Probing Dense Plasmas for HEDS and ICF

Otto "Nino" Landen

Lawrence Livermore National Laboratory

HEDS Seminar Series
Nov. 16th, 2023

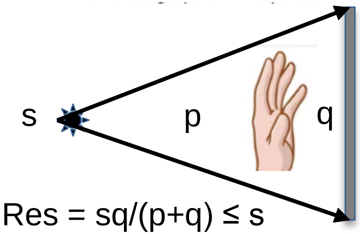
LLNL-PRES-

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

Point Projection X-ray Radiography
125+ years ago

W. Roentgen 1895

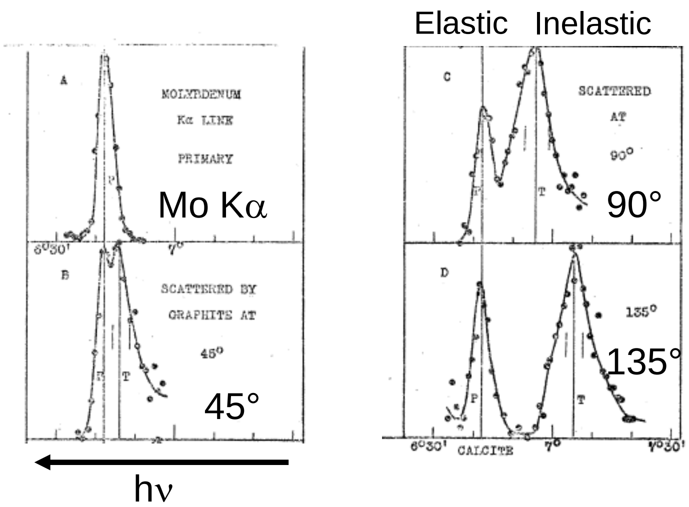


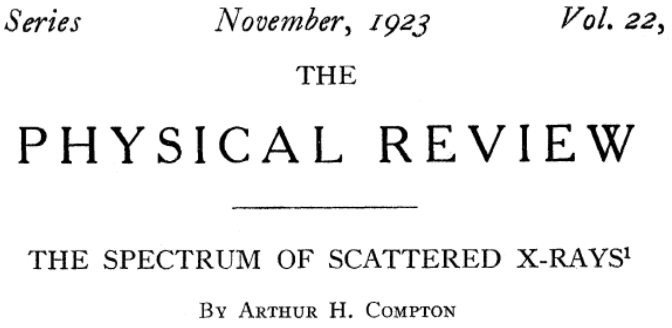
$Res = sq/(p+q) \le s$

Compton Scattering
100 years ago

W. Roentgen 1895

A. Compton 1923




Series November, 1923 Vol. 22,

THE

PHYSICAL REVIEW

THE SPECTRUM OF SCATTERED X-RAYS[1]

By Arthur H. Compton

Free or bound e^- with I.P. < Compton shift scatter with downshift; tightly bound e^- scatter unshifted

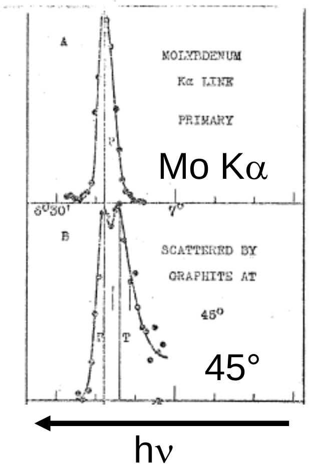
Free and bound e- will exhibit different velocity distributions

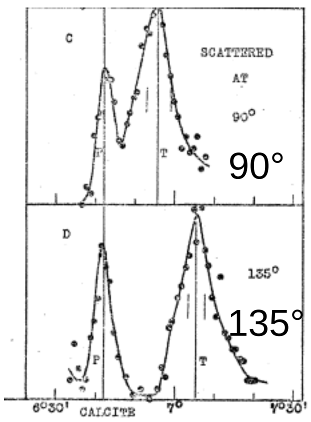
So we have potential measure of ionization state and velocity distributions

Compton Scattering and Fermi Statistics 100 years ago

W. Roentgen 1895

A. Compton 1923





The Compton Scattering and the New Statistics.

By S. CHANDRASEKHAR, The Presidency College, Madras.

(Communicated by R. H. Fowler, F.R.S.—Received June 20, 1929.)

However, at the time, paraphrasing:

”Compton scattering by electron-gas or bound electrons (in solid) will not be influenced by range of temperatures available in the laboratory”

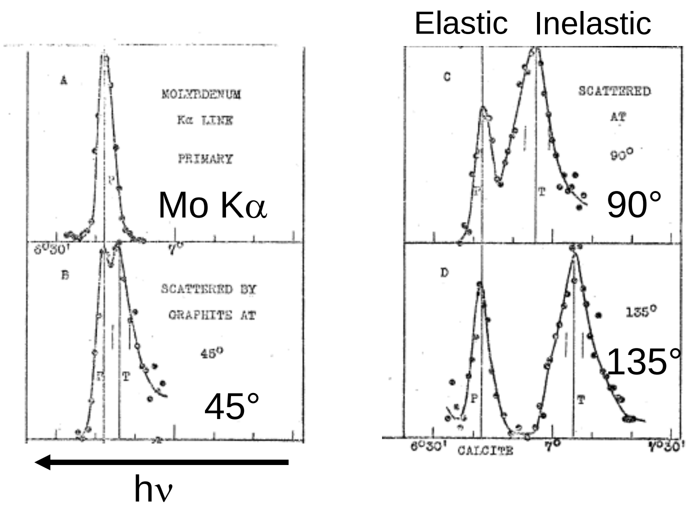
10 eV I.P. and T_{Fermi} >> Static T_e

Clear challenge and motivation to extend to plasma domain

But that connection to the distant past was not the trigger

W. Roentgen 1895

A. Compton 1923



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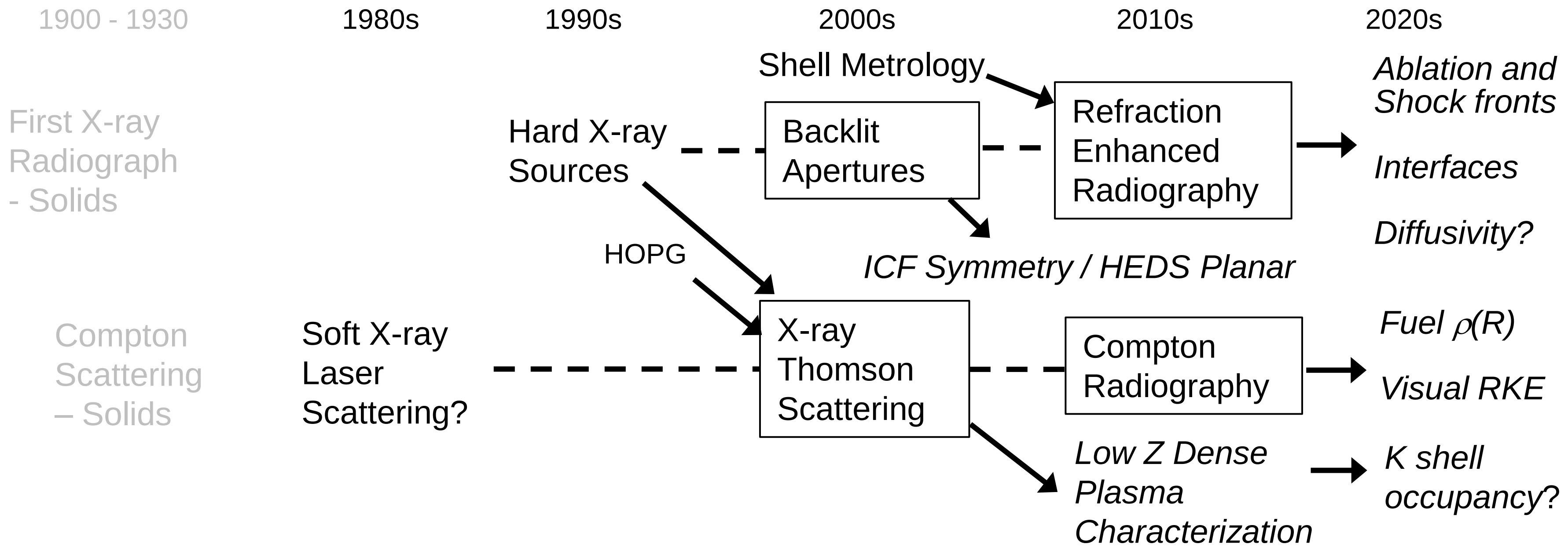
~~Clear challenge and motivation to extend to plasma domain~~

Instead each capability (realized or not) spawned (- - - - -) the next
Reality was closer in spirit to what E. Teller once said about NIF

We develop/envisage new capabilities precisely because we don't know what those capabilities will enable

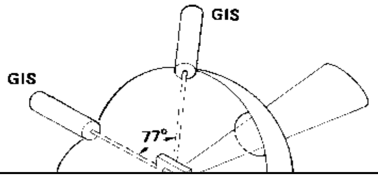


1985 - Novette Soft X-ray laser at λ = 200 Å
Can we measure Thomson scatter off its own plasma?

lengths approach the soft x-ray regime.

The purpose of this Letter is to report the first results from new experiments on the neonlike collisional excitation scheme. We describe the first conclusive demonstration of a macroscopic-sized gain medium which exhibits substantial amplification of at least four $2p^5 3p$-$2p^5 3s$ transitions in selenium, with the largest being observed for the $J=2$ to 1 lines at 206.3 and 209.6 Å. The transition with the largest predicted gain,[4–9] the $J=0$ to 1 transition at approxi-

cm long by displacing the two beams axially.

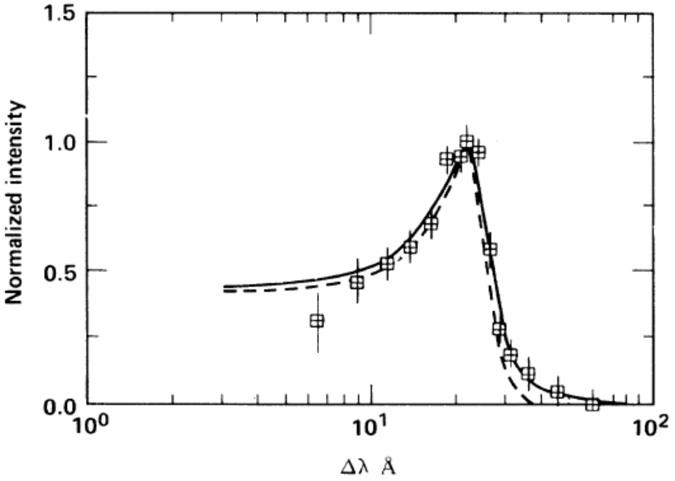


1986 - Motivation: Transpose optical scattering fresh in mind to shorter wavelength

4, NUMBER 15 PHYSICAL REVIEW LETTERS 15 APRIL 1985

Laser Scattering from Dense Cesium Plasmas

O. L. Landen[a] and R. J. Winfield[b]
Imperial College, The Blackett Laboratory, London SW7 2BZ, United Kingdom
(Received 19 October 1984)



2ω
n_e = 3-5e16 /cc
T_e = 0.4-0.9 eV
N_D = 2-8

1986 - Back-of-the envelope assessment

lengths approach the soft x-ray regime.

