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Beam-driven afterburners for extending the spectral reach of XFELs

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- PSI Swiss FEL team: S. Reiche, R. Ischebeck, C. Vicario, E. Prat, P. Craievich, P. Juranic, M. Huppert, R. Dadashi
- SLAC: M. Hogan, C. Emma
- UCLA: A. Fisher, M. Lenz, P. Denham, E. Cropp, S. Crisp, D. Garcia, G. Andonian

- Looking to expand the effort. Get in touch if interested

radiabeam TECHNOLOGIES

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GORDON AND BETTY MOORE FOUNDATION

Outline

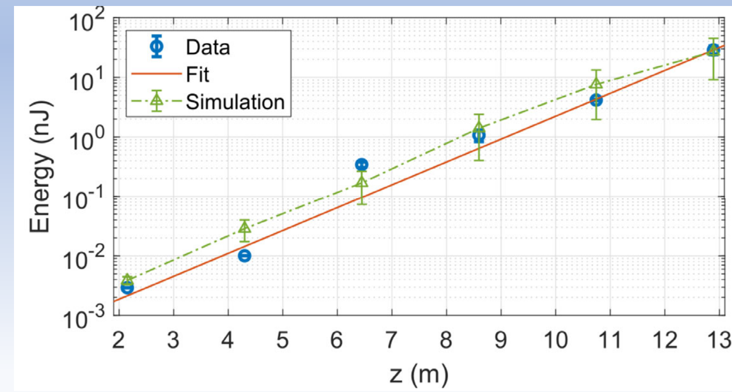
- Background and motivations
  - Recent plasma-based FELs
  - Spectral reach of XFELs
  - Pump-probe / driver-witness generation
- Plasma and dielectric wakefield approaches
- Ongoing effort at PSI

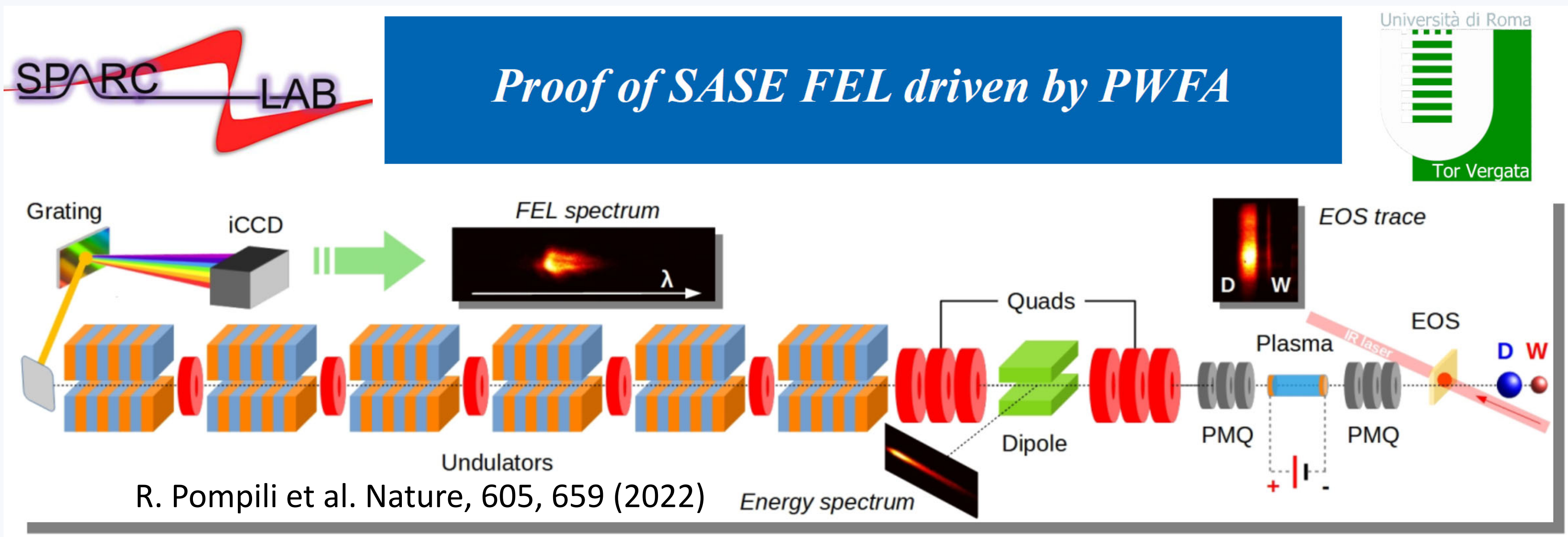
Beam driven plasma-based FEL at SPARC

- Witness beam 87.5 MeV -> 94 MeV lasing (200 MV/m gradient)
- From a different perspective:

