Laser-driven x-ray sources for high energy density science

DOE Frontiers of Plasma Science Workshop

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Lawrence Livermore National Laboratory

Acknowledgements

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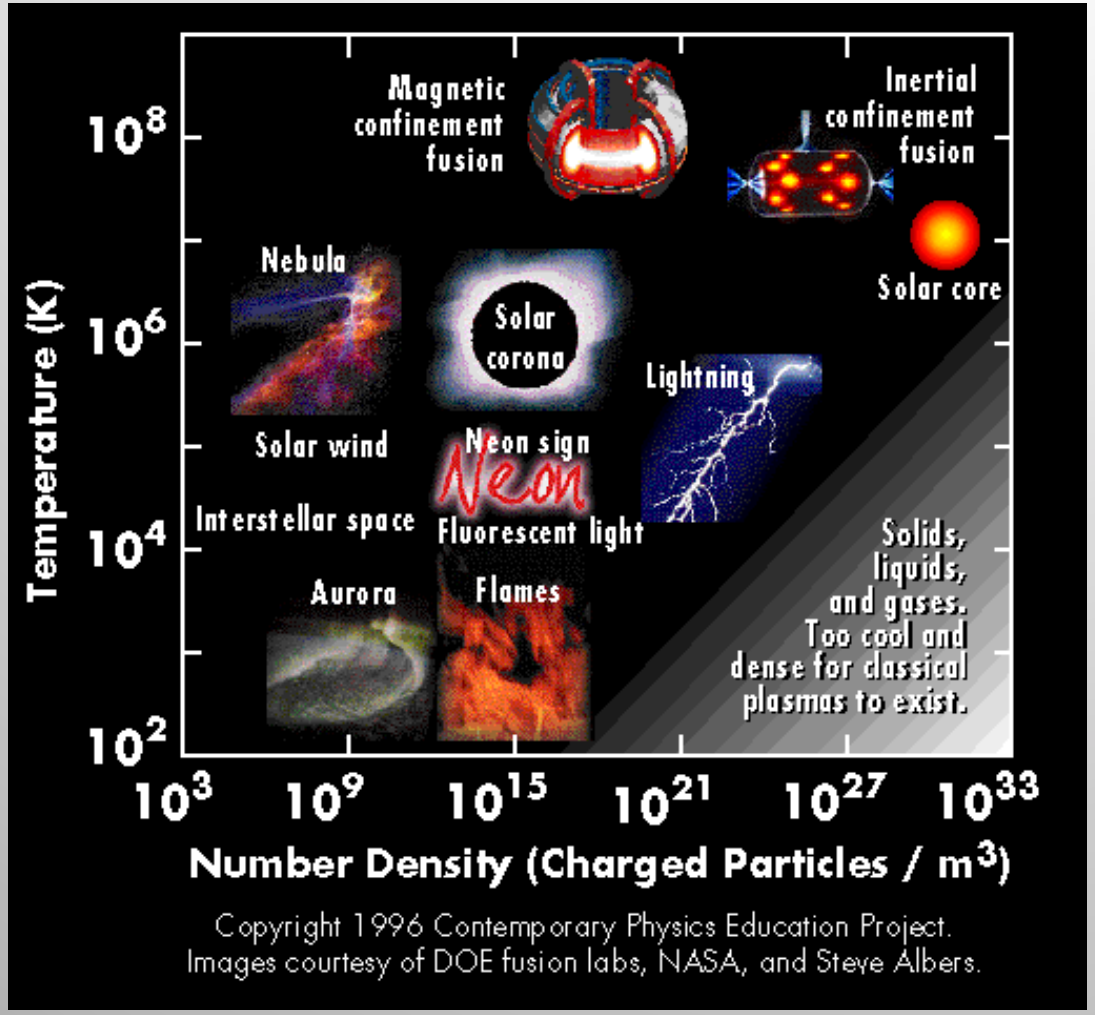
Grand challenges of high energy density science



Examples of big HED science questions

- How does the sun work?
- How did Jupiter form?
- Can we re-create the power of stars in the laboratory to provide future sources of energy?
- What are the mechanisms of stellar explosions?

It is critical to understand relationships between temperature, pressure and density in such environments

