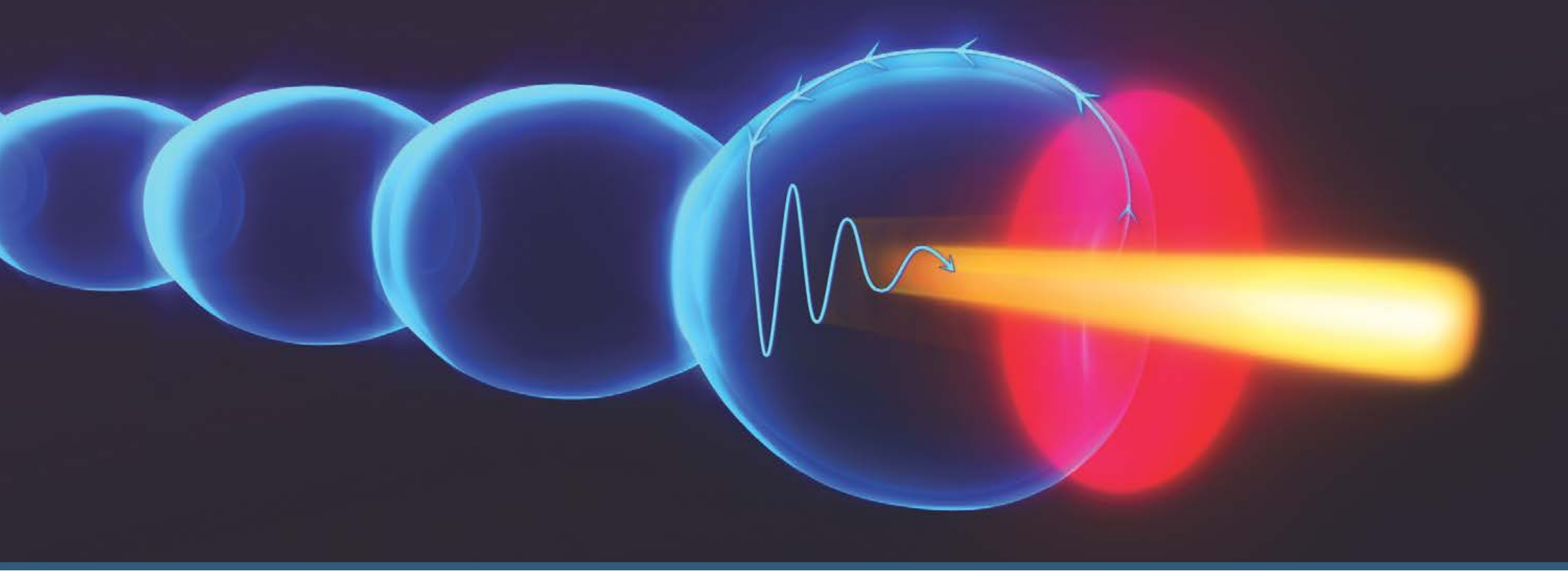


Lawrence Livermore National Laboratory

U.S. DEPARTMENT OF ENERGY

X-ray light sources driven by laser plasma accelerators for high energy density science experiments

Félicie Albert, PhD
Physicist
Deputy Director, LLNL High Energy Density Science center

LLNL-PRES-742828 This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Collaborators

N. Lemos, P. M. King, B. B. Pollock, C. Goyon, A. Pak, J. E. Ralph, Y. Ping, A. Fernandez-Panella, S. Hau-Riege, T. Ogitsu, A. Saunders, J. D. Moody

M. Sinclair, 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)

P. M. King, I. Pagano, M. C. Downer, B. M. Hegelich (UT Austin)

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

A.G.R. Thomas, C. Kuranz

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

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

D. Kraus, R.W. Falcone, C. Geddes (UCB/LBNL)

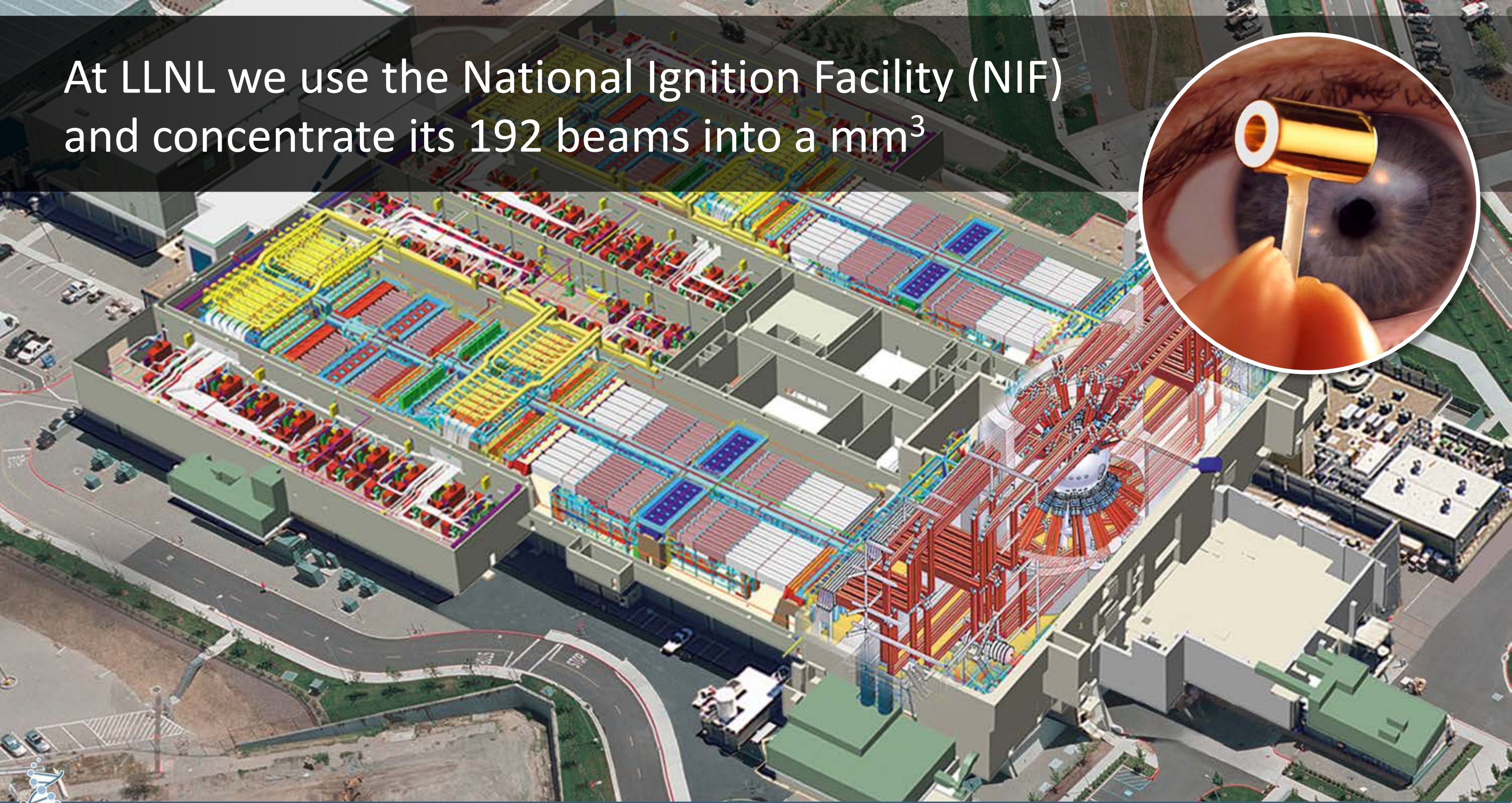
P. Zeitoun (LOA)

J. L. Shaw, D. H. Froula (LLE)

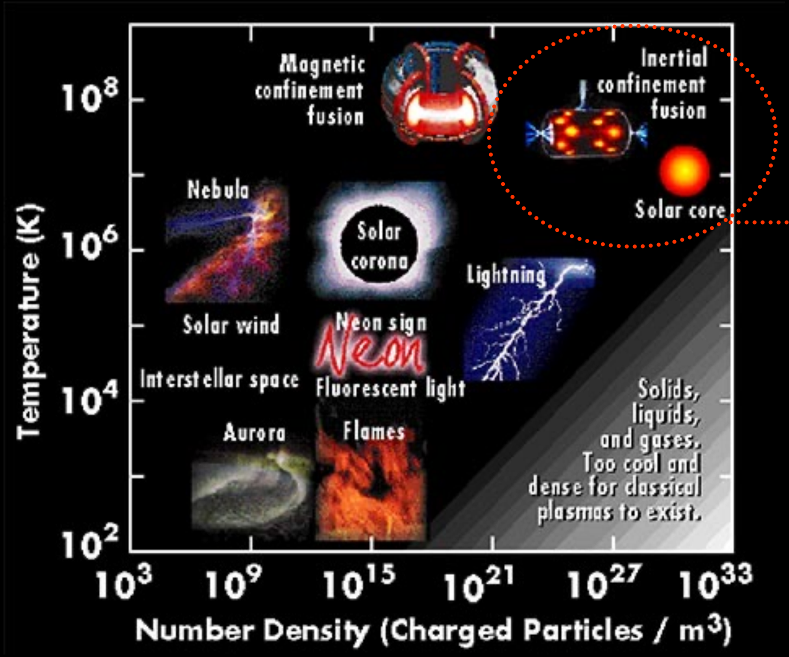
Outline

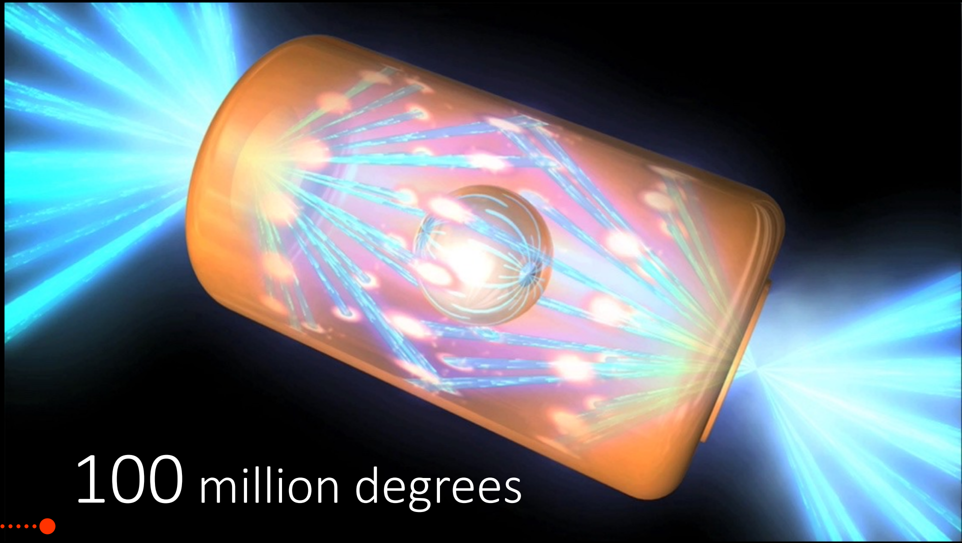
- X-rays: a powerful tool for high energy density science experiments
- Using high power lasers to generate laser plasma accelerators and x-rays
- Two applications of x-rays from laser plasma accelerators
  - Imaging complex high energy density science experiments
  - Understanding electron-ion equilibration in warm dense matter
- Conclusion

At LLNL we use the National Ignition Facility (NIF) and concentrate its 192 beams into a mm^3



Such experiments create extreme, transient conditions of temperature and pressure that are hard to diagnose



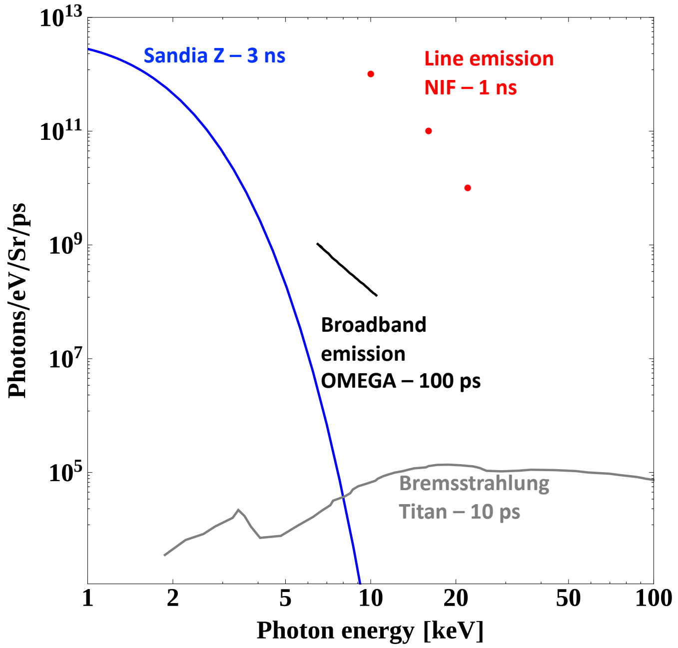


100 million degrees

20x the density of lead

Many High Energy Density Science experiments rely on x-ray backlighters with unique properties

X-ray sources for HEDS experiments



🟧 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)

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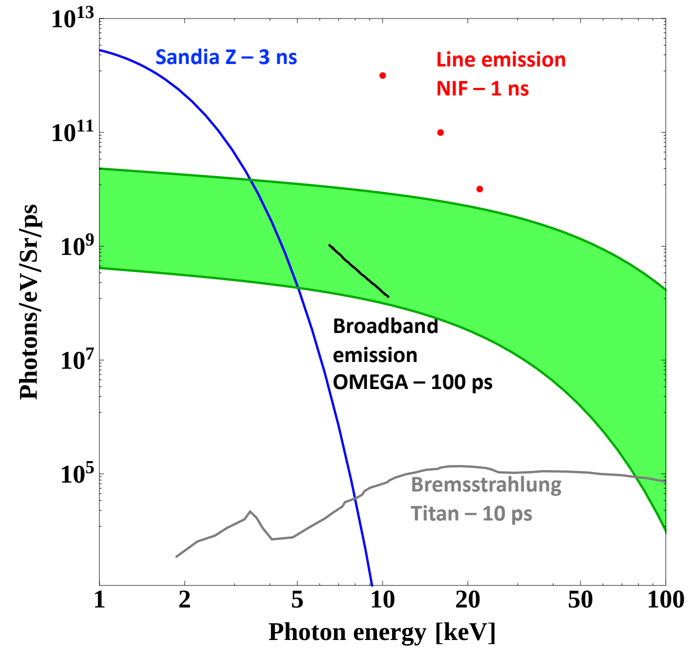
X-ray sources for HEDS experiments



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- X-ray opacity

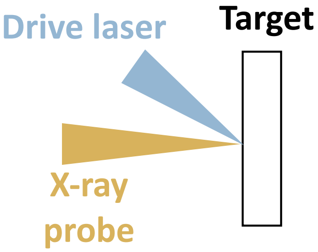
— Jarrott et al, POP 21 031201 (2014)

— This work – x-rays driven by laser wakefield acceleration

Unique properties of sources driven by LWFA can enable applications

Unique properties

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



Applications

- Shock physics
  - Phase contrast imaging of laser driven shocks
- Hydrodynamic instabilities motion
  - µm resolution imaging without motion blur
- Radiography of dense targets
  - MeV x-rays with small source size
- Opacity
  - Broadbad backlighter over 100’s of eV
- Electron-ion equilibration/warm dense matter
  - X-ray absorption spectroscopy with sub ps resolution

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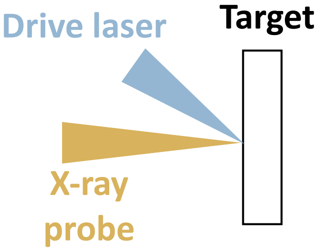

Applications

Shock physics

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- MeV x-rays with small source size

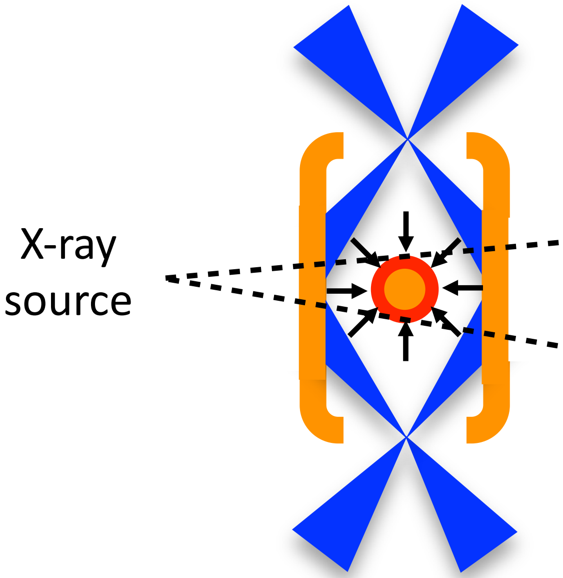
Opacity

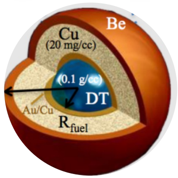
- Broadbad backlighter over 100’s of eV

Electron-ion equilibration/warm dense matter

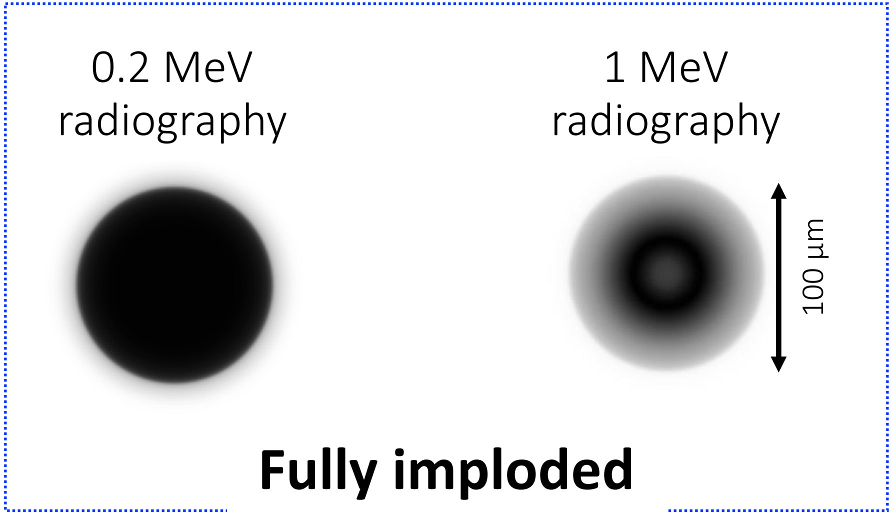
- X-ray absorption spectroscopy with sub ps resolution

