X-ray sources from laser-plasma acceleration: development and applications for high energy density sciences

HEDS Center Seminar

Presented by Félicie Albert
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LLNL
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Laboratory Directed Research and Development

U.S. DEPARTMENT OF ENERGY | Office of Science

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Lawrence Livermore National Laboratory

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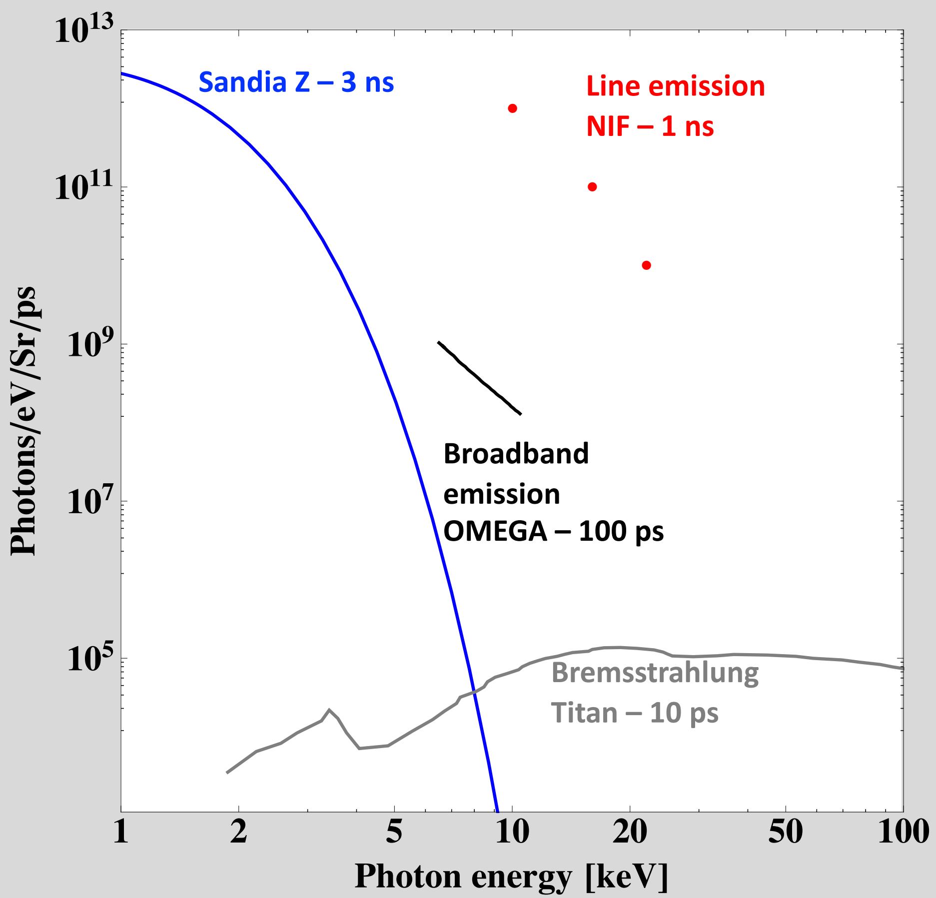
X-ray sources are widely used to probe high energy density science experiments

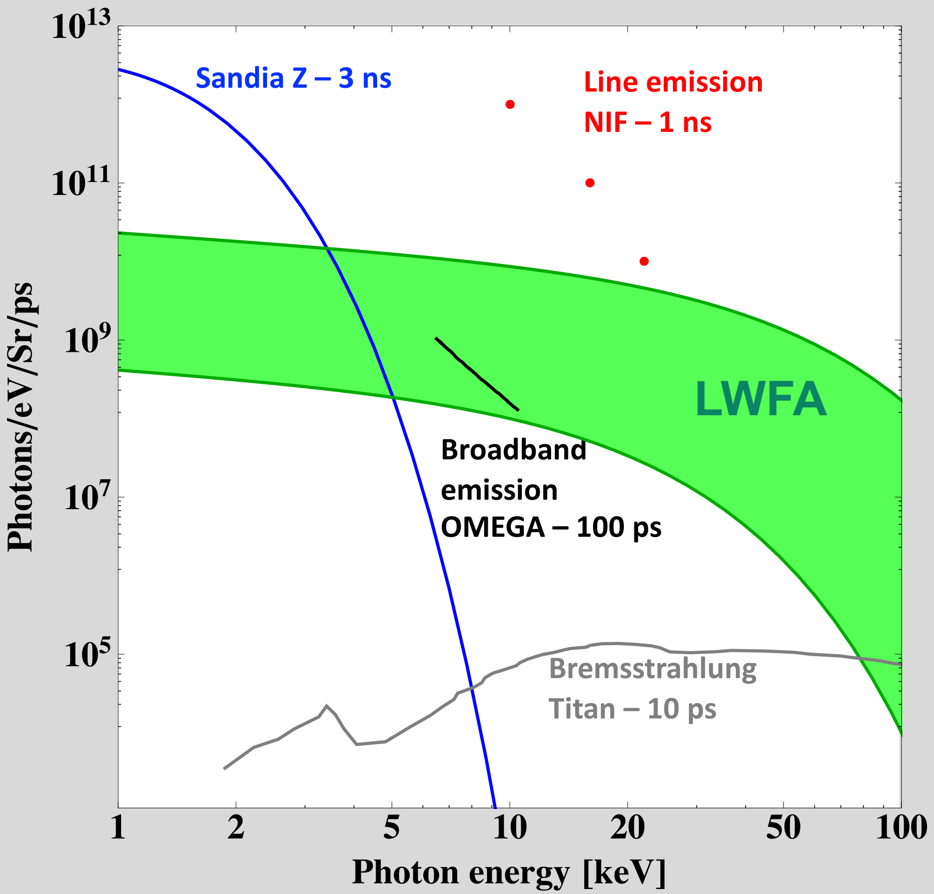
X-ray sources – Picosecond phenomena



- Barrios et al, HEDP 9, 626 (2013)
  - Radiography
  - X-ray diffraction
- Ping et al 84, RSI 123105 (2013)
  - X-ray absorption spectroscopy
- Bailey et al, Nature 517, 56 (2015)
  - X-ray opacity
- Jarrott et al, POP 21 031201 (2014)

We are developing x-ray sources based on laser-plasma acceleration to fill a gap in HED science

X-ray sources – Picosecond phenomena



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Albert et al, PRL 118, 134801 (2017)
Albert et al, PRL 111, 235004 (2013)
Lemos et al, PPCF 58 034108 (2016)
Lemos et al, PRL (in review)

Outline

- Laser-plasma acceleration: an alternative for high brightness x-ray sources
- Self modulated and blowout laser-wakefield acceleration regimes for high brightness x-ray source development
- X-ray source development at LLNL and applications
- Betatron x-ray source development at LCLS and applications
- Conclusion and perspectives

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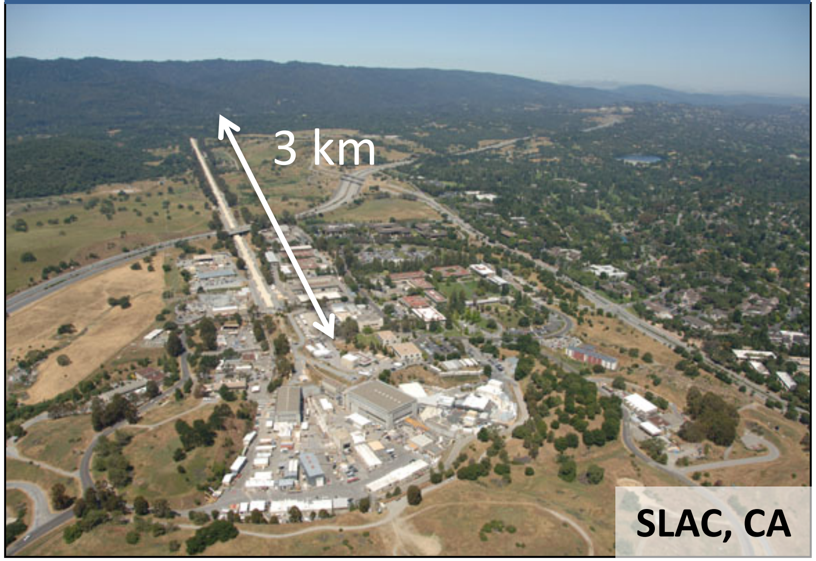
Conventional x-ray light sources are large scale national facilities

X-ray free electron laser: LCLS



Synchrotron: APS

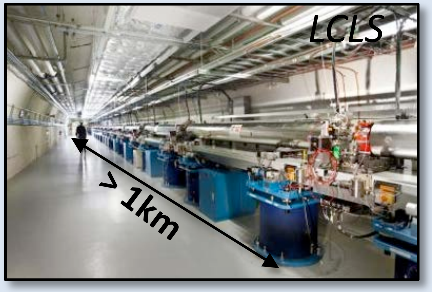
Sources driven by laser-plasma accelerators offer an alternative

Synchrotron

Electrons from storage ring wiggled by undulators

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

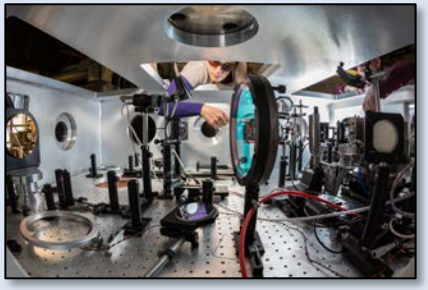
Free Electron Laser



Electrons from linac wiggled by undulators

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

Laser-plasma

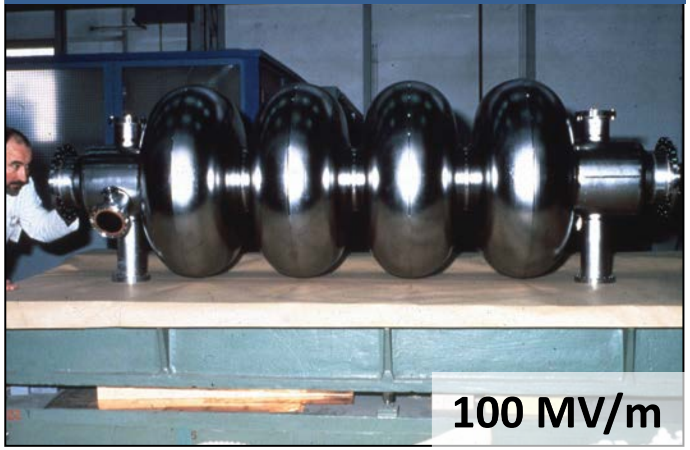
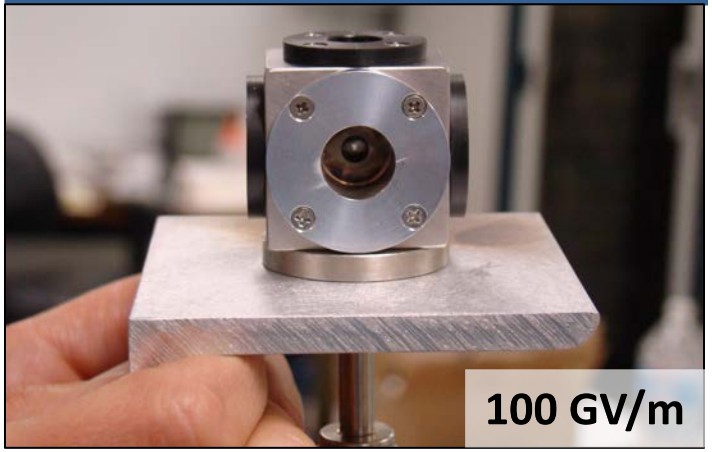


Electrons from laser-produced plasma wiggled by plasma

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

F. Albert, *Laser wakefield accelerators: Next Generation Light Sources,* **Optics and Photonics News**, 29, 1, 42-49 (2018)

Plasmas can naturally sustain large acceleration gradients

RF Cavity	Gas cell – laser plasma
	
100 MV/m	100 GV/m

Acceleration gradient

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

Plasma frequency

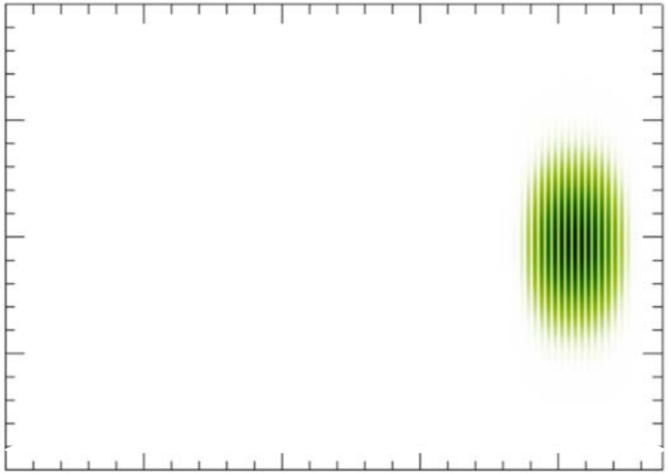
$$\omega_p = \sqrt{\frac{n_e e^2}{m\varepsilon_0}}$$

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

Intense laser pulses drive electron plasma waves

Wake behind a boat

Plasma wave behind a laser



Nuno Lemos, LLNL

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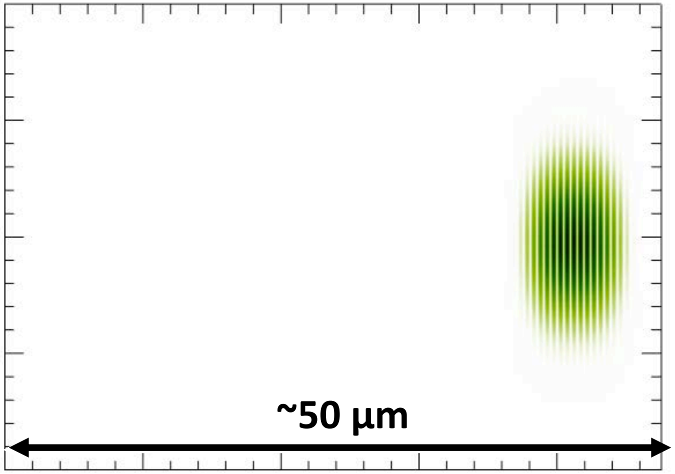
Plasma wave behind a laser



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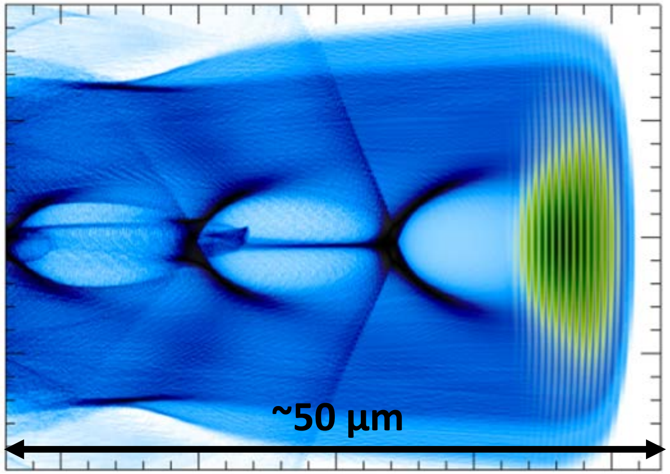

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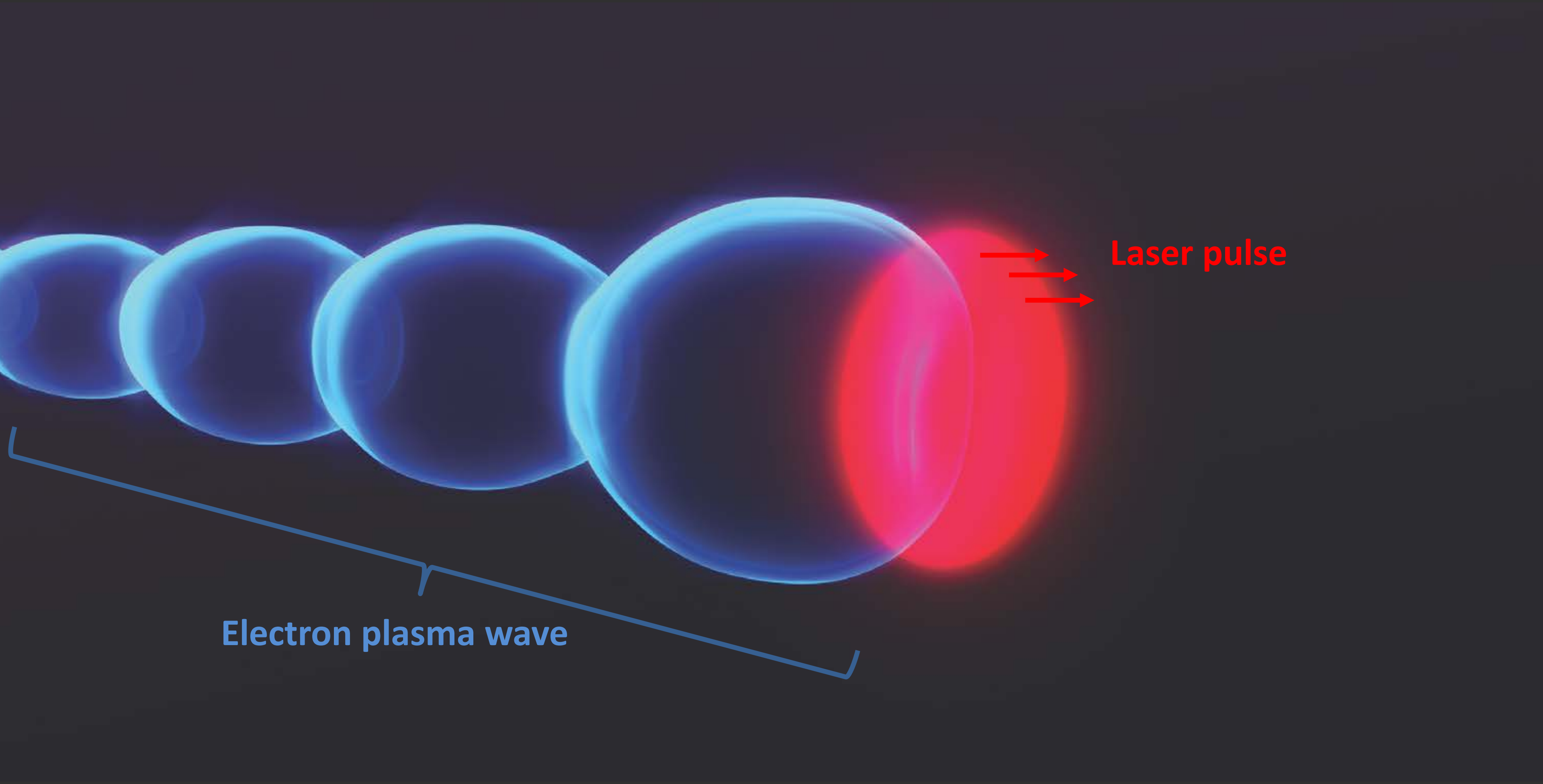
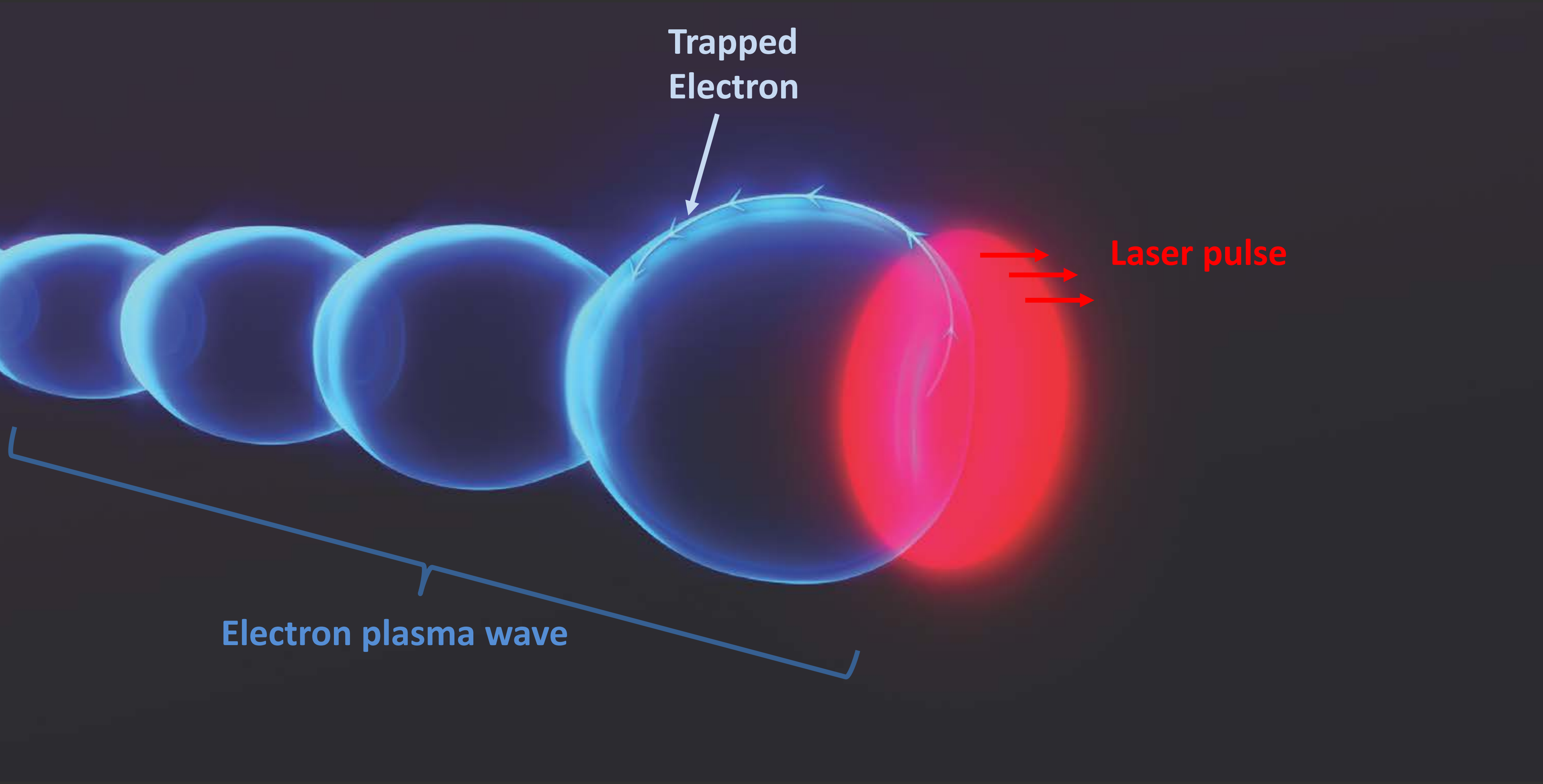


F. Albert et al, Laser wakefield accelerator based light sources: potential applications and requirements, *Plasma Phys. Control. Fusion* 56 084015 (2014)



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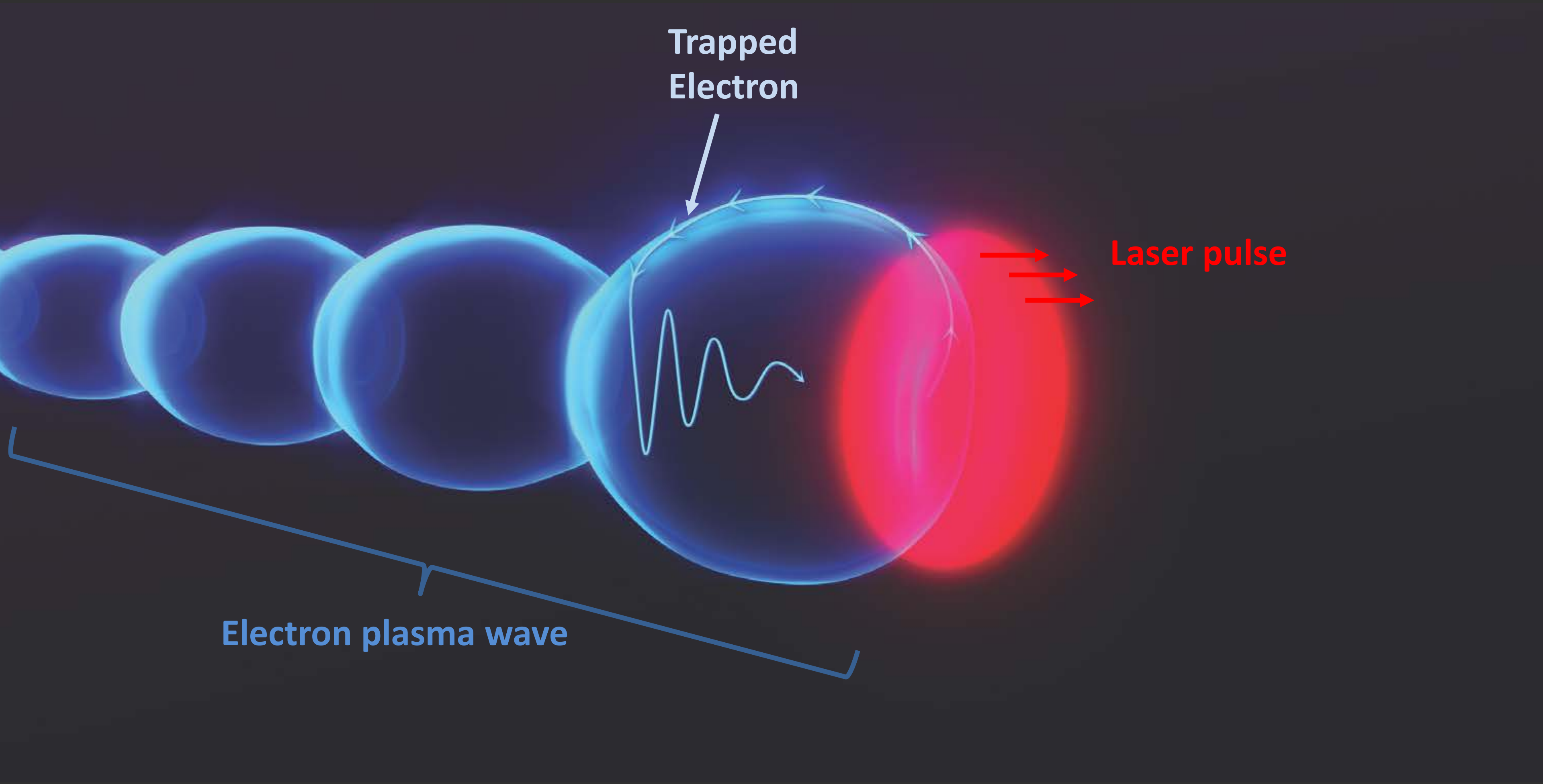

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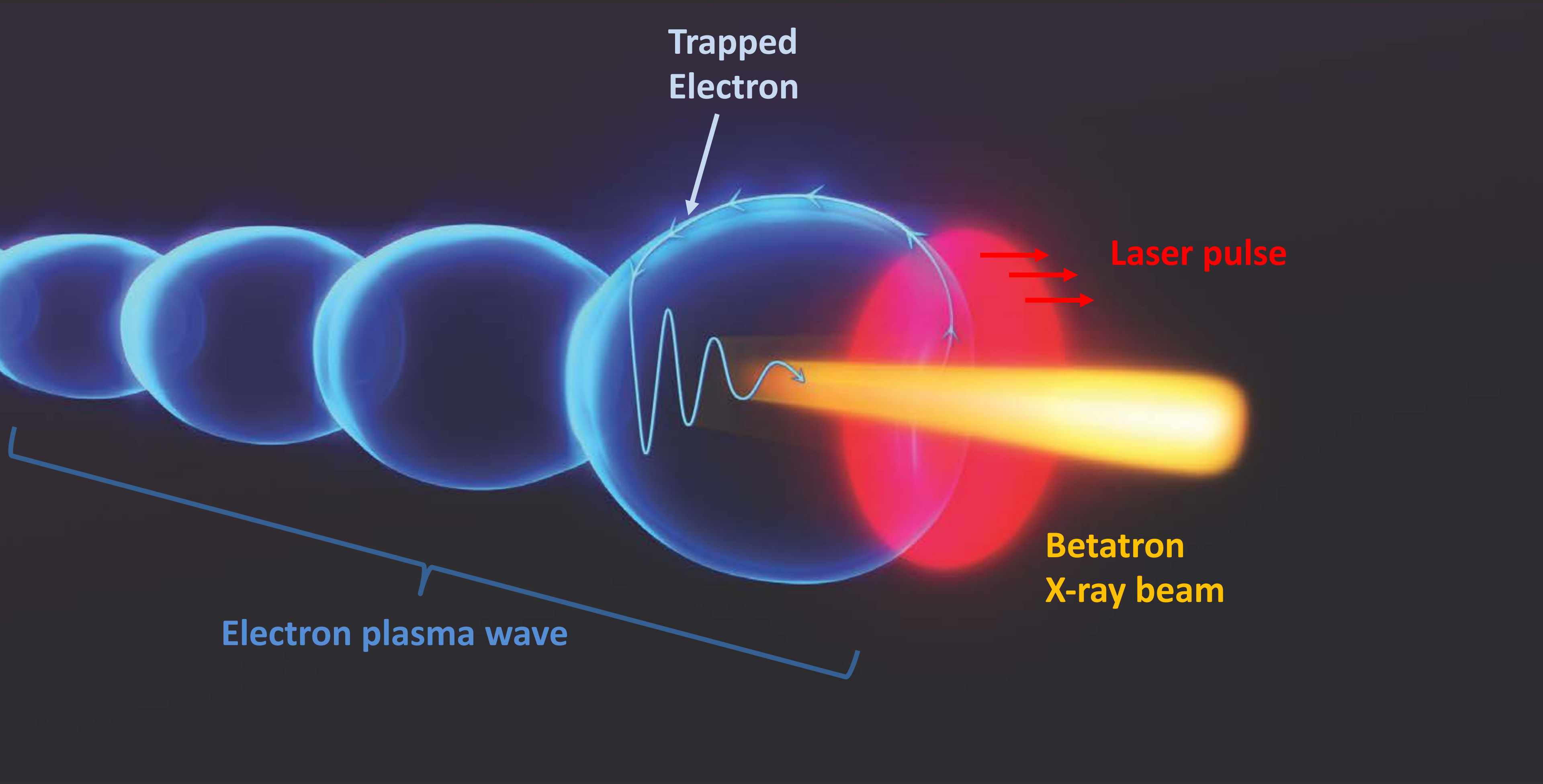

