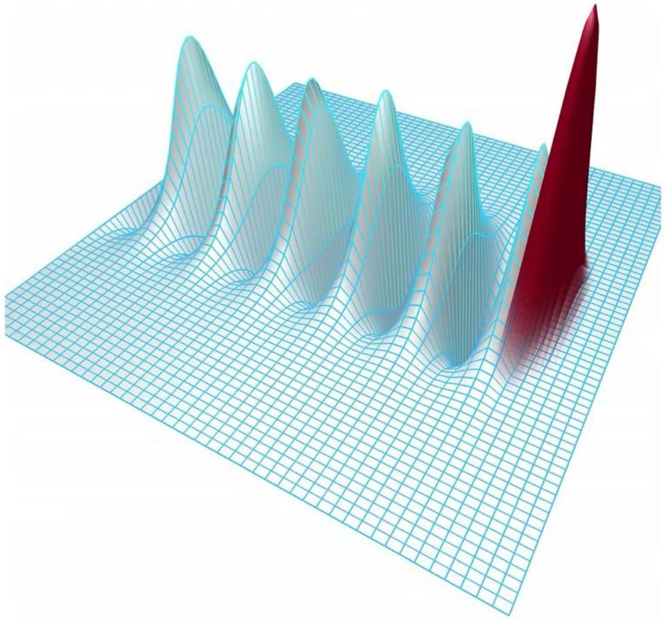
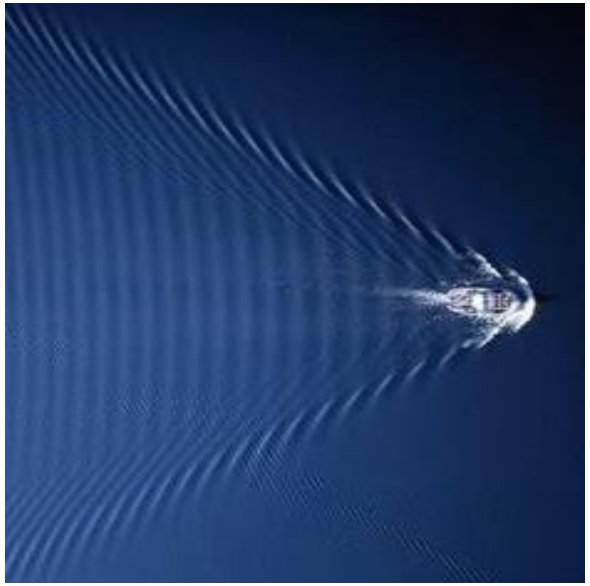
40 Years of Development on Plasma Wakefield Acceleration





Guoxing Xia

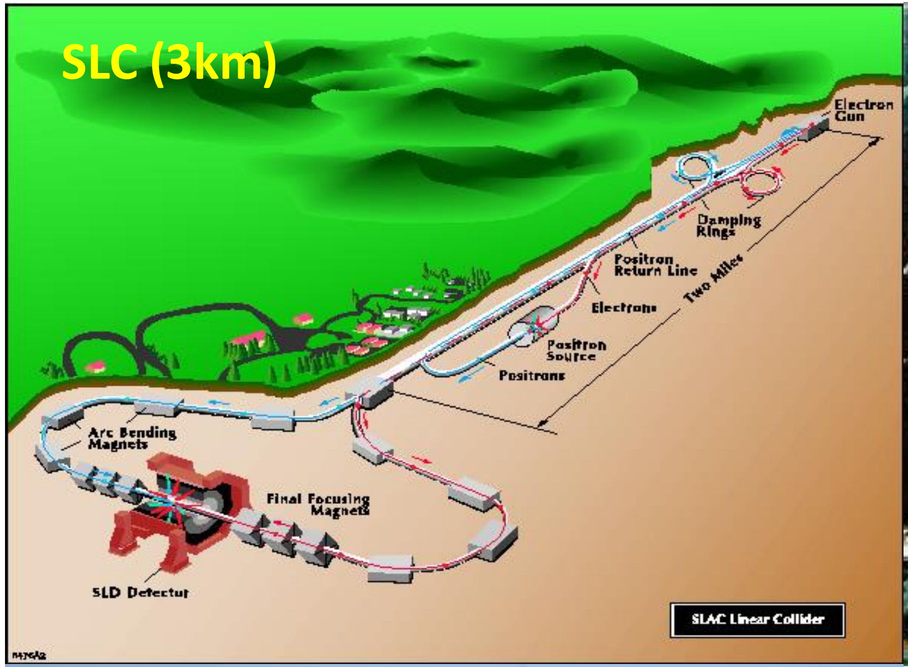
University of Manchester / Cockcroft Institute

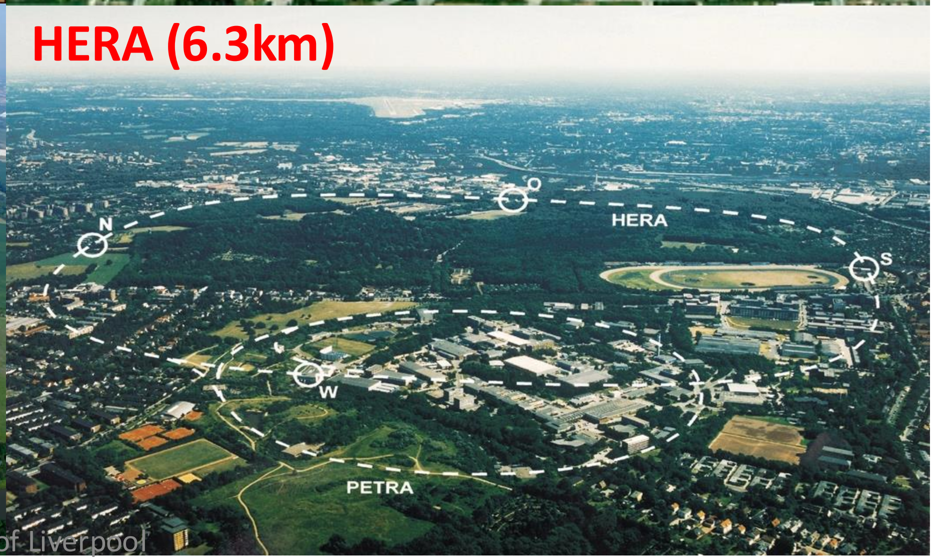
Contents

- Motivation
- Plasma Wakefield Acceleration (PWFA)
  - Electron driven PWFA
  - Positron driven PWFA
  - Proton driven PWFA
- Future Applications
- Conclusion

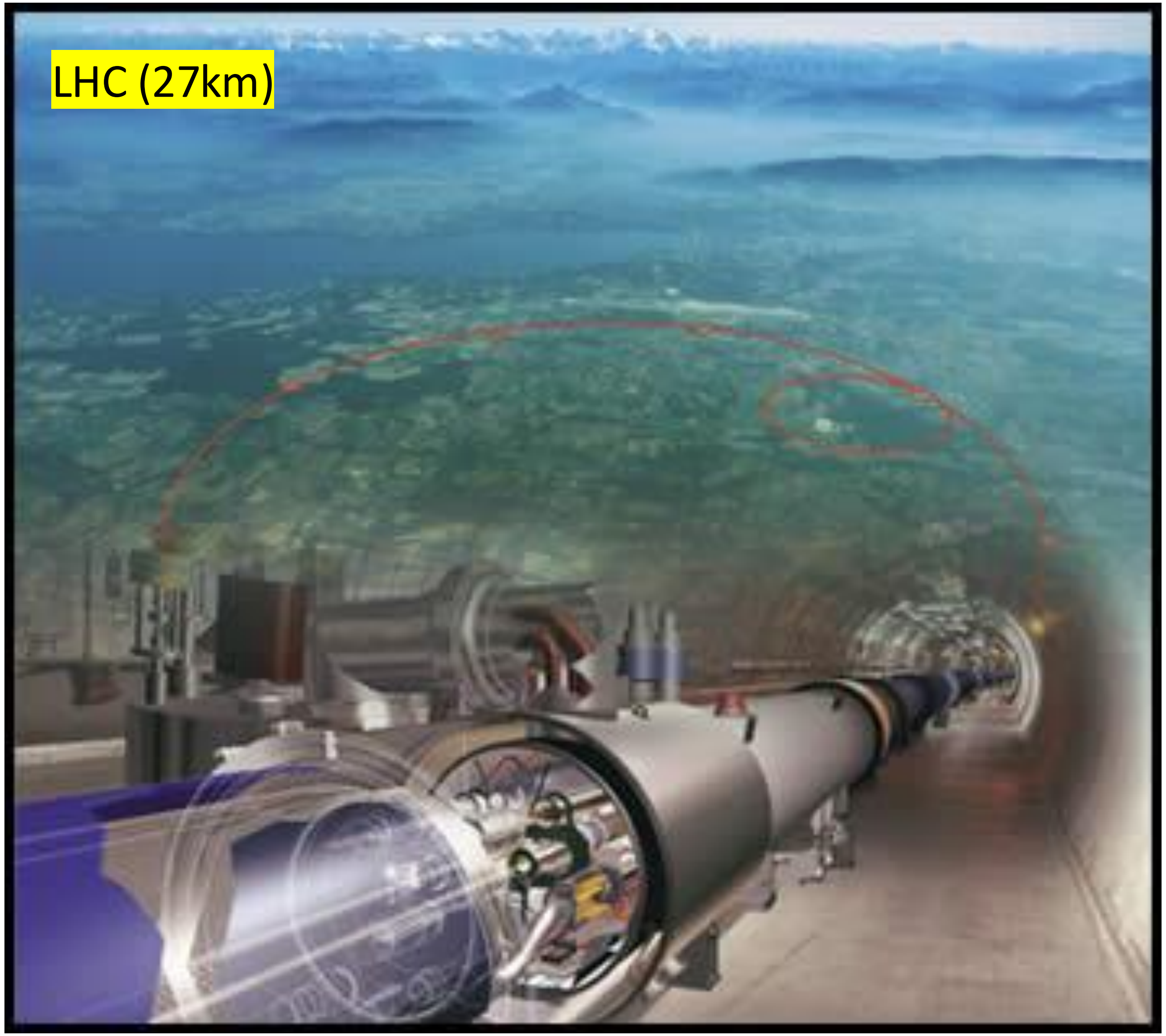
Giant machines today

Motivation



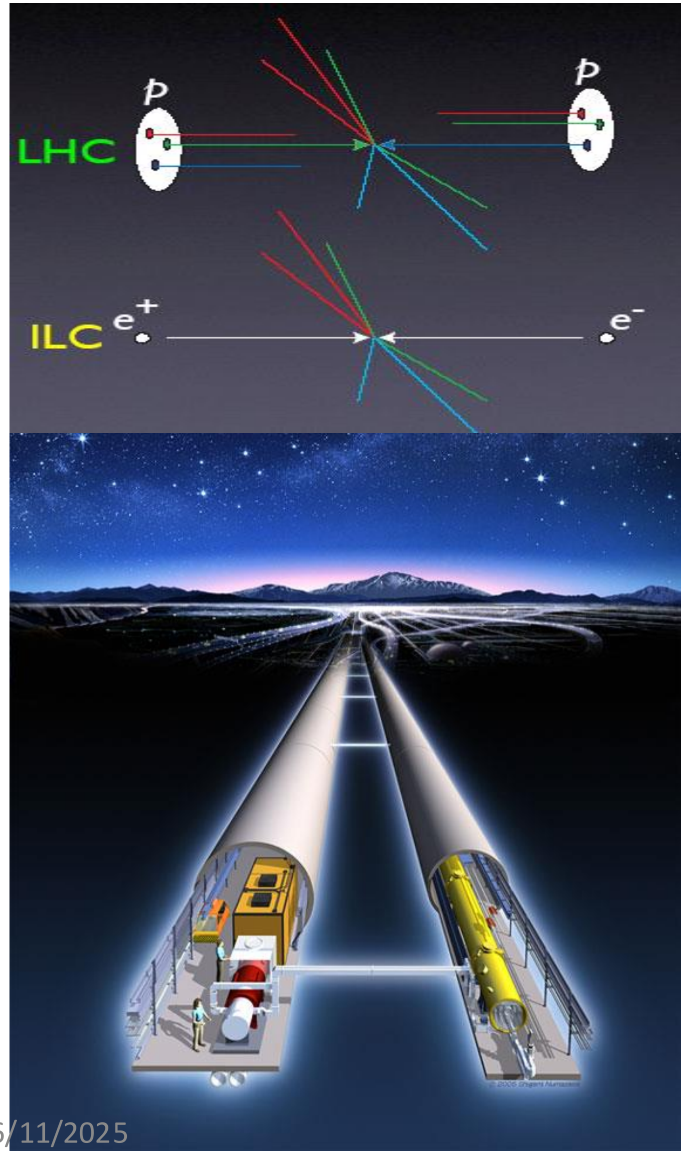


Biggest machine - LHC

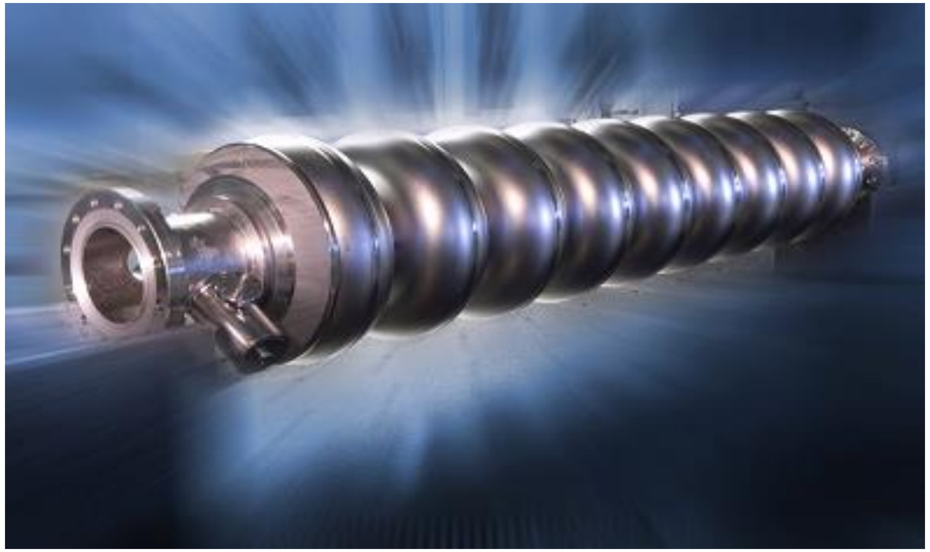


- **LHC**: the world biggest accelerator, both in energy and size
- Grand start-up and perfect function at injection energy in September 2008
- An electrical fault halted the machine running
- First collisions in late 2009 (2.36 TeV)
- 7 TeV collisions in March 2010
- Higgs boson has been found in July 2012 !
- Nobel Prize in Physics in 2013
- Record beam energy 6.5 TeV in April 2015
- Shut down late 2018-2022
- Run 3, beam energy 6.8 TeV, May 2022

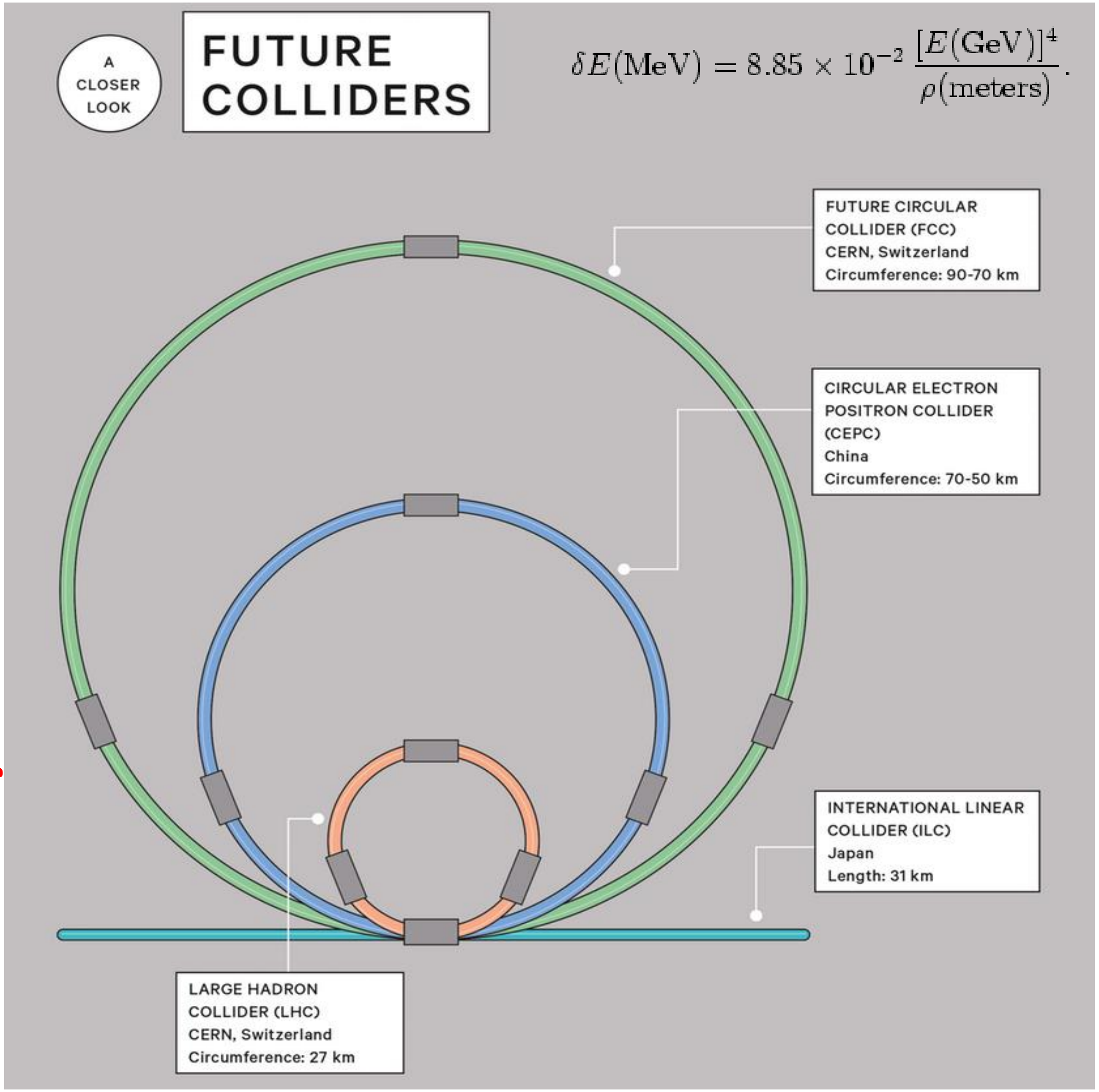
International Linear Collider - ILC



The next *big* thing. After LHC, a Linear Collider of over 30 km length, will be needed.



