AWAKE and Future Colliders

Edda Gschwendtner, CERN, Geneva, Switzerland
For the AWAKE Collaboration

6th European Advanced Accelerator Concepts Workshop,
La Biodola, Elba, Italy, September 17 – 23, 2022

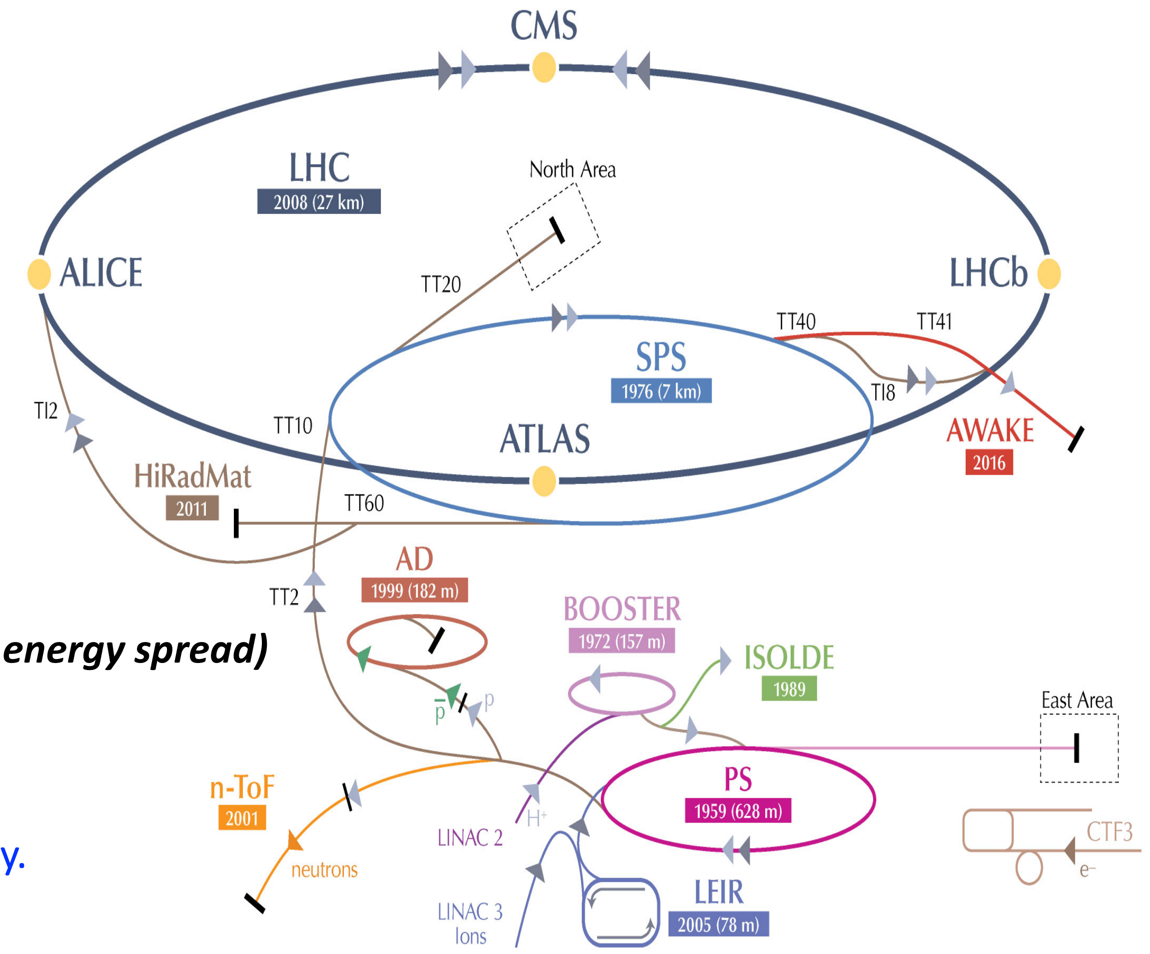
With input from Matthew Wing, UCL

AWAKE at CERN

➔AWAKE is an international Collaboration, consisting of 23 institutes.

➔Developed a clear scientific roadmap towards first particle physics applications within the next decade.

➔In AWAKE many general issues are studied, which are relevant for concepts that are based on plasma wakefield acceleration.



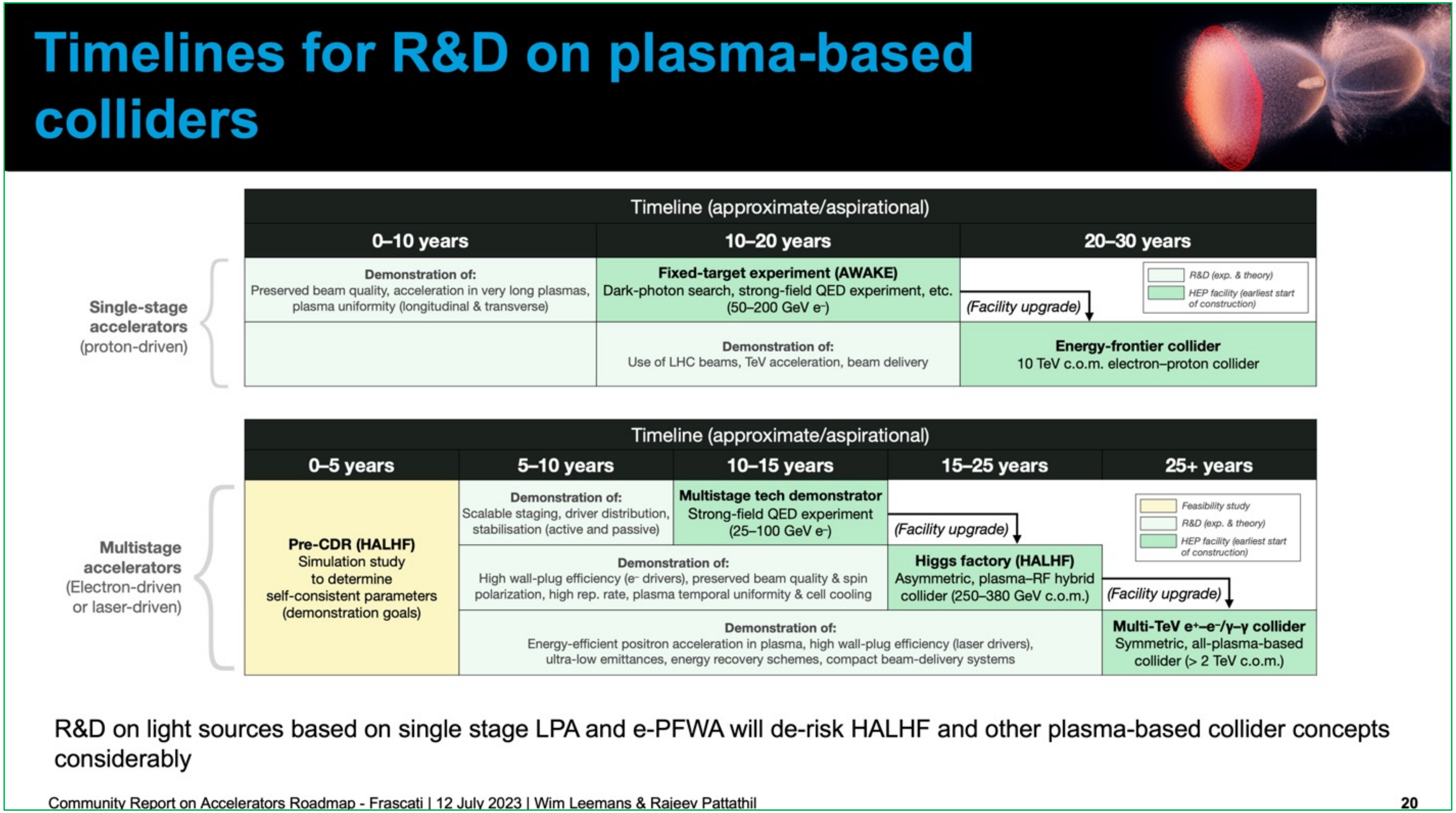
AWAKE Run 2 (2021 – ~2029) Goals:

- Accelerate an ***electron beam to high energies (gradient of 0.5-1GV/m)***
- while controlling the ***electron beam quality (1-10 mm-mrad emittance, 10% energy spread)***
- demonstrate ***scalable plasma source technology.***

Once AWAKE Run 2 demonstrated: First application of the AWAKE-like technology.

