Laser plasma accelerators: next generation x-ray light sources

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Heraeus seminar
Science and Applications of Plasma-Based Accelerators
May 16th 2022

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Lawrence Livermore National Laboratory

Outline

- **Laser plasma acceleration: an alternative to synchrotrons and XFELs for novel x-ray probes**
- Role of mid-scale laser facilities - LaserNetUS
- Development and applications of x-ray sources based on laser plasma acceleration at LaserNetUS facilities
- Conclusion and perspectives

Conventional x-ray light sources are large scale national facilities

X-ray free electron laser: LCLS

SLAC, CA

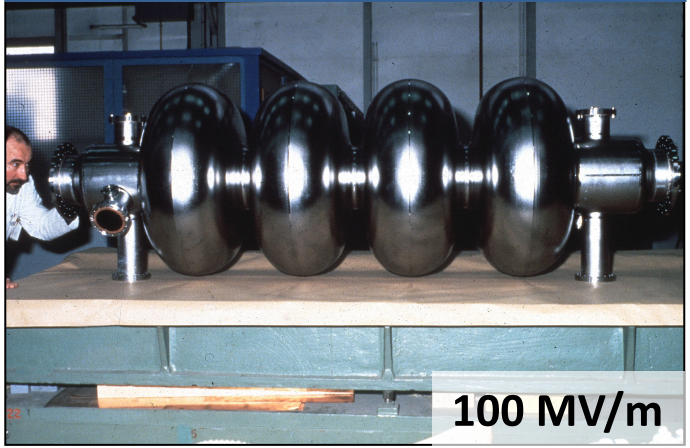
Synchrotron: APS

Argonne Nat. Lab., IL

Coupling such sources to large lasers is currently impractical

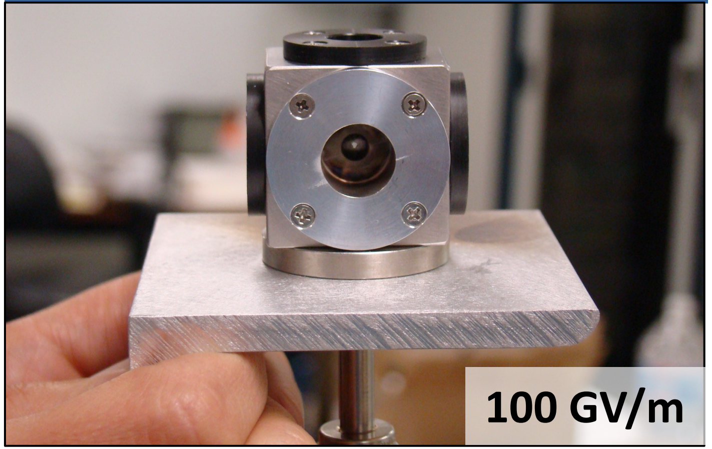
Laser-produced plasmas can naturally sustain large acceleration gradients

SRF Cavity



100 MV/m

Gas cell – laser plasma



100 GV/m

Acceleration gradient

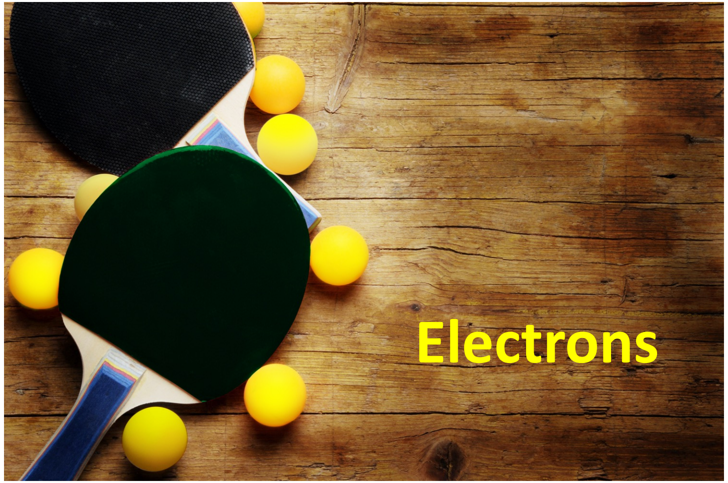
$$E_0 = \frac{mc\omega_p}{e}$$

Plasma frequency

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

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

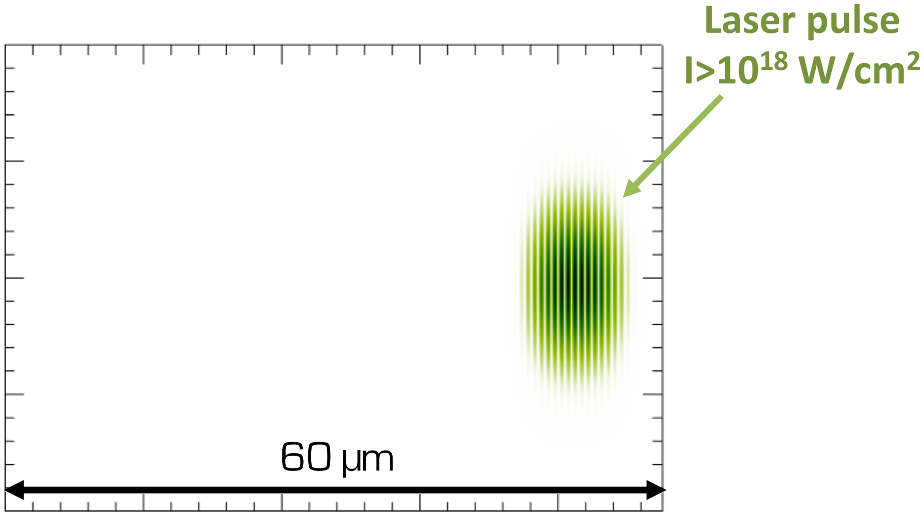
In a plasma, electrons are much lighter than ions and move around faster



An intense laser pulses drive electron plasma waves

Wake behind a boat

Plasma wave behind a laser



Nuno Lemos, LLNL

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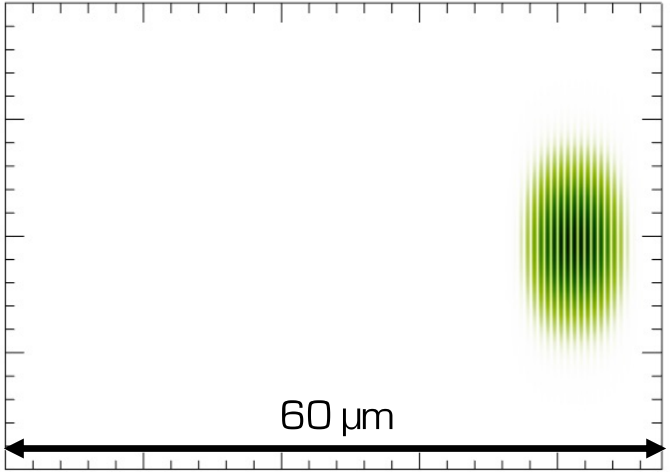

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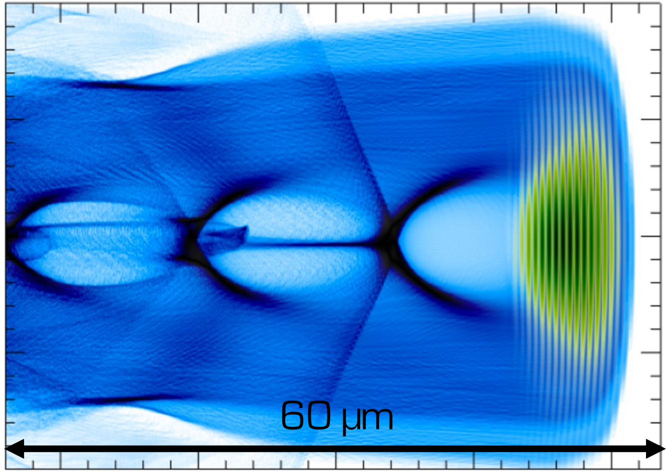

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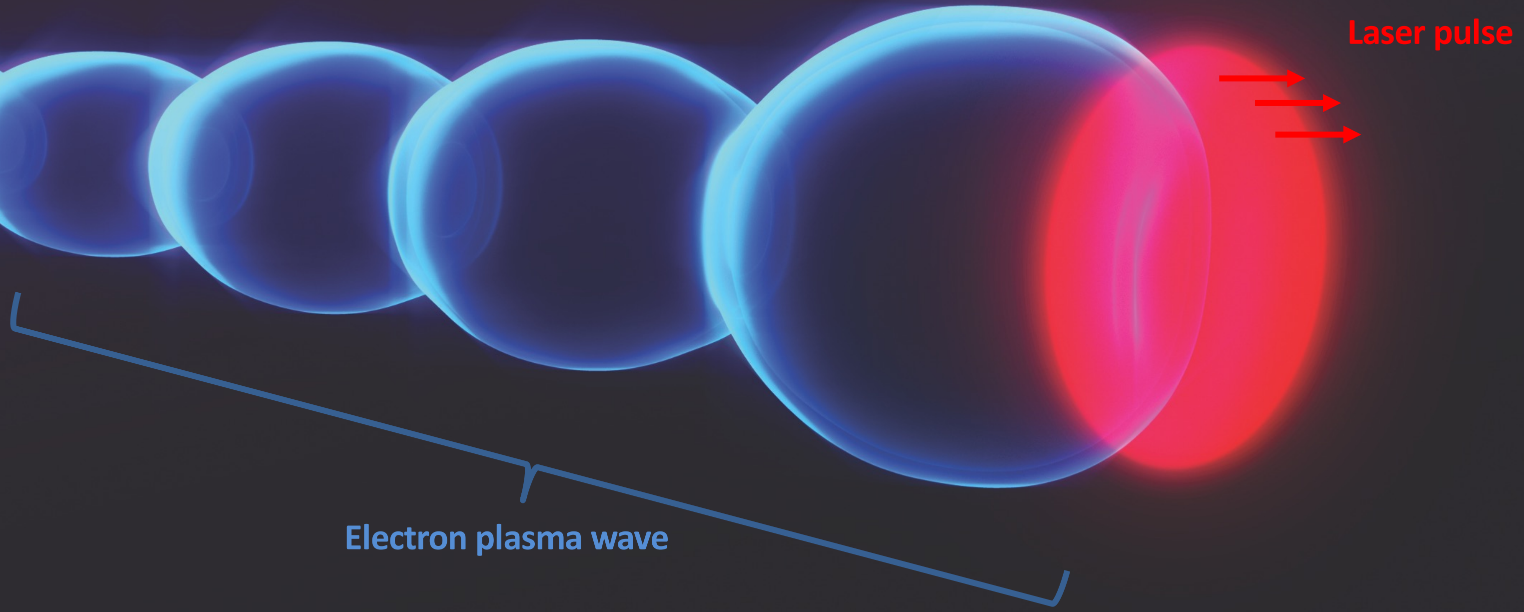
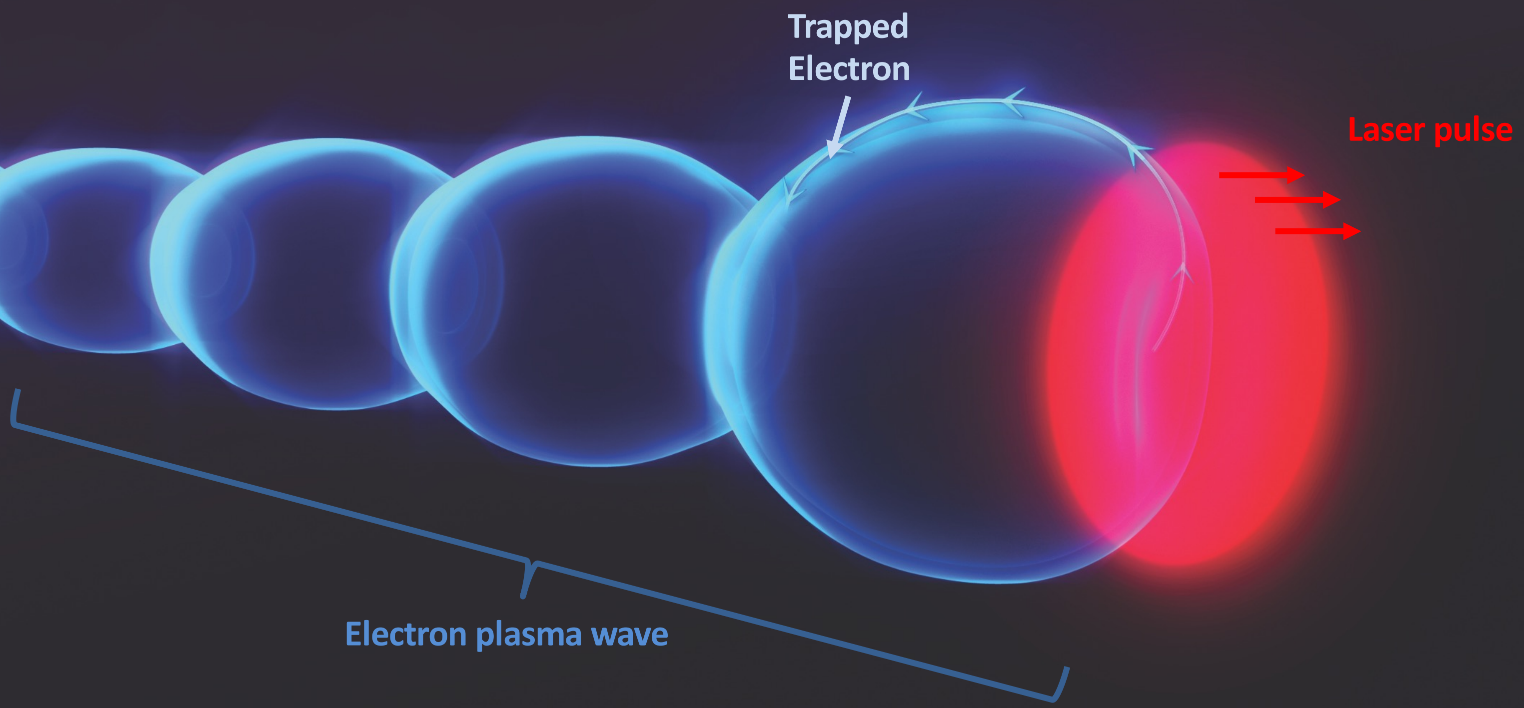


F. Albert et al, Laser wakefield accelerator based light sources: potential applications and requirements, *Plasma Phys. Control. Fusion* 56 084015 (2014)



