Applications of light sources driven by laser wakefield acceleration

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LDRD Laboratory Directed Research and Development

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Outline

- Laser-plasma acceleration: an alternative for compact light sources – Betatron x-ray radiation
- Two regimes of laser-plasma acceleration to produce betatron x-ray radiation
- Experimental characterization of betatron x-ray radiation
- Applications

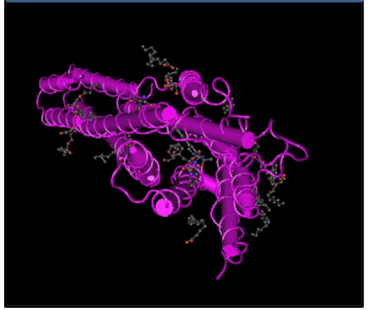
Conventional x-ray light sources are large scale national facilities

X-ray free electron laser: LCLS

Synchrotron: APS

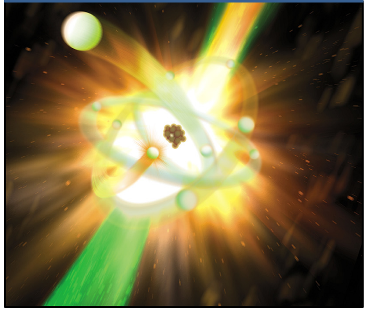
These light sources have enabled seminal discoveries

Structure of proteins



Liu Science 2013

Atomic x-ray laser

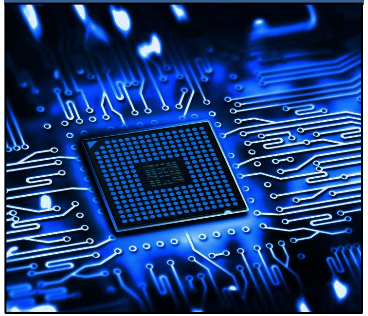


Rohringer Nature 2012

Material strain studies

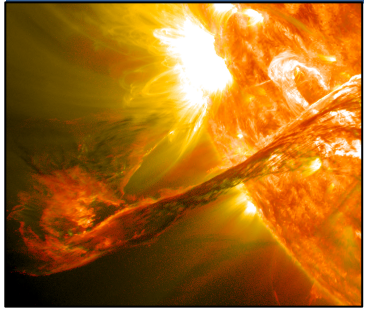
http://www.diamond .ac.uk/industry/

Semiconductor research



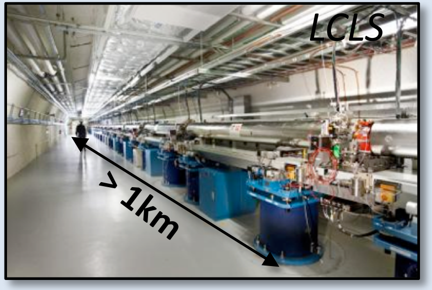
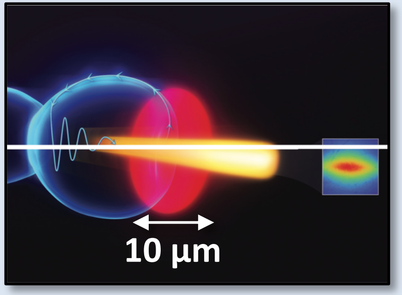
Margaritondo, J. Phys. IV 2006

Solar plasmas



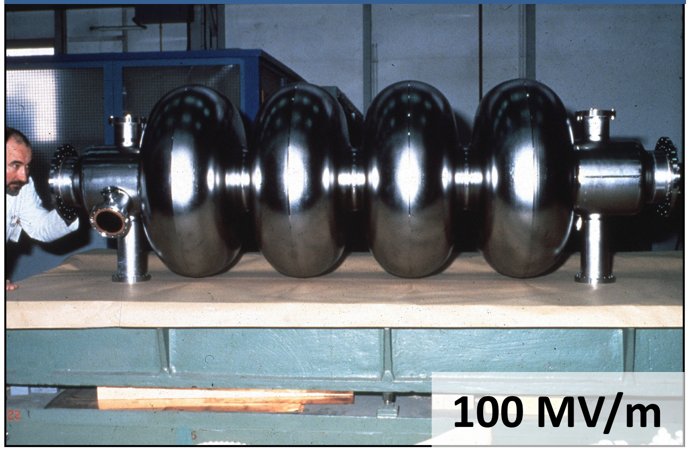
Vinko Nature 2012

Sources driven by laser-plasma accelerators offer an alternative

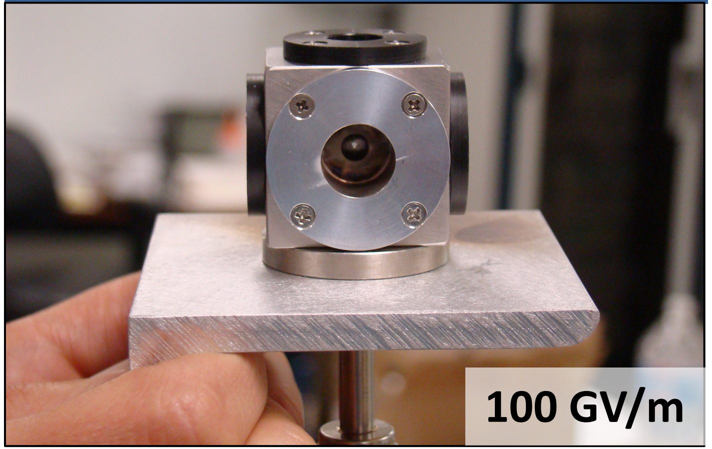
Synchrotron	Free Electron Laser	Laser-plasma
		
Electrons from storage ring wiggled by undulators	Electrons from linac wiggled by undulators	Electrons from laser-produced plasma wiggled by plasma
✓ Hard X-rays	✓ Soft X-rays (8 keV)	✓ Hard X-rays (up to 100 keV)
✓ High brightness	✓ Very High brightness	✓ High brightness
✓ Multiple beamlines	✓ One beamline	✓ Small scale
✓ Not ultrafast (ps)	✓ Ultrafast (fs)	✓ Ultrafast (fs)
✓ Not coherent	✓ Coherent	✓ Some spatial coherence

Plasmas can naturally sustain large acceleration gradients

RF Cavity



Gas cell – laser plasma



Acceleration gradient

$$E_0 = \frac{mc\omega_p}{e}$$

Plasma frequency

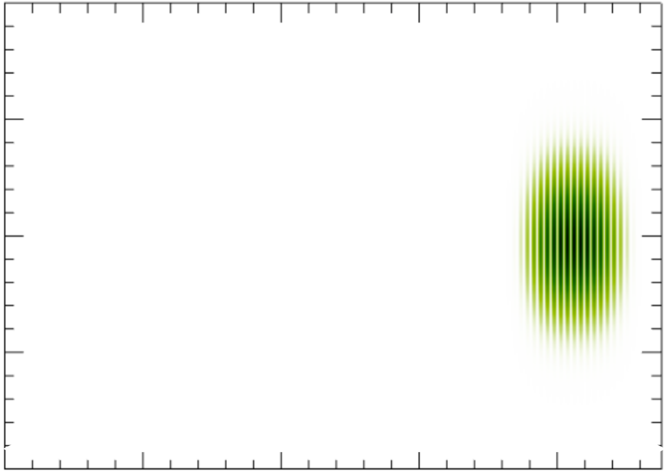
$$\omega_p = \sqrt{\frac{n_e e^2}{m\varepsilon_0}}$$

$$n_e = 10^{18}\ \mathrm{cm}^{-3} \rightarrow E_0 = 96\ \mathrm{GV/m}$$

Intense laser pulses drive electron plasma waves

Wake behind a boat

Plasma wave behind a laser



Nuno Lemos, LLNL

Intense laser pulses drive electron plasma waves

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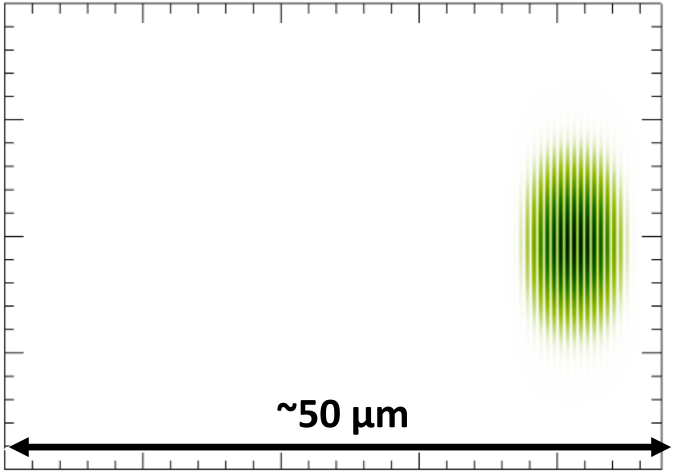
Plasma wave behind a laser



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Intense laser pulses drive electron plasma waves

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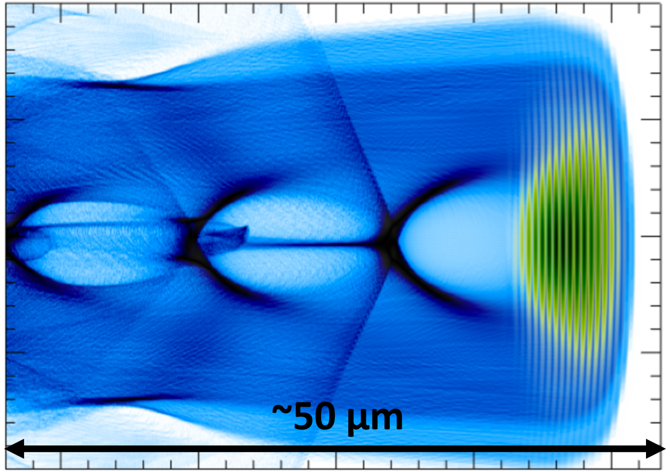
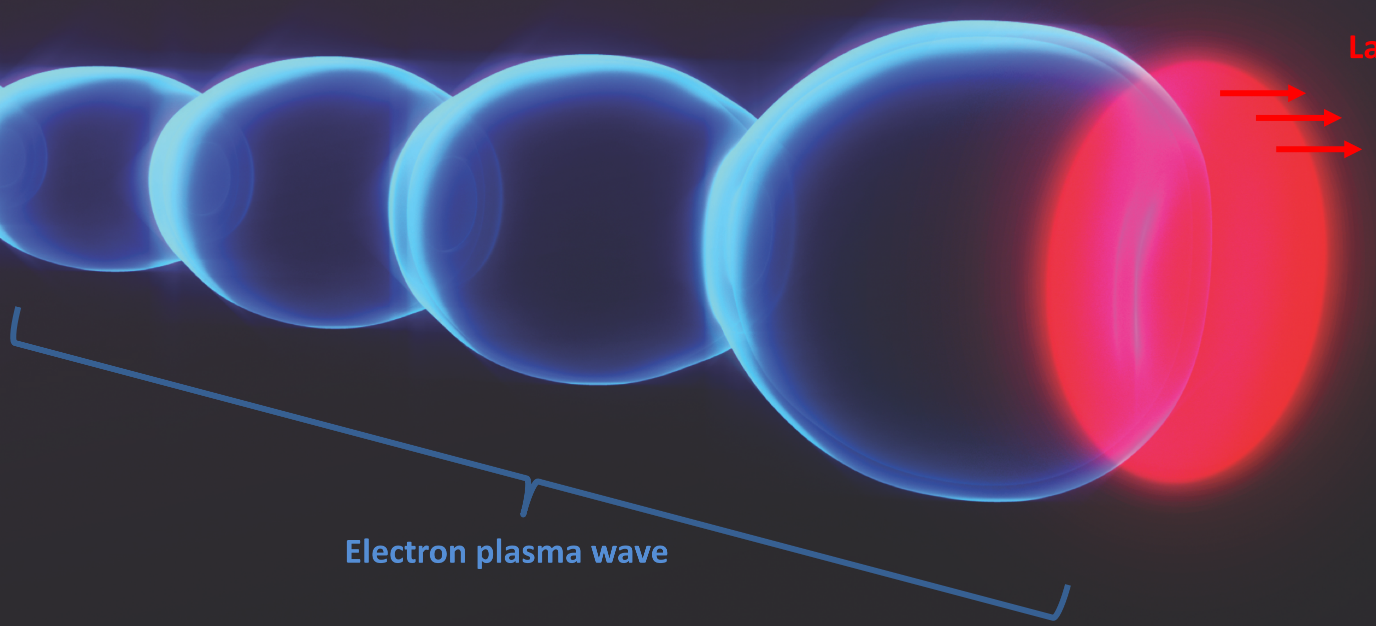
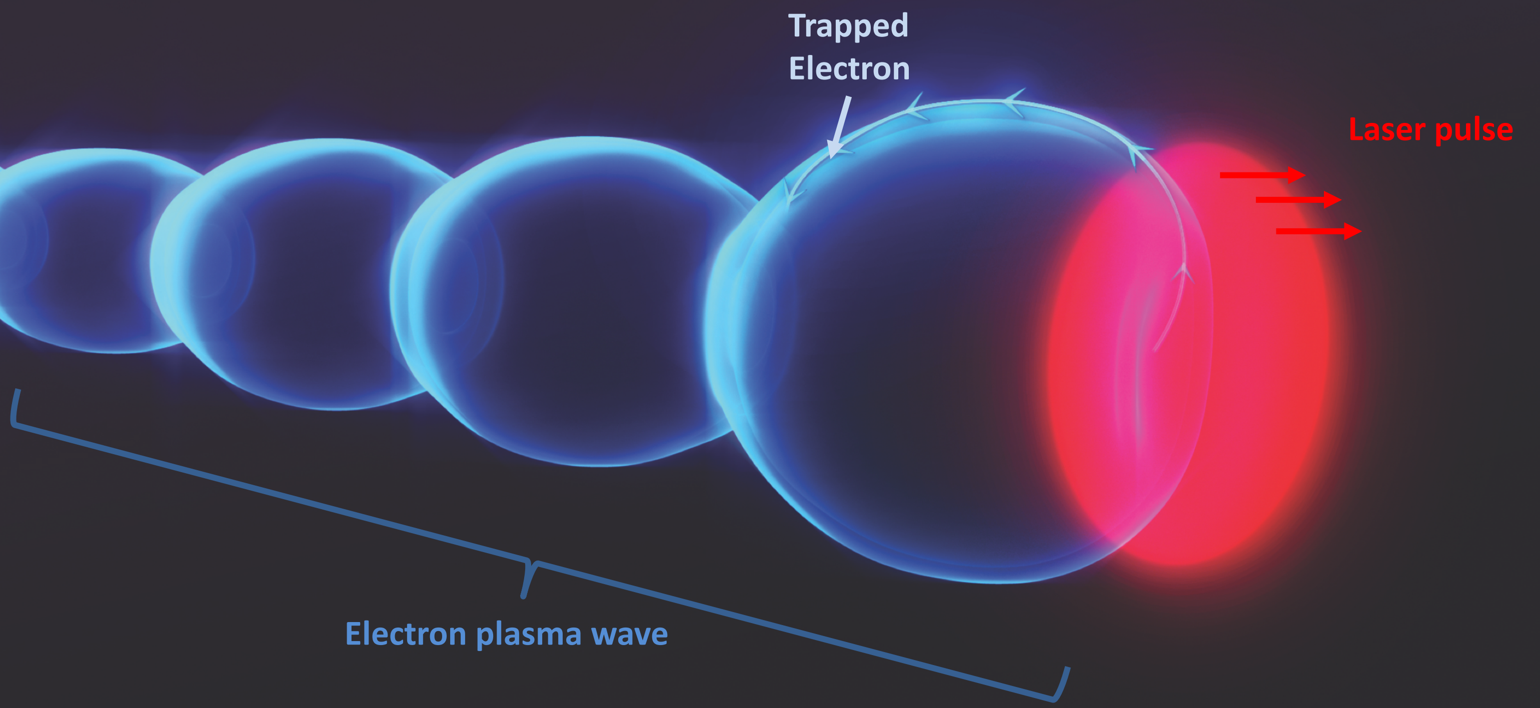