➔ *develop physics case for particle physics experiments*

AWAKE in the Global ESPP



Timelines for R&D on plasma-based colliders

	Timeline (approximate/aspirational)		
	0–10 years	10–20 years	20–30 years
Single-stage accelerators (proton-driven)	**Demonstration of:** Preserved beam quality, acceleration in very long plasmas, plasma uniformity (longitudinal & transverse)	**Fixed-target experiment (AWAKE)** Dark-photon search, strong-field QED experiment, etc. (50–200 GeV e^-)	*(Facility upgrade)*
		Demonstration of: Use of LHC beams, TeV acceleration, beam delivery	**Energy-frontier collider** 10 TeV c.o.m. electron–proton collider

▭ *R&D (exp. & theory)*
🟩 *HEP facility (earliest start of construction)*

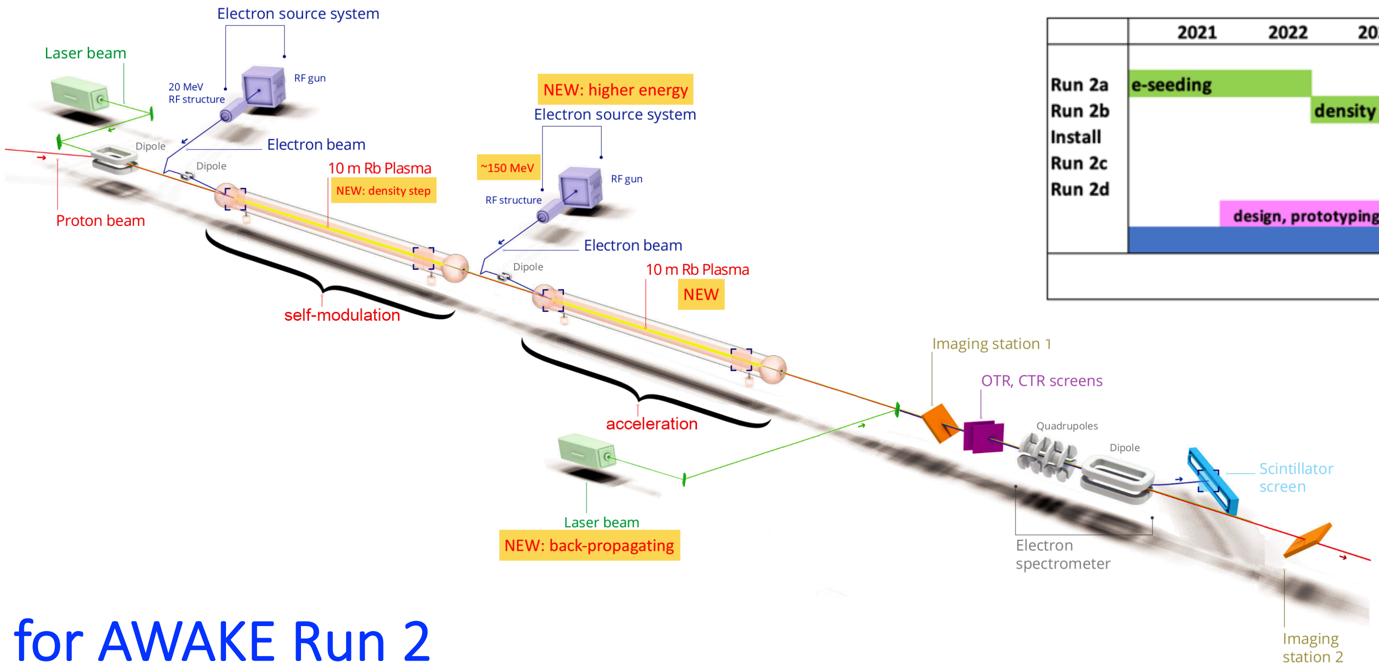
	Timeline (approximate/aspirational)				
	0–5 years	5–10 years	10–15 years	15–25 years	25+ years
Multistage accelerators (Electron-driven or laser-driven)	**Pre-CDR (HALHF)** Simulation study to determine self-consistent parameters (demonstration goals)	**Demonstration of:** Scalable staging, driver distribution, stabilisation (active and passive)	**Multistage tech demonstrator** Strong-field QED experiment (25–100 GeV e^-)	*(Facility upgrade)*	
		Demonstration of: High wall-plug efficiency (e^- drivers), preserved beam quality & spin polarization, high rep. rate, plasma temporal uniformity & cell cooling		**Higgs factory (HALHF)** Asymmetric, plasma–RF hybrid collider (250–380 GeV c.o.m.)	*(Facility upgrade)*
		Demonstration of: Energy-efficient positron acceleration in plasma, high wall-plug efficiency (laser drivers), ultra-low emittances, energy recovery schemes, compact beam-delivery systems			**Multi-TeV e^+–e^-/γ–γ collider** Symmetric, all-plasma-based collider (> 2 TeV c.o.m.)

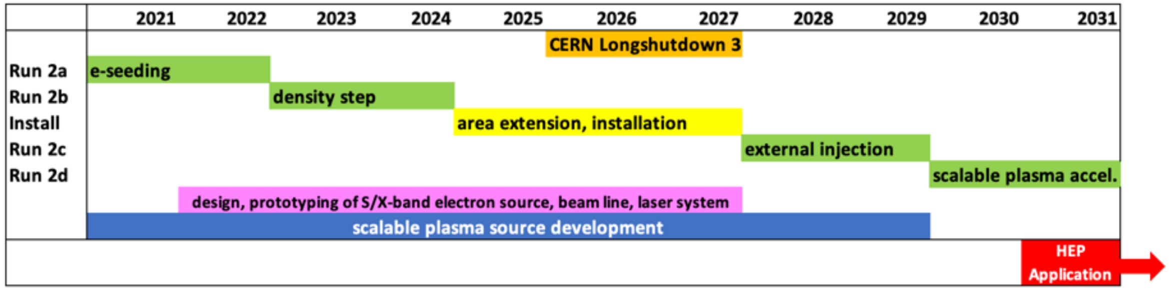
🟨 *Feasibility study*
▭ *R&D (exp. & theory)*
🟩 *HEP facility (earliest start of construction)*

R&D on light sources based on single stage LPA and e-PFWA will de-risk HALHF and other plasma-based collider concepts considerably

Community Report on Accelerators Roadmap - Frascati | 12 July 2023 | Wim Leemans & Rajeev Pattathil 20

AWAKE Run 2 Scientific Roadmap – Milestones



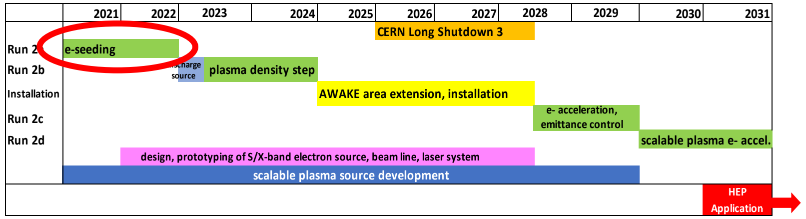


Milestones for AWAKE Run 2

- Run 2a (2021-2022): demonstrate the ***seeding of the self-modulation of the entire proton bunch with an electron bunch***
- Run 2b (2023-2024): ***maintain large wakefield amplitudes*** over long plasma distances by introducing a step in the plasma density → on-going
- *CERN Long Shutdown LS3 (2025-2027): CNGS dismantling, installation of Run 2c*
- Run 2c (2028-2029): demonstrate ***electron acceleration and emittance control of externally injected electrons***.
- Run 2d (2021-): ***development of scalable plasma sources to 100s meters length with sub-% level plasma density uniformity.***

➔ Propose first applications for particle physics experiments with 50-200 GeV electron bunches!