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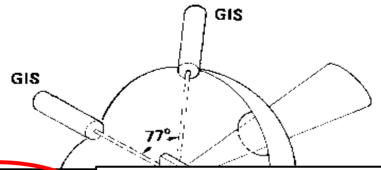


*Landen, PRL (1985)

X-Ray laser Thomson Scattering

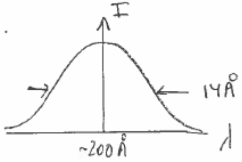
Feb. 28th, 1986

Aim: Use X-ray laser as its own probe for finding N_e and T_e by 90° Thomson scattering.

Numbers: For $N_e = 5\times10^{20}\,cm^{-3}$, $T_e = 500\,eV$, $\lambda = 200\,Å$, $\theta = 90°$

$\Rightarrow \alpha = 0.3$ $Z = 23$ $T_e/T_i = 10$?

Spectrum for Maxwellian will look like this:



$S_i \propto \frac{\alpha^2 T_i}{T_e} \ll 1$

⇒ All electron feature

⇒ Need ~ $\lambda/\Delta\lambda$ = 50-100 resolution

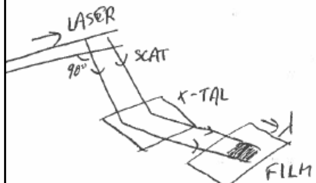
Fraction of Photons scattered (mainly at ends of plasma where I_{LASER} has built up to saturation value):

$N\sigma l = 6.6\times10^{-25} \times 5\times10^{20} \times 1\,cm = 3\times10^{-4}$

If 1mJ of laser energy ⇒ 10^{14} photons ⇒ 3×10^{10} scattered

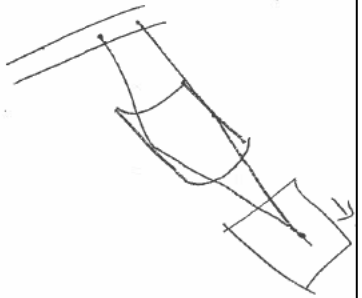
For 10 mrad acceptance ⇒ 3×10^{5} collected

Use multilayer with resolution of 100 (perhaps cylindrical for focussing) For $\theta \simeq 45°$ ⇒ $\Delta\theta$ = 10 mrad ≡ 2Å



Put intensifier on photon collector and gate like MCP16S for adequate signal-to-noise

Really need focussing:



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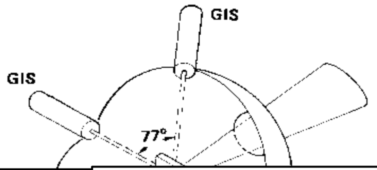

But n_e accessible by UV TS, so why bother?

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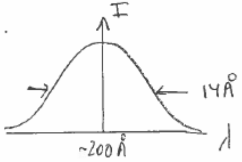

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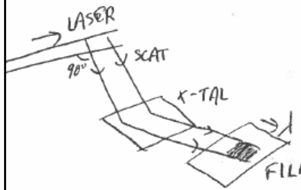

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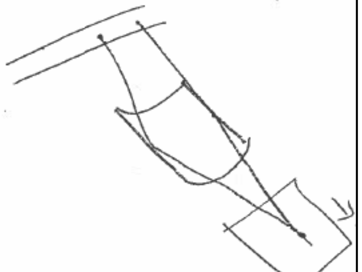
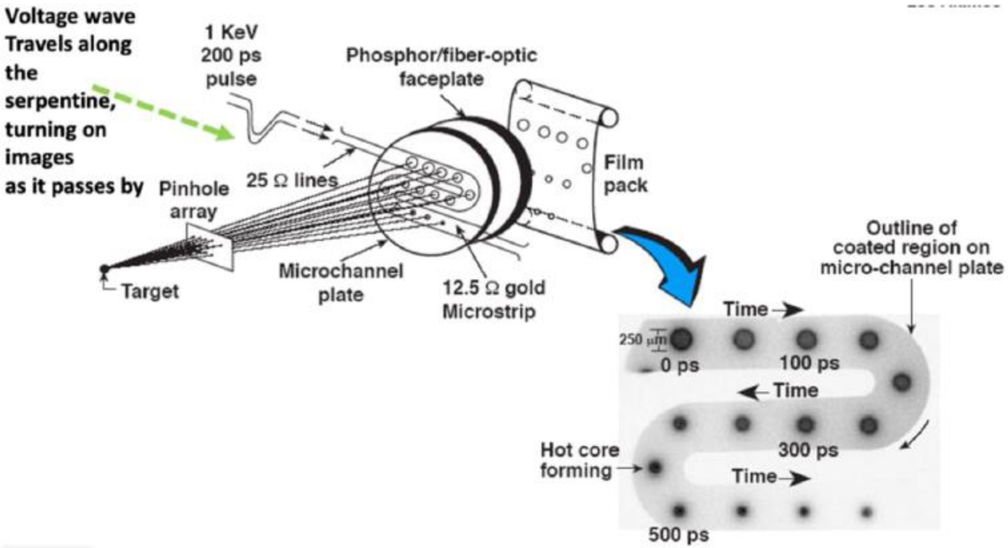
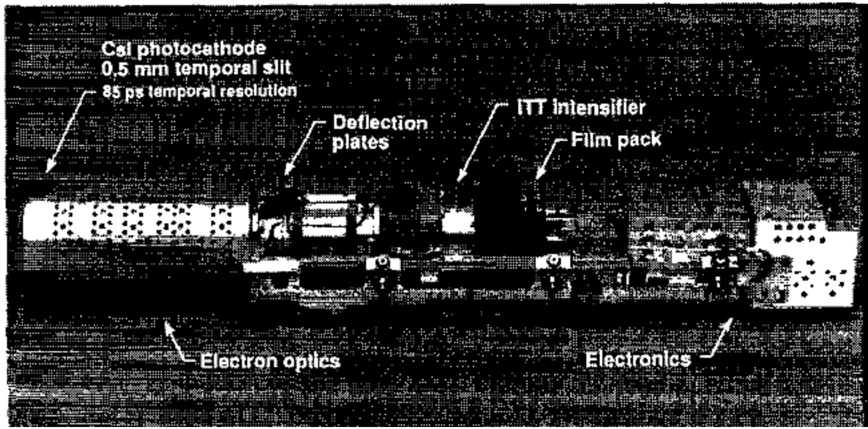


⇒ Need intensifier

Onward to 1990s – Robust, Sub 100 ps Gated and Streaked Detectors

Gated and streaked detectors (J. Kilkenny RSI 1995, B. Hammel, P Bell, D. Bradley)





Precursors to NIF X-ray cameras

M. Campbell, R. McCrory

And equally essential: State-of-the art Target and Laser facilities at LLNL, LLE and GA

Also in 1990s, and equally essential: efficient > 5 keV X-ray sources

X-ray radiographic imaging of hydrodynamic phenomena in radiation-driven materials—Shock propagation, material compression, and shear flow*

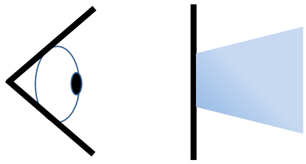
B. A. Hammel,† J. D. Kilkenny, D. Munro, B. A. Remington, H. N. Kornblum, T. S. Perry, D. W. Phillion, and R. J. Wallace
Lawrence Livermore National Laboratory, Livermore, California 94550

(Received 5 November 1993; accepted 24 January 1994)

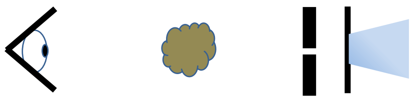
One- and two-dimensional, time-resolved x-ray radiographic imaging at high photon energy (5–7 keV) is used to study shock propagation, material motion and compression, and the effects of shear flow in solid density samples which are driven by x-ray ablation with the Nova laser. By

Made possible by higher power, larger smoothed spots

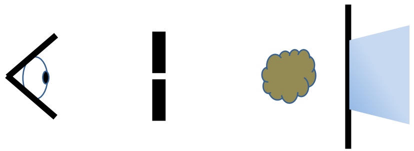
Furthermore: Allowed backlighter beams to hit backside of foil since elements > S (Ti) transparent to own He-α (Ly-α) that led to…



Backlit Apertures



vs traditional area



1900 - 1930	1980s	1990s	2000s	2010s	2020s

First X-ray Radiograph - Solids

Hard X-ray Sources

Shell Metrology

Backlit Apertures

Refraction Enhanced Radiography

Ablation and Shock fronts

Interfaces

Diffusivity?

HOPG

ICF Symmetry / HEDS Planar

Compton Scattering – Solids

Soft X-ray Laser Scattering?

X-ray Thomson Scattering

Compton Radiography

Fuel ρ(R)

Visual RKE

Low Z Dense Plasma Characterization

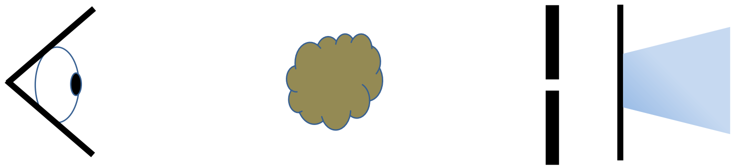
K shell occupancy?

Backlit Pinhole Radiography – For Large Implosions/Objects when laser power limited

D. Farley, T. Bullock, B. Blue, D. Bradley

Landen RSI 2001

Backlit pinhole



Allowed imaging large NIF-like objects at Omega with less laser power but still using more efficient gatable, long pulse backlighters

Issue tackled: While soft x-rays reabsorbed by foil, closure of pinholes by hard x-rays

JOURNAL OF APPLIED PHYSICS **100**, 043301 (2006)

X-ray induced pinhole closure in point-projection x-ray radiography

A. B. Bullock,[a] O. L. Landen,[b] B. E. Blue, J. Edwards, and D. K. Bradley
Lawrence Livermore National Laboratory, Livermore, California 94550

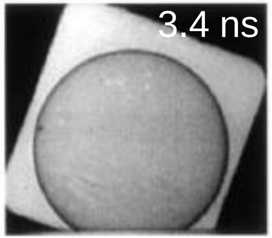
Efficient, 1–100-keV x-ray radiography with high spatial and temporal resolution

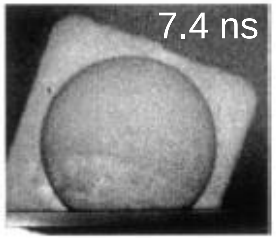
D. K. Bradley, O. L. Landen, A. B. Bullock, S. G. Glendinning, and R. E. Turner
Lawrence Livermore National Laboratory, P.O. Box 5508, Livermore, California 94551

