

Advanced Acceleration Techniques and Novel Particle Sources

Edda Gschwendtner, CERN

IPAC'26 Student Tutorials

Deauville, France

17 May 2026



Advanced Acceleration Techniques and Novel Particle Sources

Talks at IPAC2026, Deauville, France

Tue, 19 May 2026

Chair: Tadashi Koseki
High quality electron beams with tunable energy produced by laser-plasma acceleration , Brigitte Cros, Uni. Paris Saclay
First direct observation of a wakefield generated with structured light , Aaron Liberman, Weizman

Wed, 20 May 2026

Chair: Enrica Chiadroni
Controlled injection and acceleration of 10 GeV-class electron beams in a laser wakefield accelerator , Alex Picksley, LBNL
Progress Towards High-Repetition-Rate Plasma Wakefield Acceleration at FLASHForward , Judita Beinortaitė, DESY
Short-pulse driven photogun for very hard x-ray free-electron laser , Wei Hou Tan, SLAC
A Portable Muon Source for artificial muon muography , Masao Kuriki, Hiroshima Uni.

Thu, 21 May 2026

Chair: Sarah Cousineau
Laser Plasma Accelerated Proton Bunches surpassing 100 MeV , Ulrich Schramm, HZDR
Wakefield dephasing measurement of a self-modulating proton bunch , Helena Jaworska, Uni. Düsseldorf
Terahertz Techniques in the Advanced Accelerator Landscape , Morgan Hibberd, Uni. Manchester
Generation of tunable sub-femtosecond XFEL pulses by electron bunch recompression using reverse-energy chirp , Kenji Yasutome, RIKEN

→ Topics on recent results and first applications

Outline

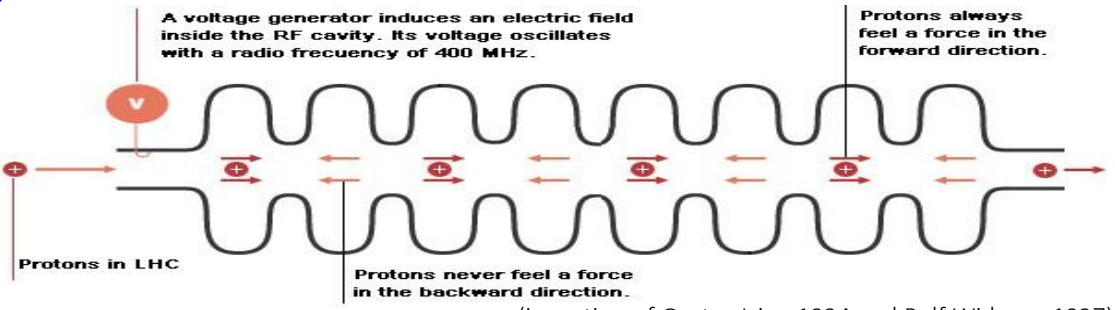
- Introduction to plasma wakefield acceleration
- State-of-the-art
- Plasma wakefield acceleration applications

- **Introduction to plasma wakefield acceleration**

- State-of-the-art

- Plasma wakefield acceleration applications

Conventional Acceleration Technology



(invention of Gustav Ising 1924 and Rolf Wideroe 1927)

LHC cavity



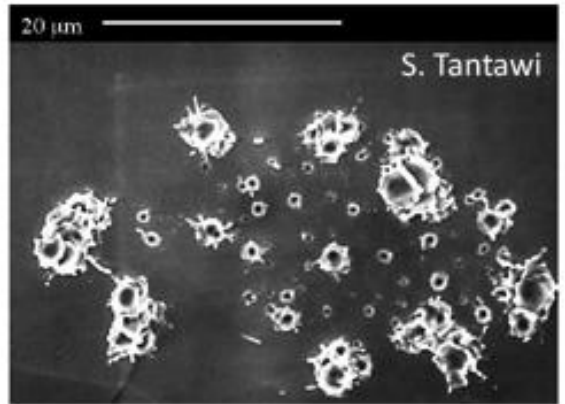
- Typical gradients:
- LHC: 5 MV/m
 - ILC: 35 MV/m
 - CLIC: 100 MV/m

Very successfully used in all accelerators (hospitals, scientific labs,...) in the last 100 years.

➔ More than 30000 accelerators worldwide!

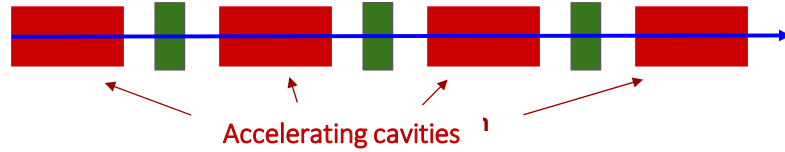
Accelerating fields are **limited to <100 MV/m**

Surface of Copper Cell After Breakdown Events



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.

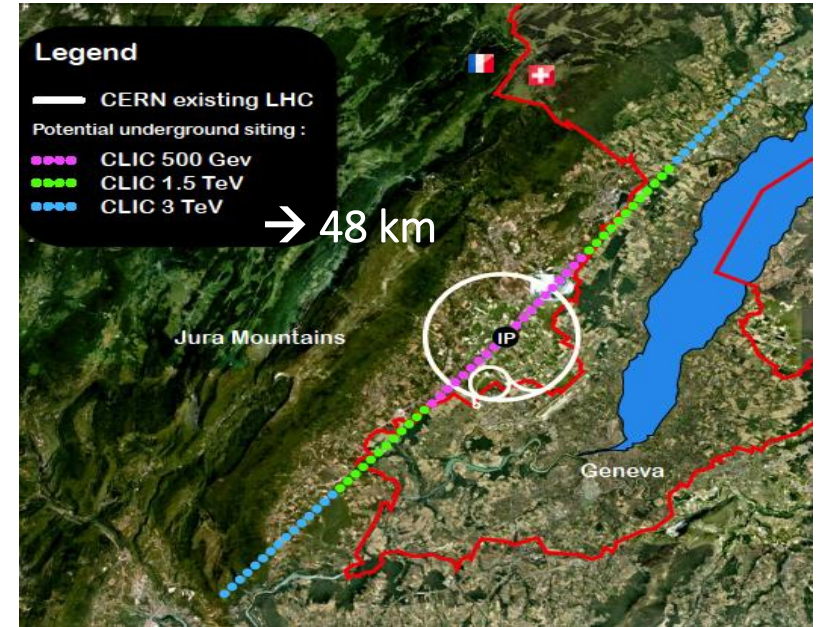
Linear Accelerators



👍 Favorable for acceleration of low mass particles to high energies.

🗨️ **Limitations** to linear colliders:
Linear machines accelerate particles in a **single pass**.

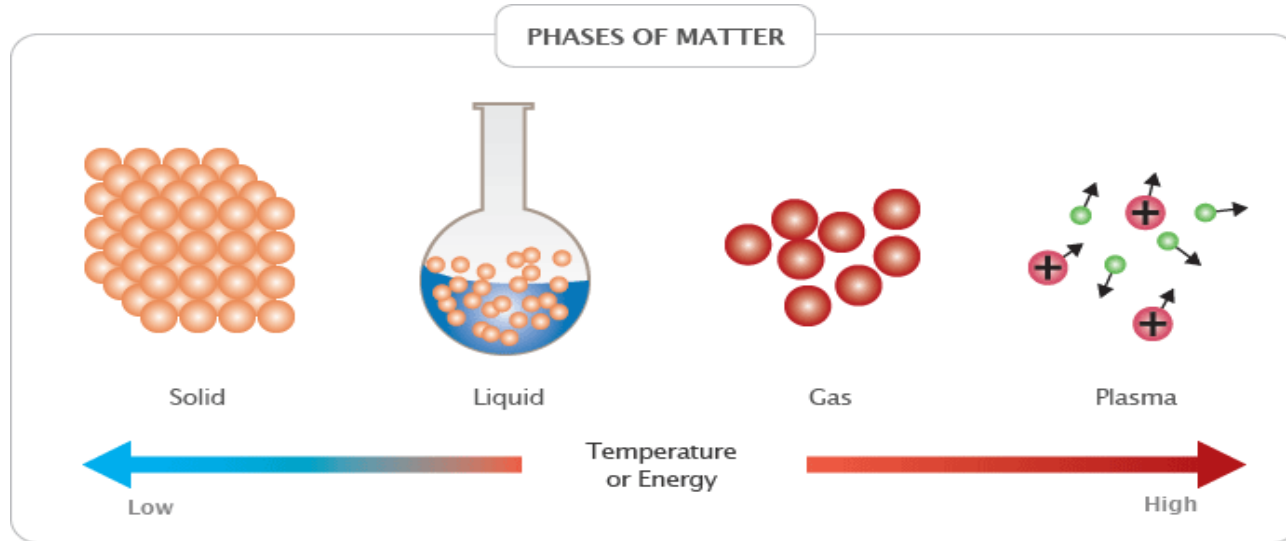
➔ The higher the required particle energy, the longer (and more costly) is the accelerator.



CLIC, electron-positron collider with 3 TeV energy



Plasma Wakefield Acceleration



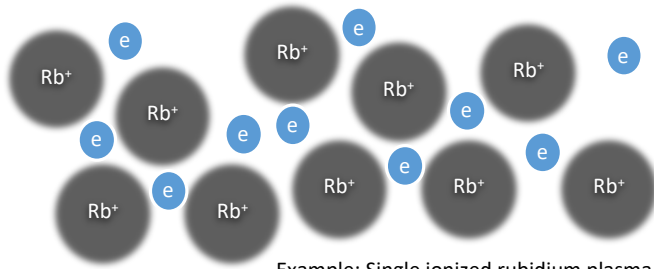
- Plasma is already ionized or “broken-down”
- Can sustain **electric fields up to three orders of magnitude higher gradients.**

→ order of 100 GV/m.

→ ~1000 factor stronger acceleration!

→ makes this technology very interesting **for reducing the size (and cost)** for future linear colliders.

Plasma Wakefield Acceleration



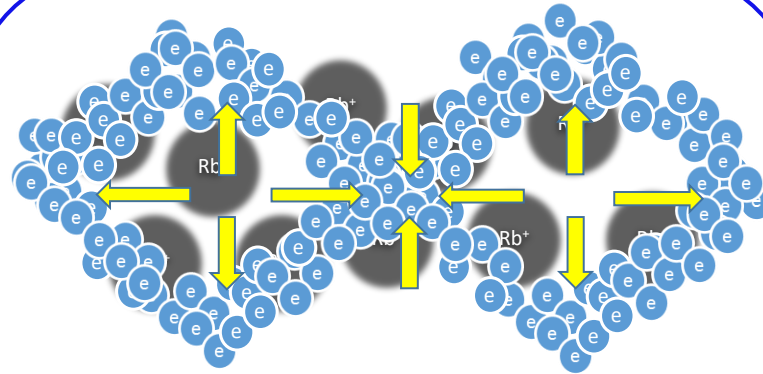
Example: Single ionized rubidium plasma

PLASMA is the 4th state of matter

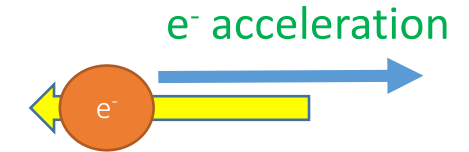
Quasi-neutrality: the overall charge of a plasma is about zero.

Collective effects: Charged particles must be close enough together so that each particle influences many nearby charged particles.

Electrostatic interactions dominate over collisions or ordinary gas kinetics.

