Stewardship Science Academic Programs (SSAP) Symposium (15 February 2023)

Award No.: DE-NA0004081 (Started 9-1-2022)

Radiography of High Energy Density Phenomena using X-rays from Laser-Plasma Accelerators

PI: *Mike Downer*

University of Texas at Austin

NL collaborator: Dr. Félicie Albert (LLNL)

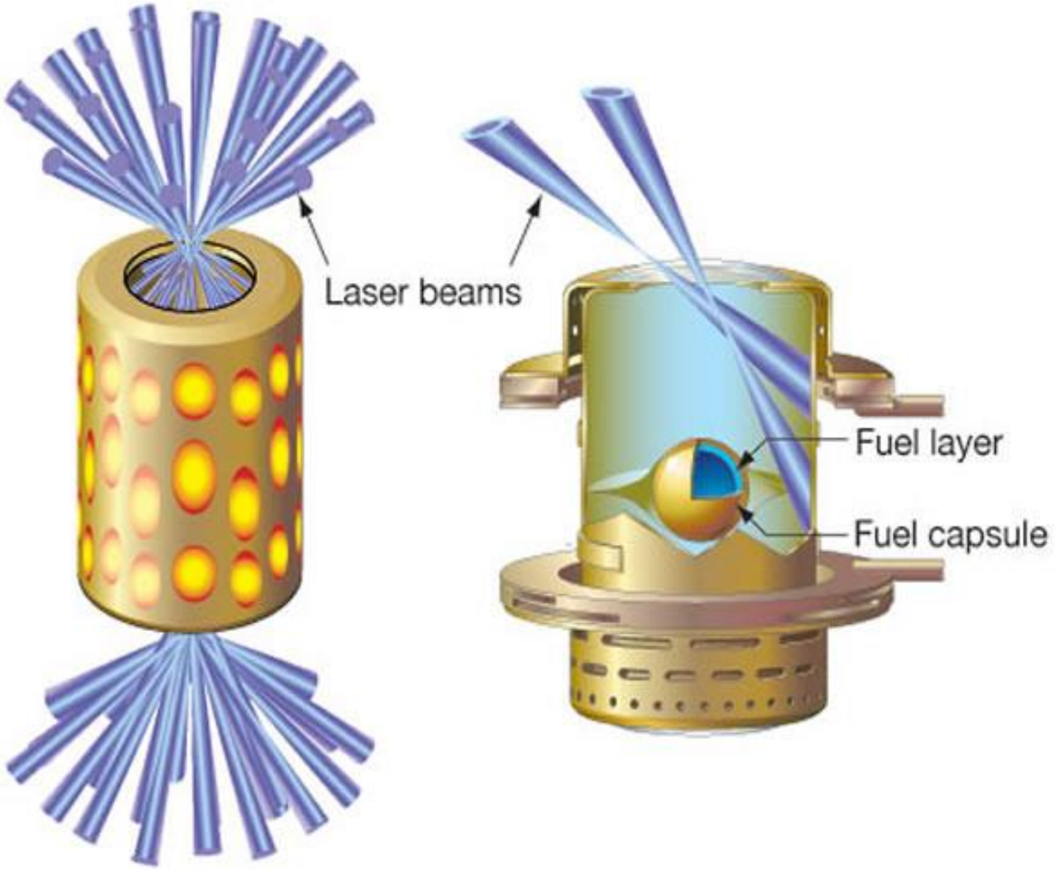
Supported PhD student: Isabella Pagano (UT-Austin) currently in residence at LLNL

Topical Areas: Properties of Materials under Extreme Conditions and Energetic Environments; Novel Characterization, Diagnostics, and Algorithms

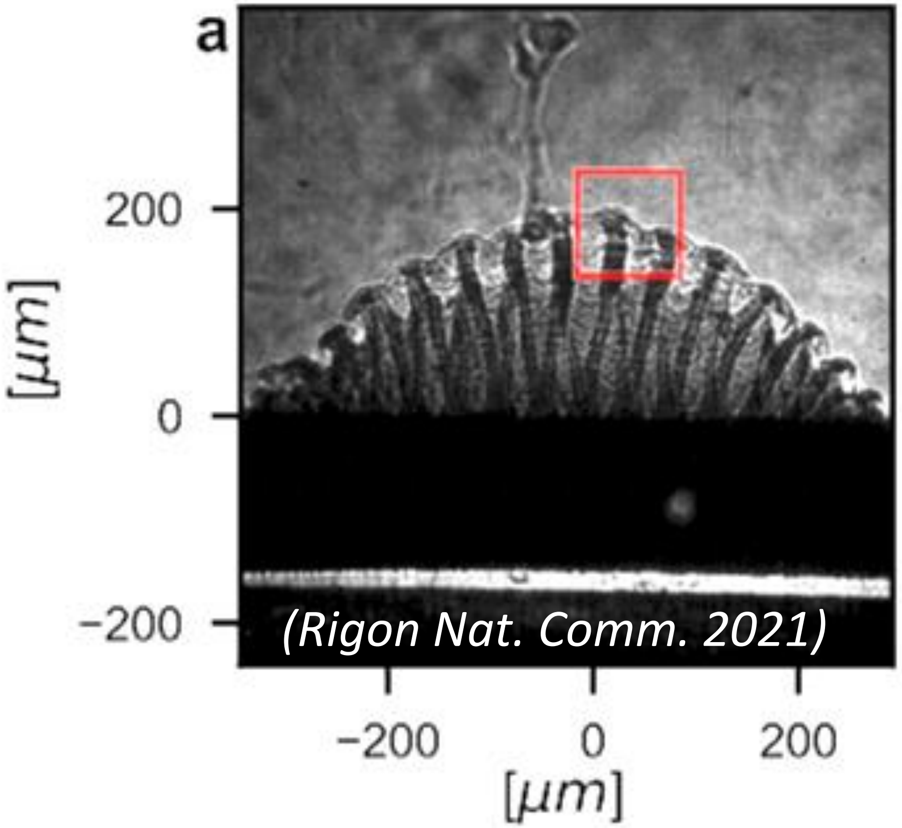
GOAL: Develop a compact X-ray source for Stockpile Stewardship radiography applications based on Laser Wakefield Acceleration (LWFA) that offers **sub-10-µm**/**sub-10-ps** space/time resolution, and keV-MeV photon energies.