Received September 5, 2001

Omega

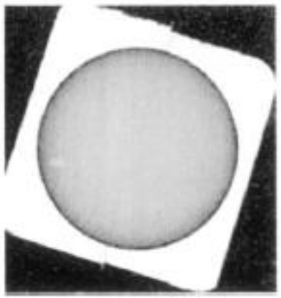
Inflight 4.7 keV





2 mm

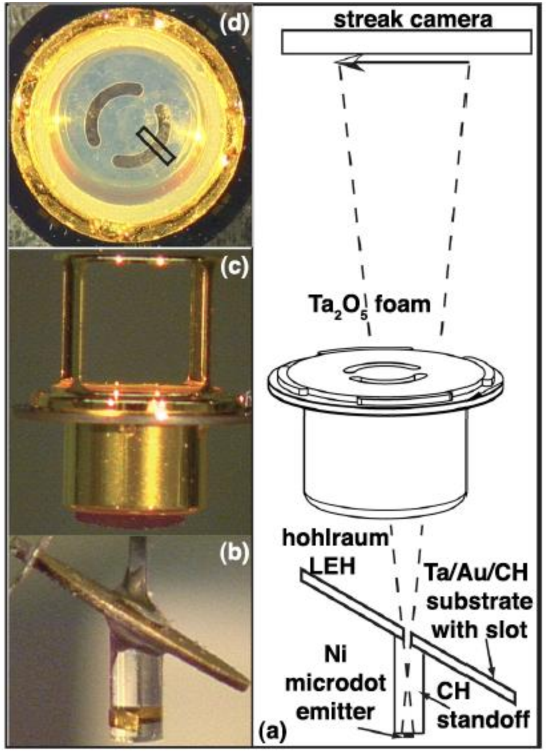
Preshot 2.3 keV



c.f. Area Backlighter

Power starved

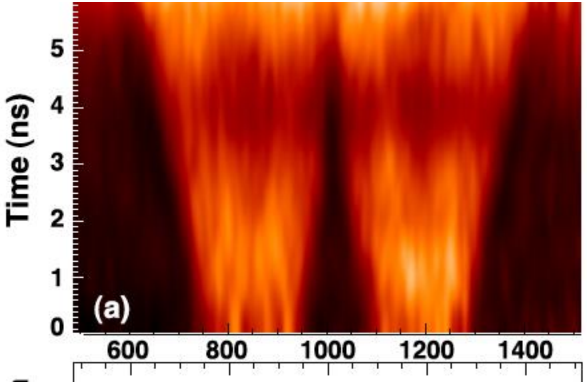
Ironically, we then proceeded to use backlit slits (built to not close) to radiograph closure of larger features



Streaked radiography of an irradiated foam sample on the National Ignition Facility

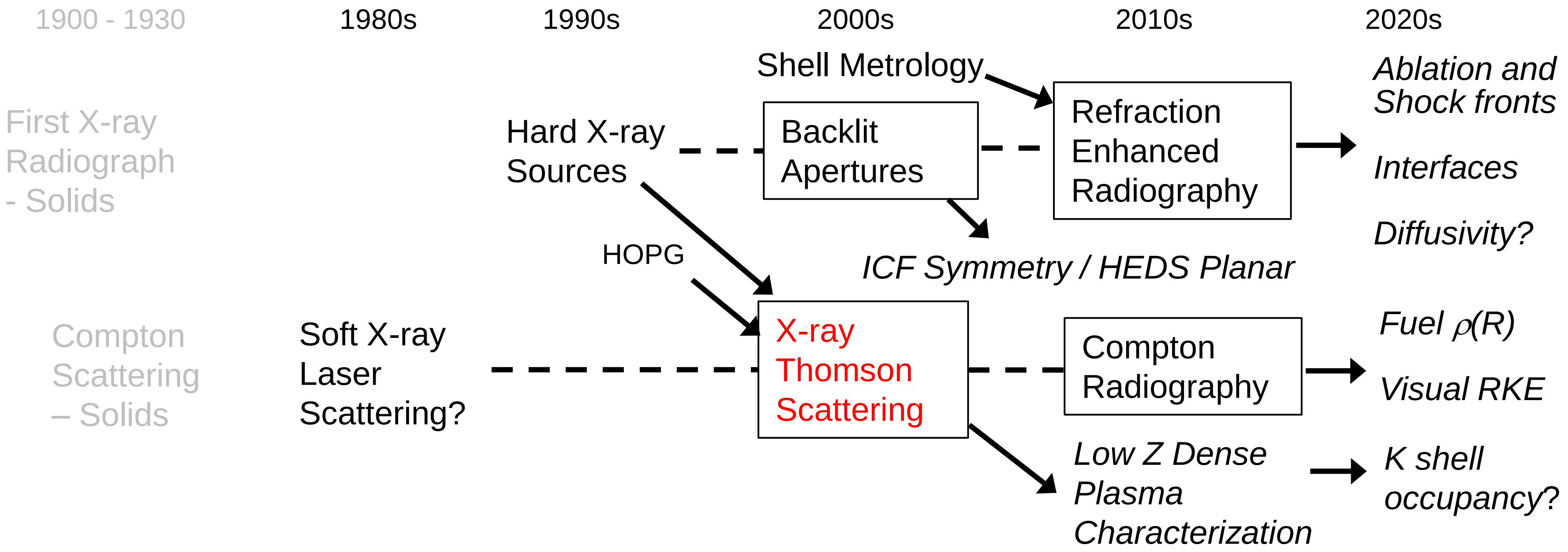
A. B. R. Cooper,[1,a)] M. B. Schneider,[1] S. A. MacLaren,[1] A. S. Moore,[2] P. E. Young,[1] W. W. Hsing,[1] R. Seugling,[1] M. E. Foord,[1] J. D. Sain,[1] M. J. May,[1] R. E. Marrs,[1] B. R. Maddox,[1] K. Lu,[1] K. Dodson,[1] V. Smalyuk,[1] P. Graham,[2] J. M. Foster,[2] C. A. Back,[3] and J. F. Hund[3]

[1]*Lawrence Livermore National Laboratory, 7000 East Ave Livermore, California 94550, USA*
[2]*Atomic Weapons Establishment, Aldermaston, Reading RG7 4PR, United Kingdom*
[3]*General Atomics, San Diego, California 92121, USA*



Because NIF provided higher power for area backlighting that does not suffer from signal swamped by self-emission from hotter targets, backlit apertures usage was discontinued…for a while

Meanwhile, X-ray Thomson Scattering started up using same multi-keV resonance line sources ….



… after realization in 1999 that XRTS doesn't need an X-ray Laser

S. Glenzer, G. Gregori, B. Hammel, A. Pak

Use multi-keV resonance lines

10^3x shorter wavelength than UV lasers
= 10^6x higher densities accessible –
Strongly coupled and degenerate plasmas

$$\alpha(90^o) \approx \frac{\lambda}{9\lambda_s}$$

$\lambda_S \sim \sqrt{T_e/n_e}$ Debye limit

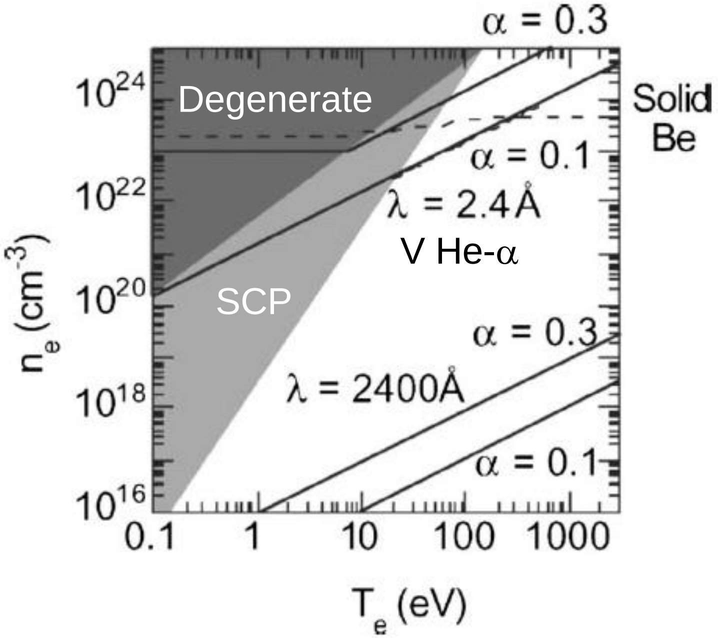
$\lambda_S \sim \sqrt{T_F/n_e} \sim 1/n_e^{1/6}$ Degenerate limit

Use efficient Bragg "parafocussing" crystal – HOPG

Pak RSI 2004

Lack of high temporal coherence does not preclude collective scattering – source size and bandwidth sets spectral blurring Gregori EPL 2006

Plasma Parameter Space



X-ray “Thomson” Scattering – First unambiguous data 2002

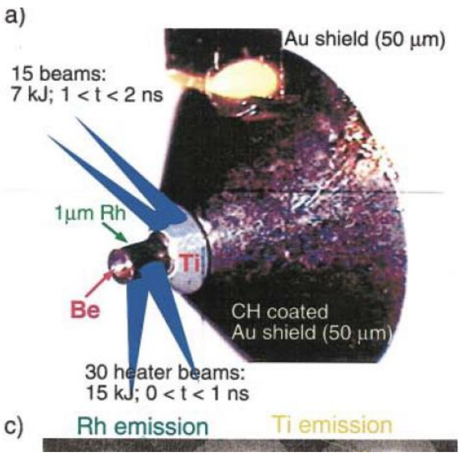
VOLUME 90, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 2 MAY 2003

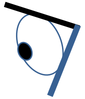
Demonstration of Spectrally Resolved X-Ray Scattering in Dense Plasmas

S. H. Glenzer, G. Gregori, R.W. Lee, F. J. Rogers, S.W. Pollaine, and O. L. Landen
L-399, Lawrence Livermore National Laboratory, University of California, P.O. Box 808, Livermore, California 94551, USA
(Received 10 October 2002; published 2 May 2003)

Omega

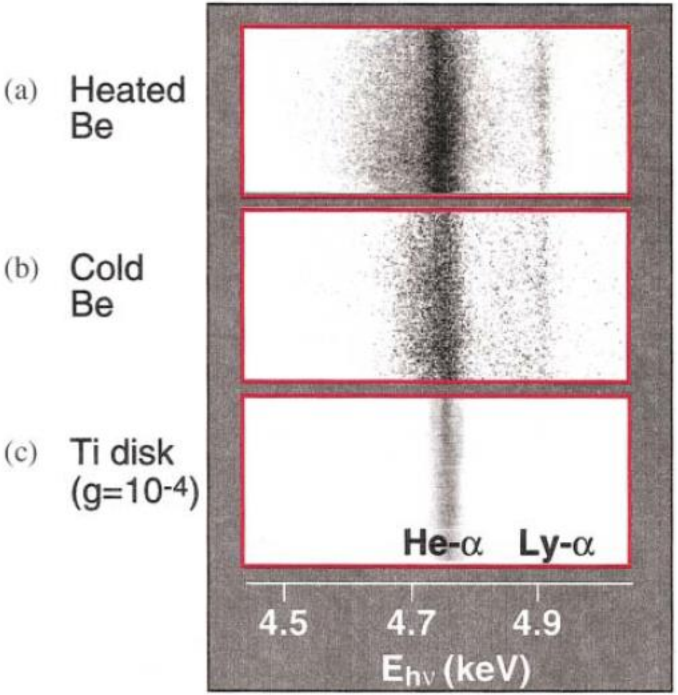
Volumetrically heated Be in near backscatter geometry





