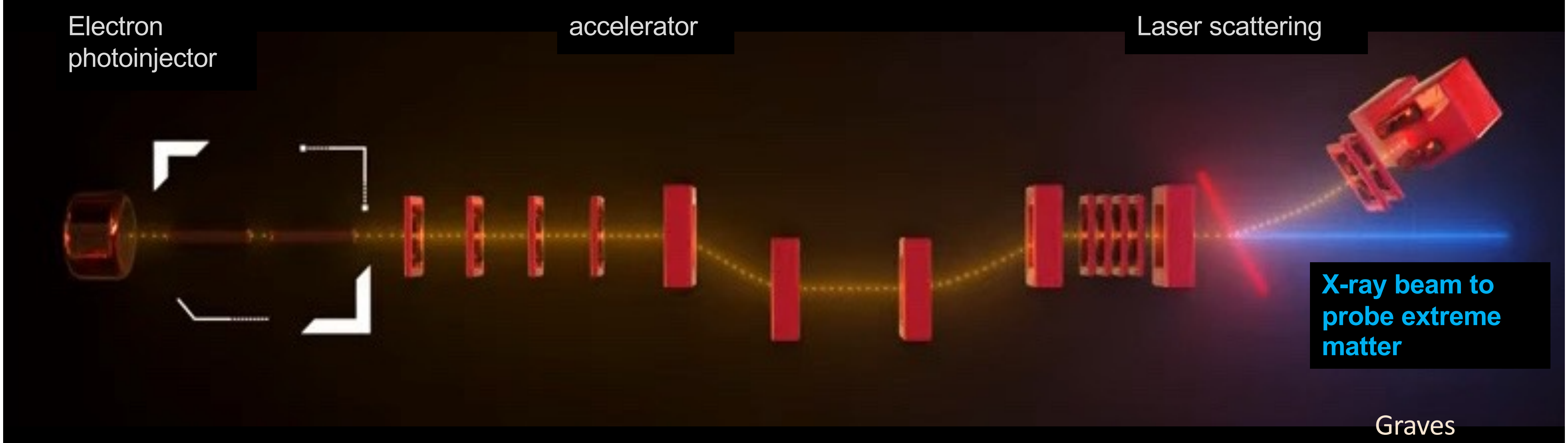
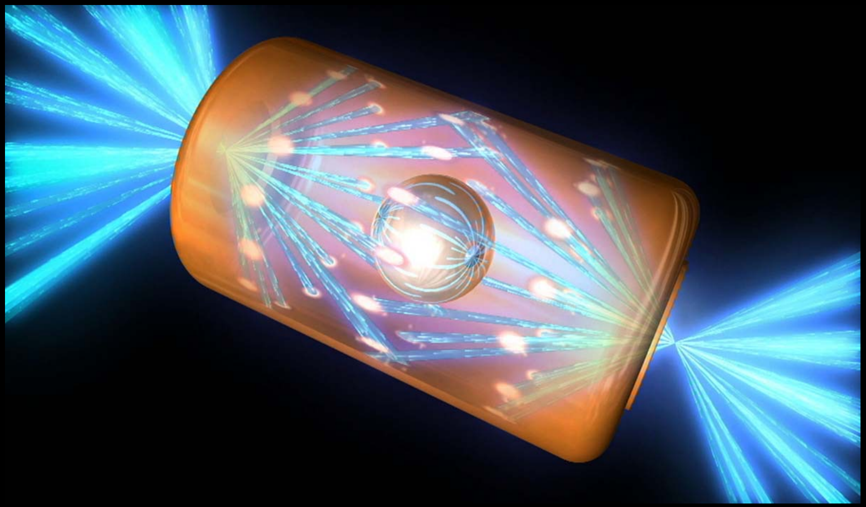
Exploring extreme matter: accelerators required



LLE/UR: Gilbert 'Rip' Collins, D. Ramsey, J. Palastro, H. G. Rinderknecht, R. Spielman, S. Regan, R. Rygg, D. Bishel, A. Chin, N. Kabadi, J. Zuegel, H. Poole, C. Deeney
Oxford: V. Musat, G. Gregori
LANL: G. Bruhaug, B. Carlsten, N. Yampolsky

High energy density (HED) science is at the nexus of some of the major science breakthroughs of our time



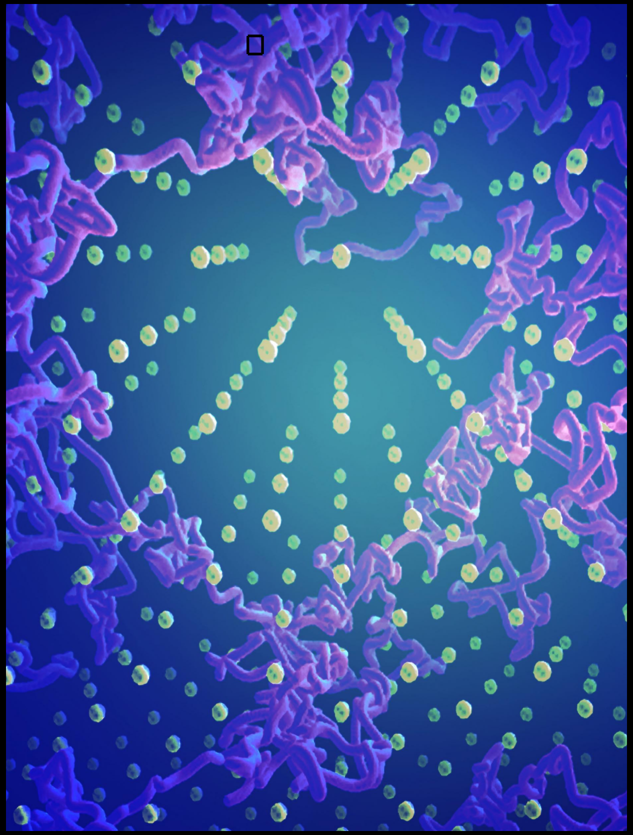
Controlling fusion

Revolutionary states of matter

Astrophysical implications

National Nuclear Security Administration
DEFENSEPROGRAMS

NSF Center for Matter at Atomic Pressures: exploring extreme matter at the heart of compact astrophysical objects and revolutionary states of matter



Predicting new states

Realizing what is possible

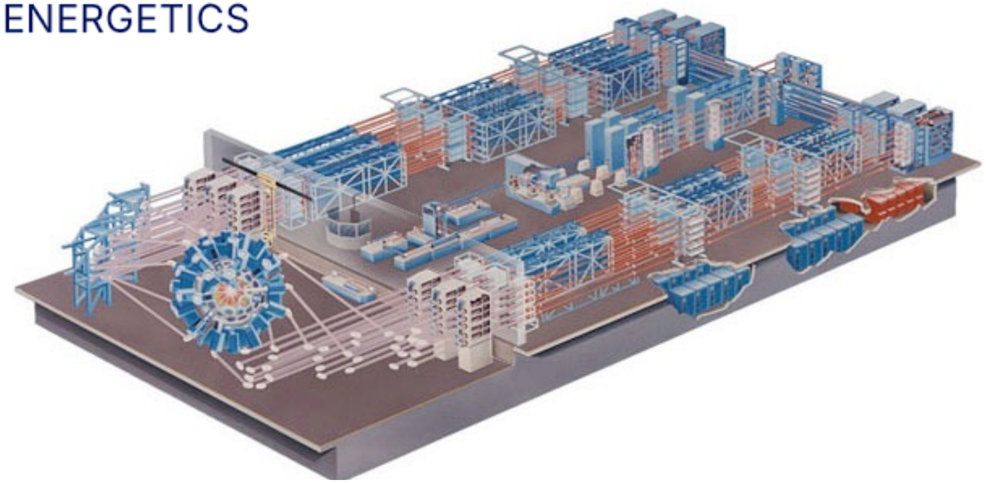
Making the impossible -> possible

To access these extreme conditions we use a variety of high energy density (HED) facilities

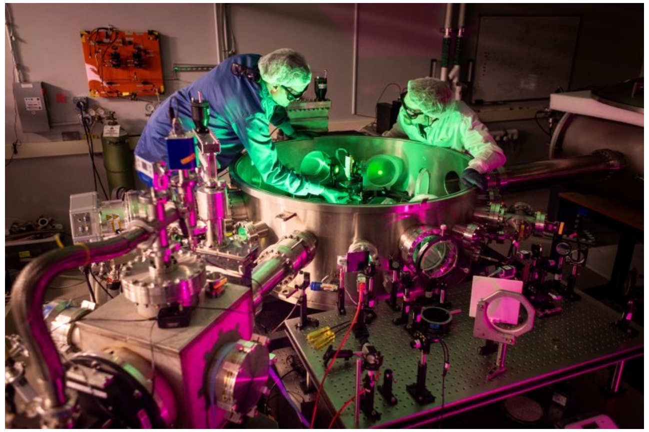
National Ignition Facility

Omega Laser

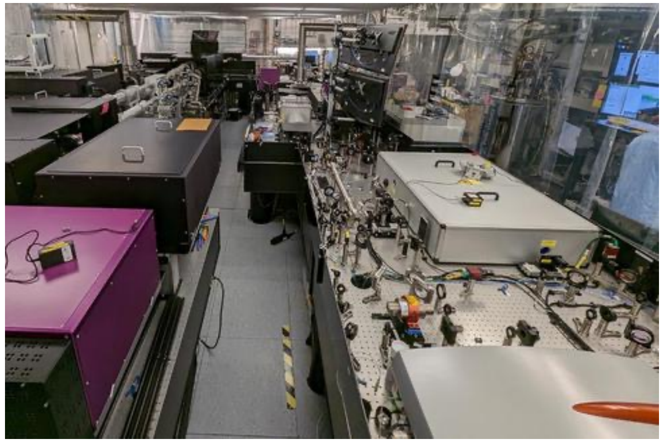
LABORATORY FOR LASER ENERGETICS



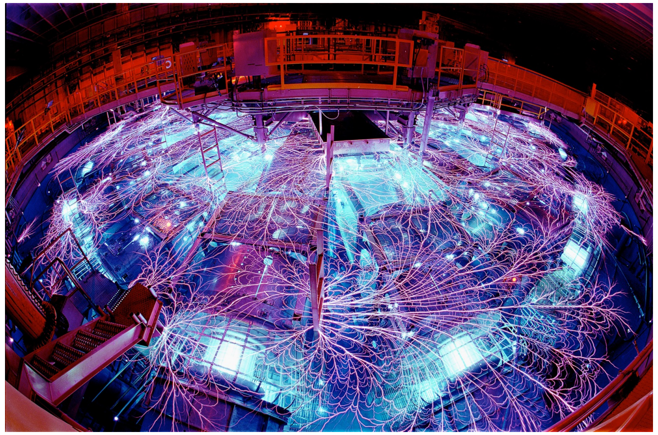
ZEUS NSF OPAL



Mid-scale drivers at LCLS and APS

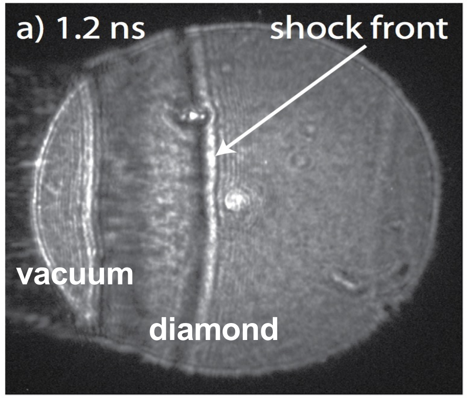


Z pulsed power facility



New diagnostic techniques have been developed to test micro to mesoscale HED science and processes