Motivation: Diagnose fusion-relevant instabilities with high spatio-temporal resolution

ICF Fuel Capsules

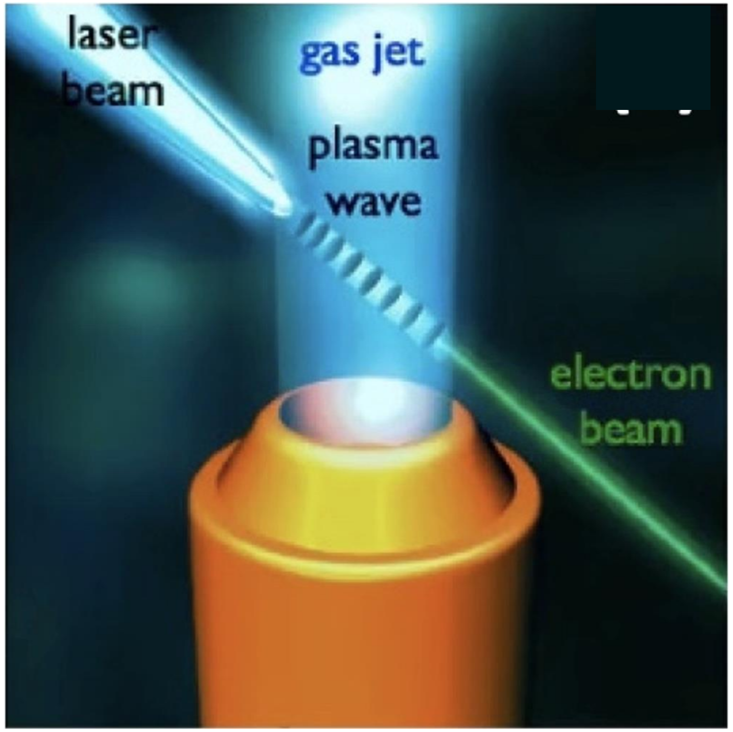


Rayleigh-Taylor instability

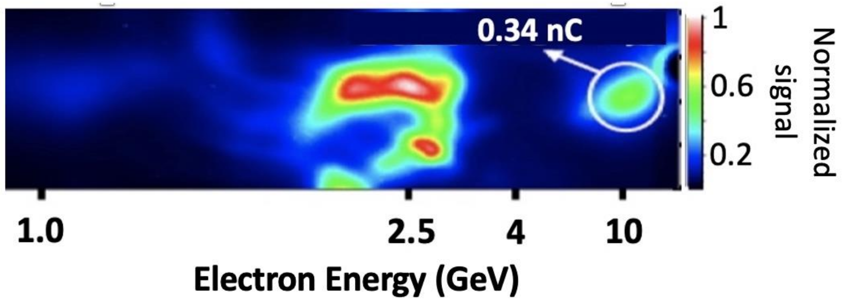


LWFA X-rays combine ultrashort, ultrasmall, and ultrabright

Laser Wakefield Accelerators (LWFAS) come in different flavors.



Laser Wakefield Acceleration (LWFA)



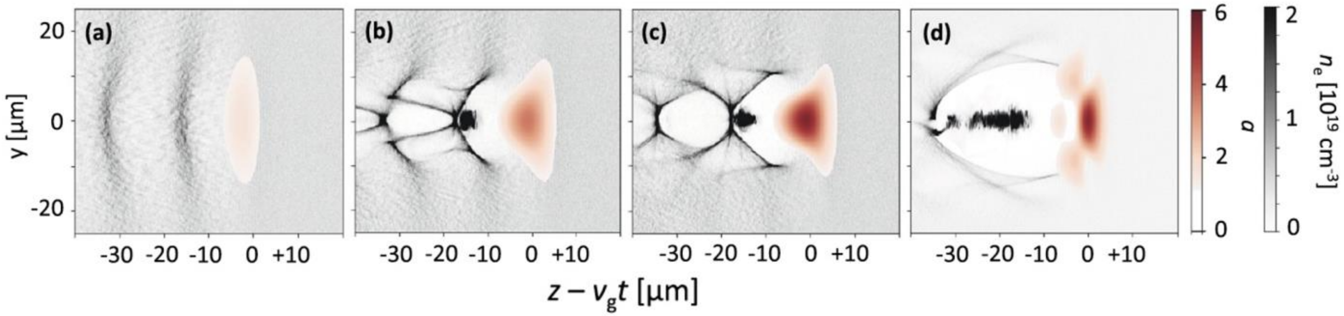
Aniculaesi *et al*. "High-charge 10 GeV electron acceleration in a 10 cm nanoparticle-assisted hybrid wakefield accelerator," ArXiv 2207.11492 (2022)

(a) Bubble regime (Texas Petawatt Laser @ U. Texas-Austin)

+ other LaserNetUS facilities

$\tau_{pulse} < \omega_p^{-1}$

Downer *et al*., "Diagnostics for plasma-based electron accelerators," *Rev. Mod. Phys*. **90**, 035002 (2018)