Beyond the LHC



Tevatron, 6.3 km, ~120M$

LHC, 27 km, ~5B$

ILC, 30 km, ~7B$

CEPC, 100km, ~5.2B$

FCC, 100 km, ~23B$

What is next ???

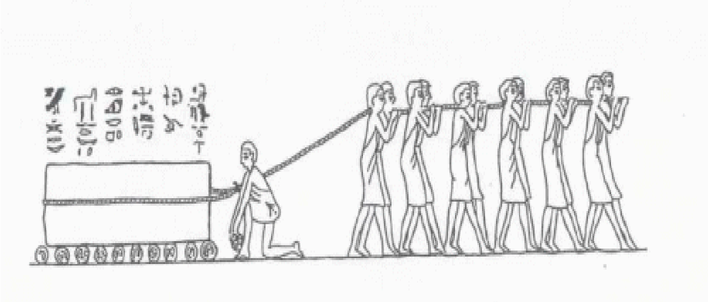
Conventional accelerators have reached the size and cost limit !

CEPC not funded in recent China's 15th Five-Year Plan (2026-2030)

A sustainable, more efficient, cost effective method for particle acceleration should be explored !

Seminal work on laser wakefield accelerator

Collective dynamics



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/cm^2 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.

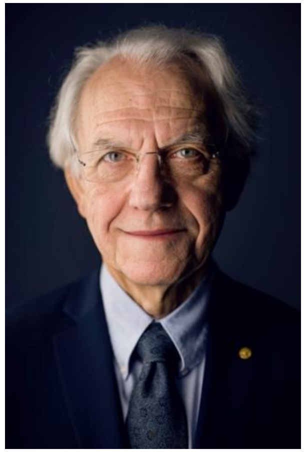
Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective accelerators, 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

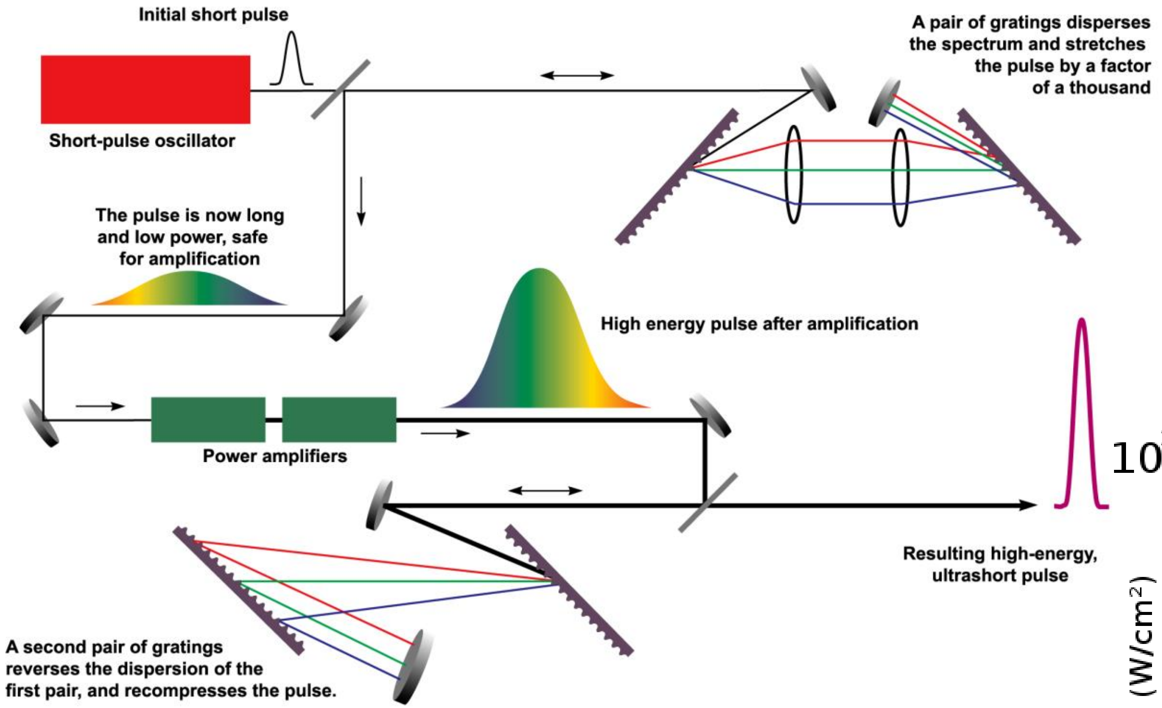
Accelerating field in plasma is **3-4 orders of magnitude** higher than conventional accelerators!

Chirped-pulse amplification (CPA)



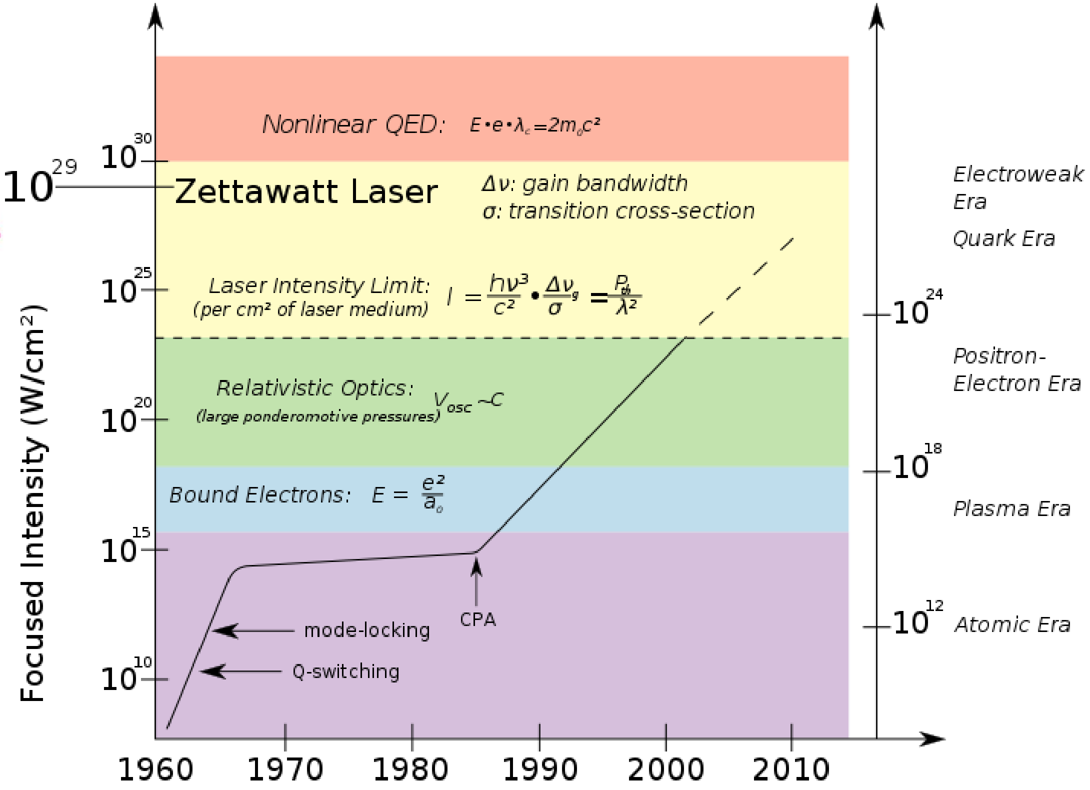
G. Mourou

D. Strickland

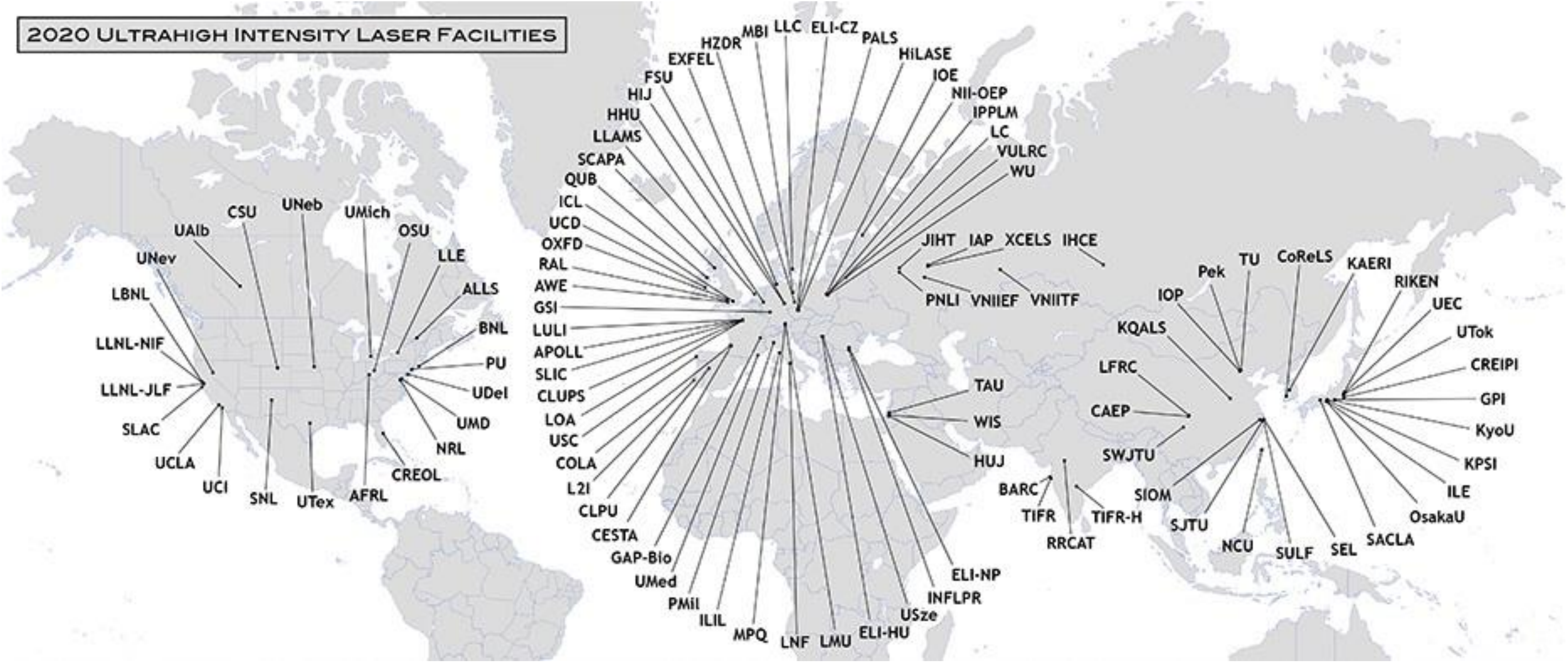


2018 Nobel Prize in Physics !

D. Strickland and G. Mourou, *Opt. Commun.* 56, 219 (1985)



Ultrahigh Intensity Laser Facilities



Plasma Wakefield Acceleration-PWFA

- Owing to the limited research facilities, PWFAs trailed much behind LWFAs in their development
- PWFA drivers propagate through plasma at close to the speed of light, *c*, leading to a plasma wave phase velocity much higher than that in LWFA, where laser pulses propagate at their group velocity, v_g, which is less than *c.* Limiting effect such as overtaking and dephasing of accelerated particles are mitigated.
- In PWFAs, strong transverse focusing fields in the plasma prevent the driver beam expansion, allowing much longer acceleration lengths than that in LWFAs. Meters long plasma was demonstrated
- The increased wake phase velocity reduces unwanted self injection of plasma electrons into the wakefield, mitigating the dark current
- Beam drivers have much greater parameter stability than the high intensity laser drivers
- Particle beams for PWFAs can be generated with megawatt power with high efficiencies of ~10%. In contrast, state of the art high intensity laser systems deliver output power of ~100W with 0.1% level wall-plug efficiency

Brief history

- Concept on laser plasma-based accelerator was proposed by Tajima & Dawson in 1979.
- P. Chen et al. proposed to use electron bunch to excite the plasma electron wave (**1985**) and this idea was confirmed by Rosenzweig et al.(1988) experimentally.
- The PWFA experiments conducted by UCLA/USC/SLAC collaboration achieved many highlights (FFTB/FACET at SLAC).
- Several other labs, such as ANL, BNL, DESY, INFN, CERN, Daresbury Lab joined in this exciting research field

Seminal papers on PWFA

VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

Acceleration of Electrons by the Interaction c

Pisin Ch
Stanford Linear Accelerator Center, Stanfor
and
J. M. Dawson, Robert W.
Department of Physics, University of Cali
(Received 20 De

A new scheme for accelerating electrons, empl
cold plasma, is analyzed. We show that energy gra
electrons can be accelerated from $\gamma_0 mc^2$ to $3\gamma_0 mc^2$
degrade the plasma wave. If the driving electrons a
plasma wave, energies up to $4\gamma_0^2 mc^2$ are possible.
order that the driving electrons can be removed.

PACS numbers: 52.75.Di, 29.15.−n

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

SVDM/afm

CERN/PS/85-65 (AA)
CLIC Note No. 3

IMPROVING THE POWER EFFICIENCY

OF THE

PLASMA WAKEFIELD ACCELERATOR

S. van der Meer

ABSTRACT

Some methods are proposed to improve the efficiency of energy transfer from the primary beam to the secondary one. The first suggestion is to use beam diameters small compared to the plasma wavelength; in this regime the longitudinal wakefield depends little on the diameter. The second possibility is to use a continuous sequence of primary and secondary bunches without letting the plasma oscillations decay in between. It is shown how a steady-state solution providing equal deceleration or acceleration for all particles exists in first approximation.

Particle Accelerators, 1985, Vol. 17, pp. 171–189
0031-2460/85/1704–0171/$20.00/0

IA WAKE FIELD ACCELERATOR†

. W. CHAO, P. L. MORTON and P. B. WILSON
Stanford Linear Accelerator Center
ord University, Stanford, California, 94305

(Received December 14, 1984)

meters that determines the next generation of high energy
eleration gradient. Recently there has been interest in the
waves for obtaining high acceleration gradients. The Plasma
Tajima and Dawson uses two beating lasers to excite the
t frequency.[1] The driven plasma provides an accelerating
can be of the order of several GeV/m.[2-5] This scheme has
the Surfatron,[6-8] although the basic principle is similar.

Beam driven facilities: status

Facility	Where	Drive (D) beam	Witness (W) beam	Start	End	Goal
AWAKE	CERN, Geneva, Switzerland	400 GeV **protons**	Externally injected electron beam (PHIN 15 MeV)	2016	2020+	**Use for future high energy e-/e+ collider.** - Study Self-Modulation Instability (SMI). - Accelerate externally injected electrons. - Demonstrate scalability of acceleration scheme.
SLAC-FACET	SLAC, Stanford, USA	20 GeV **electrons** and **positrons**	Two-bunch formed with mask (e^-/e^+ and e^--e^+ bunches)	2012	Sept 2016	- Acceleration of witness bunch with high **quality and efficiency** - Acceleration of positrons - FACET II preparation, starting 2018
DESY-Zeuthen	PITZ, DESY, Zeuthen, Germany	20 MeV **electron** beam	No witness (W) beam, only D beam from RF-gun.	2015	~2017	- Study Self-Modulation Instability **(SMI)**
DESY-FLASH Forward	DESY, Hamburg, Germany	X-ray FEL type **electron** beam 1 GeV	D + W in FEL bunch. Or independent W-bunch (LWFA).	2016	2020+	- **Application (mostly) for x-ray FEL** - Energy-doubling of Flash-beam energy - Upgrade-stage: use 2 GeV FEL D beam
Brookhaven ATF	BNL, Brookhaven, USA	60 MeV **electrons**	Several bunches, D+W formed with mask.	On going		- **Study quasi-nonlinear PWFA regime.** - Study PWFA driven by multiple bunches - Visualisation with optical techniques
SPARC Lab	Frascati, Italy	150 MeV	Several bunches	On going		- Multi-purpose user facility: includes laser- and beam-driven plasma wakefield experiments
CLARA	Daresbury Lab	35-250 MeV	D+W bunches	on going		- LWFA with external injection energy boost, ICS, plasma energy recovery

Courtesy to Edda Gschwendtner (CERN)

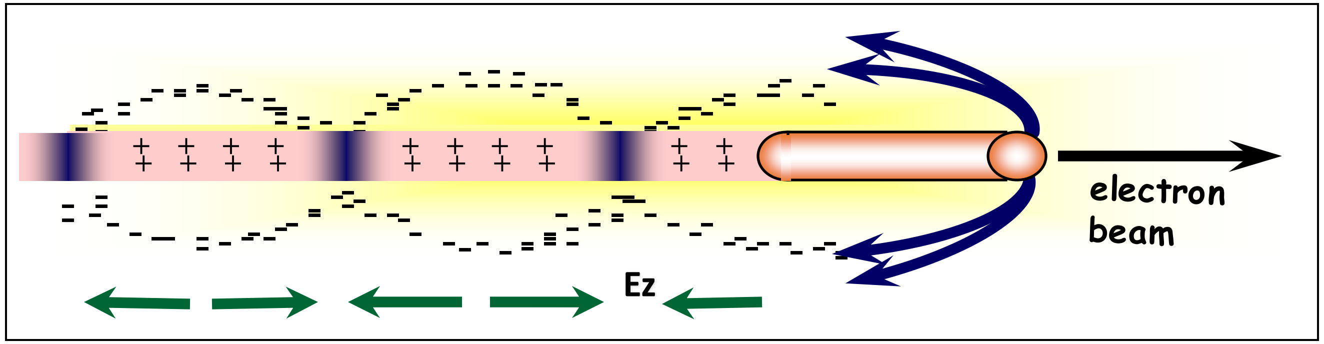
Plasma wakefield acceleration-PWFA

Electron motion solved with ...

driving force: Space charge of drive beam displaces plasma electrons.

restoring force: Plasma ions exert restoring force

Space charge oscillations (Harmonic oscillator)



Longitudinal fields can accelerate and decelerate!

