雷射驅動電漿高增益自由電子雷射
LPA-driven High Gain FELs

2025.01.07

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Outline

- *Short review for high gain FELs*
- *Electron Beams from Plasma Acceleration*
- *Beam Manipulation: Making LPA Beams FEL-Ready*
- *FEL simulation examples for LPA Beams*
- *Experimental Progress and Ongoing works*
- *Summary*

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https://www.youtube.com/watch?v=YTj4Hi1HdJQ

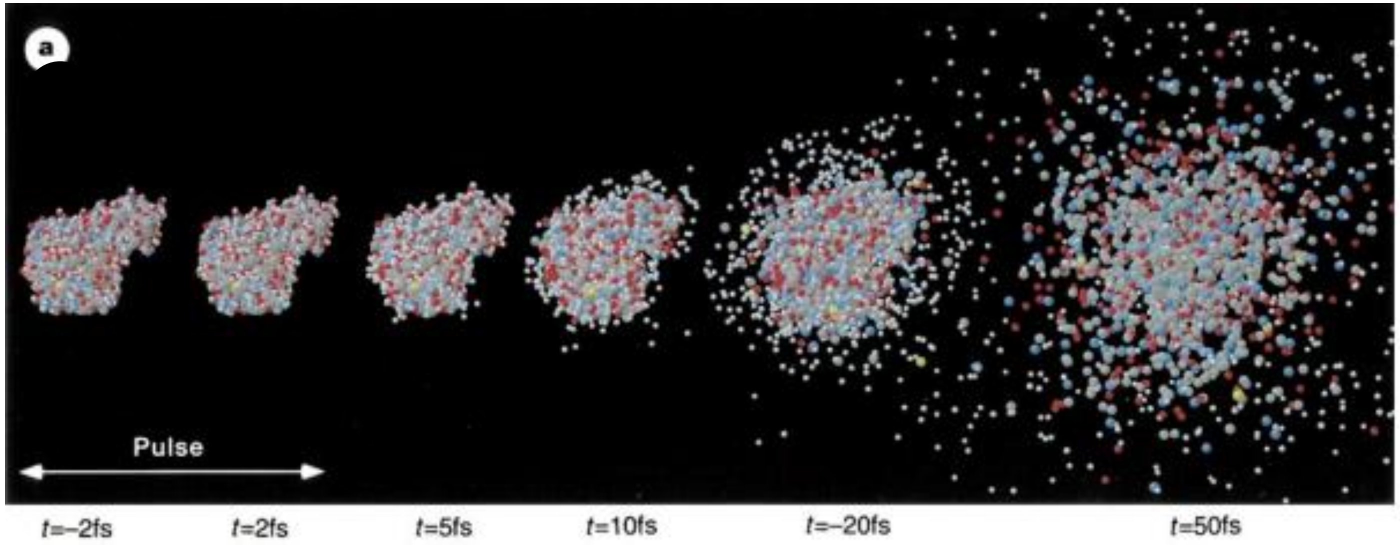
Static properties of matter

Static picture of a macro-molecule

Need light !

Required properties

- Short wavelength (X-ray)
- Ultra-short pulse (few femtoseconds)
- Coherence
- High energy per pulse

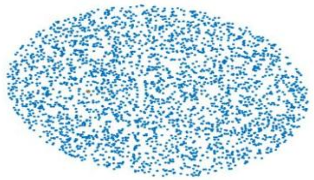


Free electron laser

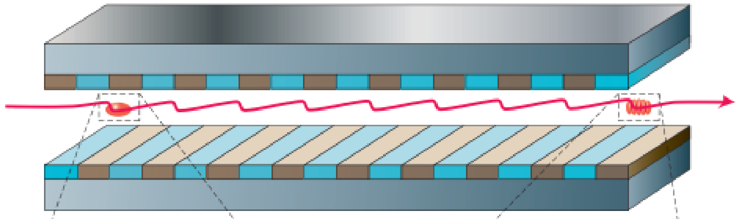
- A Free electron laser is an accelerator based light source that can generate intense radiation from a relativistic electron beam in a periodic magnetic field

Basic components

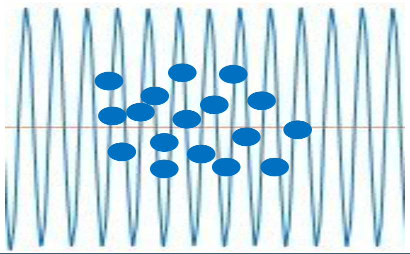
- Relativistic electron beam



- Undulator : periodic magnetic field



- Electromagnetic field : propagating with electron beam and getting amplified.



Energy (γ)
Current (I)
Emittance (ε)
Energy spread ($\Delta\gamma$)

Undulator period (λ_u)
Undulator parameter (K)
Undulator length (L)

Resonant wavelength (λ)
Saturation power (P)

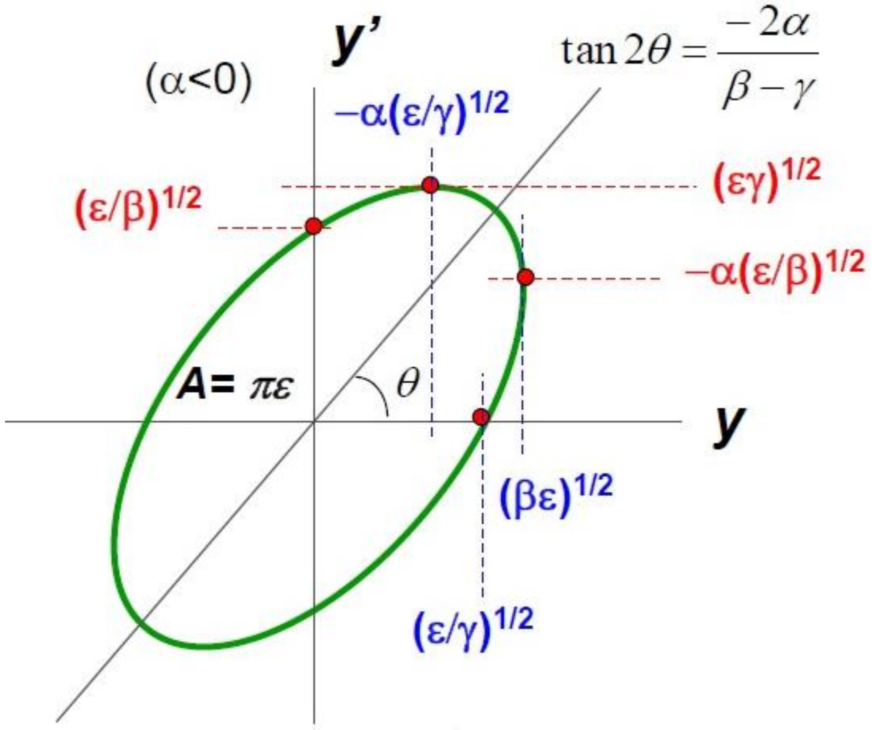
Resonant condition $\lambda = \frac{\lambda_u}{2\gamma^2}(1+\frac{K^2}{2})$

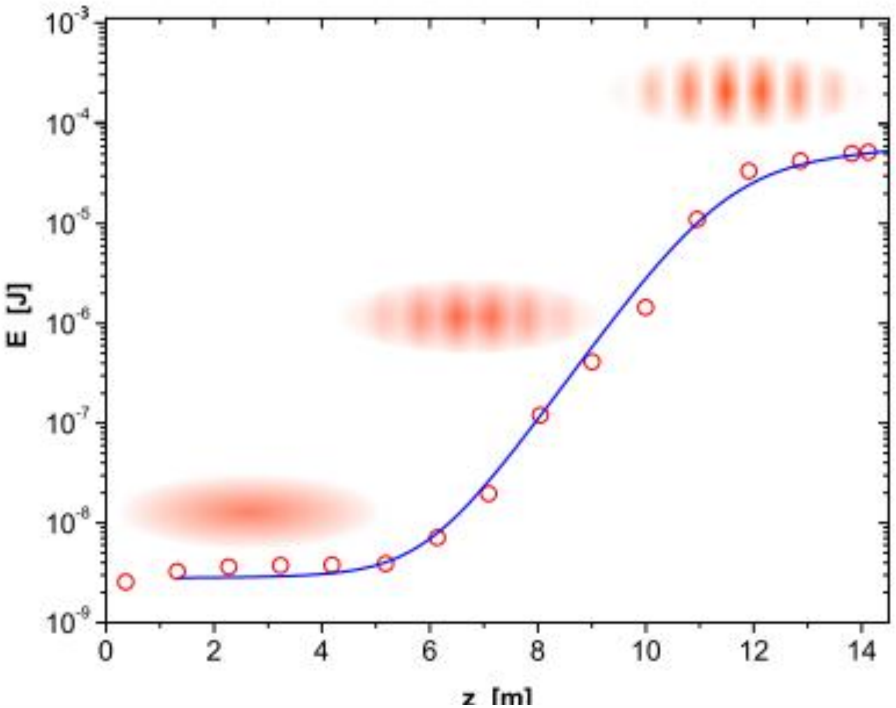
Key parameters for FELs

$$P_{sat} \approx \rho P_{beam}$$

$$L_{g(1D)} = \lambda_u / 4\pi\sqrt{3}\rho$$

emittance





Pierce parameter: $\rho = \left[\frac{1}{16} \frac{I_p}{I_A} \frac{K_0^2 [JJ]^2}{\gamma_0^3 \sigma_\perp^2 k_u^2} \right]^{\frac{1}{3}}$

For high gain FEL: $\sigma_\delta \leq \rho$, $\epsilon \leq \lambda_r / 4\pi$ ⇒

- High peak current
- Low energy spread
- Small emittance

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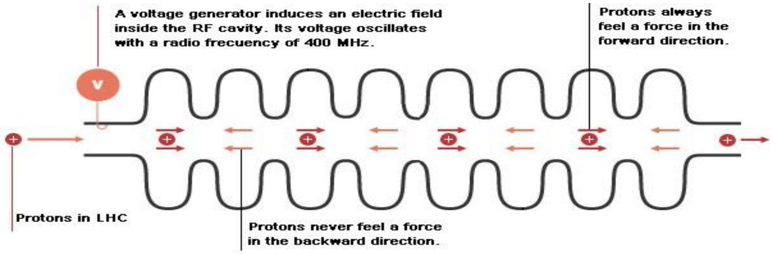
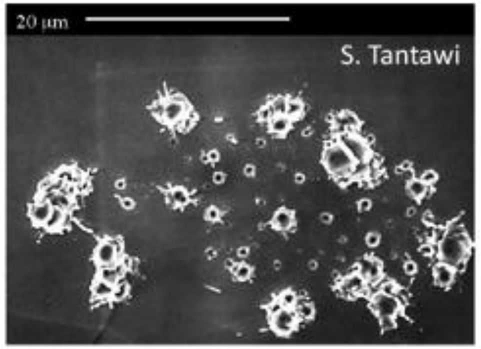
Accelerating Gradient

Conventional RF Cavities



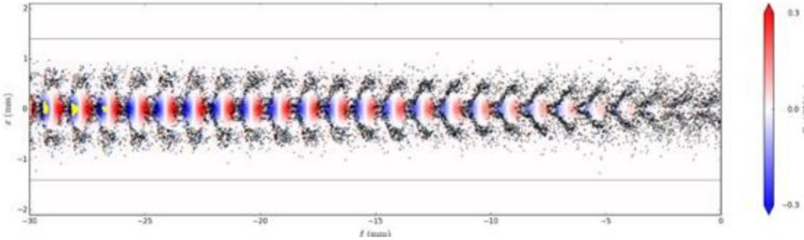
Surface of Copper Cell After Breakdown Events

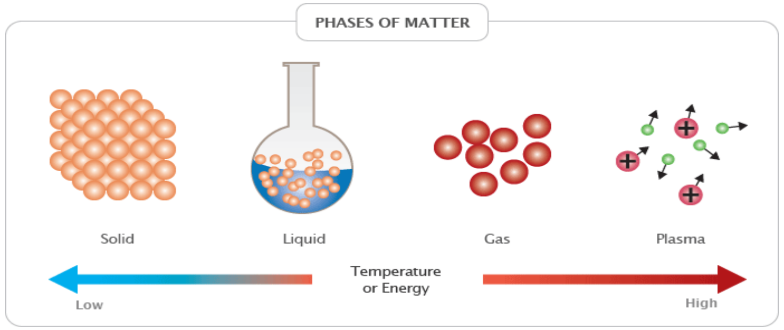


Accelerating fields are **limited to <100 MV/m**

In metallic structures, a too high field level leads to **break down** of surfaces, creating electric discharge. Fields cannot be sustained; structures might be damaged.

Plasma Acceleration



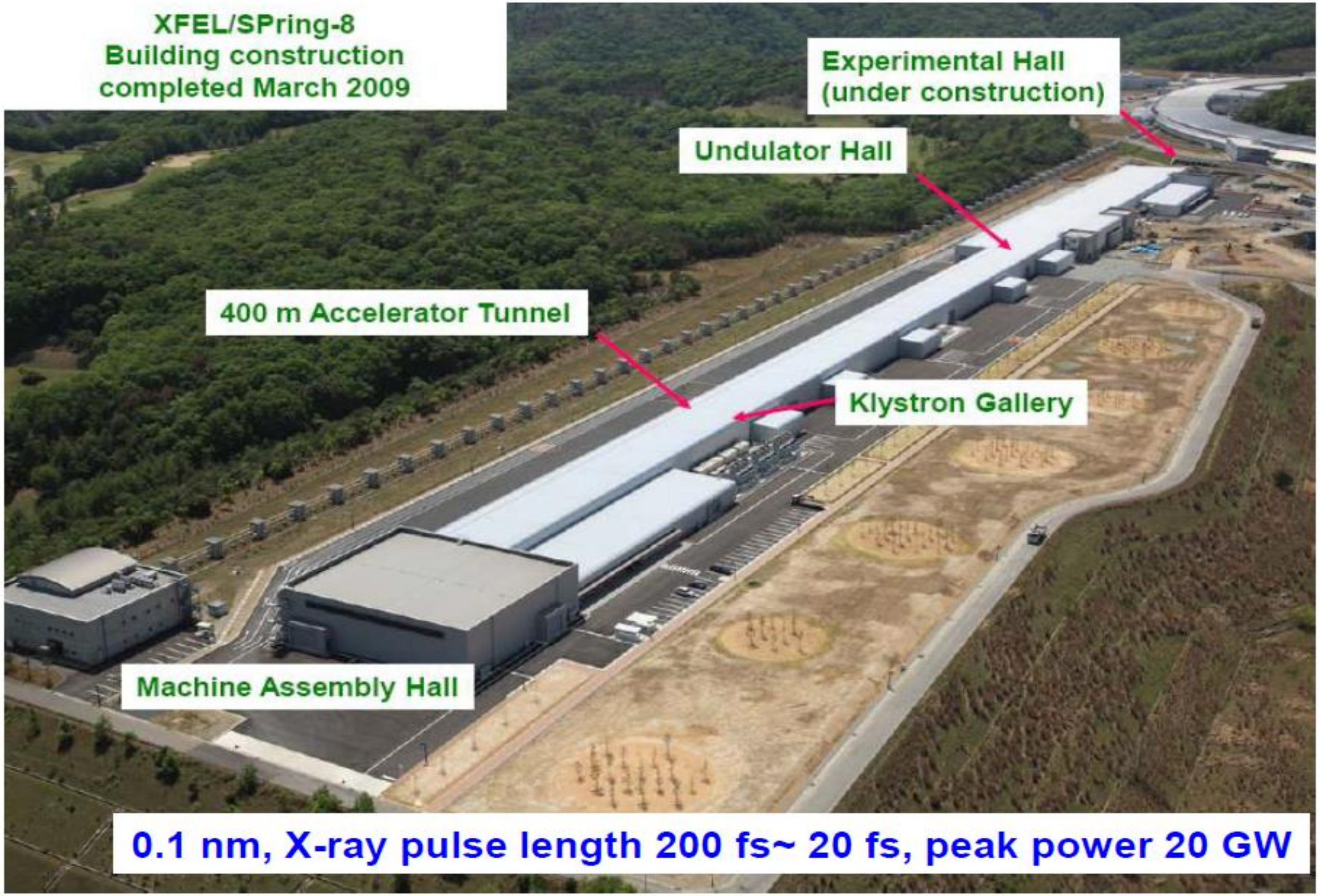


Plasma is already ionized or "broken-down" and can sustain **electric fields up to three orders of magnitude higher gradients**