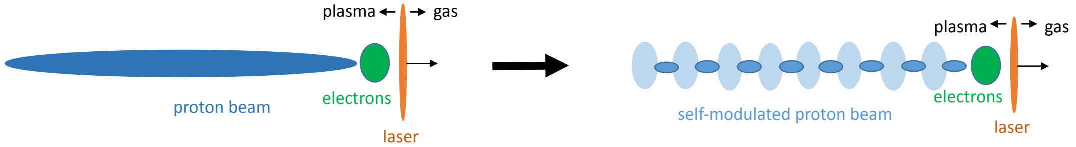
Results AWAKE Run 2a (2021-22)

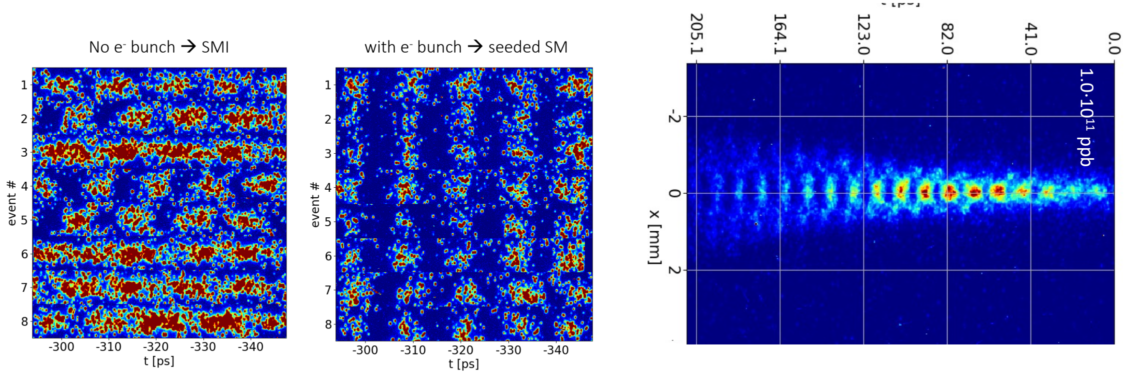


➔ Electron seeding

➔ Demonstrate electron seeding of self-modulation in first plasma cell with phase reproducibility.

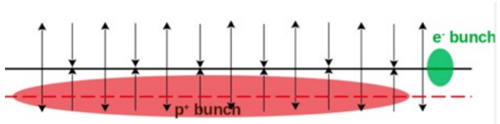
AWAKE Run 2: the entire proton bunch to be modulated before the 2nd cell

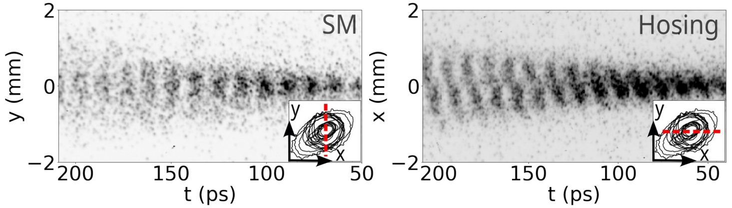




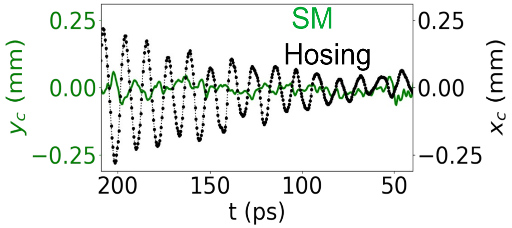
L. Verra et al. (AWAKE Collaboration), Phys. Rev. Lett. 129, 024802 (2022)

➔ Hosing instability





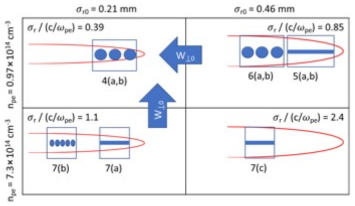
oscillation of the proton bunch centroid position

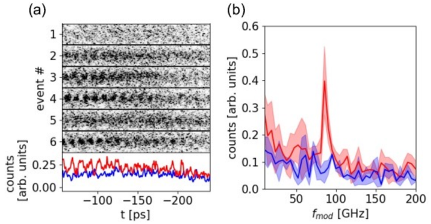


T. Nechaeva, MPP et al. (AWAKE Collaboration), https://arxiv.org/abs/2309.03785

➔ SMI development

Wide p bunch, later time range.

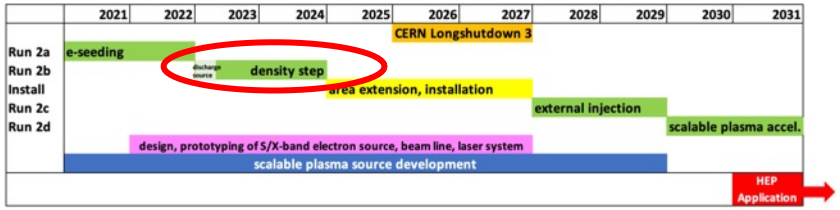


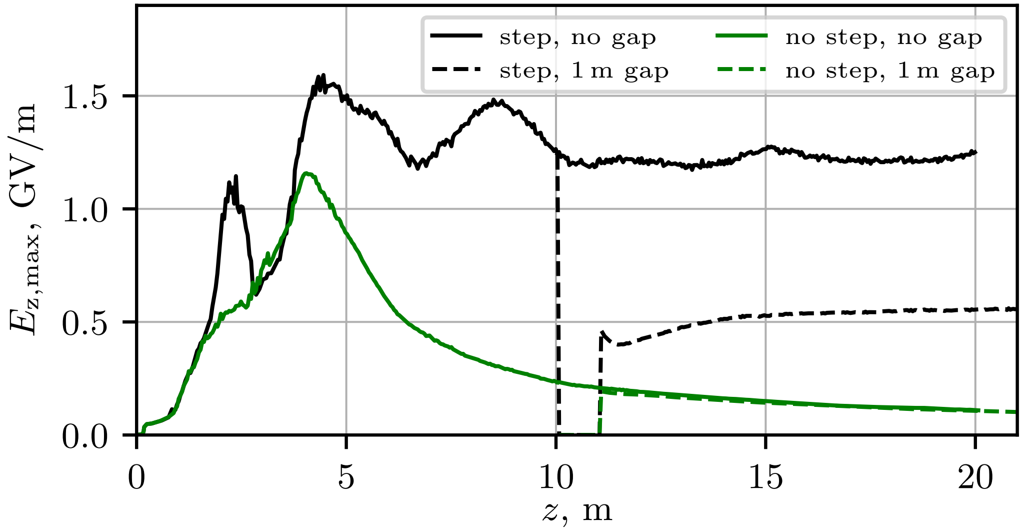


L. Verra, S. Wyler et al. (AWAKE Collaboration), Physics of Plasma 30, 083104 (2023)

AWAKE Run 2b (2023/24)