HOPG Spectrometer

First Data 2002



X-ray "Thomson" Scattering – Applications ongoing over two decades, motivating advances in *theory*

S. Glenzer, G. Gregori, A. Kritcher, T. Doeppner, T. Ma,
L. Fletcher, H-J Lee, D. Kraus…

Supersonic radiation transport

Gregori PRL 2008

Structure factors in dense plasma S_{ii}

Ma PRL 2013 *Baczewski PRL 2016*

Plasmons for Strongly Coupled Plasma collisionality and detailed balance for T_e

Glenzer PRL 2007 Doeppner HEDP 2009 Neumayer PRL 2010

Adiabat (T_e/T_F)

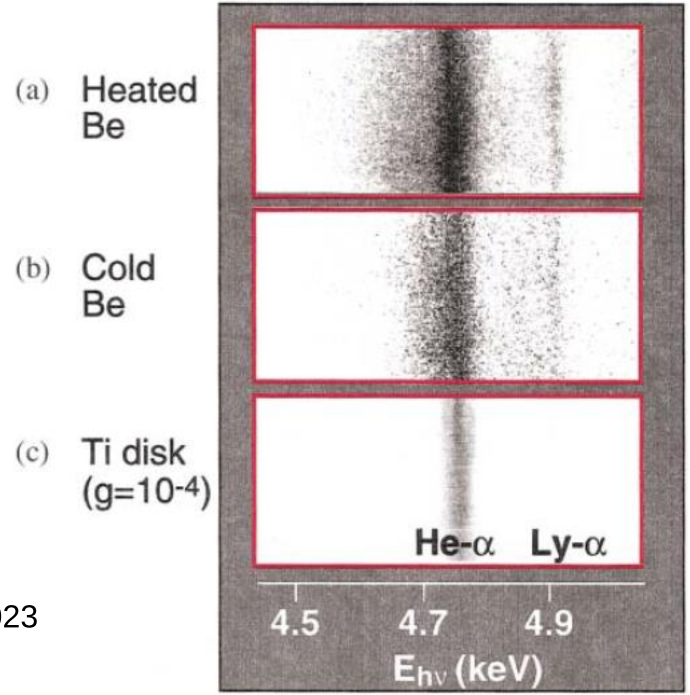
Kritcher PRL 2011

Ionization balance (inelastic/elastic)

Fletcher PoP 2013, PRL 2014 Kraus PRE 2016 Doeppner Nature 2023
Bethkenhagen PRR 2020

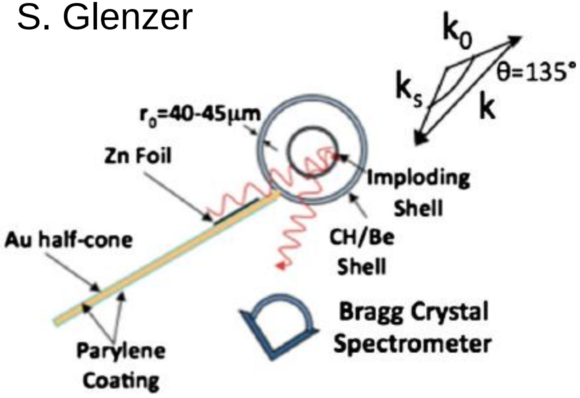
Mid-term Review: Glenzer and *Redmer* Rev. Mod. Phys. 2009

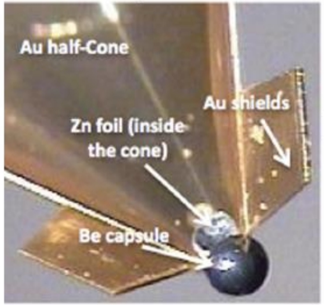
First Data 2002



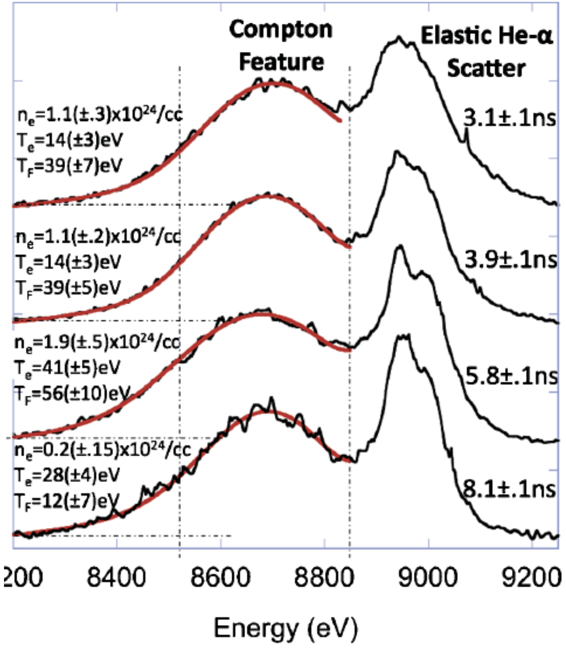
Implosion adiabat = f(Te/TF)

A. Kritcher, T. Doeppner, T. Ma, S. Glenzer

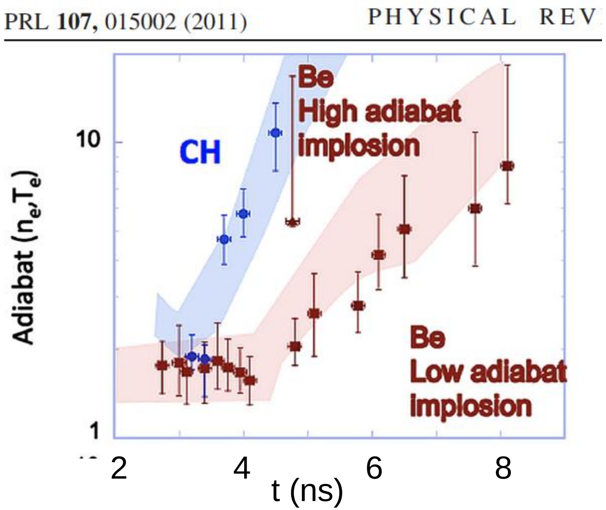




Scattered spectra fit for n_e, T_e, T_F



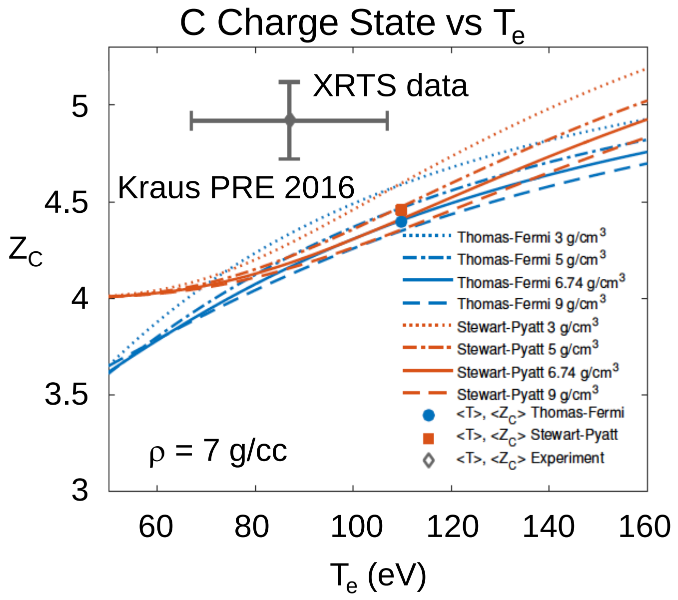
Inferred adiabat vs time

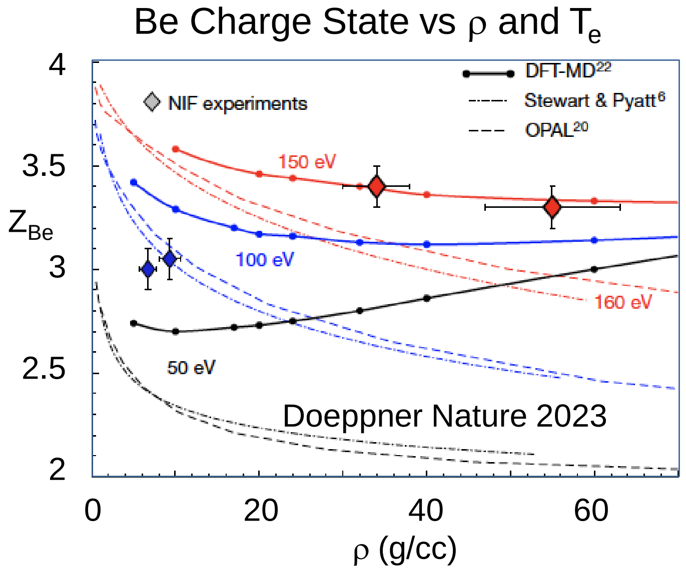


$$\alpha = \frac{P}{P_F} \approx \frac{{}^{2}\!/_{5}\, n_e T_F \sqrt{1 + 8.2(T_e/T_F)^2} + n_i T_i}{{}^{2}\!/_{5}\, n_e T_F}$$

From ratio of inelastic to elastic, we found that K Shell ionization at compressed densities more than expected at given Te

T. Doeppner, L. Fletcher, D. Gericke, D. Kraus, D. Chapman, M. Bethkenhagen, S. Glenzer



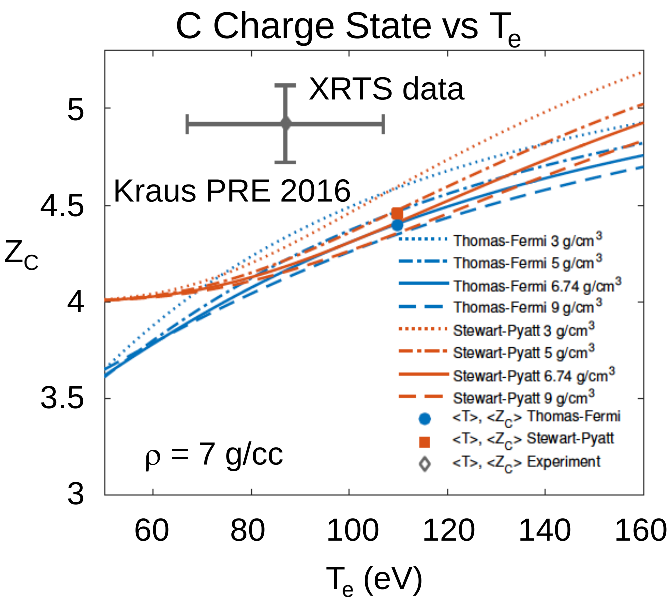


Motivating improved theory

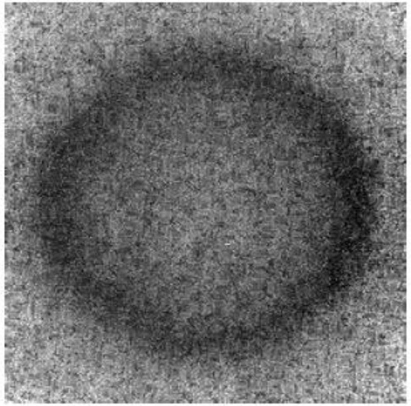
Bethkenhagen PRR 2020

Gated monochromatic implosion radiography* so far confirms lower K shell occupancy per lower opacity