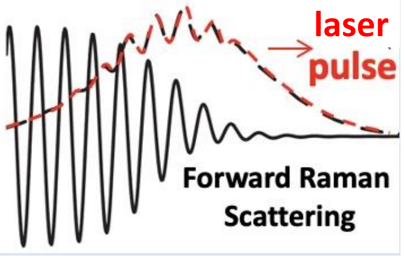


electron <u>properties</u>

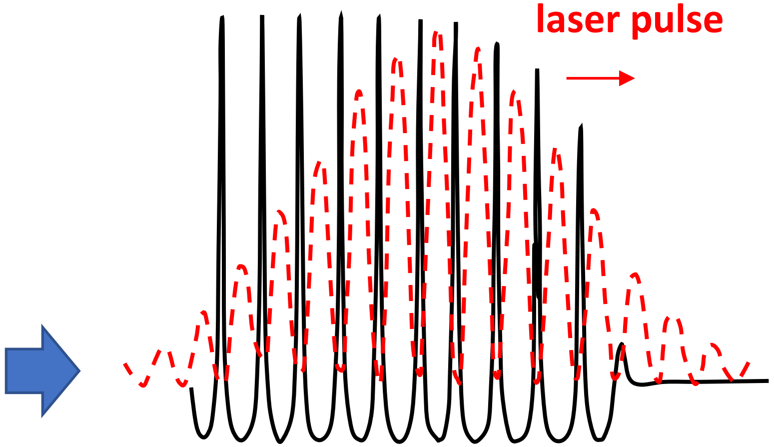
- up to ~10 GeV
- quasi-mono-energetic
- $\sigma_\perp \approx$ few μm
- $\sigma_z/c \approx$ few fs

(b) Self-modulated LWFA (Jupiter Laser Facility @ LLNL)

$\tau_{pulse} > \omega_p^{-1}$



linear wake



nonlinear wake

electron <u>properties</u>

- MeV energy
- wide energy spread
- $\sigma_\perp \approx$ tens of μm
- $\sigma_z/c \approx$ few ps

F. Albert *et al*., "Observation of betatron X-ray radiation in a self-modulated LWFA driven with picosecond laser pulses," *Phys. Rev. Lett*. **118**, 134801 (2017).

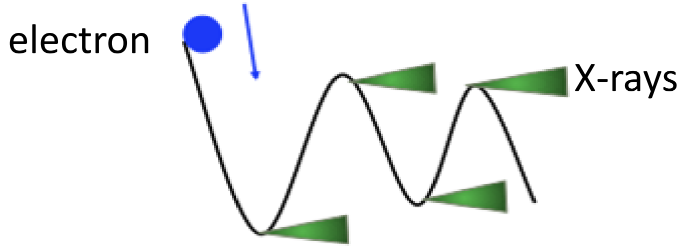
How do LWFA electrons generate X-rays?

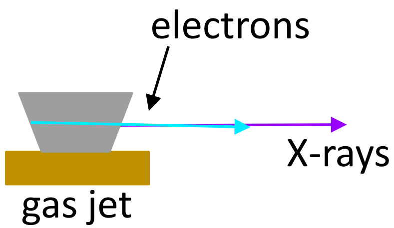
Let me count the ways...

Type of Radiation | **Diagram of Process** | **Experimental Set-up**

Betatron

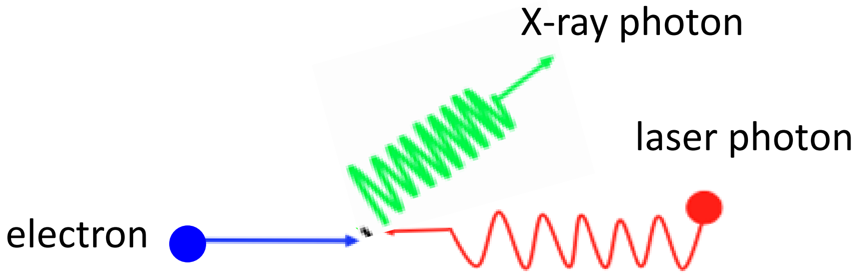
$E_X \sim \gamma^2 n_e r_0$ (keV)

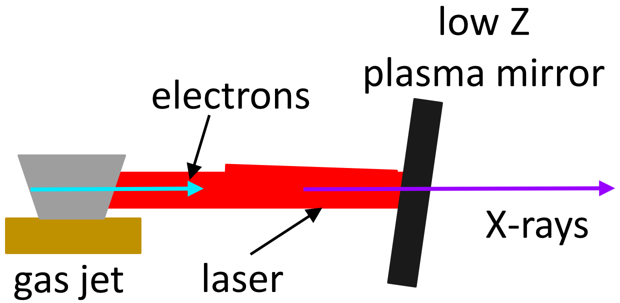




Inverse Compton Scattering

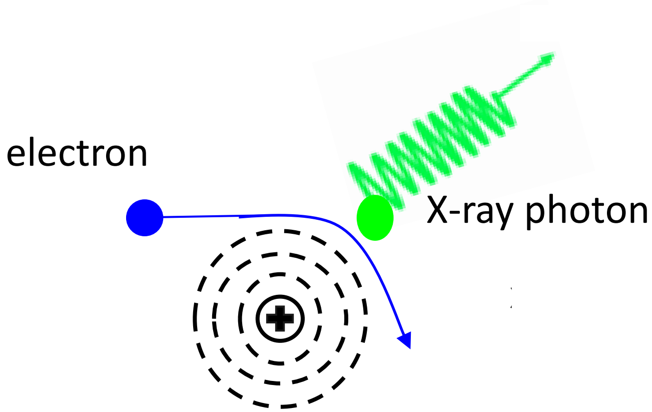
$E_X \sim 4\gamma^2 E_{laser}$ (keV-MeV)

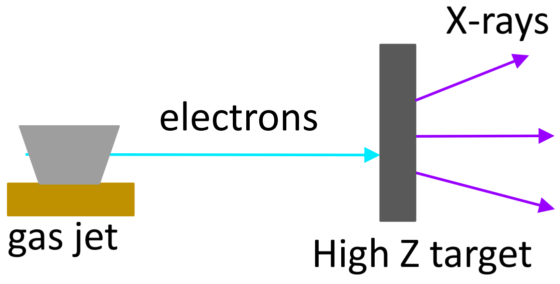




Bremsstrahlung

$E_X \sim \gamma$ (MeV)





Summary of Accomplishments to Date

1) Measurement of betatron, ICS, & bremsstrahlung X-ray source sizes $\sigma_r^{(X)}$ from Self-Modulated LWFAs for the first time.

