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

IPAC 2022

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FACET-II

SLAC NATIONAL ACCELERATOR LABORATORY

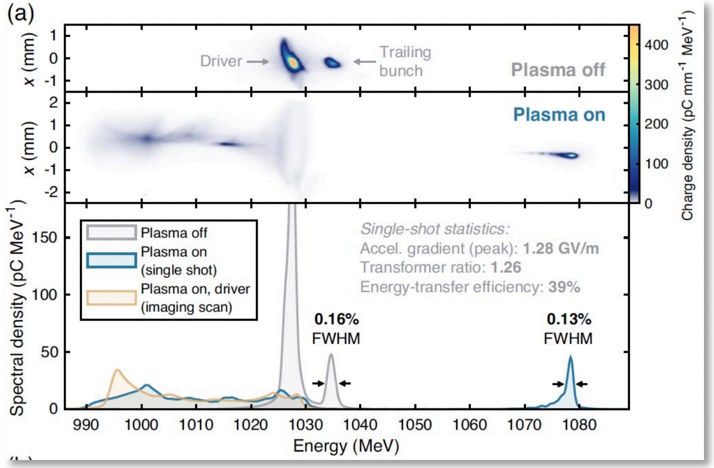
Stanford University | U.S. DEPARTMENT OF ENERGY

Outline

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

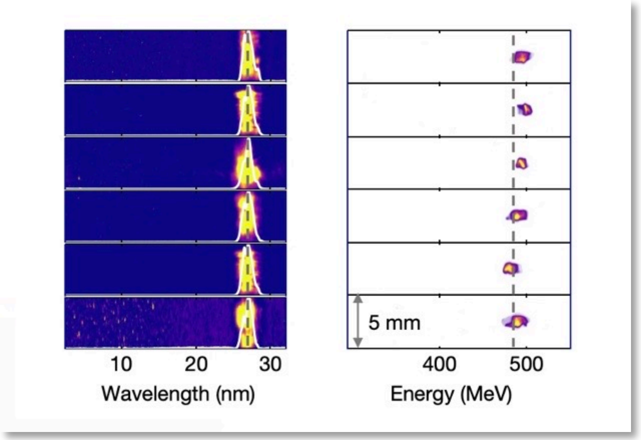
Plasma-accelerators: recent highlights

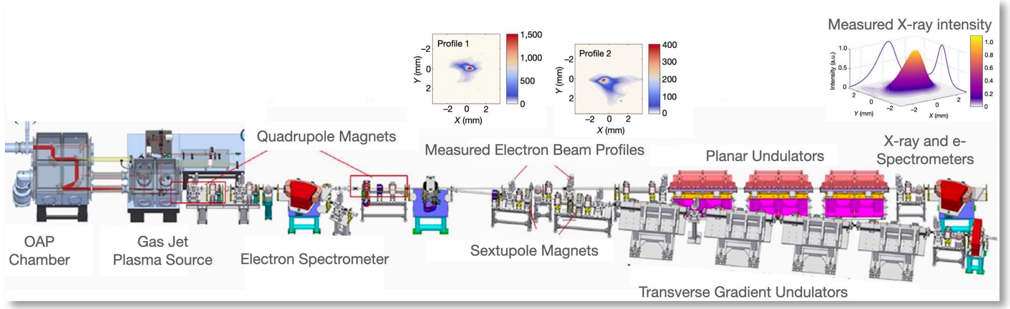
Sub-% energy spread preservation



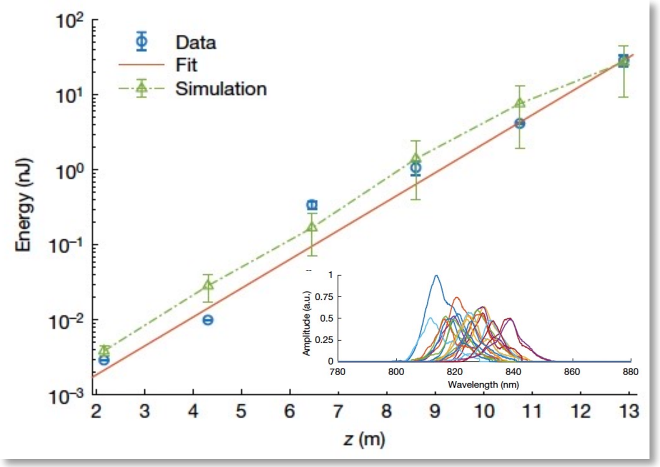
C. Lindstrom et al., PRL 126, 014801 (2021)

