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Challenges of Plasma Wakefield Accelerator Beams as Drivers for Free-Electron Lasers

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Challenging Path to Compact X-ray FELS

- The PWFA community is targeting compact x-ray FELS, but..
- We consider the seeded free-electron laser (FEL) tests at 276 nm at HZDR in Germany and the self-amplified spontaneous emission (SASE) FEL test at 27 nm in China.
- Note: To obtain exponential gain in an X-ray SASE FEL, one will need significantly better beam quality than these cases.
- The basic slippage of e-beam behind seed laser or FEL pulse is considered for these two experiments.
- I compare the Pierce parameter at LCLS-1 at 1.5 angstroms to plasma wakefield accelerator (PWFA) case.
- Summary of rf linac-driven FEL parameters is also provided for comparison. Include ~1 angstrom cases at LCLS-1 and SACLA.

Slippage of e-beam Relative to Seed Laser and/or FEL

- The e-beam slips behind in z one resonant wavelength, λ_1, in traveling one undulator period.
- The total slippage at 276 nm for 97 periods is 26.9 µm.

  $dz = N_u \lambda_1 = 26.9$ µm → dt=80 fs compared to original ~30-fs e-beam pulse where N_u is total period number. Gain issue.
- The chicane is used to lengthen the 30-fs e-beam pulse to 0.9 ps and is matched to the seed laser pulse of about 1 ps. Timing/synchronization argument, but this step also makes slippage small compared to the pulse length.

- For Chinese 27-nm case, slippage is 13 fs at L_u=4.5 m, but would be more limiting at L_u=20 m and 63-fs slippage. Laser bunch length of 25 fs (FWHM) so expect similar for e-beam.

French-German test at HZDR

- This was a seeded FEL test with a single 2-m long undulator.
- Gain detected at a red-shifted wavelength 276 nm from the seed wavelength of 270 nm. If not red shifted, hard to detect.
- Moreover, difficult to select only the FEL radiation for a user.

