Betatron x-rays from laser-wakefield accelerators: a novel probe for time-resolved high energy density science experiments

Workshop on High Energy Density Science with BELLA-i

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Presented by Félicie Albert
Lawrence Livermore National Laboratory

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Collaborators

B. B. Pollock, A. Pak, J. Ralph, Y. Ping, S. Hau-Riege, T. Ogitsu, 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)

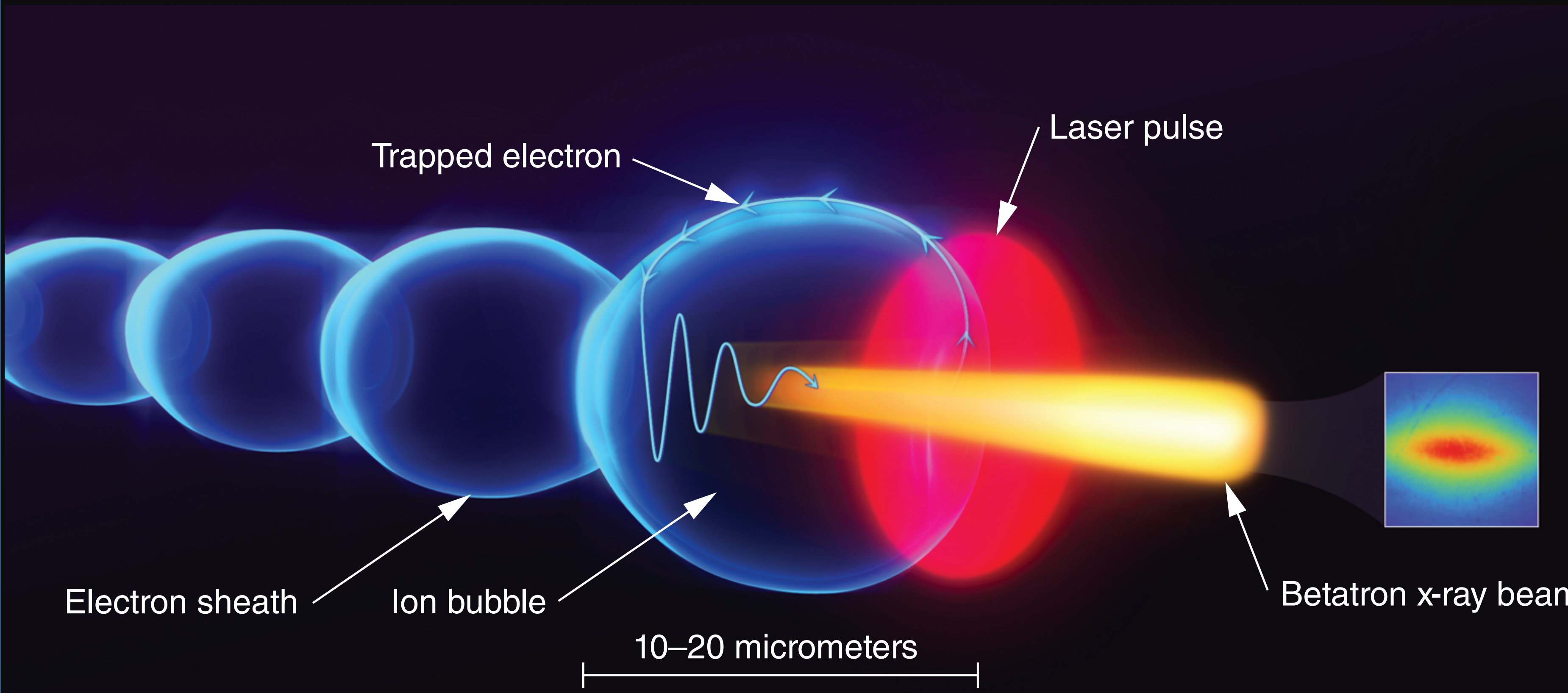
A. Ravasio, F. Condamine, M. Koenig (LULI)