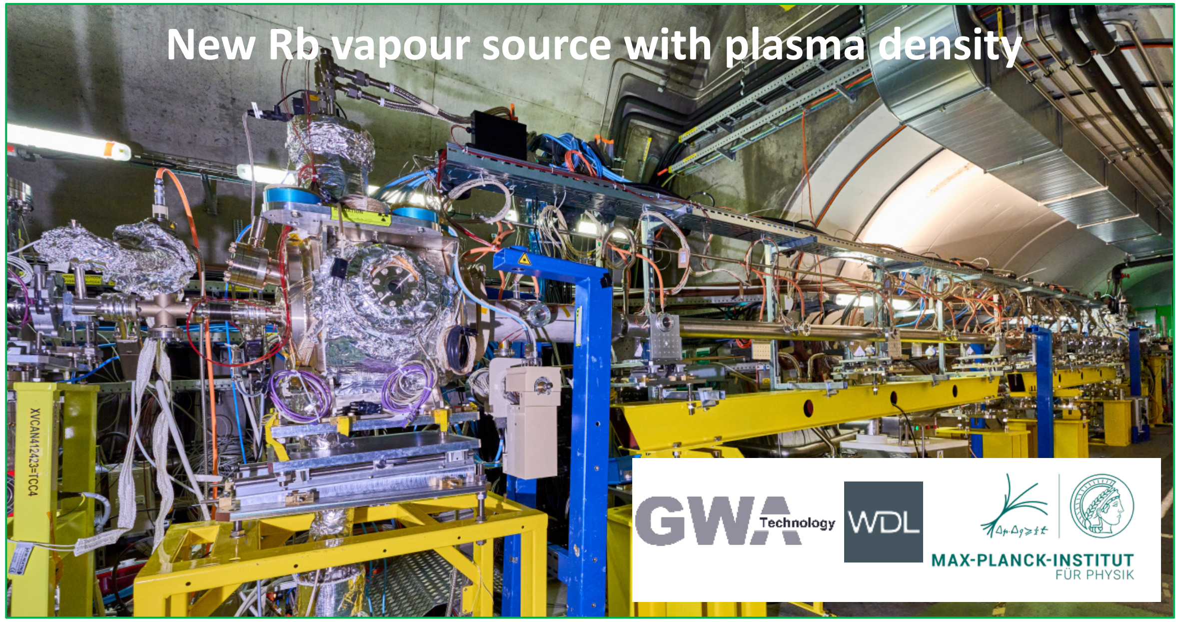
➔ Demonstrate stabilisation of micro-bunches with a density step in the plasma



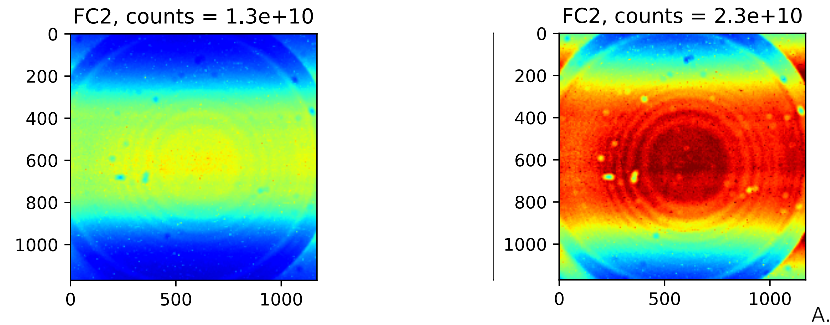


E. Gschwendtner, K. Lotov, P. Muggli, M.. Wing et al. (AWAKE Collaboration), Symmetry **2022**,*14*,1680.

- → In constant-density plasma, wakefield amplitude decreases after saturation.
- → In a plasma with density step during SM growth: wakefield amplitude **maintains larger** after saturation.



Promising preliminary results



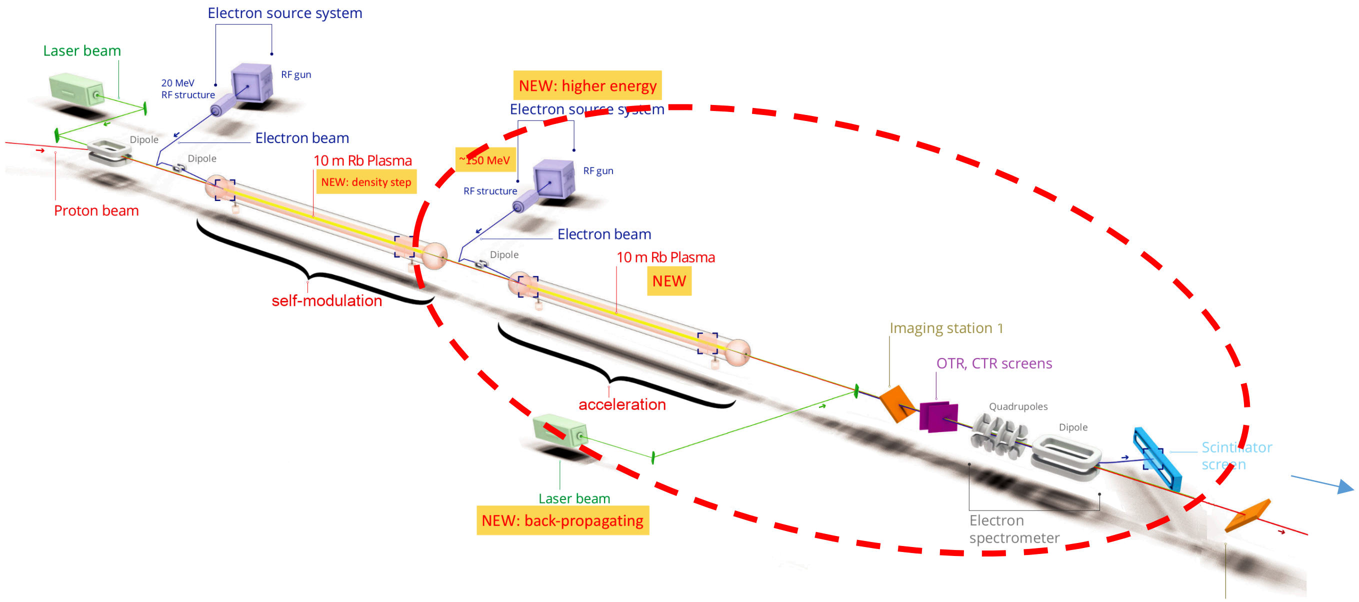
A. Clairembaud, CERN

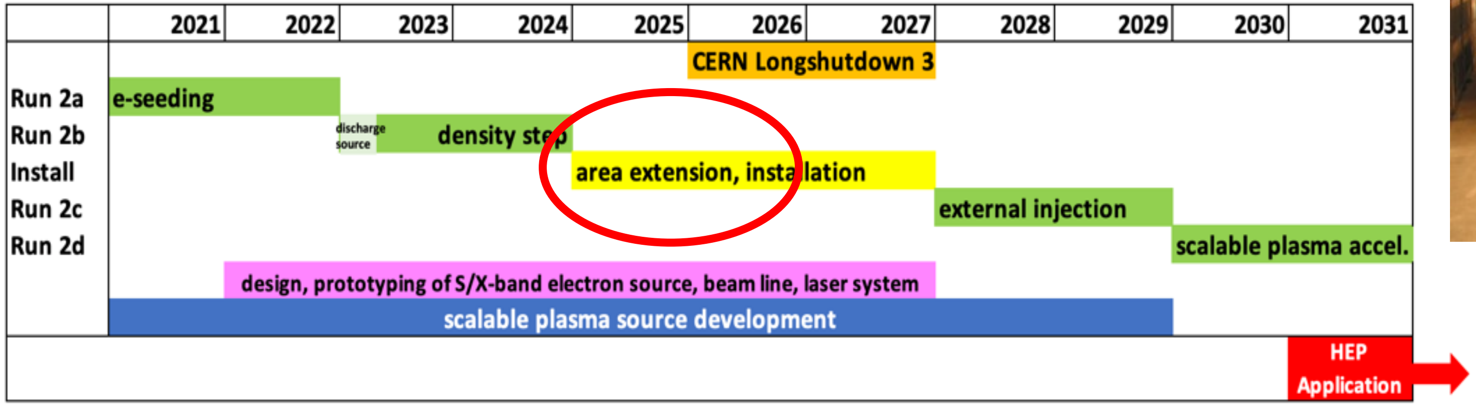
No density step

1.5% density step

➔ See E. G., Tue Plenary Talk

Preparing for AWAKE Run 2c, 2d → CNGS Dismantling





	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
						CERN Longshutdown 3					
Run 2a	e-seeding										
Run 2b			discharge source density step								
Install					area extension, installation						
Run 2c								external injection			
Run 2d										scalable plasma accel.	
		design, prototyping of S/X-band electron source, beam line, laser system									
	scalable plasma source development										
											HEP Application

