4. Science Opportunities for Matter in Extreme Conditions

Related Sections

3.5 Non-linear X-ray physics and physics beyond the Standard Model with XFELs
8.2 Properties of shocked materials for engineering and defence

Science Team : Andy Higginbotham (York), Andy Comley (AWE), Sam Vinko (Oxford), Marco Borghesi (QUB), Malcolm McMahon (Edinburgh), Justin Wark (Oxford)

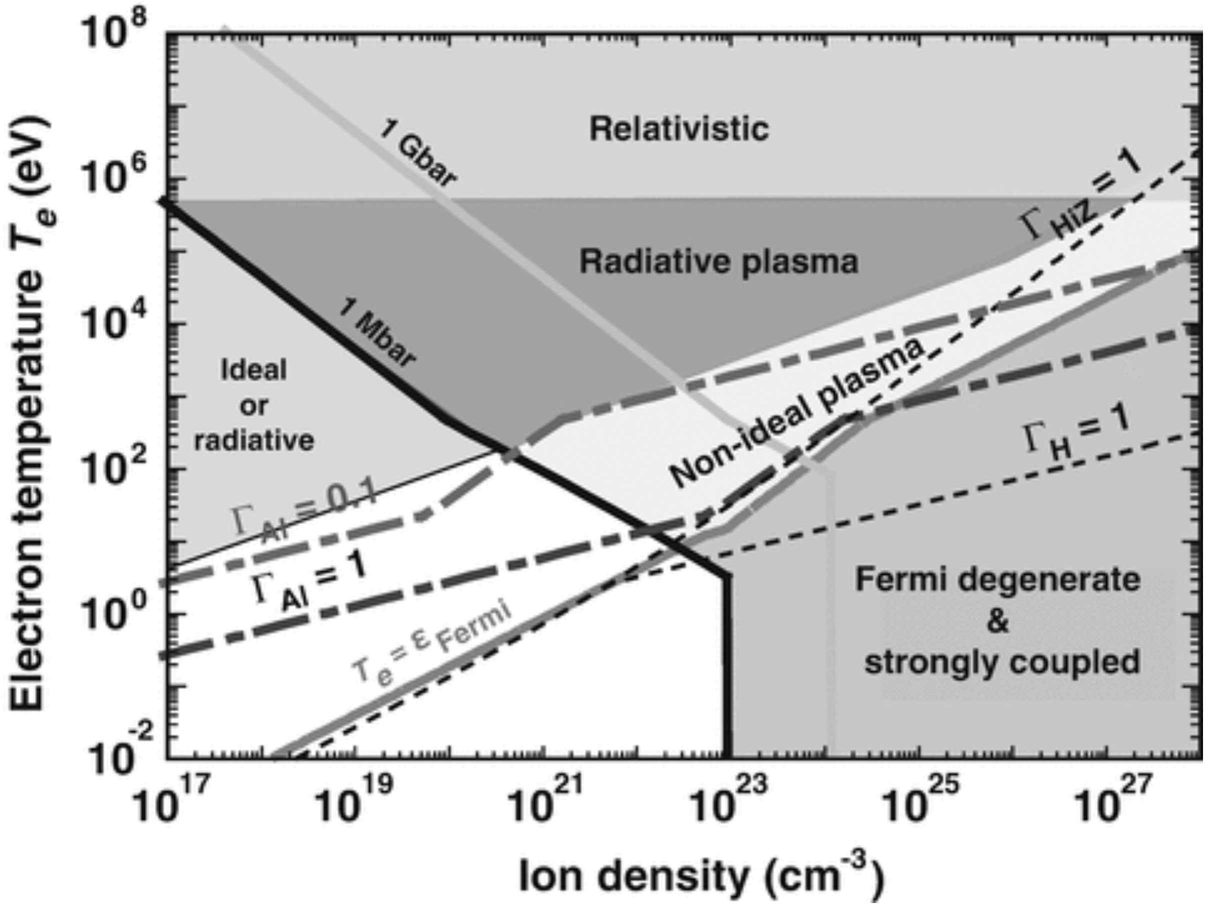
Matter in Extreme Conditions

- Matter with an energy density in excess of
  - 10^{11} J/m^3
  - 100 GPa
  - 1 Mbar

- Relevant to astrophysical, impact engineering, ICF and defense applications.

- Earth's core : 3.6 Mbar
- Jupiter core : ~70 Mbar

- Chemical energy density : ~1Mbar
- Atomic energy density : ~100Mbar



‘Existing’ XFEL Infrastructure

Facility	Long Pulse	Short Pulse	Additional Drivers
LCLS (MEC)	4x15J @ 527nm, 7min rep rate (3.5 if interleaving beams)	Ti:S - 1 J (@ 5 Hz), 10 mJ (at 120 Hz), 40fs	-
Euro XFEL (HED)	100J @1030nm DiPOLE-X, 10Hz, full temporal shaping	Ti:S 7 J @ 5 Hz on sample, 40fs	Support for DAC compression 50T pulsed magnetic fields
SACLA (EH5/EH6)	60J @ 532nm (10ns pulse), 0.1Hz, temporal shaping	Ti:S – 2x12.5J @ 1Hz, 25ps (EH6)	-

+ The XFEL beam itself!