When: Fall 2022 **Where:** Jupiter Laser Facility @ LLNL **Who:** Isabella Pagano & collaborators

Findings: $\sigma_r^{(betatron)} \approx 30$ μm (laser spot size @ gas jet) $\tau_X \lesssim 1$ ps

$\sigma_r^{(ICS)} \approx 100$ μm (e-beam size @ plasma mirror)

$\sigma_r^{(bremsstrahlung)} \approx 250$ μm (particle shower size in foil)

Publication: I. Pagano *et al.*, "Source size analysis of self-modulated LWFA-generated X-rays," (in preparation).

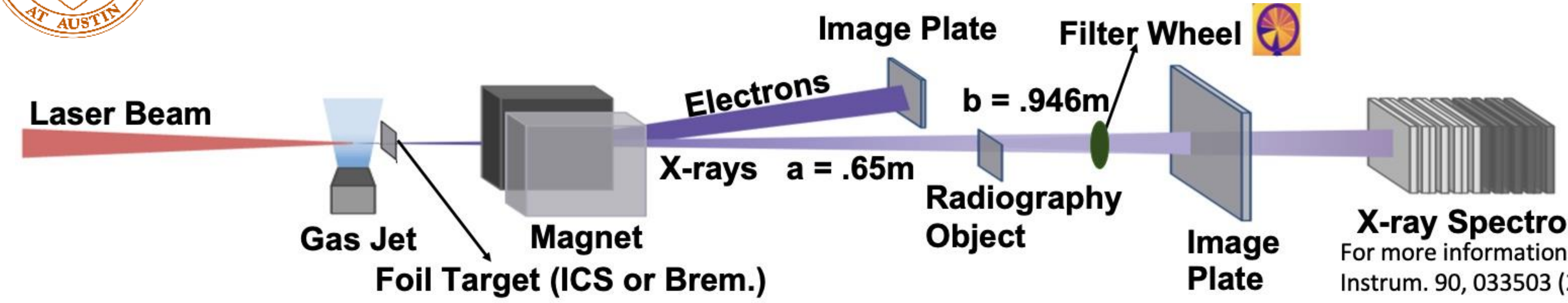
2) X-ray Phase-Contrast Imaging (XPCI) and 3D tomography of ICF capsules using betatron X-rays from bubble-regime LWFA

When: Fall 2022 **Where:** Advanced Laser Light Source (ALLS)@ INRS **Who:** Isabella Pagano & collaborators

Preliminary Findings: $\sigma_r^{(betatron)} \approx 3$ μm (<< laser spot size @ gas jet)

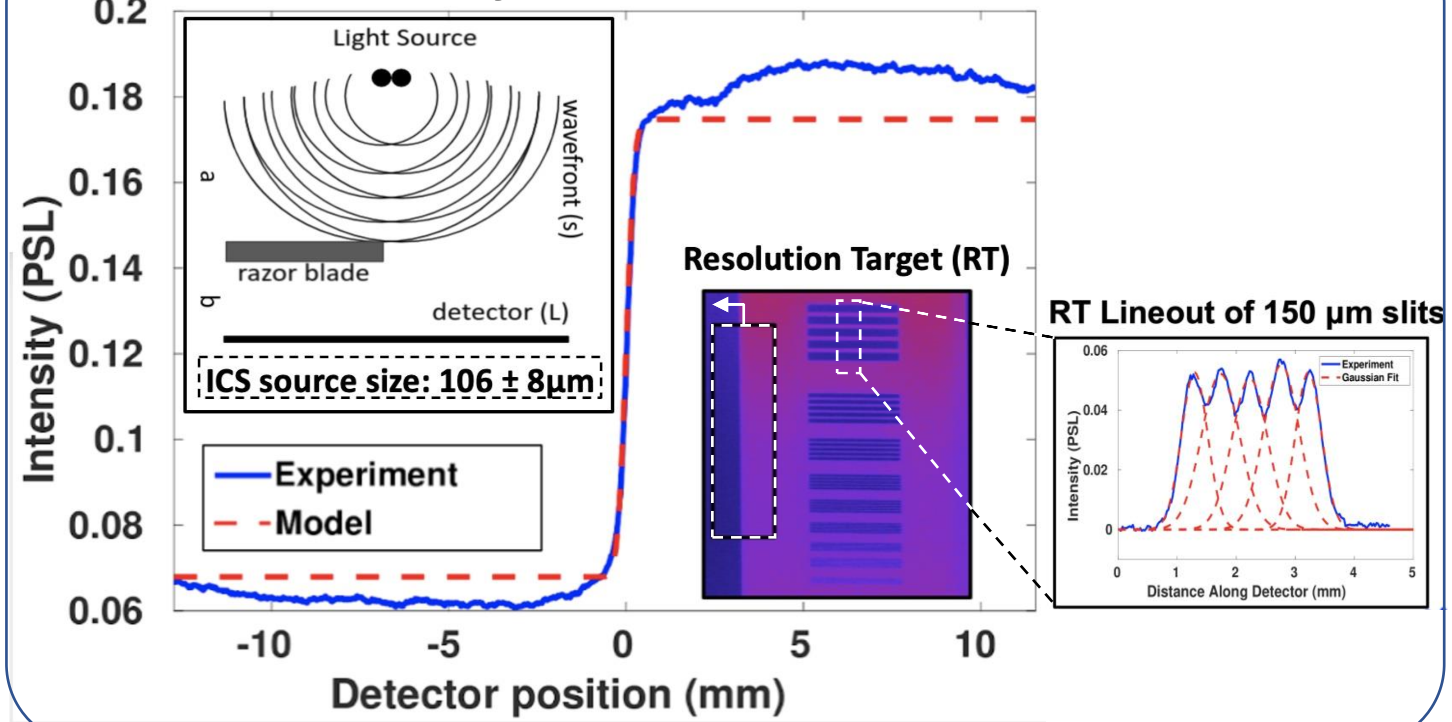
LaserNetUS Proposal (2023): Machine-learning-based optimization of the betatron source