  7.5 % beam energy increase -> 15 % higher energy photons

$$\lambda_\ell = \frac{\lambda_u}{2\gamma_r^2}\left(1 + \frac{K^2}{2}\right)$$

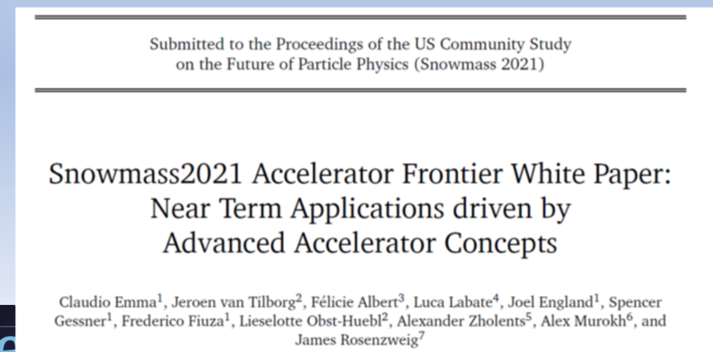




R. Pompili et al. Nature, 605, 659 (2022)

Need for near-term applications of advanced accelerator technology

- 15 TeV advanced accelerator-based collider decades away
- Real-world applications will strengthen the case and demonstrate key-milestones before next planning exercise
- Identified as priority in AF6 Snowmass report
- Look out for scientific opportunities to make big impact



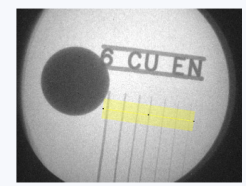
Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

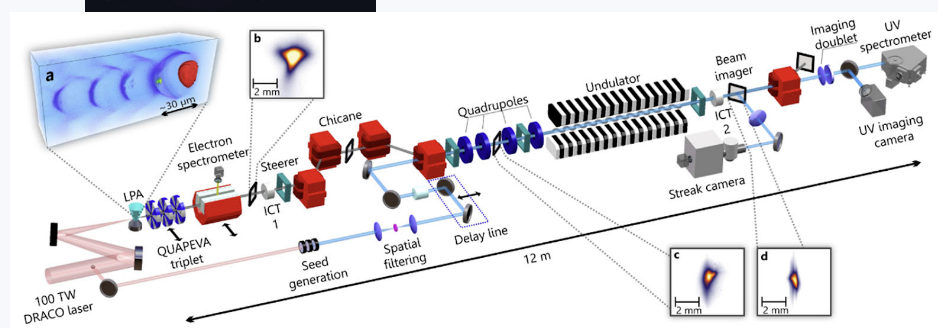
Snowmass2021 Accelerator Frontier White Paper: Near Term Applications driven by Advanced Accelerator Concepts

Claudio Emma[1], Jeroen van Tilborg[2], Félicie Albert[3], Luca Labate[4], Joel England[1], Spencer Gessner[1], Frederico Fiuza[1], Lieselotte Obst-Huebl[2], Alexander Zholents[5], Alex Murokh[6], and James Rosenzweig[7]

LWFA FEL: W. Wang et. al, Nature Vol 595 (2021)

