International Linear Accelerator Conference 2022

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Exponential Growth of Radiation in an EUV FEL Driven by an Electron Beam Generated in a Plasma Wakefield Accelerators

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Reference papers:

Shanghai Institute of Optics and Fine Mechanics
&
Laboratori Nazionali di Frascati (INFN)

Article | Published: 21 July 2021

Free-electron lasing at 27 nanometres based on a laser wakefield accelerator

Wentao Wang, Ke Feng, Lintong Ke, Changhai Yu, Yi Xu, Rong Qi, Yu Chen, Zhiyong Qin, Zhijun Zhang, Ming Fang, Jiaqi Liu, Kangnan Jiang, Hao Wang, Cheng Wang, Xiaojun Yang, Fenxiang Wu, Yuxin Leng, Jiansheng Liu, Ruxin Li & Zhizhan Xu

Nature **595**, 516–520 (2021) | Cite this article

SIOM

Article | Published: 25 May 2022

Free-electron lasing with compact beam-driven plasma wakefield accelerator

R. Pompili, D. Alesini, M. P. Anania, S. Arjmand, M. Behtouei, M. Bellaveglia, A. Biagioni, B. Buonomo, F. Cardelli, M. Carpanese, E. Chiadroni, A. Cianchi, G. Costa, A. Del Dotto, M. Del Giorno, F. Dipace, A. Doria, F. Filippi, M. Galletti, L. Giannessi, A. Giribono, P. Iovine, V. Lollo, A. Mostacci, F. Nguyen, M. Opromolla, E. Di Palma, L. Pellegrino, A. Petralia, V. Petrillo, L. Piersanti, G. Di Pirro, S. Romeo, A. R. Rossi, J. Scifo, A. Selce, V. Shpakov, A. Stella, C. Vaccarezza, F. Villa, A. Zigler & M. Ferrario

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Nature **605**, 659–662 (2022) | Cite this article

LNF

Optical physics

A step closer to compact X-ray lasers

Luca Giannessi

Light sources known as free-electron lasers can produce intense X-ray radiation for a wide range of applications. The process usually needs huge particle accelerators, but an experiment shows how to overcome this limitation. **See p.516**

The advent of new tools for investigating our world has always led to discoveries. Light sources called free-electron lasers (FELs) are examples of such tools. FELs can produce

part of its kinetic energy to the laser light. As a result, the light is amplified by several orders of magnitude while propagating through the undulator. FELs therefore require high-energy

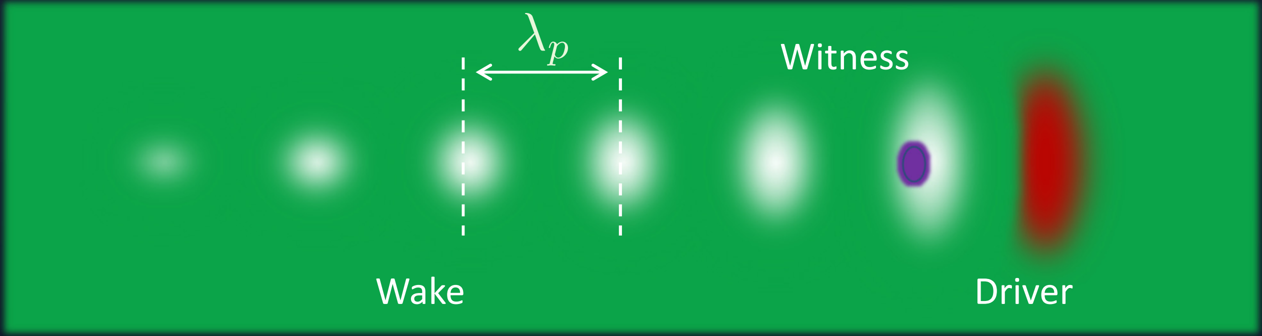
The concept

Precursor: "A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields." **Enrico Fermi**

The idea was proposed in 1979 by Tajima and Dawson: use the electric fields generated in a plasma to accelerate electrons to reduce the typical sizes of the accelerating structures down to the centimetre scale and develop futuristic tabletop machines.

LPWA *"An intense electromagnetic pulse can create a wake of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^8W/cm shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance."* **T. Tajima and J. M. Dawson PRL 43, 267 (1979)**

With respect to conventional radiofrequency (RF) technology limited to low gradients by electric breakdown, plasma-based devices can sustain fields that are orders of magnitude larger, up to hundreds of gigavolts per metre.



$$E[V/m] = \frac{m_e c \omega_p}{e_0} \sim 100\sqrt{n_0[cm^{-3}]}$$

$$\lambda_p[\mu m] \sim \frac{3.3 \cdot 10^{10}}{\sqrt{n_0[cm^{-3}]}}$$

$$n_0 \sim 10^{18}[cm^{-3}]$$

The driver

- Plasma wake: 10–30 μm for electron densities n_e=10^{18}–10^{19} cm^{-3} → store large amount of energy in a short pulse (as short as the plasma wake).
- Two Ingredients in LPWA:
  - *Short pulse - > Ti:Sa bandwidth*
  - *High energy Chirped Pulse Amplification: G.A. Mourou D. Strickland*

- Other schemes than LPWA have been proposed and realized by employing **high-current electrons or proton beams** to excite waves in confined plasma structures.

EBWA "A new scheme for accelerating electrons, employing a bunched relativistic electron beam in a cold plasma, is analyzed. We show that energy gradients can exceed 1 GeV/m and that the driven electrons can be accelerated from $\gamma m_0 c^2$ to 3 $\gamma m_0 c^2$ before the driving beam slows down enough to degrade the plasma wave. " **P. Chen, J. M. Dawson, Robert W. Huff, and T. Katsouleas PRL 54, 693 (1985) (INFN Frascati & several places)**

PBWA "... we introduce the possibility of proton-bunch-driven plasma-wakefield acceleration, and demonstrate through numerical simulations that this energy regime could be reached in a single accelerating stage. " **A. Caldwell, K. Lotov, A. Pukhov and F. Simonm, Nat. Phys. 5 363 (2009) (AWAKE - CERN)**

When driven by ultrarelativistic particle beams, the EBWA/PBWA are less limited by diffraction or dephasing, making in principle large acceleration lengths possible (see AWAKE, 10 m).

The Challenges:

- **Timing:** the accelerating field changes over the scale of the plasma wavelength (energy/energy spread)
- **Injection and dephasing** between laser and electrons
- Diffraction and **depletion of the driver**
- Electron **beam loading**
- **Electron beam matching** – low beam size β_T and large divergence α_T
- Stability of the driver/plasma parameters

First experiments demonstrated acceleration, not "energy confined beams".

Then ...

- **Ultrashort laser pulses**, control of electron injection in the wake via different methods, control of beam loading and longitudinal wakes greatly improved the energy spread figures
- Permanent magnet high gradient quadrupoles allow electron matching to a conventional beam transport system
- **New ideas** like TGU undulator contribute to mitigate the energy spread effect on the FEL

Reasons for a plasma accelerated beam driven FEL

1) It's a CHALLENGE: the FEL is extremely sensitive to the beam quality.

Low (geometric) emittances: $\epsilon_{x,y} < \frac{\lambda_0}{4\pi}$

Low relative energy spread σ_γ: $\sigma_\gamma < \frac{1}{2}\rho_{fel}$

where $\rho_{fel} = \frac{1}{4\pi}\left[\frac{2\pi^2}{\gamma^3}\left(\lambda_u K\,[JJ]\right)^2 \frac{I_{peak}}{\Sigma_e I_A}\right]^{1/3}$

Low emittances
Low energy spread
High current

Exponential growth

$$P(z) = \frac{1}{9}P_0 e^{z/L_g}$$

gain length

$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{fel}}$$

saturation

$$P_F \sim 1.6\,\rho_{fel} P_{beam}$$

A poor beam quality causes an increase of L_g and a reduction of P_F

2) Compact light sources: university/small lab scale sources would increase the opportunities for access and the mode of access to these types of sources.

