High intensity attosecond electron and photon beams

C. Emma, X. Xu, J. P. MacArthur, J. Cryan, M. J. Hogan, A. Marinelli

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Motivation - PWFA driven Attosecond X-rays (PAX)

- 50-100as pulses desirable for studying electron motion in molecules
- FEL pulse length limited by emittance $\Delta t_{min} \propto \epsilon^{5/6}$
- XFELs currently limited to ~200as ~100GW

PWFA beams may offer path to shorter higher power pulses than XFELs

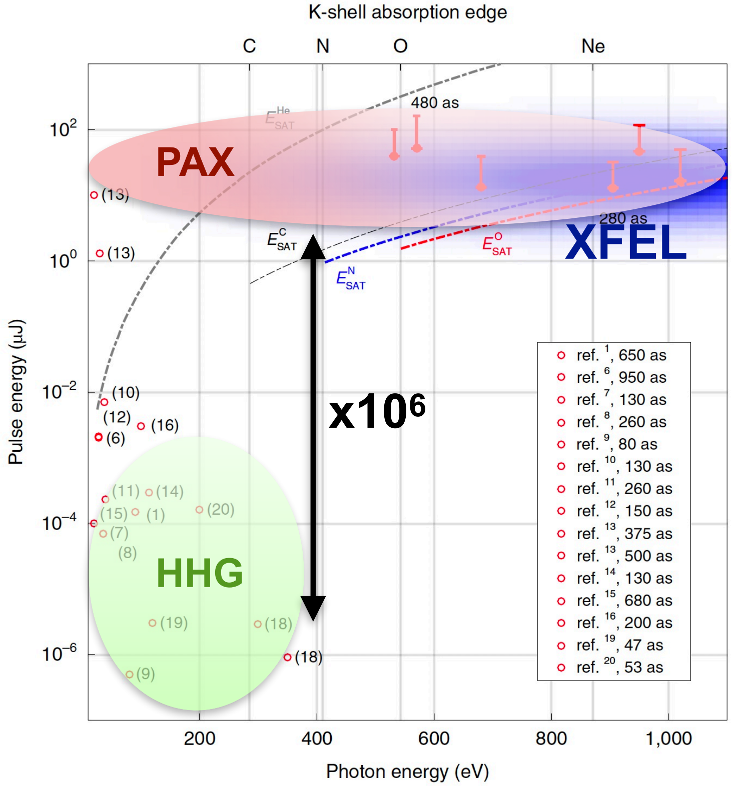


Fig. 4 | Comparison to state-of-the-art attosecond sources.

Motivation - Attosecond beams for NpQED collider

Physics Opportunities at a Lepton Collider in the Fully Nonperturbative QED Regime

07-09 August, 2019 https://conf.slac.stanford.edu/npqed-2019/

Parameter	[Unit]	NPQED Collider	LCLS	PAX
Beam energy	[GeV]	125	10	1-5+
Bunch charge	[nC]	0.14–1.4	0.01-0.1	>0.1
Peak current	[kA]	1700	1-5	~1000
Energy spread (rms)	[%]	0.1	0.01	1
Bunch length (rms)	[μm]	0.01–0.1	1-100	0.005
Bunch size (rms)	[μm]	0.01 0.01	10 10	3 3

[1] V. Yakimenko et al. **On the Prospect of Studying Nonperturbative QED with Beam-Beam Collisions**, Phys. Rev. Lett. 122, 190404 (2019)

- Small intense e+/e- bunches required for high luminosity
- Large field of opposite bunch results in strong acceleration producing synchrotron radiation ("beamstrahlung")
- What if the bunch length was made small enough to "switch off" beamstrahlung?

PWFA beams may offer opportunity to study MA-compression relevant for short-bunch colliders

PWFA-driven Attosecond X-ray (PAX) source

- PAX uses a pre-bunched nm-long MA e-beam instead of startup from noise to generate X-rays