First experiment in 1988

21 MeV drive beam,
15 MeV Witness beam,
Delay distance is variable.
Plasma density 10^{12}-10^{13} cm^{-3}

VOLUME 61, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1988

Experimental Observation of Plasma Wake-Field Acceleration

J. B. Rosenzweig, D. B. Cline,[a] B. Cole,[b] H. Figueroa,[c] W. Gai, R. Konecny, J. Norem, P. Schoessow, and J. Simpson

High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

(Received 21 March 1988)

We report the first experimental test of the physics of plasma wake-field acceleration performed at the Argonne National Laboratory Advanced Accelerator Test Facility. Megavolt-per-meter plasma wake fields are excited by a intense 21-MeV, multipicosecond bunch of electrons in a plasma of density $n_e \simeq 10^{13}$ cm^{-3}, and probed by a low-intensity 15-MeV witness pulse with a variable delay time behind the intense bunch. Accelerating and deflecting wake-field measurements are presented, and the results compared to theoretical predictions.

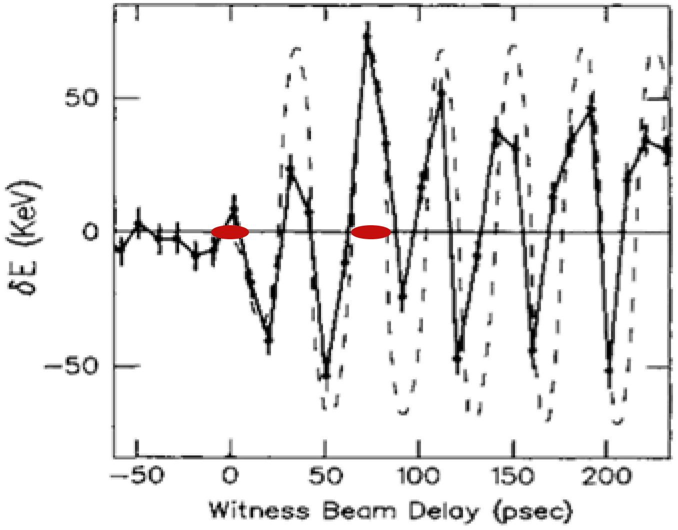


FIG. 2. Scan 1: Witness-beam energy-centroid change δE vs time delay behind driver. Total driver-beam charge $Q = 2.1$ nC; plasma parameters $L = 28$ cm and $n_e = 8.6\times10^{12}$ cm^{-3}. Theoretical predictions are given by the dashed line.

VOLUME 61, NUMBER 1 PHYSICAL RE

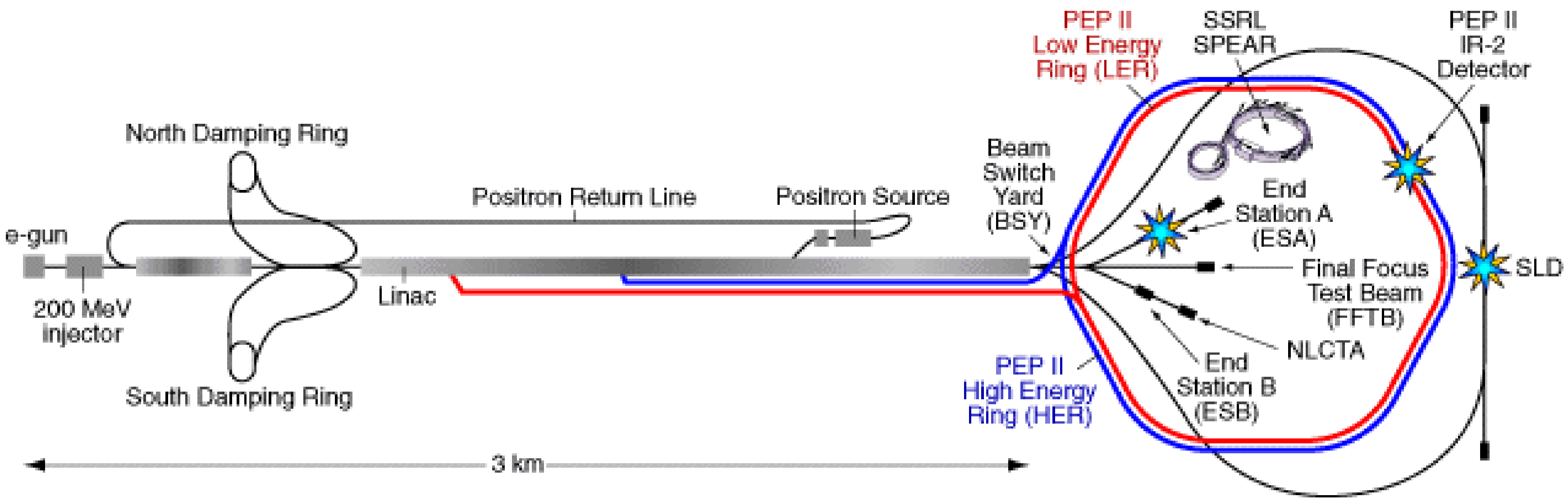
Experimental Observation of I

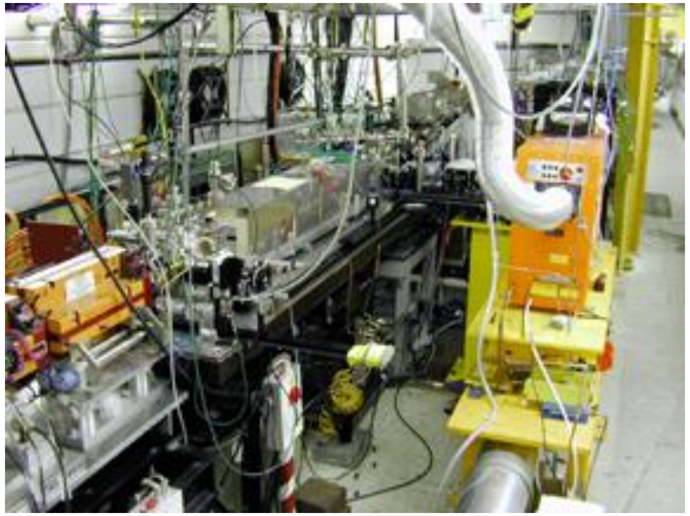
J. B. Rosenzweig, D. B. Cline,[a] B. Cole,[b]
P. Schoessow

High Energy Physics Division, Argonne I
(Received 2

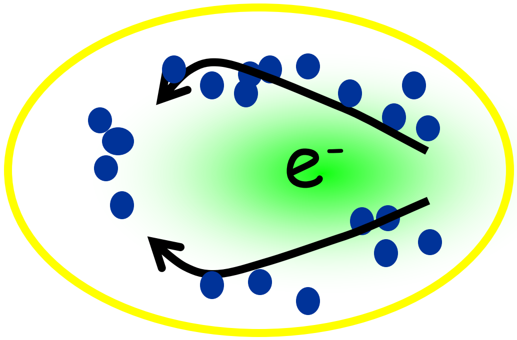
We report the first experimental test of the phys
Argonne National Laboratory Advanced Acceler
fields are excited by a intense 21-MeV, multipi

Experiments at FFTB@SLAC





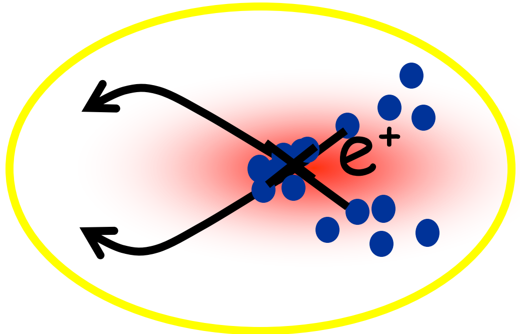
e^+ and e^- as drive beams

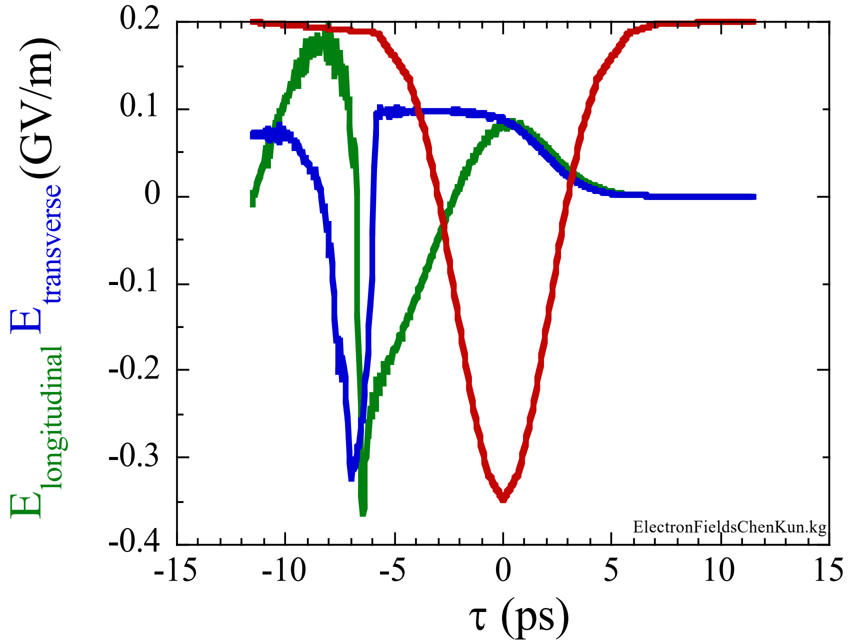


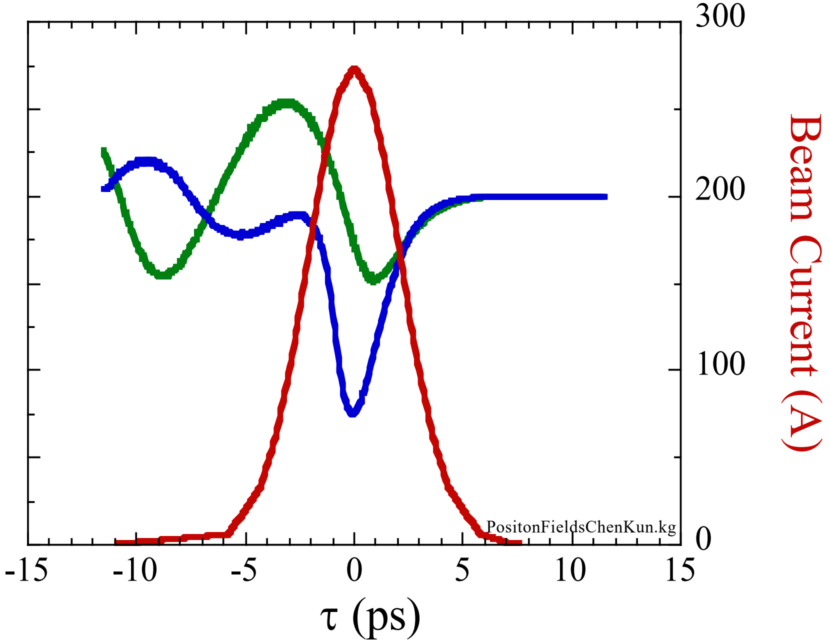
$\sigma_r = 35\ \mu m$

$N = 1.8\times10^{10}$

n_p=1.5×10^{14} cm^{-3}
homogeneous, QUICKPIC



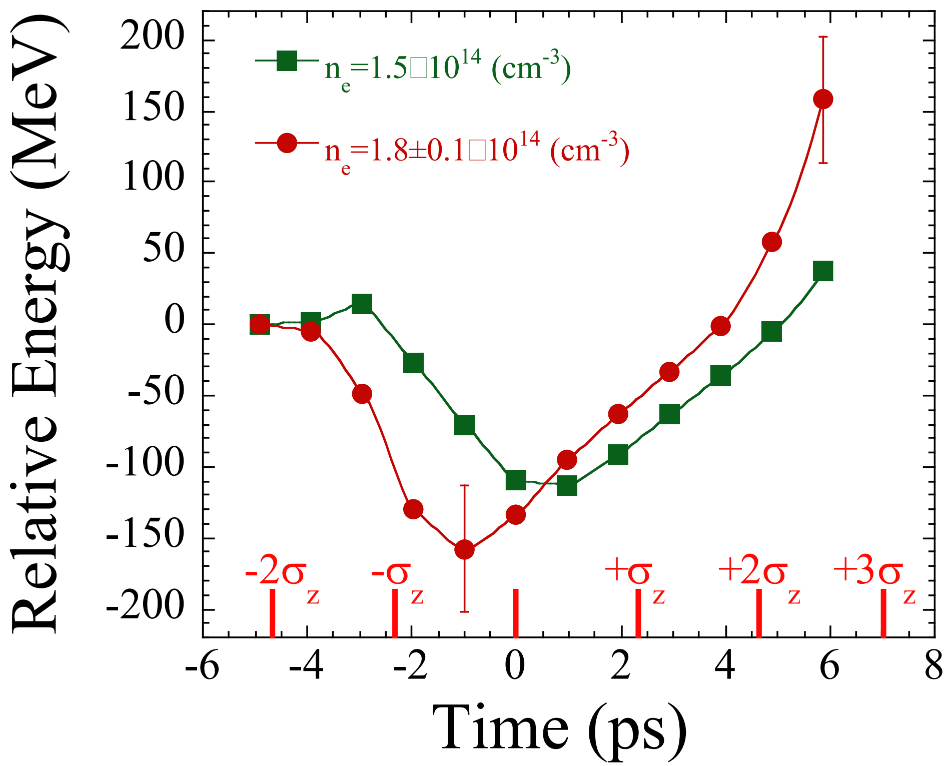




- Blow-Out
- Accelerating “Spike”

- Fields vary along r, stronger
- Less Acceleration, “linear-like”

e^+ acceleration



PRE-IONIZED plasma
LONG bunch operation

$\sigma_z \approx 730$ µm
$N = 1.2\times10^{10}$ e^+
$k_p\sigma_z \approx \surd 2$

PRL 90, 214801 (2003)
PRL 90, 205002 (2003)
PRL 101, 055001 (2008)

Energy gain smaller than, hidden by, incoming energy spread

Time resolution needed, but shows the physics

Peak energy gain: 279 MeV, L=1.4 m, ≈200 MeV/m

Positrons in hollow plasma

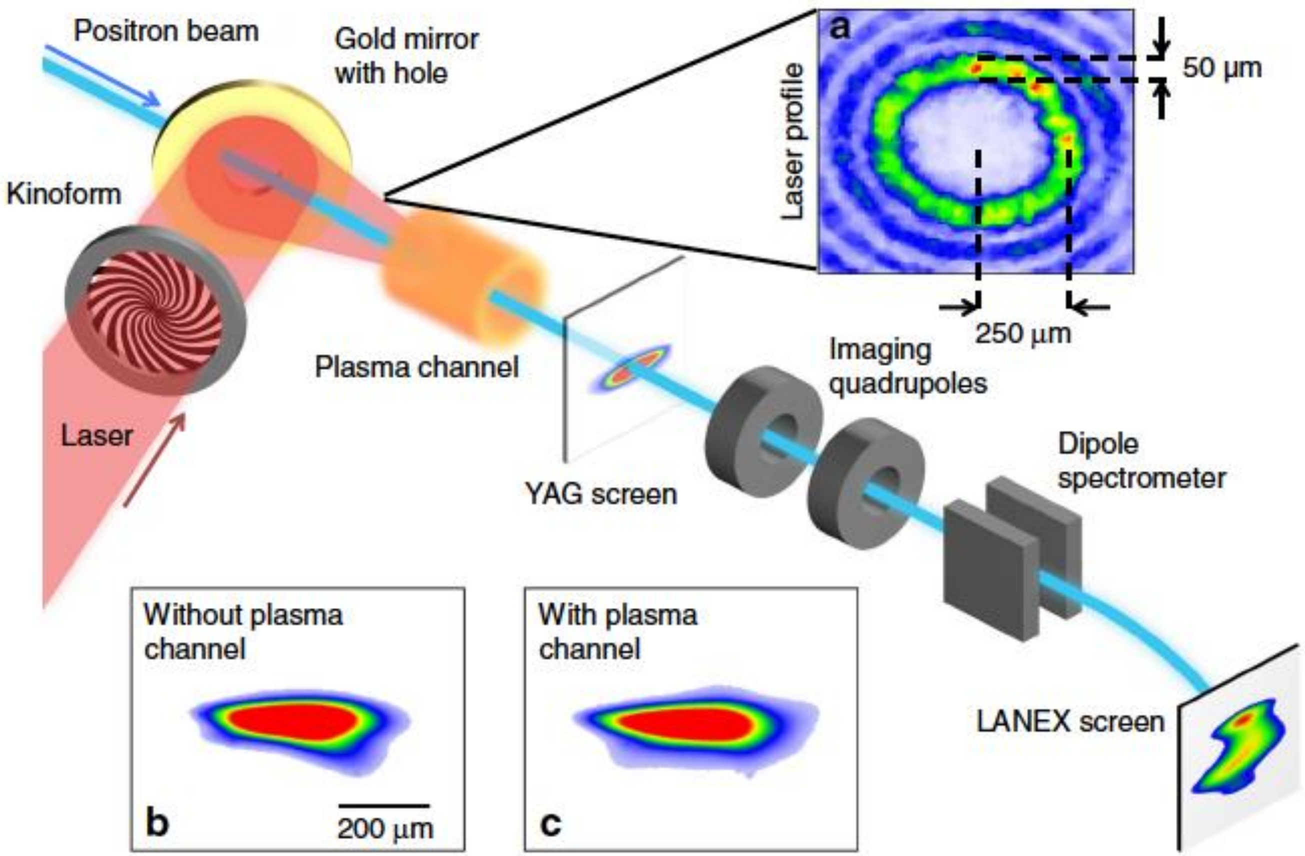


Figure 1 | Experimental layout. The laser passes through the kinoform and is coupled to the beam axis by a gold mirror with a small central hole. Inset (**a**) shows the laser profile upstream of the lithium oven. A scintillating YAG screen 1.95 m downstream of plasma is used to measure the positron beam profile. Inset (**b**) shows the positron beam spatial profile as imaged on the YAG screen with the laser off and no plasma present. Inset (**c**) shows the beam profile with the laser on when the positron beam propagates through the plasma channel. The two profiles are similar, indicating that there are no net focusing forces because of the plasma channel. A scintillating Lanex screen downstream of the dipole measures the beam energy spectrum.