UK MEC Science Output

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Direct imaging of ultrafast lattice dynamics

S. Brennan Brown[1]*, A. E. Gleason[2,3], E. Galtier[4], A. Higginbotham[5], B. Arnold[4], A. Fry[4], E. Granados[4], A. Hashim[6], C. G. Schroer[7,8], A. Schropp[7], F. Seiboth[4,7], F. Tavella[4], Z. Xing[4], W. Mao[3,9], H. J. Lee[4], B. Nagler[4]

PHYSICAL REVIEW LETTERS **122,** 255704 (2019)

Identification of Phase Transitions and Metastability in Dynamically Compressed Antimony Using Ultrafast X-Ray Diffraction

A. L. Coleman,[1,2,*] M. G. Gorman,[1,2] R. Briggs,[1,2] R. S. McWilliams,[1] D. McGonegle,[3] C. A. Bolme,[4] A. E. Gleason,[4,5] D. E. Fratanduono,[2] R. F. Smith,[2] E. Galtier,[6] H. J. Lee,[6] B. Nagler,[6] E. Granados,[6] G. W. Collins,[7] J. H. Eggert,[2] J. S. Wark,[3] and M. I. McMahon[1]

11 OCTOBER 2013 VOL 342 **SCIENCE**

Femtosecond Visualization of Lattice Dynamics in Shock-Compressed Matter

D. Milathianaki,[1]* S. Boutet,[1] G. J. Williams,[1] A. Higginbotham,[2] D. Ratner,[1] A. E. Gleason,[3] M. Messerschmidt,[1] M. M. Seibert,[1,4] D. C. Swift,[5] P. Hering,[1] J. Robinson,[1] W. E. White,[1] J. S. Wark[2]

LETTER

doi:10.1038/nature10746

Creation and diagnosis of a solid-density plasma with an X-ray free-electron laser

S. M. Vinko[1], O. Ciricosta[1], B. I. Cho[2], K. Engelhorn[2], H.-K. Chung[3], C. R. D. Brown[4], T. Burian[5], J. Chalupský[5], R. W. Falcone[2,6],

LETTER

doi:10.1038/nature24061

In situ X-ray diffraction measurement of shock-wave-driven twinning and lattice dynamics

C. E. Wehrenberg[1], D. McGonegle[2], C. Bolme[3], A. Higginbotham[4], A. Lazicki[1], H. J. Lee[5], B. Nagler[5], H.-S. Park[1], B. A. Remington[1], R. E. Rudd[1], M. Sliwa[2], M. Suggit[2], D. Swift[1], F. Tavella[5], L. Zepeda-Ruiz[1] & J. S. Wark[2]

nature physics ARTICLES
https://doi.org/10.1038/s41567-018-0290-x

Phase transition lowering in dynamically compressed silicon

E. E. McBride[1,10,11*], A. Krygier[2], A. Ehnes[1], E. Galtier[3], M. Harmand[2], Z. Konôpková[1,11], H. J. Lee[3], H.-P. Liermann[1], B. Nagler[3], A. Pelka[4], M. Rödel[4], A. Schropp[1], R. F. Smith[5], C. Spindloe[6], D. Swift[5], F. Tavella[3], S. Toleikis[1], T. Tschentscher[7], J. S. Wark[8] and A. Higginbotham[9]

PRL **118,** 025501 (2017) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2017

Ultrafast X-Ray Diffraction Studies of the Phase Transitions and Equation of State of Scandium Shock Compressed to 82 GPa