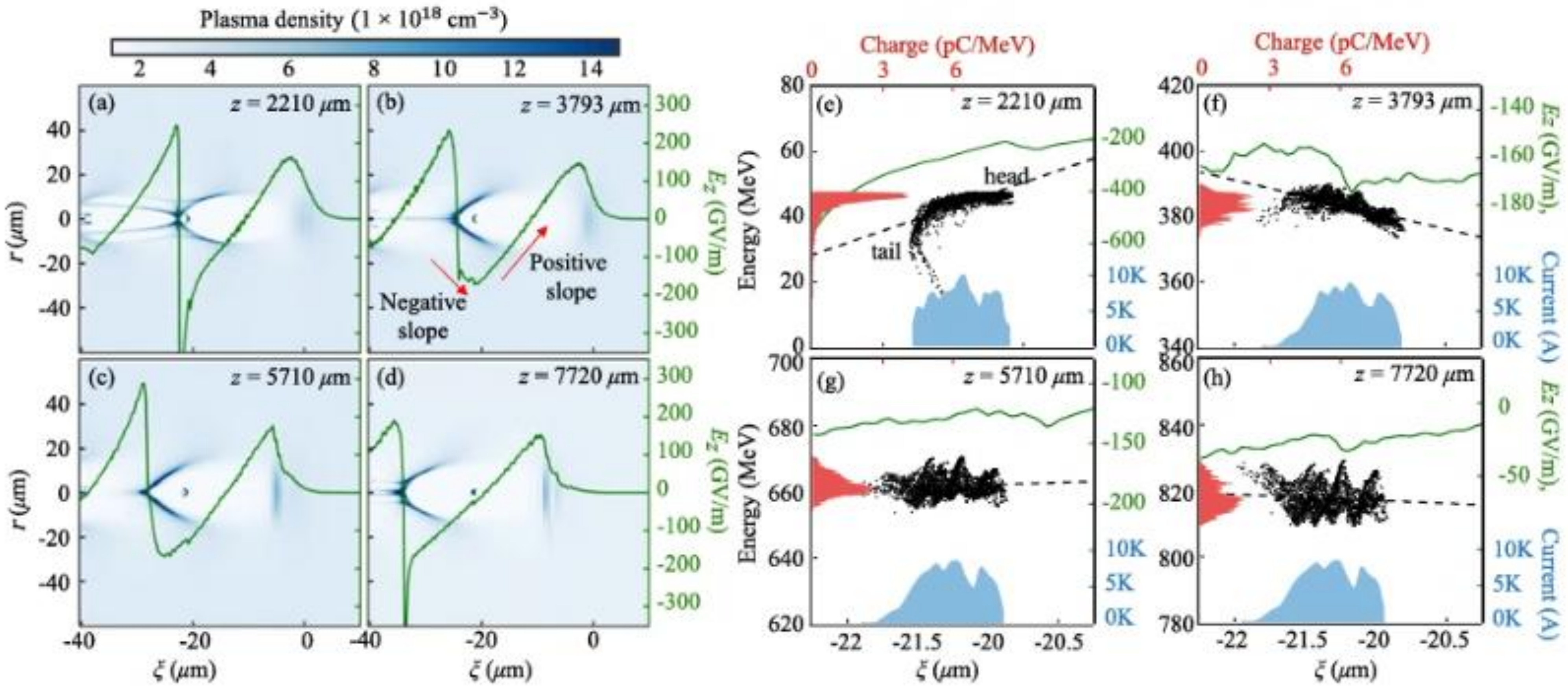
→ **order of 100 GV/m.**

→ **~1000 factor stronger acceleration!**

Example: Spring-8

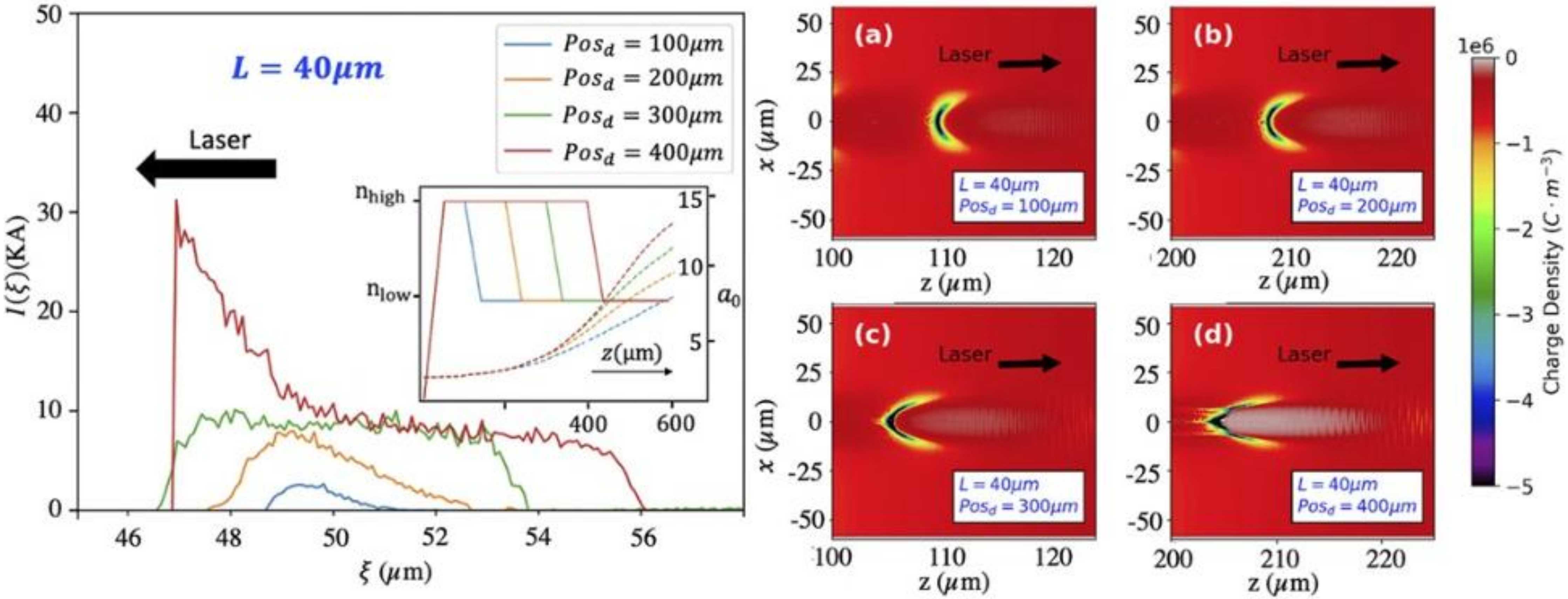


Electron energy and energy spread



- Both the density down ramp and the laser self-focusing contributed to the occurrence of injection
- The energy spread was compensated due to the evolution of the laser and the beam loading effects.
- The accelerating gradient was reached to 142 GV/m on average.
- The electron beam energy can reach 0.8GeV with sub percent energy spread and μm emittance

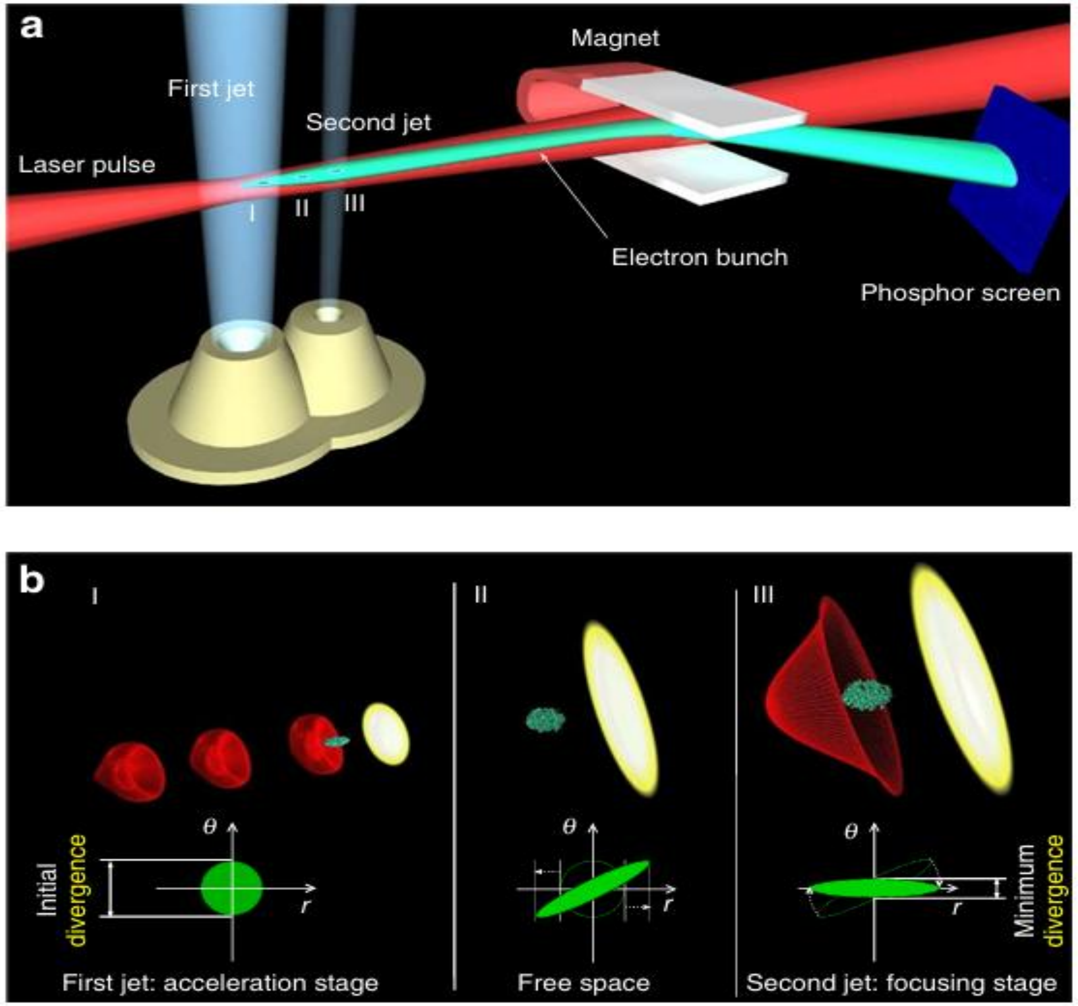
Peak current and bunch length

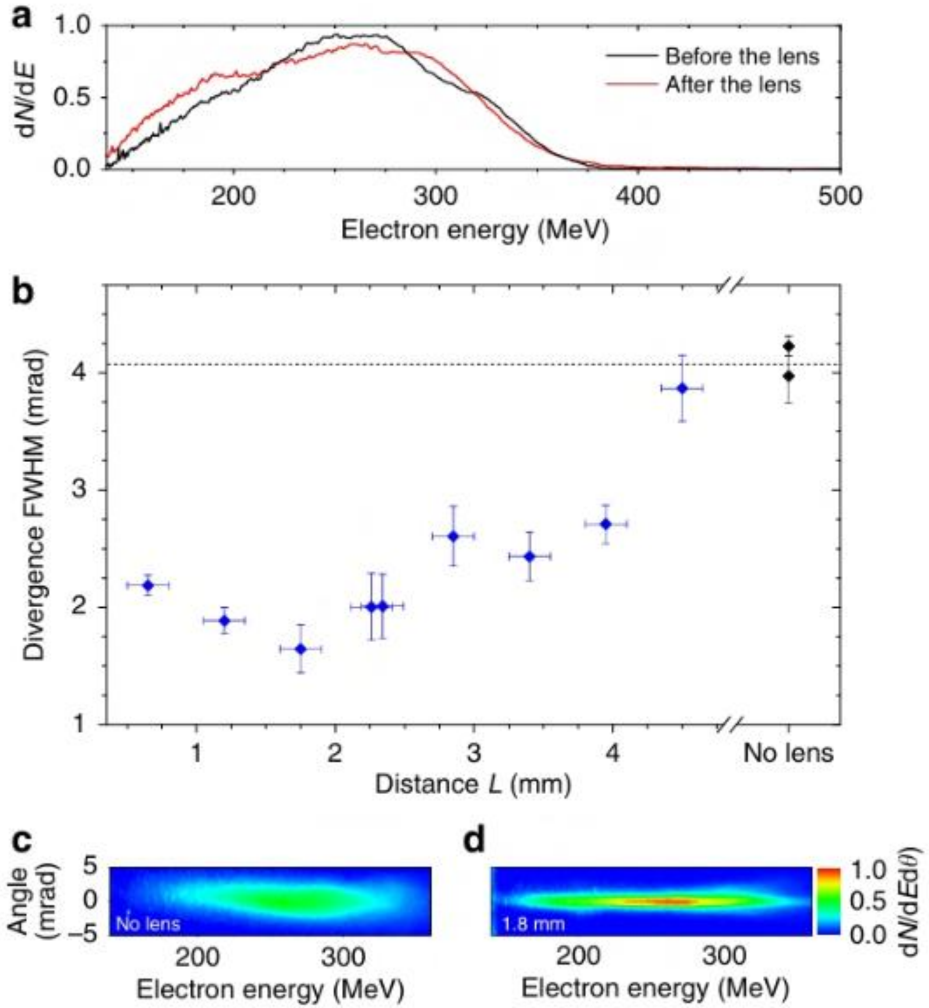


- Injected beam current can be tuned by varying the plasma length
- Typically, LPA can generate electron with peak current up to tens of kA and μm bunch length

Céline S. Hue, et.al. Control of electron beam current, charge, and energy spread using density downramp injection in laser wakefield accelerators

Beam divergence





- An electron beam is accelerated in the first gas jet (accelerator), then it enters free space where it diverges and is eventually focused in the second gas jet (lens).
- Beam divergence can be focused using a plasma lens from 4.1mrad to 1.5 mrad

Thaury, C., Guillaume, E., Döpp, A. et al. Demonstration of relativistic electron beam focusing by a laser-plasma lens. Nat Commun 6, 6860 (2015).