LWFA Thomson precision imaging

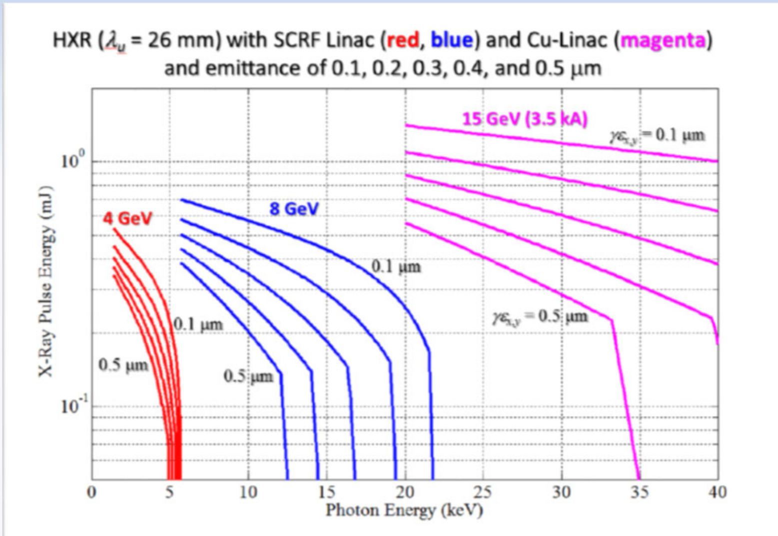


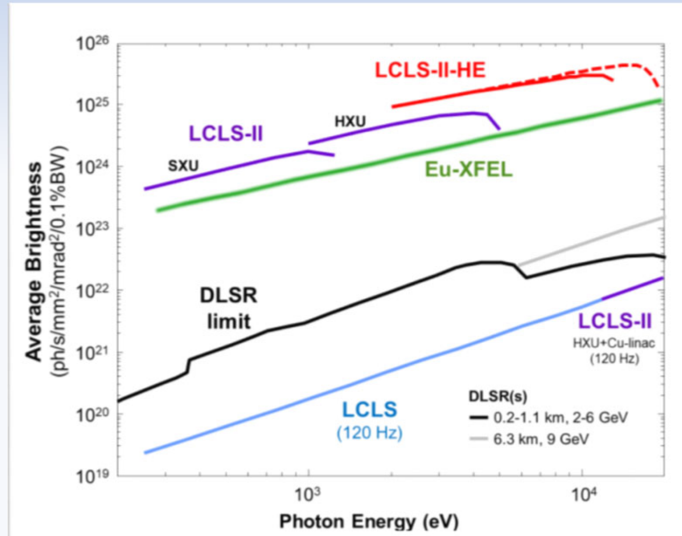


Seeded FEL: M. Labat et al.: DOI:10.21203/rs.3.rs-1692828/v1

LCLS-II-HE project

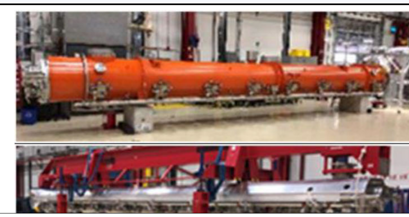
- Increase SRF linac energy to 8 GeV
- Need to improve beam emittance to laser at 4x photon energy (20 keV)
- Big project





From L. Horton presentation (DOE BESAC April 2022)

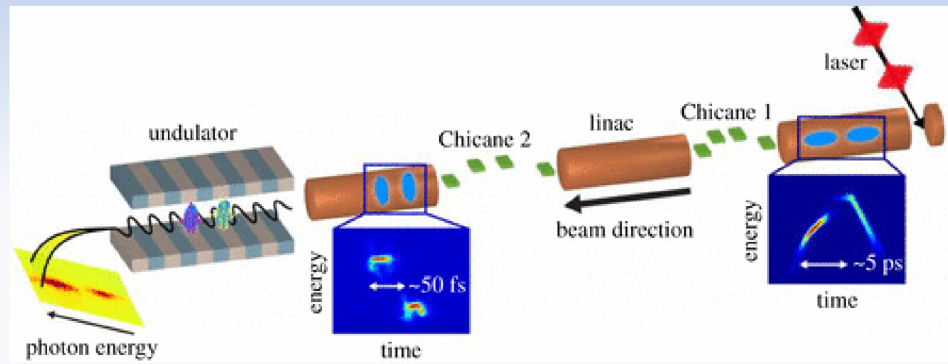
- **LCLS-II-HE: CD-1** (9/21/2018), **3A** (5/12/2020) Scope includes a low-emittance superconducting electron gun & independent cryoplant (current TPC estimate is $660M); R&D, design, prototyping, and long lead time procurements underway. COVID impacts and need for increased cost contingency delay CD-2/3 & could impact TPC. CD-2/3 now planned for 4Q FY 2023; CD-4 for 2Q FY 2031.