B. Barbrel, J. Gaudin, F. Dorchies (CELIA)

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

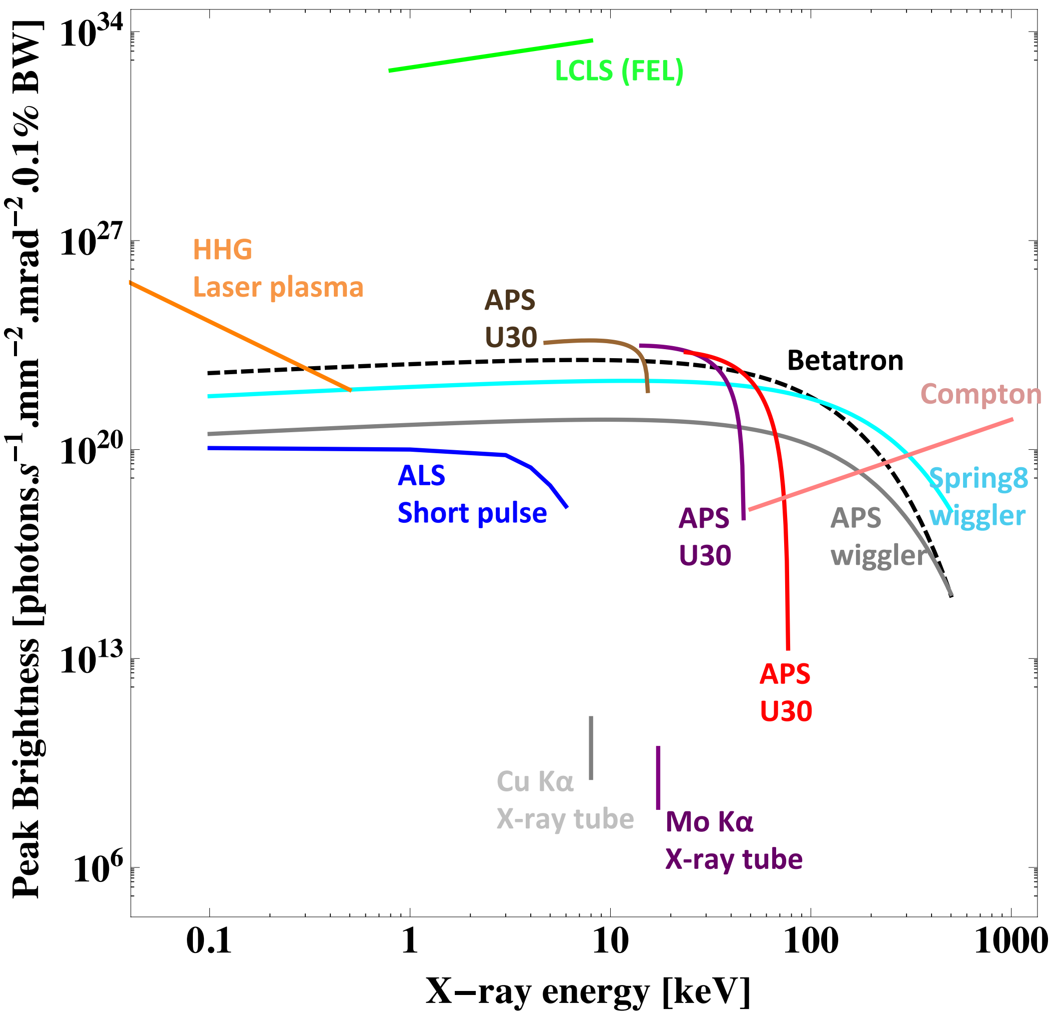
A. Saunders, D. Kraus, R.W. Falcone (LBNL)

P. Zeitoun (LOA)



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

Notable features of betatron radiation – peak brightness



Collimated (mrad)