X-rays from Self-Modulated LWFA

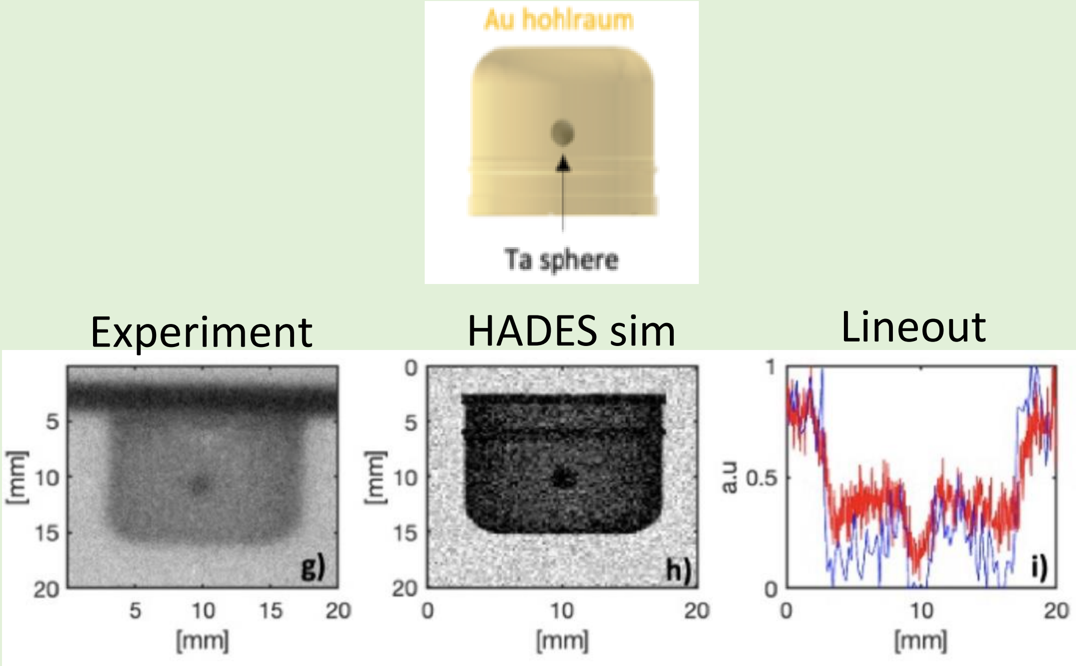


For more information about X-ray spectra see King, Rev. Sci. Instrum. 90, 033503 (2019) and Lemos, PRL, *in preparation*.

ICS X-ray measurements



Bremsstrahlung X-ray measurements



Lemos *et al.*, in preparation

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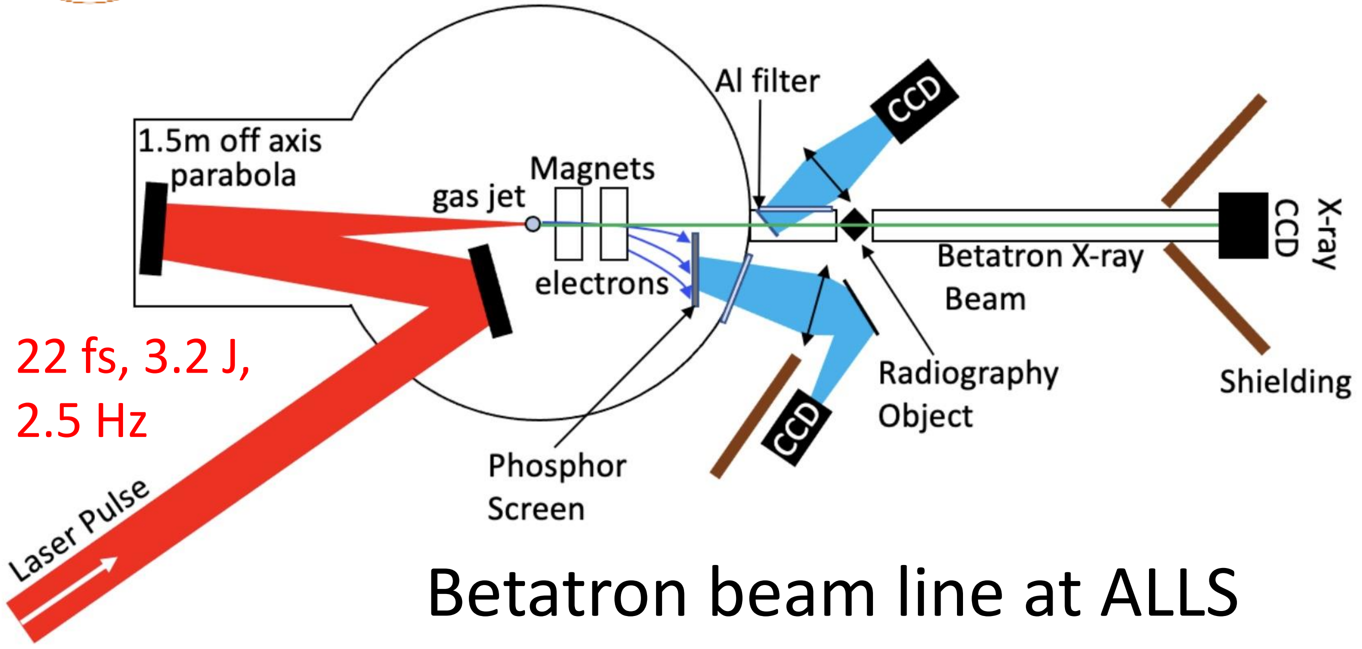
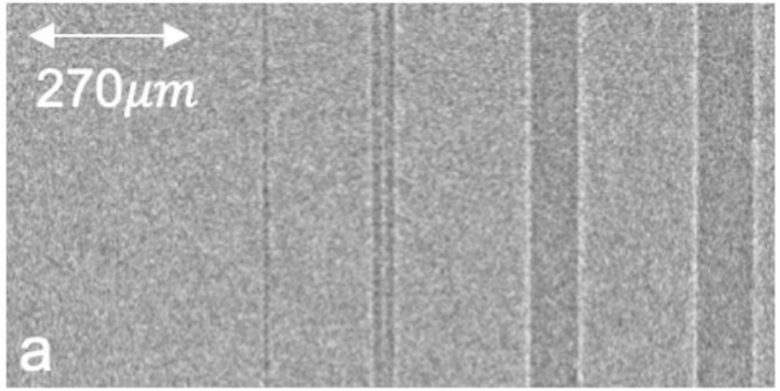
Betatron X-rays from Bubble-Regime LWFA:

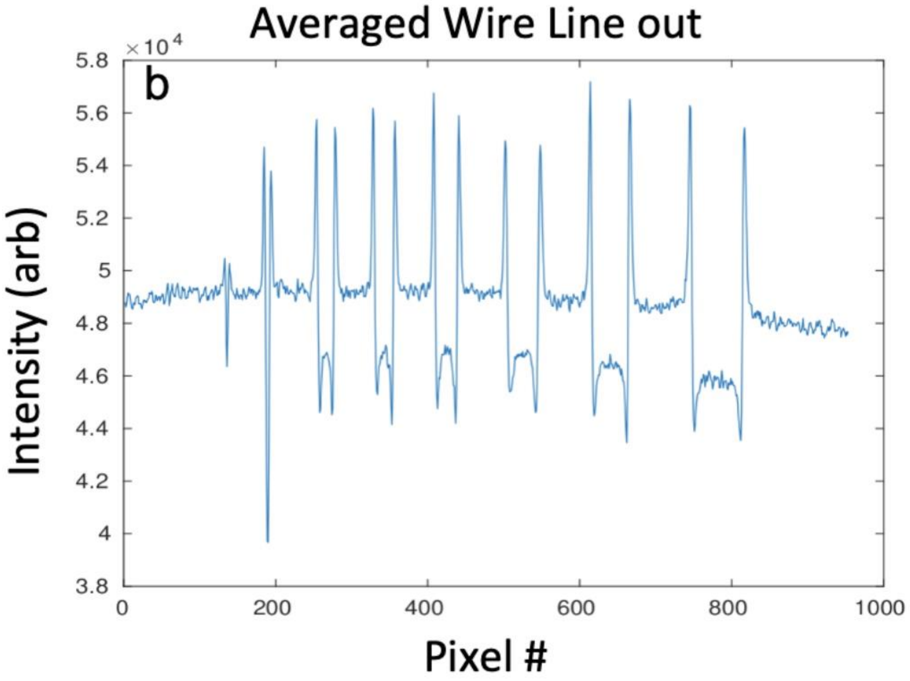
Phase-Contrast Imaging

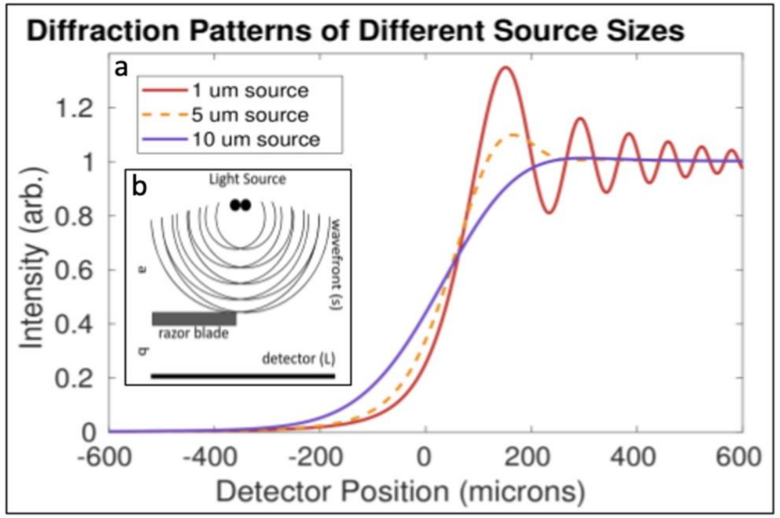


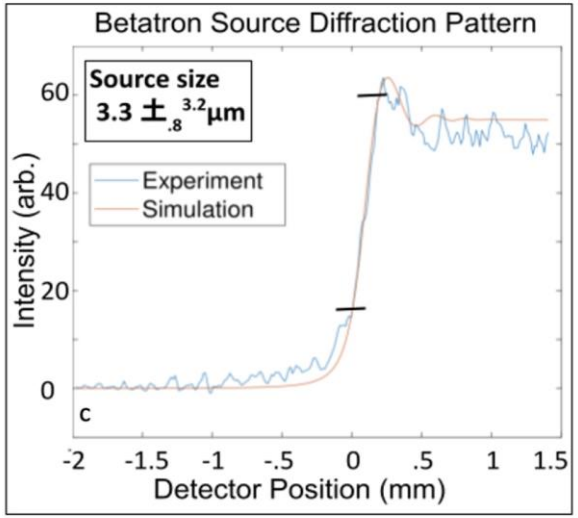
Betatron beam line at ALLS

Betatron X-ray radiograph of plastic wires









We have proposed a machine-learning-based optimization of the ALLS betatron beam line

SENSOR: β-tron X-ray radiographs (analyzed via ray-trace simulations)

OBSERVABLES: $\sigma_r^{(betatron)}$, photon #

CONTROL PARAMETERS:

- laser focus in gas jet (via DM)
- laser pulse shape (via Dazzler)