FEL gain demonstrations

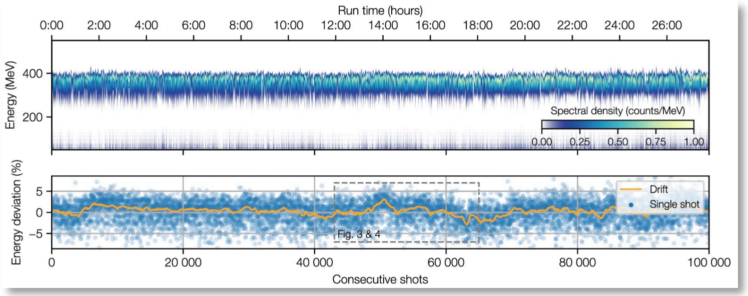


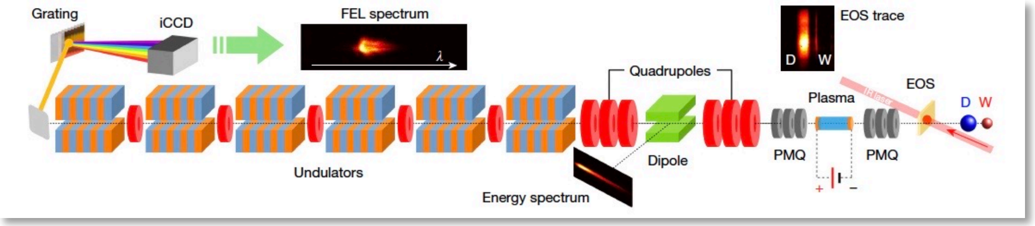


W. Wang et al., Nature, **595**, 516–520 (2021)



Day-long operation stability





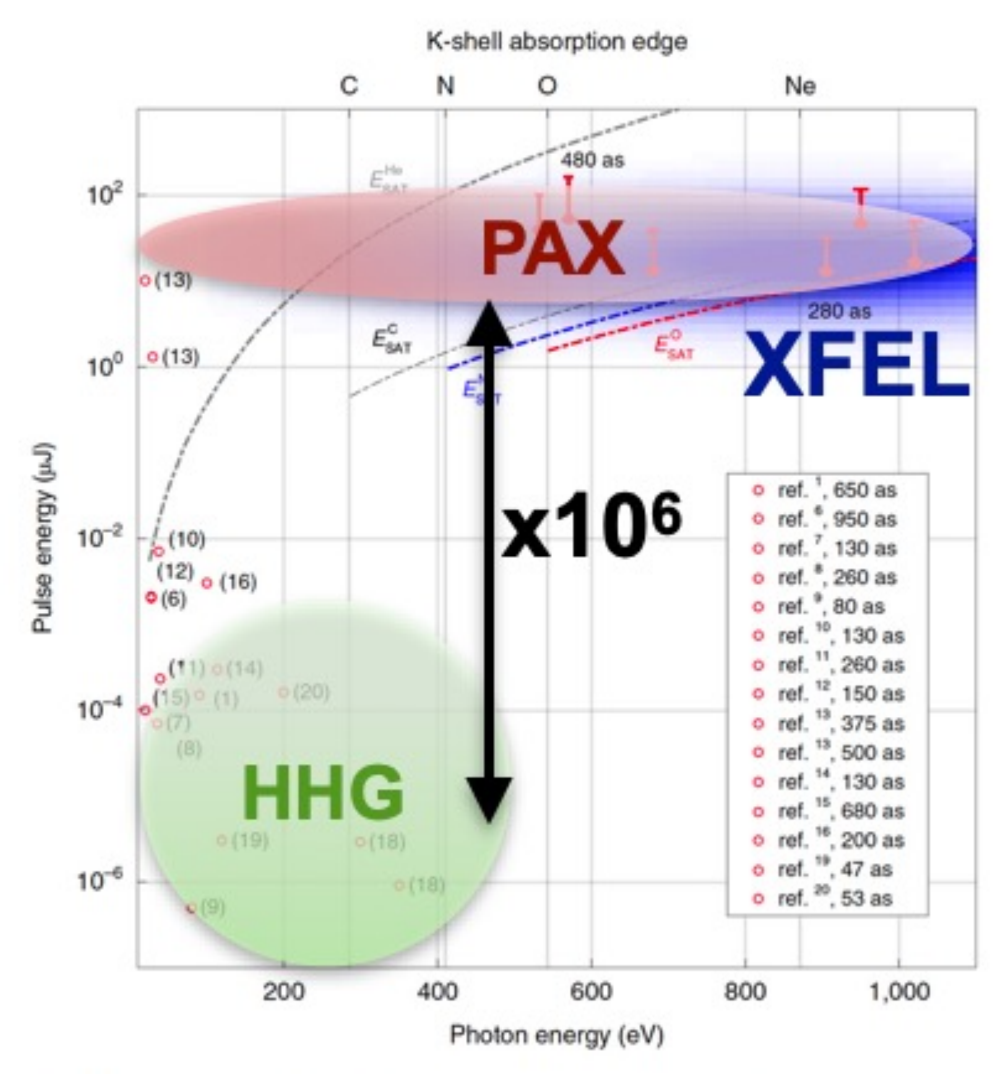
R. Pompili et al., Nature, **605**, pages659–662 (2022)