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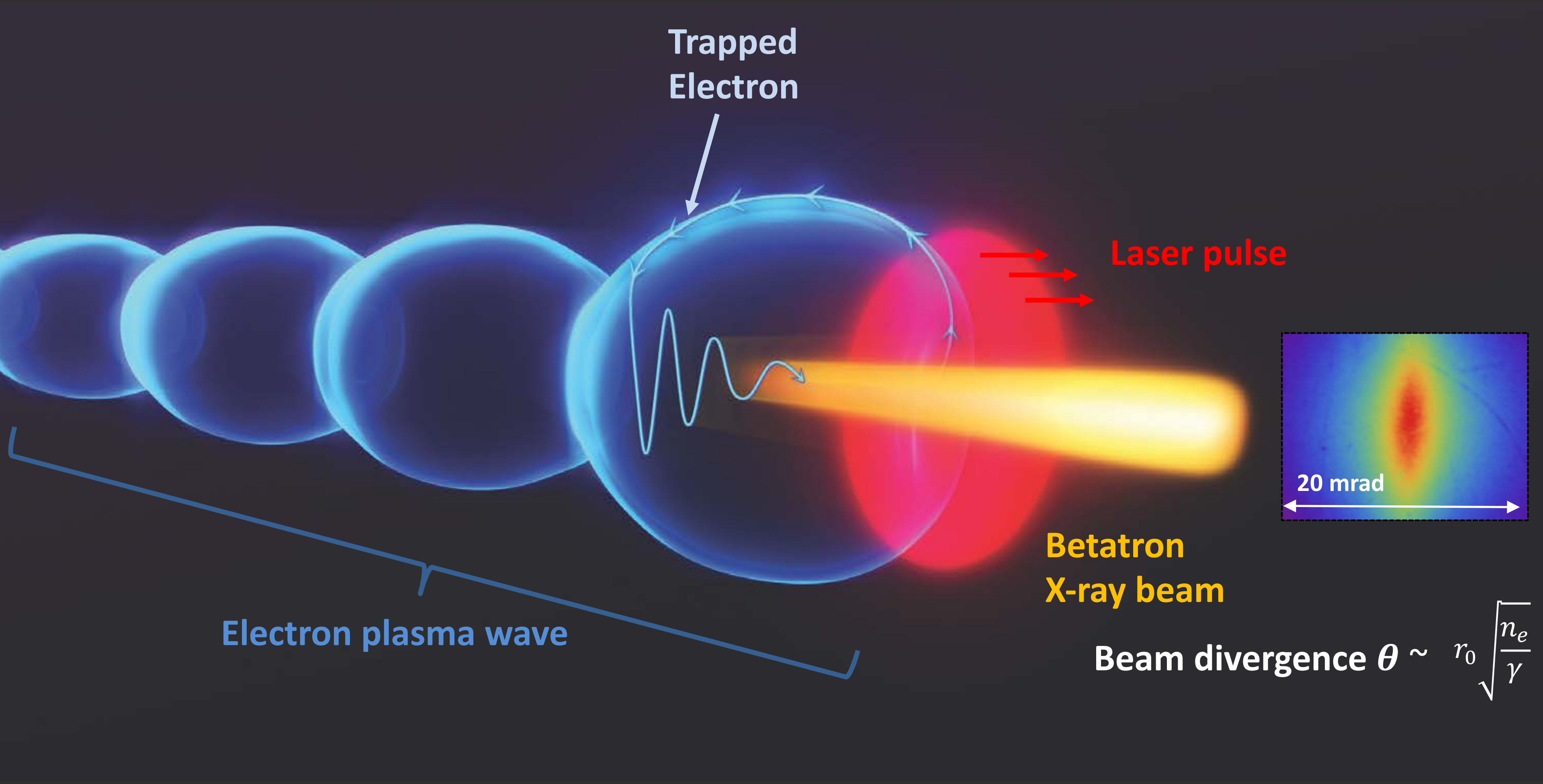

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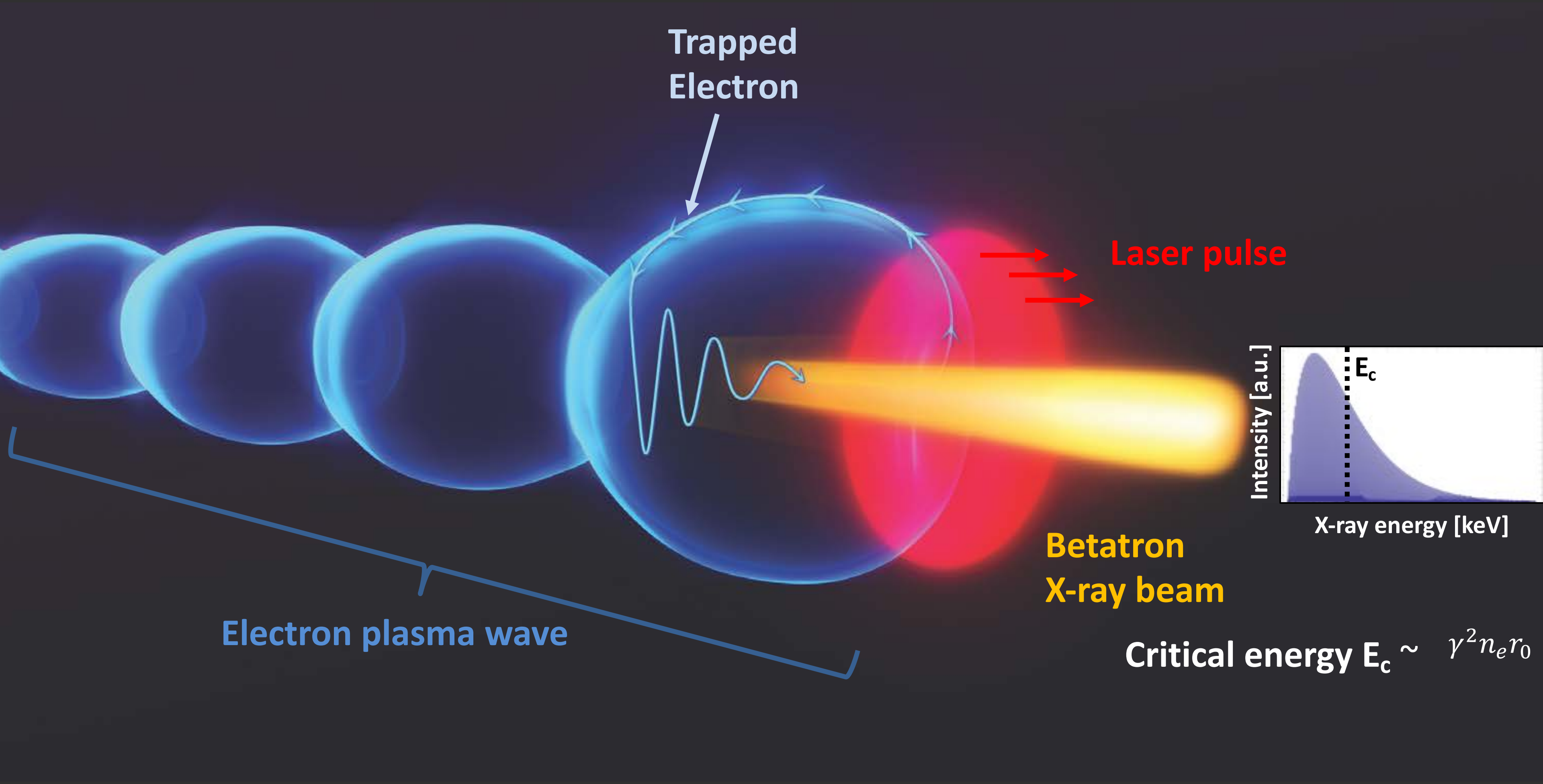
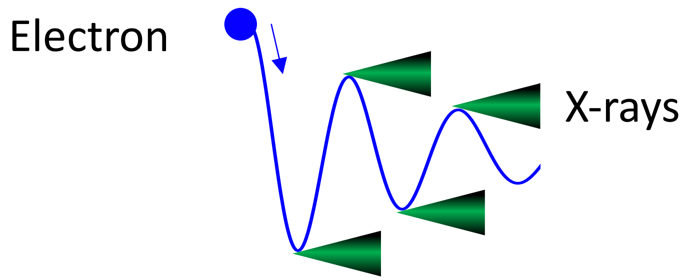


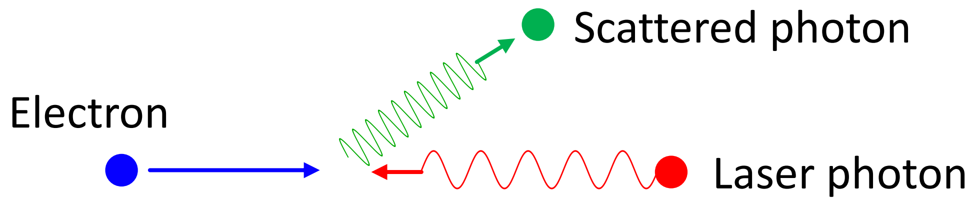
F. Albert et al, Laser wakefield accelerator based light sources: potential applications and requirements, *Plasma Phys. Control. Fusion* 56 084015 (2014)

Laser wakefield acceleration can produce x-ray and gamma-ray sources using several processes

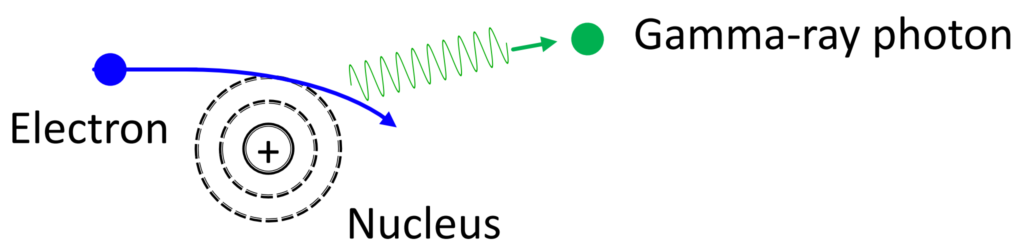
1 **Betatron x-ray radiation**
keV



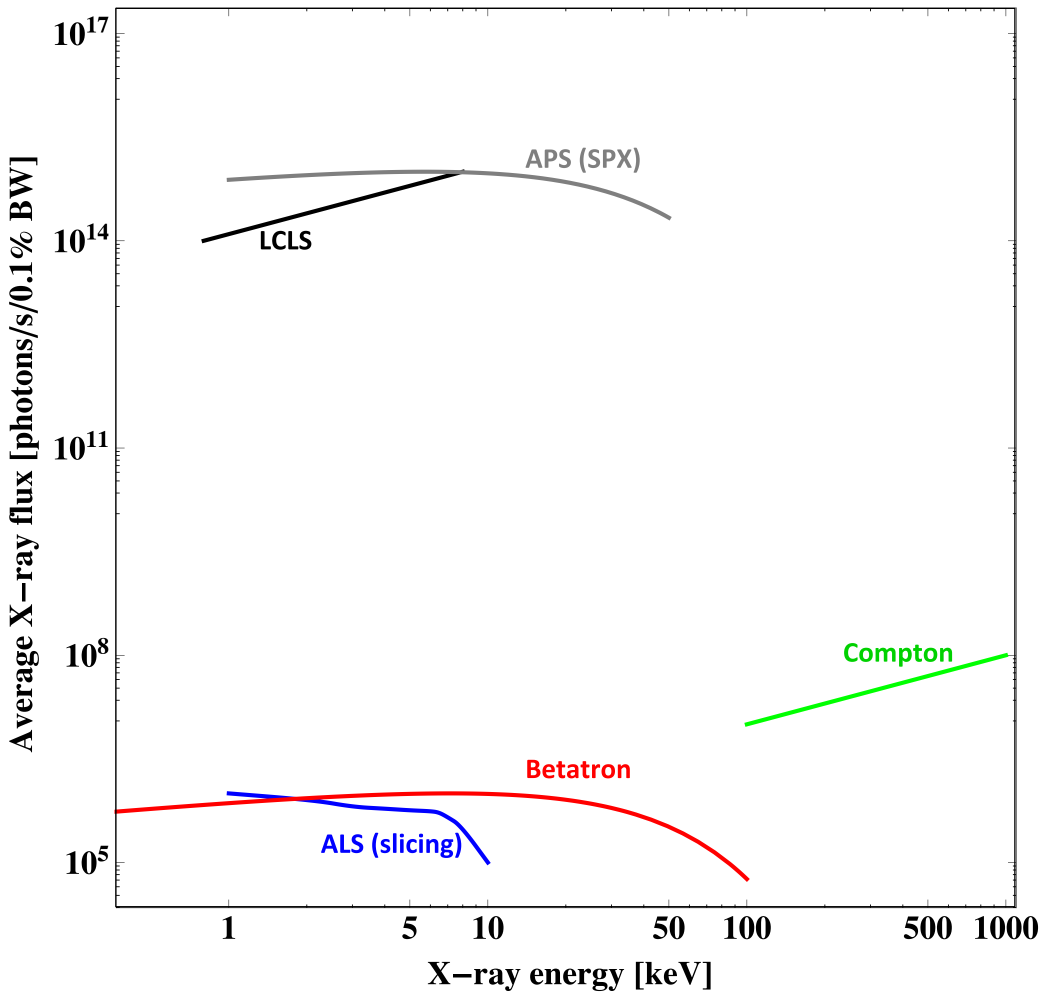
2 **Compton scattering**
keV – MeV



3 **Bremsstrahlung**
MeV



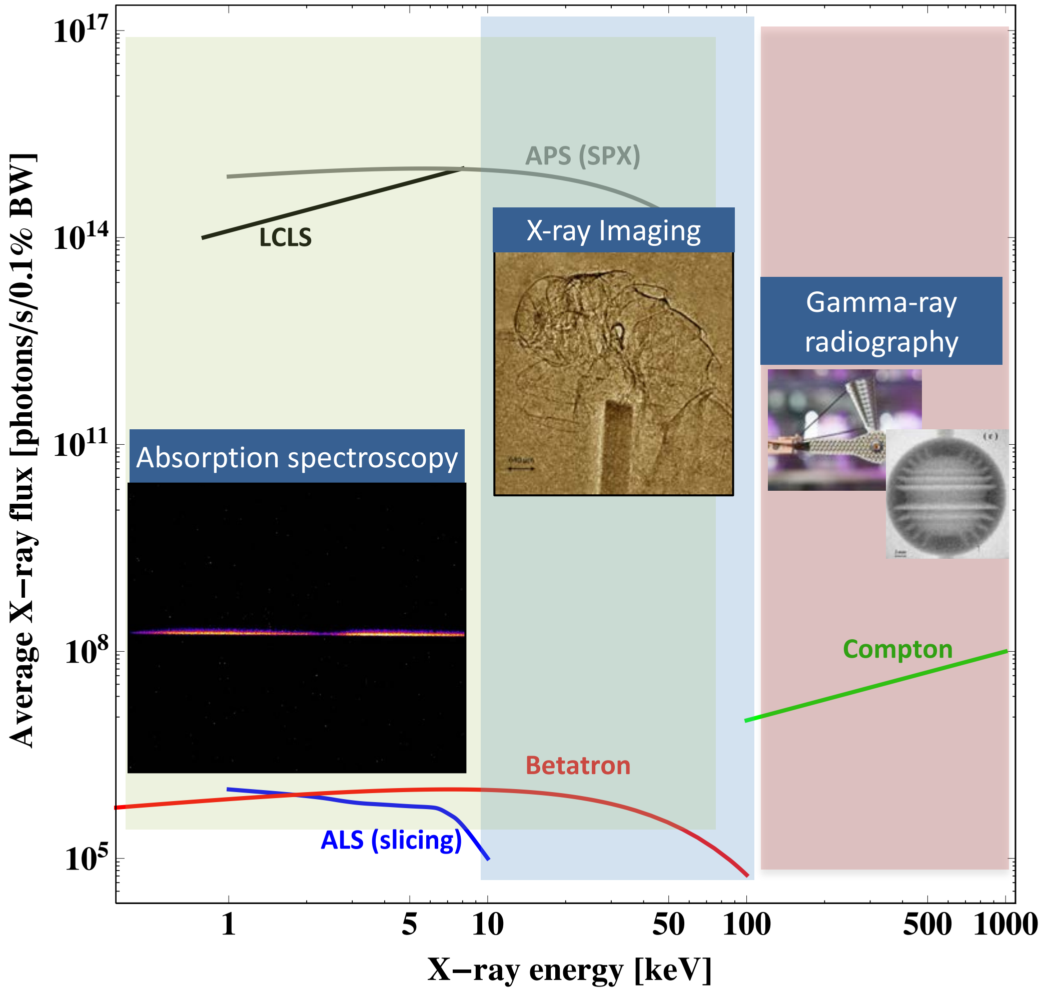
X-ray sources from LWFA have unique properties compared to conventional light sources



Unique properties

- Broadband (keV - MeV)
- Ultrafast (fs-ps)
- Collimated (mrad)
- Small source size (µm)
- Synchronized with drive laser or XFEL within <ps

X-ray sources from LWFA have unique properties compared to conventional light sources



Unique properties

- Broadband (keV - MeV)
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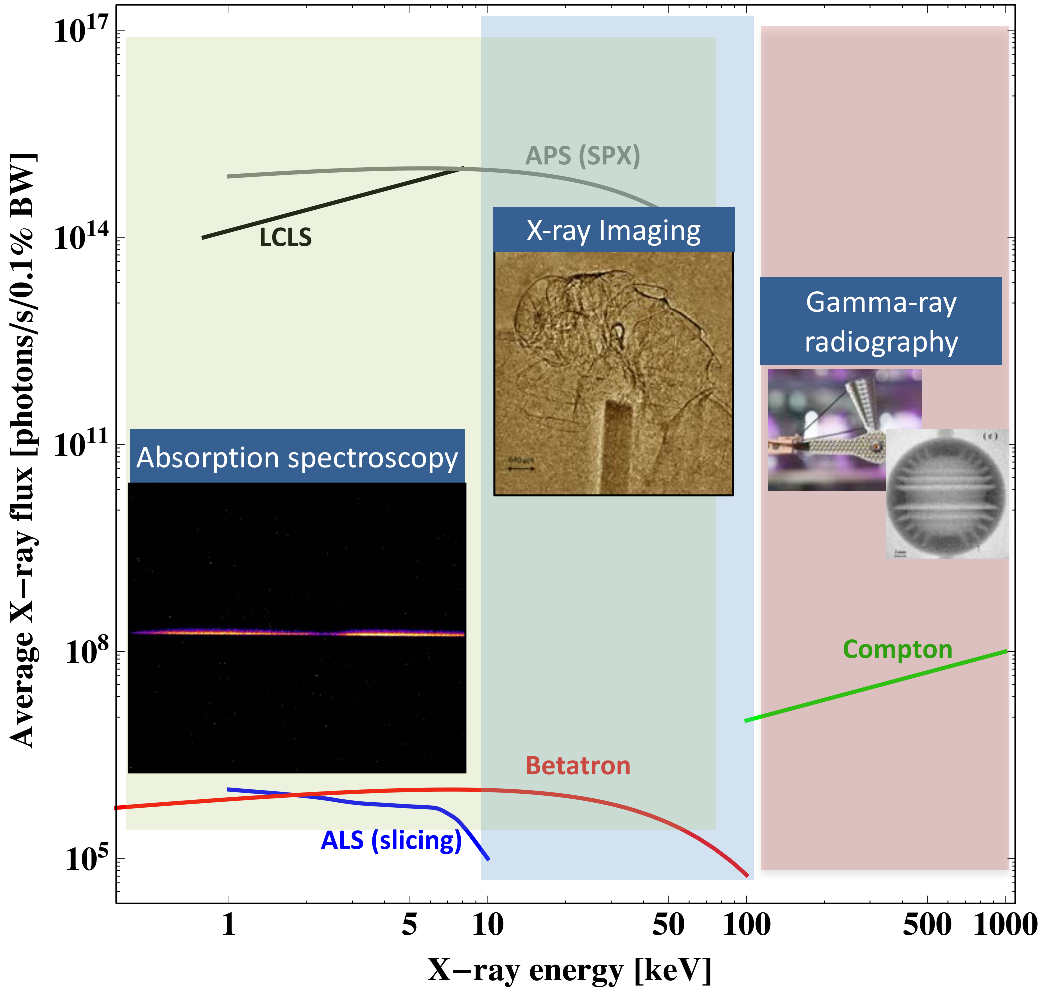
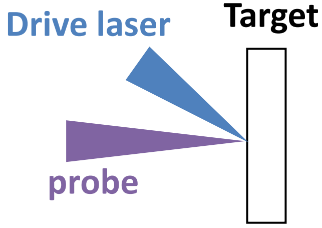
The sources and techniques we are developing are important for applications in HED science



Applications

- High pressure and shock physics
- Equation of state
- Material strength
- Phase transitions
- Opacity
- Laboratory astrophysics



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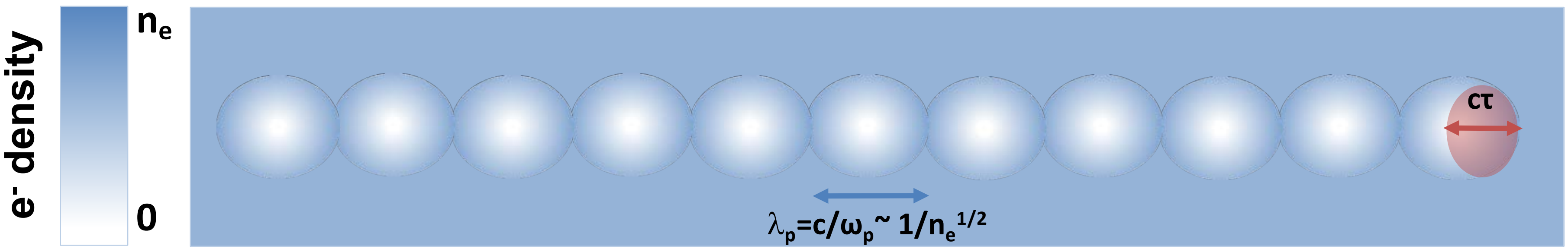
LWFA light sources are typically produced with ultrashort laser pulses in the blowout regime ($c\tau \sim \lambda_p/2$)



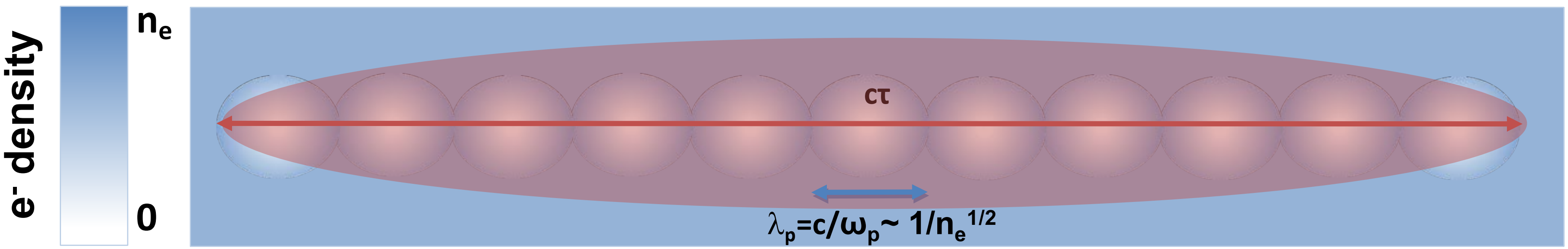
Condition to be in the blowout regime $c\tau \sim 1/n_e^{1/2}$

- 30 fs $n_e \sim 10^{19}$ cm^{-3}
- 1 ps $n_e \sim 10^{16}$ cm^{-3}

To drive a wake we need $P > P_c \sim 1/n_e \sim \tau^2$

- 30 fs $P_c \sim 2$ TW
- 1 ps $P_c \sim 2$ PW

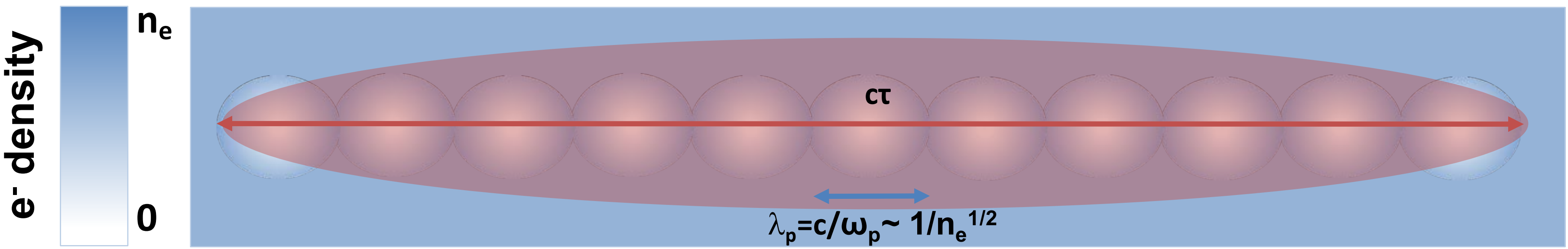
Self modulated laser wakefield acceleration (SMLWFA) is easier to achieve with picosecond scale lasers ($c\tau >> \lambda_p$)

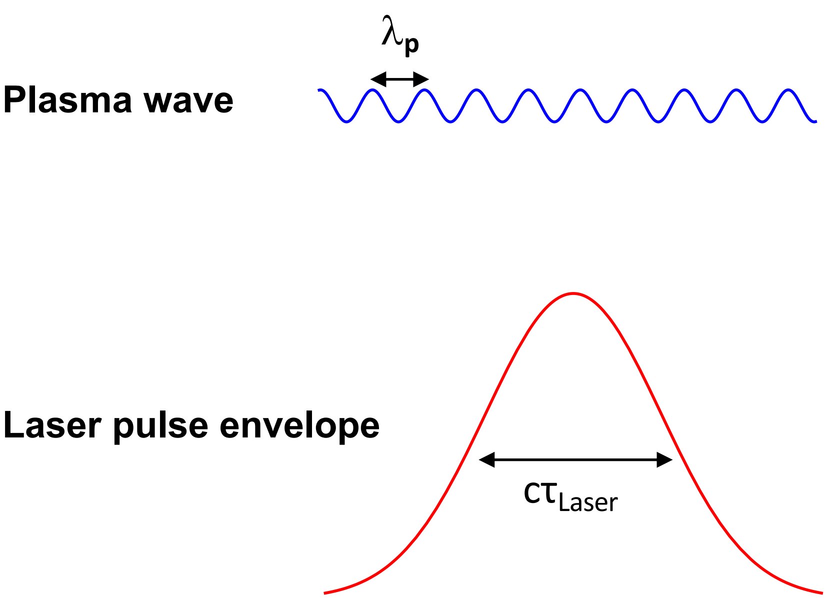


Condition to be in the self modulated regime $c\tau >>\sim 1/n_e^{1/2}$ ➡ 1 ps $n_e \sim 10^{19}$ cm^{-3}

To drive a wake we need $P > P_c \sim 1/n_e$ ➡ 1 ps $P_c \sim 2$ TW

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



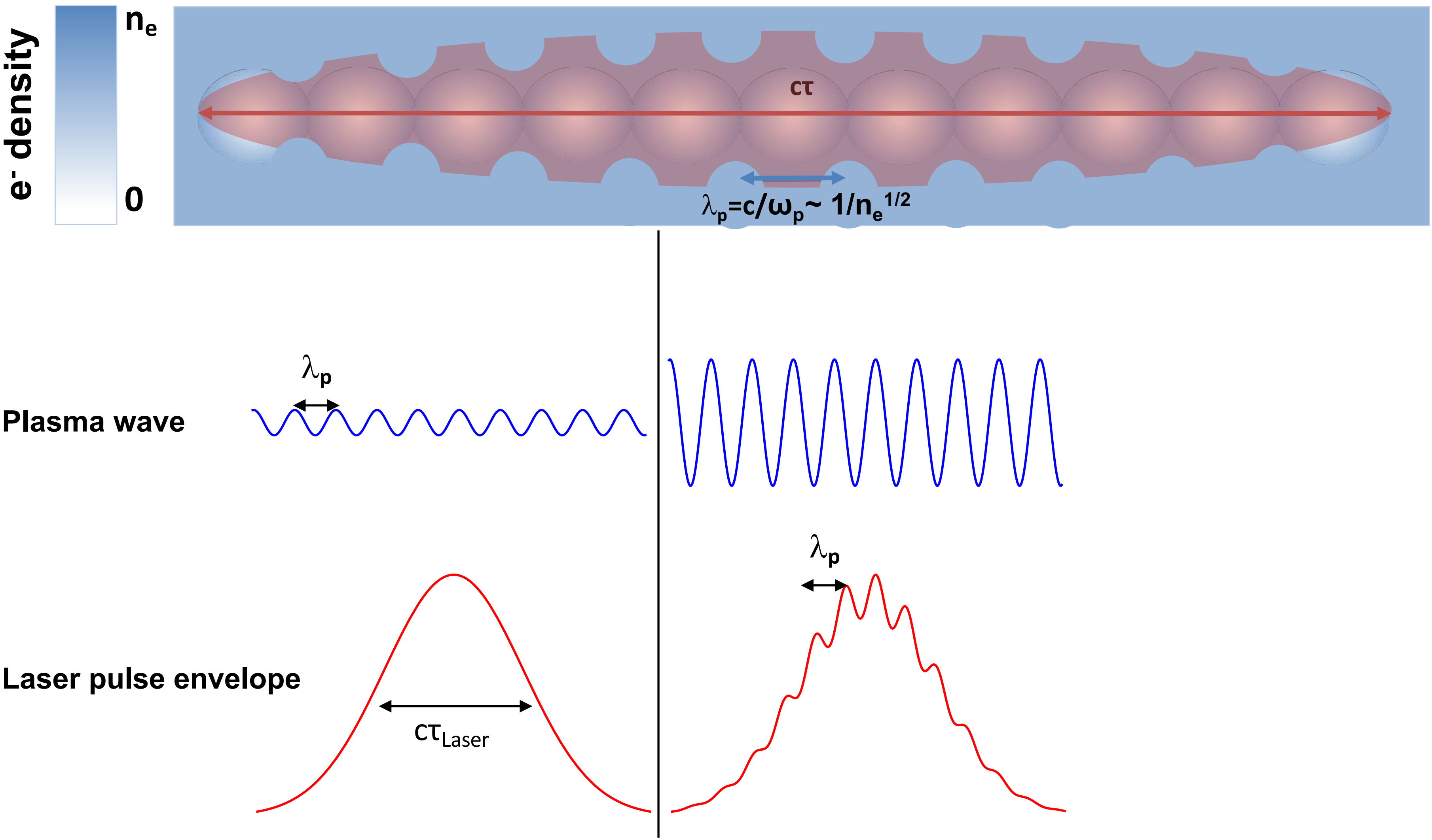


Matching conditions

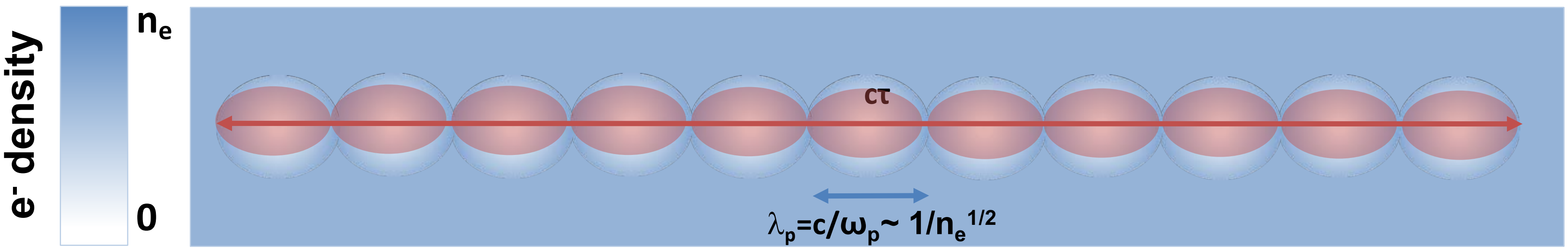
$\omega_0 = \omega_s \, +/- m\omega_{plasma}$

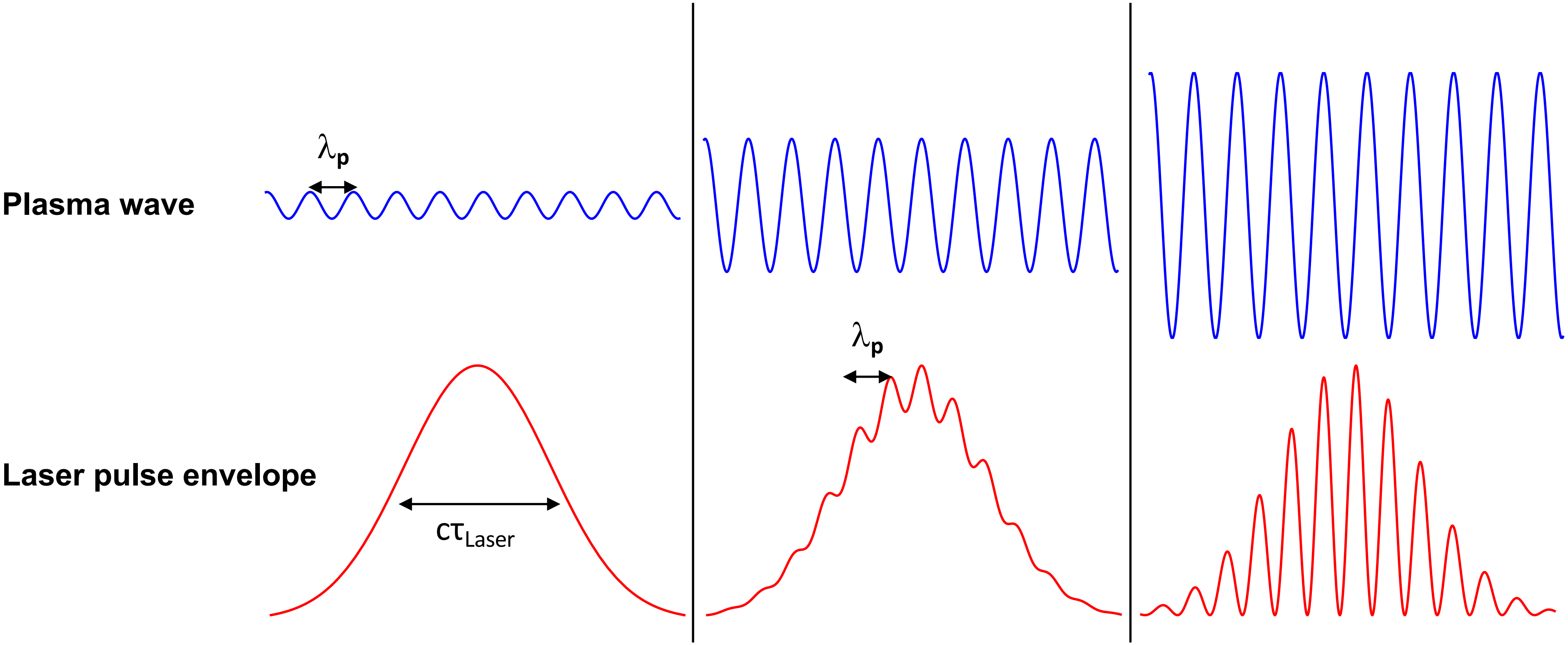
$\mathbf{k_0} = \mathbf{k}_s \, +/- m\mathbf{k}_{plasma}$