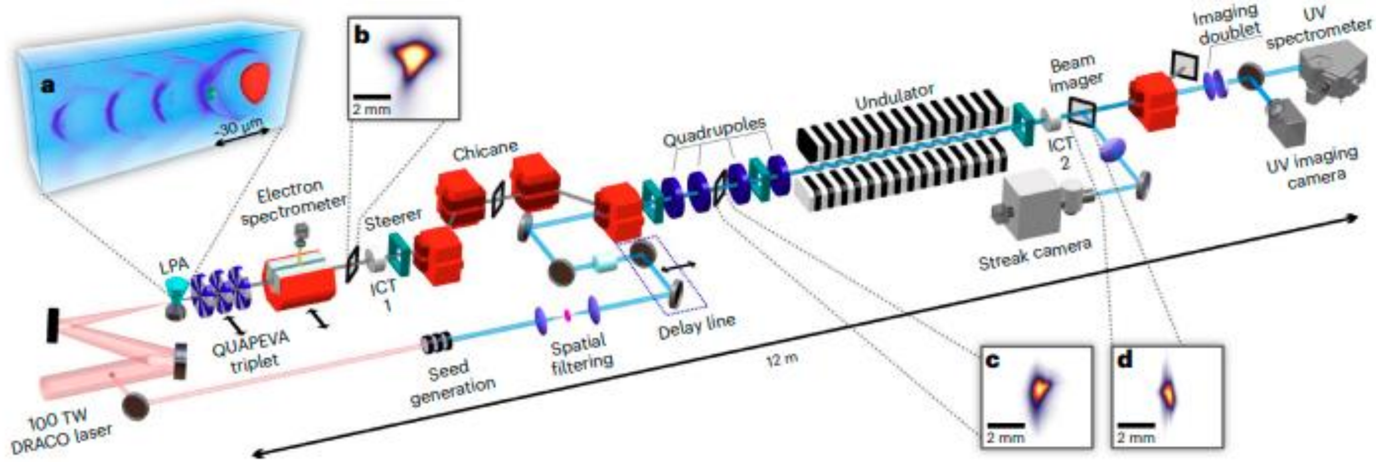

Fig. 1 | Experimental layout. The LPA is driven by the DRACO laser (for more details on the DRACO footprint, see ref. [55]). The electron beam generated in the LPA is first characterized using a removable electron spectrometer and then sent through a triplet of quadrupoles (QUAPEVAs) for beam transport to the undulator and FEL radiation generation. ICTs, integrated current transformers. Non-labelled elements: dipoles, red blocks; optical lenses, blue disks; mirrors, grey circled black disks. **a**, Particle-in-cell simulation rendering of the accelerating structure driven by the laser pulse (red); the electron cavity sheet formed from the plasma medium (light blue) is in purple and the accelerated electron bunch in green. **b**–**d**, Electron-beam transverse distribution measured at the LPA exit (**b**), the undulator entrance (**c**) and the undulator exit (**d**).

Labat, M. et al., Seeded free-electron laser driven by a compact laser plasma accelerator. Nat. Phys. 17, 150–156 (2022).

Seeded FEL Results with Red-shifted Output

- Investigators report radiation gain at a 6-nm longer wavelength than the seed laser.
- This is not user friendly since seed laser energy is larger.