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

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

Attosecond pulses with plasma-driven FELs

- 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

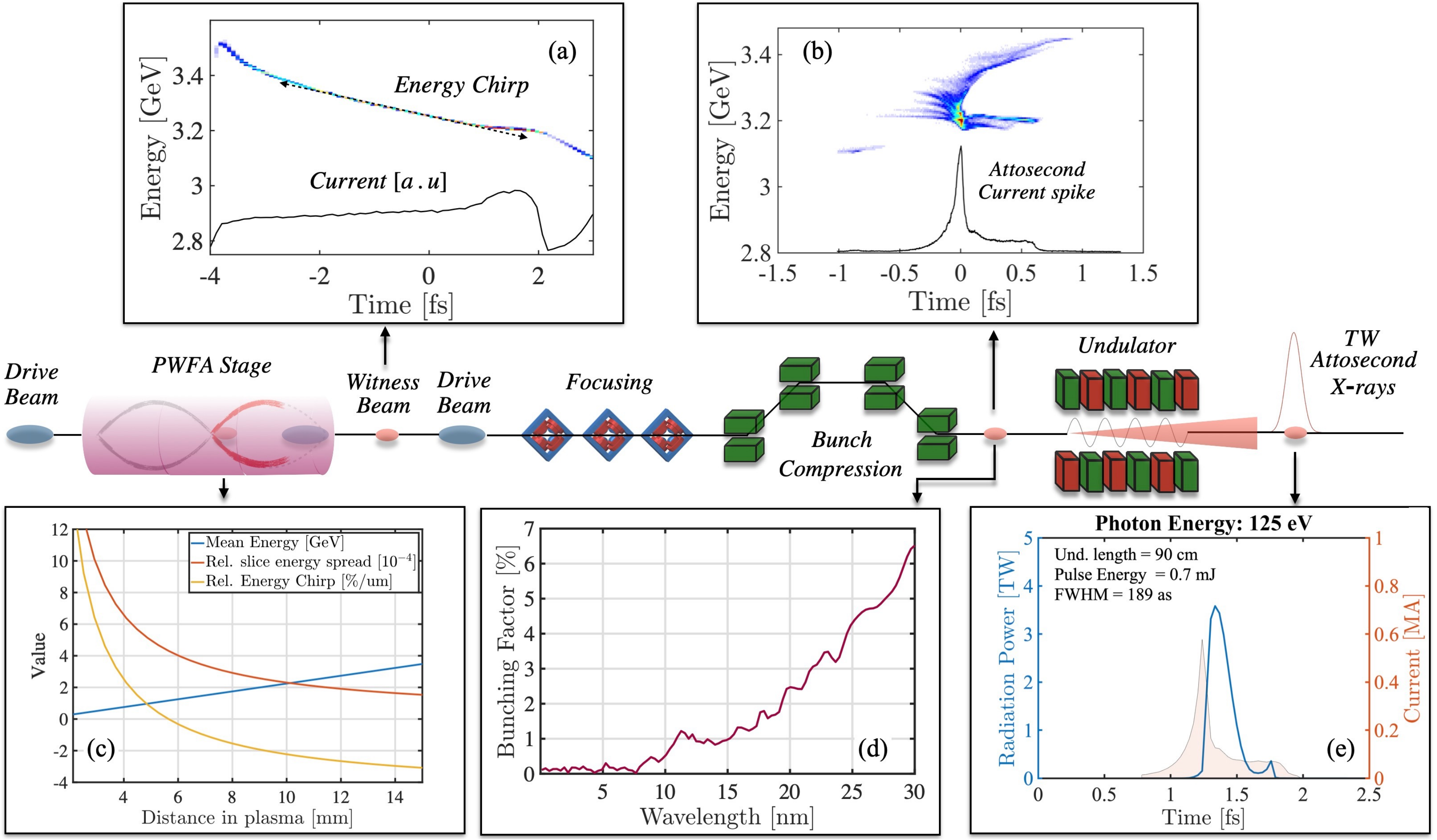
PAX: a Plasma-driven Attosecond X-ray Source

Large plasma fields impart large energy chirp

Weak chicane compresses e-beam to as-duration

Beam is bunched at soft X-ray wavelengths

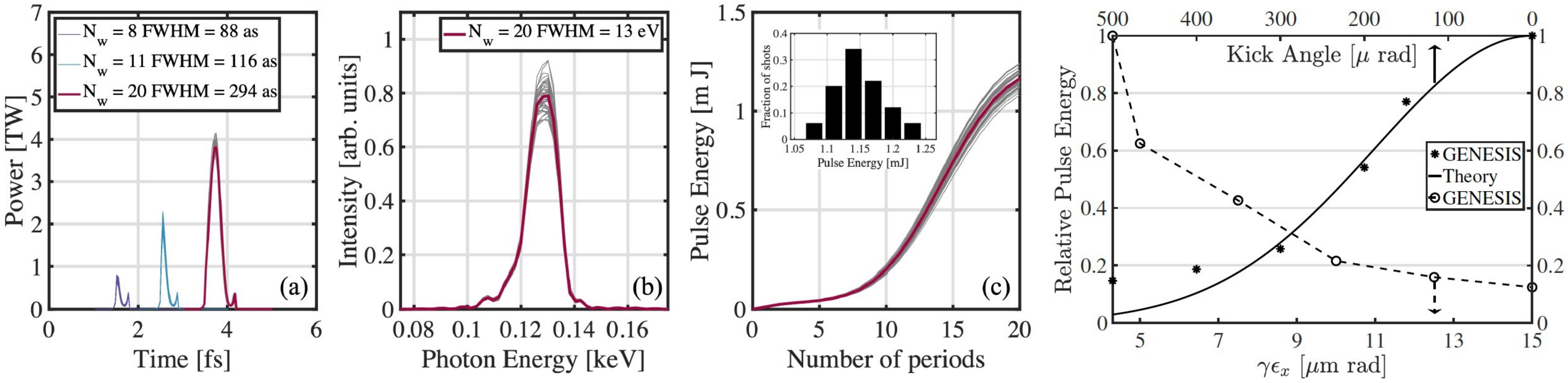
Pre-bunching relaxes tolerance on energy spread, emittance, pointing stability



