Surfing the Plasma Wave: The AWAKE Experiment at CERN

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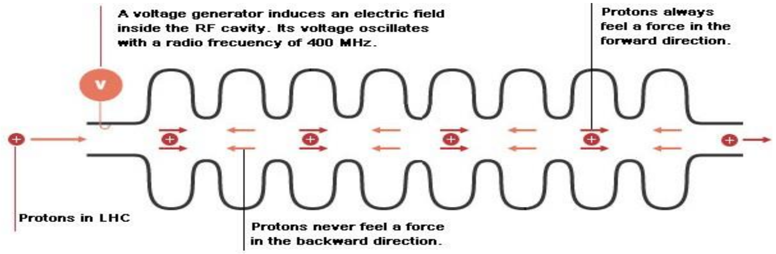
61st International Winter Meeting on Nuclear Physics,
27 – 31 January 2025, Bormio, Italy

Outline

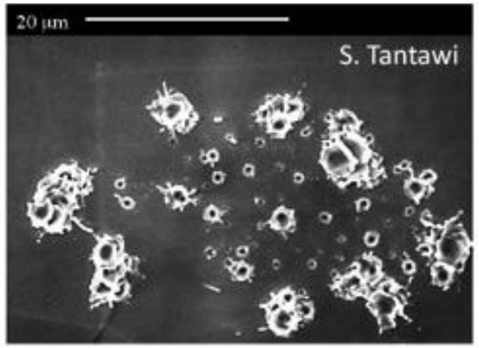
- Introduction to plasma wakefield acceleration and state-of-the-art
- AWAKE
- Examples of R&D efforts towards applications and colliders within the Particle Physics Planning Exercises

Accelerating Particles to High Energies

Conventional RF Cavities



Surface of Copper Cell After Breakdown Events



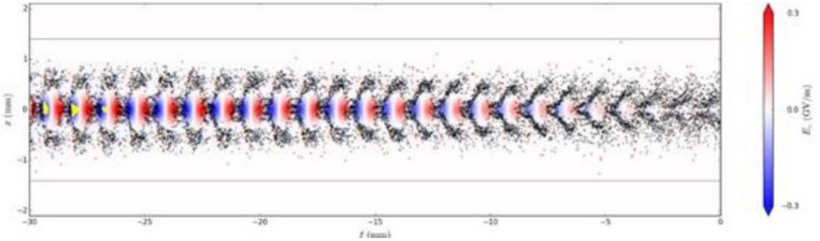
Typical gradients:

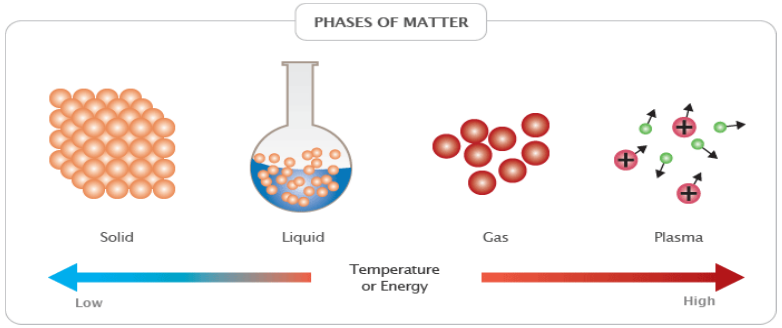
- LHC: 5 MV/m
- ILC: 35 MV/m
- CLIC: 100 MV/m

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

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.

Plasma Acceleration





Plasma is already ionized or "broken-down" and can sustain **electric fields up to three orders of magnitude higher gradients**

→ **order of 100 GV/m.**

→ **~1000 factor stronger acceleration!**

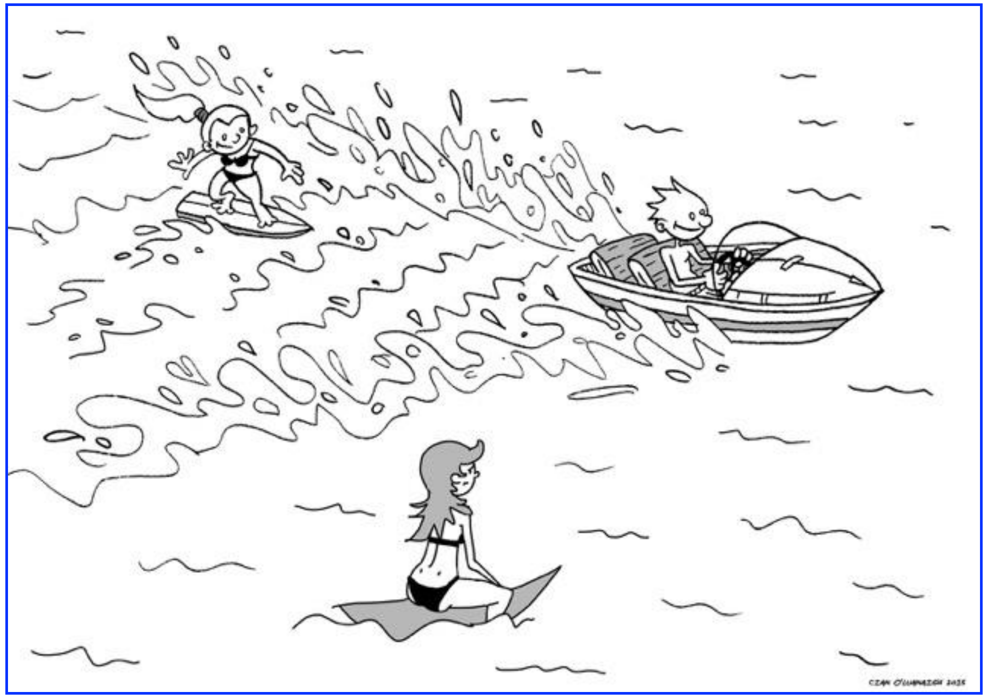
Plasma Wakefield Acceleration

Using plasma to convert **the transverse electric field** of a drive bunch into a **longitudinal electric field in the plasma.**