Large scale laser facilities can now recreate HED plasmas

NIF

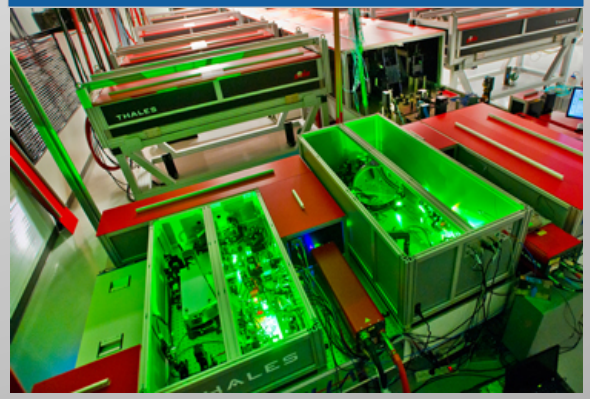
OMEGA

Jupiter Laser Facility

LCLS

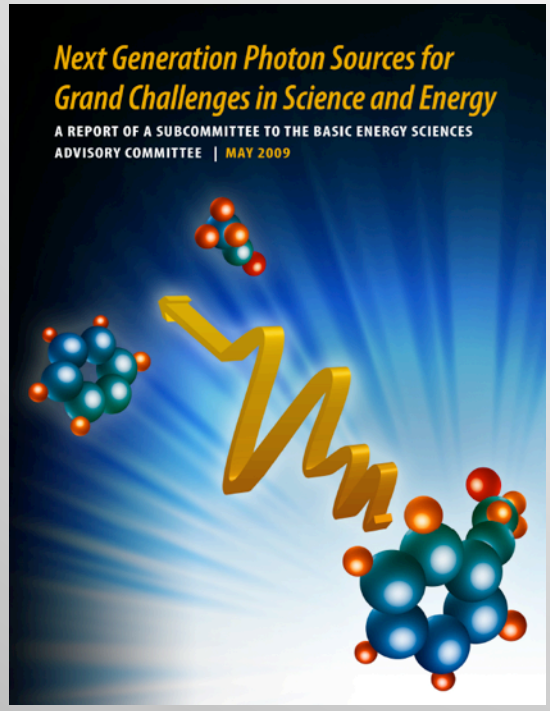
Texas Petawatt

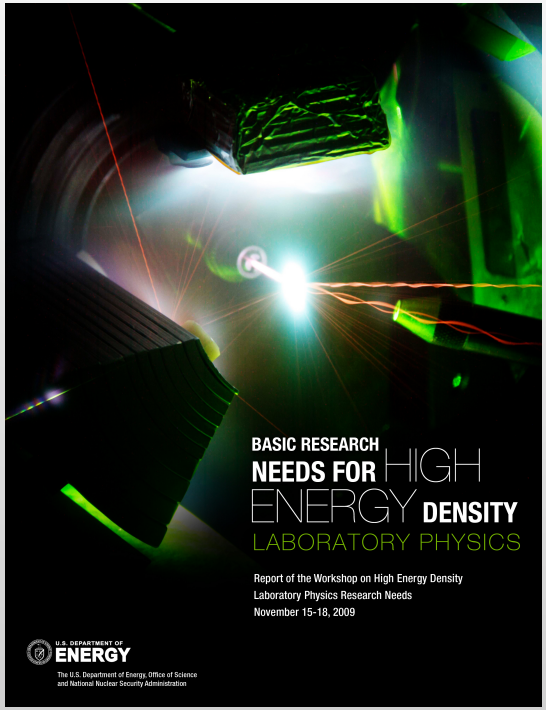
BELLA



HED plasmas are often in non-equilibrium states and extremely difficult to probe

X-ray sources are transformational tools for HED science





"Ultra-bright X-ray sources will be a transformational tool because of their ability to probe matter down to the atomic scale with unprecedented time resolution."

"Unfortunately, both synchrotron and XFEL sources are kilometer-scale sizes and cannot be used in conjunction with large scale drivers such as NIF."

We need to develop new x-ray sources to probe HED conditions at the sub-ps time and couple then with large HED science drivers

Laser-driven x-ray sources can complement synchrotrons and free electron lasers

Synchrotron

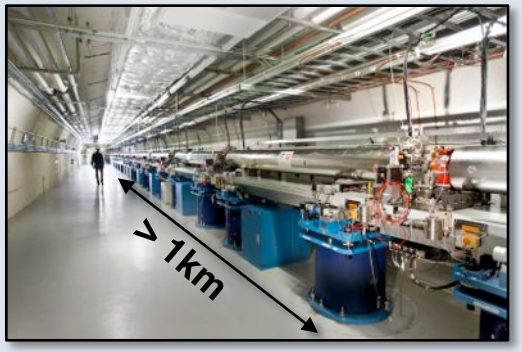
APS

Electrons from storage ring wiggled by undulators

- ✓ Hard X-rays
- ✓ High brightness
- ✓ Multiple beamlines
- ✗ Not ultrafast (ps)
- ✗ Not coherent

Free Electron Laser

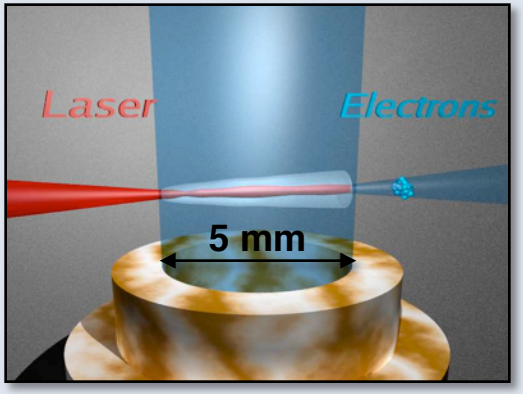
LCLS undulator



Electrons from linac wiggled by undulators

- ✗ Soft X-rays (8 keV)
- ✓ Very High brightness
- ✗ One beamline
- ✓ Ultrafast (fs)
- ✓ Coherent