Advanced radiography



X-ray Thompson scattering

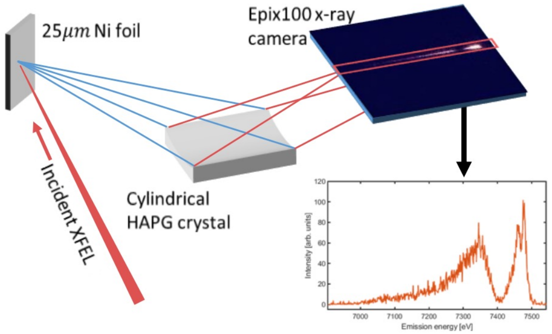
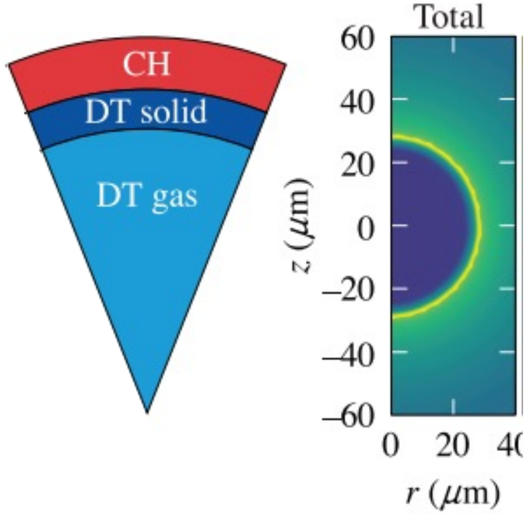
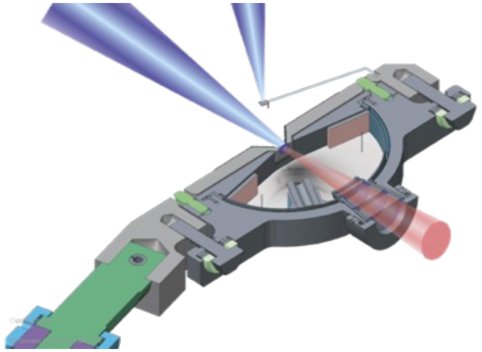


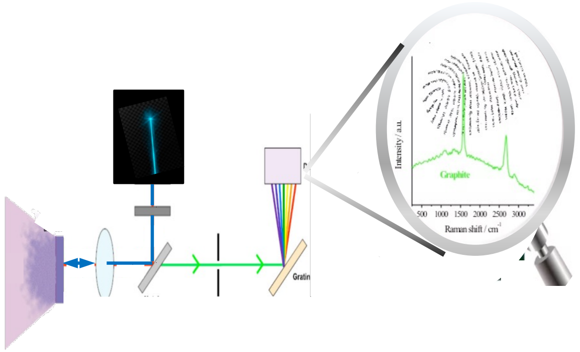
Image or determine state of fuel in ICF



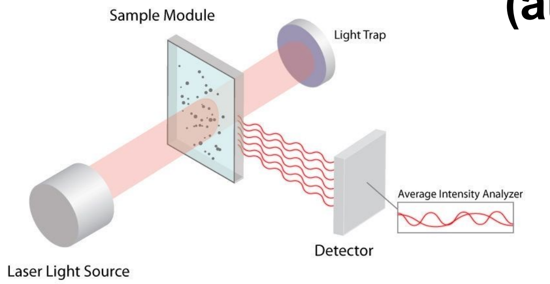
Diffraction



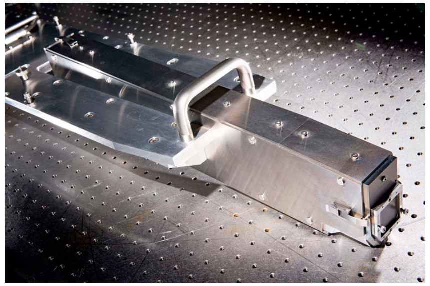
Raman Spectroscopy



Viscosity

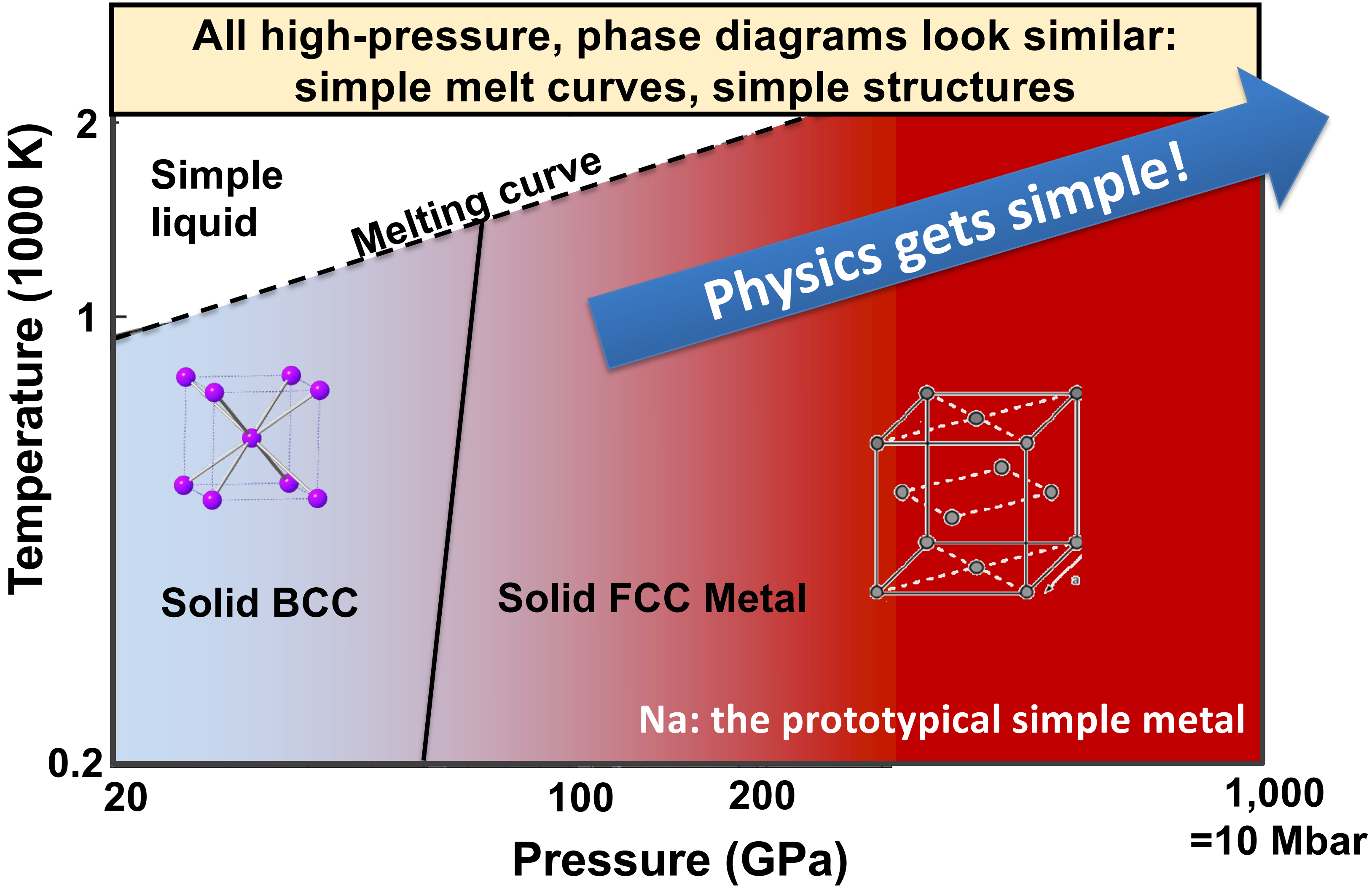


High res. spectroscopy (atomic physics, EXAFS, etc)



However, these techniques are all limited by available x-ray sources at the major HED facilities

Just a few years ago, ultrahigh-pressure phase diagrams for materials were very simple



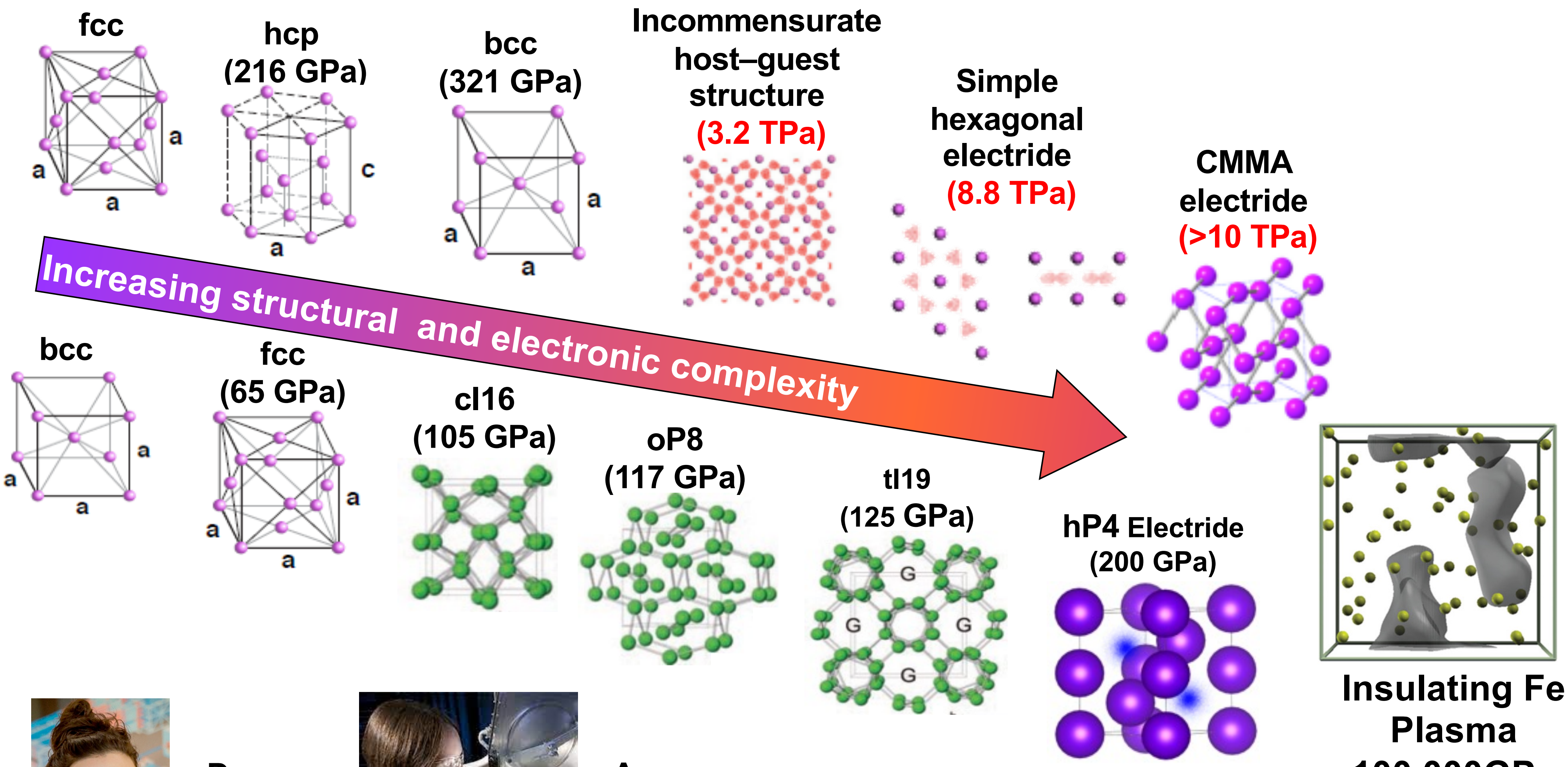
* M. Marques *et al.*, *Physical Review B* 83, 184106 (2011)

However what we are finding is many materials evolve with pressure to complex matter (topological insulating electrides)

Aluminum

Sodium

Li
K
Mg
C



Insulating Fe Plasma 100,000GPa

Dai PRL 14

Danae Polsin

Amy Jenei

OPEN

Structural complexity in ramp-compressed sodium to 480 GPa

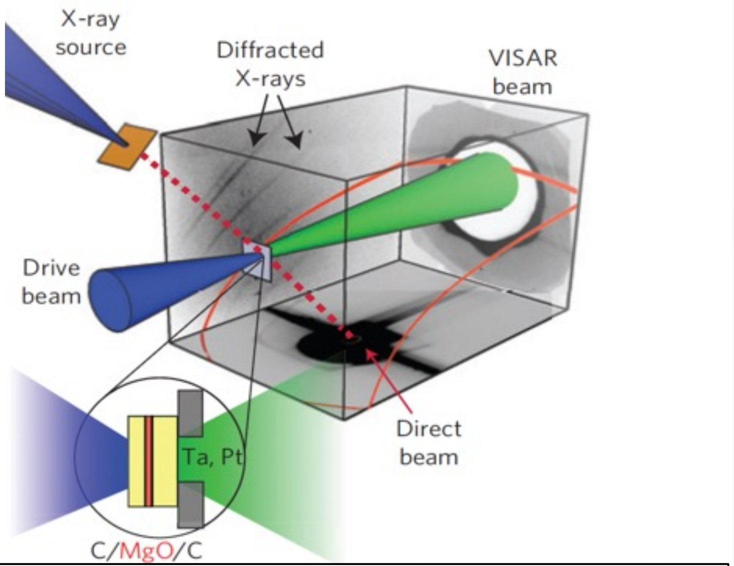
OPEN

Experimental observation of open structures in elemental magnesium at terapascal pressures

UNIVERSITY of ROCHESTER

HED X-ray diffraction was developed at Omega and NIF over ten years, resolving several longstanding questions…….But

Diffraction at Omega, 2008–2025
>1000 shots, many tens of publications



PRL 115, 075502 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

X-Ray Diffraction of Solid Tin to 1.2 TPa

A. Lazicki,[1] J. R. Rygg,[1] F. Coppari,[1] R. Smith,[1] D... G. W. Collins,[1] R. Briggs,[2] D. G. Braun,[1] D. C...
[1]Lawrence Livermore National Laboratory, 7000 East Avenu...
[2]The University of Edinburgh, Mayfield Road, Edinbur...
(Received 30 April 2015; published 12...