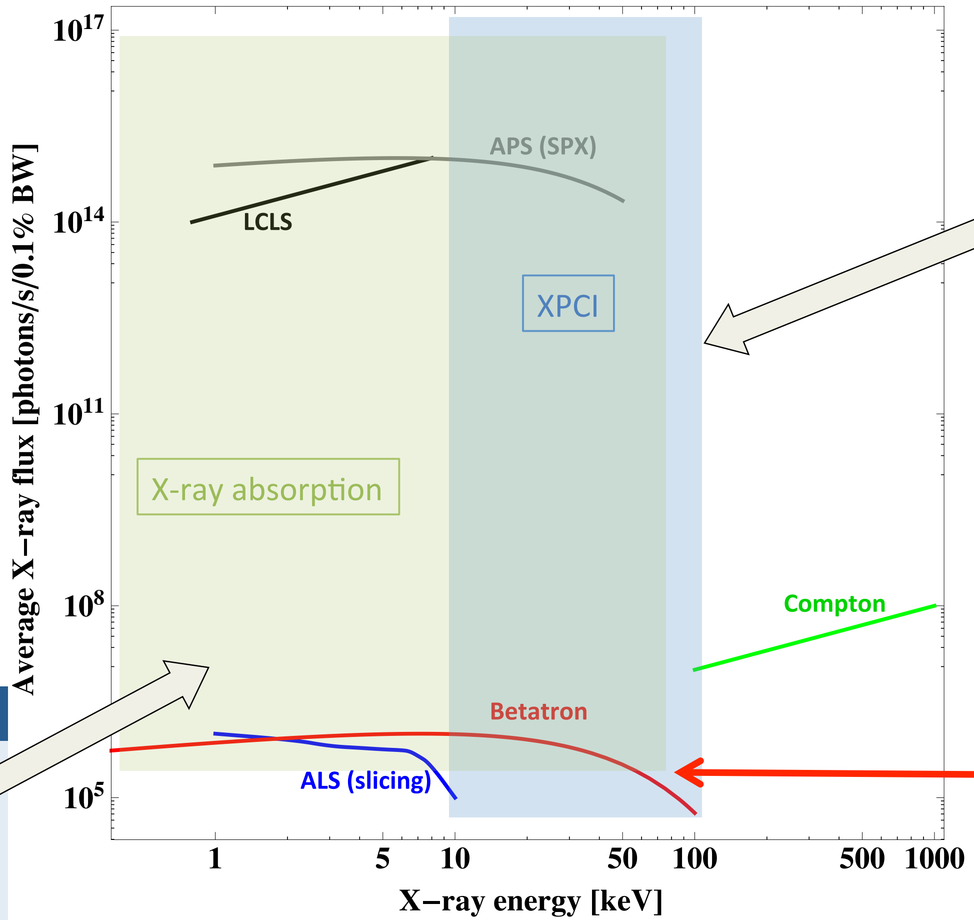
Broadband (1-100 keV)

Small source size (μm)

Short pulse (fs)

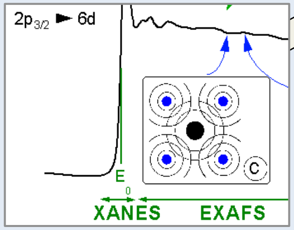
Synchronized with drive laser (fs)

Some experiments require a large average photon flux



Phase contrast imaging

Absorption spectroscopy

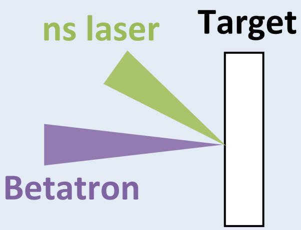
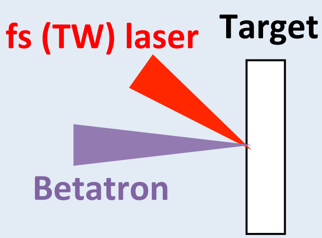
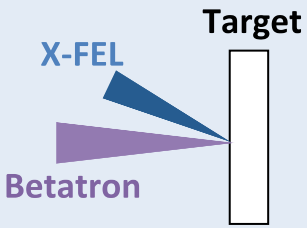


Laser wakefield accelerator based light sources: potential applications and requirements
F. Albert, A. G. R. Thomas, S. P. D. Mangles, S. Banerjee, S. Corde, A. Flacco, M. Litos, D. Neely, J. Vieira, Z. Najmudin, R. Bingham, C. Joshi, and T. Katsouleas, *Plasma Physics and Controlled Fusion* (2014).