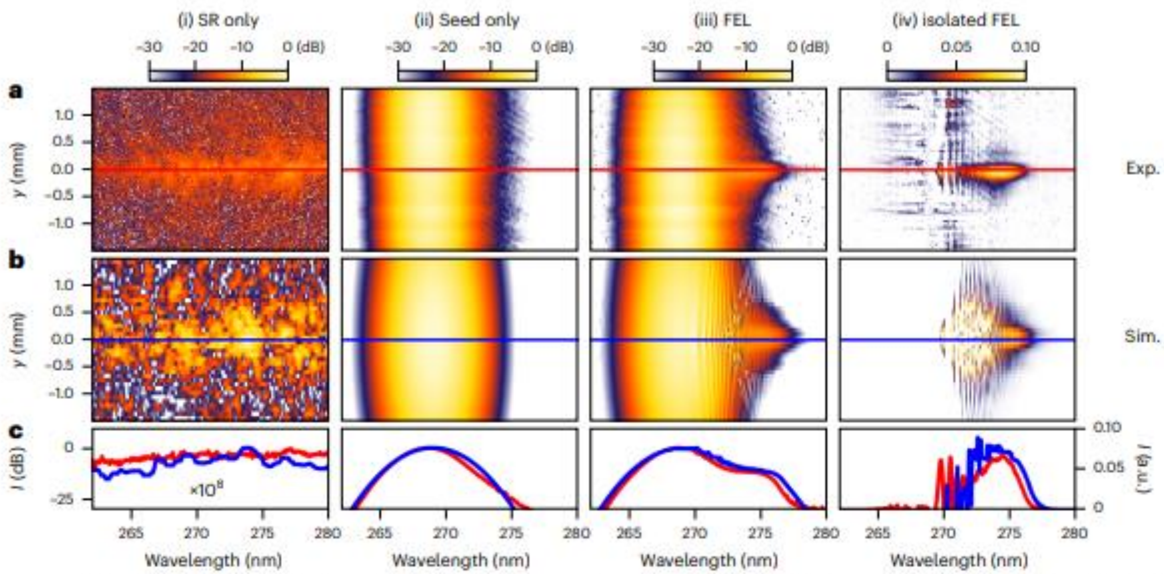

Fig. 2 | Spatio-spectral distributions of the radiation at the undulator exit. **a**,**b**, Spatio-spectral distributions for an undulator gap of 4.3 mm ($K_u = 2.35$) and an optimum delay of +0.1 ps: experimental measurements (**a**) and simulation (**b**) of SR only (i), seed only (ii), SR with seed (iii) and the difference between the (iii) and (ii) images (iv). **c**, On-axis spectral intensity I extracted along the red line in **a** and blue line in **b** with integration over $\Delta y = 0.3$ mm and median filtering of the simulated profile. In **a**,**b**,**c**(**i**–**iii**), distributions are normalized to their maximum intensity and displayed in logarithmic (dB) scale. In **a**,**b**,**c**(**iv**), the distributions are displayed in a linear scale. Simulation parameters (electron-beam parameters given at the source point): $E_e = 188.8$ MeV, charge = 150 pC, $\sigma_z = 2$ µm (r.m.s.), normalized emittance $\epsilon_{x,y} = (1.5; 1.0)$ mm mrad, divergence $\sigma_{x',y'} = (1.5; 1.0)$ mrad (r.m.s.), $\sigma_\epsilon = 5\%$ (r.m.s.), $R_{56} = -1.8$ mm, QUAPEVA 2 strength detuned by −2%, $E_{seed} = 0.5$ µJ, $\lambda_{seed} = 269$ nm, $\Delta\lambda_{seed} = 3.9$ nm (FWHM) and $\Delta T_{seed} = 1.0$ ps (FWHM).

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Pierce Parameter for SASE FEL

- Dimensionless scaling parameter, ρ, determines the main characteristics of high gain FEL systems and enables order of magnitude estimates. (p.97 of Kim, Huang, Lindberg Book.)
- $\rho = [1/8\pi\ I/I_A\ (K(JJ)/1+ K^2/2)^2\ \gamma\lambda_1^{\ 2}/2\pi\sigma_x^{\ 2}]^{1/3}$ where I is peak current, I_A is the Alfven Current, K is undulator parameter, γ is Lorentz factor, λ_1 is the resonant fundamental wavelength, σ_x is the transverse e-beam size.
- Gain length ~ $\lambda_u/4\pi\rho$
- Saturation power ~ ρ x (e-beam power)
- Saturation length L_{sat}~ λ_u/ρ
- Transverse mode size σ_r~ $[\lambda_1\ \lambda_u\ /16\ \pi^2\rho]^{1/2}$
- LCLS-1, $\rho = 4 \times 10^{-4}$
- Chinese case $\rho = 5 \times 10^{-3}$ reported.

(Kim et al. Book.)