X-ray sources with MeV photons and <10 µm resolution are required to understand some of the experiments done at the NIF





Double shell implosion, 1800 g/cc

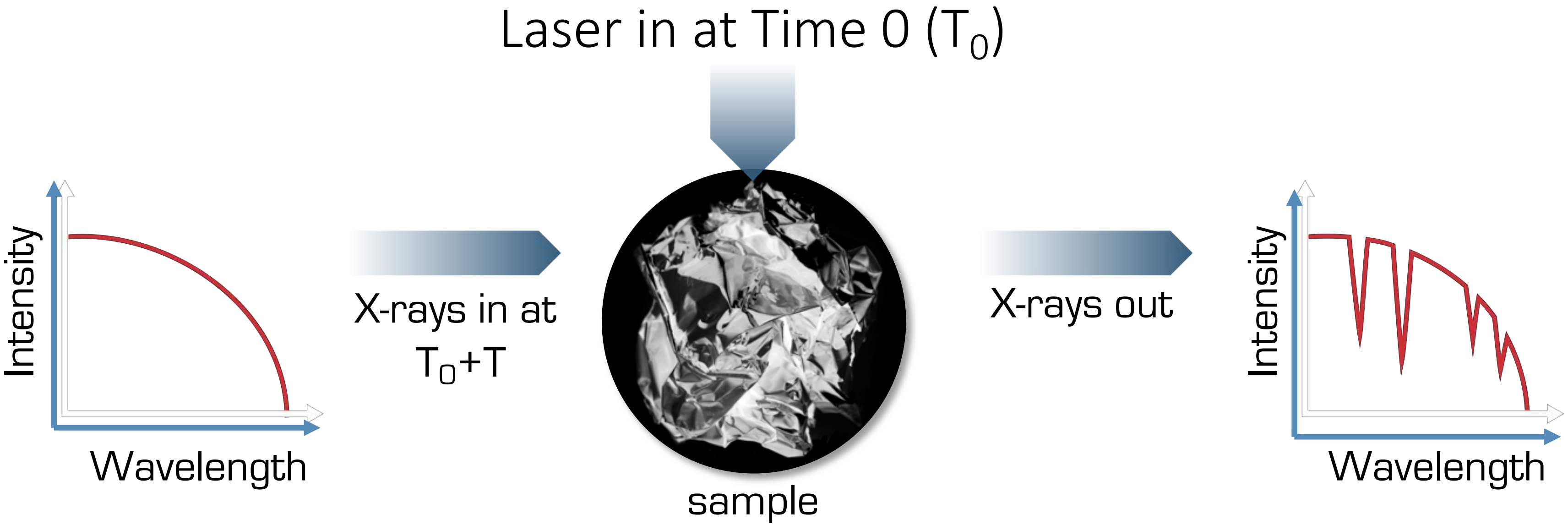


Fully imploded capsule

We use ”pump-probe” experiments and x-ray measurement techniques to understand these conditions

X-ray absorption spectroscopy

We use "pump-probe" experiments and x-ray measurement techniques to understand these conditions



Laser in at Time 0 (T_0)

X-rays in at T_0+T

sample

X-rays out

4th generation x-ray light sources used for scientific applications could be used but are billion dollar-scale national facilities

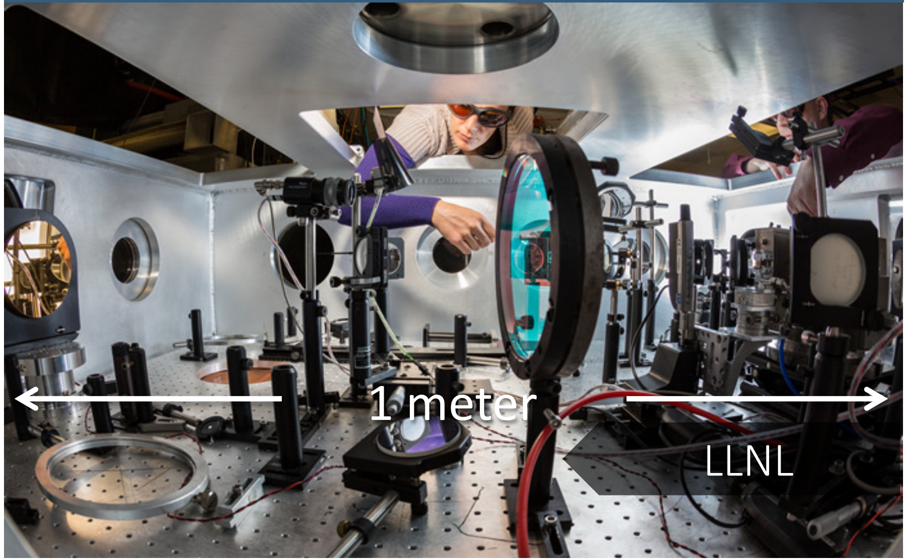
X-ray free electron laser: LCLS

Synchrotron: APS

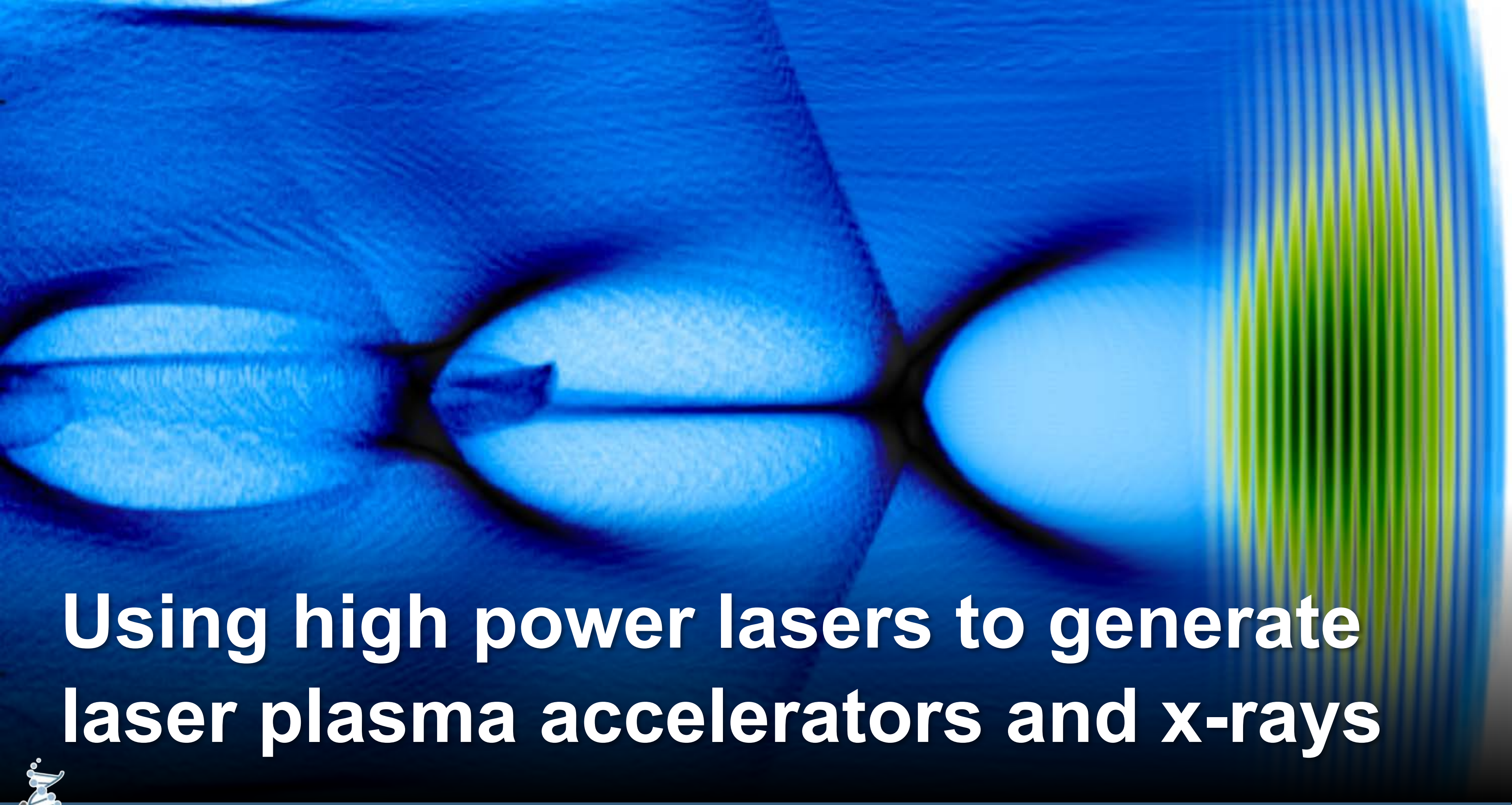
Laser plasma accelerators offer a compact alternative to these big machines

X-ray free electron laser: LCLS

Laser plasma accelerator



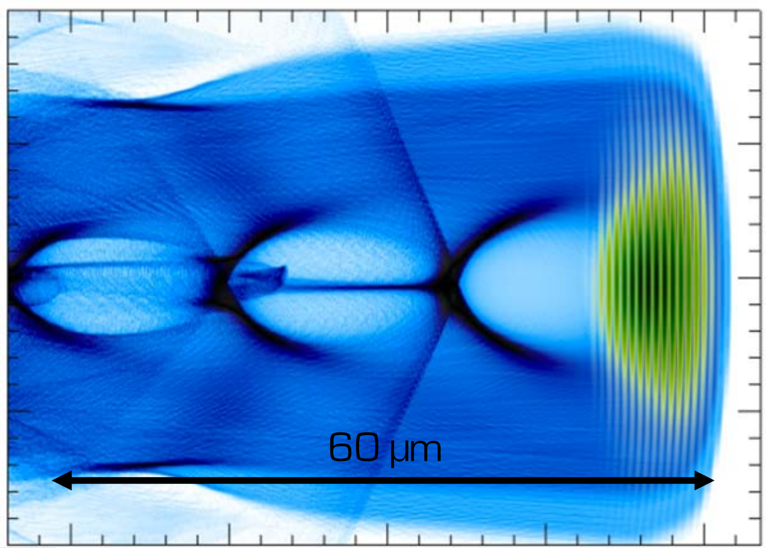
Accelerating electrical field is 1000 times stronger than in a regular accelerator



Using high power lasers to generate laser plasma accelerators and x-rays

An intense laser pulses drives electron plasma waves

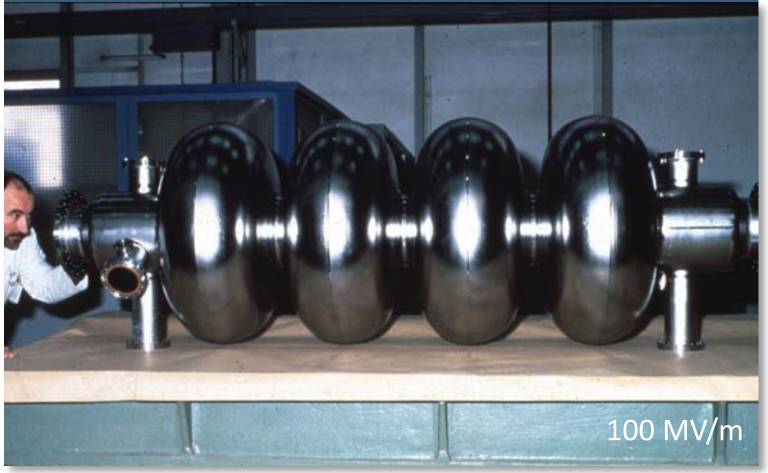
Plasma wave behind a laser



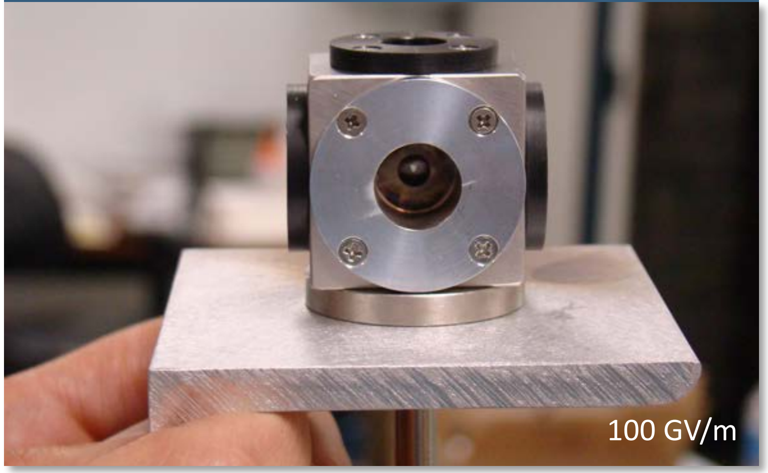
Nuno Lemos, LLNL

Laser-produced plasmas can naturally sustain large acceleration gradients which makes laser plasma accelerators 1000 x smaller

SRF Cavity



Gas cell – laser plasma



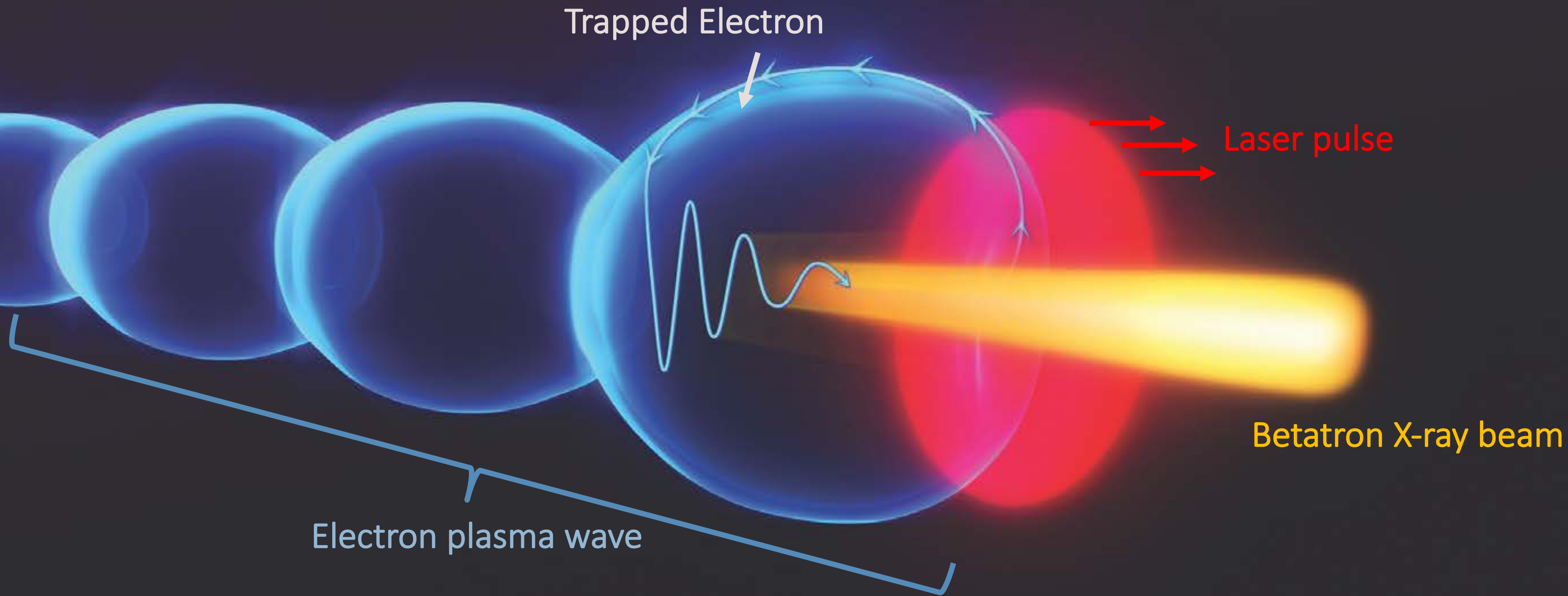
Acceleration gradient

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

Plasma frequency

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

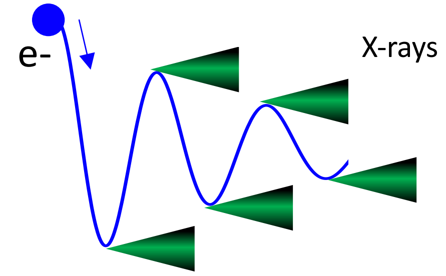
$$n_e = 10^{18}\ \mathrm{cm}^{-3} \rightarrow E_0 = 96\ \mathrm{GV/m}$$