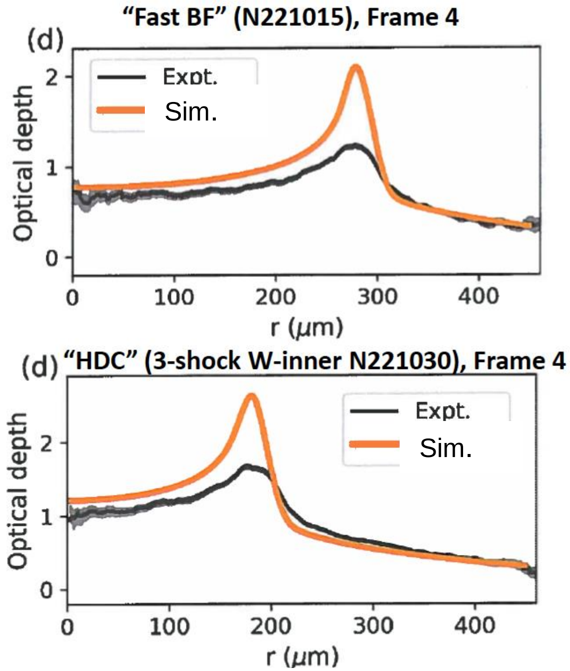
G. Hall, C. Weber, V. Smalyuk, S. Davidovits, T. Ebert



9 keV gated radiograph



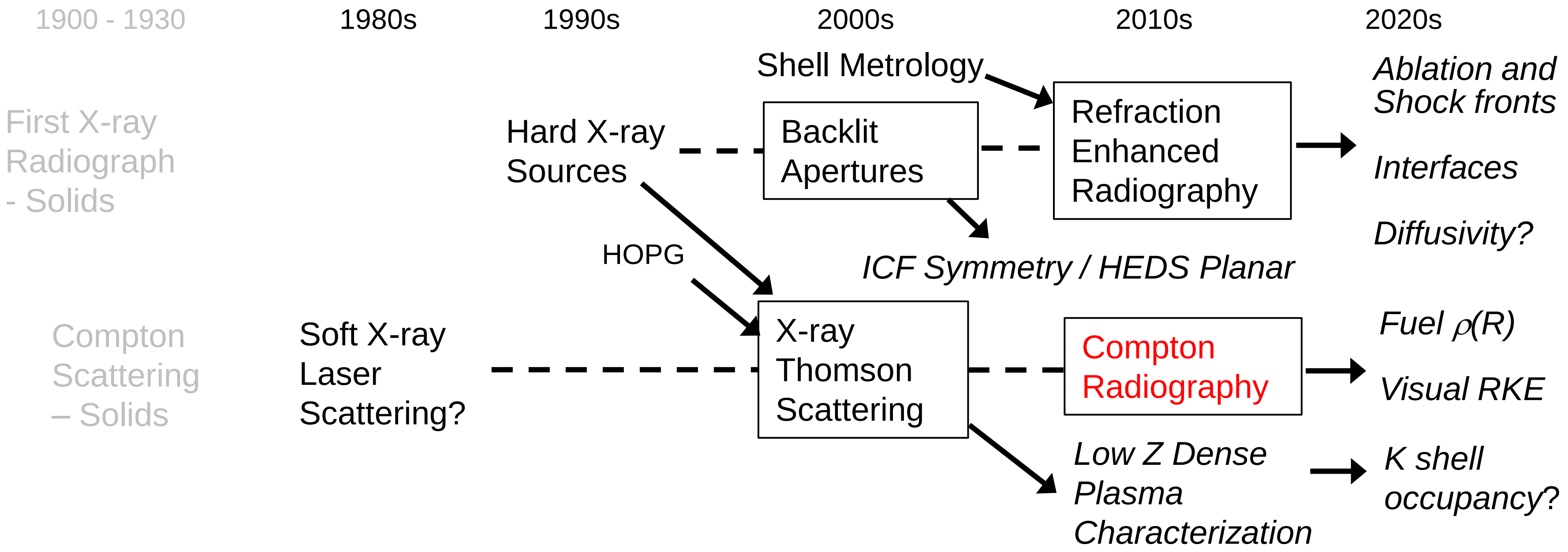
*Hall PoP submitted



Future:
Space resolve XRTS with FEL x-ray beams

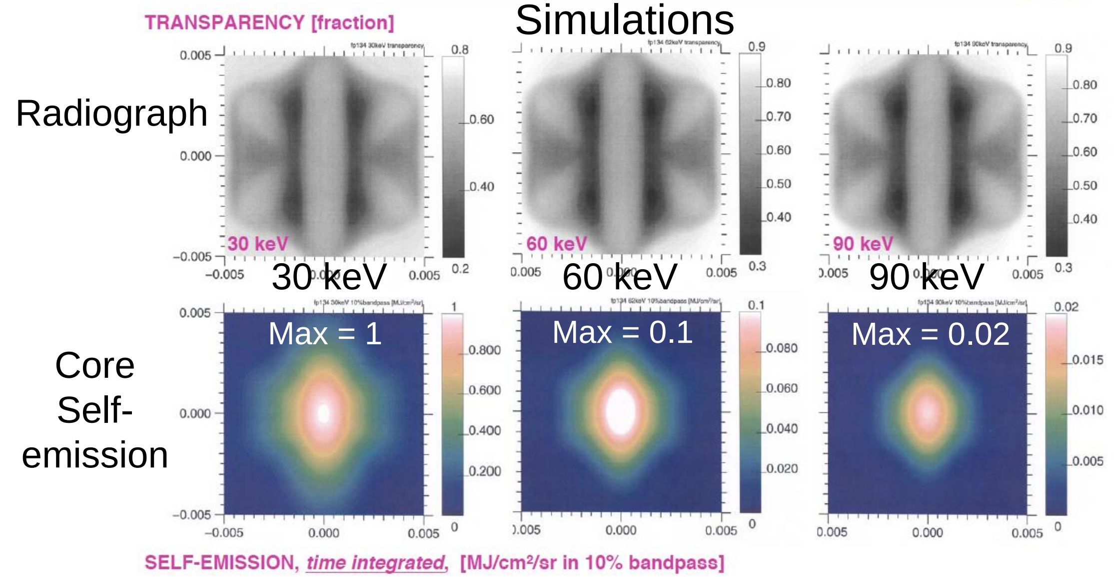
Motivating further radiography experiments

Meanwhile, we eventually applied point projection radiography to > 50 keV Low Z "Compton" Radiography…



… but only because of Aha moment looking at 2006 Simulations

S. Hatchett, R. Tommasini, N. Izumi, G. Hall, J. Holder. W. Hsing



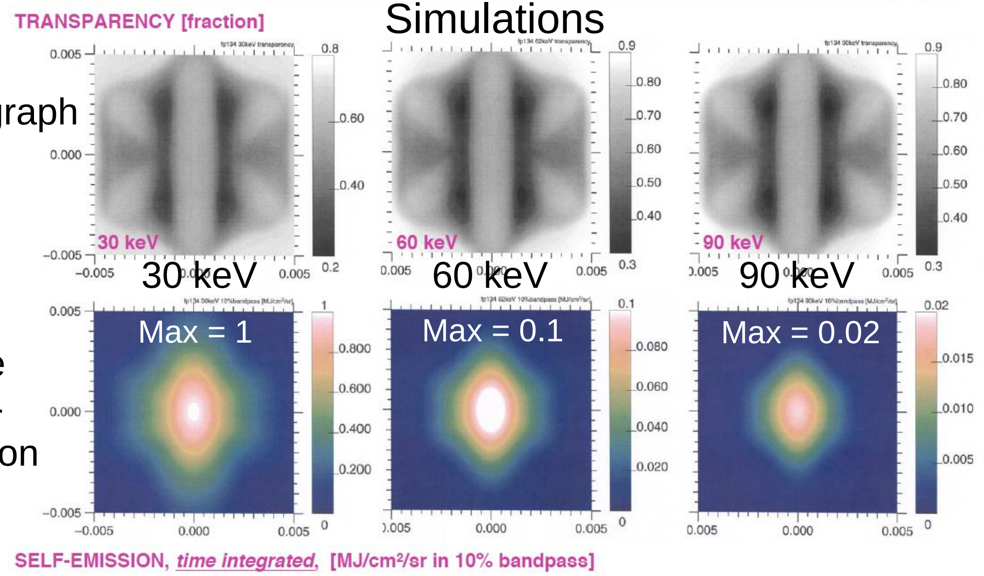
Realization **after** started XRTS: What is scattered is lost to transmission, so should cast shadow
Appeared we had done the harder experiment first (A. Comptons) vs (W. Roentgens)!

And the community now had the backlighter source and hard x-ray detectors needed

S. Hatchett, R. Tommasini, N. Izumi, G. Hall, J. Holder, W. Hsing

Simulations

Radiograph



30 keV 60 keV 90 keV

Core Self-emission

160 OPTICS LETTERS / Vol. 24, No. 3 / February 1, 1999

Petawatt laser pulses

M. D. Perry, D. Pennington, B. C. Stuart, G. Tietbohl, J. A. Britten, C. Brown, S. Herman, B. Golick, M. Kartz, J. Miller, H. T. Powell, M. Vergino, and V. Yanovsky

Lawrence Livermore National Laboratory, P.O. Box 808, L-477, Livermore, California 94550

M. Perry

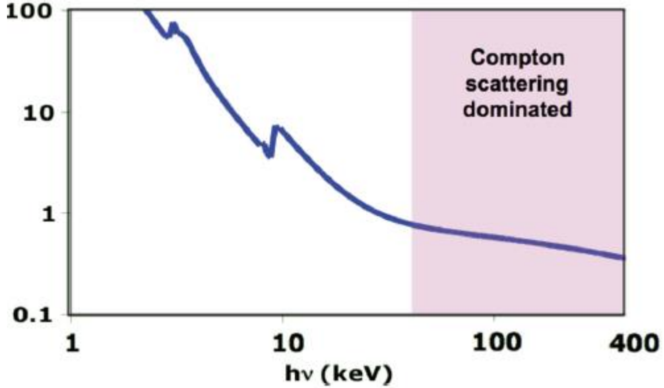
Go to high enough x-ray energy to overcome capsule emission – 1ω short pulse laser backlighter
Overcome hohlraum self-emission – Gated dual MCP (AXIS project), with Image Plate as back-up