Overview of LPA beam

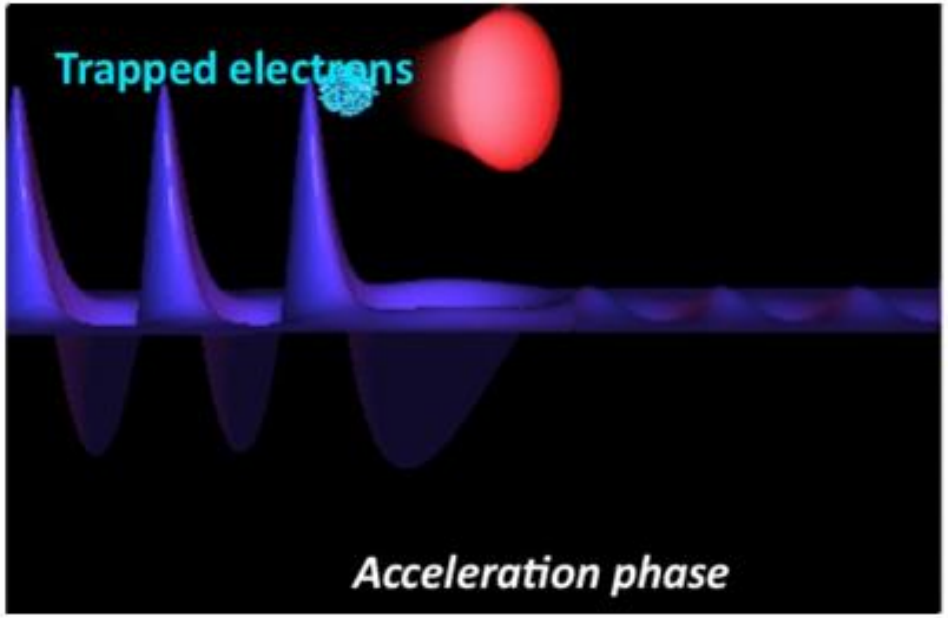
LPAs electron beam

Pros

- High energy: GeV level
- High peak current : a few kA
- Low emittance: sub mm·mrad

Cons

- Energy spread: few % level
- High divergence : mrad level
- Shot to shot jitter



T. Tajima and J. M. Dawson, Phys. Rev. Lett. 43, 267 (1979).

Table 1. Summary of parameters from different laboratories

Laboratory	Energy [1] (GeV)	Energy Spread [1] (%)	Charge [1] (pC)	Emittance [1] (mm mrad)
SIOM	0.8	0.2–1.2	10–50	0.4
DESY	0.3	0.4	500	1.5/0.3
LBNL	7.8	0.2–1	25	0.3–1
LOA	1.1	3.1	120	NA

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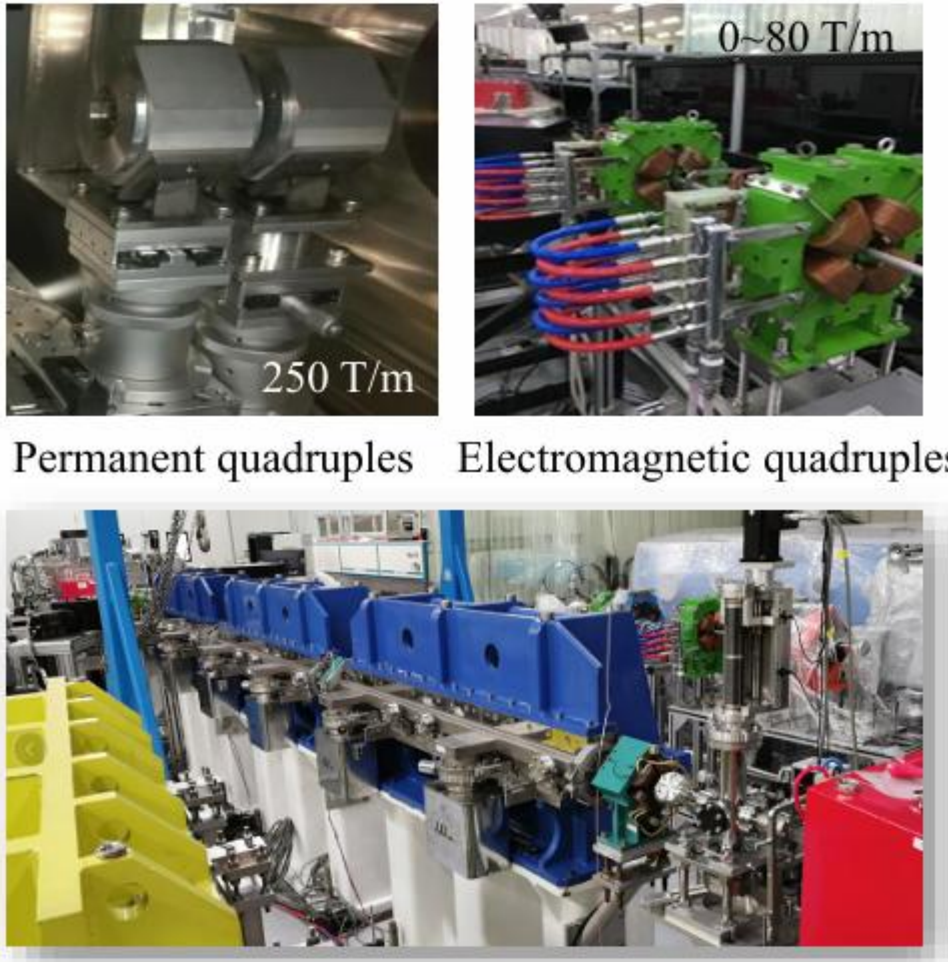
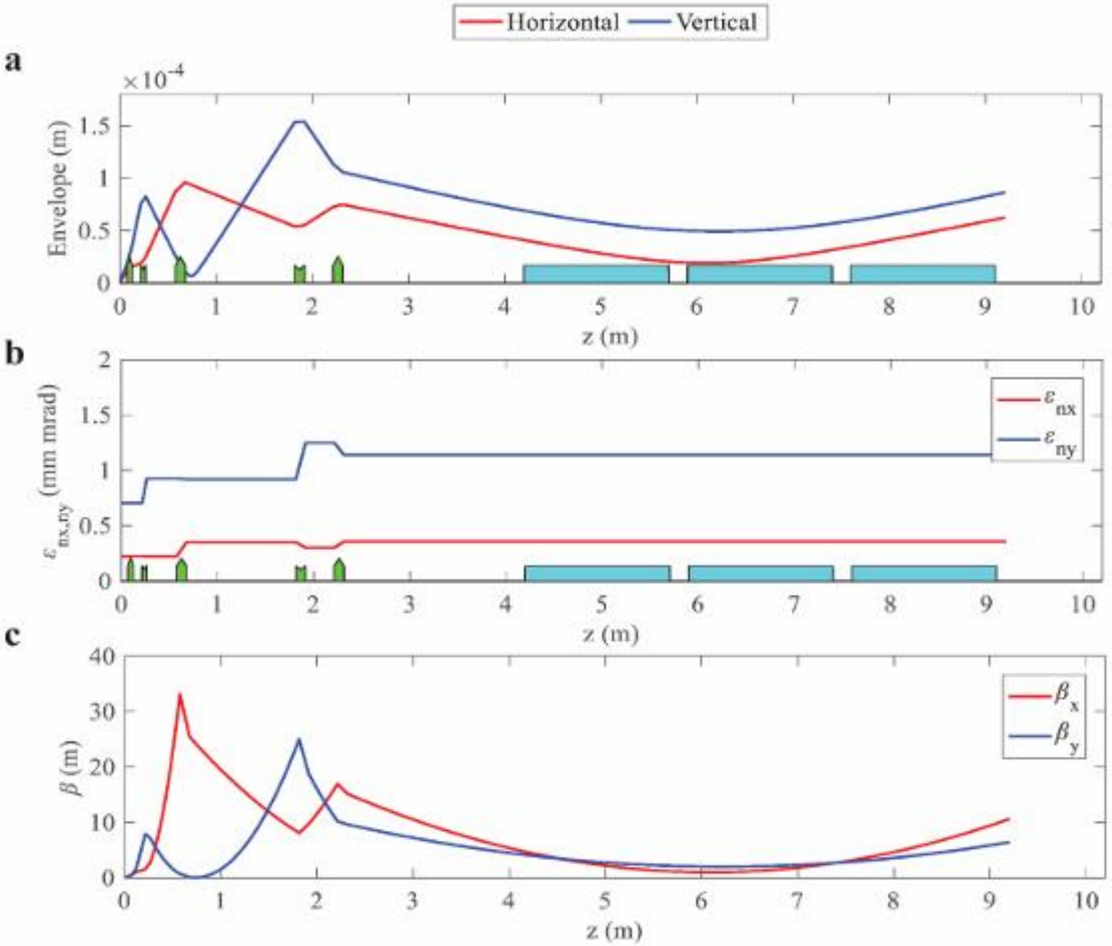
Beam Manipulation: Making LPA Beams FEL-Ready



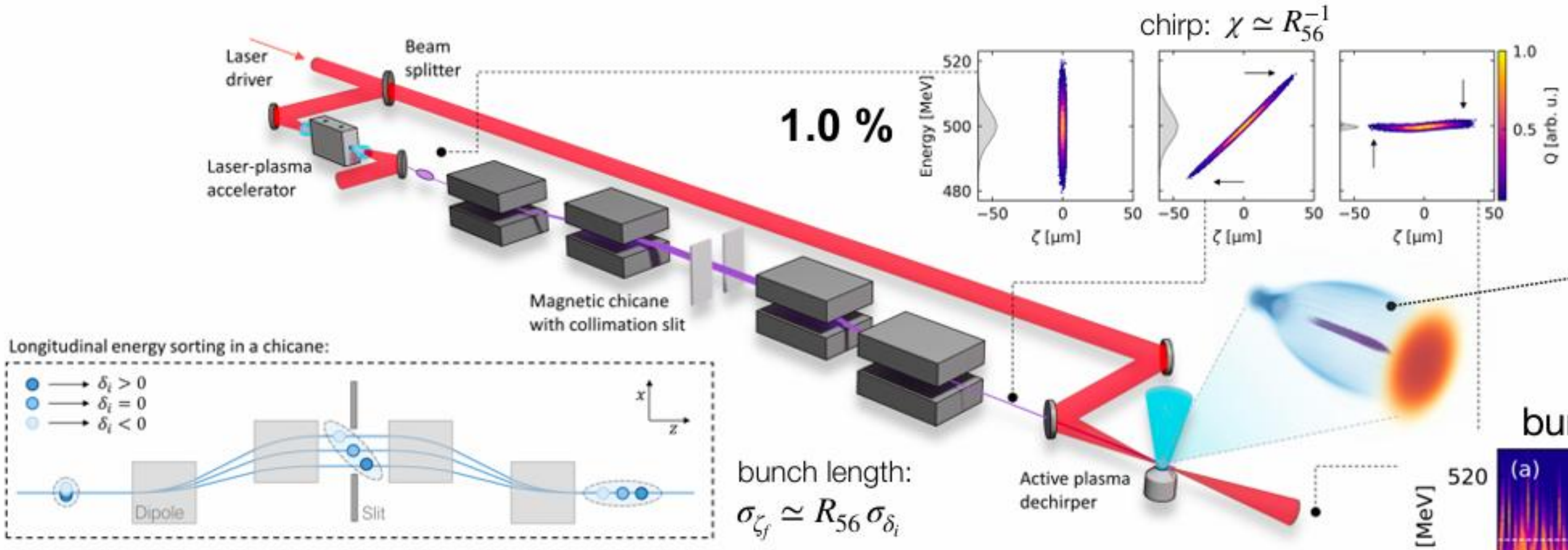
Permanent quadruples Electromagnetic quadruples

Three undulators with each length of 1.5 m



Simulated evolution of the beam envelope, transverse emittance and the Twiss parameter along the beamline.

Energy Compression and Stabilization of Laser-Plasma Accelerators



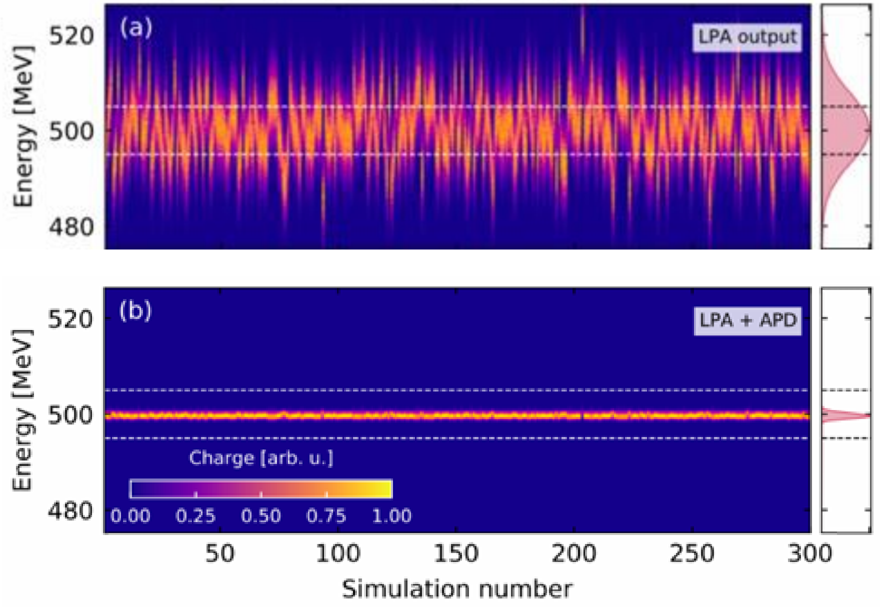
final energy spread:

$$\sigma_{\delta_f} = \frac{\sigma_{\zeta_i}}{R_{56}} \simeq \frac{\sigma_{\delta_i}}{S}$$

dechirping strength:

$$eE_{z,0}k_pL = E_{\mathrm{ref}}/R_{56}$$

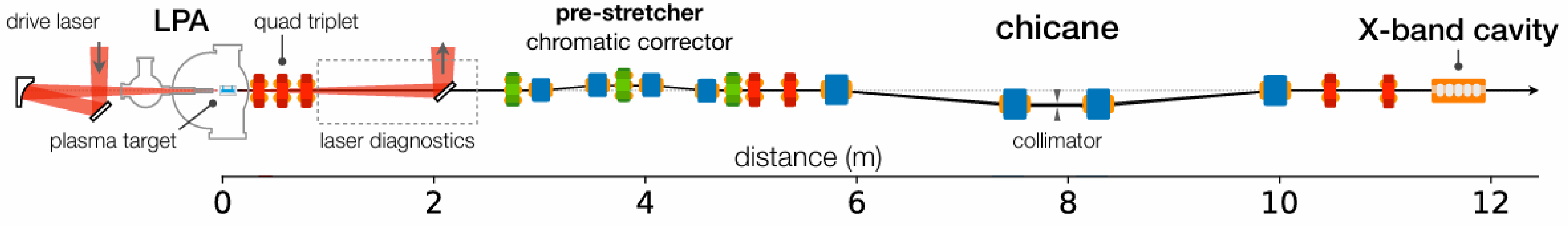
bunches before and after



- Sub % energy spread required for lasing slice
- Disperse/stretch electron beam
- Using an active plasma dechirper enables kA-level peak currents for FEL operation with improved performance and stability

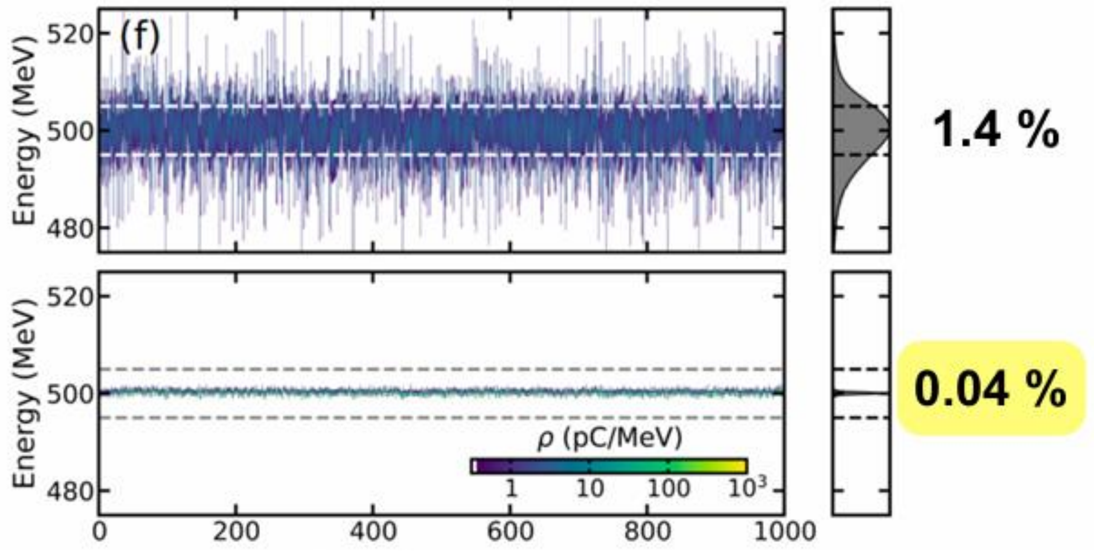
Ref: A. Ferran Pousa et al. Physical Review Letters 129, 094801 (2022)

