Light-source applications of advanced accelerators

PAX: Plasma-driven Attosecond X-ray Source

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Expert Panel on High-Gradient Accelerator Townhall

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(Virtual)

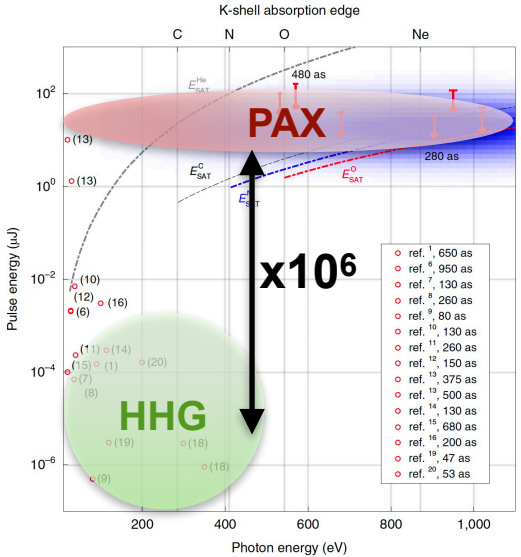
U.S. DEPARTMENT OF ENERGY | Stanford University

SLAC NATIONAL ACCELERATOR LABORATORY

Attosecond photon and e- beams from plasma accelerators

Attosecond photon beams in plasma-driven FELs

- X-ray pulses with 50-100as and μJ-energy desirable for studying e-motion in atoms on its natural timescale.
- HHG (XFEL) sources reach 40 (200) as length with pJ (uJ)-level energy.
- XFELs min pulse length limited to ~ 200as by emittance ($\Delta t_{min} \propto \epsilon^{5/6}$)
- A plasma-driven attosecond photon source can combine the benefits of HHG sources & XFELs based enabling new capabilities.



Plasma accelerators offers path to short, higher power photon pulses than state-of-the-art attosecond HHG/XFEL sources

- J. Duris *et al. Nat. Photonics* 14, 30–36 (2020)
- Z. Zhang *et al.* New J. Phys. 22 083030 (2020)

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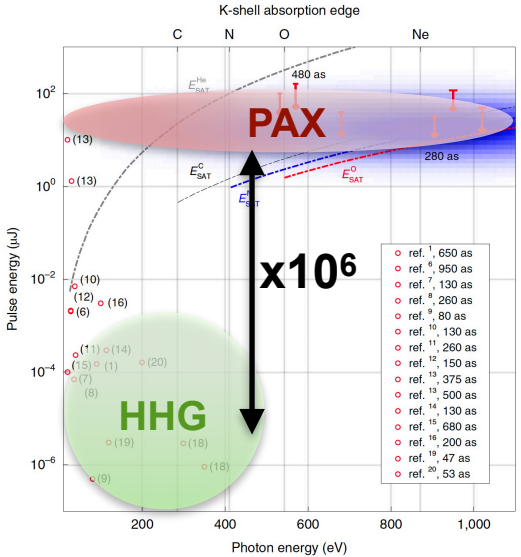

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Attosecond e-beams for short bunch colliders

- Ultra-short bunches are being considered for next gen. e+/e- colliders due to reduced beamstrahlung
- Beamstrahlung effects can be "switched off" if the bunch length is made small enough (attosecond-level)