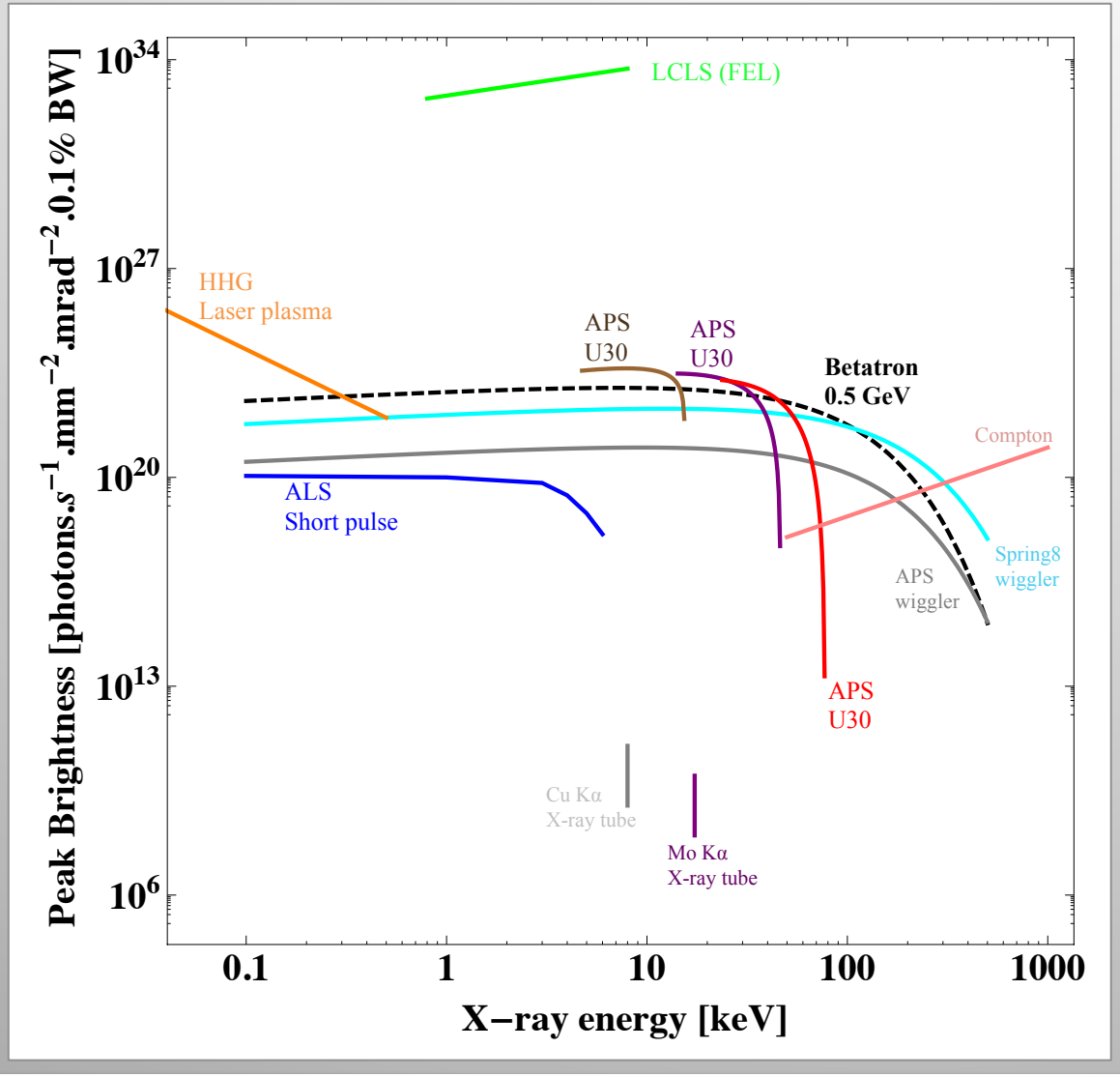
Laser-plasma approach



Electrons from laser-produced plasma wiggled by plasma

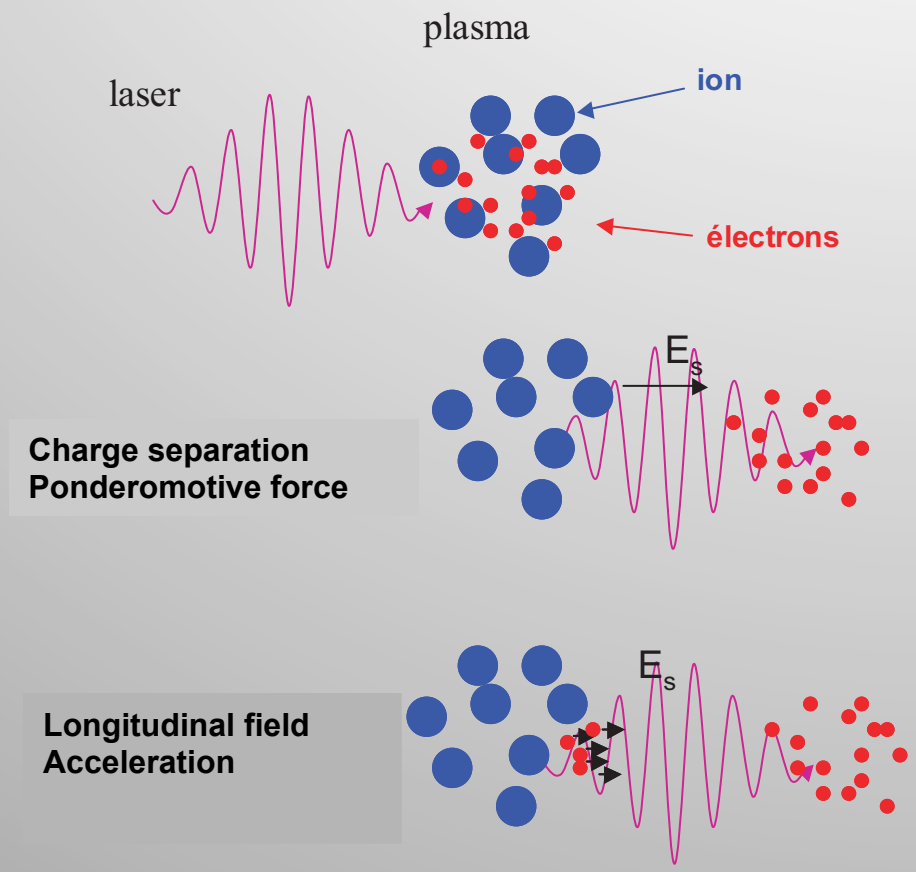
- ✓ Hard X-rays (up to 100 keV)
- ✓ High brightness
- ✓ Small scale
- ✓ Ultrafast (fs)
- ✓ Some spatial coherence

