High-precision ionization balance measurements in warm dense matter at the NIF

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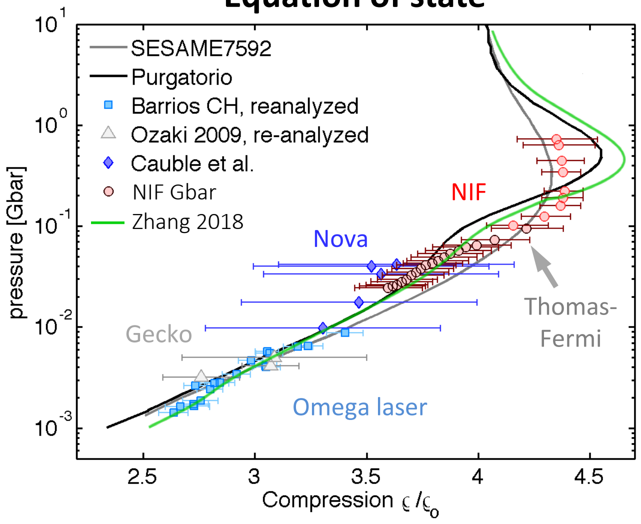
Lawrence Livermore National Laboratory

Why do we care about ionization models in warm dense matter?

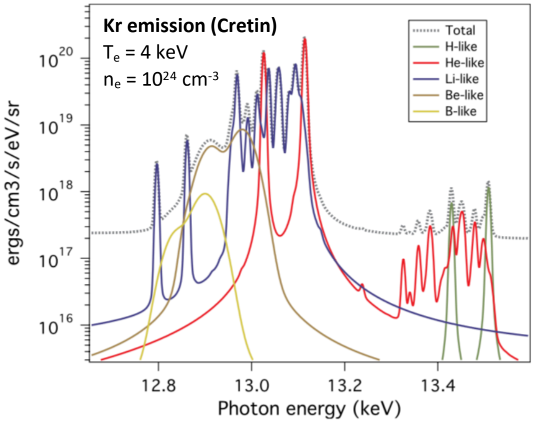
- Ionization is a fundamental parameter in plasma physics
  - Plays an important role in equation of state, opacity, transport properties, heat capacity, …

Equation of state



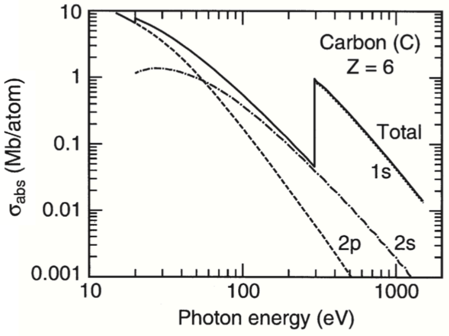
Adapted from A. Kritcher *et al.*, 2015 LDRD annual report

X-ray spectroscopy



H. Chen *et al.*, Phys. Plasmas **24**, 072715 (2017)

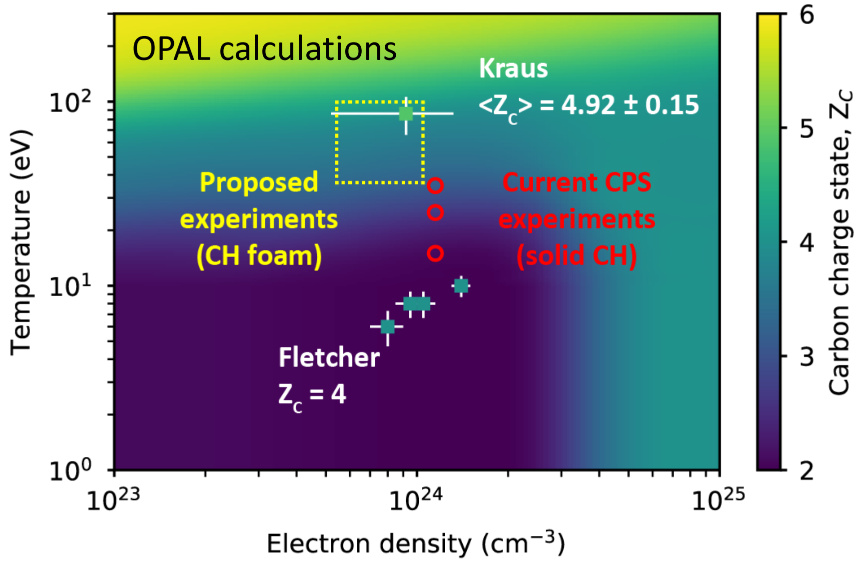
Opacity



X-ray data booklet (2009)

Improved measurements of warm dense matter conditions are needed to adequately benchmark theoretical models

Measured carbon ionization in CH plasmas disagrees with modeling



Warm dense matter

Coulomb coupling parameter ~ 1

$$\Gamma_{ee} = \frac{E_C}{k_B T}, \quad E_C = \frac{e^2}{4\pi\epsilon_0 r_s}$$

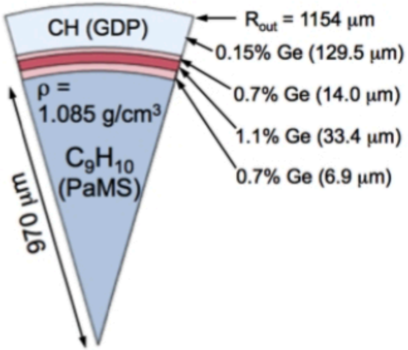
Degeneracy parameter ~ 1

$$\Theta = \frac{k_B T}{\epsilon_F}, \quad \epsilon_F = \frac{\hbar^2}{2m_e}\left(3\pi^2 n_e\right)^{2/3}$$

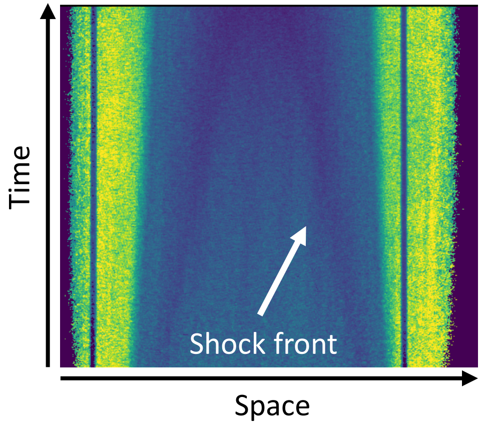
D. Kraus et al., Phys. Rev. E **94**, 11202 (2016)
L. B. Fletcher et al., Phys. Rev. Lett. **112**, 1 (2014)

