Status and Prospects for the Plasma-Driven Attosecond X-Ray (PAX) Experiment at FACET-II

AAC 2022

Claudio Emma on behalf of the PAX collaboration

AAC, 8 November 2022, Long Island, USA

FACET-II

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University

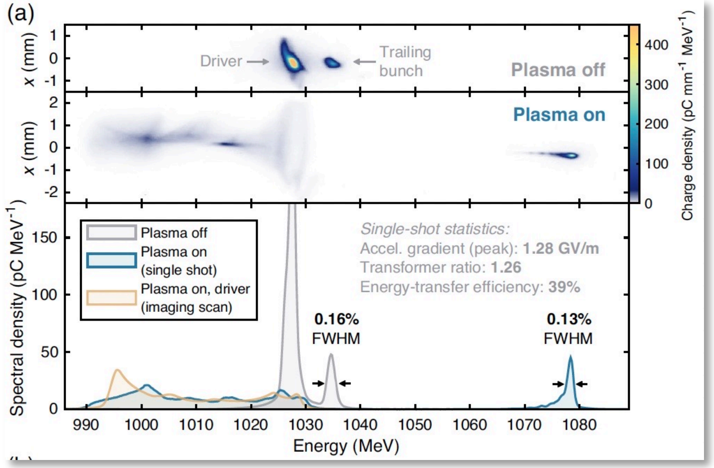
U.S. DEPARTMENT OF ENERGY

Outline

- Context and Motivation
- PAX conceptual presentation
- PAX experimental realization at FACET-II
- Hardware installations and diagnostics for FACET-II experiment
- Summary