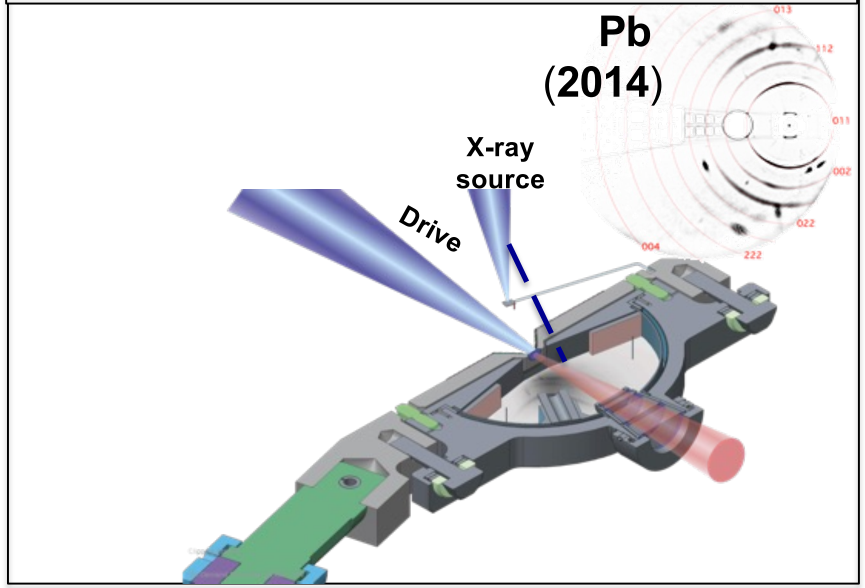
Physical Review Letters
APS

nature COMMUNICATIONS
https://doi.org/10.1038/s41467-022-29813-4 OPEN

Structural complexity in ramp-compressed sodium to 480 GPa

Polsin, 2022

Diffraction on the NIF, 2013–2025
>200 classified and basic-science shots.



X-ray diffraction at the National Ignition Facility

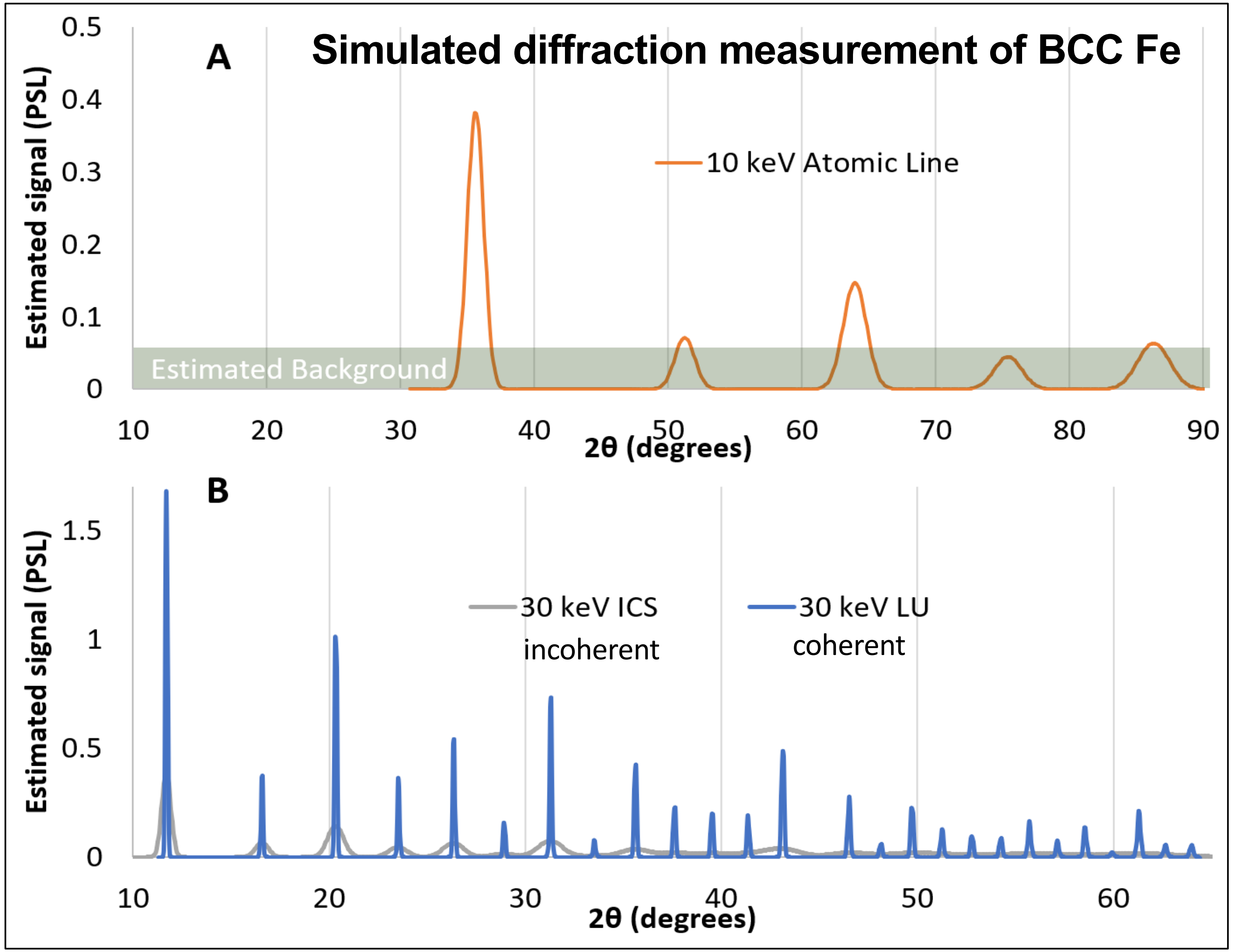
J. R. Rygg,[1,2,3,4,a)] R. F. Smith,[1] A. E. Lazicki,[1] D. G. Braun,[1] D. E. Fratanduono,[1] R. G. Kraus,[1] J. M. McNaney,[1] D. C. Swift,[1] C. E. Wehrenberg,[1] F. Coppari,[1] M. F. Ahmed,[1] M. A. Barrios,[1] K. J. M. Blobaum,[1] G. W. Collins,[1,2,3,4] A. L. Cook,[1] P. Di Nicola,[1] E. G. Dzenitis,[1] S. Gonzales,[1] B. F. Heidl,[1] M. Hohenberger,[1] A. House,[1] N. Izumi,[1] D. H. Kalantar,[1] S. F. Khan,[1] T. R. Kohut,[1] C. Kumar,[1] N. D. Masters,[1] D. N. Polsin,[2] S. P. Regan,[2] C. A. Smith,[1] R. M. Vignes,[1] M. A. Wall,[1] J. Ward,[1] J. S. Wark,[5] T. L. Zobrist,[1] A. Arsenlis,[1] and J. H. Eggert[1]

PLANETARY SCIENCE

Measuring the melting curve of iron at super-Earth core conditions

Science AAAS

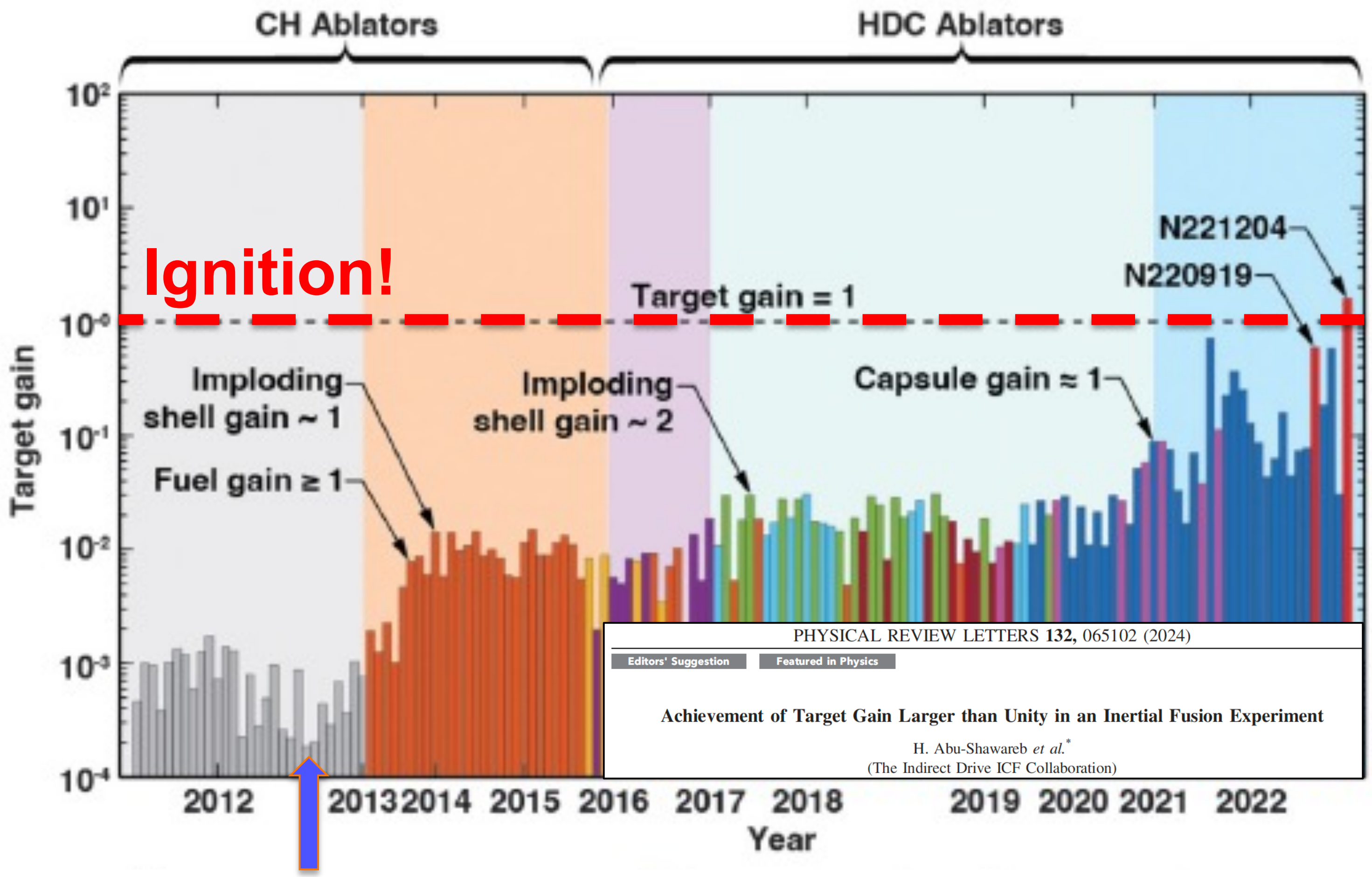
However, current sources are unable to determine complex solid structure, liquid structure, defects, anisotropy…



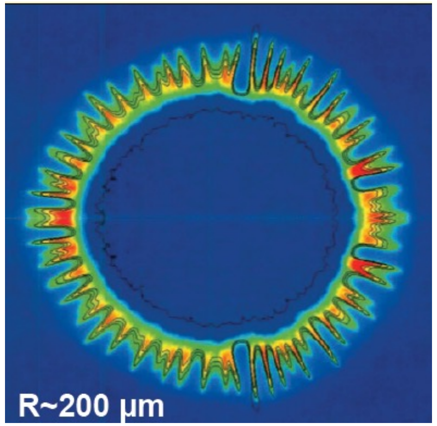
- Significant background present at 10 keV from driver and back-lighter foil