Double bunch generation schemes

- Multiple schemes **already** available to generate two bunches with nearly arbitrary (and adjustable) delays for pump-probe studies
- Shape could be optimized for drive/witness wakefield temporal format
- Beam-driven advanced accelerators (plasma or dielectric) can easily provide GeV-class energy gains in meter long structures

R. Coffee et al.
https://doi.org/10.1098/rsta.2018.0386



From C. Vicario et al. PRAB **24**, 060703 (2021)

P. Dijkstal et al., Phys. Rev. Accel. Beams 23, 030703 (2020).
Y.-C. Chao et al., Phys. Rev. Lett. 121, 064802 (2018).
E. Ferrari et al., Nat. Commun. 7, 10343 (2016).
C. Ronsivalle et al., New J. Phys. 16, 033018 (2014).

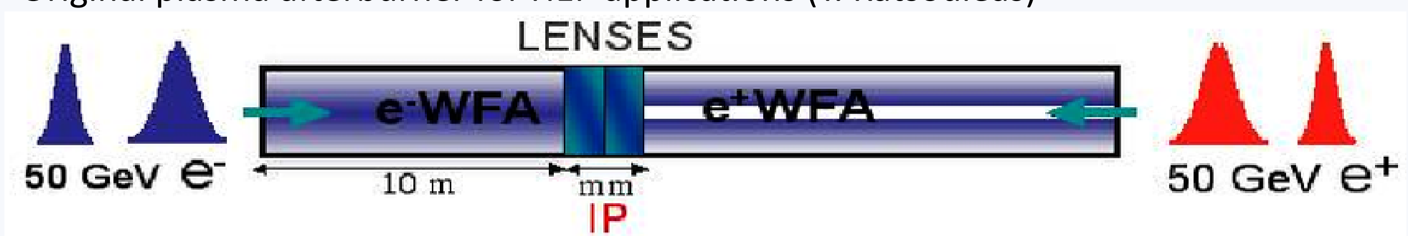
A. Marinelli et al., Nat. Commun. 6, 6369 (2015).
S. Bettoni et al., Phys. Rev. Accel. Beams 19, 050702 (2016).
A. S. Hernández et al., PRAB 22, 030702 (2019).
A. Marinelli et al., Phys. Rev. Lett. 116, 254801 (2016).

Two-color methods	Specific advantages	Specific limitations	Maximum power	Common features
Laser emittance spoiler (this article)	Simple, usable at any rep. rate	Two different laser pulses required	Potentially full saturation power	Δt and $\Delta\lambda$ tunability limited by the e beam duration and energy, Δt-$\Delta\lambda$ correlation, same longitudinal FEL source point
Twin bunches [24]	High FEL pulse energy	Complex setup		
Two-bucket bunches	ns delay, same color feasible	Complex setup		
Double-slot foil [26]	Simple	Beam losses		
Sextupole [19]	Usable at any rep. rate	Tilted beam		
Wakefield structures [25]	Low pump and probe jitter	Passive structure needed		

The FEL afterburner

- Many facilities could take advantage of drive/witness bunch generation and properly design advanced accelerator structure to increase beam energy.
- Lasing after 5-10 % scale relative energy gain has already been demonstrated
- Large impact could be obtained even with relatively conservative afterburner stage design.
  - Essentially free energy upgrade (no construction or drive power needed).
- Examples:
  - PSI need upgrade from 6 to 7 GeV to cover wavelength range in third undulator line
  - Eupraxia already includes PWFA to increase beam energy. Flash-Forward? FERMI?

Original plasma afterburner for HEP applications (T. Katsouleas)