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

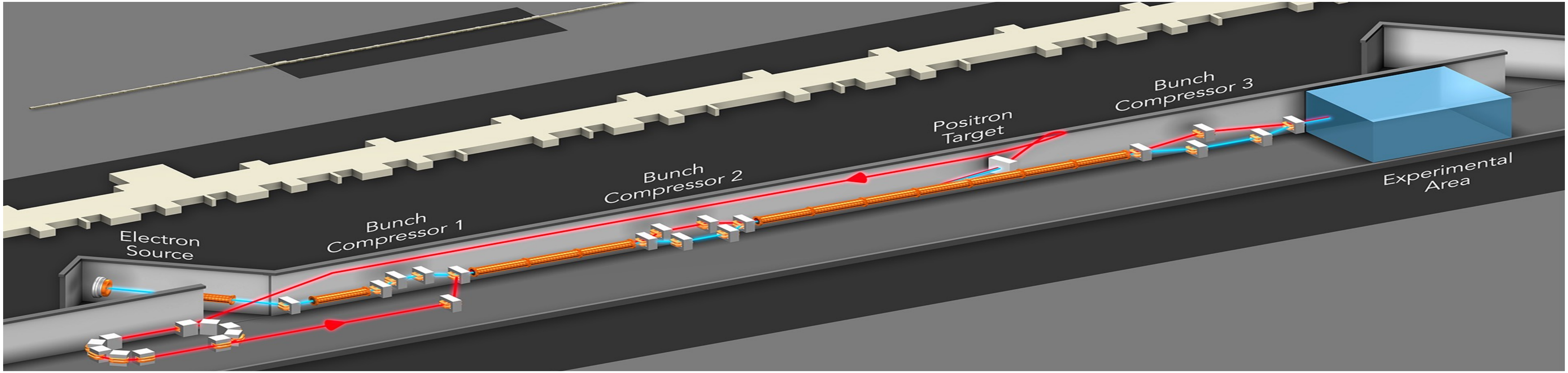


- 5-10x higher peak power compared to attosecond XFELs
- Pulse energy stability 10x better than attosecond XFELs due to coherent emission process **not** SASE starting from noise
- Tunable pulse length/peak power depending on experiment

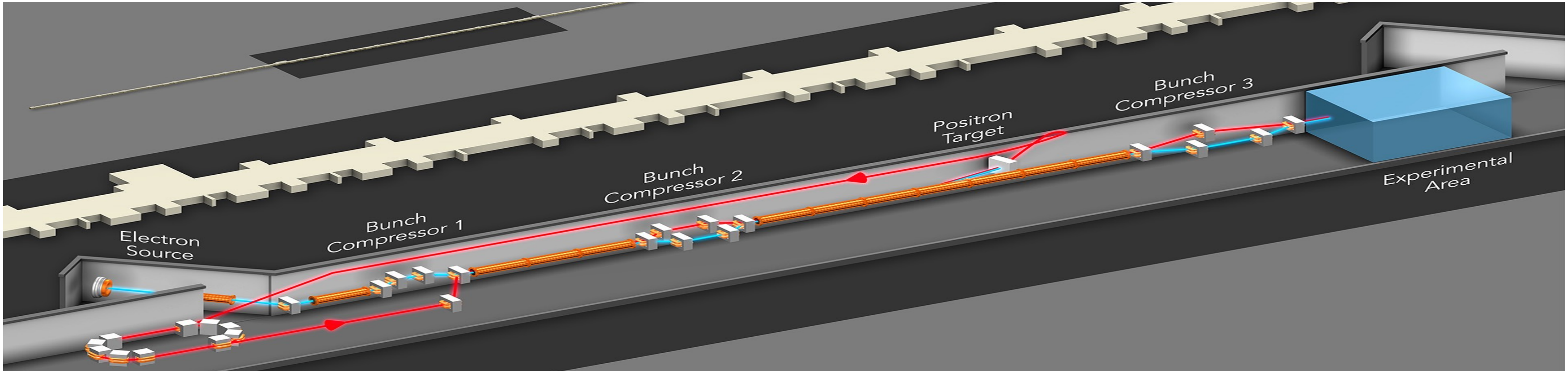
C. Emma et al., APL Photonics, **6**, 076107 (2021)