Nuno Lemos, LLNL



F. Albert et al, Laser wakefield accelerator based light sources: potential applications and requirements, *Plasma Phys. Control. Fusion* 56 084015 (2014)



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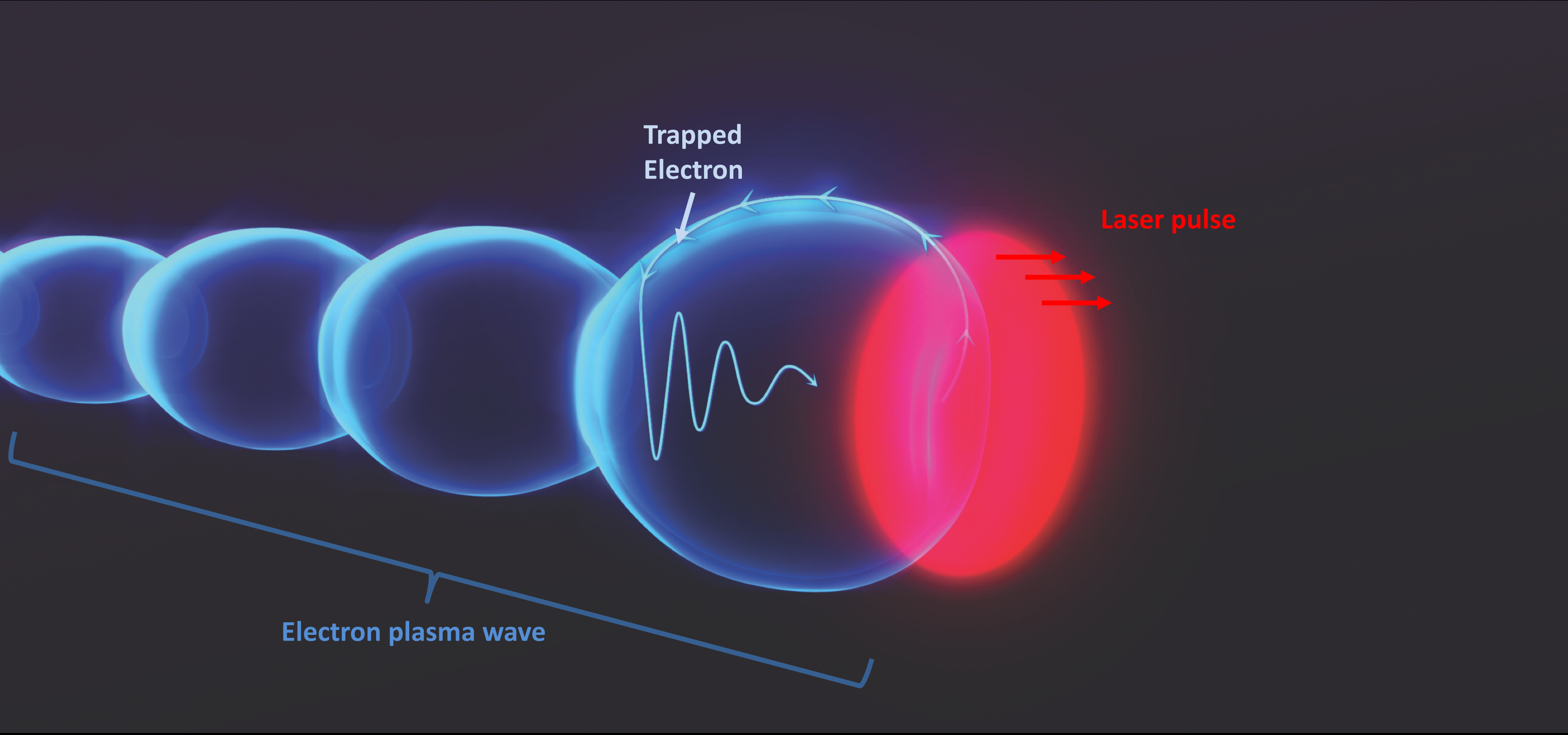

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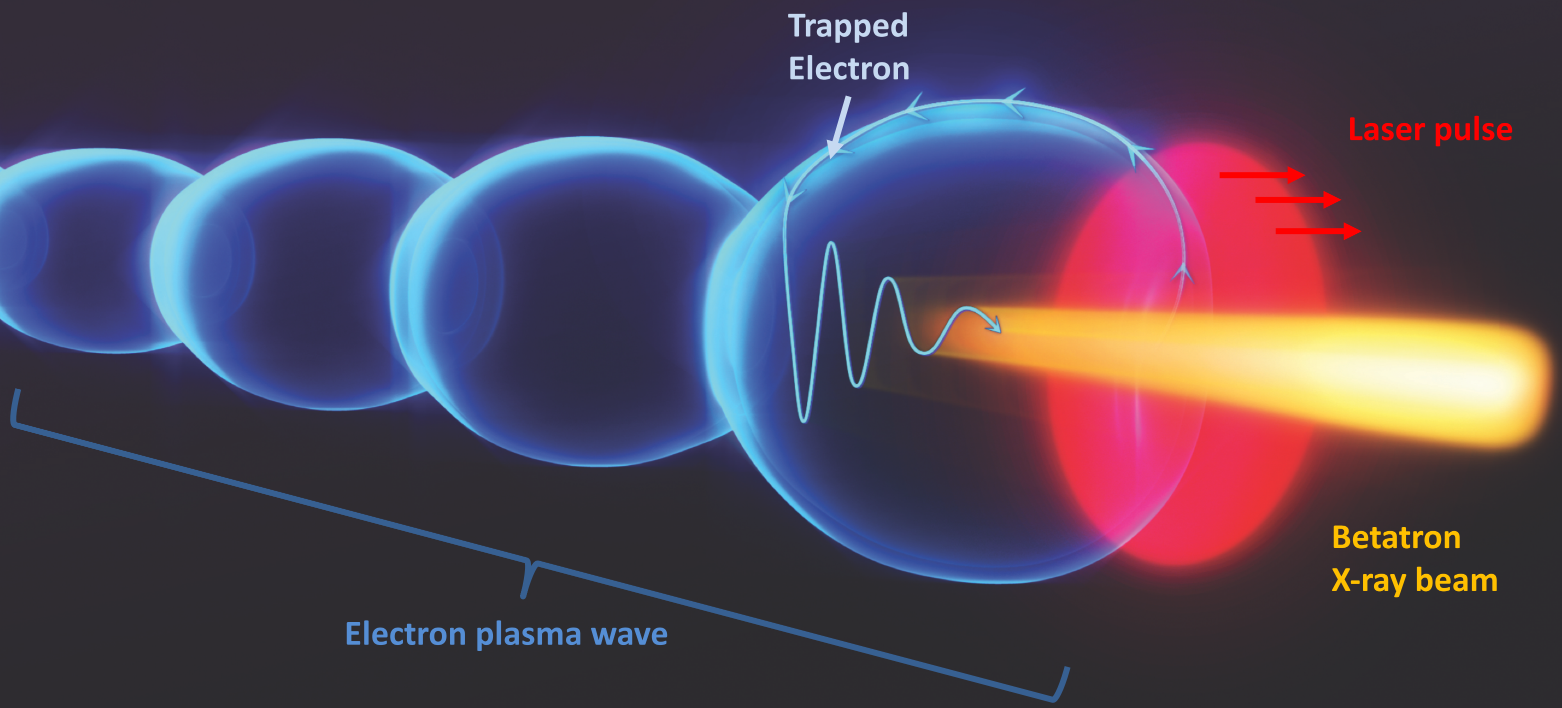

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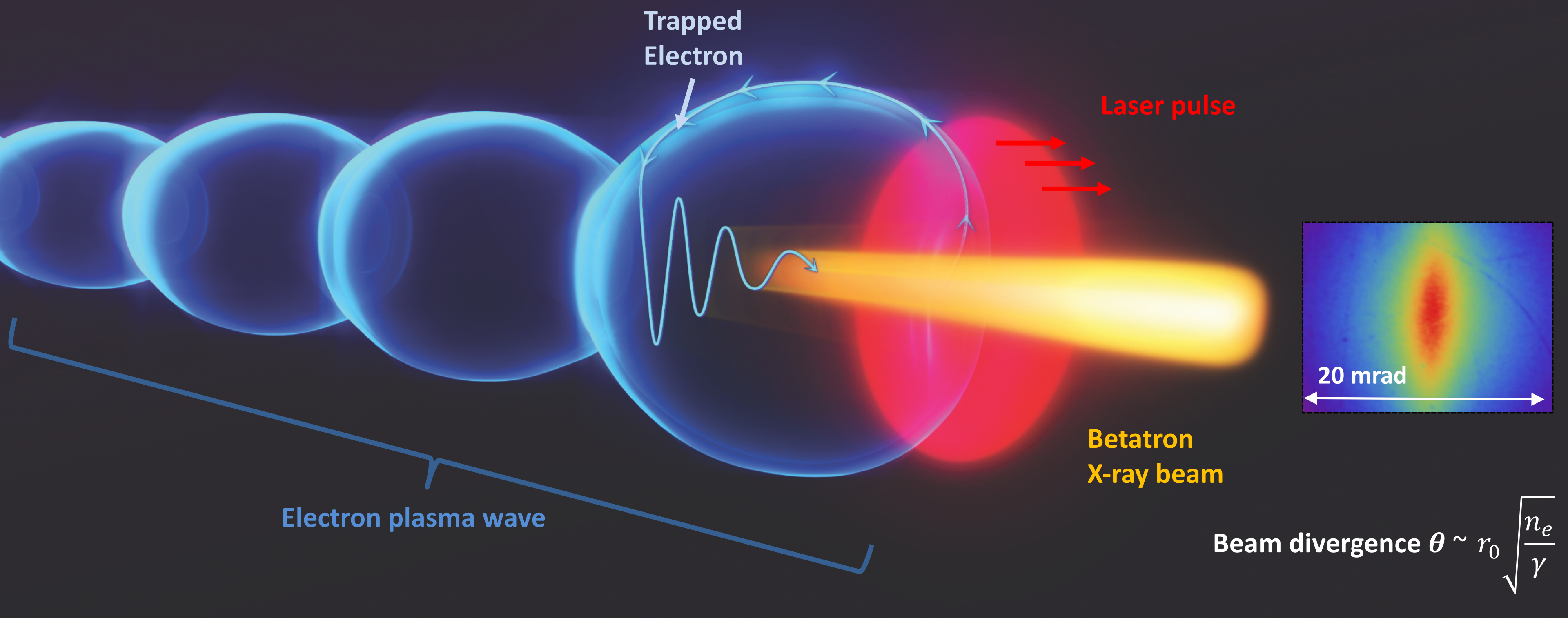