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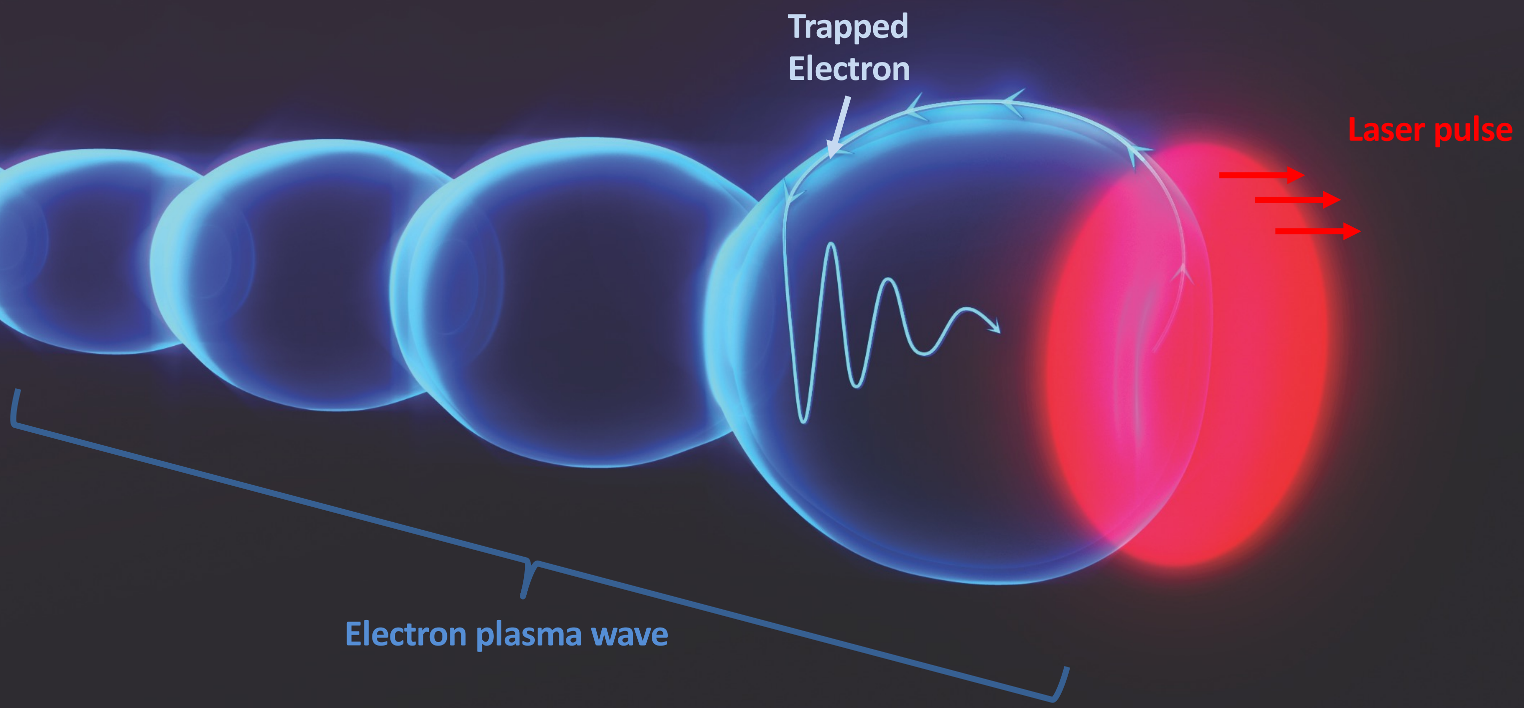

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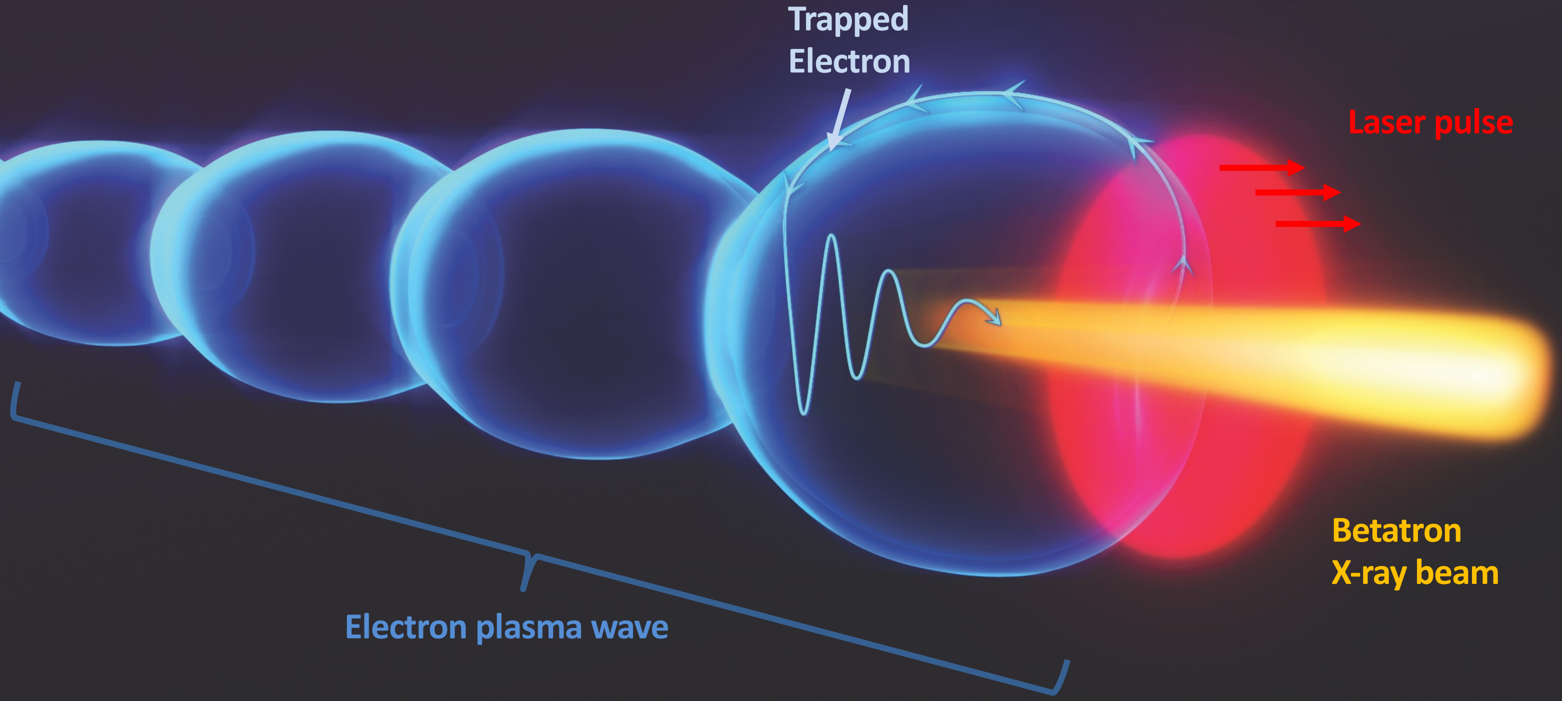
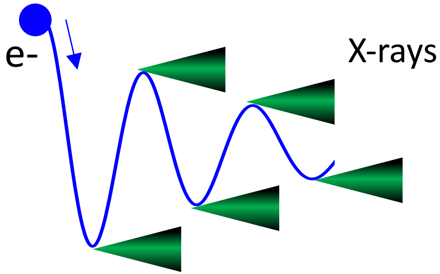
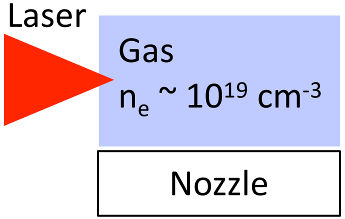


F. Albert et al, Laser wakefield accelerator based light sources: potential applications and requirements, *Plasma Phys. Control. Fusion* 56 084015 (2014)

Laser wakefield acceleration can produce x-rays using several processes

1 **Betatron x-ray radiation**

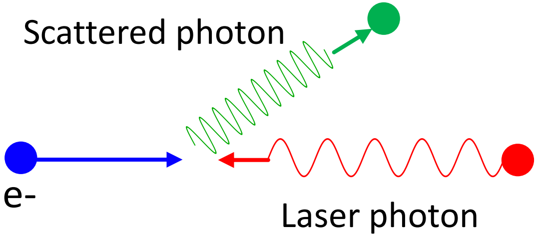


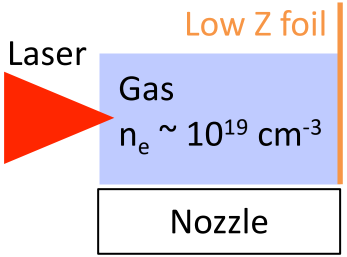


$$E_x \sim \gamma^2 n_e r_0$$

keV

2 **Compton scattering**

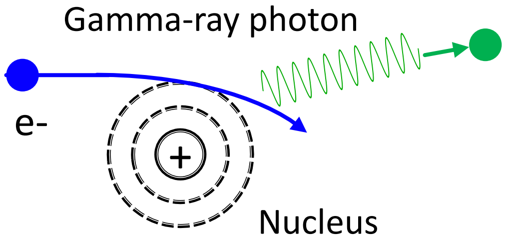


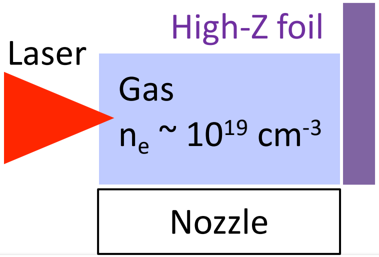


$$E_x \sim 4\gamma^2 E_L$$

keV - MeV

3 **Bremsstrahlung**

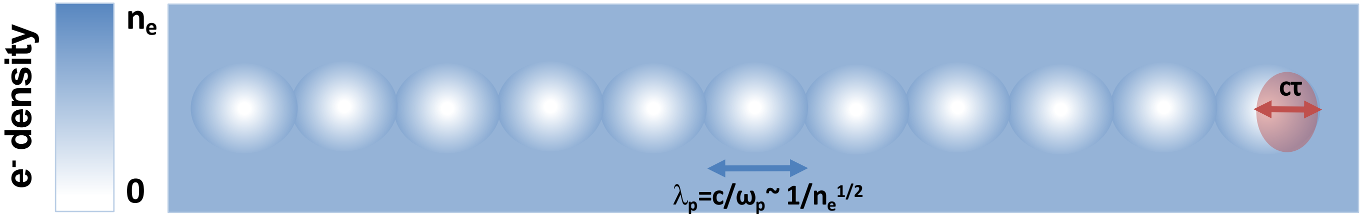




$$E_x \sim \gamma$$

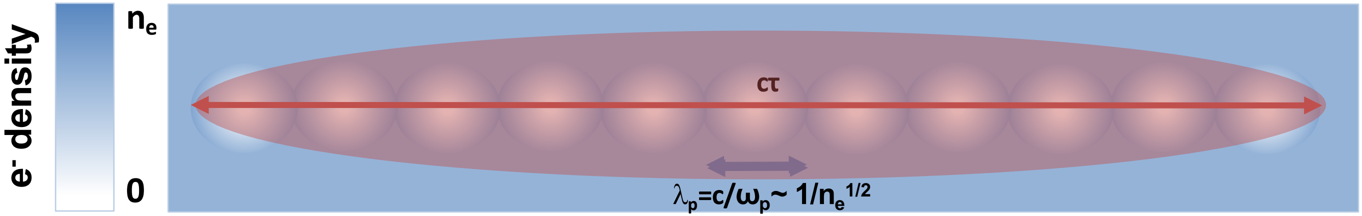
MeV

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



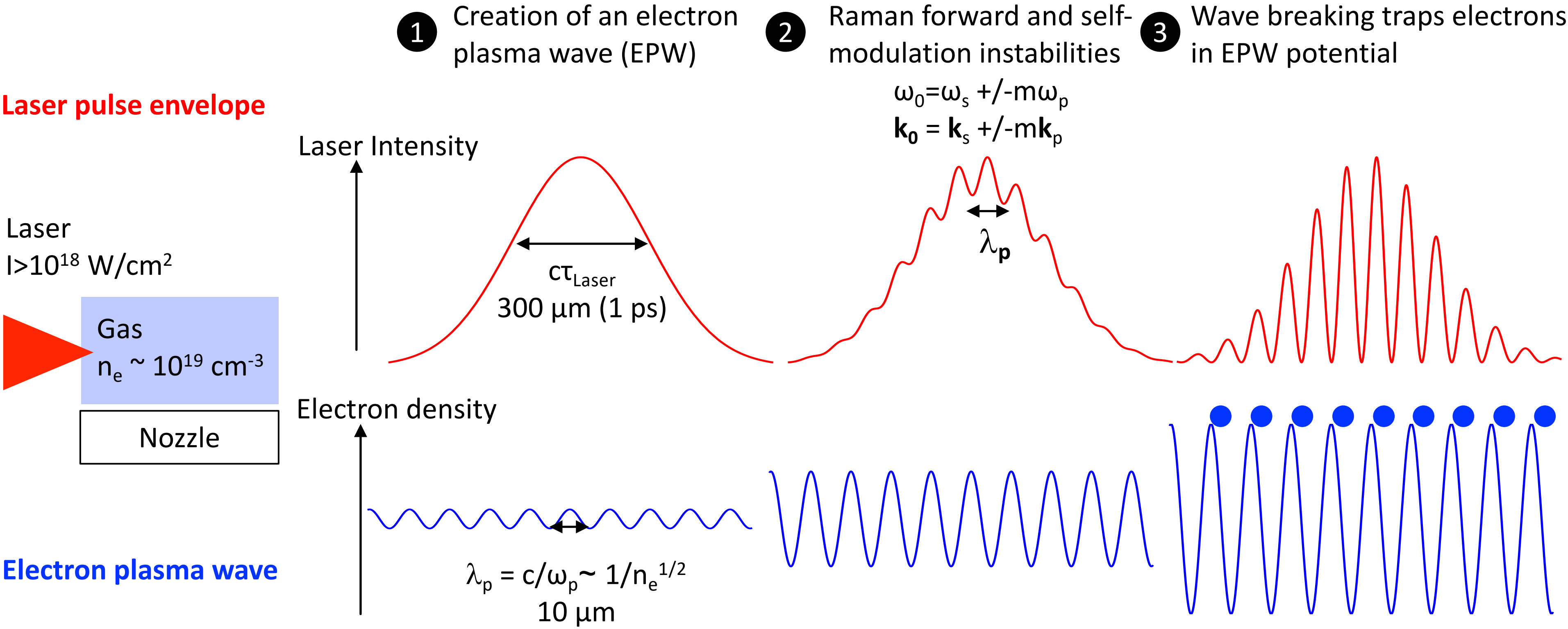
Condition to be in the blowout regime $c\tau \sim 1/n_e^{1/2}$ ➡ 30 fs $n_e \sim 10^{19}$ cm^{-3}