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

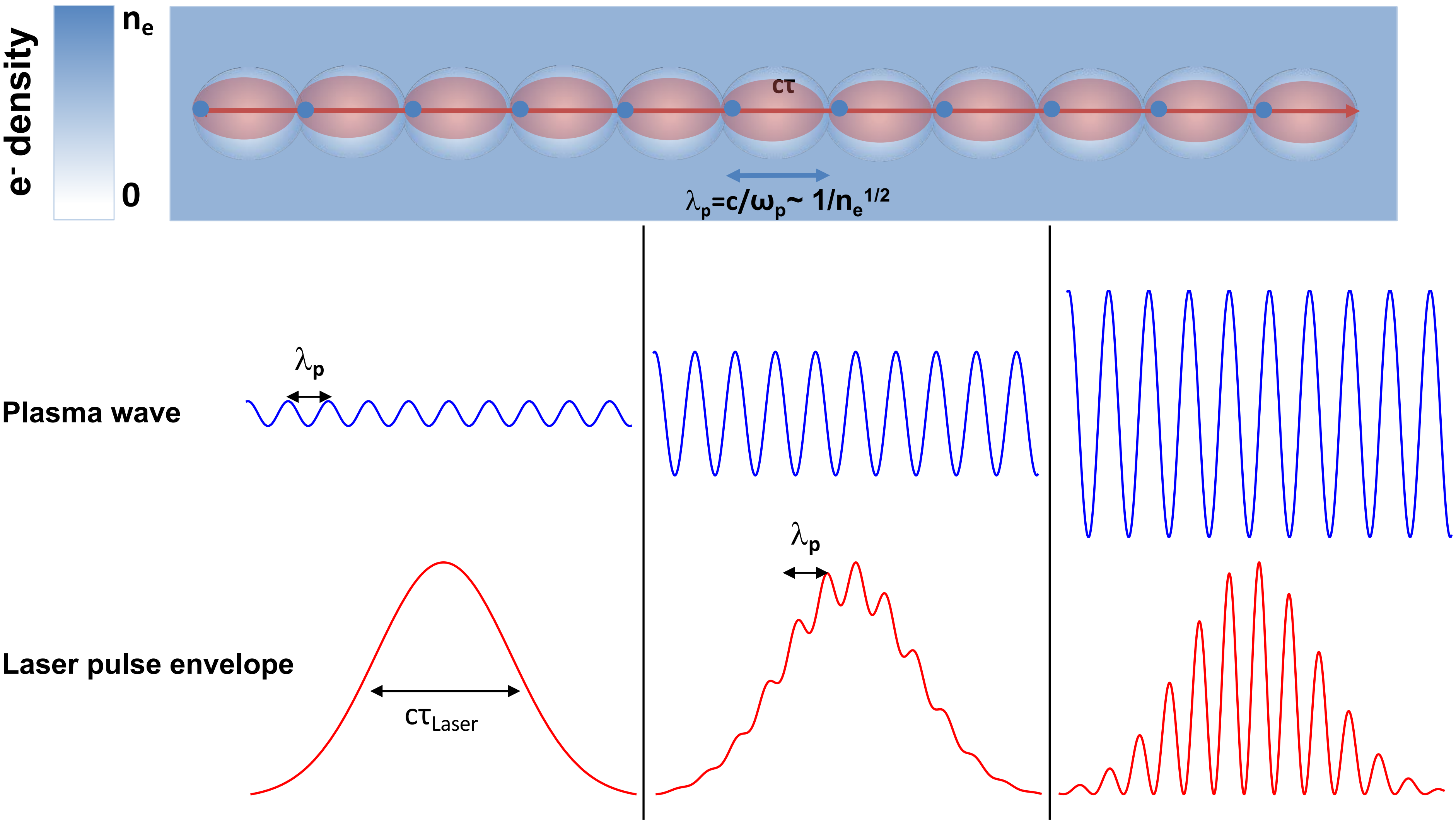


This beat pattern exerts a force on the plasma electrons and the plasma wave amplitude grows until wave breaking

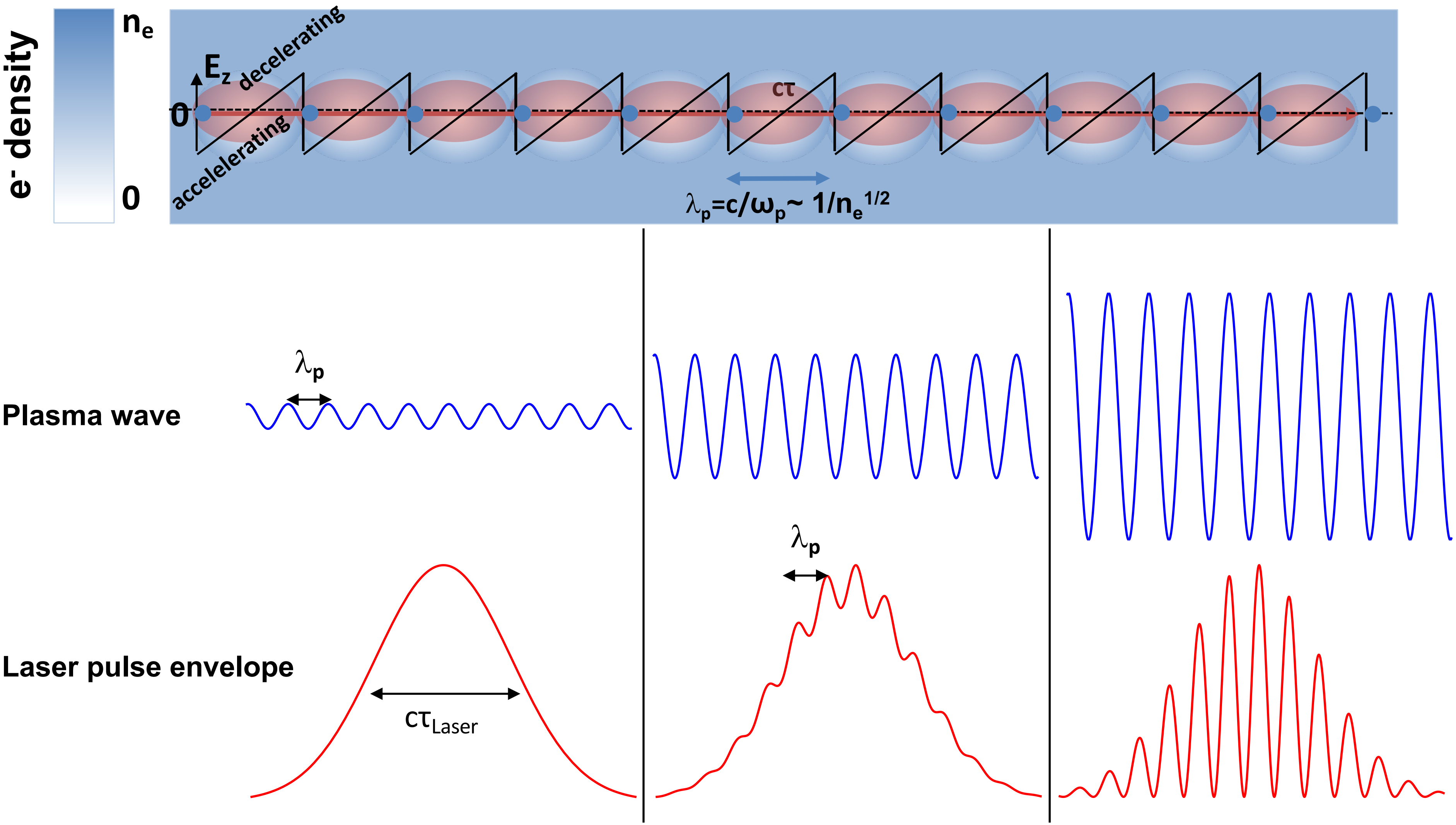




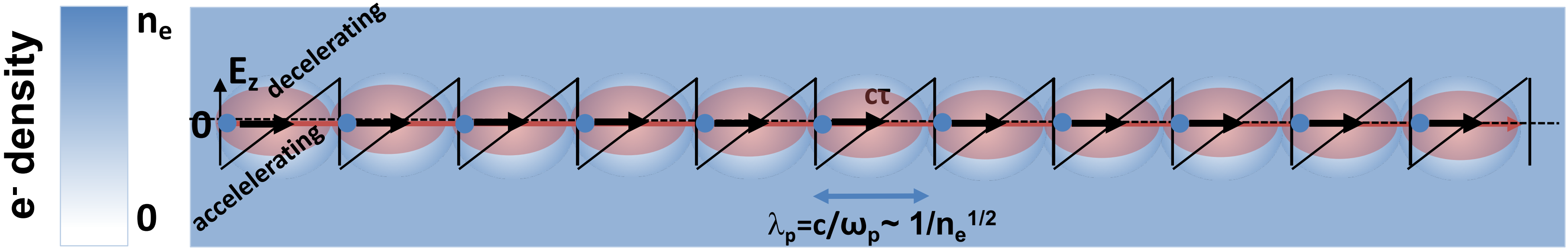
Upon wave breaking electrons are trapped into the plasma wave



Trapped electrons undergo acceleration in the longitudinal field of the plasma wave



Electrons trapped in plasma wave are accelerated to relativistic energies



Electron acceleration

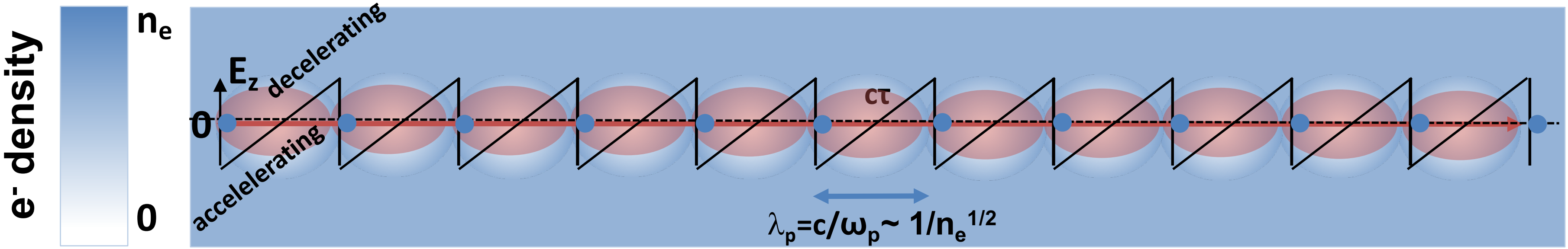
Longitudinal E field from plasma wave: **self-modulated wakefield acceleration (SMLWFA)**[1]

Electrons overlap with laser field: **direct laser acceleration (DLA)[2],** dominant if $I > 10^{20}$ W/cm^2

Electrons trapped into several plasma wave periods: **continuous energy spectrum**

[1] ***Modena et al, Nature (1995), Joshi et al, PRL (1984)***
[2] ***S. Mangles et al, PRL (2006), Gahn et al, PRL (1999)***

Electrons trapped off-axis undergo betatron oscillations, reinforced by overlap with laser field



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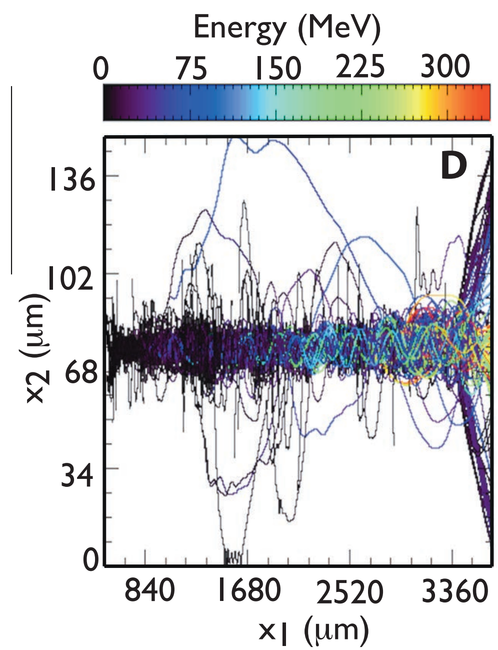
Betatron oscillations



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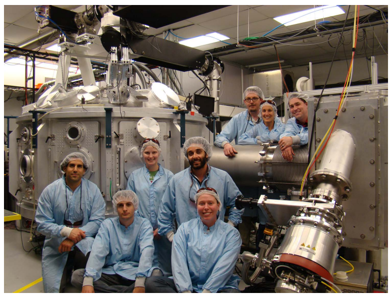
Our work is part of a plan to develop LWFA-driven sources on large picosecond lasers

Titan

Energy: 150 J

Pulse duration: 0.7 ps

F/10



✓ Experiments done

OMEGA-EP

Energy: 400 J

Pulse duration: 1 ps

F/2

✓ 2 shot days in 2019

NIF-ARC

Energy: 250 J /beamlet

Pulse duration: 1 ps

~ F/ 30 x 60

✓ 2 Shot days 2019-2020

LMJ-PETAL

Energy: 2 kJ

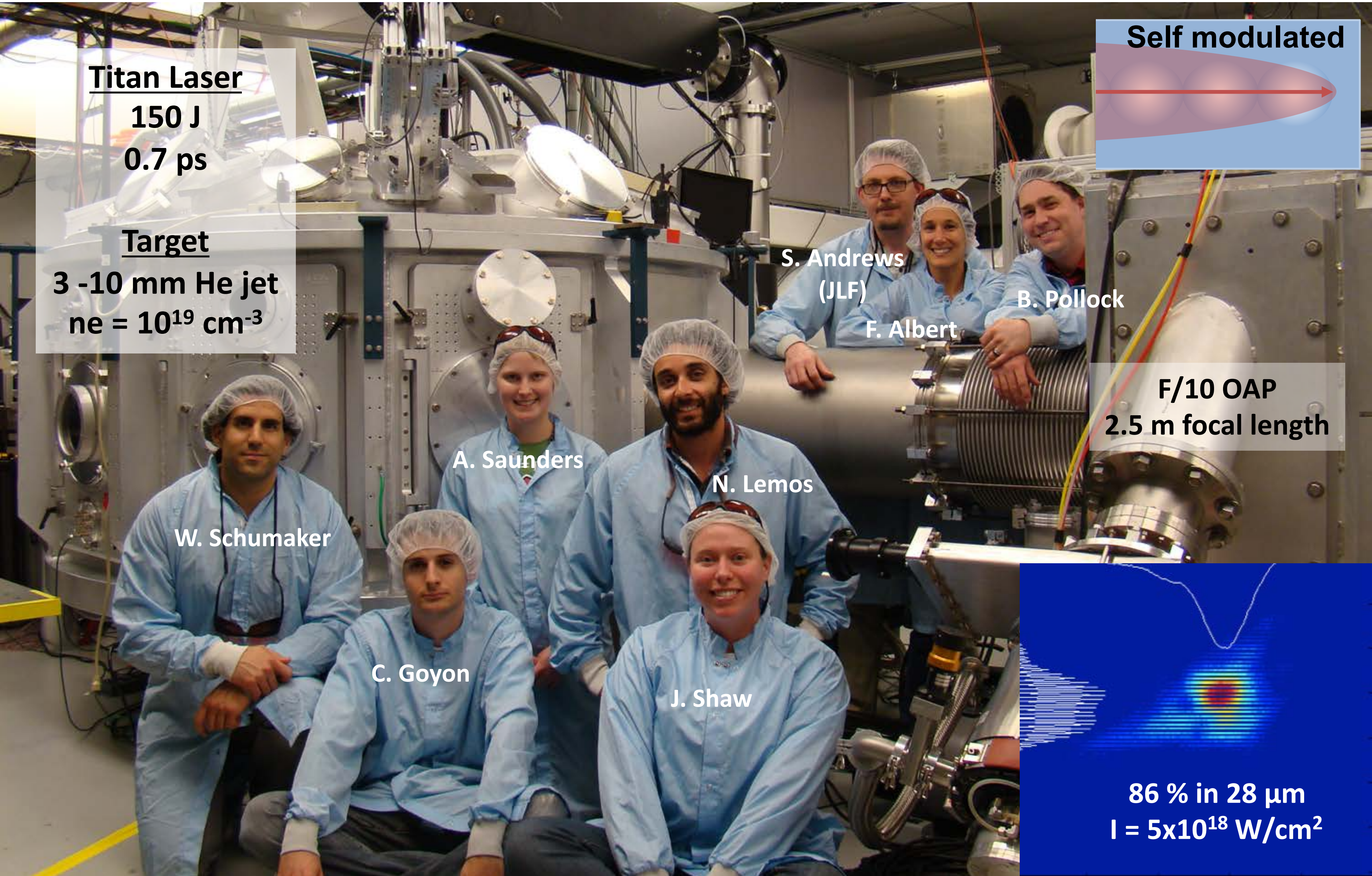
Pulse duration: 0.5 ps

~ F/40

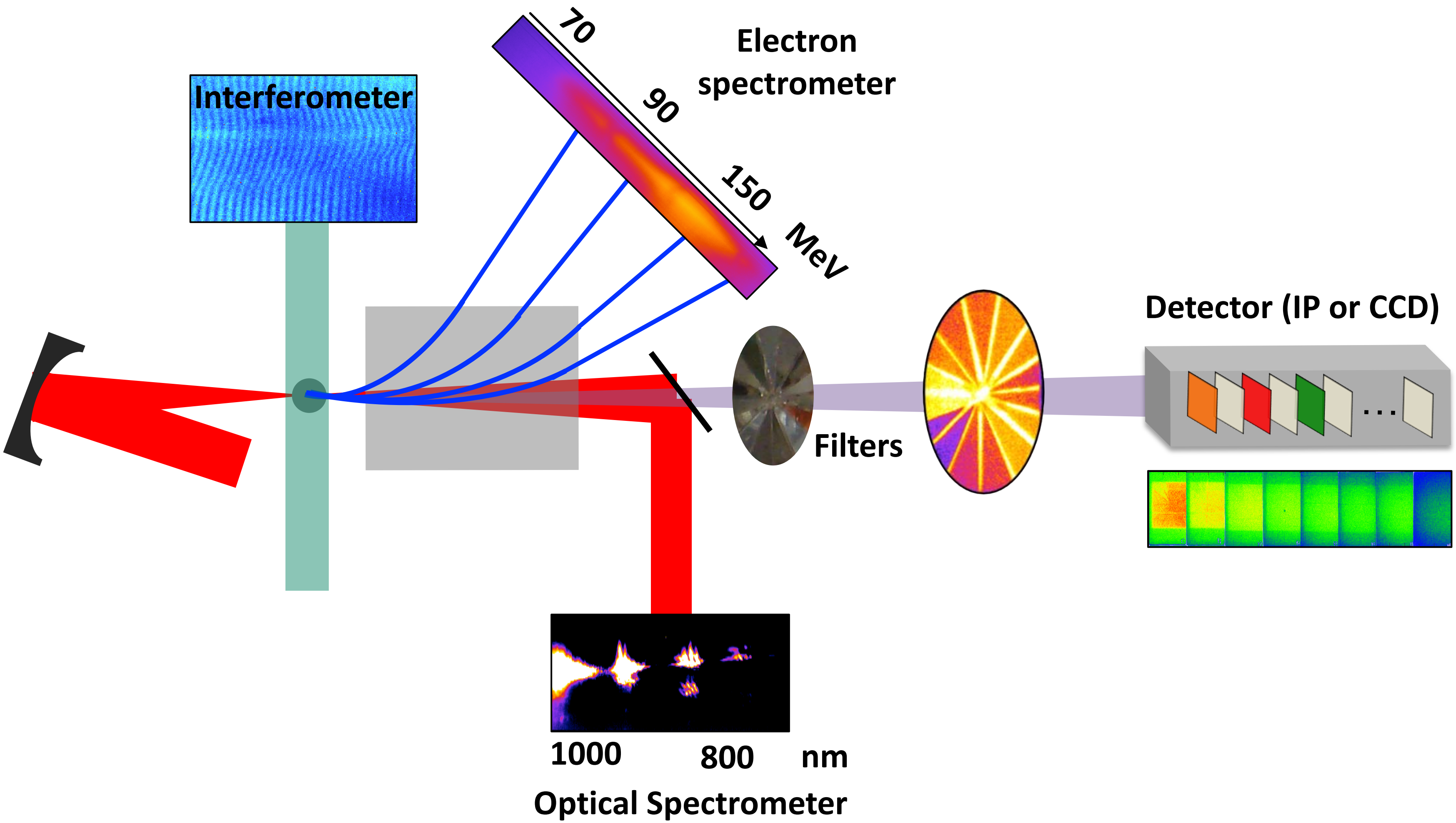
Collaboration with CEA

✓ Proposal short listed

Laser Wakefield Acceleration on Titan

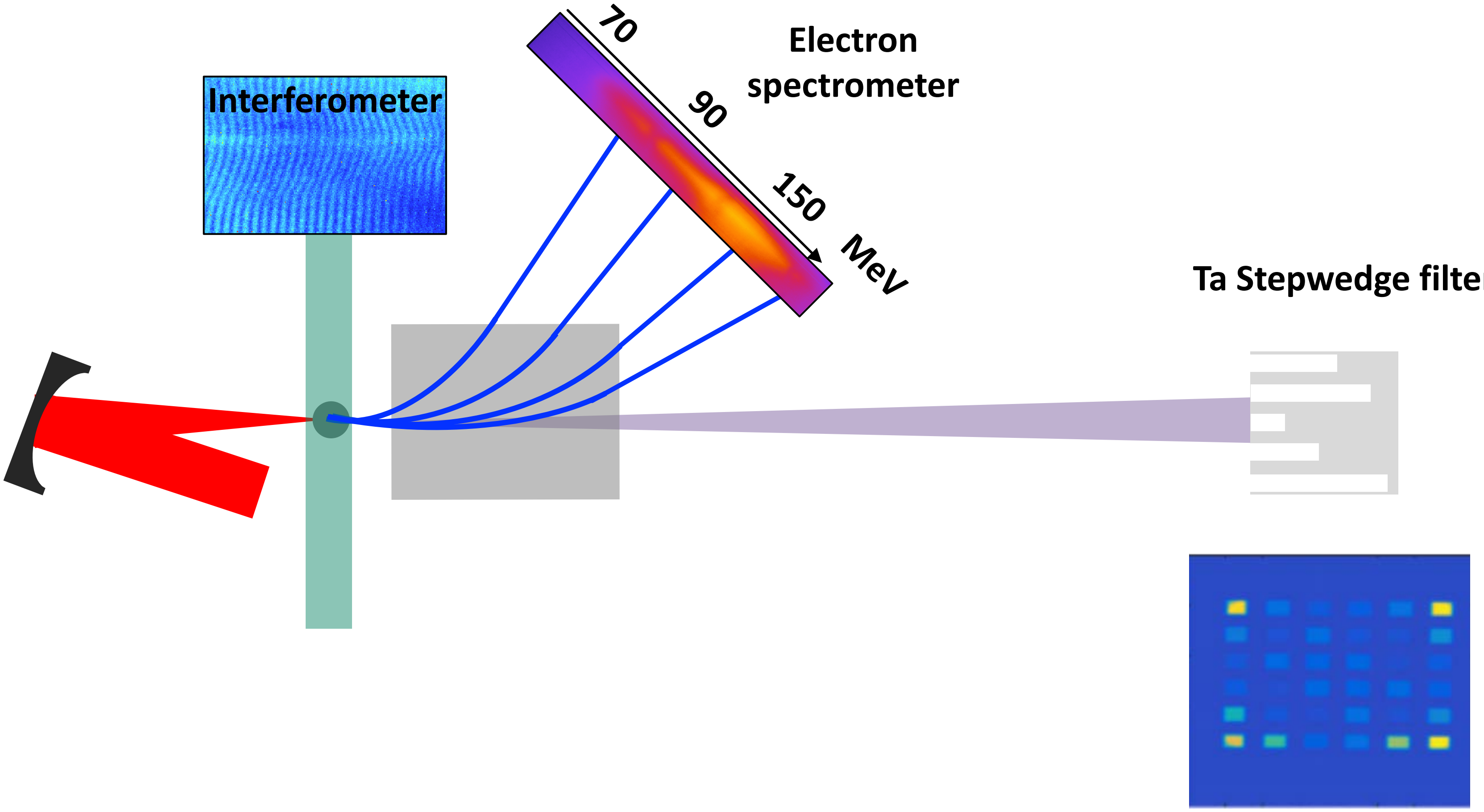


We have demonstrated the production of betatron radiation in the blowout and self-modulated regimes



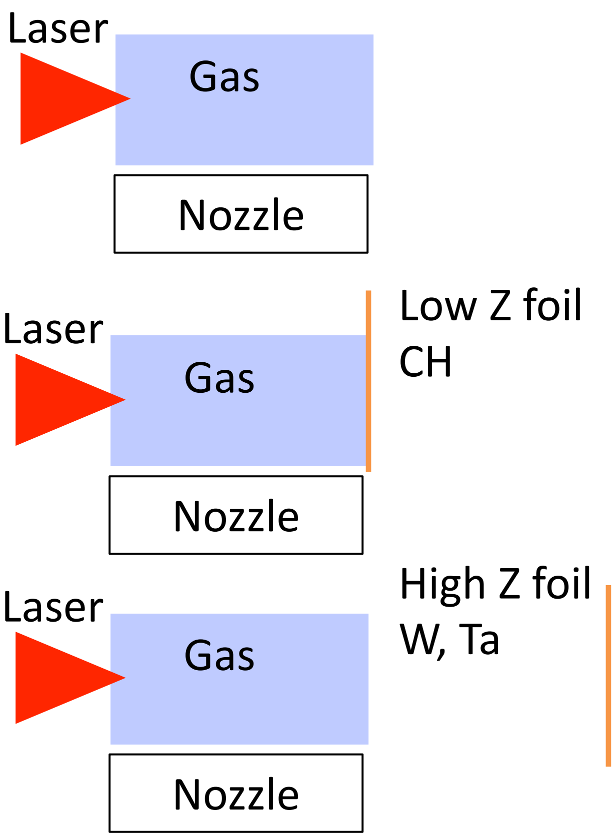
F. Albert et. al, *Phys. Rev. Lett.* 118, 134801 (2017)

We have demonstrated the production of radiation in the SMLWFA regime

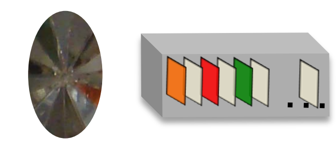


G. Williams et al, Rev. Sci. Instr. (2018)

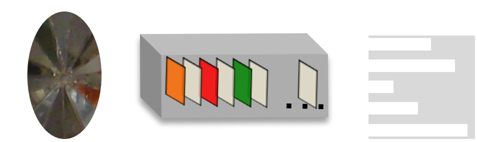
We have characterized these processes producing keV – MeV photons from SMLWFA electron beams



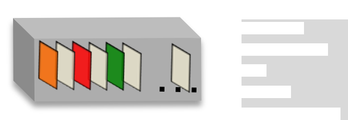
1. **Betatron x-ray radiation**
   keV



2. **Compton scattering**
   keV – MeV



3. **Bremsstrahlung (LWFA)**
   MeV

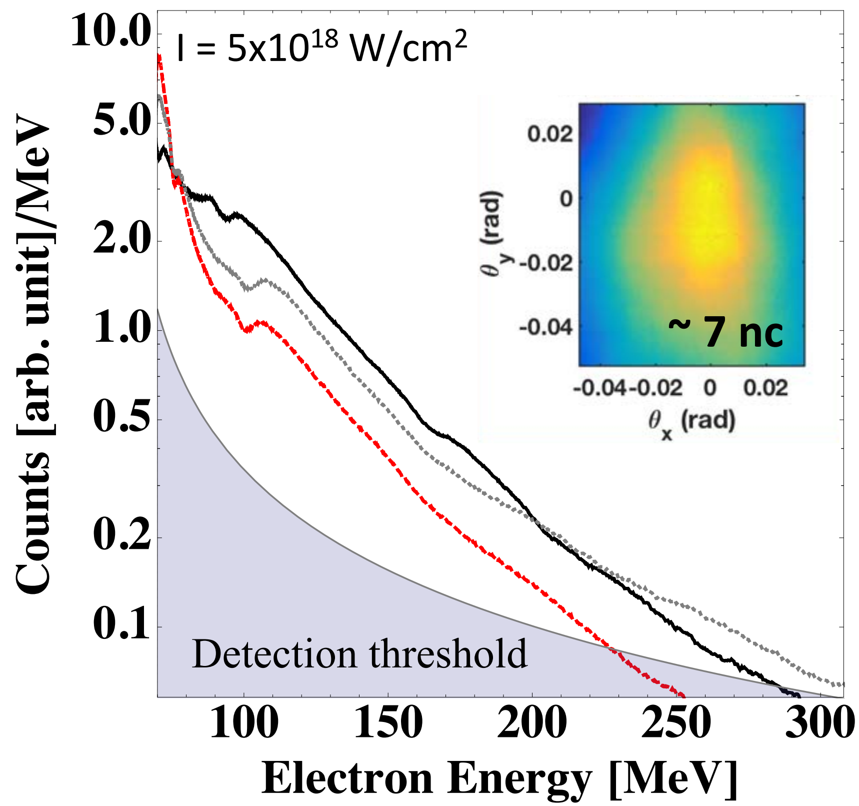


These sources provide opportunities for new x-ray diagnostics development

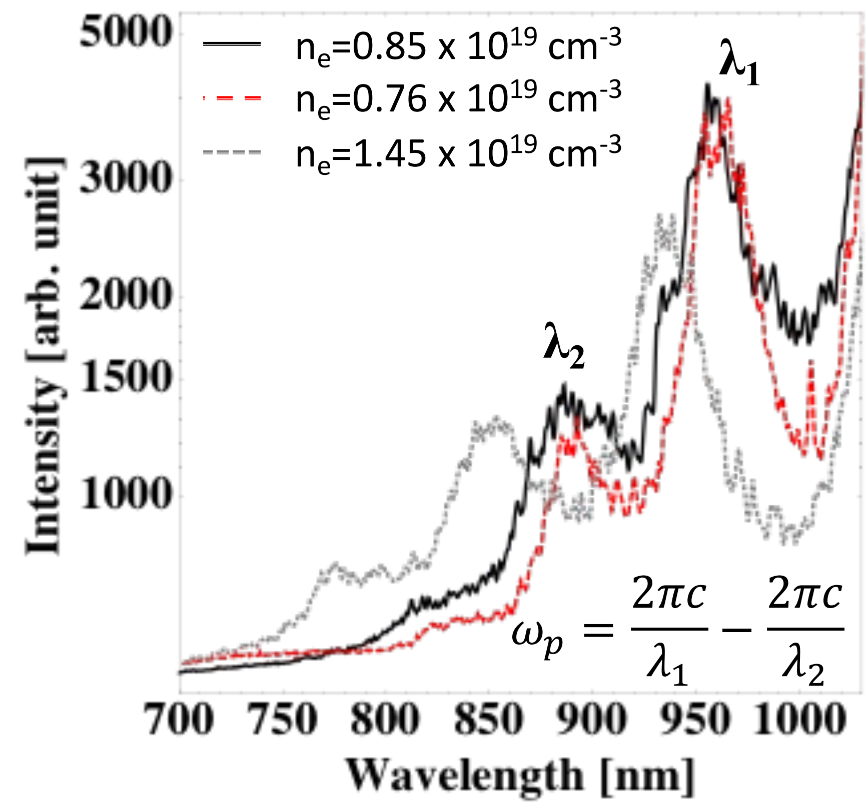
P. M. King et. al, RSI 90, 033503 (2019)