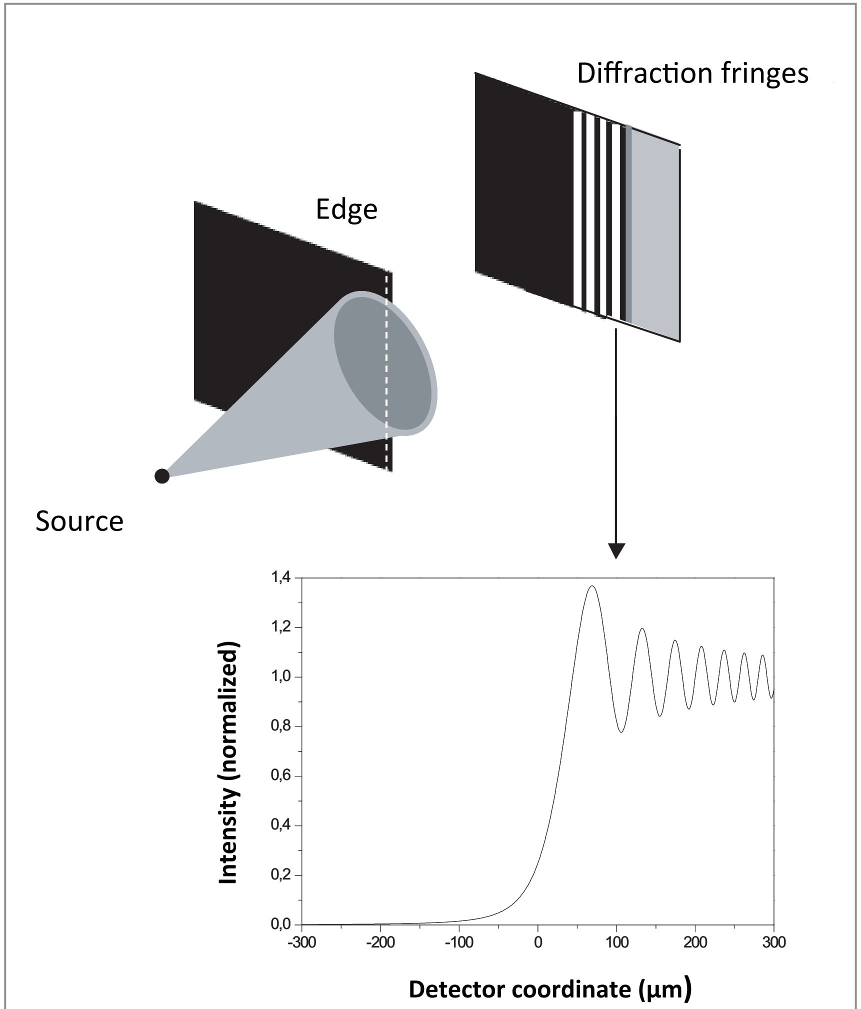
Betatron radiation is being produced at various facilities

Laser Facility	Pulse energy (J)	Duration (fs)	Spot size (µm fwhm)	a0	Electron density cm^{-3}	# x-ray photons	X-ray energy (keV)	Year	Reference
S. Jaune (LOA)	1	30	18	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	Cole Sc. Rep.
Hercules (U Mich)	2.3	32	11.2	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	Fourmaux NJP
JETI (Jena)	0.73	27	12	1.9	$2\text{-}20 \times 10^{18}$	5×10^7	N.A.	2013	Schnell Ncomm
LCLS-MEC	1	45	8		1×10^{19}	10^8	1-10	2015	Recent LCLS exp
Vulcan (RAL)	280	630	3.2	9-29	1×10^{19}	~ 5×10^8	1-50	2008	Kneip PRL
Titan (LLNL)	150	1000	20	1-3	1×10^{19}	N. A.	1-50	2015	Albert et al Experiments
BELLA-i	**40**	**30**	**5-55**	**~45**	$\mathbf{10^{18}\text{-}10^{19}}$	**>10^9**	**>100**	**2017**	**Predictions**

Perspectives: classes of possible HED experiments with laser driven betatron radiation

Probe Configuration	Facilities	HED science
	Titan LCLS MEC ns optical laser OMEGA EP NIF ARC LFEX-GEKKO **BELLA**	High pressure and shock physics Equation of state Material strength Phase transitions Opacity
	LCLS MEC short pulse Hercules Astra-Gemini **BELLA**	laser-matter interaction Relativistic laser-plasma interactions Laboratory astrophysics Laser-plasma accelerators Ultrafast phase transitions Opacity
	LCLS MEC SACLA HERMES European XFEL	X-ray matter interaction Isochoric heating 100's eV plasmas Ultrafast phase transitions Nuclear Physics Opacity