Area content (~600m^3):

- ~500 large shielding blocks (0,05-0,6 mSv/h)
- A few **high dose-rate elements** (2-20mSv/h)
- 70-meter-long aluminum **He-tank**
- **Various** supports, ducts…

CNGS Dismantling: Q2024 – mid 2026)

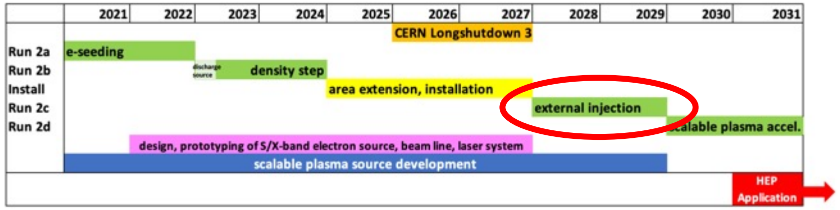
AWAKE Run 2c – Accelerating Electrons

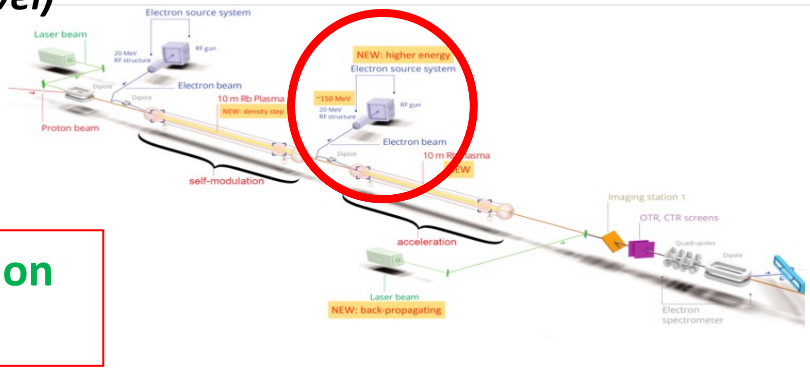
➔ External injection of witness electron

Control electron beam quality (emittance control at 10 mm mrad level)

Electron parameters must be suitable to reach full blow-out regime (ensure linear focusing), load the wakefields (→ small ∂E/E), Match to focusing force of the plasma ion column

➔ Studies/Prototyping ongoing to be ready for installation in 2026/27 to be ready for proton run in 2028



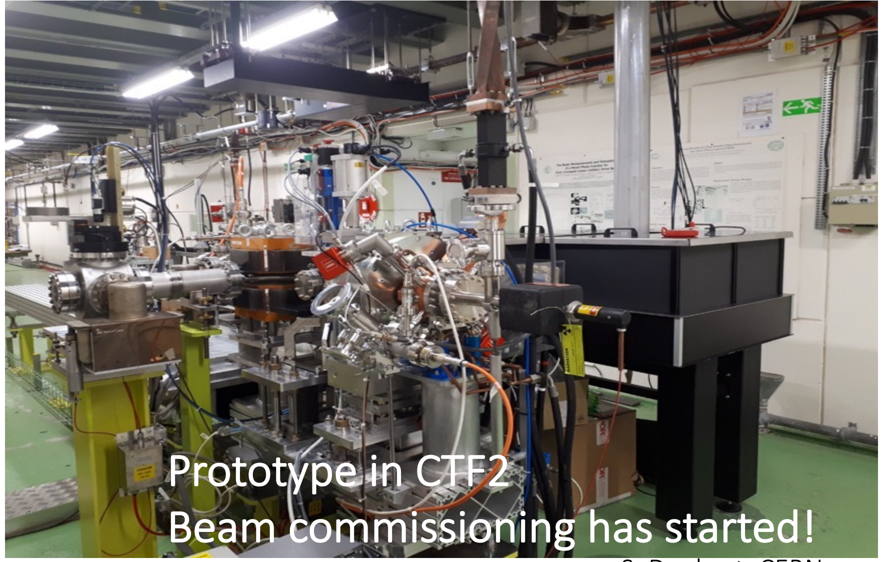


At injection point

Parameter	Nominal value
Dispersion	0
$\sigma_{x,y}$	5.75 µm
Bunch length	200 fs/60 µm
Electron energy	150 MeV
$\epsilon_{x,y}$	<2 mm mrad
Mom. spread	<0.2%
Charge	100 pC

New electron-source:

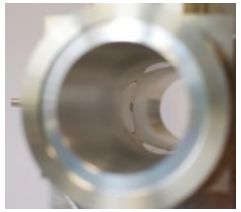
→ S-band e-gun with X-band accelerator, Prototyping with CLIC/CLEAR



Prototype in CTF2
Beam commissioning has started!

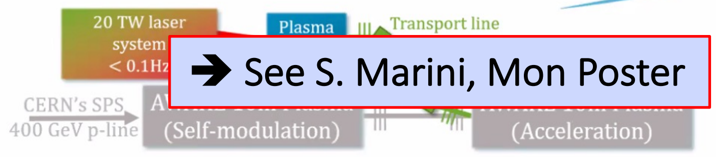
S. Doebert, CERN

Beam Instrumentation



BPMs 10 µm resolution

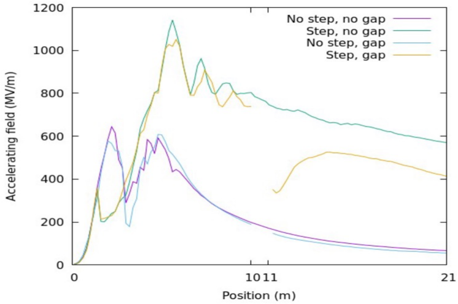
Alternative e-source studies based on LWFA