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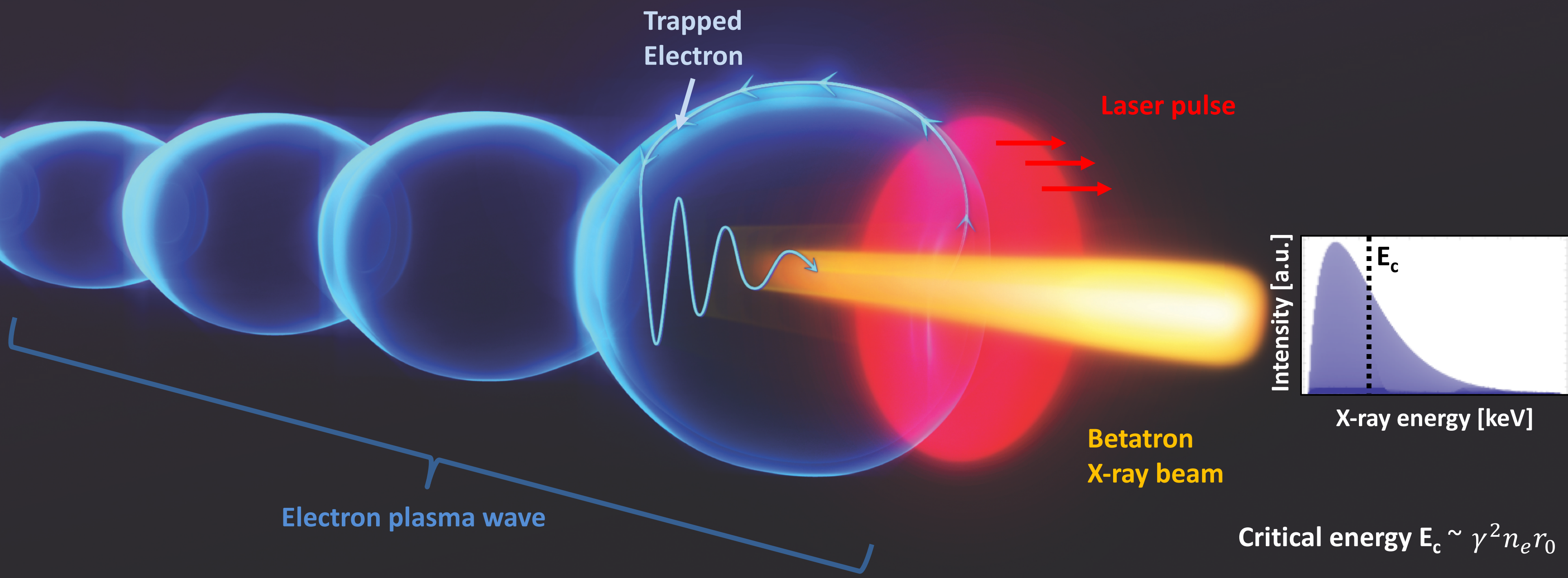
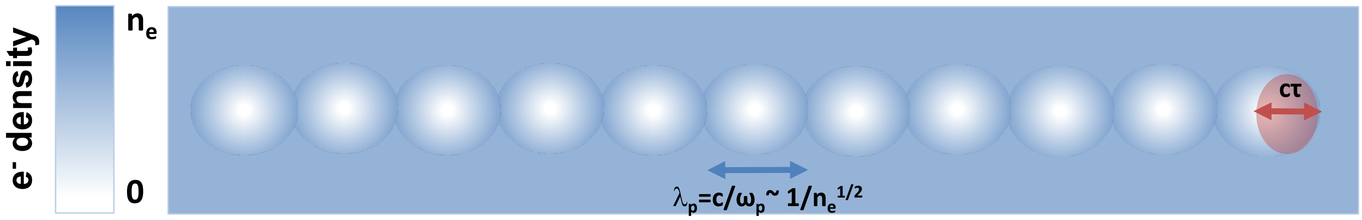


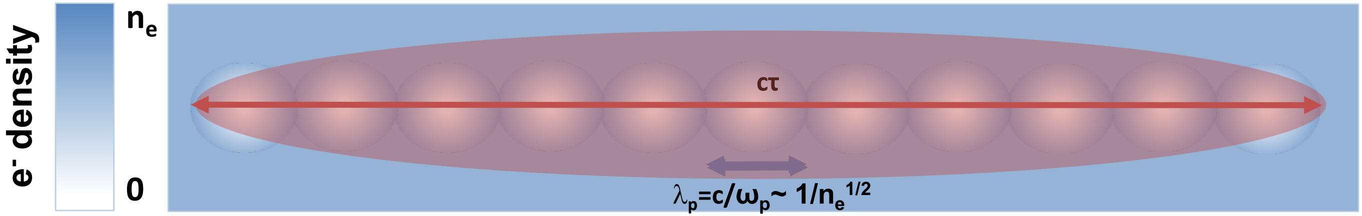
F. Albert et al, Laser wakefield accelerator based light sources: potential applications and requirements, *Plasma Phys. Control. Fusion* 56 084015 (2014)

Betatron radiation is typically produced with ultrashort laser pulses in the blowout regime ($c\tau \sim \lambda_p/2$)



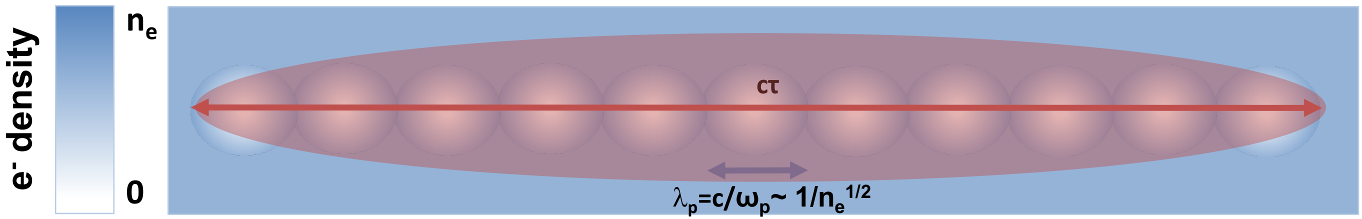
Condition to be in the blowout regime $c\tau \sim 1/n_e^{1/2}$ ➡ 30 fs $n_e \sim 10^{19}$ cm^{-3}

Self modulated laser wakefield acceleration is easier to achieve with picosecond scale lasers ($c\tau >> \lambda_p$)

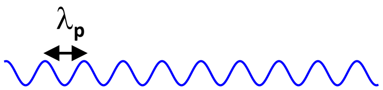


Condition to be in the self modulated regime $c\tau >\sim 1/n_e^{1/2}$ → 1 ps $n_e \sim 10^{19}$ cm^{-3}

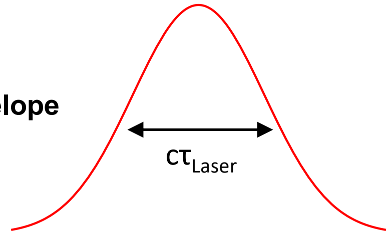
The laser propagates in the plasma and decays into an electron plasma wave and forward scattered waves



Plasma wave



Laser pulse envelope

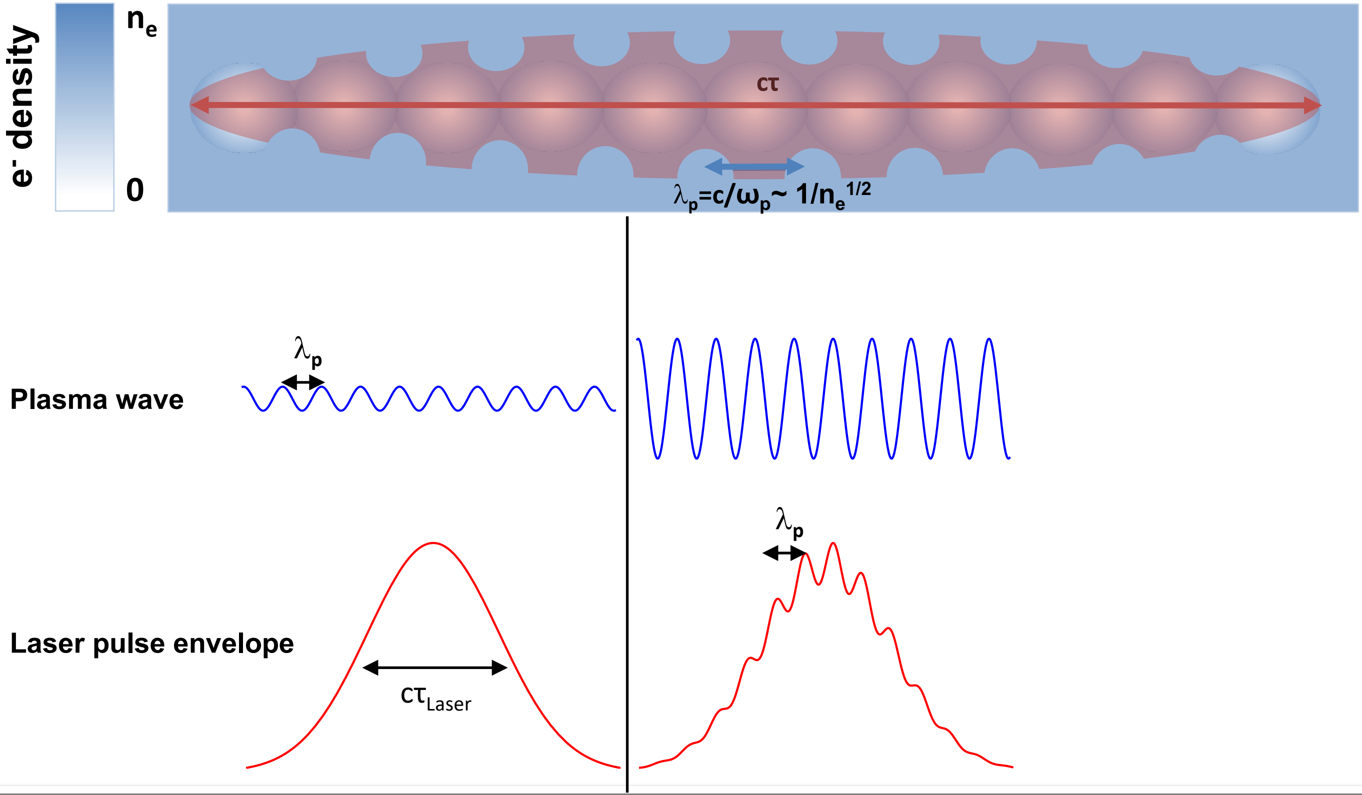


Matching conditions

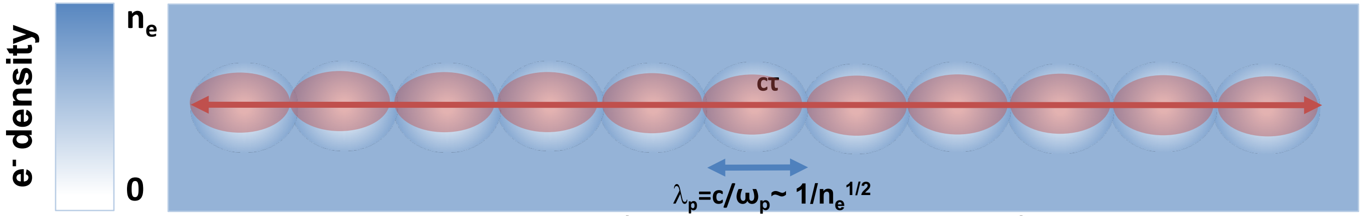
$\omega_0 = \omega_s$ +/-$m\omega_{plasma}$

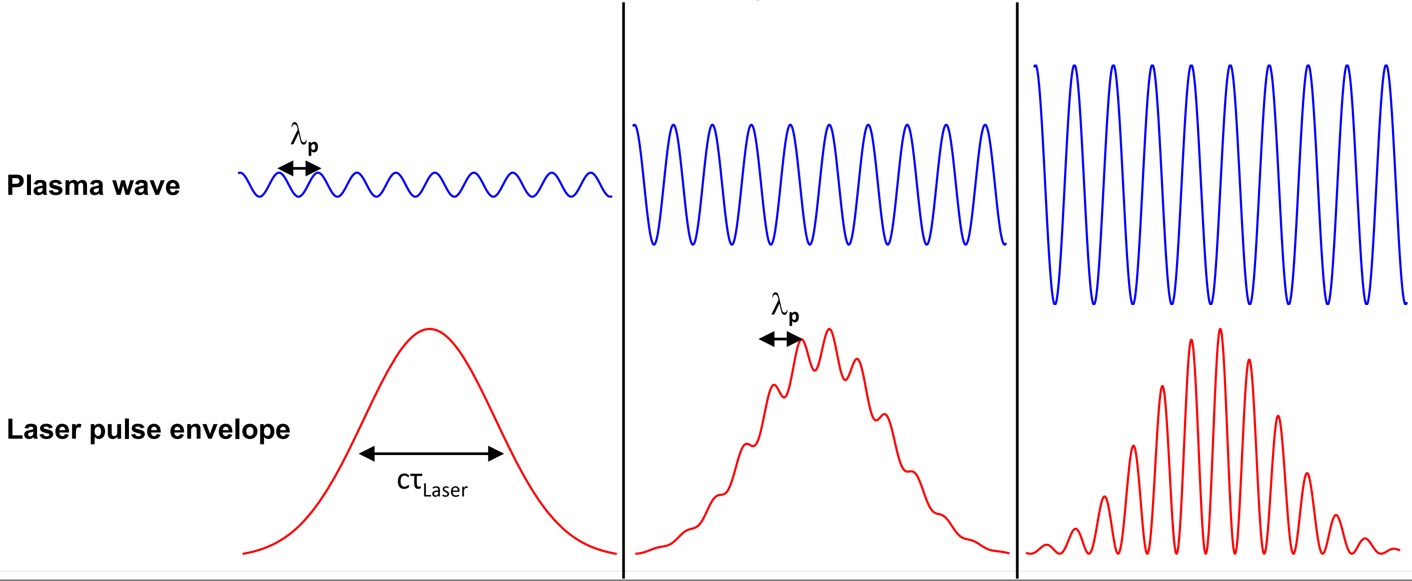
$\mathbf{k_0} = \mathbf{k}_s$ +/-$m\mathbf{k}_{plasma}$

The index of refraction variations due to the plasma wave cause the laser to focus/defocus