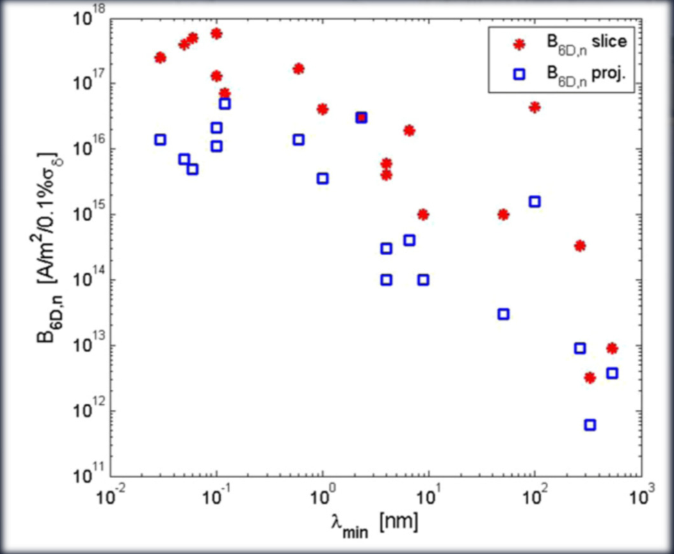
Electron beams for FELs

S. Di Mitri, M. Cornacchia, Physics Reports 539 (2014) 1–48

Table 1.1
Single-pass VUV and X-ray FEL facilities [1,13] currently operational (O), under construction C, in advanced technical design (T) and advanced design study (D). The accelerator type is normal (NC) or superconducting (SC). The wavelength is the minimum proposed. The peak current is the maximum foreseen. Final brightness is evaluated both for projected (p) and slice (s) beam parameters.

Name	Location	Status	Type	λ_{min} (nm)	E (GeV)	Q (pC)	I (kA)	$B_{4D,n}$ (A/m^2)	$B_{6D,n}$ (A/m^2/0.1%)
EuXFEL	Germany	C	SC	0.05	14.0	250	5.0	2.0×10^{16} (s) 2.2×10^{15} (p)	$<4 \times 10^{17}$ (s) 7×10^{15} (p)
SACLA	Japan	O	NC	0.06	8.45	300	4.0	5×10^{16} (s) 5×10^{15} (p)	5×10^{17} (s) 5×10^{15} (p)
PAL XFEL	South Korea	C	NC	0.1	10.0	200	3.0	1.9×10^{16} (s) 3.1×10^{15} (p)	1.3×10^{17} (s) 2.1×10^{16} (p)
SwissFEL	Switzerland	C	NC	0.1	5.8	200	3.0	4.0×10^{16} (s) 1.1×10^{16} (p)	5.8×10^{17} (s) 1.1×10^{16} (p)
LCLS	USA	O	NC	0.12	14	250	3.0	8.3×10^{15} (s) 4.3×10^{15} (p)	7.1×10^{16} (s) 5×10^{16} (p)
LCLS II	USA	T	NC	0.6	15.4	150	3.5	2.2×10^{16} (s) 1.4×10^{16} (p)	1.7×10^{17} (s) 1.4×10^{16} (p)
NGLS	USA	D	SC	1	2.4	300	0.6	1.7×10^{15} (s) 1.2×10^{15} (p)	4.1×10^{16} (s) 3.6×10^{15} (p)
WiFEL	USA	D	SC	2.3	1.7	200	1.0	1×10^{15} (s) 1×10^{15} (s)	3×10^{16} (s) 3×10^{16} (p)
FERMI	Italy	O	NC	4	1.5	500	0.6	6×10^{14} (s) 3×10^{14} (p)	6×10^{15} (s) 3×10^{14} (p)
FLASH I	Germany	O	SC	6.5	1.0	500	2.5	3.8×10^{15} (s) 0.7×10^{15} (p)	1.9×10^{16} (s) 0.4×10^{15} (p)
FLASH II	Germany	C	SC	4	1.0	1000	1.2	5×10^{14} (s) 3×10^{14} (p)	4×10^{15} (s) 1×10^{14} (p)
SXFEL	China	D	NC	8.8	0.84	500	0.6	1.5×10^{14} (s) 1.0×10^{14} (p)	1×10^{15} (s) 1×10^{14} (p)
SCSS	Japan	Shut-down	NC	50	0.25	300	0.3	5.0×10^{14} (s) 5.0×10^{13} (p)	1×10^{15} (s) 3×10^{13} (p)
CLARA	UK	T	NC	100	0.25	250	0.4	4.4×10^{15} (s) 1.6×10^{15} (p)	4.4×10^{16} (s) 1.6×10^{15} (p)
DUVFEL	USA	Shut-down	NC	266	0.18	300	0.3	3.3×10^{13} (s) 1.3×10^{13} (p)	3.3×10^{14} (s) 0.9×10^{13} (p)
SDUV FEL	China	O	NC	328	0.14	500	0.05	3.2×10^{12} (s) 1.6×10^{12} (p)	3.2×10^{12} (s) 0.6×10^{12} (p)
SPARC	Italy	O	NC	530	0.10	300	0.12	4.7×10^{13} (s) 3.8×10^{13} (p)	0.9×10^{13} (s) 3.8×10^{12} (p)
MaRIE	USA	D	NC	0.03	20	100	3.4	3.8×10^{16} (s) 1.4×10^{16} (p)	2.5×10^{17} (s) 1.4×10^{16} (p)

$$B_{6D} \propto \frac{I_{peak}}{\epsilon_x \epsilon_y \sigma_{\gamma r}\,[0.1\%]}$$



The electron beam sources

LPWA FEL and EBWA FEL beam optimization

LPWA FEL

PRL 117, 124801 (2016) PHYSICAL REVIEW LETTERS week ending 16 SEPTEMBER 2016

High-Brightness High-Energy Electron Beams from a Laser Wakefield Accelerator via Energy Chirp Control

W. T. Wang,[1] W. T. Li,[1] J. S. Liu,[1,2,*] Z. J. Zhang,[1] R. Qi,[1] C. H. Yu,[1] J. Q. Liu,[1] M. Fang,[1] Z. Y. Qin,[1] C. Wang,[1] Y. Xu,[1] F. X. Wu,[1] Y. X. Leng,[1] R. X. Li,[1,2,3,†] and Z. Z. Xu[1,2,3,‡]
[1]*State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China*
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(Received 4 May 2016; published 16 September 2016)

By designing a structured gas density profile between the dual-stage gas jets to manipulate electron seeding and energy chirp reversal for compressing the energy spread, we have experimentally produced high-brightness high-energy electron beams from a cascaded laser wakefield accelerator with peak energies in the range of 200–600 MeV, 0.4%–1.2% rms energy spread, 10–80 pC charge, and ~0.2 mrad rms divergence.