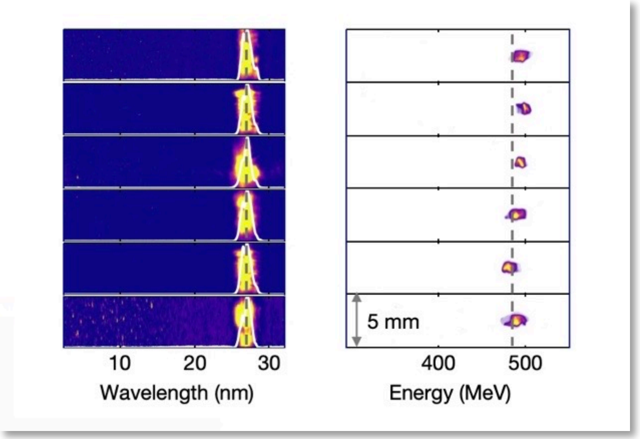
Plasma-accelerators: recent highlights

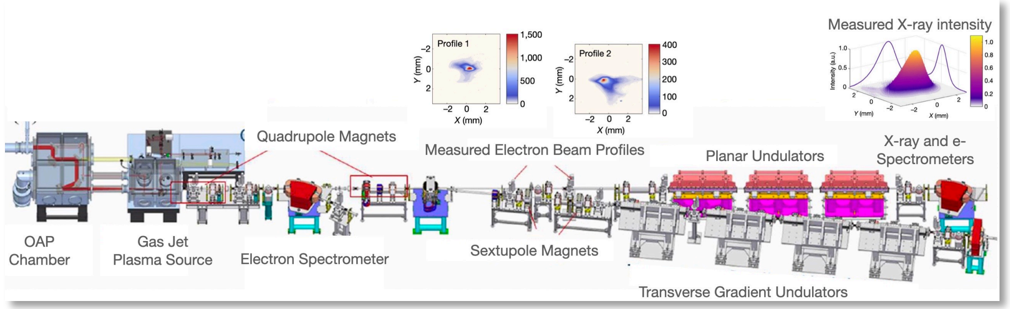
Sub-% energy spread preservation



C. Lindstrom et al., PRL 126, 014801 (2021)

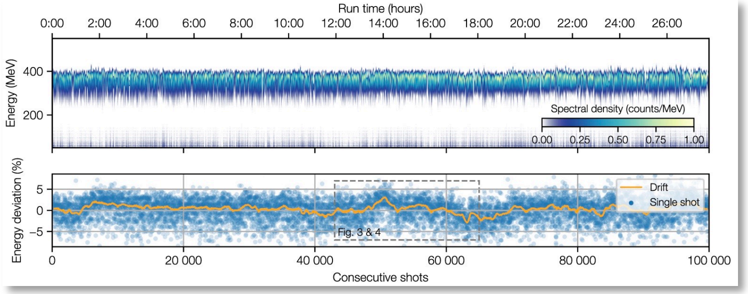
FEL gain demonstrations



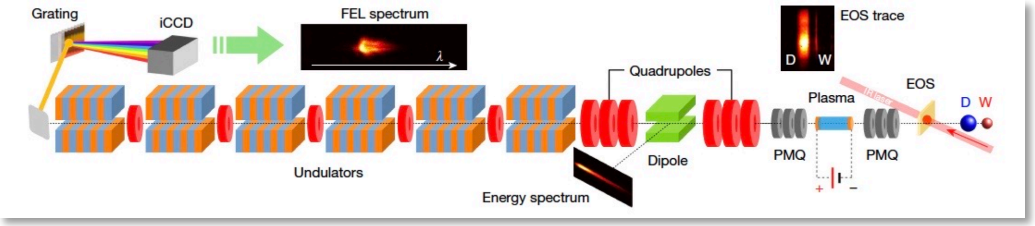


W. Wang et al., Nature, **595**, 516–520 (2021)

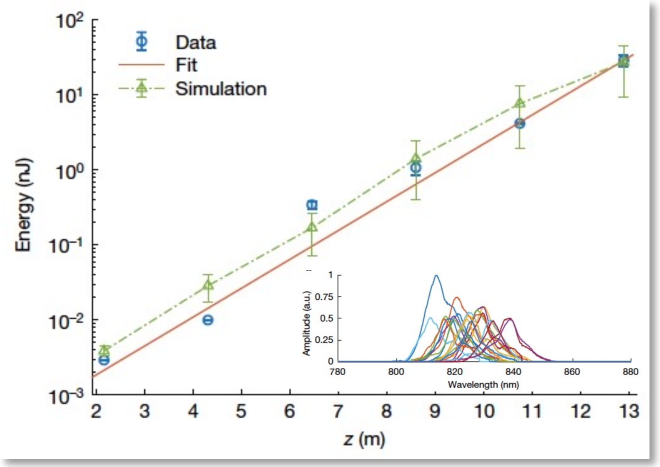
Day-long operation stability



A. Maier et al., PRX **10**, 031039 (2020)



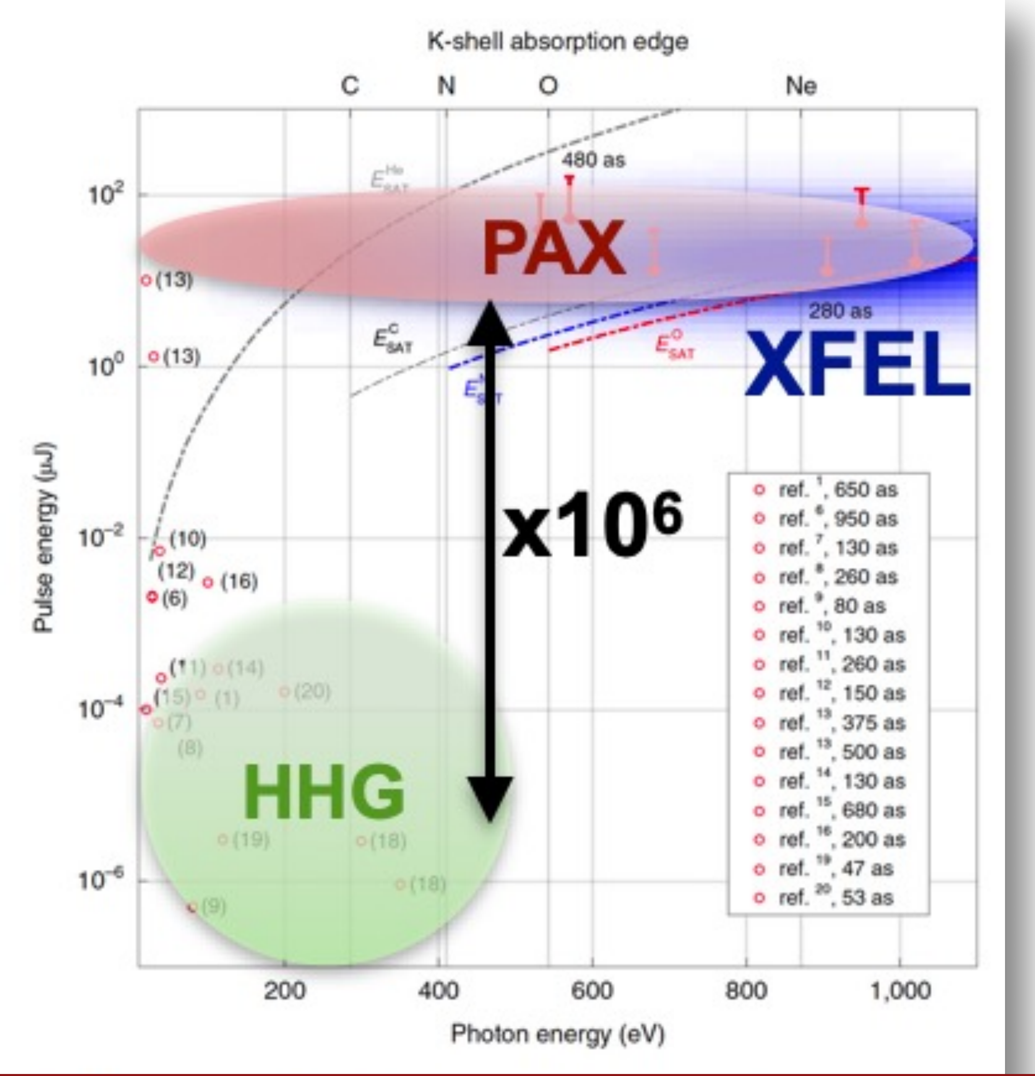
R. Pompili et al., Nature, **605**, pages659–662 (2022)



Plasma accelerators are now making beams with the quality and stability needed for applications

Attosecond pulses with plasma-driven light sources

- 50-100as X-rays with μJ-energy are desirable for studying e- motion in atoms on its natural timescale.
- HHG sources can reach 40 as length with pJ-level energy.
- XFELs reach μJ energy with min pulse length limited to ~ 200as by emittance ($t_{min} \sim \varepsilon^{5/6}$)
- An attosecond photon source based on plasma-driven e-beams can enable new capabilities by combining the benefits of HHG sources & XFELs.



PAX combines the benefits of HHG (short pulses) with power and flexibility of XFELs

PAX: a Plasma-driven Attosecond X-ray Source

Large plasma fields impart large energy chirp

↓

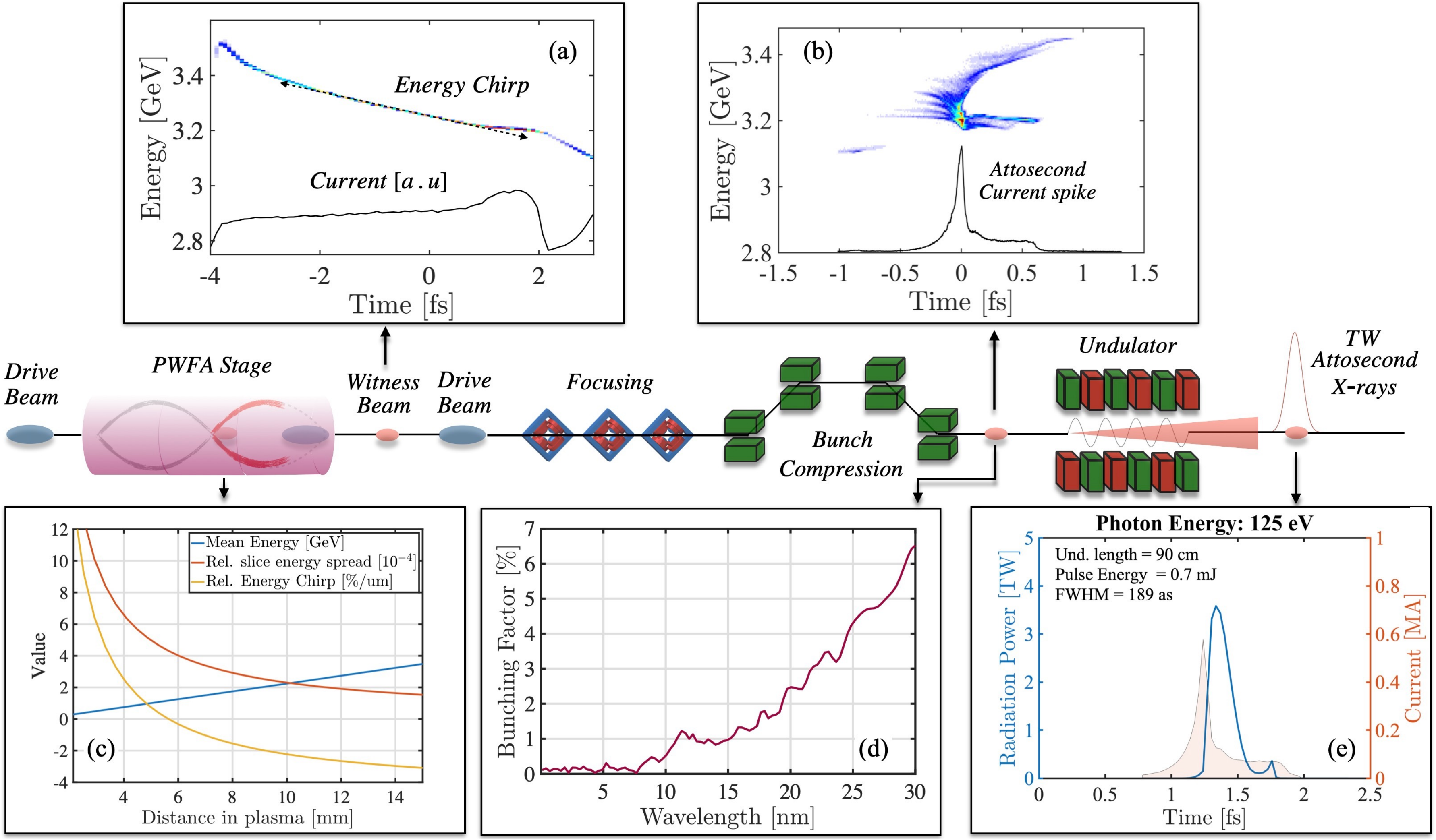
Weak chicane compresses e-beam to as-duration