R. Briggs, M. G. Gorman, A. L. Coleman, and R. S. McWilliams

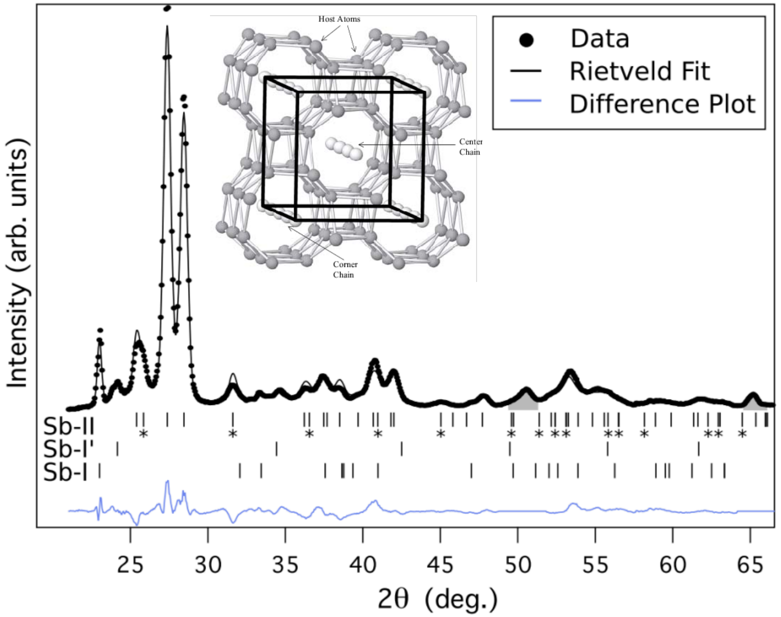
nature COMMUNICATIONS

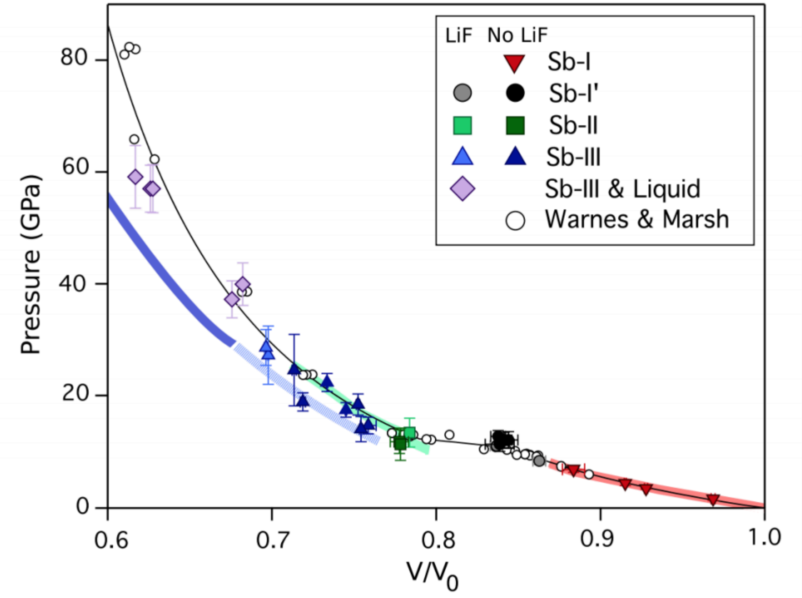
Investigation of femtosecond collisional ionization rates in a solid-density aluminium plasma

S.M. Vinko[1], O. Ciricosta[1], T.R. Preston[1], D.S. Rackstraw[1], C.R.D. Brown[2], T. Burian[3], J. Chalupský[3], B.I. Cho[4,5],

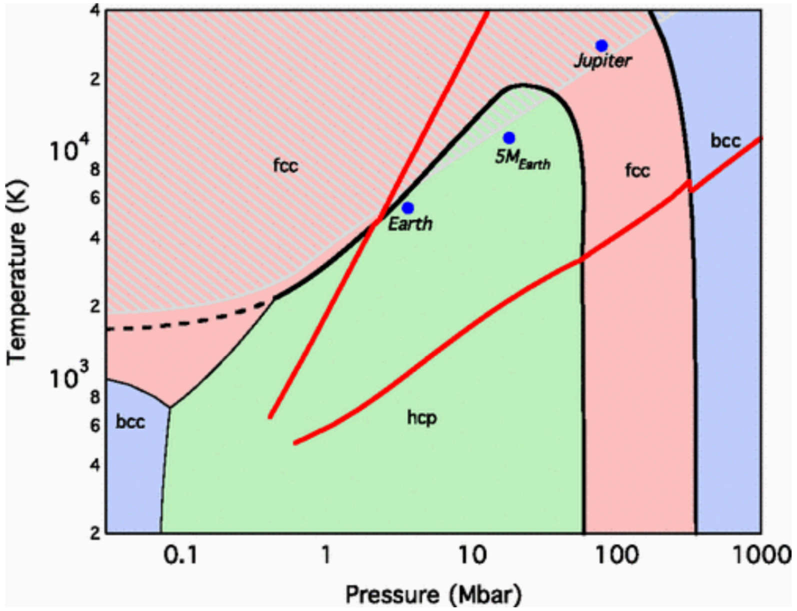
4.1 Shocked material and matter at extremes

Scattering and spectroscopy of dynamically compressed material at planetary core conditions
Determination of crystallographic phase at high pressure and a search for metastable structures
Understand the underlying deformation pathways and implications for dynamically produced conditions





A.L. Coleman et al. Phys. Rev. Lett. 122, 255704 (2019)