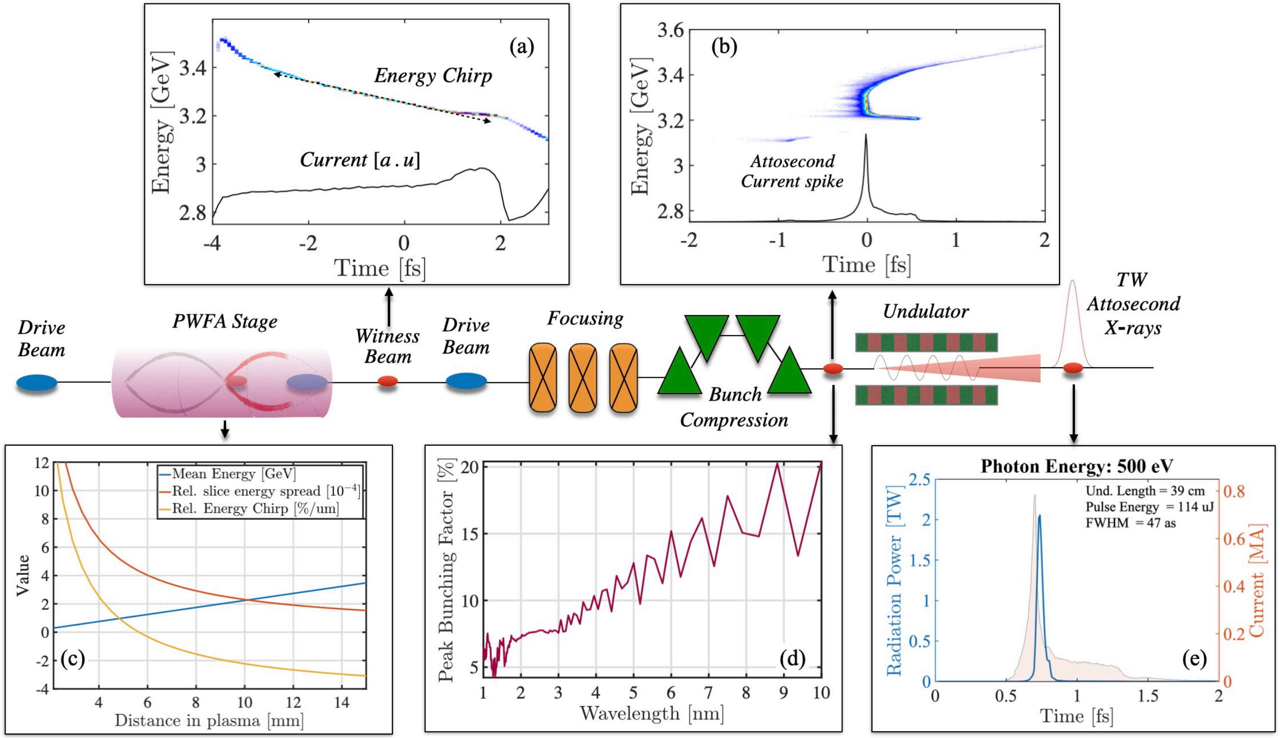
- **Pre-bunched beam means scheme is less sensitive to:**

(1) Emittance in undulator (5x)

(2) Slice energy spread in undulator (10x)

(3) Pointing jitter going into undulator (10x)

- Drive beam may be separated in chicane with transverse collimation



PAX in context of state-of-the art LWFA-FEL schemes

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<u>Comparison between PAX and LWFA-FEL parameters</u>

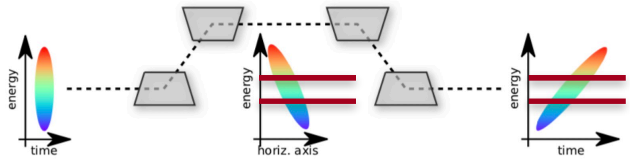
Energy -> 10x

Charge -> 10-100x

Energy spread -> 1x

Divergence -> 0.1-0.01x

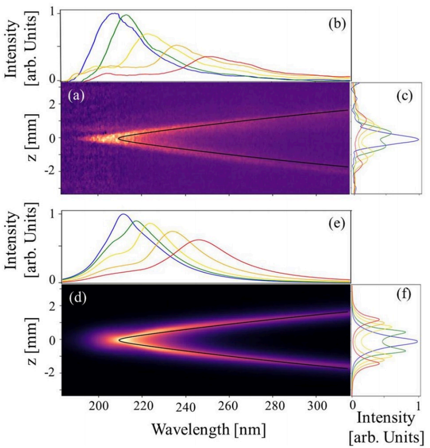
LWFA-FEL Concept



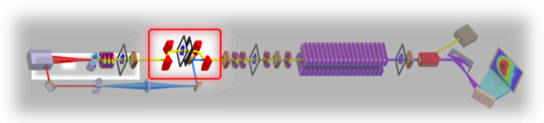
[A.R. Maier et al., Phys. Rev. X **2**, 031019 (2012)]