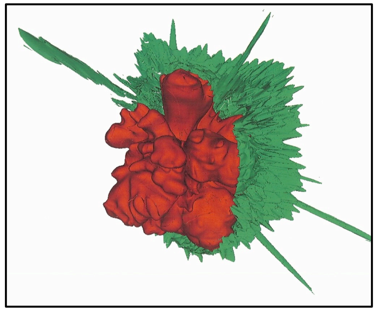
- Both incoherent Compton and coherent laser-undulator sources will provide a dramatic improvement in the quality of x-ray diffraction

Tremendous progress towards controlling fusion, but significant effort needed (micro and macrophysics) to understand and exploit such implosions



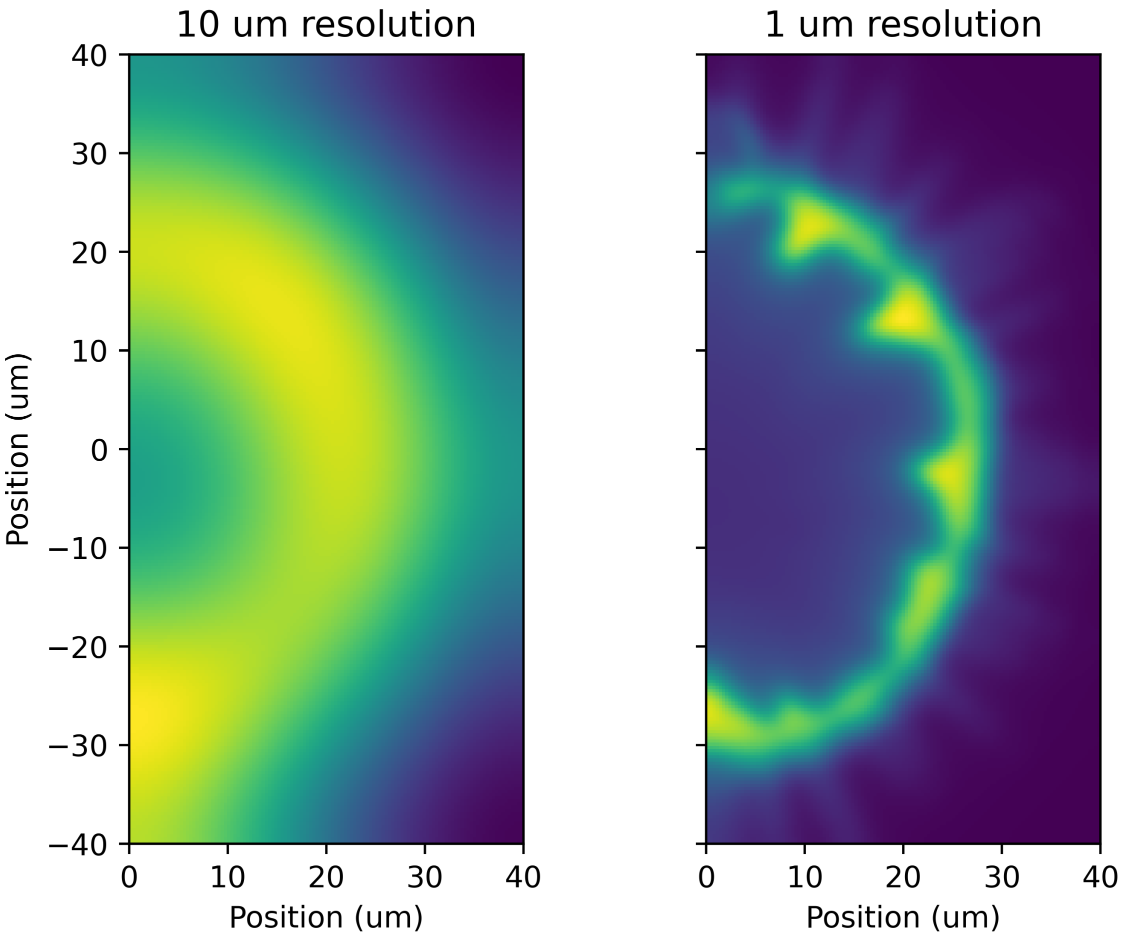
Each implosion experiment





Imaging the core at stagnation would dramatically improve our understanding of these implosions

<1 μm and ps resolution or better is required to resolve perturbations in ICF fuel layers



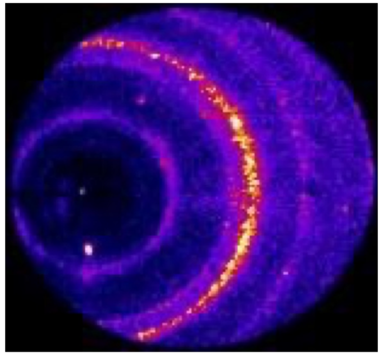
Need > 30 KeV photons
Sub ps time resolution
10^{10} photons

2D mass density profile of a Draco simulation at stagnation on OMEGA-60

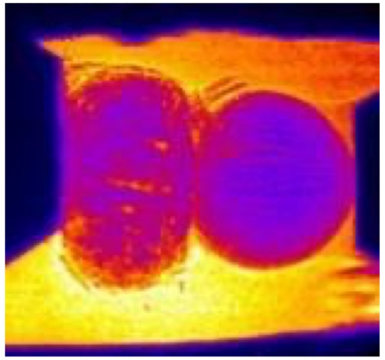
There has been growing effort to bring pressure drivers to light-sources over the last decade

- **Advanced Photon Source**

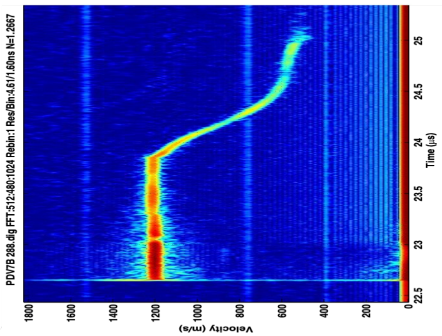
X-ray Diffraction



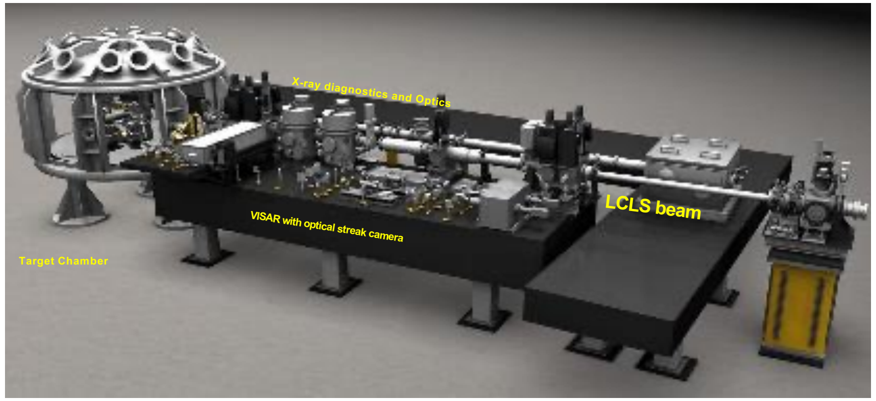
Phase Contrast



Continuum Measurements



- **Current MEC at LCLS and Dipole at EXFEL**



- **HED endstation at Eu-XFEL**

Control room during 1st experiments at Eu-XFEL

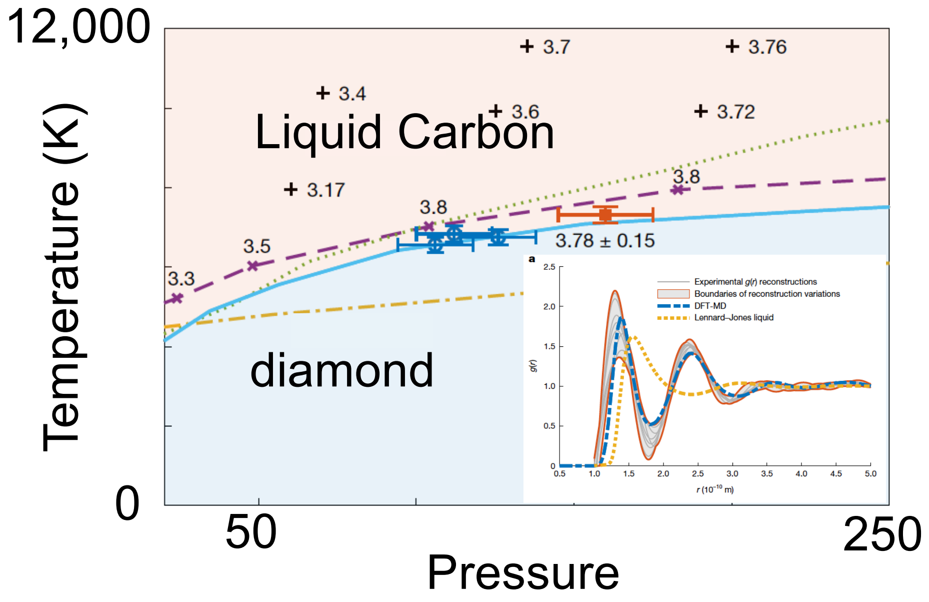
But, driver energy is low and it is a challenge to get a compact megajoule laser driver

Such light sources are pioneering new materials directions
But again, the accessible pressure range is limited

Recent liquid diffraction providing both the coordination in the dense fluid/plasma phase and melt boundaries.

nature
International weekly journal of science

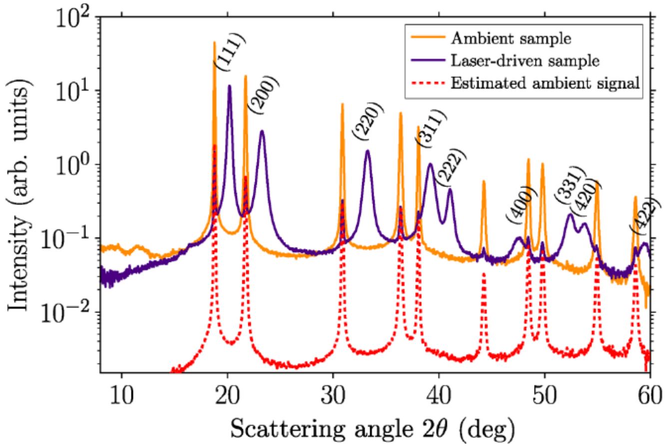
The structure of liquid carbon elucidated by in situ X-ray diffraction Kraus et al.



Journal of Applied Physics

RESEARCH ARTICLE | APRIL 23 2024

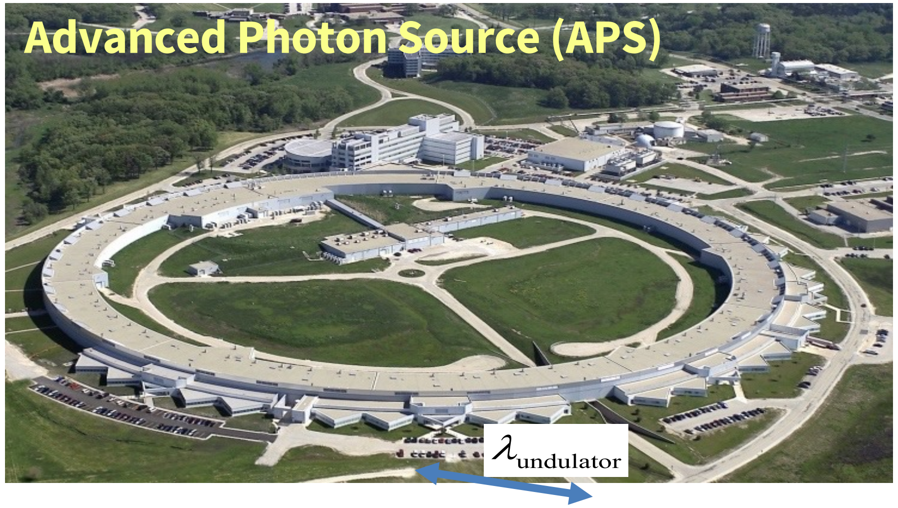
Shock compression experiments using the DiPOLE 100-X laser on the high energy density instrument at the European x-ray free electron laser: Quantitative structural analysis of liquid Sn Gorman et al.



Journal of Applied Physics

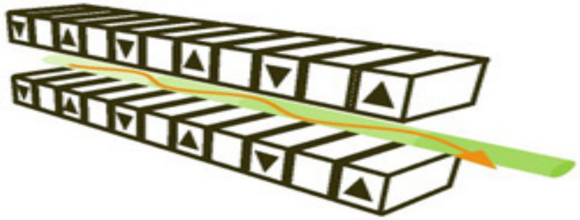
Femtosecond temperature measurements of laser-shocked copper deduced from the intensity of the x-ray thermal diffuse scattering Wark et al.