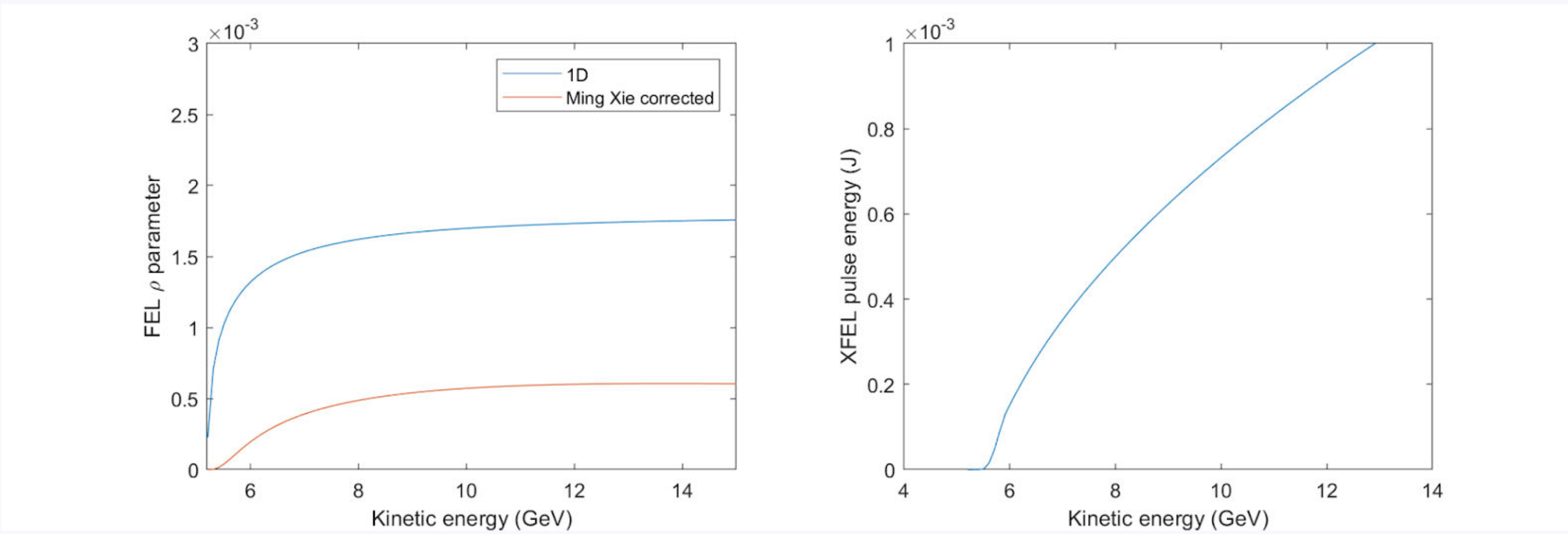


FEL afterburner advantages

For a fixed wavelength – adjusting K parameter to keep lasing at constant photon energy

- Increase brightness / reduce undulator length

Parameter	Value
Charge	100 pC
Norm. emittance	0.2 um
Peak current	2 kA
Lasing photon energy	10 keV
Undulator period	2.6 cm
Undulator length	150 m