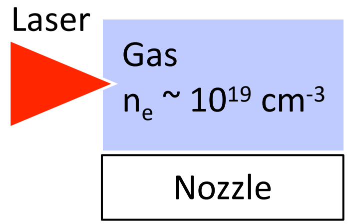


F. Albert et al, *Plasma Phys. Control. Fusion* (2014)

Laser wakefield acceleration can produce x-rays using several processes

1. Betatron x-ray radiation

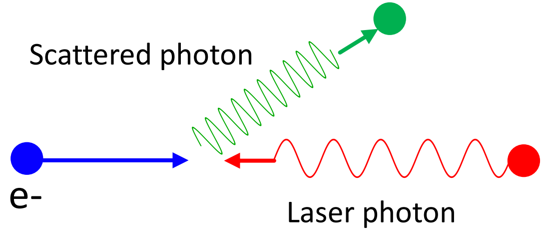


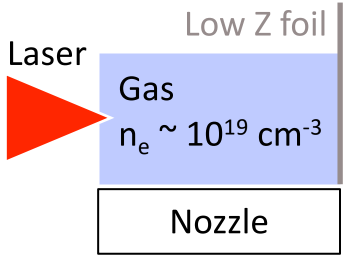


$E_x \sim \gamma^2 n_e r_0$

keV

2. Compton scattering

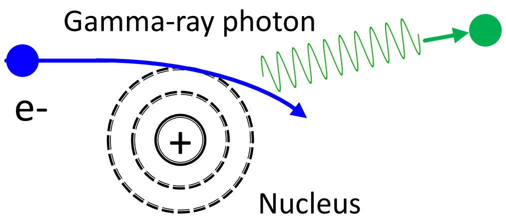


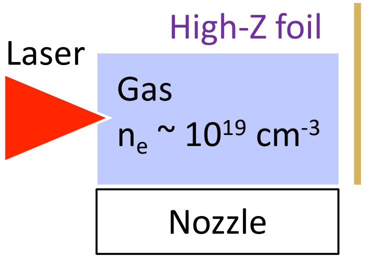


$E_x \sim 4\gamma^2 E_L$

keV - MeV

3. Bremsstrahlung

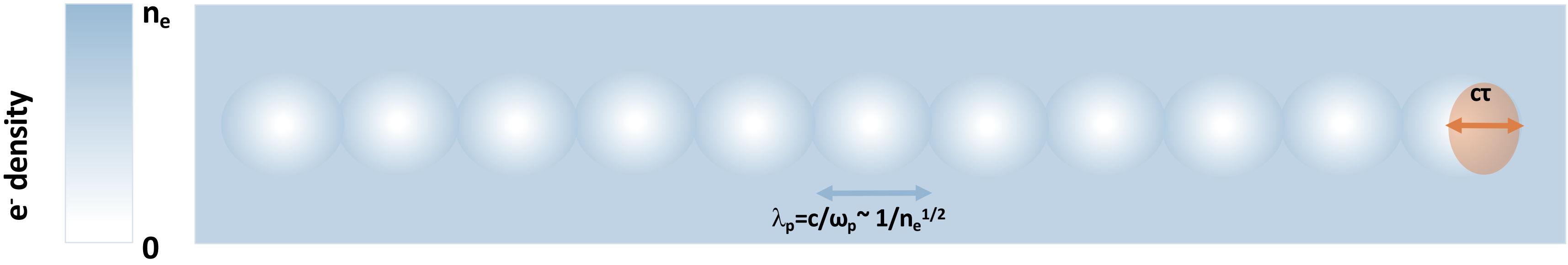




$E_x \sim \gamma$

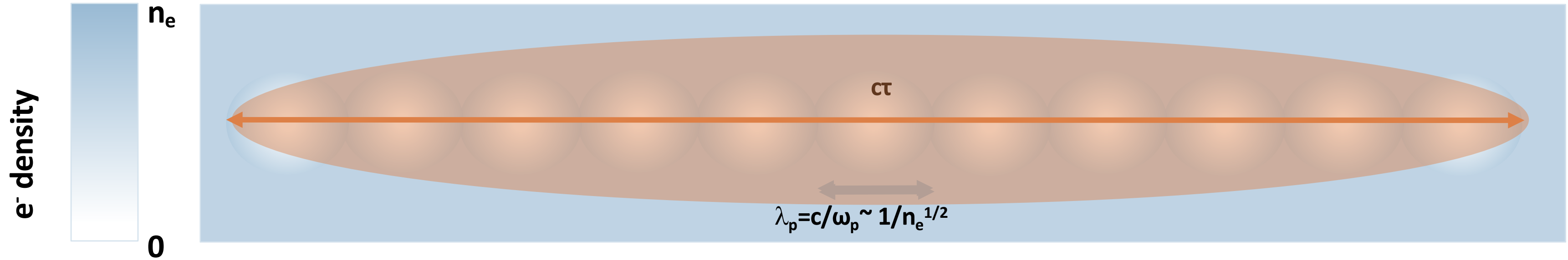
MeV

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



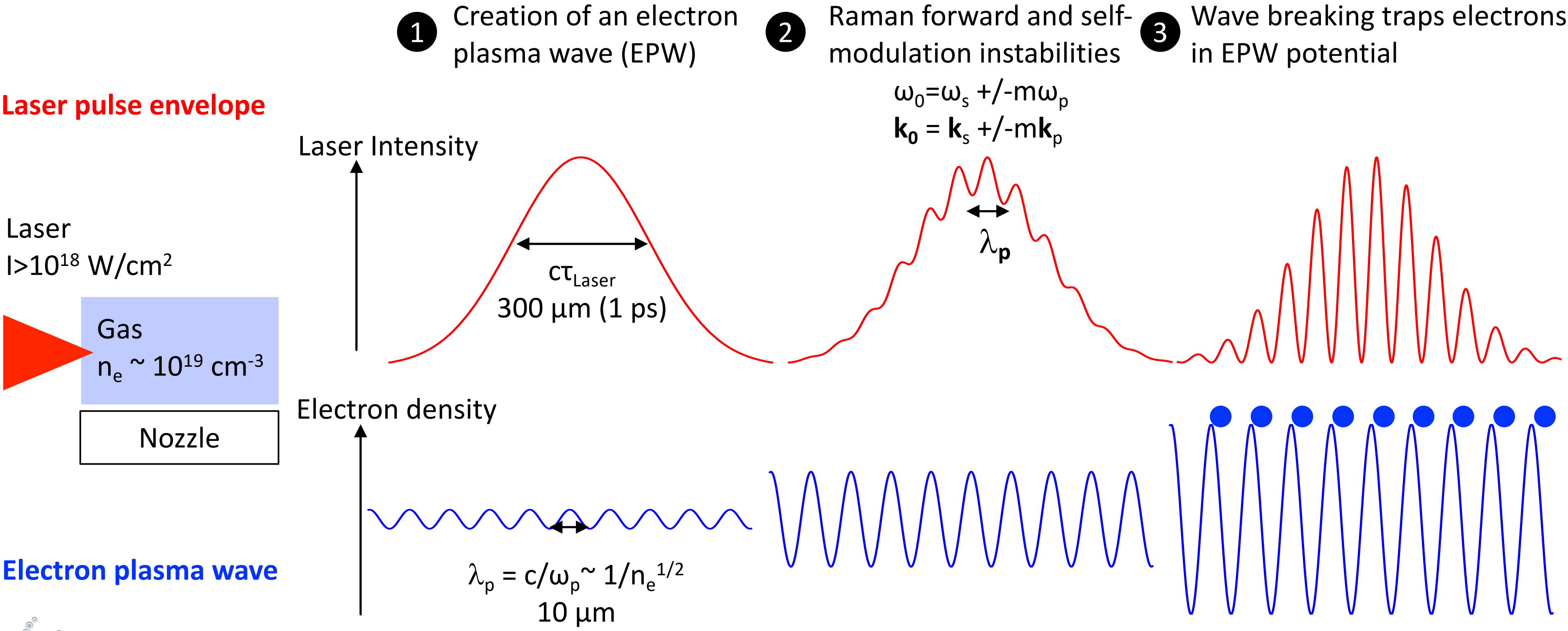
Condition to be in the blowout regime $c\tau \sim 1/n_e^{1/2}$ → 30 fs $n_e \sim 10^{19}$ cm^{-3}

Self modulated laser wakefield acceleration is easier to achieve with picosecond scale lasers ($c\tau \gg \lambda p$)



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

High charge, relativistic electron beams are accelerated through self-modulated laser wakefield acceleration



1 Creation of an electron plasma wave (EPW)

2 Raman forward and self-modulation instabilities

3 Wave breaking traps electrons in EPW potential

Laser pulse envelope

Laser

$I>10^{18}$ W/cm^2

Gas

$n_e \sim 10^{19}$ cm^{-3}

Nozzle

Laser Intensity

$c\tau_{Laser}$

300 µm (1 ps)

$\omega_0=\omega_s$ +/-$m\omega_p$

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

$\lambda_\mathbf{p}$

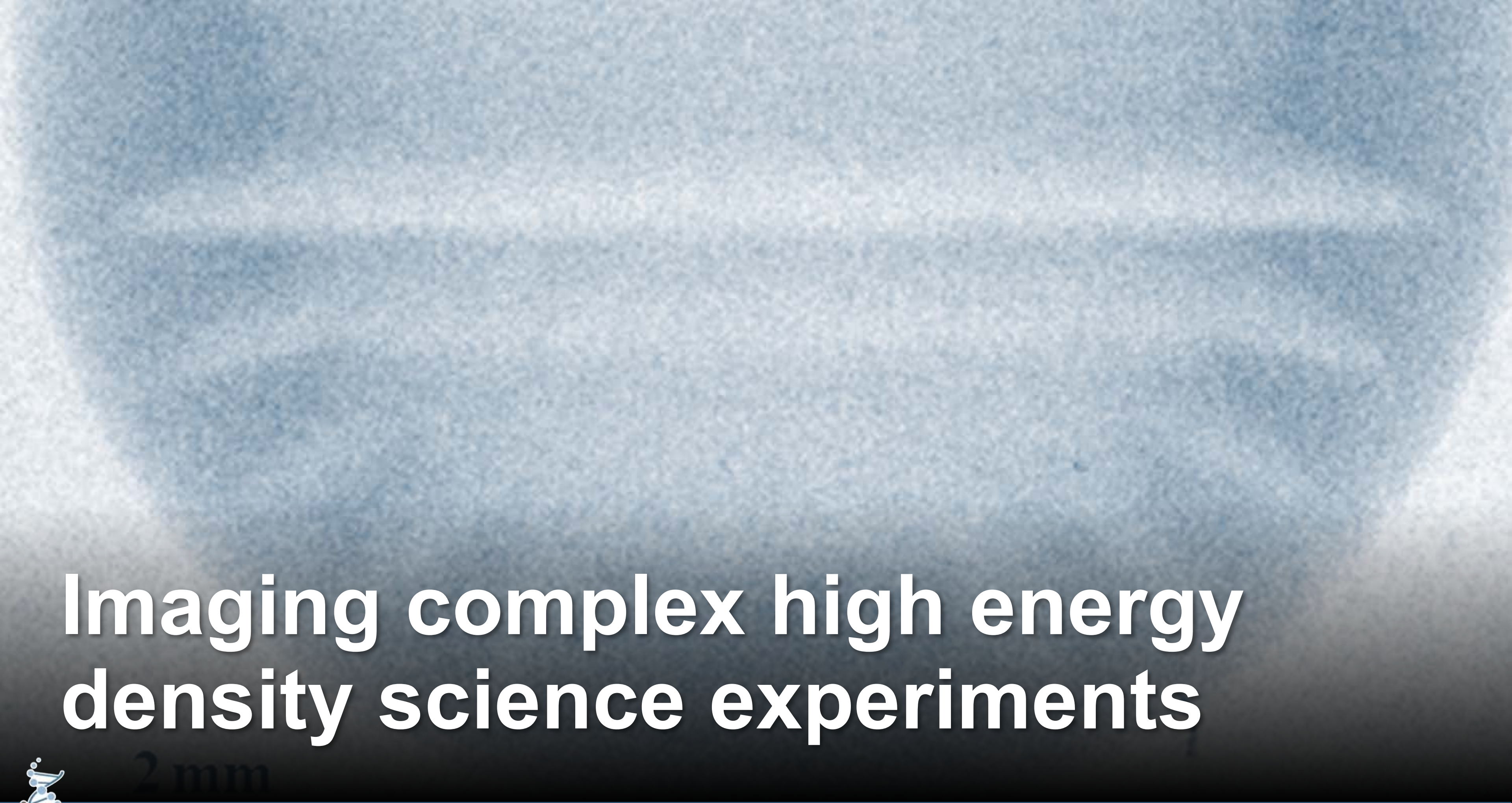
Electron density

$\lambda_p = c/\omega_p \sim 1/n_e^{1/2}$

10 µm

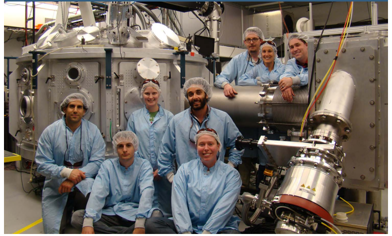
Electron plasma wave

Imaging complex high energy density science experiments



Our project is developing laser plasma accelerators on large kJ-class picosecond lasers

Titan, LLNL



OMEGA-EP, LLE

NIF – ARC, LLNL

LMJ – PETAL, CEA

2015 2016 2017 2018 2019 2020 2021

Titan
SMLWFA electrons
Betatron radiation

Titan
Compton scattering/Bremsstahlung

Titan
Radiography

OMEGA-EP
SMLWFA electrons

OMEGA-EP
X-ray sources

OMEGA-EP
Radiography

NIF - ARC
SMLWFA electrons

NIF - ARC
X-ray sources

LMJ – PETAL
SMLWFA electrons

Laser wakefield – betatron experiments – Titan LLNL

self-modulated regime

86 % in 28 µm

$I = 5\text{x}10^{18}$ W/cm^2

Titan Laser

150 J

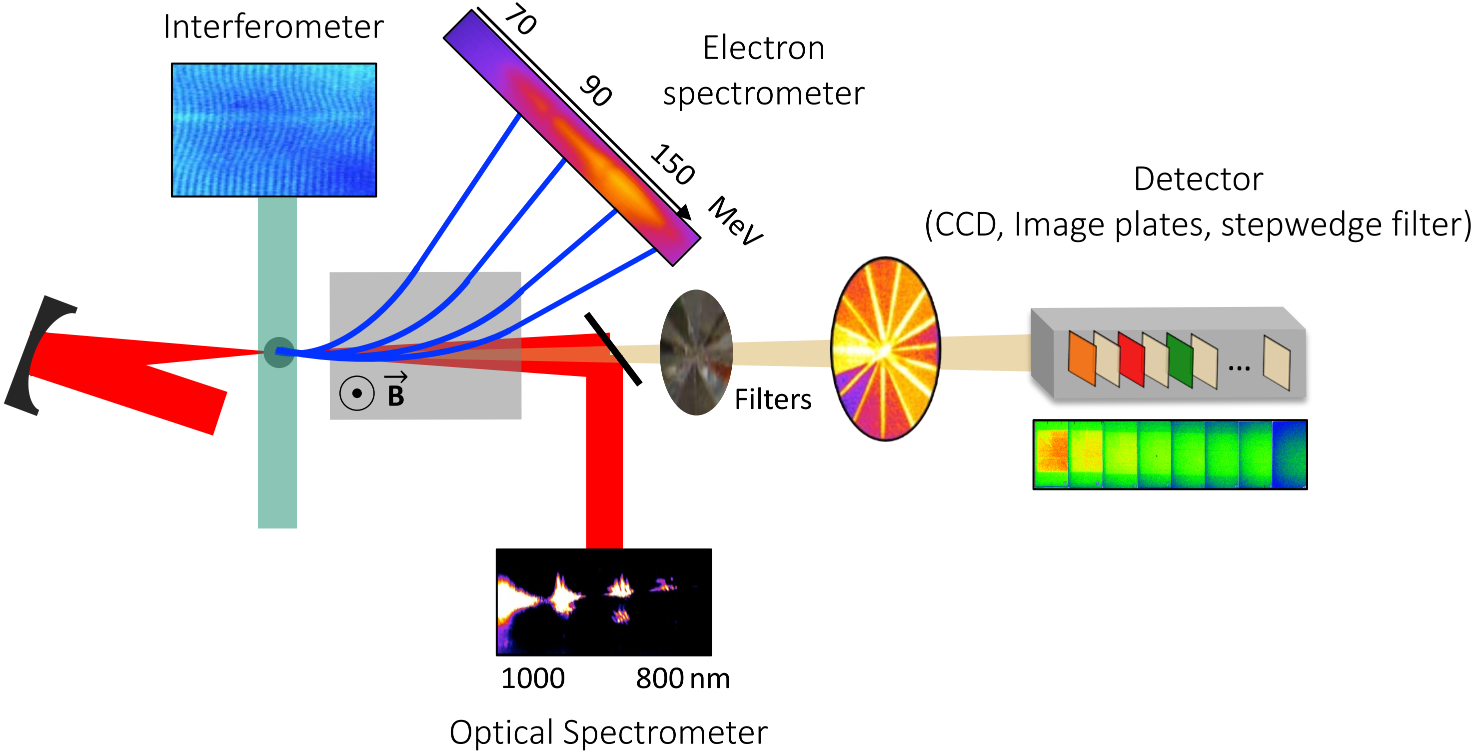
0.7 ps

Target

3 mm He jet

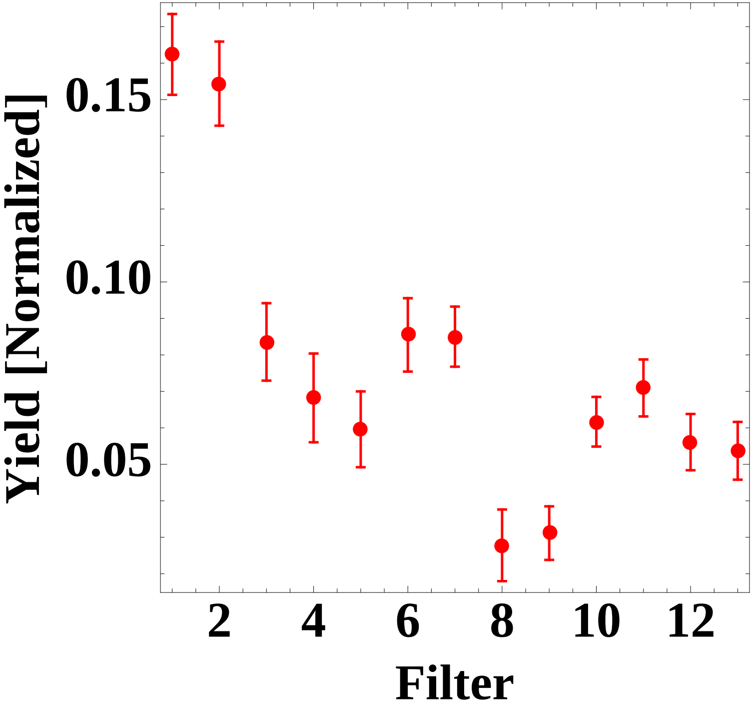
$n_e = 10^{19}$ cm^{-3}

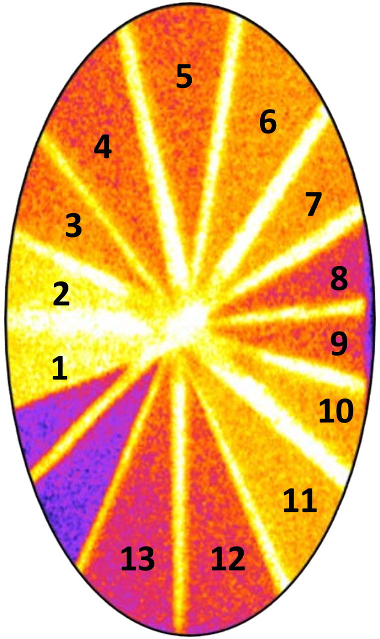
We have developed a platform to produce x-rays in the self modulated laser wakefield acceleration regime