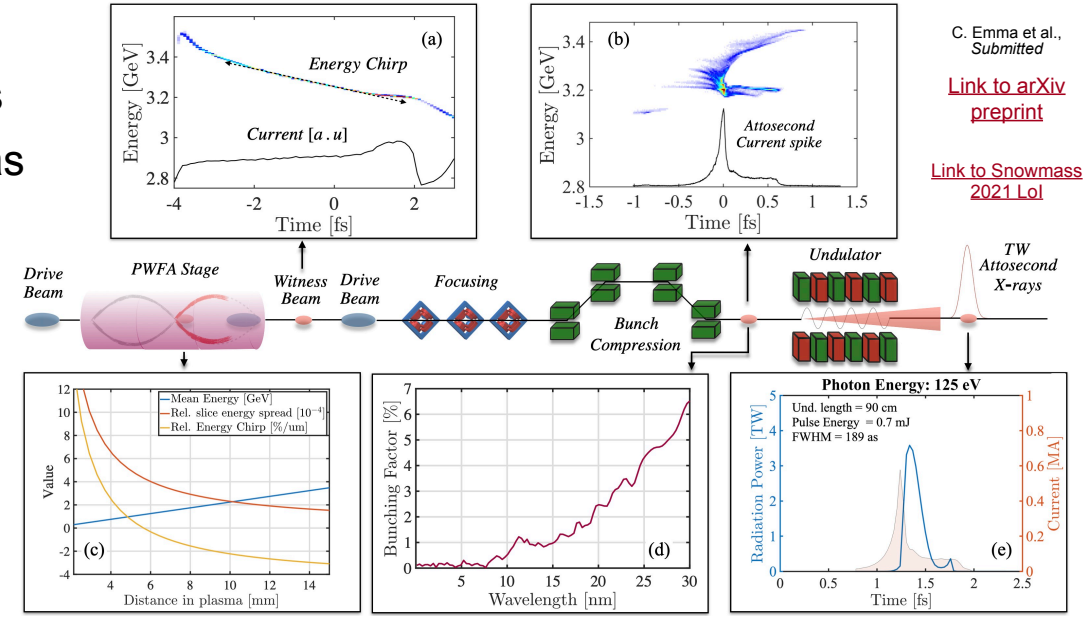
Parameter	NPQED Collider	LCLS	PAX
Beam Energy [GeV]	125	3-15	1-10
Bunch Charge [nC]	0.14 - 1.4	0.01-0.2	0.01 - 0.1
Peak Current [kA]	1700	1-5	10-700
Energy Spread [%]	0.1	0.01	1
RMS Bunch Length [μm]	0.01 - 0.1	1-100	0.003 - 0.1
RMS Spot Size [μm]	0.01	10	1-10

Attosecond e- beams allow the study of MA-compression relevant for short-bunch colliders

- 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

PAX: A plasma-driven attosecond X-ray source

- Large fields in PWFAs can produce high strongly chirped high brightness e-beams
- Small chicane compresses e- beams to as length preserving good beam quality.
- These e-beams can generate TW X-rays via coherent radiation in short (m-length) undulators.
- ***Not an XFEL starting from noise -*** relaxed tolerances on energy spread, emittance and pointing stability.
- HEP facilities e.g. FACET-II can enable initial experimental tests and conceptual demonstration in next 2-5 years.



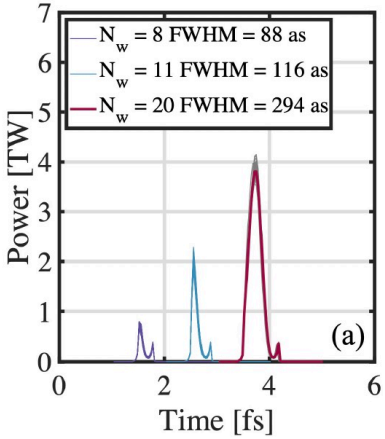
C. Emma et al., *Submitted*

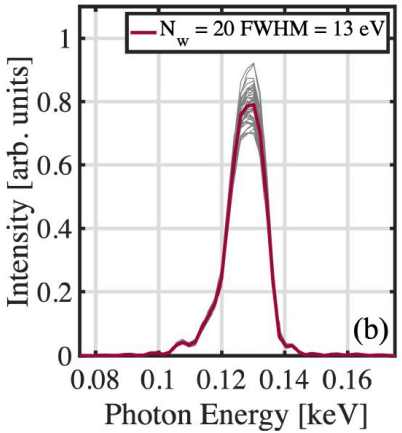
Link to arXiv preprint

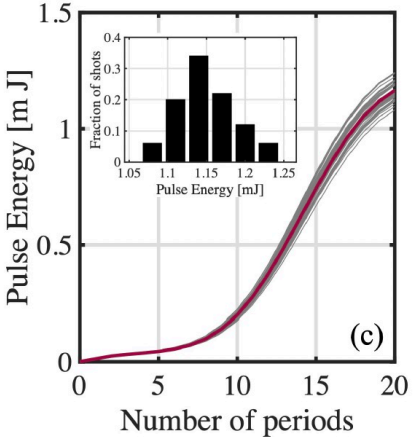
Link to Snowmass 2021 LoI

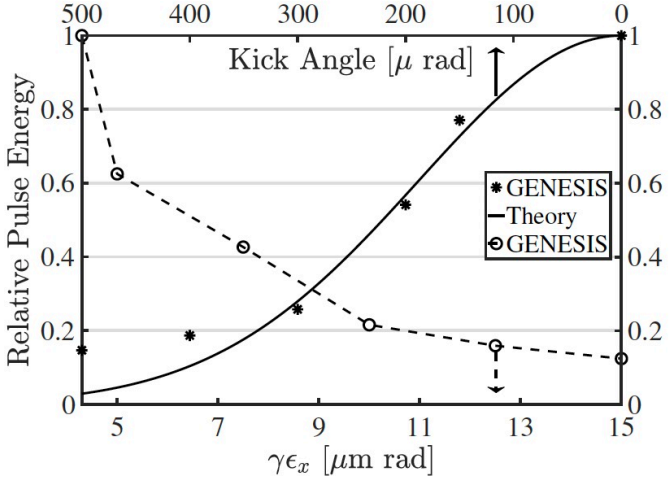
R&D in this direction in line with P(L)WFA roadmap towards near-term applications