Gessner et al., Nat. Commun. 7: 11785 (2016)

Positrons in hollow plasma

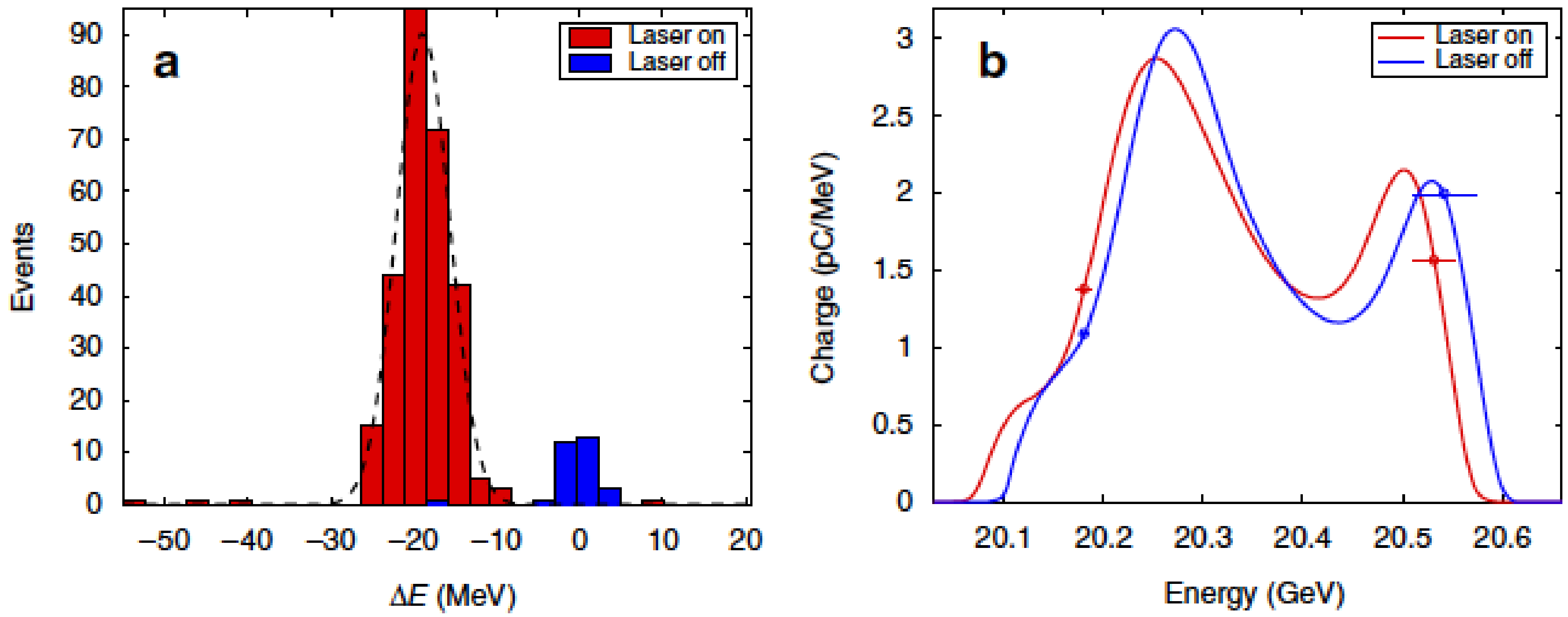
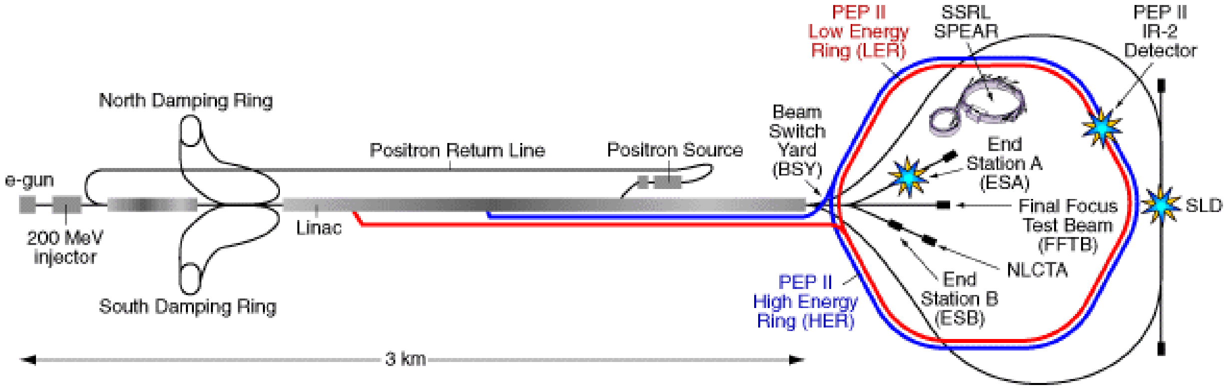


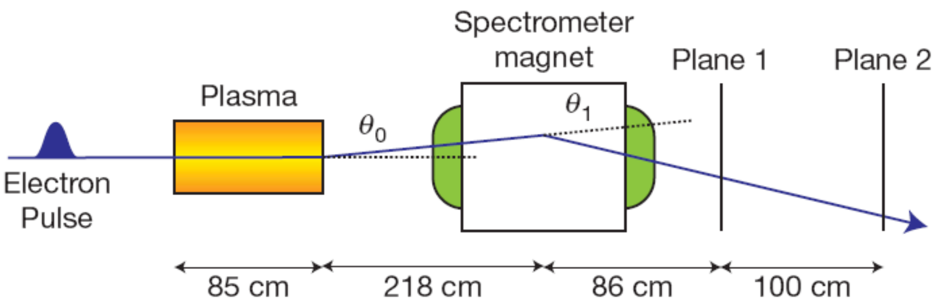
Figure 4 | Energy loss measurements. (**a**) A histogram of the beam energy loss for all 315 shots corrected for incoming energy jitter (see the Methods for details). The plasma channel is present when the laser is on (red). When the laser is off (blue) the beam is propagating through neutral lithium vapour. We fit the laser-on data to a gaussian (black dashed curve) with mean energy loss 18.9 MeV and width 3.2 MeV. (**b**) A comparison of the average beam energy spectra for laser on and laser off shots. The s.d. error bars represent the statistical uncertainty in the upper and lower regions of the spectrum due to averaging (see Supplementary Fig. 4 for details). The error has been multiplied by a factor of five so that it is visible in the plot.

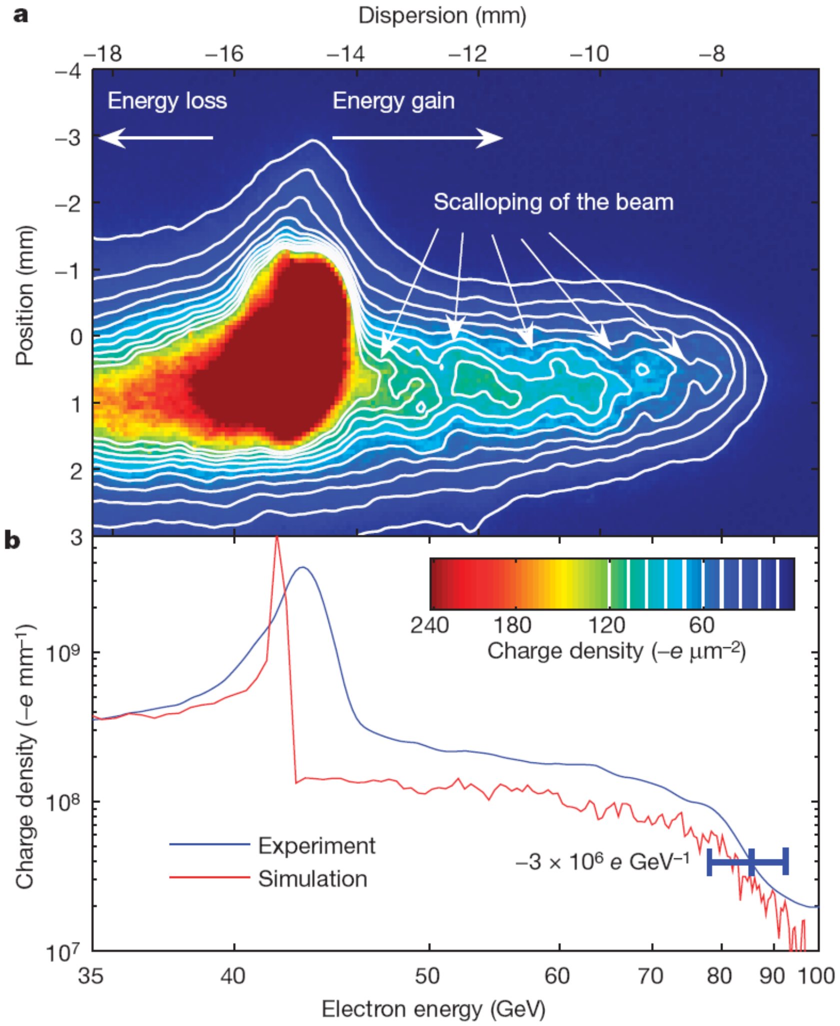
Deceleration field: 220 MV/m!

Gessner et al., Nat. Commun. 7: 11785 (2016)

Energy doubling experiment







Electron beam (beam energy 42 GeV, bunch length 50 fs rms, bunch charge 2.9 nC)

Plasma (heat Li oven, length 85 cm, density 2.7e17 cm-3)

Max. energy gain
43 GeV (85 cm column) = 52 GeV/m !

Energy spectrum of the electrons in the 35-100 GeV range as observed in plane 2

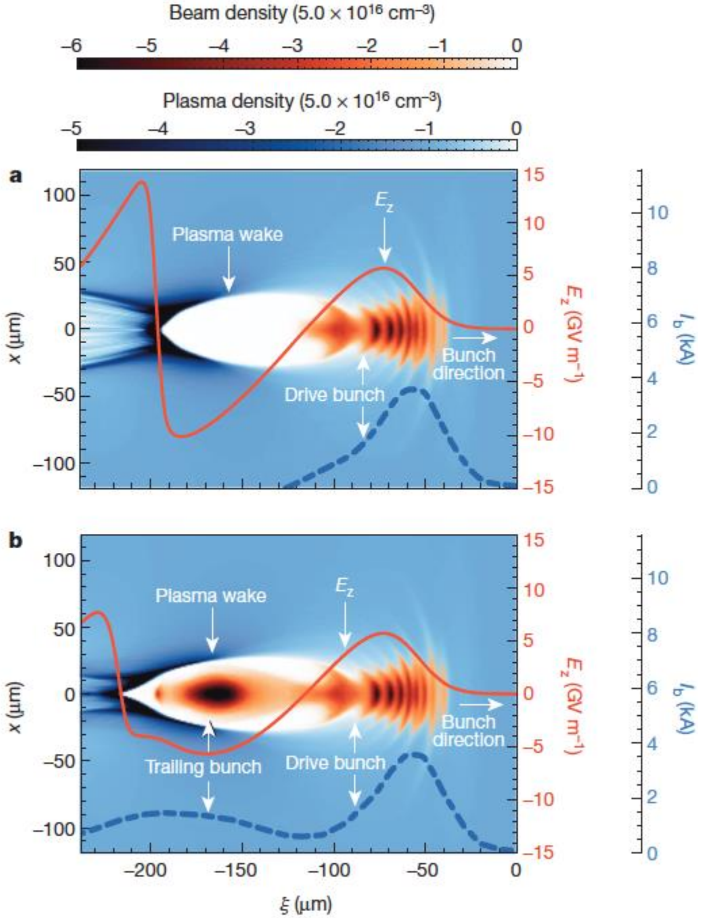
Blumenfeld et al., Nature 445 (2007) 741

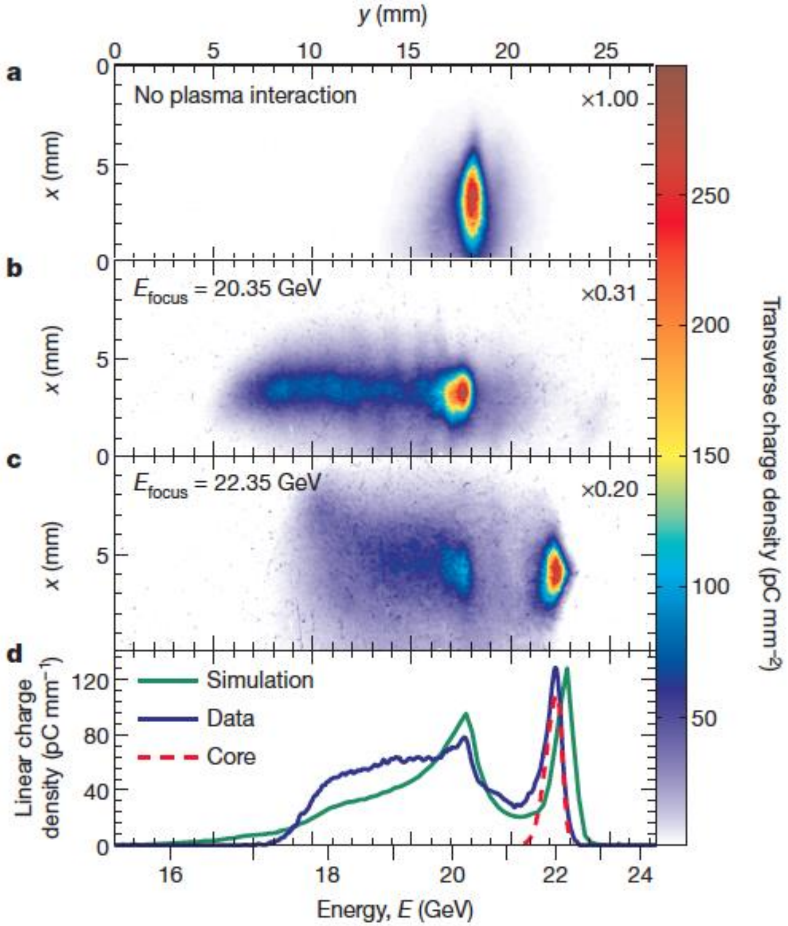
LETTER

doi:10.1038/nature13882

High-efficiency acceleration of an electron beam in a plasma wakefield accelerator

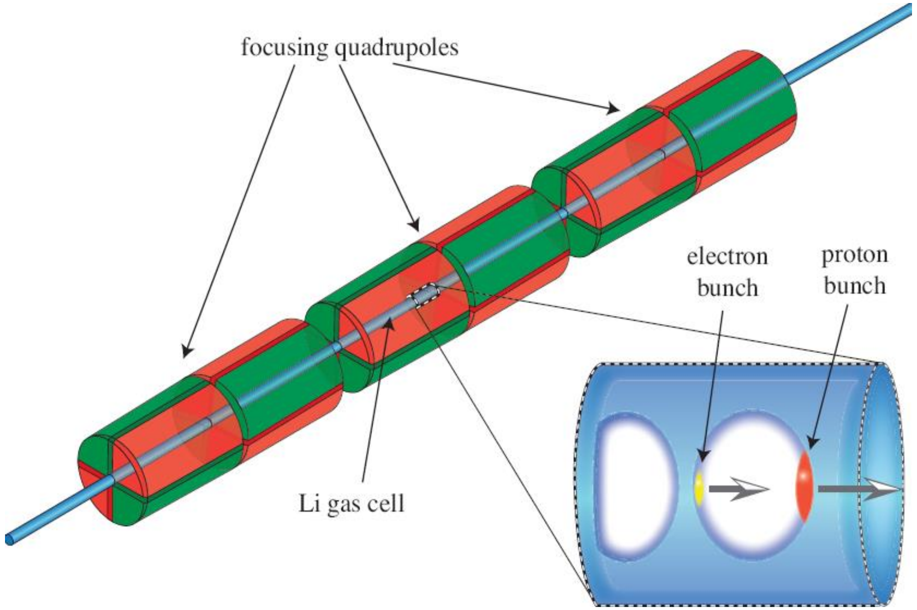
M. Litos[1], E. Adli[1,2], W. An[3], C. I. Clarke[1], C. E. Clayton[4], S. Corde[1], J. P. Delahaye[1], R. J. England[1], A. S. Fisher[1], J. Frederico[1], S. Gessner[1], S. Z. Green[1], M. J. Hogan[1], C. Joshi[4], W. Lu[5], K. A. Marsh[4], W. B. Mori[3], P. Muggli[6], N. Vafaei-Najafabadi[4], D. Walz[1], G. White[1], Z. Wu[1], V. Yakimenko[1] & G. Yocky[1]