Comparison of betatron radiation with existing light sources



Parameter	Specification
Energy range	1-100 keV (broadband)
X-ray flux	10^8 photons/shot
Source size	1 micron
Source divergence	1-10 mrad (collimated)
Source duration	30-50 fs
Source maximum peak brightness	10^{22} photons/(mm^2 x mrad^2 x s. x 0.1 % BW)

Plasmas can naturally sustain large acceleration gradients > 100 GV/m



Key parameters

Plasma frequency $\omega_p = \sqrt{\frac{n_e e^2}{m\varepsilon_0}}$

Resonance condition $\tau_{laser} \sim \tau_{plasma}$

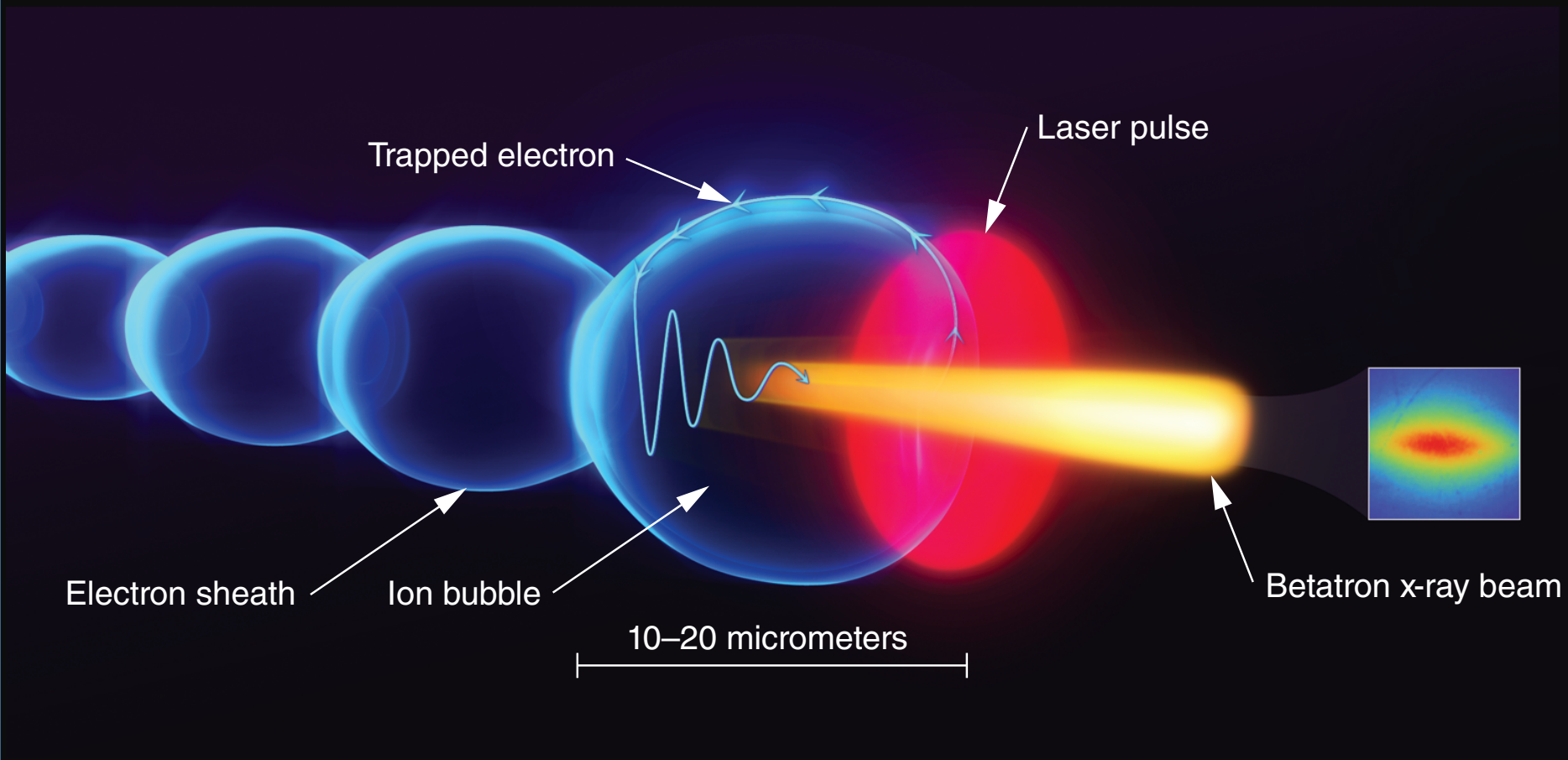
$$n_e = 10^{18}\ \mathrm{cm}^{-3} \rightarrow \tau_p = 111 \times 10^{-15} s$$