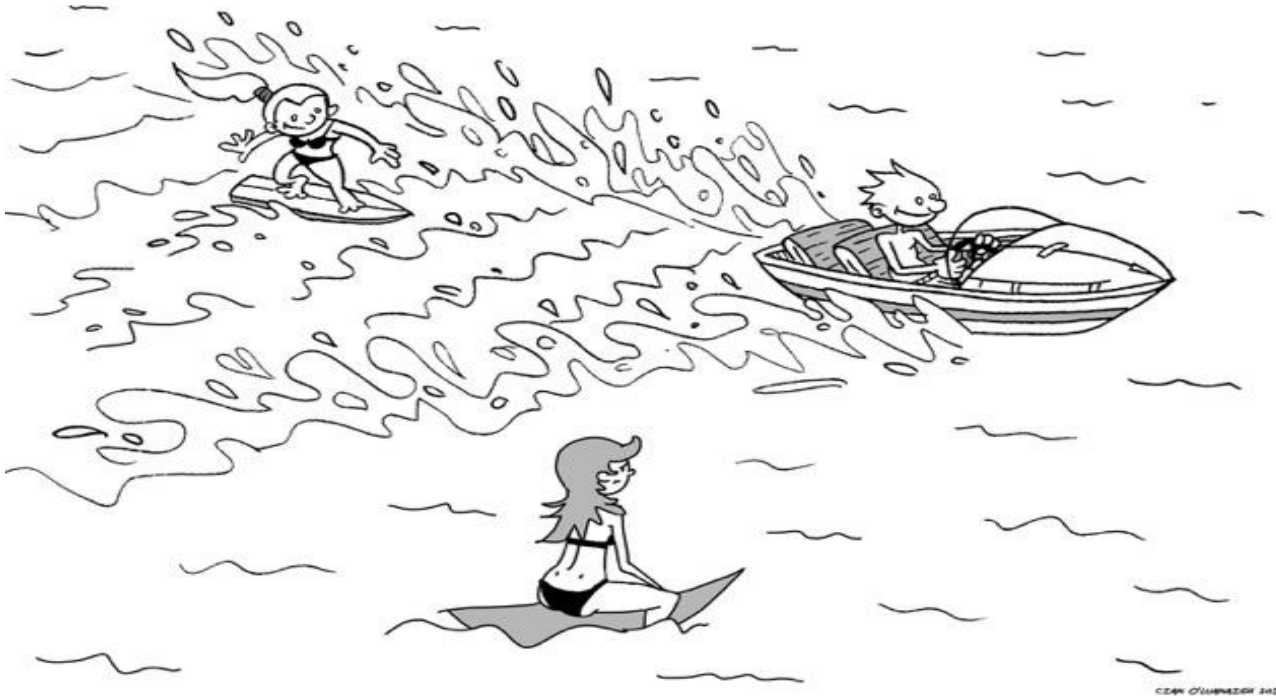


Plasma WAKEFIELDS are the fields created by collective motion of plasma particles are called.



ACCELERATION of charged particles when they experience an electric field.
Strength of the acceleration:
'Accelerating gradient' : \sim MV/m

How to Create a Plasma Wakefield?



Analogy:

lake → plasma

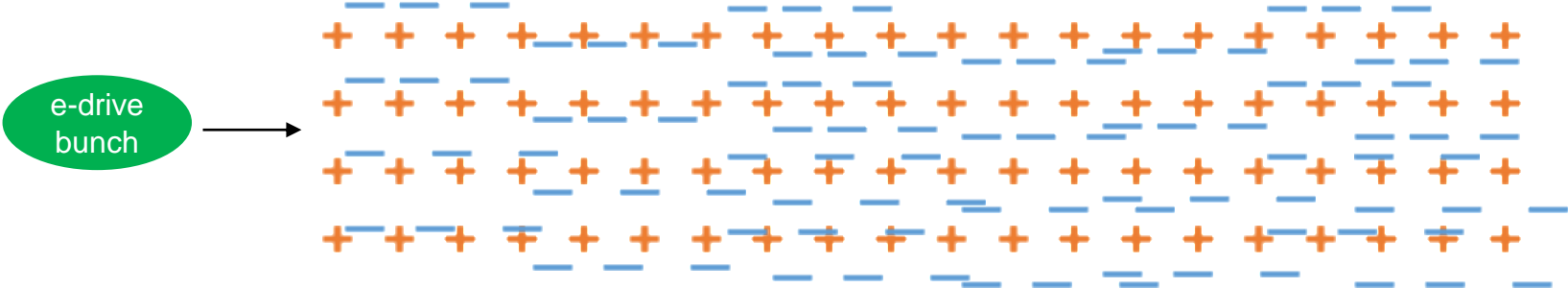
Boat → particle beam (drive beam)

Surfer → accelerated particle beam (witness beam)

Principle of Plasma Wakefield Acceleration

Drive beam:

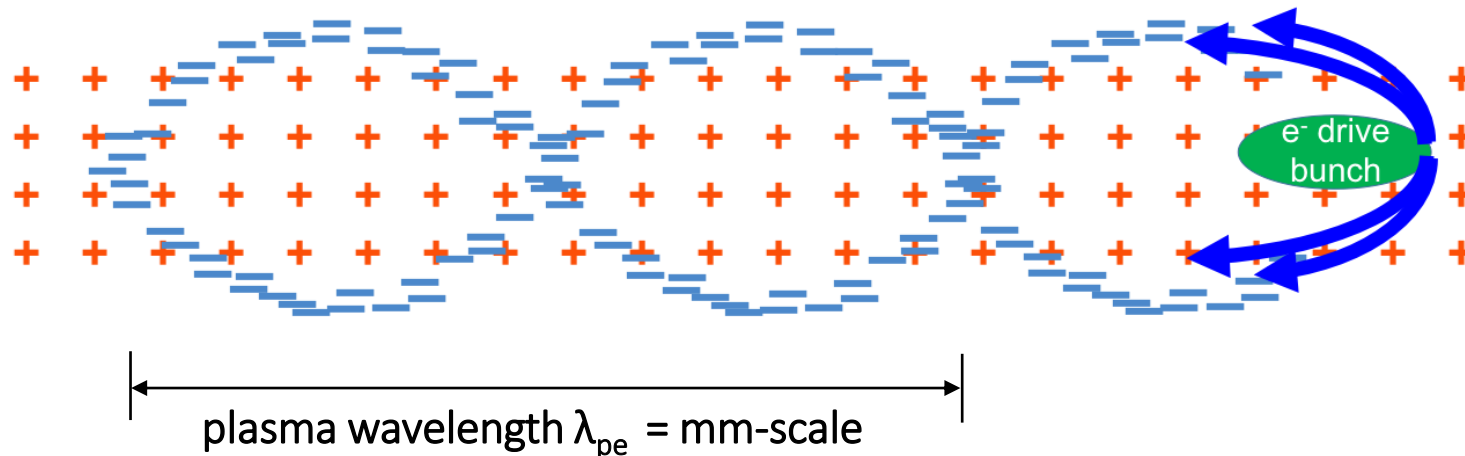
- Laser drive beam → LWFA
- Charged particle drive beam → PWFA



Principle of Plasma Wakefield Acceleration

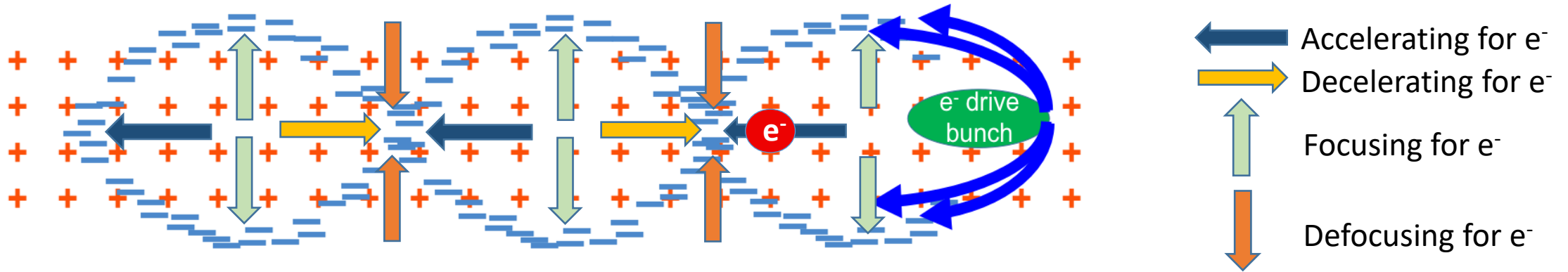
Drive beam:

- Laser drive beam → LWFA
- Charged particle drive beam → PWFA

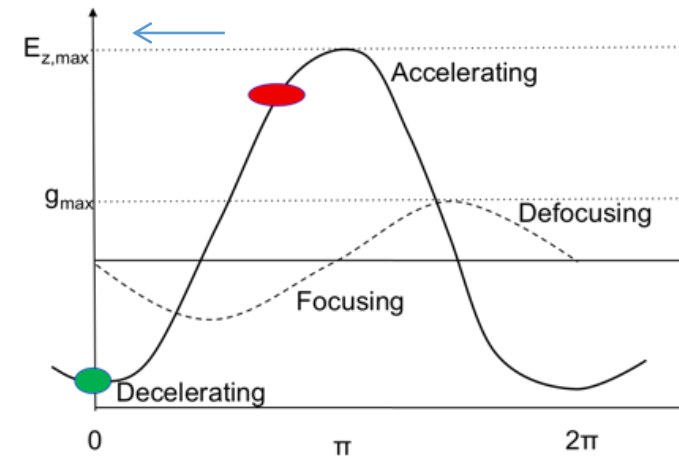


- Plasma wave excited by relativistic particle bunch.
- Plasma e⁻ are expelled by space charge force.
- Plasma e⁻ rush back on axis.
- Acceleration physics identical for LWFA, PWFA.

Where to Place the Witness Beam?



Longitudinal and transverse wakefields are $\pi/2$ out of phase.
 → Only $1/4$ of the electron oscillation length is focusing and accelerating for charged particles!



Plasma Wakefield, Density Scaling

Drive bunch traveling inside a plasma perturbs the plasma electron distribution.

$$\rightarrow \text{oscillation with } \omega_{pe} = \sqrt{\frac{n_{pe}e^2}{m_e\epsilon_0}} \quad \lambda_{pe} = 2\pi \frac{c}{\omega_{pe}}$$

→ Plasma electron wavelength decreases with increasing plasma density.

The plasma oscillation leads to a longitudinal accelerating field:

The maximum accelerating field (wave-breaking field) is: $E_0 \approx 0.96\sqrt{n(10^{14} \text{ cm}^{-3})}[\text{GV/m}]$

Example: $n_{pe} = 1 \times 10^{18} \text{ cm}^{-3}$

→ $E_{WB} = \sim 100 \text{ GV/m}$

→ $\lambda_{pe} = \sim 30 \mu\text{m}$

Example: $n_{pe} = 7 \times 10^{14} \text{ cm}^{-3}$ (AWAKE)

→ $E_{WB} = 2.5 \text{ GV/m}$

→ $\lambda_{pe} = 1.2 \text{ mm}$

→ Maximum accelerating gradient increases with increasing plasma density.

→ Advantage of PWFA

→ LWFA: **dephasing**: laser group velocity depends on plasma density, is slower than c.

→ Electron energy reach is limited by dephasing: → move to lower densities and longer accelerators

→ Lower density needs higher laser power.