EBWA FEL

nature physics LETTERS
https://doi.org/10.1038/s41567-020-01116-9
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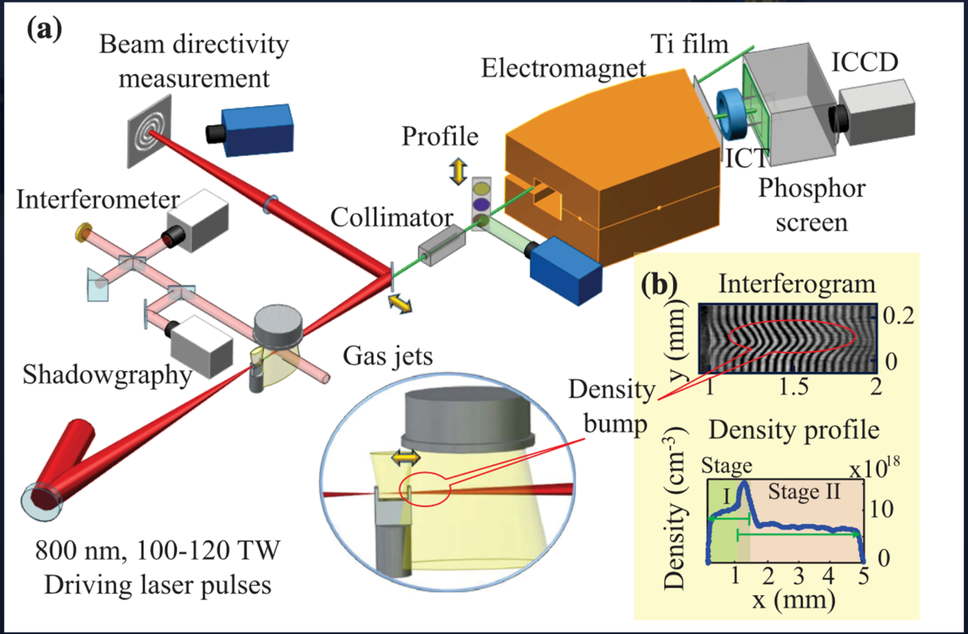
Energy spread minimization in a beam-driven plasma wakefield accelerator

R. Pompili[1✉], D. Alesini[1], M. P. Anania[1], M. Behtouei[1], M. Bellaveglia[1], A. Biagioni[1], F. G. Bisesto[1], M. Cesarini[1,2], E. Chiadroni[1], A. Cianchi[3], G. Costa[1], M. Croia[1], A. Del Dotto[1], D. Di Giovenale[1], M. Diomede[1], F. Dipace[1], M. Ferrario[1], A. Giribono[1], V. Lollo[1], L. Magnisi[1], M. Marongiu[1], A. Mostacci[2], L. Piersanti[1], G. Di Pirro[1], S. Romeo[1], A. R. Rossi[4], J. Scifo[1], V. Shpakov[1], C. Vaccarezza[1], F. Villa[1] and A. Zigler[1,5]

... By setting a positive energy chirp on the witness bunch, its longitudinal phase space is rotated during accel- eration, resulting in an ultralow energy spread that is even lower than the spread at the plasma entrance. This result will significantly impact the optimization of the plasma acceleration process and its implementation in forthcoming compact machines for user-oriented applications.

Setup: injection & double stage acceleration

Control of plasma wave wavelength & phase velocity via structured plasma density profile: by adjusting the horizontal span between two gas nozzles, a structured gas profile with a steep density bump (250 micron) between two-segment gases is produced



- 200-TW laser system – 1 to 5 Hz
- Intensity 3.8 10^{18}W/cm^2 (a_0=1.3)

- The first-segment 0.8-mm-thick gas flow using pure He atoms was operated with a high plasma density of 1.1×10^{19} cm^{-3} and the second-segment 4-mm-thick gas flow with an average density of 6.0×10^{18} cm^{-3}.

- The measurements from the interferometer indicated there was a rapid increase in the density profile (density bump) from 1 to 1.25 mm at ~200 μm away from the exit of the first gas nozzle.

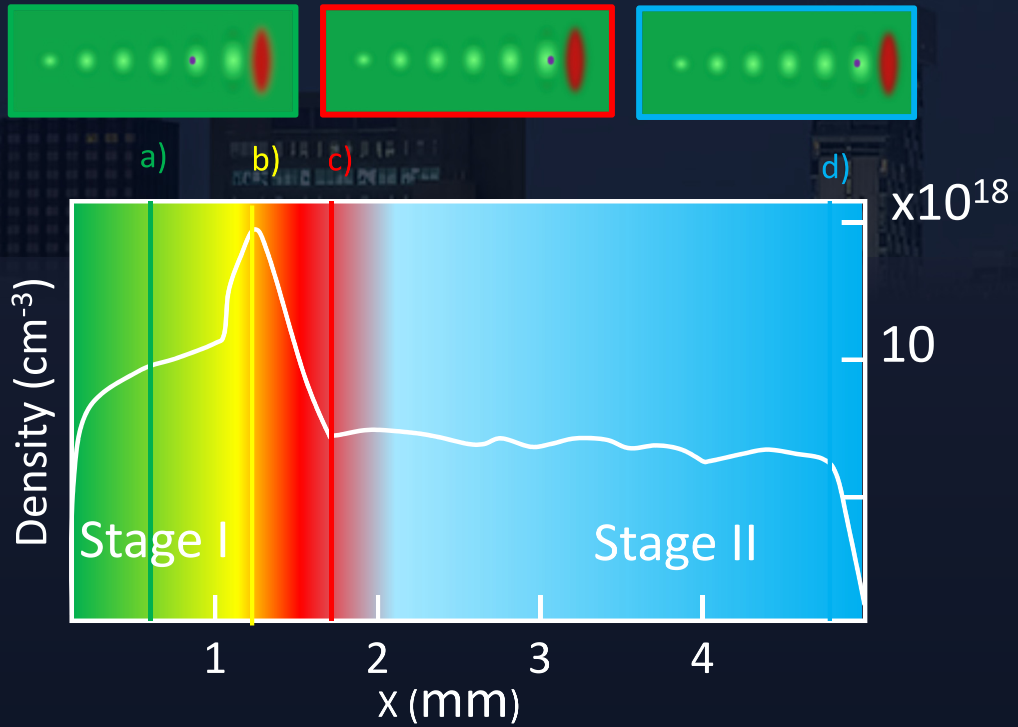
Plasma density profile shaping

A decrease in plasma density along the laser propagation:

(1) increases the wavelength of the wakefield → changes the phase position of trapped electrons relative to the wakefield

(2) reduces the phase velocity of the plasma wave modifies the group velocity of the laser pulse.

These two effects depend nonlinearly on normalized laser amplitude a0 and its evolution.



a) Field intensity increases because of tight laser focus. This causes decrease of phase velocity -> **electron injection in the second plasma bucket**

a-b) increase of plasma density compensates phase shift due to laser intensity: **control phase of injected electrons during stage I**

b-c) sudden decrease in plasma density increases plasma wavelength and decreases phase velocity: **electrons captured in first plasma wake.**

The energy chirp impressed to the beam is reversed.

c-d) acceleration in second stage. Energy spread compensated by chirp imprinted in b-c.

Results

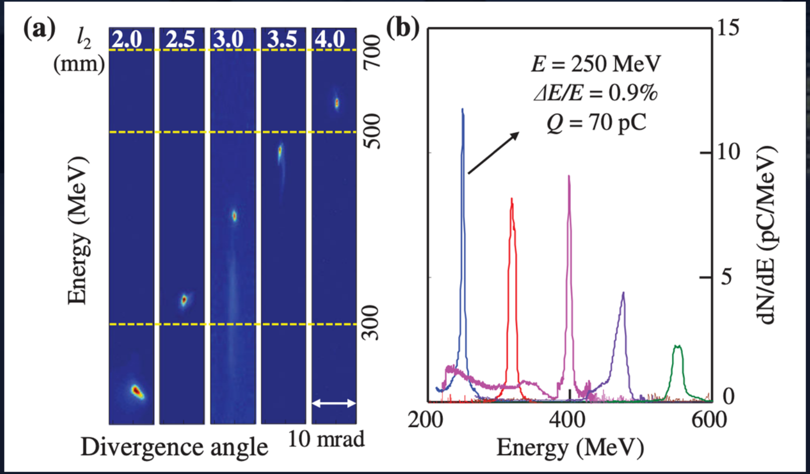
Performances:

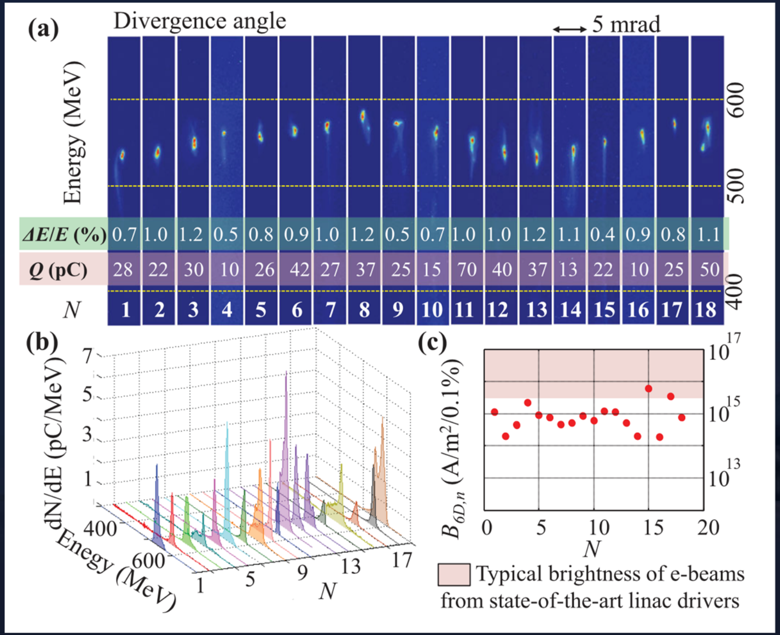
Charge 10-80 pC

Energy spread < 1% (0.4%)

Divergence 0.1 mrad

Estimated 6D Brightness: 10^{15} A/m²/0.1%$\sigma_{\gamma r}$



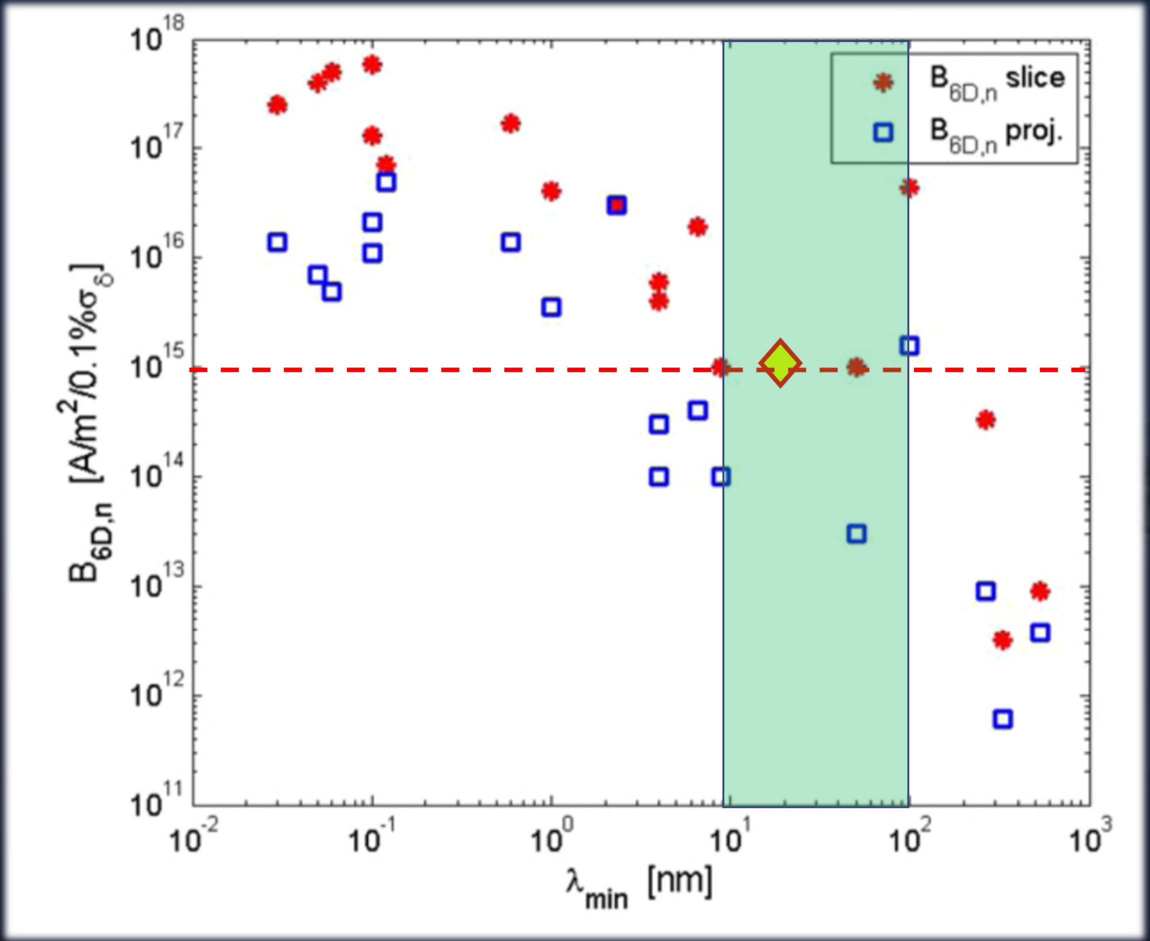


Stability: Energy fluctuation 5%; fluctuations mainly attributed to the shot-to-shot fluctuation in laser power (3%) and jitter in gas density.

Energy tuning: by adjusting the length of the acceleration stage, peak energy (E) tunable from 200 to 600 MeV

Brightness scenario

The achieved brightness is compatible with FEL operation in the VUV – EUV



The LWFA FEL setup

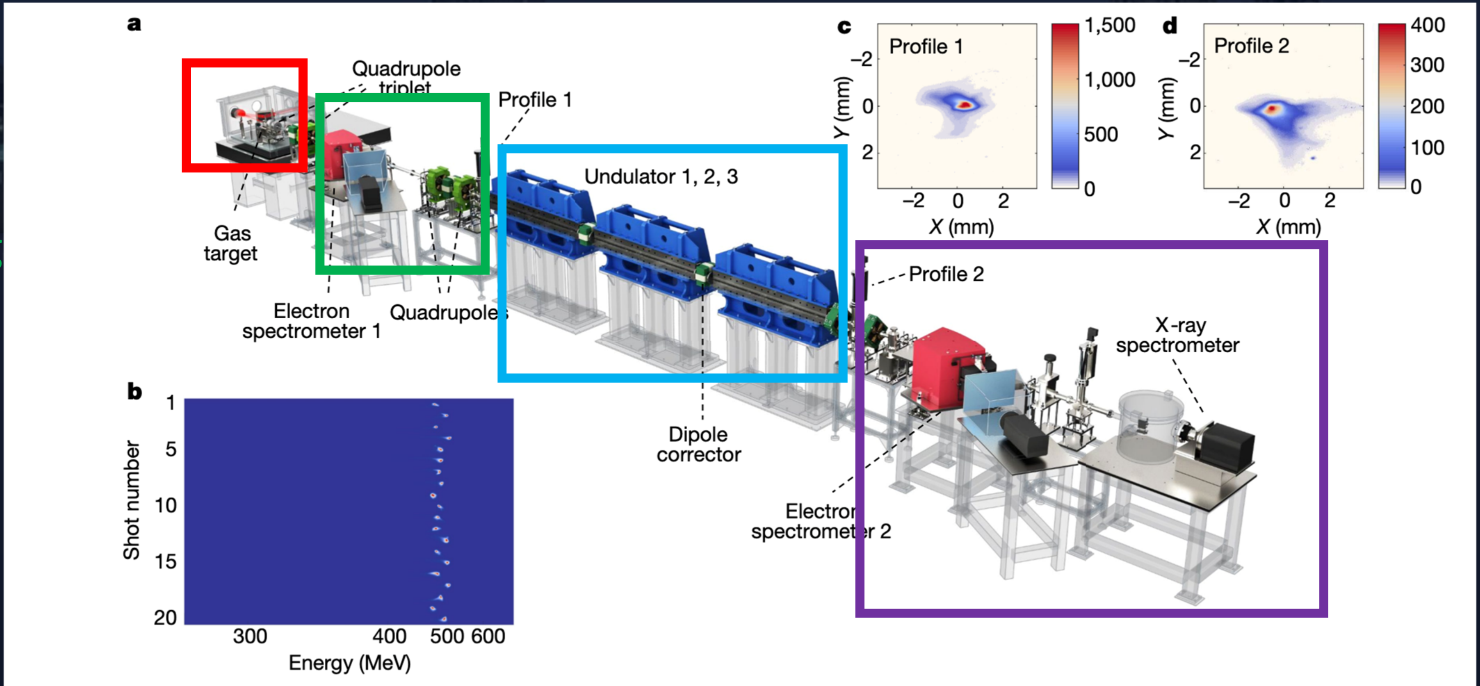
Improved stability – laser energy fluctuations 0.5 %
Further optimization of plasma paraemters

Accelerator:
490 MeV 0.5% En. spread/3% fluctuations
30 pC charge and
0.2 mrad div.