GOALS

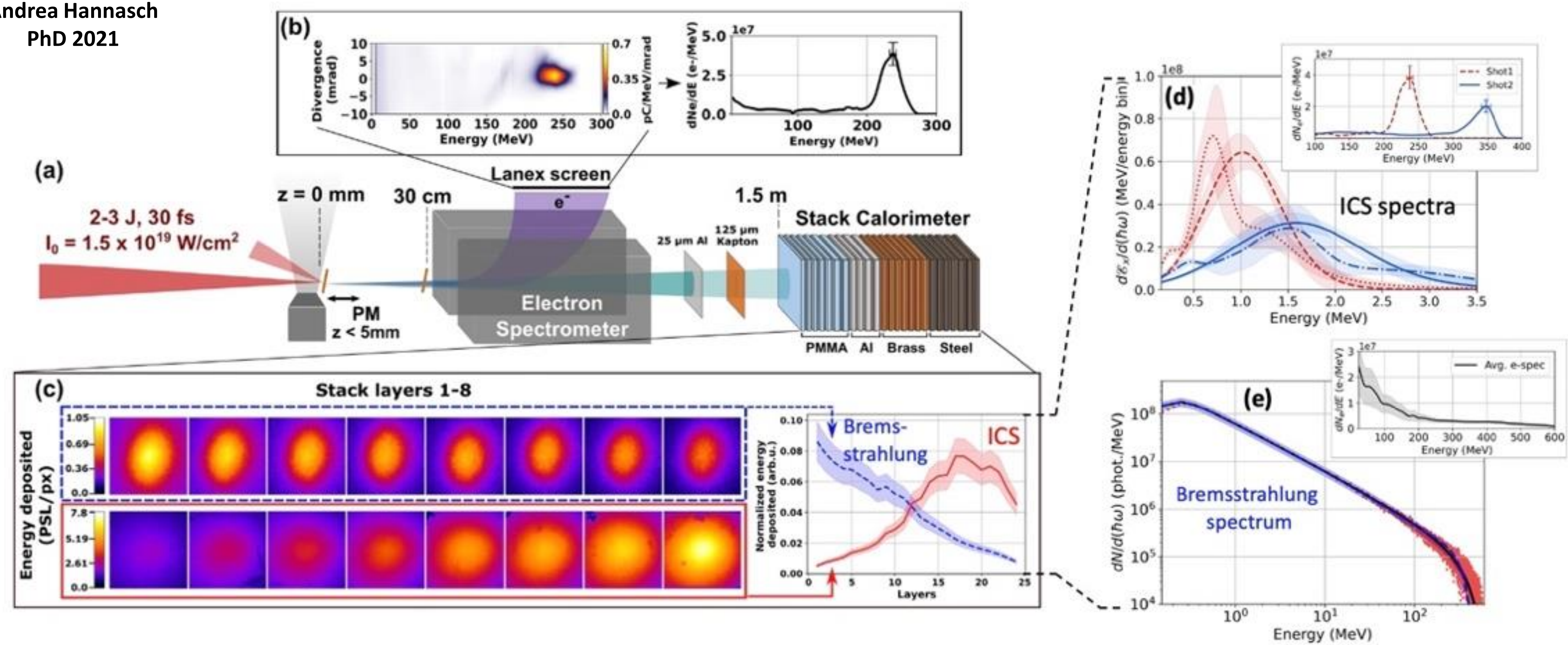
$\sigma_r^{(betatron)}$: 3 μm → < 1μm

brightness: 10^{11} → 10^{12} photons

Andrea Hannasch
PhD 2021

Compact calorimetry of keV to MeV X-rays from LWFAs: betatron, ICS, bremsstrahlung, and mixtures thereof

Hannasch *et al.*, *Sci. Rpts*. **11**, 14368 (2021);
Laso-Garcia *et al.*, *Rev. Sci. Instrum*. **93**, 043102 (2022)