↓

Beam is bunched at soft X-ray wavelengths

↓

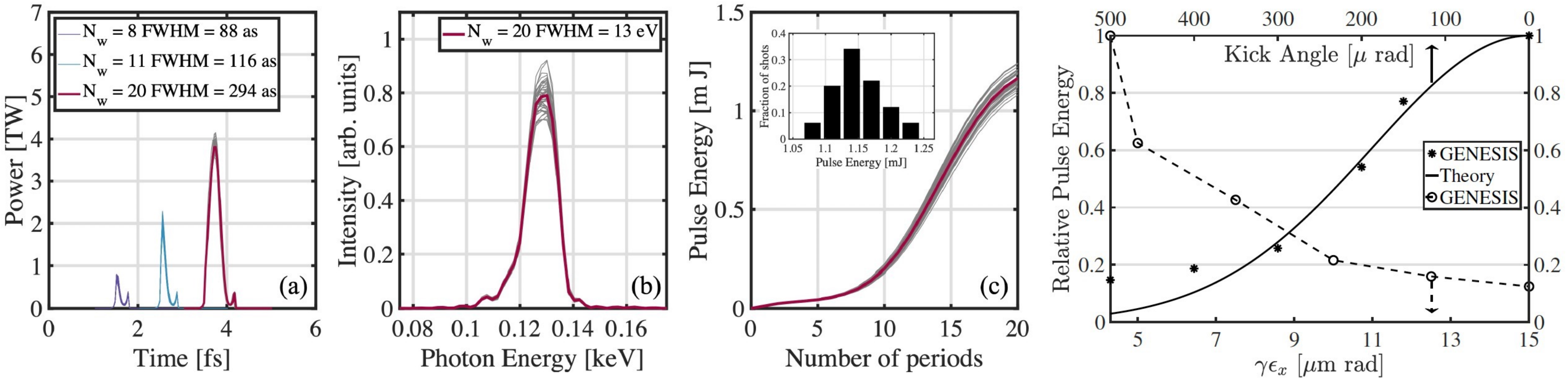
Pre-bunching relaxes tolerance on energy spread, emittance, pointing stability



C. Emma et al., APL Photonics, **6**, 076107 (2021)

Unique properties of plasma accelerated beams can add new capabilities to future light sources

PAX source properties

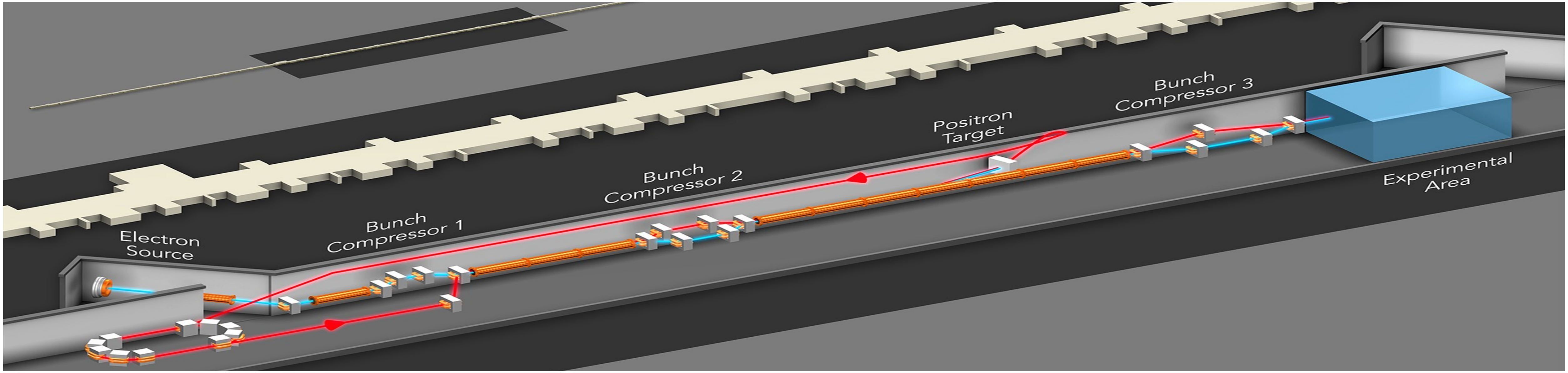


- 5-10x higher peak power compared to attosecond XFELs
- Pulse energy stability 10x better than attosecond XFELs due to coherent emission process **not** SASE starting from noise
- Tunable pulse length/peak power depending on experiment

C. Emma et al., APL Photonics, **6**, 076107 (2021)

Unique source properties and soft tolerances due to high peak current, pre-bunching and short undulator length

Experimental Demonstration at FACET-II



Experimental Demonstration at FACET-II

Ambitious experimental program

- Energy doubling of two-bunch PWFA while preserving beam quality
- Bright gamma ray generation via beam filamentation
- Strong field QED
- Plasma source design/optimization
- Ultra-bright beam generation (plasma injector)
- Advanced diagnostics, including AI/ML methods
- **Plasma-driven attosecond X-ray source**

Talks

- Z. Nie WG1 14:00, C. Zhang WG4 13:45, D. Storey WG4 today
- D. Storey 14:30 WG4 Wed
- A. Knetsch WG4 Wed, P. San Miguel WG4 Thur
- M. Hogan plenary 8:30 today
- No beam time yet
- C. Emma 13:45 WG5 tomorrow
- **This talk**

FACET-II operational parameters

- 2nC, 10 GeV, 10 um emittance
- Single bunch, two bunch, low energy spread operating mode
- Ultra-high peak current (10s-100s kA)

Description of Scope	*Units*	*Threshold KPP*	*Objective KPP*
Beam Energy	*[GeV]*	*9*	*10*
Bunch Charge (e-)	*[nC]*	*0.1*	*2*
Normalized Emittance in S19 (e-)	*[μm]*	*50*	*20*
Bunch Length (e-)	*[μm]*	*100*	*20*

FACET-II has met objective KPPs. Work continues to commission new operation modes, optimize beam quality

Experimental Demonstration at FACET-II

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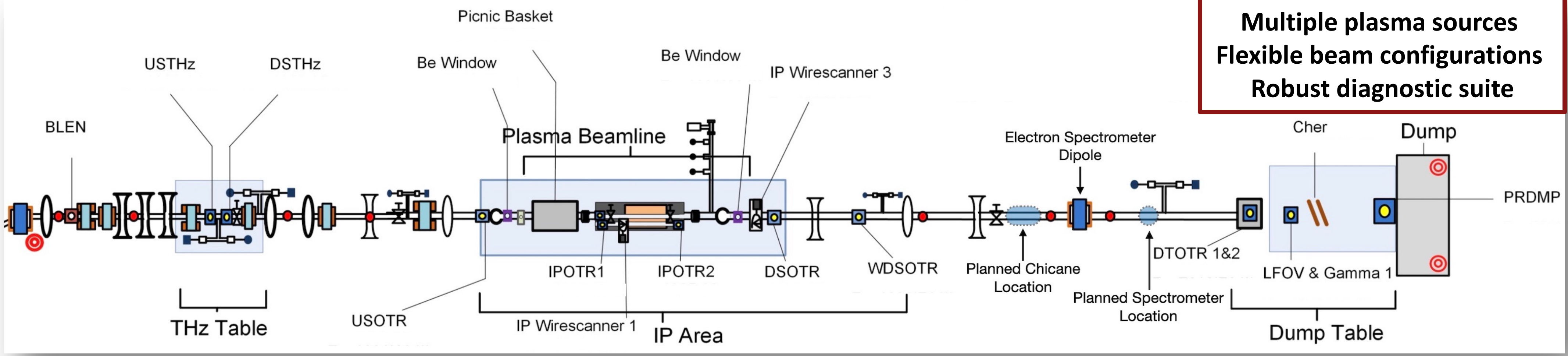
Multiple plasma sources
Flexible beam configurations
Robust diagnostic suite