Diagnostics:
Spectrometers electron/radiation
profile monitors / energy. meter

Matching optics.
8cm 2 PM Quads.
1 EM. Q. for tuning

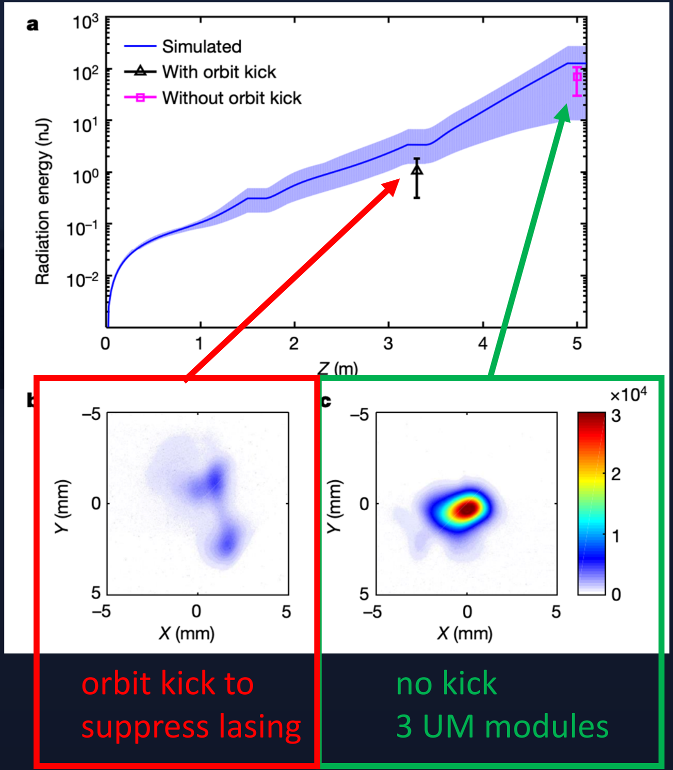
Undulator:
3 Modules
60 periods each
Period 25 mm
K=1.41

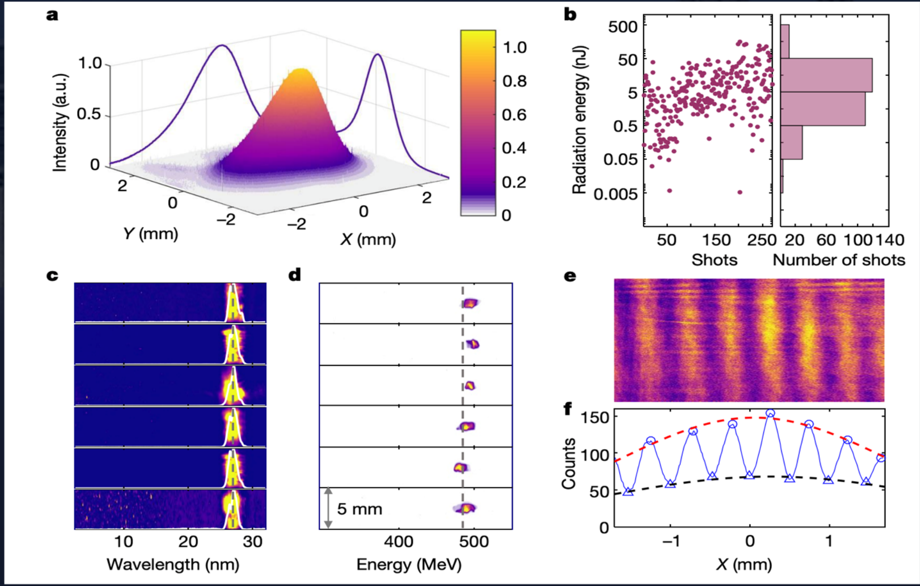


FEL Performances

- Output energy up to 150 nJ
- Amplification up to 2 orders of magnitudes in the last UM

no way without gain !





Large energy fluctuations: operation with reduced number of longitudinal modes (about one) - single spike in spectrum 100% fluctuations

The electron beam sources

Both the experiments LPWA FEL and EBWA FEL were anticipated by a study devoted to beam optimization

LPWA FEL

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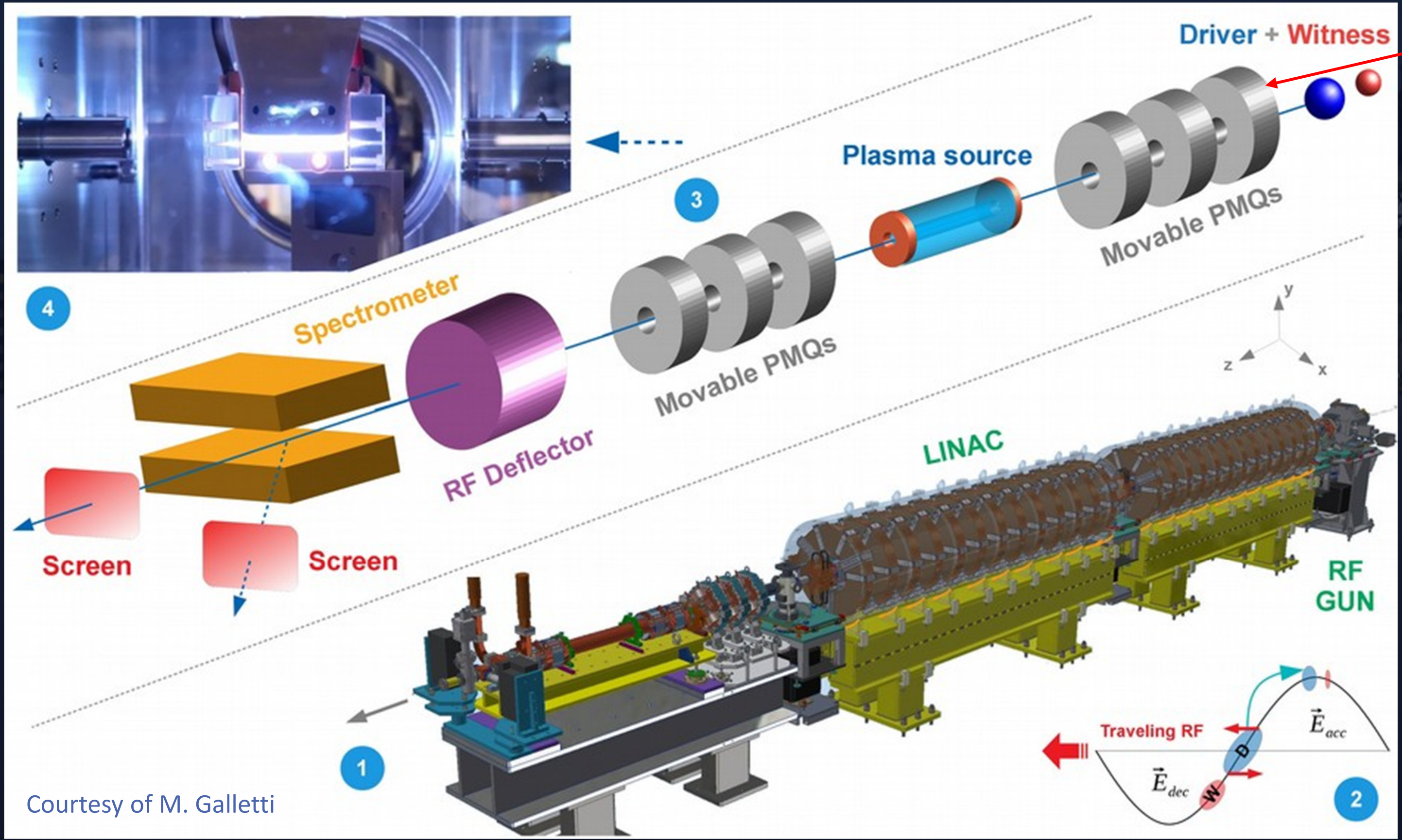
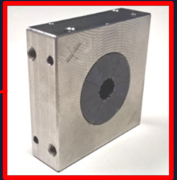
Plasma acceleration at LNF