COXINEL collaboration

A. Gaith, Nature Sci. Reports (2019)



Insertion of a slit in the middle of the chicane



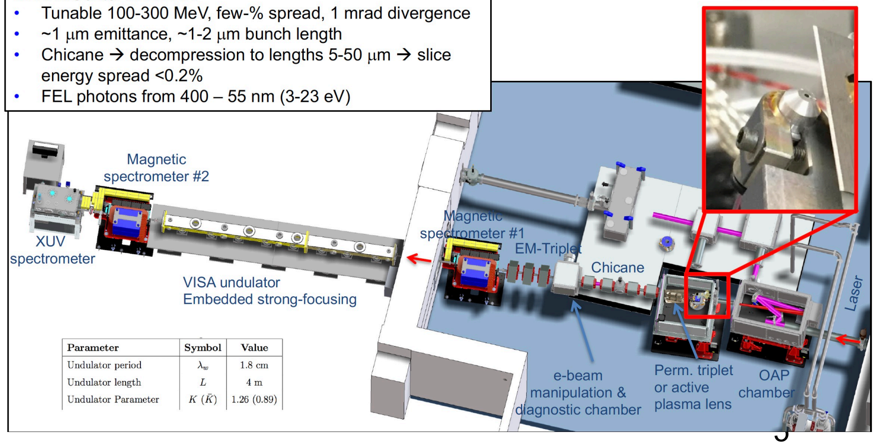
E	Slit	σ_γ	σ_x	σ'_x	σ_z	σ'_z	σ_l	Q
MeV	mm	%	μm	μrad	μm	μrad	μm	pC
176	3	3.0	800	650	240	1100	140	2.5
161	4	3.1	860	580	120	1450	135	5.6
161	3	2.6	800	570	115	1390	115	4.8
161	2	2.0	740	560	120	1290	90	3.7
161	1	1.4	680	550	130	1060	60	2.1

Undulator radiation @ 200 nm observed

LBNL

BELLA Center LPA FEL:

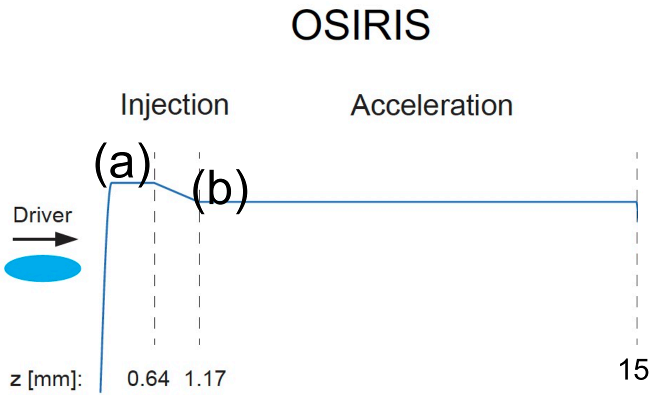
- Tunable 100-300 MeV, few-% spread, 1 mrad divergence
- ~1 μm emittance, ~1-2 μm bunch length
- Chicane → decompression to lengths 5-50 μm → slice energy spread <0.2%
- FEL photons from 400 – 55 nm (3-23 eV)

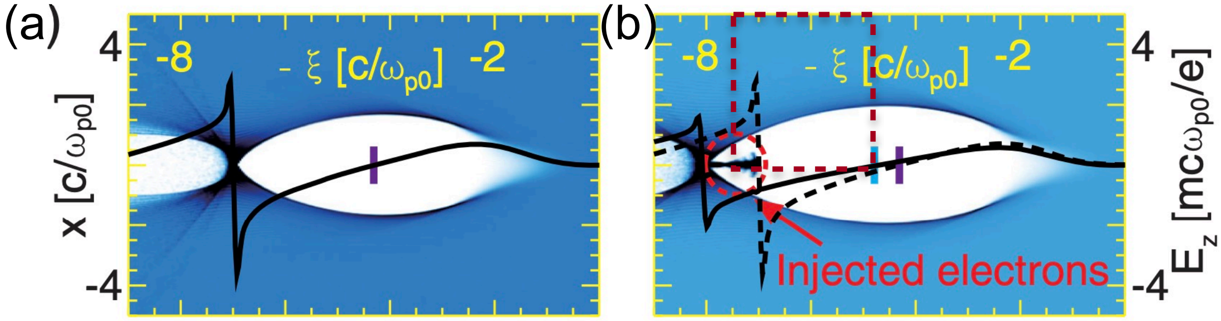


Parameter	Symbol	Value
Undulator period	λ_u	1.8 cm
Undulator length	L	4 m
Undulator Parameter	K ($\bar{K}$)	1.26 (0.89)