F. Albert et. al, *Phys. Rev. Lett*. (2013), *Phys. Rev. Lett.* (2017)

Electrons accelerated in the SMLWFA regime produce betatron x-rays





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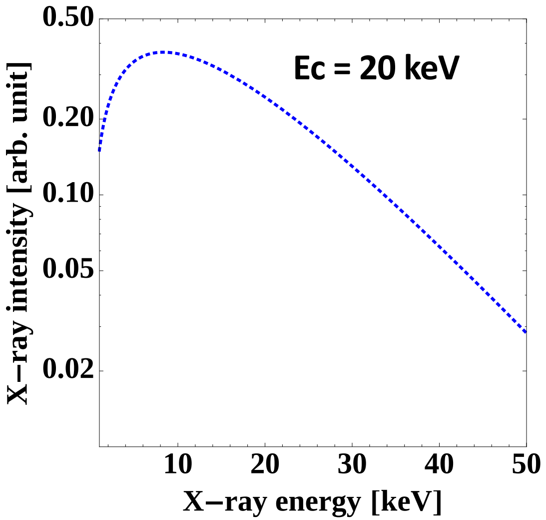
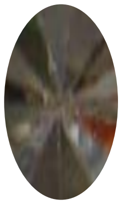


X



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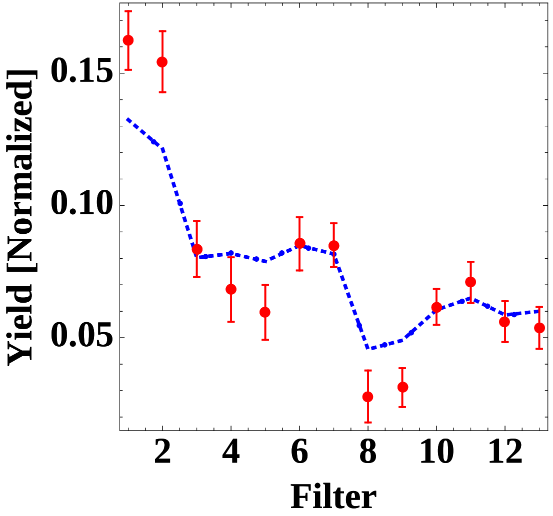
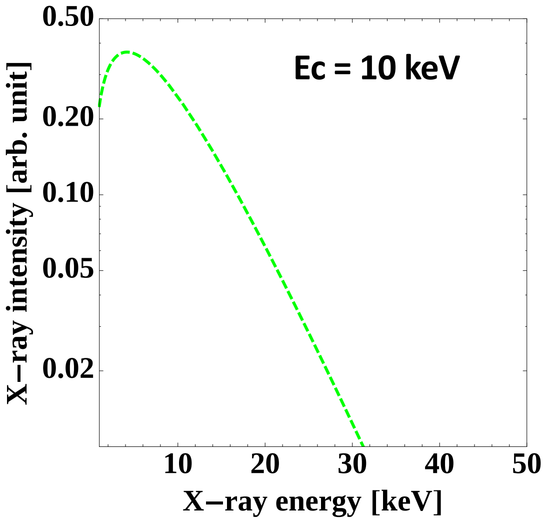
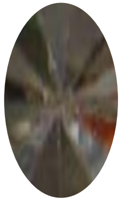


$$\frac{d^2 I}{dE\,d\Omega} \propto \left(\frac{E}{E_c}\right)^2 K^2_{2/3}[E/E_c]$$

Electrons accelerated in the SMLWFA regime produce betatron x-rays



X



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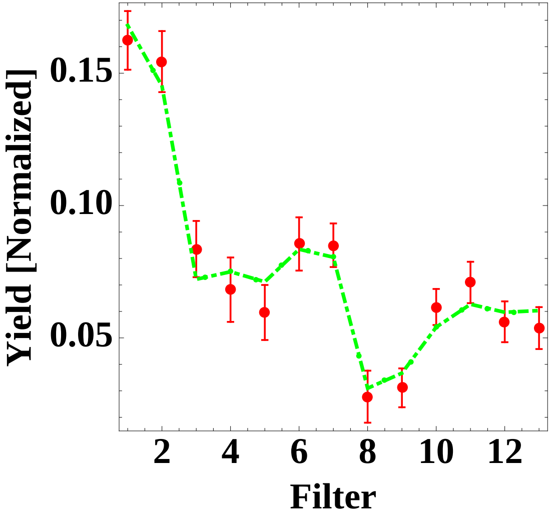

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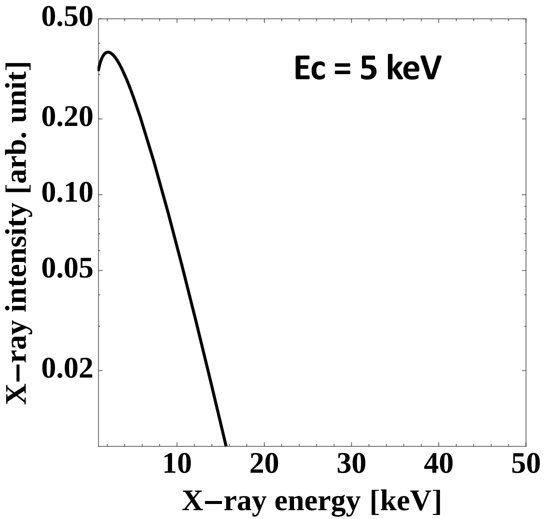

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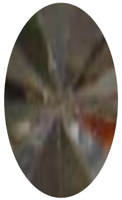

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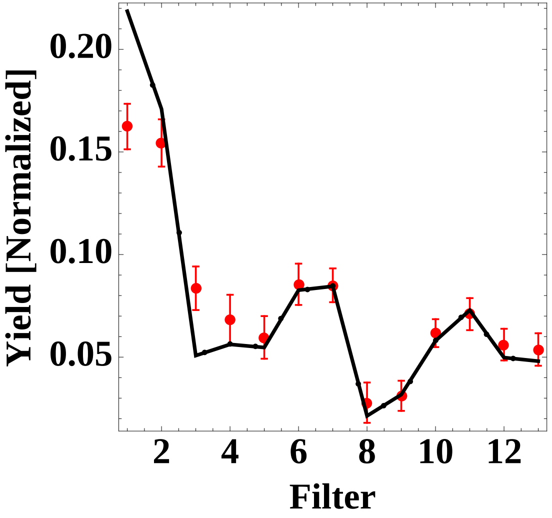

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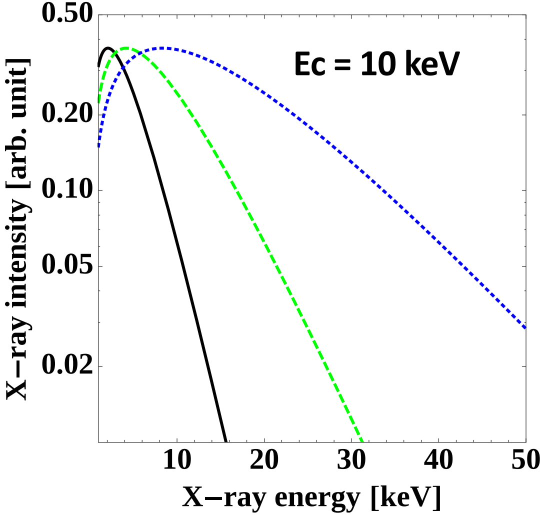
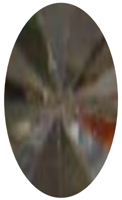
P.M. King et al, RSI (2019)

Electrons accelerated in the SMLWFA regime produce betatron x-rays



X



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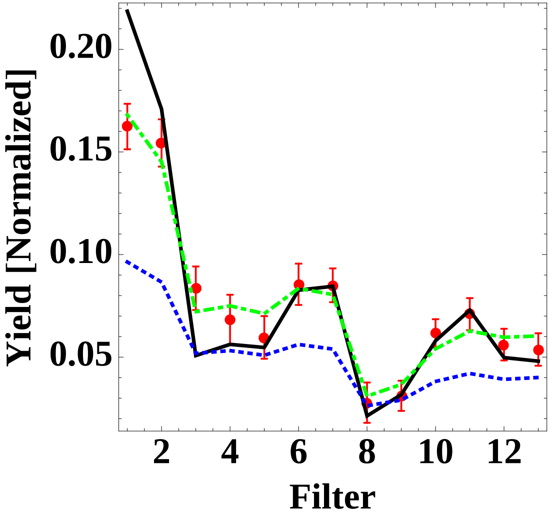
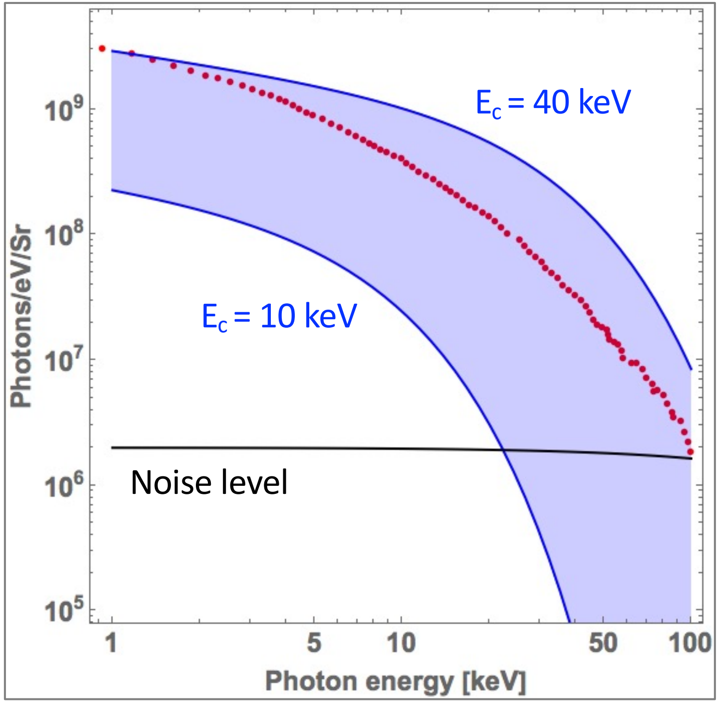


Best fit for E_c = 10 keV +/- 2 keV (least squares fit) – 10^9 photons/eV/Sr

Betatron x-rays have critical energies of 10-40 keV

Measured/calculated x-ray spectrum

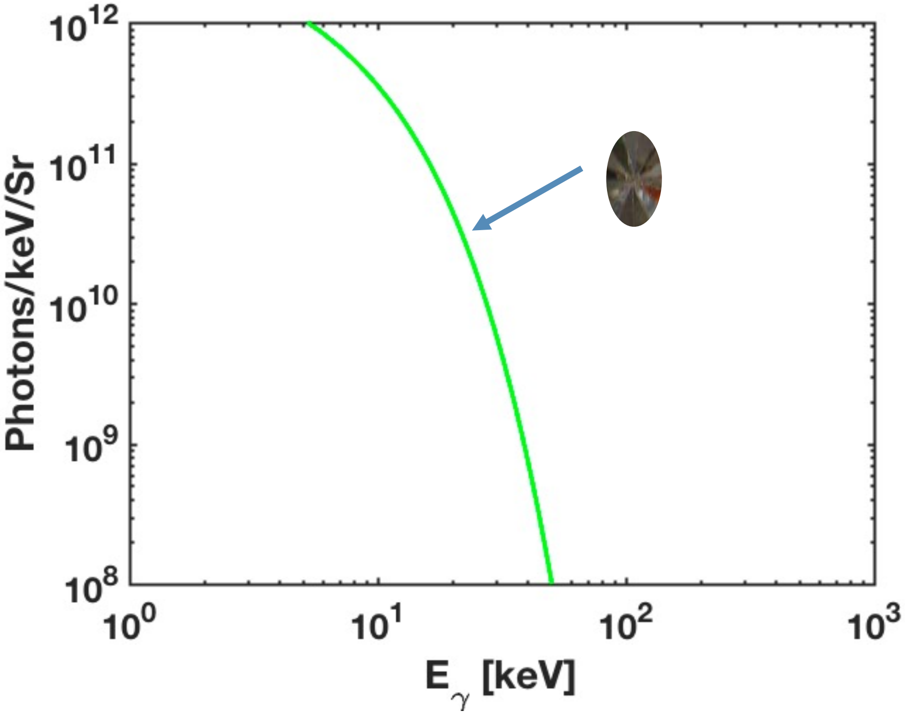


Betatron - Experiment

PIC simulation

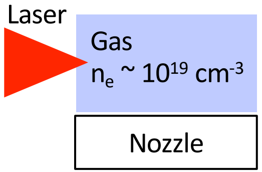
F. Albert et. al, *Phys. Rev. Lett.* (2017)

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



Betatron, E_c = 10 keV

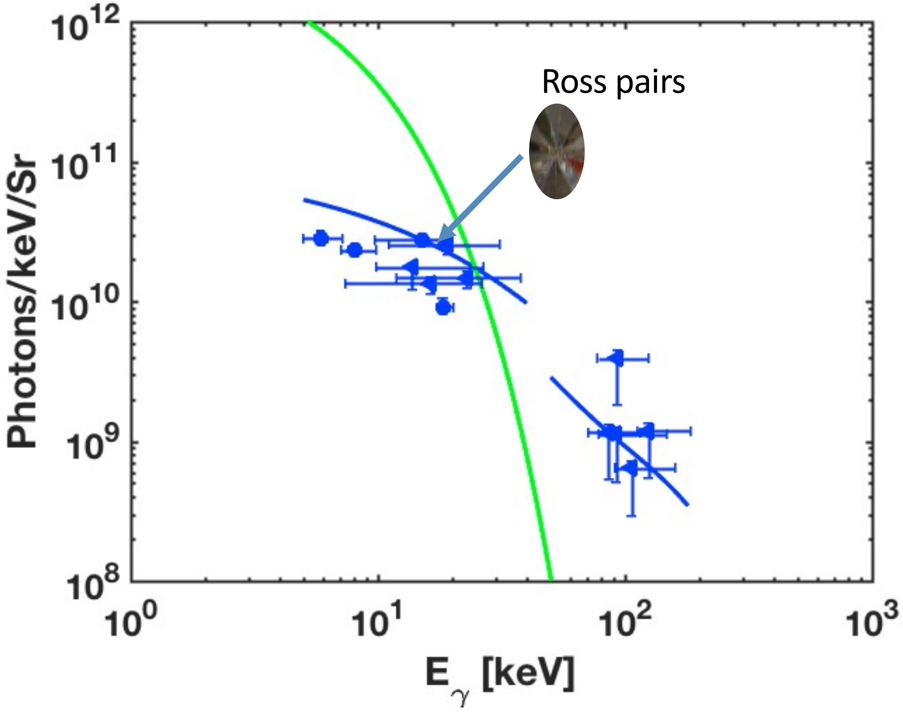
$$f(E) \sim \left(\frac{E}{E_c}\right)^2 K_{2/3}^2\left(\frac{E}{E_c}\right)$$



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

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

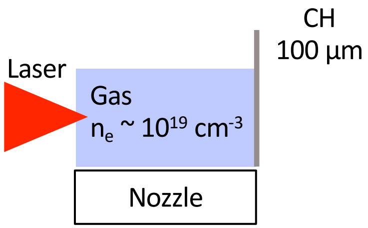
Compton scattering allows for increased photon flux up to a few 100 keV