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



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}

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

Electron plasma wave

Laser

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

Gas

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

Nozzle

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

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

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

10 µm

Outline

- Laser plasma acceleration: an alternative to synchrotrons and XFELs for novel x-ray probes
- **Role of mid-scale laser facilities - LaserNetUS**
- Development and applications of x-ray sources based on laser plasma acceleration at LaserNetUS facilities
- Conclusion and perspectives

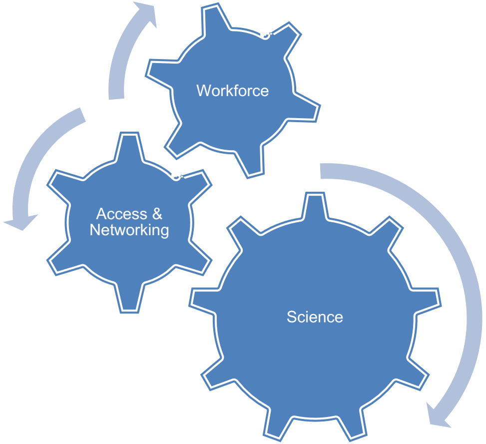
LaserNetUS

U.S. DEPARTMENT OF ENERGY | Office of Science

The mission of LaserNetUS

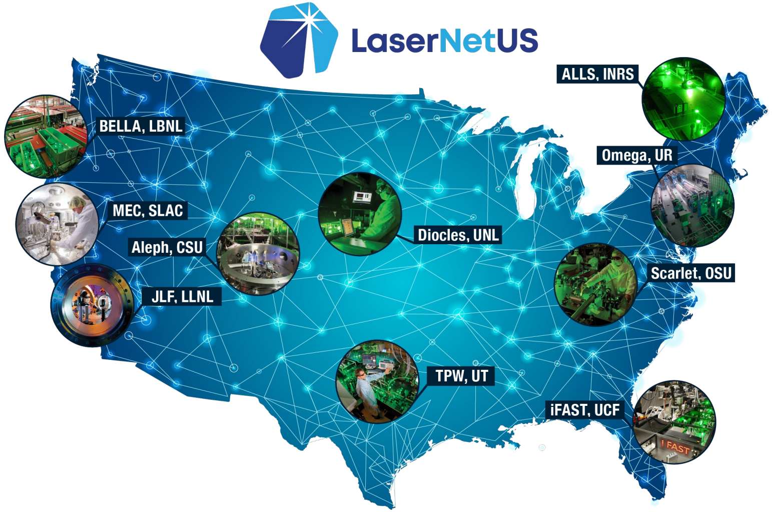
LaserNetUS was established in August 2018 to enable US scientific leadership in laser-driven High Energy Density and High Field Optical Sciences by:

1. Advancing the frontiers of laser-science research.
2. Providing students and scientists with broad access to unique facilities and enabling technologies.
3. Fostering collaboration among researchers and networks from around the world.



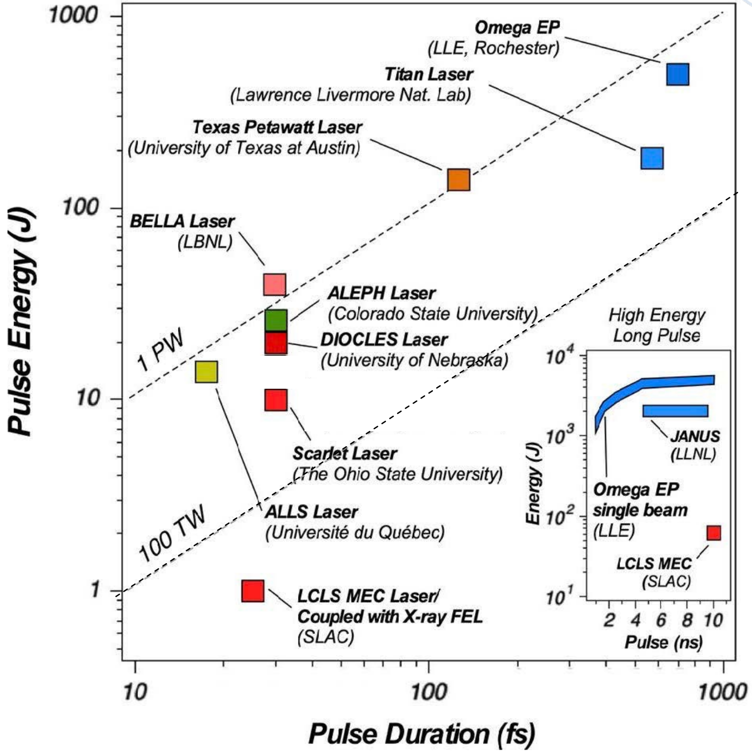
LaserNetUS has been successful. However, it requires coordination and planning, and we have more work to do!
We are committed to our mission and vision.

Summary of capabilities

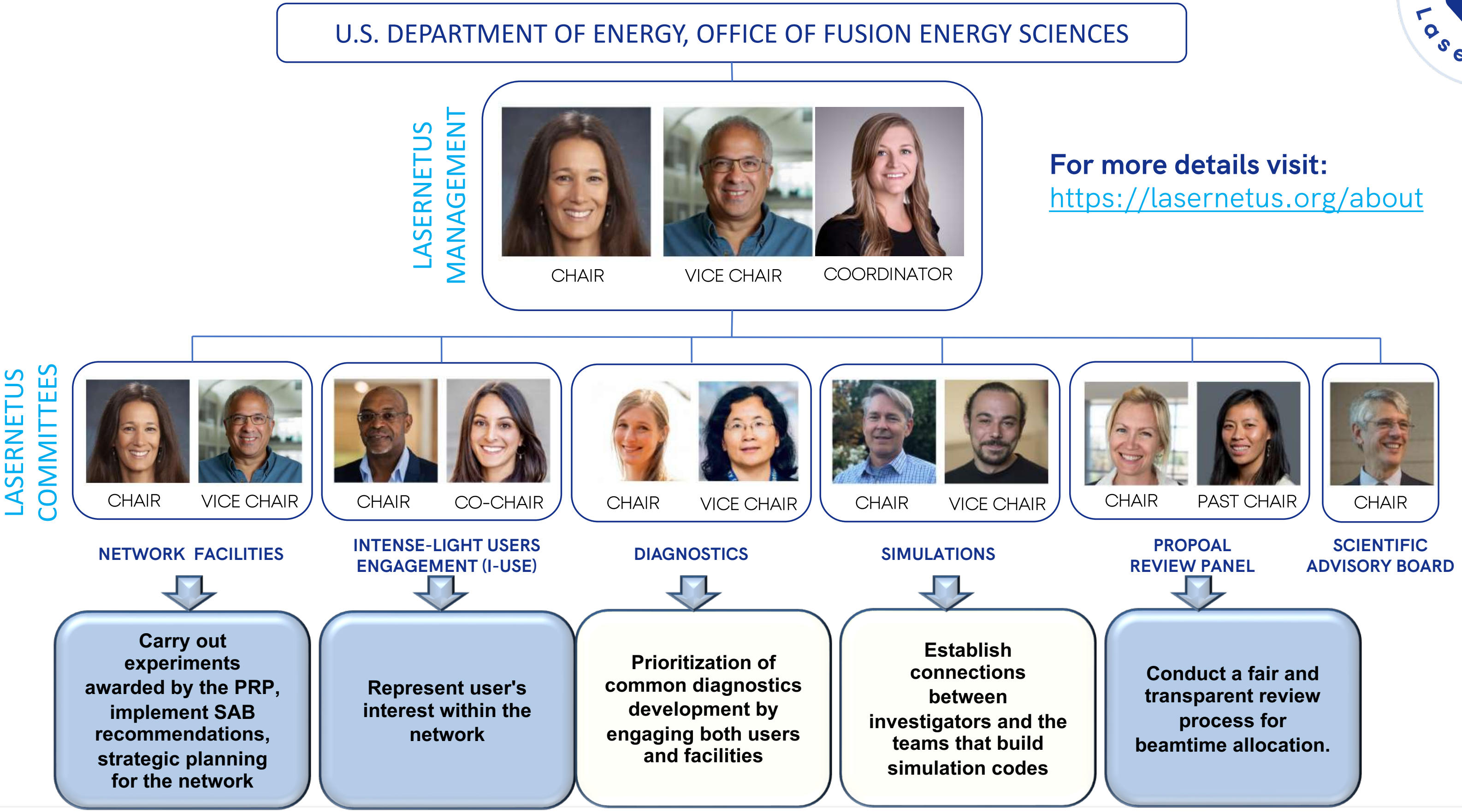


- **10** high power laser facilities*
- Includes the **6** most powerful lasers housed at Universities
- Highest powers exceed **1 petawatt**
- Dedicated to the proposition that **ALL** research groups should have access to the brightest light

*UCF not yet offering beam time



LaserNetUS organization



U.S. DEPARTMENT OF ENERGY, OFFICE OF FUSION ENERGY SCIENCES

LASERNETUS MANAGEMENT

CHAIR

VICE CHAIR

COORDINATOR

For more details visit:
https://lasernetus.org/about

LASERNETUS COMMITTEES

NETWORK FACILITIES

CHAIR

VICE CHAIR

Carry out experiments awarded by the PRP, implement SAB recommendations, strategic planning for the network

INTENSE-LIGHT USERS ENGAGEMENT (I-USE)

CHAIR

CO-CHAIR

Represent user's interest within the network

DIAGNOSTICS

CHAIR

VICE CHAIR

Prioritization of common diagnostics development by engaging both users and facilities

SIMULATIONS

CHAIR

VICE CHAIR

Establish connections between investigators and the teams that build simulation codes

PROPOAL REVIEW PANEL

CHAIR

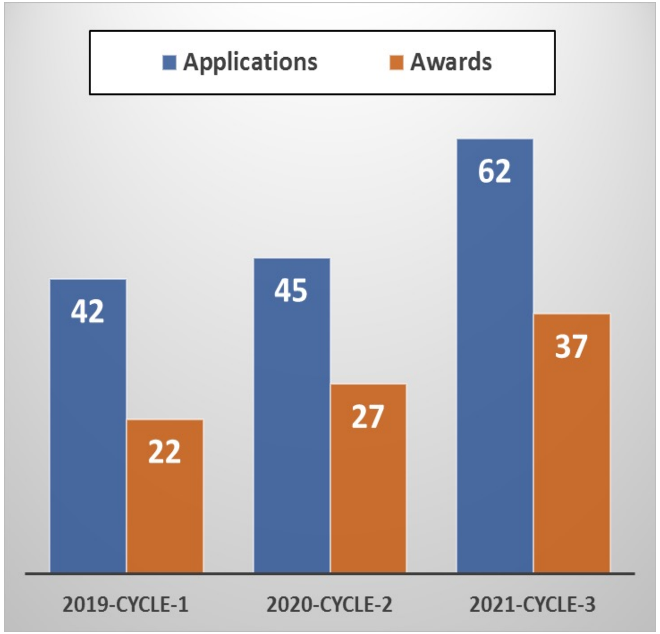
PAST CHAIR

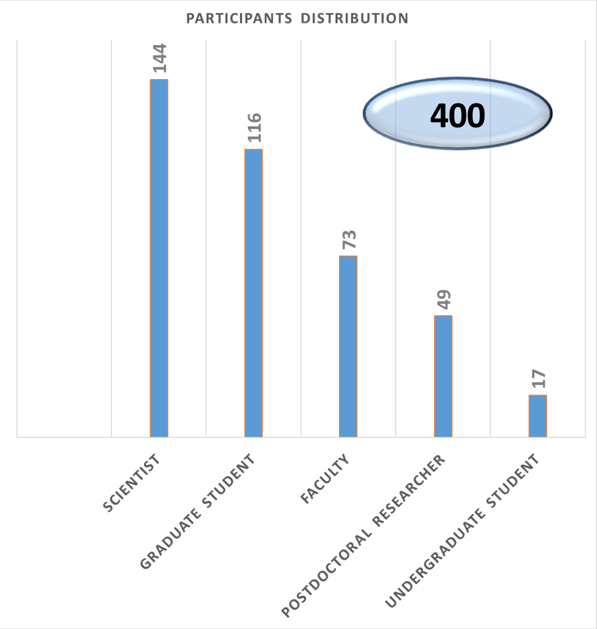
Conduct a fair and transparent review process for beamtime allocation.