Electron and forward laser spectra confirm that we are in the SMLWFA regime

Electron spectra



Forward laser spectra

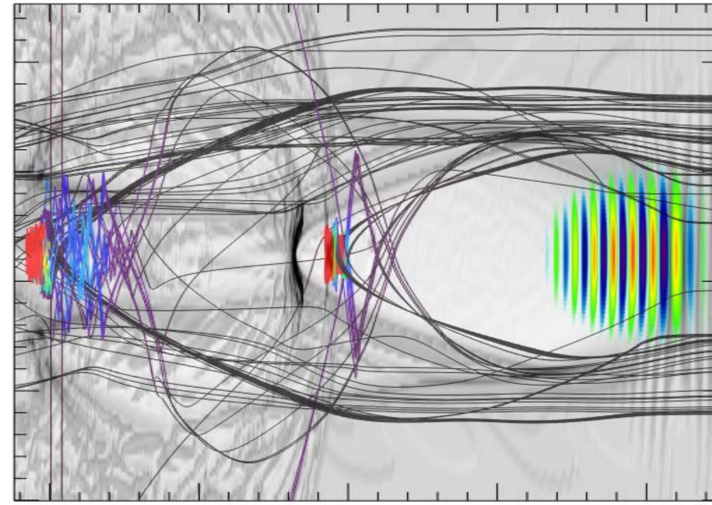


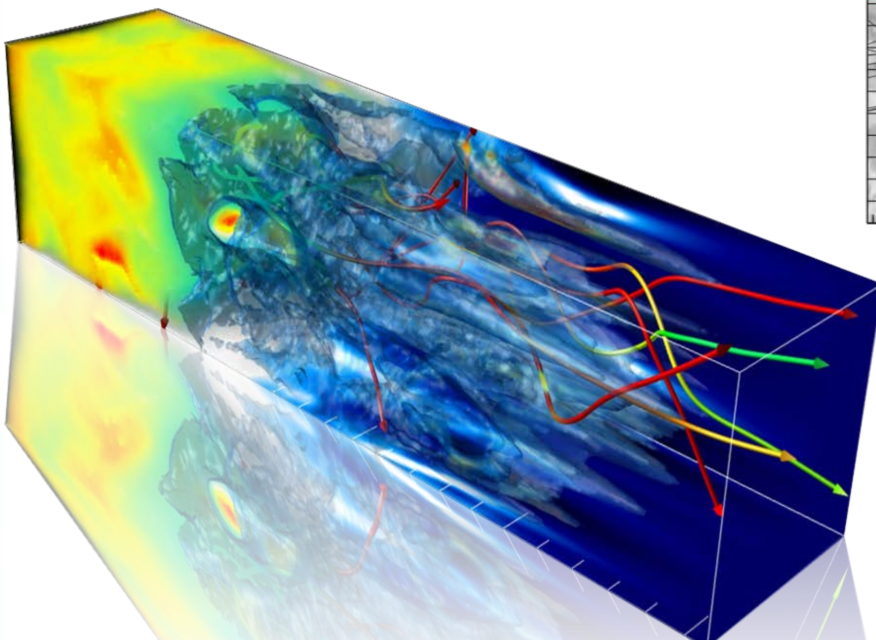
F. Albert et. al, *Phys. Rev. Lett.* 118, 134801 (2017)

Particle-in-cell simulations performed with OSIRIS

- Massively Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium

⇒ UCLA + IST





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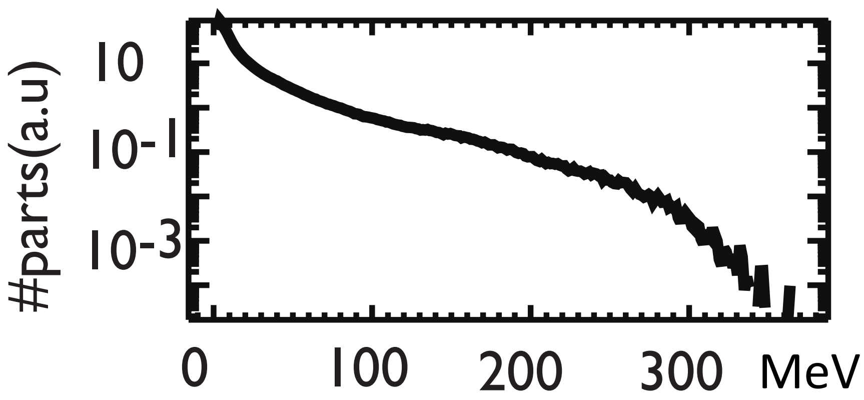
Frank Tsung: tsung@physics.ucla.edu
http://exodus.physics.ucla.edu/http://cfp.ist.utl.pt/golp/epp/

New Features in v2.0

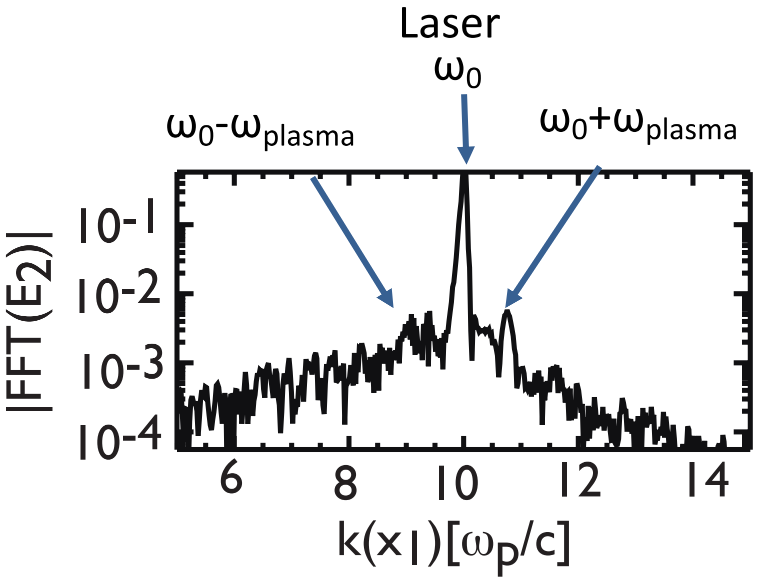
- Bessel Beams
- Binary Collision Module
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing
- PML absorbing BC
- Parallel I/O

2D PIC simulations of electron and forward laser spectrum also confirm signatures of SMLWFA

Electron spectrum

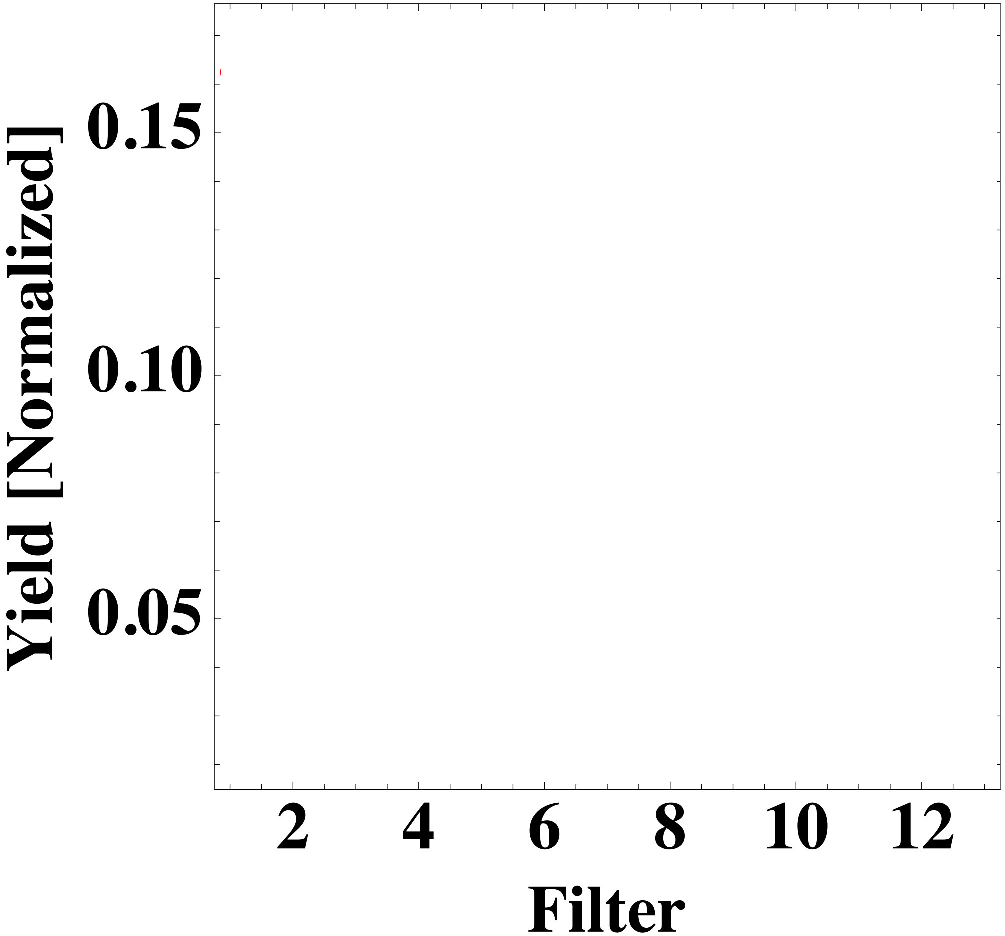


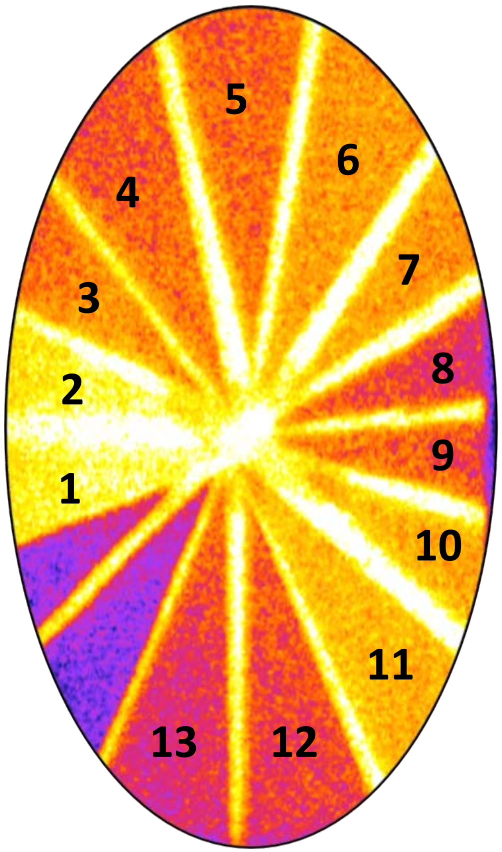
Forward laser spectrum



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

Electrons accelerated in the SMLWFA regime produce betatron x-rays





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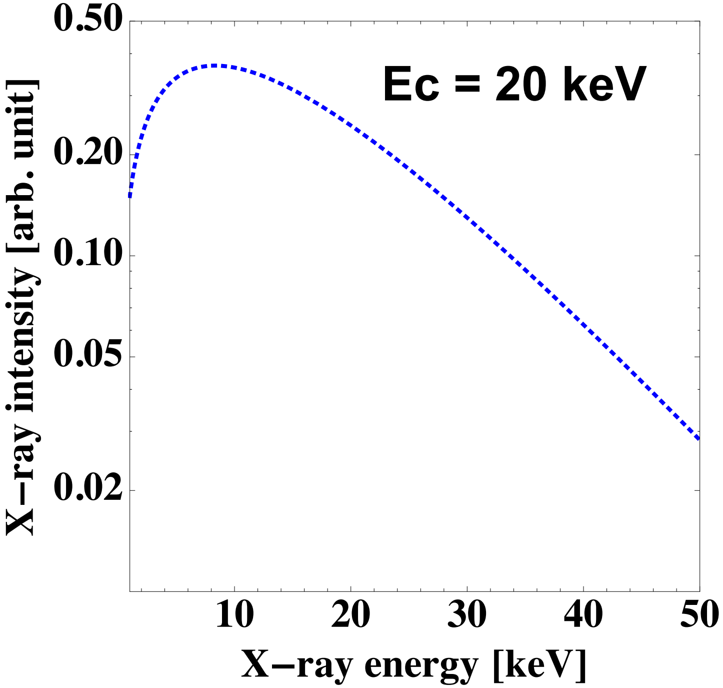
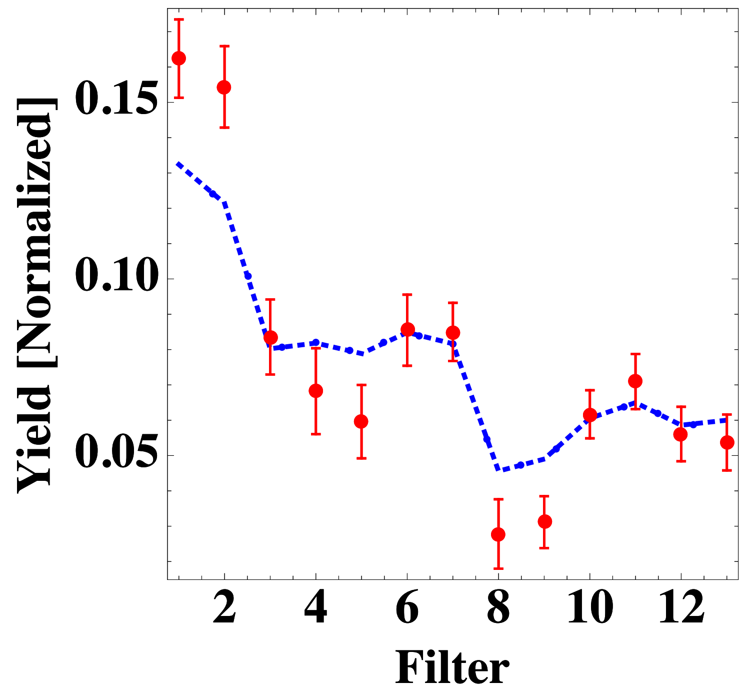


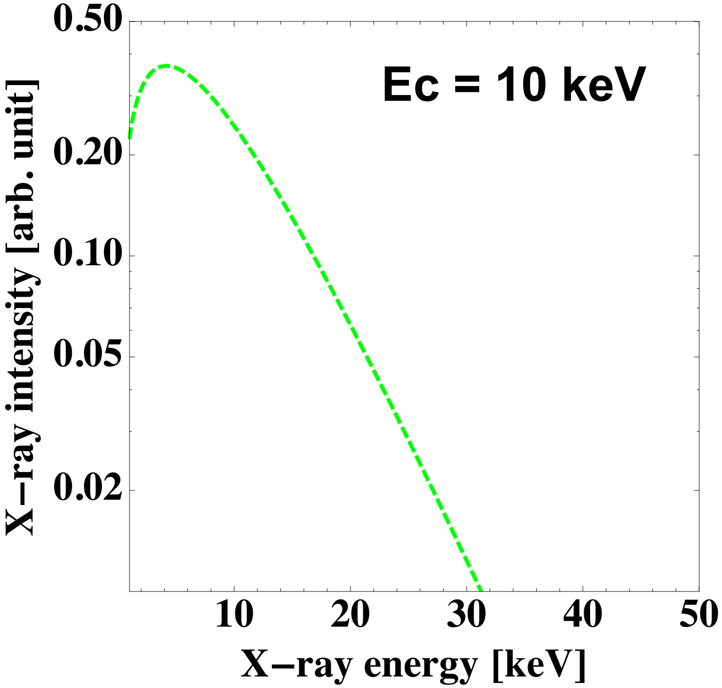
X

=



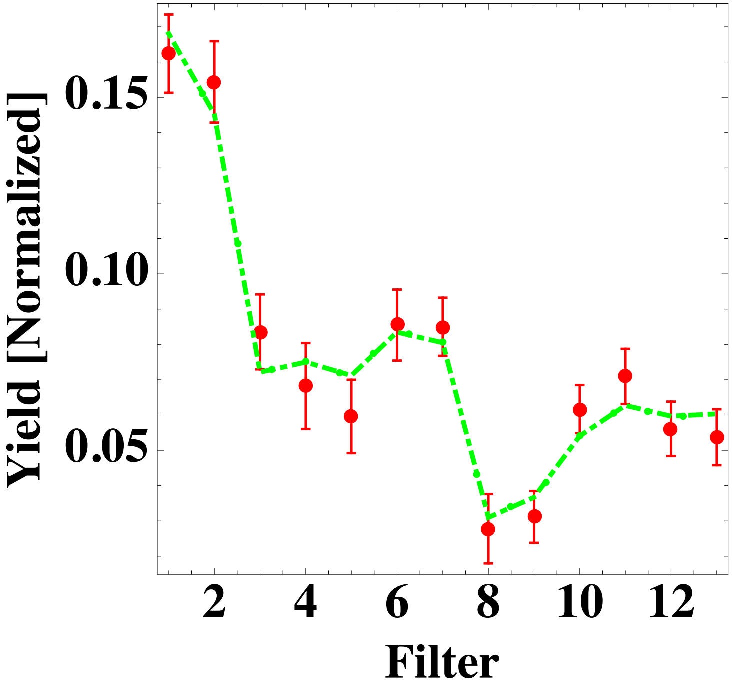
$$\frac{d^2 I}{dE d\Omega} \propto \left(\frac{E}{E_c}\right)^2 K_{2/3}^2[E/E_c]$$

Electrons accelerated in the SMLWFA regime produce betatron x-rays



X

=



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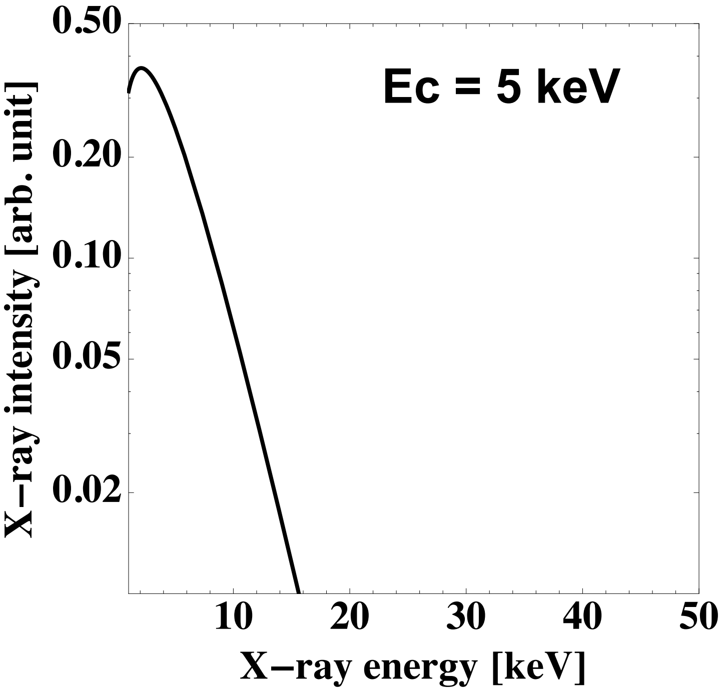
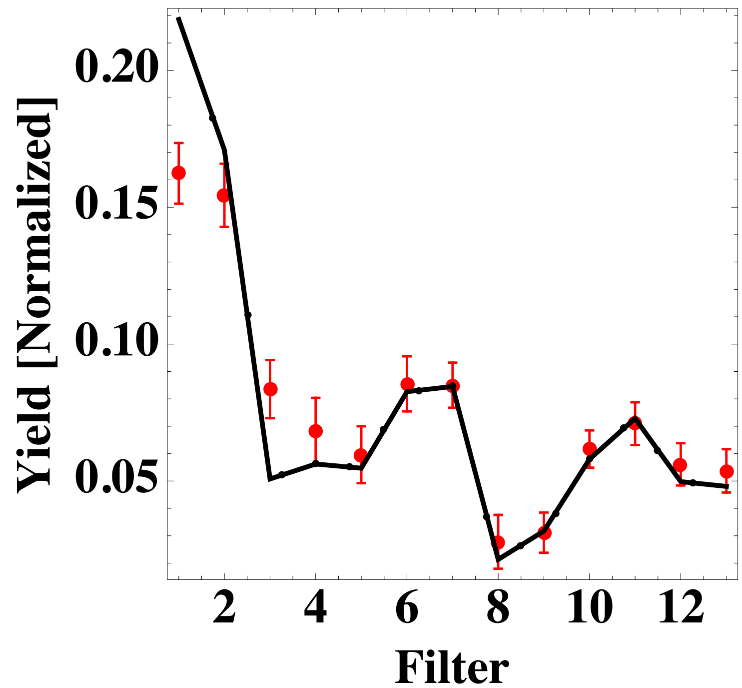


x

=



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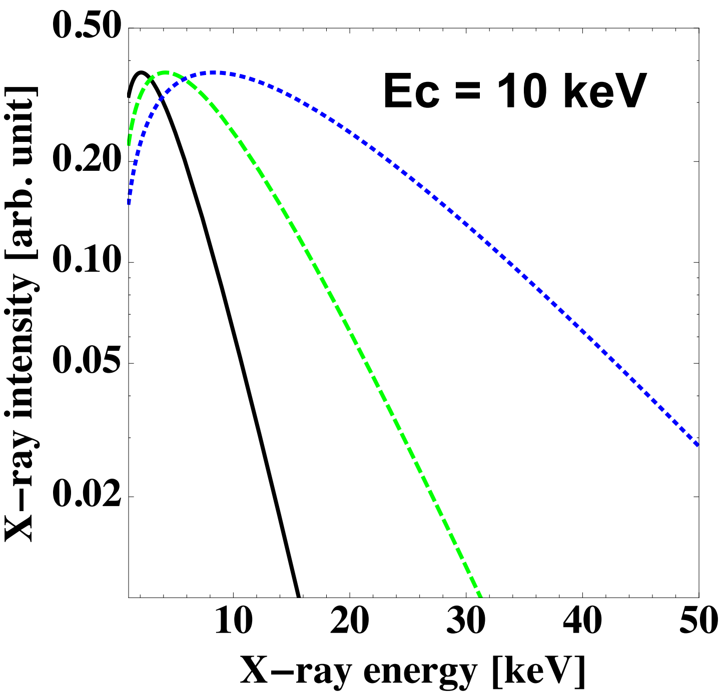
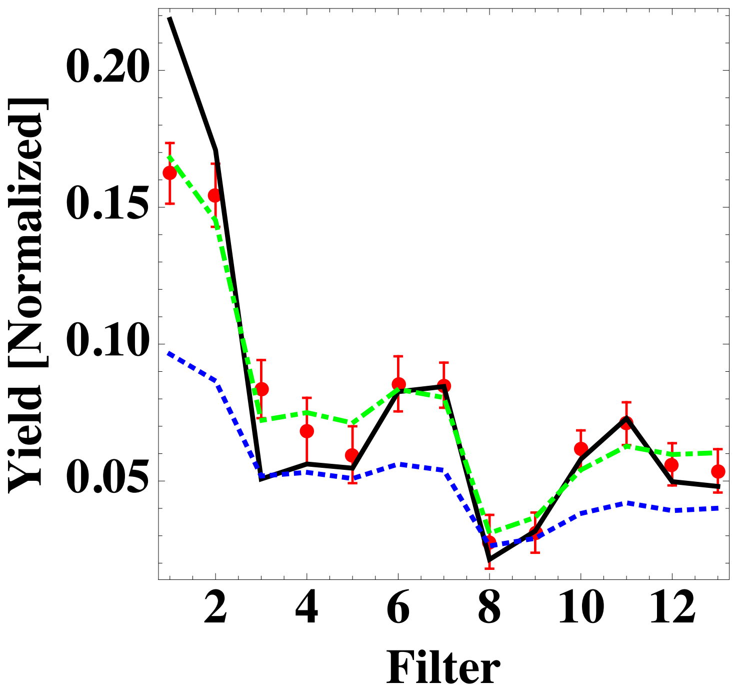


X

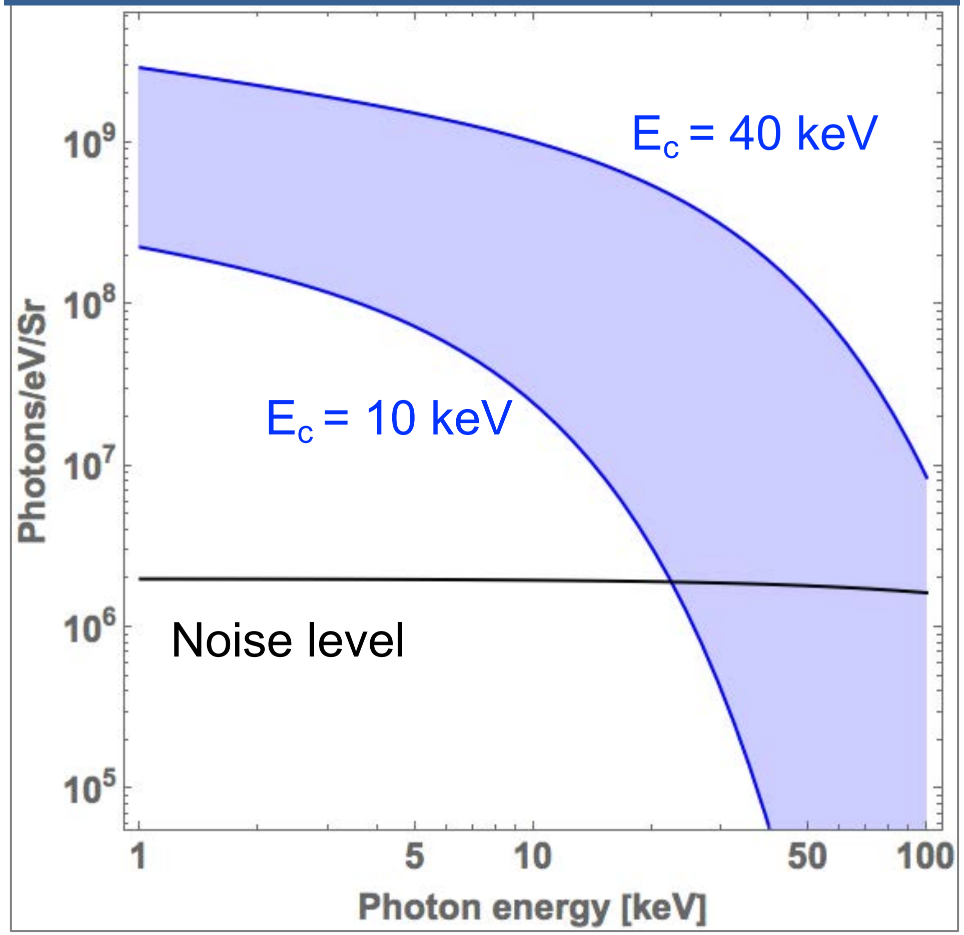
=



Best fit for E_c = 10 keV +/- 2 keV (least squares fit) – 10^9 photons/eV/Sr

Electrons accelerated in the SMLWFA regime produce betatron x-rays with critical energies of 10-40 keV

Measured/calculated x-ray spectrum

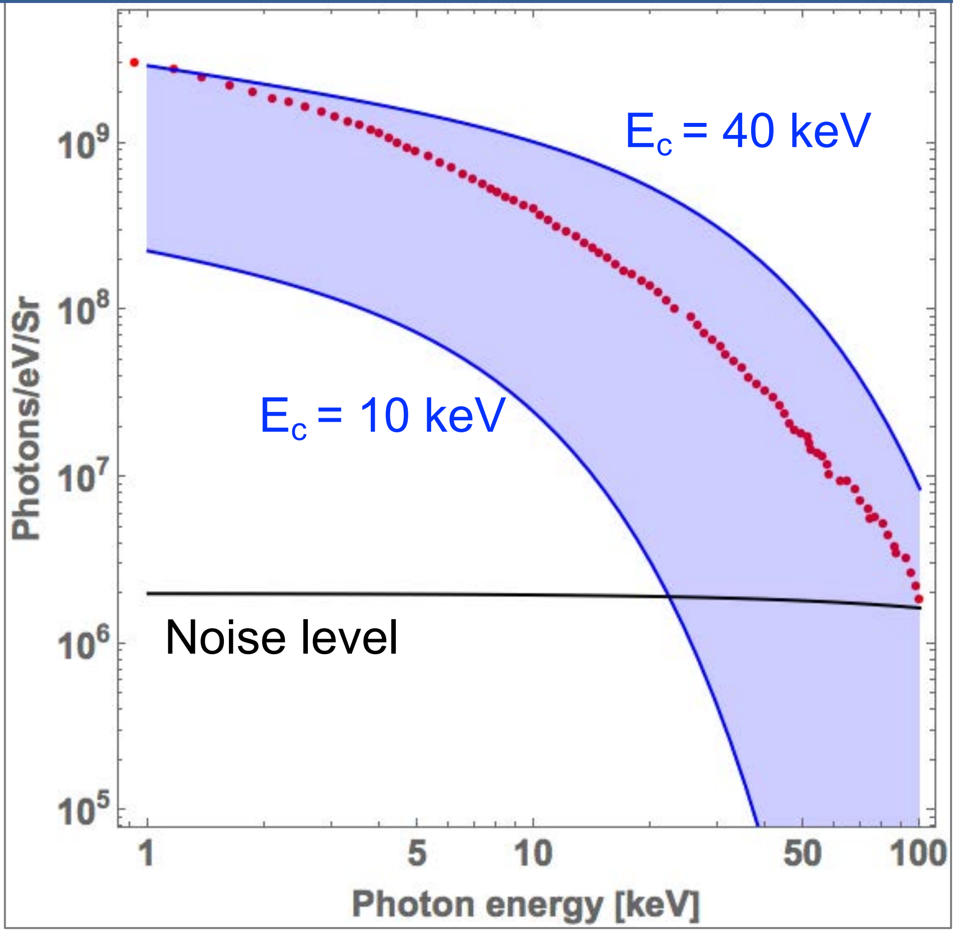


Betatron - Experiment

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

Electrons accelerated in the SMLWFA regime produce betatron x-rays with critical energies of 10-40 keV