T. Tajima and J. Dawson, PRL 1979
W. Lu et al., PRSTAB 2007

This field has been growing since the observation of monoenergetic beams in 2004

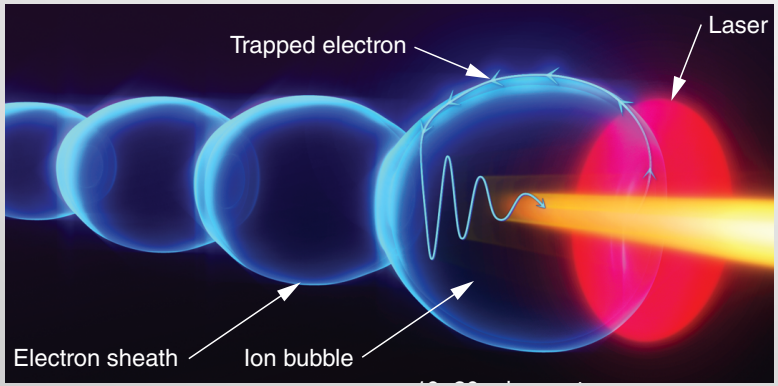
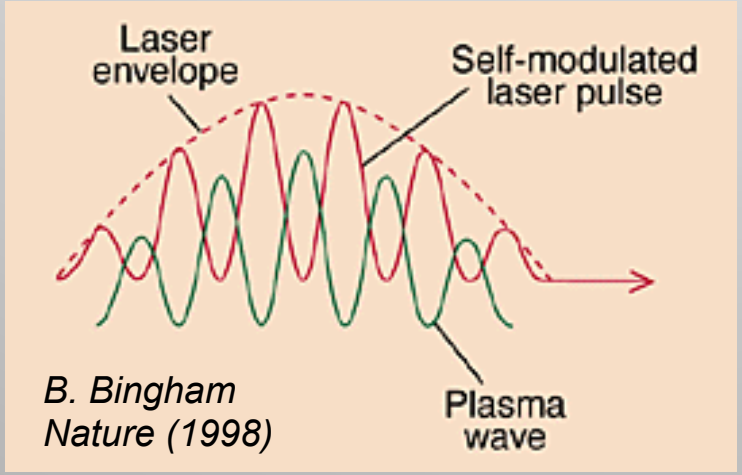
Several groups are now producing GeV beams

Laser Facility	Pulse enrgy (J)	Duration (fs)	Spot size (μm fwhm)	a0	Electron density cm^{-3}	Energy (GeV)	Year	Reference
Astra - Gemini (RAL)	10-15	45-55	20	2.5-3.5	$3\text{-}10 \times 10^{18}$	~ 1	2014	Experiments
Hercules (U Mich)	2.3	32	11.2	4.7	$4\text{-}22 \times 10^{18}$	0.8	2010	Experiments
BELLA (LBNL)	16	40	50	1.6	7×10^{17}	4.25	2014	Leemans PRL
Callisto (LLNL)	4-8	60	12	2	5×10^{18}	1.4	2010	Clayton PRL
Texas Petawatt	170	150	60	~ 2	2×10^{17}	2	2013	Wang NComm
APRI (Korea)	30	30-60	25	3.7	0.8×10^{18}	3	2013	Kim PRL



"Betatron x-rays bring focus to a very small, very fast world", LLNL S&T Review, January/February 2014

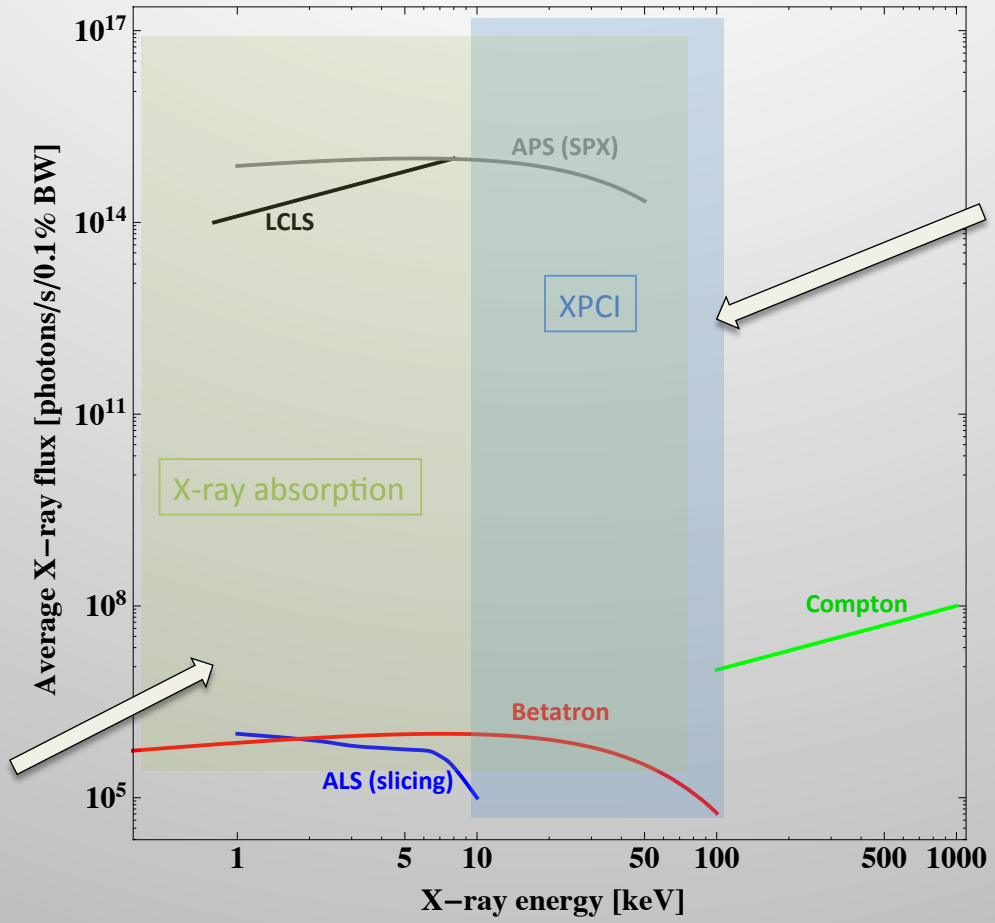
There are different regimes of laser-plasma acceleration that produce electrons and x-ray sources