Small size of betatron x-ray source allows for spatial coherence

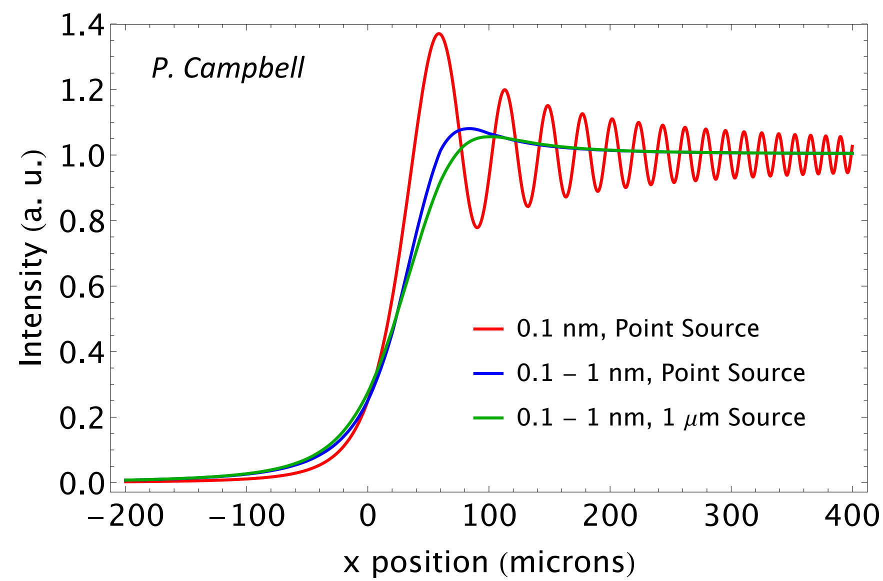


$$I(x,\lambda) = \frac{I_0}{2}\left\{\left(\frac{1}{2} + C(w(x,\lambda))\right)^2 + \left(\frac{1}{2} + S(w(x,\lambda))\right)^2\right\}$$

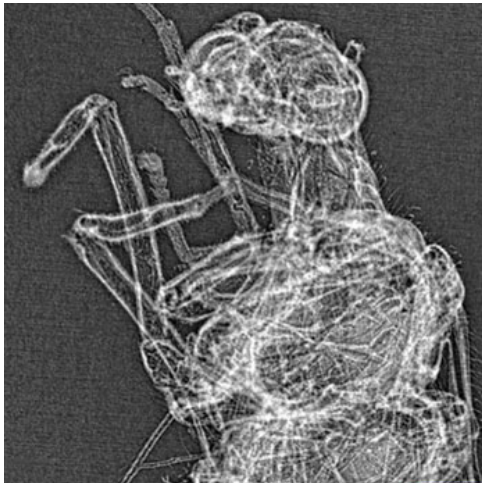
$$w(x,\lambda) = x\left(\frac{u}{v+u}\right)\sqrt{\frac{2}{\lambda}\left(\frac{1}{u} + \frac{1}{v}\right)}$$

u – distance from source to edge

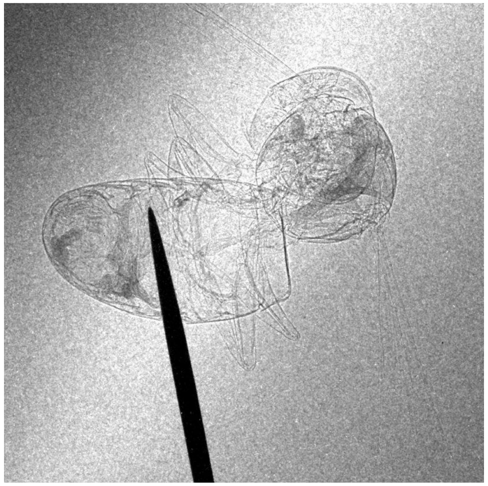
v – distance from obstruction edge to detector



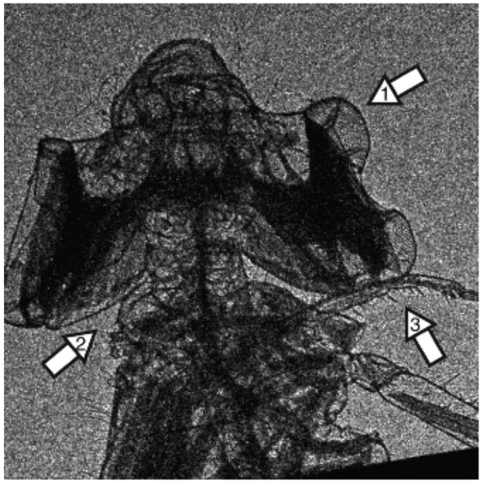
Phase contrast imaging of biological objects with betatron x-rays