SCIENTIFIC ADVISORY BOARD

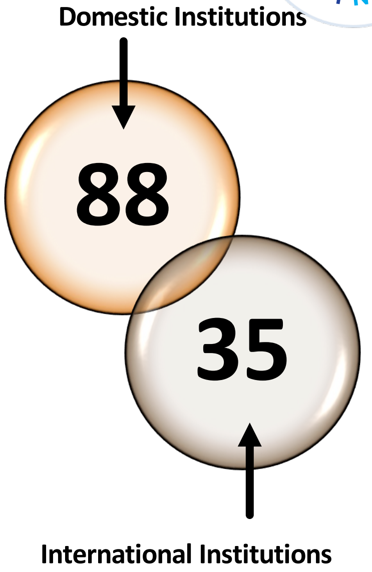
CHAIR

LaserNetUS by the numbers





90 graduate students from U.S. and Canada



Total # of institutions: 123

Annual call for proposals at lasernetus.org – Independent peer review process

We have an annual meeting to share results, discuss plans and welcome new participants

Kick-off Meeting at the University of Nebraska Lincoln – August 20-21st 2018

3d Annual Meeting – Fort Collins, CO – August 16-18 2022

- Primarily user talks and posters
- Plenary talks and panels

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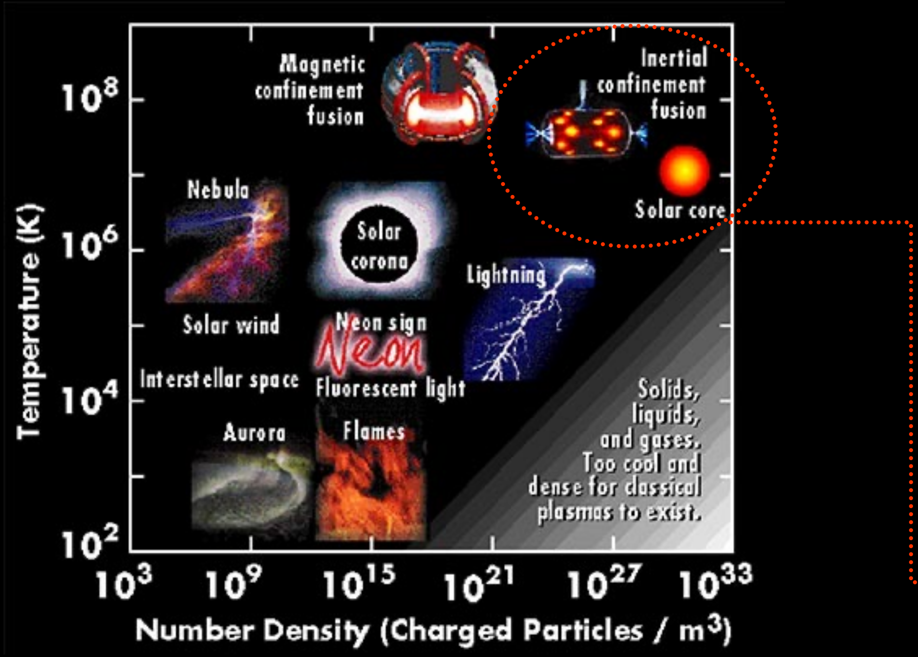
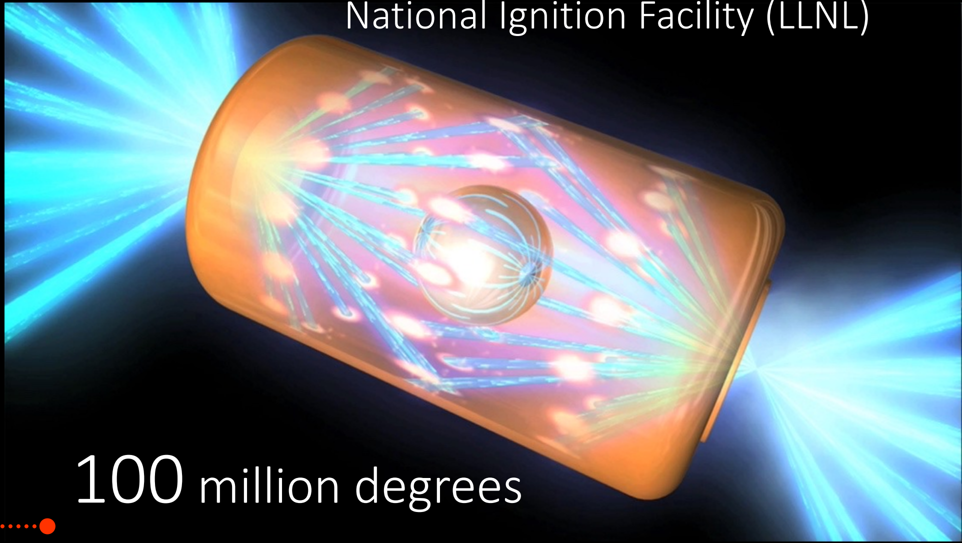
- Role of mid-scale laser facilities - LaserNetUS
- **Development and applications of x-ray sources based on laser plasma acceleration at LaserNetUS facilities**
  - **Picosecond scale**
- Conclusion and perspectives

HEDS experiments create extreme, transient conditions of temperature and pressure hard to diagnose



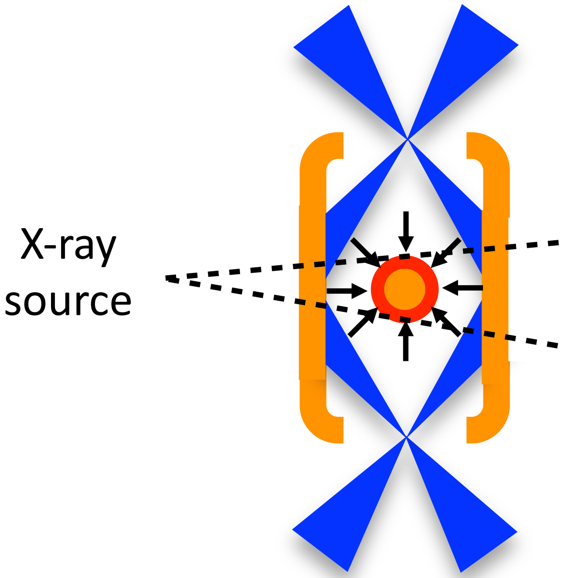


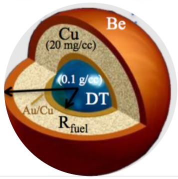
National Ignition Facility (LLNL)

100 million degrees

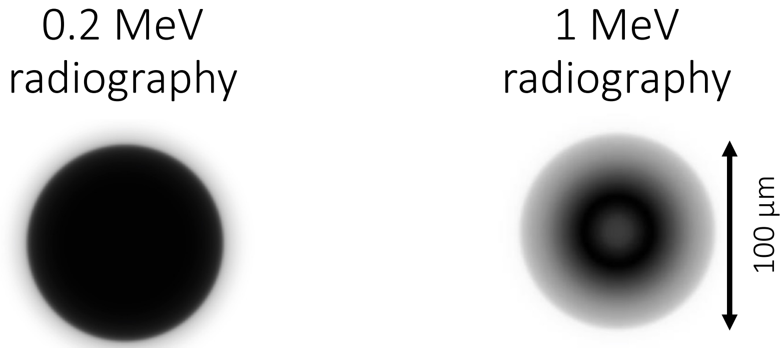
> 20x the density of lead

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





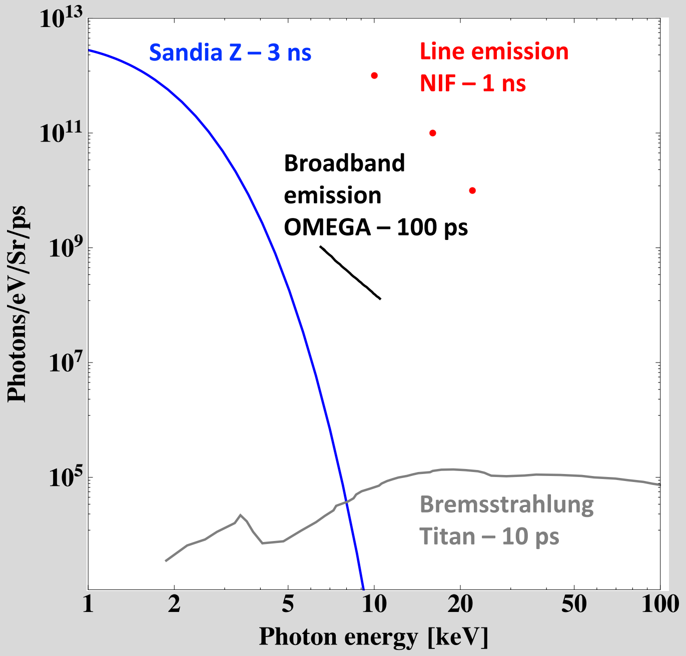
Double shell implosion, 1800 g/cc



Fully imploded capsule

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)

🟩 **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 preparation)

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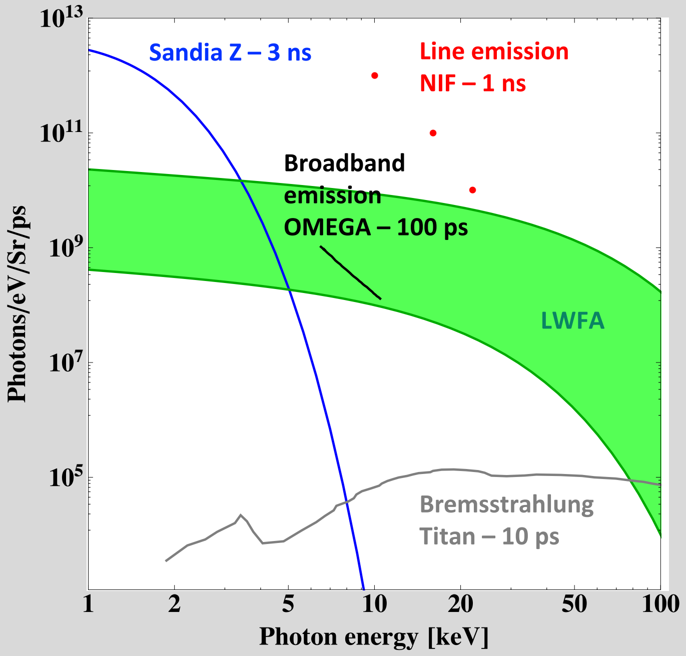

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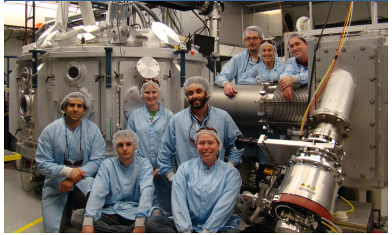
Lemos et al, PRL (in preparation)

Our project is developing LWFA-driven sources on large kJ-class picosecond lasers

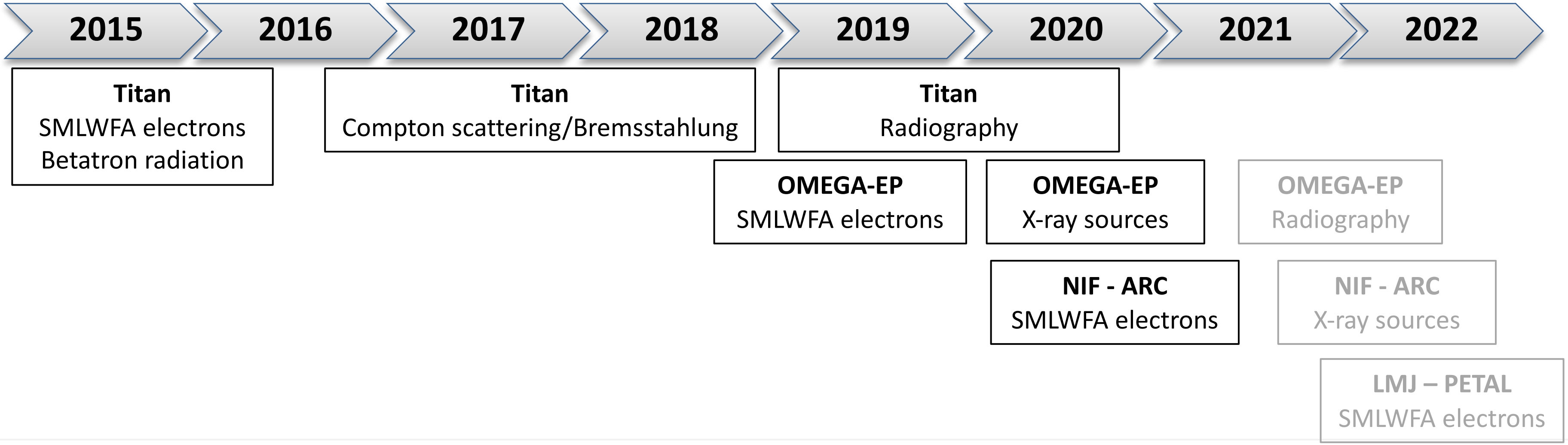
Titan, LLNL



OMEGA-EP, LLE

NIF – ARC, LLNL

LMJ – PETAL, CEA



2015 2016 2017 2018 2019 2020 2021 2022

Titan
SMLWFA electrons
Betatron radiation

Titan
Compton scattering/Bremsstahlung

Titan
Radiography

OMEGA-EP
SMLWFA electrons

OMEGA-EP
X-ray sources

OMEGA-EP
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NIF - ARC
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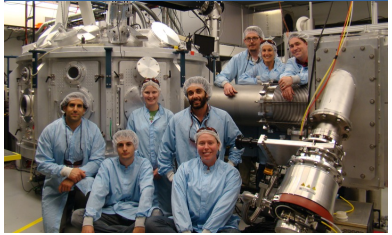

OMEGA-EP, LLE

NIF – ARC, LLNL

LMJ – PETAL, CEA

2015 2016 2017 2018 2019 2020 2021 2022

Titan
SMLWFA electrons
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OMEGA-EP
SMLWFA electrons

OMEGA-EP
X-ray sources

OMEGA-EP
Radiography

NIF - ARC
SMLWFA electrons

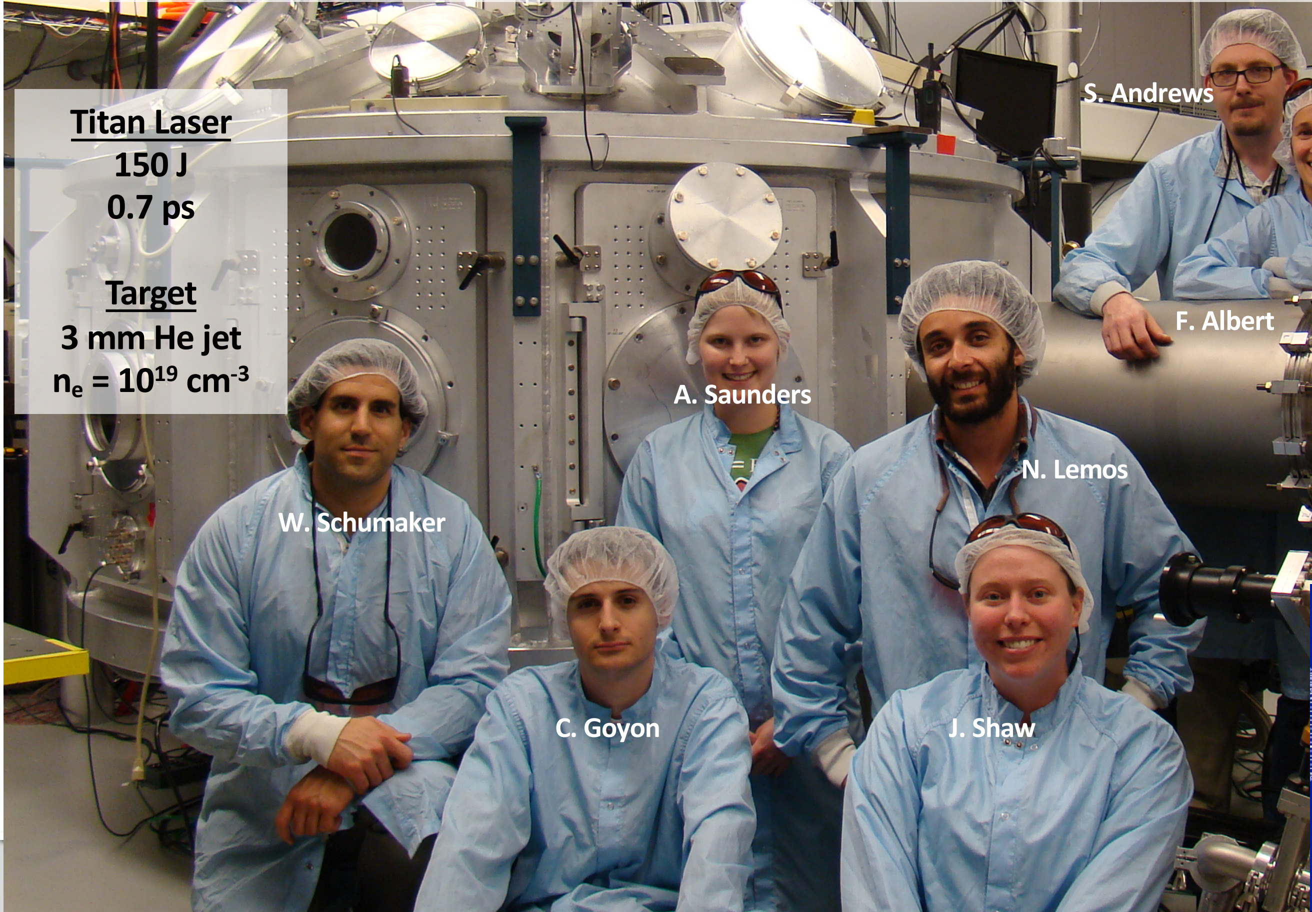
NIF - ARC
X-ray sources

LMJ – PETAL
SMLWFA electrons

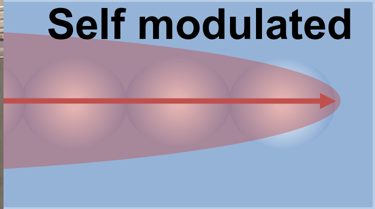
Laser wakefield – betatron experiments – Titan LLNL