FACET-II has met objective KPPs. Work continues to commission new operation modes, optimize beam quality

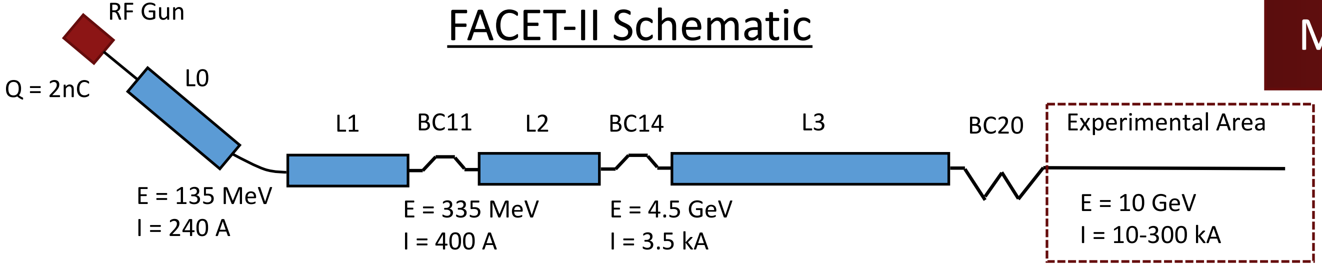
Experimental Demonstration at FACET-II

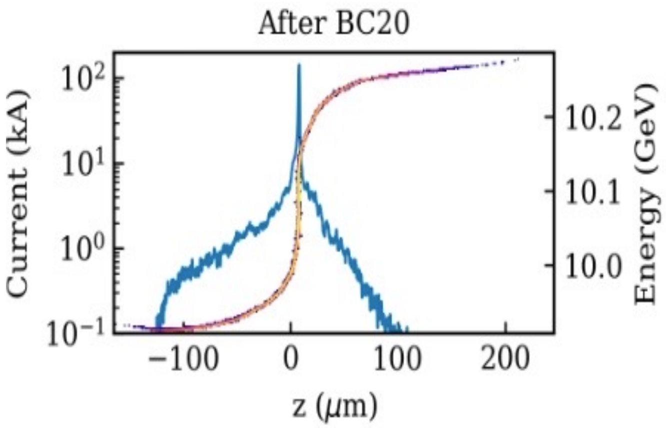
Demonstrate post-plasma sub-fs e-beam compression

Generate + measure XUV CSR from sub fs-long e-beams

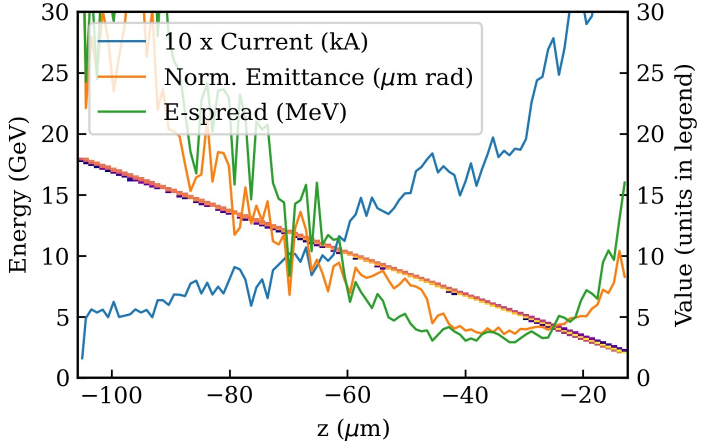
Measure attosecond coherent XUV undulator radiation

FACET-II Schematic

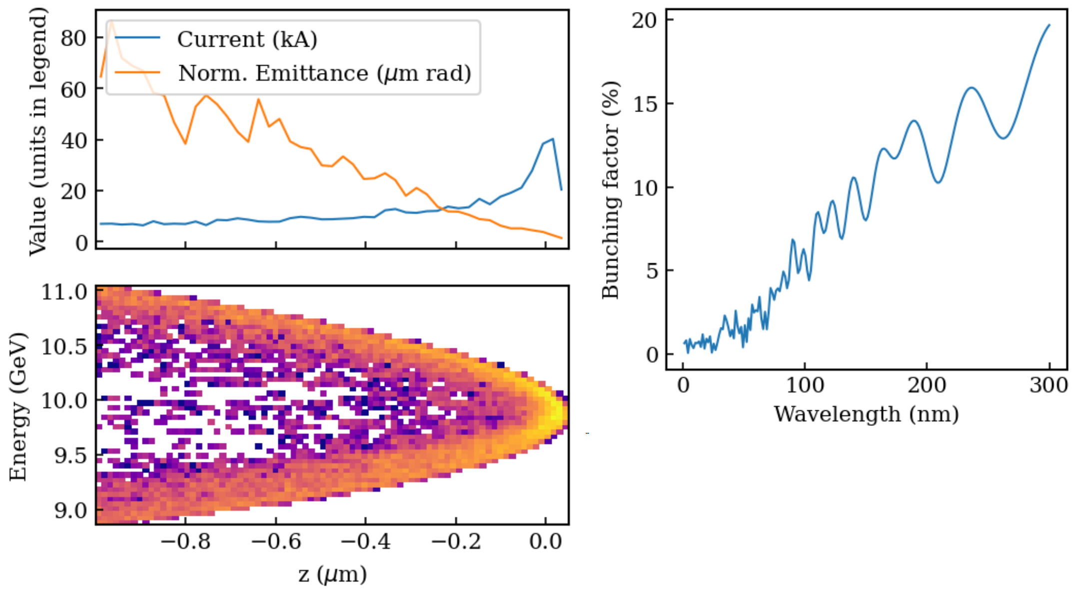




After plasma



After chicane



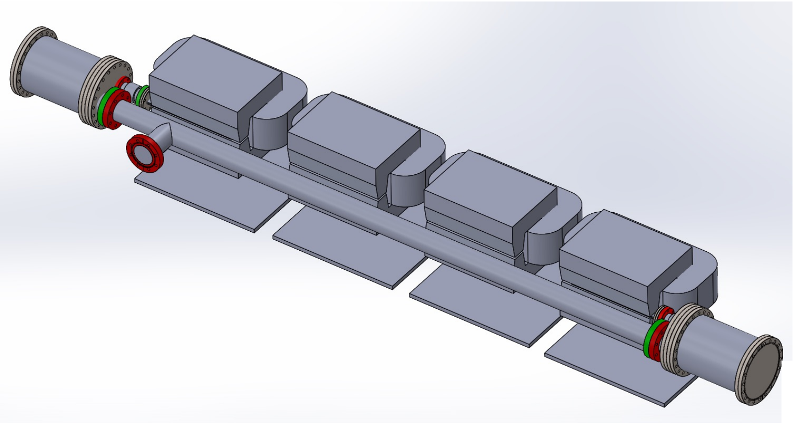
FACET-II provides ideal test-bed for PAX staged demonstration