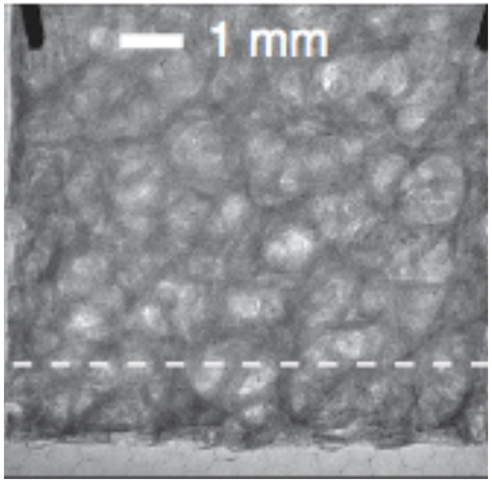
Chrysoperia carnea
Wenz et al, Nat. Comm (2015)



Bee
Fourmaux et al, Opt Lett. (2011)

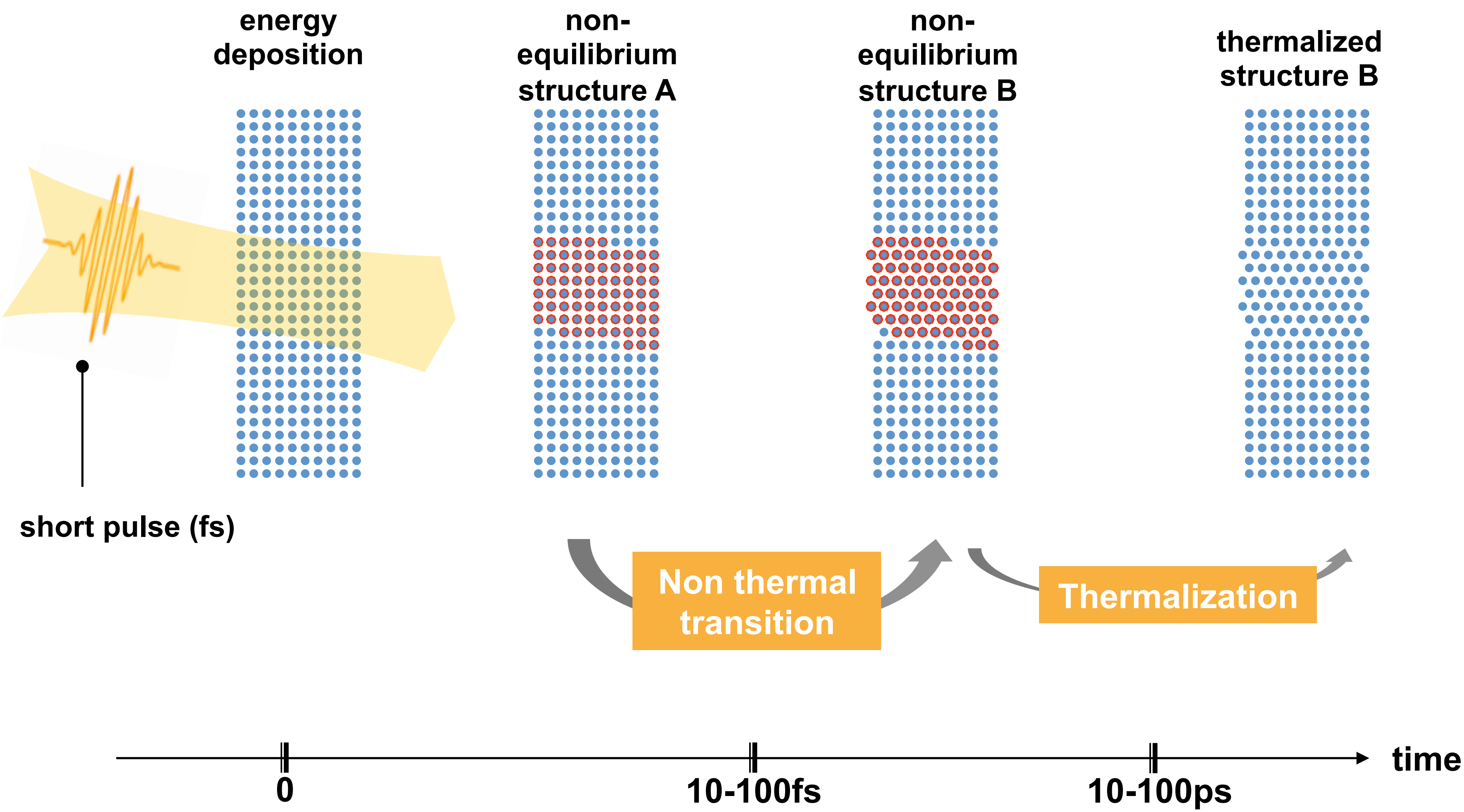


Damselfly