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



FACET-II operational parameters

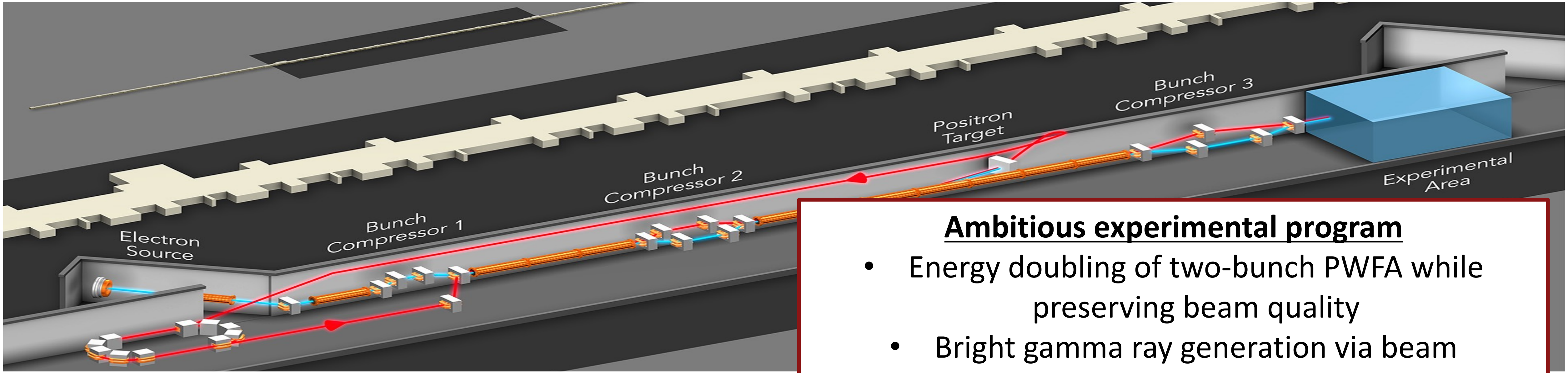
- 2nC, 10 GeV, 10 um emittance
- Single bunch, two bunch, low energy spread operating mode
- Ultra-high peak current (10s-100s kA)

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

V. Yakimenko et al., PRAB **22** 101301, (2019)

Experimental Demonstration at FACET-II



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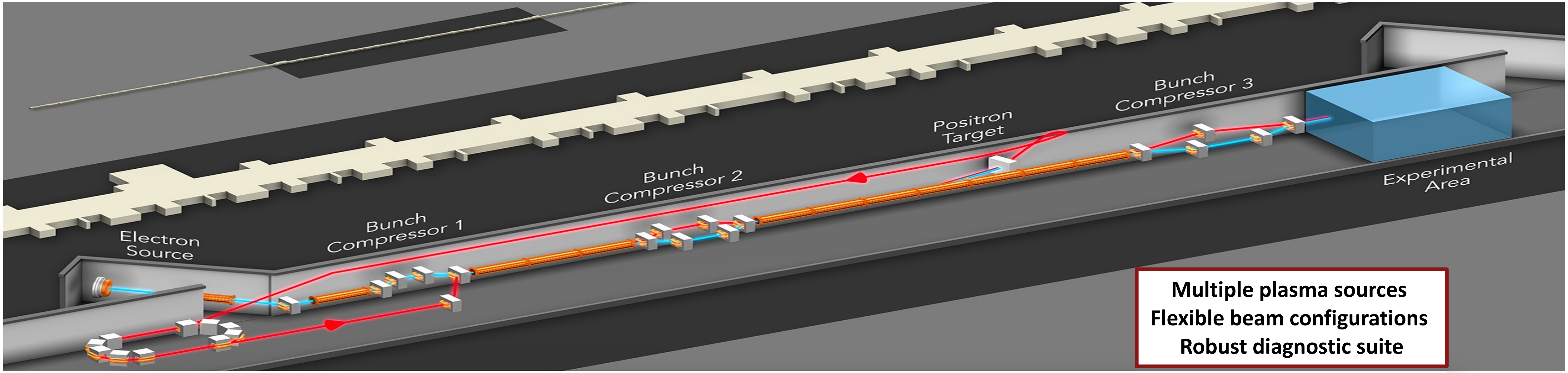
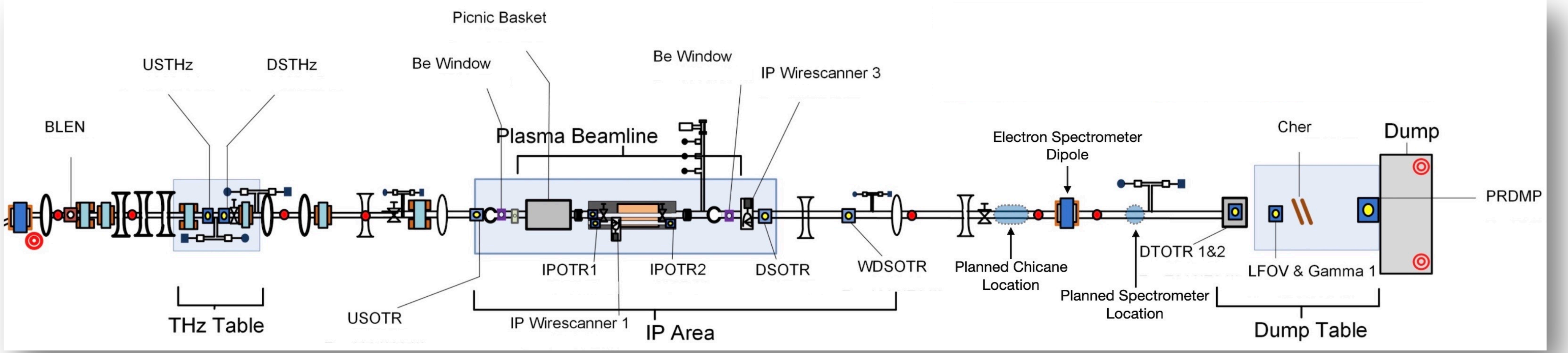
Ambitious experimental program