Linear Theory

(R. D. Ruth, P. Chen, SLAC-PUB-3906, 1986)

When drive beam density is smaller than plasma density ($n_b \ll n_p$) \rightarrow linear theory:

- Peak accelerating field in plasma resulting from drive beam with Gaussian distribution:

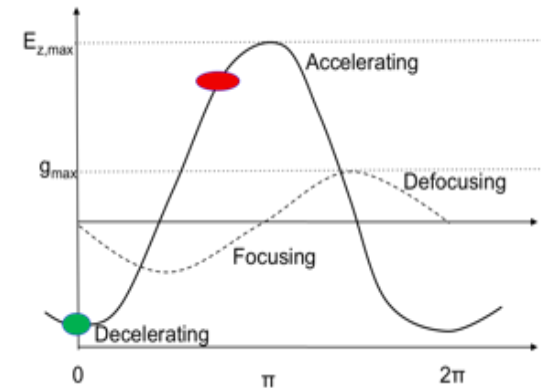
$$eE_z = \sqrt{n_p} \frac{n_b}{n_p} \frac{\sqrt{2\pi} k_p \sigma_z e^{-k_p^2 \sigma_z^2 / 2}}{1 + \frac{1}{k_p^2 \sigma_r^2}} \sin k_p (z - ct) \quad (eV/cm)$$

B.E. Blue 2003

$$\rightarrow eE_z \approx N/\sigma_z^2$$

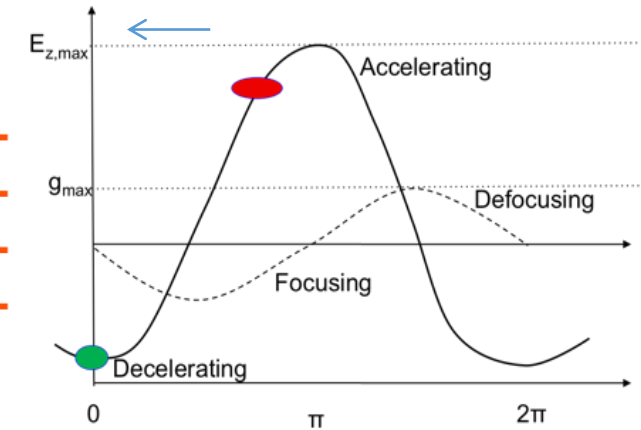
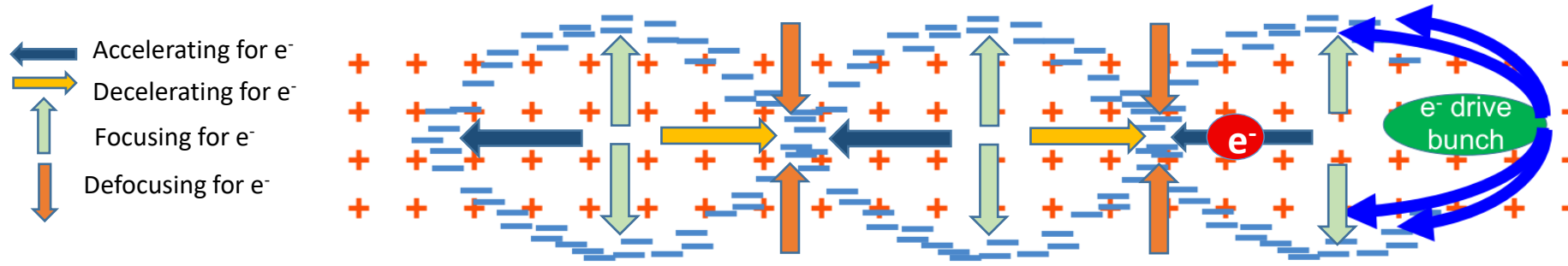
- Wakefield excited by bunch oscillates **sinusoidally** with frequency determined by plasma density.
- Fields excited by electrons and protons/positrons are **equal in magnitude but opposite in phase**.
- The accelerating field is maximized for a value of

$$\begin{aligned} k_{pe} \sigma_z &\approx \sqrt{2} \\ k_{pe} \sigma_r &\leq 1 \end{aligned}$$



Example: $n_{pe} = 7 \times 10^{14} \text{ cm}^{-3}$ (AWAKE), $k_{pe} = 5 \text{ mm}^{-1} \rightarrow$ drive beam: $\sigma_z = 300 \mu\text{m}$, $\sigma_r = 200 \mu\text{m}$

Linear Theory



Linear Theory: Maximum accelerating electric field reached with drive beam of N and σ_z :

$$E_{\text{acc}} = 110 \frac{\text{MV}}{\text{m}} \frac{N / (2 \times 10^{10})}{(\sigma_z / 0.6 \text{mm})^2}$$

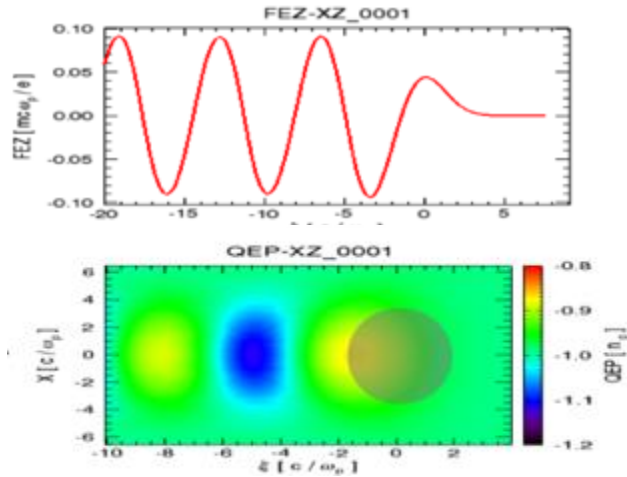
← Driver must be short compared to plasma wavelength, easy for laser and electron bunches.

Examples of accelerating fields for different beam parameters and plasma parameters fields:

$$N = 3 \times 10^{10}, \sigma_z = 20 \mu\text{m}, n_{pe} = 2 \times 10^{17} \text{ cm}^{-3} \rightarrow E_{\text{acc}} = 15 \text{ GV/m}$$

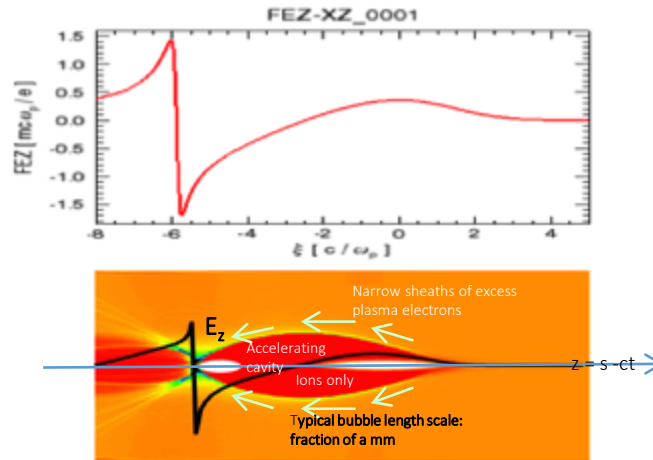
Different Regimes, Quality

Linear regime: $n_{\text{beam}} \ll n_{\text{pe}}$



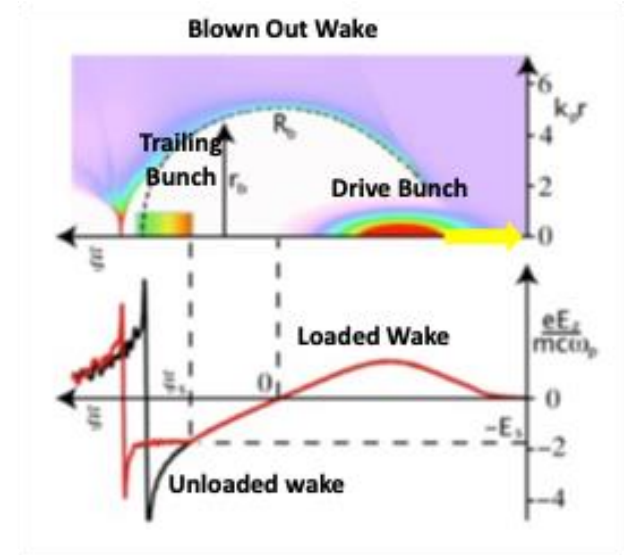
- lower wakefields
- transverse forces not linear in r
- + Symmetric for positive and negative witness bunches
- + Well described by theory

Blow-out regime: $n_{\text{beam}} \gg n_{\text{pe}}$



- + Higher wakefields
- + transverse forces linear in r (emittance preservation)
- + High charge witness acceleration possible
- Requires more intense drivers
- Not ideal for positron acceleration

Beam loading (Simon van der Meer, 1985)



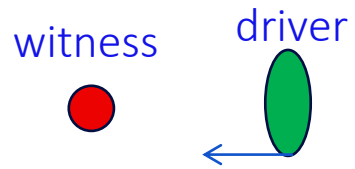
Reduce energy spread

→ Sufficient charge in the witness bunch to flatten the accelerating field

Plasma Acts Like a Transformer

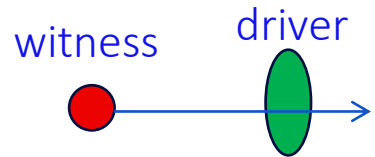
→ Drive beam deposits energy, witness beam gains energy

Acceleration distance (and witness energy) typically limited by one of the **3 Ds**



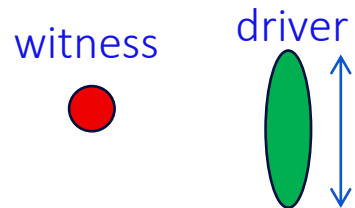
Depletion: The drive bunch/pulse running out of energy.

→ Solution: couple in a new driver or use a more energetic driver.



Dephasing: The witness bunch outruns the driver.

→ Solution: couple in a new driver or change plasma parameters.



Diffraction: (mainly for laser pulses): Drive beam evolution.

→ Solution: Guiding.

- Introduction to plasma wakefield acceleration
- **State-of-the-art**
- Plasma wakefield acceleration applications

Seminal Paper 1979, T. Tajima, J. Dawson

Use a plasma to convert the transverse space charge force of a beam driver into a longitudinal electrical field in the plasma.

VOLUME 43, NUMBER 4

PHYSICAL REVIEW LETTERS

23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson

Department of Physics, University of California, Los Angeles, California 90024

(Received 9 March 1979)

An intense electromagnetic pulse can create a weak 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^{18} W/cm² shone on plasmas of densities 10^{18} cm⁻³ can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

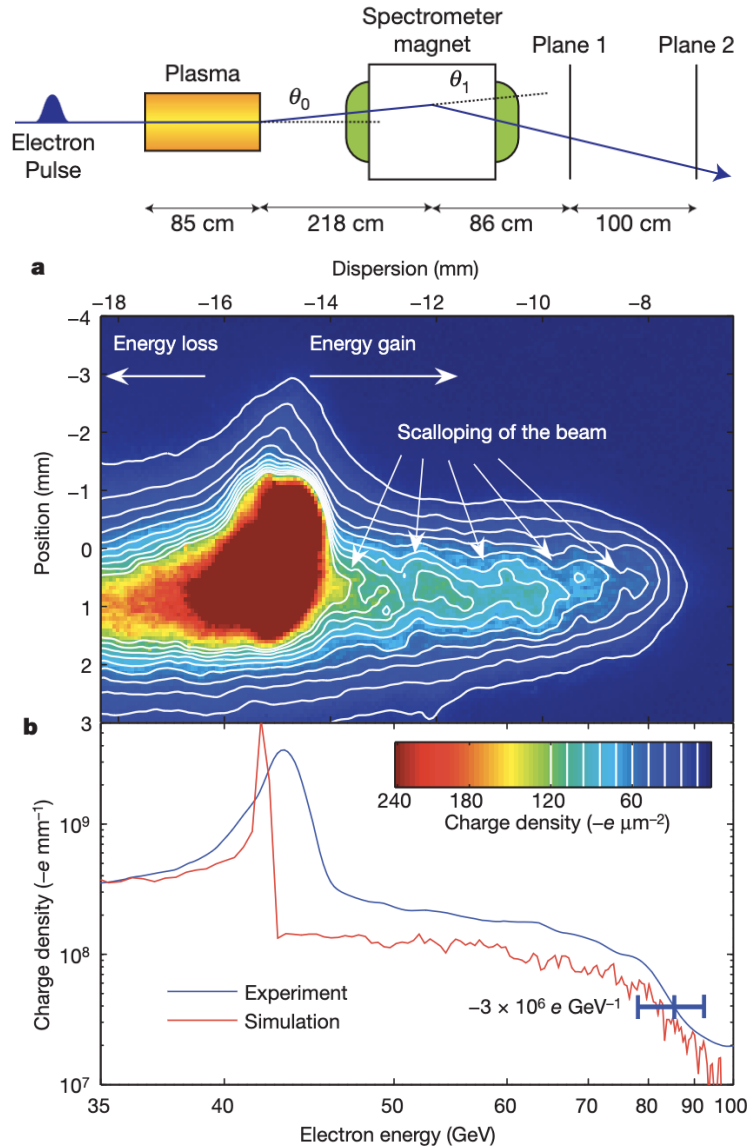
Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi¹ and McMillan² considered cosmic-ray particle acceleration by moving magnetic fields¹ or electromagnetic waves.² In terms of the realizable laboratory technology for collective accelerators, present-day electron beams³ yield electric fields of $\sim 10^7$ V/cm and power densities of 10^{13} W/cm².

the wavelength of the plasma waves in the wake:

$$L_t = \lambda_w/2 = \pi c/\omega_p. \quad (2)$$

An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes $2\pi c/\omega_p$. The mechanism for generating the wakes can be simply seen by the following approximate

Electron-Driven, SLAC



E. Gschwendtner, CERN

85cm Lithium vapour source, $2.7 \times 10^{17} \text{ cm}^{-3}$

➔ Accelerated electrons from 42 GeV to 85 GeV in 85 cm.