Regime of laser-plasma acceleration	Laser/plasma parameters	Facilities
Blowout 	1-40 J 25-60 fs $n_e=10^{19}$ cm^{-3} $\tau_{laser}\sim\tau_{plasma}$	LCLS-MEC (SLAC) Hercules (U. Mich) BELLA (LBNL) Texas Petawatt
Self modulated Or Direct laser acceleration  *B. Bingham Nature (1998)*	50-1000 J 1 ps $n_e=10^{19}$ cm^{-3} $\tau_{laser}>>\tau_{plasma}$	Titan (LLNL) NIF-ARC (LLNL) OMEGA EP (LLE)

Betatron radiation has been produced at many laser facilities

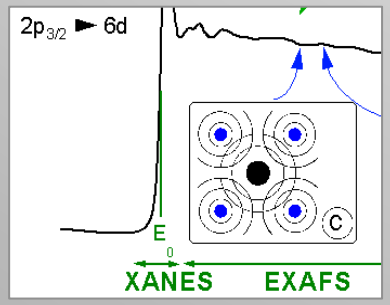
Laser Facility	Pulse enrgy (J)	Duration (fs)	Spot size (μm fwhm)/ % energy	a0	Electron density cm^{-3}	# x-ray photons	X-ray energy (keV)	Year	Reference
S. Jaune (LOA)	1	30	18 / 50	1.2	8×10^{18}	10^8	1-10	2004	Rousse PRL
Gemini (RAL)	10-15	45-55	20	2.5-3.5	$3\text{-}10 \times 10^{18}$	10^9	1-100	2014	Recent experiments
Hercules (U Mich)	2.3	32	11.2 / 55	4.7	$4\text{-}22 \times 10^{18}$	$10^6\text{-}10^8$	1-84	2010	Kneip NPhys
T-REX (LBNL)	1.3	24	28	1	$4\text{-}10 \times 10^{18}$	N.A.	2-20	2012	Plateau PRL
Callisto (LLNL)	4-8	60	12	2	5×10^{18}	10^8	1-80	2013	Albert PRL
Texas Petawatt	170	150	60	~ 2	2×10^{17}	$10^8\text{-}10^9$	1-80	2013	Wang NComm
ALLS (INRS)	2.5	30	24	1.2	5.4×10^{18}	3.6×10^7	1-20	2011	Plateau NJP
JETI (Jena)	0.73	27	12	1.9	$2\text{-}20 \times 10^{18}$	5×10^7	N.A.	2013	Schnell Ncomm
Vulcan (RAL)	280	630	3.2	13-29	1×10^{19}	$\sim 5 \times 10^8$	1-50	2008	Kneip PRL
Titan (LLNL)	150	1000	20	1-3	1×10^{19}	N. A.	1-50	2015	Albert et al Experiments

Laser-driven light sources have tremendous potential for applications



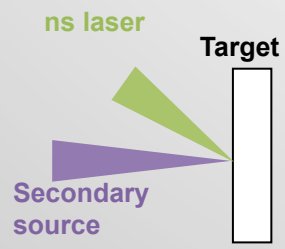
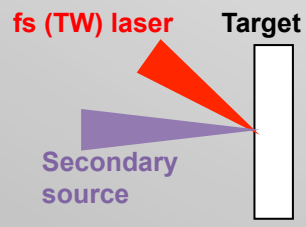
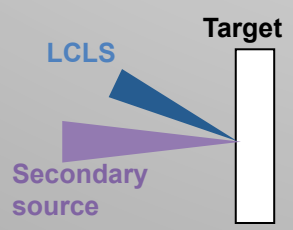
Phase contrast imaging

Absorption spectroscopy

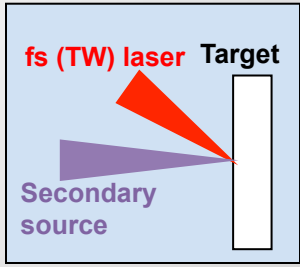


Laser wakefield accelerator based light sources: potential applications and requirements
F. Albert, A. G. R. Thomas, S. P. D. Mangles, S. Banerjee, S. Corde, A. Flacco, M. Litos, D. Neely, J. Vieira, Z. Najmudin, R. Bingham, C. Joshi, and T. Katsouleas, *Plasma Physics and Controlled Fusion* (2014).