Use high Z Bremsstrahlung as Compton cross-section ≈ flat

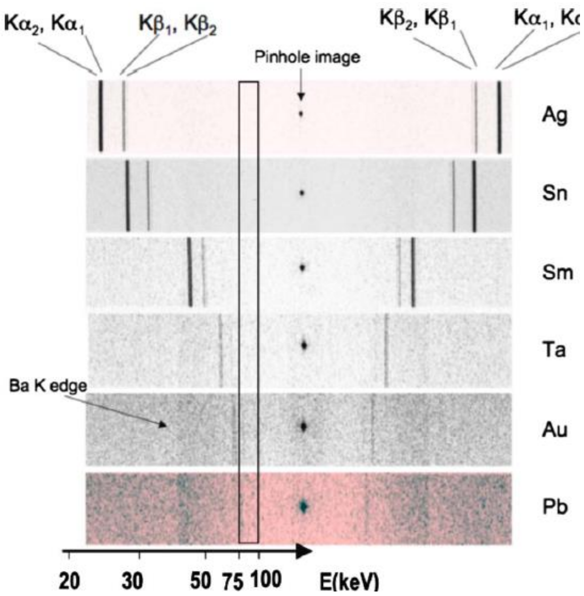
R. Tommasini, H-S Park, A. Mackinnon,…

Titan 1ω laser

Optical depth stagnated implosion



$\sigma \approx$ 1b as for neutrons = $\kappa_{DT} \approx 0.12\ cm^2/g$
So for limb areal density 2 g/cm^2, 25% peak contrast – still challenging



Tommasini RSI 2008

Added benefit:

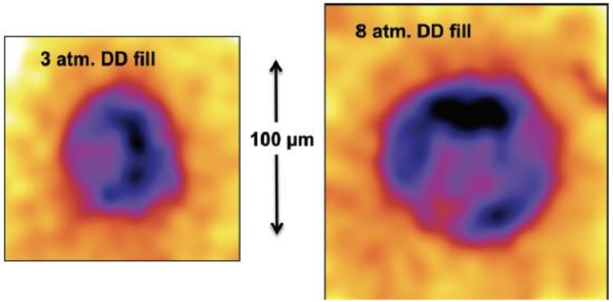
Au Bremsstrahlung C.E. ≈ .001, 4x greater than K_{α}

Demonstrate on warm capsules on Omega/EP, 4 years later (mainly Compton as low Z)

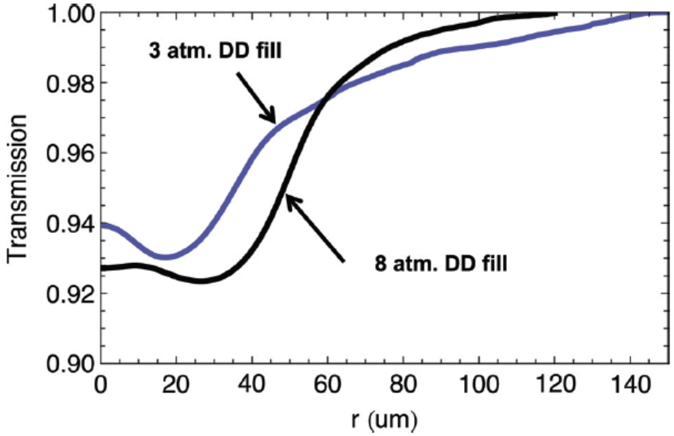
R. Tommasini, C. Stoeckl

Omega/EP

60-100 keV 10 ps
radiographs of CH implosions



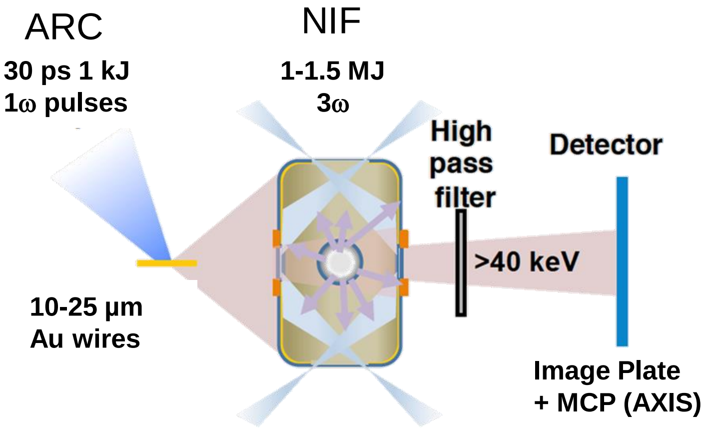
Tommasini PoP 2011



High SNR even though peak contrast < 10% because backlighter source close to implosion (10 mm), so 40000 detected photons/resolution element

NIF/ARC data on layered implosions, 12 years later

R. Tommasini, N. Izumi, G. Hall, J. Holder. H. Chen,
D. Kalantar, W. Hsing



PHYSICAL REVIEW LETTERS **125,** 155003 (2020)

Time-Resolved Fuel Density Profiles of the Stagnation Phase of Indirect-Drive Inertial Confinement Implosions

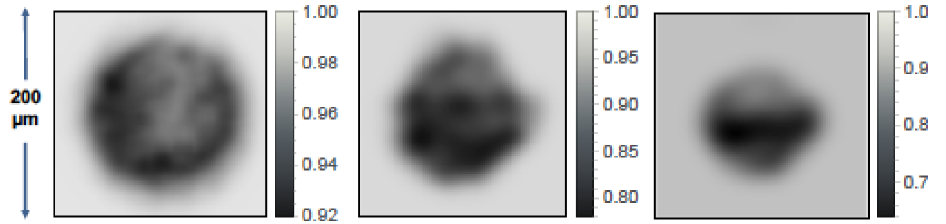
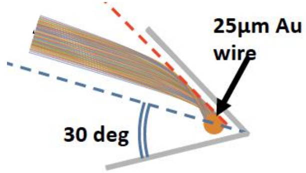


FIG.2. Compton radiographs of cryogenic THD layered implosion, recorded at BT-50ps, BT-10ps and BT+160ps.

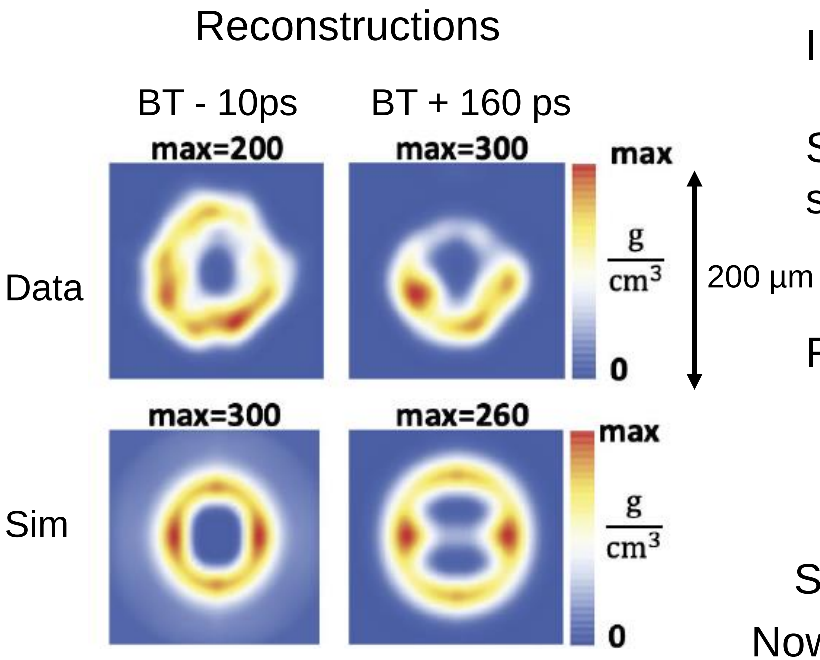
Windfalls that led to eventual success (even after extensive collimation, shielding and baffling):

ICF program switched to low gas-fill = low hot e- Bremsstrahlung hohlraums
Time-integrating Image Plate proved sufficient to get early data
Wires placed in V and U-flags allowed for unexpected wire drift



Reconstructing Multi-frame Compton Radiography - Implosion Residual Kinetic Energy directly visualized

R. Tommasini, L. Berzak Hopkins



Insights gained:

Stagnating fuel may not bounce as predicted on many shots (radial KE left)

$$Radial\ KE = \frac{1}{2} M \left(\frac{\Delta a_0}{\Delta t}\right)^2$$ 4% of peak KE

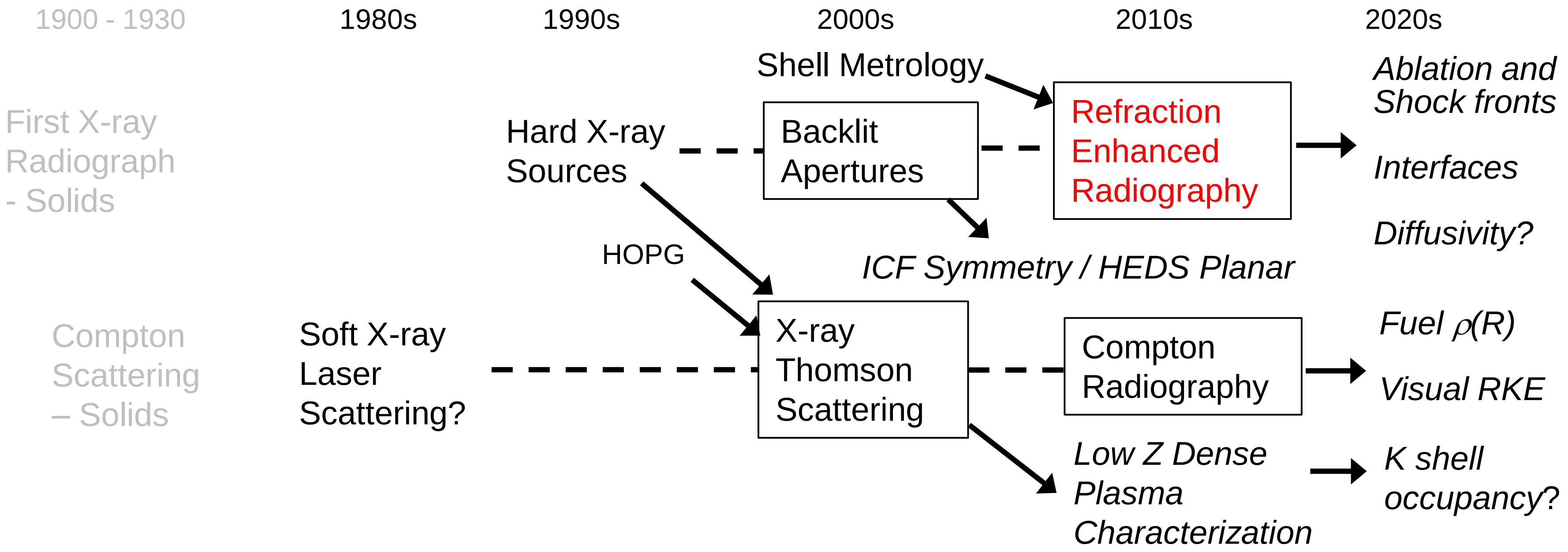
Rotational KE here is 1.5%, even smaller at modes n > 1

$$Rotational\ KE = \frac{1}{2} M a_0^2 \sum_1^n \left(\frac{\Delta(M_n/M)}{\Delta t}\right)^2 \Big/ n(n+1)(2n+2)$$

Sensitive measure of RKE

Now, as coast times decrease, need gated detector (AXIS)
Ongoing: Higher compression systems, higher Z implosions

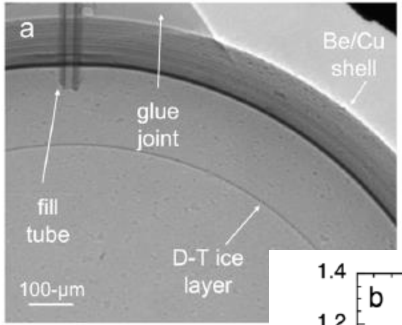
In same period, backlit apertures were resurrected for "Refraction Enhanced Radiography" because…