➔ See S. Marini, Mon Poster

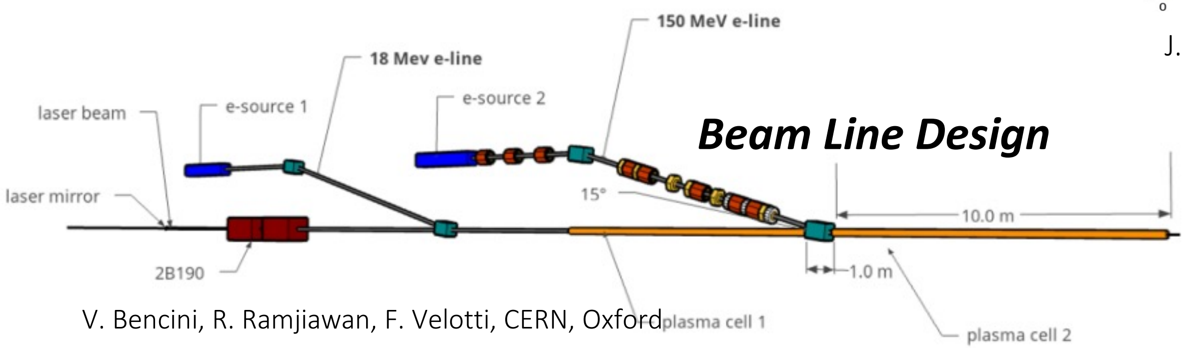
CEA, CNRS, Thales, MPP, CERN

Simulations



J. Farmer, MPP

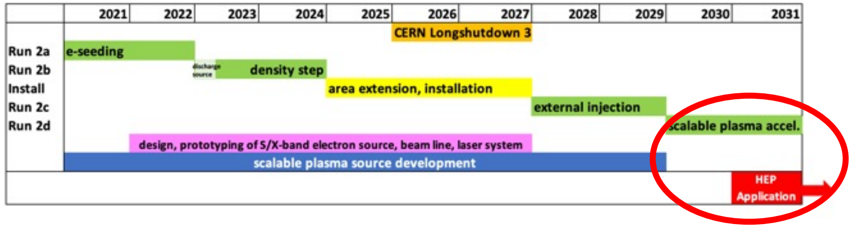
Beam Line Design

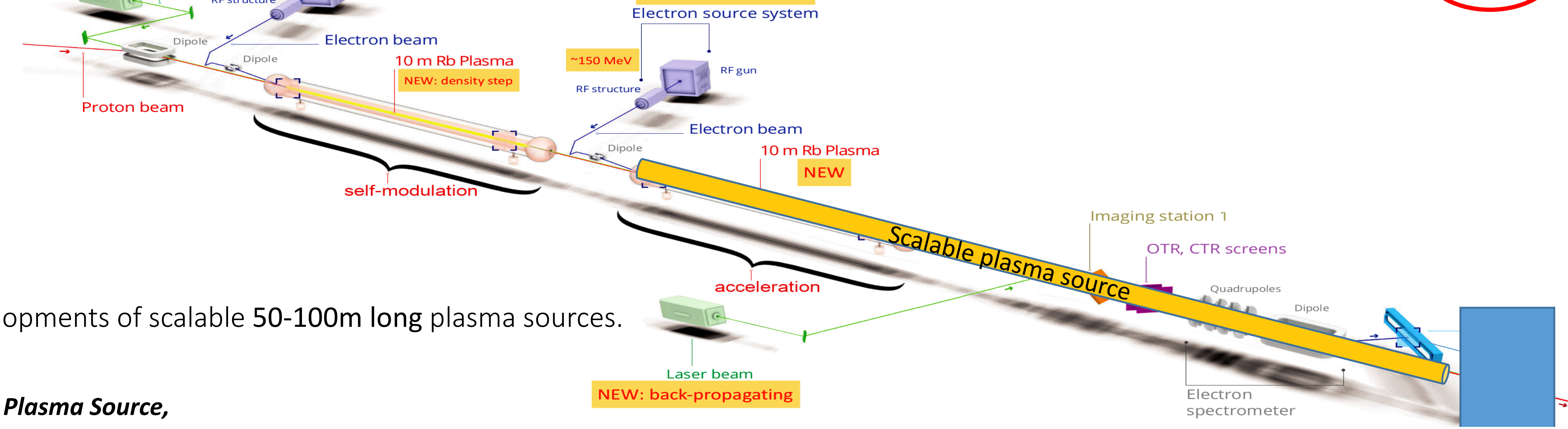


V. Bencini, R. Ramjiawan, F. Velotti, CERN, Oxford

AWAKE Run 2d: Towards first Particle Physics Experiments

➔ R&D of scalable plasma source

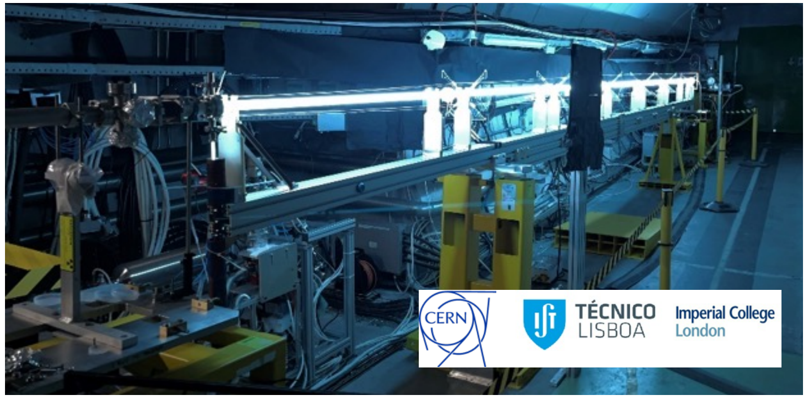




Laboratory developments of scalable **50-100m long** plasma sources.

Particle physics experiment

10m Discharge Plasma Source, Tested in the AWAKE experiment in May 2023!



1m Helicon Plasma Source

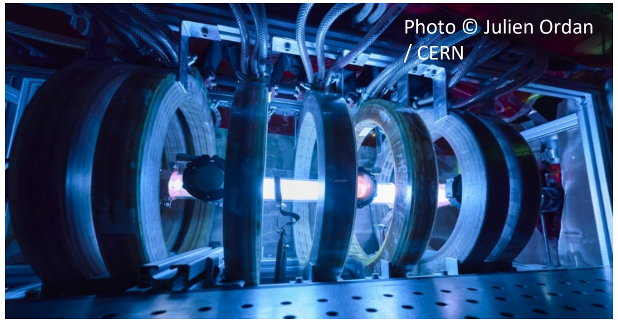


Photo © Julien Ordan / CERN

CERN, SPC-EPFL, IPP Greifswald, U. Wisconsin

Electron Beam Parameters for Applications

Latest Results show that we can increase the energy up to 200 GeV, 10^9 electrons, ~1% energy resolution after ~300 m.

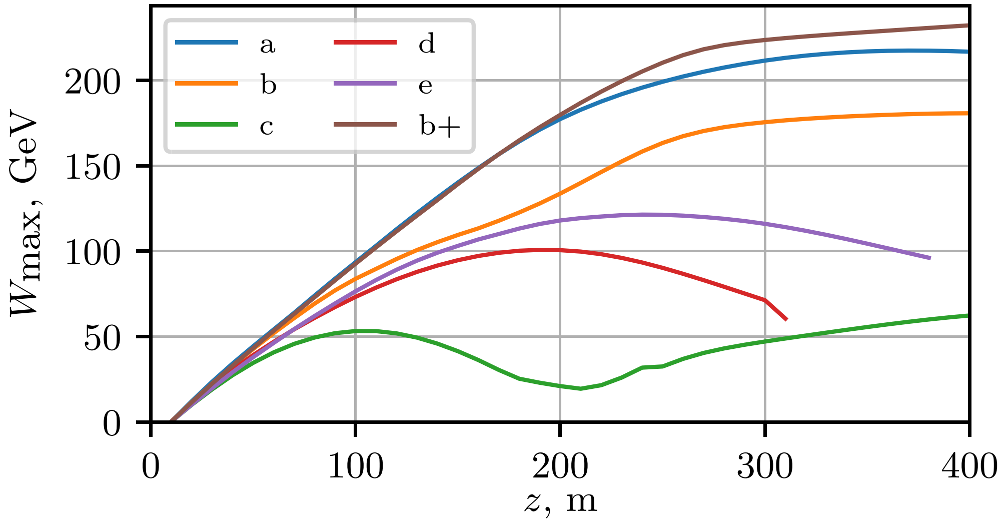


Figure 7. The estimated maximum witness energy $W_{\max}(z)$ for the considered variants.

