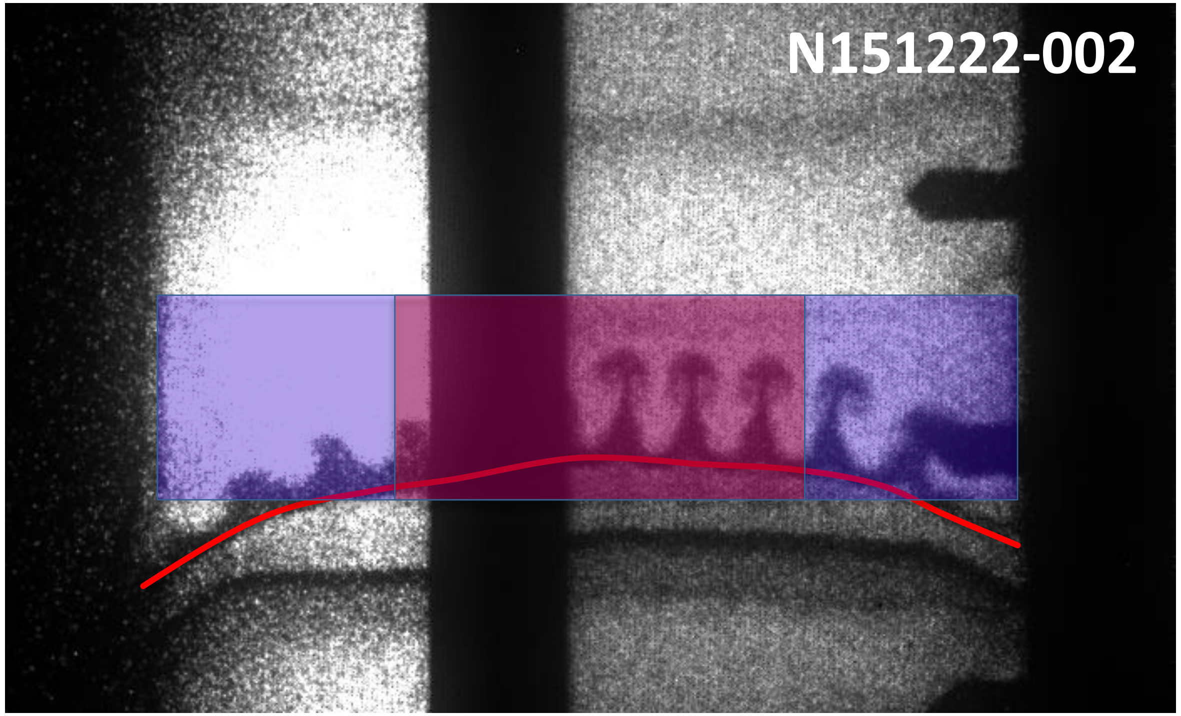




We can mitigate the curvature effect by reducing integration length

Hydrodynamic simulations and data suggest wall effect to curve the plastic-foam interface in 2 directions which exacerbate the refraction



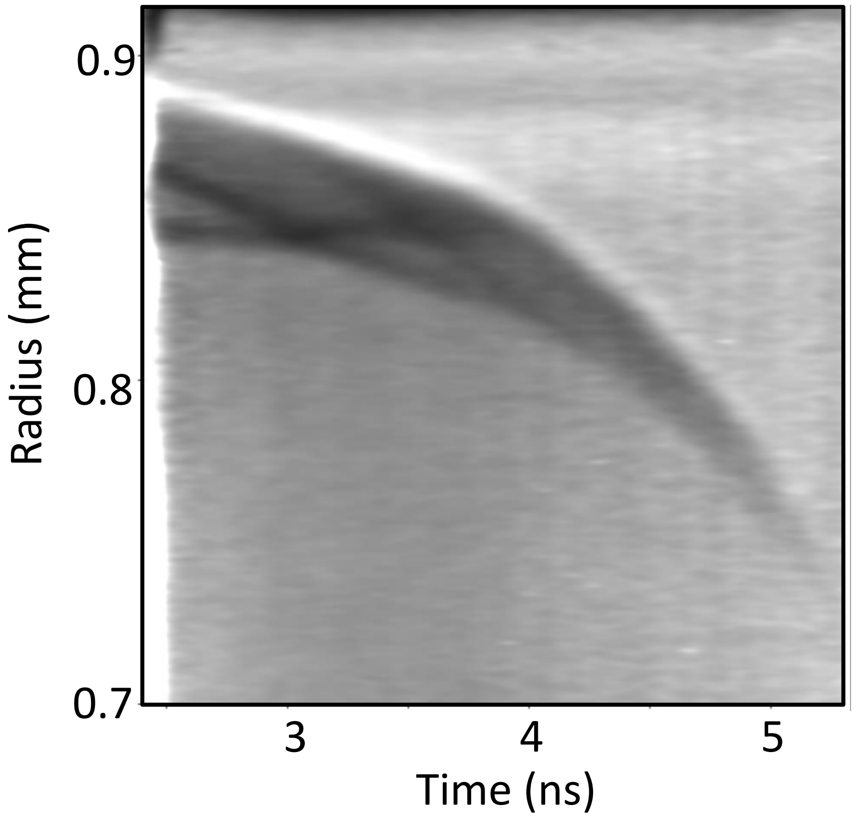


We can mitigate the curvature effect by reducing integration length

Refraction Enhanced Radiography (RER) is a useful tool for experiments at the National Ignition Facility

- High spatial (< 10 µm) and time resolution (<100 ps) 1D x-ray radiograph are required on NIF.
- RER has higher contrast than classic absorption experiments
- Used to retrieve density gradients and follow interfaces trajectory in capsule physics:
  - N+1 shock effect
  - Ice-ablator interface trajectory
- Thermal conductivity measurement in warm dense matter.
- Used to look at shock trajectory and timing inside a shocktube for hydrodynamic experiments.

RER data of capsule implosion



Lawrence Livermore National Laboratory