Chinese SASE FEL Results at 27 nm

- Demonstration of gain~100 after 3rd undulator

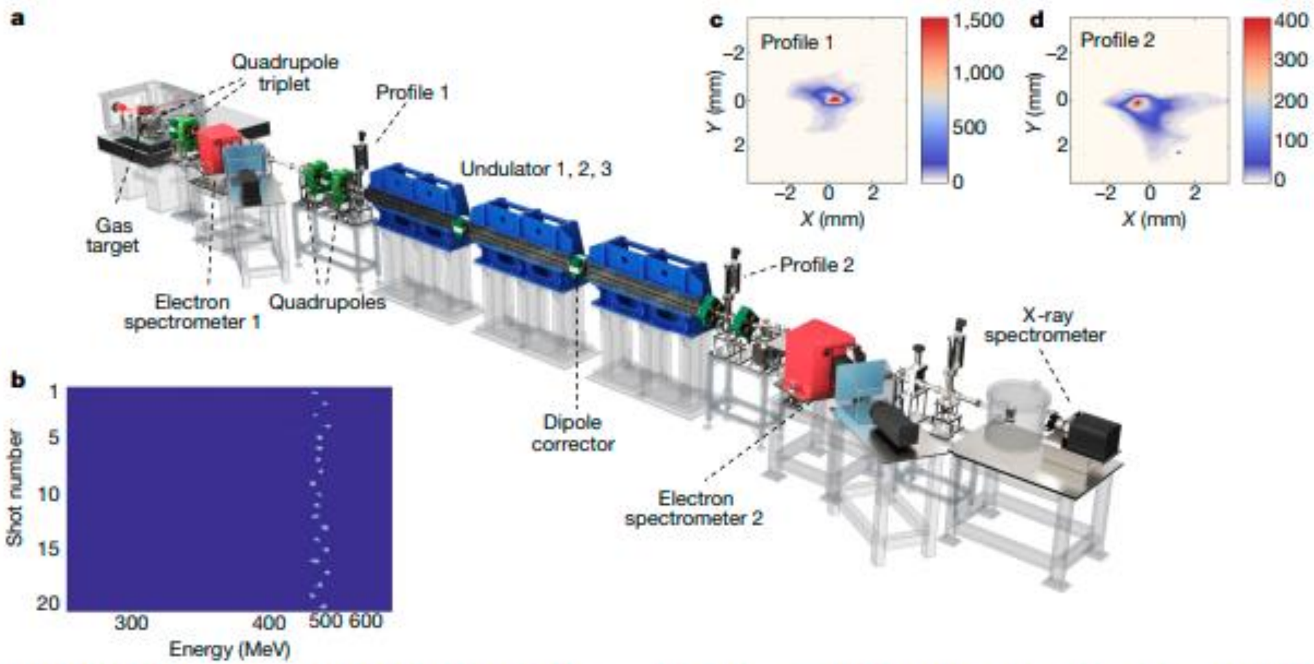

Fig. 1 | Schematic layout of LWFA-based free electron laser experiment. **a**, Undulator beamline with a total length of approximately 12 m from the gas target for the LWFA to the X-ray spectrometer. **b**, Typical spectra of electron beams from the LWFA for 20 consecutive shots. **c**, **d**, Measured transverse profiles of the electron beam at the entrance (**c**) and exit (**d**) of the undulators. The scale bars are normalized.

Wang, W. et al. Free-electron lasing at 27 nanometres based on a laser wakefield accelerator. Nature 595, 516–520 (2021).

Chinese SASE FEL results initially reported in 2021

- Output at 27 nm with e-beam energy of 490 MeV: Q=30 pC.
- SASE FEL exponential gain of 100 reported after 4.5 m.
- ρ~5 x 10^{-3} estimated implied gain length of 0.23 m, but effectively ~ 1m obtained. Saturation needs 20 gain lengths.
- FEL performance is best electron-beam diagnostic.

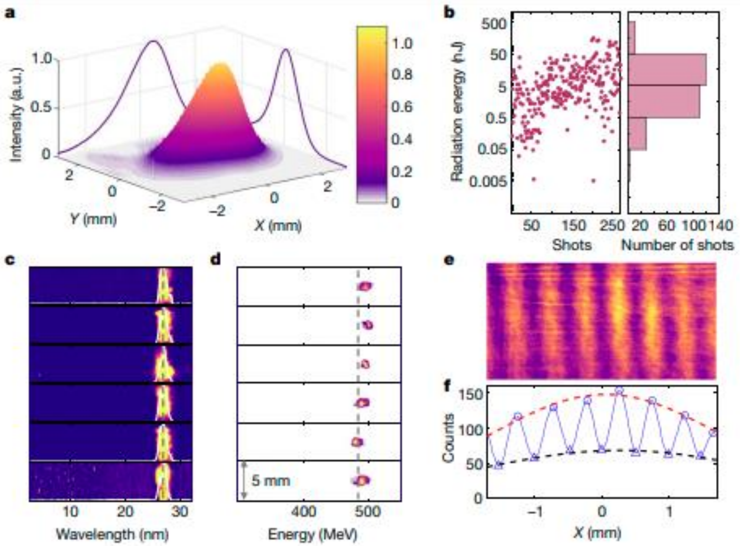

Fig. 2 | Measurement of undulator radiation. a, Measured transverse radiation pattern of a typical pulse on the X-ray CCD camera located 12 m downstream from the gas target. The scale bar is normalized. **b**, Shot-to-shot radiation energy over 270 pulses. **c**, **d**, Measured radiation spectra (**c**) and the corresponding electron-beam energy spectra (**d**) detected by the second spectrometer located at the exit of the undulator. **e**, **f**, Image (**e**) and count profile (**f**) of the interference pattern generated when radiation propagates through two 10-μm slits with a slit separation of 40 μm.

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Summary Table of SASE FELs Driven by rf Linac Beams

Table 1. Representative parameters of some FEL experiments and facilities.* Somewhat dated from 2017. New SC rf linacs now.