Compton scattering

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

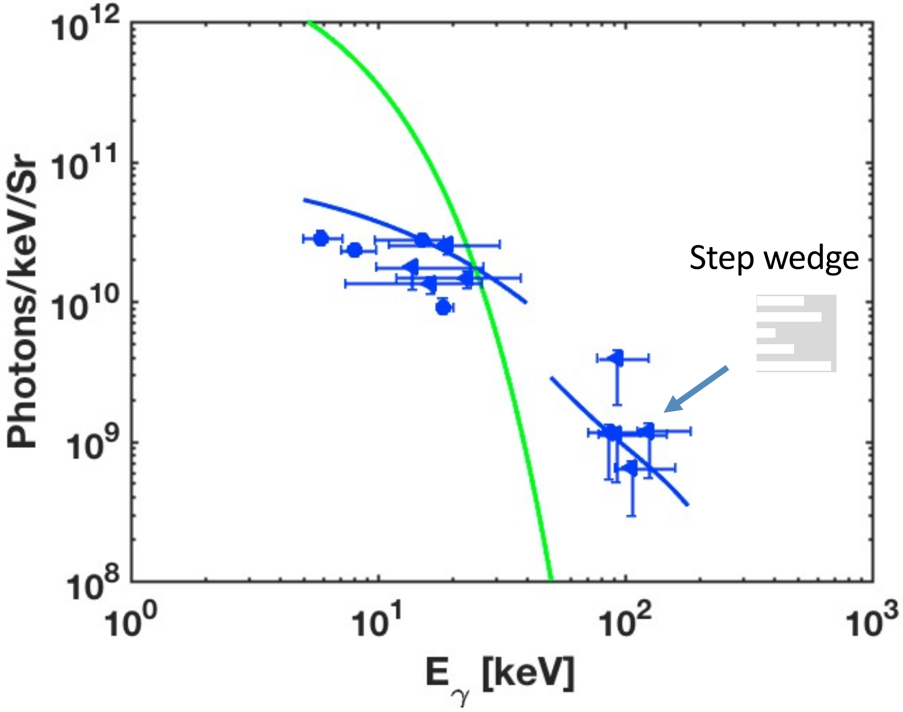
T_1 = 36 keV (Filter wheel)


CH
100 µm
Laser
Gas
$n_e \sim 10^{19}$ cm^{-3}
Nozzle

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

N. Lemos et. al, Phys. Plasmas (2019)

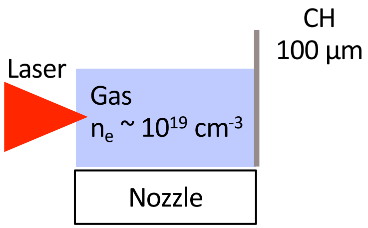
Compton scattering allows for increased photon flux up to a few 100 keV



Compton scattering

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

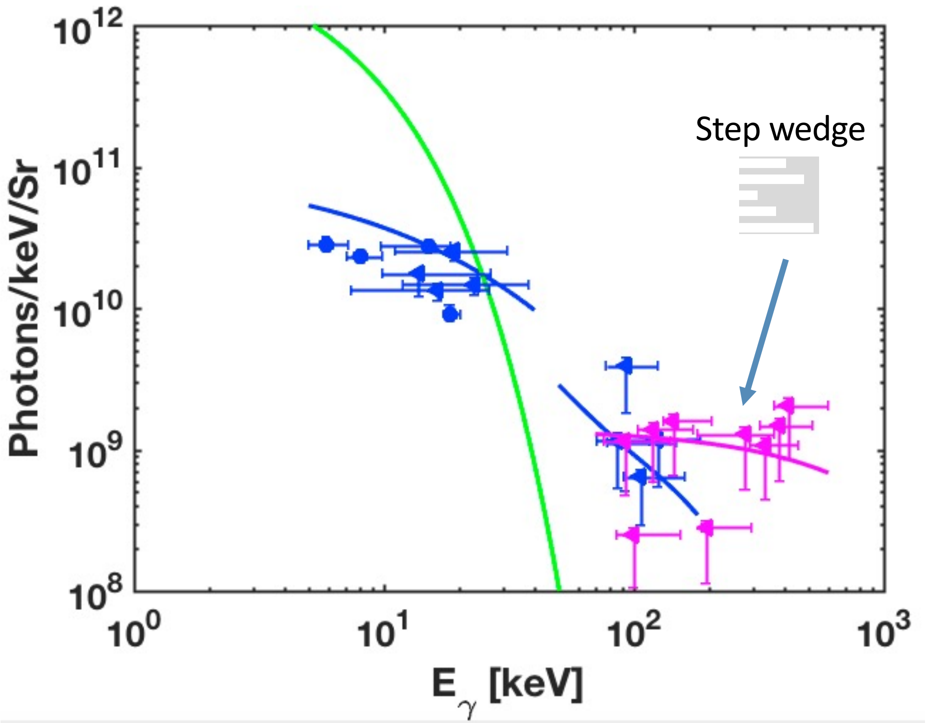
T_2 = 78 keV (Step wedge)



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

N. Lemos et. al, Phys. Plasmas (2019)

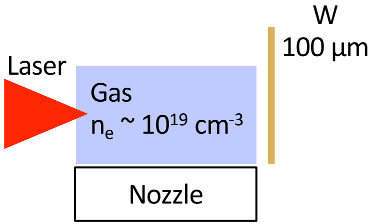
LWFA-driven bremsstrahlung produces the most photons at MeV energies



LWFA-driven bremsstrahlung

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

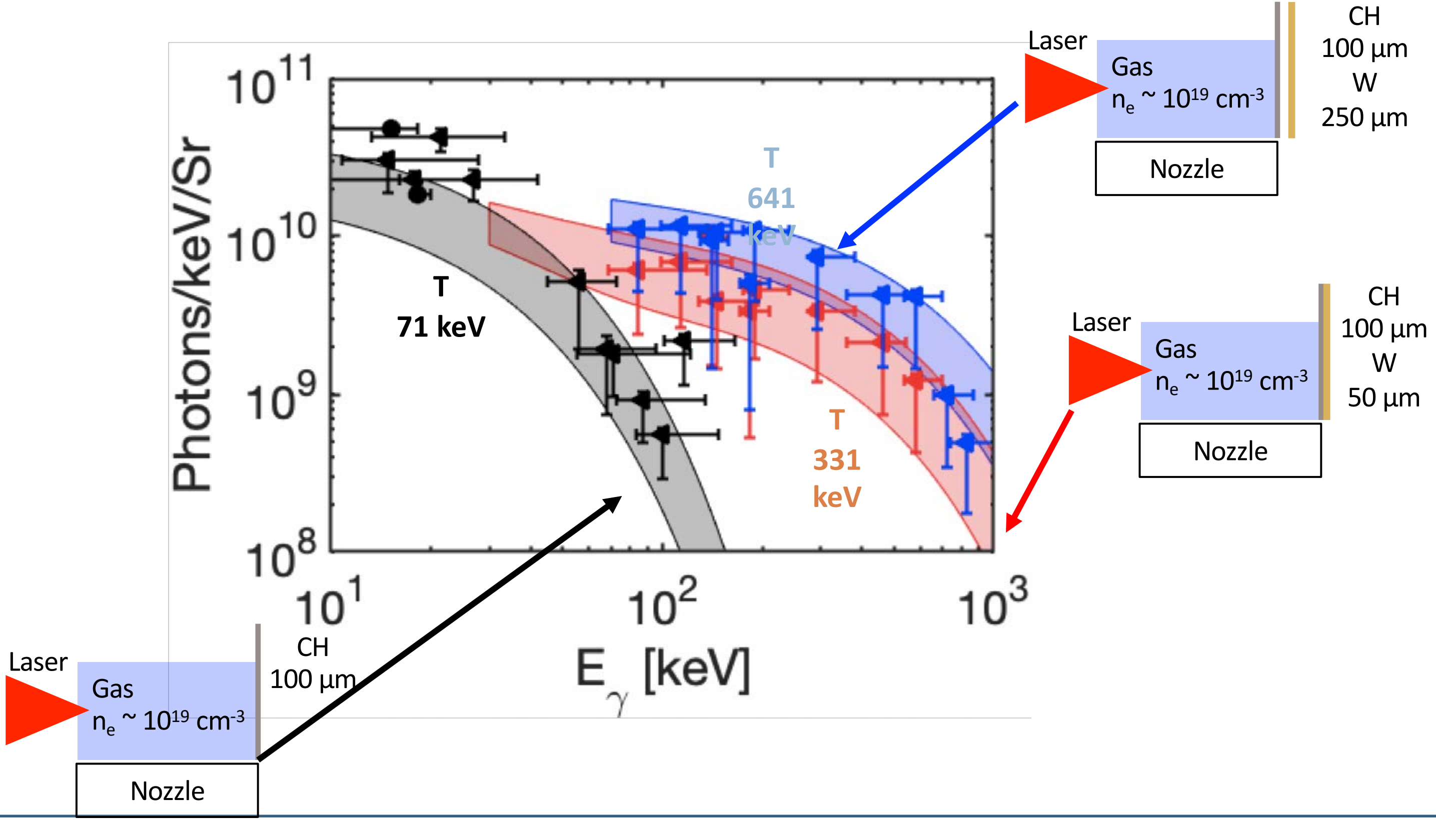
T = 838 keV (Step wedge)



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

N. Lemos et. al, *PPCF* (2018)

We can control the x-ray flux and energy by combining several processes



Laser

Gas

$n_e \sim 10^{19}$ cm^{-3}

CH

100 µm

W

250 µm

Nozzle

Laser

Gas

$n_e \sim 10^{19}$ cm^{-3}

CH

100 µm

W

50 µm

Nozzle

Laser

Gas

$n_e \sim 10^{19}$ cm^{-3}

CH

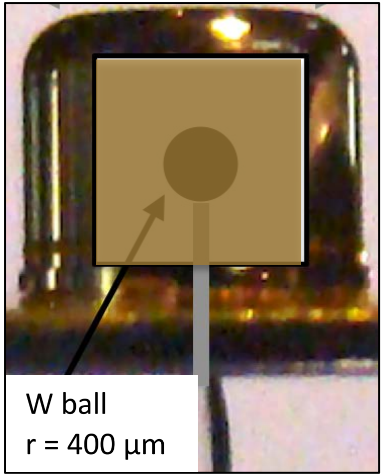
100 µm

Nozzle

N. Lemos et. al, In preparation

Spectral and flux tuning allows for optimized radiography applications

Half hohlraum – 30 µm Au



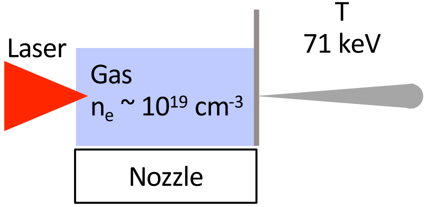
W ball

r = 400 µm

W ball areal density

~ 0.7 g/cm^2

Magnification = 3



Laser

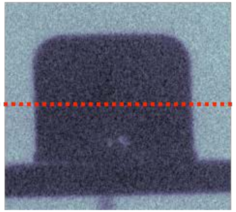
Gas

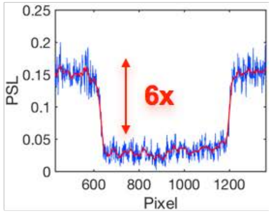
n_e ~ 10^{19} cm^{-3}

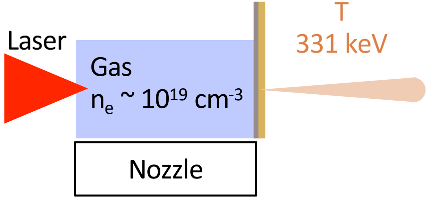
Nozzle

T

71 keV







Laser

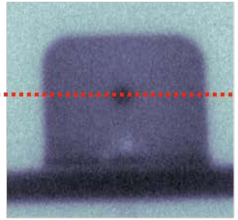
Gas

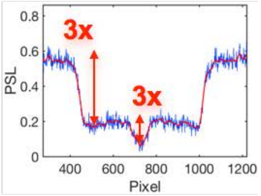
n_e ~ 10^{19} cm^{-3}

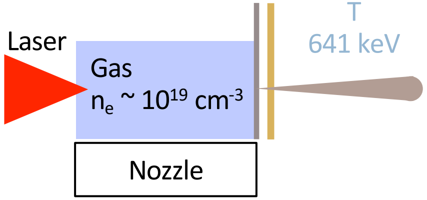
Nozzle

T

331 keV







Laser

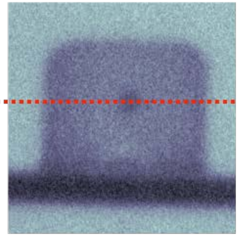
Gas

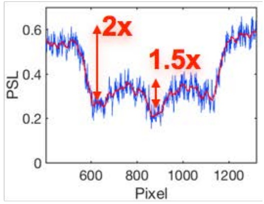
n_e ~ 10^{19} cm^{-3}

Nozzle

T

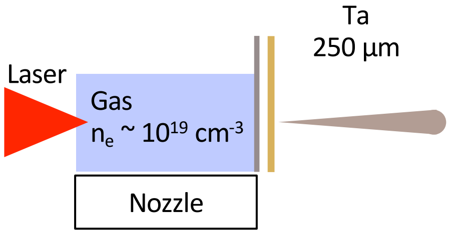
641 keV

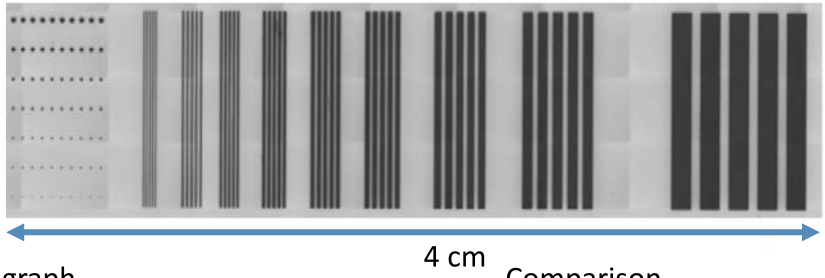




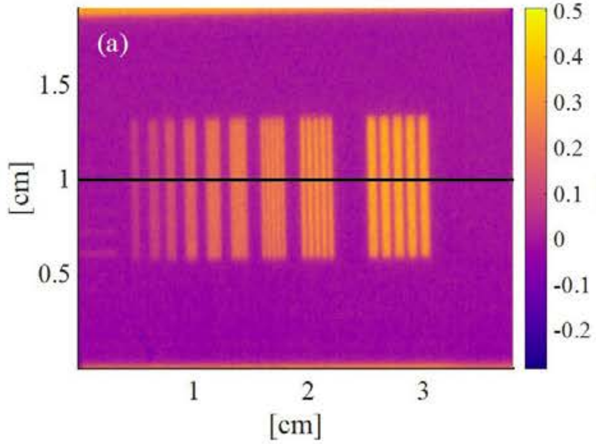
N. Lemos et. al, In preparation

We can reproduce radiographs of test objects using the x-ray ray tracing code HADES

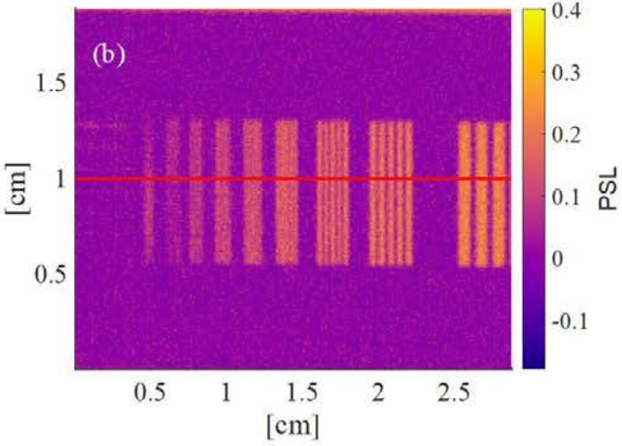

Ta
250 µm
Laser
Gas
$n_e \sim 10^{19}\ \text{cm}^{-3}$
Nozzle



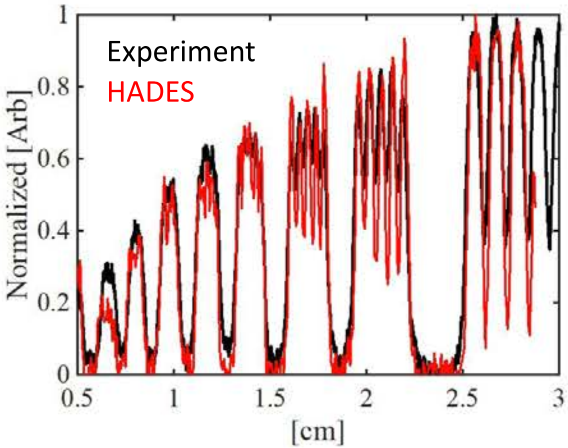
Experimental Radiograph



Simulated Radiograph

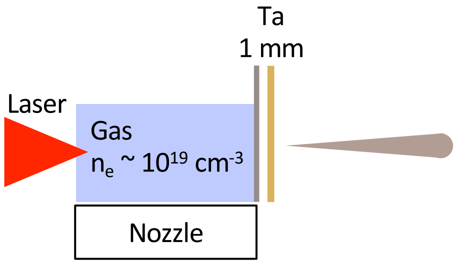


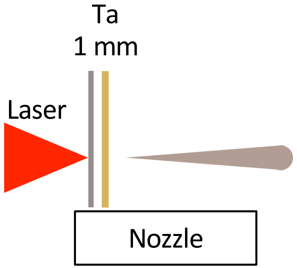
Comparison

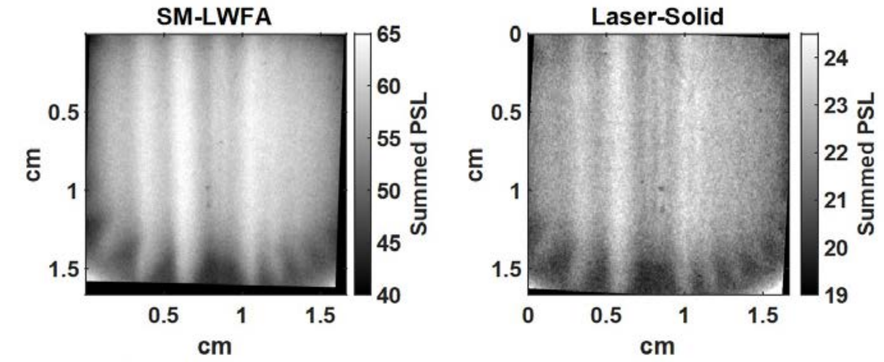


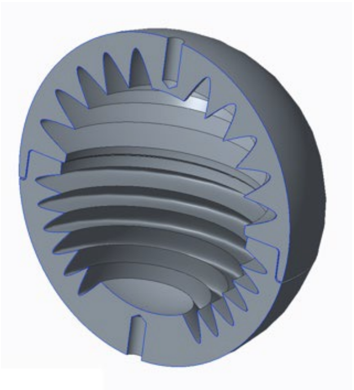
I. Pagano et. al, In preparation

SM-LWFA driven x-ray source shows 1.4x higher radiography SNR for the same conditions