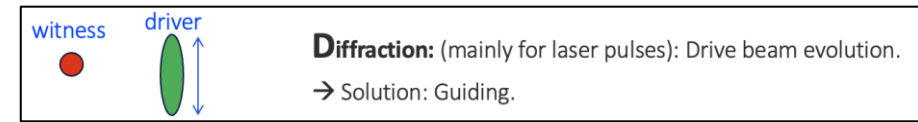
➔ Reached accelerating gradient of **52 GeV/m**

I. Blumenfeld et al, Nature 455, p 741 (2007)



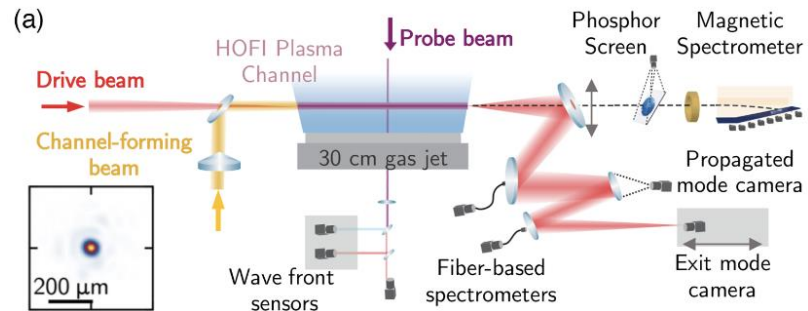
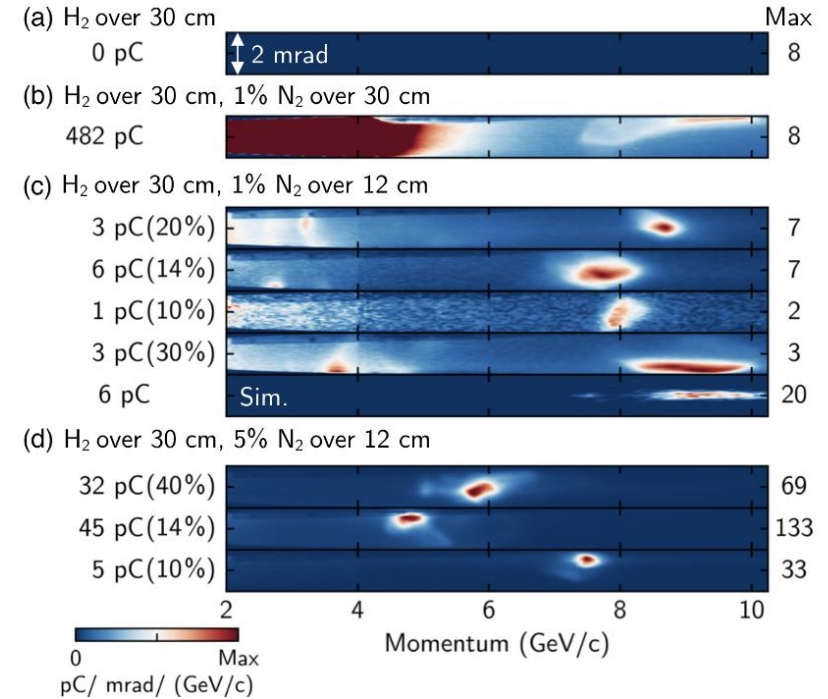
Final Focus Test Beam Facility, **FFTB** at SLAC

Laser-Driven, BELLA, Berkeley



BELLA, Berkeley Lab, USA

40 J, 30 fs \rightarrow 1.2 PW Focused to $\sigma_r = 50 \mu\text{m}$

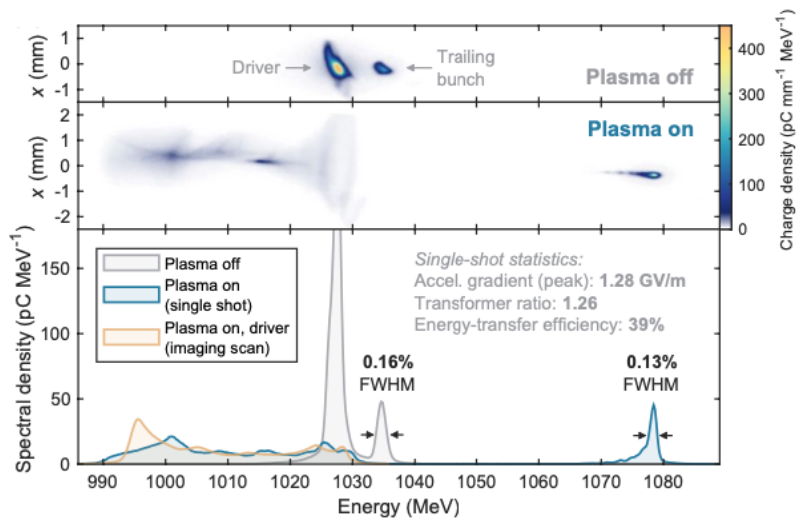
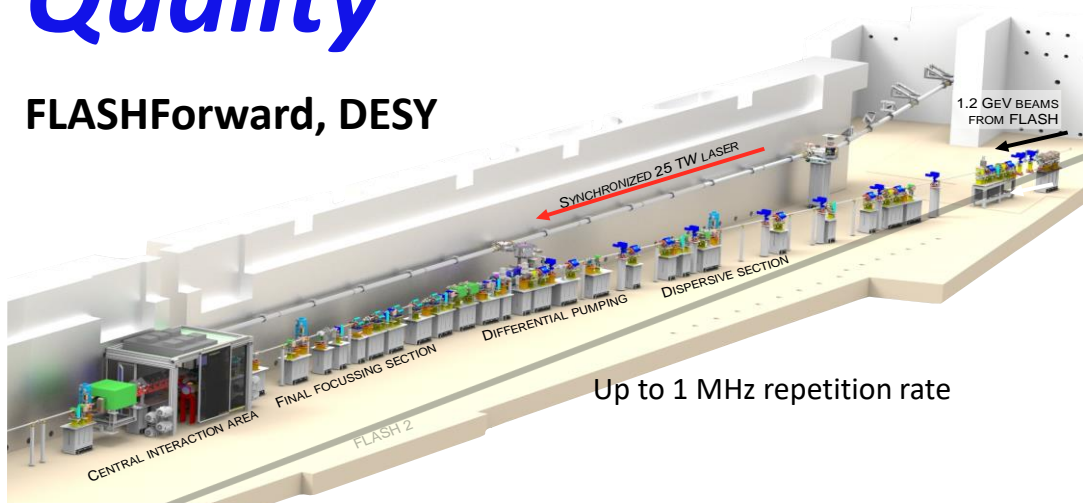


Laser guiding

9.2 GeV in 30 cm of plasma
 \rightarrow **30.6 GeV/m**

Quality

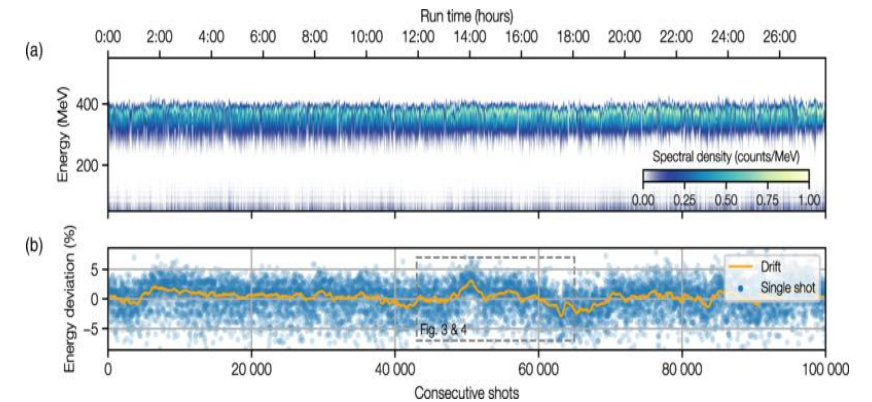
FLASHForward, DESY



Transfer efficiency 42+/-4% with 0.2% energy spread,
up to 70% with energy spread increase

C.A. Lindstrøm et al., Phys.Rev.Lett. 126, 014801 (2021)

LUX laser plasma accelerator, DESY



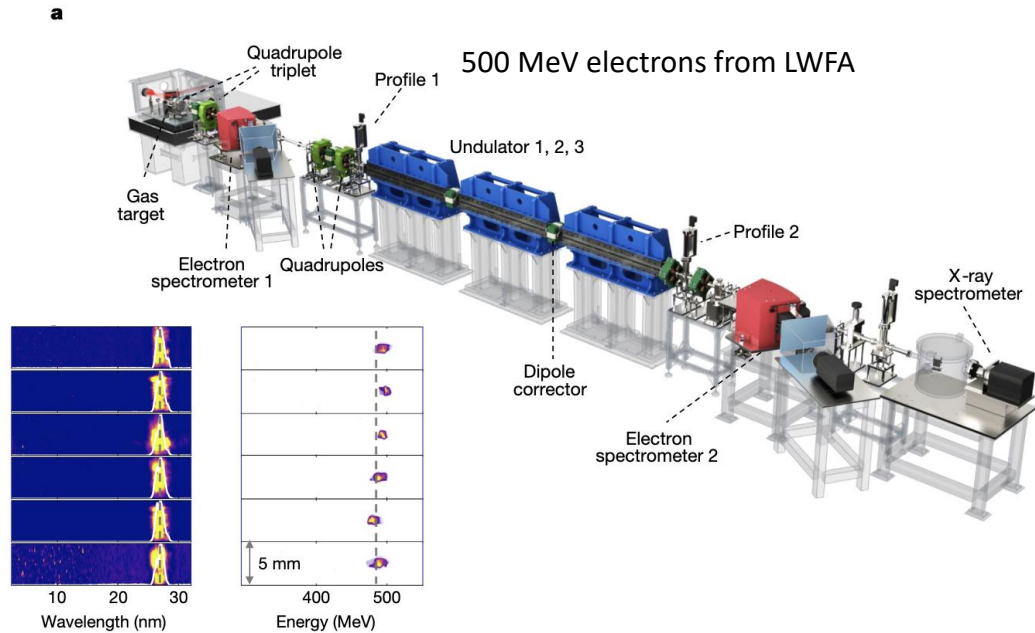
Stable 24hr operation

A. Maier et al., Phys. Rev. X 10, 031039 (2020)

FEL Demonstration

Laser Driven based FEL: First demonstration

SIOM, Shanghai, China

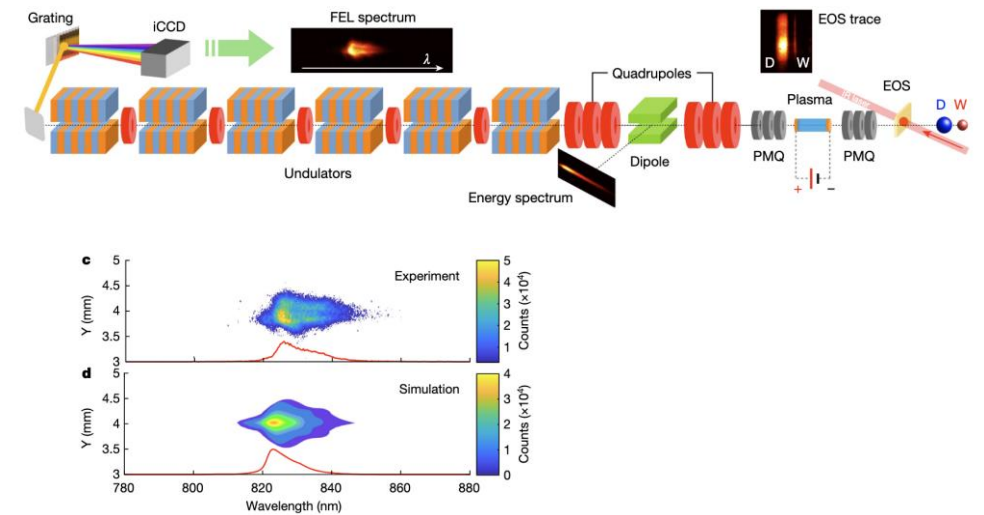


FEL lasing amplification of 100 reached at 27 nm wavelength

W.T. Wang, K. Feng, et al., Nature, 595, 561 (2021)