Kneip et al, Appl. Phys. Lett. (2011)



Trabecular hip bone sample
Cole et al, Sc. Rep (2015)

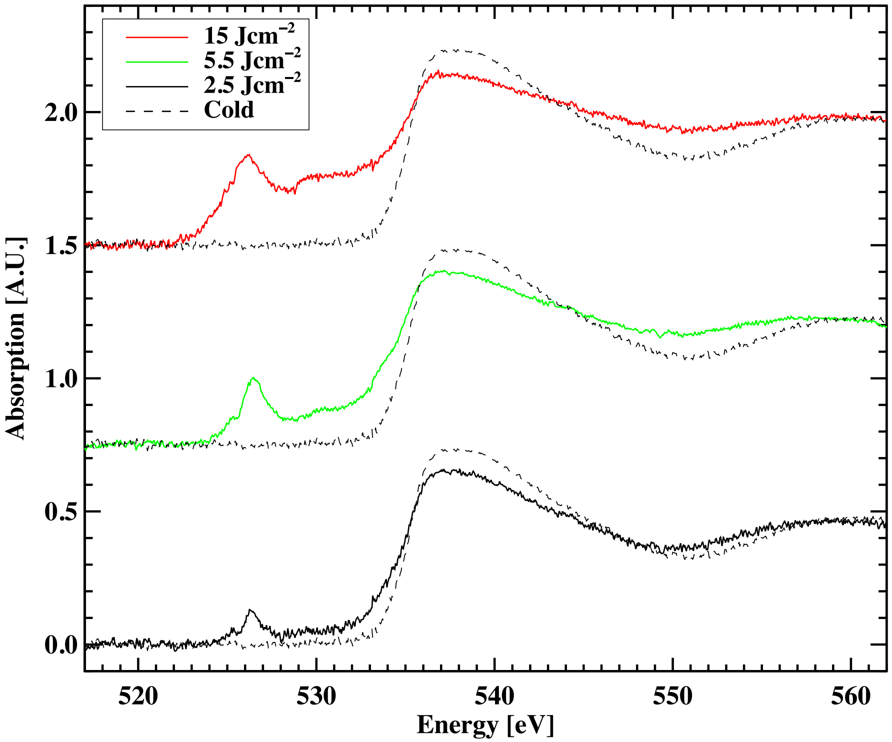
Example 2: study of SiO_2 in WDM conditions