X. Xu, et al., PRAB 20, 111303 (2017)
X. Xu, FACET-II Science Workshop 2019

PWFA Stage beam dynamics - injection





$-eE_z = 2.5$ GeV/cm

$eE_z' = 90$ MeV/cm/um

	E_d [GeV]	I [kA]	σ_r [um]	σ_z [um]	ε_n [um]	Q [nC]
Driver beam	2	34 (Λ=4)	2.7	5.3	5.3	1.5

	$n_{p,h}$ [cm^{-3}]	n_{p0} [cm^{-3}]	L_{ramp} [mm]	L_{acc} [mm]	Initial T [eV]
Plasma	1.1e18	1e18	0.53	5.22	[0.5, 0.5, 0.5]

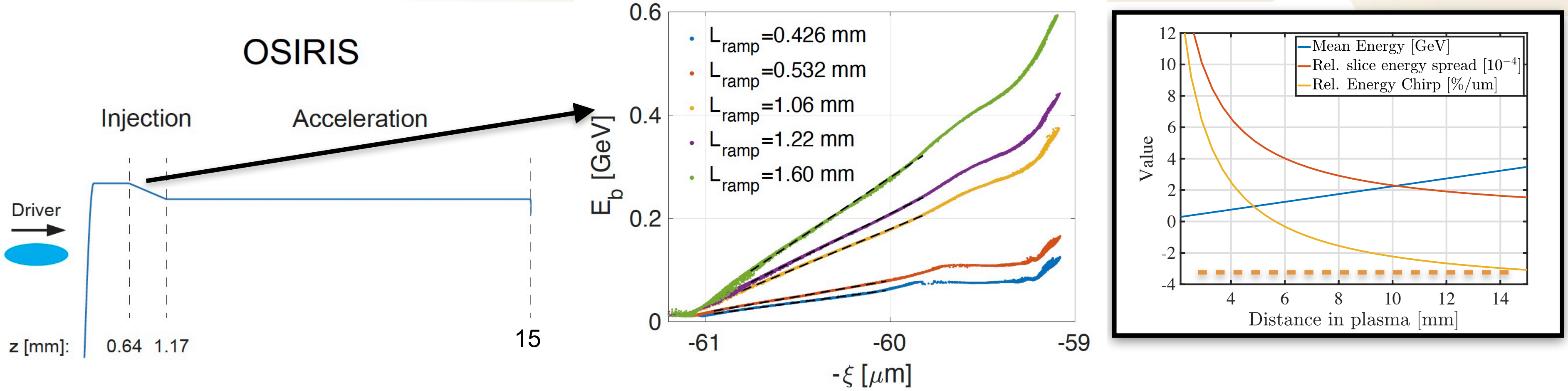
Skin Depth

$c/\omega_{p0} = 5.3\mu m$

X. Xu, et al., PRAB 20, 111303 (2017)

X. Xu, FACET-II Science Workshop 2019

PWFA Stage beam dynamics - acceleration



- After plasma chicane will compress beam to a bunch length $\sigma_{z,f}^2 = (1 + hR_{56})^2\sigma_{z,i}^2 + R_{5,6}^2\sigma_{\delta,i}^2$
- Relative chirp tends to asymptotic value h = $E_z'/E_z \approx \ \propto \omega_p$ = -3.6%/um
- R_{56} needed for full compression = |1/h| = 28 um
- Shortest σ_z limited by slice energy spread $\sigma_{z,min} = R_{56}\sigma_\delta = \sigma_\delta / h$ ~ 5 nm
- **Take-away:** want large h to allow compression with small R_{56} and small slice energy spread to reach shorter final bunch length