Electron Driven based FEL: First demonstration

Sparc-Lab, INFN Frascati, Italy



94 MeV electrons from PWFA, FEL lasing at 830 nm

R. Pompili et al., Nature 605, 659-662 (2022)

→ Since then several more groups: Soleil/HZDresden, Berkeley

State of the Art and Goals towards HEP Collider

R&D Efforts

Parameter	Current	FEL (Intermediate Goal)	Collider (Final Goal)
Charge (nC)	0.01 – 0.1	0.01 – 0.1	0.1– 1
Energy (GeV)	10	0.1 – 10	1000
Energy spread (%)	0.1	0.1	0.1
Emittance (um)	>3 (PWFA), 0.1 (LWFA)	0.1– 1	0.01
Staging	single, two	single, two	multiple
Wall plug efficiency (%)	5-20 (PWFA), 0.01-1 (LWFA)	<0.1 - 10	>10
Driver to witness (%)	10-40 (PWFA), 0.1-10 (LWFA)	>10	>50
Rep Rate (Hz)	10	$10^1 - 10^6$	$10^4 - 10^5$
Continuous run	24/1	24/1 – 24/7	24/365
Parameter stability	1%	0.1%	0.1%
Simulations	days	days - 10^7	improvements by 10^7
Positron acceleration	acceleration		emittance preservation
Plasma cell (p-driver)	10 m		100s m
Proton drivers	SSM, acceleration		emittance control

ESPP 2020:
Plasma R&D Roadmap



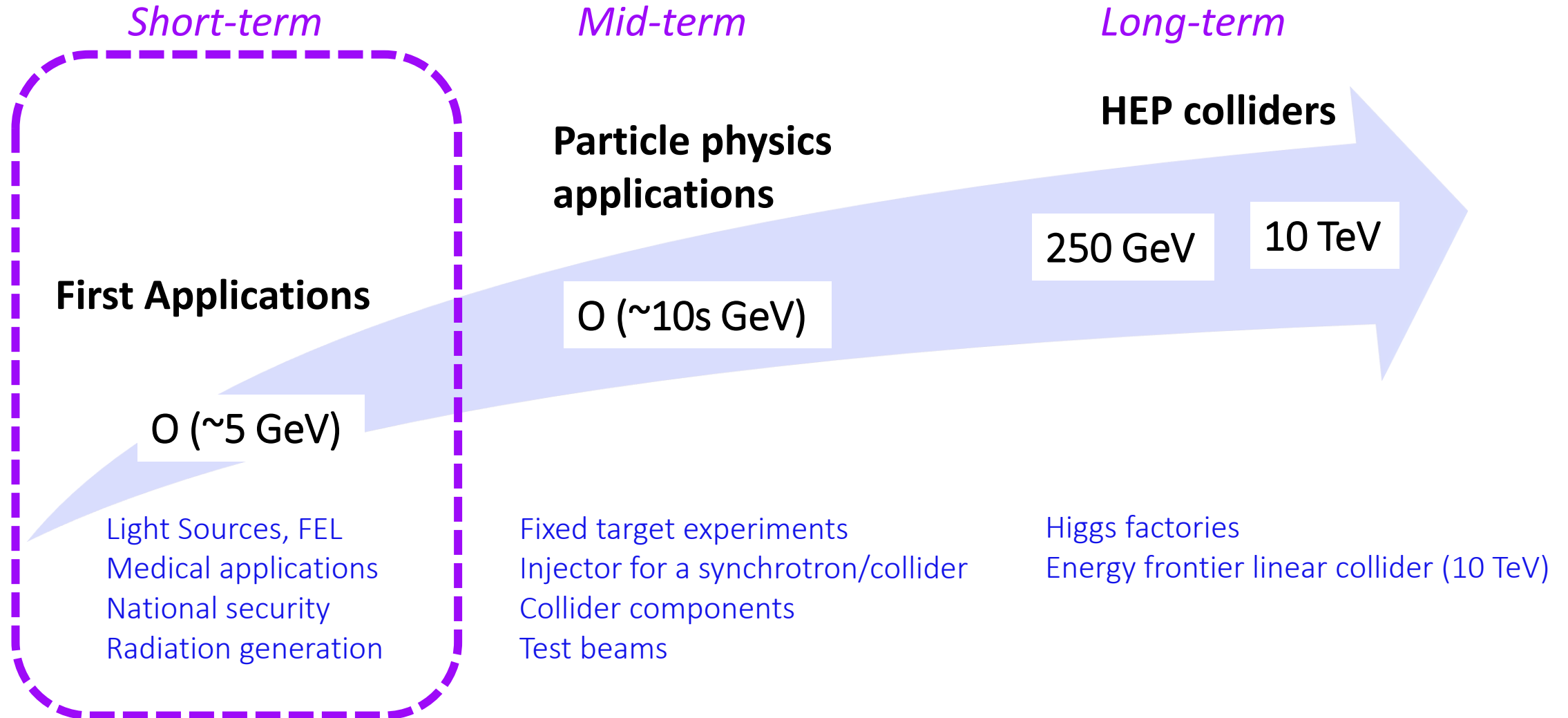
US Snowmass and P5



➔ Requires international, multi-dimensional R&D efforts.

- Introduction to plasma wakefield acceleration
- State-of-the-art
- **Plasma wakefield acceleration applications**

Plasma Wakefield Acceleration Applications



EuPRAXIA

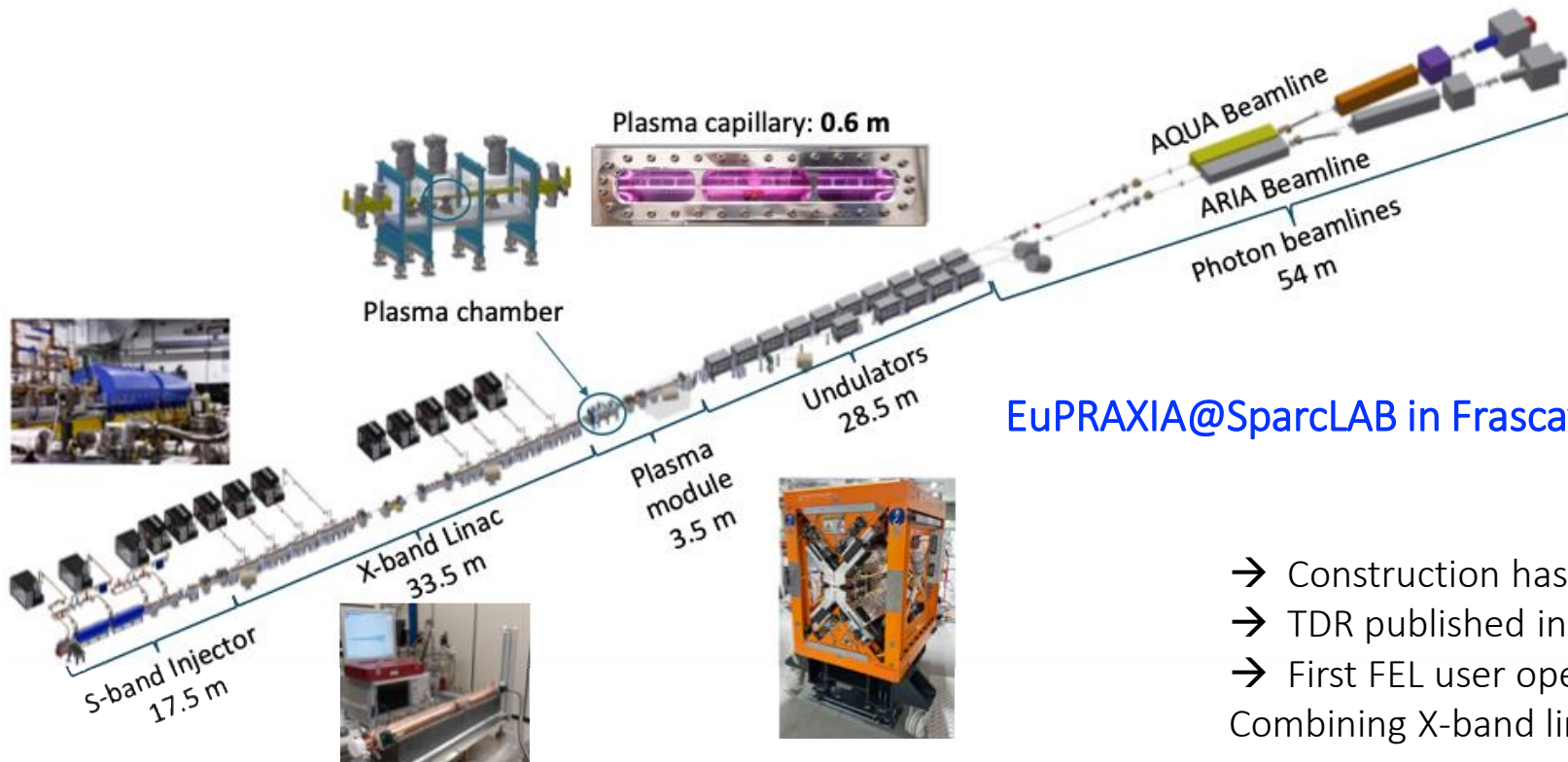


European Plasma Research Accelerator with eXcellence in Applications

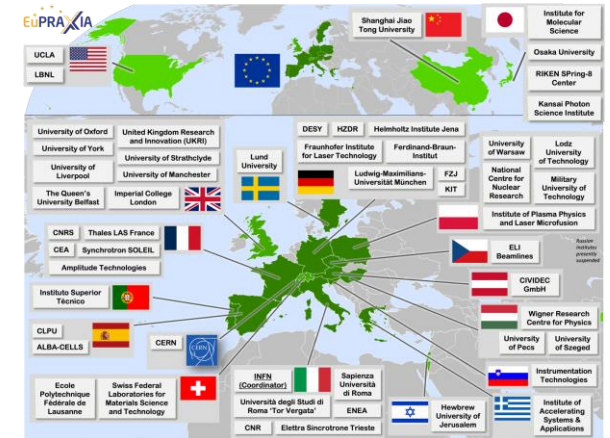
EuPRAXIA is a design and an ESFRI project for a distributed European Research Infrastructure based on novel plasma-acceleration concepts (1-5 GeV), building two plasma-driven Free Electron Lasers, FELs, in Europe.

Aims at offering a significant reduction in size and possible savings in cost over current state-of-the-art RF-based accelerators.

- Site 1: EuPRAXIA FEL in Frascati LNF-INFN (beam-driven)
- Site 2: EuPRAXIA FEL (laser-driven) at ELI-ERIC, Czech Republic.