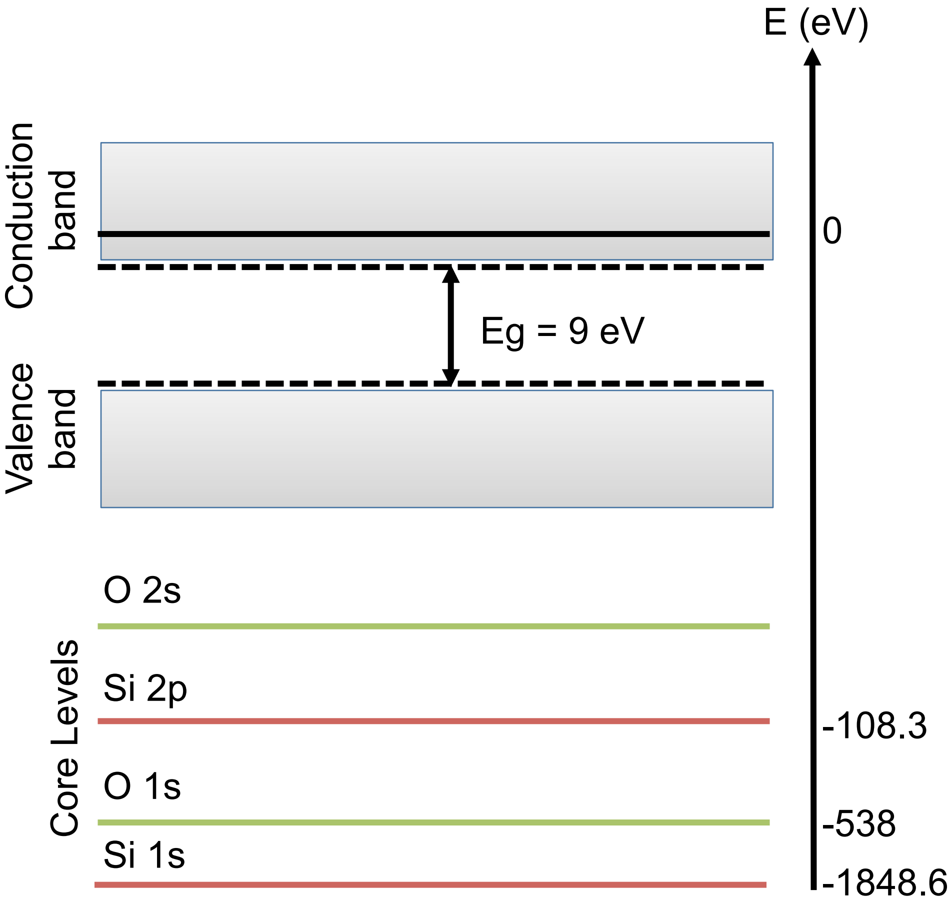
Electron heating -> phase transition -> thermalization
Electronic and ionic structural changes

Electronic structure changes investigated with x-ray absorption spectroscopy

Absorption spectroscopy (XANES)
at the O K-edge (520-560 eV)

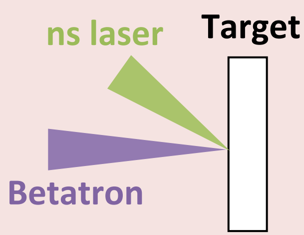
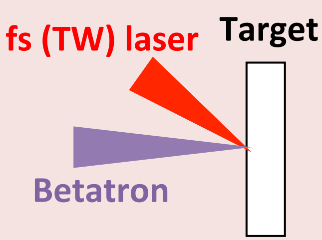
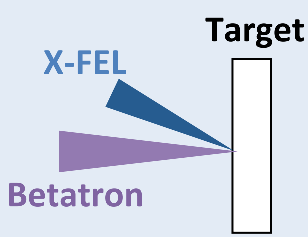


K. Engelhorn et al, PRB, 91, 214305 (2015)



Need a broadband, fs x-ray source : betatron radiation

How could we do HED science experiments at BELLA with betatron x-rays?

Probe Configuration	Facilities	HED science
	Titan LCLS MEC ns optical laser OMEGA EP NIF ARC LFEX-GEKKO **BELLA**	High pressure and shock physics Equation of state Material strength Phase transitions Opacity
	LCLS MEC short pulse Hercules Astra-Gemini **BELLA**	laser-matter interaction Relativistic laser-plasma interactions Laboratory astrophysics Laser-plasma accelerators Ultrafast phase transitions Opacity
	LCLS MEC SACLA HERMES European XFEL	X-ray matter interaction Isochoric heating 100's eV plasmas Ultrafast phase transitions Nuclear Physics Opacity

Betatron x-rays with BELLA

- Betatron source requirements/needs for HED experiments with BELLA
  - **Photon energy**
  - **Photometrics**
  - Source size

Application	Photon/eV/Sr	Current betatron	BELLA-I niche
Radiography XPCI	1e9	Yes	Harder x-rays: XPCI of dense plasmas
EXAFS/XANES	1e9	Yes	Higher Z materials (Ag, Fe)
Diffraction	1e12	No	Could have enough photons

- We need to discuss the capabilities required for a HED betatron source
  - Laser spot size
  - Laser pulse duration
  - Electron density/gas composition
  - Are planned BELLA-I specs optimized for betatron x-rays?

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