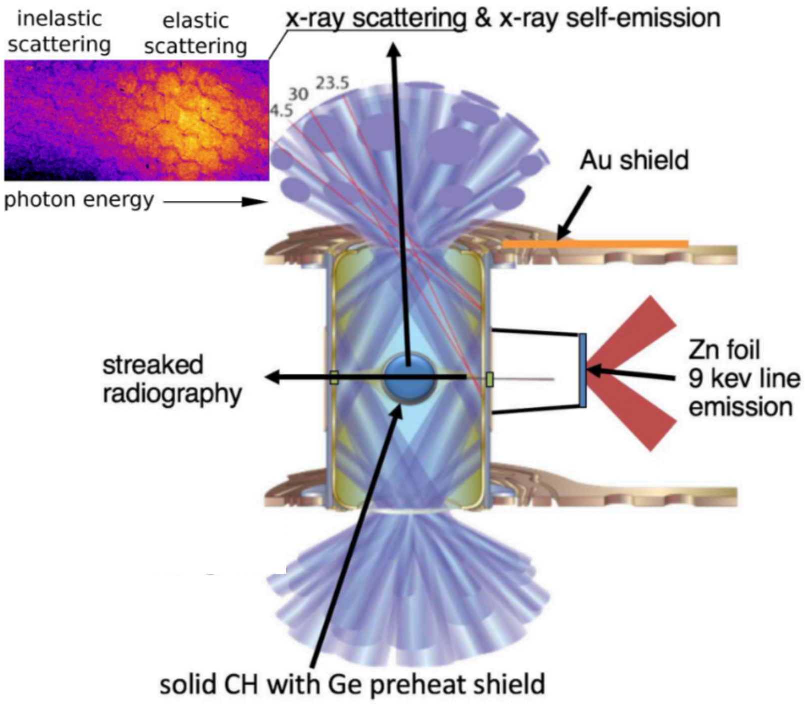
The Gbar platform at NIF uses spherically convergent shock waves to probe extreme states of matter

- Density profiles from streaked radiography
- Plasma conditions from x-ray Thomson scattering (XRTS)



Streaked radiography

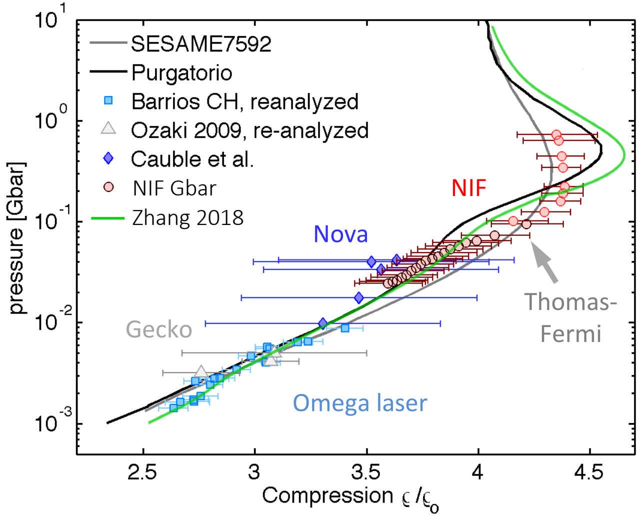




D. Kraus *et al.*, Phys. Rev. E **94**, 11202 (2016)
A. L. Kritcher *et al.*, HEDP **10**, 27 (2014)

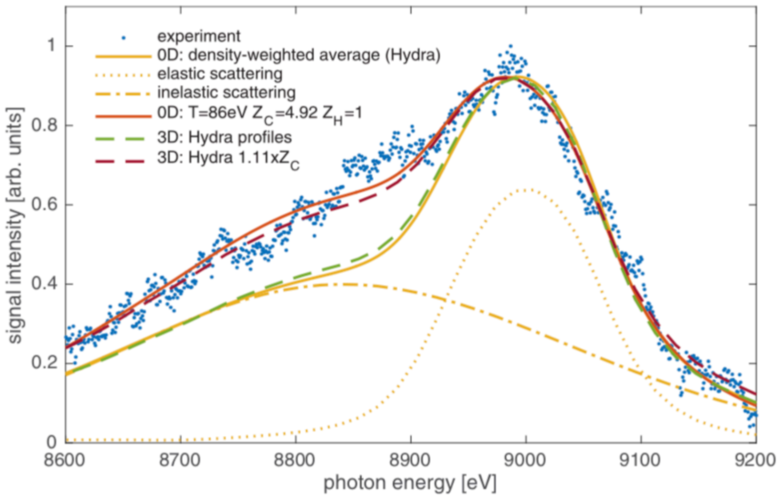
The Gbar platform at NIF uses spherically convergent shock waves to probe extreme states of matter

Absolute Hugoniot measurements using streaked x-ray radiography



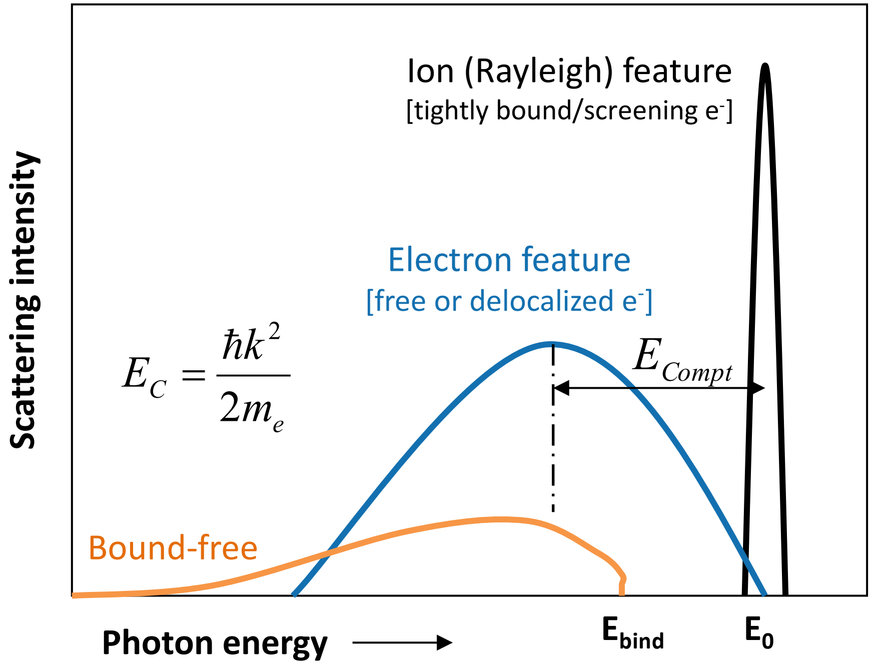
T. Döppner *et al.*, Phys. Rev. Lett. **121**, 025001 (2018)
D. C. Swift *et al.*, Rev. Sci. Inst. **89**, 053505 (2018)
S. Zhang, *et al.*, J. Chem. Phys. **148**, 102318 (2018)
A. L. Kricther *et al.*, submitted to Nature