Design of a prototype laser-plasma injector for an electron synchrotron



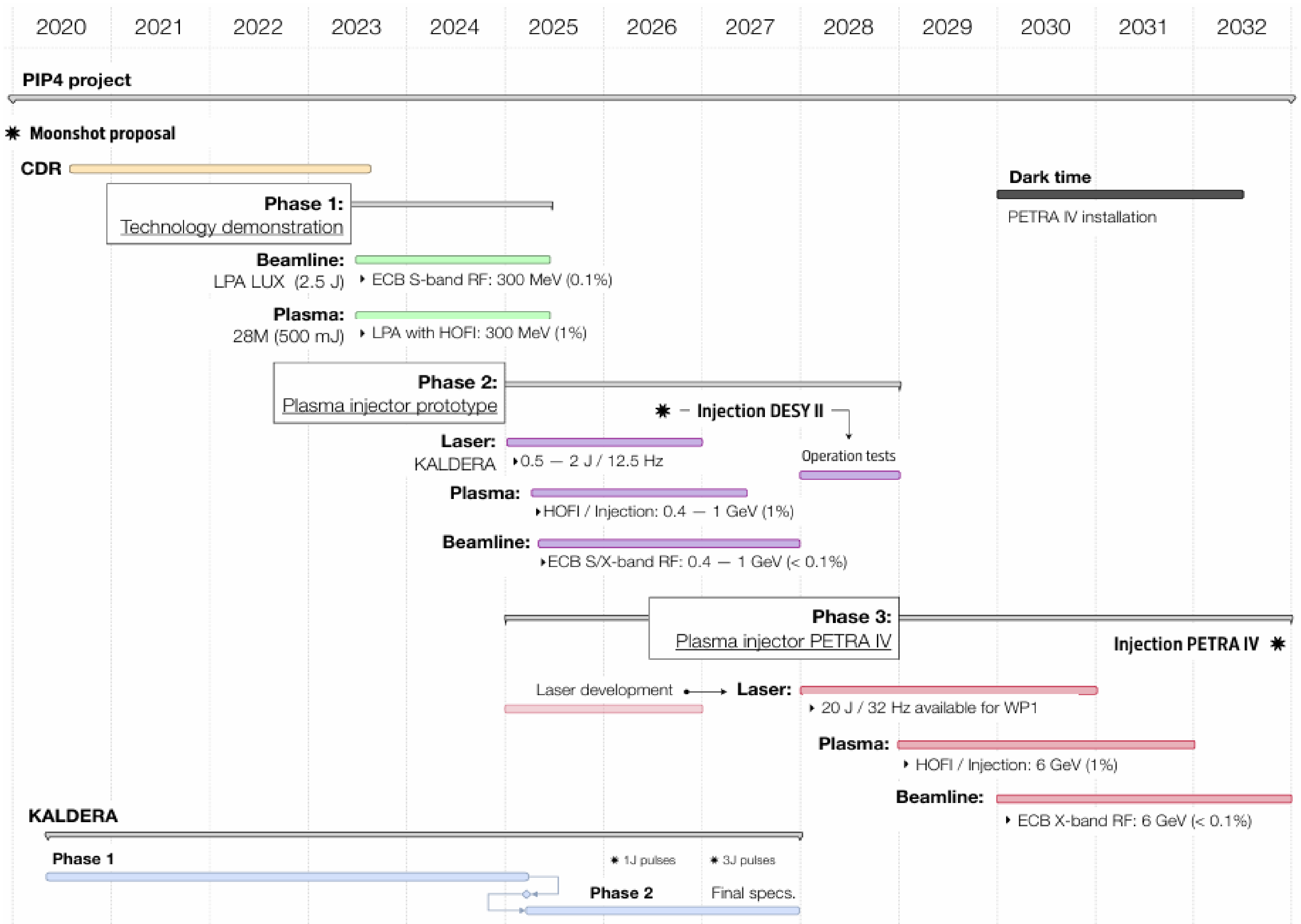
Prototype injector with X-band energy compression

- LUX LPA optimized for lowest energy spread (0.8%) beams at 500MeV by means of PIC simulations with FBPIC.
- Beamline simulations ($R_{56} = 10$ cm, 12GHz) show a reduction of the relative energy spread down to 0.005%.
- Statistics of 1000 bunches with 1% energy jitter exhibits a final beam energy distribution with 0.04% rms.
- Bunches become 430 times longer (~6ps FWHM): suitable for injection in storage ring.

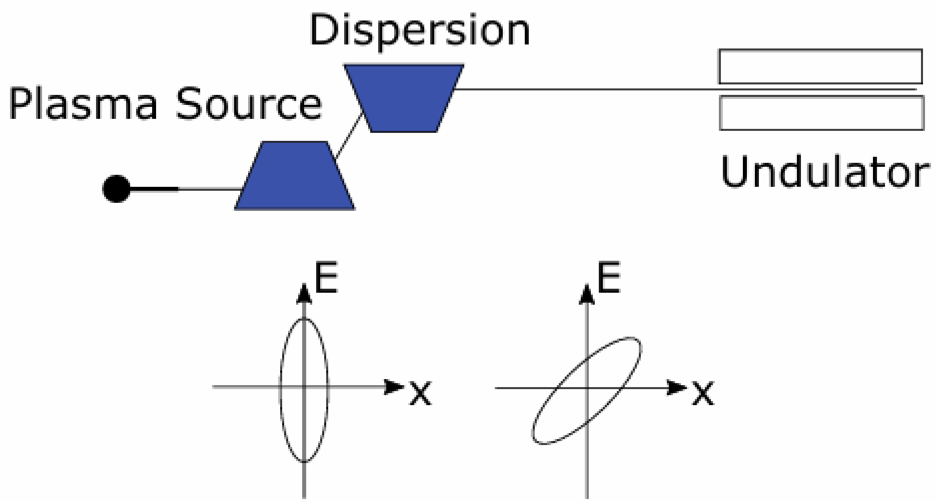


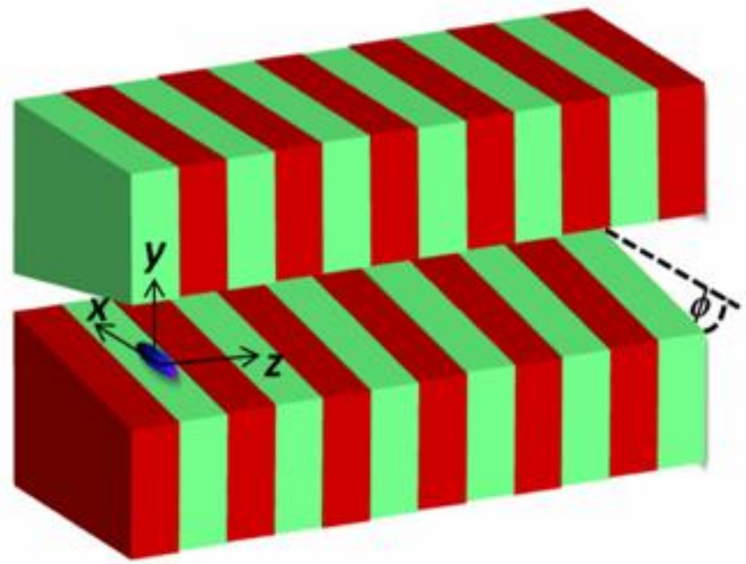
 Ref: S.A. Antipov et al. Physical Accelerator and Beams 24, 111301 (2021)

timeline for the implementation of the PIP4 project (as of early 2024).



Transverse gradient undulator (TGU)





$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

- Such a big energy spread cause different wavelength;
- How to compensate? K varied with energy also.

$$x = \eta \frac{\Delta\gamma}{\gamma_0} \qquad \frac{\Delta K}{K_0} = \alpha x$$

- Transverse Gradient Undulator (TGU) introduced at dispersion section. Resonance can be satisfied for all beam energies if

$$\eta = \frac{2 + K_0^2}{\alpha K_0^2}$$

Ref: Compact X-ray Free-Electron Laser from a Laser-Plasma Accelerator Using a Transverse-Gradient Undulator Phys. Rev. Lett. 109, 204801

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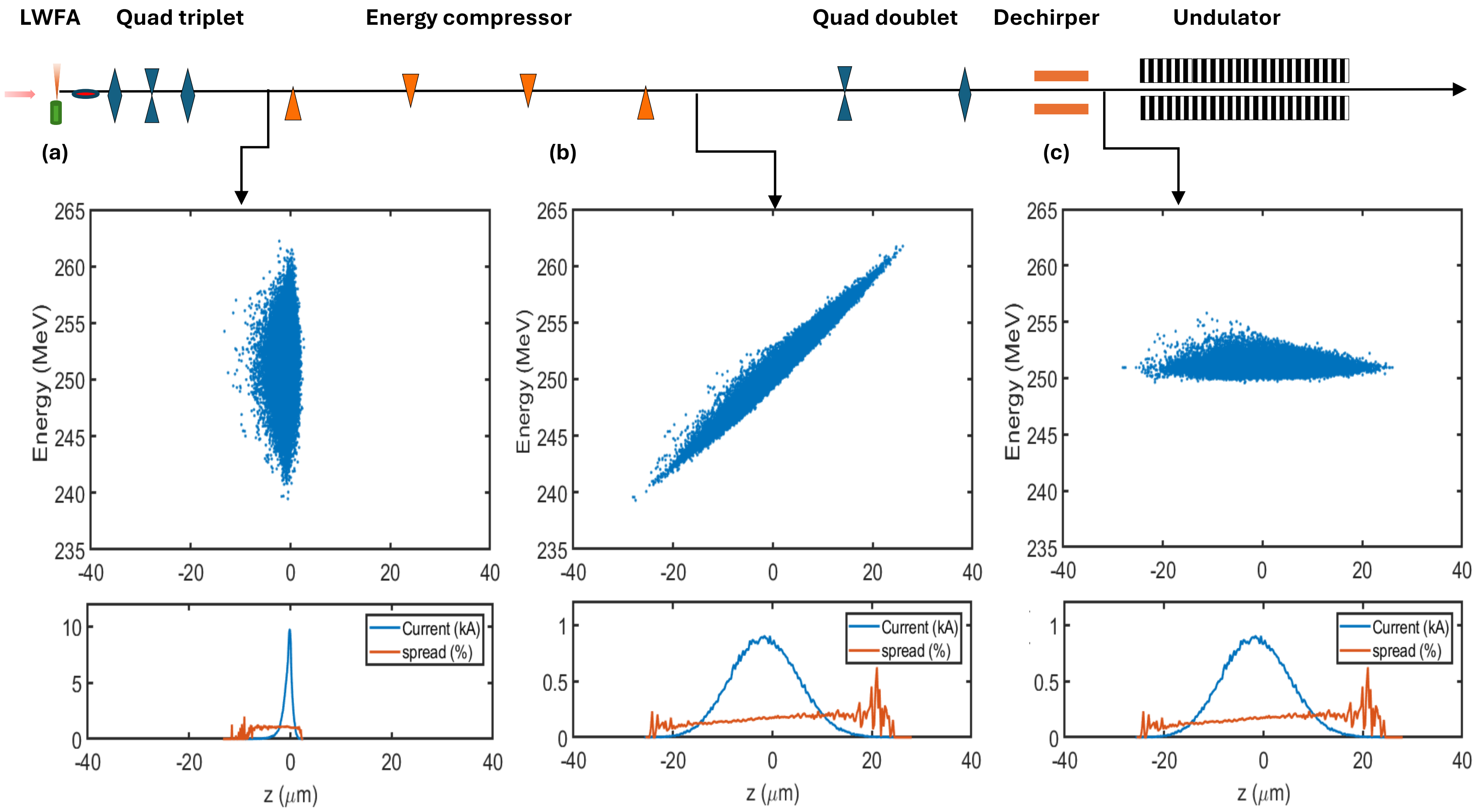
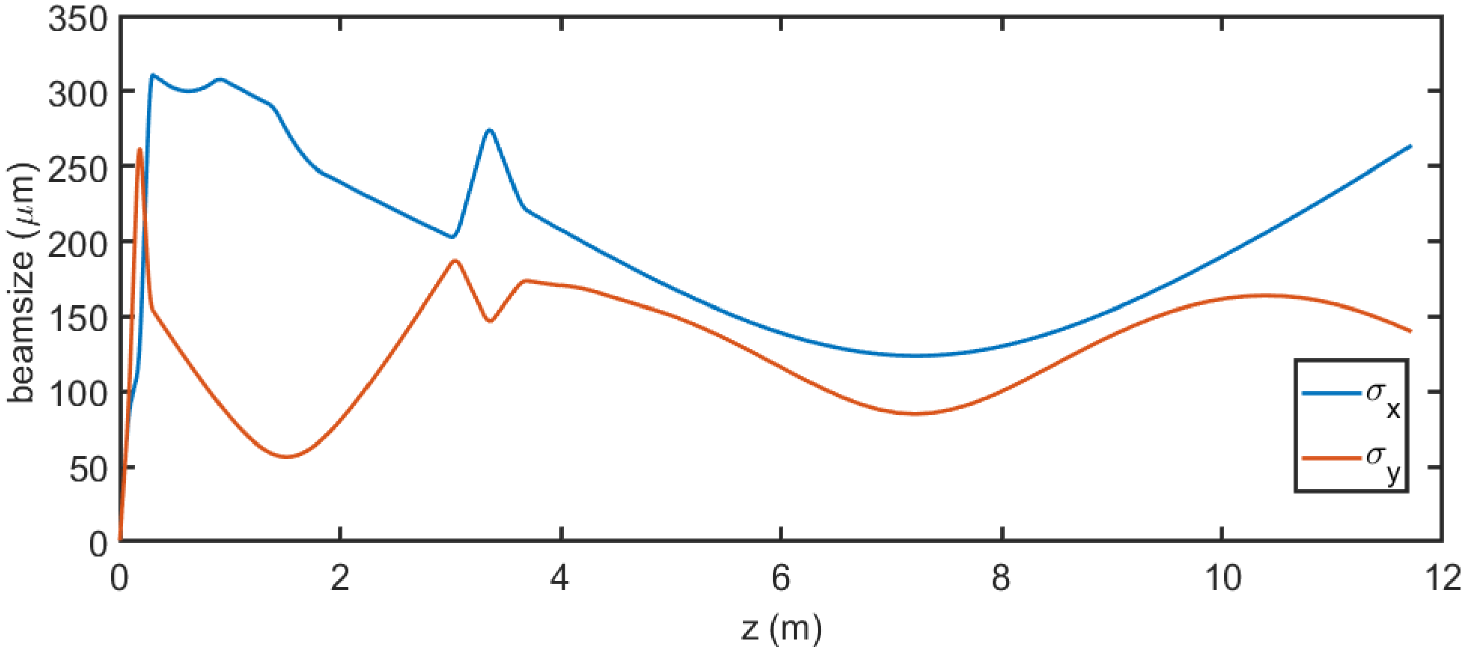
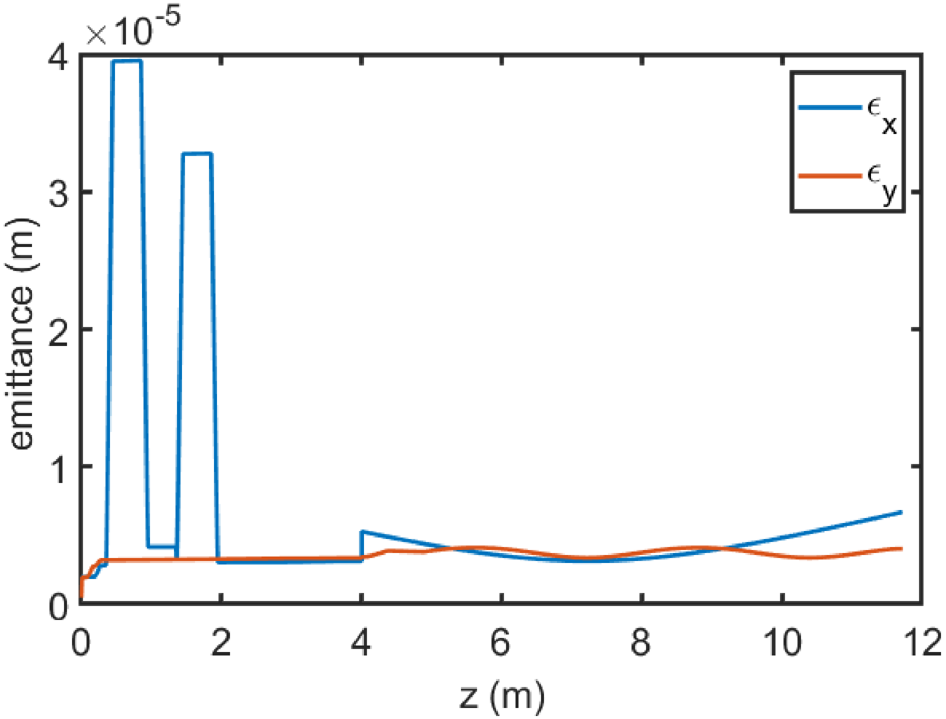
FEL simulation examples for LPA Beams