Measured/calculated x-ray spectrum

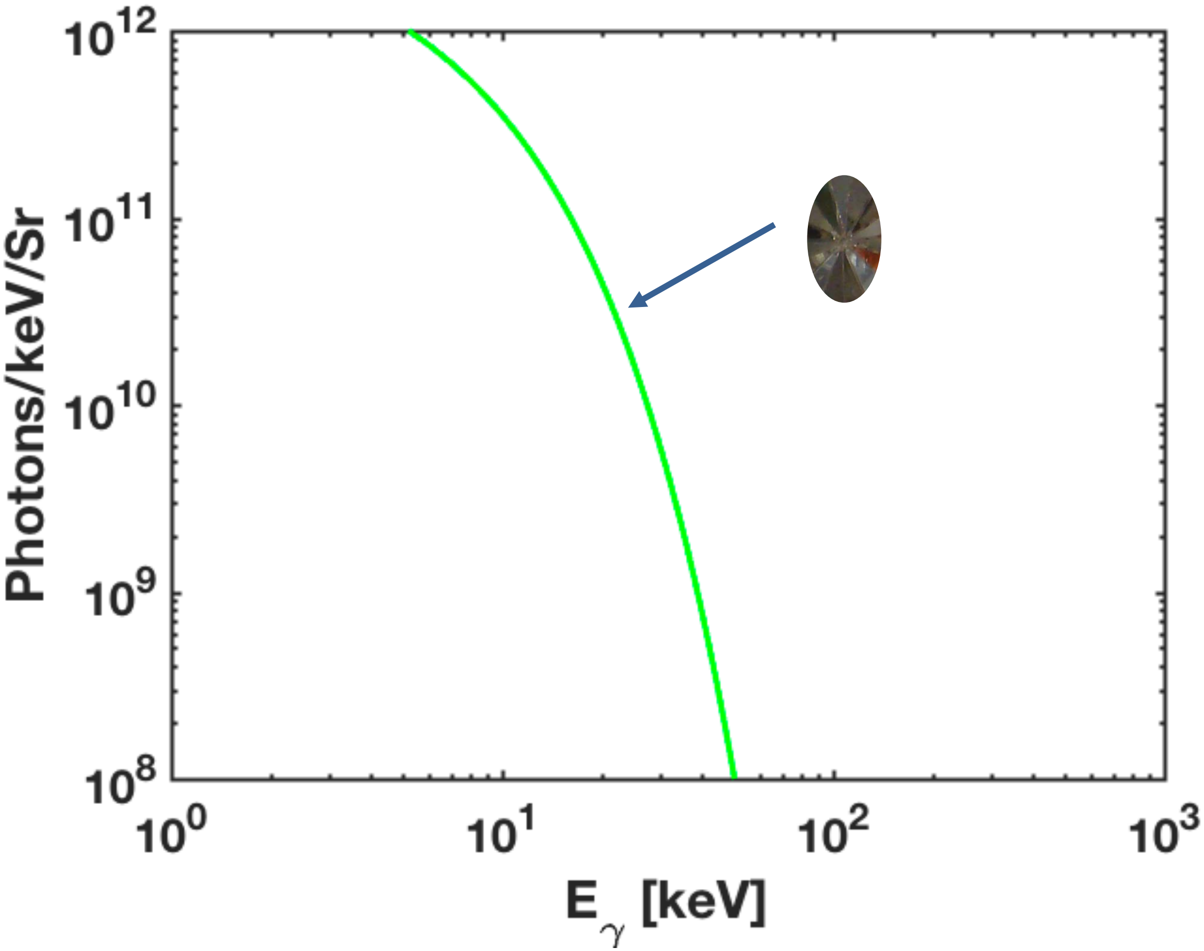


Betatron - Experiment

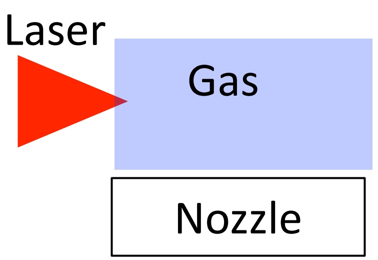
PIC simulation

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

Optimized betatron radiation produces the most photons for energies <40 keV



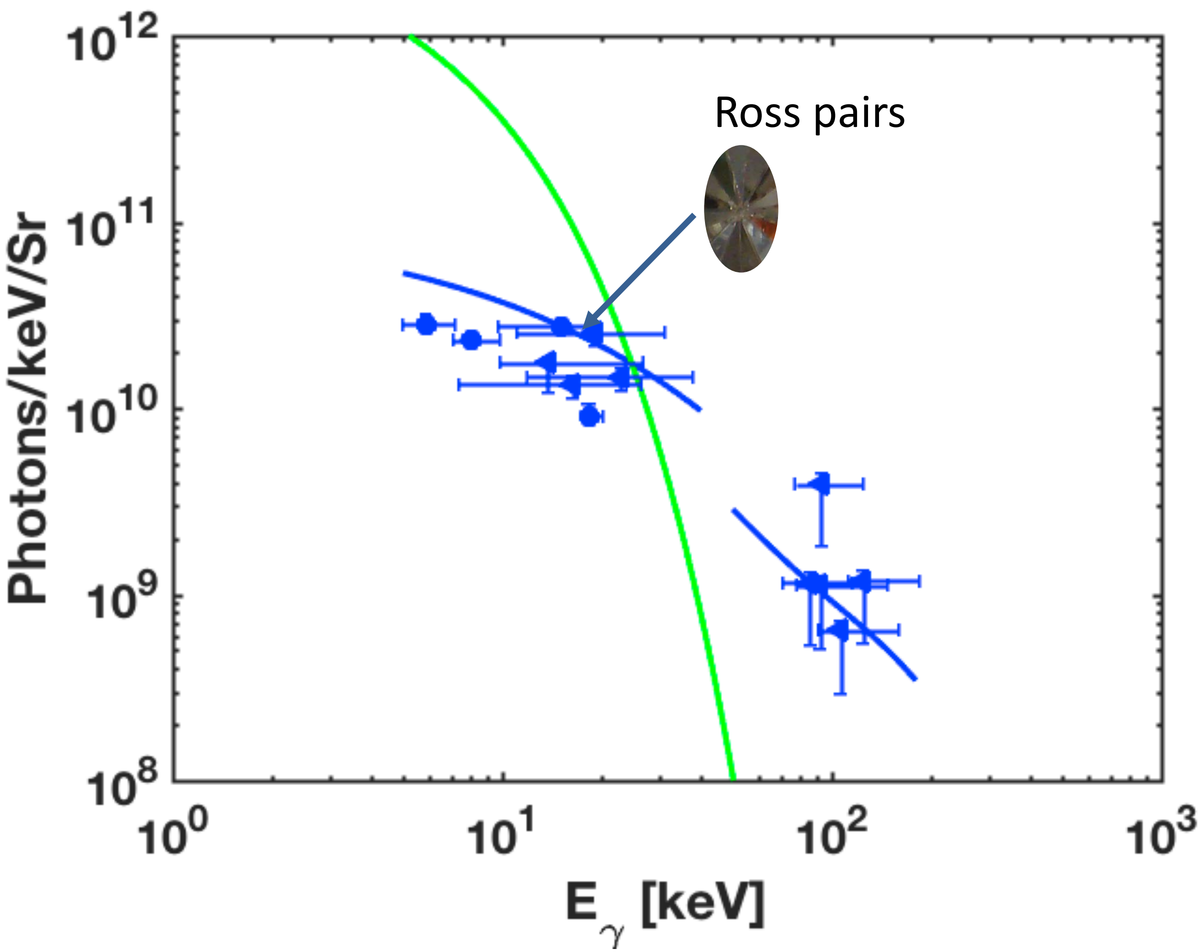
Betatron, E_c = 10 keV



$n_e = 1.5 \times 10^{19}\ cm^{-3}$
E_{laser} = 150 J
$a_0 \sim 3$

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

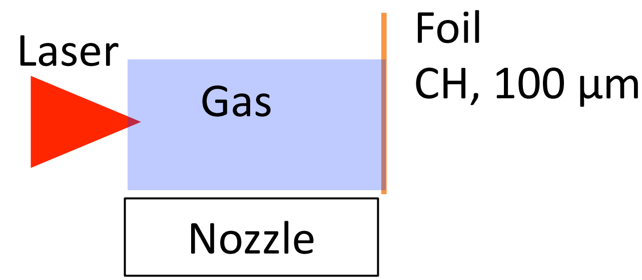
Compton scattering allows for increased photon flux up to a few 100 keV



Compton scattering

$$f(E) \propto Exp\left[-\frac{E}{T_1}\right] + Exp\left[-\frac{E}{T_2}\right]$$

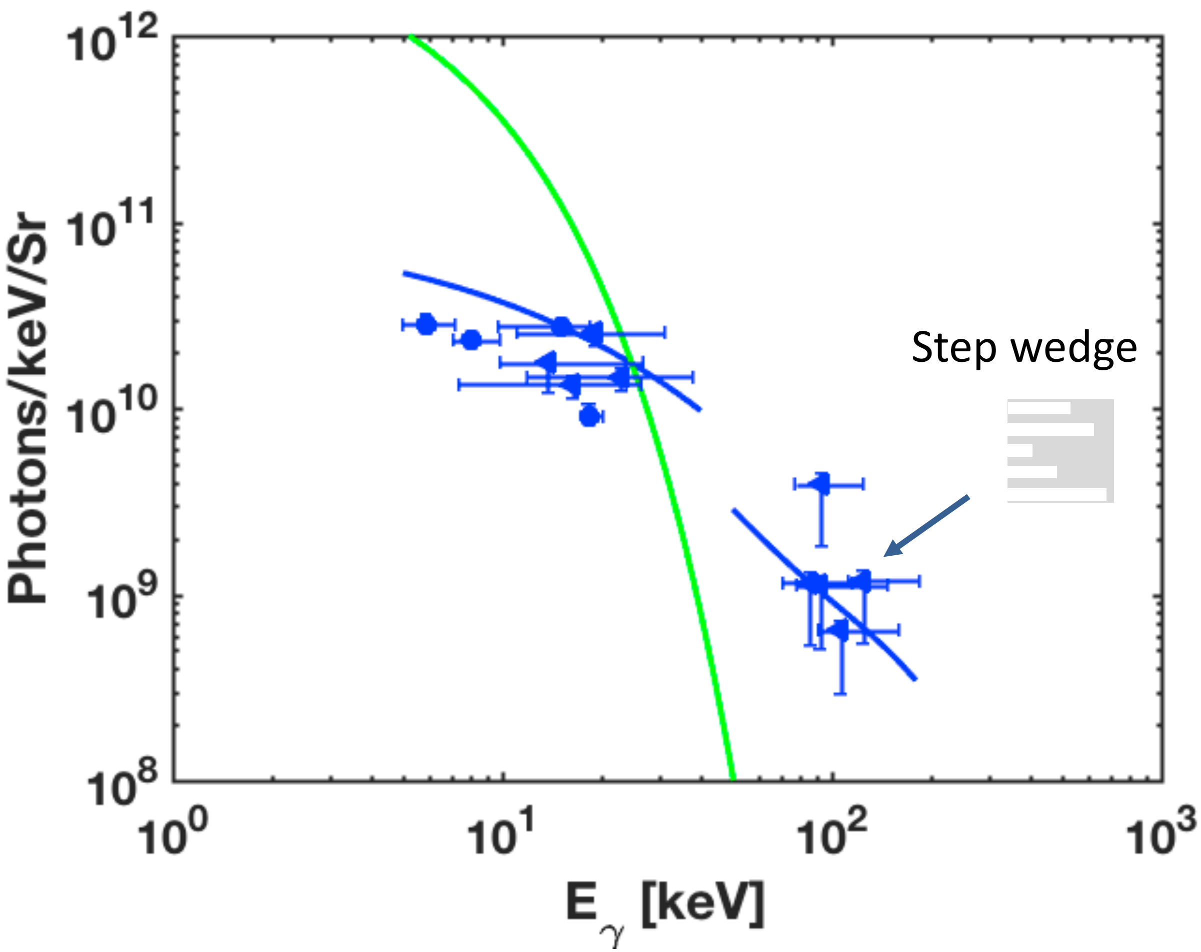
T_1 = 36 keV (Filter wheel)



$n_e = 4 \times 10^{18}$ cm^{-3}
E_{laser} = 120 J
$a_0 \sim 3$

N. Lemos et. al Phys. Rev. Lett. (in review)

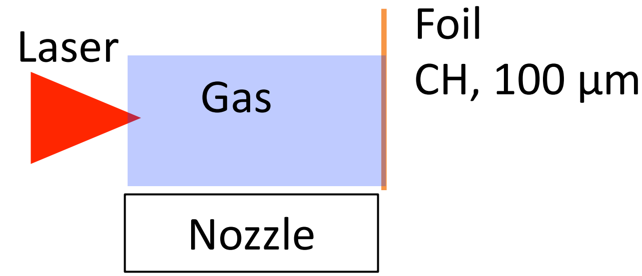
Compton scattering allows for increased photon flux up to a few 100 keV



Compton scattering

$$f(E) \propto Exp\left[-\frac{E}{T_1}\right] + Exp\left[-\frac{E}{T_2}\right]$$

T_2 = 78 keV (Step wedge)

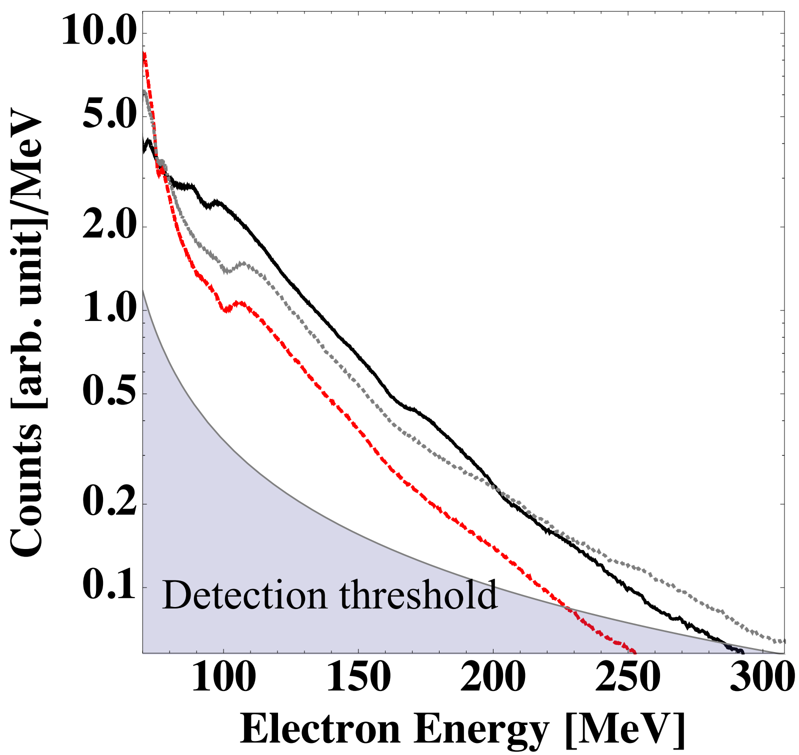


$n_e = 4 \times 10^{18}$ cm^{-3}
E_{laser} = 120 J
$a_0 \sim 3$

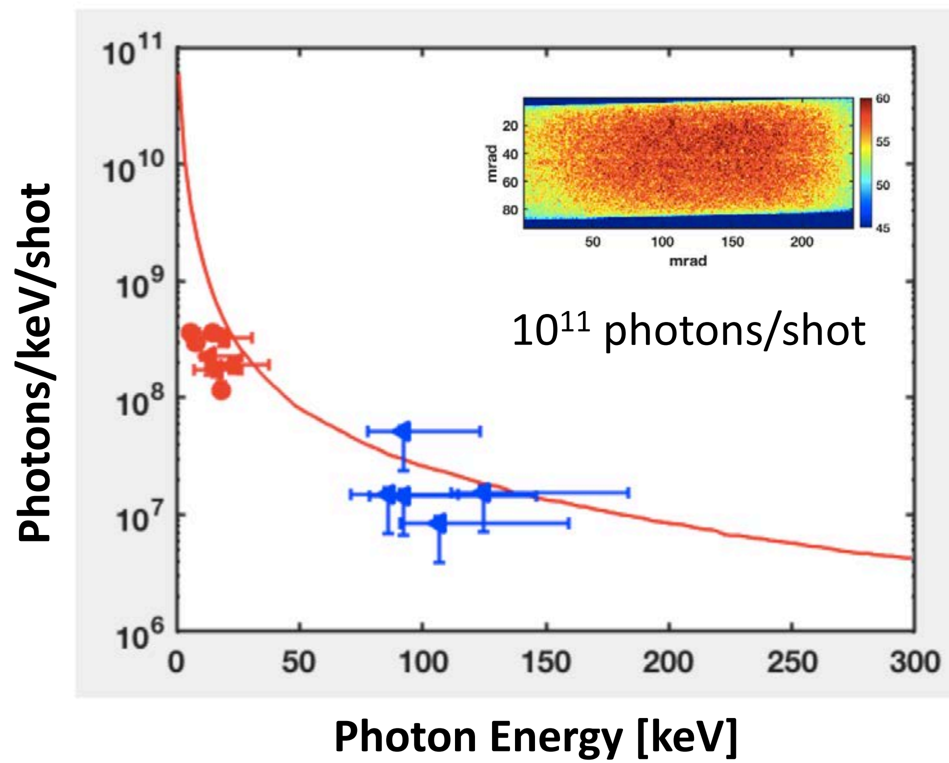
N. Lemos et. al Phys. Rev. Lett. (in review)

A multi-temperature Compton scattering distribution is consistent with predictions from measured electron beam energy

Electron beam spectrum



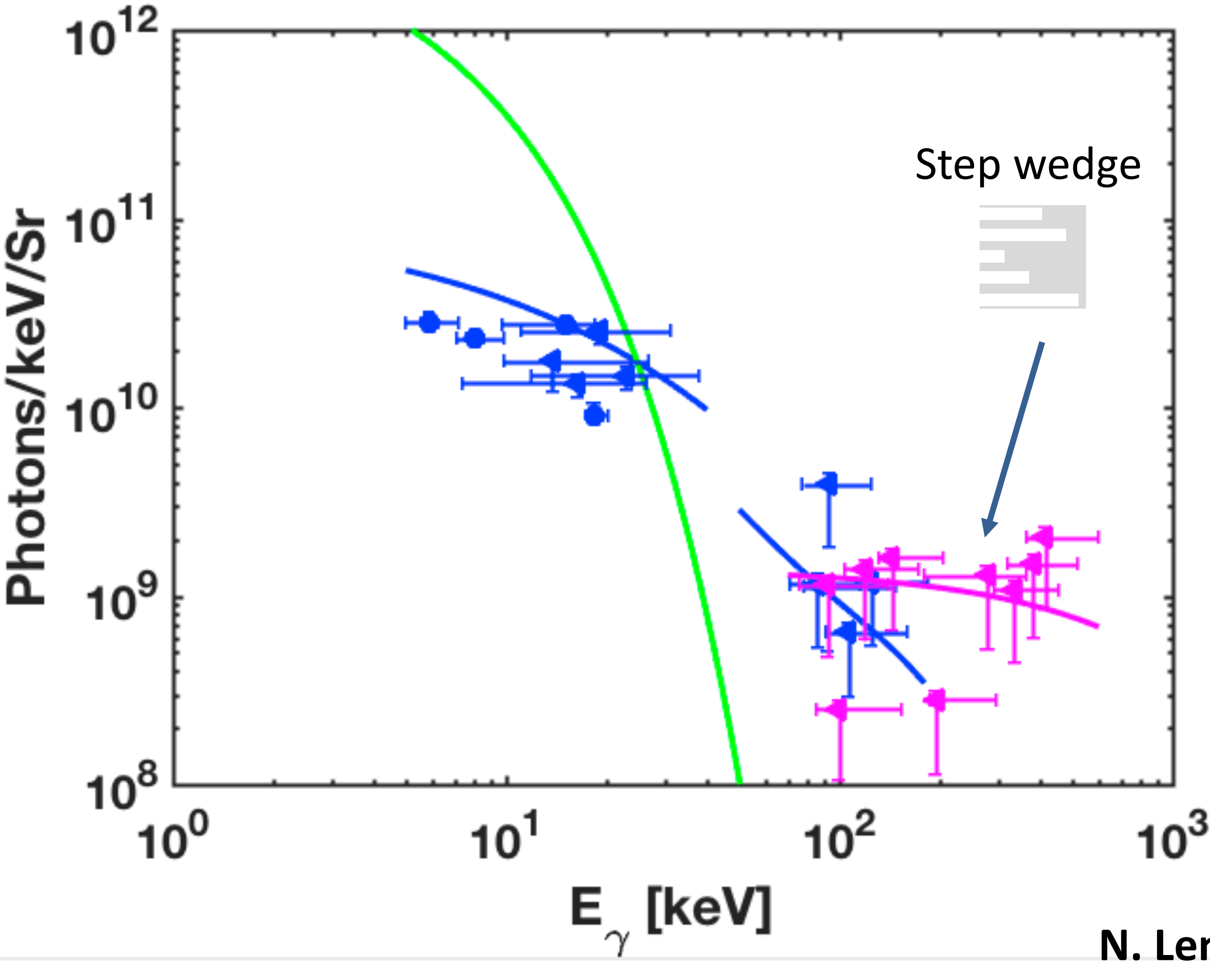
Compton scattering spectrum



$$E_x \propto 4\gamma^2 \ E_L$$

N. Lemos et. al Phys. Rev. Lett. (in review)

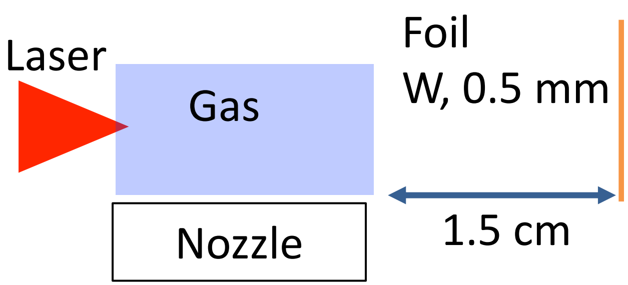
LWFA-driven bremsstrahlung produces the most photons at MeV energies



LWFA-driven bremsstrahlung

$f(E) \propto Exp[-E/T]$

T = 838 keV (Stepwedge)

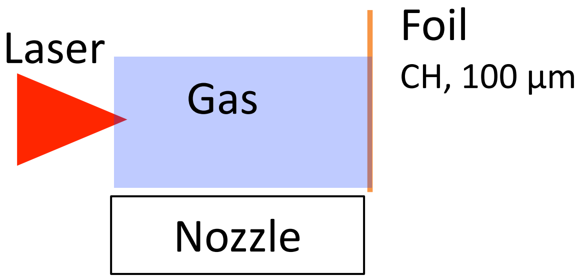


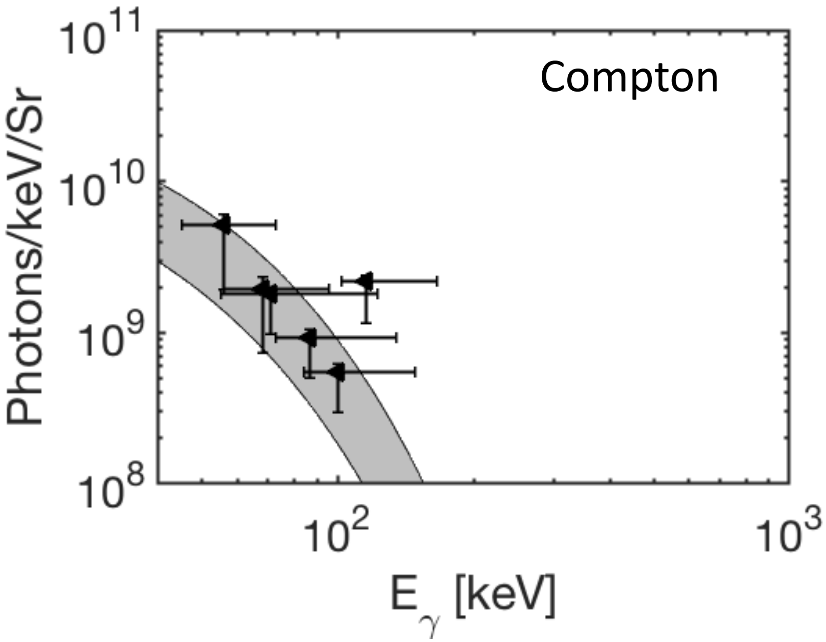
N. Lemos et. al, PPCF, 60, 054008 (2018)

N. Lemos et. al, PRL (in review)

P. M. King et. al, RSI 90, 033503 (2019)

The combined target can be varied to control the photon flux and temperature of the emitted x-rays





P. M. King et. al, In preparation (2019)

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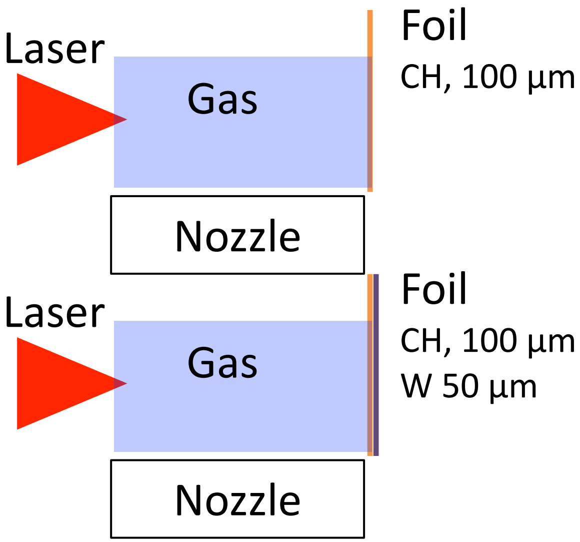

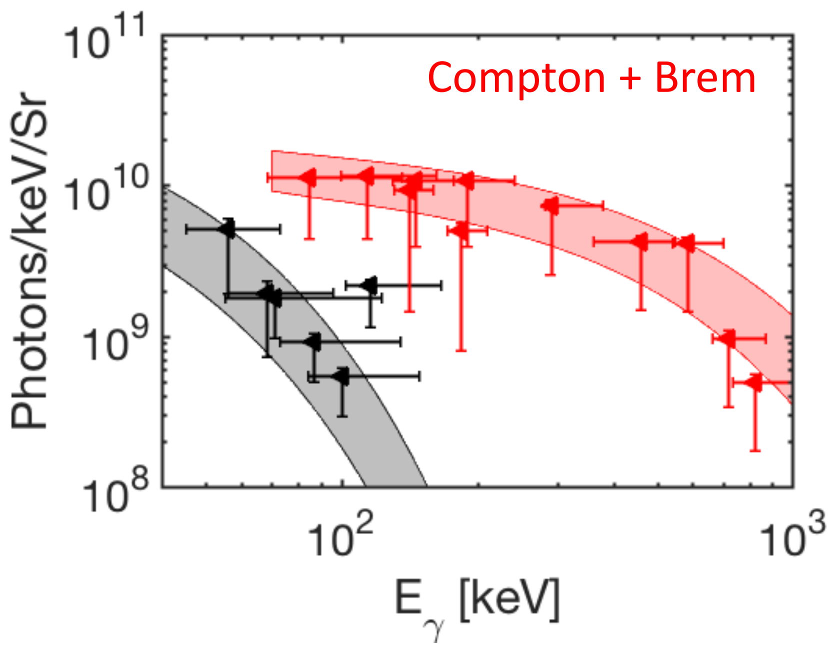

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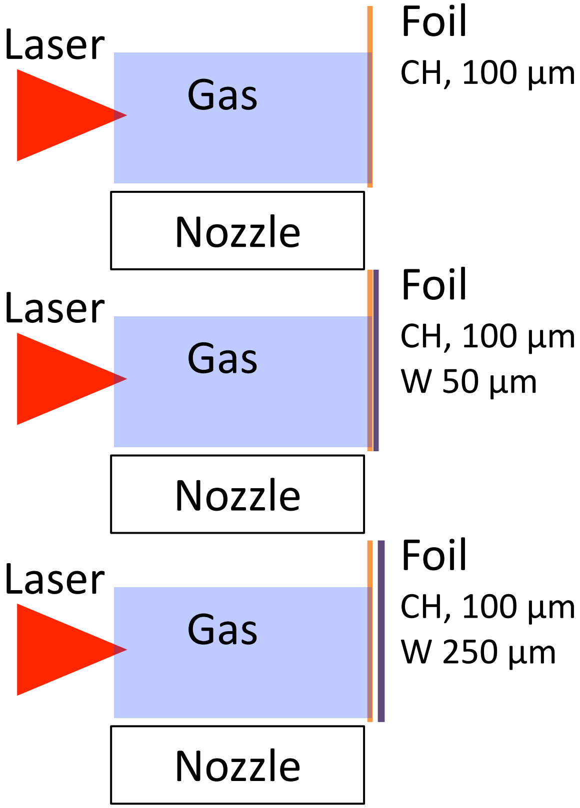
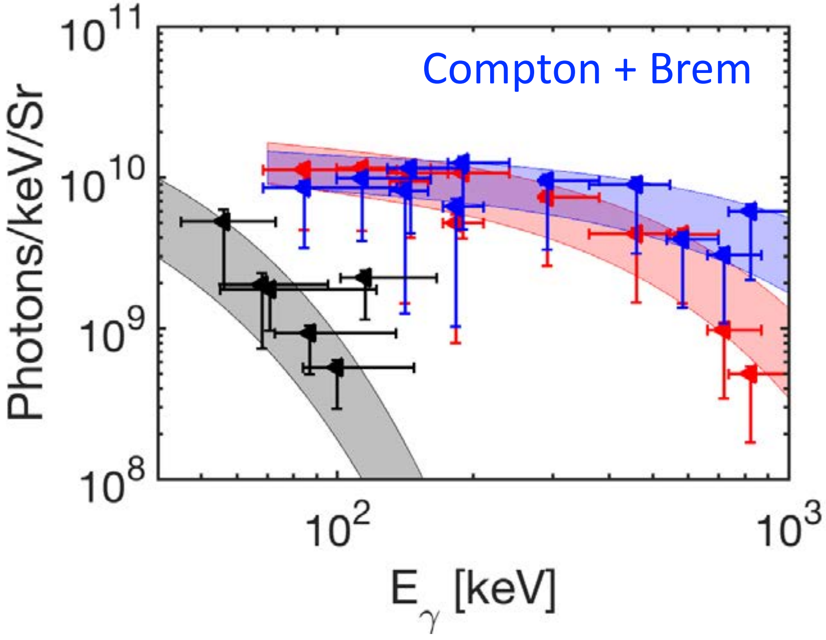
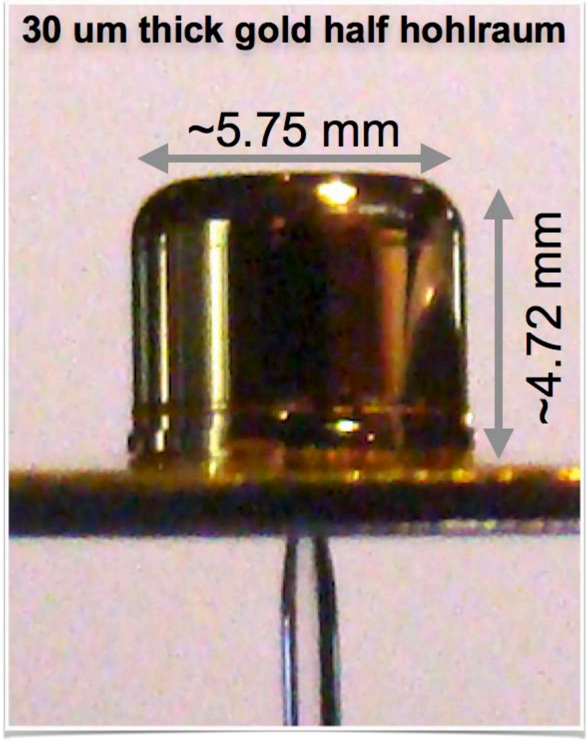




P. M. King et. al, In preparation (2019)

We can radiograph typical NIF targets with this source



P. M. King et. al, In preparation (2019)

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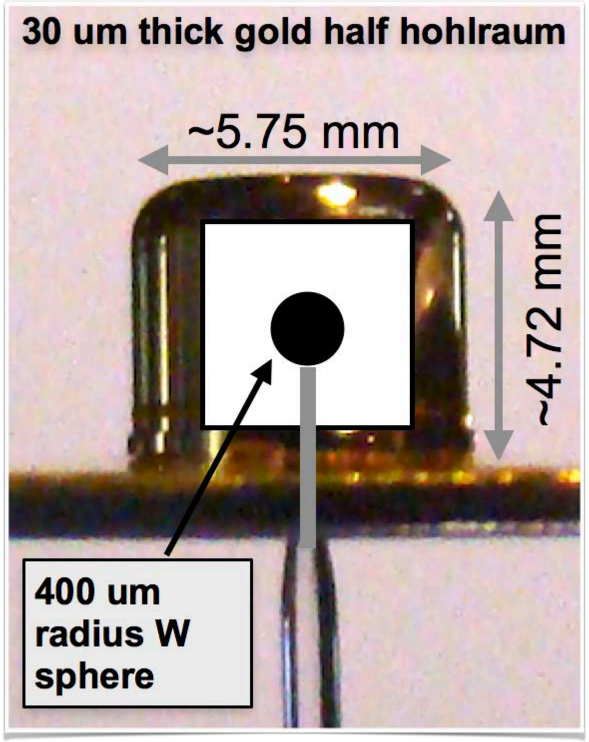