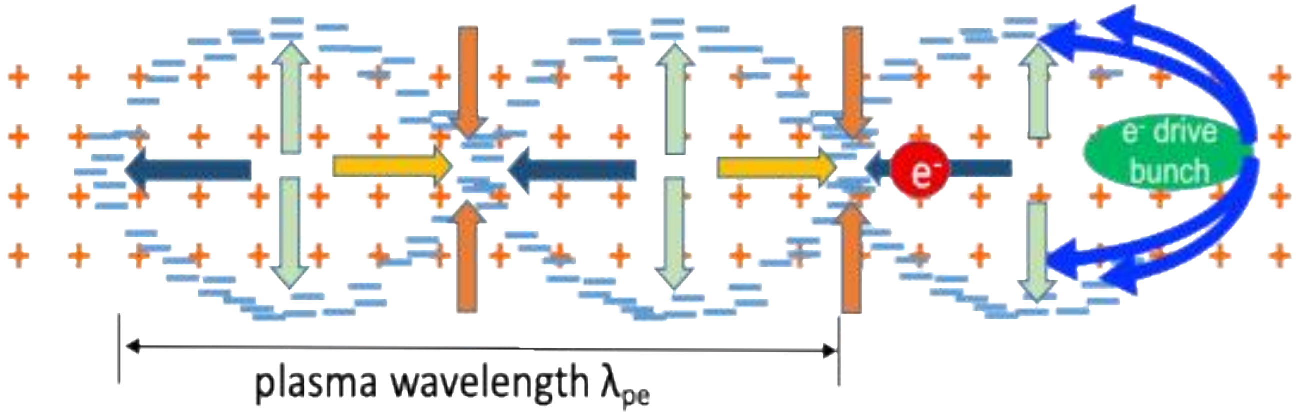
Plasma:
quasi-neutral, electrostatic interactions dominate, charge particles are dense enough to support collective behaviour.

Drive-bunch or pulse:
relativistic charged particles bunches
or
laser pulse.

Witness-bunch:
accelerated in the longitudinal electric field.



Plasma Wakefield Acceleration



$$\omega_{pe} = \sqrt{\frac{n_{pe} e^2}{m_e \varepsilon_0}}$$

$$\lambda_{pe} = 2\pi \frac{c}{\omega_{pe}}$$

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

Example: $n_{pe} = 1\times10^{18}$ cm^{-3} ➔ E_{WB} = ~100 GV/m ➔ λ_{pe} = ~30 µm

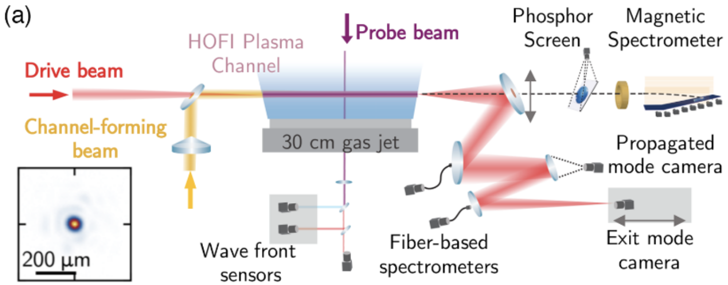
Example: $n_{pe} = 7\times10^{14}$ cm^{-3} (AWAKE) ➔ E_{WB} = 2.5 GV/m ➔ λ_{pe} = 1.2 mm

➔ Smaller collider, less costly

State-of-the-Art

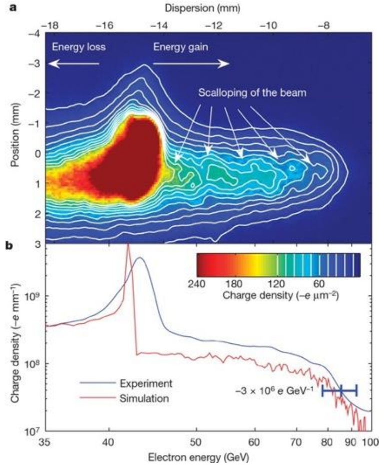
9.2 GeV in 30 cm → 30.7 GeV/m

Laser Driven



A. Picksley et al., PRL 133, 255001 (2024)

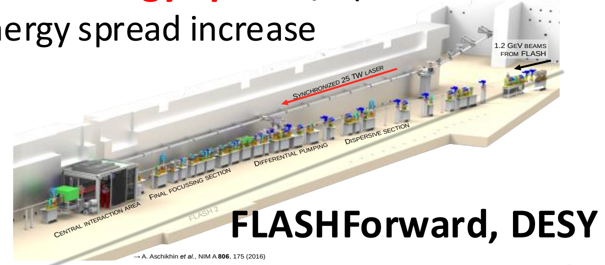
42 GeV in 85 cm → 52 GeV/m



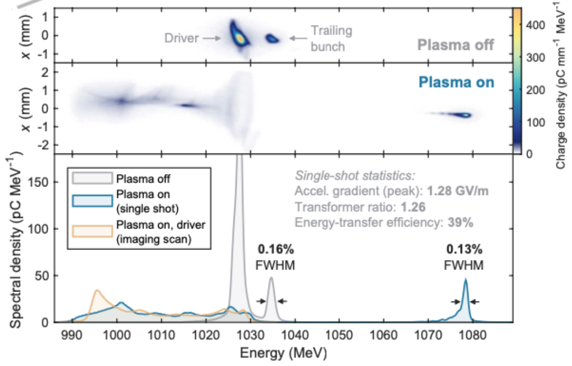
I. Blumenfeld et al, Nature 455, p 741 (2007)