Accelerating gradient 4.4 GeV/m
Final energy spread of training bunch:0.7%

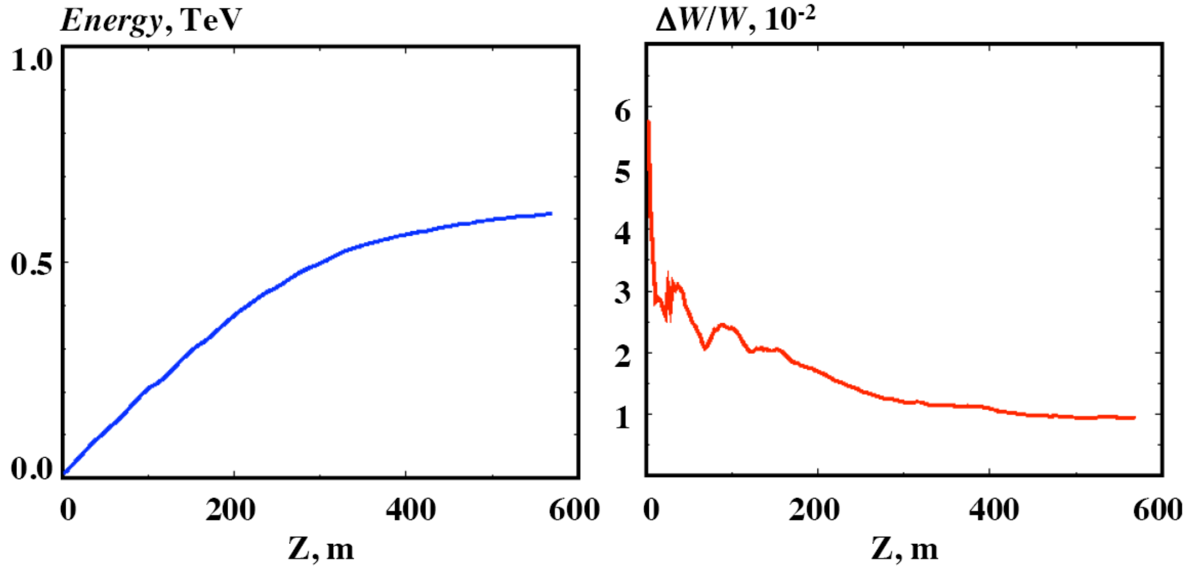
Proton-driven PWFA



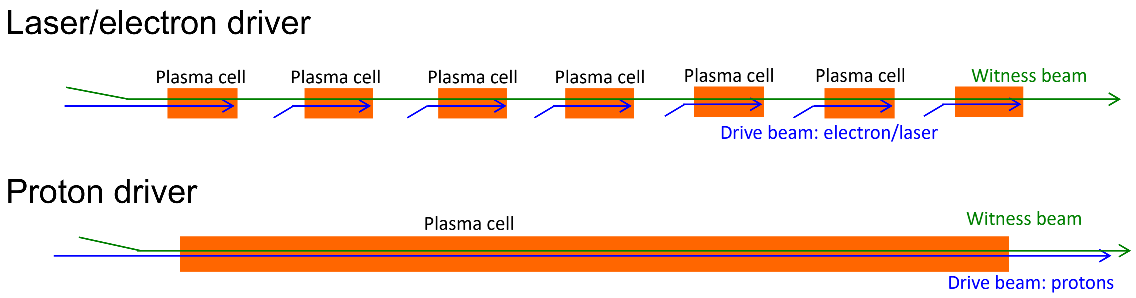
- **SPS (400 GeV, 3e11 p/bunch) ~ 19.2 kJ**
- **LHC (7 TeV, 1.15e11 p/bunch) ~ 140 kJ**

- **SLAC (50 GeV, 2e10 e-/bunch) ~ 0.16 kJ**
- **Ultrashort pulse lasers ~ 0.1 kJ**

- **ILC (250 GeV, 2e10 e-/bunch) ~ 0.8 kJ**



ONE STAGE acceleration to energy frontier !



E. Gschwendtner

The mean electron energy in TeV and the r.m.s. variation of the energy in the bunch as a function of the distance travelled in the plasma.

A. Caldwell et al., Nature Physics 5, 363 (2009)

From concept to experiment

CERN COURIER

Feb 24, 2010

Workshop pushes proton-driven plasma wakefield acceleration

PPA09

PPA09, a workshop held at CERN on proton-driven plasma wakefield acceleration, has launched discussions about a first demonstration experiment using a proton beam. Steve Myers, CERN's director for Accelerators and Technology, opened the event and described its underlying motivation. Reaching higher-energy collisions for future particle-physics experiments beyond the LHC requires a novel accelerator technology, and "shooting a high-energy proton beam into a plasma" could be a promising first step. The workshop, which brought together participants from Germany, Russia, Switzerland, the UK and the US, was supported by the EuCARD AccNet accelerator-science network (**CERN Courier November 2009 p16**).

Plasma acceleration

AWAKE: to high energies in a single leap

Proton-driven plasma wakefield acceleration could accelerate electrons to the terascale in a single plasma stage. The AWAKE project is set to verify this novel technique using proton beams at CERN.

To complement the results that will come from the LHC at CERN, the particle-physics community is looking for options for future lepton colliders at the tera-electron-volt energy scale. These will need to be huge circular or linear colliders. With the accelerating gradients of today's RF cavities or microwave technology limited to about 100 MV/m, the length of the linear machines would be tens of kilometres. However, plasma can sustain much higher gradients and the idea of harnessing them in plasma wakefield acceleration is gathering momentum. One attractive idea is to use a high-energy proton beam as the driver of a wakefield in a single plasma section.

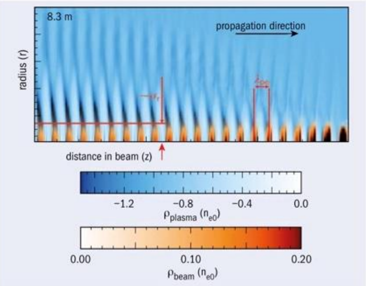
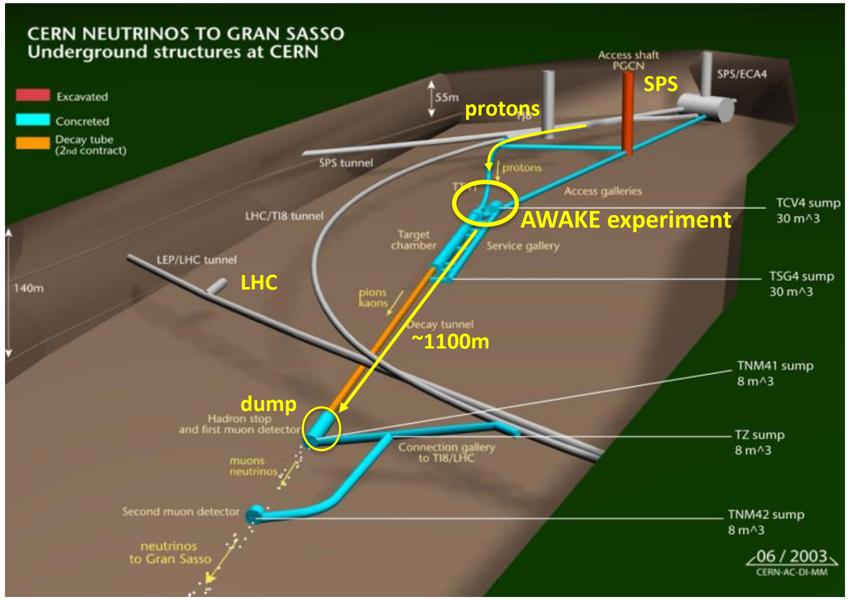


Fig. 1. Simulation of a self-modulated proton bunch resonantly driving plasma wakefields sustained by the plasma-density perturbation. The plasma density is shown increasing from white to blue and the proton density increasing fr



J. Plasma Physics: page 1 of 7. © Cambridge University Press 2012
doi:10.1017/S0022377812000086

A proposed demonstration of an experiment of proton-driven plasma wakefield acceleration based on CERN SPS

G. XIA[1], R. ASSMANN[2], R. A. FONSECA[3], C. HUANG[4], W. MORI[5], L. O. SILVA[3], J. VIEIRA[3], F. ZIMMERMANN[2] and P. MUGGLI[1]
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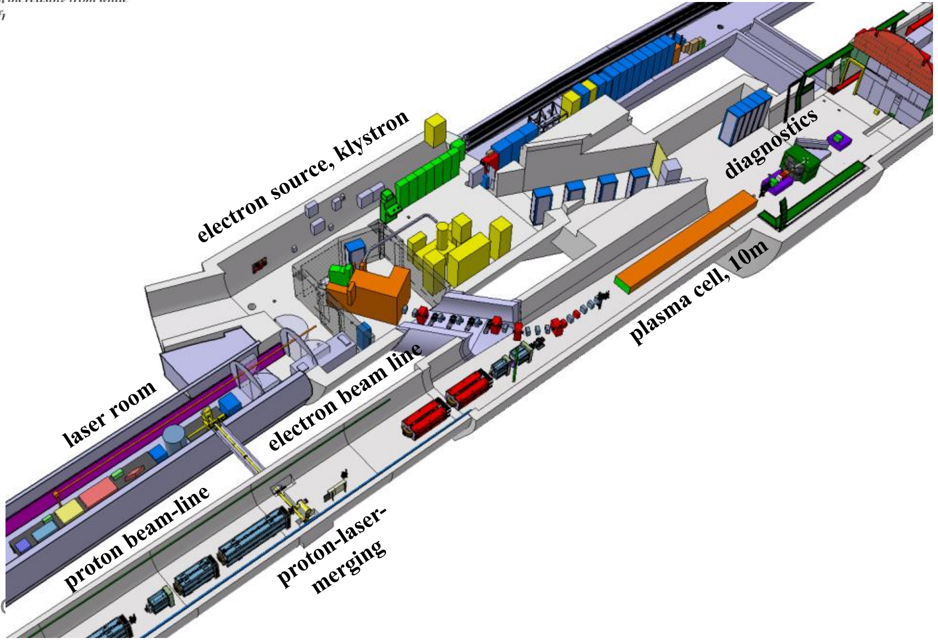
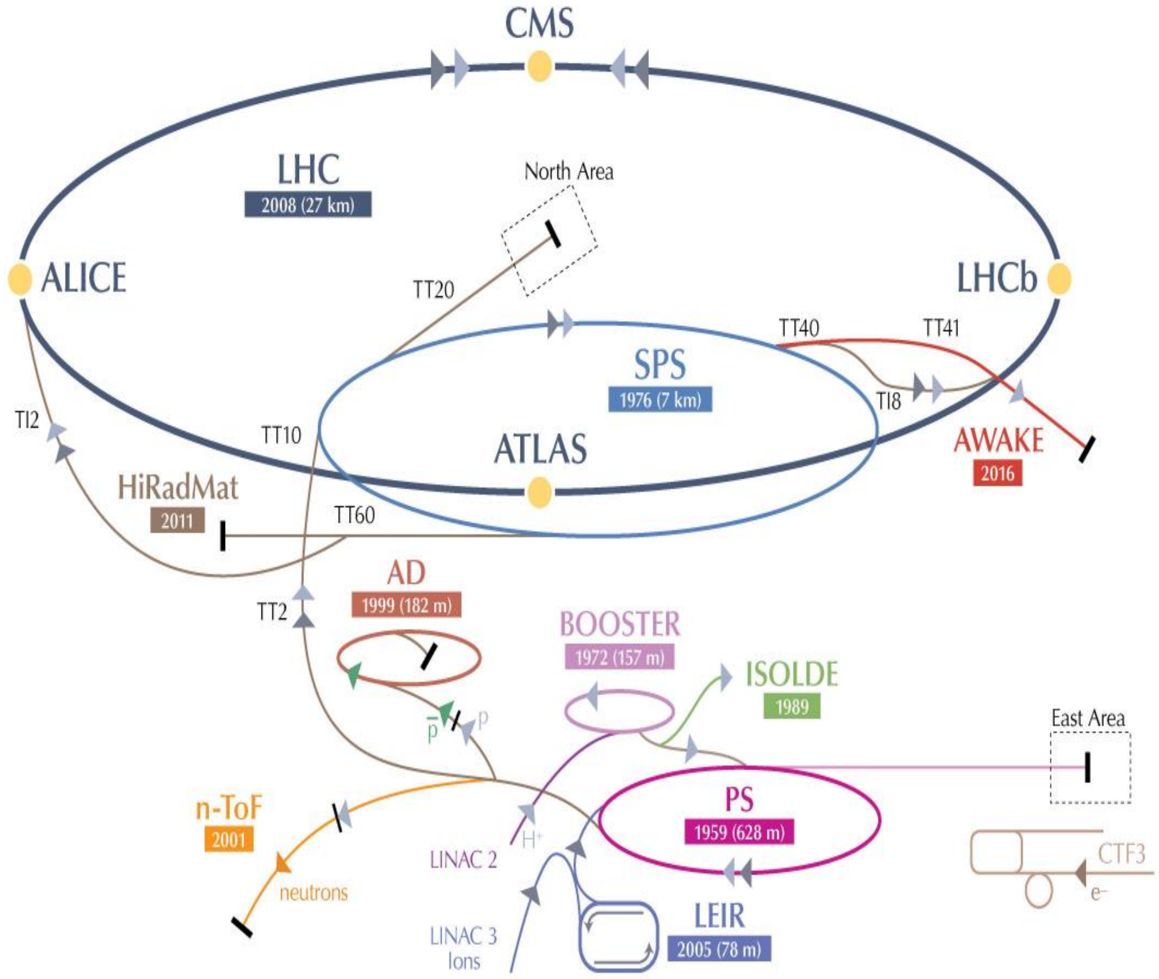
(Received 20 September 2011; accepted 2 January 2012)