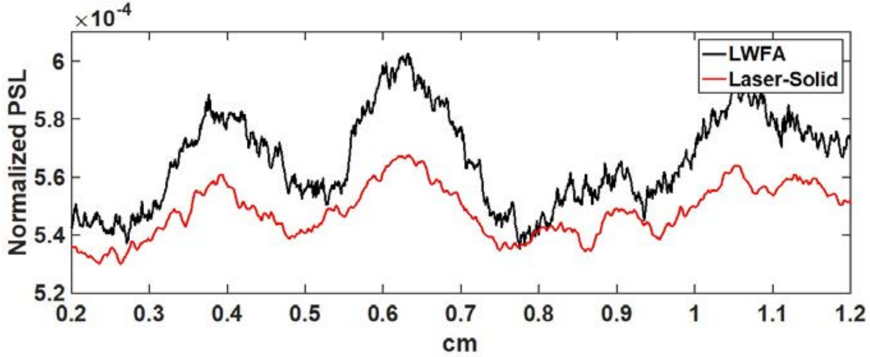




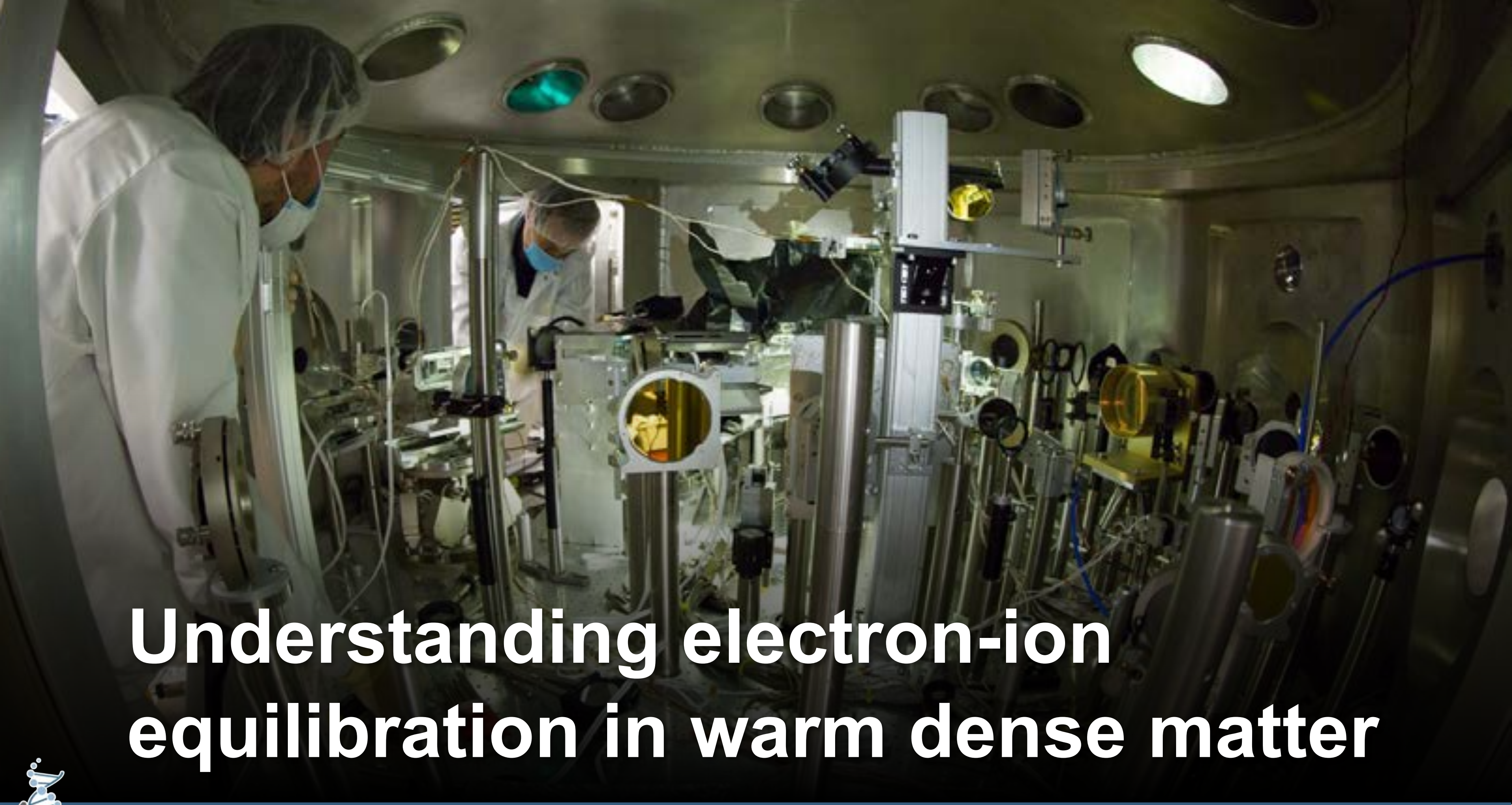




Areal density = 7.6 g/cm^2

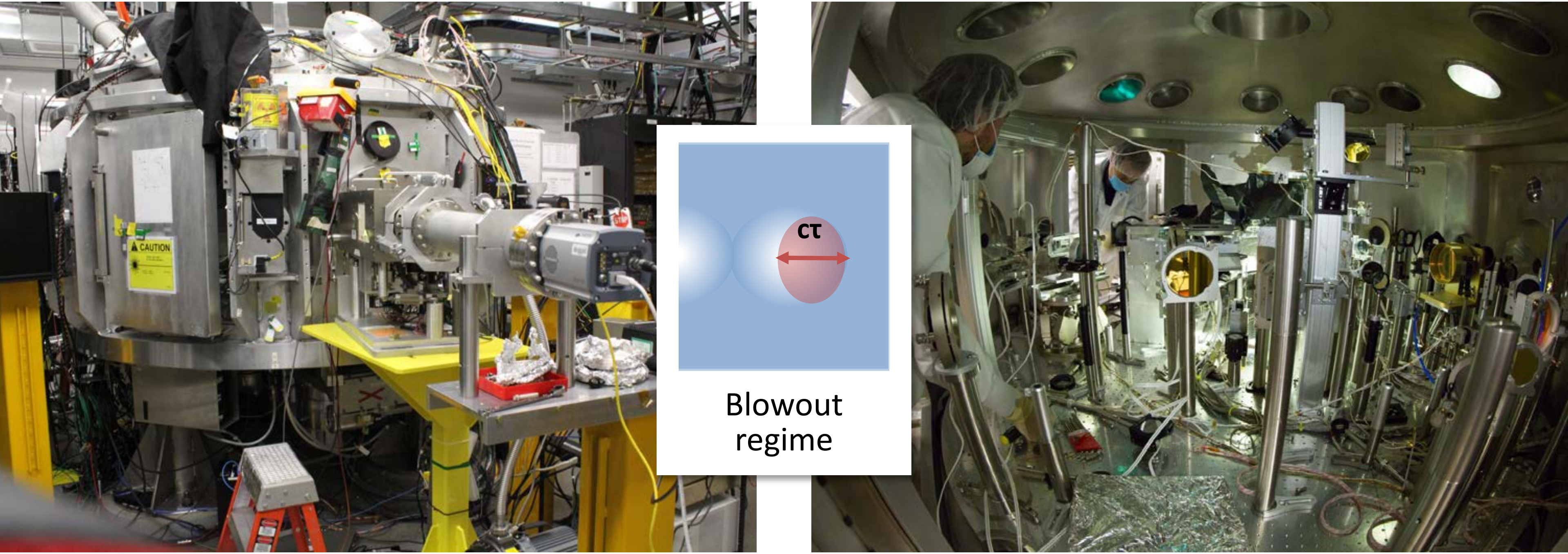


I. Pagano et. al, In preparation



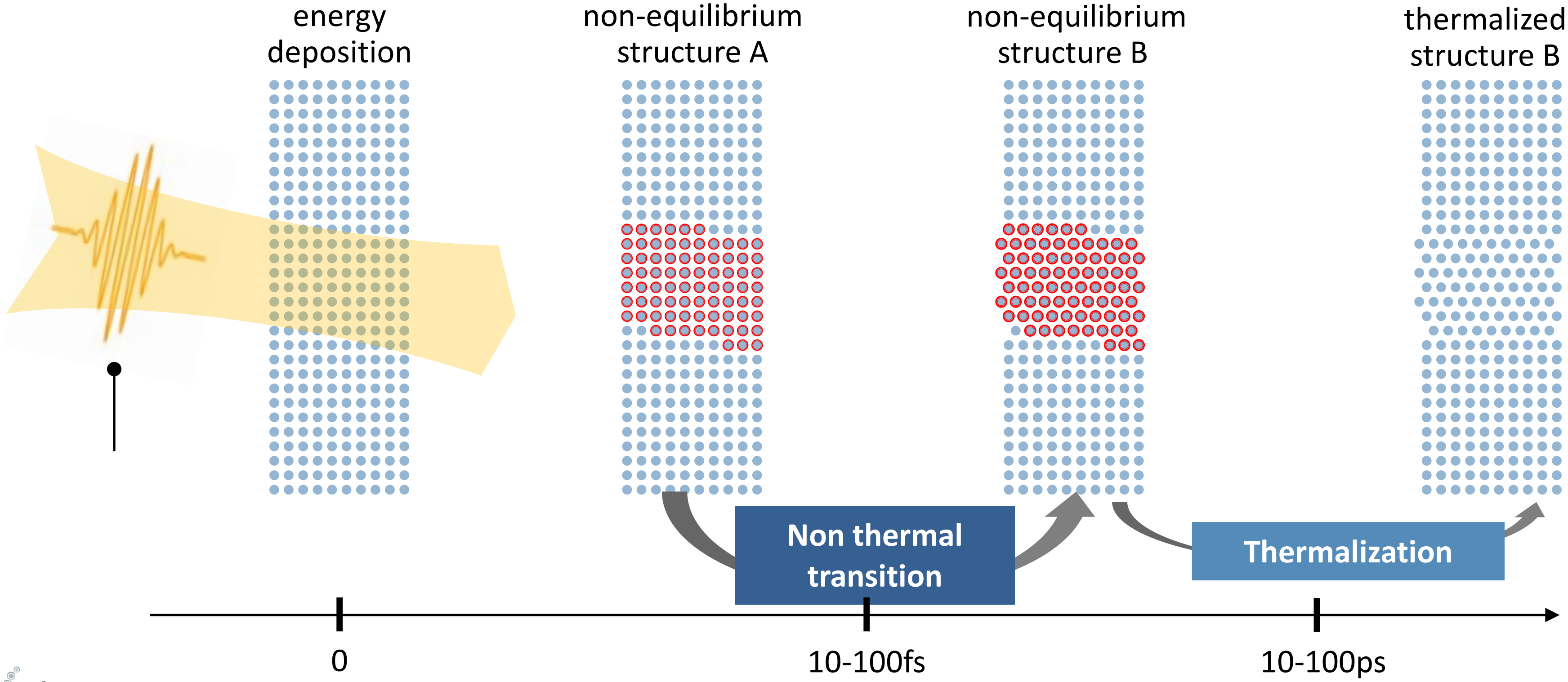
Understanding electron-ion equilibration in warm dense matter

Betatron x-ray source development at LCLS-MEC

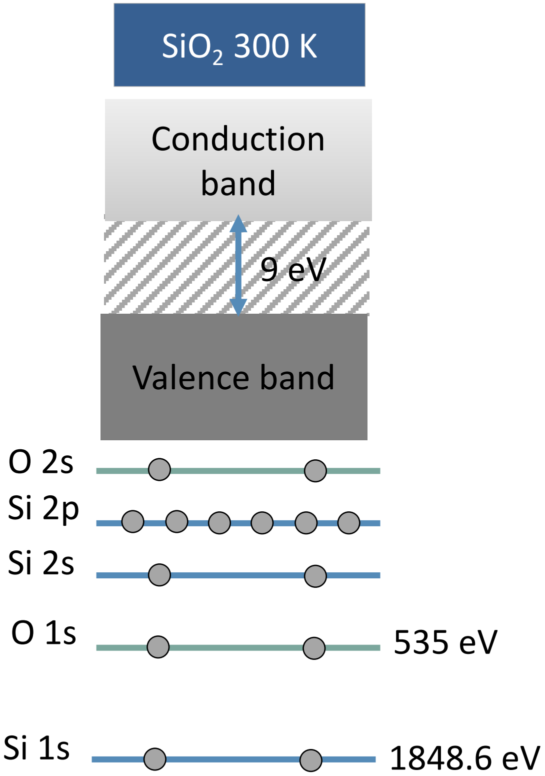


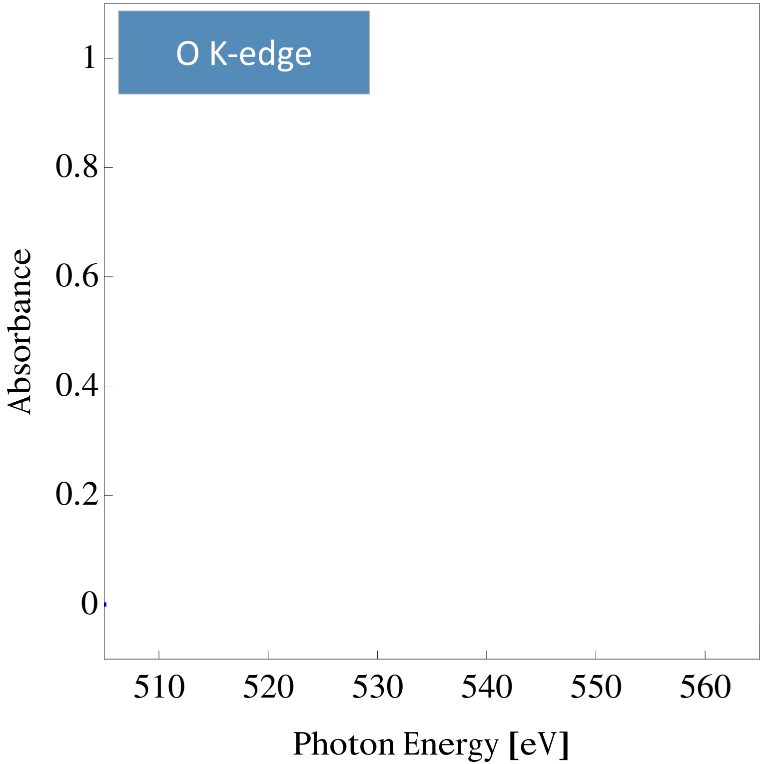
Blowout regime

Application: detection of nonthermal melting in SiO2

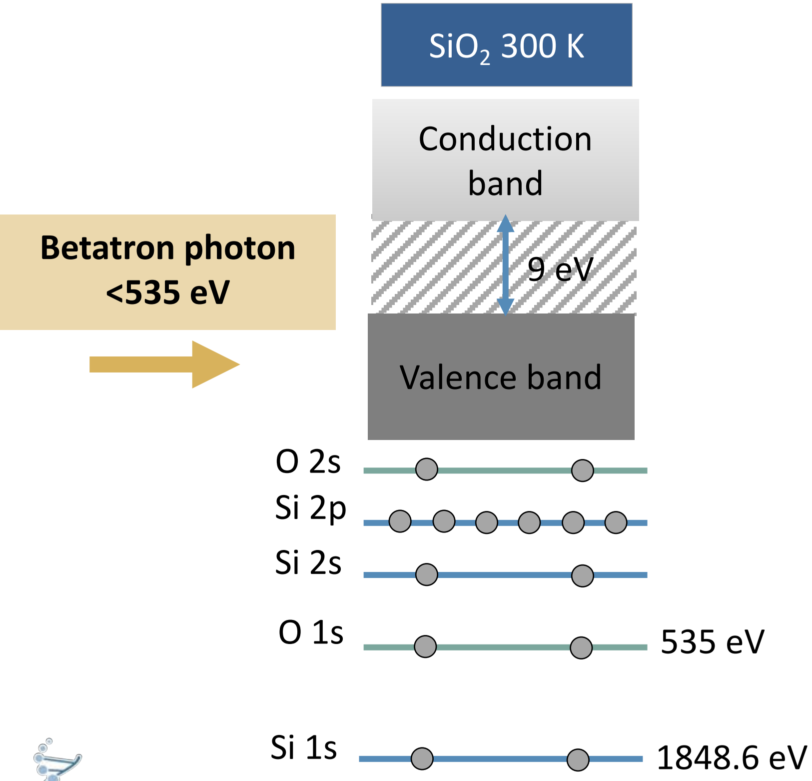


Absorption spectroscopy of SiO_2 a the O K-edge (535 eV)