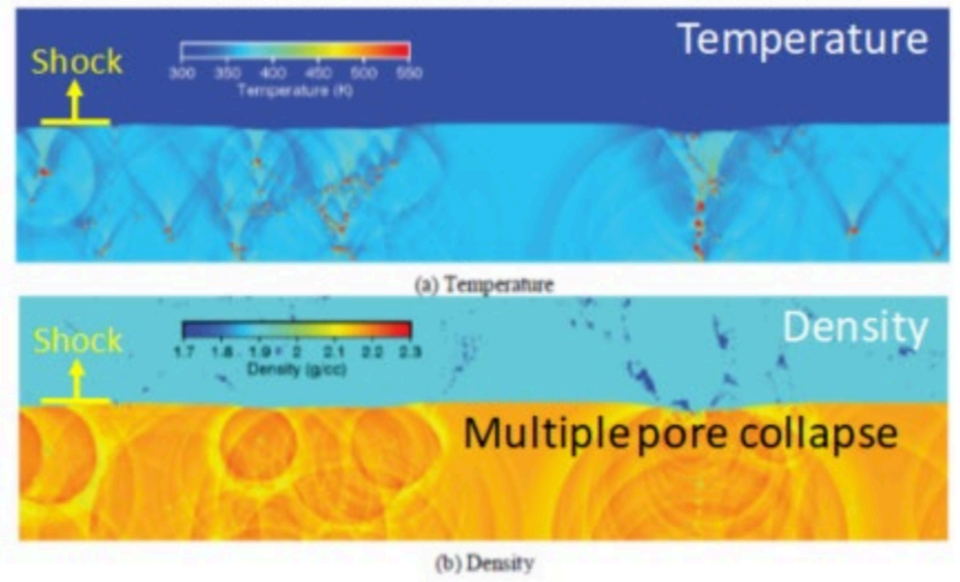


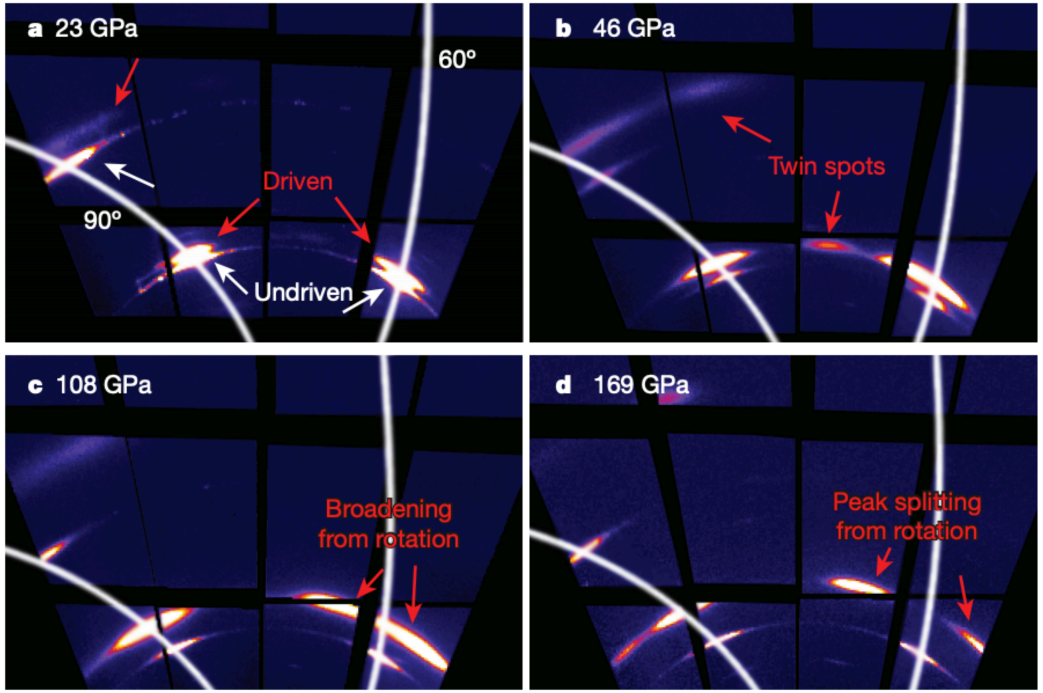
L. Stixrude at al. Phys. Rev. Lett. 108, 055505 (2012)

XFEL/Driver Requirements
High pulse energy (joule class?), 20keV (possible 2 colour mode to allow simultaneous spectroscopy)
High rep rate (10Hz minimum) multi kJ optical laser, fully temporal shaping.

8.2 Properties of shocked materials for engineering and defence

Understanding of FOD/Blade off events in turbine engines (critical to containment and thus safety)
Microscopic understanding of material processing techniques such as laser peening
Understand the underlying deformation pathways and implications for dynamically produced conditions