Demonstrated x-ray Thomson scattering (XRTS) spectra measurements at NIF

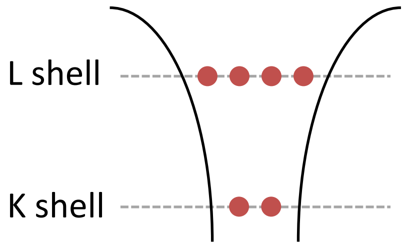


D. Kraus *et al.*, Phys. Rev. E **94**, 11202 (2016)

X-ray Thomson scattering (XRTS) is a powerful tool to probe dense plasmas



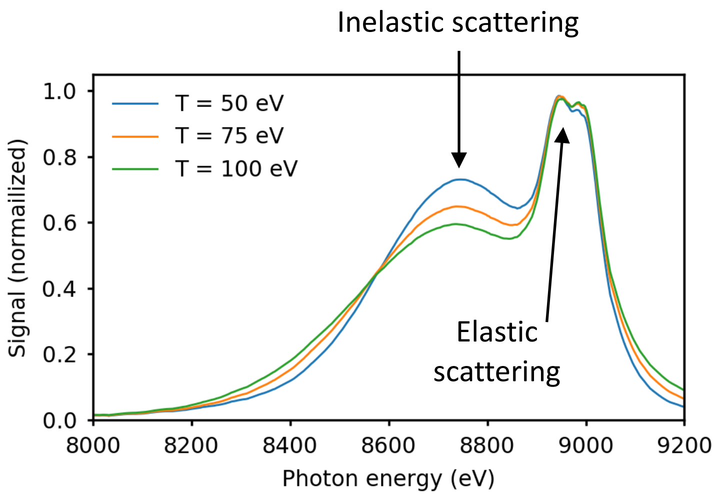
- Elastic peak strength depends on number of tightly bound electrons
- Temperature and/or density from the shape of the electron feature

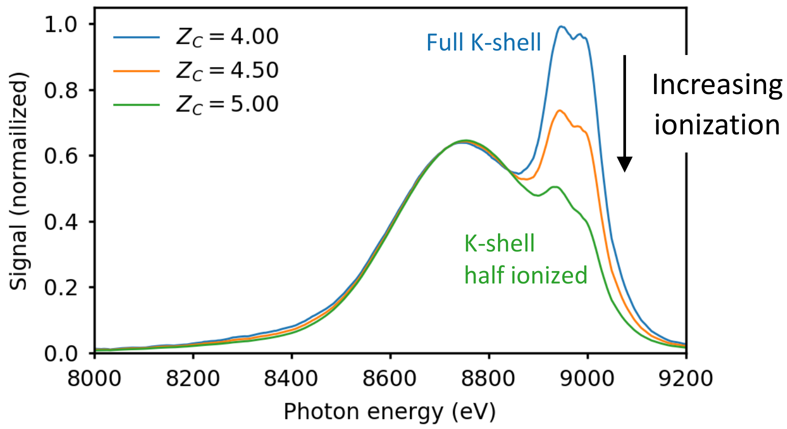


Carbon: $1s^2\ 2s^2\ 2p^2$

X-ray Thomson scattering (XRTS) is particularly sensitive to carbon K-shell ionization in this regime

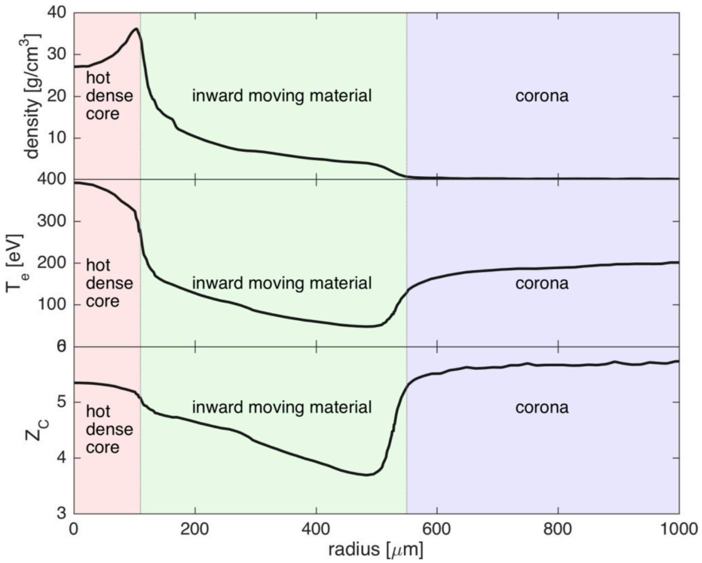
- Electron temperature and density from inelastic scattering
- Carbon ionization state from the inelastic/elastic peak ratio



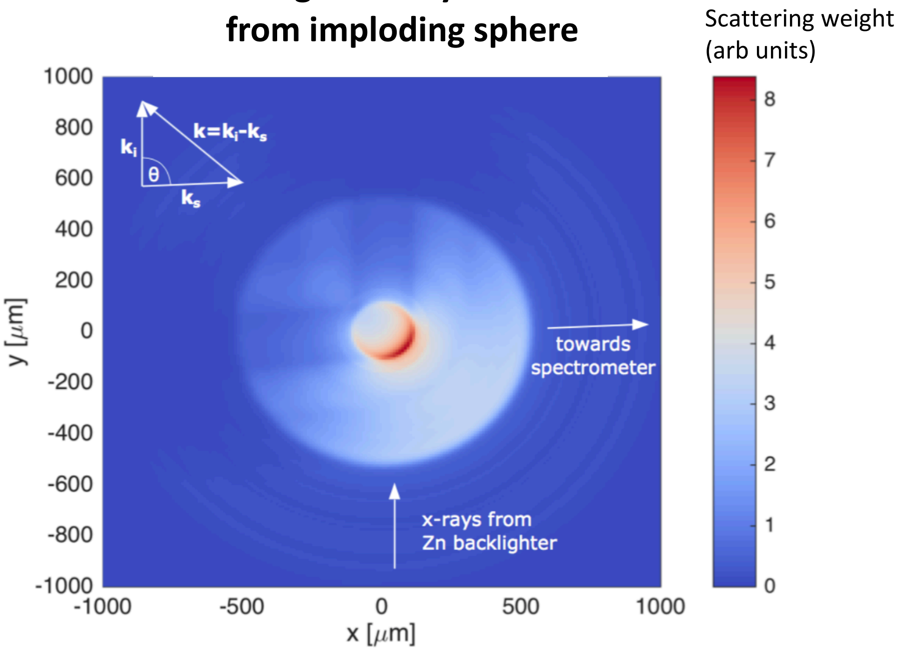


Modeling XRTS spectra from imploding spheres requires accurate hydrodynamic and x-ray opacity modeling

Post-shot simulations of radial profiles of plasma parameters of solid sphere implosion



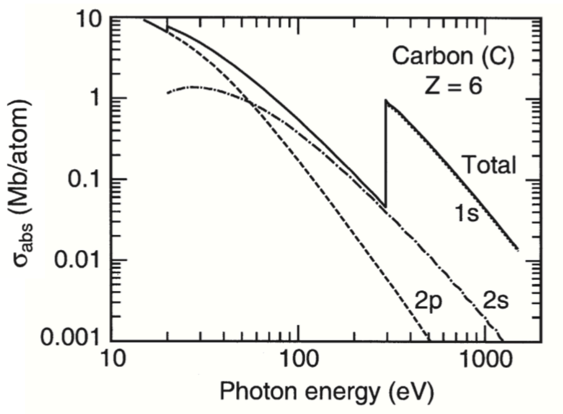
Scattering intensity calculations from imploding sphere