- 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 X-ray source development**
- …

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

Experimental Demonstration at FACET-II





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

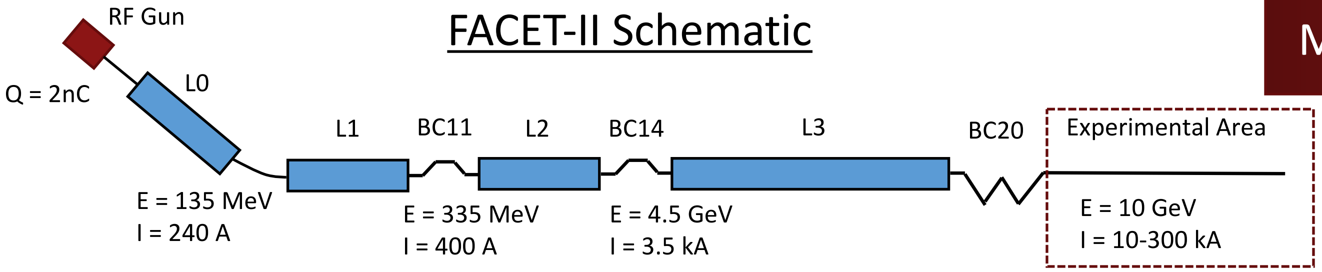
Experimental Demonstration at FACET-II

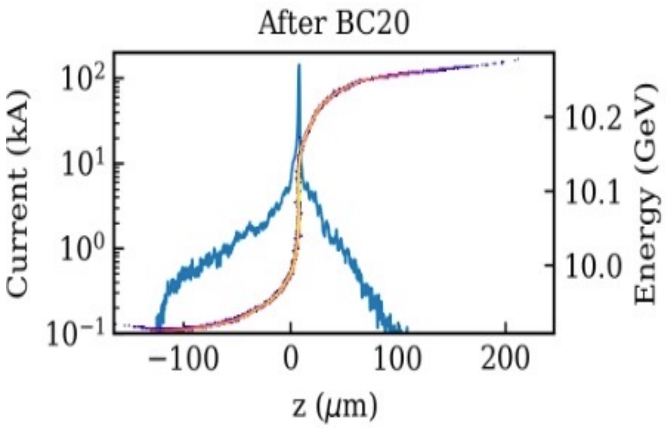
See poster by R. Robles WEPOTK064

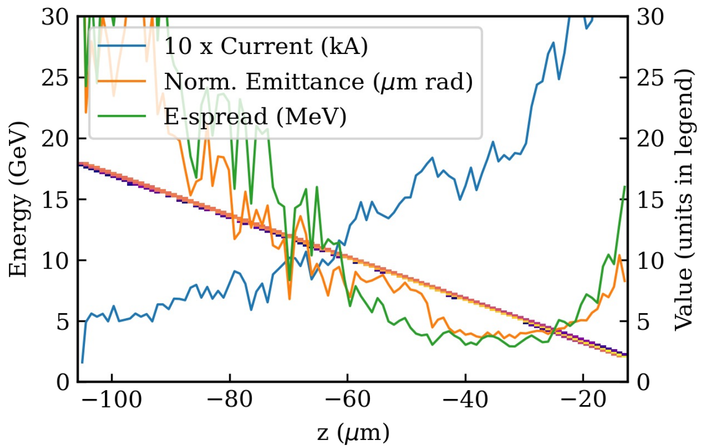
Demonstrate post-plasma sub-fs e-beam compression