Electron Driven

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



Electron Driven

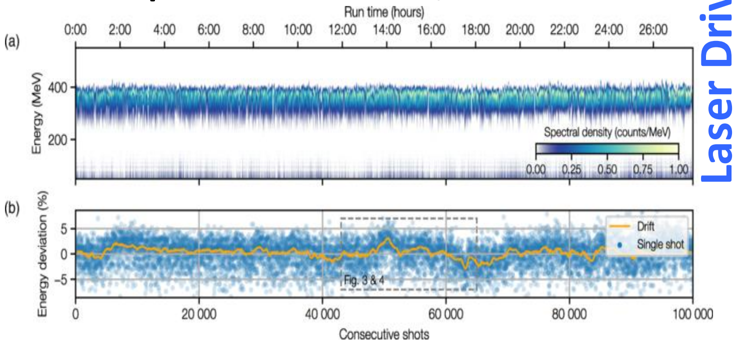


C.A. Lindstrøm et al., Phys.Rev.Lett. 126, 014801 (2021)

Stable 24hr operation

LUX laser plasma accelerator, DESY

Laser Driven

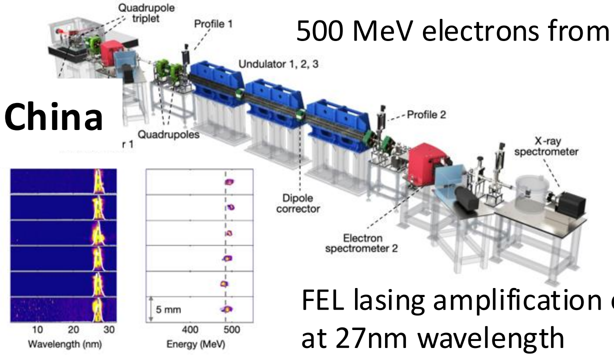


A. Maier et al., Phys. Rev. X 10, 031039 (2020)

Laser Driven based FEL: First demonstration

500 MeV electrons from LWFA

China

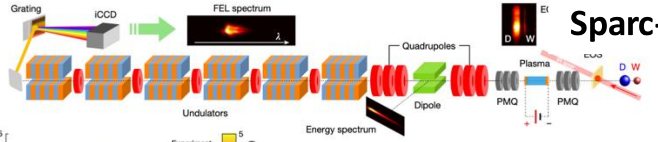


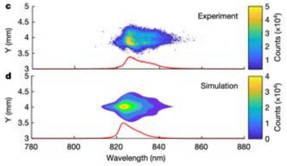
FEL lasing amplification of 100 reached at 27nm wavelength

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

Electron Driven based FEL: First demonstration

Sparc-Lab





94 MeV electrons from PWFA
FEL lasing at 830 nm

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

→ **Since then two more groups: Sparc-Lab, Soleil/HZDresden**

State of the Art and Goals for 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:

- Plasma Collider and Particle Physics Feasibility and pre-CDR study
- Technical demonstration
- Ongoing projects and facilities
- Integration and outreach

Exploring the Quantum Universe

US Snowmass and P5:

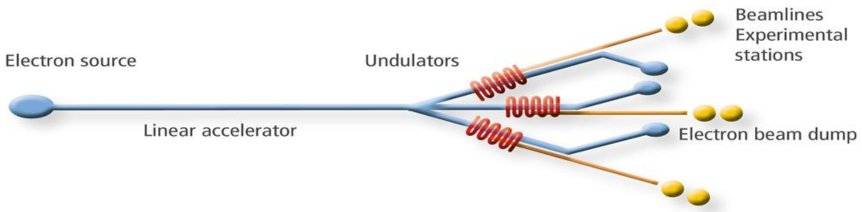
- End-to-end design concept of a 10 TeV parton-center-of-mass collider

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

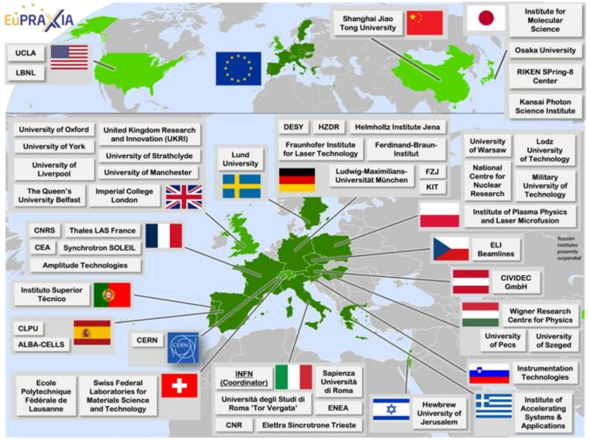
EuPRAXIA

European Plasma Research Accelerator with eXcellence in Applications

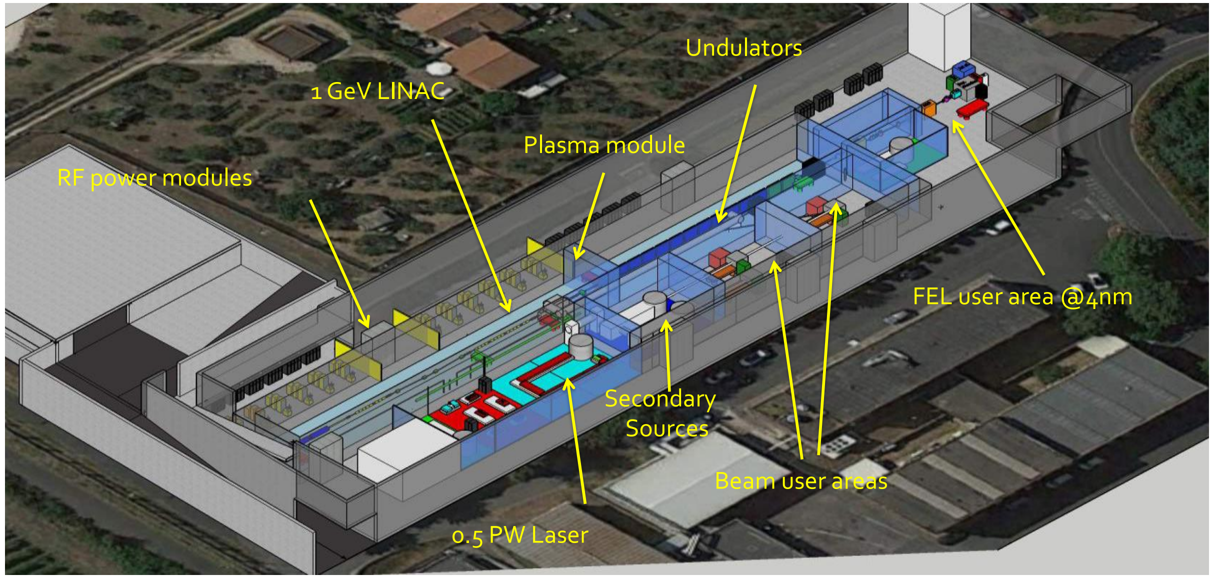
EuPRAXIA is a design and an ESFRI project for a distributed **European Research Infrastructure based on novel plasma-acceleration concepts (1-5 GeV), building two plasma-driven Free Electron Lasers, FELs, in Europe**.
Aims at offering a significant reduction in size and possible savings in cost over current state-of-the-art RF-based accelerators.