(a) An ultra-short electron beam directly transports from the LWFA to the undulator. (b) a decompressed electron beam with lower slice energy spread by adding a 4-dipole decompressor. (c) a dechirped electron beam that cancelled out the energy chirp by an artificial dechirper.

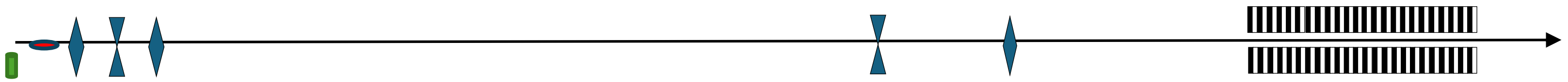
Beam transport simulation for LPA Beams

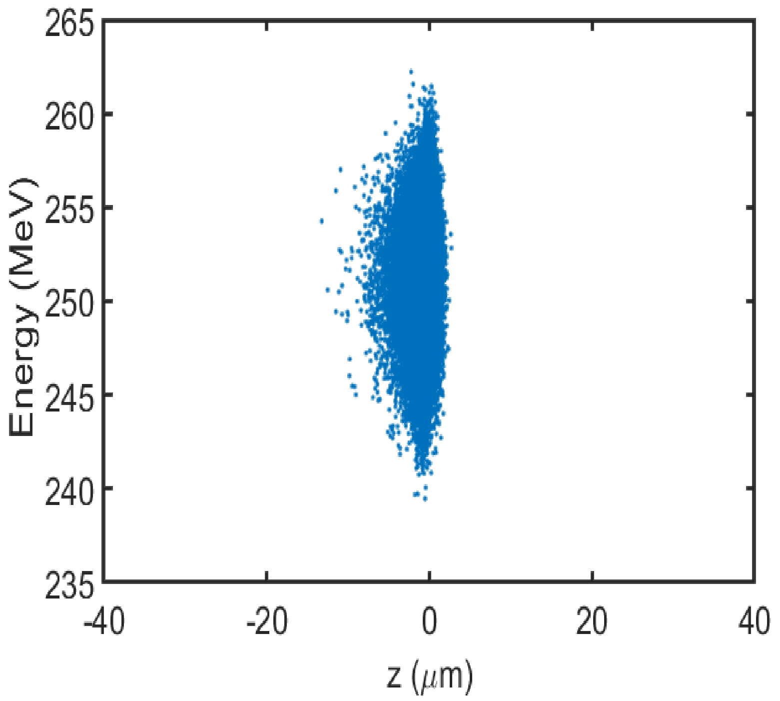


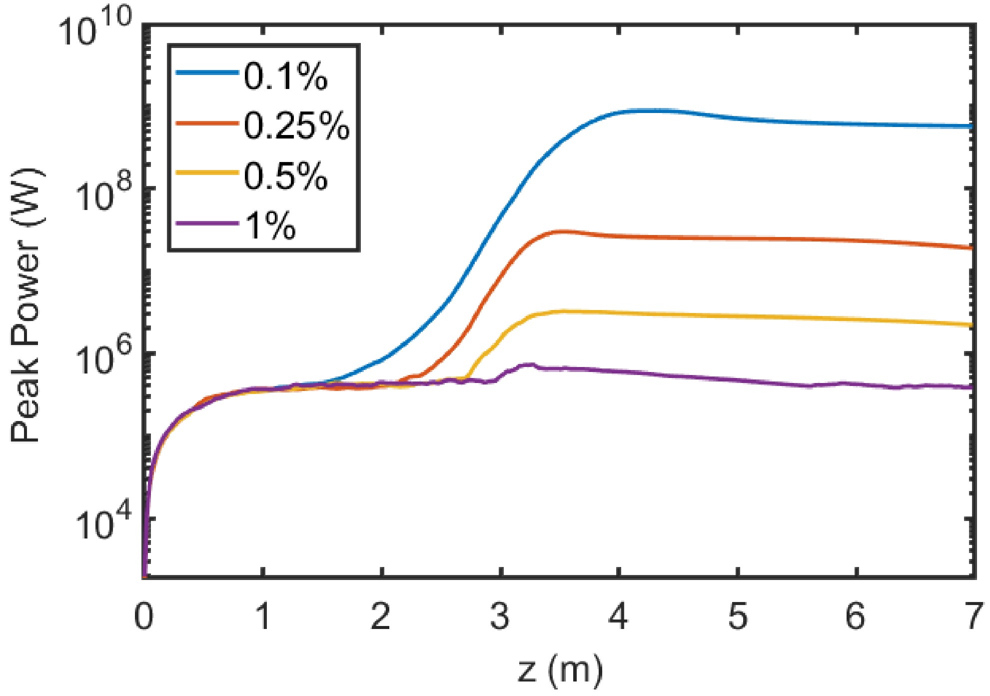


Transverse beamsize and emittance evolution along the whole beamline

SASE example for directly injected electron beam



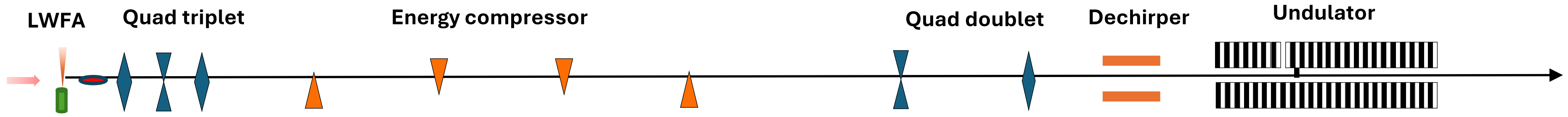


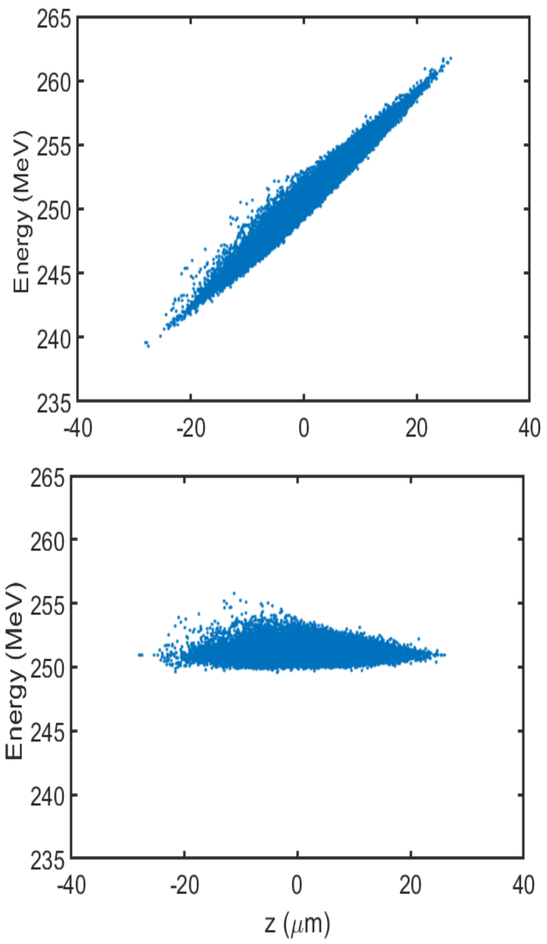


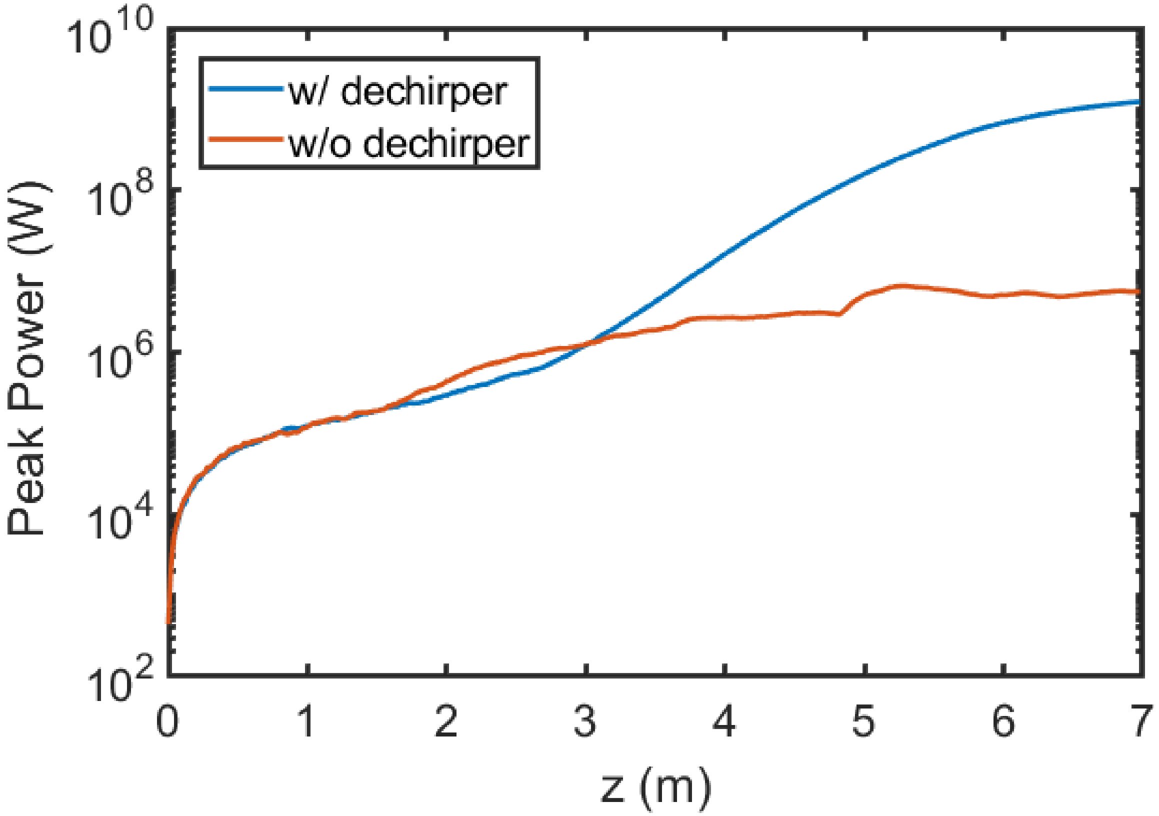
Evolution of the SASE FEL peak power for electron beams with initial electron beam energy spreads of 0.1%, 0.25%, 0.5%, and 1%, respectively.

- When the energy spread exceeds the FEL Pierce parameter ($\rho = 0.0082$), no gain is observed.