P. M. King et. al, In preparation (2019)

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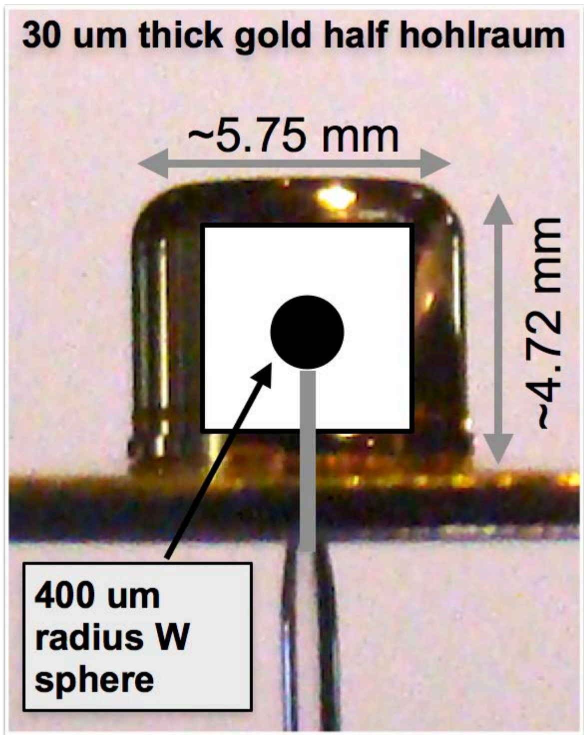
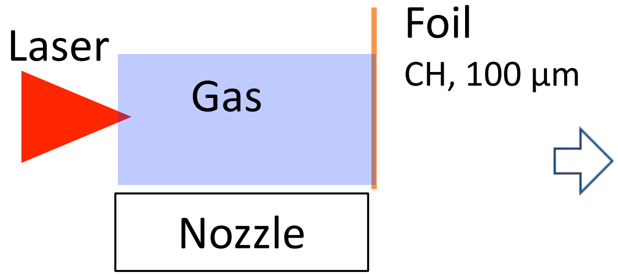
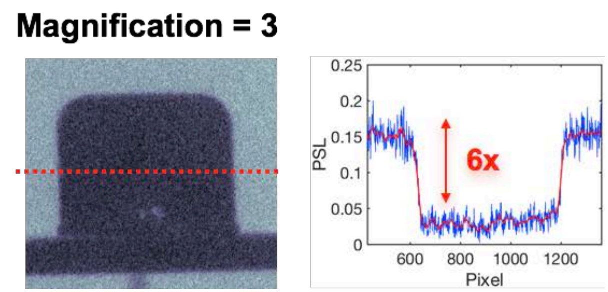
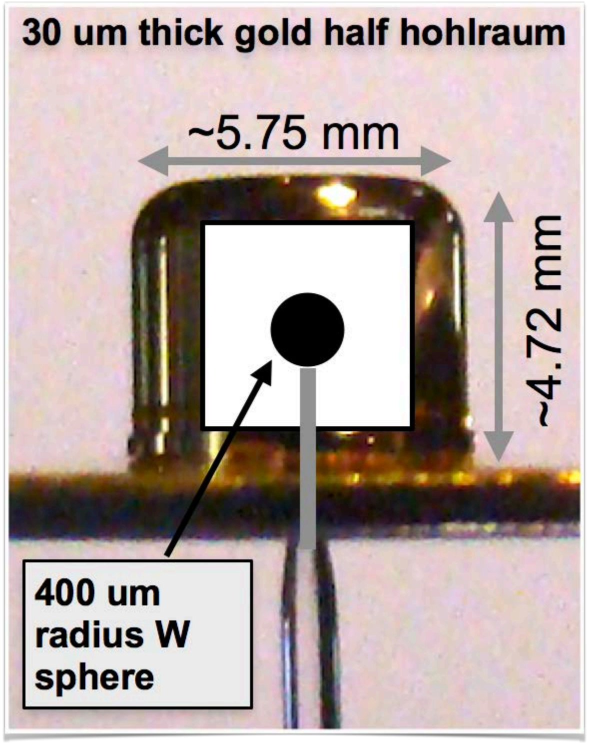


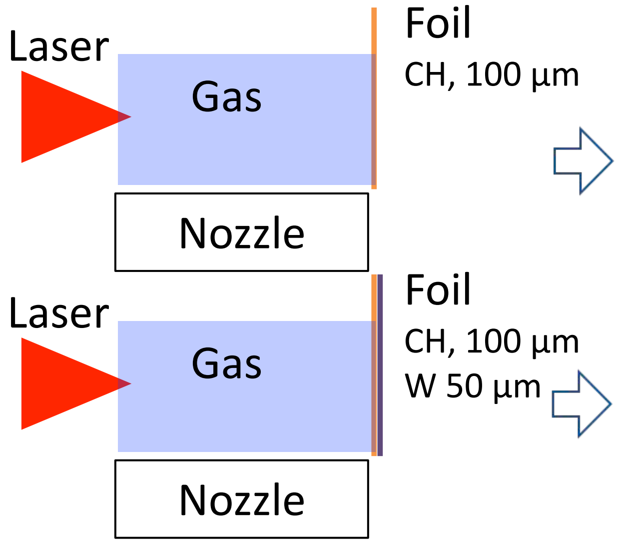




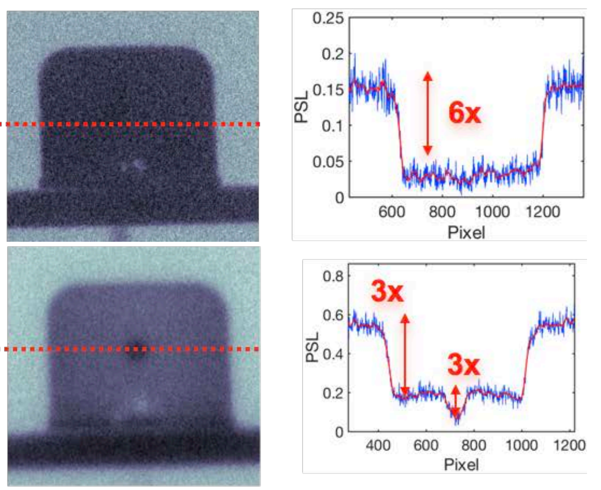
P. M. King et. al, In preparation (2019)

We can tune the source to provide the radiograph with the best contrast and resolution





Magnification = 3



P. M. King et. al, In preparation (2019)

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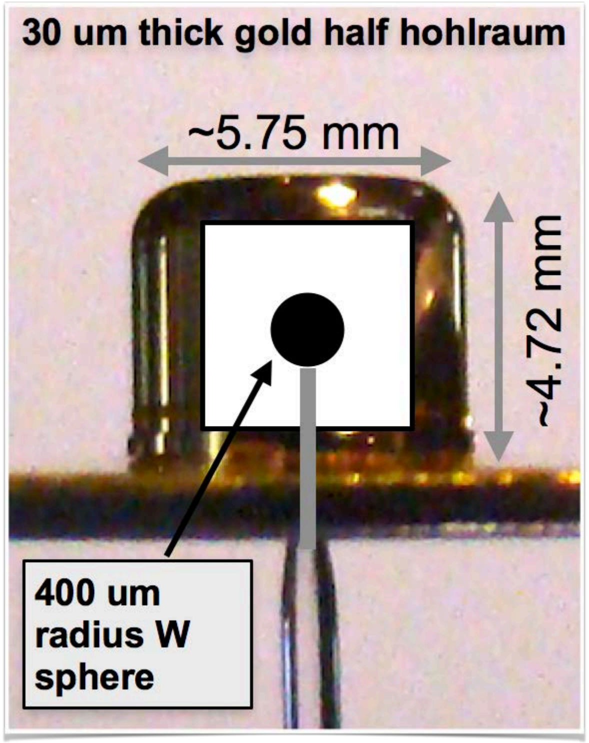
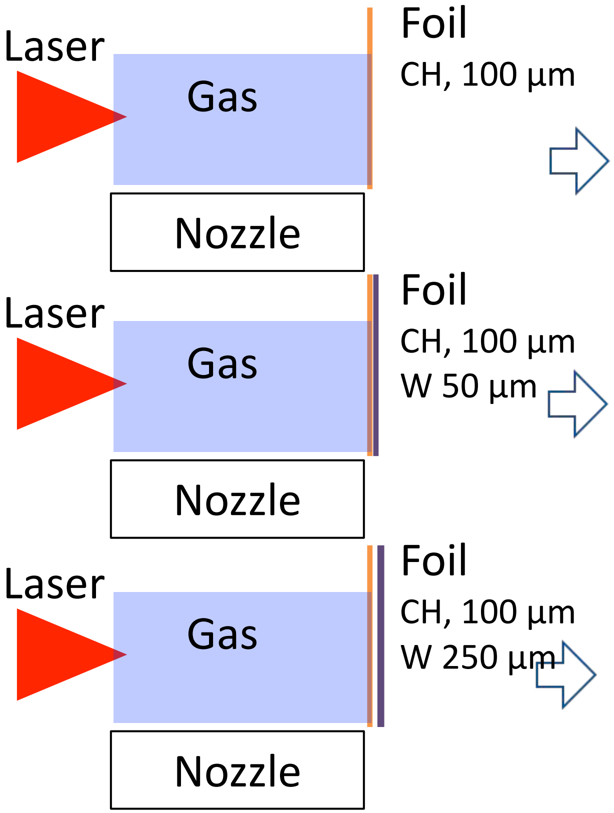
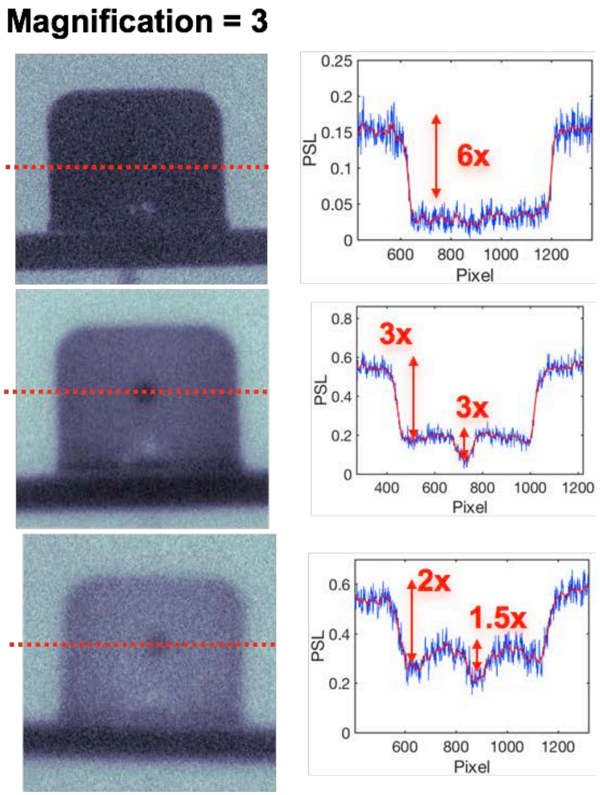
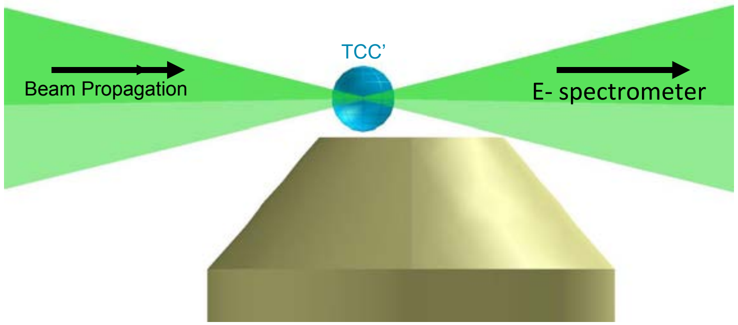


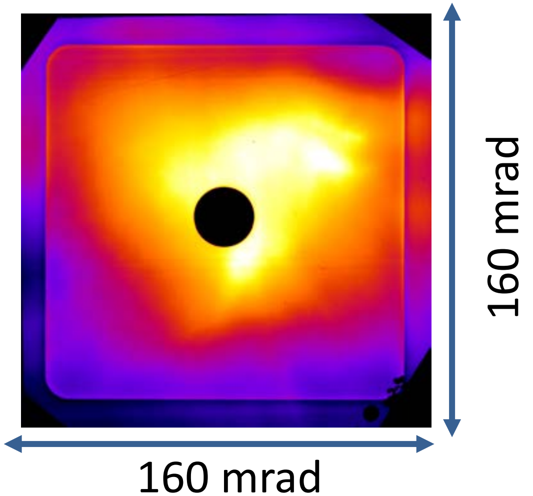




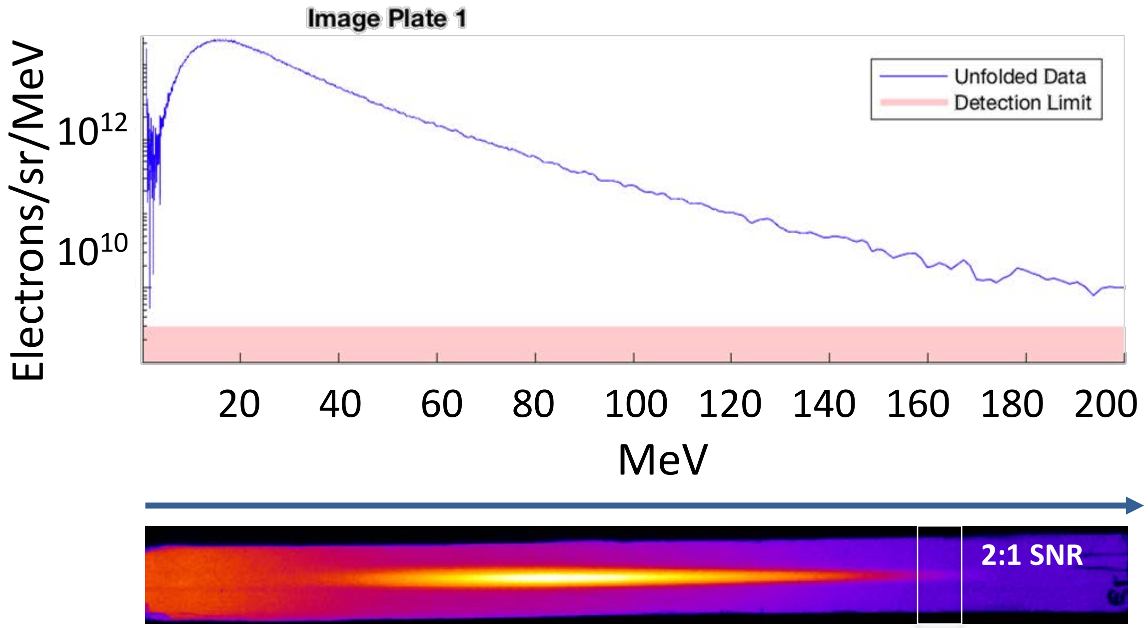
First Results at the OMEGA-EP laser show similar electron beam properties in SMLWFA conditions

$a_0=3$
$n_e = 5\times10^{18}\ cm^{-3}$

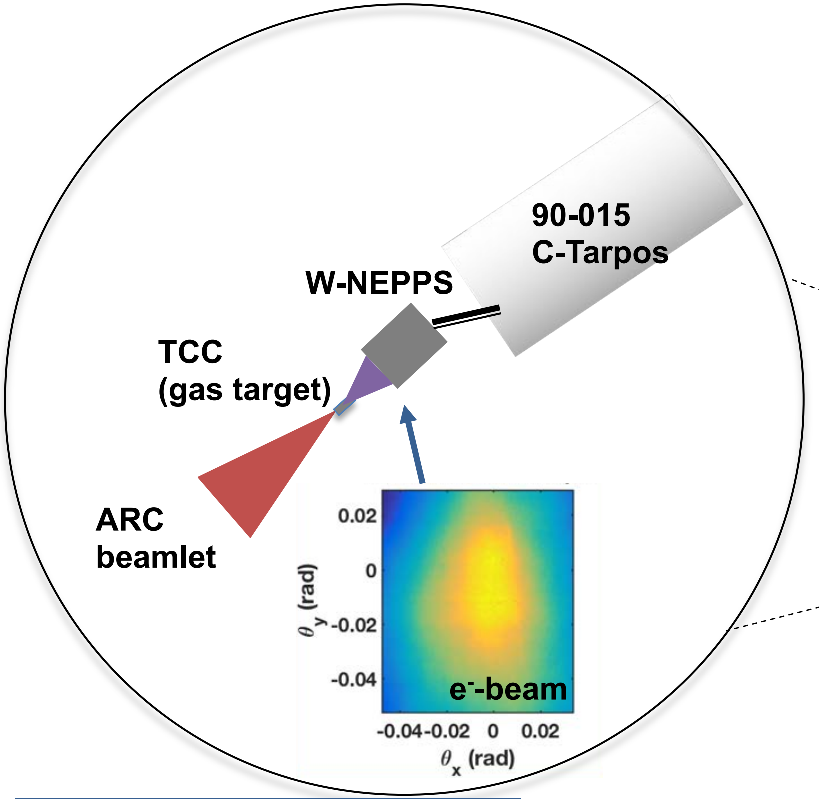


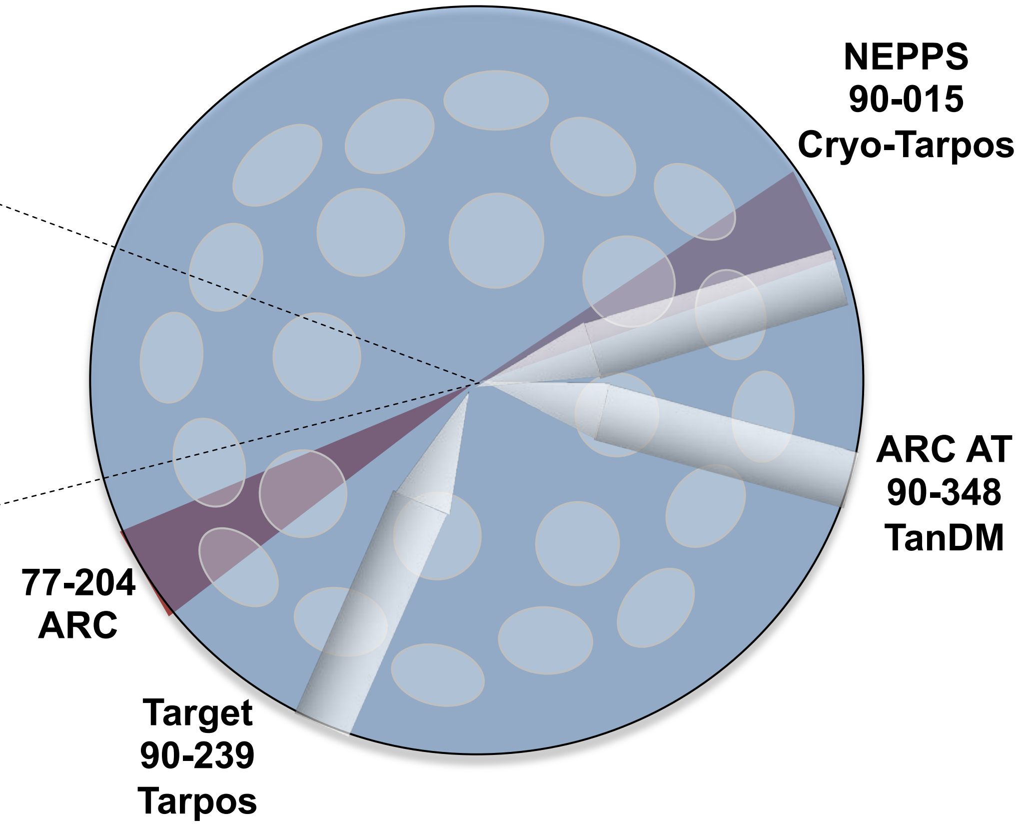


Electron spectrum



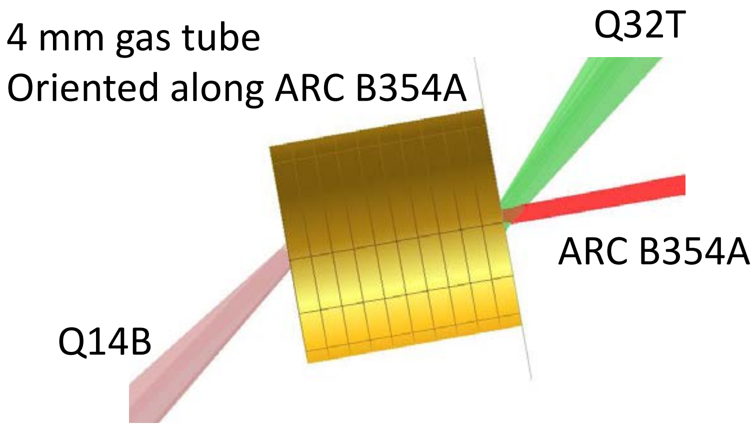
We have DS shots at NIF (9/11/2019) to develop the SMLWFA platform

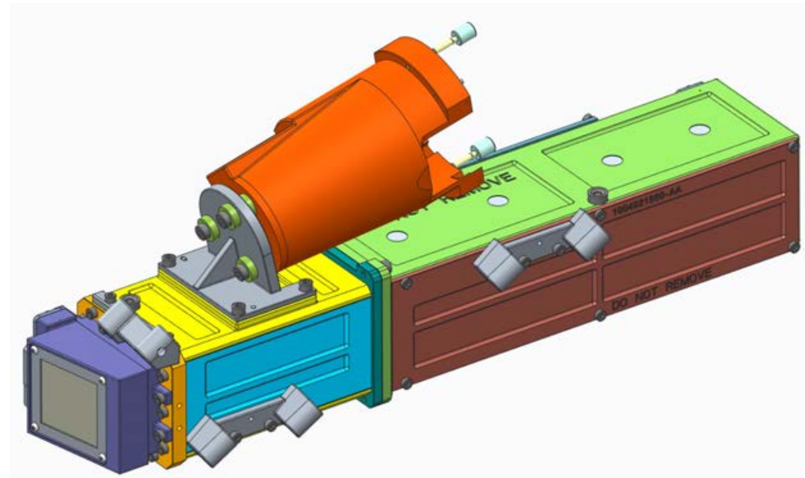


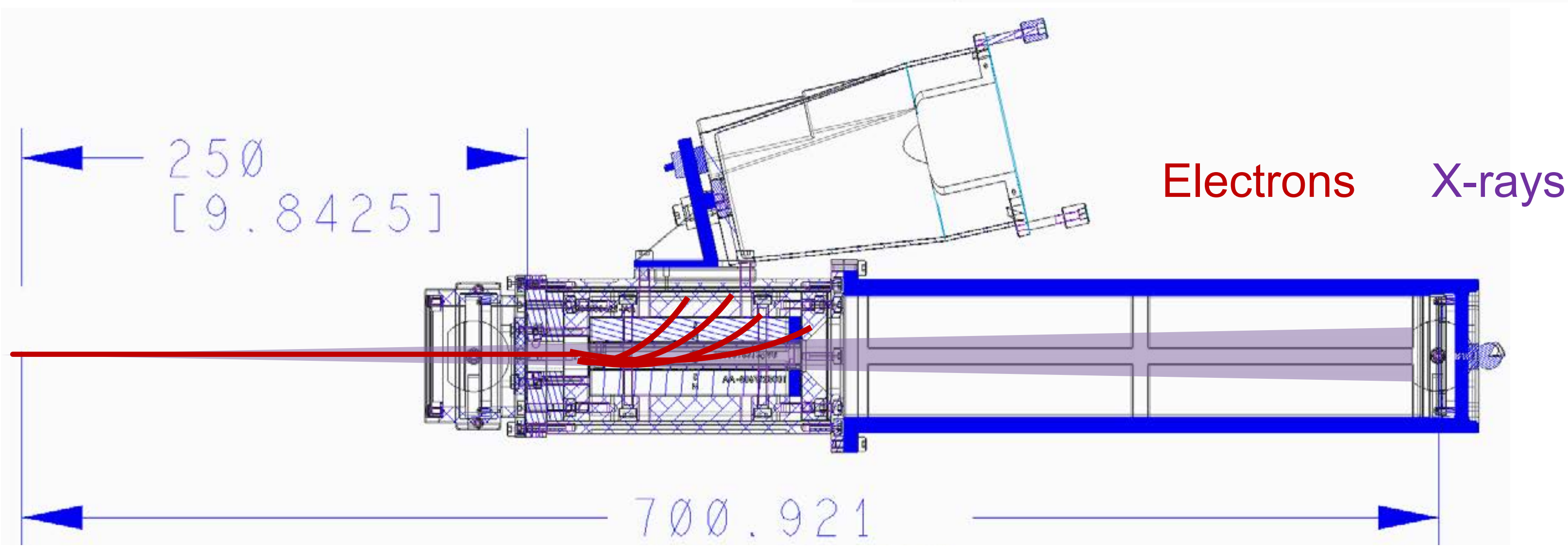


ARC Parameters
1 beamlet Shortest pulse duration: 1 ps Energy: Maximum (>250 J) Intensity: 0.5 – 1 x 10^{18} W/cm

We will use gas tubes and a modified version of NEPPS to produce and characterize electrons up to 150 MeV







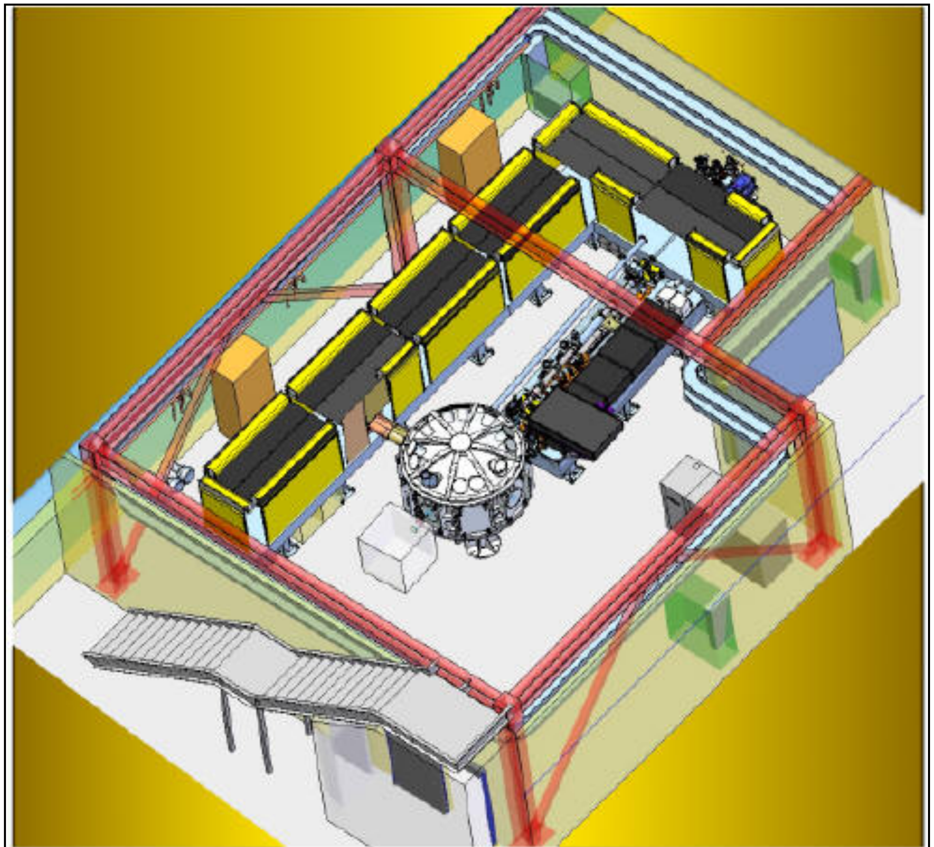
Outline

- Laser-plasma acceleration: an alternative for high brightness x-ray sources
- Self modulated and blowout laser-wakefield acceleration regimes for high brightness x-ray source development
- X-ray source development at LLNL and applications
- Betatron x-ray source development at LCLS and applications
- Conclusion and perspectives

We performed experiments at LCLS MEC end station

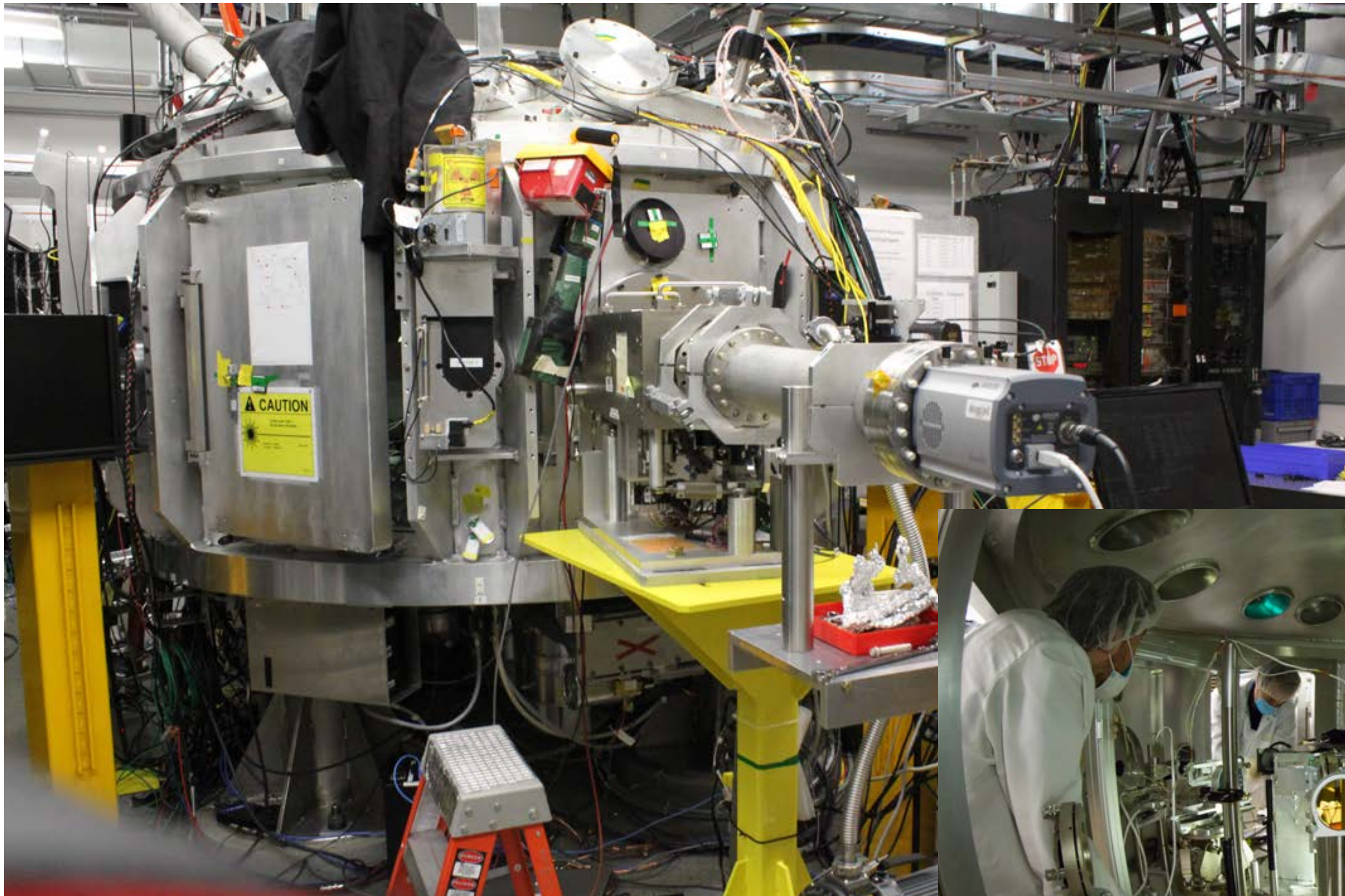
MATTER IN EXTREME CONDITIONS (MEC)

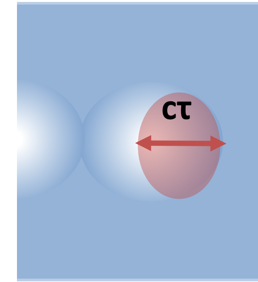
LCLS



- Colocation of three laser systems
  - XFEL (8 keV, 70 fs, 3 mJ)
  - ns optical laser (20 J, ns)
  - fs optical laser (1-7 J, 40 fs)
- Type of experiments
  - **ns laser pump / Betatron x-ray probe**
  - **fs laser pump / Betatron x-ray and LCLS probe**
  - **LCLS pump / Betatron x-ray probe**