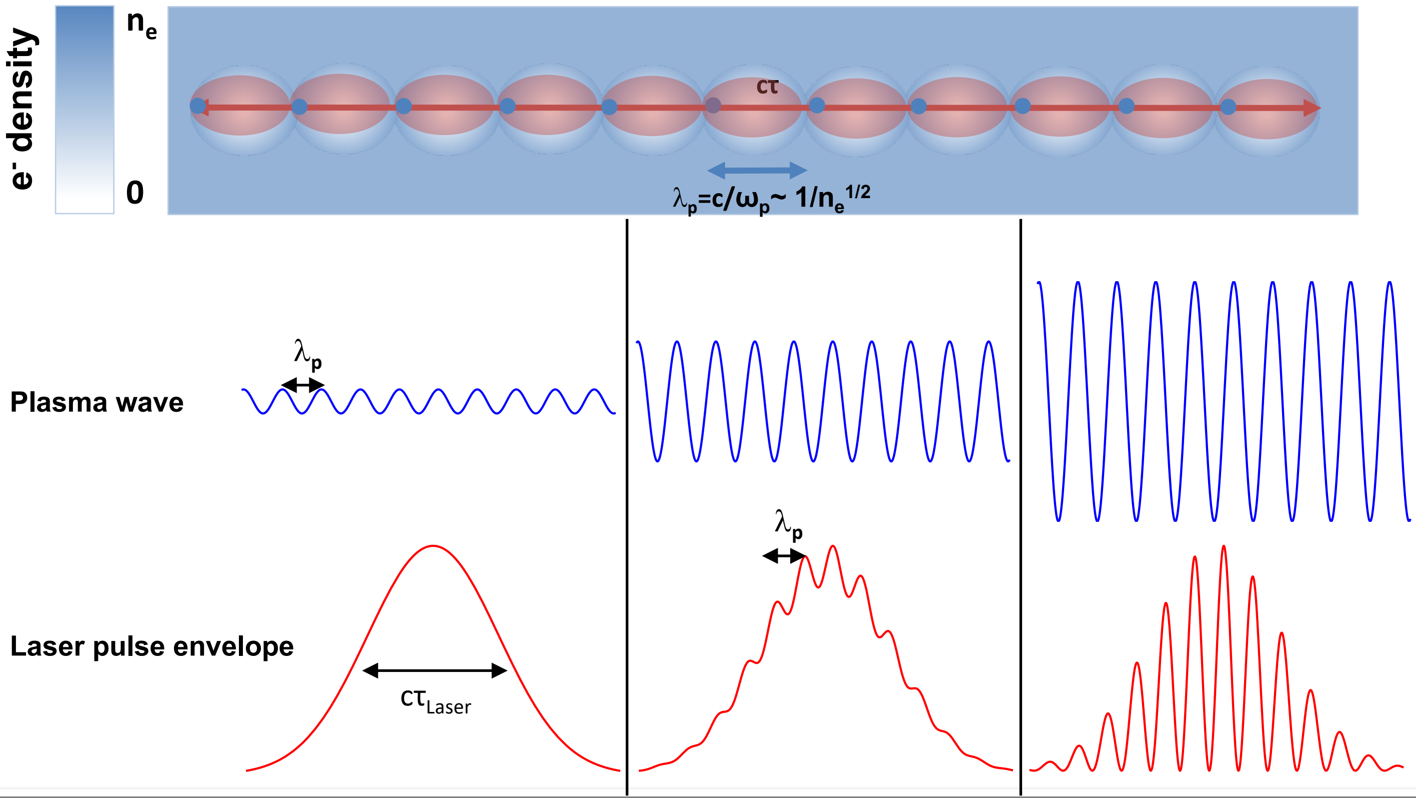


This beat pattern exerts a force on the plasma electrons and the plasma wave amplitude grows until wave breaking

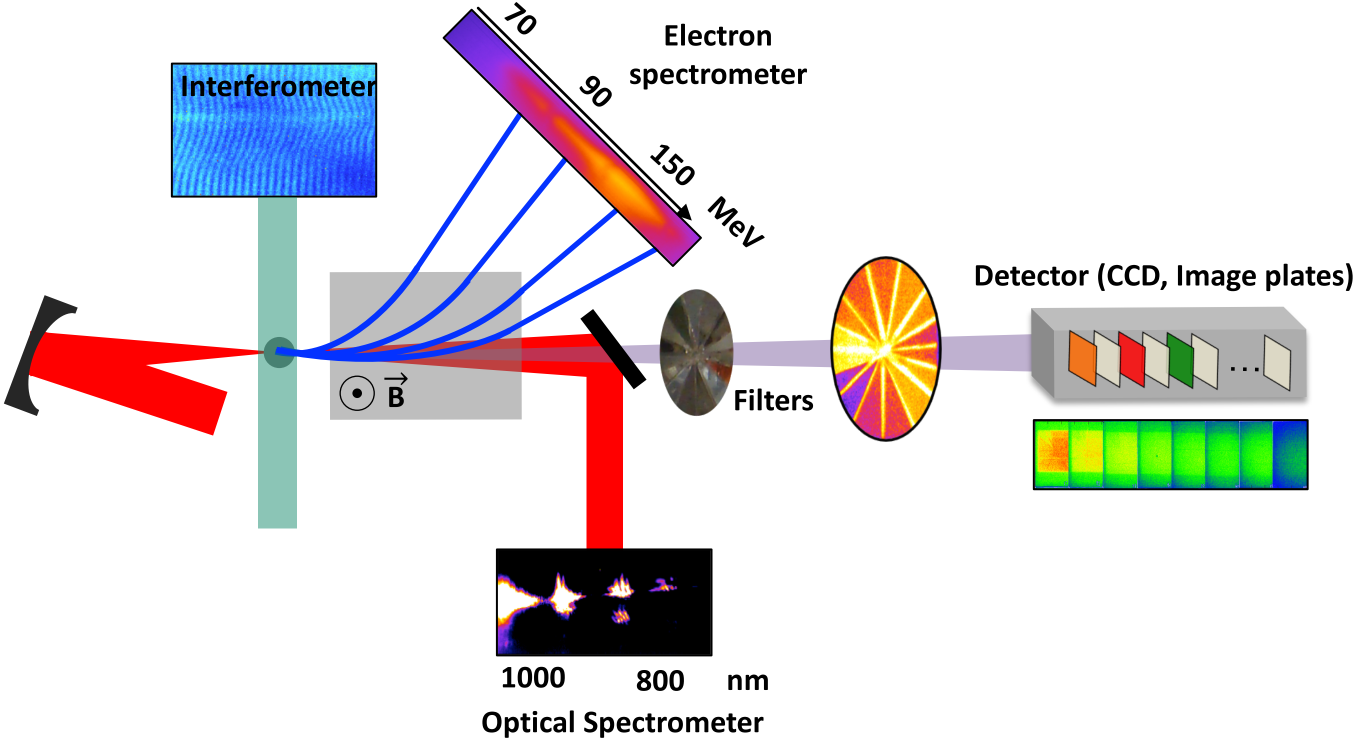




Upon wave breaking electrons are trapped into the plasma wave undergo acceleration in the longitudinal electrical field