But as discussed here, we can make a compact light source



~300 meters

Need ~10 m



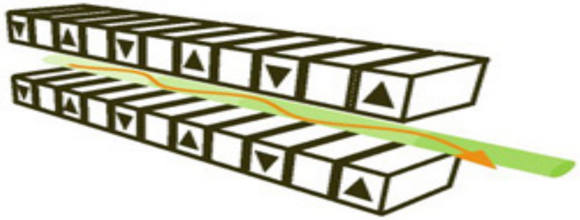
$$\lambda_{x-ray} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \sim \frac{\lambda_{undulator}}{E^2}$$

$K \sim magnetic\ field\ strength,$
$E = electron\ kinetic\ energy$

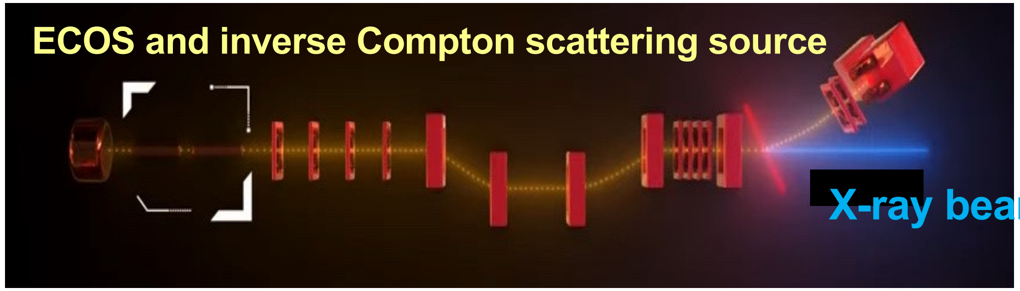
$$\gamma = \frac{1}{\sqrt{1 - \left(\frac{v_e}{c}\right)^2}}$$

Photon-electron interaction based x-ray sources use a laser instead of large magnets and lower electron beam energy

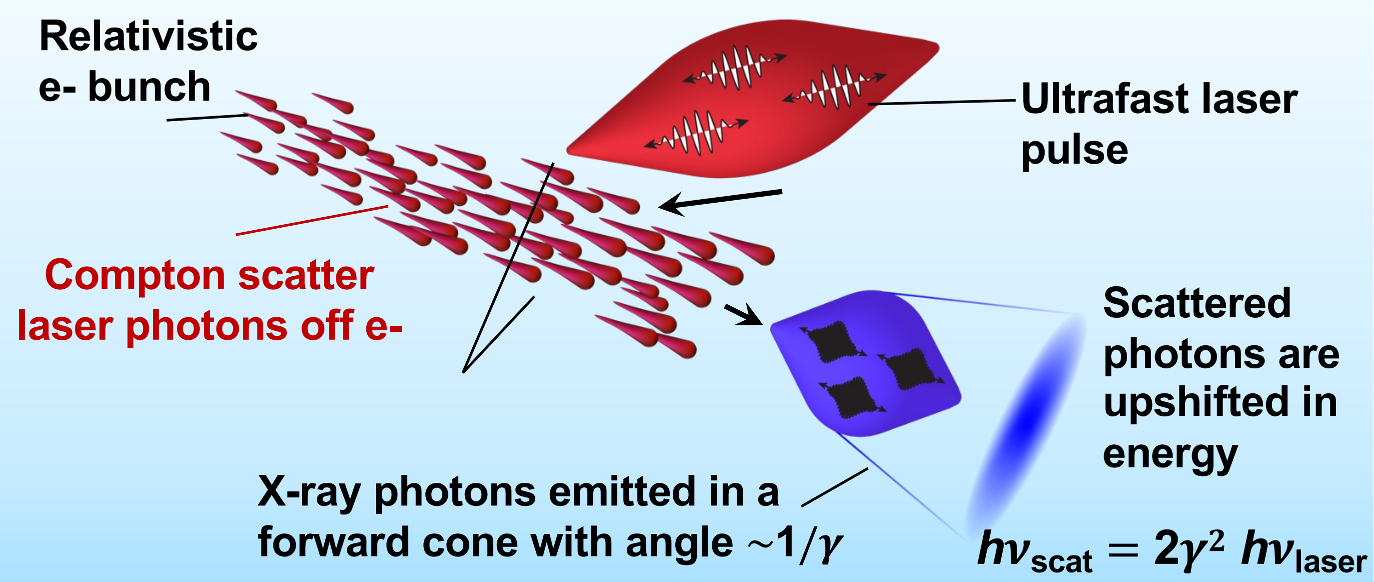
~ 300 meters



$$\lambda_{x-ray} \sim \frac{\lambda_{undulator}}{E^2}$$



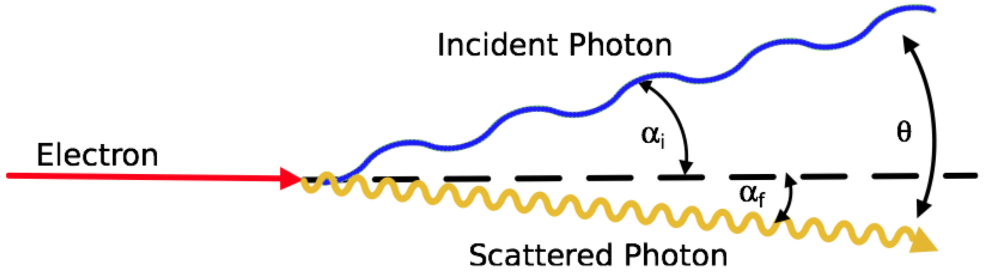
~10 meters



Laser-electron beam interactions provide 2 methods of generating improved and compact x-ray sources as compared to typical HED sources

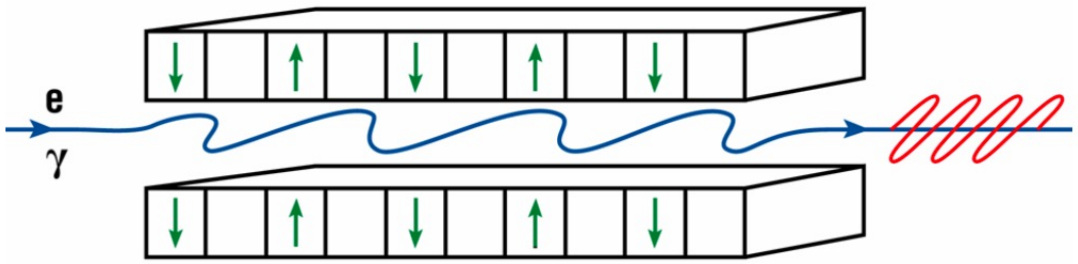
Incoherent Compton Scattering**

- e- up-scatters(in energy) photons
- Incoherent source
- <2.5% bandwidth possible
- Tunable
- Most photons in <10 mRad cone



Coherent "Laser-Undulators"*

- Laser fields are used as undulator on electron beam
- Coherent source
- <<0.1% bandwidth
- Tunable
- <1 mRad emission angle

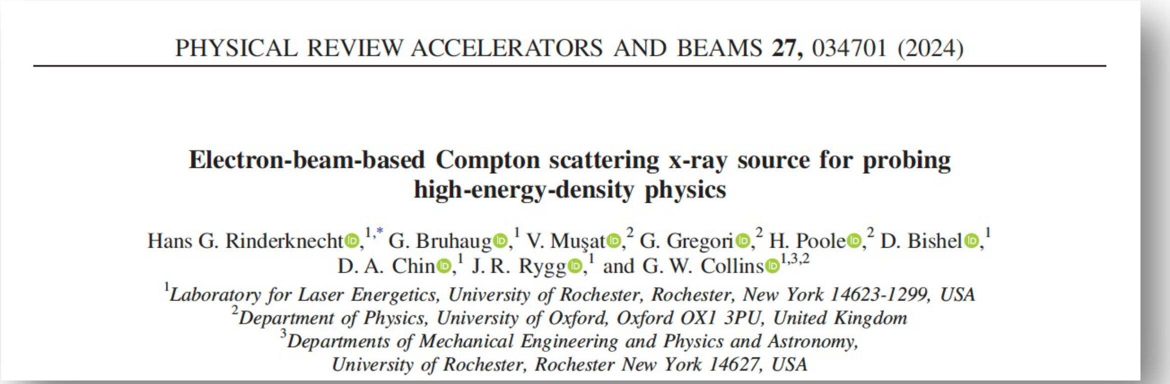


* Bonifacio, R., et al, Experimental requirements for x-ray compact free electron lasers with a laser wiggler, Nuc Instr and Meth A, 577, 745-750, 2007

**Rinderknecht, H.G, *et al*, An electron-beam based Compton scattering x-ray source for probing high-energy density physics, PRAB, 27, 034701, (2024)

Using these concepts we developed a design for single shot, 2.5% bandwidth, x-ray source with photon energies to 50 KeV

Electron bunch charge (nC)	14
Electron bunch length (ps)	90
Electron transverse size (μm)	41
Laser energy (J)	133
Laser pulse length (ps)	90
Laser transverse size (um)	41
ICS peak wavelength (nm)	0.025
ICS peak energy (keV)	50
Number of ICS photons	3E10
X-ray bandwidth	2.5%
Emission angle (collimated)	~4 mRad


PHYSICAL REVIEW ACCELERATORS AND BEAMS **27,** 034701 (2024)

Electron-beam-based Compton scattering x-ray source for probing high-energy-density physics

Hans G. Rinderknecht[1,*] G. Bruhaug[1] V. Muşat[2] G. Gregori[2] H. Poole[2] D. Bishel[1] D. A. Chin[1] J. R. Rygg[1] and G. W. Collins[1,3,2]
[1]*Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623-1299, USA*
[2]*Department of Physics, University of Oxford, Oxford OX1 3PU, United Kingdom*
[3]*Departments of Mechanical Engineering and Physics and Astronomy, University of Rochester, Rochester New York 14627, USA*

X-rays to target	>10^{10}
Bandwidth	~2%
Energy	Variable, 1-50 keV

*Rinderknecht, H.G, *et al*, An electron-beam based Compton scattering x-ray source for probing high-energy density physics, PRAB, 27, 034701, (2024)