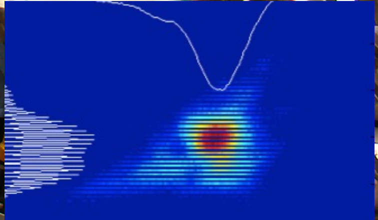
Titan Laser
150 J
0.7 ps

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



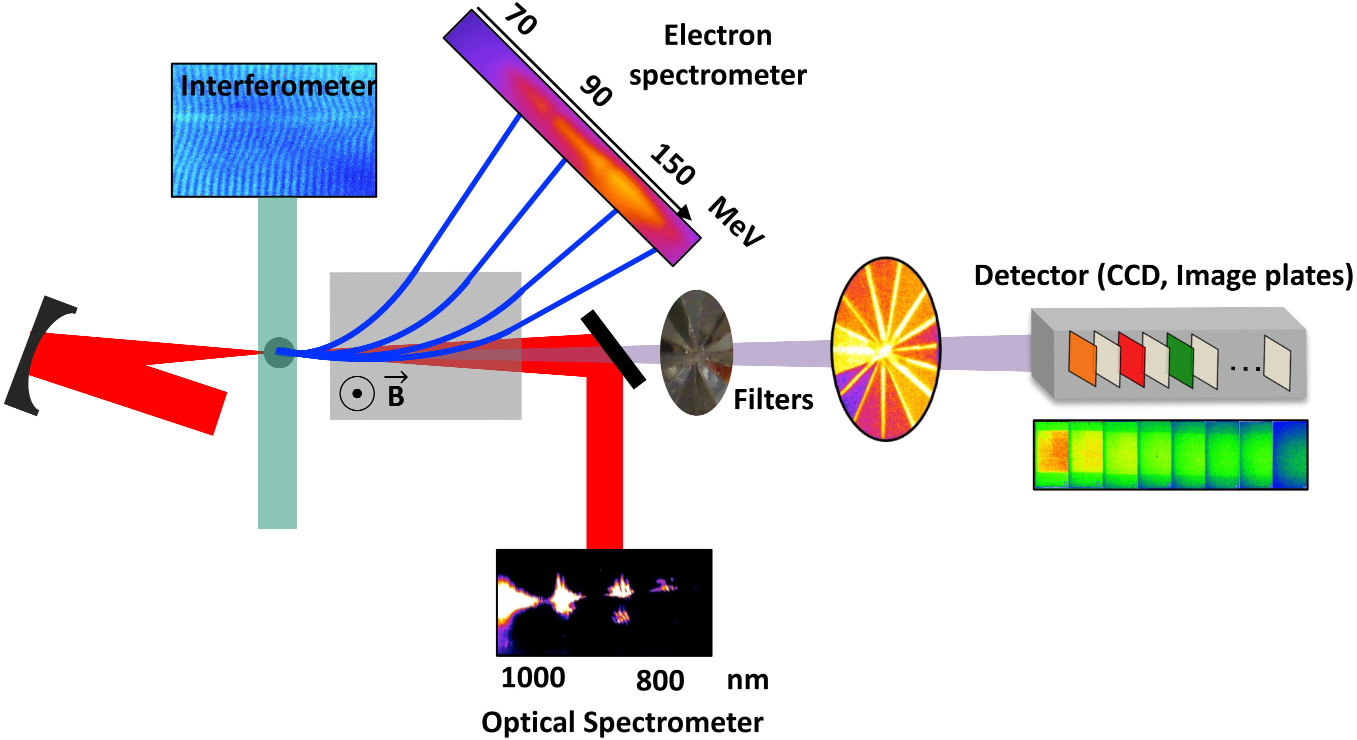
F/10 OAP
2.5 m focal length





86 % in 28 μm
I = 5×10^{18} W/cm^2

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



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

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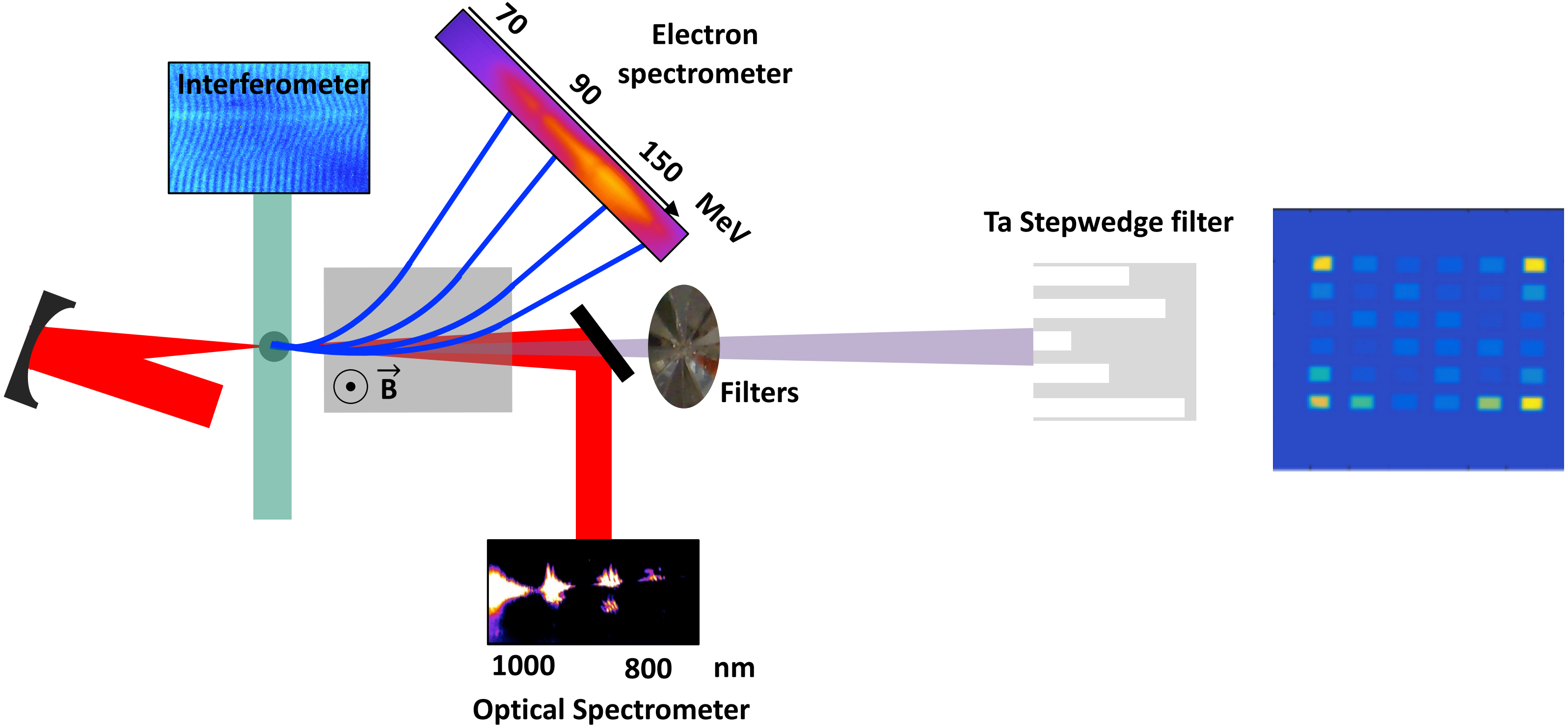
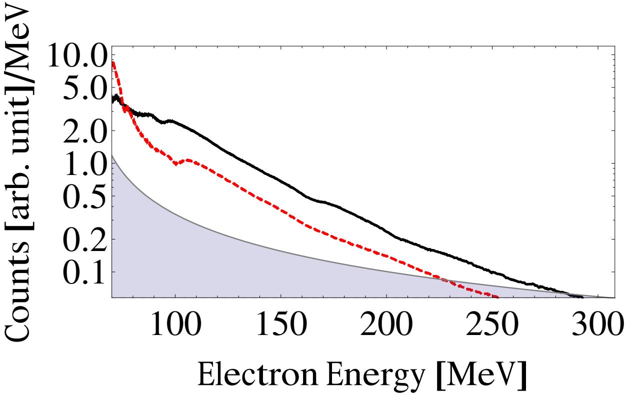


G. Williams et al, Rev. Sci. Instr. (2018)

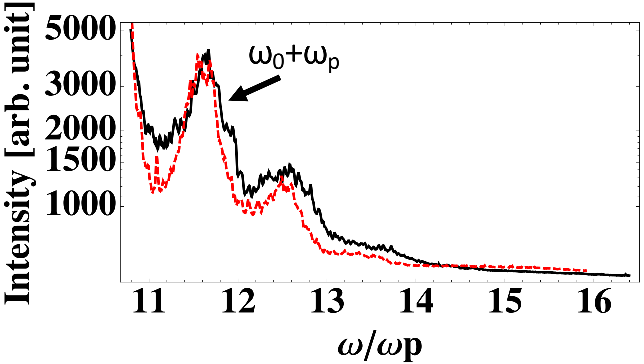
Electron beams and transmitted laser spectra have signatures of SMLWFA

Experiment

Electron beam spectrum



Transmitted laser spectrum

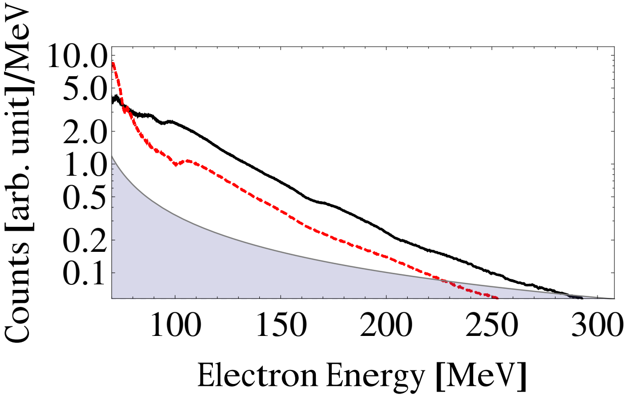


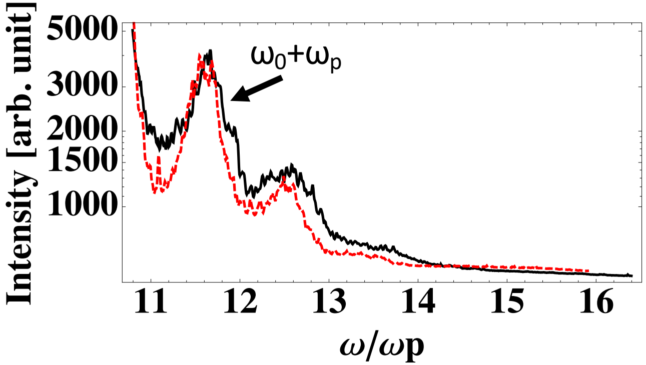
OSIRIS 2D PIC simulations of electron and forward laser spectrum also confirm signatures of SMLWFA