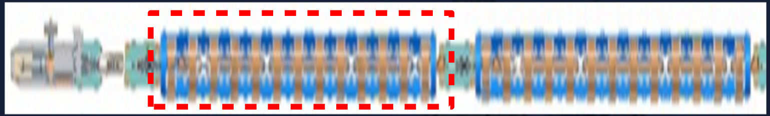




Permanent magnets Q

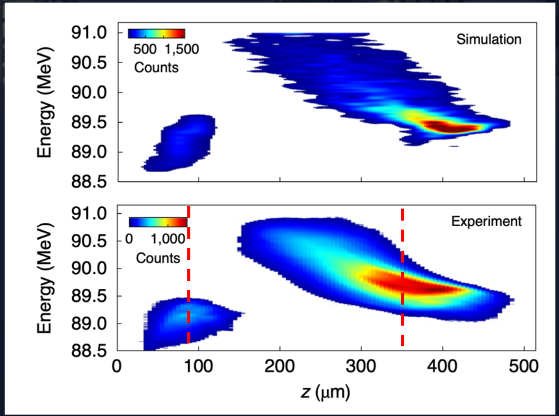
Beam preparation (1-2): acceleration and compression via velocity bunching

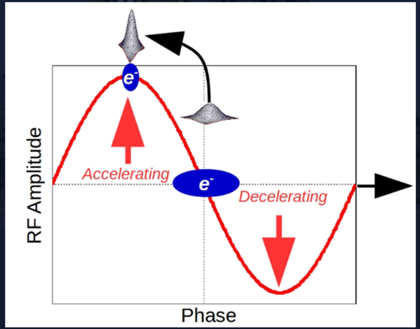
- Injection in the first section close to zero crossing causes compression due to velocity dispersion



200+20 pC GPT simulation

Beam at the injection in the plasma



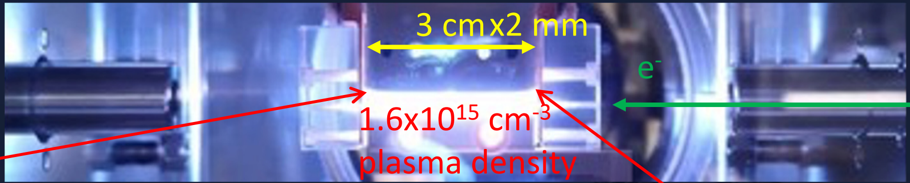


Measured by RF deflector + dipole spectrometer separation ~1.1 ps

The driver 200pC charge and 230fs duration. Witness 20 pC charge and 30-40 fs duration. Peak current ~500A

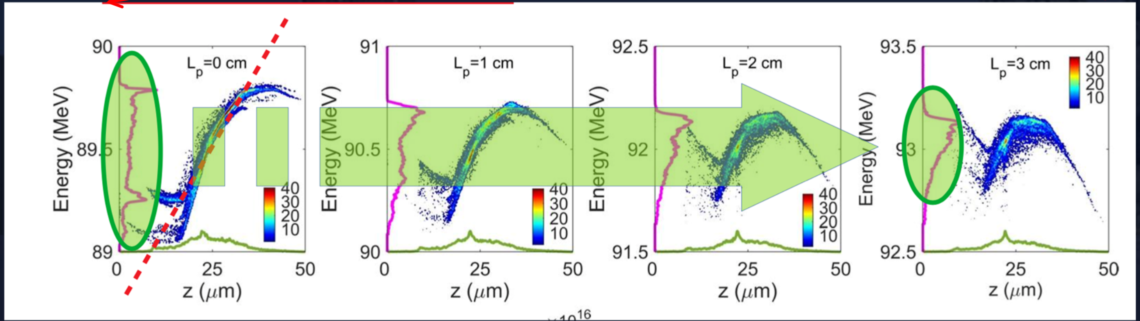
The plasma accelerator (3-4)

- Plasma in the quasi-nonlinear (QNL) regime, where the density of the driver bunch exceeds that of the plasma and induces blow-out

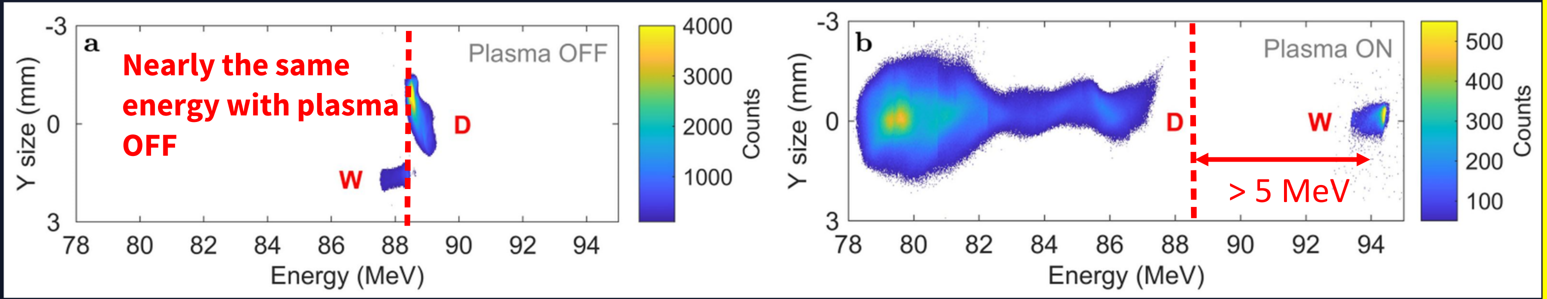


Assisted beam-loading technique: pre-chirped beam to compensate PWBA chirp

in Pompili, R., et al., Nature Physics 17.4 (2021): 499-503
Total projected spread: 0.2 MeV → 0.12 MeV



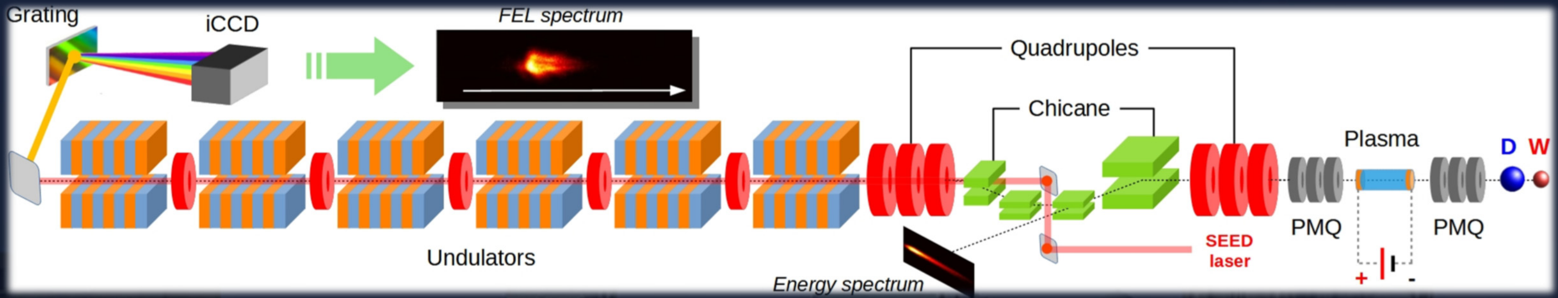
to the FEL



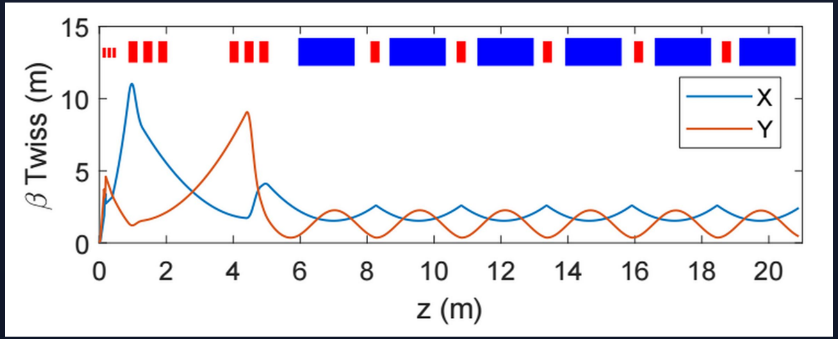
~200 MV/m accelerating gradient

Accelerated witness:
Energy: 94 MeV, 0.3 MeV spread
Emittances: 2.7(X) μm, 1.3(Y) μm
Driver decelerated by almost 10 MeV