Parameter	UCLA /LANL	VISA	LEUTL	TTF	FERMI	LCLS-1	SACLA
γmc^2 (GeV)	0.018	0.071	0.22	0.233	1.2	13.6	6.14
σ_γ/γ (%)	0.25	0.18	0.2	0.15	0.015	0.01	0.01
I (kA)	0.17	0.25	0.2	0.4	0.8	3	3
ε_{xn} (μm)	4	2	7	6	0.8	0.4	0.85
$2\pi\beta_x$ (m)	1.2	1.8	9	6	50	140	185
λ_u (cm)	2.05	1.8	3.3	2.7	3.5	3	1.5
K	1.2	1.04	3.1	1.2	~1	3.5	1.36
L_u (m)	2	4	20	27	20	110	100
λ_1 (nm)	12000	800	385	100	4	0.15	0.1

*Kim, Huang, Lindberg, "Synchrotron Radiation and FELs" book, p 225.

SUMMARY

- The two discussed PWFA cases show promise, but also reveal challenges on e-beam quality: Charge, energy spread, pulse length, transverse emittance, beam-parameter fluctuations.
- Pierce parameter can be a guide for high gain FEL scaling.
- Slippage of e-beam within undulator should be checked.
- FEL performance can be electron-beam-quality diagnostic.
- The step to x-ray wavelengths carries serious challenges.
- SASE FEL has spiky spectra due to starting from noise which will also have the PWFA beam energy fluctuations.
- Solutions to enhance microbunching at short wavelengths would help. Laser Seeding at harmonics, long. compression of e-beam, laser undulator (?), High-gain harmonic generation…
- Single-shot microbunching diagnostics at visible wavelengths: LaBerge talk Wed. AM, also recent *Nature Photonics* article.

Beam-based Plasma-wakefield Acceleration: Rome, Italy

- Electron Source is PC rf gun plus three rf accelerating sections giving 88 MeV acceleration of driver and witness bunches.
- Witness is accelerated by wakefields in a capillary to 93 MeV and directed into 6 undulators. Exponential gain was reported for FEL at 826 $\pm$9 nm. L_g ~1.2 m

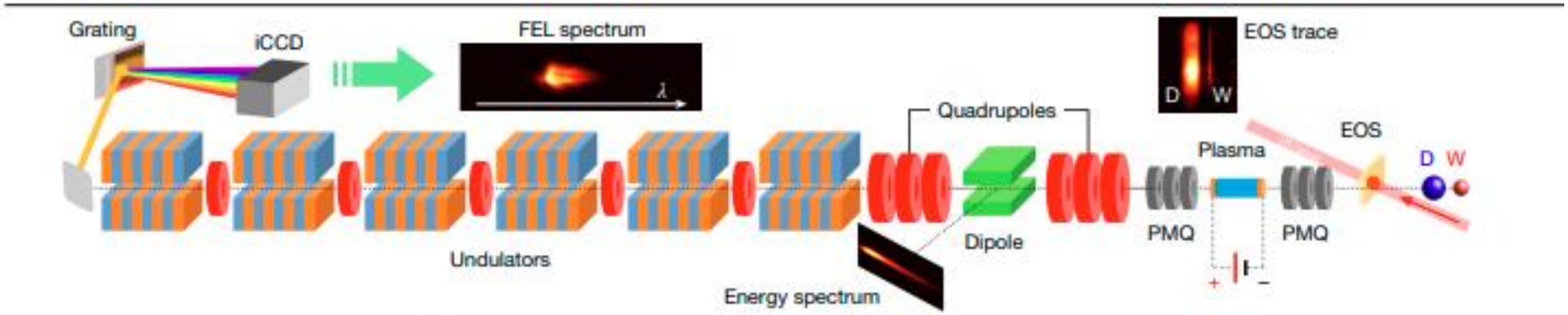

Fig. 1 | Experimental setup. The driver (D) and witness (W) electron bunches are produced by the photo-injector and their temporal separation is continuously monitored with a non-intercepting EOS diagnostics. The bunches are focused by a triplet of PMQs in a 3-cm-long capillary containing the plasma produced by ionizing hydrogen gas with a high-voltage discharge. The accelerated witness is extracted by a second triplet of PMQs and transported using six electromagnetic quadrupoles. A dipole spectrometer is used to measure its energy with a scintillator screen installed on a 14° beamline. The FEL beamline consists of six planar undulators with tunable gaps and five quadrupoles in between to transport the beam. The emitted FEL radiation is collected by an in-vacuum metallic mirror and measured with an imaging spectrometer equipped with a diffraction grating and a cooled intensified camera (iCCD).