Electron beam spectrum

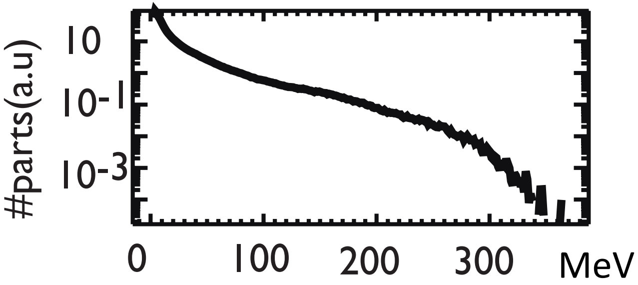
Transmitted laser spectrum

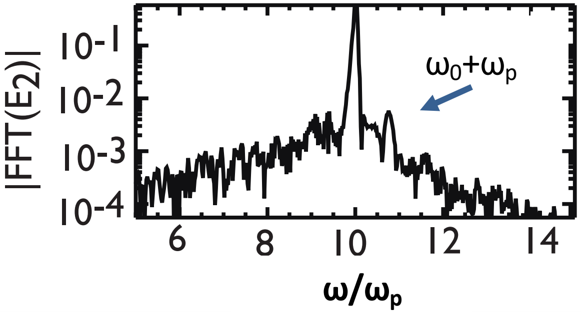
Experiment



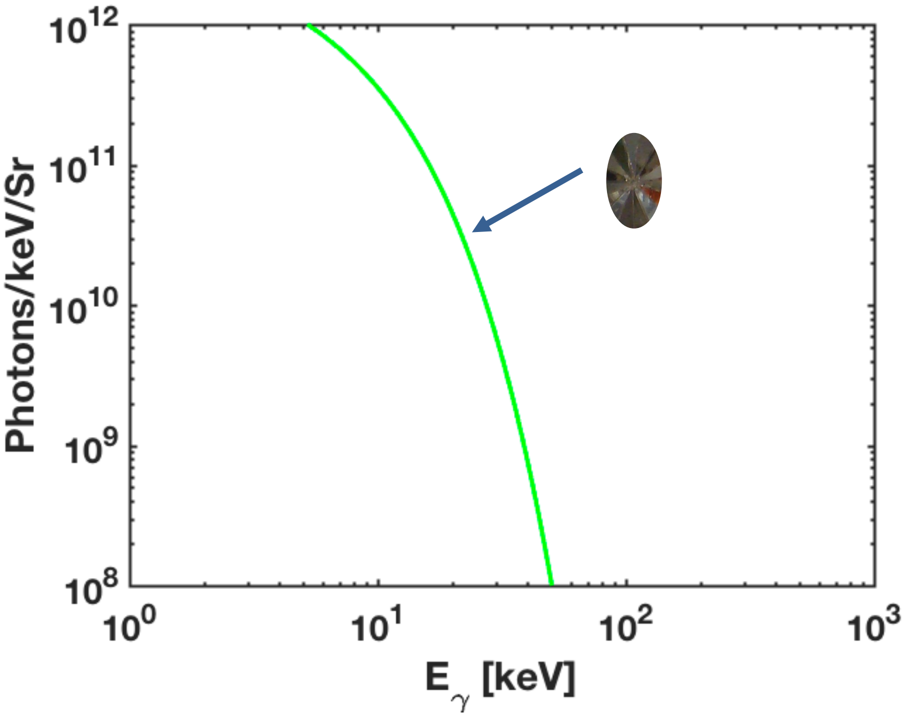


2D PIC simulation



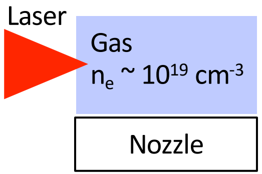


Optimized betatron radiation produces the most photons for energies <40 keV



Betatron, E_c = 10 keV

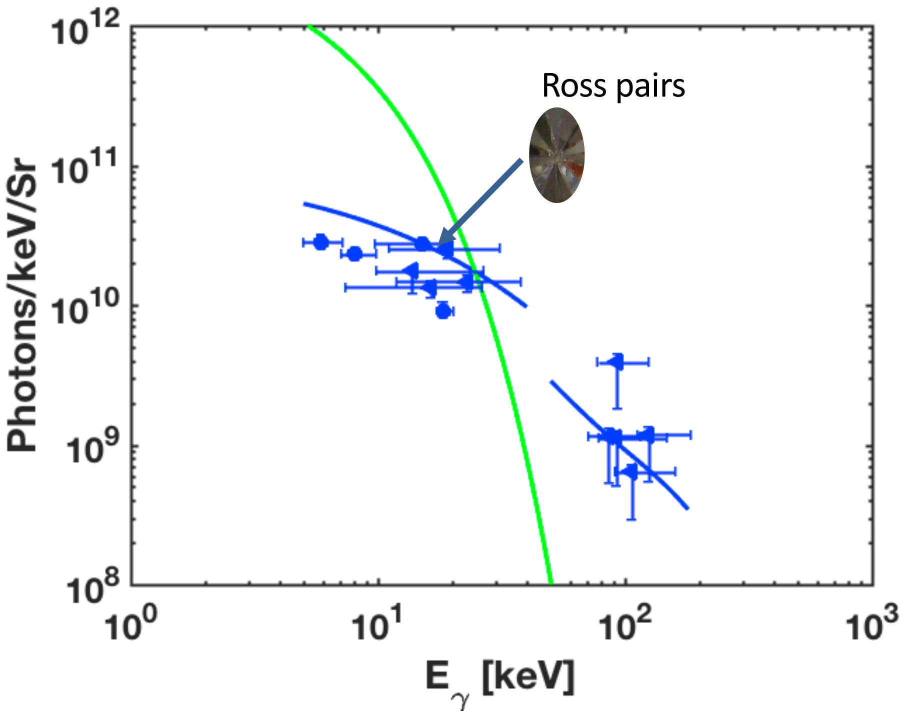
$$f(E) \sim \left(\frac{E}{E_c}\right)^2 K_{2/3}^2\left(\frac{E}{E_c}\right)$$



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

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

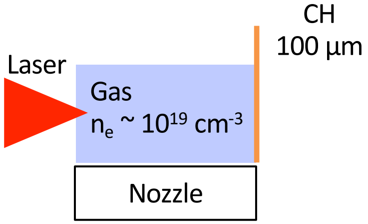
Compton scattering allows for increased photon flux up to a few 100 keV



Compton scattering

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

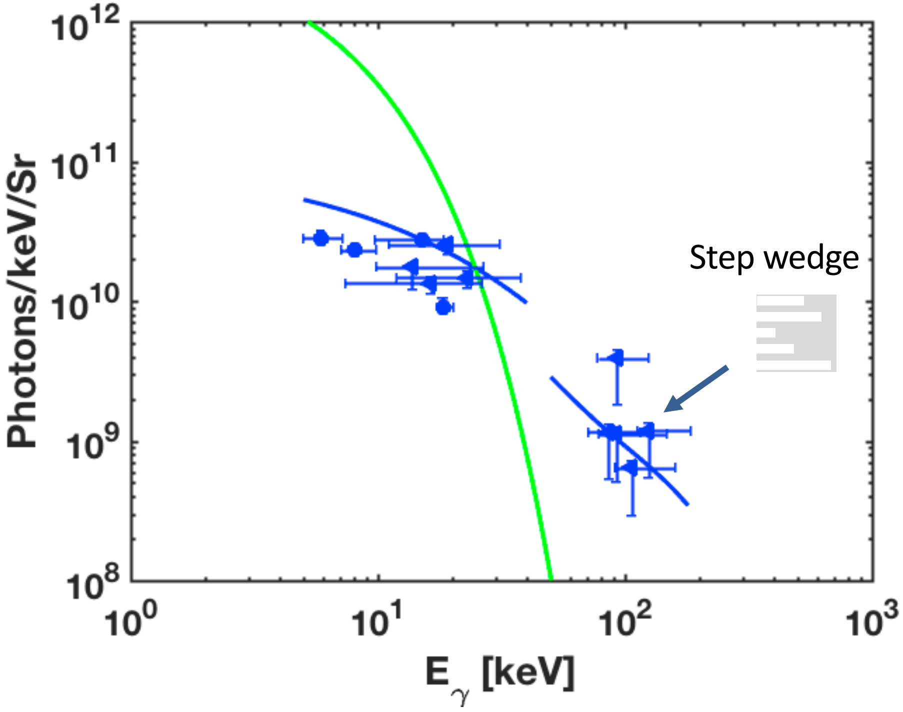
T_1 = 36 keV (Filter wheel)



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

N. Lemos et. al, Phys. Rev. Lett. (in preparation)

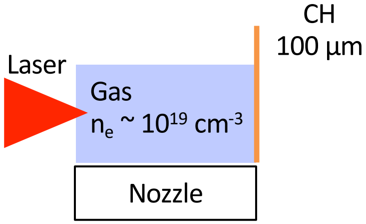
Compton scattering allows for increased photon flux up to a few 100 keV



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)



CH
100 µm

Laser

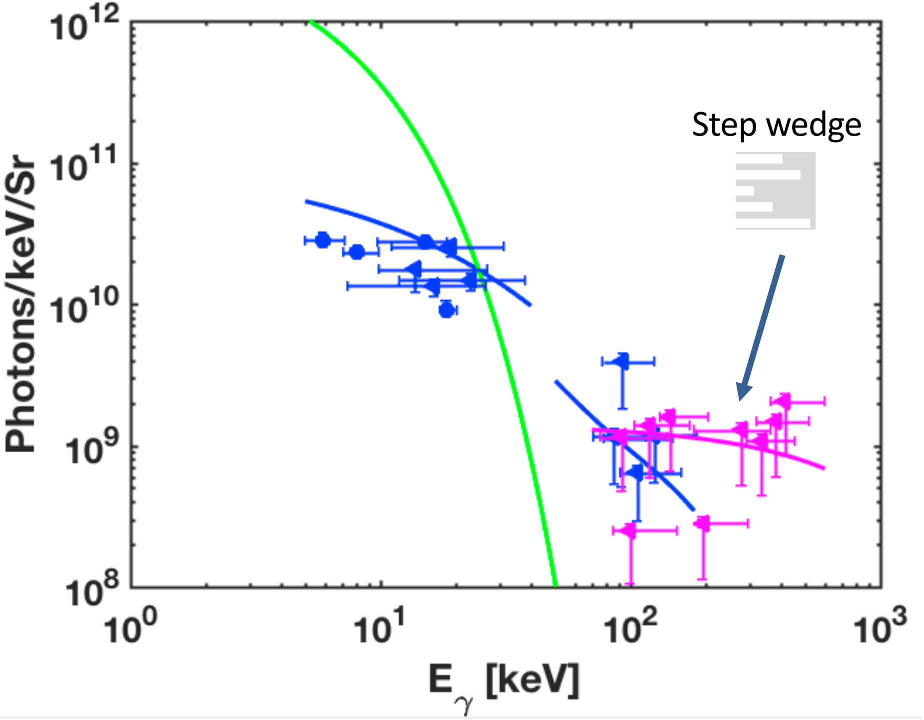
Gas
$n_e \sim 10^{19}$ cm^{-3}

Nozzle

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

N. Lemos et. al, Phys. Rev. Lett. (in preparation)

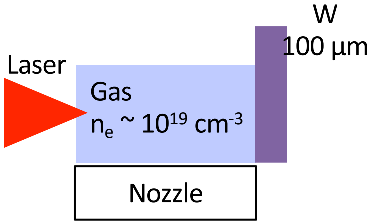
LWFA-driven bremsstrahlung produces the most photons at MeV energies



LWFA-driven bremsstrahlung

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

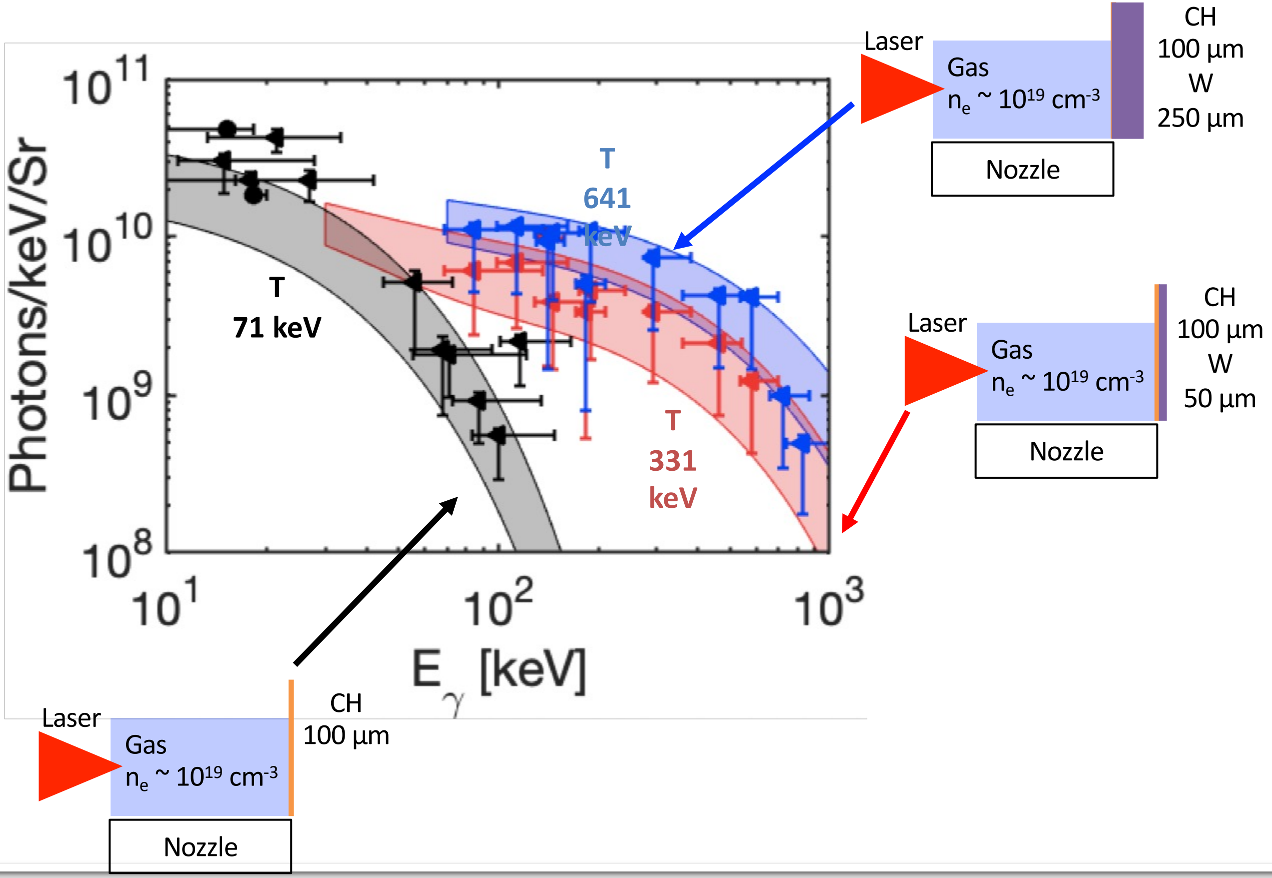
T = 838 keV (Step wedge)



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

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

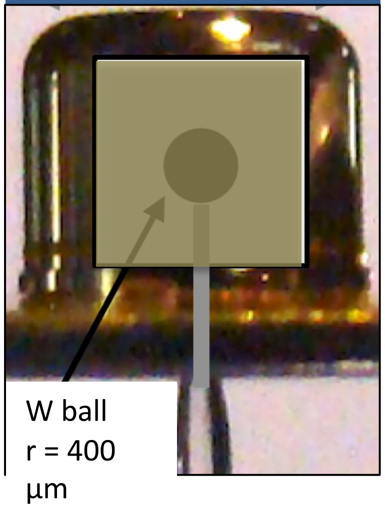
We can control the x-ray flux and energy by combining several processes