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



Betatron photon <535 eV

SiO_2 300 K

Conduction band

9 eV

Valence band

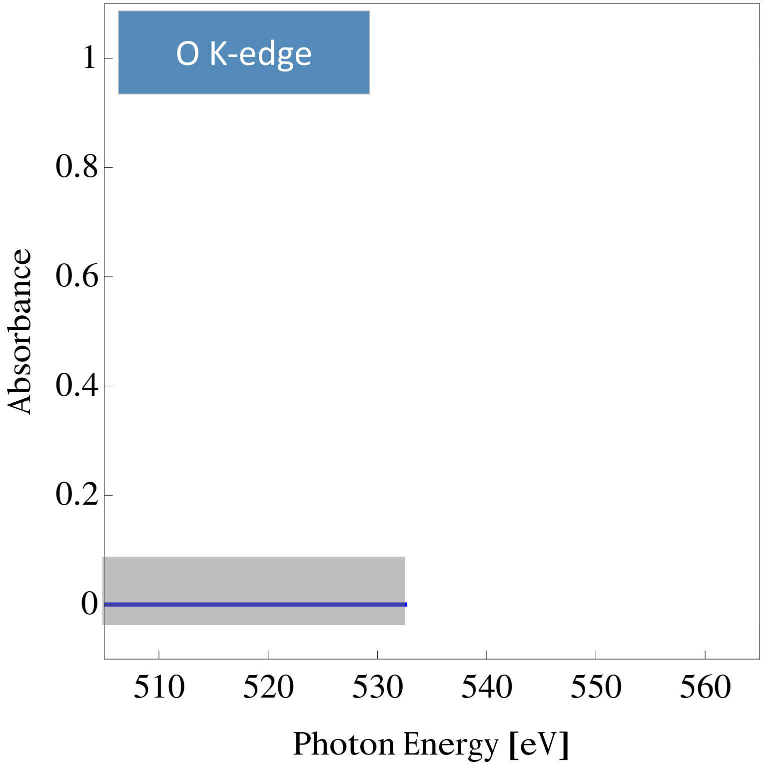
O 2s

Si 2p

Si 2s

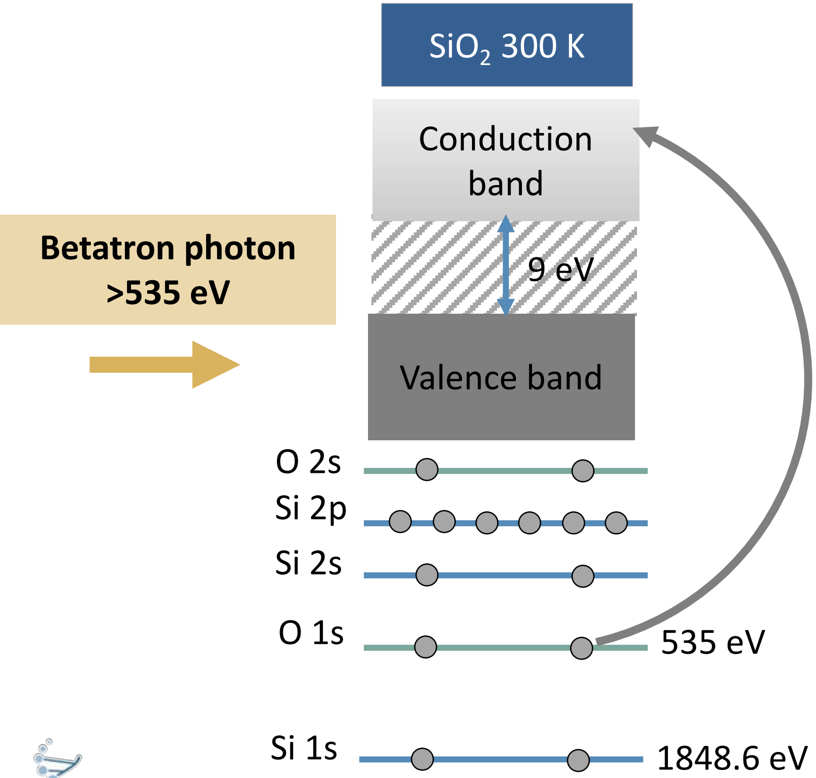
O 1s 535 eV

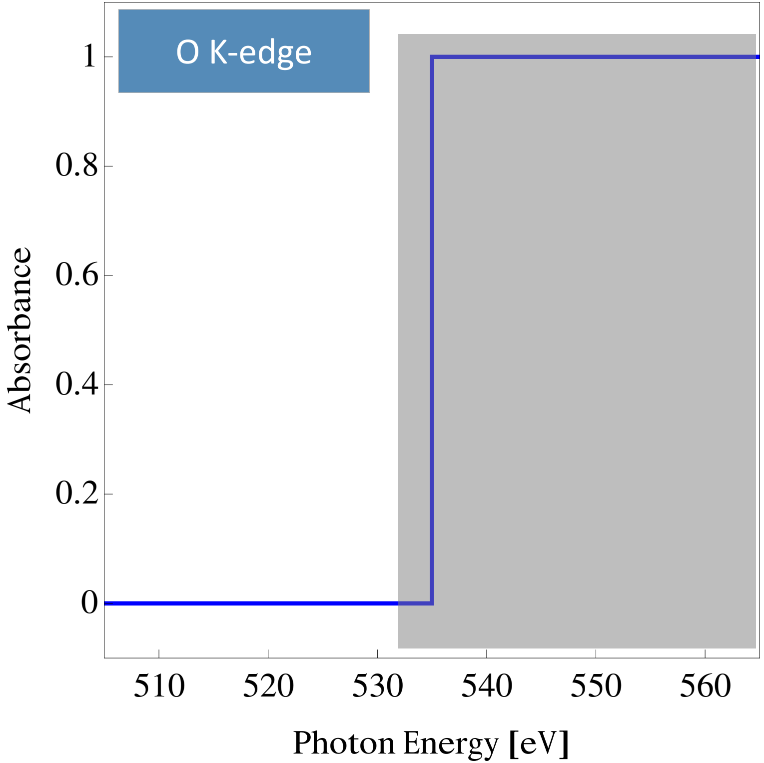
Si 1s 1848.6 eV



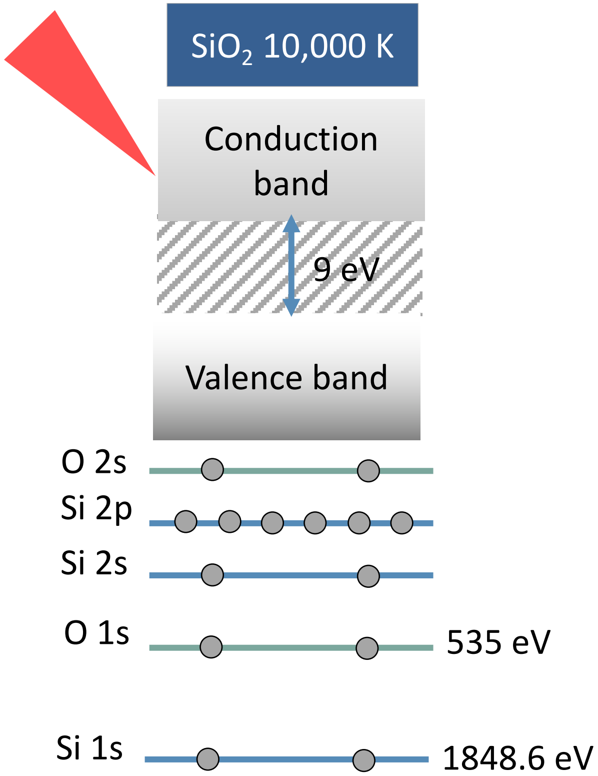
Sharp transition corresponds to strong absorption of x-ray photons for energies above the O K-edge

Betatron photon
>535 eV

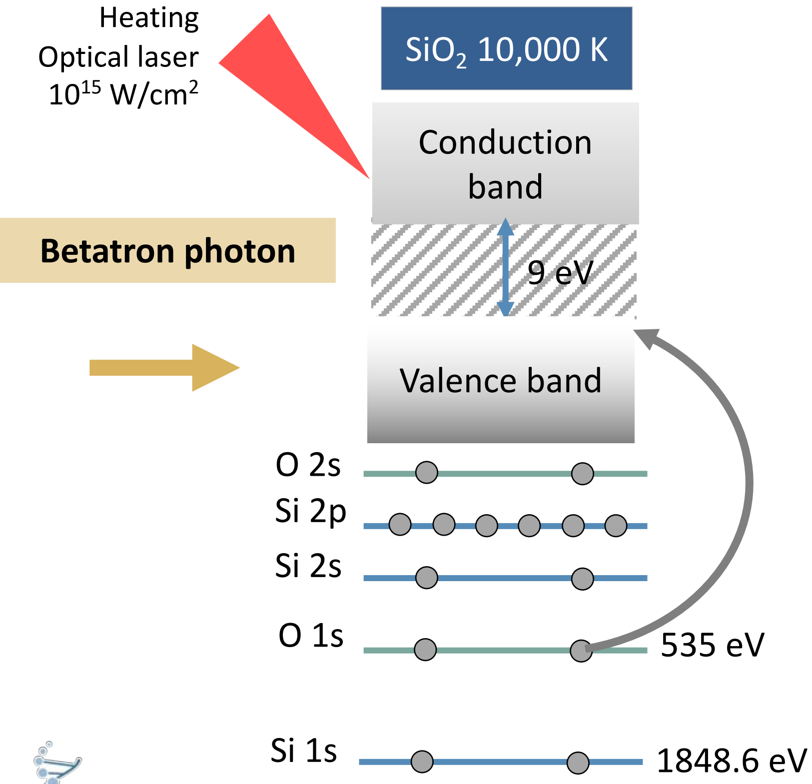


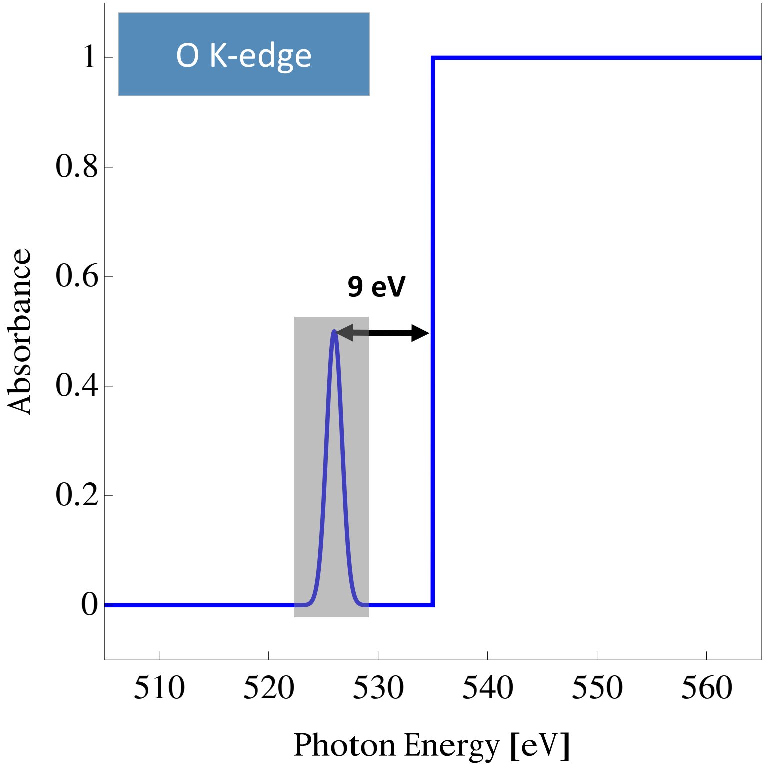


Multiphoton absorption causes electrons to cross the bandgap and leave vacancies in the valence band

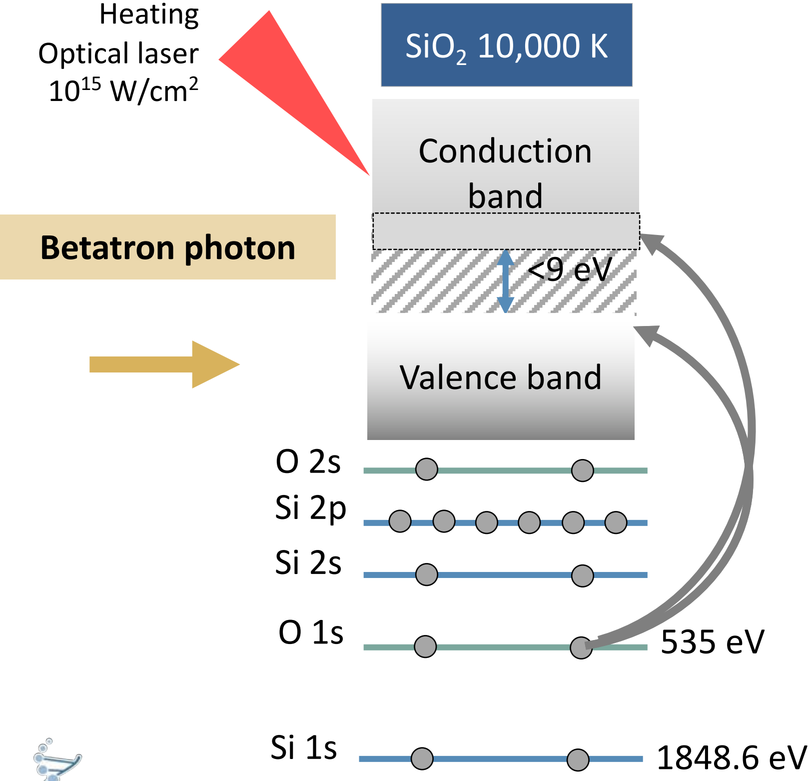


1s-valence band transitions are now authorized: strong absorption peak 9 eV below the edge