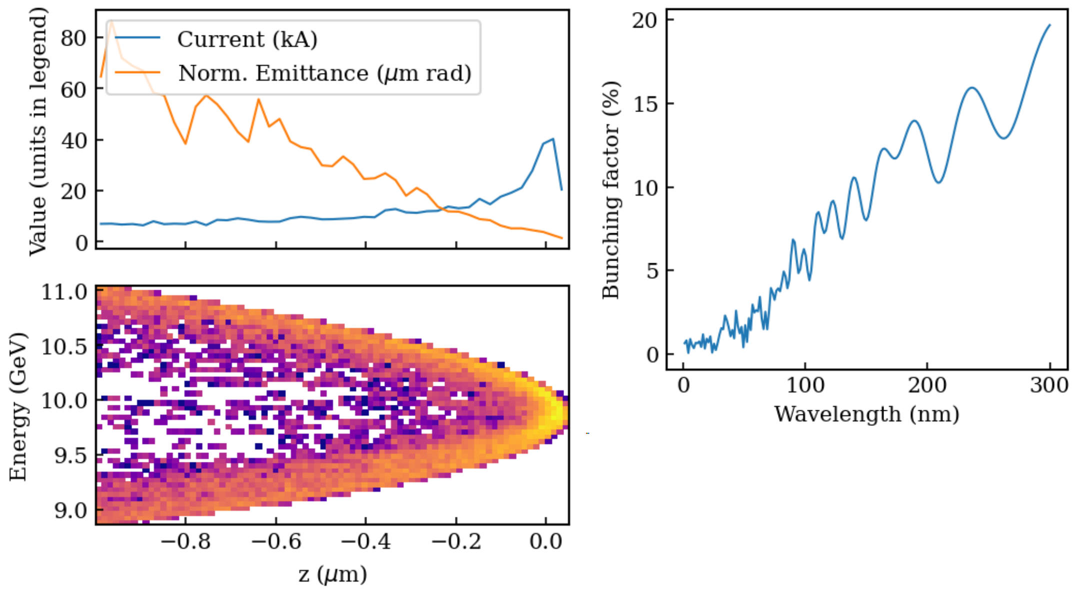
Generate + measure XUV CSR from sub fs-long e-beams

Measure attosecond coherent XUV undulator radiation









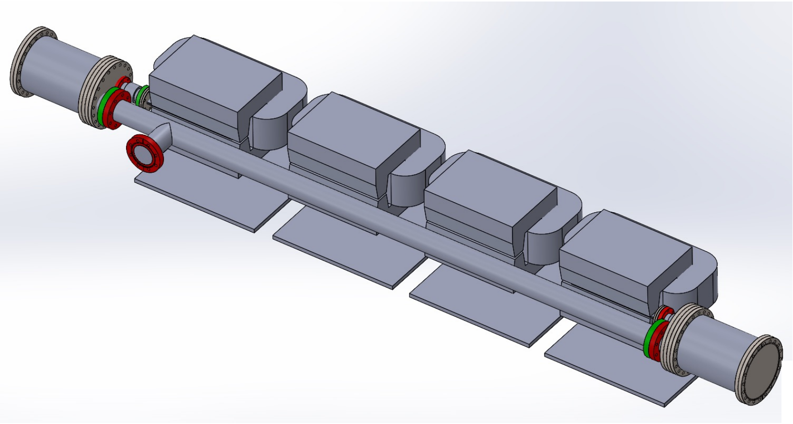
FACET-II provides ideal test-bed for PAX staged demonstration