X. Xu, et al., PRAB 20, 111303 (2017)
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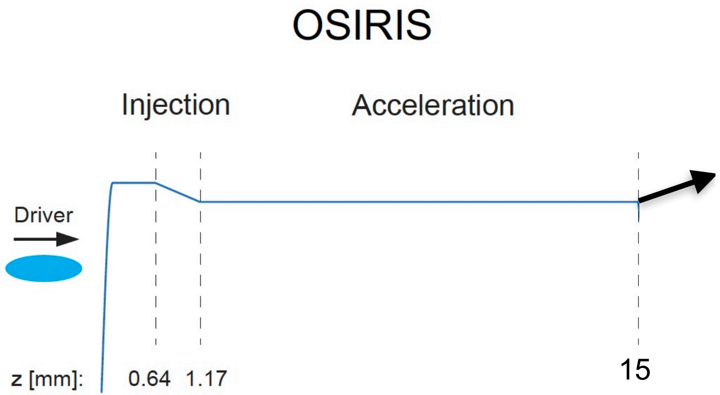
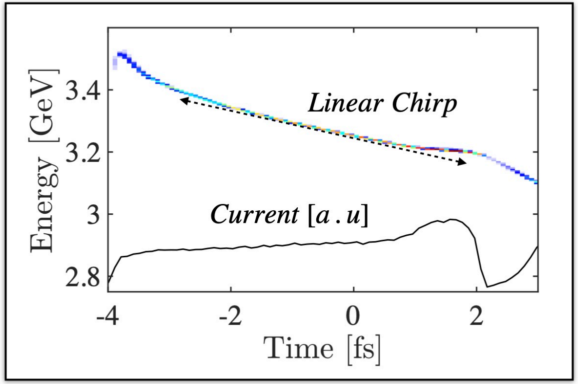
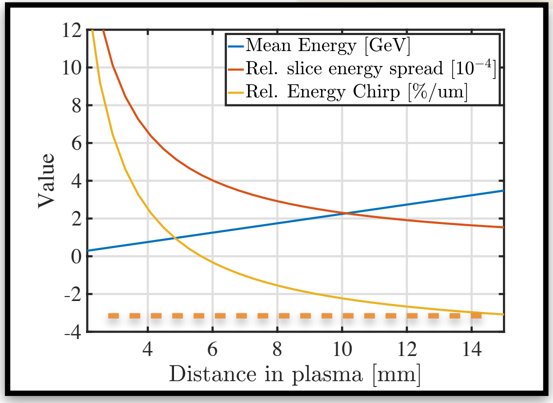
PWFA Stage beam dynamics - acceleration







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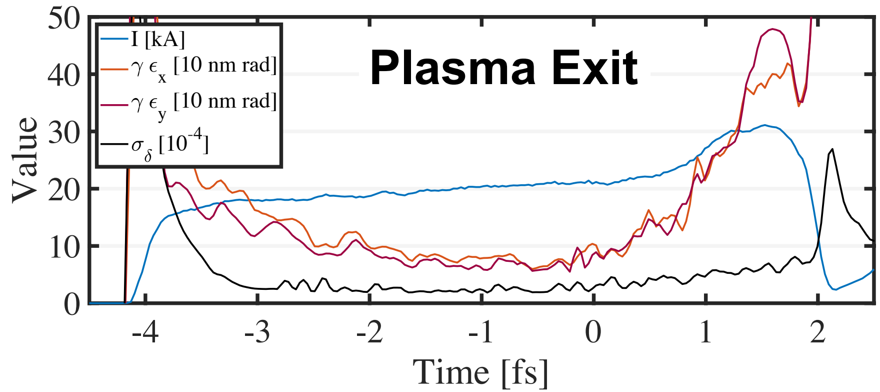
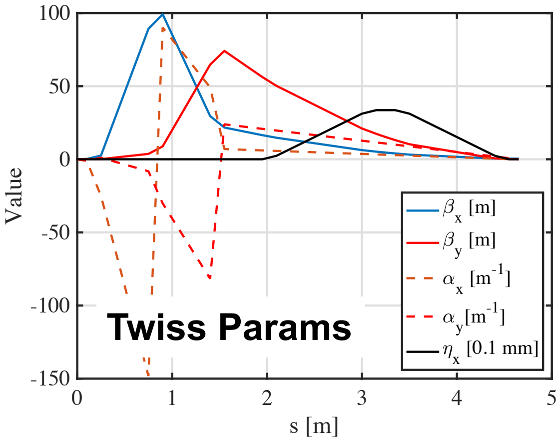
Beam dynamics from plasma to undulator