XUV Spectrometer and radiation detection for PAX at FACET-II

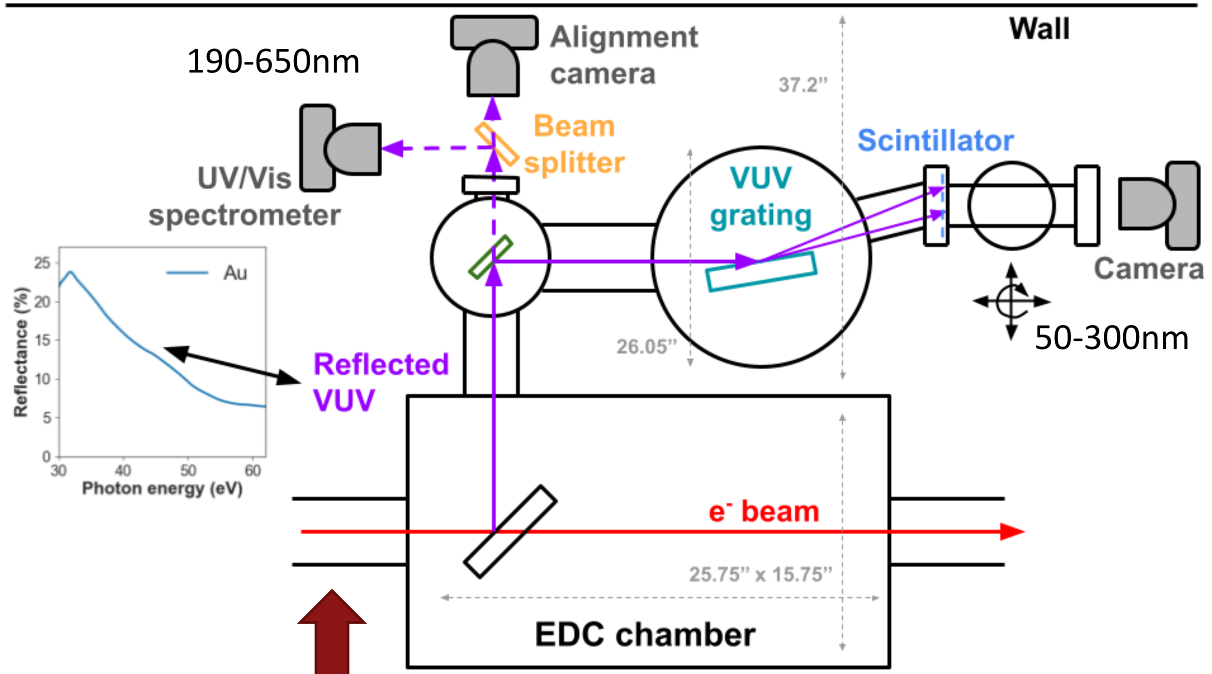
Plasma Sources

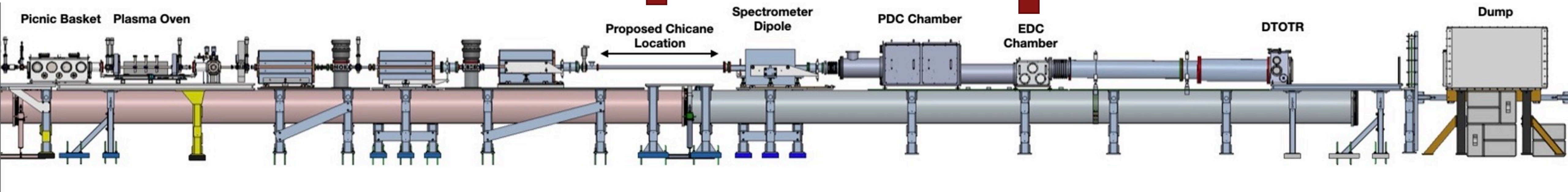
- Gas Jet
  ne = 1e18 – 1e20 cm^-3
- Li Oven
  ne = 1e16 cm^-3

Chicane + bypass line design



Spectral Measurement Setup





Radiation setup detects broadband spectral content to map bunching factor of fully-compressed e-beam

XUV Spectrometer and radiation detection for PAX at FACET-II

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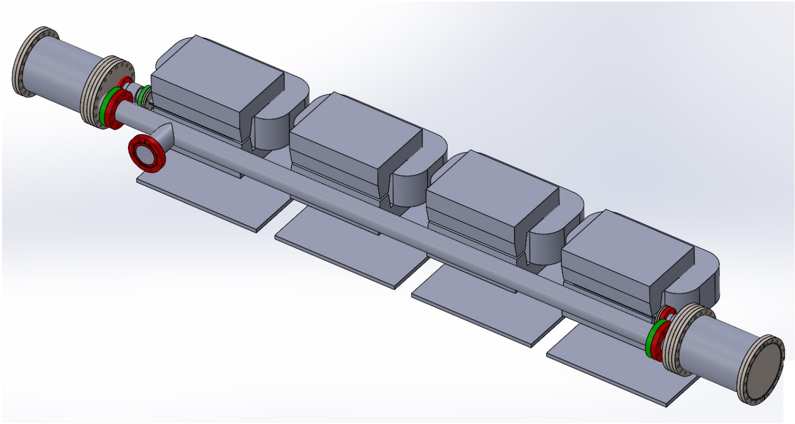
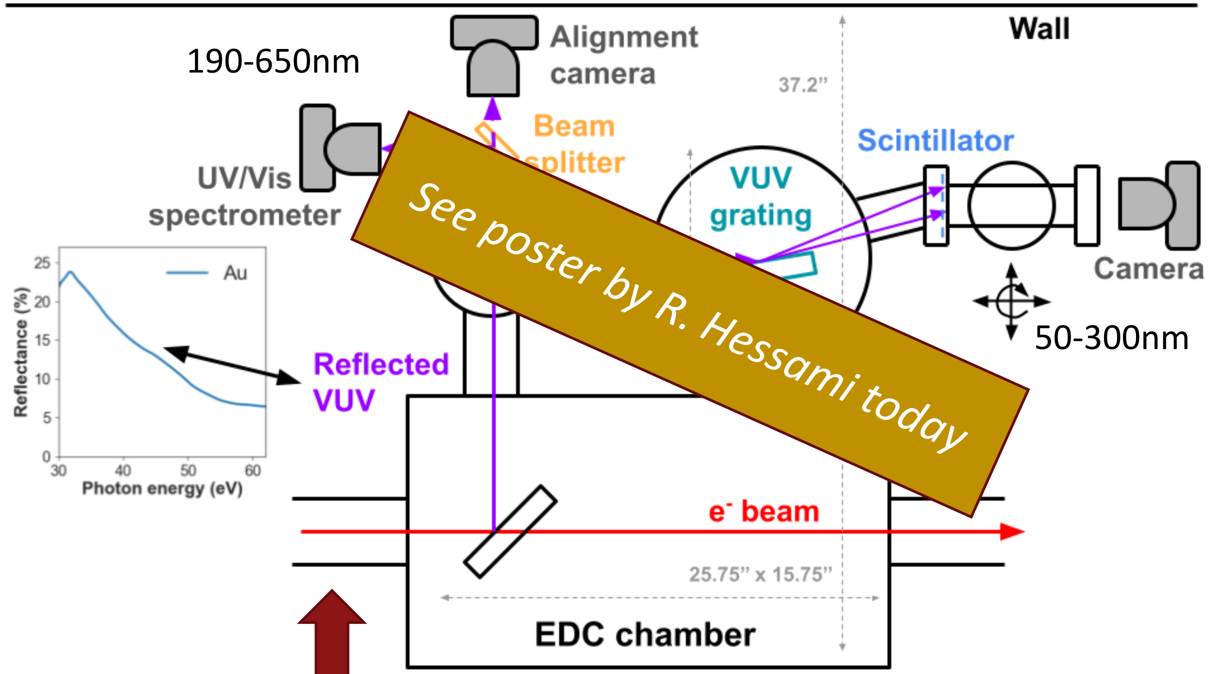
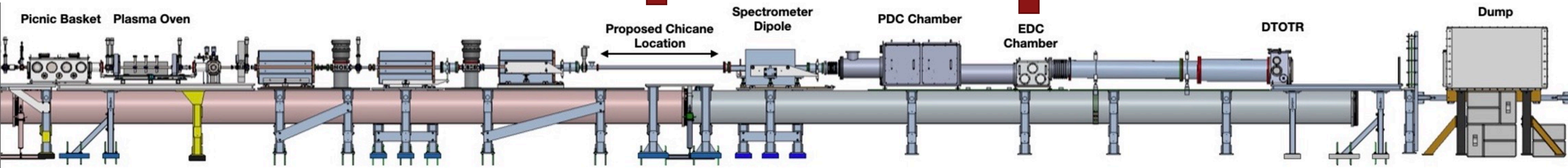