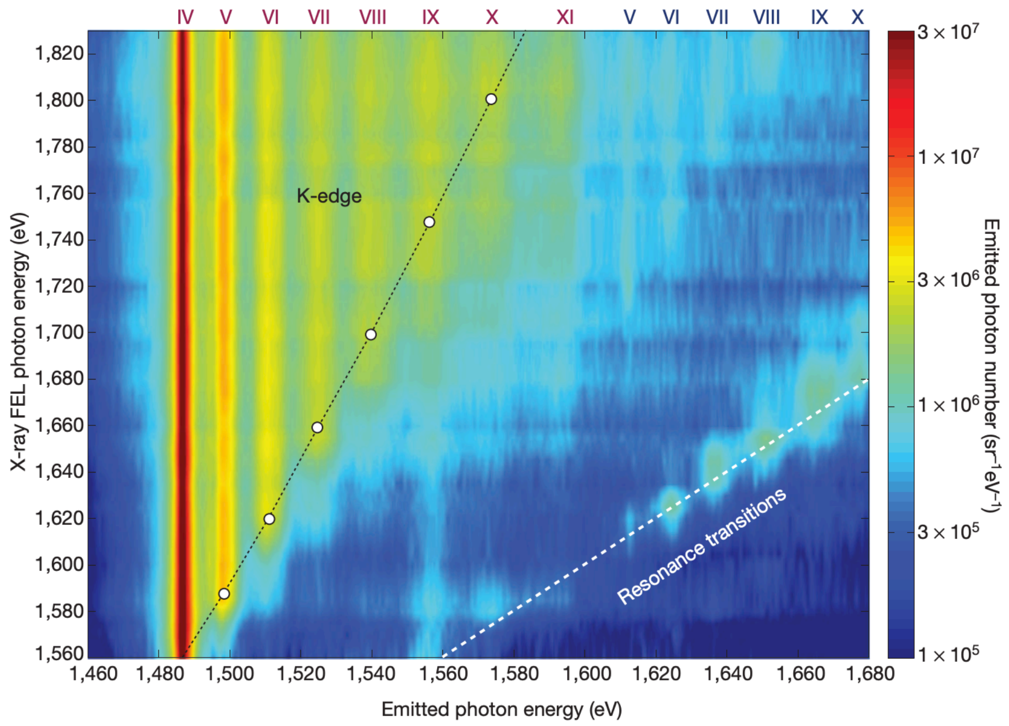


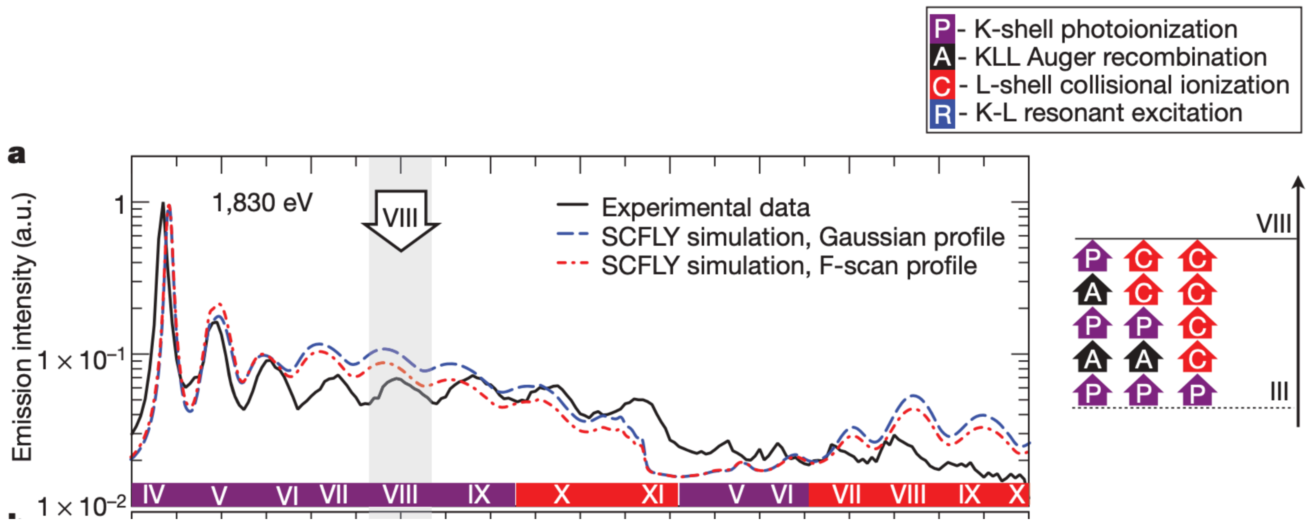
Wehrenberg et al. Nature volume 550, 496–499 (2017)

XFEL/Driver Requirements
High pulse energy, 20keV (possible 2 colour mode to allow simultaneous spectroscopy)
High rep rate (10Hz minimum) multi kJ optical laser, fully temporal shaping.

4.2 Quantum plasmas: warm and hot dense matter

Create and diagnose warm dense (electron degenerate) matter of astrophysical and/or ICF relevance
Study properties such as opacity in WDM/HDM regions with relevance to stellar structure
Access transport properties in WDM (e.g viscosity and thermal diffusivity)





S. M Vinko et al. Nature 482, 59–62 (2012)

XFEL/Driver Requirements

Joule class XFEL to allow isochoric heating well into HDM regime and better increased single for photon-hungry inelastic scattering techniques. Optical pump lasers to generate WDM/HDM states.