Simulated performance of a PAX source



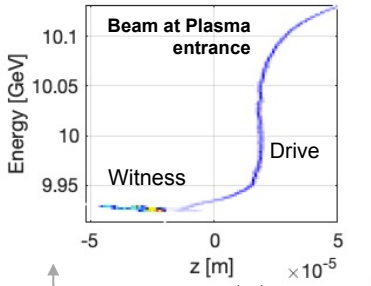


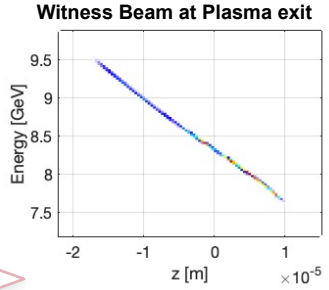


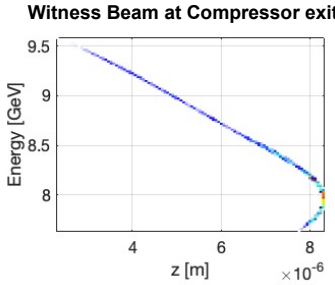


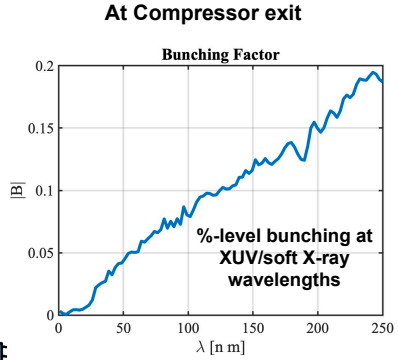
- Peak power 5-10x compared to attosecond XFEL
- Energy fluctuations 10x smaller than attosecond XFELs due to emission process not starting from noise
- Less restrictive tolerance on beam emittance compared to SASE XFEL
- >10x less restrictive tolerance on angular trajectory jitter compared to SASE XFEL
- Softened tolerances are due to pre-bunching, high current and short undulator