AWAKE experiment at CERN

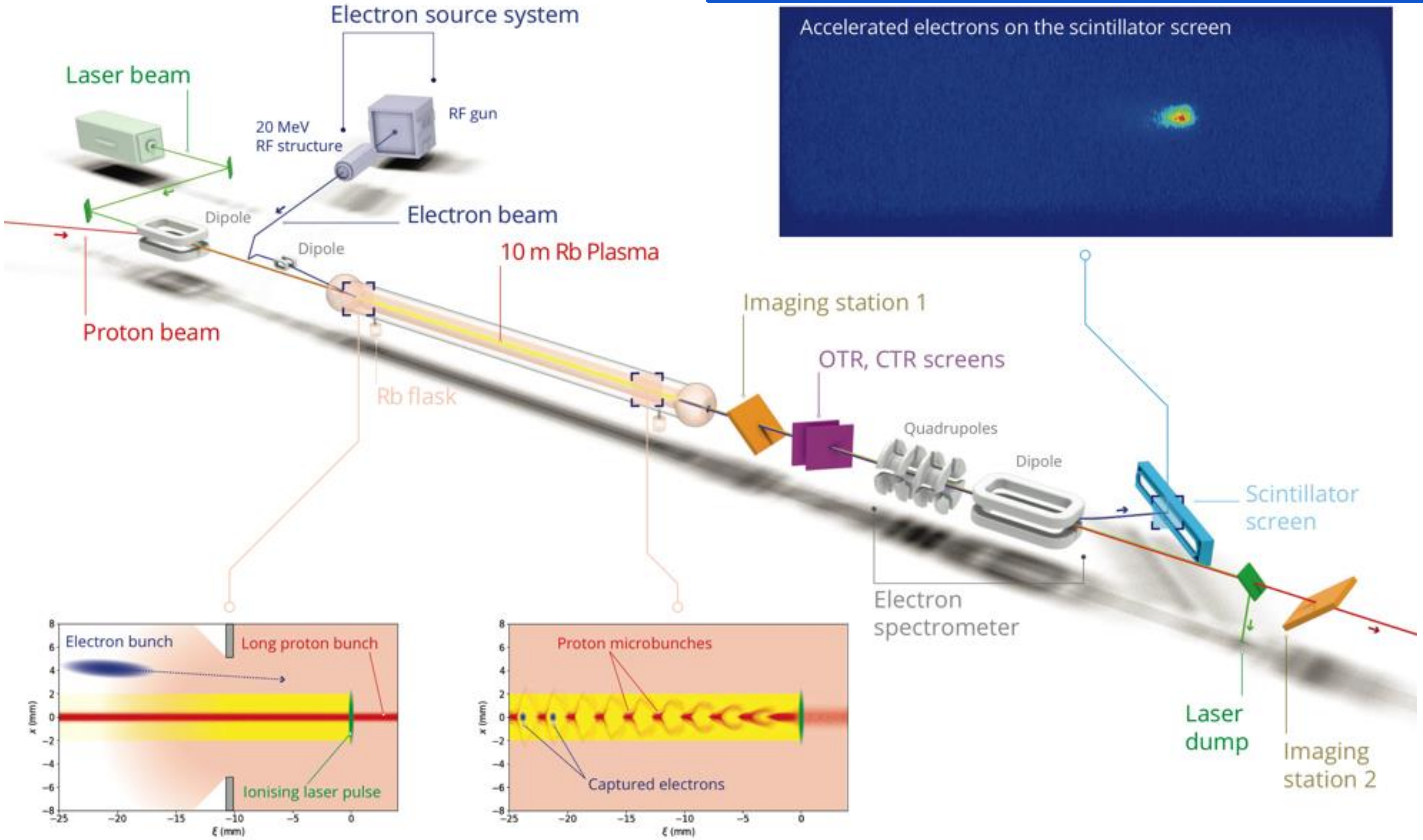


Advanced WAKEfield Experiment

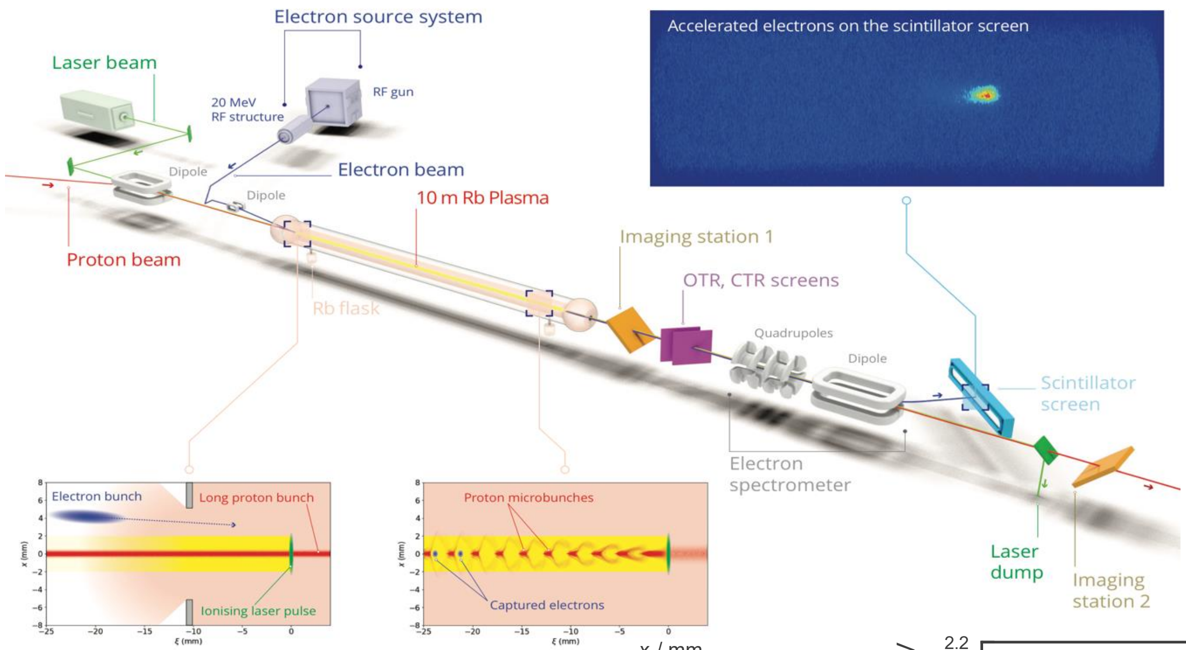
- Proof-of-Principle Accelerator R&D experiment at CERN to study proton-driven plasma wakefield acceleration.
- Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.
- Approved in August 2013
- First proton beam sent to plasma end 2016
- First electron acceleration in 2018
- AWAKE Run 2 program started in 2021

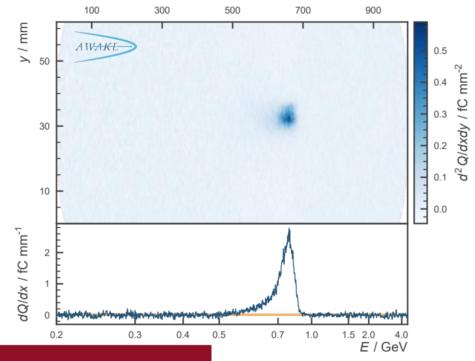
AWAKE Run 1 (2016-18)

AWAKE Run 1: Proof-of Concept
2016/17: Seeded Self-Modulation of proton beam in plasma
2018: Electron acceleration in plasma

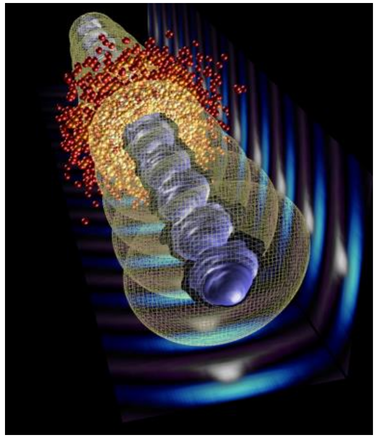


AWAKE highlights in 2018





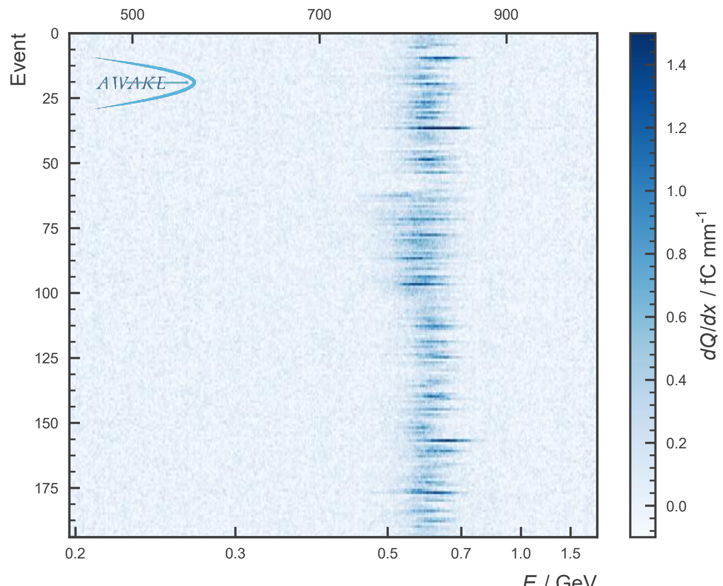
nature
International journal of science

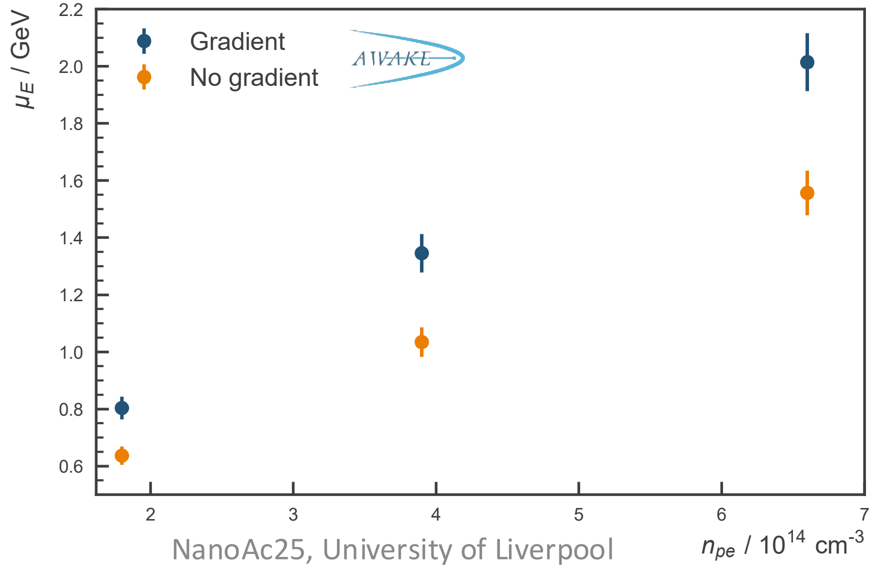


J. Vieira, IST

CERN's pioneering mini-accelerator passes first test

Physicists achieve powerful acceleration by 'surfing' electrons on proton waves over short distances.

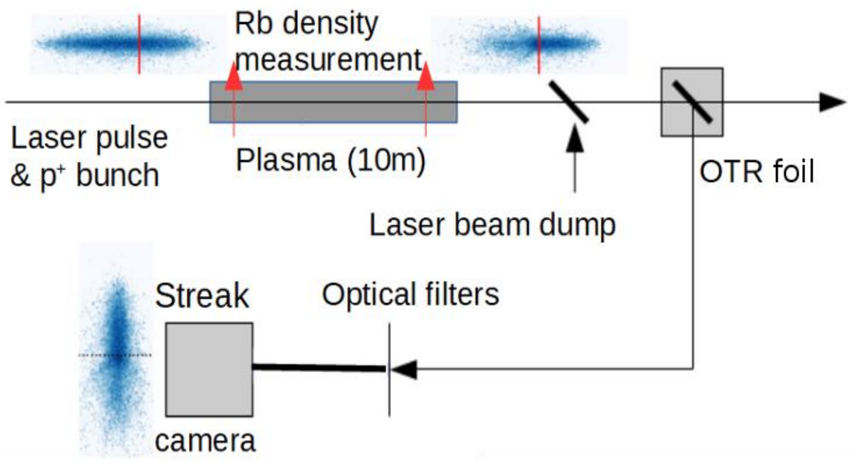


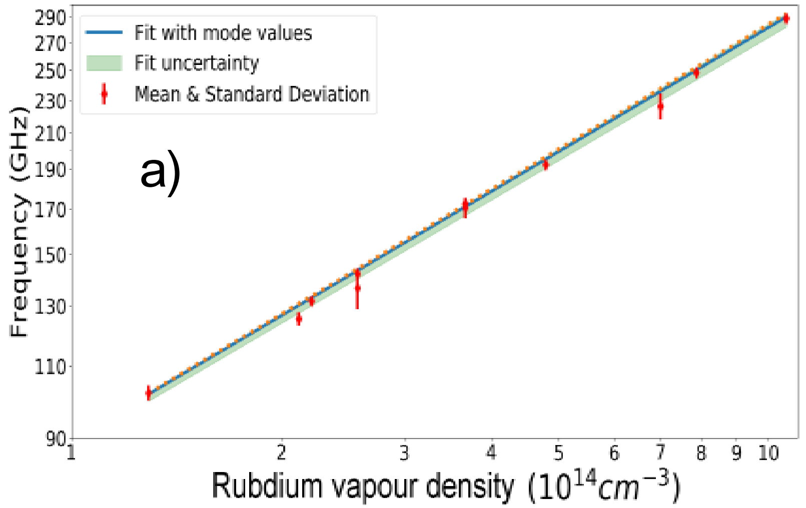


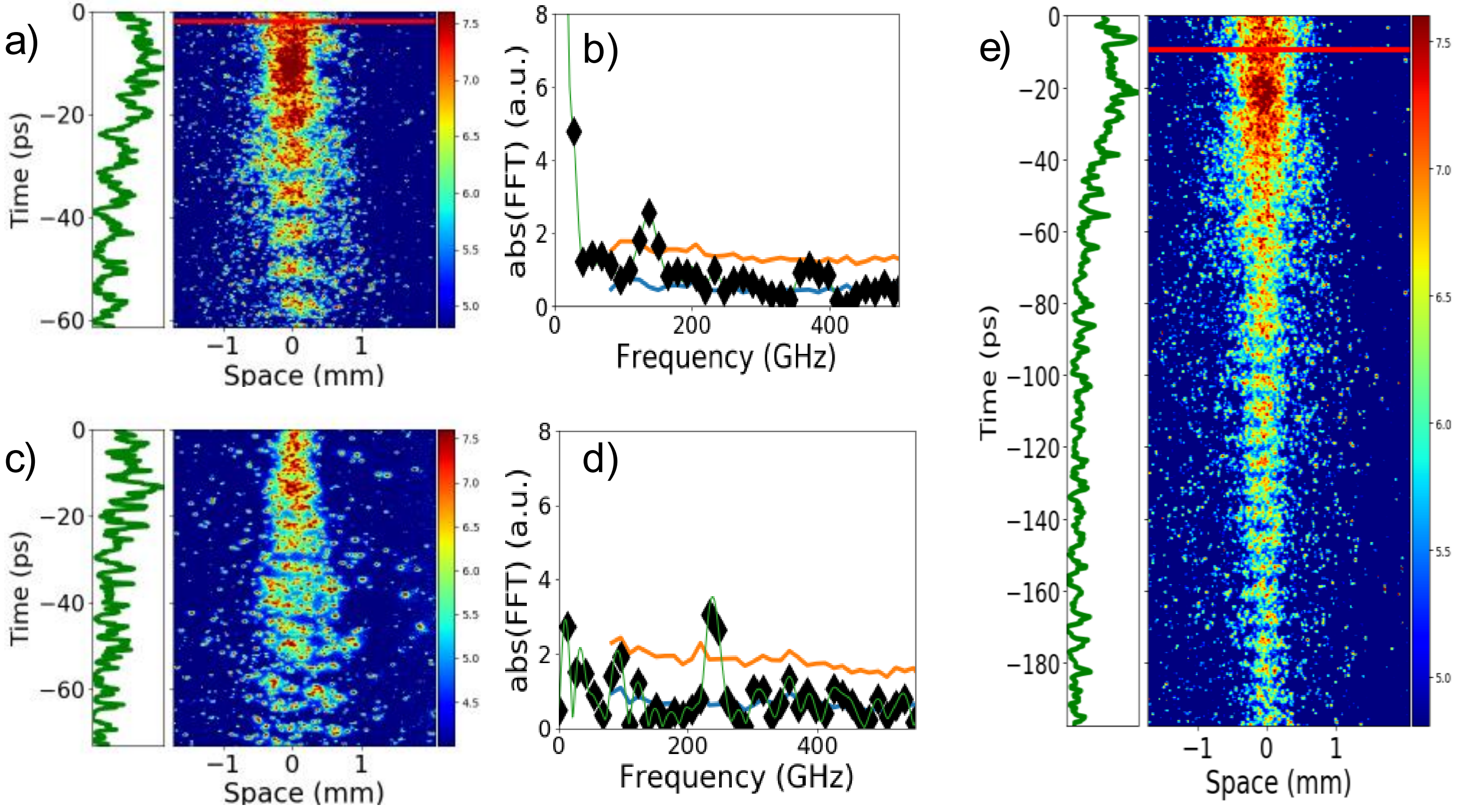
20% (100 pC) of electrons are trapped and accelerated!

AWAKE Collaboration, Nature 561, 363-367 (2018).

AWAKE Run 1 highlights

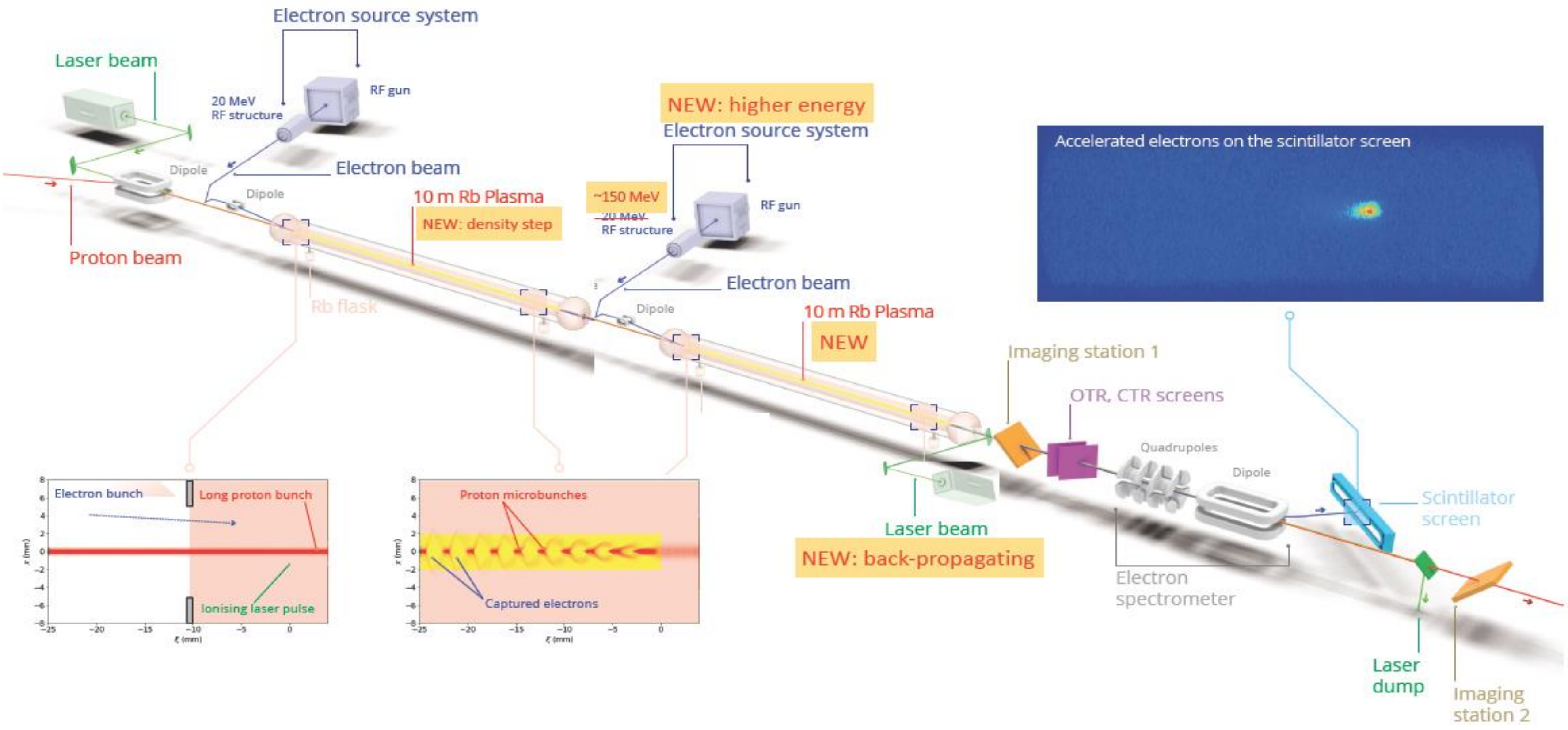






M. Turner et al. (AWAKE Collaboration), Phys. Rev. Lett. 122, (5) 054801 (2019).
E. Adli et al. (AWAKE Collaboration), Phys. Rev. Lett. 122, (5) 054802 (2019).
F. Braunmueller et al. (AWAKE Collaboration), Phys. Rev. Lett. 125 (26) 264801(2020).
F. Batsch et al. (AWAKE Collaboration), Phys. Rev. Lett. 126 (16) 164802 (2021).