- Site 1: EuPRAXIA FEL in Frascati LNF-INFN (beam-driven) is sufficiently funding
- Site 2: EuPRAXIA FEL (laser-driven)will be selected within next 3 months



Today: 54 institutes in Consortia

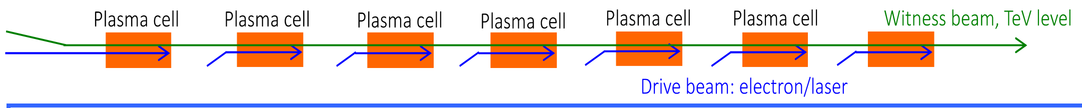


EuPRAXIA@SparcLAB in Frascati, Budget today: > 130 MEuros

→ Construction has started.
→ First FEL user operation in 2029.
Combining X-band linac with beam-driven plasma acceleration.

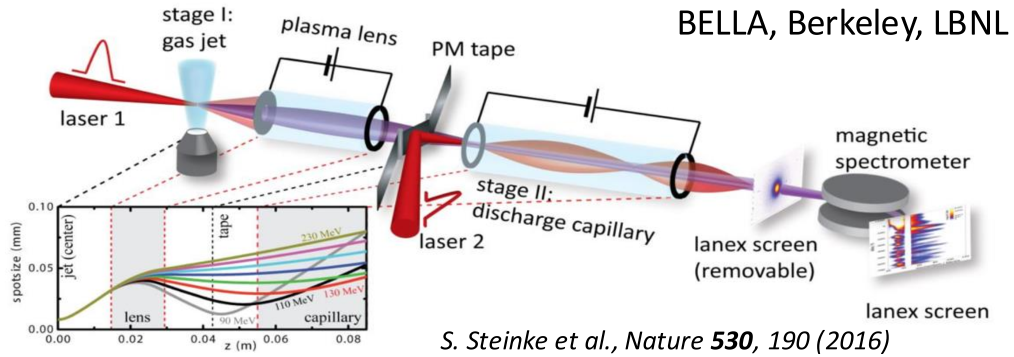
Towards Higher Energies

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



Proton bunch driver: ➔ single plasma cell
~SPS 19 kJ/bunch, LHC 112 kJ/bunch

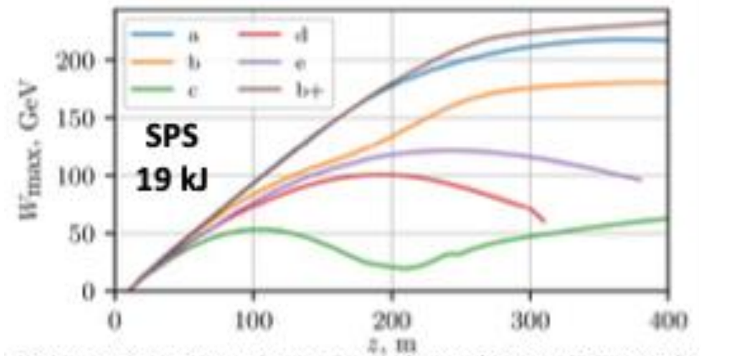
BELLA, Berkeley, LBNL



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

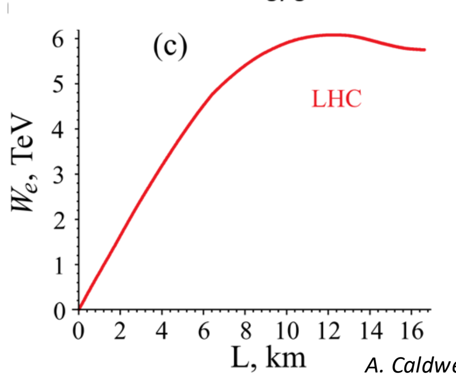
- **Staging of 2 plasma cells demonstrated** at 100MeVs level (laser driven).
- Experiments ongoing at GeVs level.
- **No beam-driven staging** yet demonstrated (no facility).
- Matching between stages with plasma lenses/ conventional magnets.

2D numerical simulation results



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

Electron energy gain

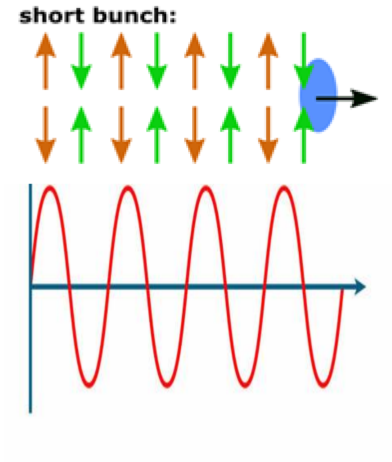


A. Caldwell, K. V. Lotov, Phys. Plasmas 18, 13101 (2011)

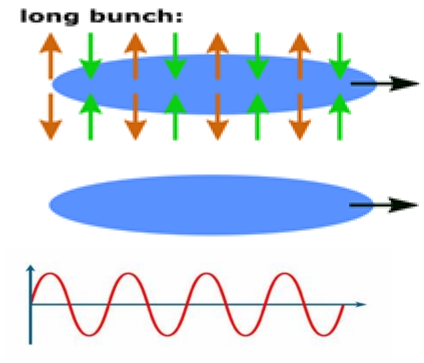
SPS p^+ (450 GeV): accelerate to 200 GeV electrons.
LHC p^+ can yield to 3 TeV electrons

Proton Bunch as a Drive Beam

In order to create high wakefield amplitudes, the drive bunch length must be in the order of the plasma wavelength.