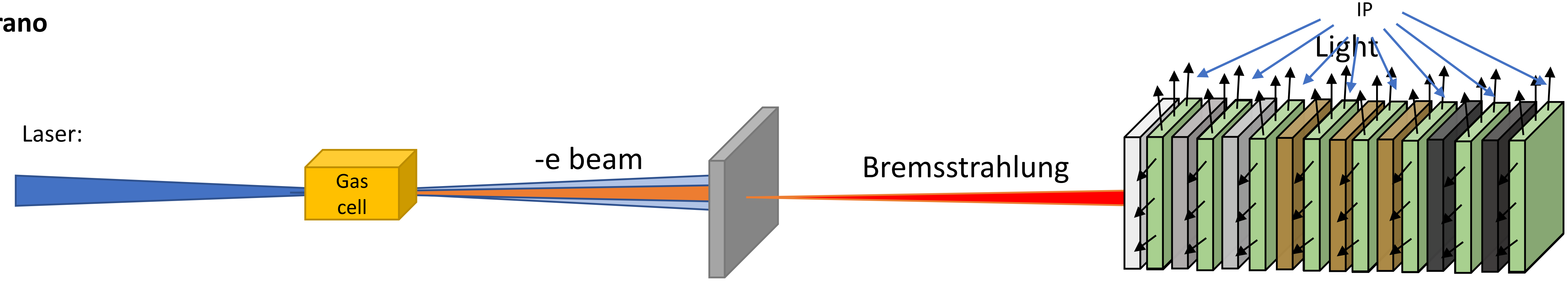


Scintillator-based calorimetry of LWFA X-rays: Rep-rated X-ray spectrometry

Jose Franco Altamirano

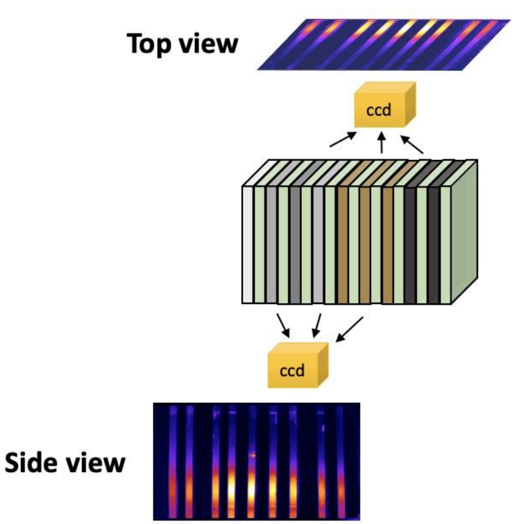
Image plate based -> Single shot

Scintillator-based -> high rep rate

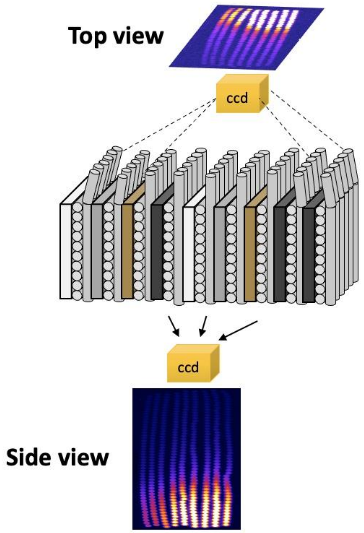


Stack calorimeter

Slab-based calorimeter



Optical Fiber-based calorimeter



Year	Milestones
1	Generate/characterize/ simulate/evaluate LWFA-based X-rays
2	
3	Carry out X-ray Radiography Experiments

Details

<u>X-ray characteristics</u>

- source size
- spectrum
- yield
- time structure

<u>X-ray generation</u>

- betatron
- ICS
- Bremsstrahlung

<u>LWFA types</u>

- bubble regime
- self-modulated

<u>Types of Experiments</u>

- static: knife-edge → Hohlraum — μm space resolution
- dynamic: laser pump, X-ray probe — fs time resolution

<u>Methodologies</u>

- 1-2 experimental campaigns/year at Texas Petawatt (TPW)[1] and Jupiter Laser Facility (JLF)[2]

  [1] bubble (+ self-modulated?) LWFA regime(s) [2] self-modulated LWFA regime

  (+ other LaserNetUS facilities as science dictates)
- Particle-in-Cell and HADES simulations

(a) Directly funded personnel

Isabella Pagano
(UT-Austin PhD student)

Jose Franco Altamirano
UT-Austin PhD student

Prof. Mike Downer
(PI, UT Prof. of Physics)

Dr. Rafal Zgadzaj
(Research Scientist)

(b) Collaborators not funded by this project

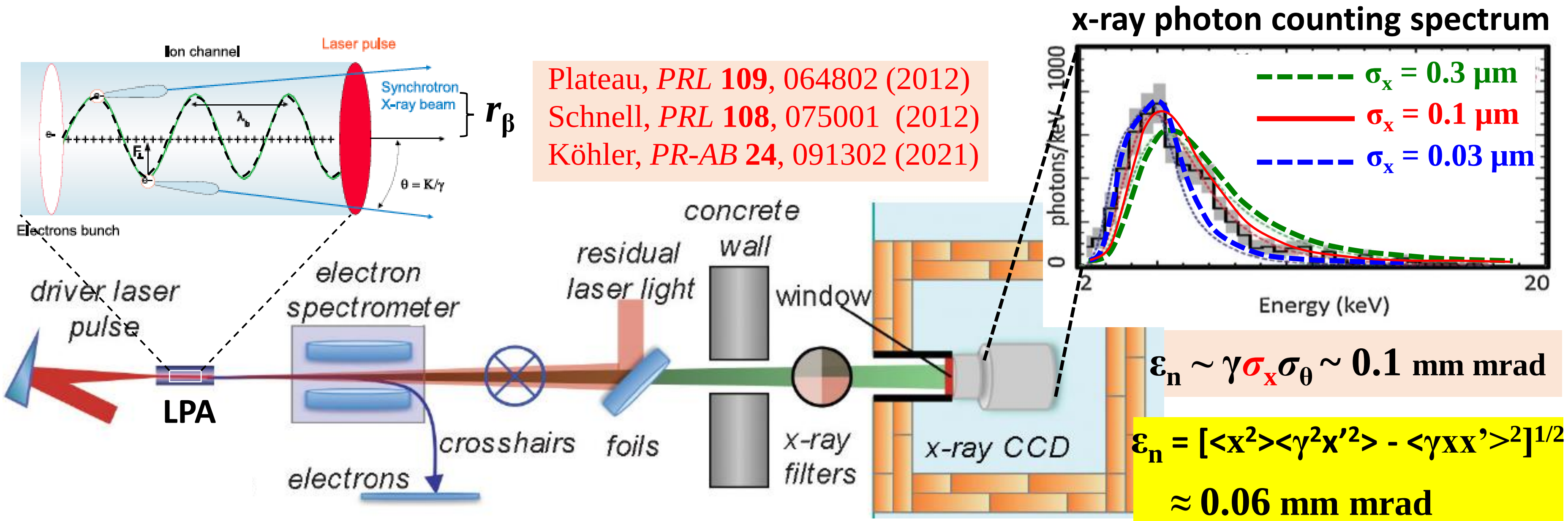
Adeola Aghedo
(FAMU PhD student)

Andrea Hannasch
(Focused Energy, Inc.)

Dr. Félicie Albert
(LLNL scientist)

BACKUP SLIDE

Betatron X-ray spectroscopy has shown that electron bunches in bubble-regime LWFAs have $\sigma_x \sim 0.1$ μm



Plateau, *PRL* **109**, 064802 (2012)
Schnell, *PRL* **108**, 075001 (2012)
Köhler, *PR-AB* **24**, 091302 (2021)

$\varepsilon_n \sim \gamma\sigma_x\sigma_\theta \sim$ **0.1 mm mrad**

$\varepsilon_n = [\langle x^2\rangle\langle\gamma^2 x'^2\rangle - \langle\gamma x x'\rangle^2]^{1/2}$

$\approx$ **0.06 mm mrad**

Curcio, *PR-AB* **20**, 012801 (2017)