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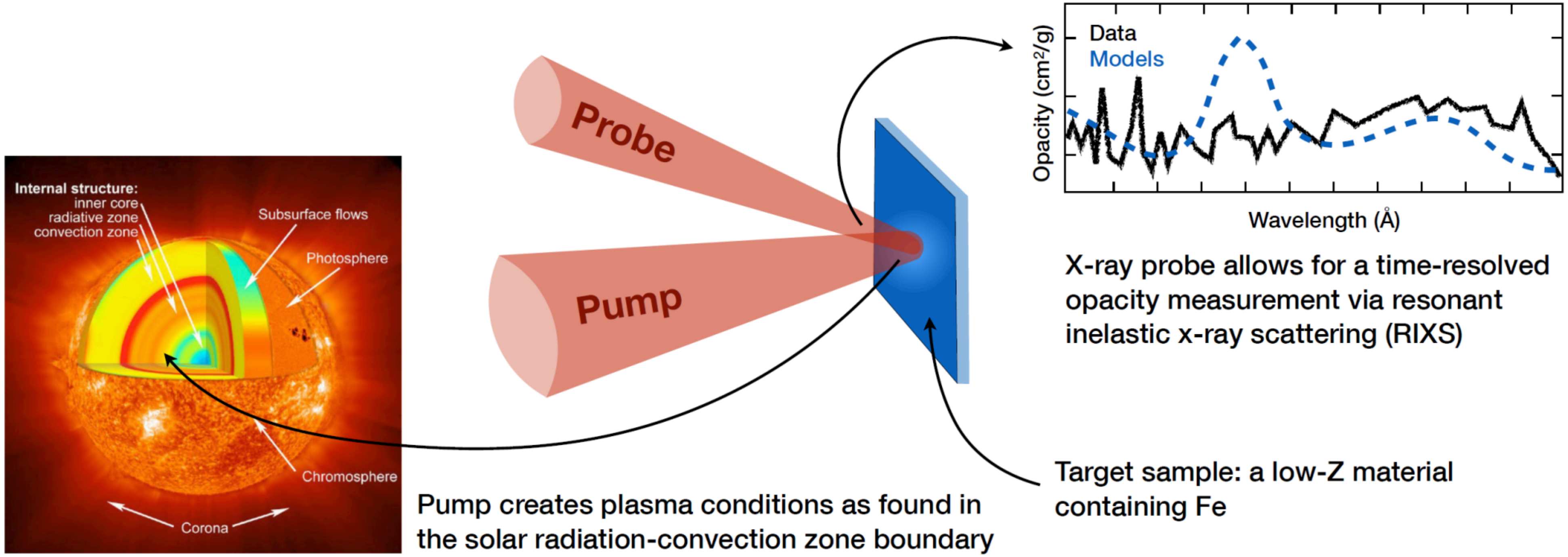
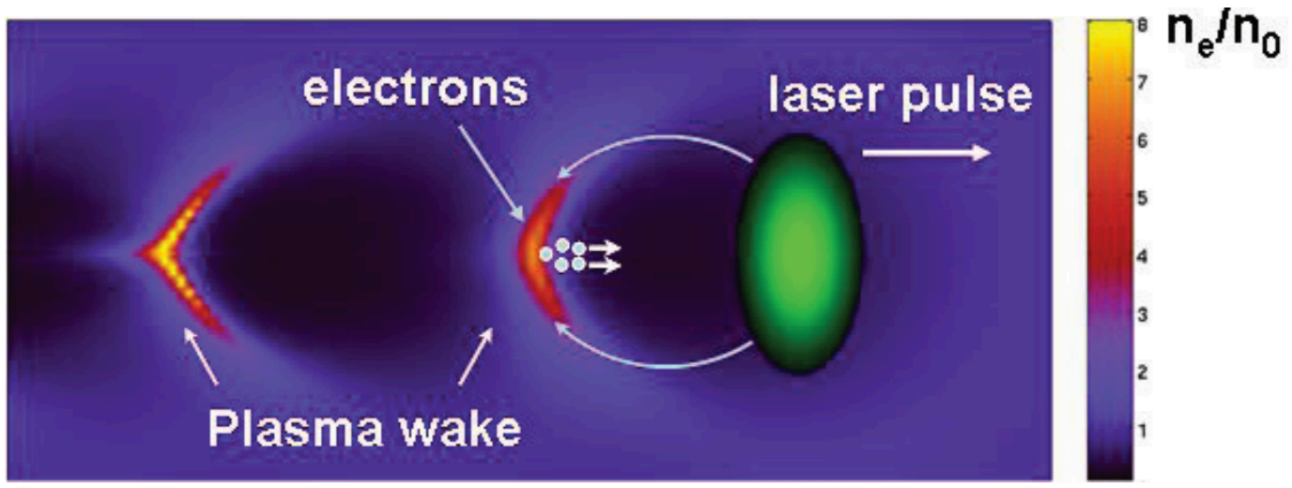
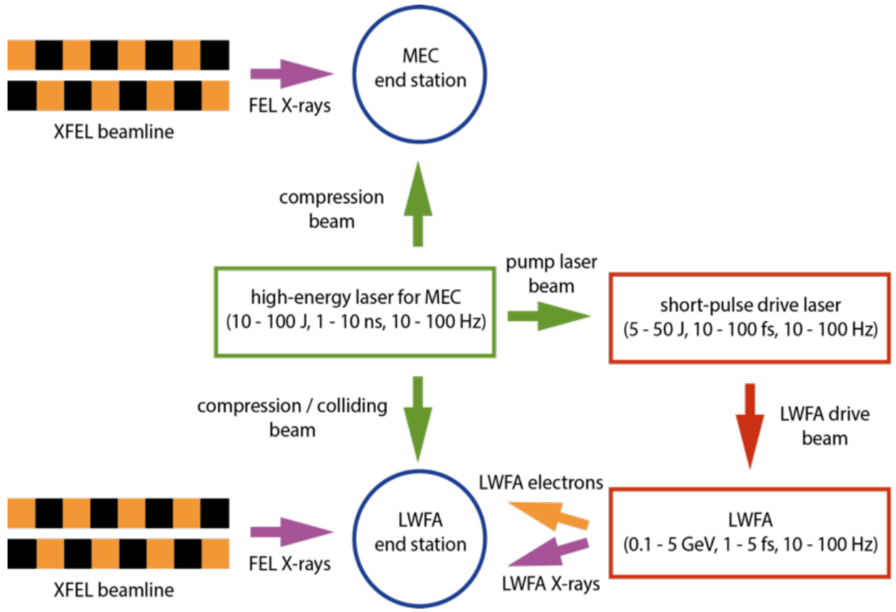


XFEL/Driver Requirements
Joule class XFEL to allow isochoric heating well into HDM regime and better increased single for photon-hungry inelastic scattering techniques. Optical pump lasers to generate WDM/HDM states.