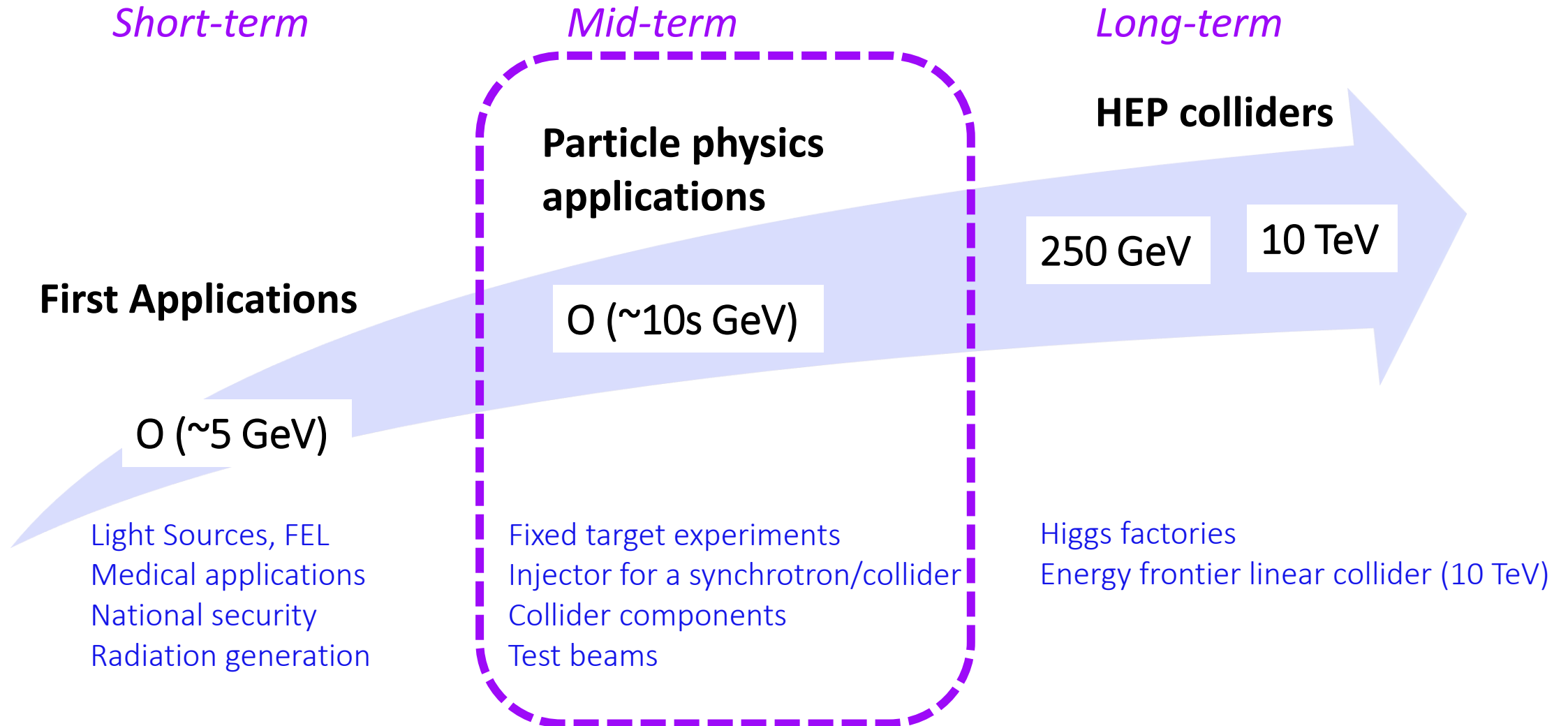
EuPRAXIA@SparcLAB in Frascati



Today: 54 institutes in Consortia

- Construction has started.
 - TDR published in Feb 2026.
 - First FEL user operation in 2031.
- Combining X-band linac with beam-driven plasma acceleration.

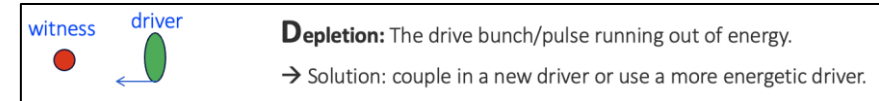
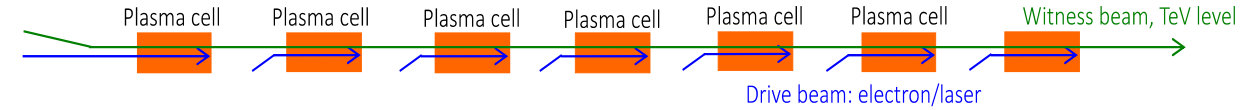
Plasma Wakefield Acceleration Applications



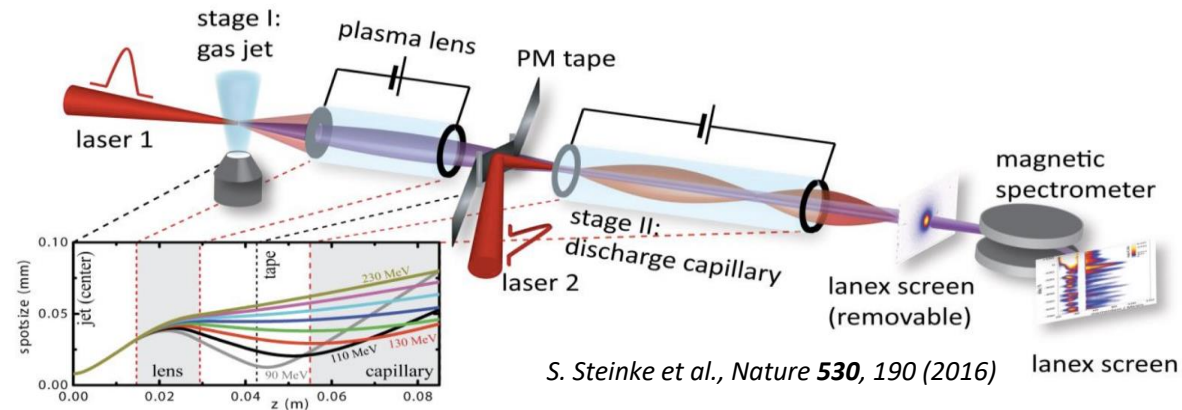
Towards Higher Energies

Lasers or electron bunch drivers: ~ 10 s of J/bunch

→ Staging



BELLA, Berkeley, LBNL



S. Steinke et al., *Nature* **530**, 190 (2016)

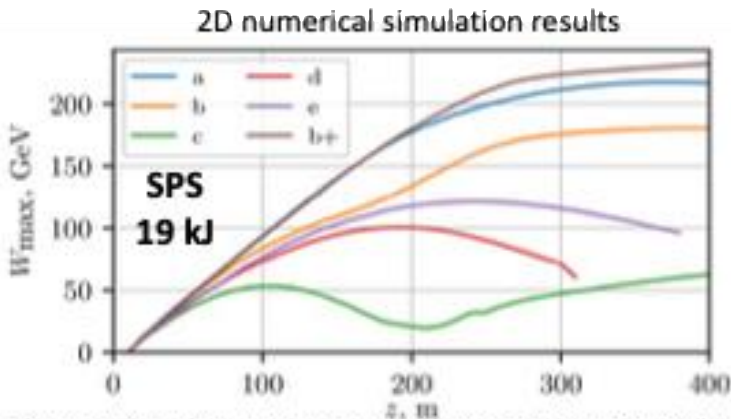
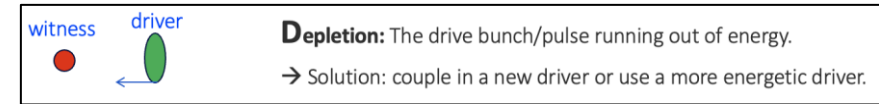
- Staging of 2 plasma cells demonstrated at 100MeVs level (laser driven).
- Experiments ongoing at GeVs level.
- Matching between stages with plasma lenses/conventional magnets.
- No beam-driven staging yet demonstrated (no facility).

Towards Higher Energies

Proton bunch driver:

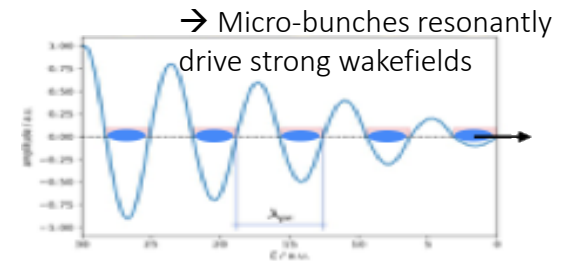
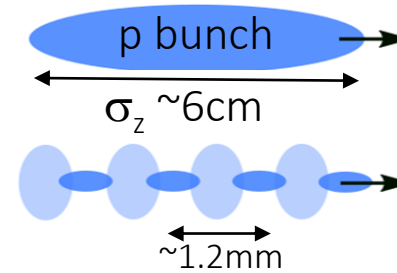
~SPS 19 kJ/bunch, LHC 112 kJ/bunch

→ single plasma cell



K. V. Lotov & P. V. Tuv, *Plasma Phys. and Control. Fusion*, 63, 125027 (2021)

→ Rely on self-modulation of the proton-bunch



→ Immediate use of SPS proton bunch for driving strong wakefields!

With existing proton beams: reach energy frontier with electrons

- SPS p⁺ (450 GeV): accelerate to 200 GeV electrons.
- LHC p⁺ can yield to 3 TeV electrons.

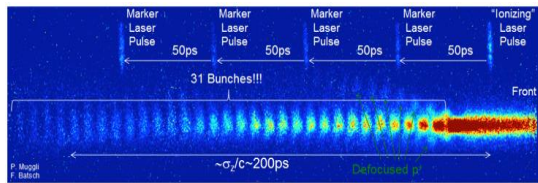
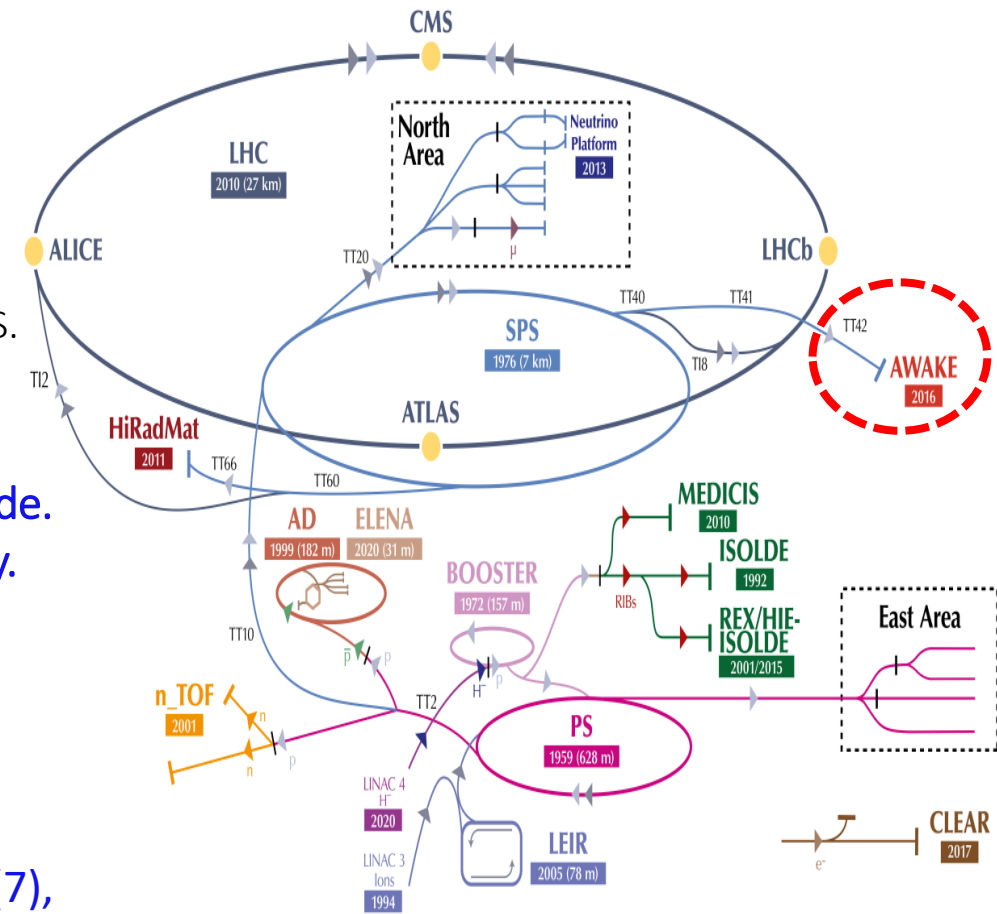
AWAKE at CERN

Advanced WAKEfield Experiment

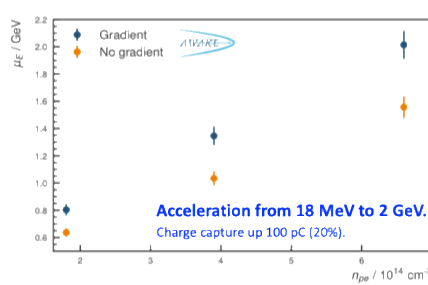
- Accelerator R&D experiment.
- International **collaboration with 19 institutes**.
- Unique facility driving wakefields in plasma with 400 GeV proton bunch from the SPS.
- Accelerating externally injected electrons to GeV scale.