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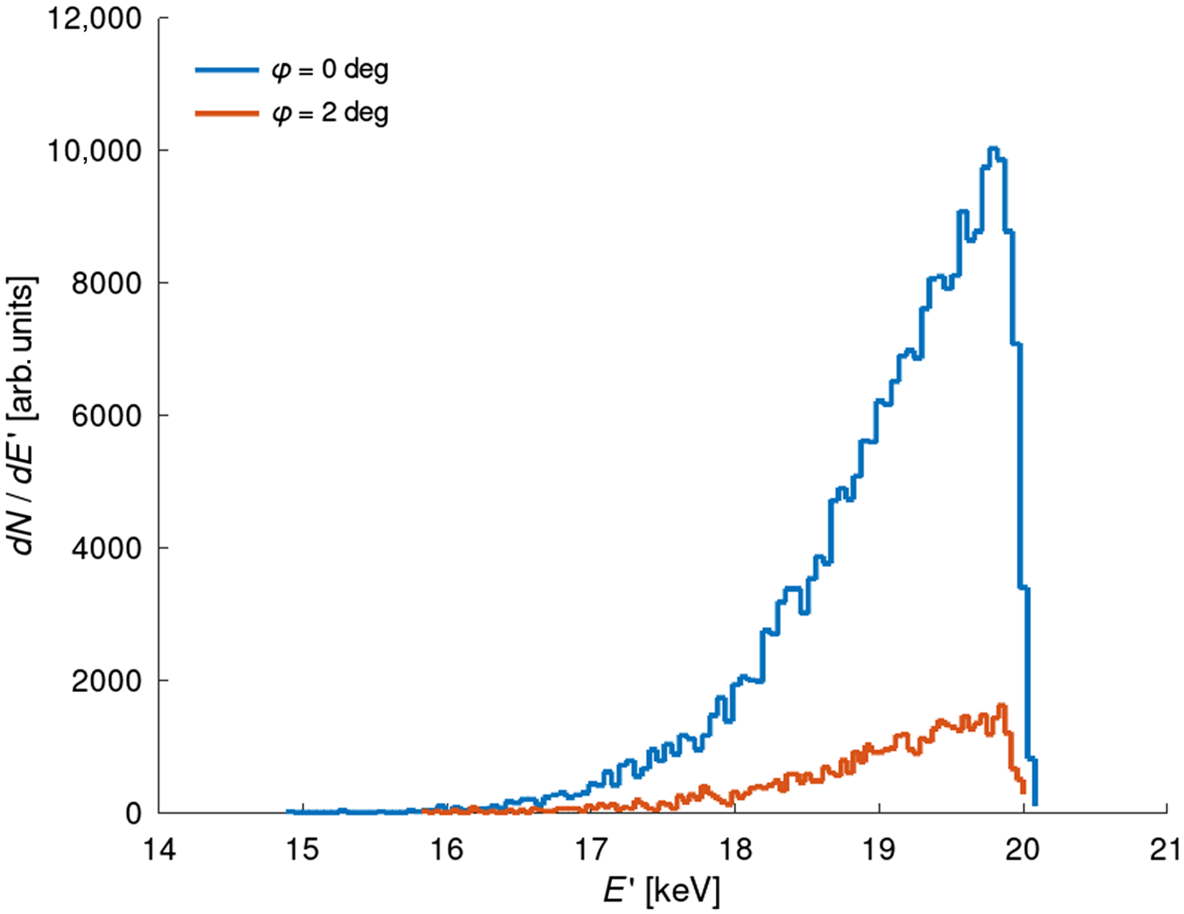
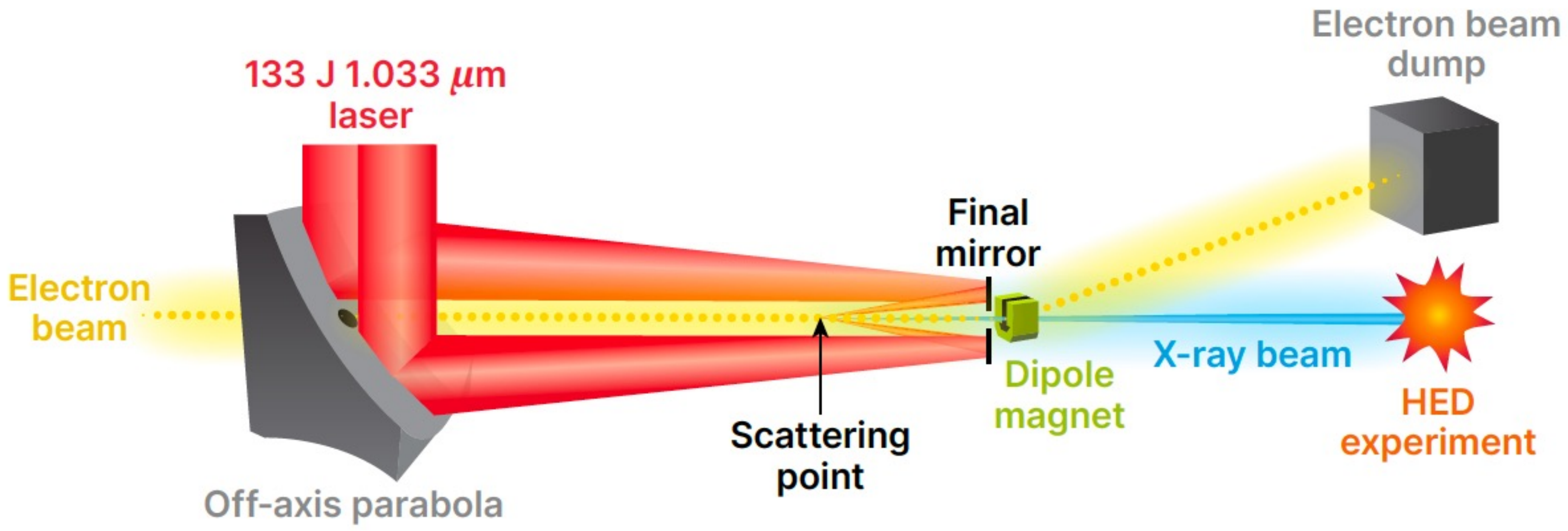
Number of ICS photons	3E10
X-ray bandwidth	2.5%
Emission angle (collimated)	~4 mRad

Predicted 20 keV spectrum



*Rinderknecht, H.G, *et al*, An electron-beam based Compton scattering x-ray source for probing high-energy density physics, PRAB, 27, 034701, (2024)

This source is buildable with ~standard “off the shelf” rf linear accelerators and mature glass laser technologies



- 1.3 GHz copper accelerator (~4 meters)
- Copper photo-cathode, although other materials would provide more charge
- OPCA front-end laser with Nd-doped glass amplifier
- Still, this needs to be tested

Los Alamos NATIONAL LABORATORY EST.1943

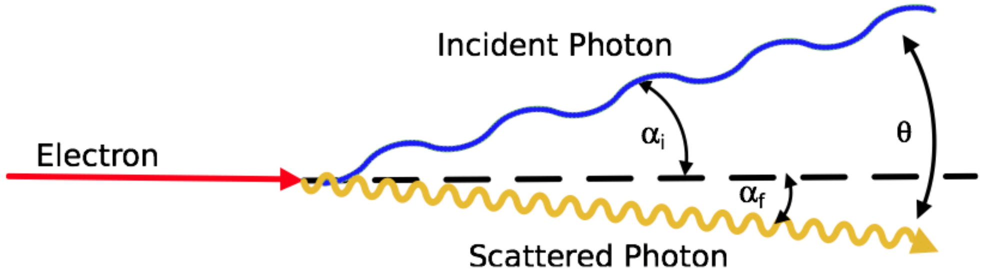
UNIVERSITY of ROCHESTER

*Rinderknecht, H.G, *et al*, An electron-beam based Compton scattering x-ray source for probing high-energy density physics, PRAB, 27, 034701, (2024)

Laser-electron beam interactions provide two methods of generating better x-ray sources in much smaller packages than traditional accelerator sources

Incoherent Compton Scattering**

- Relativistic electron scatters laser photon up in energy
- Incoherent source
- <2.5% bandwidth possible
- Tunable
- Most photons in <10 mRad cone



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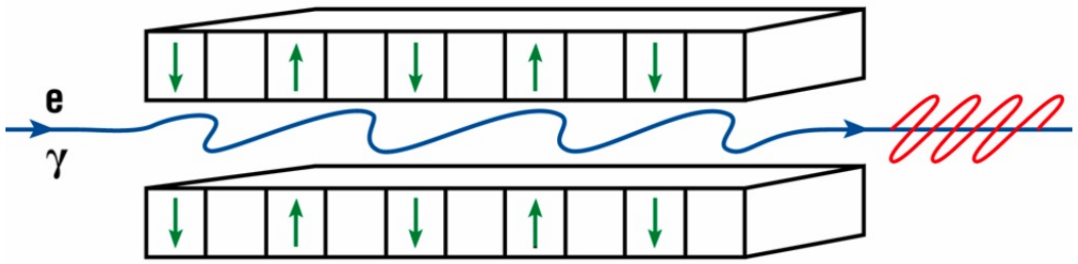
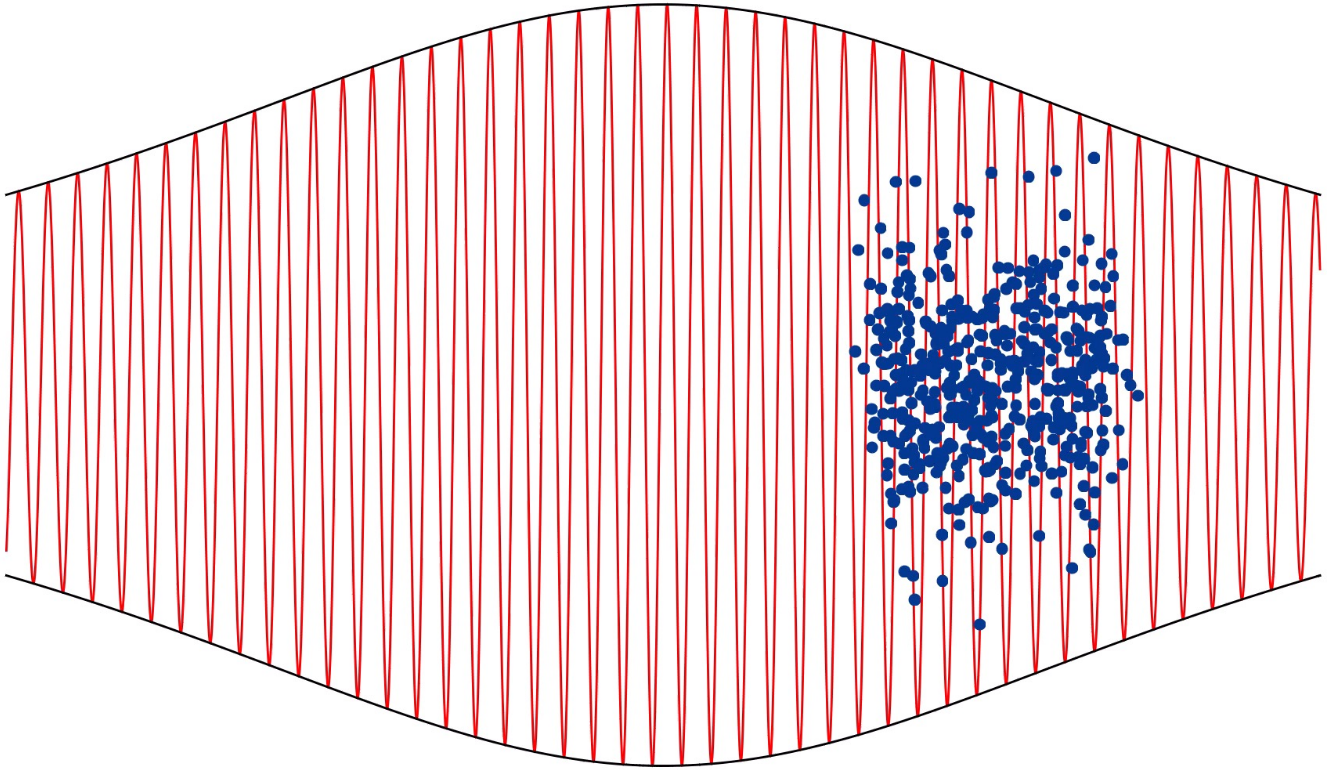


[*] Bonifacio, R., et al, Experimental requirements for x-ray compact free electron lasers with a laser wiggler, Nuc Instr and Meth A, 577, 745-750, 2007

[**] Rinderknecht, H.G, et al, An electron-beam based Compton scattering x-ray source for probing high-energy density physics, PRAB in review

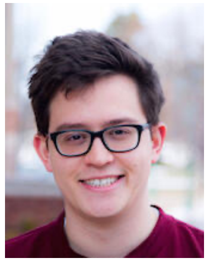
Laser-undulators (LU) rely on the same physics as large free electron lasers (FEL)

The beam begins to microbunch due to self-interaction with the incoherent x-rays emission



Laser, ~1 cm

*Courtesy of D. Ramsey and J. Palastro



***D. Ramsey *et al.* (2024), X-Ray Free-Electron Lasing in a Flying Focus**
In preparationee

Self Amplified Stimulated Emission (SASE)

* Haung, Z., Review of x-ray free-electron laser theory, PRAB, 10, 034801, (2007)