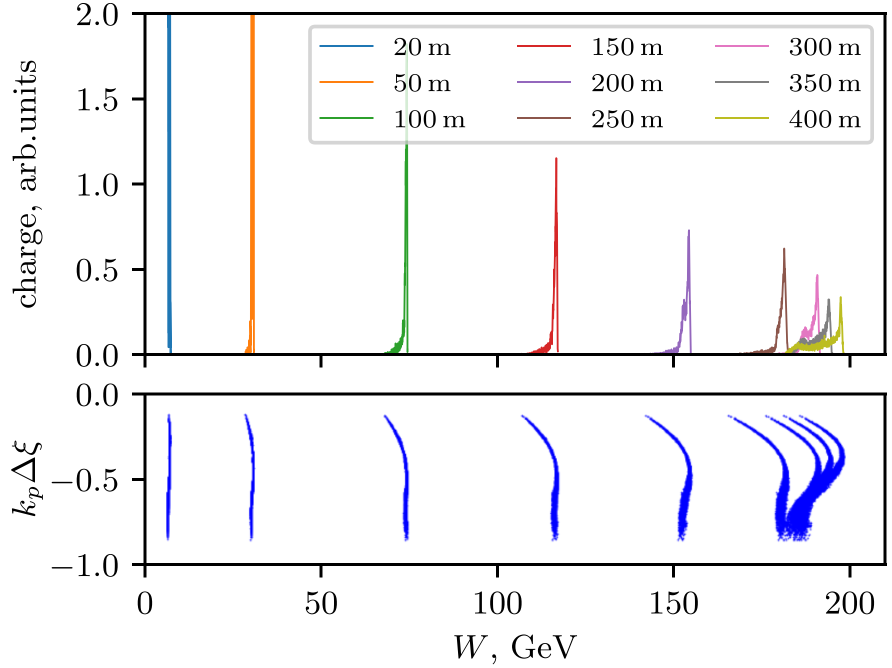
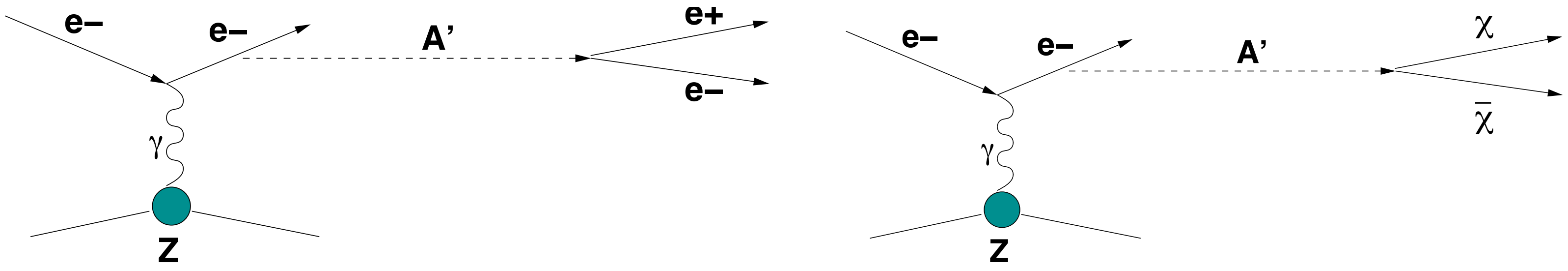


Figure 9. (Top) The energy spectra of the 100 pC electron bunch at different propagation distances; (bottom) the corresponding longitudinal phase portraits of the bunch.

K. V. Lotov and P. V. Tuev 2021 PPCF ***63 125027***

Search for Dark Photons using an AWAKE-Like Beam

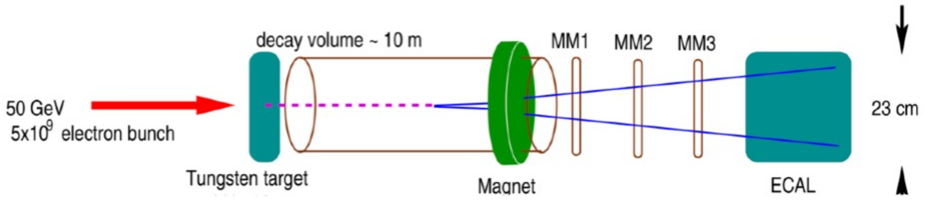
NA64@CERN are currently investigating the dark sector using high energy electrons.
An AWAKE-like beam accelerates electrons directly and should have higher intensity than SPS secondary beam.



Physics motivation

- Dark sectors with light, weakly-coupling particles are a compelling possibility for new physics.
- A light vector boson, the “dark photon”, A', results from a spontaneously broken new gauge symmetry, $U(1)D$.
- The A' kinetically mixes with the photon and couples primarily to the electromagnetic current with strength, εe.
- Search for dark photons, A', up to *GeV* mass scale via their production in a light- shining-through-a-wall type experiment.
- Use high energy electrons for beam-dump and/or fixed-target experiments.

Limits on Dark Photons

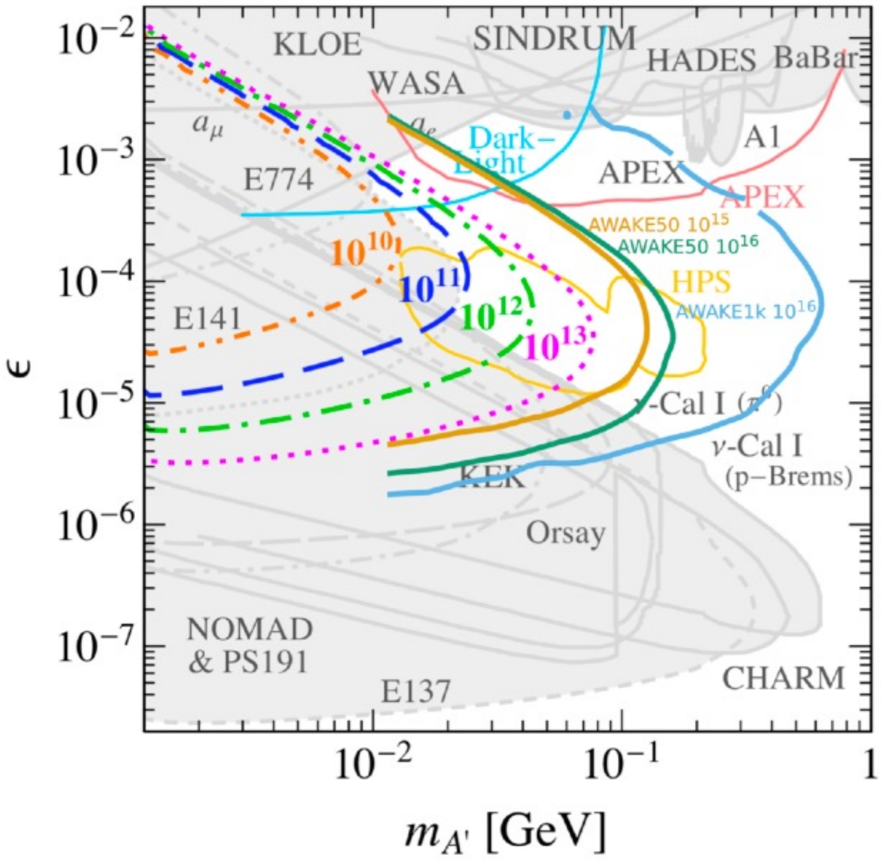


Experimental conditions modeled on NA64 experiment.

→ Decay of dark photon into visible particles (e.g. e+/e-)

→Energy and flux is important, relaxed parameters for emittance

- For *10^{10} – 10^{13}* electrons on target with NA64.
- For *10^{16}* electrons on target with AWAKE-like beam.
- Using an AWAKE-like beam would extend sensitivity further:
    - Around *$\varepsilon \sim 10^{-3} - 10^{-5}$*.
    - To high masses~*0.1 GeV*.
- A *1 TeV* beam goes to even higher masses:
    - Similar *ε* values.
    - Approaching *1 GeV*.
    - Beyond any other planned experiments.