- **The only proton driven plasma wakefield acceleration experiment worldwide.**
- **High energy gain possible because the high-energy driver is available today.**

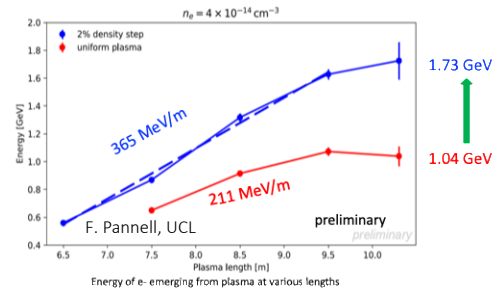
- **All milestones achieved.**
- More than 23 high-level publications such as Nature (1), Phys. Rev. Lett. (7), Phys.Rev. E (1), Physics of Plasmas (1), Phys. Rev. A&B (2),...



AWAKE Collaboration, PRL 122, 054802 (2019)
M. Turner et al. (AWAKE Collab.), PRL 122, 054801 (2019)



AWAKE Collaboration, Nature, 561, 363 (2018)



First Applications of AWAKE Technology

In AWAKE facility, could conceive of O(50 GeV) electrons.

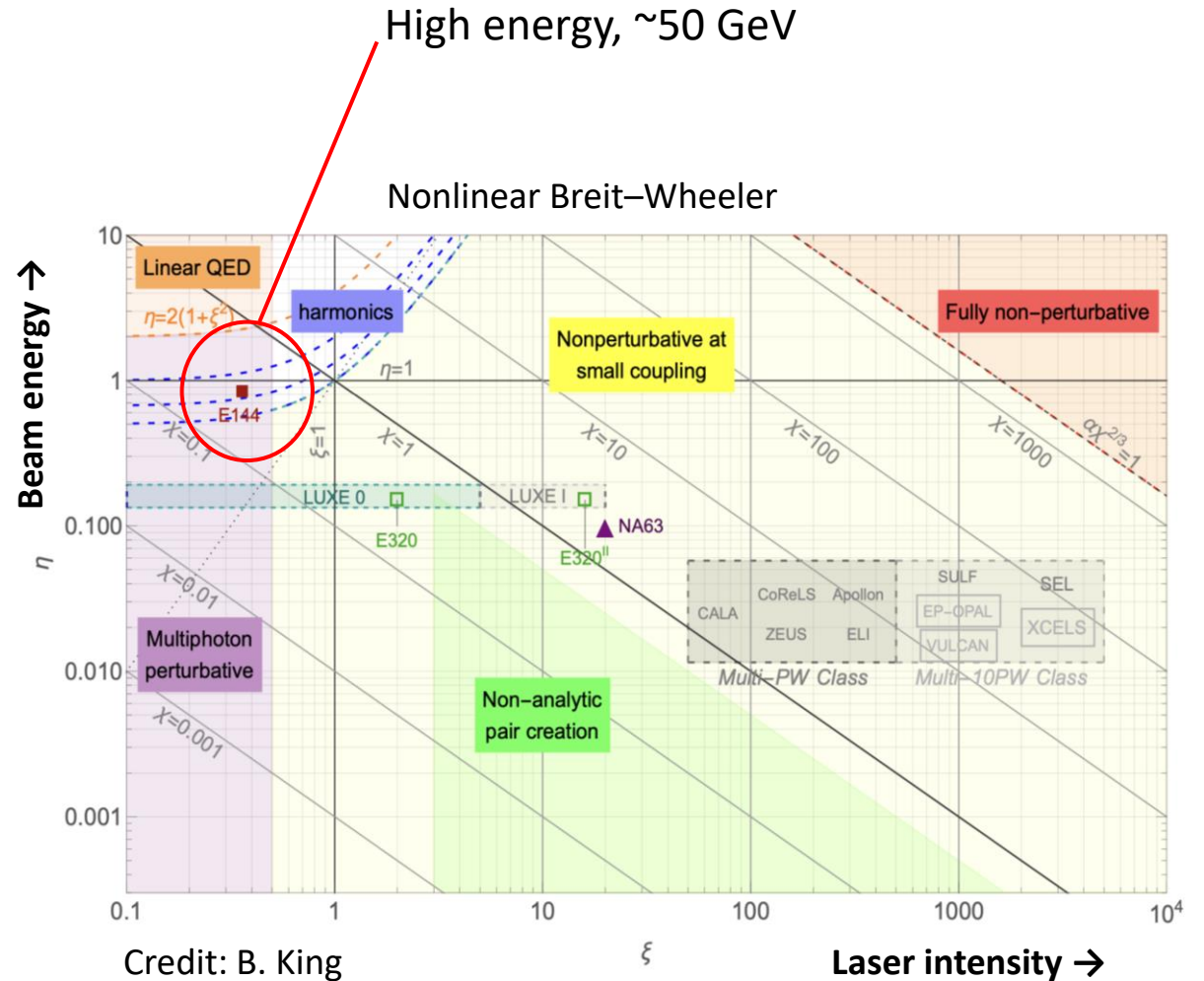
→ Requirements on emittance are moderate for first applications.

First applications to high energy physics for 50 GeV beam:

- Use for collider, e.g. *ep* collider, which would be like a low-luminosity LHeC.
- Beam-dump experiments to e.g. search for dark photons.
- Interaction with high-power laser to investigate strong-field QED.

Strong-field QED could be the obvious first experiment.

- Can investigate new region with high energy.
- Currently no competitors.
- Only modest laser needed.
- Increasing laser power → probe more phase space.

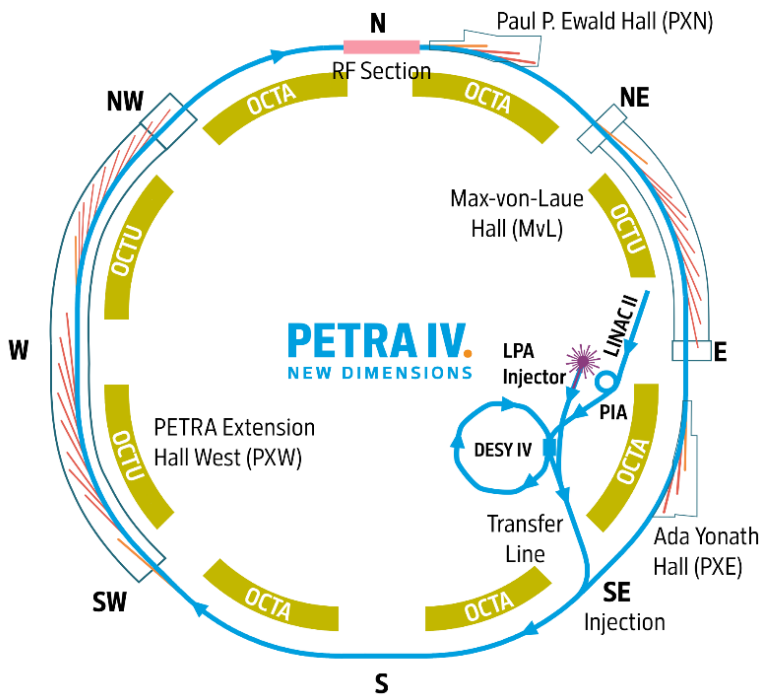


PETRA-IV Plasma Injector

DESY/Hamburg

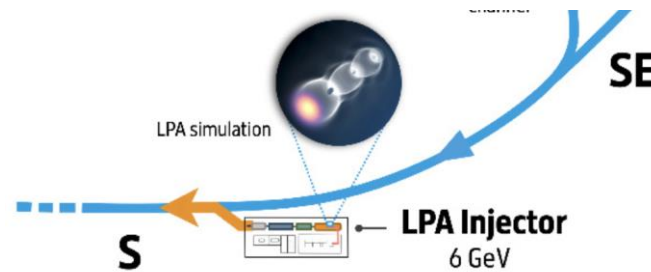
4th generation SR source:

- PETRA III to PETRA IV upgrade
- (6 GeV, 20 pm emittance)
- Final decision for PETRA IV in 2026

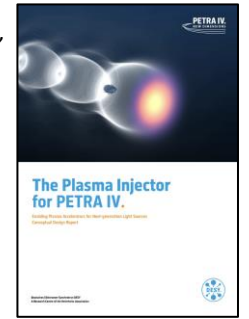


PETRA IV Plasma Injector: Alternative proposal to DESY IV injector

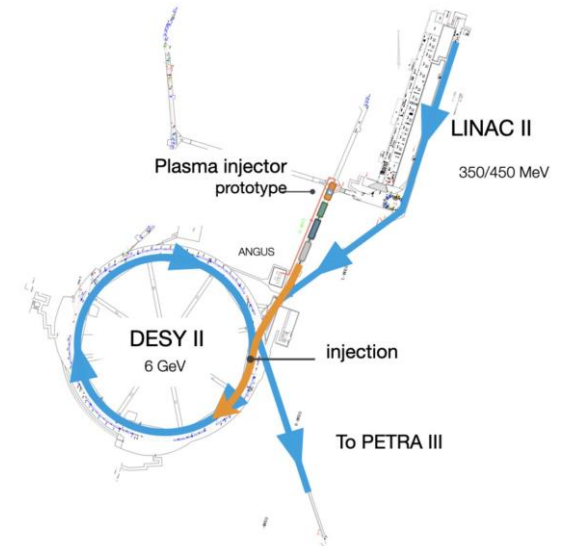
- Dedicated injector
- PW-drive laser
- 6 GeV HOFI-guiding assisted laser-plasma accelerator
- Active energy compression scheme (X-band)



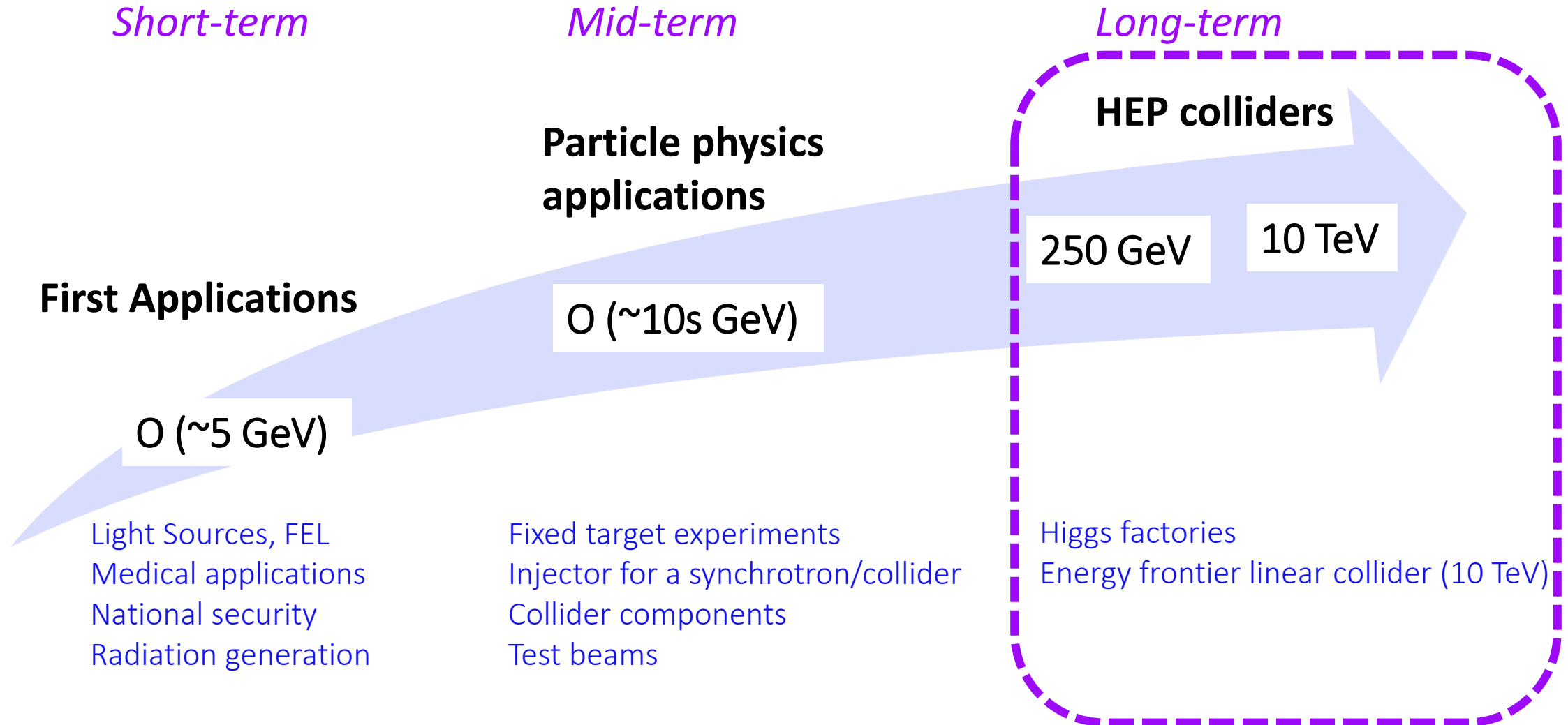
A. Martinez de la Ossa et al.,
PETRA IV Injector CDR