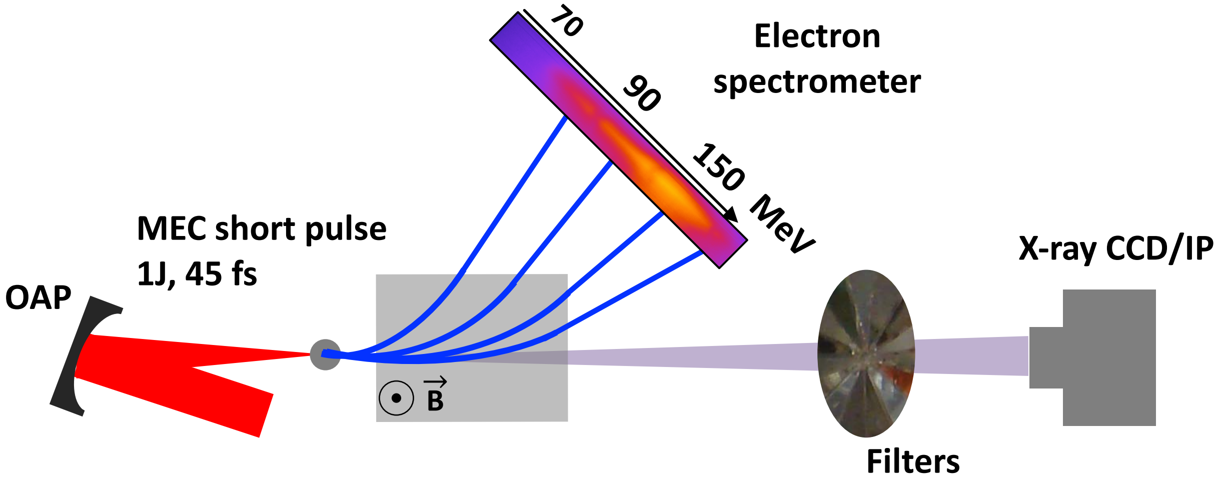
Betatron x-ray experiment at LCLS-MEC



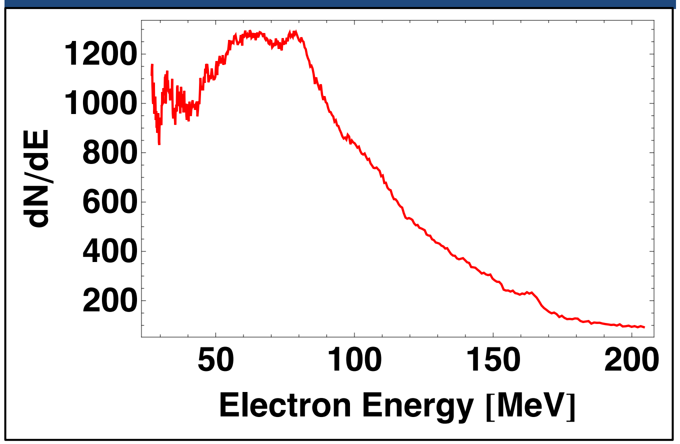


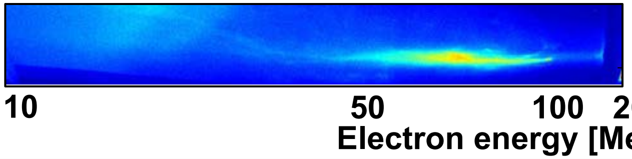
Blowout regime

Characterization of electron beam and betatron beam profile

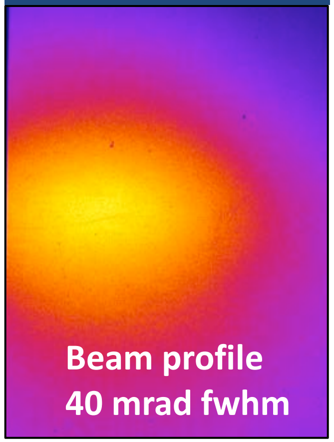


Electrons

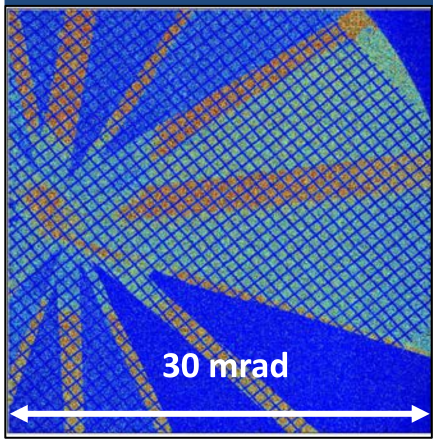




X-rays (IP)

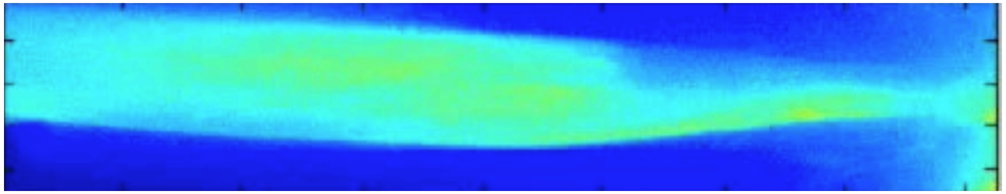


X-rays (CCD + Filters)

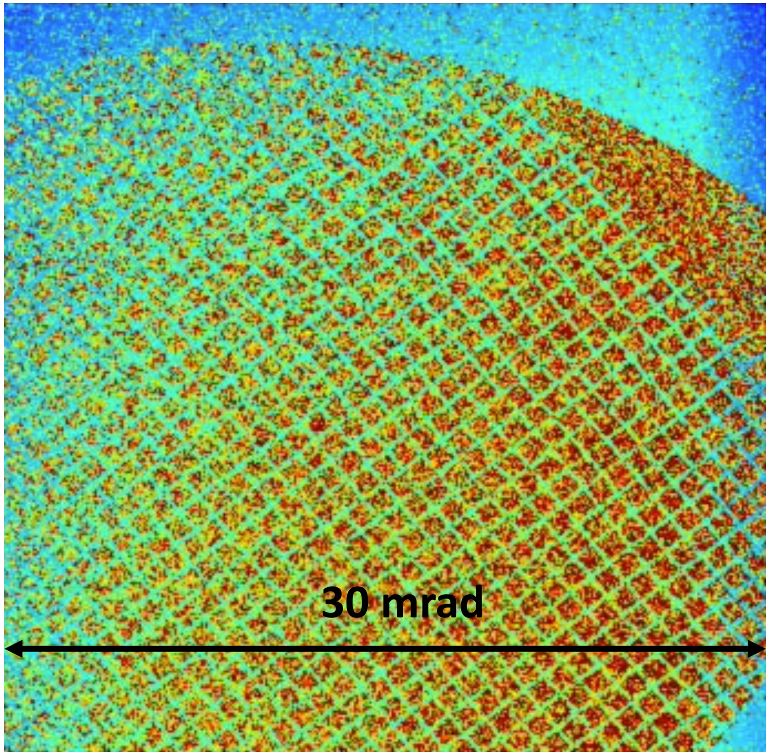


Electron beams and betatron x-rays are produced every shot

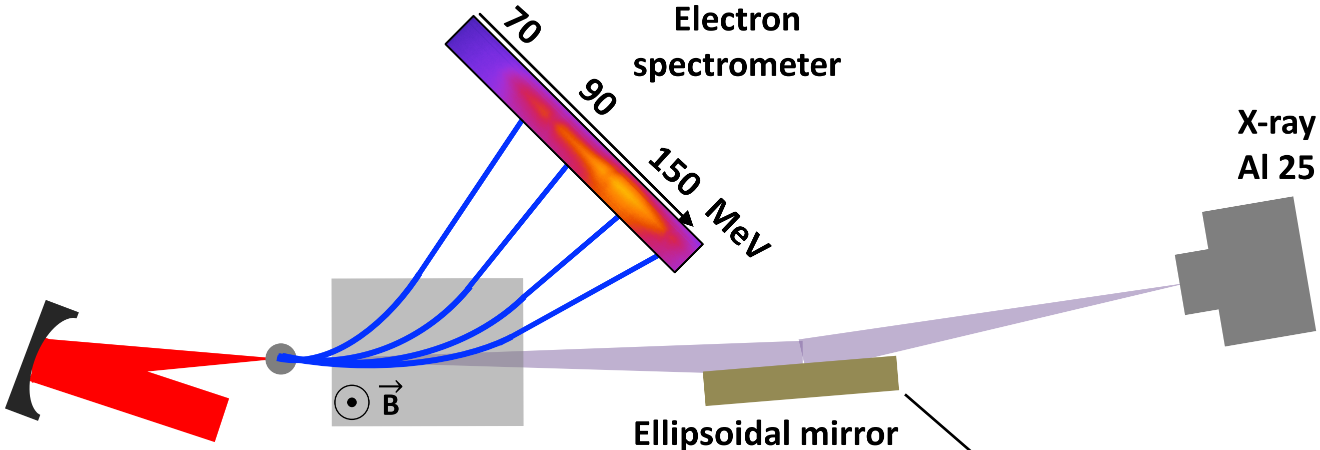
Electrons
Dispersed on LANEX screen
$n_e = 10^{19}$ cm^{-3}
90 % He, 10 % N_2 mix



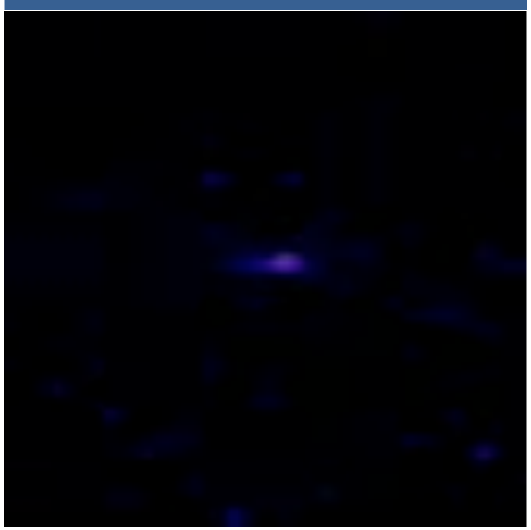
Betatron x-rays
> 4 keV on PI-MTE CCD
3 x 12.5 µm Al filters
60 µm Ag wires grid



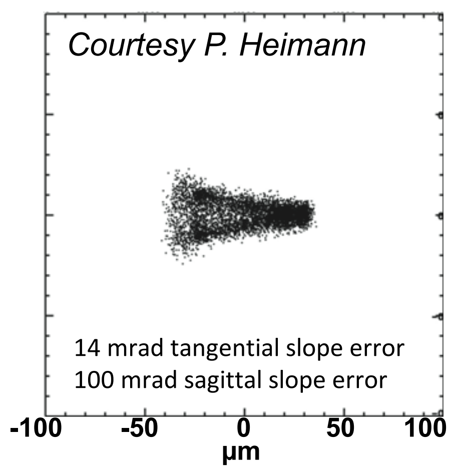
Characterization of betatron x-ray focus shows 16 % rms intensity stability

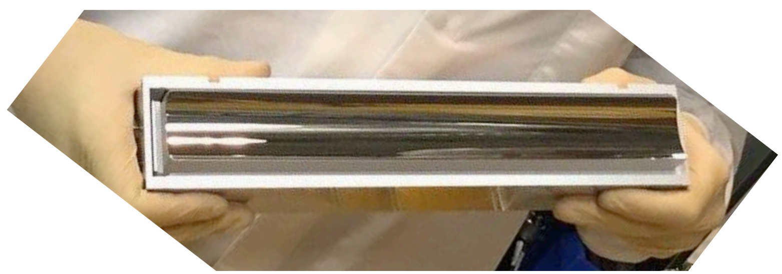


X-ray focus scan

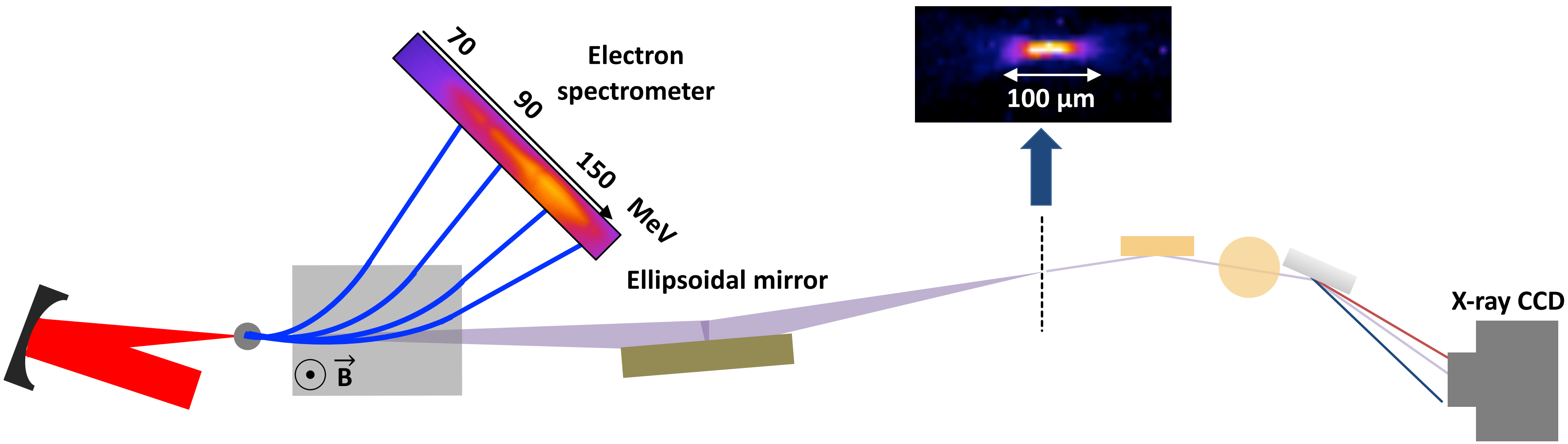


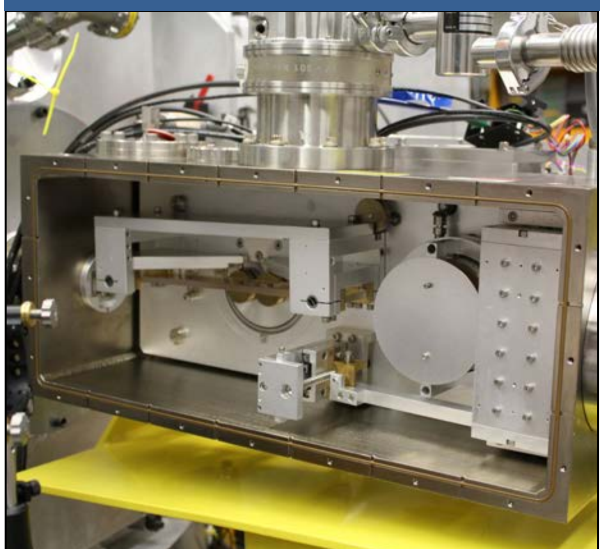
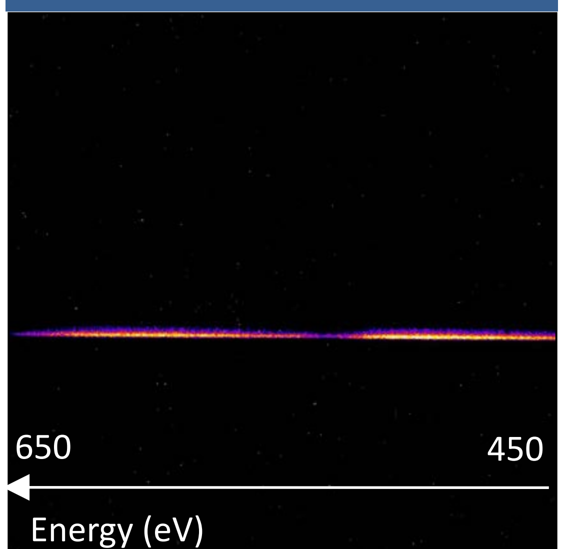
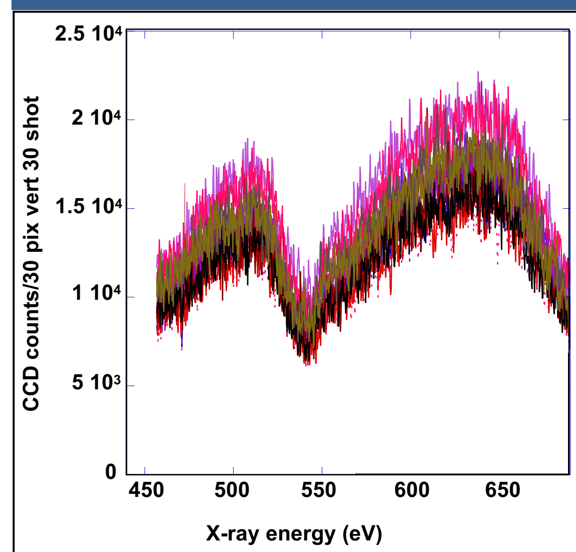
Ray tracing betatron focus



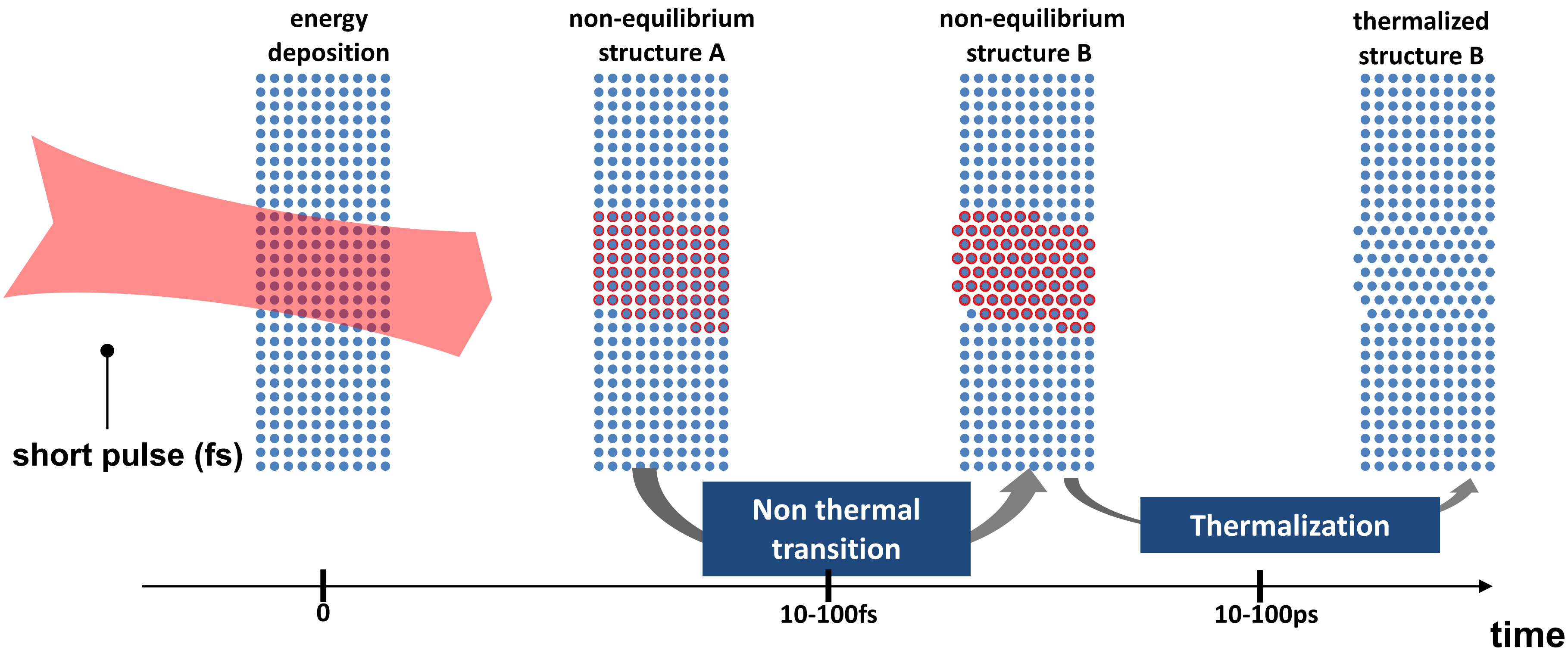


Betatron x-ray spectrum characterized with grating spectrometer

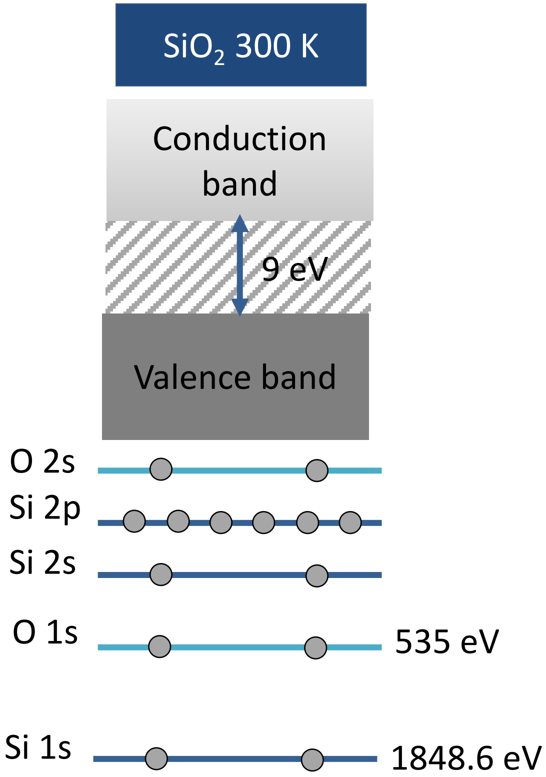


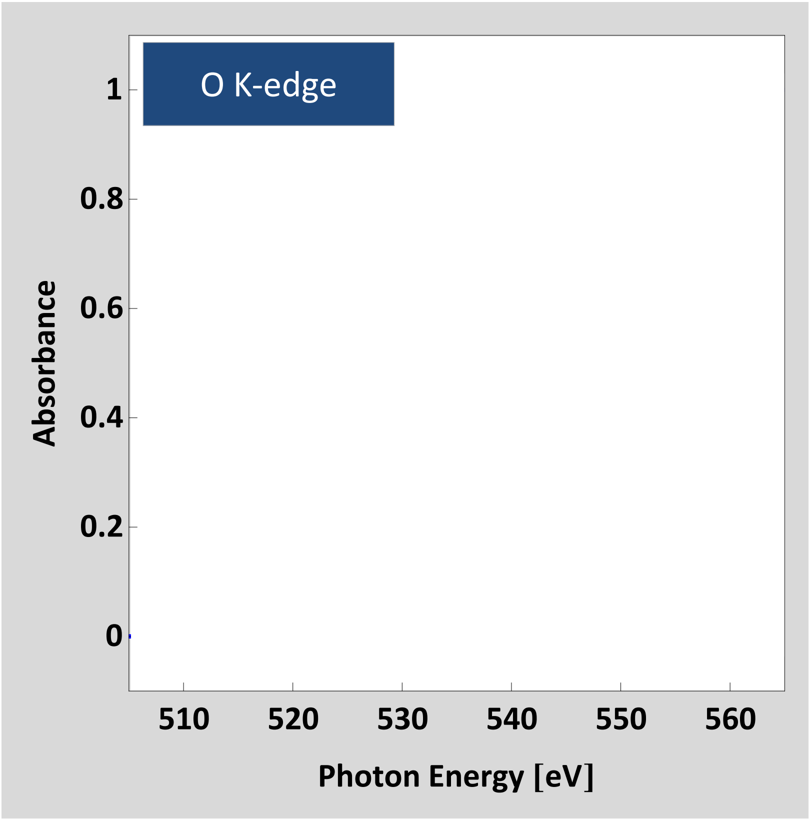
Spectrometer	Reference 30 shots	9 % rms intensity stability
		

We have probed nonthermal melting in SiO_2 using x-ray absorption spectroscopy

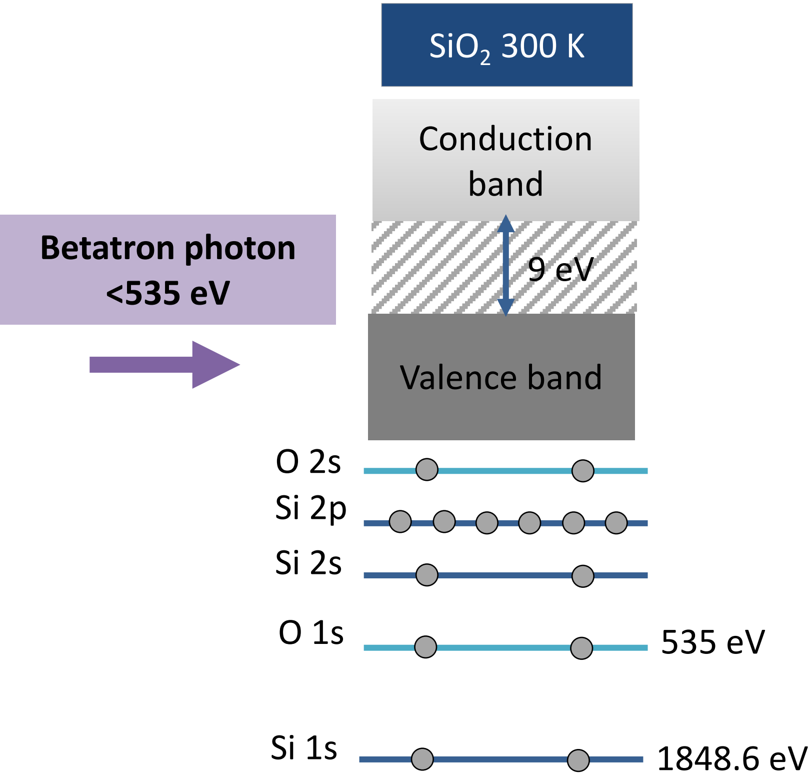


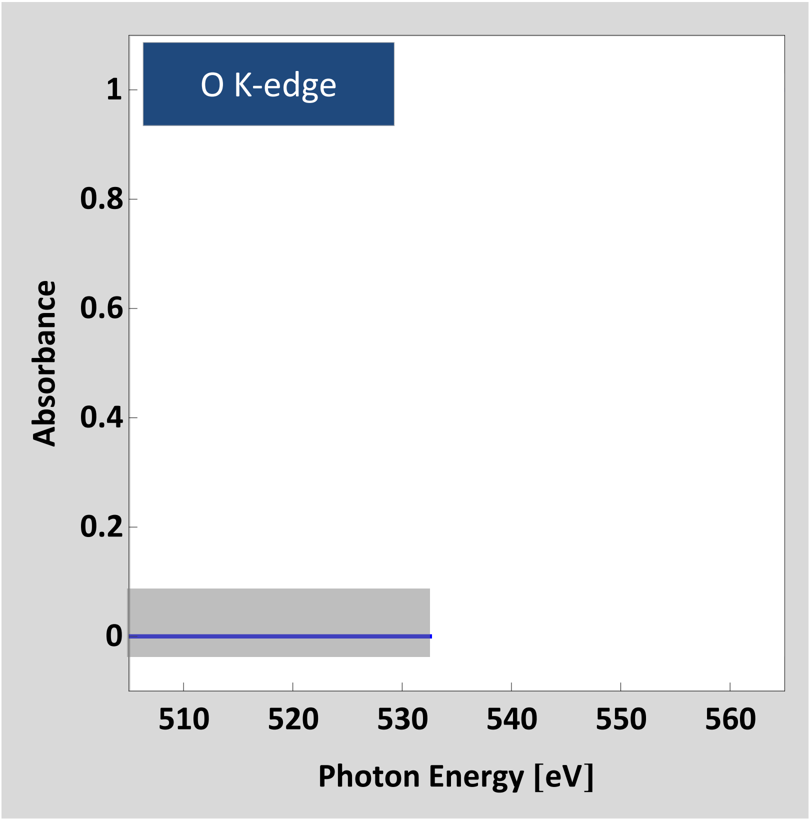
We performed absorption spectroscopy of SiO_2 a the O K-edge (535 eV)



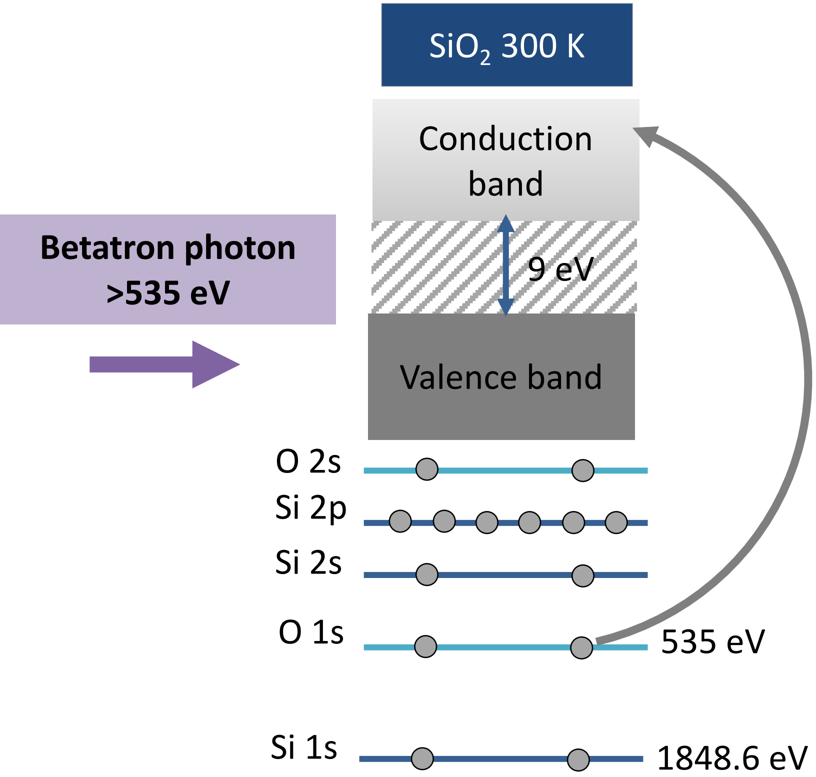


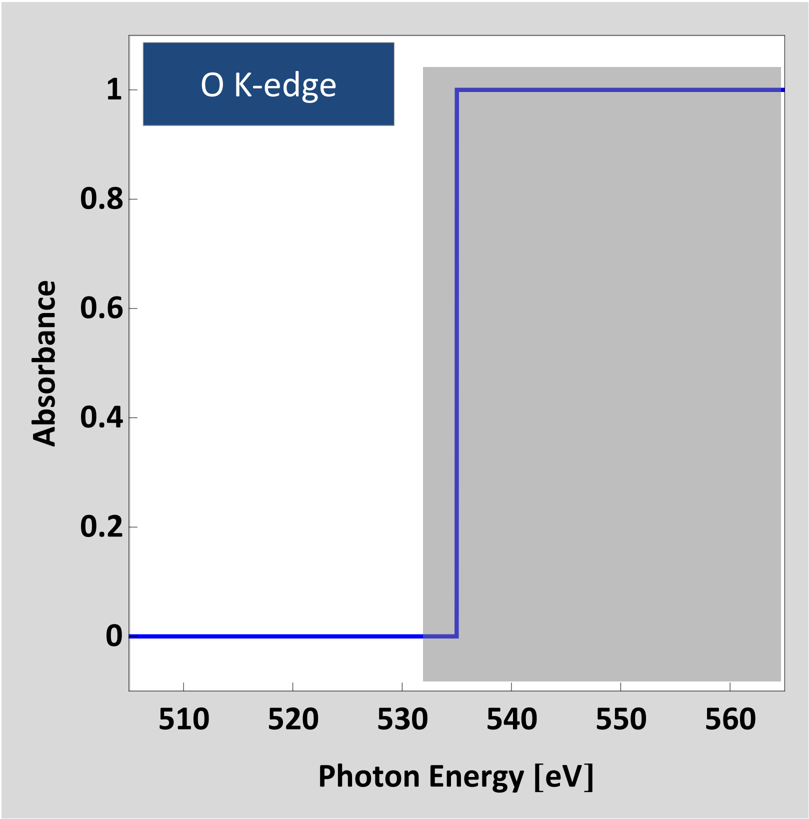
No absorption of x-ray probe photons below O K-edge energy