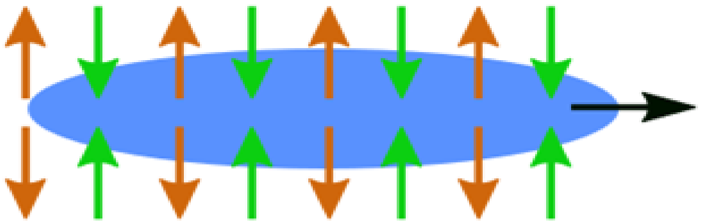


CERN SPS proton bunch: very long! (σ_z **= 6 - 10 cm**) → much longer than plasma wavelength (λ **= 1mm**)
→ Would create only small wakefield amplitudes

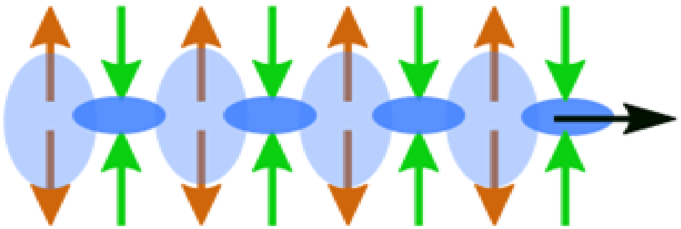


Self-Modulation of the Proton Bunch

Self-Modulation Instability:

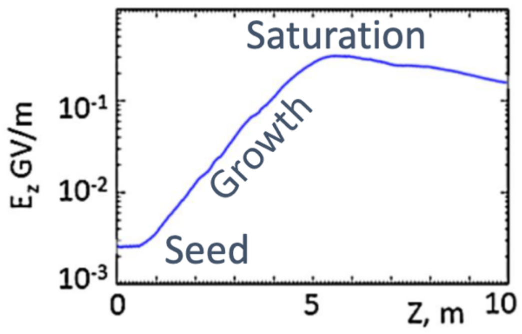


p^+ bunch



Density modulation on-axis → **micro-bunches**.

- Micro-bunches separated by λ_{pe}.
- Resonant wakefield excitation
- Large wakefield amplitudes



Pukhov, PRL107 145003 (2011)

Initial transverse wakefields

↓

Periodic focusing/defocusing fields

↓

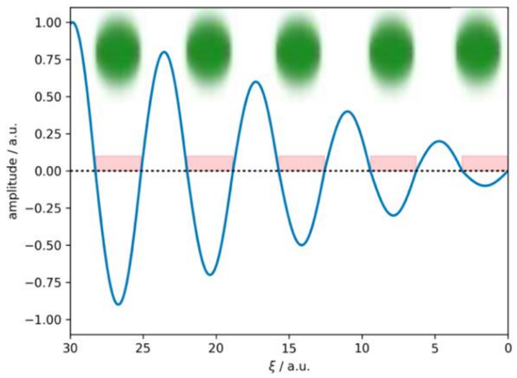
Radial bunch and plasma density modulation

↓

Stronger wakefields

↓

Full modulation



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

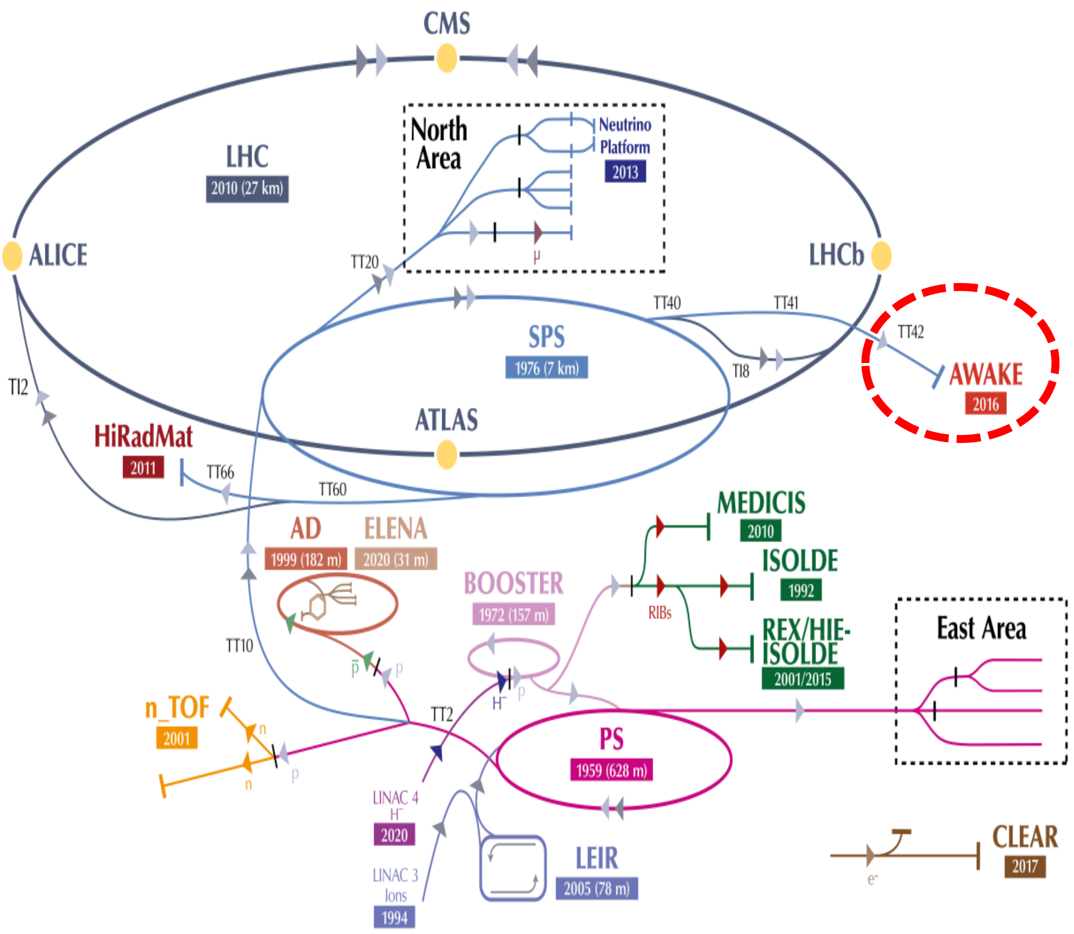
AWAKE at CERN

Advanced WAKEfield Experiment

➔ Accelerator R&D experiment at CERN.