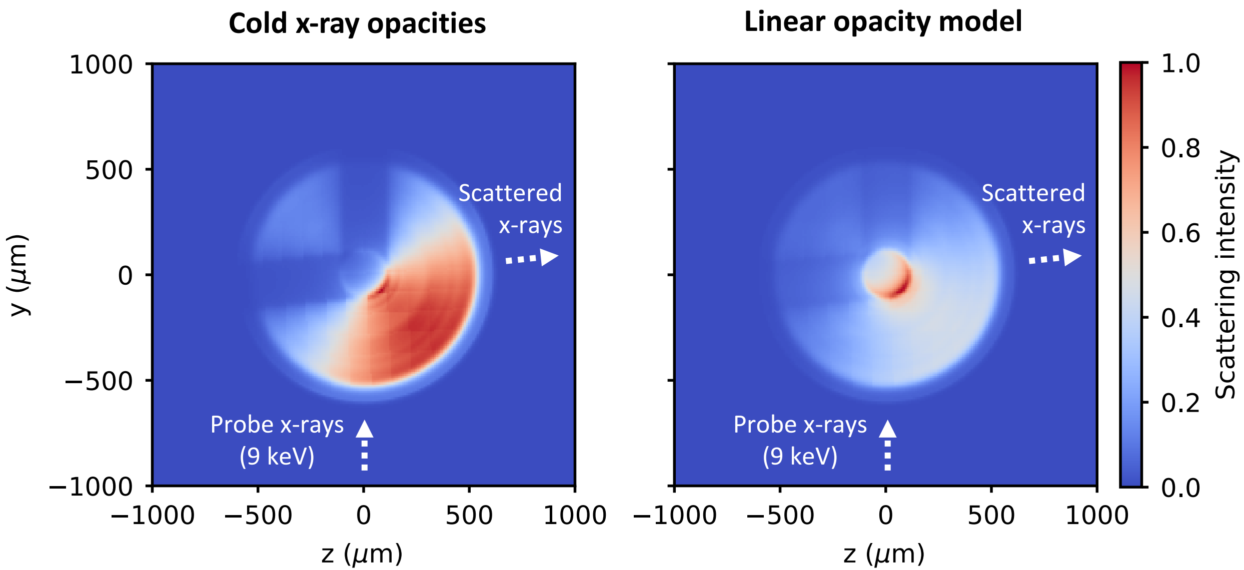
D. Kraus et al., Phys. Rev. E **94**, 11202 (2016)

X-ray scattering calculations are sensitive to opacity models when probing a large distribution of states

Carbon opacity dominated by K shell for photon energies above 300 eV

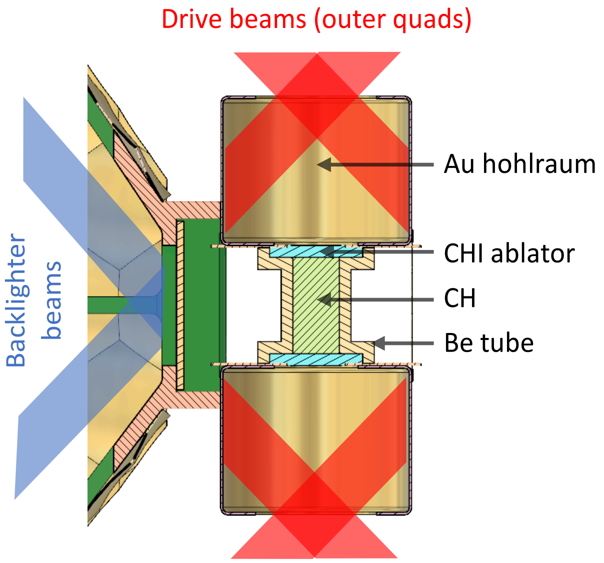


X-ray data booklet, LBNL/PUB-490 Rev. 3 (2009)

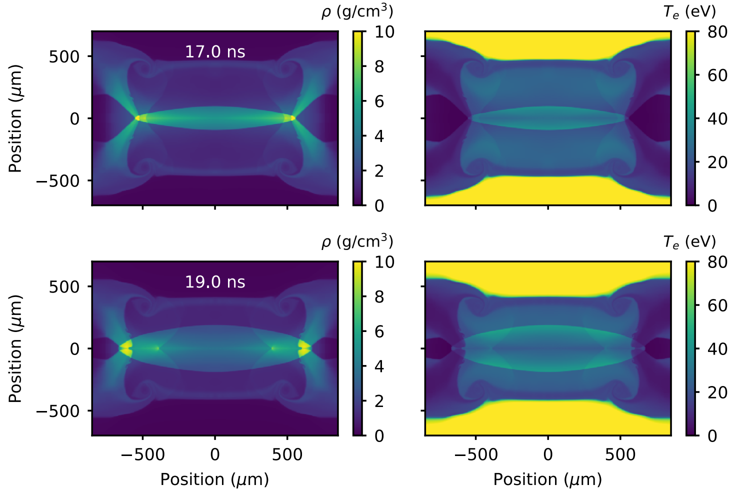


We are developing the Colliding Planar Shocks (CPS) platform to make high-precision equation of state measurements at the NIF

- Two indirectly-driven planar shocks driven by the NIF
- Plasma conditions probed using x-ray radiography and XRTS



RAGE simulations (Carlos Di Stefano, LANL)