4.3 X-ray interactions with laser-accelerated electrons

Utilise LWFA to generate particle beams and x-ray/gamma sources complementary to XFEL
Betatron radiation for EXAFS/XANES type spectroscopies of solid/WDM systems
Proton/electron sources for heating/probing compressed material

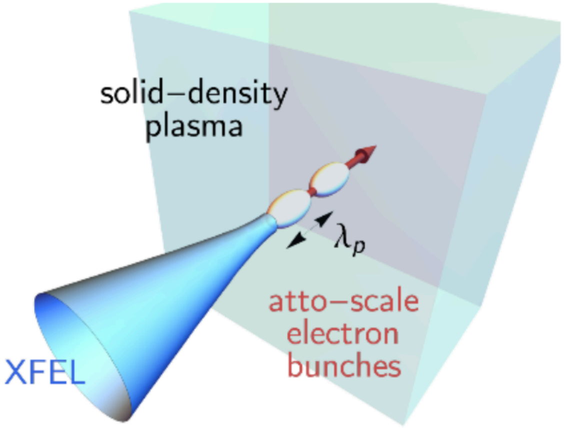


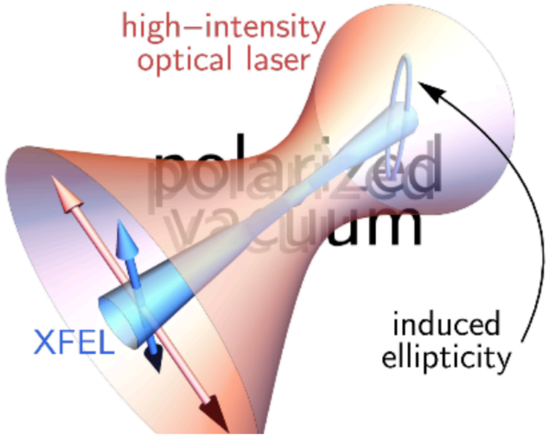


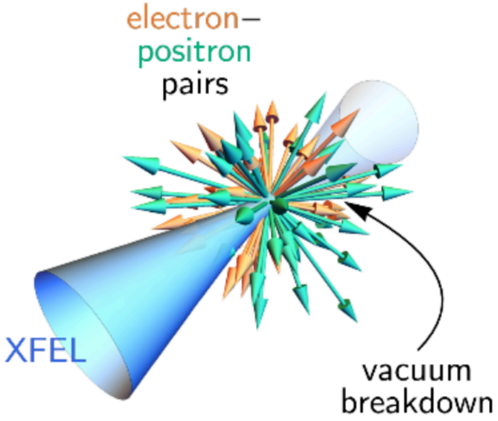
XFEL/Driver Requirements
High rep rate (>10Hz) short pulse laser optical laser at > 10^{19}W/cm^2 (complementary to high energy laser)

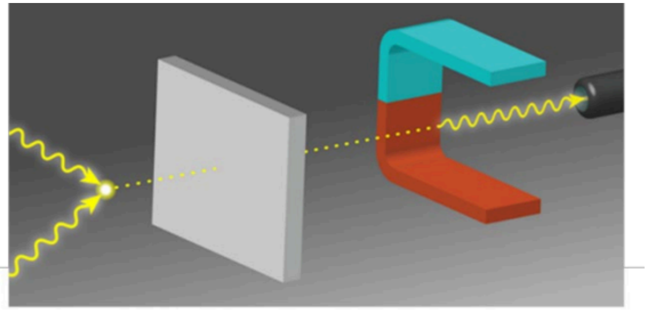
3.5 Non-linear X-ray physics and physics beyond the Standard Model

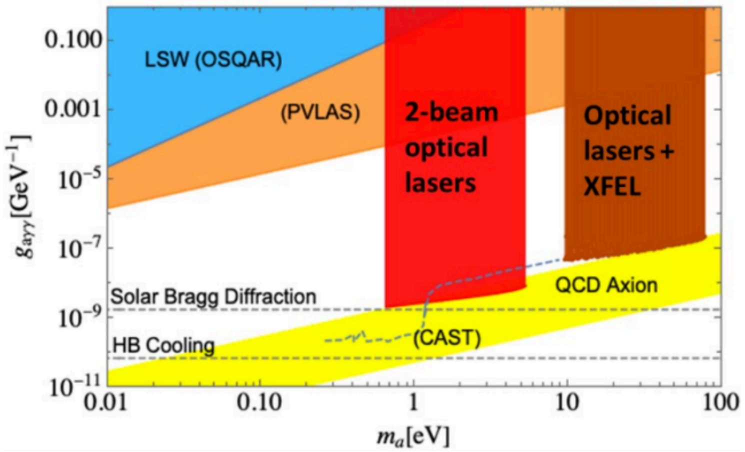
Investigate non-linear X-ray interactions with solid density matter (e.g LWFA of attosecond e^- bunches)
Study of vacuum birefringence as a test of non-perturbative QED
Vacuum breakdown and study of e^-p^+ pair production
'Beyond the standard model' axion/dark matter candidate searches