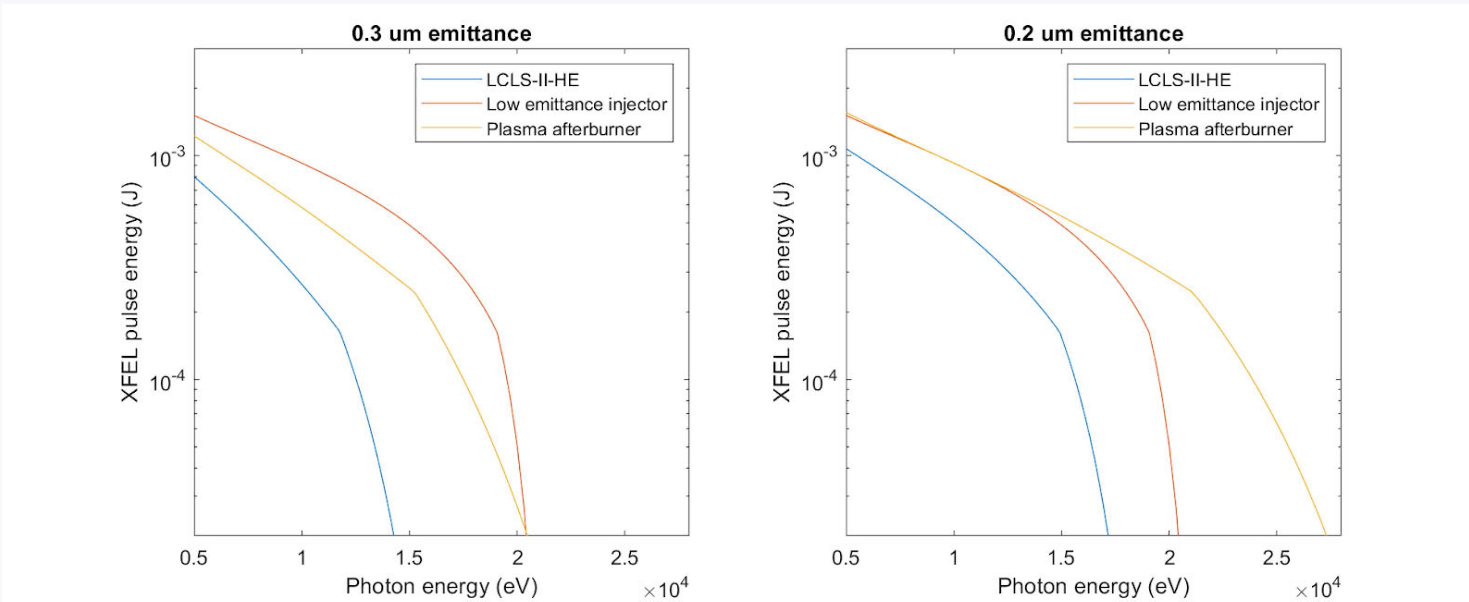


FEL afterburner advantages

12 GeV afterburner vs. original 8 GeV LCLS-II-HE case

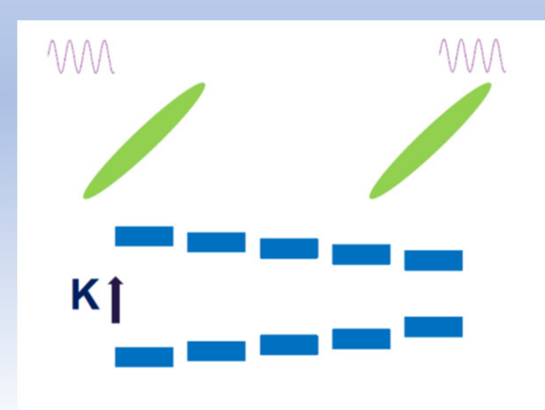
Low emittance injector gives 0.1 mm-mrad

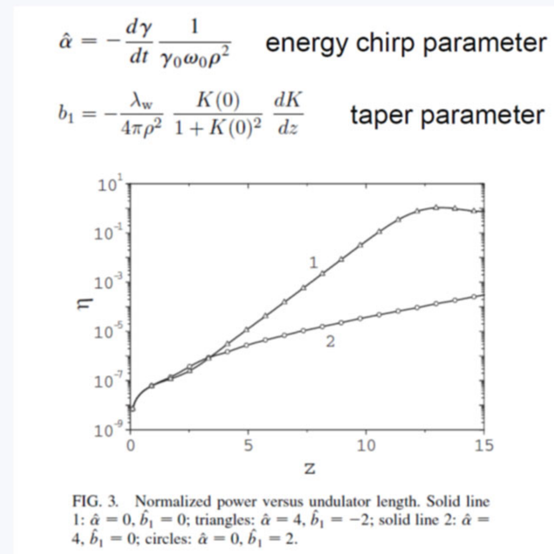
Parameter	Value
Charge	100 pC
Peak current	2 kA
Undulator period	2.6 cm
Undulator length	150 m

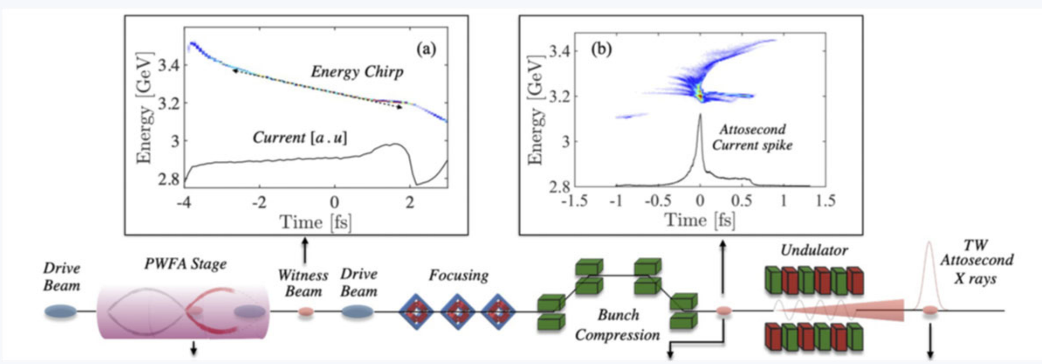


Beam quality considerations

- Witness beam emittance needs to be preserved at 100 nm level
- Energy spread < 5e-4
  - Assuming 10 ps accelerating wave period (i.e. plasma density 10^14 cc the witness injection length is < 50 fs
- Chirp and cooperation length.
  - Especially at the shortest wavelengths (where afterburner will be most useful) cooperation length can be kept very short and lasing can occur even for chirped beams (i.e. energy chirp parameter <<1)
  - Example: For 4 GeV gain, max chirp on the beam is 7 MeV/um. But L_coop is typically < 0.1 um so energy spread in a slice is much less than 5e-4.
- Chirp can be used to enhance current (PAX scheme)