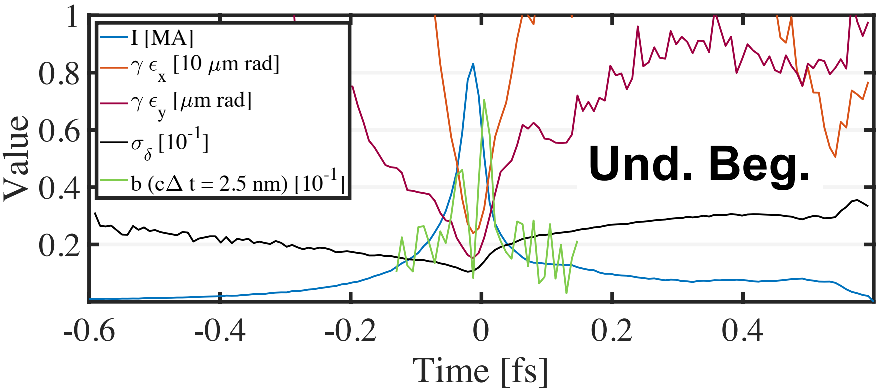




Parameter	Value
Bend Angle	3.4 mrad
R_{56}	23 um
Dispersion	3.3 mm

FWHM = 15 nm

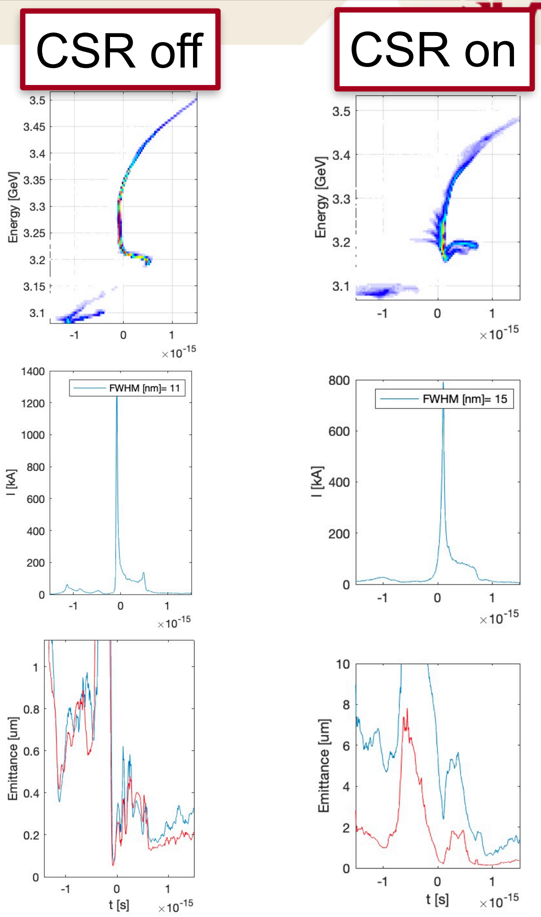
$$B_{5D} = 2I/\epsilon_x\epsilon_y$$
$$= 1.4 \times 10^{19} Am^{-2}$$
$$B_{5D,LCLS} = 6 \times 10^{16} Am^{-2}$$



- Small R_{56} enabled by large chirp going into chicane reduces CSR effects on bunch despite 40x compression factor
- 7% peak bunching @ 0.7 MA drives radiation in bunch head

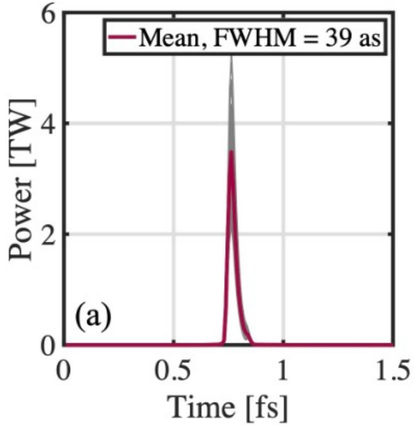
CSR in bunch compressor

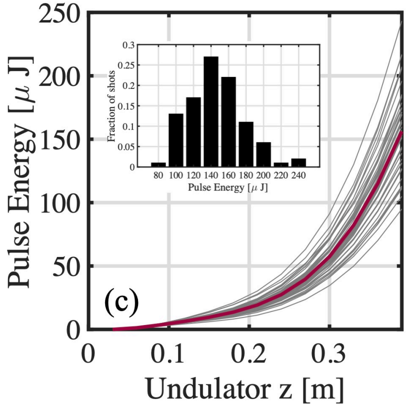
- CSR causes different energy loss along bunch and spread in angles (emittance) as beam bends in final dipole.
- We model effect in ELEGANT which assumes 1D model. This is valid provided D = $\sigma_x/\sigma_z^{1/3}R_{bend}$ < 1, where $R_{bend} \approx L_{bend}/\theta_{bend}$ (D = 0.27 for our parameters).
- CSR effect is reduced by reducing the spot-size in final dipole & increasing the bend radius.
- Relative kick <20 urad coming out of chicane
- With pre-bunched into undulator emittance of ~2 um is sufficient for lasing @ 2.5 nm (see next slides)