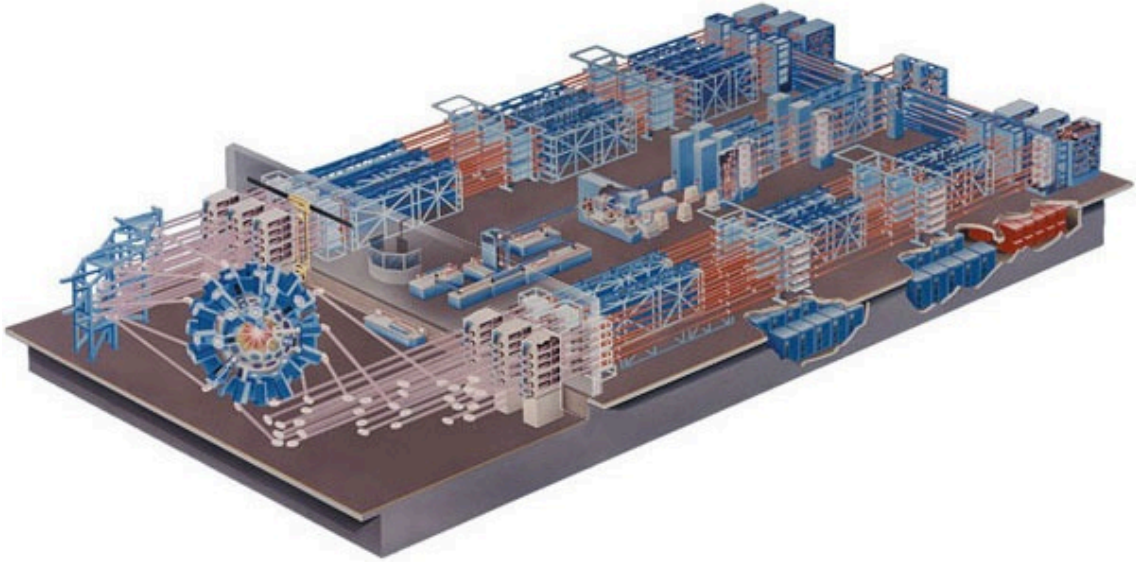


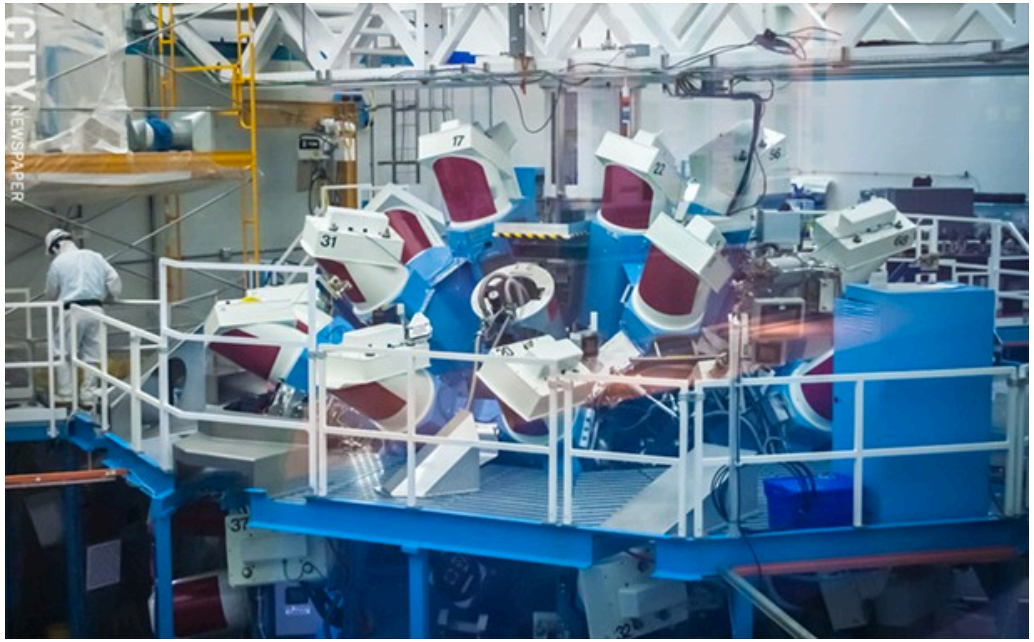


XFEL/Driver Requirements
High XFEL intensity (in excess of $I\lambda^2 = 10^{18}$ Wcm^{-2} μm^2 for LWFA). High (linear) polarization purity. Diffraction limited spots.
Short pulse laser with I>10^{22} W/cm^2

4.4 Coupling an XFEL to a spherical compression facility

Access to states of matter orders of magnitude beyond that available at current FELs
Unique ability to investigate conditions relevant to inertial confinement fusion
Potential for synergistic use of laser to drive a high-energy short pulse for fundamental physics





XFEL/Driver Requirements
Colocation with any future 10-100kJ class convergent spherical compression facility – a world leading and unique proposition.

Summary

- Significant opportunities to advance MEC beyond current limitations
- Opportunities in planetary, solar, ICF and fundamental particle physics
- Application in areas such as impact engineering, materials processing and defense
- Must take the opportunity to consider co-location with existing or future laser facilities - an option not readily available to existing XFELs