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

Plasma Wakefield Acceleration of the Witness Bunch (20 pC)

- Wakefield accelerates witness by ~5 MeV.

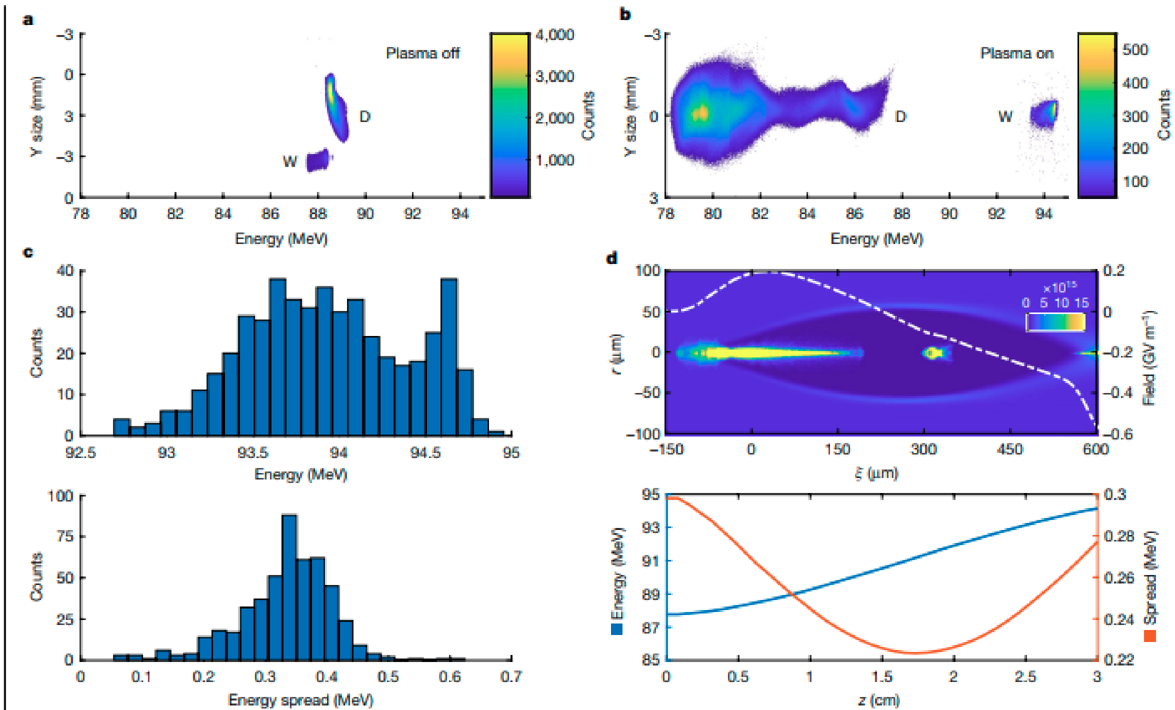

Fig. 2 | Witness acceleration in plasma. Snapshots of the driver (D) and witness (W) spectrum with plasma turned off (**a**) and on (**b**). In **a**, the RF deflector is turned on to vertically separate the two bunches. In **b**, the decelerated driver energy spectrum is obtained by merging the images obtained with different currents of the spectrometer. **c**, Energy (top) and spread (bottom) distributions of 500 consecutive shots of the accelerated witness. **d**, Numerical simulations. The top plot shows a snapshot of the two bunches moving through the plasma background. The white dashed line shows the axial accelerating field along the co-moving coordinate ξ. The plasma density is reported by the colour bar, in units of cm^{-3}. The evolution of the average energy (blue) and energy spread (red) along the capillary longitudinal coordinate z is reported in the bottom plot.