➔ Unique facility driving wakefields in plasma with a 400 GeV proton bunch from the SPS (highly relativistic protons with high energy > kJ)

➔ **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

AWAKE is an International Collaboration

Strong commitment from 19 Institutes

AWAKE's Strong Scientific and Educational Output

22 AWAKE Collaboration papers in high-level journals

Authors	Title	Journal	Year
L. Verra, et al. (AWAKE Collaboration)	Filamentation of a Relativistic Proton Bunch in Plasma		2023
T. Nechaeva, et al. (AWAKE Collaboration)	Hosing of a long relativistic particle bunch in plasma		2023
L. Verra, et al. (AWAKE Collaboration)	Development of the Self-Modulation Instability of a Relativistic Proton Bunch in Plasma	PoP	2023
E. Gschwendtner, et al. (AWAKE Collaboration)	The AWAKE Run 2 programme and beyond	Symmetry	2022
L. Verra, et al. (AWAKE Collaboration)	Controlled Growth of the Self-Modulation of a Relativistic Proton Bunch in Plasma	PRL	2022
S. Gessner, et al. (AWAKE Collaboration)	Evolution of a plasma column measured through modulation of a high-energy proton beam		2020
V. Hafych, et al. (AWAKE Collaboration)	Analysis of Proton Bunch Parameters in the AWAKE Experiment	JINST	2021
P.I. Morales Guzman, et al. (AWAKE Collaboration)	Simulation and experimental study of proton bunch self-modulation in plasma with linear density gradients	PRAB	2021
F. Batsch, et al. (AWAKE Collaboration)	Transition between Instability and Seeded Self-Modulation of a Relativistic Particle Bunch in Plasma	PRL	2021
J. Chappell, et al. (AWAKE Collaboration)	Experimental study of extended timescale dynamics of a plasma wakefield driven by a self-modulated proton bunch	PRAB	2021
F. Braunmüller, et al. (AWAKE Collaboration)	Proton Bunch Self-Modulation in Plasma with Density Gradient	PRL	2020
A. A. Gorn, et al. (AWAKE Collaboration)	Proton beam defocusing in AWAKE: comparison of simulations and measurements	PPCF	2020
M. Turner, et al. (AWAKE Collaboration)	Experimental study of wakefields driven by a self-modulating proton bunch in plasma	PRAB	2020
E. Gschwendtner, et al. (AWAKE Collaboration)	Proton-driven plasma wakefield acceleration in AWAKE	PTRSA	2019
M. Turner, et al. (AWAKE Collaboration)	Experimental Observation of Plasma Wakefield Growth Driven by the Seeded Self-Modulation of a Proton Bunch	PRL	2019
AWAKE Collaboration	Experimental Observation of Proton Bunch Modulation in a Plasma at Varying Plasma Densities	PRL	2019
AWAKE Collaboration	Acceleration of electrons in the plasma wakefield of a proton bunch	Nature	2018
P. Muggli, et al. (AWAKE Collaboration)	AWAKE readiness for the study of the seeded self-modulation of a 400 GeV proton bunch	PPCF	2018
E. Gschwendtner, et al. (AWAKE Collaboration)	AWAKE, The Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN	NIMA	2016
A. Caldwell, et al. (AWAKE Collaboration)	Path to AWAKE: Evolution of the concept	NIMA	2016
C. Bracco, et al. (AWAKE Collaboration)	AWAKE: A Proton-Driven Plasma Wakefield Acceleration Experiment at CERN	NPPP	2016
AWAKE Collaboration	Proton-driven plasma wakefield acceleration: a path to the future of high-energy particle physics	PPCF	2014

> 70 papers related to AWAKE

> 90 Conference proceedings and papers

➔ 4 doctoral thesis prizes, 2 early career awards!

AWAKE courses and seminars

EPFL

JAI John Adams Institute for Accelerator Science

CERN Teacher Program

USPAS, JUAS, CAS

> 28 PhD students

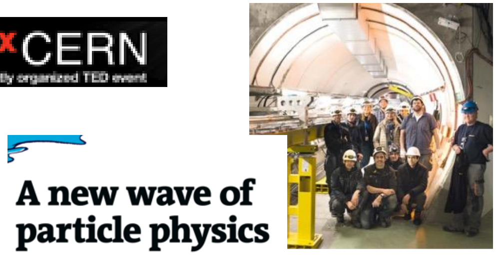
> 11 Master students

> 20 Post-docs

Outreach: Newspapers, TEDX, …

TEDxCERN x = independently organized TED event

ask symmetry



AWAKE has a Well-Defined Program

RUN 1 (2016-2018)

p+ self-modulation

2 GeV e- acceleration

RUN 2 (2021-2033)