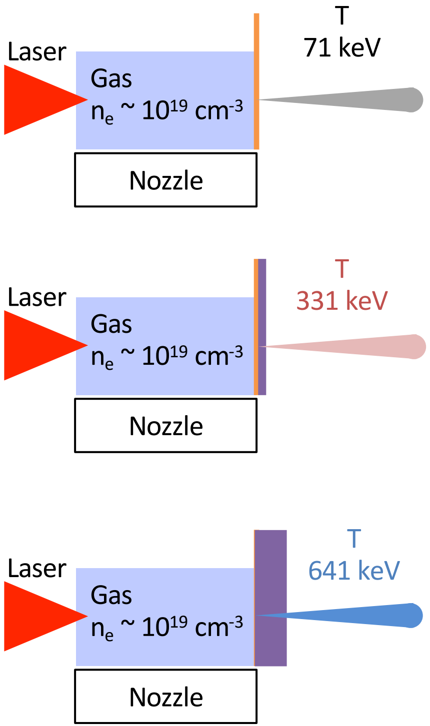
N. Lemos et. al, In preparation

Spectral and flux tuning allows for optimized radiography applications

Half hohlraum – 30 µm Au



W ball areal density ~ 0.7 g/cm^2


Laser

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

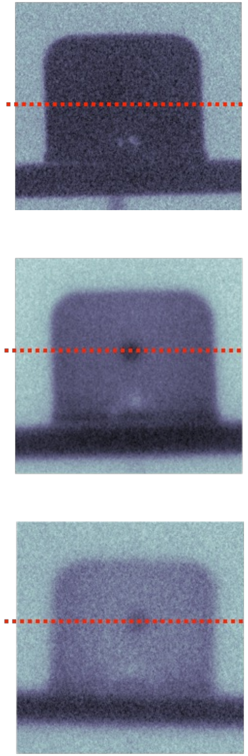
Nozzle

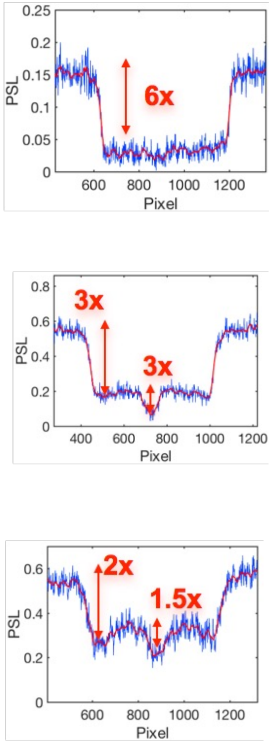
T
71 keV

T
331 keV

T
641 keV

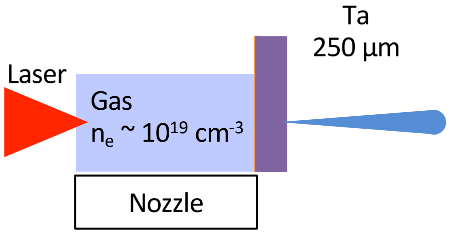
Magnification = 3





N. Lemos et. al, In preparation

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



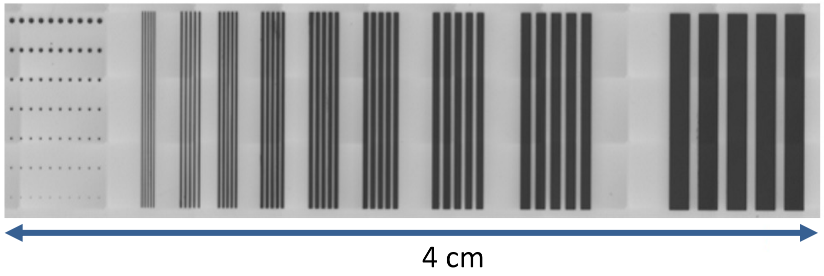
Ta
250 µm

Laser

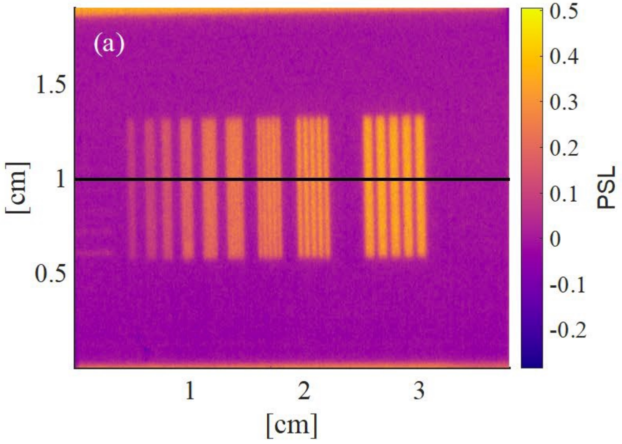
Gas
$n_e \sim 10^{19}$ cm^{-3}

Nozzle

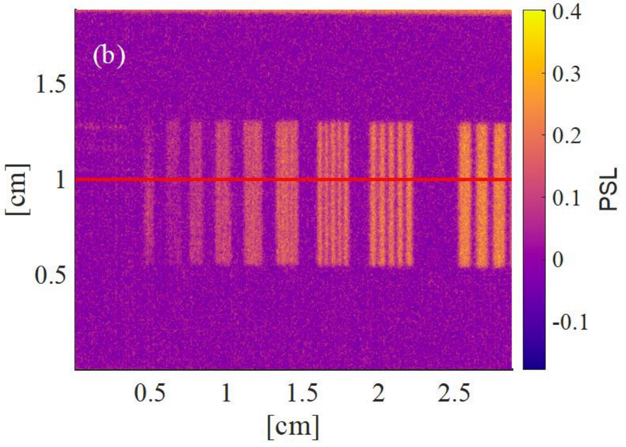
Resolution Target



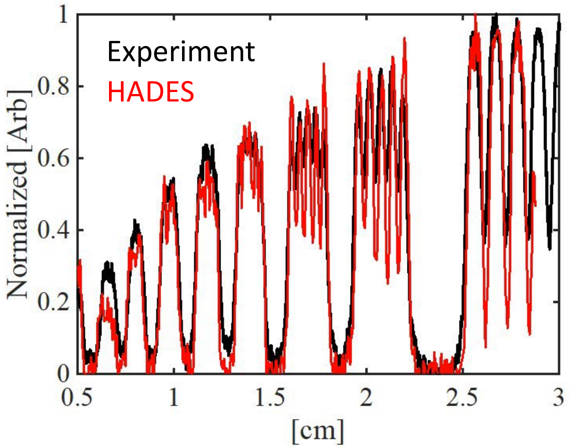
Experimental Radiograph



Simulated Radiograph

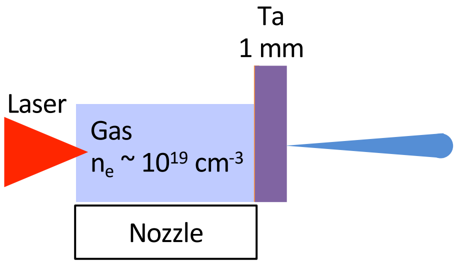


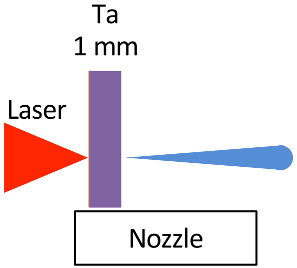
Comparison

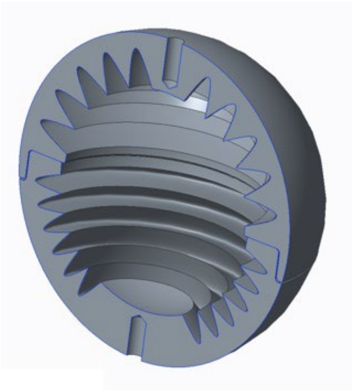


I Pagano, N. Lemos et. al, In preparation

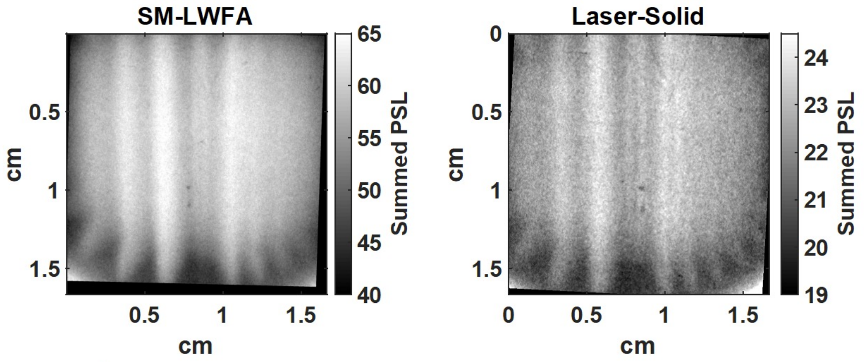
SM-LWFA driven x-ray source shows a 1.4x higher signal to noise in MeV radiography for the same laser conditions and targets

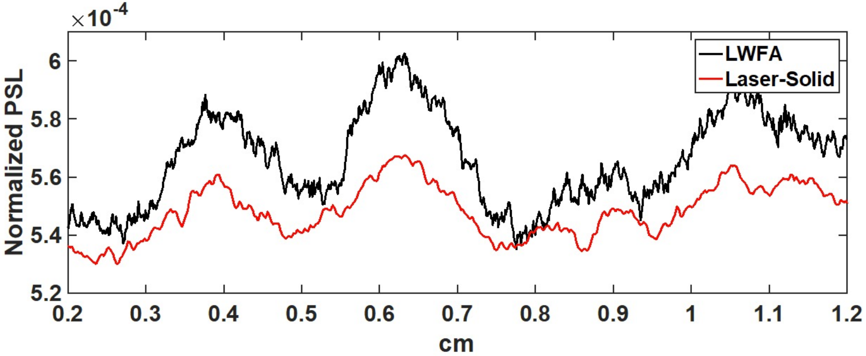






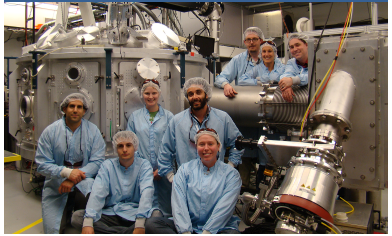
Areal density = 7.6 g/cm^2





Our project is developing LWFA-driven sources on large kJ-class picosecond lasers

Titan, LLNL



OMEGA-EP, LLE

NIF – ARC, LLNL

LMJ – PETAL, CEA

2015 2016 2017 2018 2019 2020 2021 2022

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

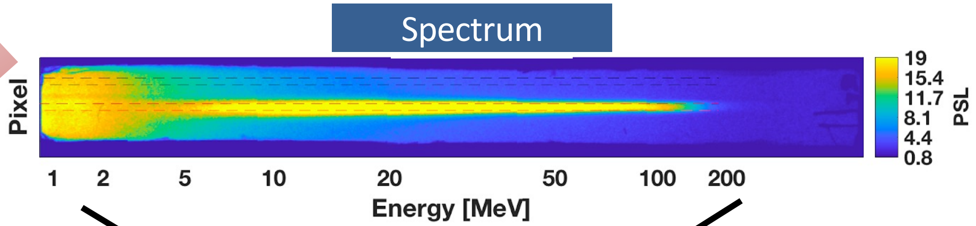
NIF - ARC
X-ray sources

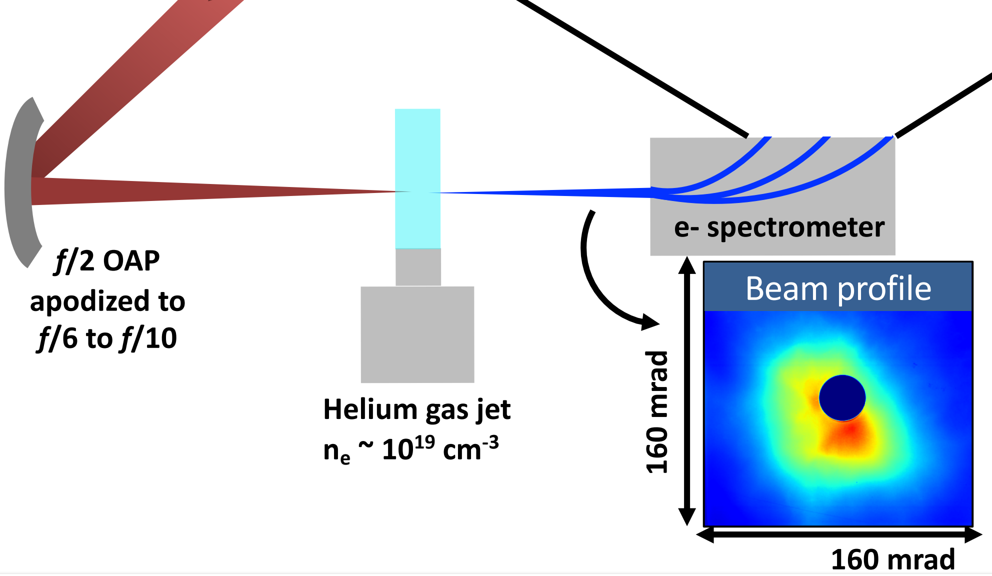
LMJ – PETAL
SMLWFA electrons

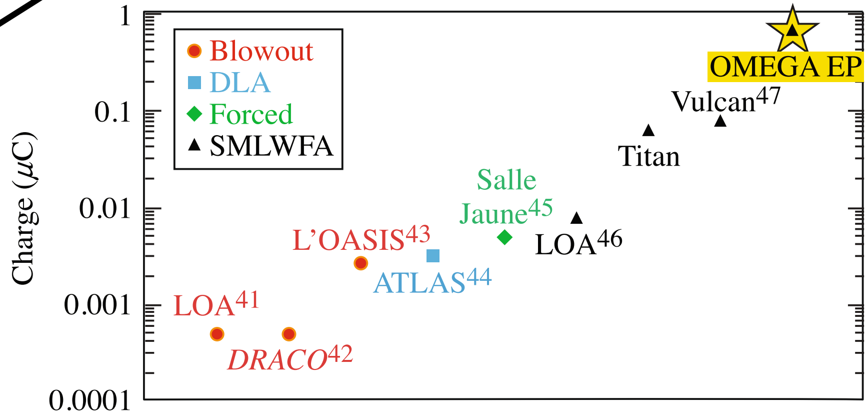
High charge, 700 nC, >100 MeV electron beams measured in SMLWFA regime at OMEGA EP

1053 nm, ~700 fs, 10 to 70 J, a_0 ~1.8 to 5.8

Spectrum





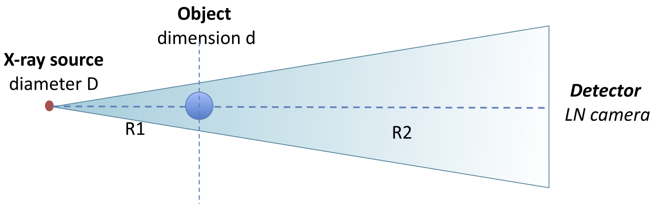


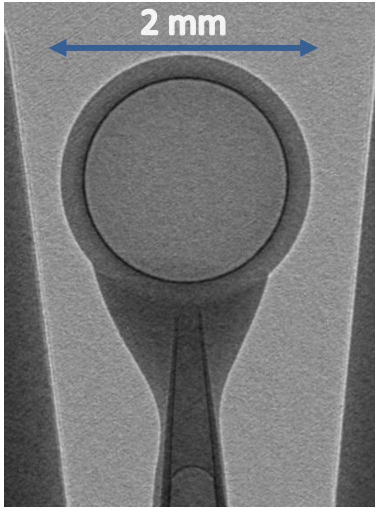
J.L. Shaw et al, Sci. Rep, 11 7498 (2021)