XUV Spectrometer and radiation detection for PAX at FACET-II

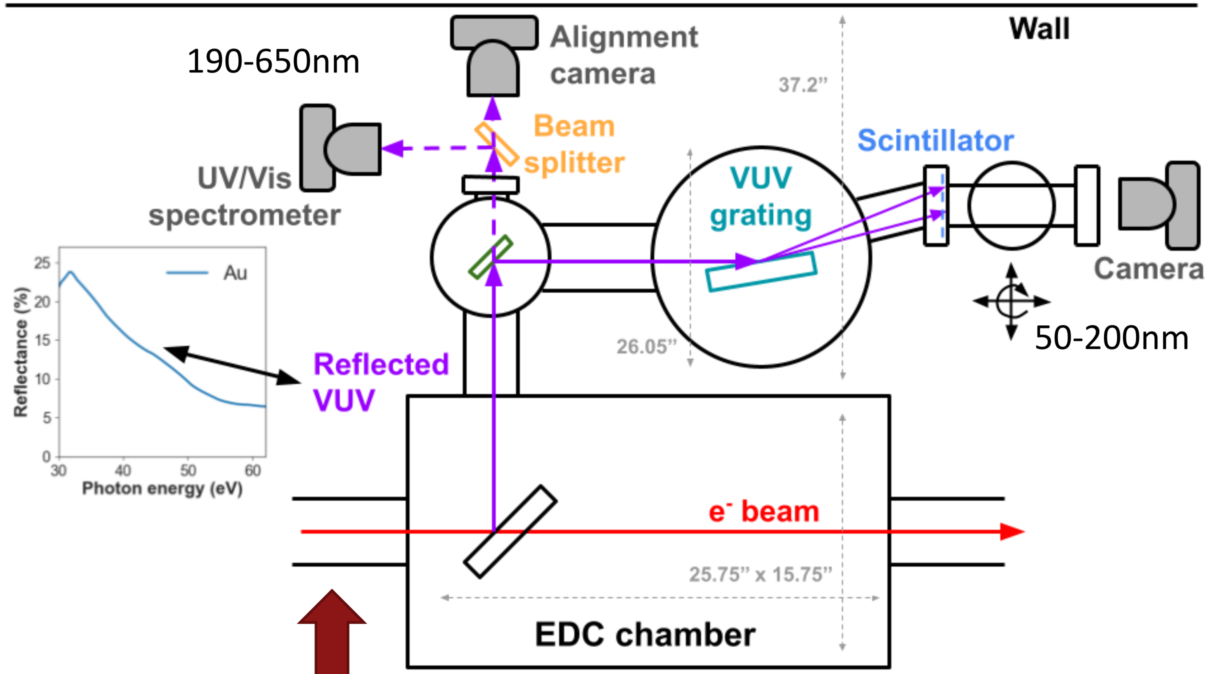
Plasma Sources

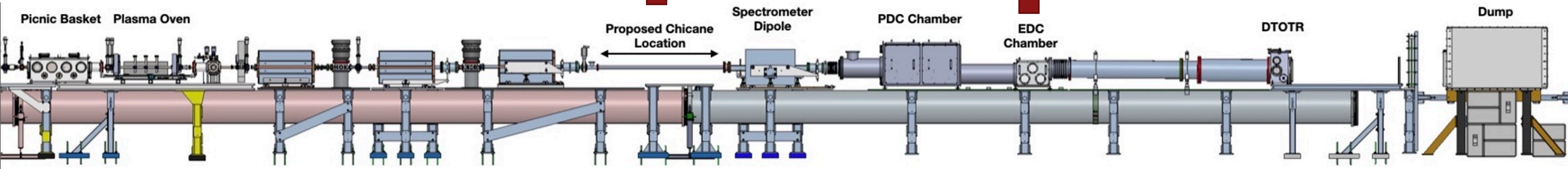
- Gas Jet
  ne = 1e18 – 1e20 cm^-3
- Li Oven
  ne = 1e16 cm^-3

Chicane + bypass line design



Spectral Measurement Setup



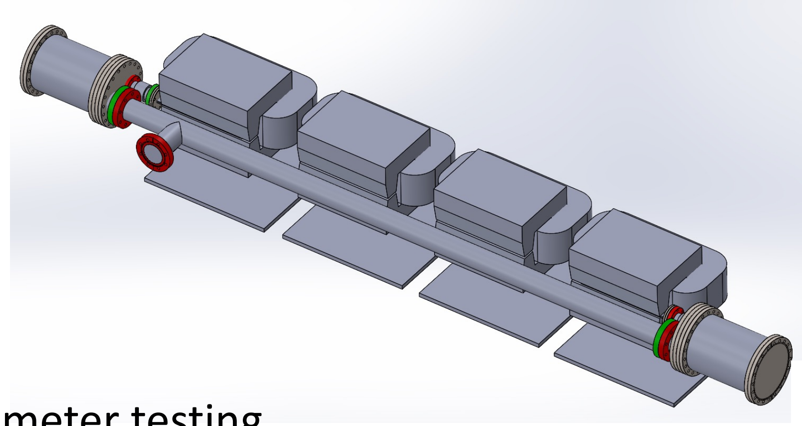


Radiation setup detects broadband spectral content to map bunching factor of fully-compressed e-beam

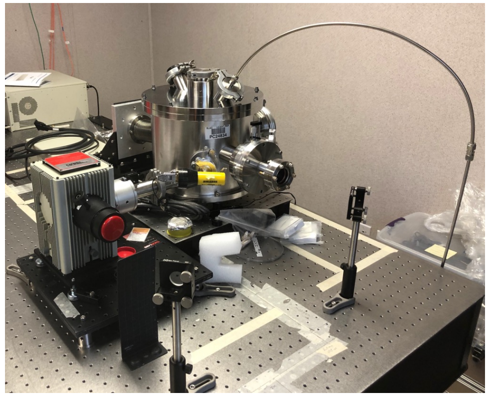
Experimental installation plans

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

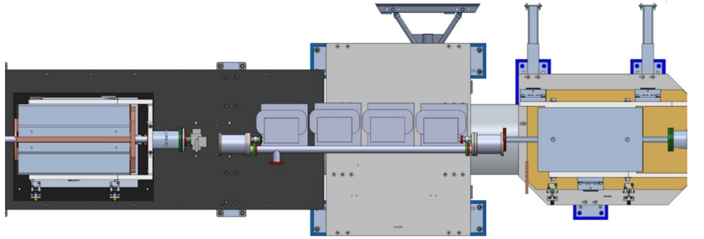
Chicane + bypass line design

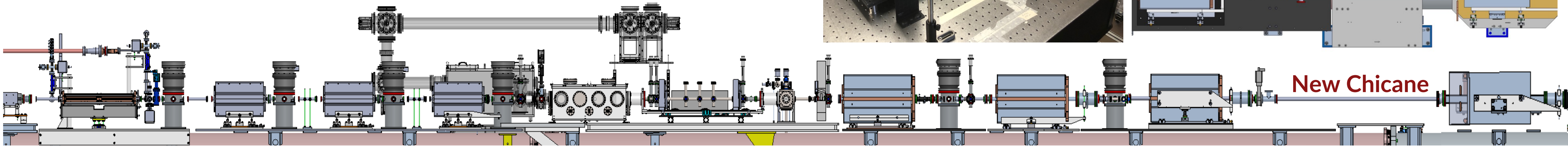


XUV spectrometer testing



Chicane location in beamline





PAX chicane + bypass line initial design completed. PAX XUV spectrometer system currently commissioning

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. Currently testing diagnostics and planning upcoming hardware installations.
- 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

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Thank you for your attention