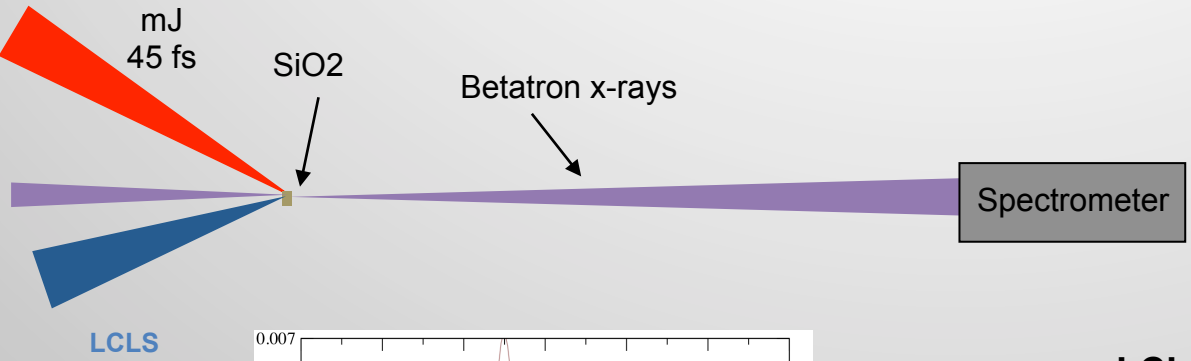
Classes of possible HED experiments with laser driven secondary sources

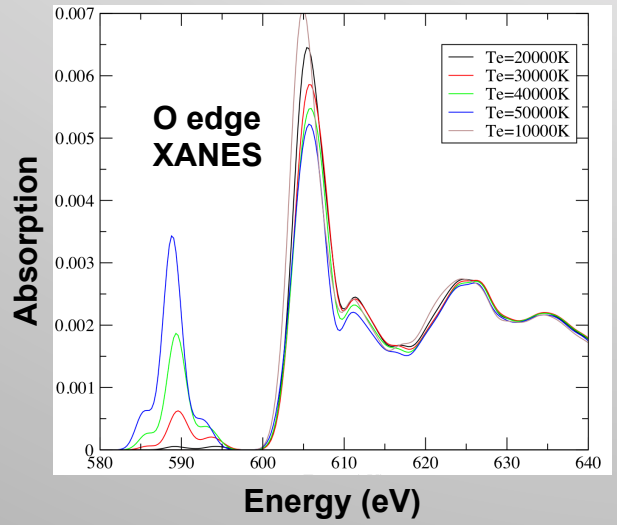
Probe Configuration	Example of facilities (US)	Frontier plasma science
	Titan LCLS MEC ns optical laser OMEGA NIF	High pressure and shock physics Equation of state Material strength Phase transitions Opacity
	LCLS MEC short pulse Hercules BELLA	High power laser-matter interaction Relativistic laser-plasma interactions Laboratory astrophysics Laser-plasma accelerators Ultrafast phase transitions
	LCLS MEC	X-ray matter interaction Isochroric heating 100's eV plasmas Ultrafast phase transitions Nuclear Physics Opacity

Non thermal melting in SiO2

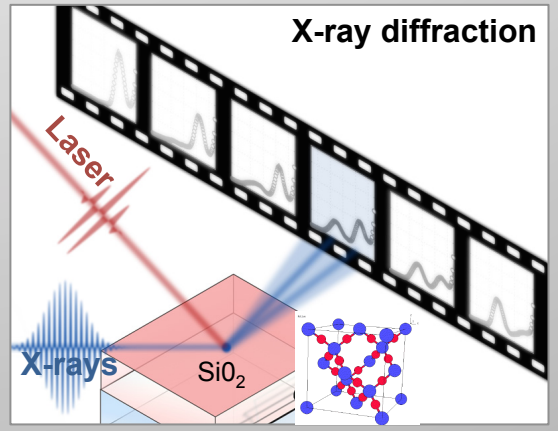


Ultrafast phase transitions



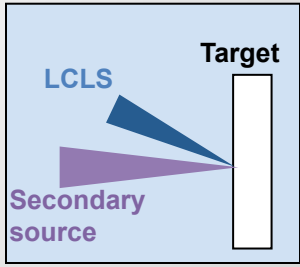


LCLS LG84 experiment (Summer 2015)