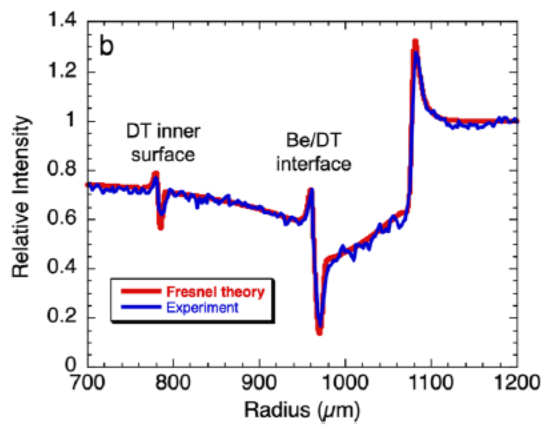
… of cross-pollination of ICF target physicists exposed to capsule metrology using "phase contrast" radiography

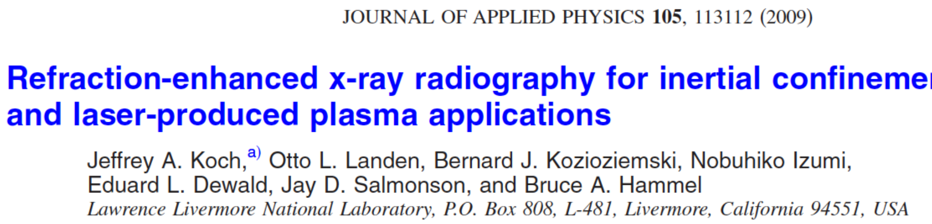
B. Kozioziemski, J. Koch, E. Dewald, N. Izumi, L. Suter, L. Masse, Y. Ping, D. Montgomery, J. Workman

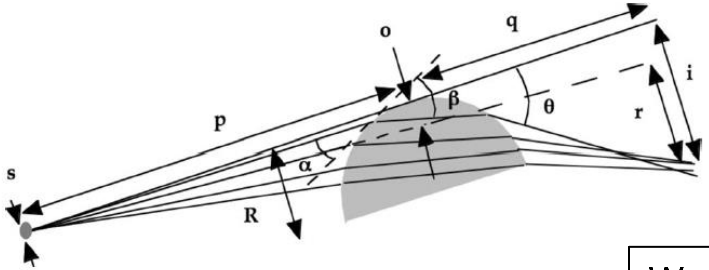
8 keV Point Projection



Be/DT Capsule Radiographs 2004







For cylindrical or spherical surfaces*:

$$s(\mu m) < 5\left[p(\mathrm{cm})|\Delta n|\left(10^{-6}\right)R(\mathrm{cm})^{1/2}\right]^{2/3},$$

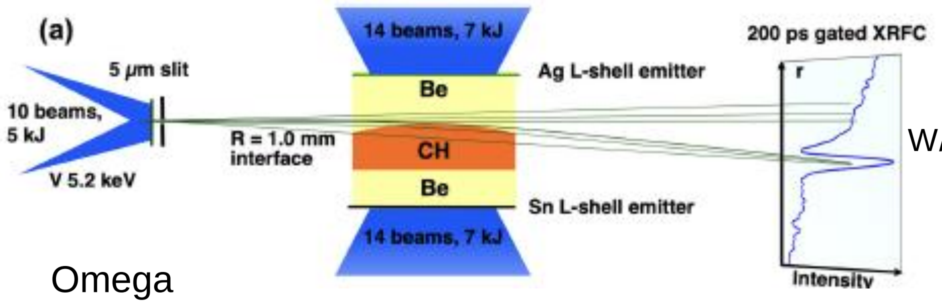
We had found a critical need for backlit apertures

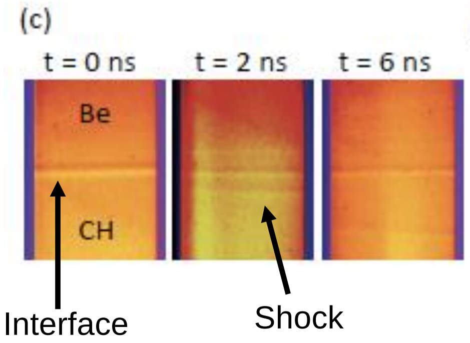
Demonstrated on Omega for profile relaxation between differentially heated materials, 2 years later

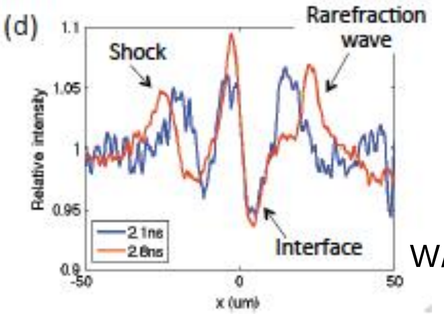
Y. Ping, J. Koch, S. Jiang, S. Hamel…

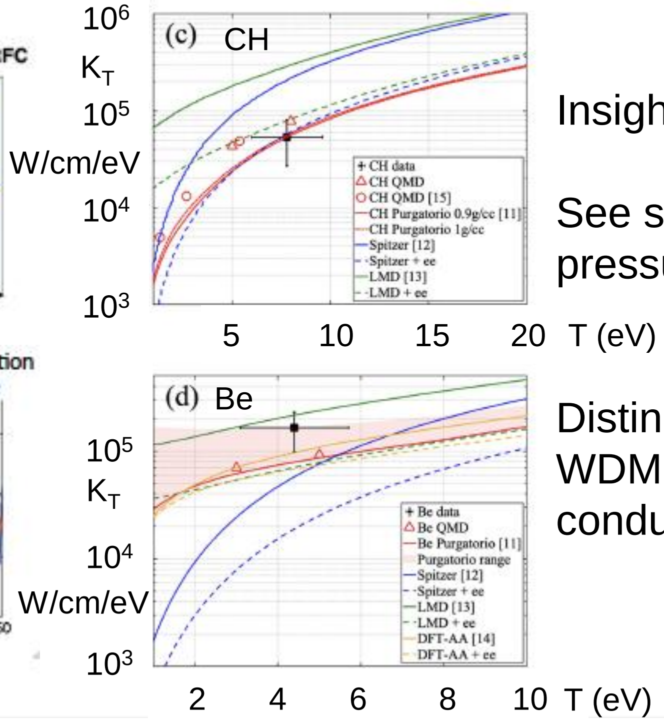
Y. Ping, J. Instrum. (2011)

S. Jiang, Commun. Phys.(2023)









Insights gained:

See shocks as well for pressure calibration

Distinguish between WDM thermal conductivity models

Inflight Cryogenic Implosions at NIF, 10 years later

E. Dewald, D. Ho, Y. Ping, L. Masse…

Contents lists available at ScienceDirect

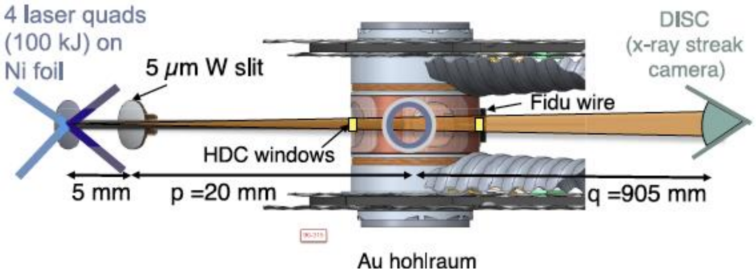
High Energy Density Physics

journal homepage: www.elsevier.com/locate/hedp

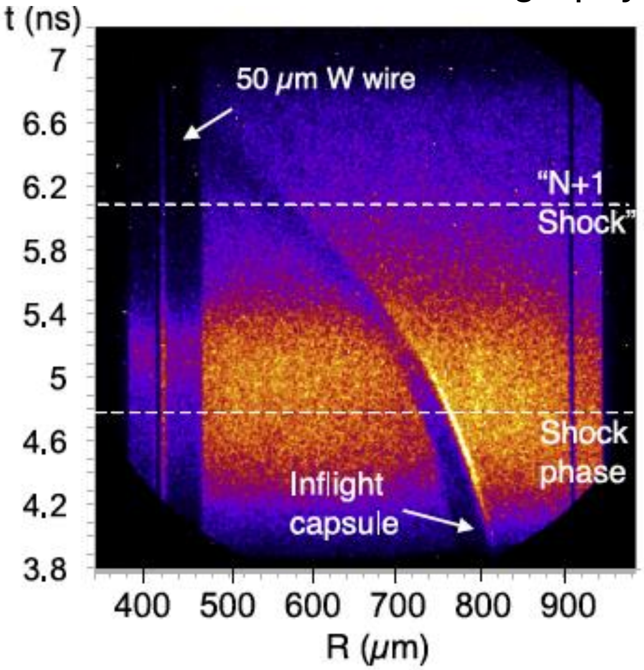
ELSEVIER

Direct observation of density gradients in ICF capsule implosions via streaked Refraction Enhanced Radiography (RER)

E.L. Dewald*, O.L. Landen, D. Ho, L. Berzak Hopkins, Y. Ping, L. Masse, D. Thorn, J. Kroll, A. Nikroo



7.8 keV Streaked Radiography



LDRD: 5 μm, 20 ps resolution

Proved too hard to look for N+1 shock effects on ablator/ice Atwood #

Instead, info on shock phase ablation front (refraction signature much less sensitive to opacity uncertainty)

Easier - Inflight Shocks and Interface, 15 years later

C. Weber, A. Do, E. Dewald, T. Doeppner, V. Smalyuk…

Pivot to measuring:

Early Shocks/rarefactions/interface motion tracking

Provides input to RM/RT instability evaluation at interface
Weber PRE 2023

PHYSICAL REVIEW E **108**, L023202 (2023)

Letter

Reduced mixing in inertial confinement fusion with early-time interface acceleration

C. R. Weber, D. S. Clark, D. T. Casey, G. N. Hall, O. Jones, O. Landen, A. Pak, and V. A. Smalyuk
Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551-0808, USA

(Received 30 June 2023; accepted 24 July 2023; published 16 August 2023)

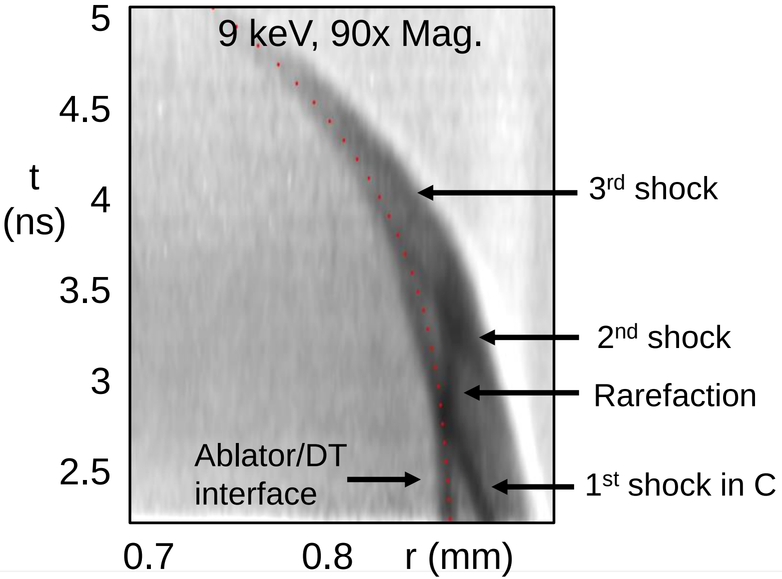
In inertial confinement fusion (ICF) implosions, the interface between the cryogenic DT fuel and the ablator