SASE example for energy compressed and dechirped beam

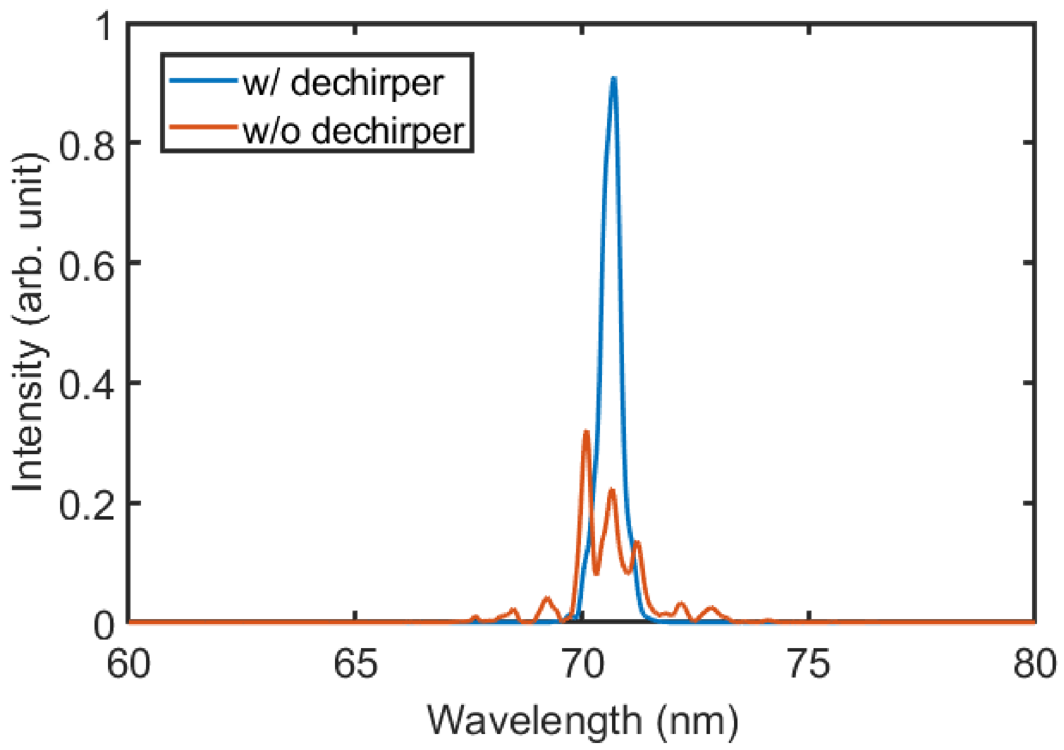


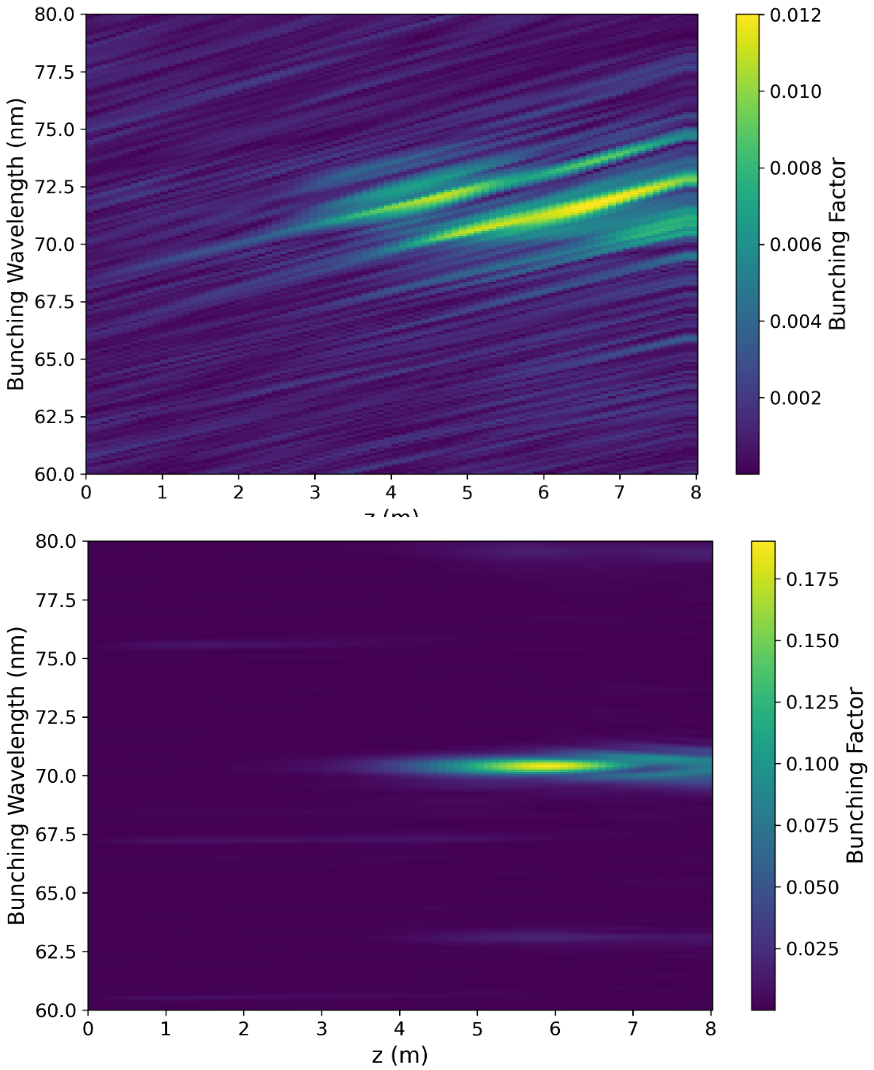




Evolution of FEL peak power along the undulator for the energy compressed LWFA beam (orange curve) without dechirper and with dechirper (blue curve).

Effects of electron beam with energy chirp





- In the energy-compressed case, the spectral peak shifts as the beam propagates. This shift reflects increased microbunch separation caused by undulator dispersion acting on an energy chirped beam

- Different slices of the chirped electron beam satisfy distinct resonant conditions due to their energy differences

Beam spectrum evolution along the undulator for the case without/with dechirper.

Compensation via Longitudinal Tapered Undulator

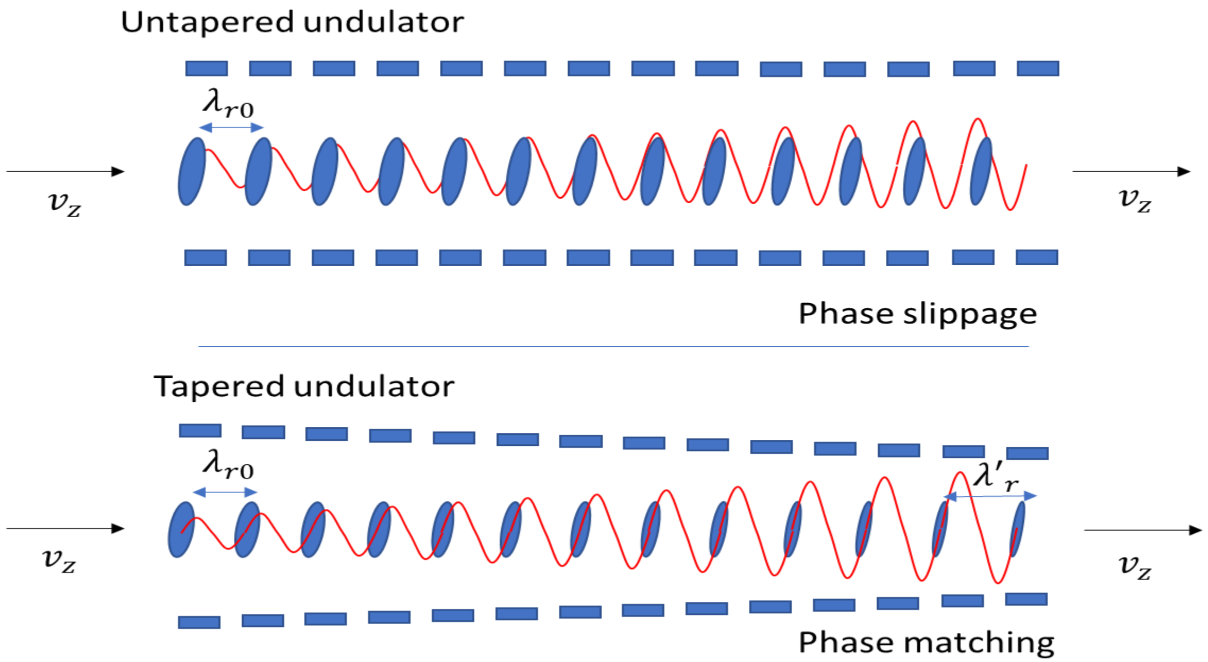
$$\frac{dz}{d\delta} \approx \frac{L_u}{\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$\Delta z \approx \frac{L_u}{\gamma^2}\left(1+\frac{K^2}{2}\right) * \frac{\mathrm{d}\gamma}{\gamma dz}\lambda_r$$

$$\lambda_r' = \lambda_r + \Delta z = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K'^2}{2}\right)$$

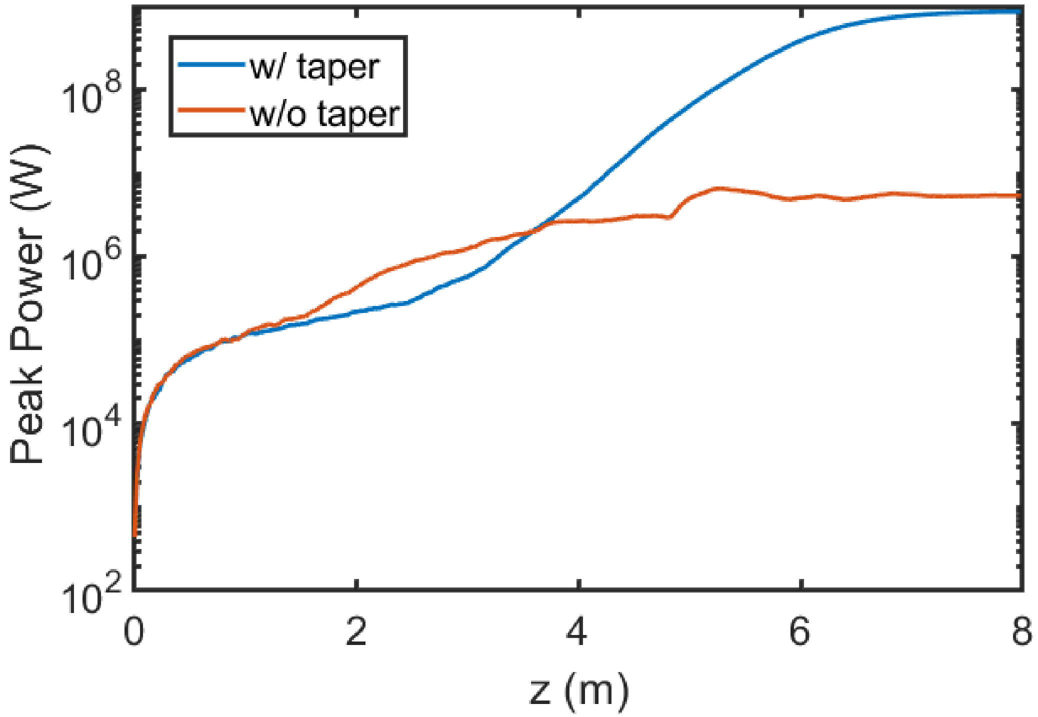
$$\frac{dK}{dz} = \frac{1}{\gamma^3}\left(1+\frac{K_0^2}{2}\right)^2 * \frac{\mathrm{d}\gamma}{dz} = -\frac{1}{\gamma^3} * \frac{d\gamma}{cdt}\left(1+\frac{K_0^2}{2}\right)^2$$

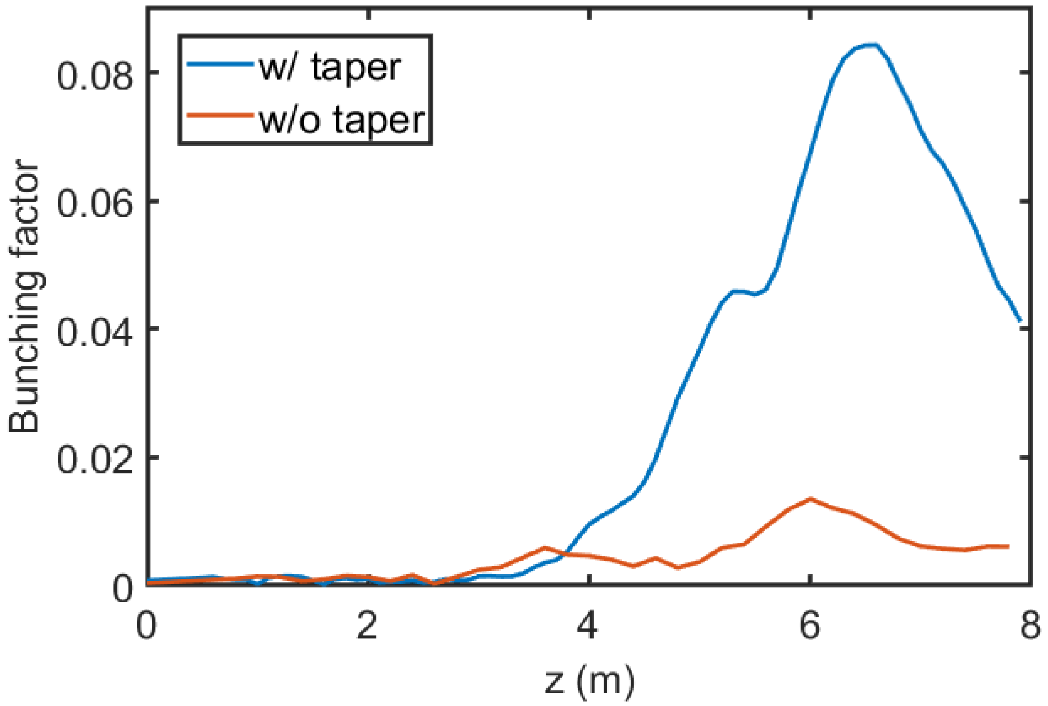
$$\frac{dK}{dz} = \frac{1}{\gamma^2}\left(1+\frac{K_0^2}{2}\right)^2 \Big/ R_{56}$$



- the resonant wavelength can be tuned to compensate for the bunch lengthening caused by undulator dispersion

FEL power evolution after applying tapered undulator

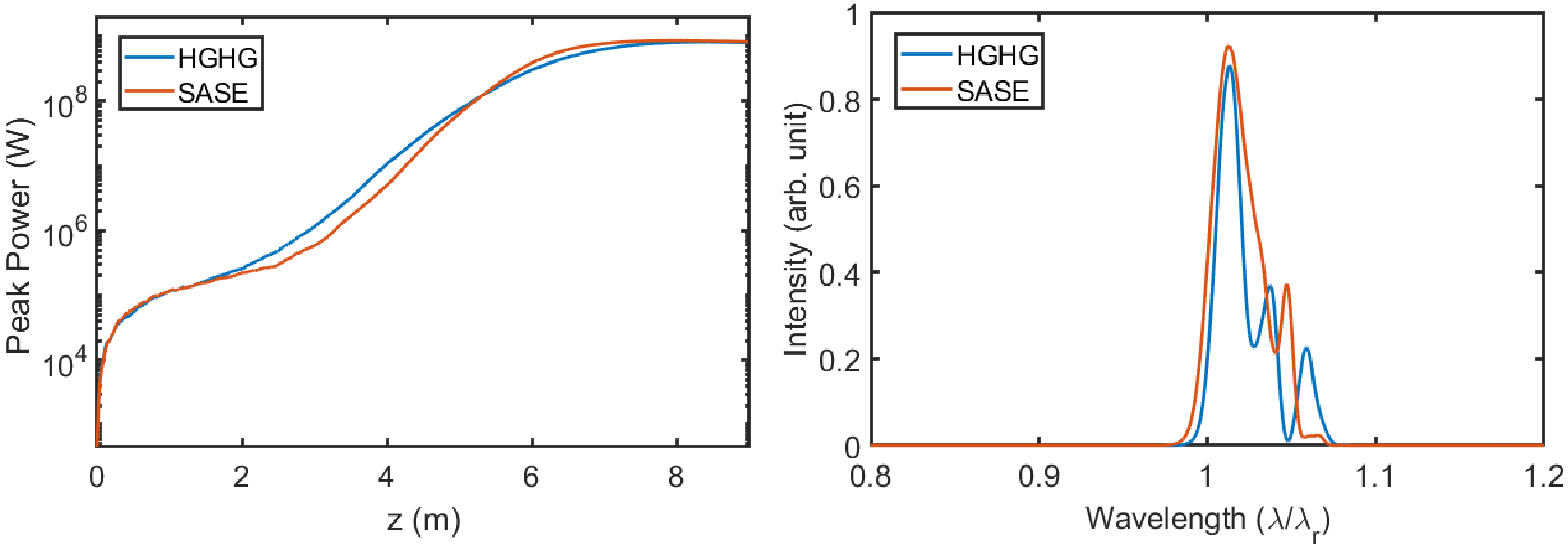




Evolution of the FEL radiation peak power and the bunching factor along the undulator for cases with (blue) and without (orange) longitudinal tapering

- The saturation power has two order of magnitude increase after applying tapered undulator

Enhanced Performance by a Seeded FEL Scheme



Comparison between HGHG (blue) and SASE (red) configurations: (a) evolution of radiation peak power along the undulator and (b) normalized output spectra.