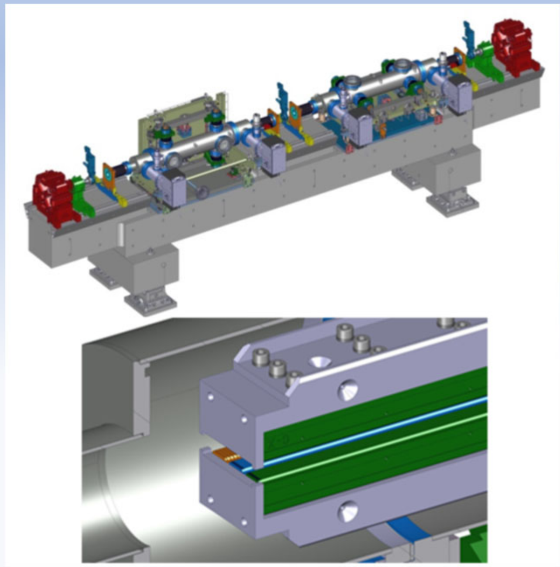




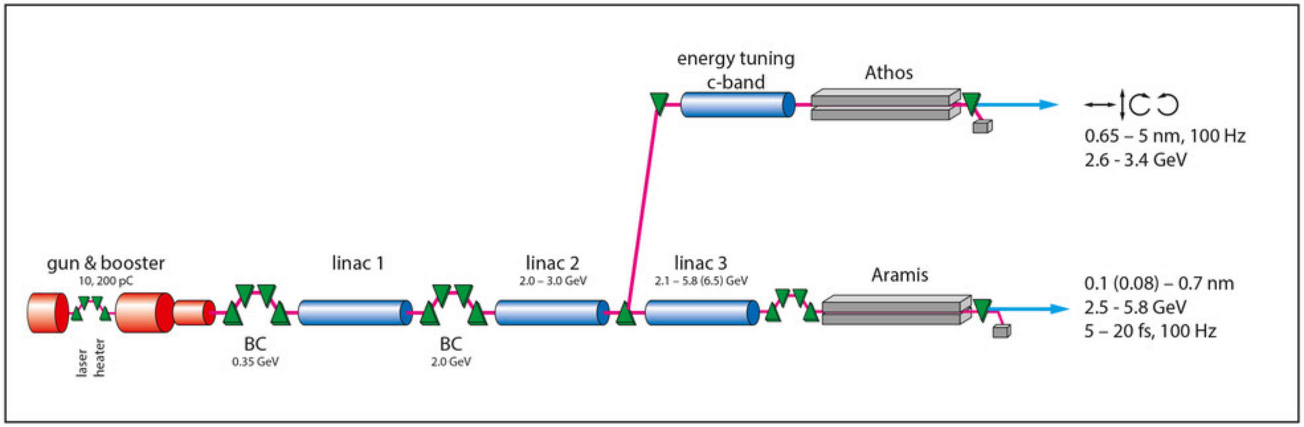


From Schneidmiller, Saldin, Yurkov, PRSTAB 2006

Dielectric Wakefield Accelerator experiment at SWISS FEL



- Aramis hard X-ray beamline
- Planar gap-adjustable 2 m long dielectric dechirper structures available
- 400 um thick Alumina coating
- Gap can be closed to < 0.5 mm
- Vertical and horizontal slabs to compensate emittance growth from quadrupole mode (C. Lu, PRAB 2016)



Conclusion

- FEL afterburner is a scientific opportunity for advanced accelerators to make impact at large scale facilities
- GeV-scale relatively modest (<50 %) energy gain in short distances would already open new capabilities in most places.
- No additional drive power requirements !

- Conservative design allows to push on beam quality preservation
- Dielectric structures already under investigation at SWISSFEL.
- Plasma afterburner for LCLS-II-HE would need high brightness acceleration of witness beam at FACET-II.