Review: D. Montgomery RSI 2023

PHYSICAL REVIEW LETTERS **129**, 215003 (2022)

Direct Measurement of Ice-Ablator Interface Motion for Instability Mitigation in Indirect Drive ICF Implosions

Alexandre Do,* Christopher R. Weber, Eduard L. Dewald, Daniel T. Casey, Daniel S. Clark, Shahab F. Khan, Otto L. Landen, Andrew G. MacPhee, and Vladimir A. Smalyuk
Lawrence Livermore National Laboratory, Livermore, California 94551, USA



Today: Micron Resolution for Diffusivity (Omega and NIF Discovery Science)

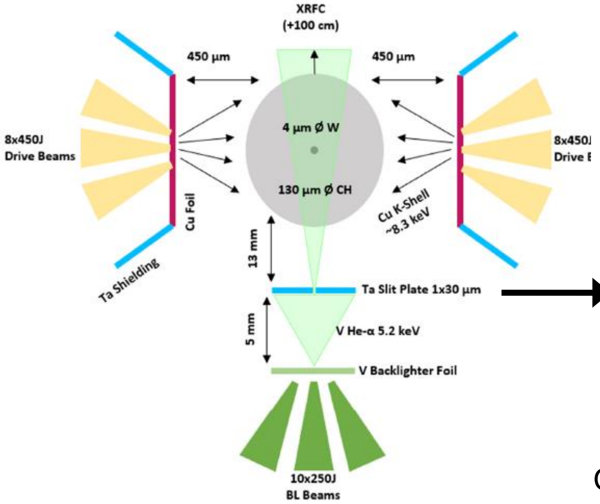
C. Allen, M. Oliver, T. Doeppner, L. Divol, T. White, Y. Ping, M. Scholmerich…

applied optics 2023

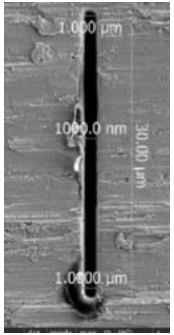
Toward an integrated platform for characterizing laser-driven, isochorically heated plasmas with 1 μm spatial resolution

C. H. Allen,[1,*] M. Oliver,[2] L. Divol,[3] O. L. Landen,[3] Y. Ping,[3] M. Schölmerich,[3] R. Wallace,[3] R. Earley,[4] W. Theobald,[4] T. G. White,[1] and T. Döppner[3]

Probe gradients after heating high Z wire in low Z

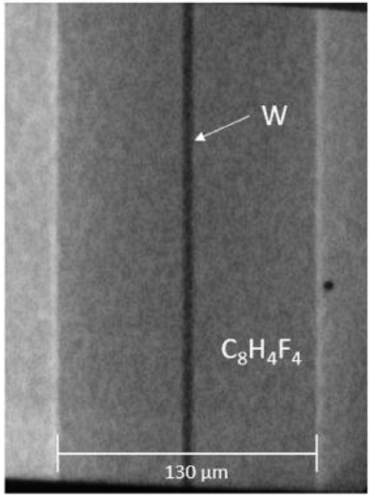


1 μm Slit

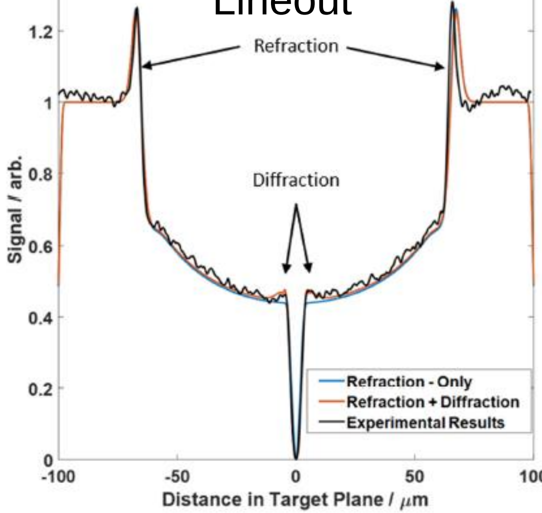


Oliver RSI 2022

5.2 keV Data



Lineout



Ongoing and Future:
Imploding shock tracking (Gbar)
Shock structure at XFEL

Thoughts in hindsight and future

What next: hard to predict, influenced by each one's unique experiences and prior knowledge base (and progress in facilities and instrumentation).

Enough free energy and time to test ideas out not just on paper, but on early shots.

Be prepared for significant technique optimization and keep an open mind to course corrections and even switching goals

Get feedback from and listen to others.

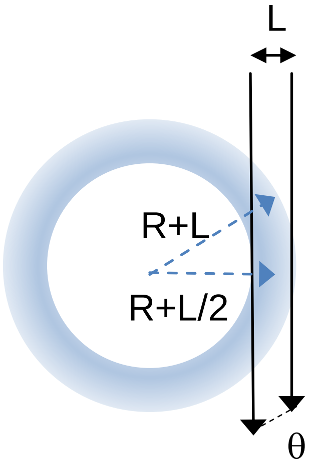
Look to stimulate creativity:

What would combining two techniques enhance or enable?

e.g. hard x-ray point projection radiography mated with the Moire interferometry already demonstrated with x-ray area backlighters (Matsuoka RSI 1999) for RT growth

What advantages or new insights could an optical technique bring if transferred to another regime, e.g. x-ray or particle probe? To a new facility (FELs already in doing this)?

e.g. Transpose Soft X-ray Grid Image Refractometry* to 10 keV+ regime to infer scale-lengths from refraction angle rather than fringe strength

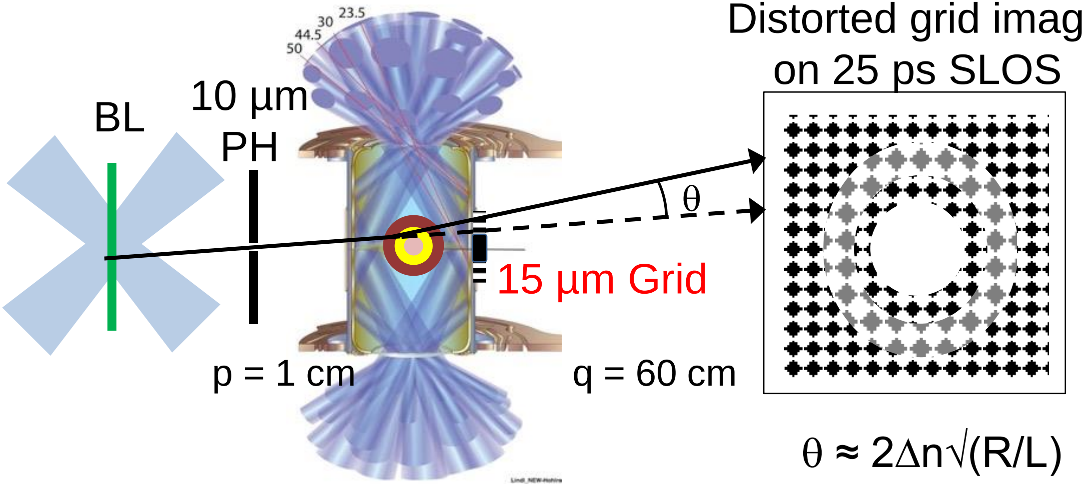


Average chord length through ablator = $2\sqrt{(RL)}$

Path length differential = $2dn\sqrt{(RL)}$

$\theta = 2\Delta n\sqrt{(RL)}/L$

Distorted grid image on 25 ps SLOS



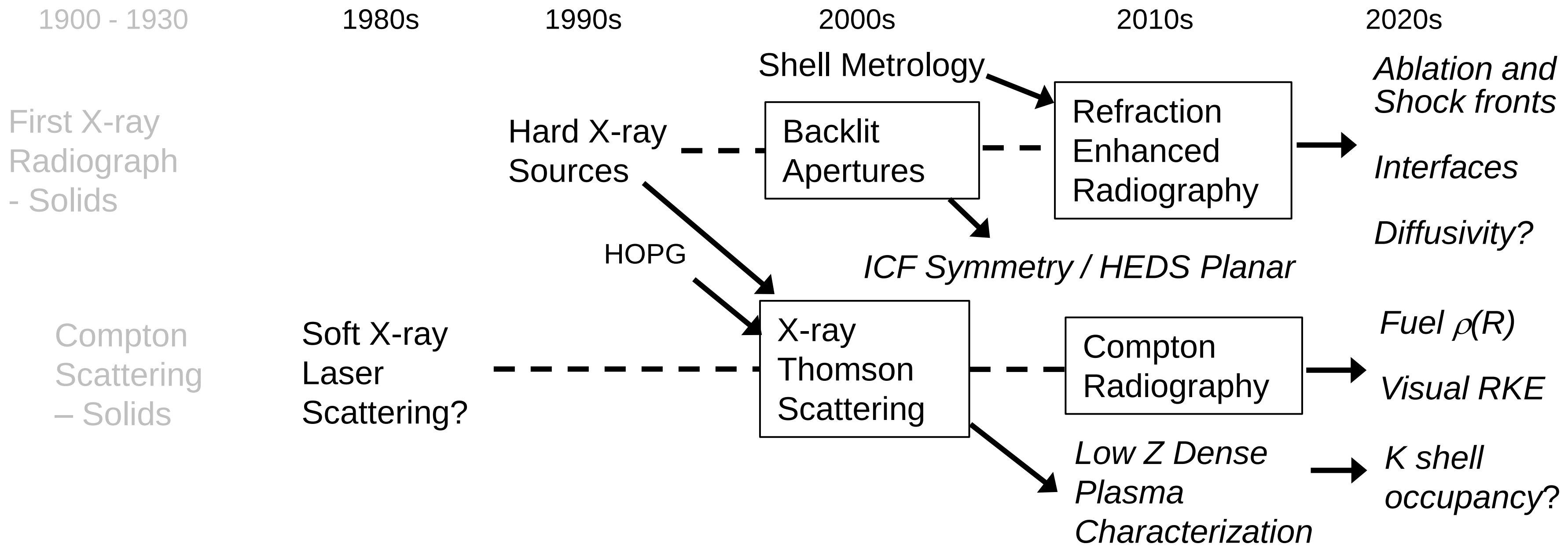
$\theta \approx 2\Delta n\sqrt{(R/L)}$

Mass conservation $M \sim \Delta n R^2 L$

Hence $\theta \approx M/R^{1.5}L^{1.5}$

*R. Benattar and J. Godart, Optics Comm (1984)

Thanks to all (and for their patience and persistence) that I was privileged to learn from and work with!



Lawrence Livermore
National Laboratory