e- acceleration to several GeV,
beam quality control, scalability

→ **First applications >2034**

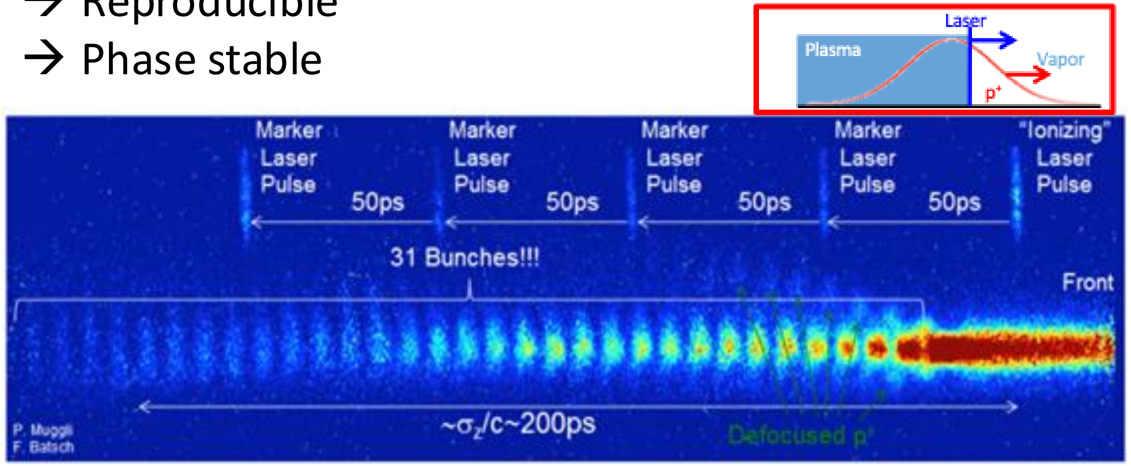
→ Move from proof-of-concept towards an accelerator

AWAKE Run 1 Highlights

Seeded self-modulation of the proton bunch

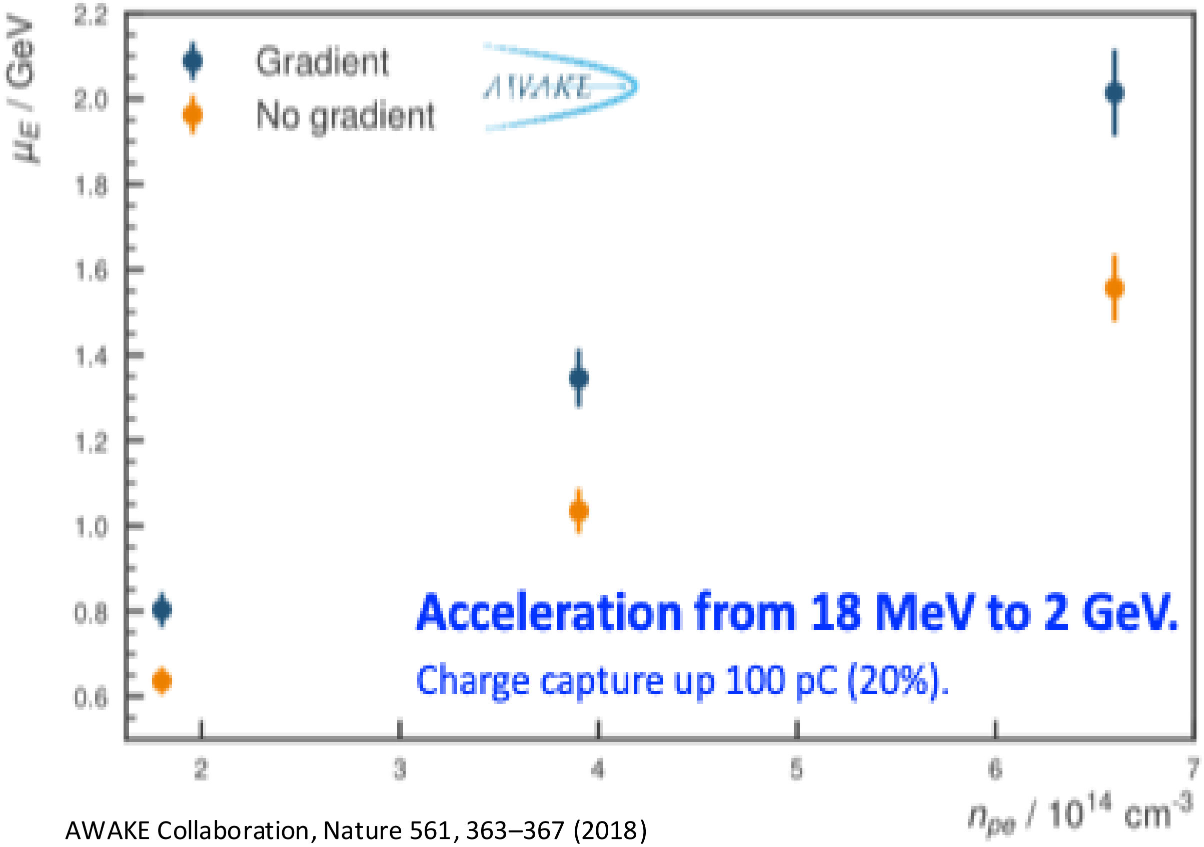
→ Reproducible

→ Phase stable



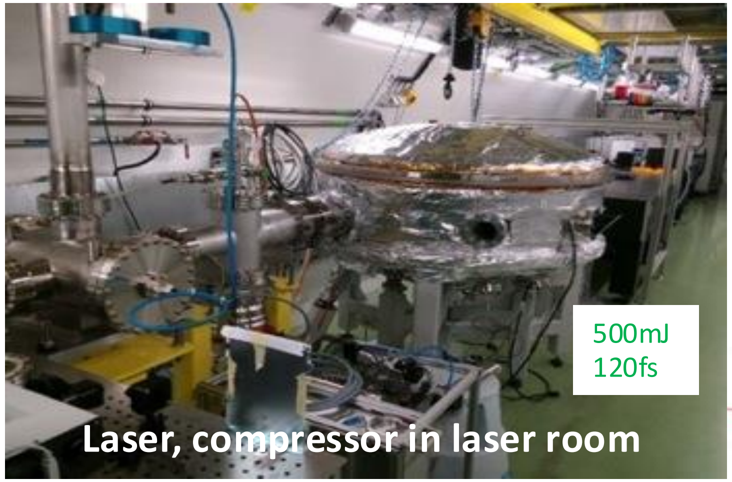
AWAKE Collaboration, Phys. Rev. Lett. 122, 054802 (2019).
M. Turner et al. (AWAKE Collaboration), Phys. Rev. Lett. 122, 054801 (2019).
M. Turner, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Accel. Beams 23, 081302 (2020)
F. Braunmueller, T. Nechaeva et al. (AWAKE Collaboration), Phys. Rev. Lett. July 30 (2020).
A.A. Gorn, M. Turner et al. (AWAKE Collaboration), Plasma Phys. Control Fusion, Vol. 62, Nr 12 (2020).
F. Batsch, P. Muggli et al. (AWAKE Collaboration), accepted in Phys. Rev. Lett. (2021)