- The FWHM bandwidth are 1.12 / 2.03 nm for HGHG and SASE , respectively

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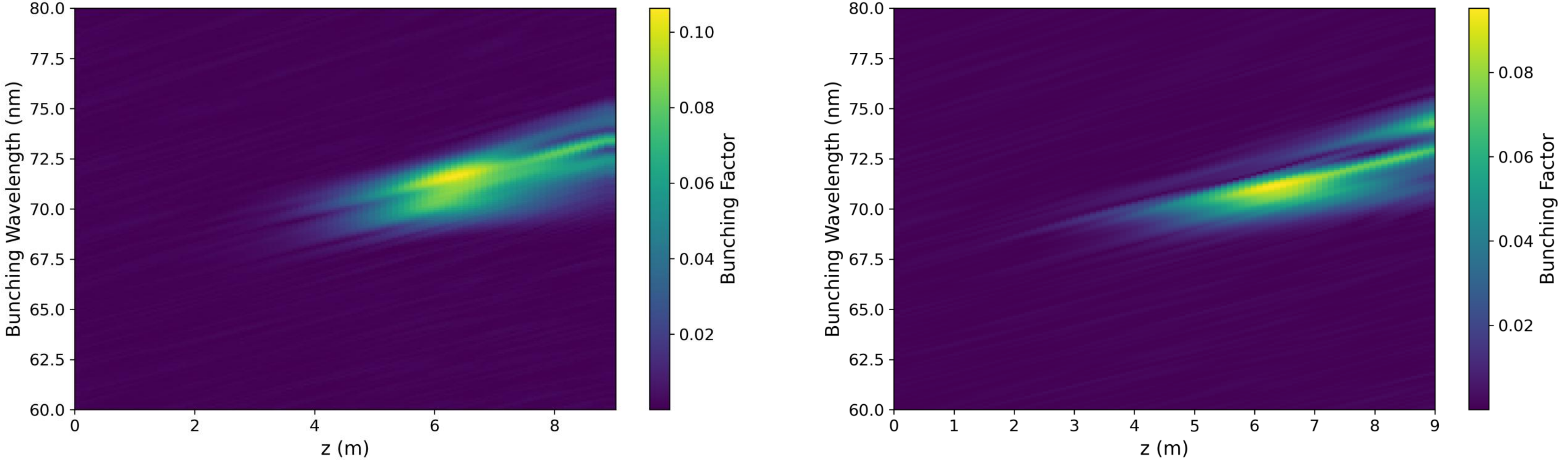

Evolution of the bunching factor as a function of wavelength and undulator position for (a) SASE and (b) HGHG configurations.

- The seeded HGHG case shows a more localized and stable bunching structure near the resonant wavelength, indicating improved spectral coherence.

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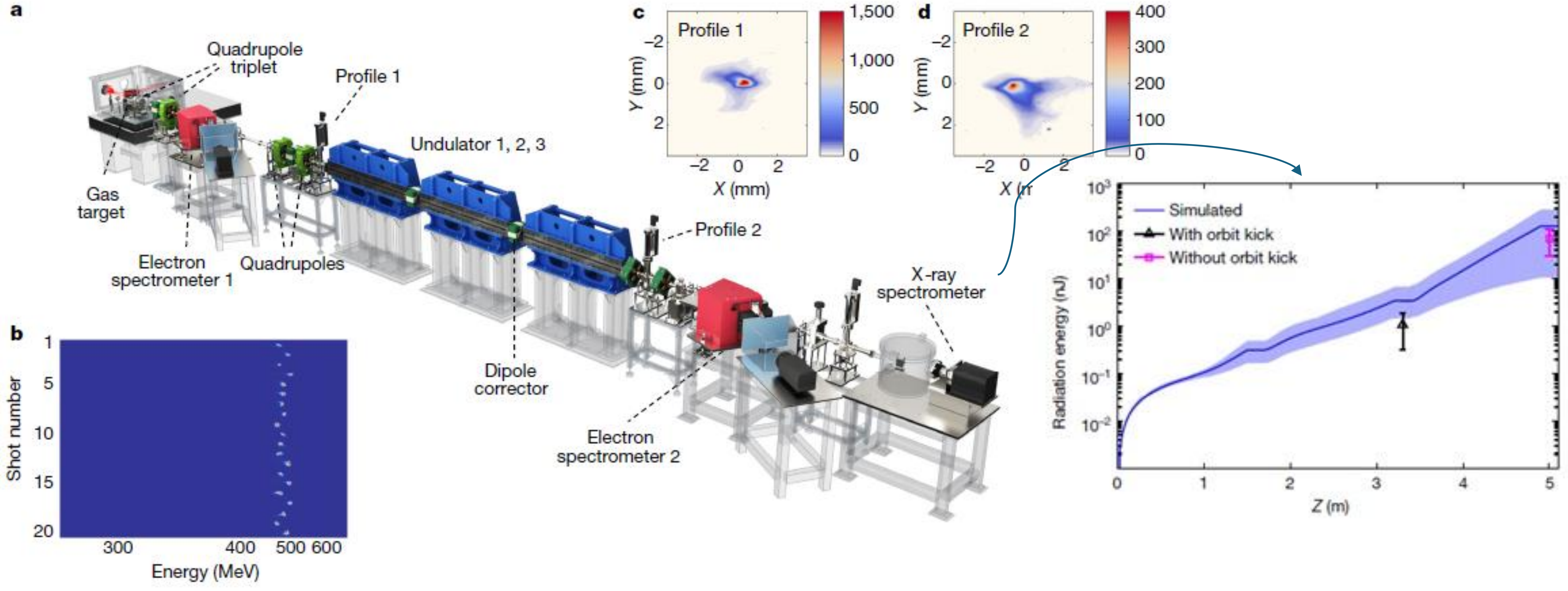
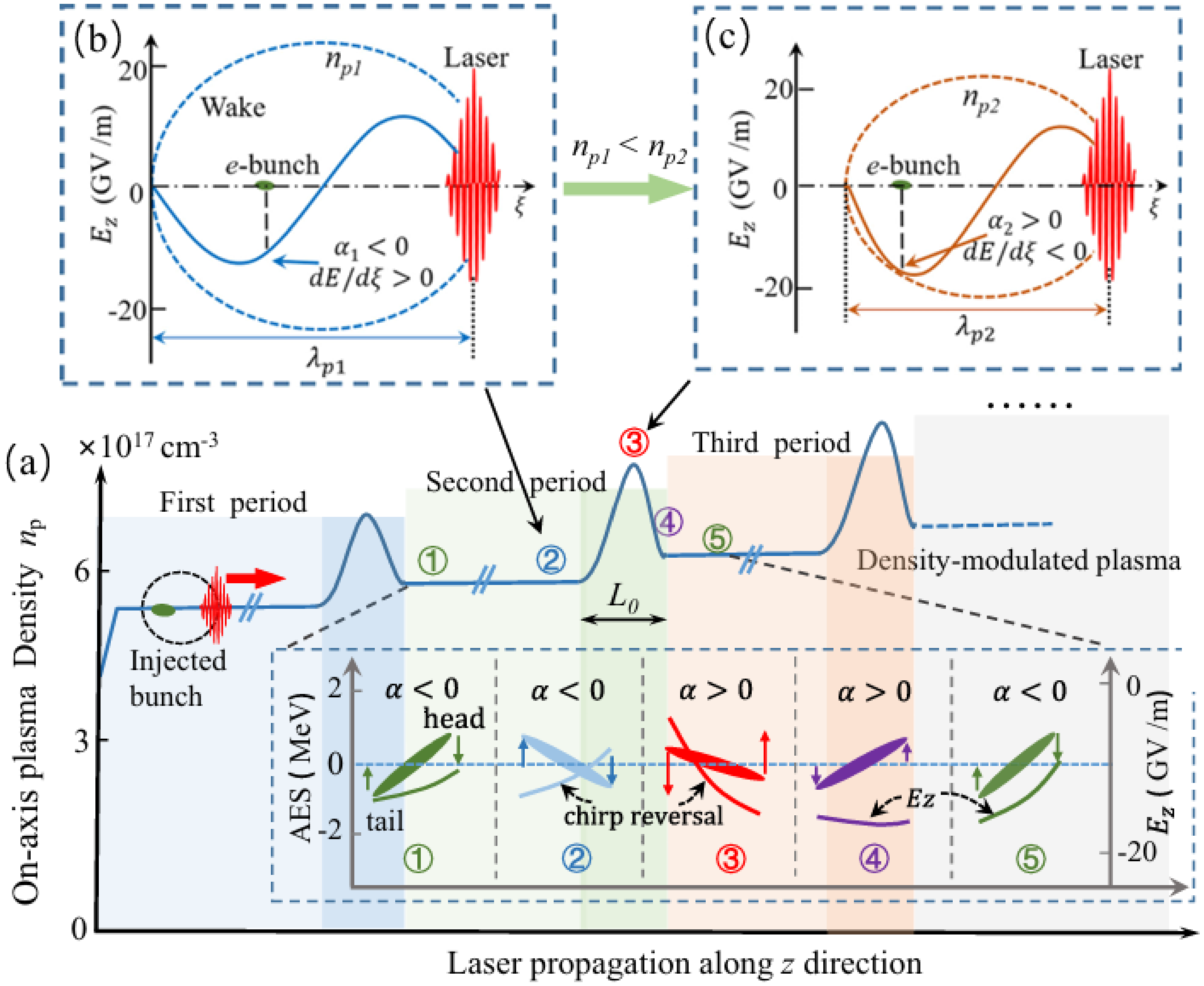
Soft X-ray LPA FEL: SIOM

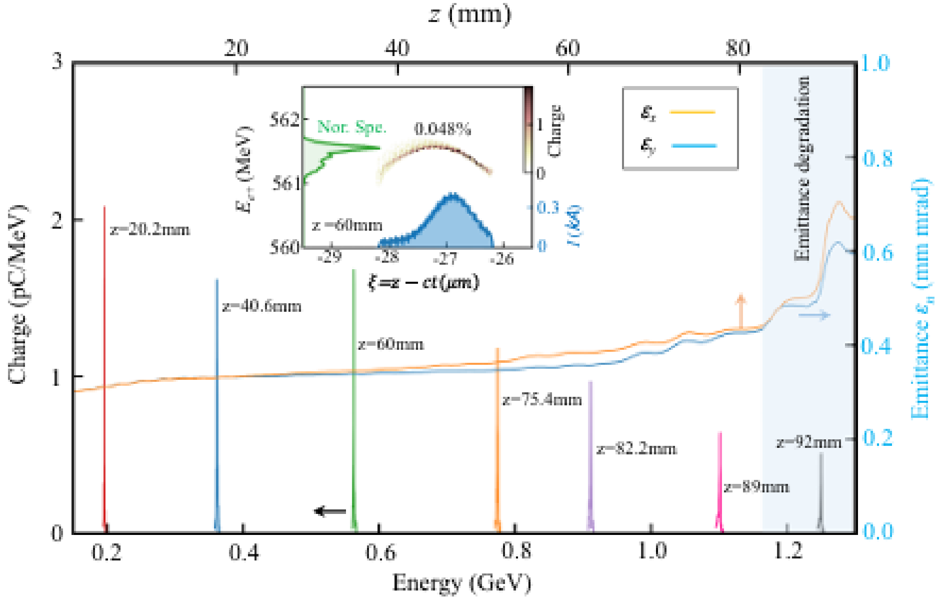


- SIOM, the first compact, table-top FEL electron source with GeV level beam energy.
- SASE lasing at 27 nm
- LWFA: two gas jets at different densities. Electron beam energy of 490 MeV within 5 mm: 98 GeV/m

Ref: Jiang, K.; Wang, W. ; Feng, K.; Li, R. Review of Quality Optimization of Electron Beam Based on Laser Wakefield Acceleration, Nature volume 595, pages516-520 (2021)

Potential method to reduce energy spread via tailoring plasma density

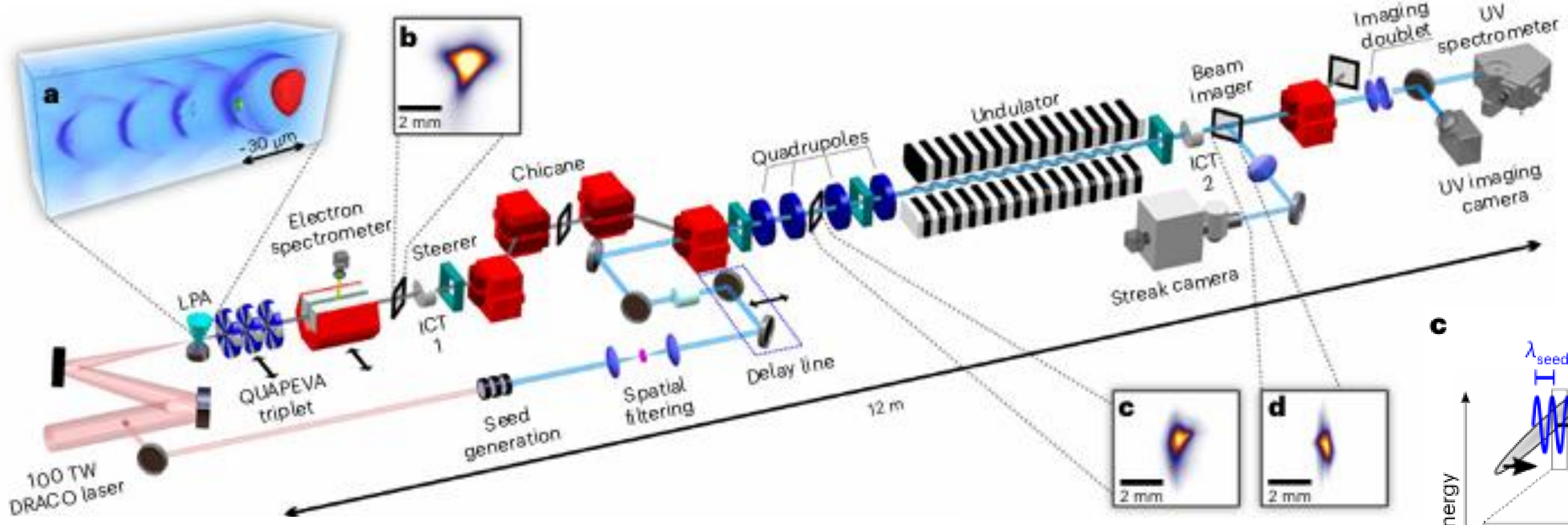


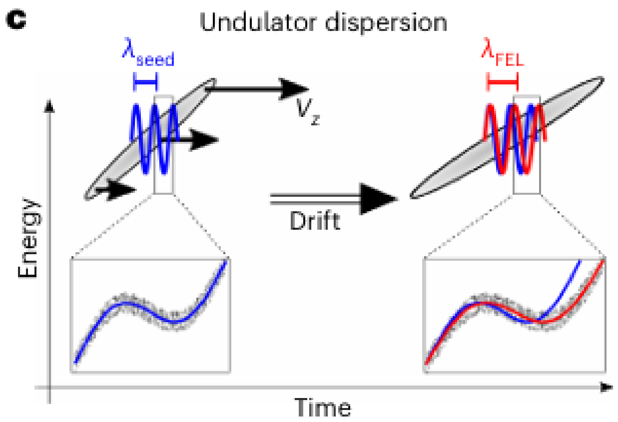


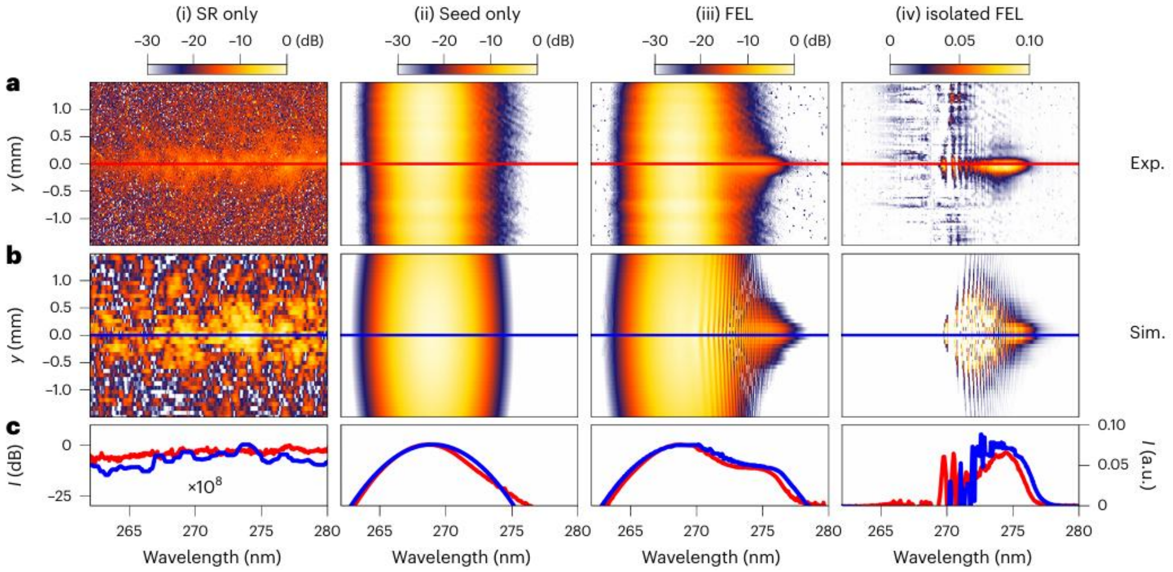
A schematic diagram of a QLWFA with a density-modulated plasma to achieve high-energy acceleration with the energy spread reduction to the one-ten-thousandth level via periodical de-chirpings.