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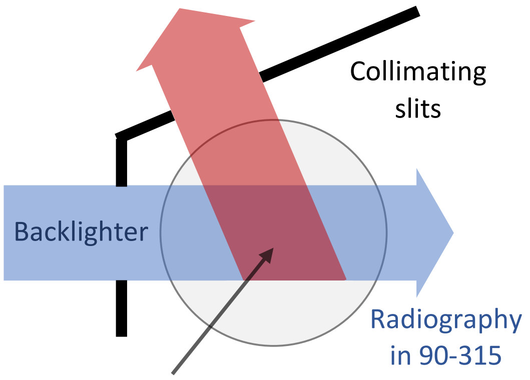
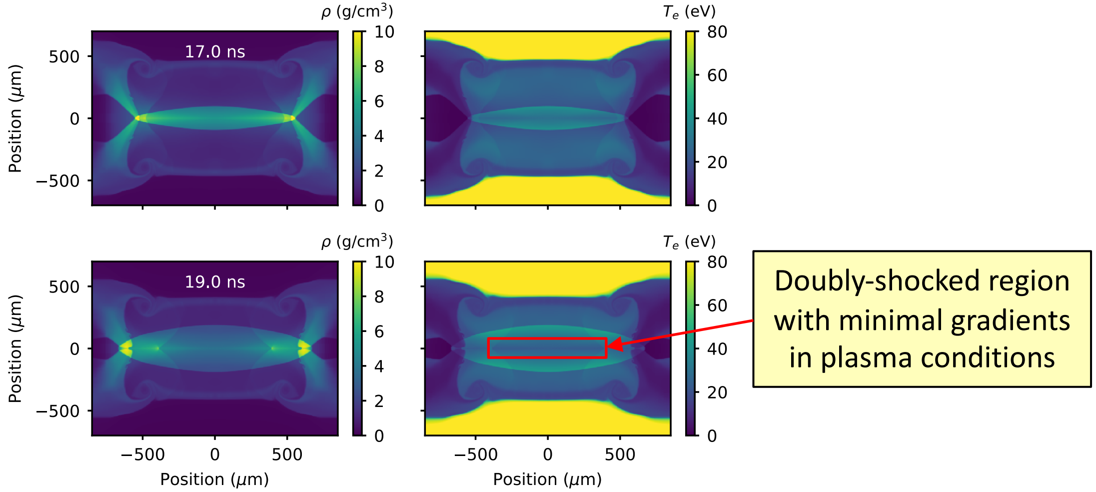
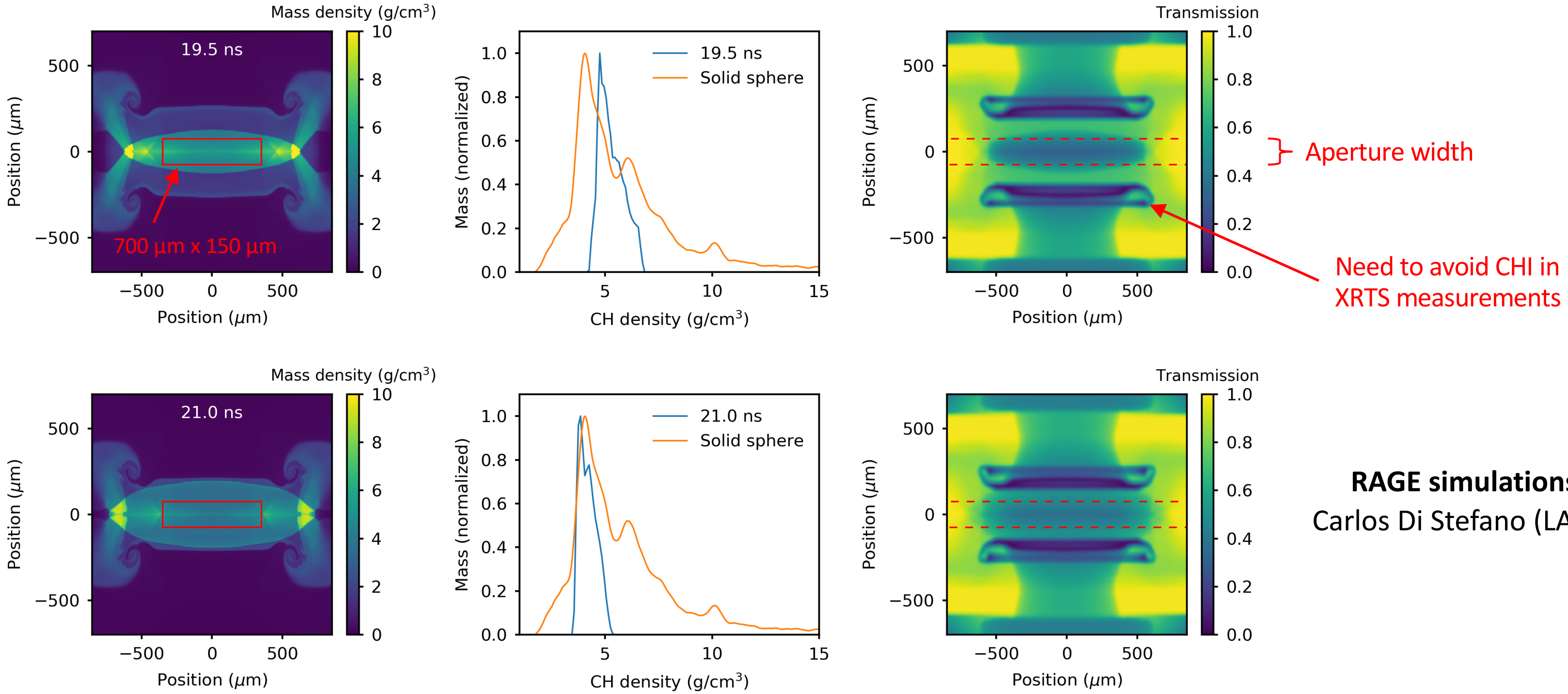


RAGE simulations (Carlos Di Stefano, LANL)



The CPS platform produces a large volume of warm dense matter with minimal spatial gradients



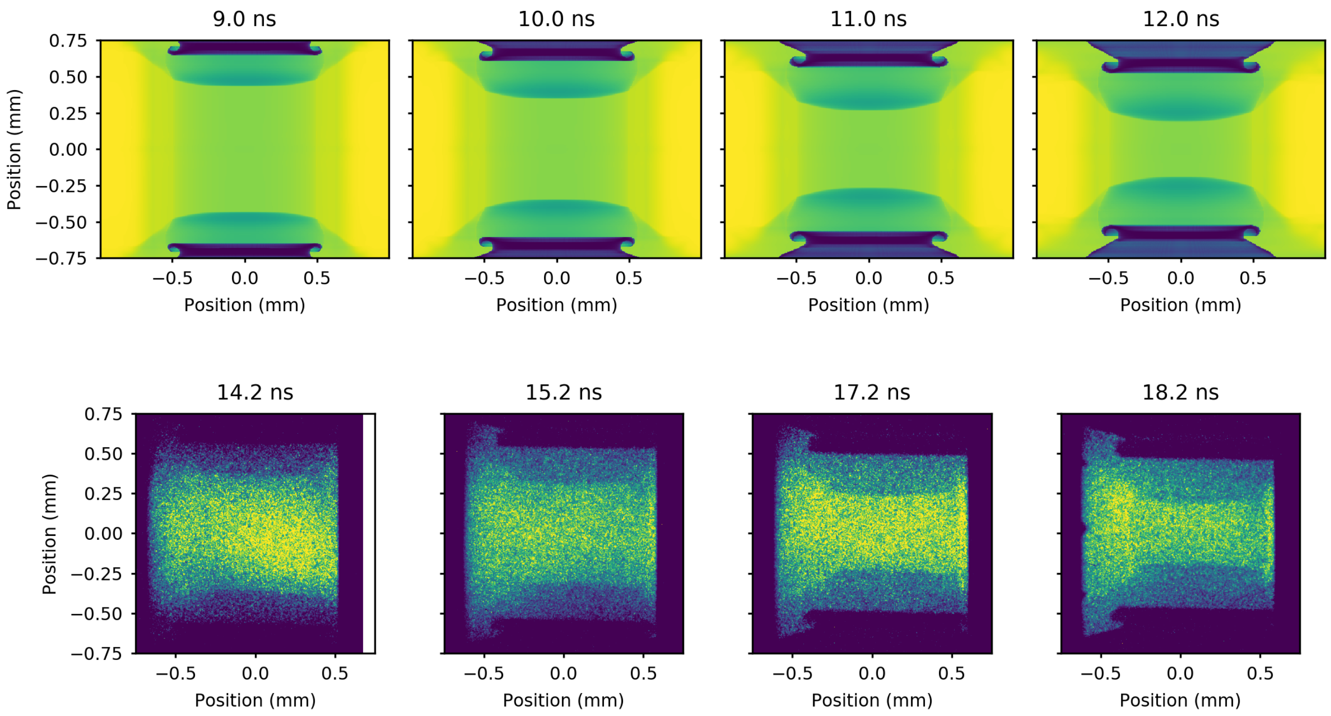
RAGE simulations
Carlos Di Stefano (LANL)