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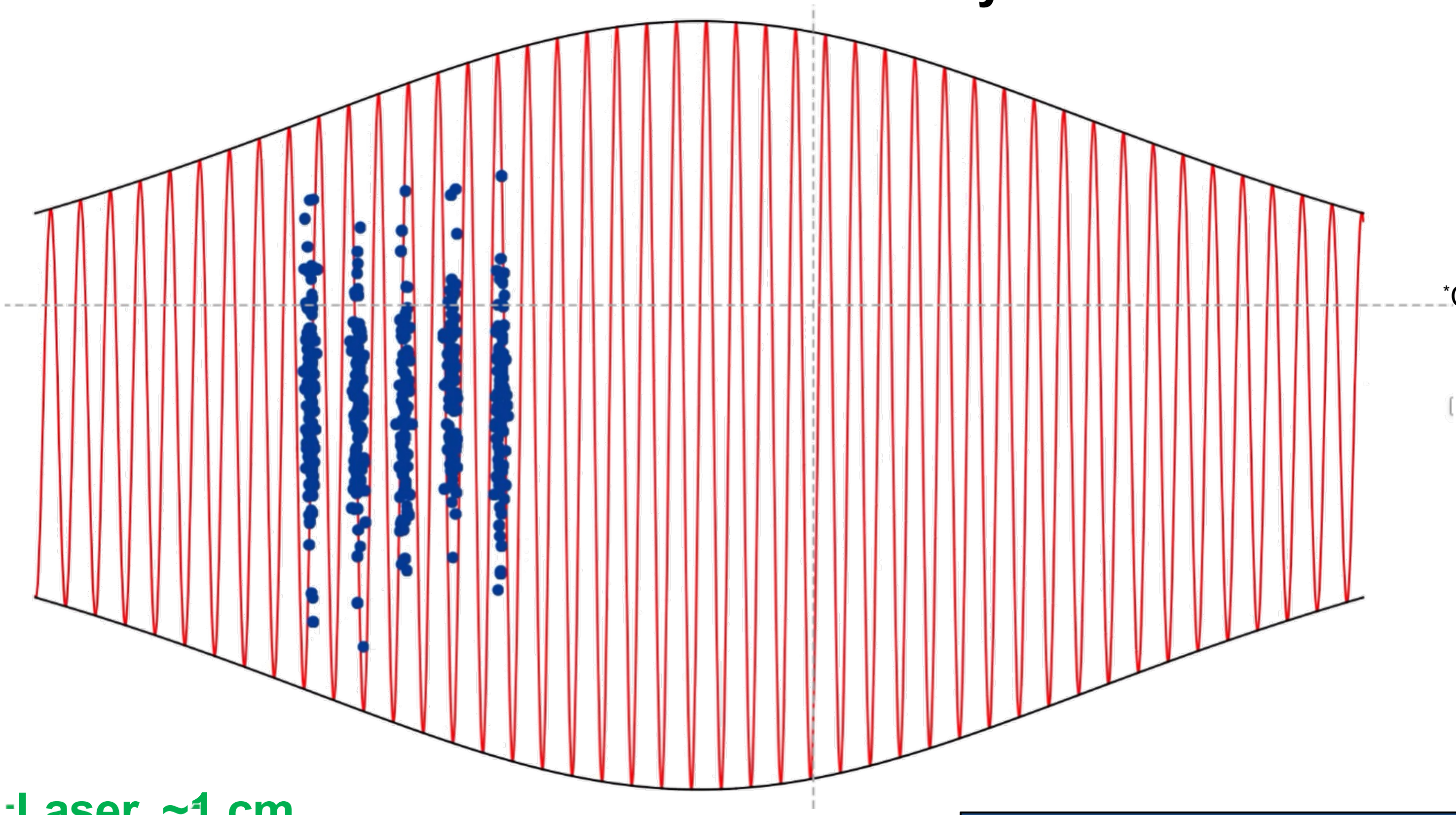

Laser, ~1 cm

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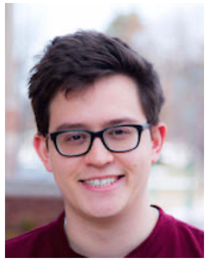

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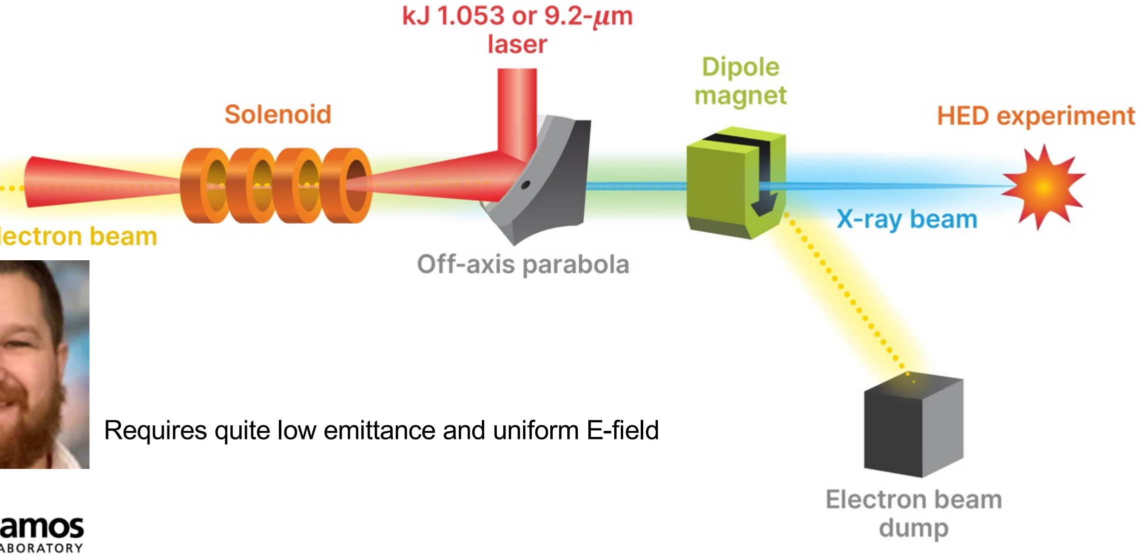
Self Amplified Stimulated Emission (SASE)

* Haung, Z., Review of x-ray free-electron laser theory, PRAB, 10, 034801, (2007)
** Bonifacio, R., *et al*, Experimental requirements for x-ray compact free electron lasers with a laser wiggler, Nuc Instr and Meth A, 577, 745-750, 2007

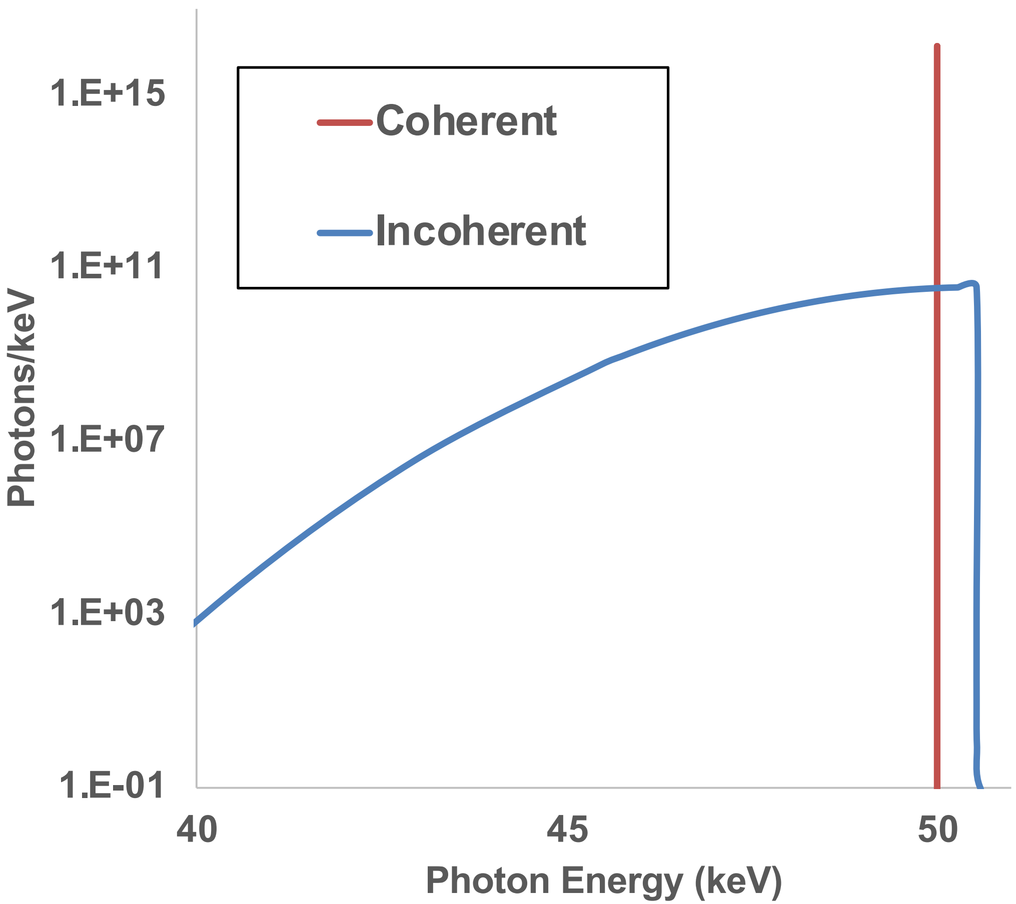
Using a brute force laser undulator as in Bonifacio et al, suggest a bright, tunable, monochromatic and *coherent* x-ray source is possible

- **~20-70 MeV electrons, kJ scale laser**
  kA peak currents, >nc bunch charge
  1 um emittance, <10 μm beam radius
- **Tunable from 10-50 keV**
- **>10^{10} coherent photons, $\Delta E/E < 10^{-4}$**



Requires quite low emittance and uniform E-field

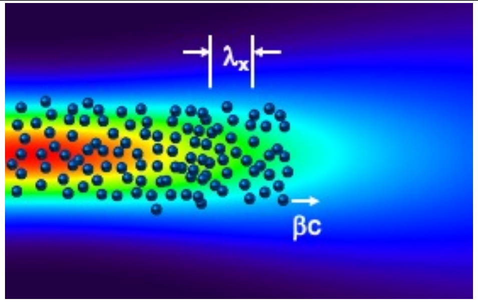
Predicted 50 keV spectrum



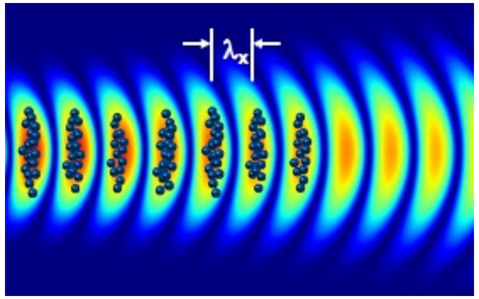
* Bonifacio, R., *et al*, Experimental requirements for x-ray compact free electron lasers with a laser wiggler, Nuc Instr and Meth A, 577, 745-750, 2007
**Rinderknecht, H.G, *et al*, An electron-beam based Compton scattering x-ray source for probing high-energy density physics, PRAB, 27, 034701, (2024)

Recent laser and electron beam advances, opens the door to still more potential advances in laser XFELs

Prebunching



Incoherent:Random electron positioning for Undulator radiation

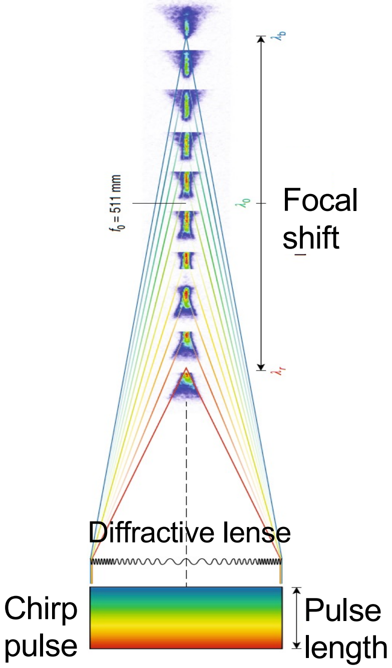


Coherently bunched electrons for **XFEL** radiation

New X-ray free-electron laser architecture for generating high fluxes of longitudinally coherent 50 keV photons

Bruce E. Carlsten , Kip A. Bishofberger , Leanne D. Duffy , Cynthia E. Heath , Quinn R. Marksteiner , Dinh C. Nguyen , Robert D. Ryne , Steven J. Russell , Evgenya I. Simakov & Nikolai A. Yampolsky

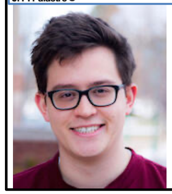
Flying focus



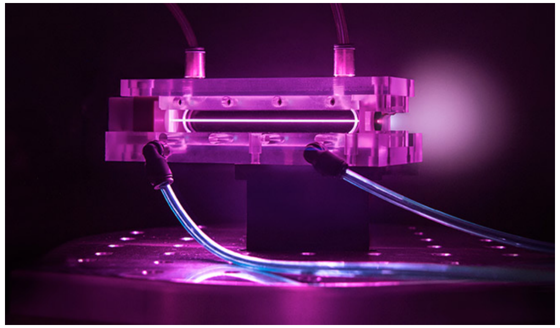
X-ray free-electron lasing in a flying-focus undulator

Check for updates

D. Ramsey[1], B. Malaca[2], T. T. Simpson[1], M. S. Formanek[3], L. S. Mack[1], J. Vieira[2], D. H. Froula[1] & J. P. Palastro[1]