Yu, C., Qin, Z., Xiang, Z. *et al.* Sub-per-mille bunch energy spread in a quasi-linear laser-wakefield accelerator via periodical de-chirpings. *Commun Phys* **8**, 137 (2025). https://doi.org/10.1038/s42005-025-02057-6

Seeded EUV LPA FEL: COXINEL



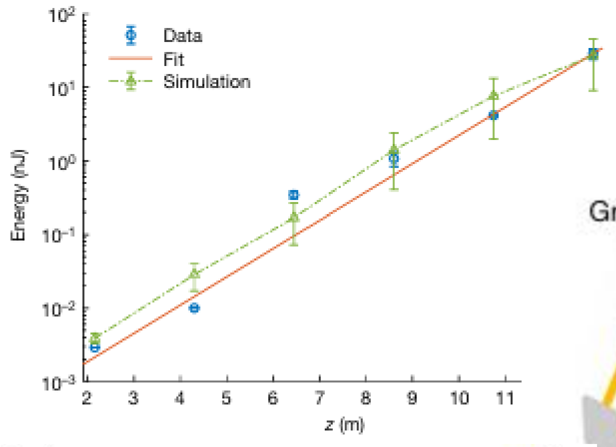


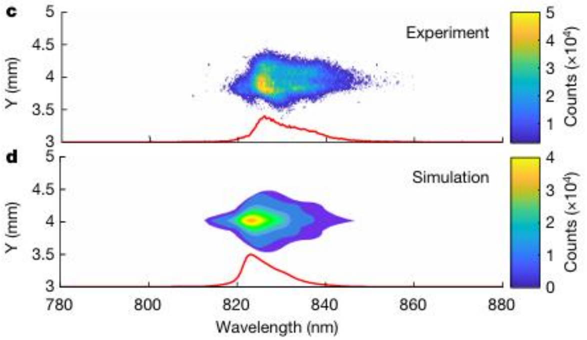


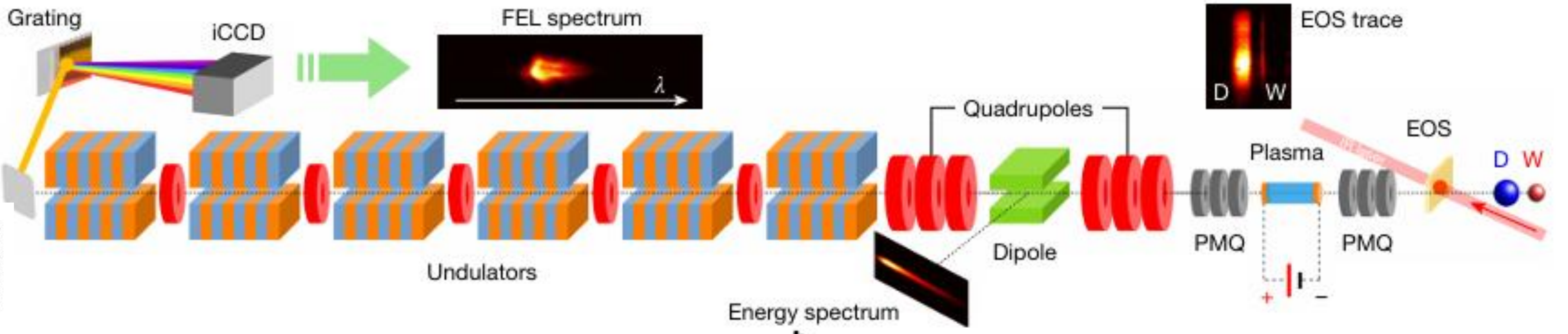
- The emitted red shift radiation can be observed from both experiments and simulations
- This is attributed to the correlated energy chirp of electron beam in an undulator

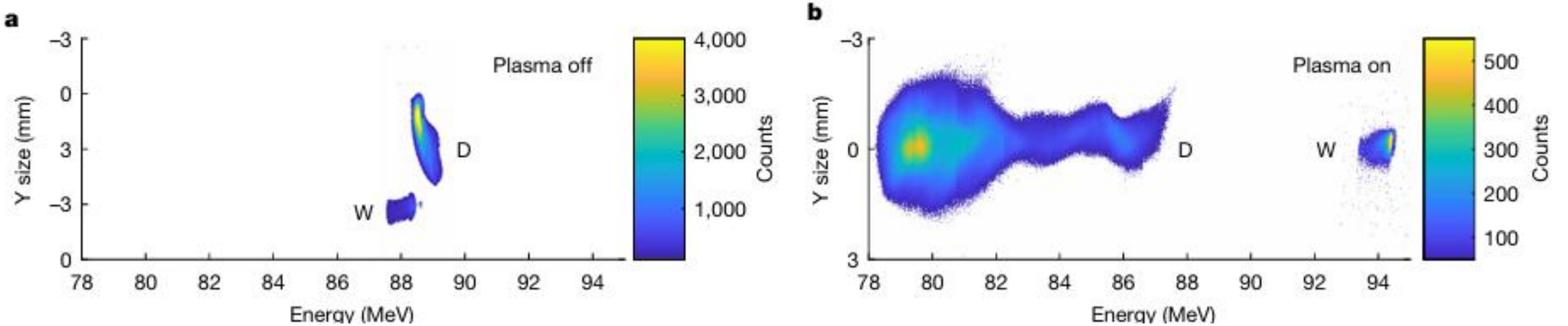
Ref: Labat, M., Cabadağ, J.C., Ghaith, A. et al. Seeded free-electron laser driven by a compact laser plasma accelerator. *Nat. Photon.* **17**, 150–156 (2023)

IR PWFA FEL: SPARC_LAB







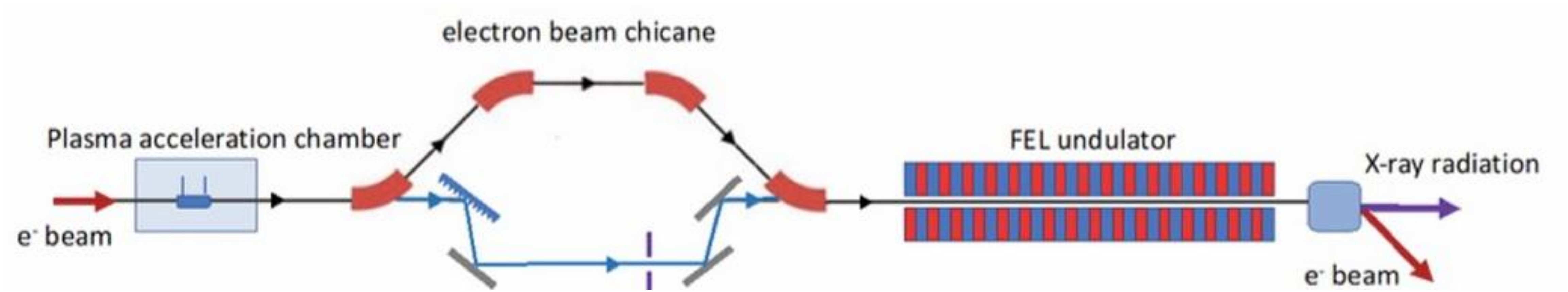


Proof-of-principle experiment to demonstrate high-quality PWFA acceleration able to drive a Free-Electron Laser

- +6 MeV in 3 cm plasma indicate the acceleration gradient of 200 MeV/m
- Exponential gain of FEL radiation (@ 830 nm). Data taken with 6 (Si) photo-diodes downstream the undulator

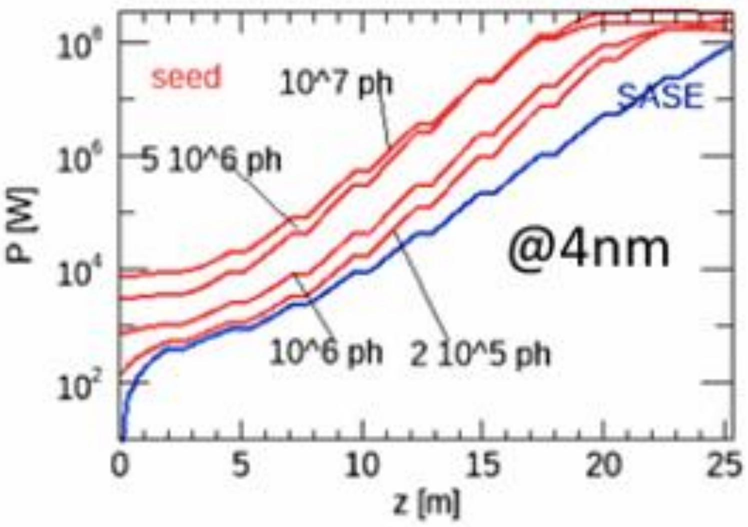
 Pompili, R., Alesini, D., Anania, M.P. et al. Free-electron lasing with compact beam-driven plasma wakefield accelerator.

Betatron-Seeded FEL – SPARC_Lab

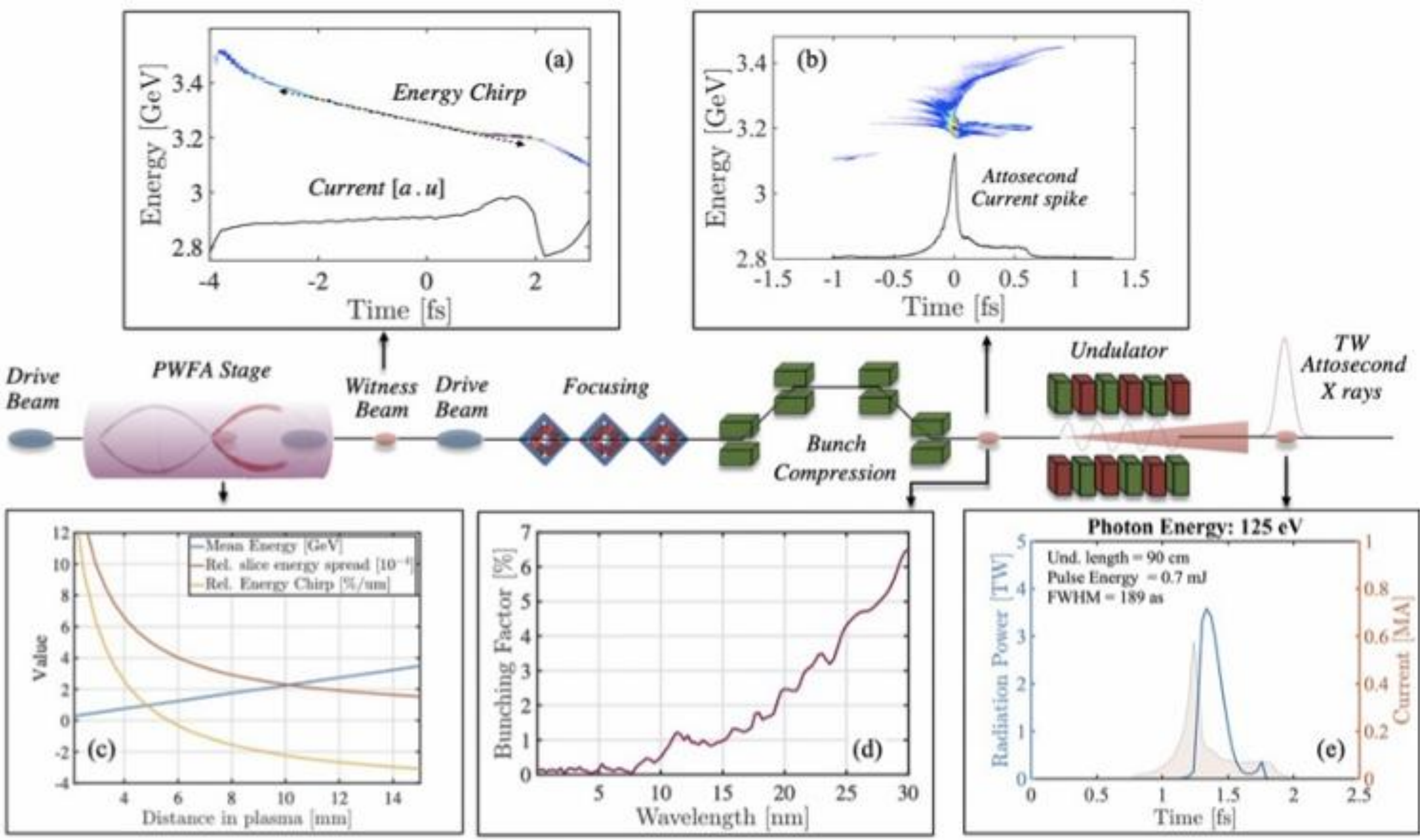


Betatron radiation monochromator

- FEL seeded by PWFA betatron radiation at SPARC_Lab, INFN, EuPRAXIA
- Chicane + monochromater to select portion of betator radiation
- Seed at short wavelength natural byproduct of PWFA
- Aiming for 4 nm seed & FEL radiation



LPA based Super-radiant FEL – SPARC_Lab



- Chirped femtosecond PWFA beam compressed to attosecond duration
- Acts like single microbunch / super-radiance in undulator

Emma, Claudio & Xu, X & Larsen, K & Cryan, J & Hogan, Mark & Macarthur, J & White, Glen & Marinelli, Agostino & Hessami, Rafi & Robles, R & Univeristy, Stanford & Stanford, Usa & Fisher, P & Musumeci, Los & Angeles,. (2021). PAX: A PLASMA-DRIVEN ATTOSECOND X-RAY SOURCE *. 10.18429/JACoW-IPAC2021-WEPAB072.

Conclusion

- Laser–plasma accelerators (LPAs) provide ultra-high accelerating gradients and open a realistic path toward compact FEL light sources, significantly reducing facility size and cost.

- Intrinsic beam quality issues—including large slice energy spread, correlated energy chirp, divergence, and shot-to-shot fluctuations—remain the primary obstacles to high-gain FEL operation.

- Beam manipulation is the key enabler:
  Beam transportation, energy compression, dechirping, and undulator tapering can effectively relax FEL requirements.

- Recent experiments (SIOM, COXINEL, SPARC-LAB) have already shown exponential gain and seeded lasing, validating the feasibility of plasma-driven FELs.

- Overall, continued progress in plasma injector control, beam manipulation, and advanced FEL schemes will be essential for realizing stable, high-repetition-rate, short-wavelength LPA-based FELs, bridging the gap between tabletop accelerators.