Spectral Measurement Setup



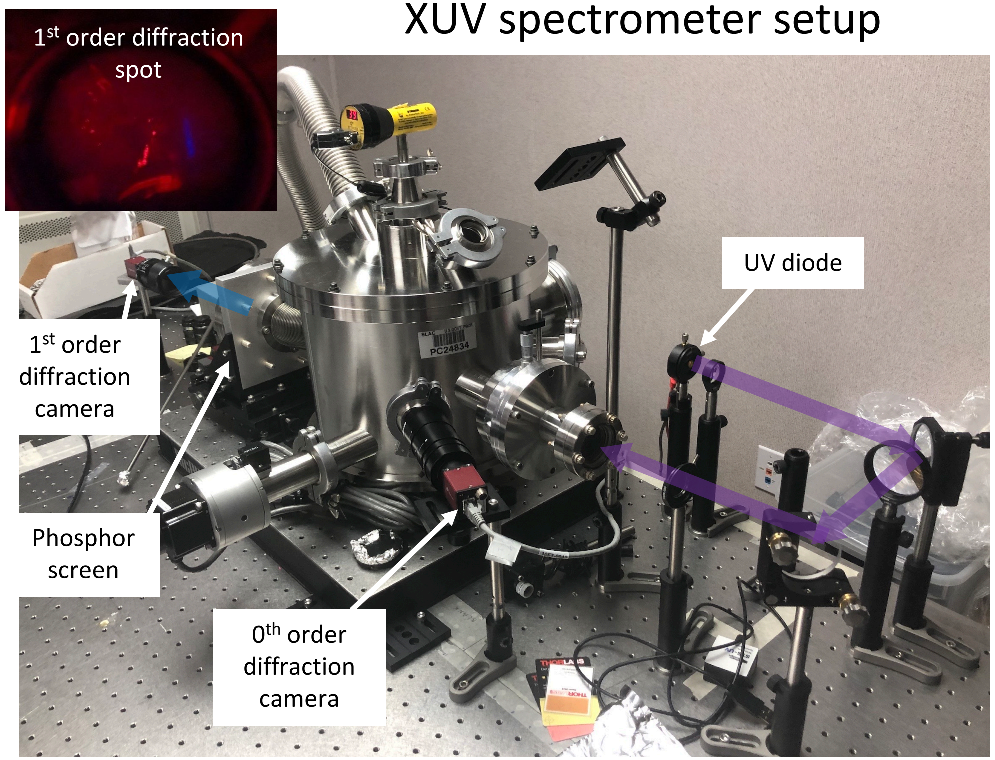


Radiation setup detects broadband spectral content to map bunching factor of fully-compressed e-beam

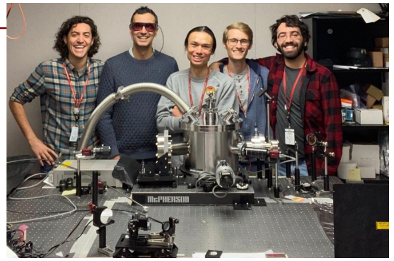
Experimental installation plans

- Chicane magnets + bypass line are conceptually designed
- XUV detection setup bench tested
- Detailed design and installation engineering under way
- Planned spectrometer installation to begin Fall 2022 and chicane for summer 2023

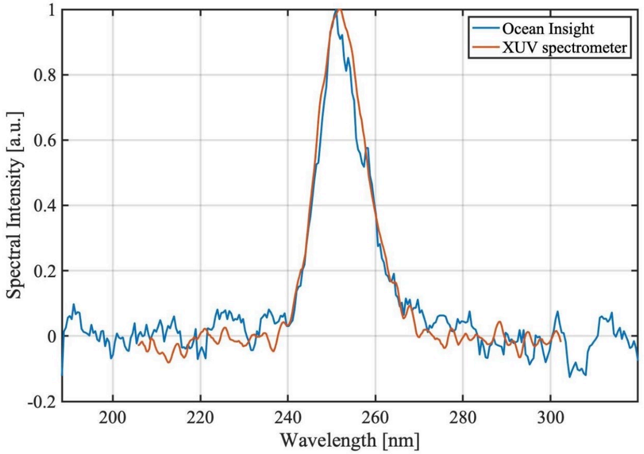
XUV spectrometer setup

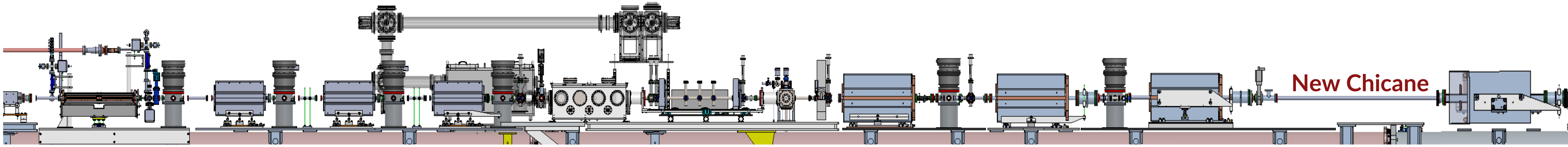


“Trailer PAX boys”



XUV and UV/Vis spectrometer cross-calibration





PAX chicane + bypass line initial design completed. XUV spectrometer system tested and ready for install

Summary

- Plasma accelerators offer beams with unique properties for light source applications.
- PAX leverages these to provide a flexible, high power X-ray source which can enable experiments in attosecond science.
- Staged demonstration experiment is underway at FACET-II. XUV diagnostics have been tested and ready for installation.
- First science targets sub-fs e-beam compression and XUV generation via CSR. Final realization will use plasma injector for as-beam generation and push to shorter wavelengths.
- Long term vision is to outline a path forward dedicated to plasma-driven attosecond science experiments.
- Strengthening dialogue with user community is important to connect the best-served experiments to plasma-driven sources

PAX is moving steadily from concept to experimental realization

Acknowledgments

Collaborators

- **SLAC**: R. Hessami, K. Larsen, R. Robles, D. Storey, G. White, X. Xu, M.J. Hogan*, C. Emma*, A. Marinelli*
- **SLAC FACET-II team**
- **UCLA Physics**: A. Fisher, P. Musumeci
- **UCLA EE**: C. Joshi, K. Marsh, C. Zhang