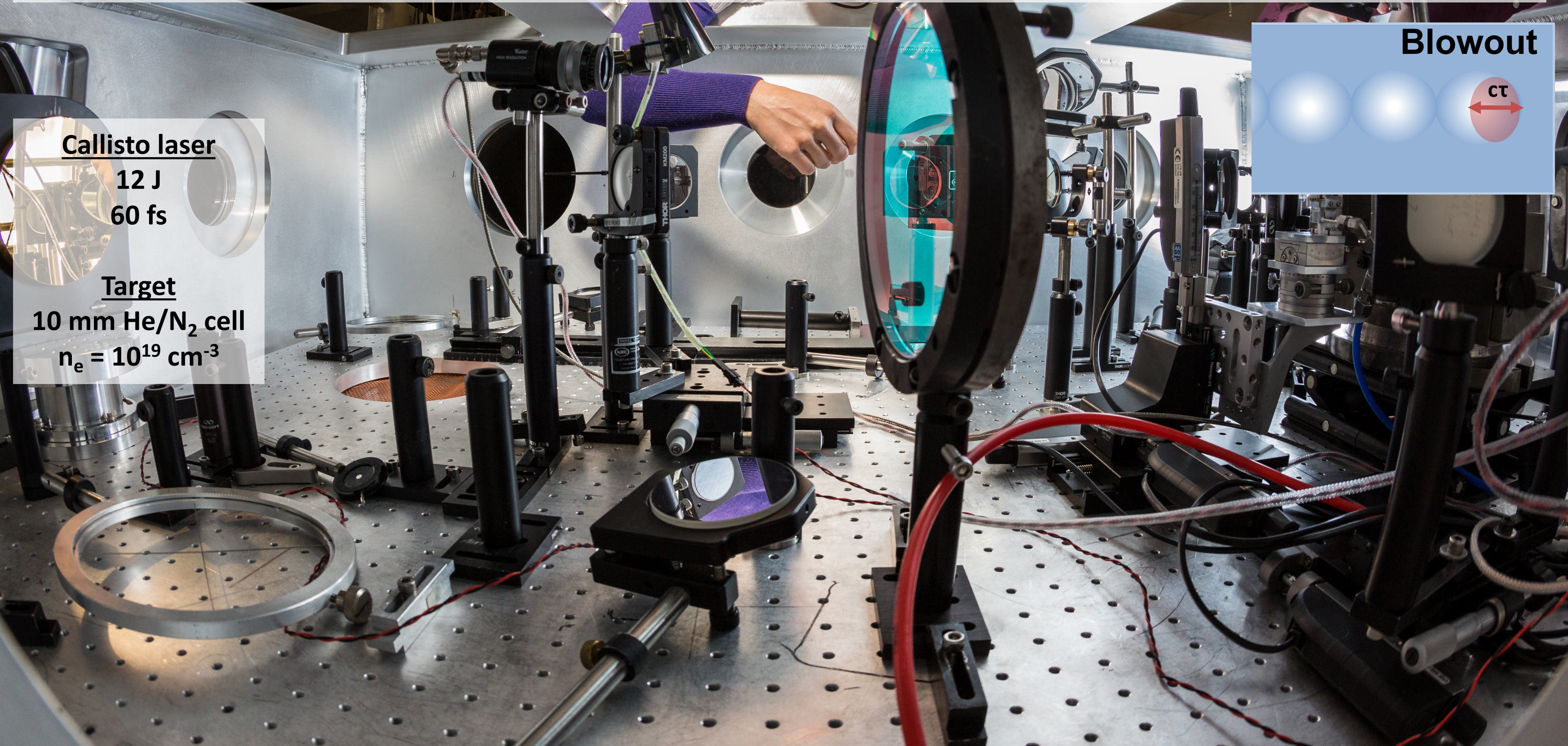


A typical betatron radiation experiment



F. Albert et. al, *Phys. Rev. Lett*. 111, 235004 (2013), *Phys. Rev. Lett*. 118, 134801 (2017)

Laser wakefield – betatron experiments – Callisto LLNL 2012-2013



Callisto laser

12 J

60 fs

Target

10 mm He/N_2 cell

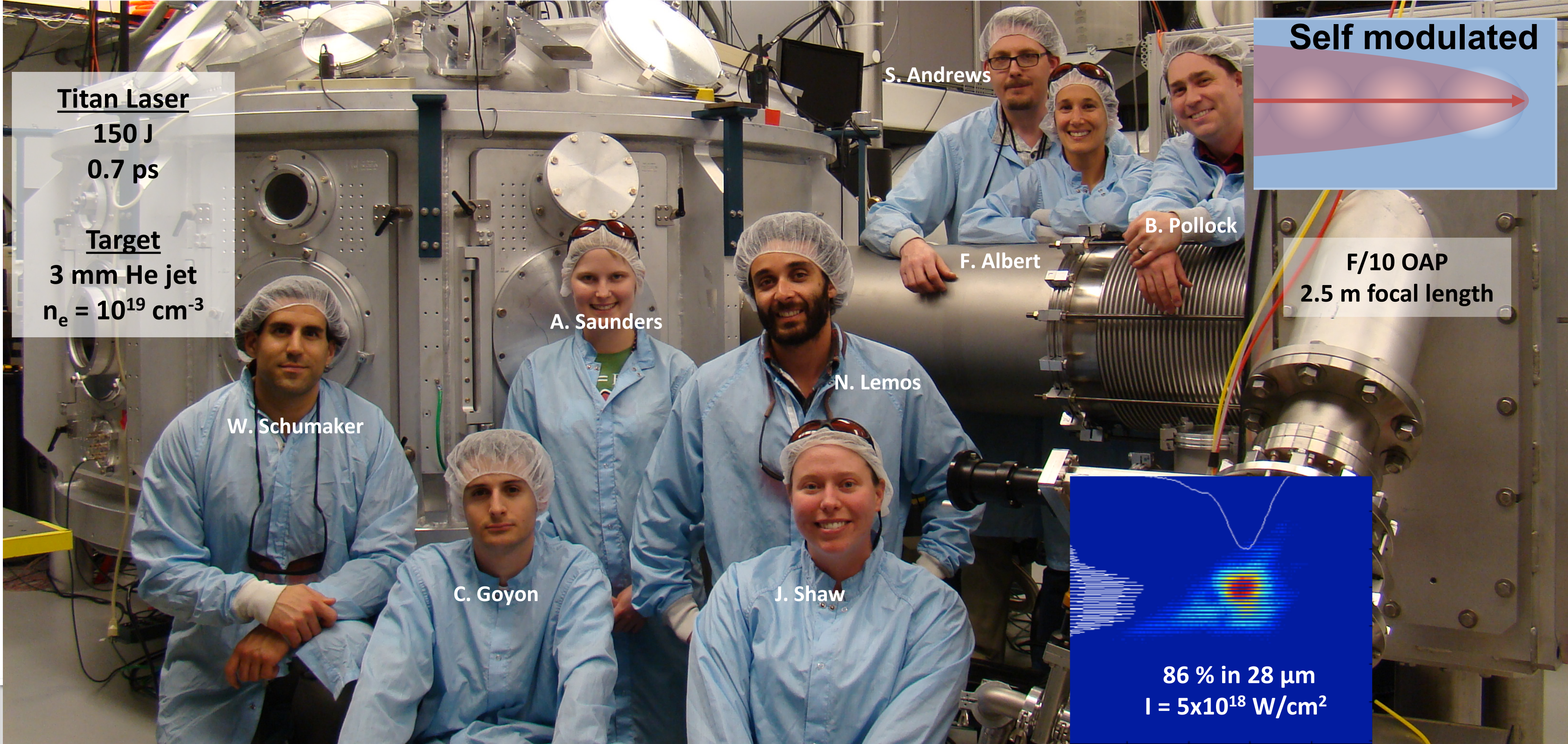
$n_e = 10^{19}$ cm^{-3}

Laser wakefield – betatron experiments – Titan LLNL 2015-2017

Titan Laser
150 J
0.7 ps

Target
3 mm He jet
$n_e = 10^{19}$ cm^{-3}

F/10 OAP
2.5 m focal length



Laser wakefield – betatron experiments – LCLS/MEC SLAC 2015 - 2016

MEC Laser

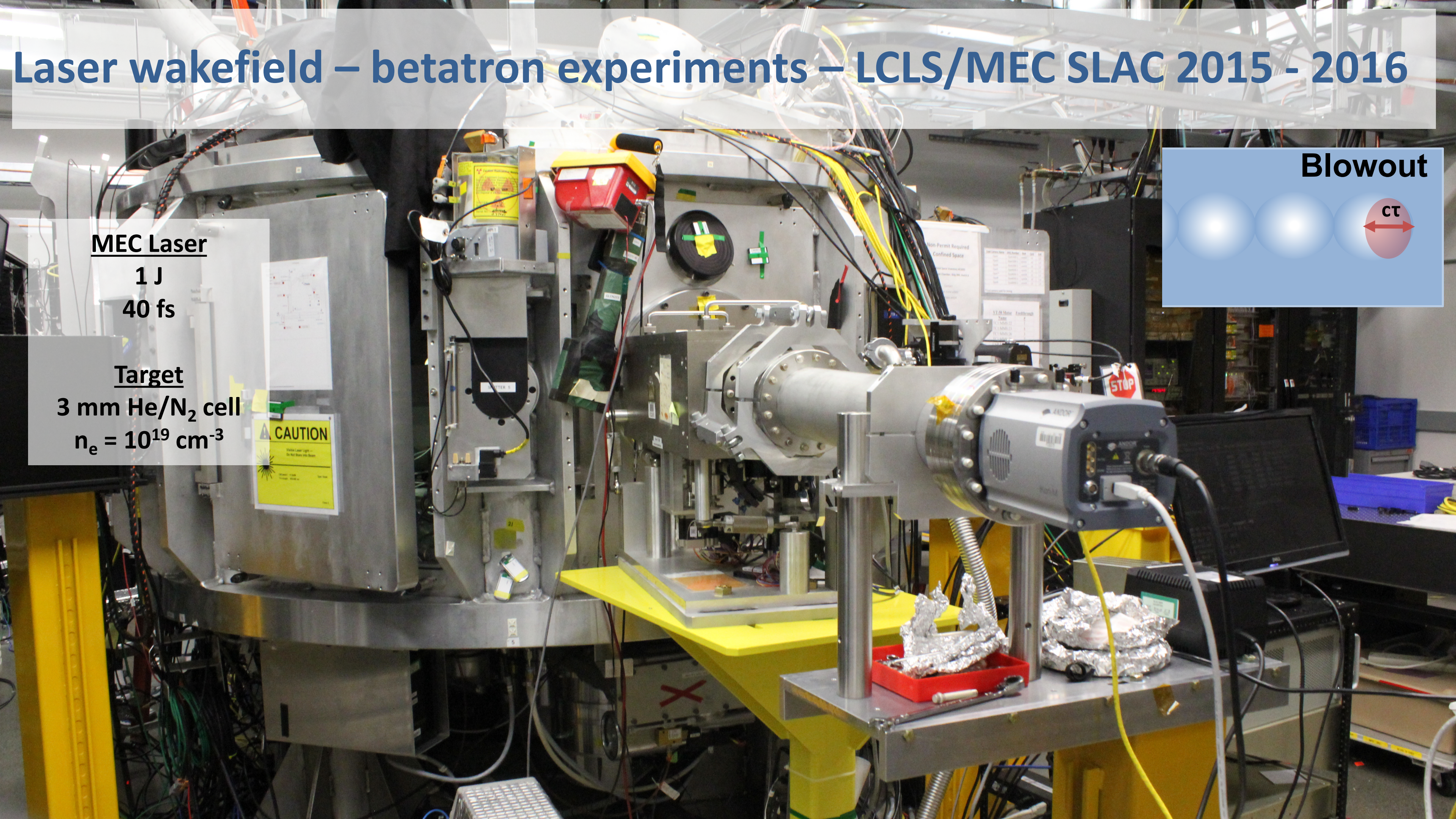
1 J

40 fs

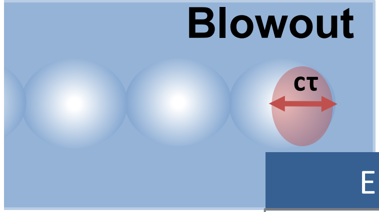
Target

3 mm He/N_2 cell

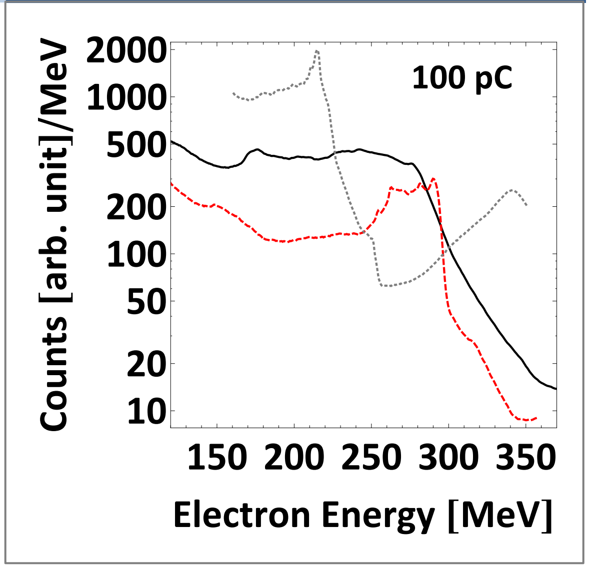
$n_e = 10^{19}$ cm^{-3}



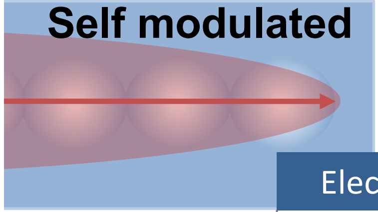
Electron beam signatures are different for each regime



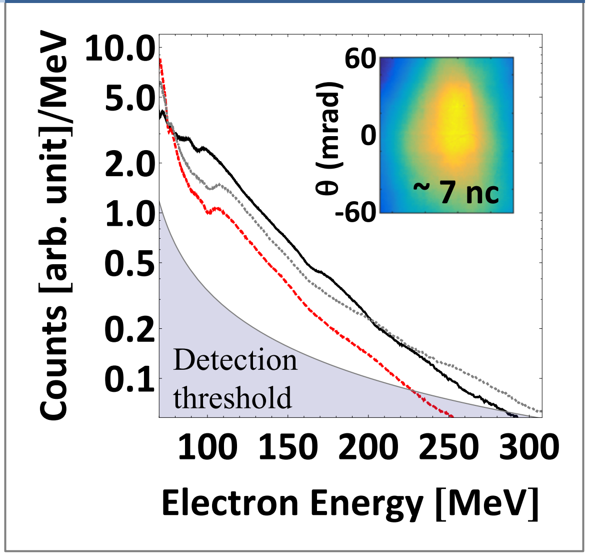
Electron spectra – Blowout



- Peaked spectrum
- Low charge



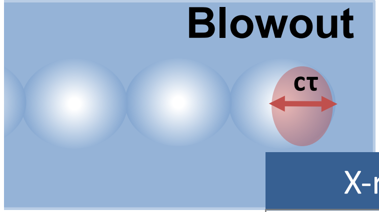
Electron spectra – Self modulated



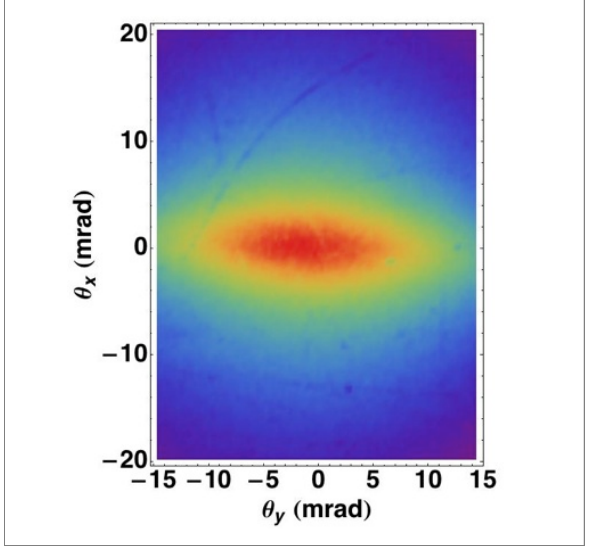
- Maxwellian spectrum
- High charge

F. Albert et. al, *Phys. Rev. Lett.* 111, 235004 (2013), *Phys. Rev. Lett.* 118, 134801 (2017)

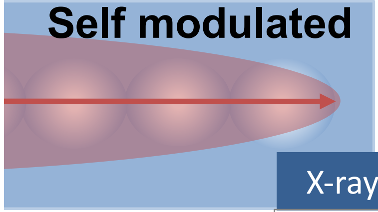
Blowout regime produces a more directed x-ray beam



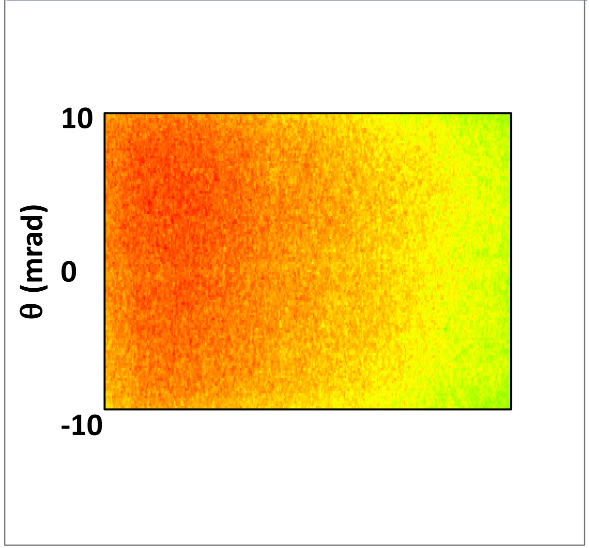
X-ray beam profile – Blowout



- Narrow divergence
- 10-20 mrad



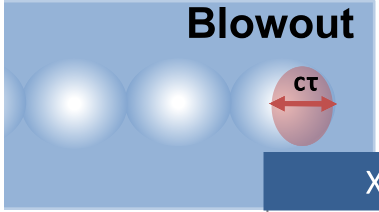
X-ray beam profile – self modulated

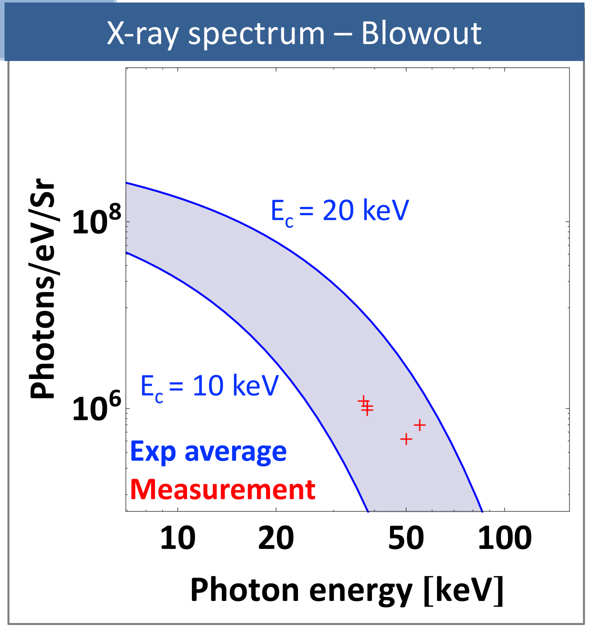


- Larger divergence
- 100-200 mrad

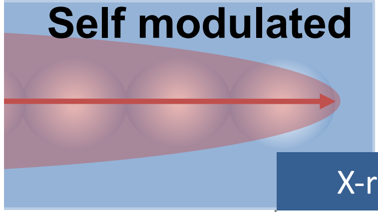
F. Albert et. al, *Phys. Rev. Lett.* 111, 235004 (2013), *Phys. Rev. Lett.* 118, 134801 (2017)

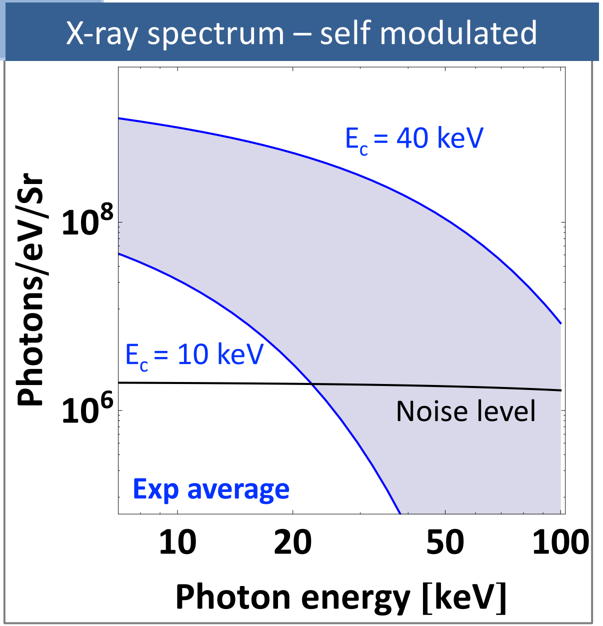
Both regimes produce similar x-ray spectra