We recorded high quality x-ray radiography data on our first shot

Shock speed was slower than expected

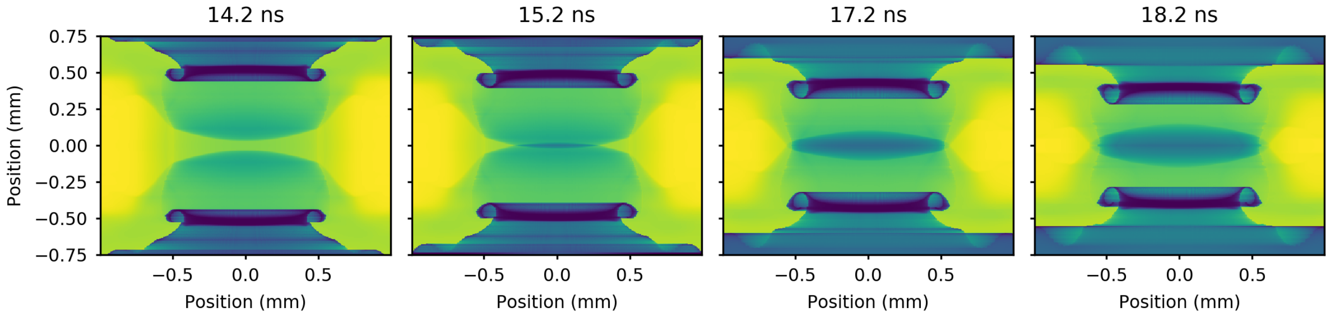
RAGE simulations
(Carlos Di Stefano)

Radiography data
N190911-002

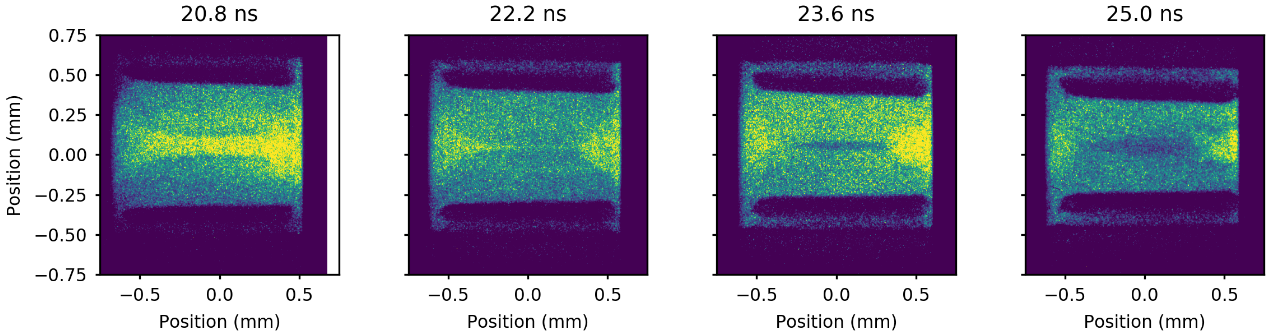


We observed the colliding planar shocks on our second shot

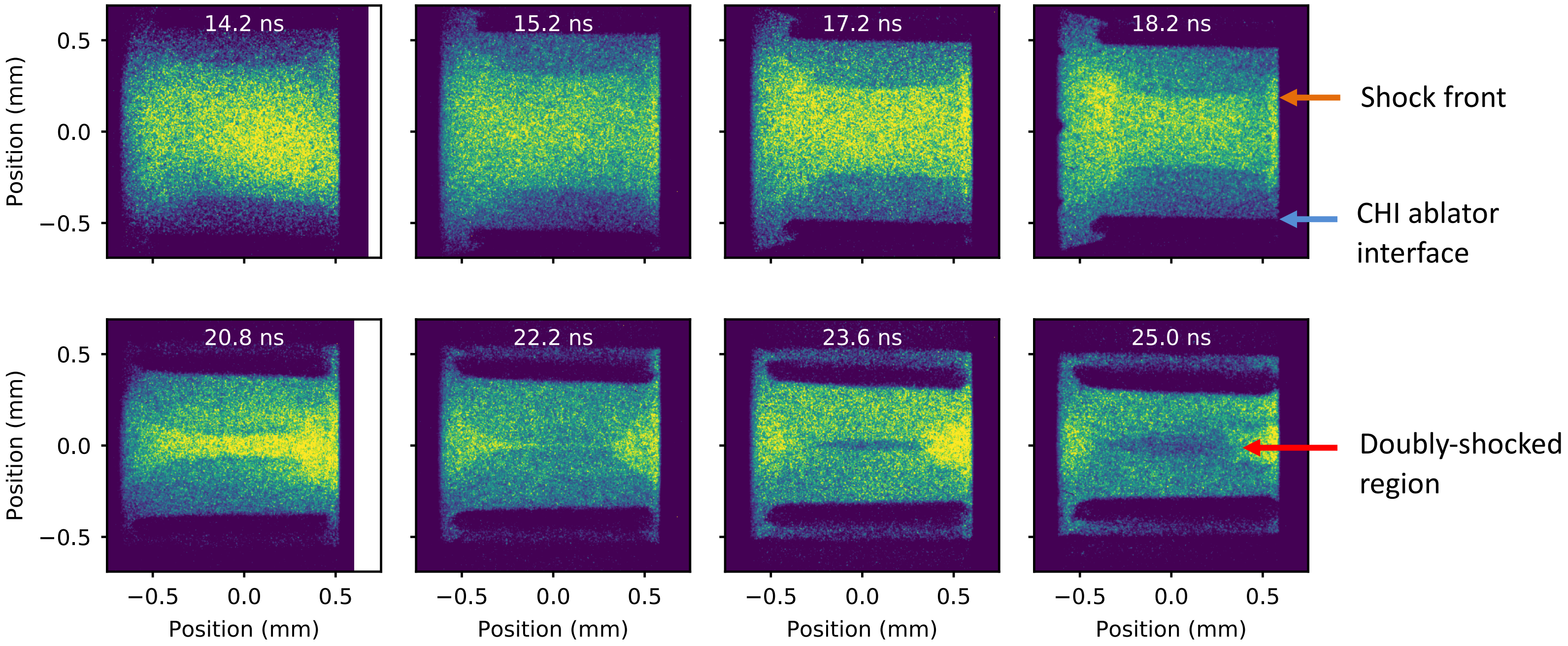
RAGE simulations
(Carlos Di Stefano)