Demonstrate full technology chain:
→ injection studies into DESY II ongoing (350 MeV)



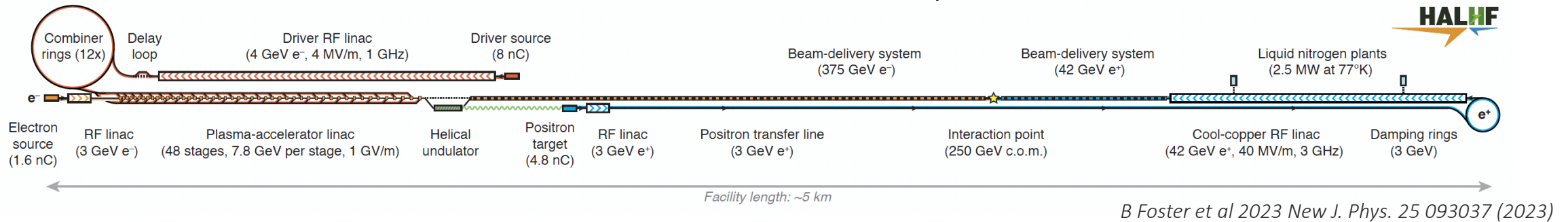
Plasma Wakefield Acceleration Applications



Higgs Factory Based on Plasma Wakefields - HALHF

New Baseline:

Electron driven plasma wakefield accelerator



- **250 GeV c.o.m., asymmetric collisions**
 - Electrons at 375 GeV accelerated in electron driven plasma wakefields
 - Positrons at 42 GeV using conventional RF linacs
- **Estimated luminosity: $\sim 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$**
- Length: 5 km
- Technology choice: CLIC (power source) + PWFA (transformer) + cool copper technology (positrons)
- PWFA Stages: 48 stages, 1 GV/m gradient, higher driver charge 5×10^{10} (8nC)
- **➔ Several key challenges still to be solved for PWA:** staging, repetition rate, plasma temperature, cooling, beam jitter

Higgs Factory Based on Plasma Wakefields - ALiVE



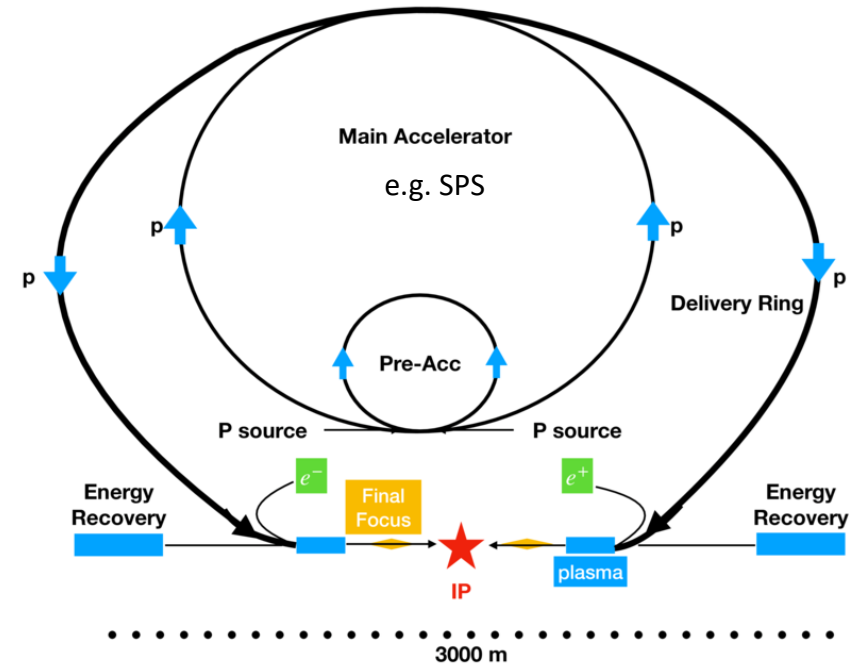
ALiVE: Advanced Linear collider for Very high Energy

Proton-driven plasma wakefield accelerator

Low repetition rate of high-energy proton bunches at CERN → limiting luminosity

ALiVE:

- **Collision energy: 250 (125 + 125) GeV, with upgrade to TeV range**
- **Estimated luminosity: $1.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$**
- Proton drive bunches from fast cycling synchrotron (HTS magnets) or FFAG to reach competitive luminosity.
- Short proton driver ($s_z = 150 \mu\text{m}$); density gradient in plasma.
- Electron and positron acceleration to very high energy in one single plasma (100s meter).



J Farmer, A. Caldwell, A. Pukhov, 2024 New J. Phys. 26 113011 (2024)

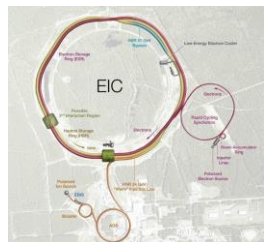
Key challenges: Short (sub-mm) driver, high (kHz) rep rate, positron acceleration in plasma.
Fewer challenges for e-p/e-A collider or asymmetric scheme.

➔ **These are exploratory studies**

E. Gschwendtner, CERN

Electron injector for the EIC based on p+
driven plasma wakefield acceleration

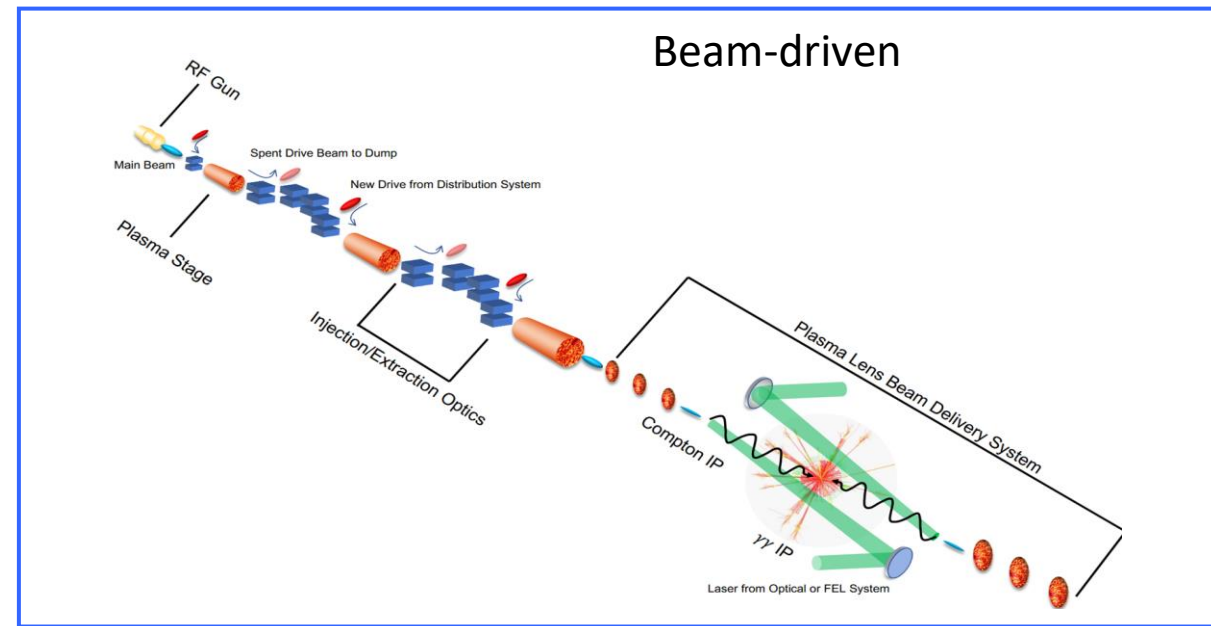
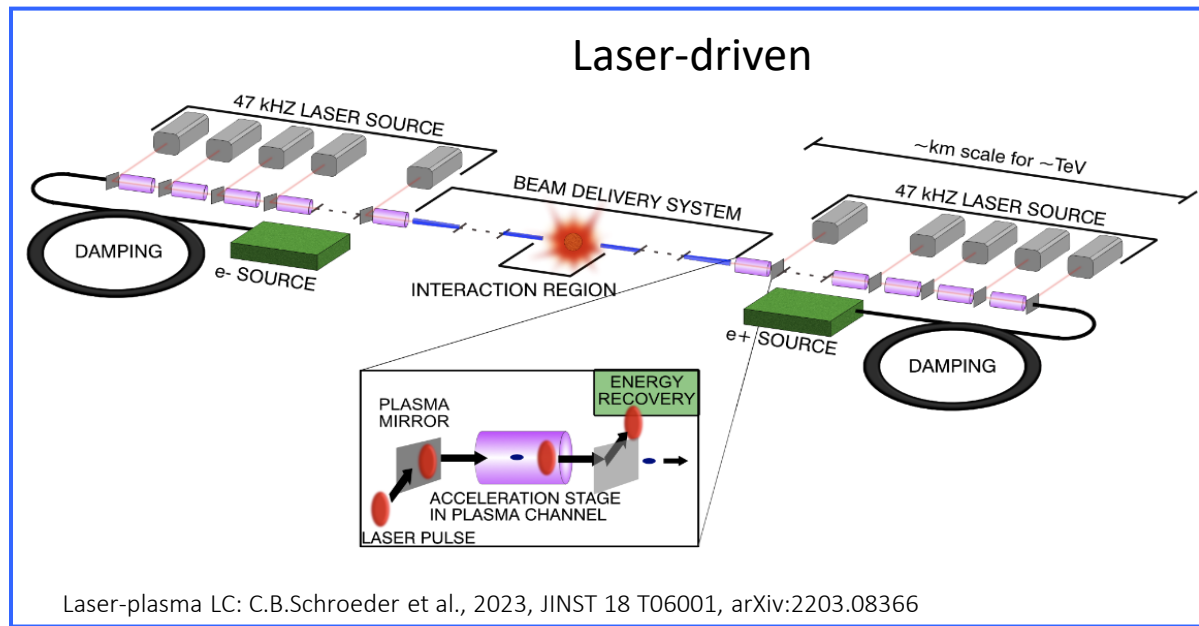
H. Jaworska et al., IPAC2026



10 TeV pCM Collider

Ongoing design effort: 10 TeV parton-center-of-mass (pCM) collider based on wakefield accelerator (WFA) technology.

Delivery of an end-to-end design concept, including cost scales, with self-consistent parameters throughout.



International effort - working group conveners from the US and Europe are organizing the study, partner with ALEGRO and other R&D efforts.

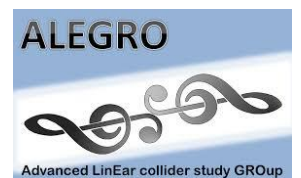
E. Gschwendtner, CERN

Collision:

$e+e-$

$e-e-$

$\gamma\gamma$



Summary

- **1. Plasma wakefields offer a $\sim 1000 \times$ gradient advantage over conventional RF.**
 - Allows smaller, potentially cheaper machines.
- **2. The field is moving from proof-of-principle to first applications.**
 - Short-term applications at the O(5 GeV) scale – FELs, medical, radiation sources – are within reach now.
 - Mid-term particle physics applications (fixed-target experiments, synchrotron injectors) are the next step.
 - Concrete collider concepts at the energy frontier (HALHF, ALiVE, 10 TeV pCM) are under active design study.
- **3. Key R&D challenges remain, and investment is essential.**
 - Continued support for high-gradient wakefield R&D is needed for this technology to contribute meaningfully to future particle physics programmes.