- Critical energy 10-20 keV
- 10^8 photons/eV/Sr

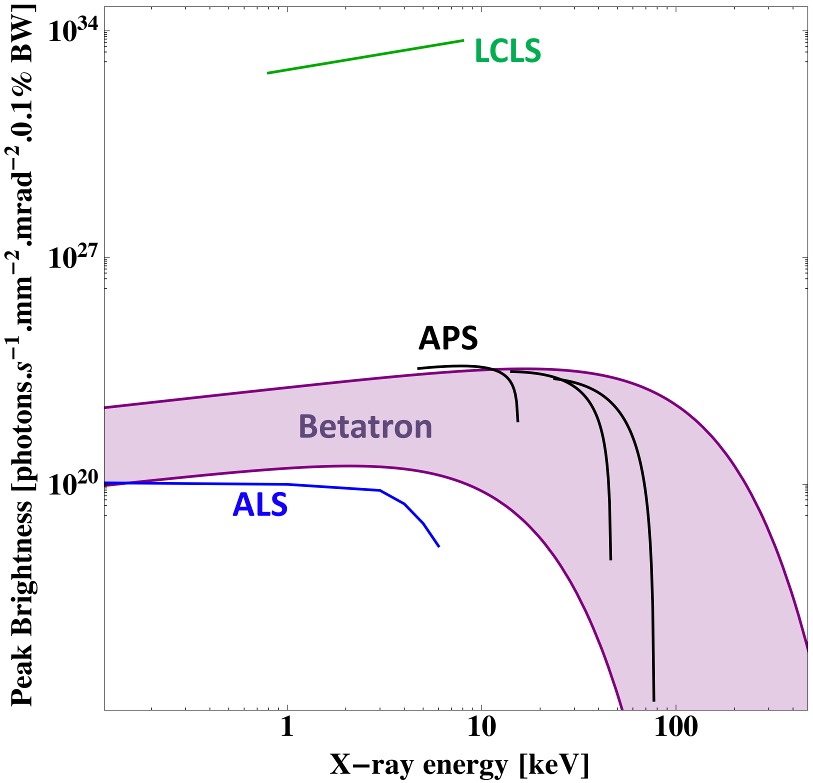




- Critical energy 10-40 keV
- 10^9 photons/eV/Sr

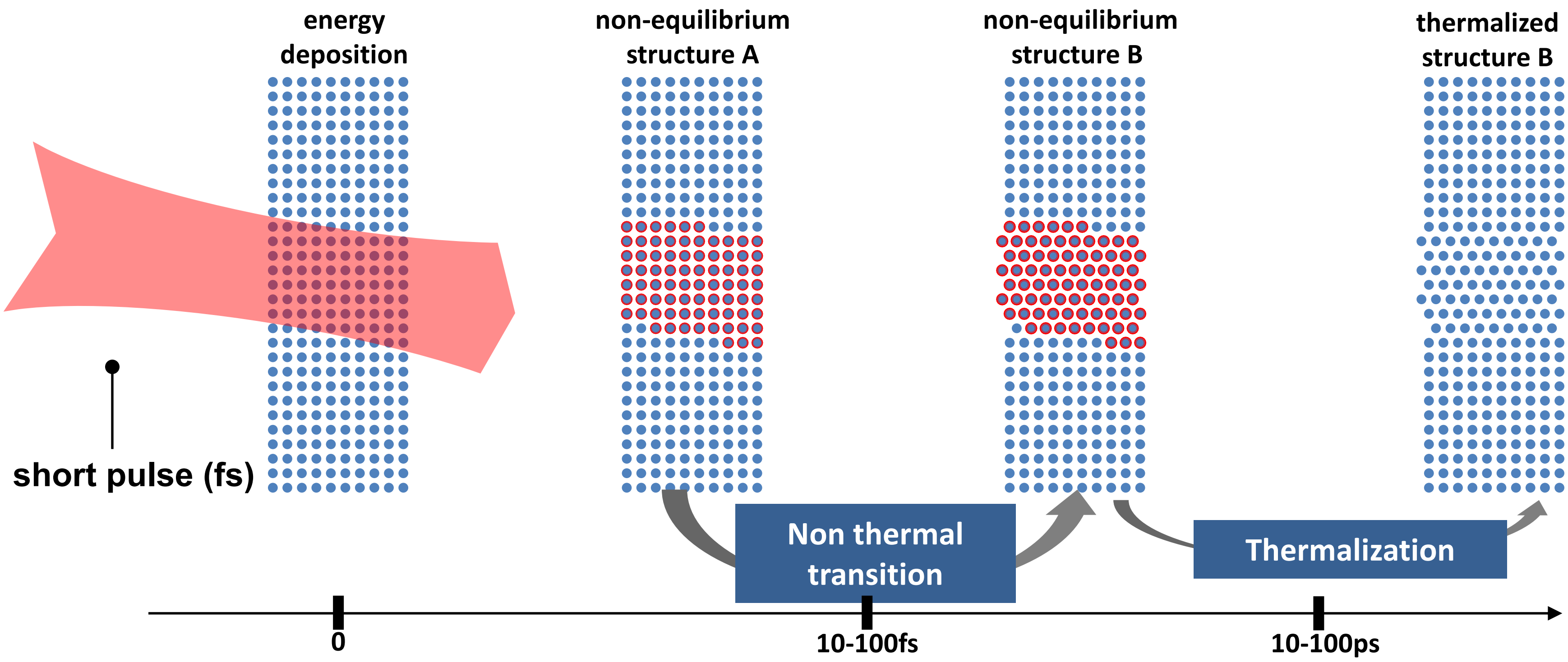
F. Albert et. al, *Phys. Rev. Lett.* 111, 235004 (2013), *Phys. Rev. Lett.* 118, 134801 (2017)

Betatron radiation from laser wakefield accelerators has unique properties compared to conventional light sources

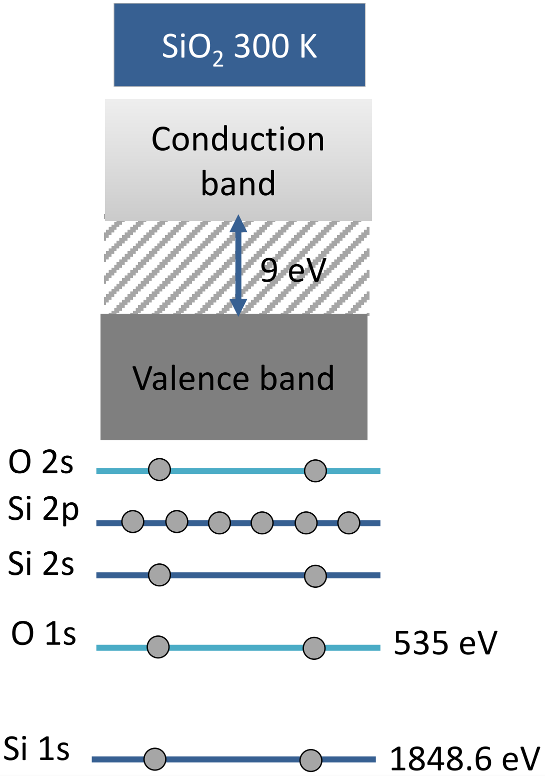


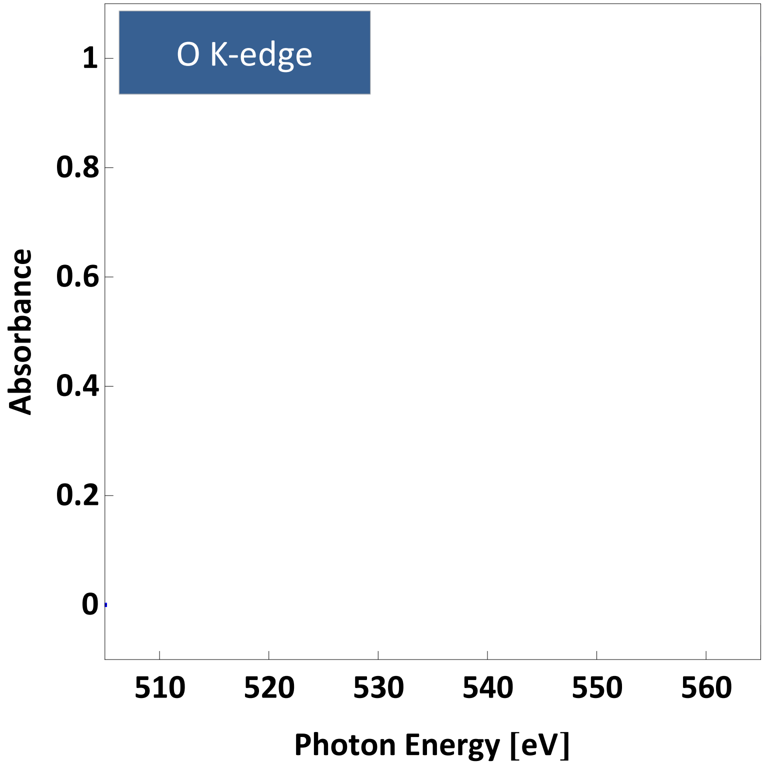
Unique properties
▪ Broadband (keV)
▪ Ultrafast (fs)
▪ Small source size (few microns)
▪ Collimated (mrad)
▪ Synchronized with drive laser within 50 fs

Nonthermal melting in SiO_2 can be probed with betatron x-ray radiation

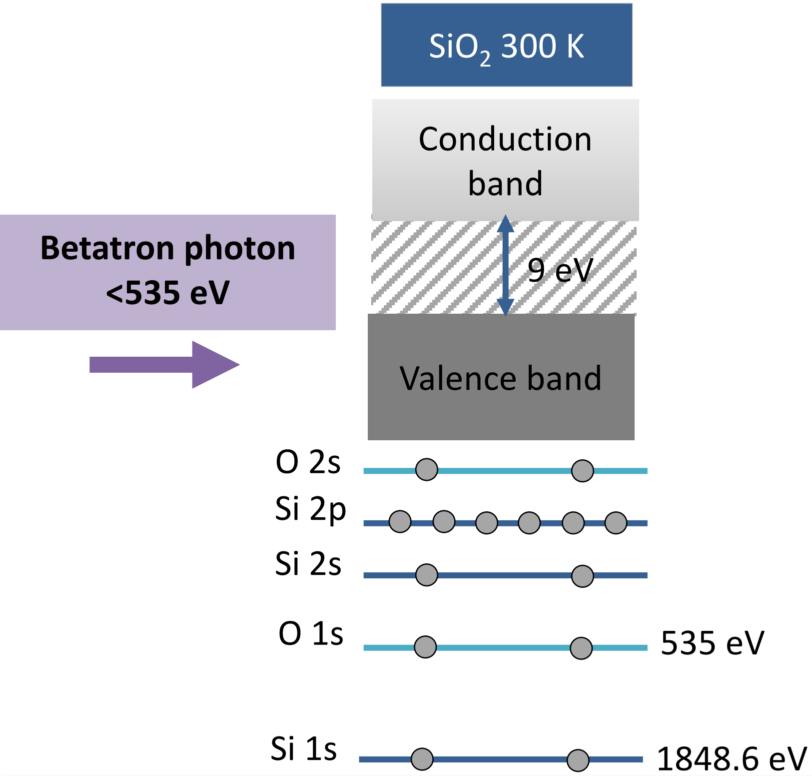


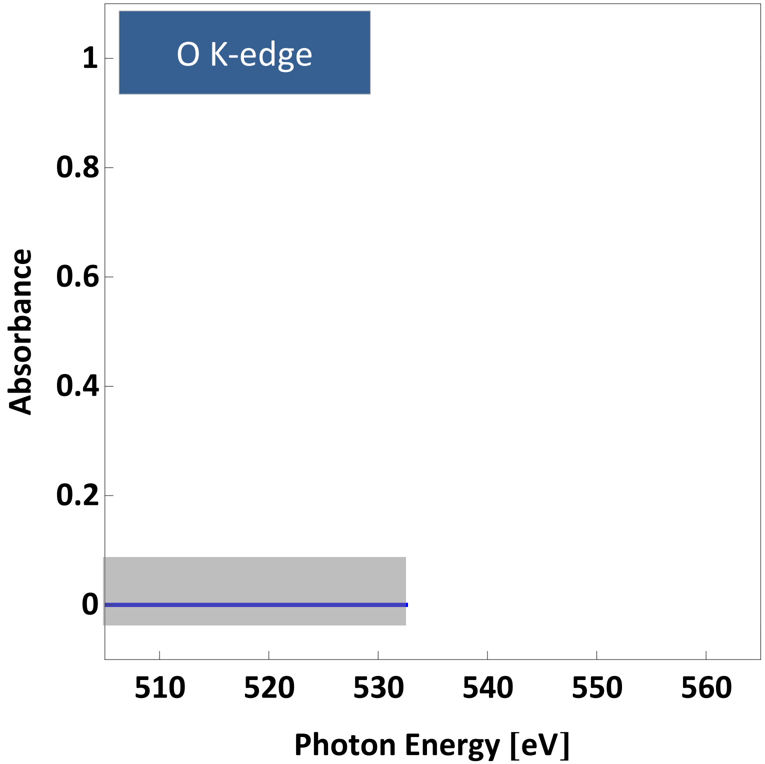
We performed absorption spectroscopy of SiO_2 a the O K-edge (535 eV)



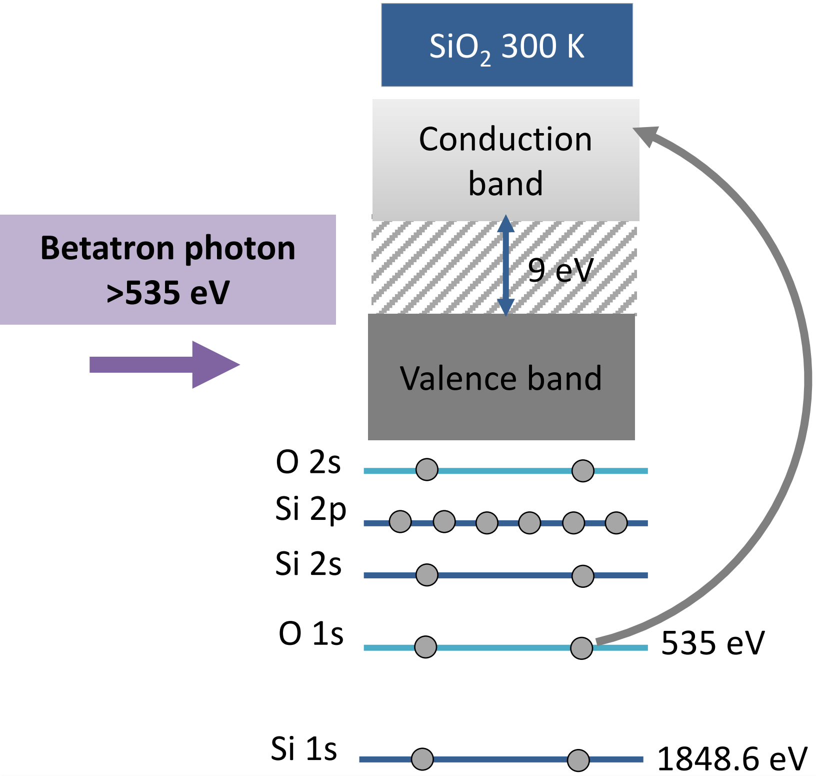


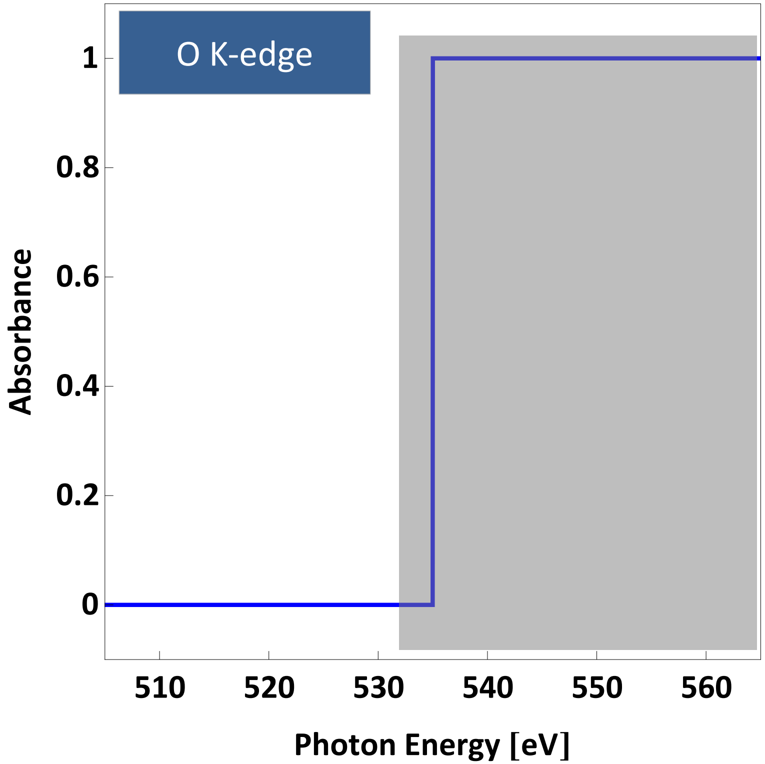
No absorption of x-ray probe photons below O K-edge energy