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



Heating
Optical laser
10^{15} W/cm^2

Betatron photon

SiO_2 10,000 K

Conduction band

<9 eV

Valence band

O 2s

Si 2p

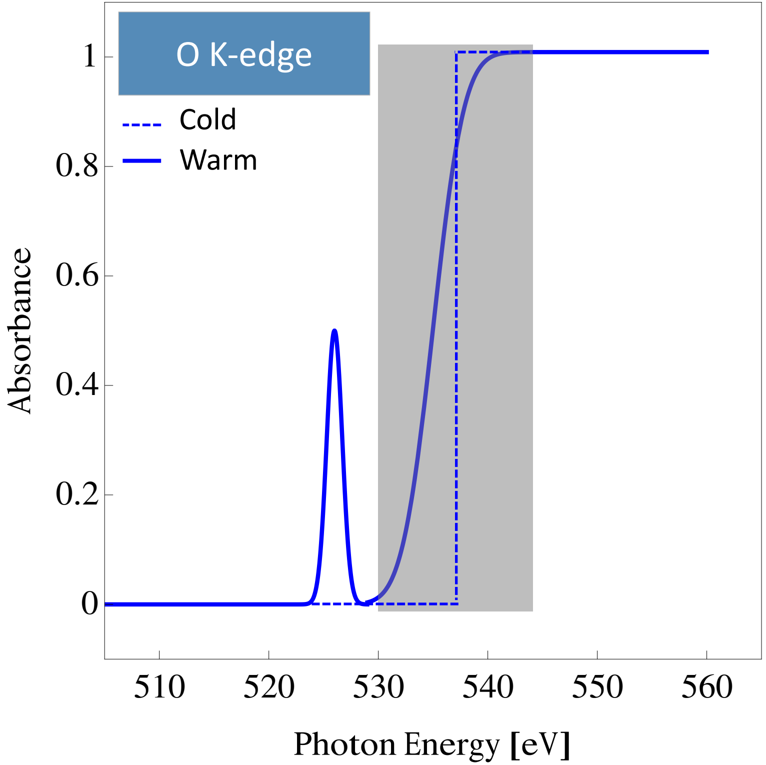
Si 2s

O 1s

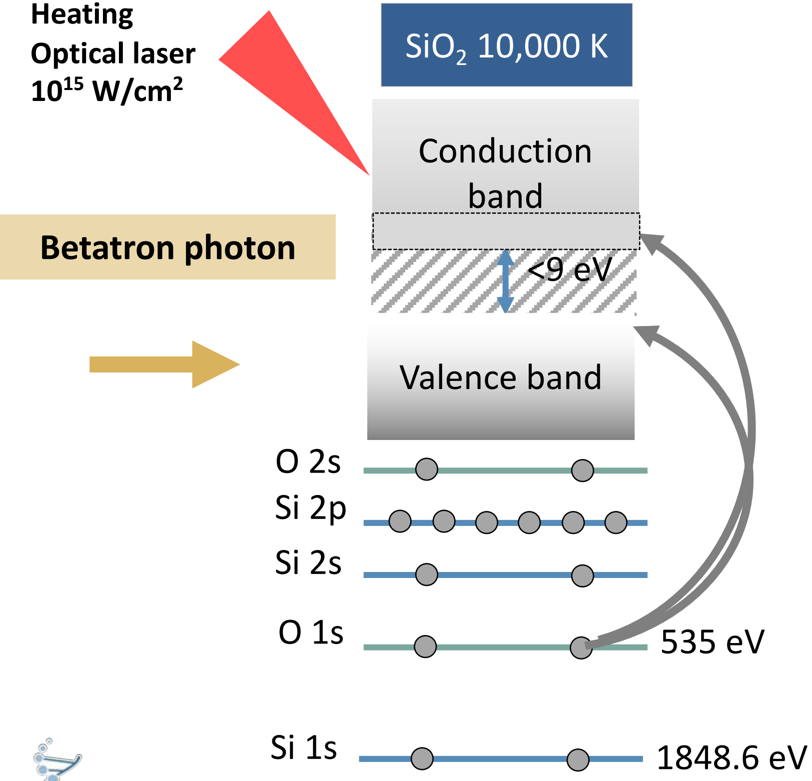
535 eV

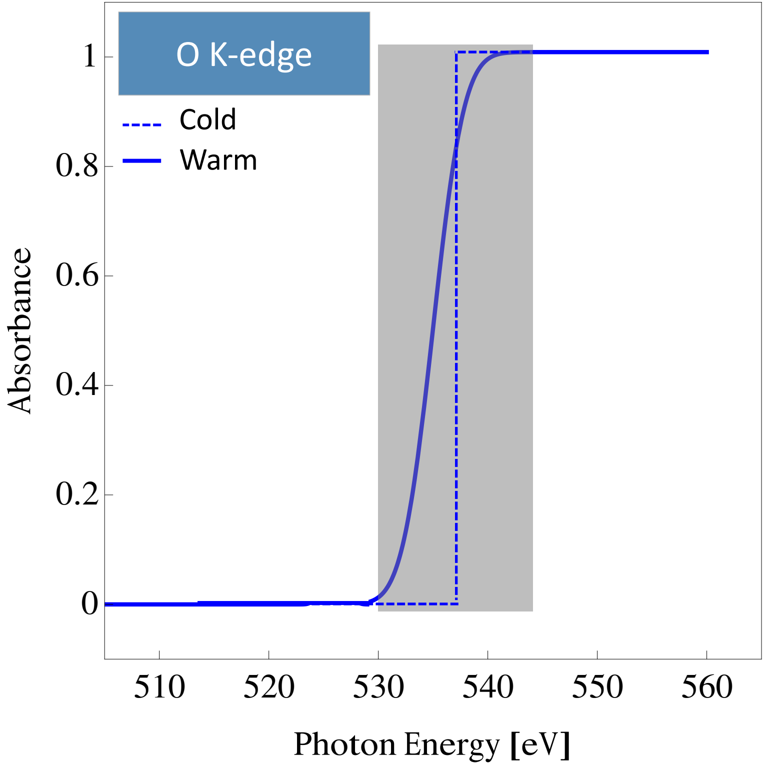
Si 1s

1848.6 eV

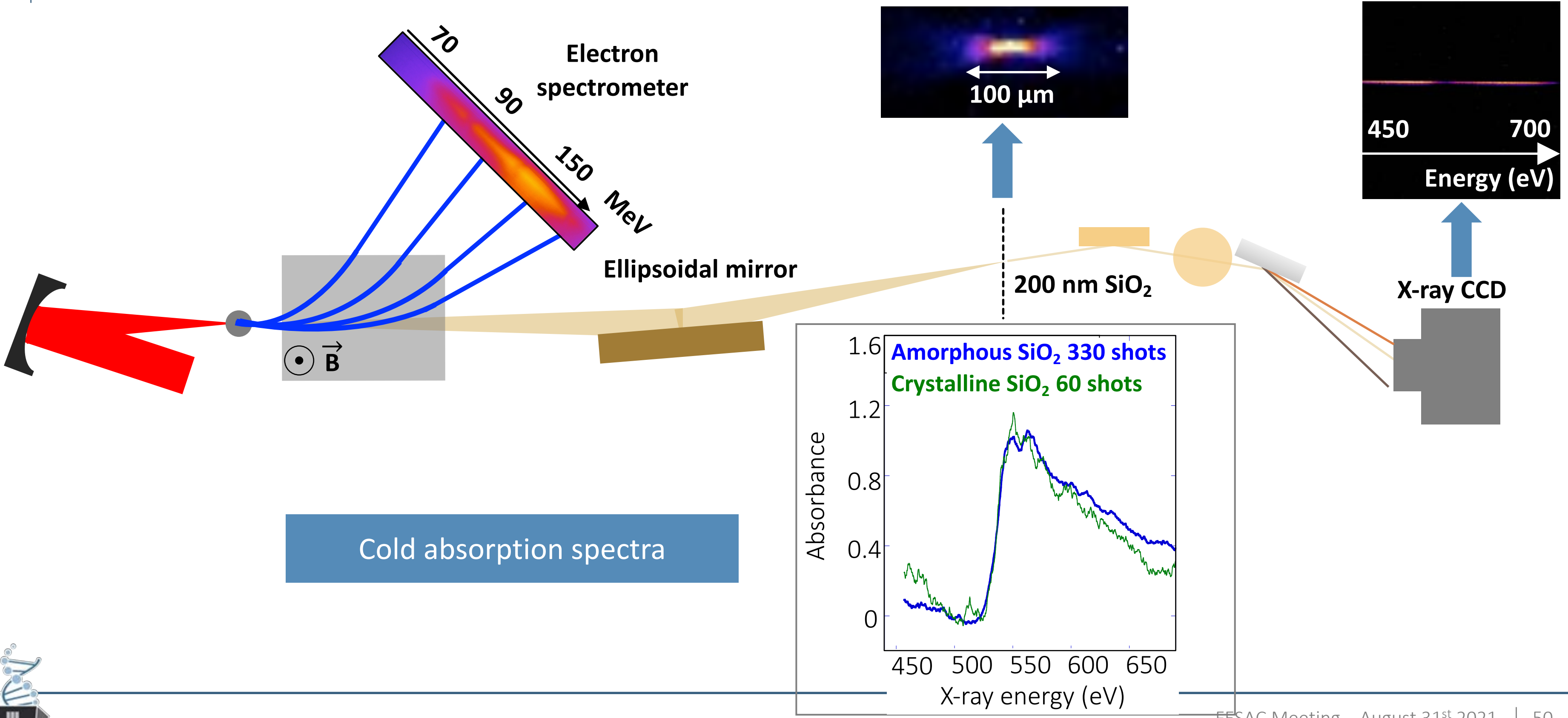


Defect states also allow absorption within bandgap upon heating, K-edge is broadened and red shifted



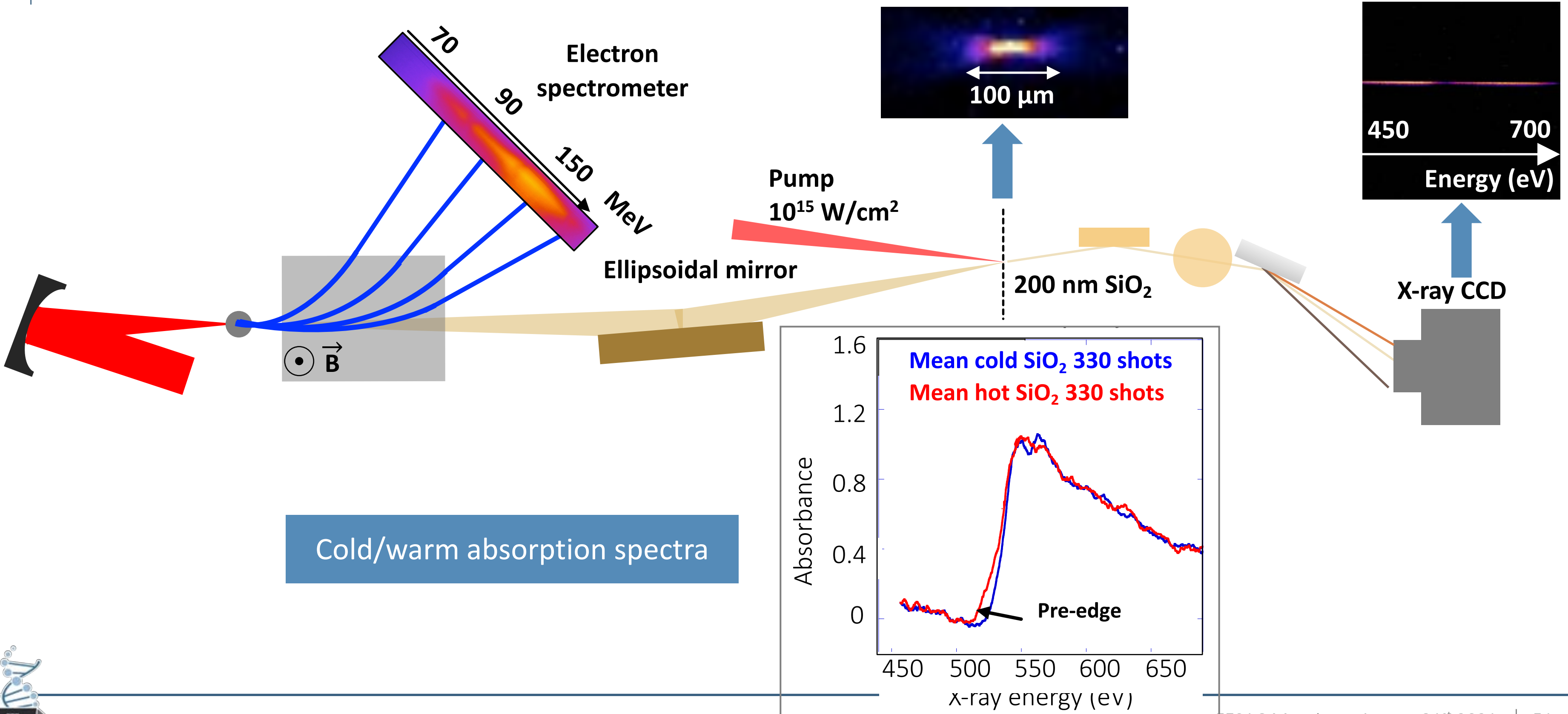


We have demonstrated the use of betatron x-rays as a tool for absorption spectroscopy



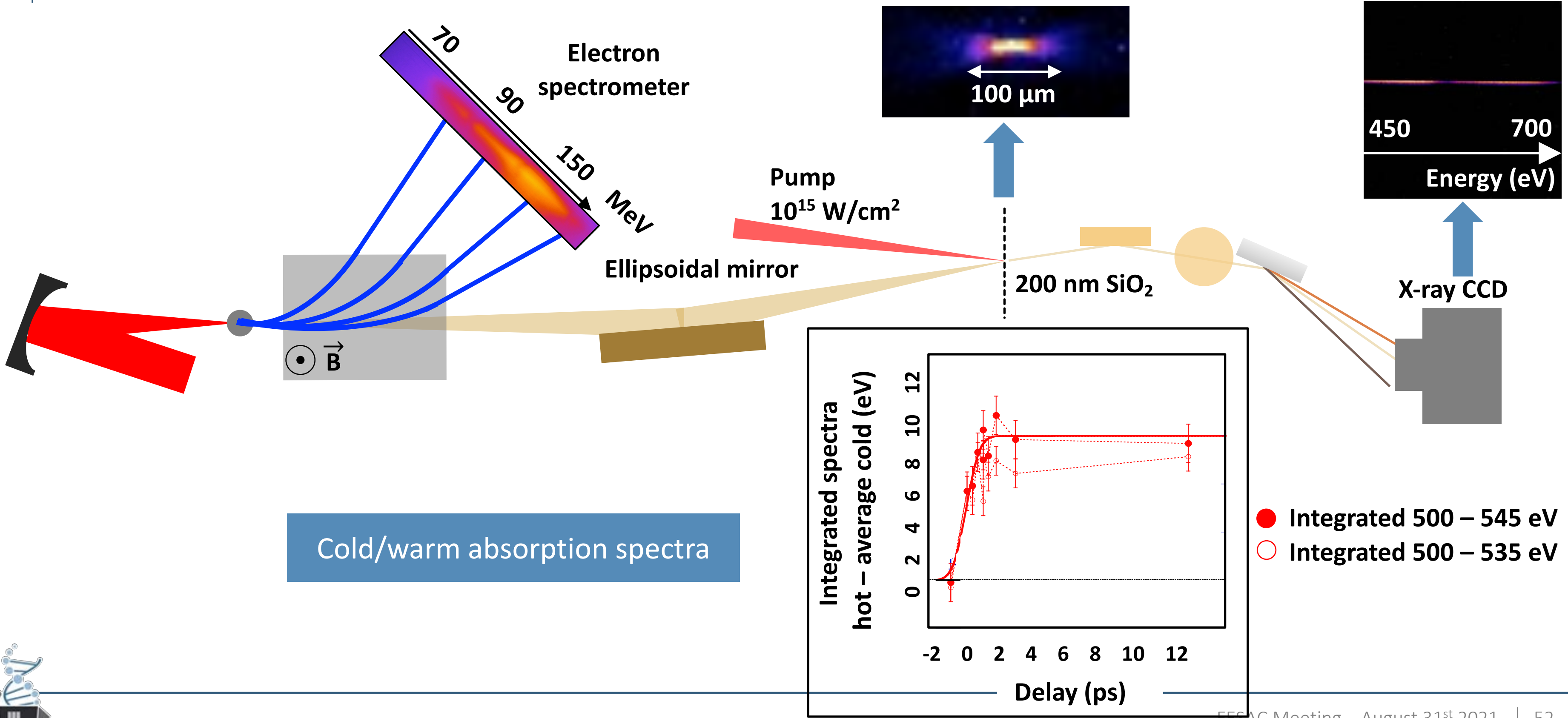
Cold absorption spectra

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



Cold/warm absorption spectra

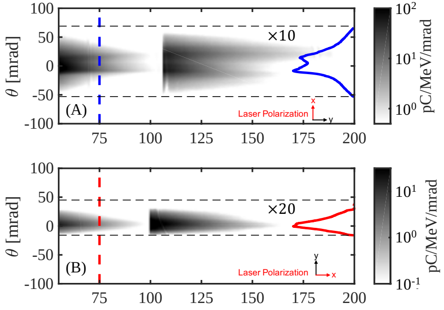
We have demonstrated betatron x-rays absorption spectroscopy with sub ps resolution



Cold/warm absorption spectra

We still have a lot of ongoing exciting projects

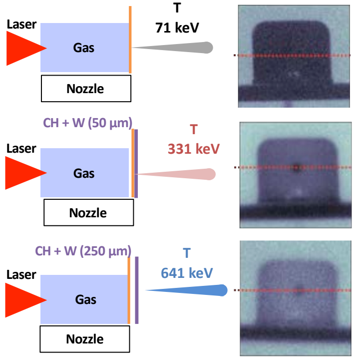
New acceleration mechanisms



- Role of Direct Laser Acceleration in Self-modulated LWFA*
- 3D OSIRIS PIC simulations confirm observation (UCLA collaboration)

*P.M. King et al, PRAB (2021)

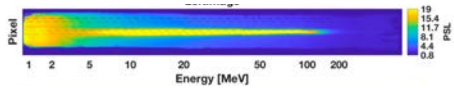
keV-MeV sources and applications



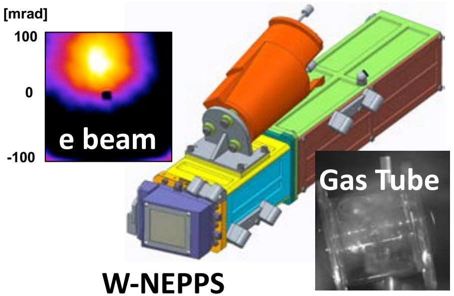
- Betatron, Bremsstrahlung, Compton sources for radiography applications
- LaserNetUS experiment at Texas Petawatt on radiography

N. Lemos (in prep)
2 new students: B. Pagano (UT Austin) and A. Aghedo (FAMU)

Platform development on larger HEDS lasers



- 150 MeV, 700 nC beams at OMEGA EP*

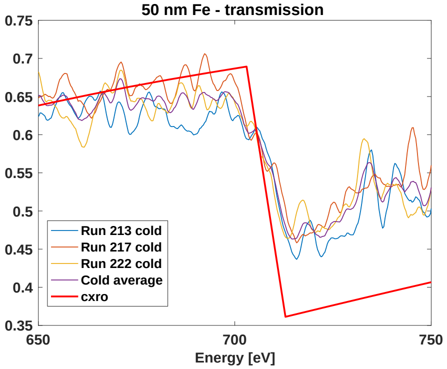


W-NEPPS

- 150 MeV > μC at NIF- ARC
- Development of new targets and diagnostics

*J.L. Shaw et al, Sc. Rep (2021)

LaserNetUS experiments using betatron source



- Study of warm dense iron with XANES
- Phase contrast imaging of laser-driven shocks in water

*M. Berboucha, E. Galtier et al
**C. Kuranz et al

Conclusions and future work

- We have demonstrated the production of novel x-ray sources from laser-plasma accelerators on several laser facilities

- They are broadband (keV - MeV), ultrafast (fs - ps), small source size (µm), collimated (mrad), synchronized with drive laser

- They enable new applications
  - Study of ultrafast non-thermal melting in SiO2
  - Radiography of dense objects
  - Phase contrast imaging of laser-driven shocks and hydrodynamic instabilities
  - 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, single shot and rep-rate

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. M. King et. al, Rev. Sc. Instr.   90, 033503 (2019)
F. Albert et al, Nuclear Fusion, 59, 032003 (2019)
P. M. King et al, PRAB, 24, 011302 (2021)
J.L. Shaw et al, Sci. Rep, 11 7498 (2021)
N. Lemos et. al, PRL (in preparation)

Access to this type of research will be facilitated by networks

Founded 2018

U.S. DEPARTMENT OF ENERGY