AWAKE Run 2 (2021-2025)



Goals:

Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)

Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)

Demonstrate scalable plasma source technology (e.g. helicon or discharge prototype)

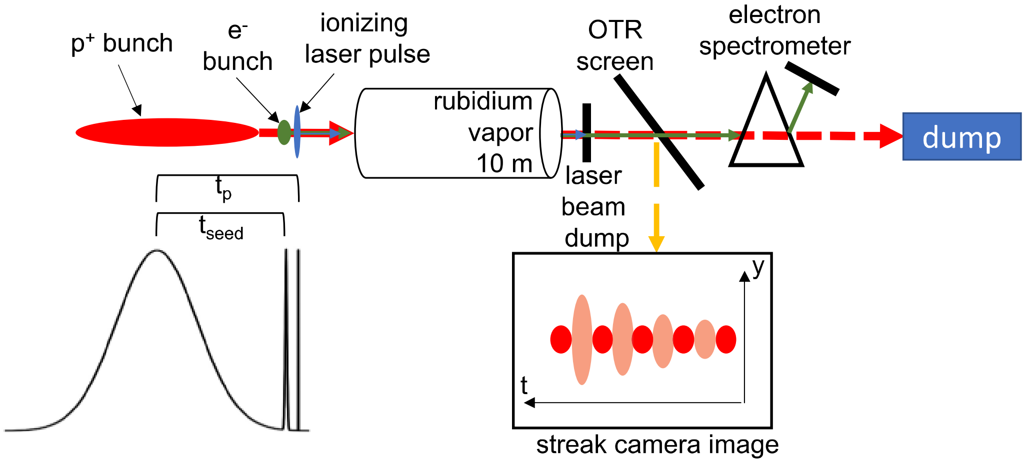
AWAKE Run 2 phases and preliminary results

Run 2a: Demonstration of the electron seeding of the proton bunch self modulation in the first plasma source.

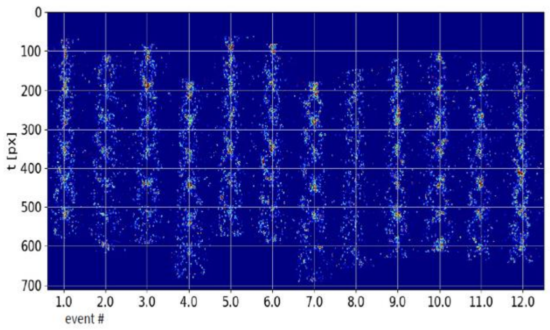
Run 2b: Demonstration of the stabilization of micro-bunches with a density step in the first plasma source.

Run 2c: Demonstration of electron acceleration and emittance control.

Run 2d: Demonstration of electron acceleration in scalable plasma sources.



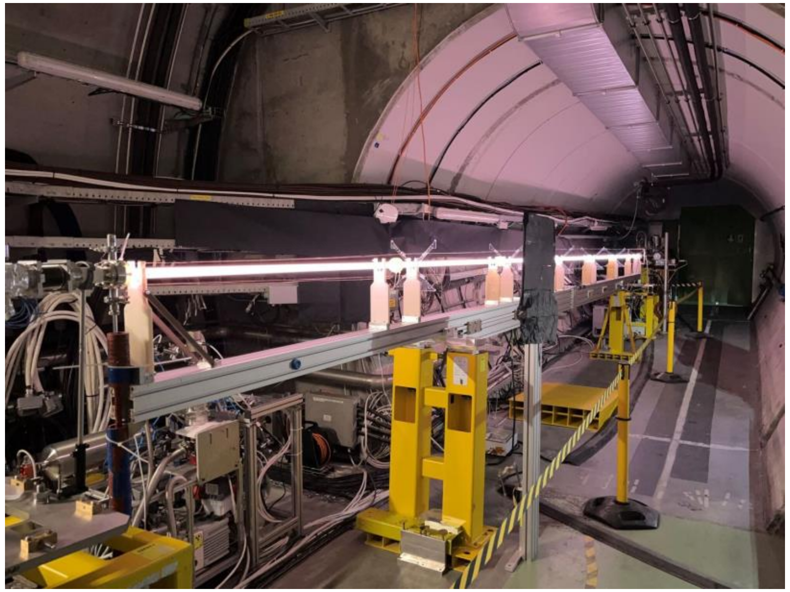
Waterfall plot: plasma + electrons

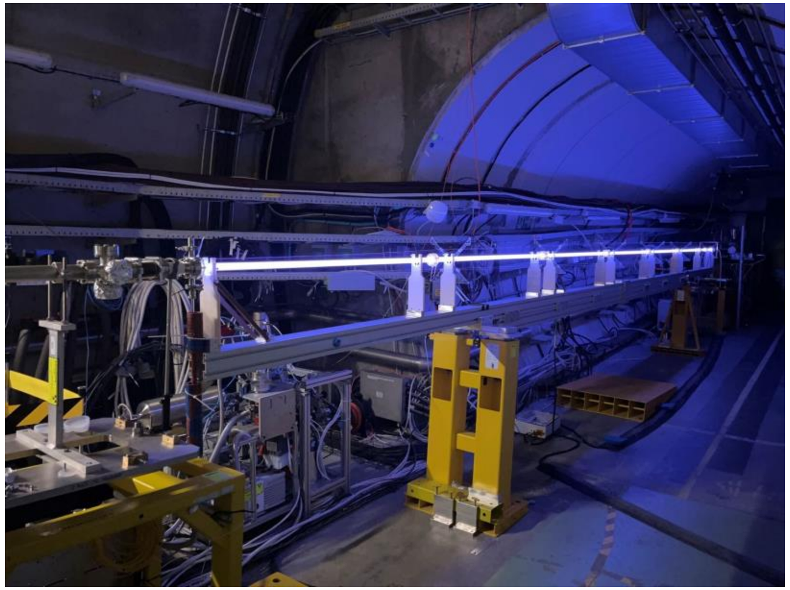


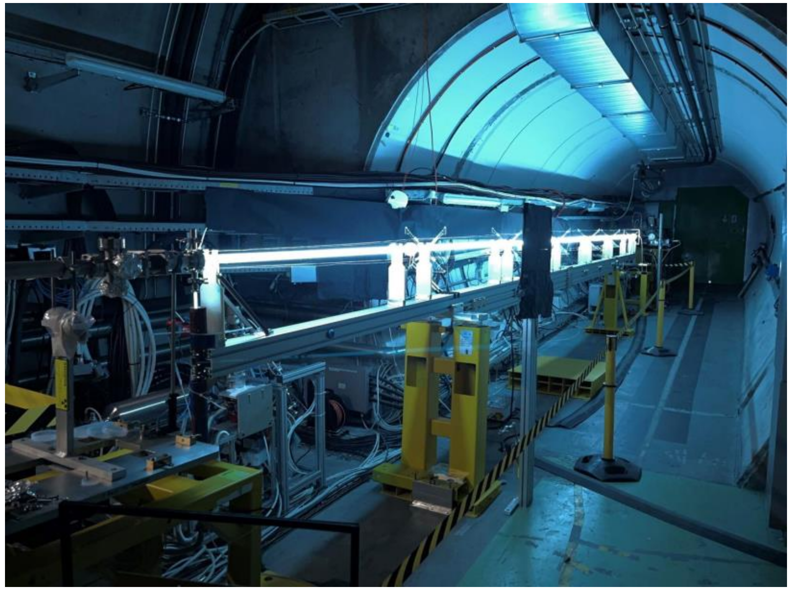
L. Verra et al. (AWAKE Collaboration), Phys. Rev. Lett. 129 (2), 024802 (2022)

(E. Gschwendtner)

Discharge plasma source at AWAKE tunnel







Xenon **Argon** **Helium**

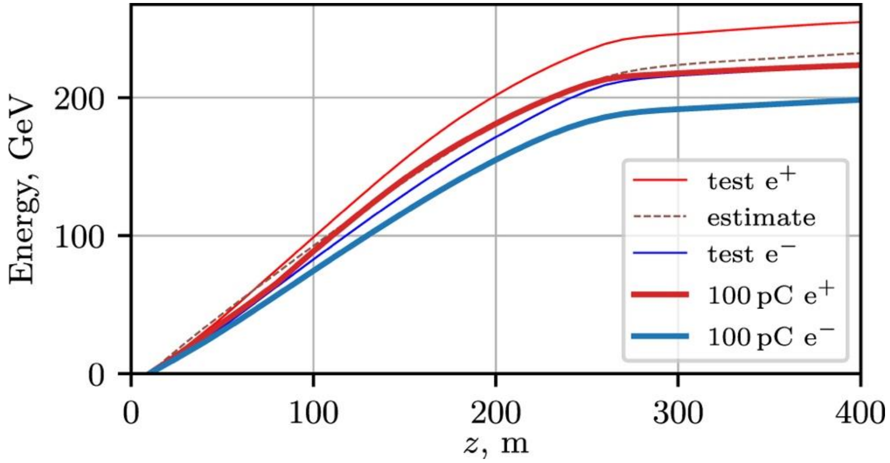
A. Sublet, N. Lopes, P. Muggli et al.

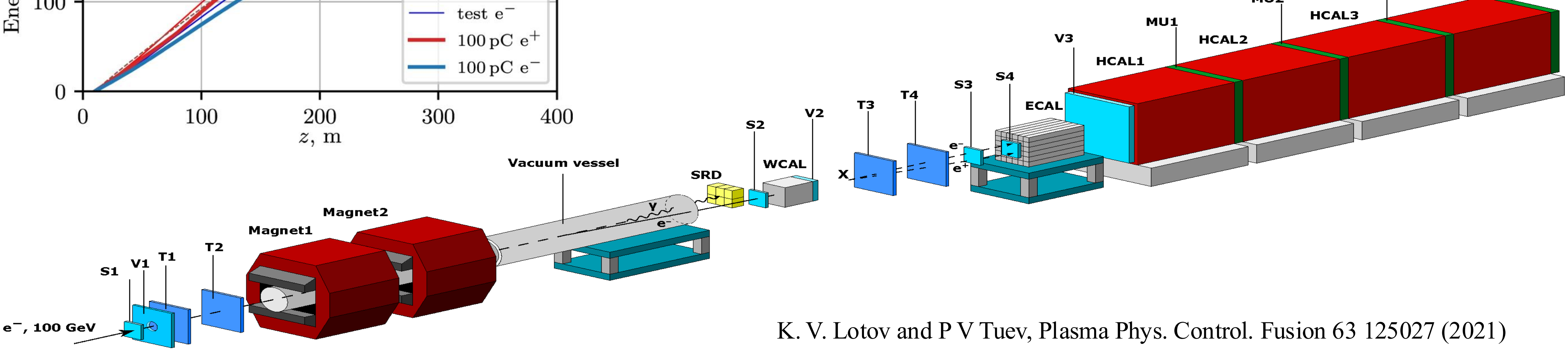
Ion motion on SMI
Hosing instability with different gas species
Plasma light diagnostics

M. Turner, Experimental Observation of the Motion of Ions in a Resonantly Driven Plasma Wakefield Accelerator, Phys. Rev. Lett. **134**, 155001 (2025)

Future applications (~2034)

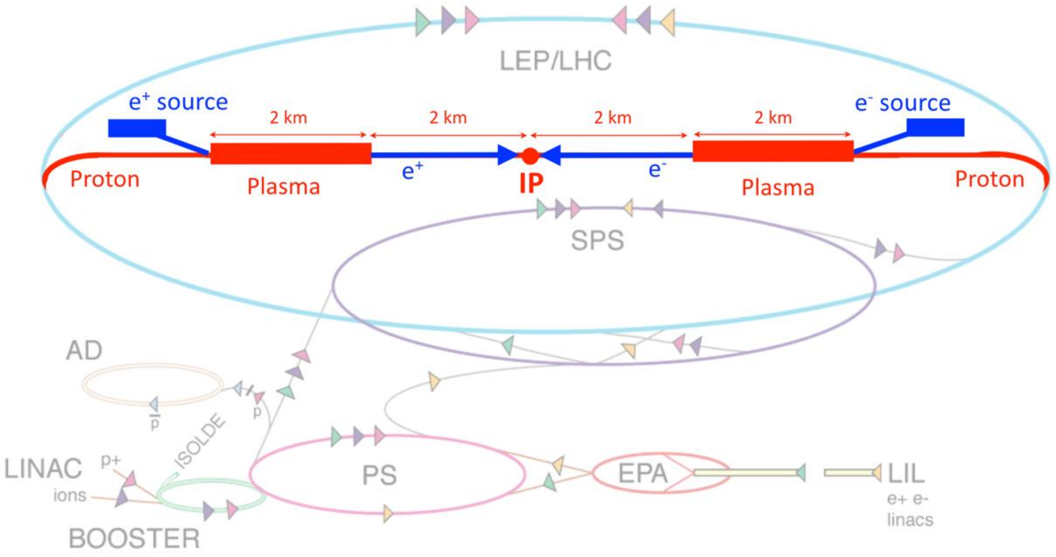
- A long and modular plasma cell to boost e- energy up to 50-100 GeV
- A fixed-target experiment at CERN (50-100 GeV electron), similar to NA64-dark side of the universe and looking for new bosons!



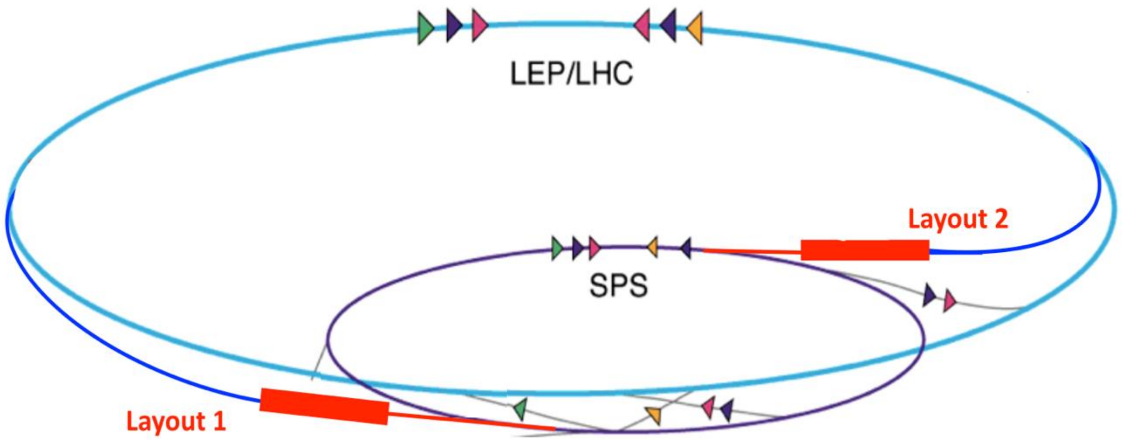


K. V. Lotov and P V Tuev, Plasma Phys. Control. Fusion 63 125027 (2021)

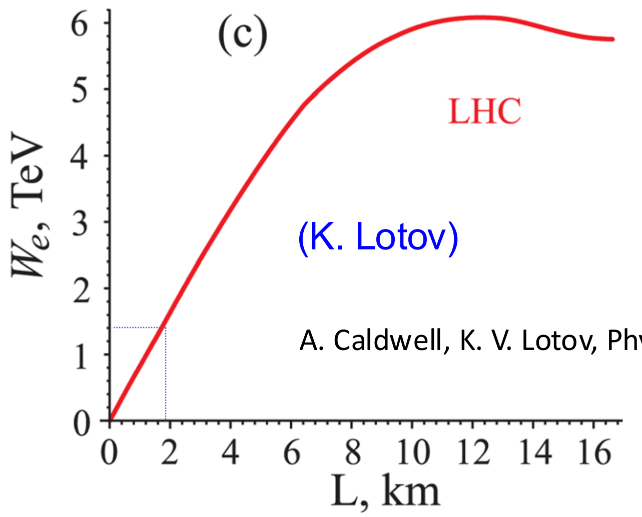
Far future: e^+e^- and e-p colliders



An e+ e- collider



An e-p collider



A. Caldwell, K. V. Lotov, Phys. Plasmas 18, 103101 (2011)

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ELSEVIER

Collider design issues based on proton-driven plasma wakefield acceleration

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[b] The Cockcroft Institute, Sci-Tech Daresbury, Daresbury, Warrington, United Kingdom
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PDPWA
Colliders
Self-modulation instability
Dephasing

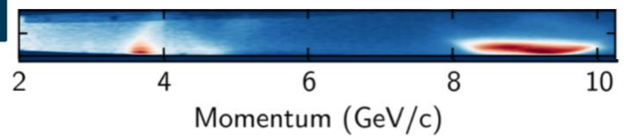
ABSTRACT

Recent simulations have shown that a high-energy proton bunch can excite strong plasma wakefields and accelerate a bunch of electrons to the energy frontier in a single stage of acceleration. It therefore paves the way towards a compact future collider design using the proton beams from existing high-energy proton machines, e.g. Tevatron or the LHC. This paper addresses some key issues in designing a compact electron–positron linear collider and an electron–proton collider based on the existing CERN accelerator infrastructure.