Performance of scheme in simulation

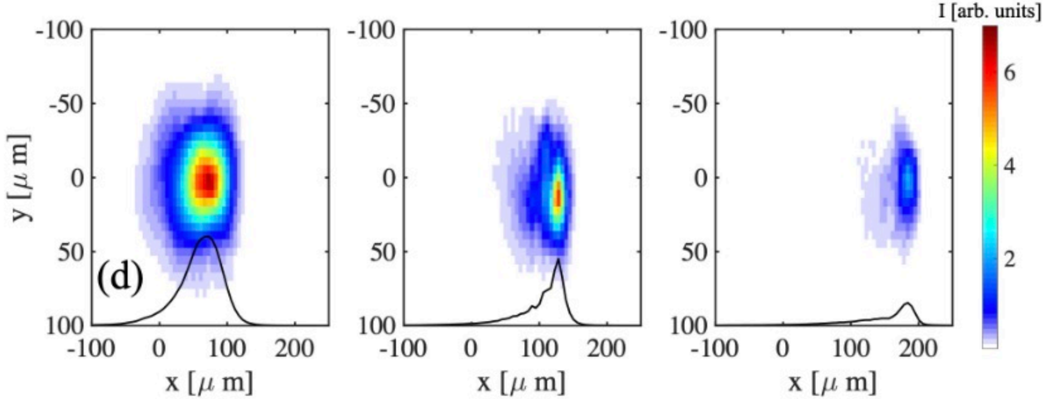
Radiation output



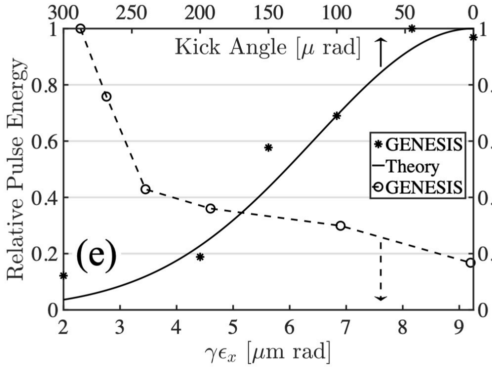


Tunable 20-100 as pulses with
1-5 TW peak power

Compared to XFEL
>10x looser tolerance to transverse jitter
>2x looser tolerance to emittance
100x larger RMS energy spread tolerable
~10x smaller pulse energy fluctuations



Transverse Tolerance



Y. Ding et al., PRSTAB **12**, 060703 (2009)
J. Duris, et al., Nature Photonics **14**, 30–36(2020)
P. Baxevanis, et al., PRSTAB 21, 110702 (2018)