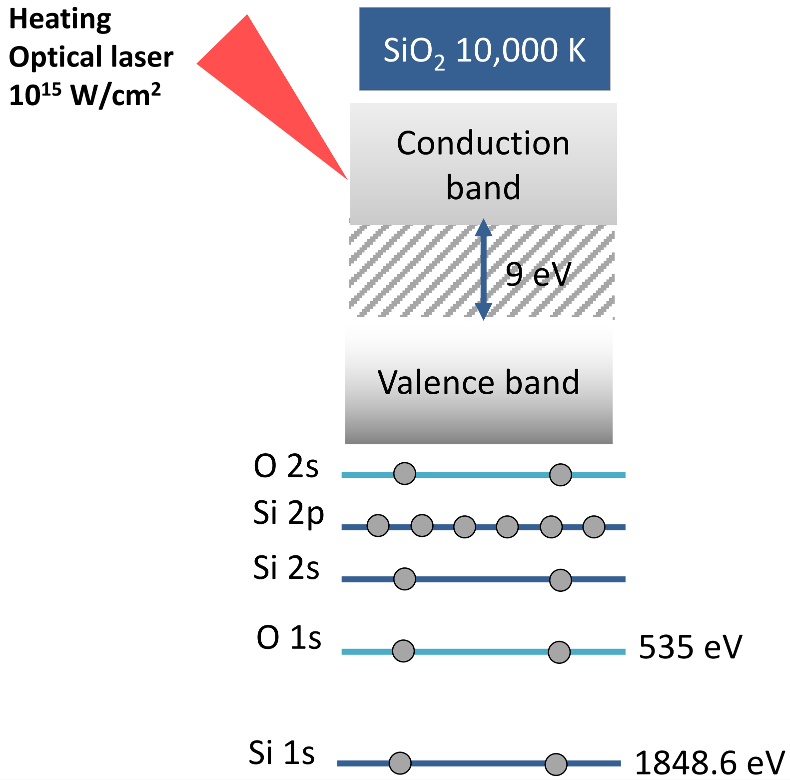


Sharp transition corresponds to strong absorption of x-ray photons for energies above the O K-edge

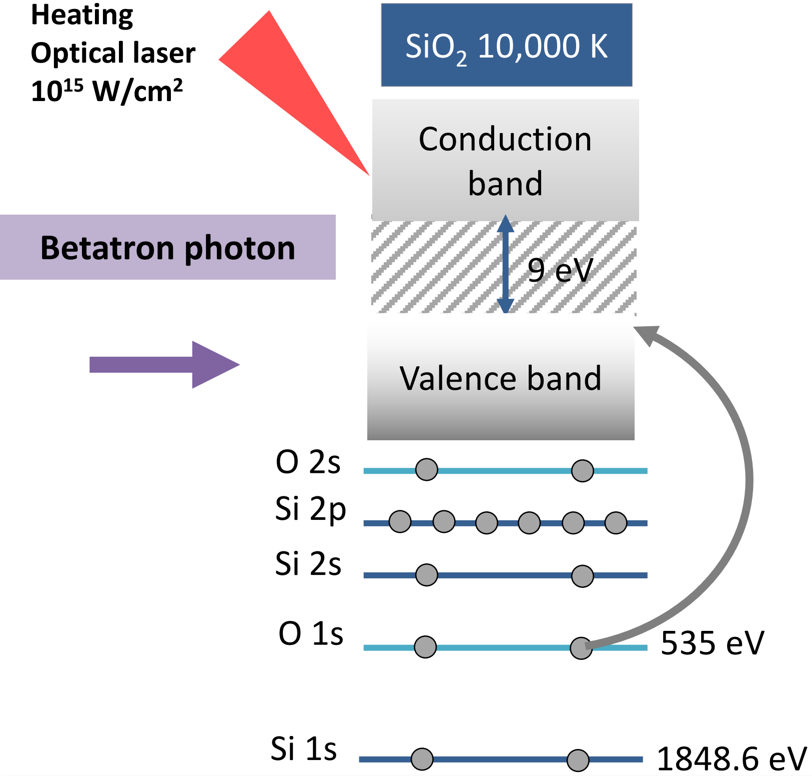


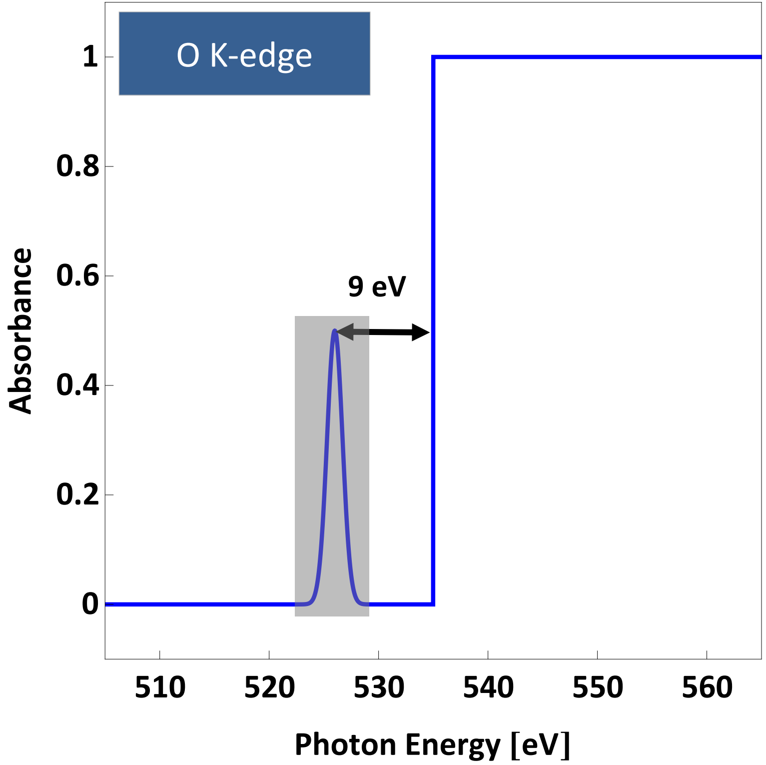


Multiphoton absorption causes electrons to cross the bandgap and leave vacancies in the valence band

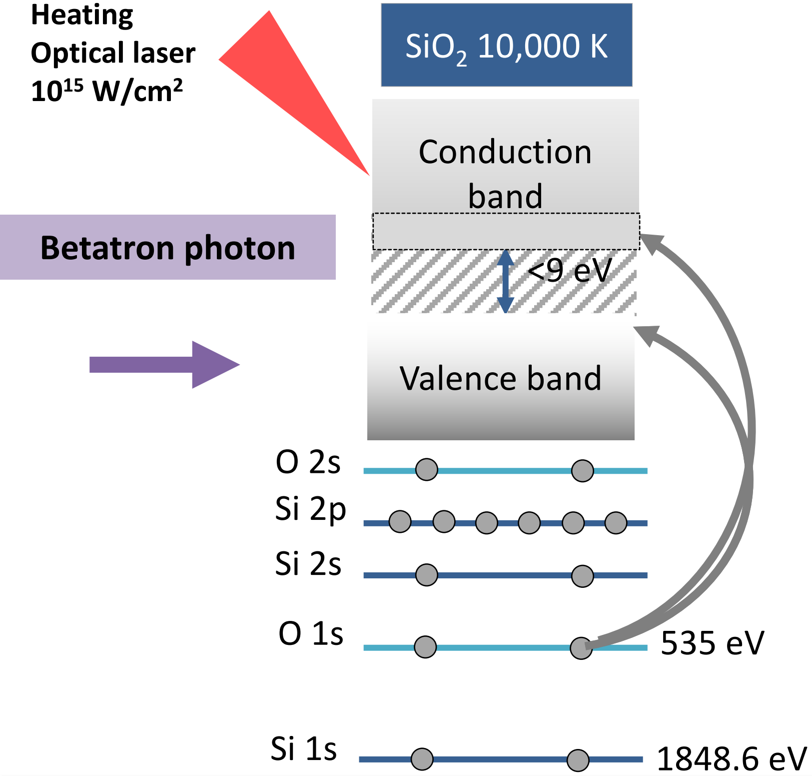


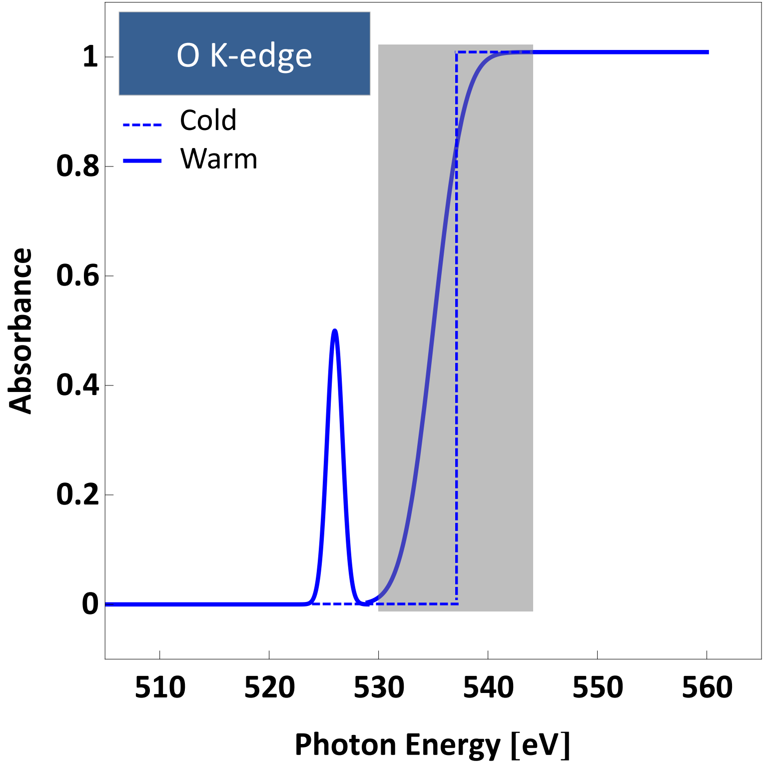
1s-valence band transitions are now authorized: strong absorption peak 9 eV below the edge



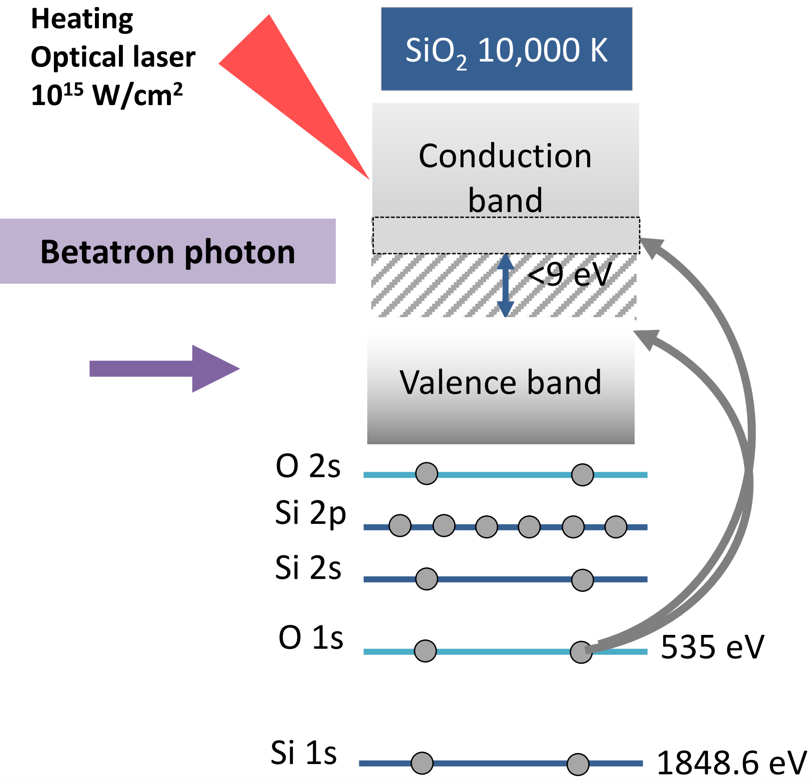


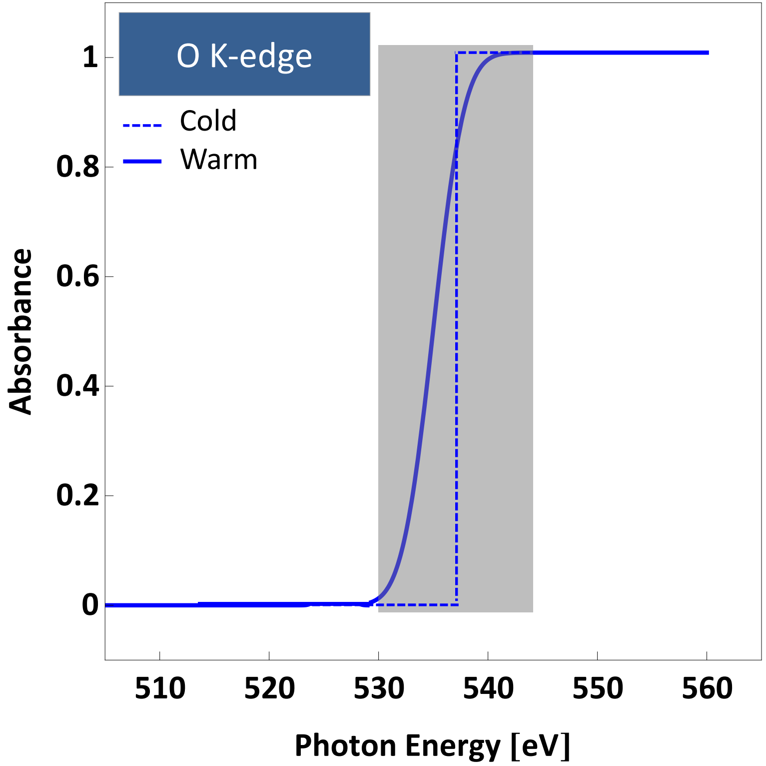
Defect states also allow absorption within bandgap upon heating, K-edge is broadened and red shifted