Funding Sources

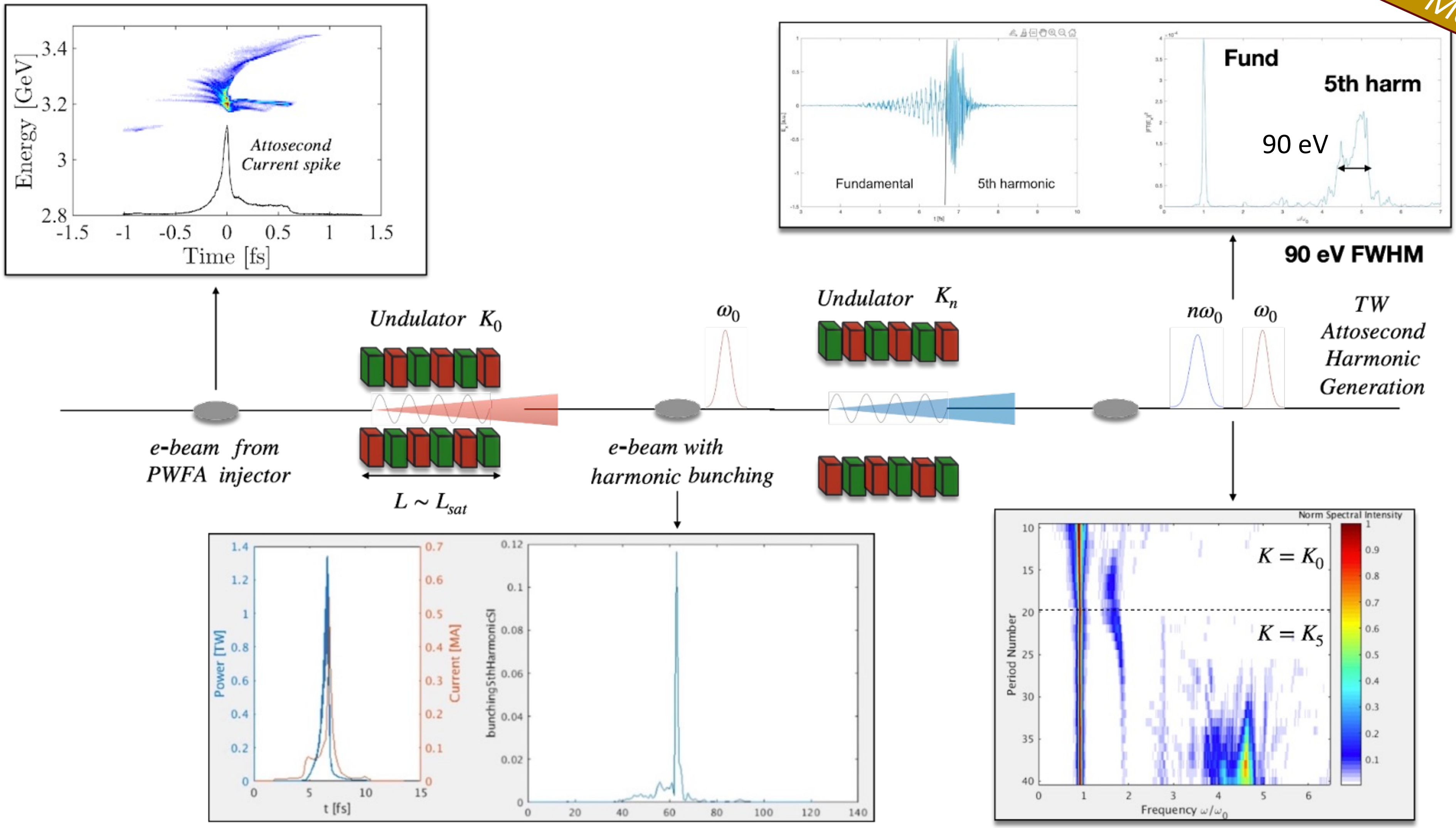
This work was supported by the Department of Energy, Laboratory Directed Research and Development program at SLAC National Accelerator Laboratory, under contract DE-AC0276SF00515. This work was also partially supported by the DOE under Grant No. DE-SC0009914. The OSIRIS simulations were performed on the National Energy Research Scientific Computing Center (NERSC).