Planned demonstration experiment at FACET-II

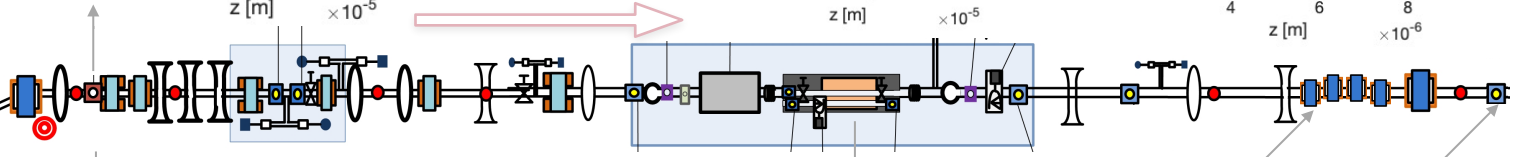








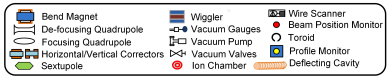
Beam Direction

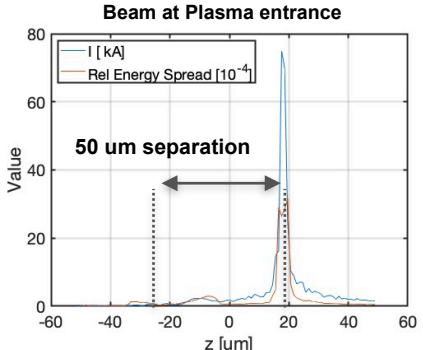


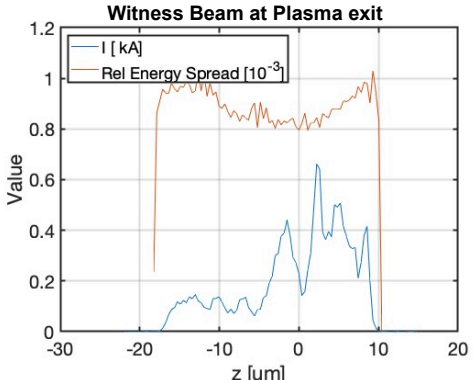
Plasma Source

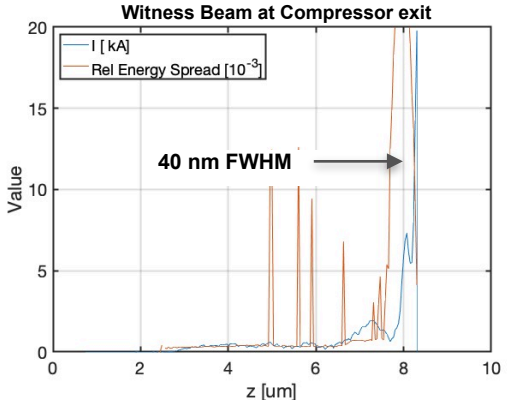
Planned Chicane Location

Planned Radiation Diagnostic









Summary

- FEL user community can benefit from new light source capabilities enabled by the unique properties of plasma-accelerated e-beams.
  - The advantage of a plasma-based FEL can extend beyond its compactness (higher power, single cycle pulses, pulse control/stability…)
- PWFA light sources offer opportunity to study MA-compression relevant for short bunch colliders.
- We have presented an example of attosecond X-ray generation based on coherent emission from an attosecond e-beam compressed after exiting a PWFA.
- ***First science goals for demonstration experiments:***
  - Measuring coherent radiation targeting XUV before X-rays.
  - Characterizing PAX source properties.
- ***Long term vision:***
  - Outline path forward dedicated to plasma-driven attosecond science experiments.

Questions Part 1

1) Where do you see HEP applications of advanced accelerators in 30 years?

2) What intermediate physics applications/steps do you see until a HEP linear collider?

Link to Snowmass Advanced Accelerator Concepts group for Near Term Applications

- Light sources based on e-beams driven by plasma wakefields (both beam- and laser-driven) and dielectric structures. This includes XUV, X-ray, and gamma emission from betatron emission, FELs, Compton/Thomson scattering, and through other particle-matter interaction mechanisms.
- Medical applications of particle beams produced at advanced accelerators (e.g. few-MeV and high-energy electron beams, protons, and ions)
- Fundamental discovery science targeting particle physics and astro-phenomena accessible with moderate energy (substantially below TeV) advanced accelerators.

3) What is the synergy with related fields?

- FEL user community (taking advantage of PWFA-FEL properties)
- High energy density physics community (utilizing PWFA facilities to study HED phenomena)
- Medical community

4) What is the role of your work here?

- Developing one example of a new capability enabled by PWFA-FEL operation.

Questions Part 2

1) What are the important milestones for the next 10 years to get there from today?

- Demonstration of coherent emission and gain from a plasma-driven FEL
- Characterization of pulse properties from plasma-driven FELs, exploration of similarities and differences between beam-driven and laser-driven parameter space
- Delivery of plasma-driven FEL pulses to user community

2) What additional support is needed to achieve these?

- Dedicated resources allocated for pursuing/demonstrating near term applications in PWFA facilities (beam time, funding, human)

3) What should be proposed as deliverables until 2026? Please list in order of priority.

- Observation of coherent radiation at a plasma-FEL
- Dedicated user experiment using a plasma FEL source

4) Is the R&D work for each of those deliverables already funded and, if not, what additional resources / support would be needed?

- Some efforts funded in the US (e.g. LBNL ECA J. Van Tilborg, SLAC PWFA-FEL Task Force & PAX LDRD, UCLA), more in Europe (e.g. DESY LUX, DESY FlashForward, Strathclyde, Eupraxia, COXINEL)

Questions Part 3

1) What key R&D needs can be achieved in existing R&D facilities?

- Demonstration of coherent emission and gain from a plasma-driven FEL

2) What is the role of the already planned future facilities in Europe and world-wide?

- Expand access and prioritize resources for PWFA light source & near-term application development

3) What can be done with the existing and planned funding base?

- Leverage cross-cutting interests (e.g. photon/user side and accelerator side) to develop near-term applications with users in mind

4) Is a completely new facility needed?

- No (beyond those that are planned)

5) Are additional structures needed beyond existing networks and projects, e.g. a design study for a collider or an advanced accelerator stage?

- Yes, a forum for dialogue between plasma accelerator and light source user-community to examine opportunities and drive priorities.

Acknowledgments

PAX Collaboration:

SLAC: C. Emma, X. Xu, K. Larsen, J. Cryan, D. Storey, G. White, J. MacArthur, M. J. Hogan, A. Marinelli
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UCLA: P. Musumeci, A. Fisher

Snowmass 2021 Near-term applications Co-Convener:
Jeroen van Tilborg
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