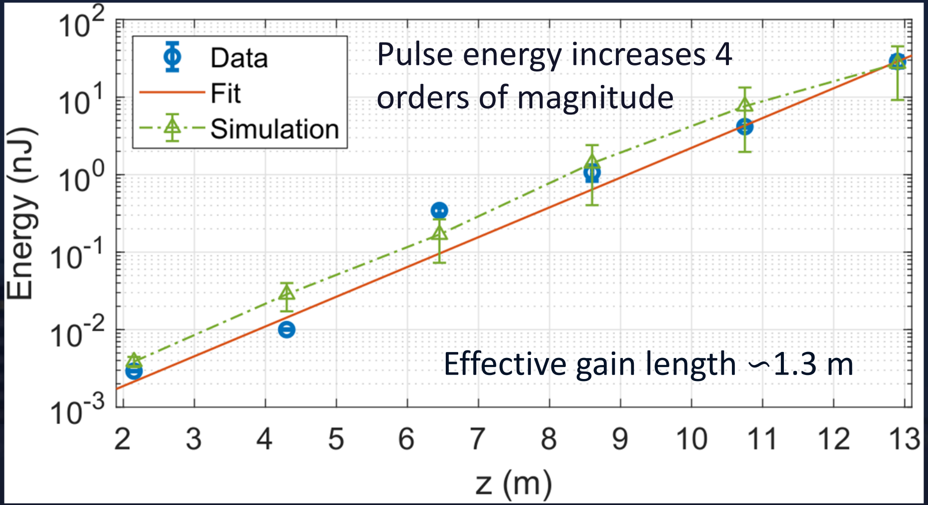
The FEL Amplifier



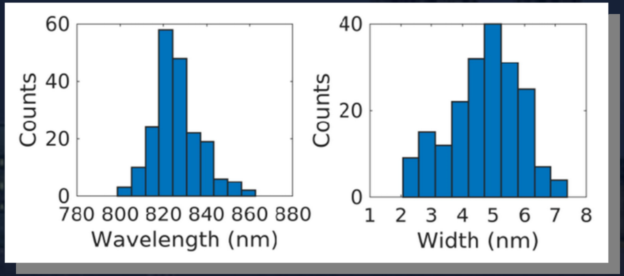
- Amplifier: 6 UM 77p, 2.8 cm period - K∽1.36
- Diagnostics - 6 photodiodes at the undulator breaks - Imaging spectrometer with iCCD used to detect FEL radiation
- Resonant wavelength 800 nm - Operated in SASE and seeded mode: seed energy ~10 nJ/600 fs in the experiment.
- Beam matched, 20 pC, 30 fs ∽500A peak current transported through the undulator

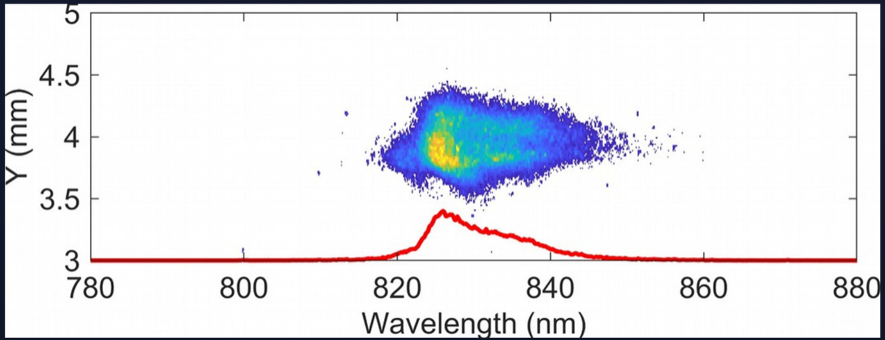


SASE operation mode



About 30% of "successful shots":
17% pulse energy (RMS) fluctuations discarding the remaining 70% shots





→ Single spike operation in exponential gain regime

- Cooperation length: 30-60 µm
- Bunch duration 30 fs

100% Intensity fluctuations are therefore expected – <u>not caused just by beam fluctuations</u>

SEEDED mode (shot noise fluctuations suppressed)

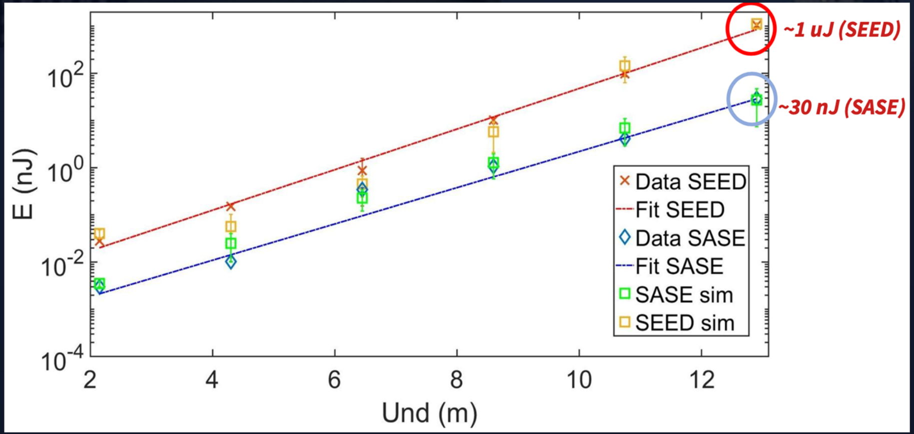
Clear signals, reproducible day by day

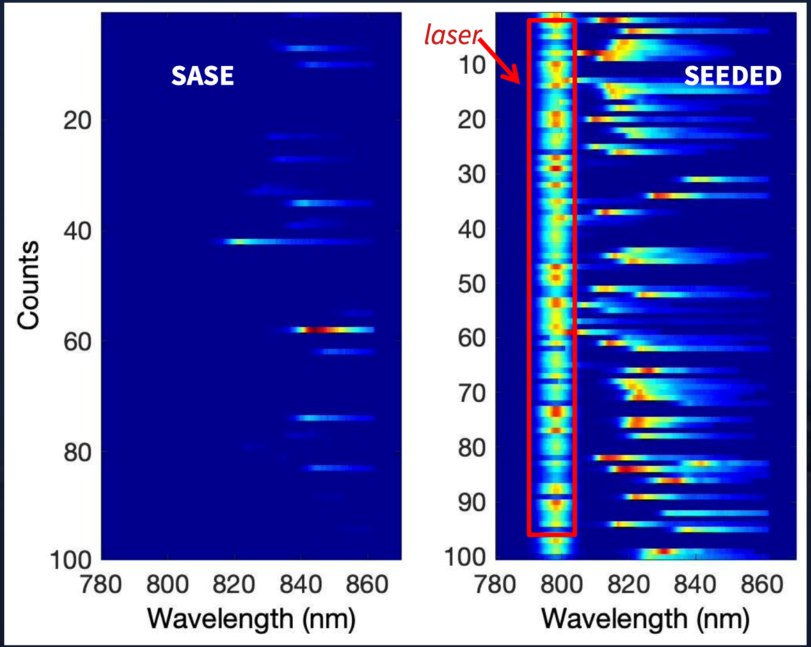
- ✓ Pulse energy up to 1 μJ
- ✓ Centered @827 nm with 5 nm BW
- ✓ 10% missing shots (vs. 70% in SASE)
- ✓ Energy fluctuation 6% (RMS)