Space Charge effects for MA-beams

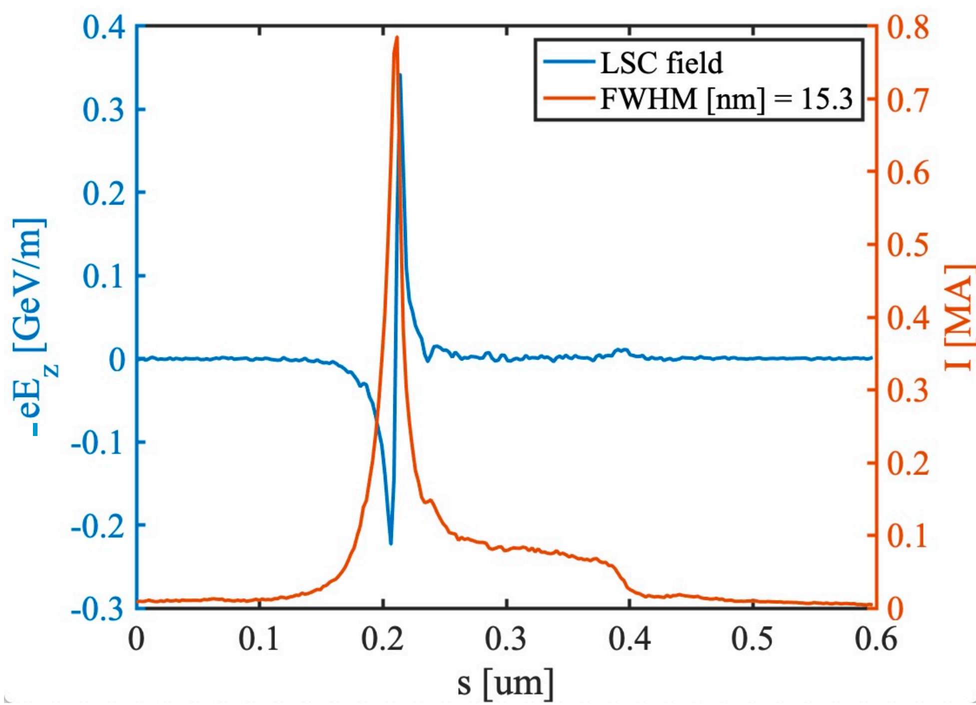
LSC field

$$E_z = \frac{Z_0 I'(s)}{4\pi\gamma_z}\left[2\log\left(\frac{\gamma_z\sigma_z}{r_b}\right)\right]$$

Chirp-taper

$$\frac{K}{1+K^2}\frac{dK_u}{dz}\lambda_w = \frac{d\gamma}{ds}\lambda_r$$

- MA beam will develop large chirp 100s of MeV over 1m of undulator due to LSC field.
- Chirp can be compensated by taper and can further reduce the pulse length below length of the spike.



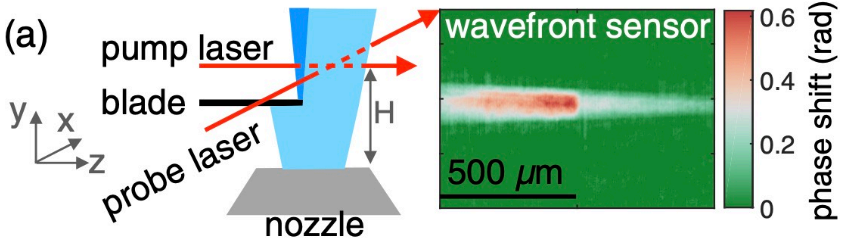
What can we do at FACET-II?

10-GeV 10-300 kA drive beam at FACET-II will enable study of chirped multi-GeV high brightness beams.

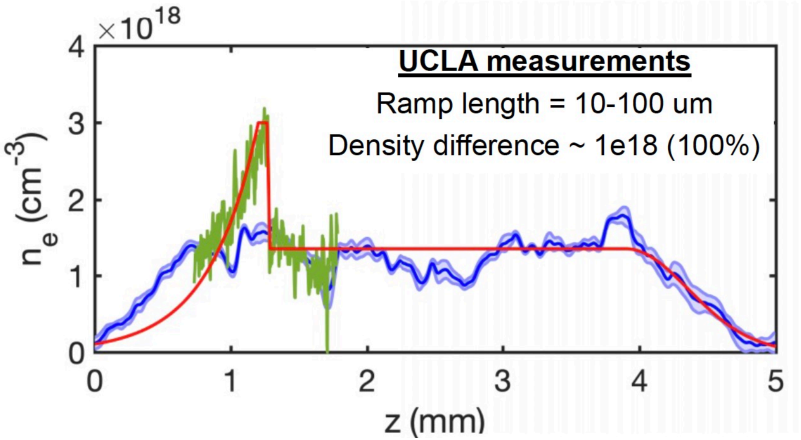
Multiple approved experiments will need similar plasma sources:

- E-301: Tailored Plasma Source for emittance preservation.
- E-304: Density Downramp Injection
- E-310: Trojan horse 2
  => We can learn a lot from success of these experiments.

- Proposal for dedicated beam time to study as-pulse generation to be submitted to PAC in fall.



C. Zhang, PRAB 22, 11301 (2019)



Conclusion

- We are studying the generation of high intensity attosecond electron and photon beams using strong chirped e-beams generated in PWFAs.

- The PAX source combines the benefits of HHG and XFELs opening up new experimental opportunities in field of attosecond science

- Extreme compression of electron beams to MA current of interest to collider applications may be achieved while preserving um level emittance and %-level energy spread.

- Synergies between BES and HEP applications - good opportunity for cross-cutting in line with DOE office for accelerator science R&D

- **Looking forward:**
  - Scaling of method to higher e- and photon energy and preservation of sub-um emittance.
  - Study drive beam separation (important for collider & light source applications).
  - Plan for experimental demonstration of extreme chirping/compression (FACET-II).