Outline

- Laser plasma acceleration: an alternative to synchrotrons and XFELs for novel x-ray probes
- Role of mid-scale laser facilities - LaserNetUS
- **Development and applications of x-ray sources based on laser plasma acceleration at LaserNetUS facilities**
  - **Femtosecond scale**
- Conclusion and perspectives

Radiography of materials and µm-size features in objects at ALLS



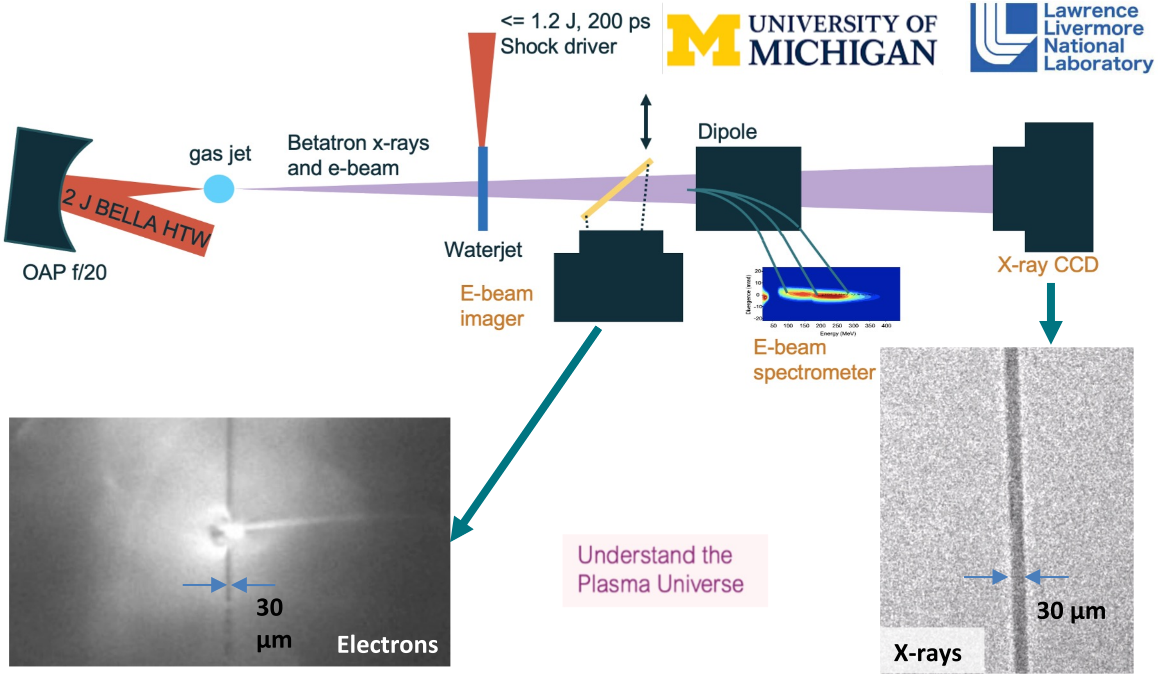


- Imaging of layered capsules
- 160 TW drive laser
- 2.7 x 10^9 photons/0.1% BW/sr/shot at 10 keV
- Spatial resolution 4.3 µm

Capsule	External diameter	Layer 1	Layer 2	Layer 3	Layer 4	Total layers thickness
Material		CH	CHGe [0.44 % at. Ge]	CHGe [0.29 % at. Ge]	CH	
1	2049.3	11.4	47.6	10.8	111.9	181.7

S. Fourmaux et al, Optics Express 13982 (2020)

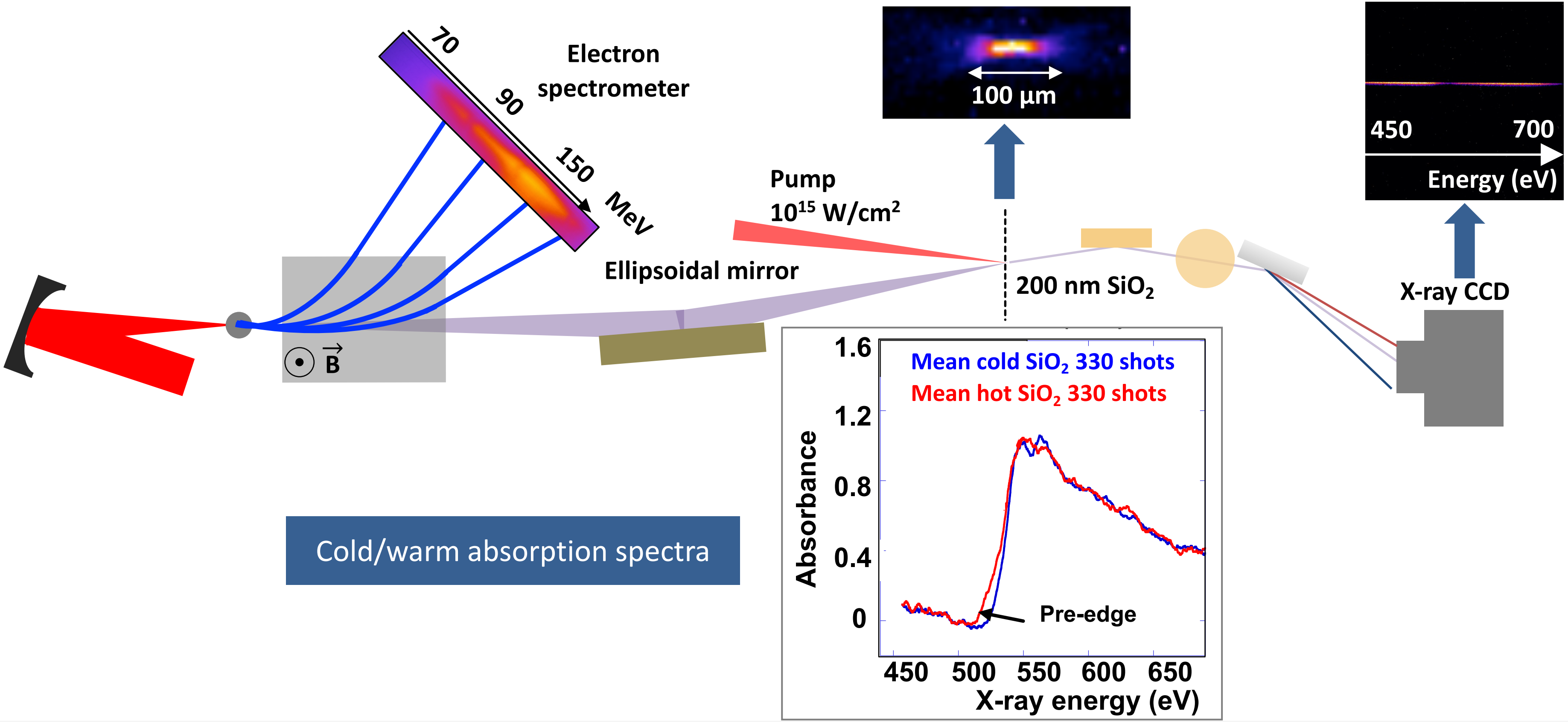
Understanding hydrodynamic shocks for plasma science at LBNL



- Imaging of laser-driven shock in water jet with betatron x-rays
- Enables resolution of sub micron turbulence and time evolution
- High resolution (µm, fs) imaging developed
- Multi-institution collaboration and diagnostic exchange (X-ray CCD from SLAC)

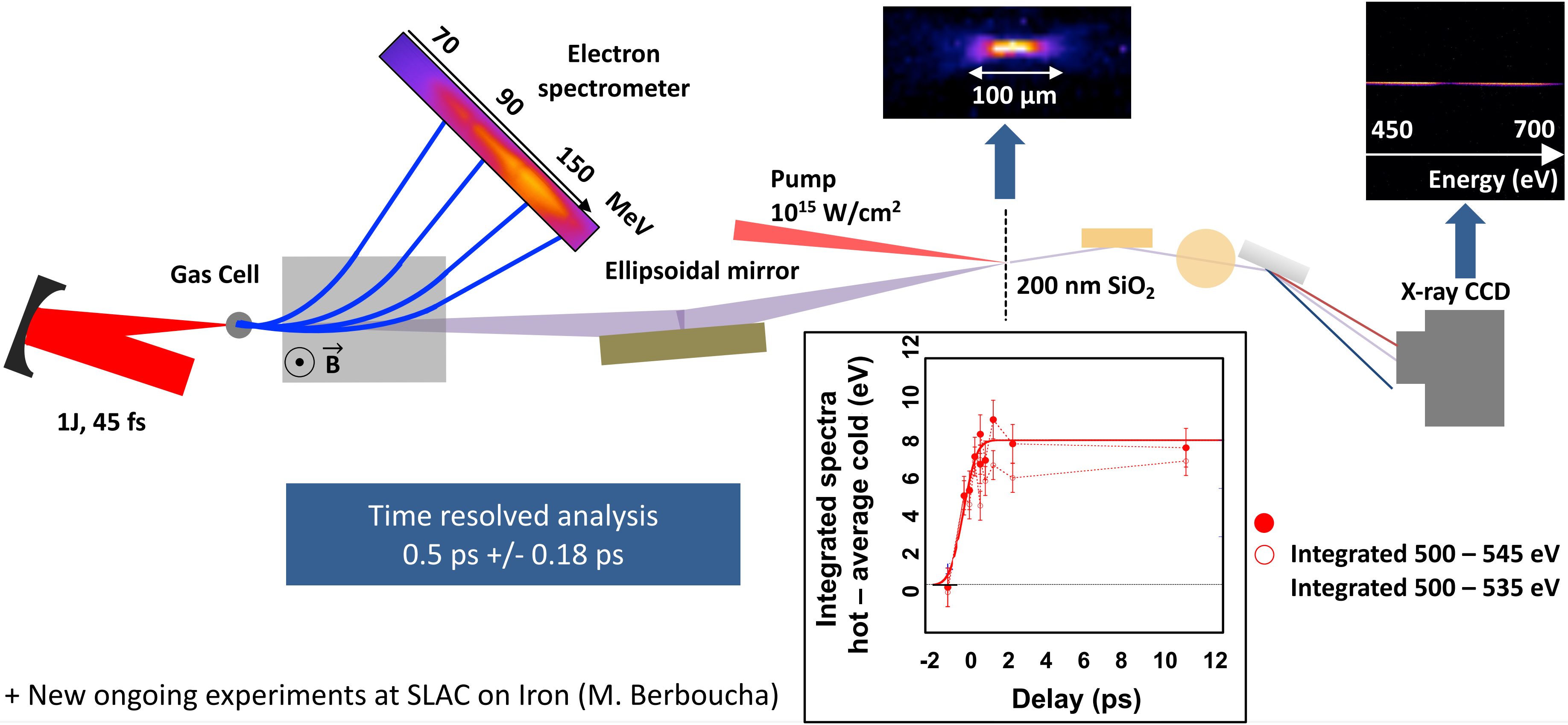
Courtesy C. Geddes (LBNL) - Exp led by C. Kuranz (UMichigan)

Betatron x-rays as a tool for absorption spectroscopy at SLAC



Cold/warm absorption spectra

Betatron x-rays as a tool for absorption spectroscopy at SLAC

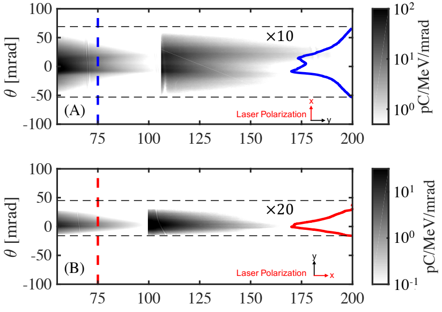


Time resolved analysis
0.5 ps +/- 0.18 ps

\+ New ongoing experiments at SLAC on Iron (M. Berboucha)

We have a lot of ongoing exciting projects

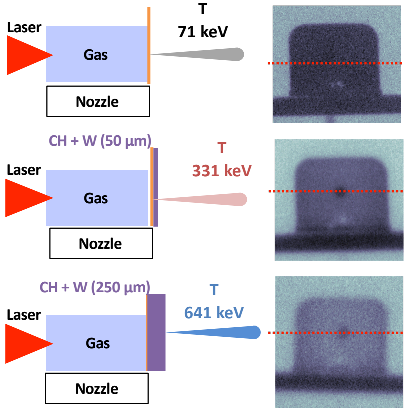
New acceleration mechanisms at Titan



- Forking structure on electron beams
- Explained by role of Direct Laser Acceleration in Self-modulated LWFA
- 3D OSIRIS PIC simulations confirm observation (UCLA collaboration)

P.M. King et al, PRAB

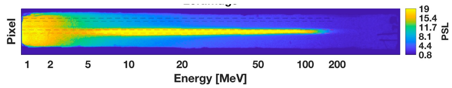
keV-MeV sources in Titan and applications



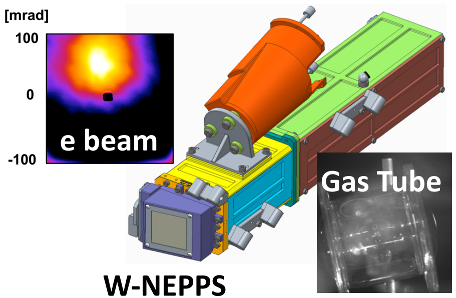
- Betatron, Bremsstrahlung, Compton sources for radiography applications

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

Platform development on larger HEDS lasers



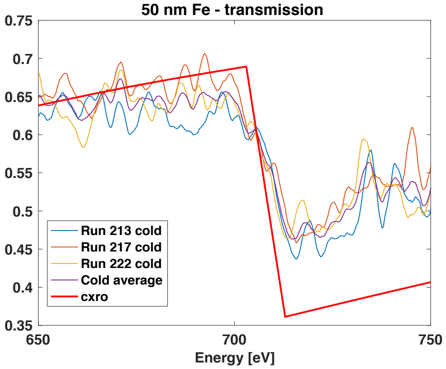
- 150 MeV, 700 nC beams at OMEGA EP



W-NEPPS

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

LaserNetUS experiments using betatron source



- Study of warm dense iron with XANES (with M. Berboucha et al)
- Phase contrast imaging of laser-driven shocks in water (with 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 within the LaserNetUS network

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

- They enable new applications
  - Radiography of dense objects
  - 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. 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)

Lawrence Livermore
National Laboratory