Non-trivial FEL configuration:

Dispersion 120 μm/undulator - 720 μm total

Current undergoing modifications along the undulator





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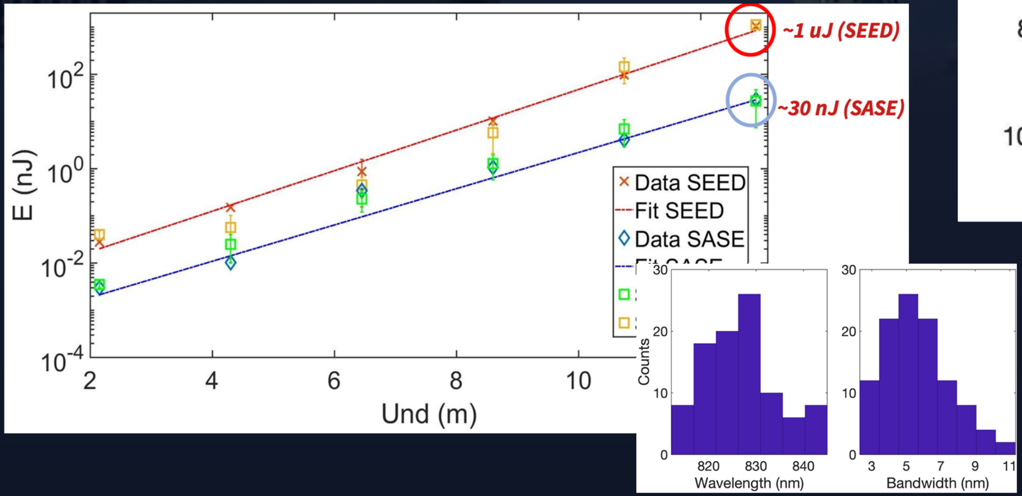

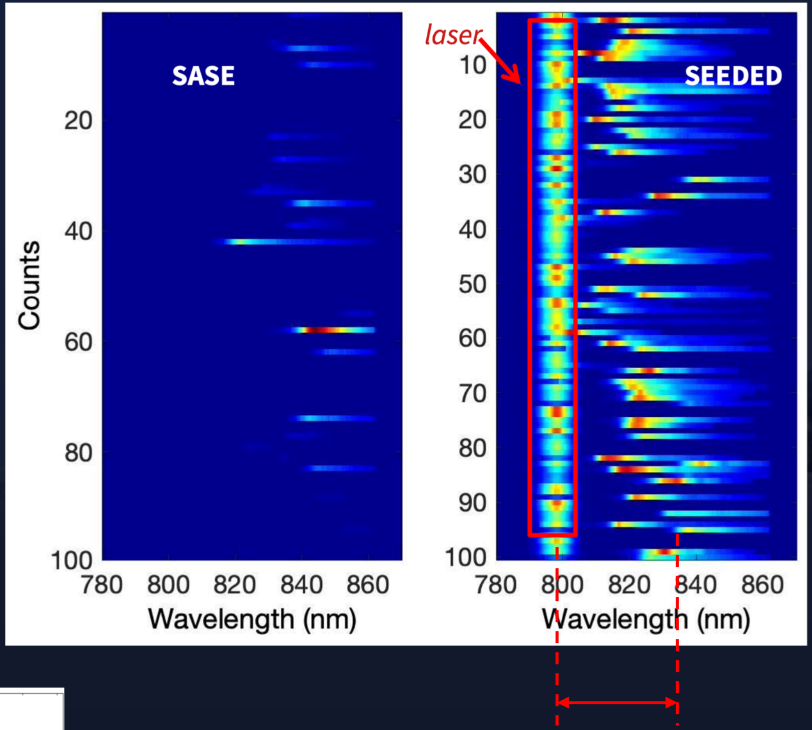

detuning and wavelength jitter (follows beam energy fluctuations ~8 nm RMS): strong frequency pulling as observed in superradiance *Mirian, N.S., Di Fraia, M., Spampinati, S. et al. Nat. Photon.* ***15****, 523–529 (2021).*

Conclusions 1

- We have the first evidences of FEL lasing from plasma accelerated beams
- The experiments operated at still large wavelengths (larger for LNF) to be critical with. emittances, major role is played by energy spread which seems under control
- Energy spread compensation in both cases. The experiments rely on unconventional acceleration stages, but use conventional undulator chains, no TGU, no exotic injection schemes, no beam conditioning stages
- SIOM Experiment:
  - Pure LWBA has the advantage of entirely suppressing the need of an accelerator and the achieved result is outstanding.
  - Expected bunch duration of few micrometers, would be optimized at a shorter wavelength, fluctuations in output intensity still consistent. Role of number of longitudinal modes to be investigated.
  - Still modest energy per pulse, seeded ?
- LNF Experiment
  - A conventional acceleration stage still needed: acceleration from existing beam.
  - Modest energy increase in present setup. Higher gradient/acceleration length required in the EUPRAXIA facility (500-> 1GeV boost). Works in simulations, still to be practically demonstrated.
  - Longer acceleration length/higher gradient required for larger transformer ratios, work in progress.
  - Stable operation in seeded mode suggests reasonably stable beam parameters. Promising for future developments as EUPRAXIA facility.

A FEL user facility has a spectral stability at the 10^{-3} level. FERMI a seeded FEL has a relative photon energy stability at the $10^{-4} \div 10^{-5}$ level. We still meet conditions where users complain. Stability may be critical (x10-10^2 times larger).

Conventional accelerator have a modest gradient, few tens of MV/m. Staged acceleration is necessary to reach GeV energies

● | *1* | *2* | | | *n* | | *N*

(A_n, ϕ_n)

Typical jitters [FERMI]: $\left\{ \begin{array}{l} \left(\frac{\delta A_n}{A_n}\right)_L < 10^{-3} \\ (\delta\phi_n)_L < 0.2\, mrad \end{array} \right.$

The low phase jitter do not affect the energy stability.

With N stages, jitters scale as $1/\sqrt{N}$. Final energy jitter $\left(\frac{\delta E}{E}\right)_L \sim 10^{-4}$

Plasma accelerators can reach GeV energies in a single stage, but *0.2 mrad* with $\lambda_p \sim 30\mu m$ correspond to about 6 as:

- temporal jitters extremely critical. Stability affected by witness – driver separation jitters in EBPW
- Staging is a challenge and easily dominates the energy jitter: the energy stability is hardly improved by multi-staged acceleration. A low $\frac{\delta A}{A}$ is required.

$\frac{\delta A}{A}$ depends on the driver. In case of LPWA linear regime $A \propto \sqrt{P_{Laser}}$ and $\frac{\delta A}{A} = \frac{1}{2}\frac{\delta P_{Laser}}{P_{Laser}} \sim 10^{-2}$

Conclusion 2

- The challenge: "make an FEL with a plasma beam" is achieved. This imply low energy spread, high quality and well controlled beams.
- Do not read it as a success in a competition with conventional facilities. The target is different:

Make it less expensive, make it more accessible: broaden the number of users with access to light sources. A key for future wide scientific growth.

"More accessible" implies less expensive, more compact, but also simpler and less expensive to run, less staff required and maybe and with some constraints on expected performaces

- EBWA still needs an accelerator
- LPWA needs a TW class laser system, to be operated in pretty stable conditions.
- Progress is ongoing with more conventional technology also, see e.g. *J B Rosenzweig et al "An ultra-compact x-ray free-electron laser", New J. Phys. 22 093067 (2020)*

The promising technology is still to be defined,

... but after these results we can say that the future looks a bit brighter..