Plasma Channel



Counter-Propagation of Electron and CO_2 Laser Beams in a Plasma Channel

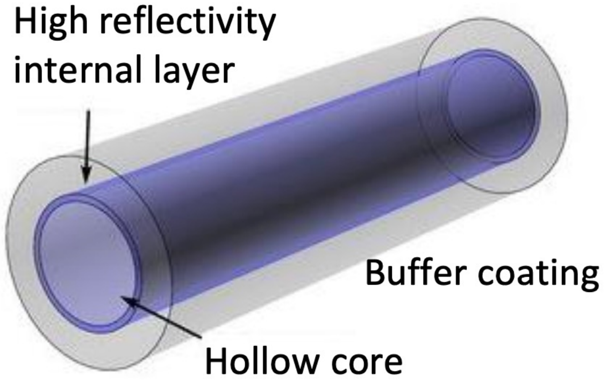
T. Hirose[a], I.V. Pogorelsky[b], I. Ben-Zvi[b], V. Yakimenko[b], K. Kusche[b], P. Siddons[b], T. Kumita[a], Y. Kamiya[a], A. Zigler[c], B. Greenberg[c], D. Kaganovich[c], I.V. Pavlishin[d], A. Diublov[d], N. Bobrova[e] and P. Sasorov[e]

Experiments on Laser and e-Beam Transport and Interaction in a Plasma Channel

I.V. Pogorelsky[a], I.V. Pavlishin[a], I. Ben-Zvi[a], V. Yakimenko[a], T. Kumita[b], Y. Kamiya[b], A. Zigler[c], A. Diublov[d], N. Andreev[e], N. Bobrova[f] and P. Sasorov[f]

[a] *Accelerator Test Facility, Brookhaven National Laboratory, 820, Upton, NY 11973, USA*
[b] *Physics Department, Tokyo Metropolitan University, Japan*
[c] *Hebrew University, Jerusalem, Israel*
[d] *Optoel Co, St. Petersburg, Russia*
[e] *Inst. High Density Energy, Moscow, Russia*
[f] *Inst. Theoretical and Experimental Phys., Moscow, Russia*

Optical waveguide



OPTICA

Toward high-gain laser-driven electron undulators

Amnon Balanov, Ron Ruimy, and Ido Kaminer*

IOP Publishing — Plasma Physics and Controlled Fusion
Plasma Phys. Control. Fusion **53** (2011) 014007 (10pp) doi:10.1088/0741-3335/53/1/014007

High efficiency x-ray source based on inverse Compton scattering in an optical Bragg structure

Vadim Karagodsky and Levi Schächter

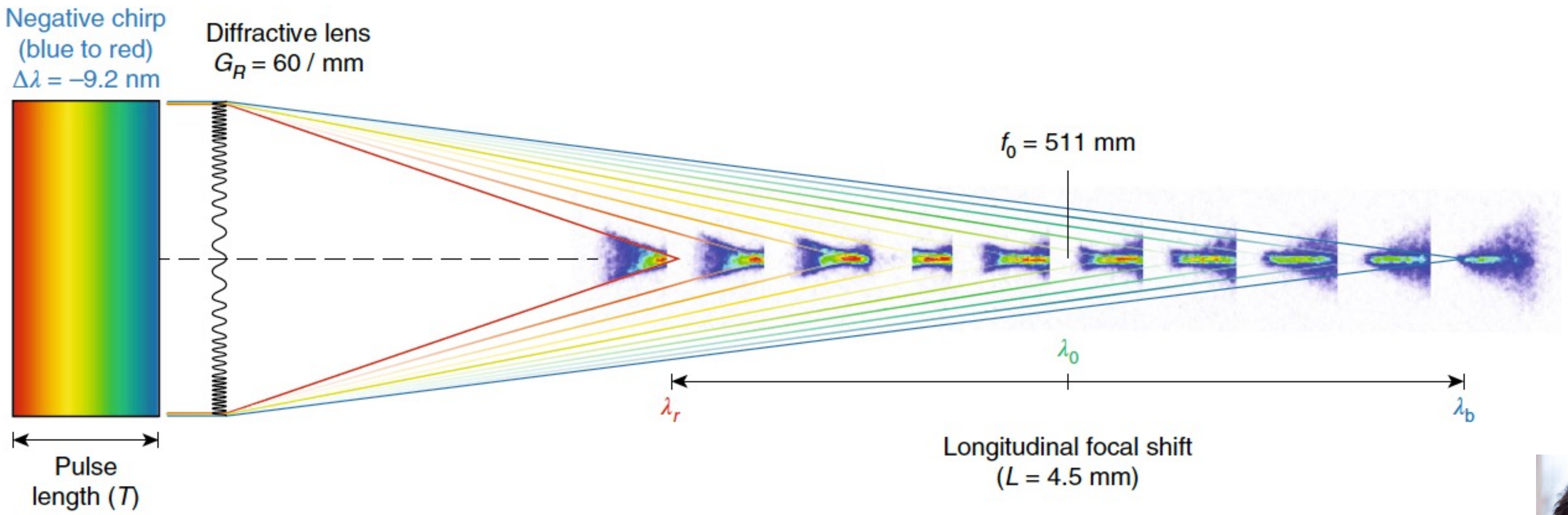
Design study of a dielectric laser undulator

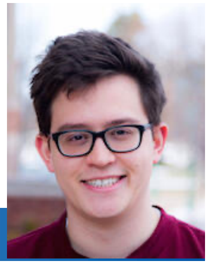
Steffen A. Schmid* and Uwe Niedermayer†
Technical University Darmstadt, Institute for Accelerator Science and Electromagnetic Fields, Schlossgartenstrasse 8, 64289 Darmstadt, Germany

(Received 31 May 2022; accepted 27 July 2022; published 6 September 2022)

”Flying Focus” laser pulse shaping reduces the laser and accelerator requirements, experiments underway to test concept

- **Laser bandwidth is used to create a moving laser focus that increases the effective Rayleigh length**





***D. Ramsey *et al.* (2025), X-Ray Free-Electron Lasing in a Flying Focus, Nat. Comm.**

** Ramsey, D., *et al,* Exact solutions for the electromagnetic fields of a flying focus, Phys Rev A, 107, 013513, (2023)

We are also expecting to test hollow waveguides to confine the laser

- **~1 mm hollow-core optical fibers can potentially confine the laser for many Rayleigh lengths**

- **Optical waveguides typically have <1 dB/km of loss**

- **Limited by the damage limits**
    - 1-10 GV/m typically

OPTICA

Toward high-gain laser-driven electron undulators

AMNON BALANOV, RON RUIMY, AND IDO KAMINER*

Design study of a dielectric laser undulator

Steffen A. Schmid* and Uwe Niedermayer†
Technical University Darmstadt, Institute for Accelerator Science and Electromagnetic Fields, Schlossgartenstrasse 8, 64289 Darmstadt, Germany

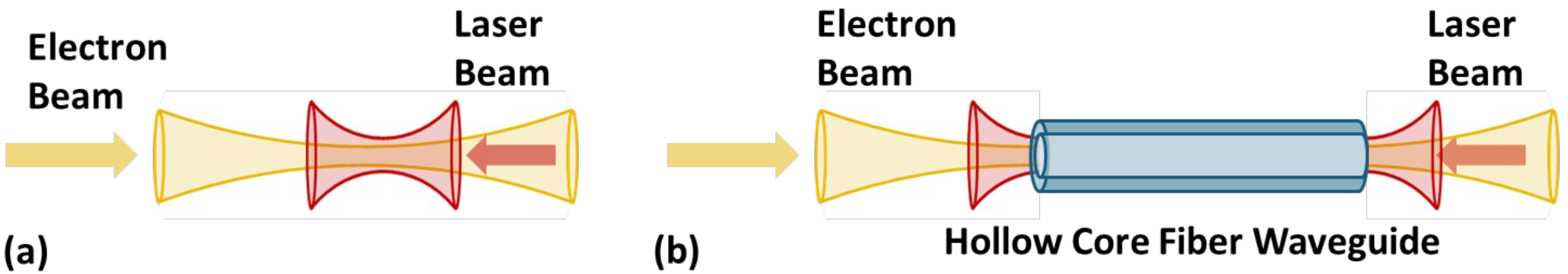
(Received 31 May 2022; accepted 27 July 2022; published 6 September 2022)

High efficiency x-ray source based on inverse Compton scattering in an optical Bragg structure

Vadim Karagodsky and Levi Schächter

HOLLOW-CORE ANTI-RESONANT FIBER OPTICS AS A PATH TOWARDS PRACTICAL LASER-UNDULATOR BASED X-RAY SOURCES*

G. Bruhaug[1,†], N. Kabadi[2], J.W. Lewellen[1], E.I. Simakov[1], M.S. Freeman[1], J.L. Schmidt[1], B.E. Carlsten[1], N. Yampolsky[1], D.A. Chin[2], G.W. Collins[2], L.P. Neukirch[1]



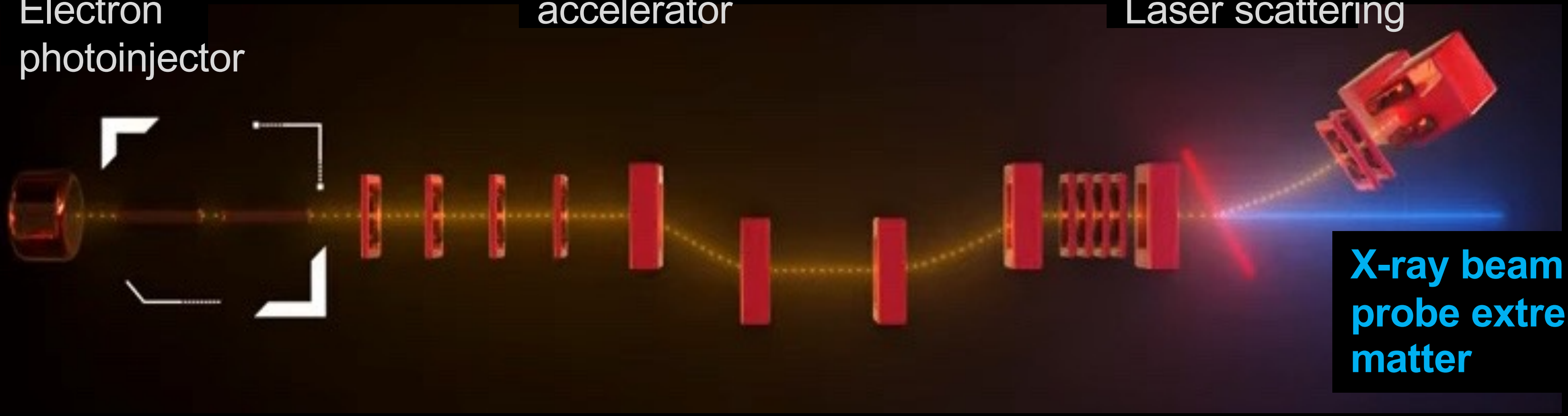
Los Alamos NATIONAL LABORATORY EST. 1943
UNIVERSITY of ROCHESTER

A very rough estimate of how these different strategies might scale, but we are hoping to test these different concepts

Concept	Classic	Flying Focus	Plasma Channel	Optical Waveguide
Wavelength (um)	1	1	1	1
Laser Energy (J)	10541	9166	100	50
a_0/K	0.5	1.4	0.0508	0.0031
Bunch Charge (nC)	3	1.7	1.7	1.7
Bunch Length (ps)	1	1.7	1.7	1.7
Quantum FEL?	Yes	Yes	Yes	Yes
3D Saturation Length (mm)	29.63	28.4	40.78	1100
# of 20 keV Photons	2.72E10	1.11E10	1.11E10	1.1E10

Exploring extreme matter: accelerators required

2026-2035

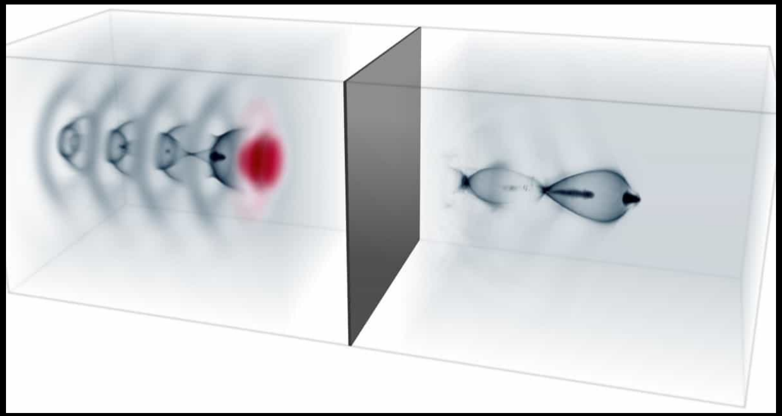


Incoherent "Compton"

Coherent " Laser Undulator"

2035-?

Can we move to an all optical system?



Physics World

Graves