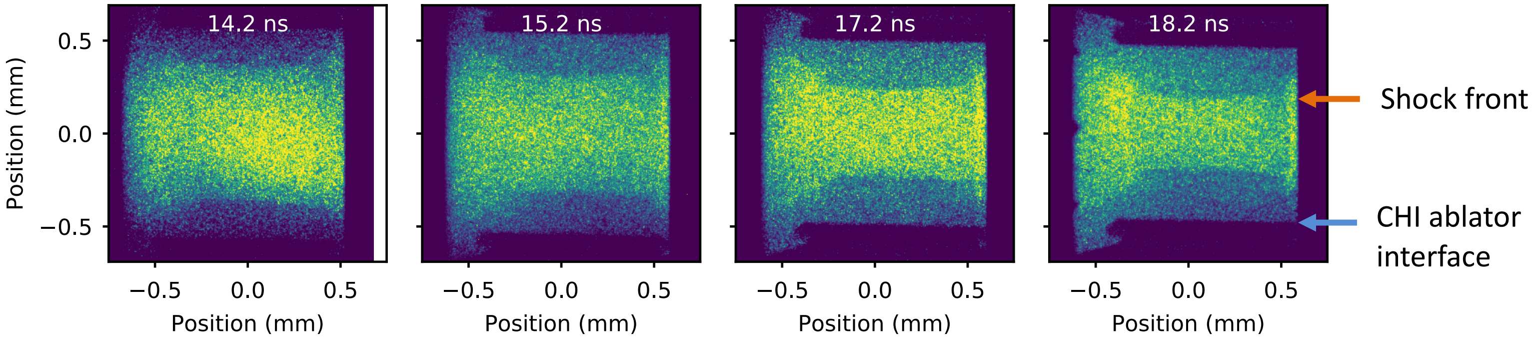
Radiography data
N190911-003

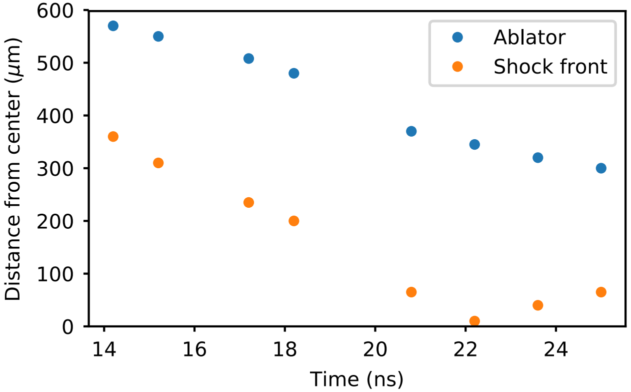


We recorded excellent radiography data on our first shot day



Initial shock timing results will be used to improve RAGE simulations for the next shot day (May 2020)

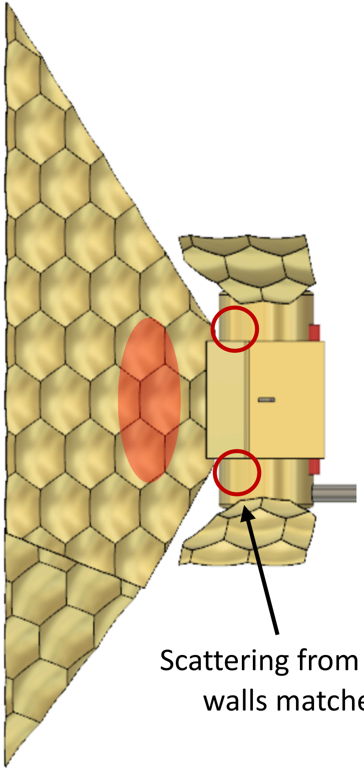




Time (ns)	Ablator (μm)	Shock front (μm)
14.2	570	360
15.2	550	320
17.2	508	235
18.2	480	200
20.8	370	65
22.2	345	10
23.6	320	40
25.0	300	65

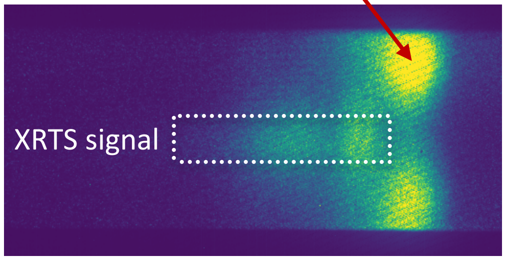
Background scattering from the hohlraum walls reduced the quality of the XRTS data