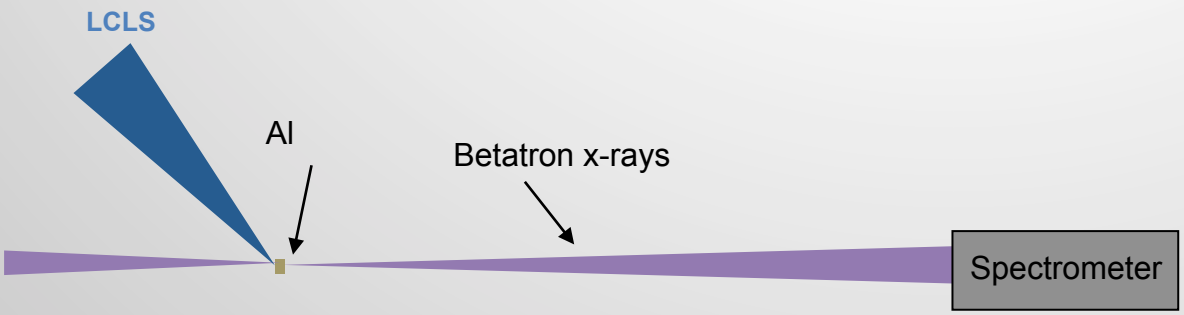


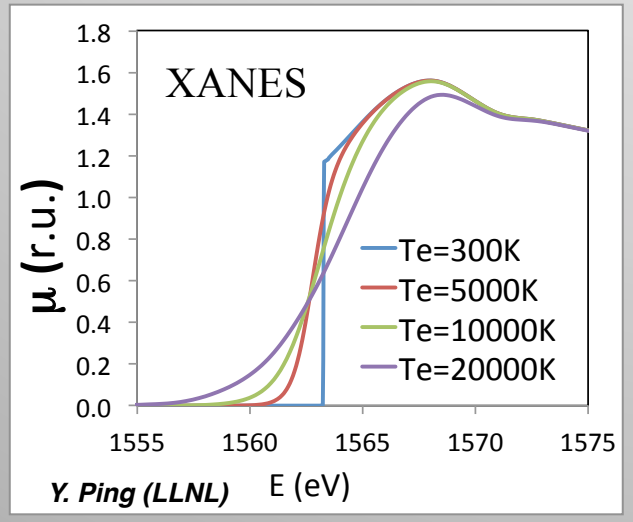
Simultaneous measurement of the local (XANES) and large-scale (diffraction) structure evolution of non thermal melting in Si02

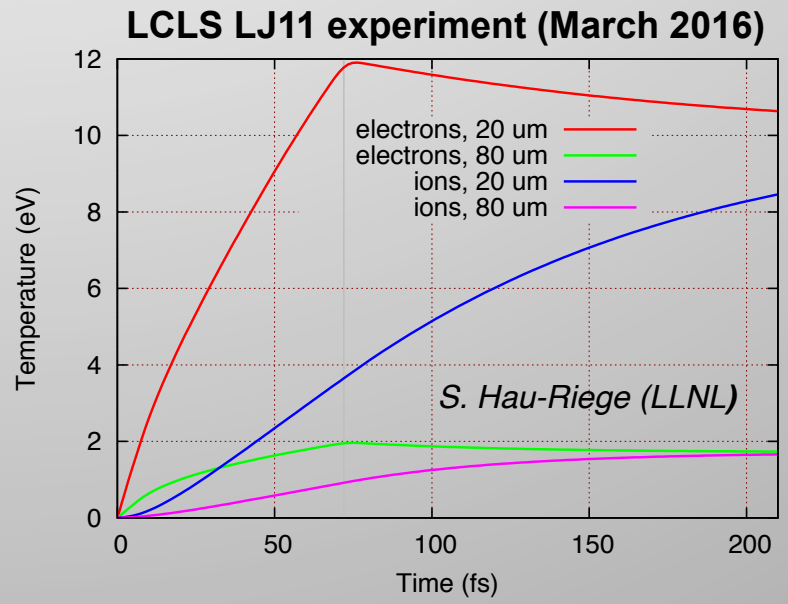
Aluminum plasma heated by XFEL



X-ray matter interactions







Electron-ion equilibration in isochorically heated Al plasma

Collaborators

B. B. Pollock, A. Pak, J. Ralph, Y. Ping, S. Hau-Riege, J. Moody (LLNL)

J. L. Shaw, N. Lemos, K.A. Marsh, C.E. Clayton, and C. Joshi (UCLA)

E. Galtier, P. Heimann, E. Granados, H. J. Lee, B. Nagler, A. Fry (LCLS)

W. Schumaker, F. Fiuza, E. Gamboa, L. Fletcher, S.H Glenzer (SLAC SIMES)

A. Ravasio, M. Koenig (LULI)

B. Barbrel, A. Saunders, R. W. Falcone (LBNL)

S. Mangles, J. Woods, K. Powder, N. Lopes, E. Hill, S. Rose, Z. Najmudin (Imperial College London)

J. King, R. Freeman (LLNL/OSU)

P. Zeitoun (LOA)

J. Luning (LCPMR)

Conclusion and outlook

- **Laser-plasma accelerators are unique sources of x-ray and electron probes for frontier plasma science**
- **They will be coupled to large HED drivers: JLF-Titan, NIF-ARC, OMEGA, LCLS-MEC**
- **X-ray sources driven by laser-plasma accelerators have tremendous potential for time-resolved HED science applications**
  - We need to quantify source parameters for given applications
  - Improvements needed to the sources driven by science applications
  - HEDP and LWFA communities
- **Other x-ray productions mechanisms (Compton scattering)**
- **Other domains of applications**
  - Nuclear physics
  - National security
  - Condensed matter and material science
  - Biology/medical

See
Alec Thomas – Wed 2:20 pm
Cameron Geddes – Wed 2:40 pm