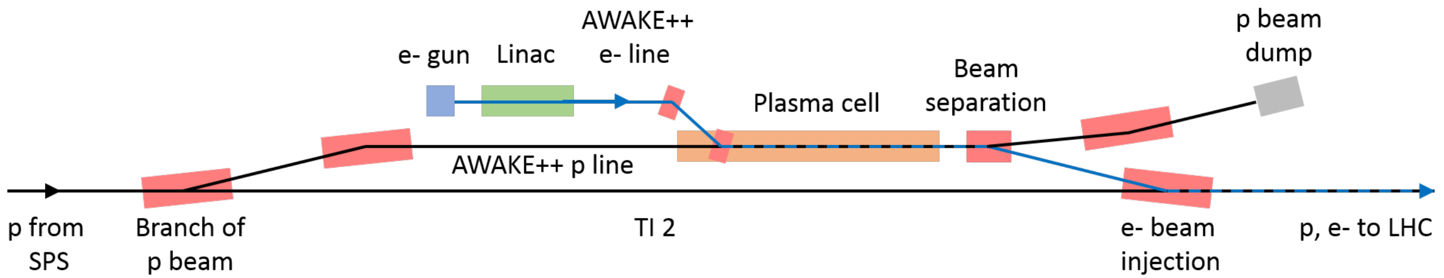
→ Extension of kinematic coverage for 50 GeV electrons and even more for 1 TeV electrons

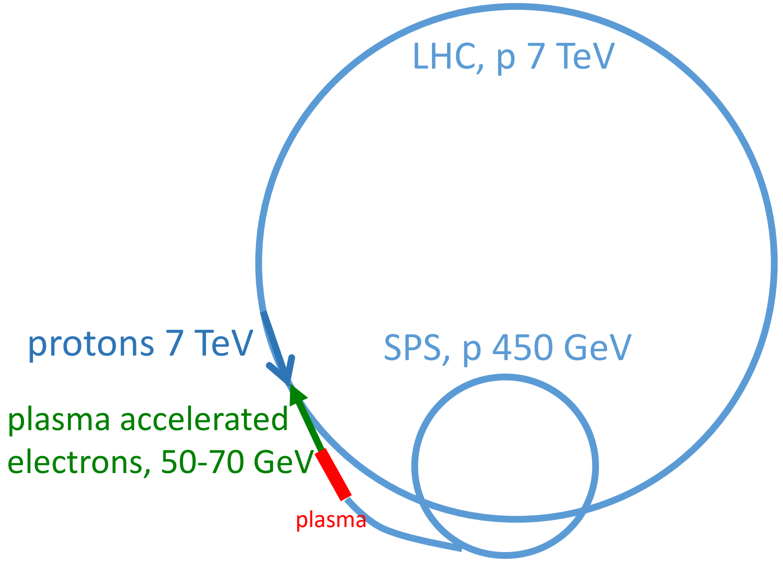
Electron-Proton and Electron-Ion Collisions

PEPIC: use the SPS to drive electron bunches to 50 GeV and collide with protons from LHC with 7 TeV, $\sqrt{s}=1.2TeV$
Can exceed HERA energies ($\sqrt{s}=300GeV$);

→ Modest luminosity (expected to be lower ~$10^{30}\ cm^{-2}s^{-1}$)→ low-lumi alternative for LHeC.

Any such experiment would have a different focus to LHeC.
Investigate physics of the strong force.
Little sensitivity to Higgs physics.





Consider design further, e.g. increasing luminosity, understanding how to build a plasma accelerator, etc. Site at CERN with minimal new infrastructure ?

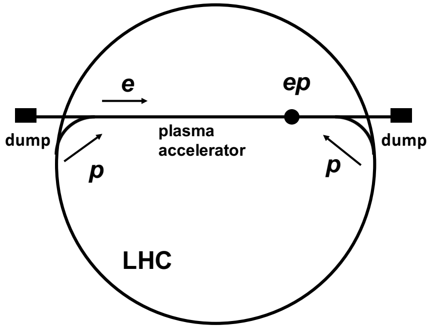
➔ See J. Farmer, G. Zevi Della Porta, Mon Poster

Very High Energy Electron-Proton Collisions, VHEeP

Use the LHC to drive electron bunches to 3 TeV and collide with protons from LHC with 7 TeV

→ Yields centre-of-mass energy of 9 TeV!

→ Reach in (high) Q^2 and (low) Bjorken x etended by ~1000 compared to HERA.



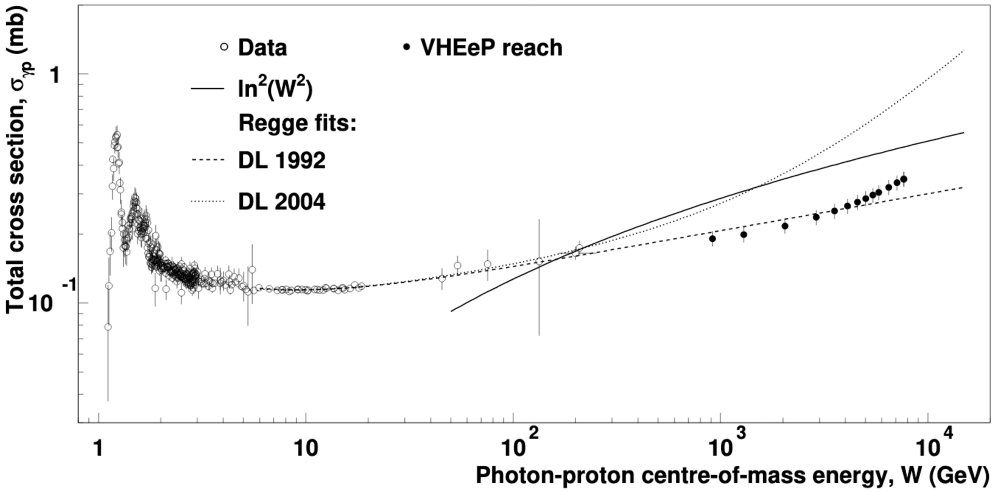
A. Caldwell and M. Wing, Eur. Phys. J. **C 76** (2016) 463

→ Luminosity is relatively modest ~$10^{28} – 10^{29}$ cm^{-2} s^{-1} , i.e. $1pb^{-1}$/yr.

→ However, physics case for very high energy.

→ → explore unchartered regions of QCD.

Energy dependence of hadronic cross-sections not understood and needs new experimental results.



→ Extends into regions of ultra-high energy cosmic rays (20PeV photons on fixed target level)!

Fixed target variants with these electron beams

Physics beyond Standard Model: e.g. search of new particles with both lepton and quark quantum numbers

Summary

- AWAKE developed a clear scientific roadmap towards first particle physics applications within the next decade.

- AWAKE Run2 addresses the requirements needed for particle physics experiments
  - Aim to sustain peak fields of up to *0.5 – 1GV/m*.
  - Control emittance during acceleration at *10 μm* level.
  - Develop scalable plasma technology.

  ➔Programme has already started and all set milestones have been achieved so far.

- Goal is to provide beams suitable for particle physics in *20 – 200 GeV* range or even *TeV* scale
  - Beam-dump or fixed-target experiments to search for dark photons or do deep inelastic scattering.
  - Investigation of strong field QED in electron–laser collisions.
  - High-energy frontier electron–proton or electron–ion collider.

AWAKE Talks and Posters in EAAC2023

Talks:

- M. Turner, Mon, 18/9, 17.45, WG1: Experimental Observation of Beam-Plasma Resonance Detuning due to Motion of Ions
- E.G., Thu 29/9, 9:00 Plenary talk: 2023 AWAKE Run Results
- L. Verra, Wed, 20/9, 17:25, WG1: Laboratory Astrophysics and Plasma Wakefield Acceleration: Experimental Study of Magnetic Field Generation by Current Filamentation Instability of a Relativistic Proton Bunch in Plasma
- A. Sublet, Wed, 20/9, 17:45, WG8: First test of a 10 m discharge plasma source with a proton beam in the AWAKE experiment
- E.G., Thu, 21/9, 17:25, WG10: AWAKE and future colliders

Posters:

- C. Amoedo: Mon 18/9, Poster: Proton Beam Self-Modulation Instability in a DC Discharge Plasma Source at AWAKE
- J. Farmer, Mon 18/9, Poster: Wakefield regeneration in a plasma accelerator
- N. Torrado, Mon 18/9, Poster: Double pulse generator for AWAKE scalable discharge plasma source
- S. Marini, Mon 18/9, Poster: Integrated beam physics for the laser wakefield accelerator project EARLI
- G. Zevi Della Porta, Tue 19/9, Poster: A tale of three beams: towards stable and reproducible operation of the AWAKE facility
- N. Z. Van Gils, Tue 19/9, Poster: External Electron Injection for the AWAKE Run 2b Experiment