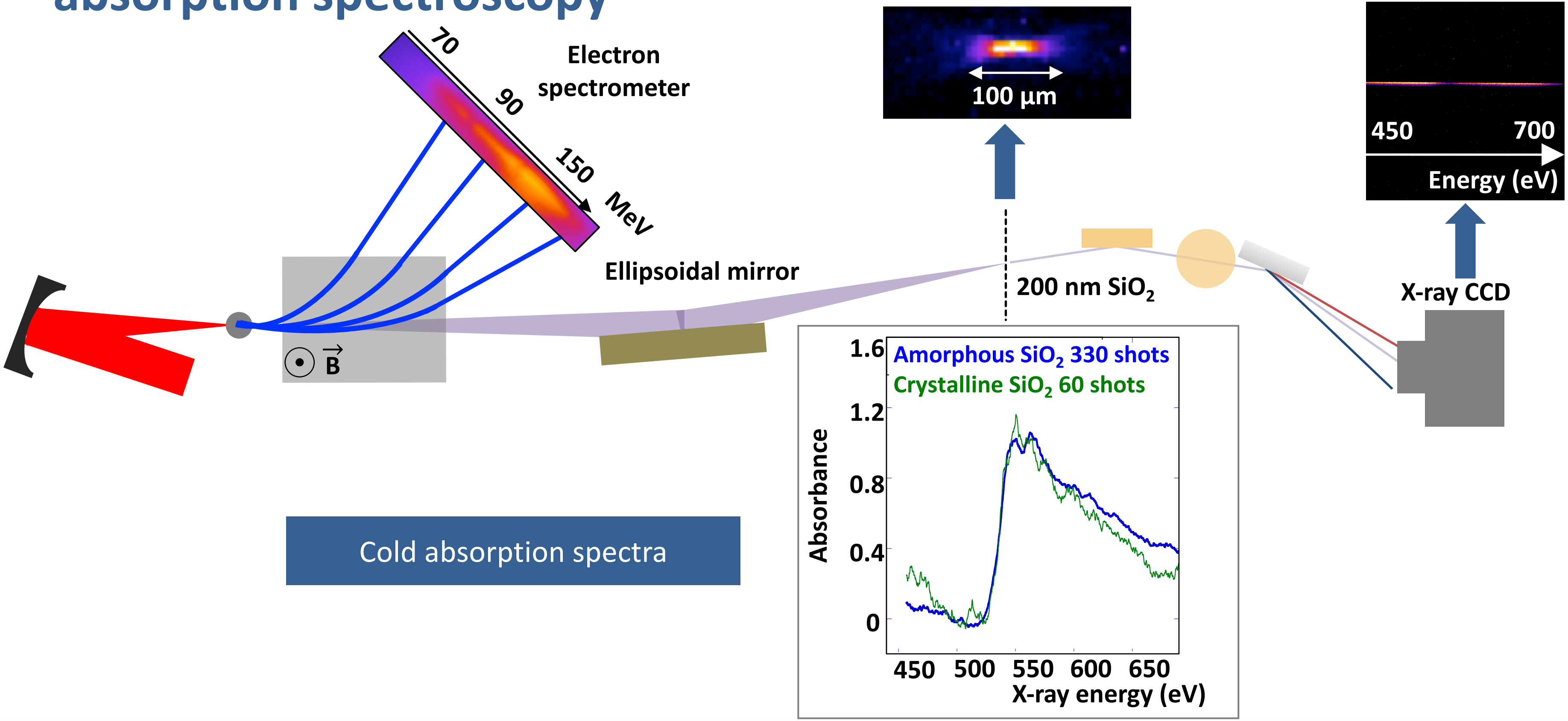


Defect states also allow absorption within bandgap upon heating, K-edge is broadened and red shifted



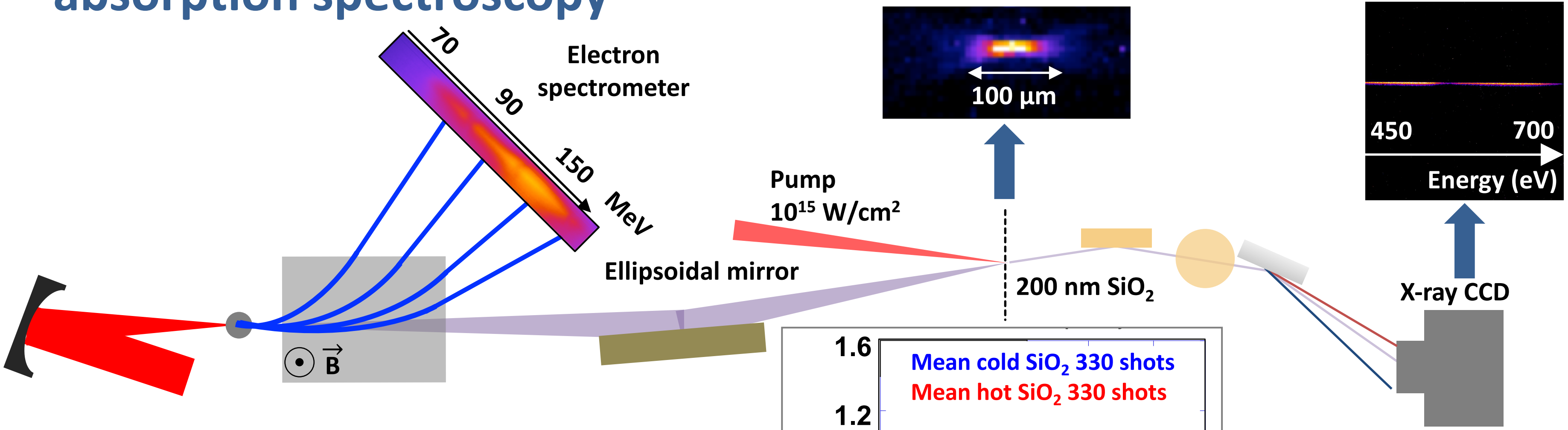


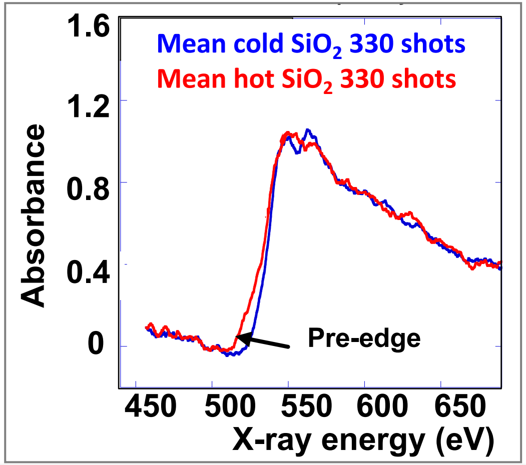
We have demonstrated the use of betatron x-rays as a tool for absorption spectroscopy



Cold absorption spectra

We have demonstrated the use of betatron x-rays as a tool for absorption spectroscopy

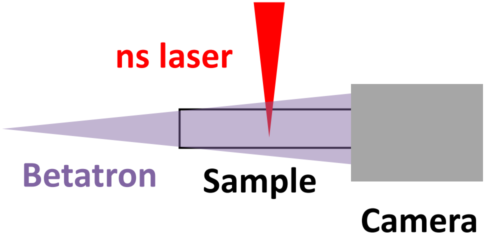


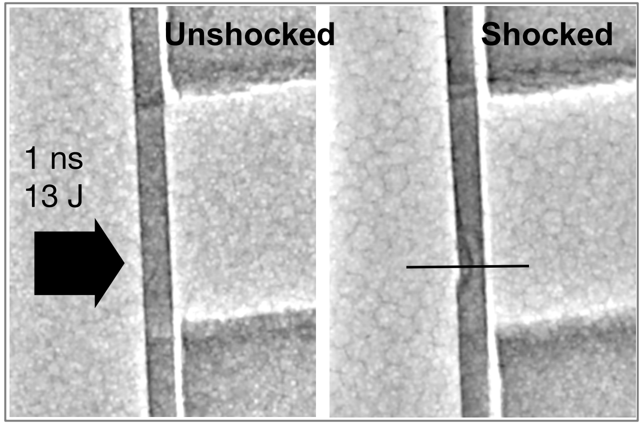


Cold/warm absorption spectra

Other applications are ongoing

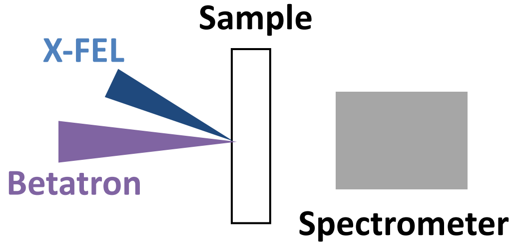
Phase contrast imaging of laser-driven shocks

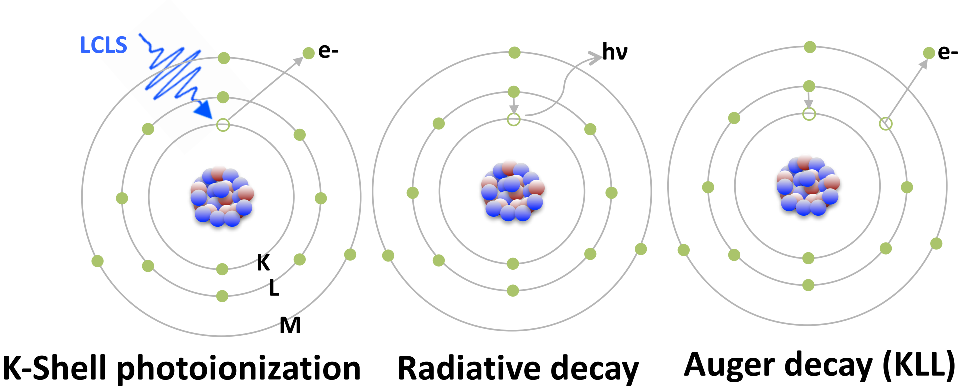




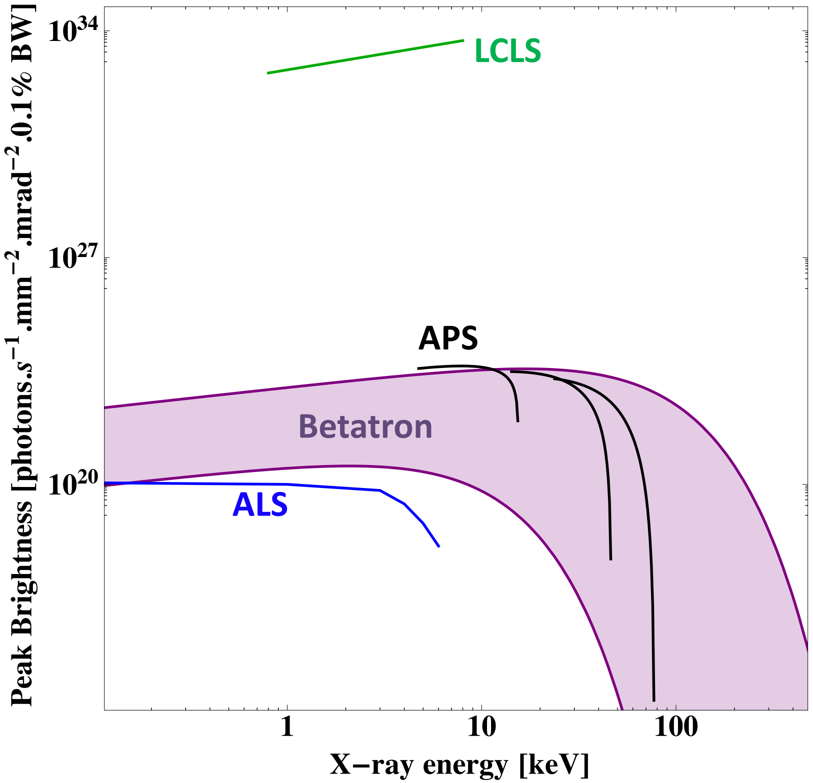
Courtesy of S. Mangles and J. Woods, Imperial College

Relaxation of metals driven by XFEL x-rays





Conclusion and perspectives



- We have demonstrated the production of ultrafast x-rays from laser-plasma accelerators with fs and ps laser pulses
- They are broadband (keV), ultrafast (fs), collimated (mrad), synchronized with drive laser within 50 fs
- They enable new applications
  - Study of ultrafast non-thermal melting in SiO2
  - Phase contrast imaging of laser-driven shocks
  - Study of opacity in HED matter
- Laser plasma accelerators can produce radiation from THz to gamma-rays and can be coupled to large scale lasers/free electron lasers

F. Albert and A.G.R. Thomas, Topical Review: Applications of laser wakefield accelerator-based light sources, *Plasma Physics and Controlled Fusion*, 58, 103001 (2016).