Recent progress in experiments

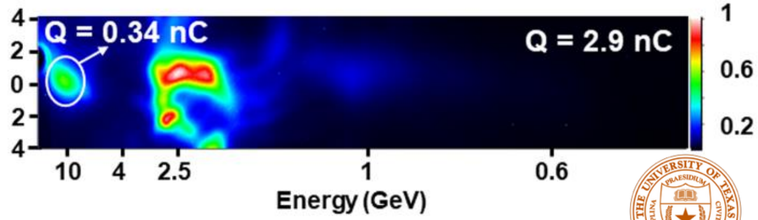
Energy

Matched Guiding and Controlled Injection in Dark-Current-Free, 10-GeV-Class, Channel-Guided Laser-Plasma Accelerators
A. Picksley et al., Phys. Rev. Lett. 133, 255001 (2024)



→ **~9.2 GeV** energy gain over 30 cm
→ Laser-created 'free-standing' plasma channels that can be recreated at t
repetition rate of the laser
→ Multiple independent results

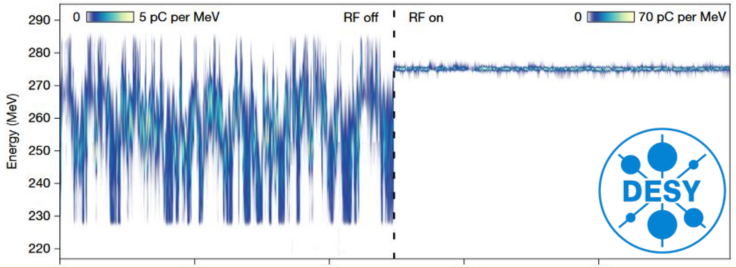
C. Aniculaesei et al., The acceleration of a high-charge el
GeV in a 10-cm nanoparticle-assisted wakefield accelerator. *Matter Radiat. Extremes* 2024; 9 (1): 014001



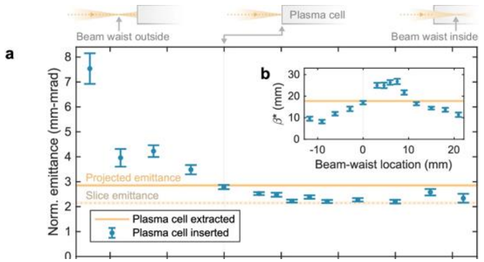
→ **~10 GeV** energy gain over 10 cm
→ Multiple acceleration regimes that may be difficult to control

Beam Quality

Winkler, P. *et al.* Active energy compression of a laser-plasma electron beam. *Nature* **640**, 907–910 (2025).



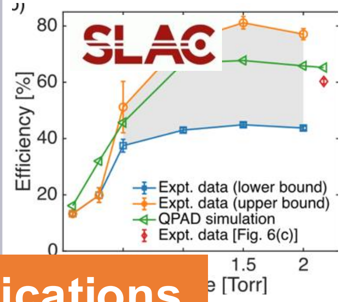
preservation in a plasma-wakefield accelerator. *Nat Commun* **15**, 6097 (2024)



→ **Emittance preservation** at micron level for 40 MeV energy gain (on top of 1 GeV)

Efficiency

C Zhang *et al* 2024 *Plasma Phys. Control. Fusion* 66 025013



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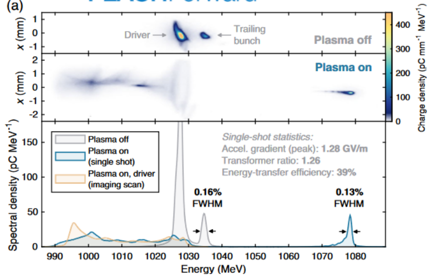
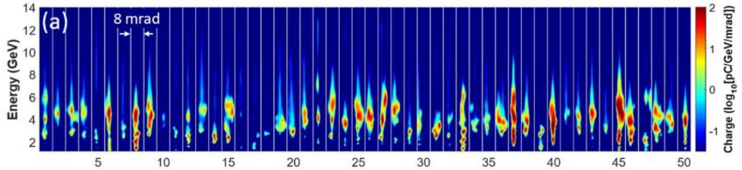
C. A. Lindstrøm et al., Phys. Rev. Lett. **126**, 014801 (2021)



→ **42%** local energy transfer efficiency

., High charge laser acceleration of electrons to 10 GeV
NIM A, Volume 1077, August 2025, 170586



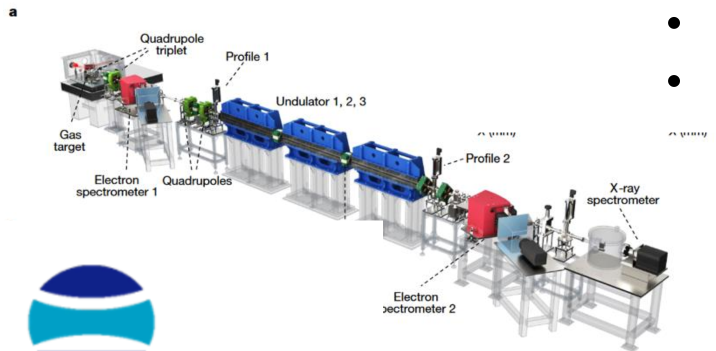
→ Laser to electron conversion efficiency of at least **~30%**
→ Multi-GeV energy gain

- → **Towards delivering beams for first applications**
- **Application will be used to mature wakefield acceleration technology**

(Courtesy to M. Turner)

FEL lasing achieved by four groups

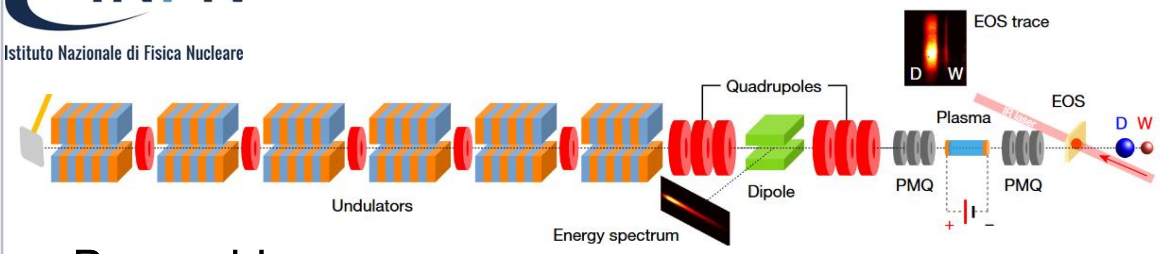
→ Enabled by Improved Beam-Quality and Stability



- Lasing at 27 nm
- 490 MeV, ~0.5% energy spread, 30 pC

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

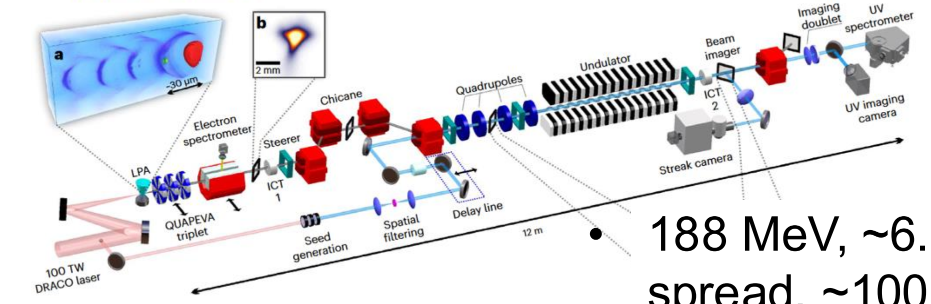
Pompili, R., *et al.* Free-electron lasing with compact beam-driven plasma wakefield accelerator. *Nature* **605**, 659–662 (2022).



- Beam-driven
- 5.8 MeV energy gain, 0.3% energy spread, 20 pC

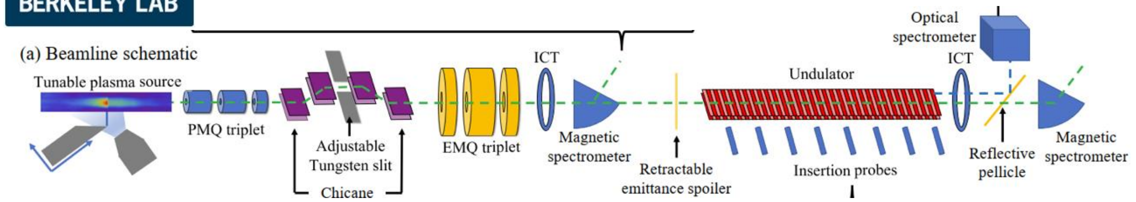
Labat, M., *et al.* Seeded free-electron laser driven by a compact laser plasma accelerator. *Nat. Photon.* **17**, 150–156 (2023).

- Seeded free-electron laser



- 188 MeV, ~6.3% energy spread, ~100 pC

S. K. Barber et al., Greater than 1000-fold gain in a free-electron laser driven by a laser plasma accelerator with high reliability, under review



- SASE gain >1000, some gain on >90% events
- ~100 MeV, 2% energy spread, ~90 pC

(Courtesy to M. Turner)

Progress towards first applications

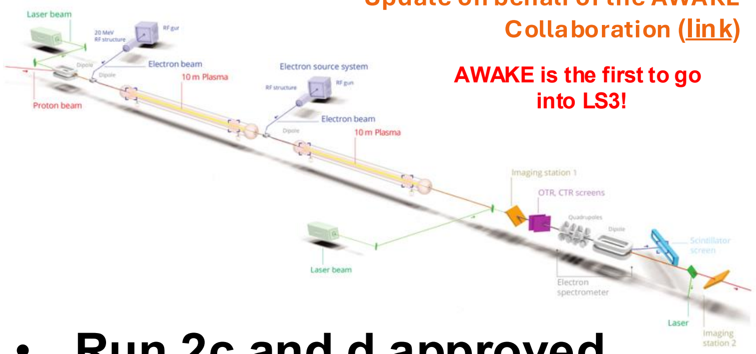
Particle accelerator research infrastructure based on novel plasma acceleration

- **High repetition rate plasma sources**
- Technology R&D and critical experimental facilities
- LPA demonstrator stages (low average power, near collider emittances)
- PWFA staging (including low-energy design at EuPRAXIA@SPARC_LAB)
- Positron beam test capabilities

FEL user facility starting in 2029

Proton-driven plasma wakefield experiment at CERN

ESPP Input #172: AWAKE - Input to the European Strategy for Particle Physics Update on behalf of the AWAKE Collaboration (link)

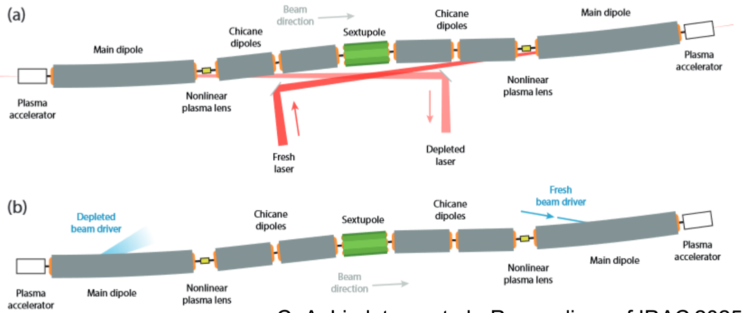


AWAKE is the first to go into LS3!

- **Run 2c and d approved**
- Separate Self-Modulation from acceleration to accelerate bunches with quality at few GeV energies
- Experiments starting in 2029

First applications after LS4

Toward a demonstrator facility for multistage plasma acceleration



C. A. Lindstrøm et al., Proceedings of IPAC 2025

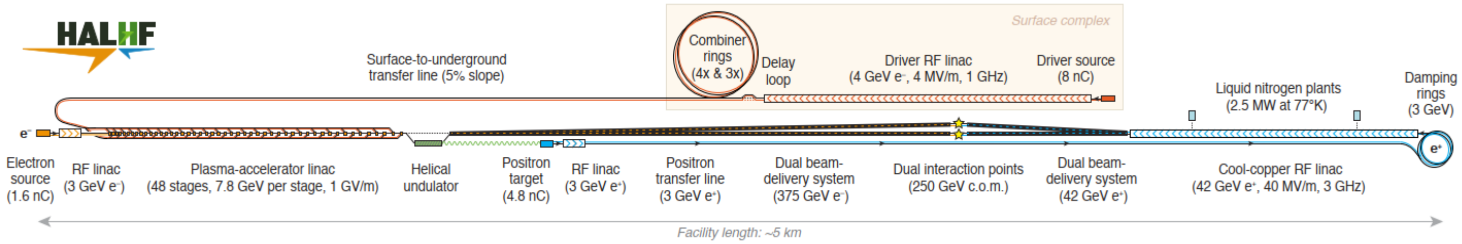
Developing:

- nonlinear plasma lenses
- self-correction mechanisms

→ *multistage demonstrator facility e.g., with 50 GeV for strong-field QED, to be implemented in a major accelerator lab.*

(Courtesy to M. Turner)

Application-colliders (ESPP26)



Foster et al., Phys. Open 23, 100261 (2025)

HALHF - **H**ybrid, **A**symmetric, **L**inear **H**iggs **F**actory

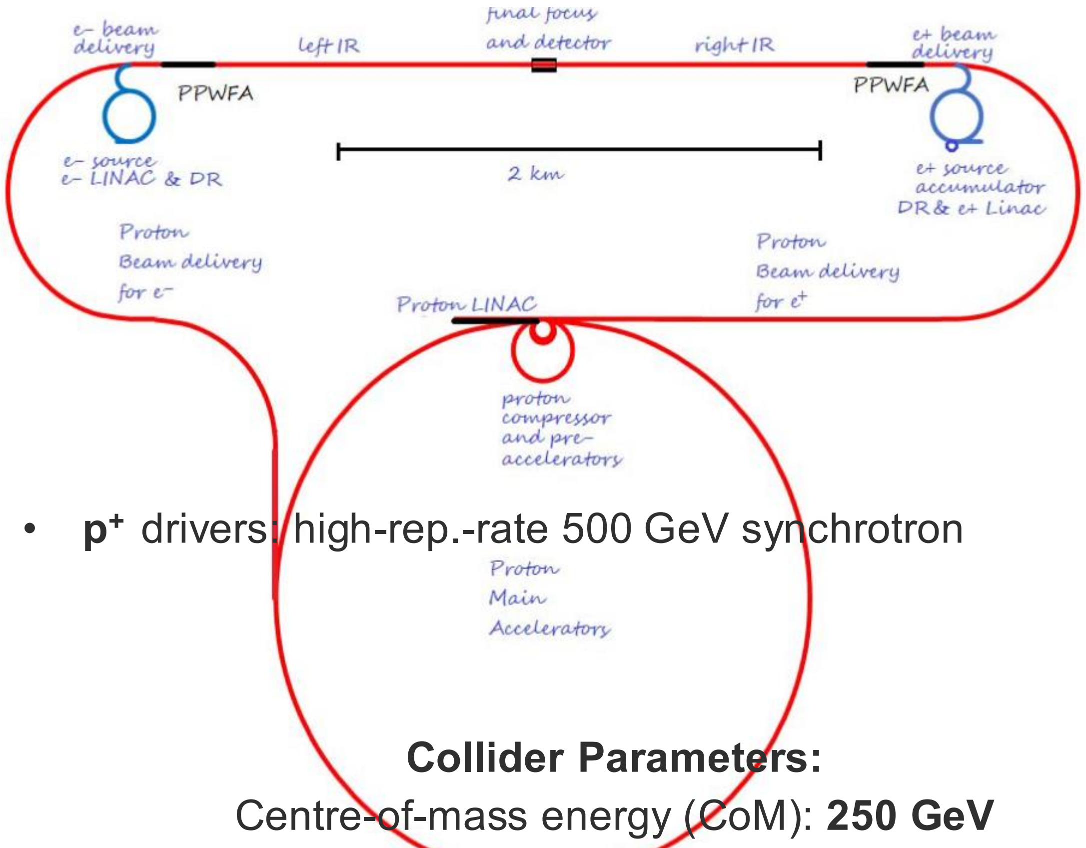
- Asymmetric collisions: **375 GeV polarized e$^-$** with **41.7 GeV polarized e$^+$** (boost: γ=1.67), Center-of-mass energy **250 GeV → upgrades 380, 550 GeV** center-of-mass energy discussed

Estimated luminosity: **1.2x10^{34} cm^{-2}s^{-1} → two IPs**
Estimated total power usage: **106 MW**
Estimated cost: **3.8 BCHF** (2024 Swiss francs)

A Linear accelerator for **V**ery high **E**nergies

ALiVE

Preliminary investigation of a Higgs factory based on proton-driven plasma wakefield acceleration
J. Farmer et al., 2024 New J. Phys. 26 113011



- **p$^+$** drivers: high-rep.-rate 500 GeV synchrotron

Collider Parameters:
Centre-of-mass energy (CoM): **250 GeV**
Estimated luminosity: **1.7x10^{34} cm^{-2}s^{-1}**
Footprint: **~4 x 2 km.**

Conclusion

- After four decades' development, LWFA and PWFA have achieved tremendous progress
- The technology will be ready for many applications in next 5-10 years
- Electron driven PWFA has demonstrated high efficiency acceleration
- AWAKE Run 1 has demonstrated 2 GeV electron acceleration in a 10 m long plasma cell
- The current AWAKE Run 2 aims for achieving high quality electron beam from scalable plasma cells
- HALHF and ALiVE as key contributions to ESPP26 update

Thank you very much !