Thank you for your attention

Backup

PAX scaling to shorter wavelength

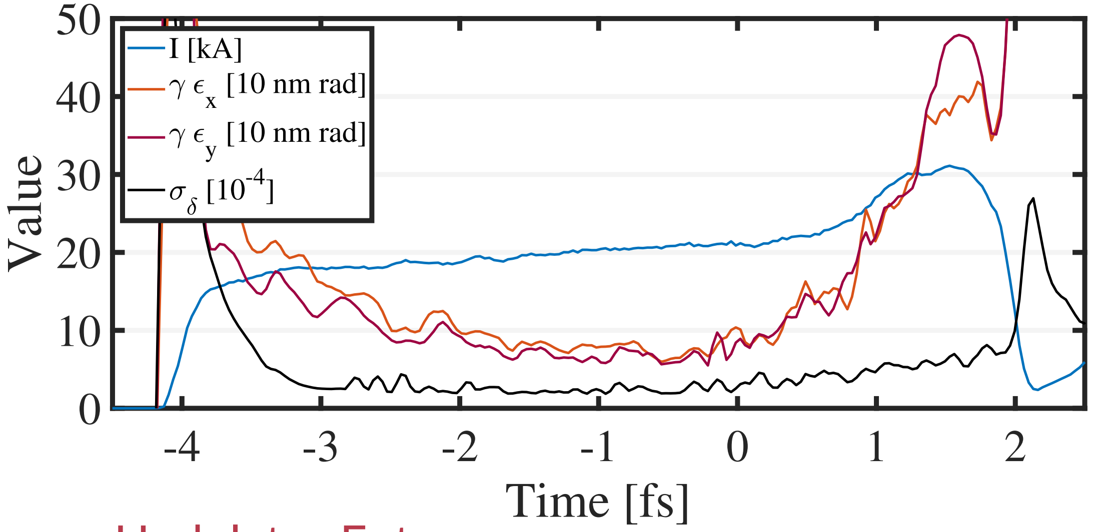
See talk by R. Hessami
WG7 Monday



PAX photon pulses at keV photon energy possible via coherent harmonic generation

PAX Simulation parameters

Plasma Exit



Undulator Entrance

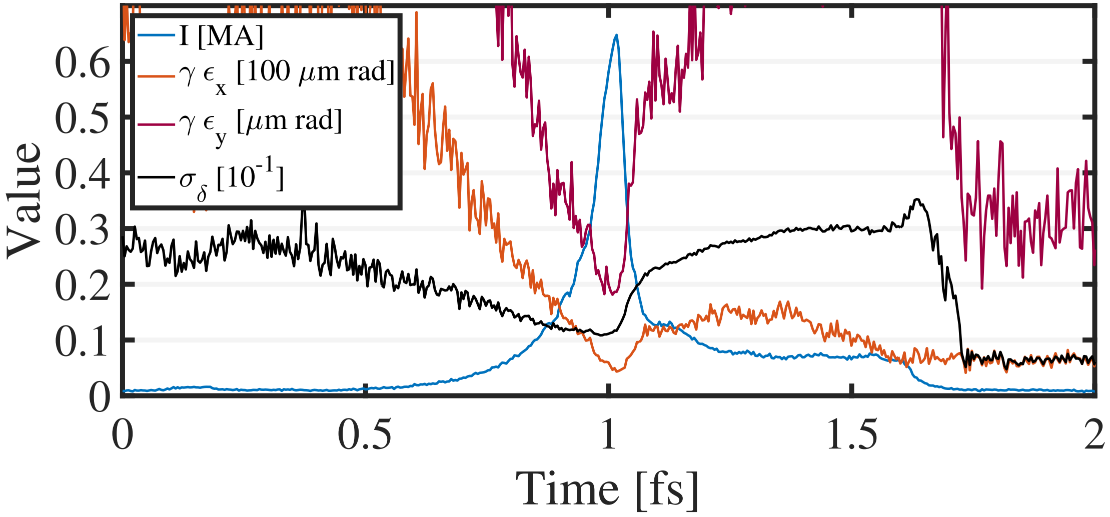
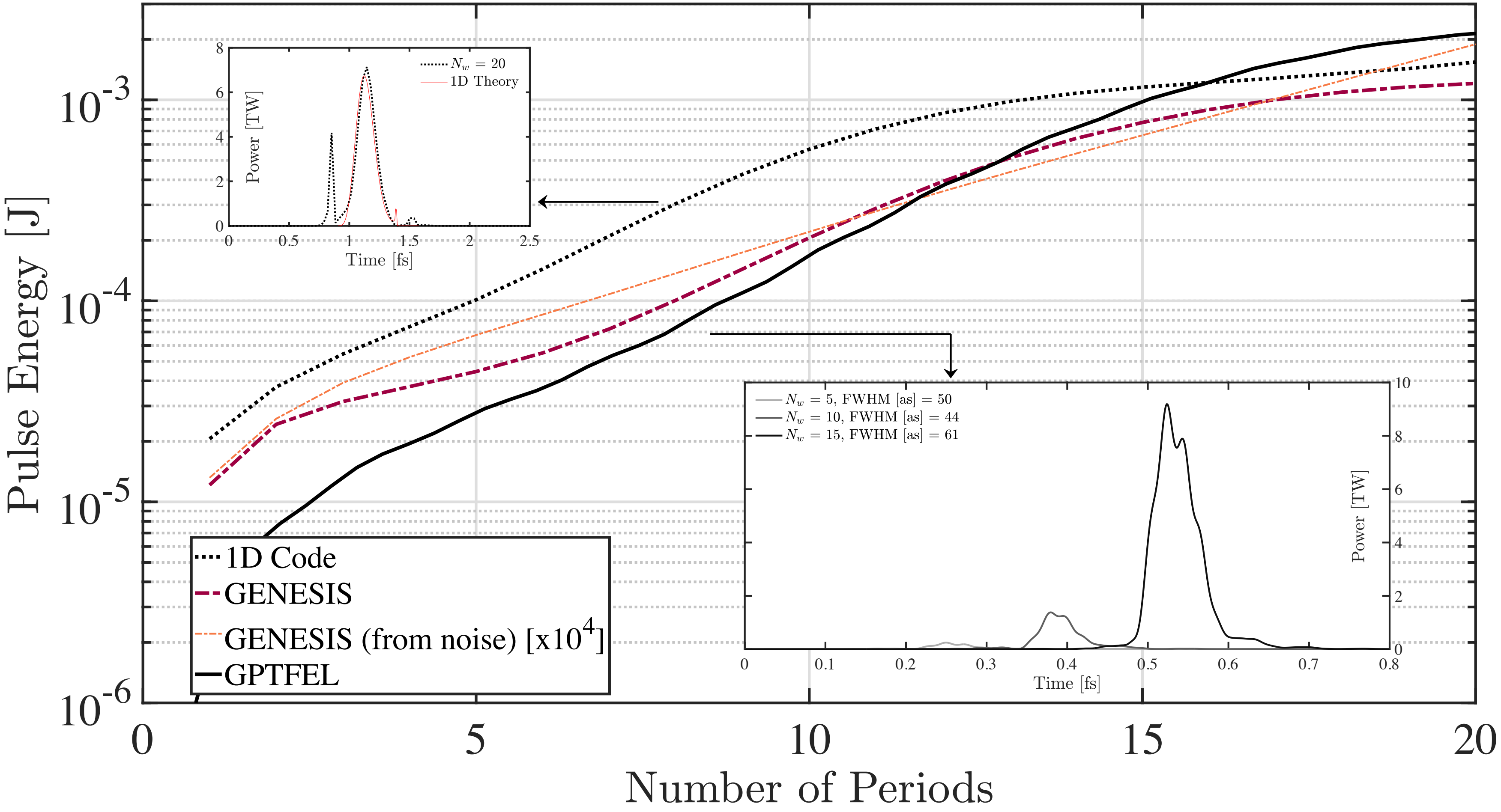


TABLE I. Simulation parameters for the PWFA-driven TW-attosecond X-ray source.

Parameter	Value	Unit
Plasma and Drive Beam		
Plasma Density	$1.1 \rightarrow 1.0 \times 10^{18}$	cm^{-3}
Downramp Length	100	c/ω_p
Beam Energy	2	GeV
RMS beam size (r,z)	(2.7,5.3)	μm
Peak Current	34	kA
Triplet and Chicane		
Quadrupole strengths	-48.8,15.3,-7.8	m^{-2}
Dipole Bend Angle	3.4	mrad
Momentum Compaction	27	μm
Witness Beam (at Undulator)		
Beam Energy	3.3	GeV
Peak Current	0.65	MA
Norm. RMS Emittance (x,y)	(4.3 , 0.18)	μm rad
FWHM Beam Size (x,y,z)	(10.8, 7.5, 0.023)	μm
RMS Slice Energy Spread	1.4	%
Undulator		
RMS Undulator Parameter	3.73	-
Undulator Period	5.6	cm
Number of Periods	20	-
Radiation		
Wavelength	10	nm
Peak Power	0.25-3.8	TW
FWHM Pulse Duration	38-294	as

C. Emma et al., APL Photonics, **6**, 076107 (2021)

PAX FEL Simulation code comparison



C. Emma et al., APL Photonics, **6**, 076107 (2021)

PAX properties compared between different codes confirm TW-as pulses in m-length undulator

Attosecond E-beams for short bunch colliders

Parameter	NPQED Collider	LCLS	PAX
Beam Energy [GeV]	125	3 - 15	1-10
Charge [nC]	0.14 – 1 .4	0.01 – 0.2	0.01 – 0.1
Peak Current [kA]	1700	1 – 5	100 - 700
Energy Spread [%]	0.1	0.01	1
RMS Bunch Length [μm]	0.01 – 0.1	1 – 100	0.003 – 0.1
RMS Spot Size [μm]	0.01	10	1 - 10

V. Yakimenko et al. Prospect of Studying Nonperturbative QED with Beam-Beam Collisions, PRL. 122, 190404 (2019).
G. White and V. Yakimenko, Ultra-Short-Z Linear Collider Parameters, Workshop on Future Linear Colliders (LCWS2018),
HEP GARD Accelerator and Beam Physics: Community-driven strategic Roadmap Workshop, LBNL December 2019

- Ultra-short bunches (attosecond level) are being considered for next generation e+/e- colliders due to reduced beamstrahlung.
- State-of-the-art high brightness e-beam facilities typically operate with 1-2 orders of magnitude less compression.

PAX allows the study of MA-compression relevant for short-bunch colliders

References

1. C. Emma, X. Xu, A. Fisher, R. Robles, J. P. MacArthur, J. Cryan, M. J. Hogan, P. Musumeci, G. White, and A. Marinelli, *"Terawatt attosecond X-ray source driven by a plasma accelerator"*, APL Photonics, 6, 076107 (2021), https://aip.scitation.org/doi/10.1063/5.0050693
2. C. Emma, J. Van Tilborg et. al., *"Free electron lasers driven by plasma accelerators: status and near-term prospects"*, High Power Laser Science and Engineering, (2021), Vol. 9, e57, 15 pages, doi: 10.1017/hpl.2021.39