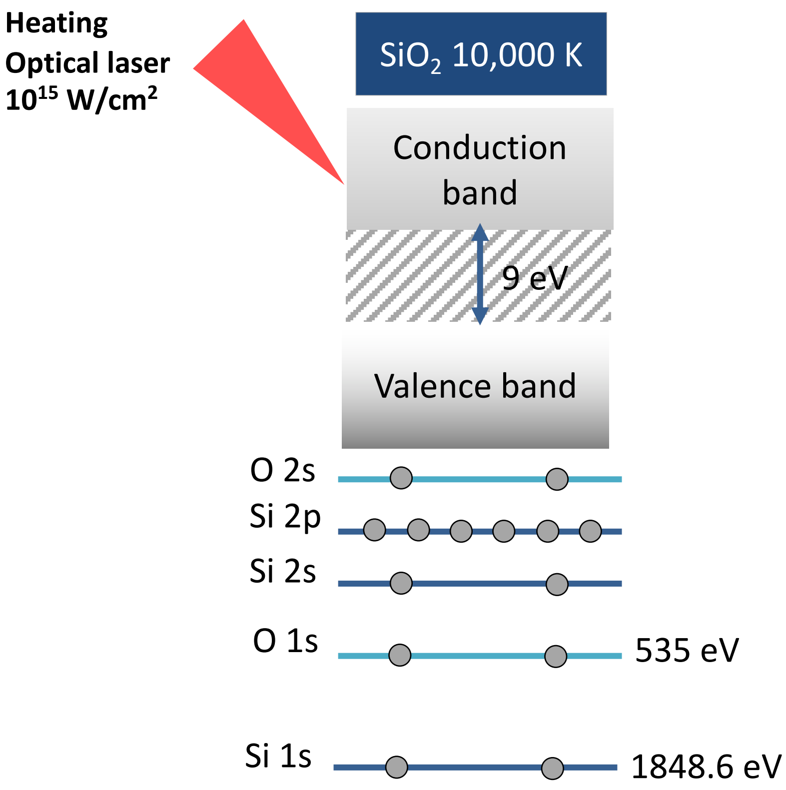


Sharp transition corresponds to strong absorption of x-ray photons for energies above the O K-edge

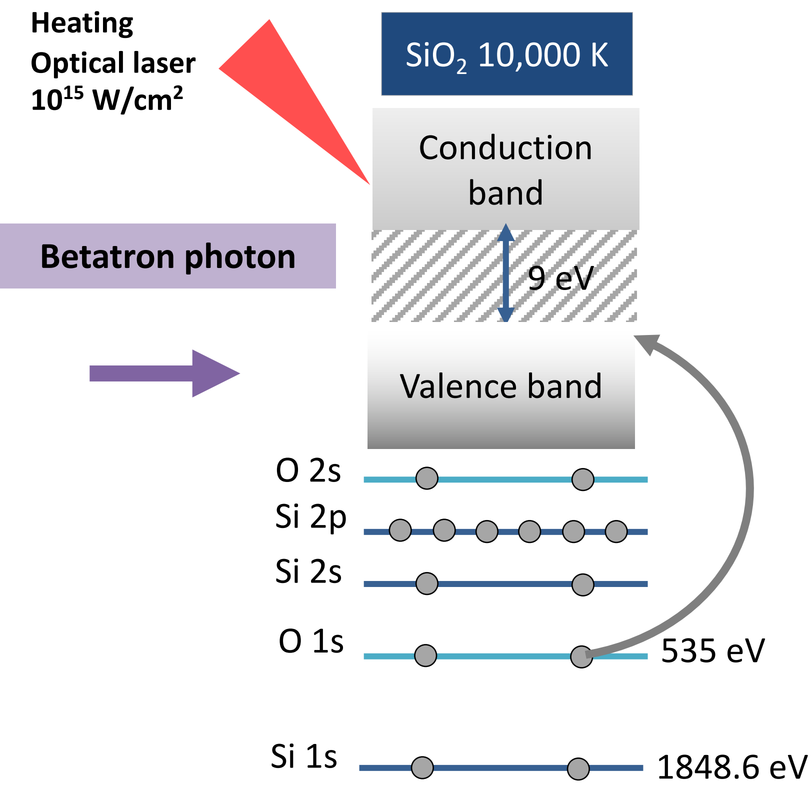


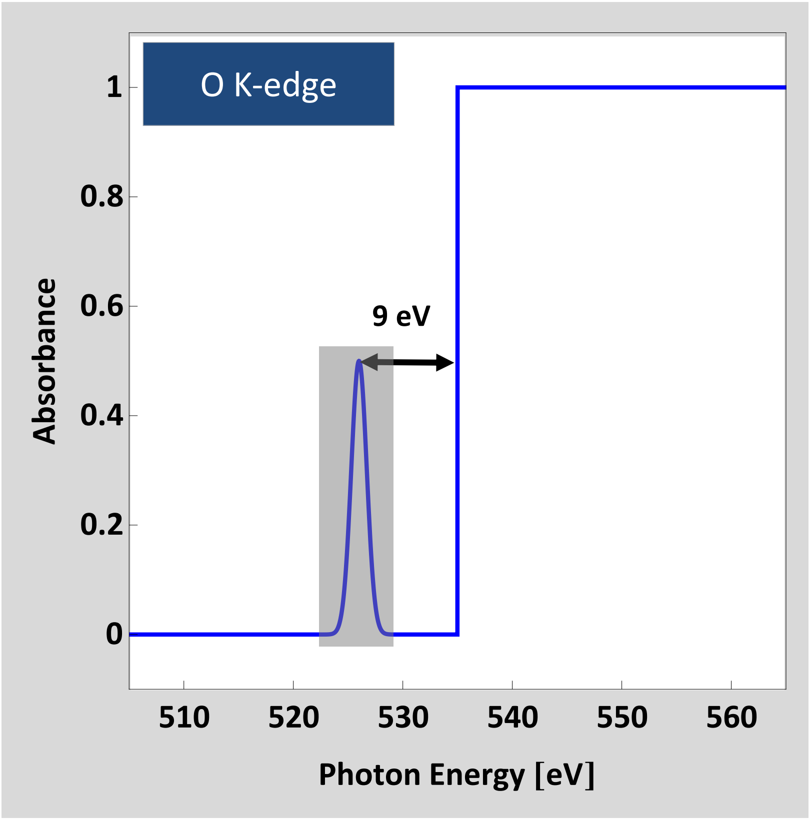


Multiphoton absorption causes electrons to cross the bandgap and leave vacancies in the valence band

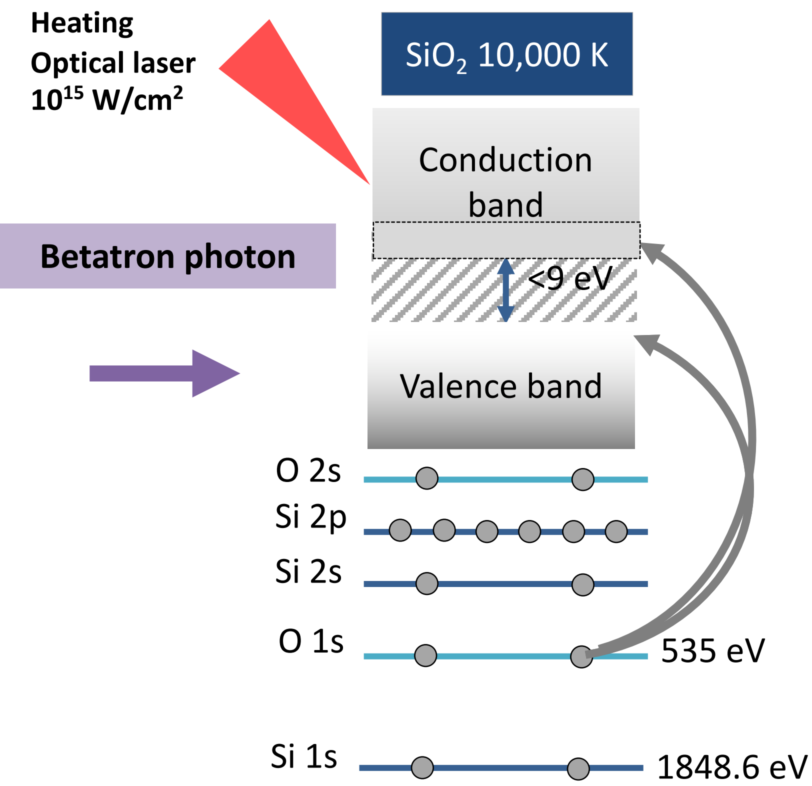


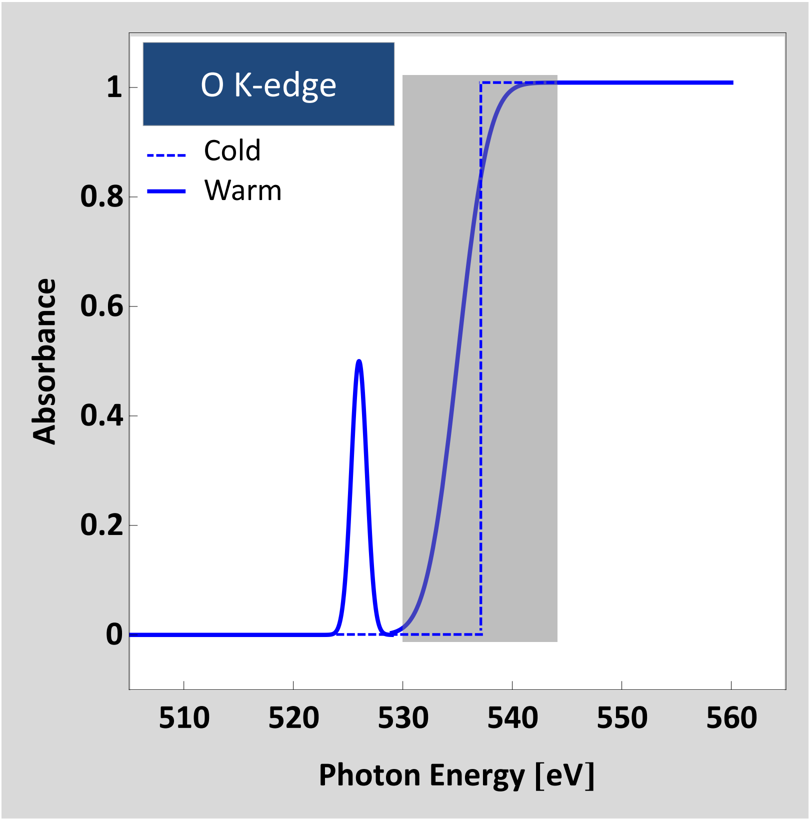
1s-valence band transitions are now authorized: strong absorption peak 9 eV below the edge





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





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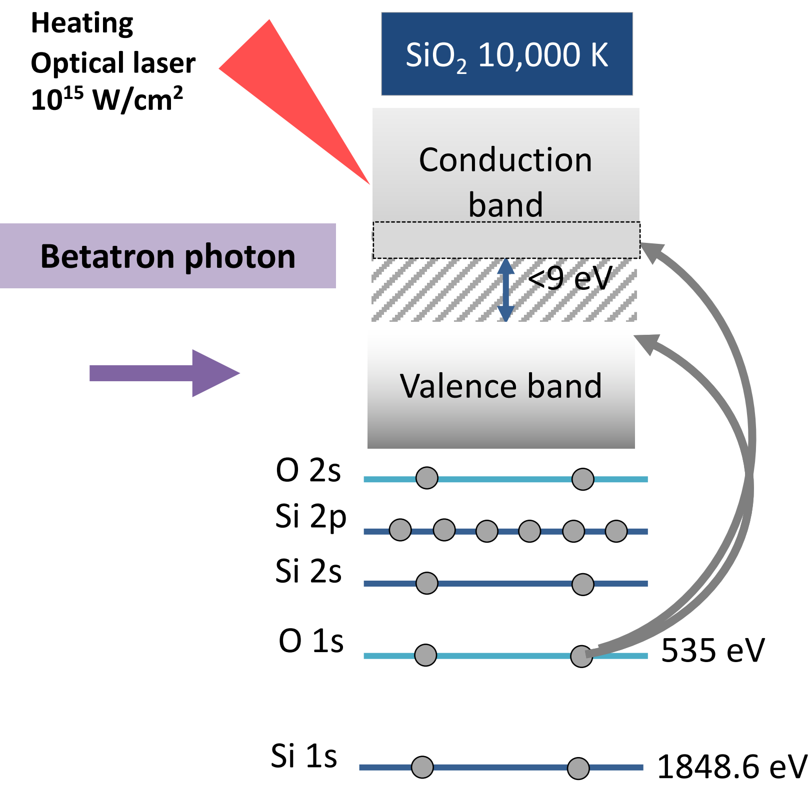
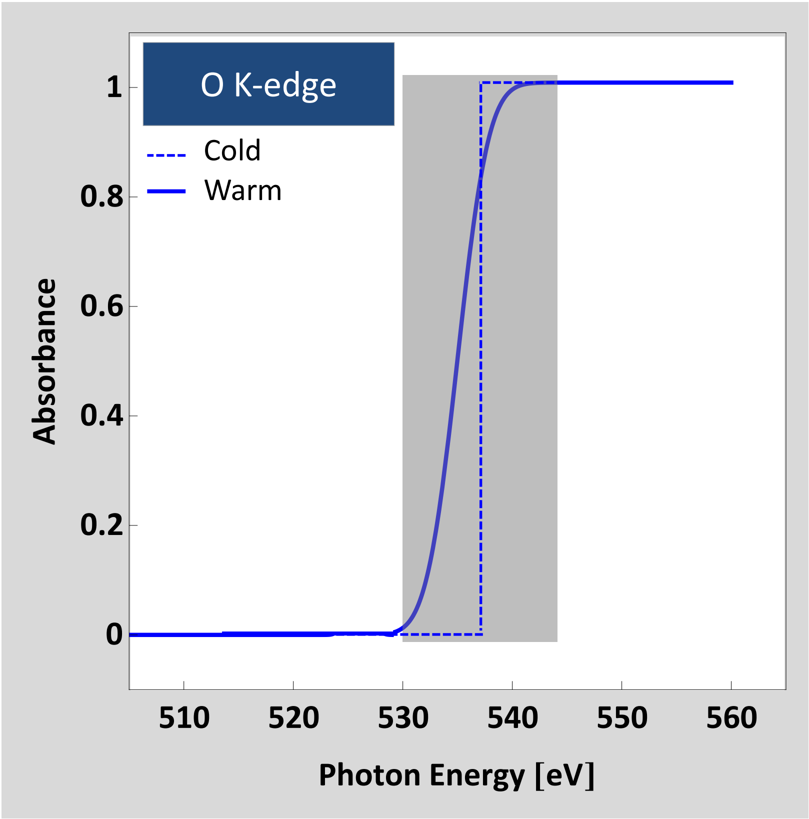
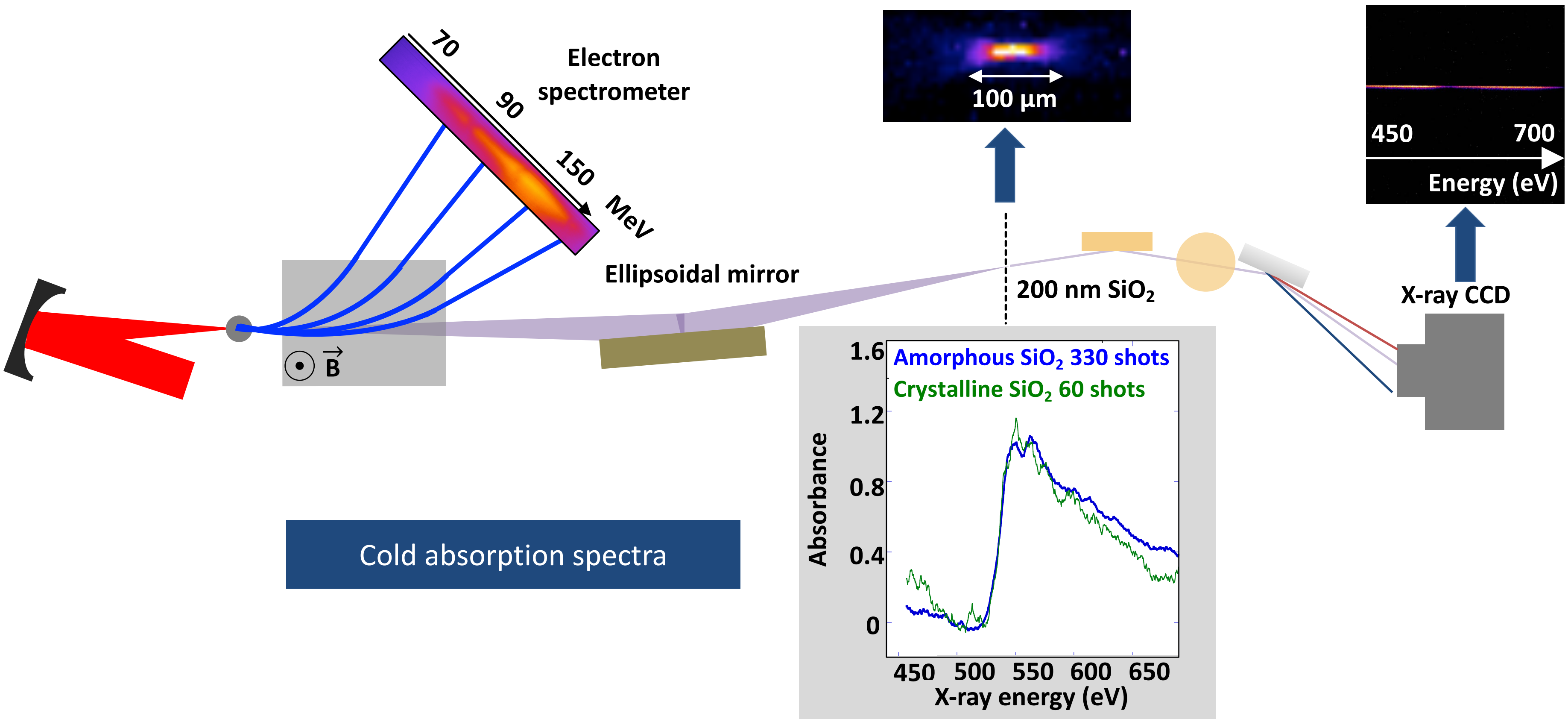




We have demonstrated the use of betatron x-rays as a tool for absorption spectroscopy



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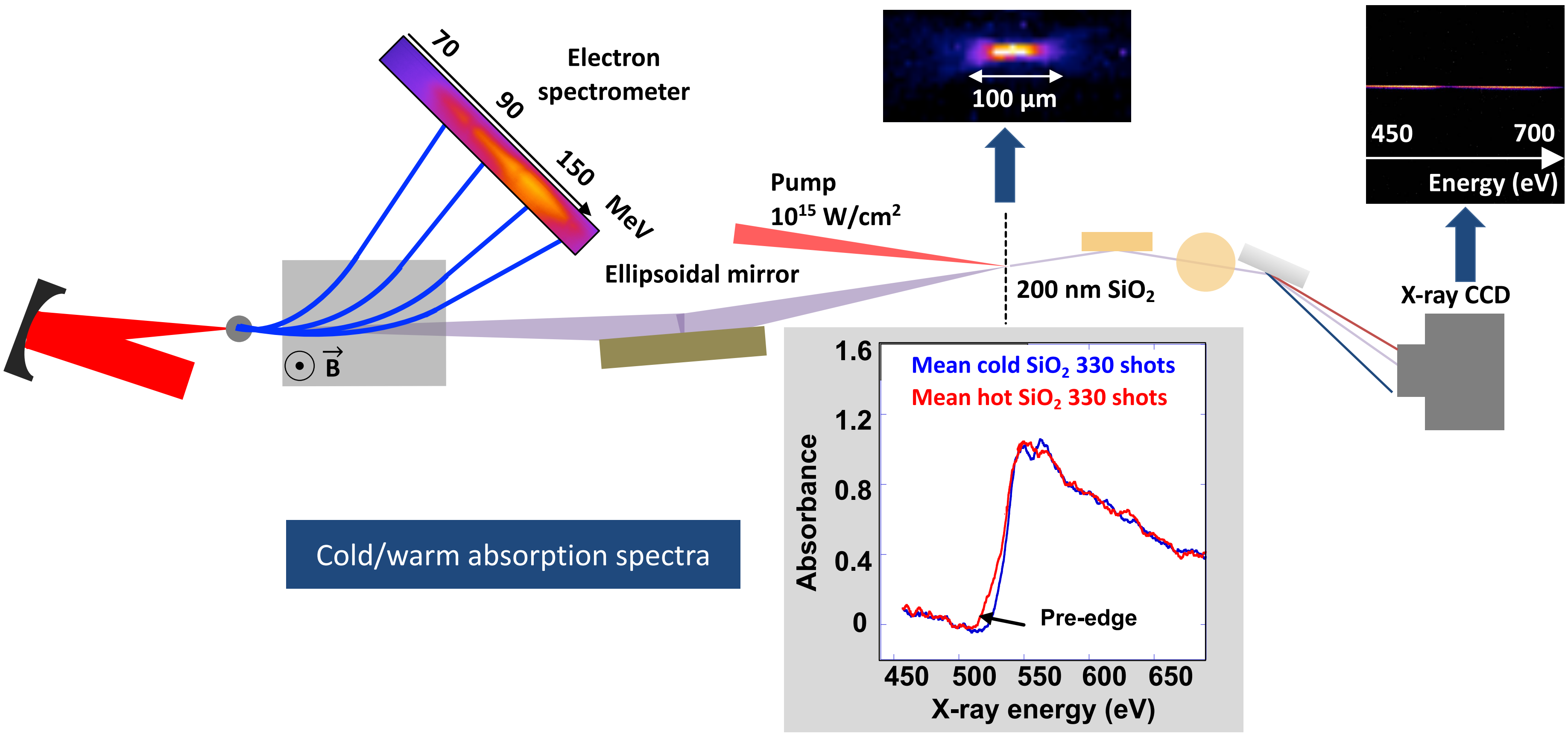
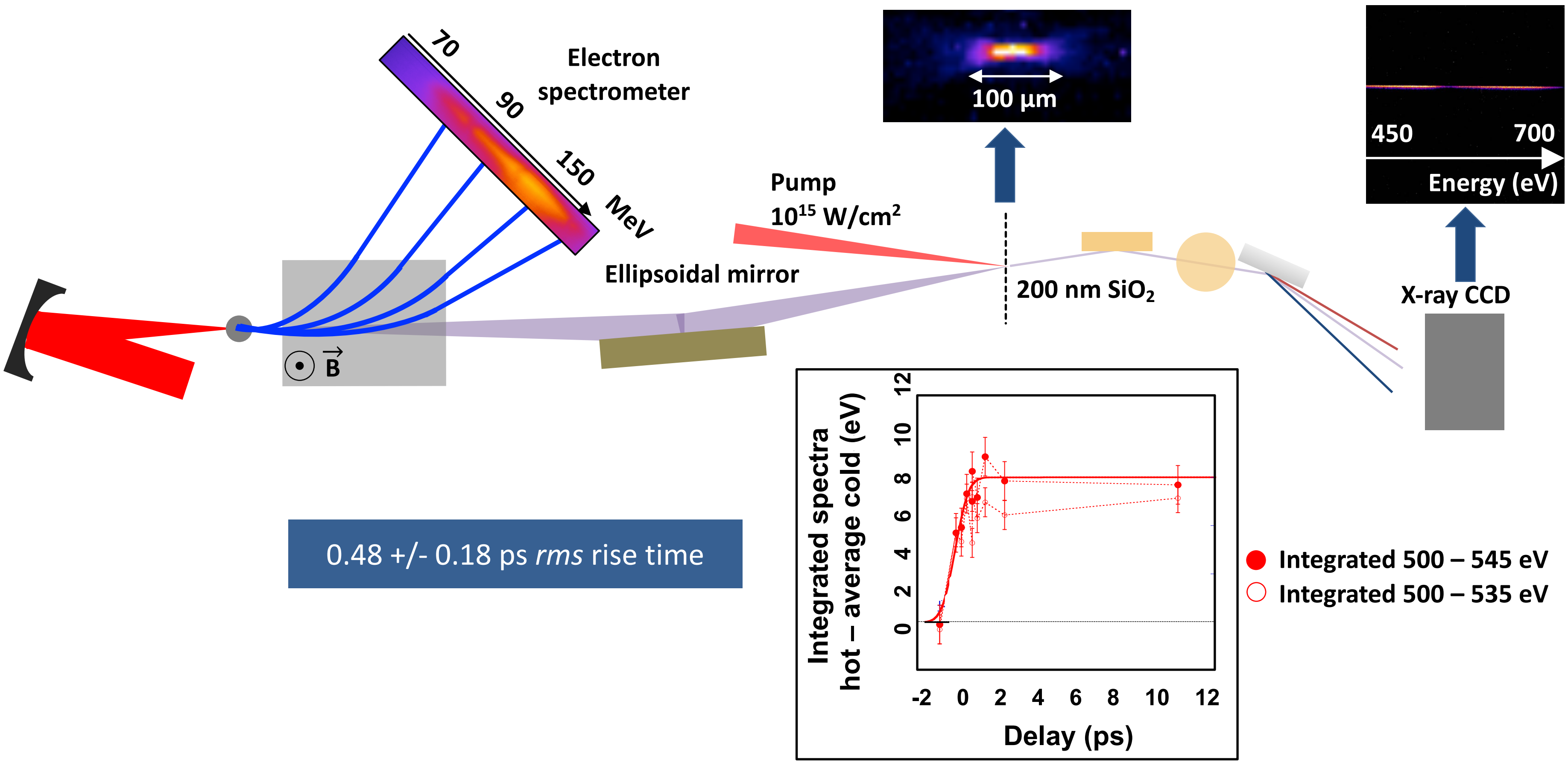


Cold/warm absorption spectra

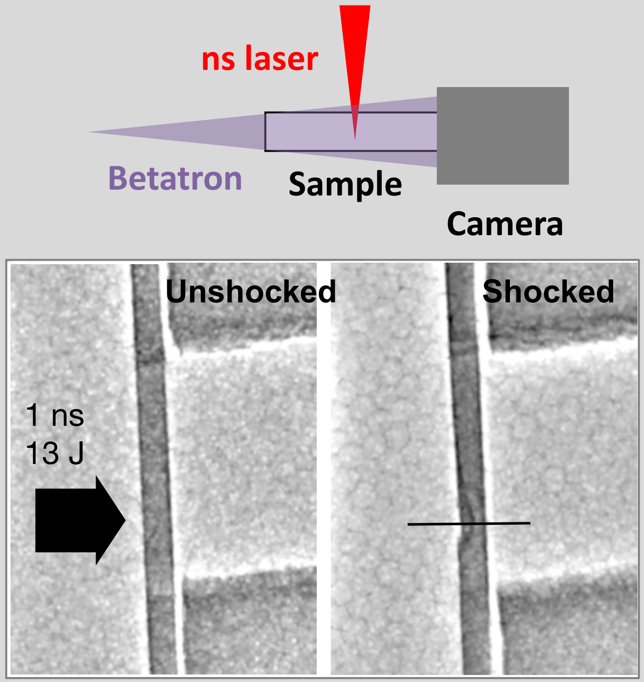
We have demonstrated the use of betatron x-rays as a tool for absorption spectroscopy with sub ps resolution



0.48 +/- 0.18 ps *rms* rise time

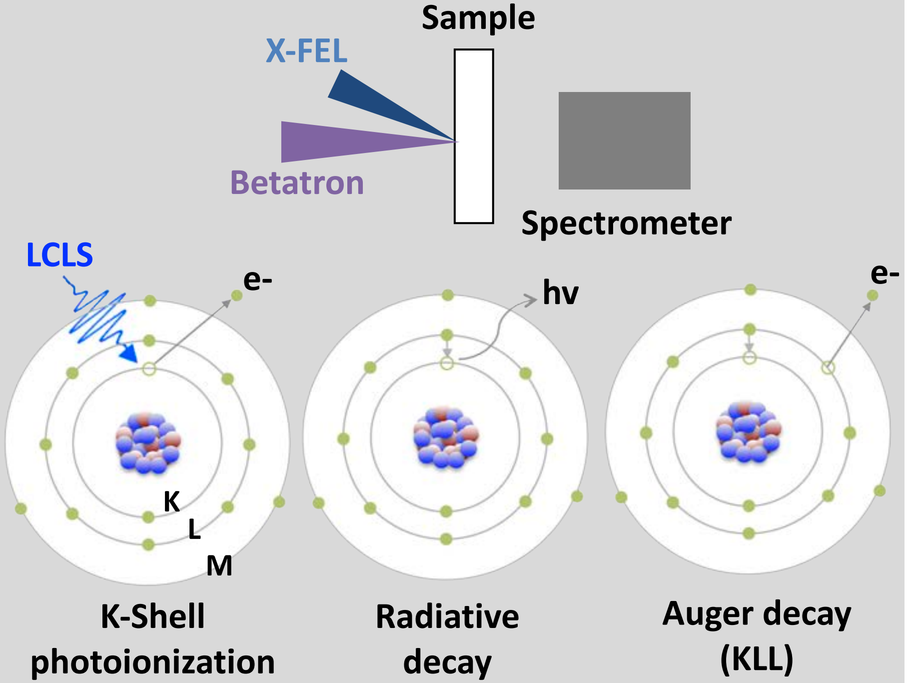
Other applications in progress

Phase contrast imaging of laser-driven shocks



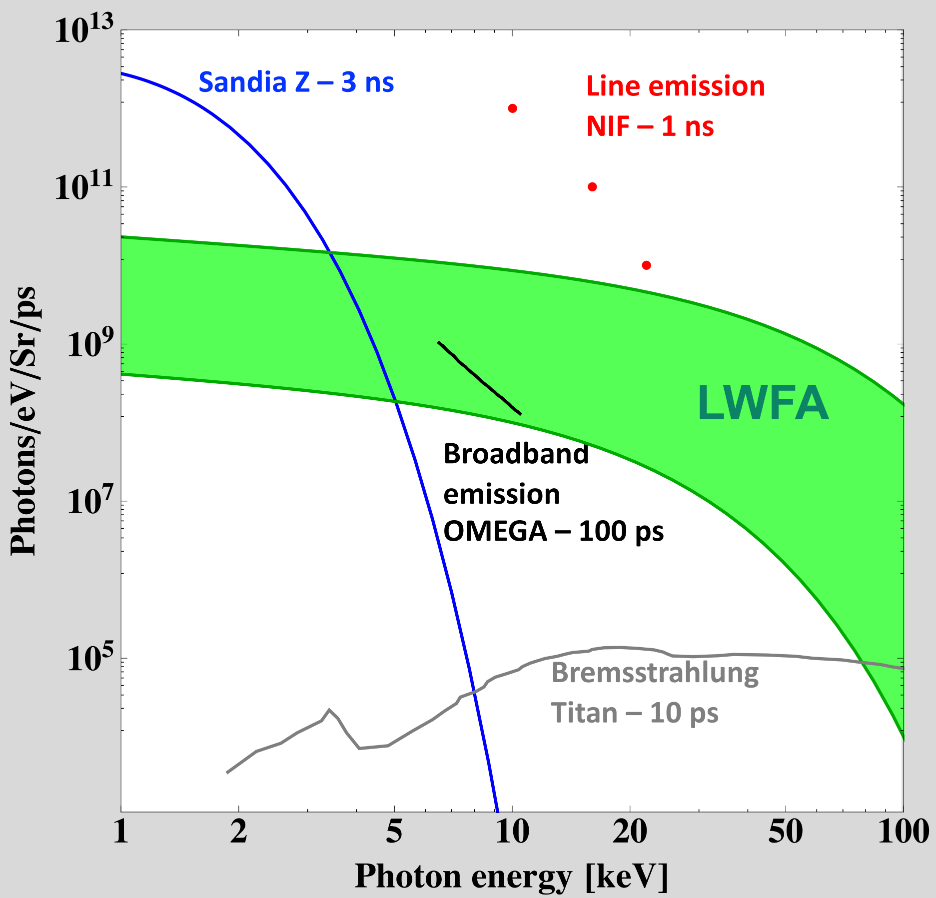
Courtesy of S. Mangles and J. Woods, Imperial College

Relaxation of metals driven by XFEL x-rays



Conclusions and future work

X-ray sources – Picosecond phenomena



- We have demonstrated the production of novel x-ray sources from laser-plasma accelerators
- They are broadband (keV - MeV), ultrafast (fs - ps), collimated (mrad), synchronized with drive laser
- 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
- Future work and challenges
  - Improving sources stability and flux
  - Applications from proof-of-principle to practical
  - LWFA sources as probes for HED science experiments

N. Lemos et al, PPCF 58 034108 (2016)
F. Albert et al, PRL 118 134801 (2017)
F. Albert et al, POP 25 056706 (2018)
N. Lemos et al, PPCF 60, 054008 (2018)
P. King et. al, Rev. Sc. Instr.   90, 033503 (2019)
F. Albert et al, Nuclear Fusion, 59, 032003 (2019)
N. Lemos et. al, PRL (in review)

It is an exciting time for short pulse laser science – LaserNetUS established in August 2018