Zn plasma



Scattering from hohlraum walls matches data

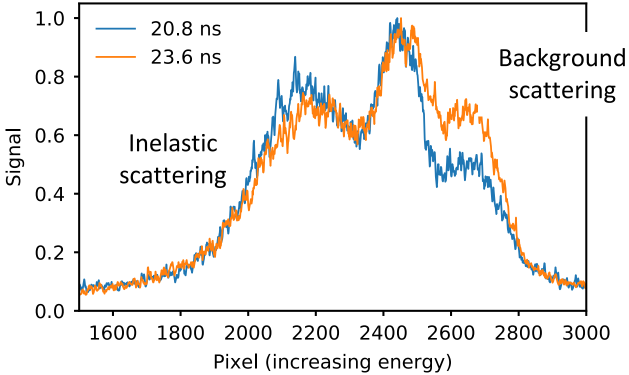
Background scattering



Position

Energy

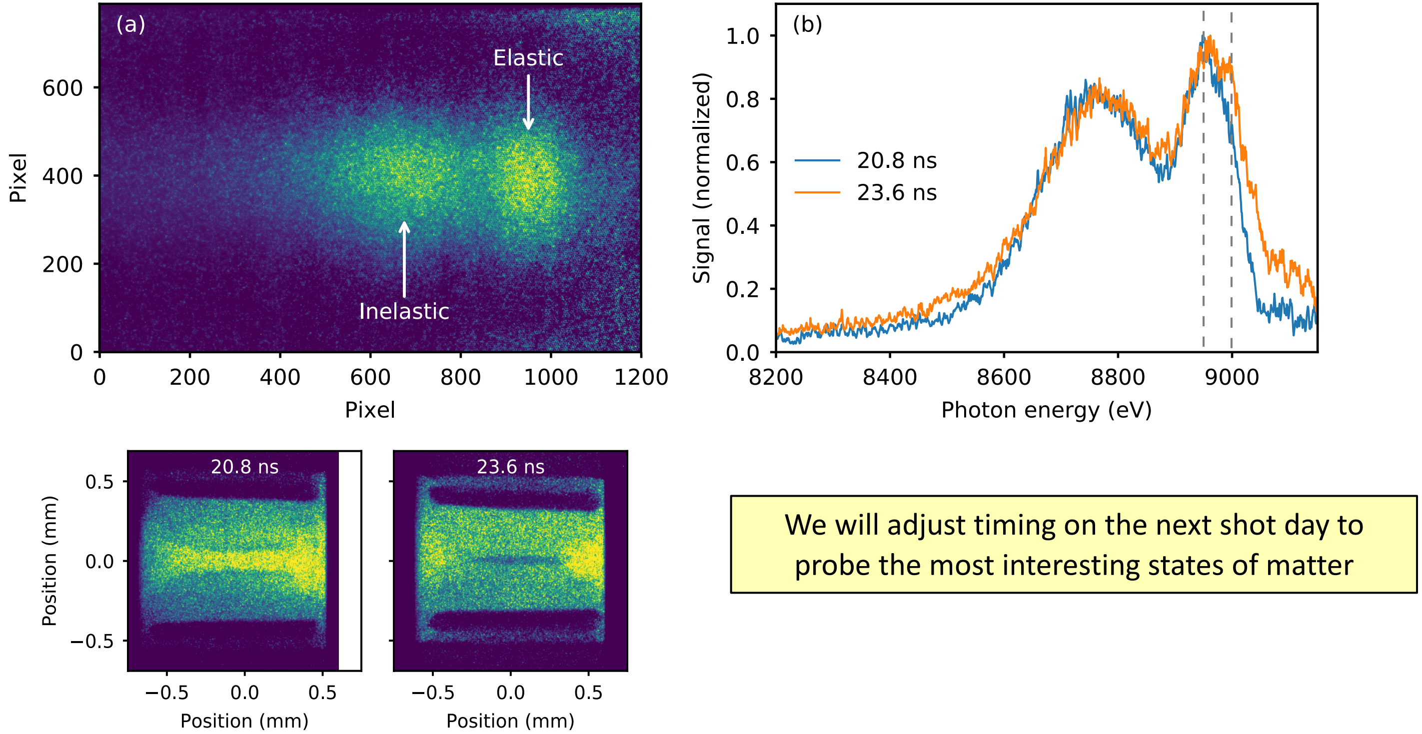
Elastic scattering



Background scattering

The target design has been modified for our upcoming shot day to eliminate these sources of background

We obtained high-quality XRTS measurements on the first shot day

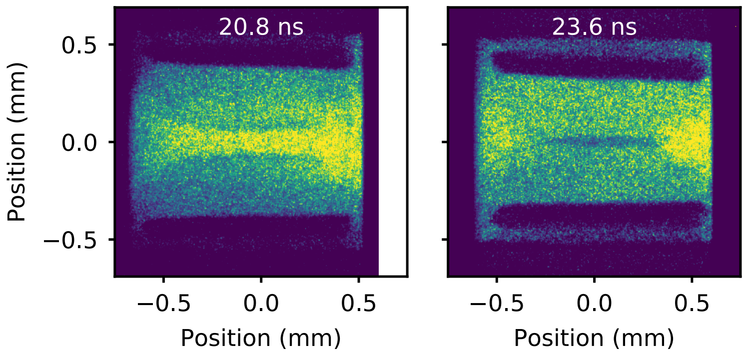


We will adjust timing on the next shot day to probe the most interesting states of matter

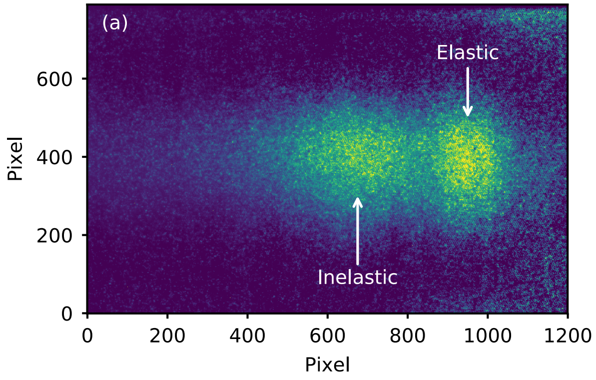
We are developing the Colliding Planar Shocks platform to make high-precision EOS measurements of warm dense matter

- We obtained excellent radiography on our first shot day (Sept 2019)
- We will improve our XRTS measurements and make measurements of solid CH (May 2020)
- We were awarded one shot day in FY21 to measure higher temperatures using CH foam

X-ray radiography data (2 of 8 images obtained)

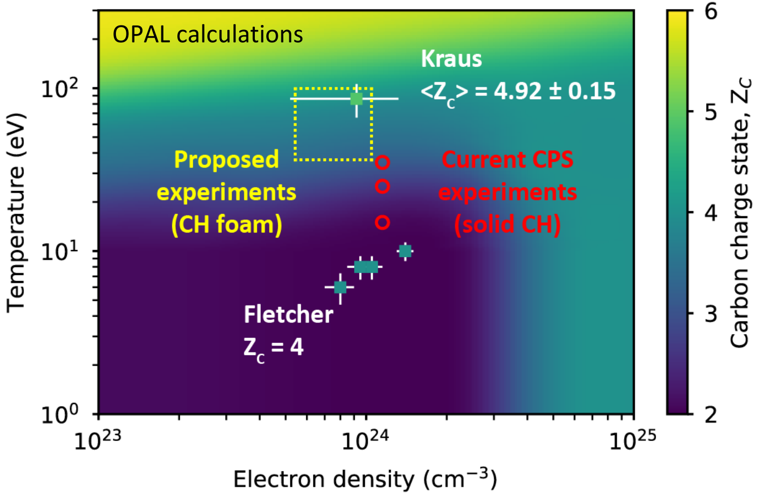


X-ray Thomson scattering (XRTS) data



We were awarded one shot day to investigate carbon K-shell ionization in CH foams at various initial densities

- We need higher temperatures to investigate K-shell ionization of carbon in CH plasmas
  - Current CPS experiments compress solid CH, reaching T_e = 15–35 eV
  - By compressing CH foams at various densities, we can reach T_e = 35–100 eV



Temperature ranges we can probe using different initial densities of CH foam

Initial CH density	Temperature
500 mg/cc	35-70 eV
250 mg/cc	50-80 eV
100 mg/cc	60-100 eV

The goal of our latest proposal is to measure ionization state of carbon in CH plasmas at T_e = 35–100 eV at $n_e \sim 10^{24}$ cm^{-3}

This work is a collaboration of national laboratories and academic institutions from around the world

Mike MacDonald	LLNL
Roger Falcone	UC Berkeley
Carlos Di Stefano	LANL
Tilo Döppner	LLNL
Kirk Flippo	LANL
Liz Merritt	LANL
Suzanne Ali	LLNL
Peter Celliers	LLNL
Rip Collins	UR/LLE
Luke Fletcher	SLAC
Jim Gaffney	LLNL
Dirk Gericke	Warwick
Siegfried Glenzer	SLAC
Dominik Kraus	HZDR
Alison Saunders	LLNL

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  - Rick Heredia, Scott Vonhof, Jean Jensen, Abbas Nikroo
- LANL Target Fabrication
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