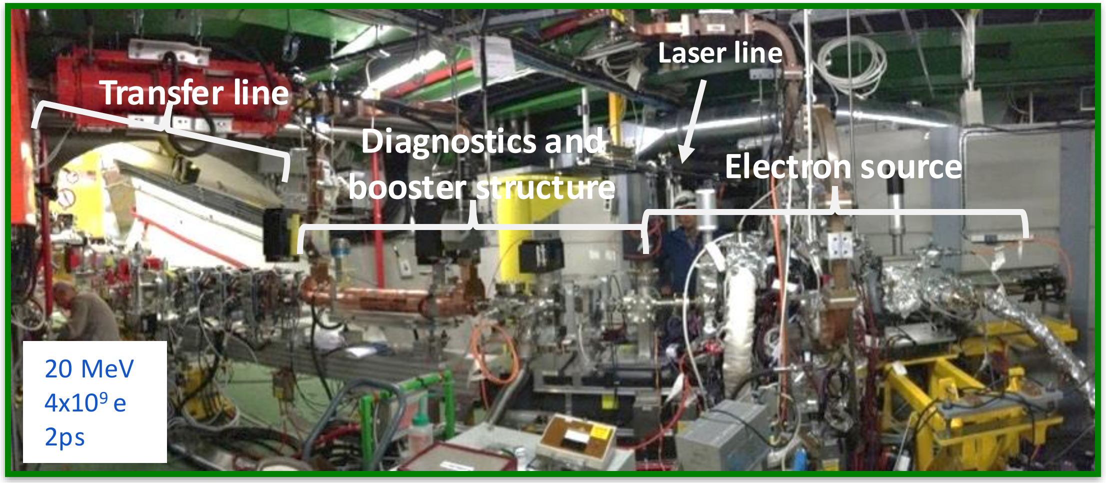
Electron acceleration from 18 MeV to 2 GeV

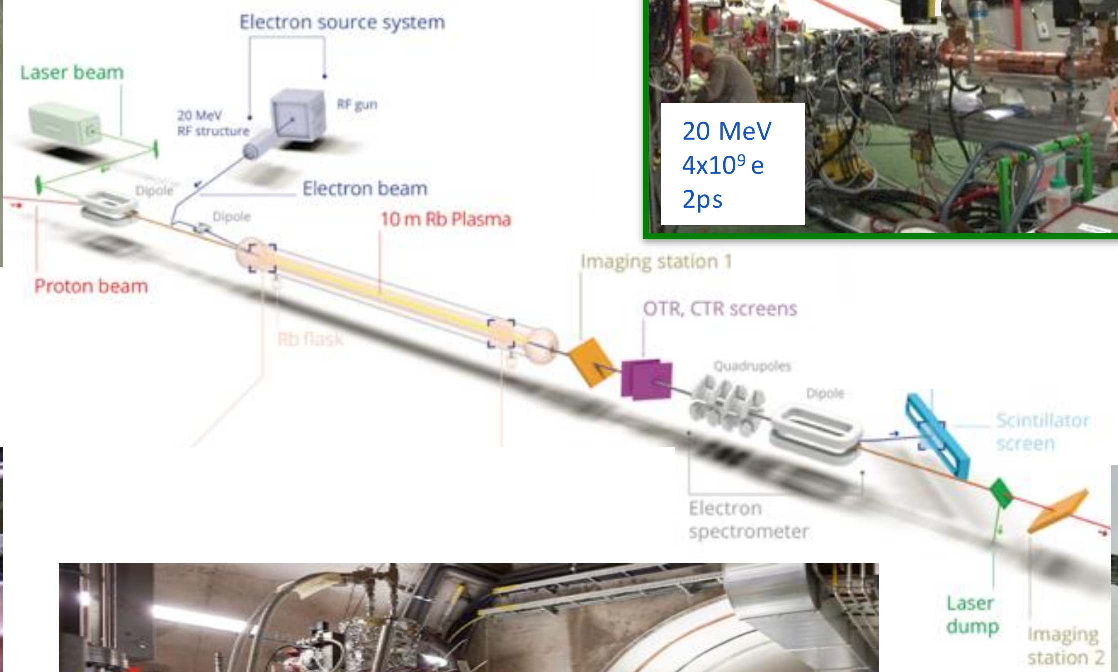


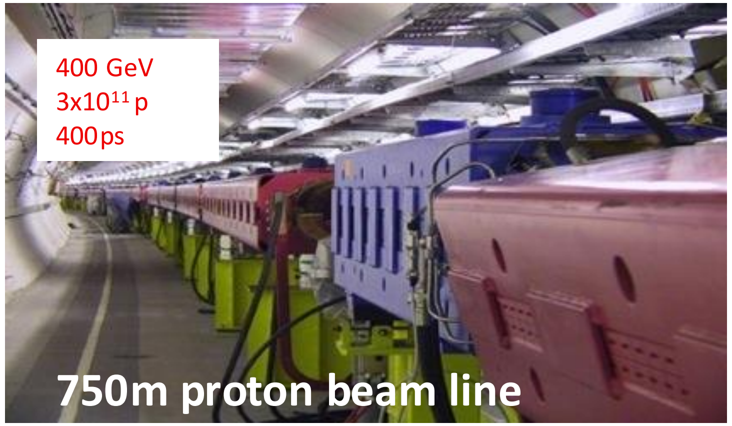
AWAKE Collaboration, Nature 561, 363–367 (2018)

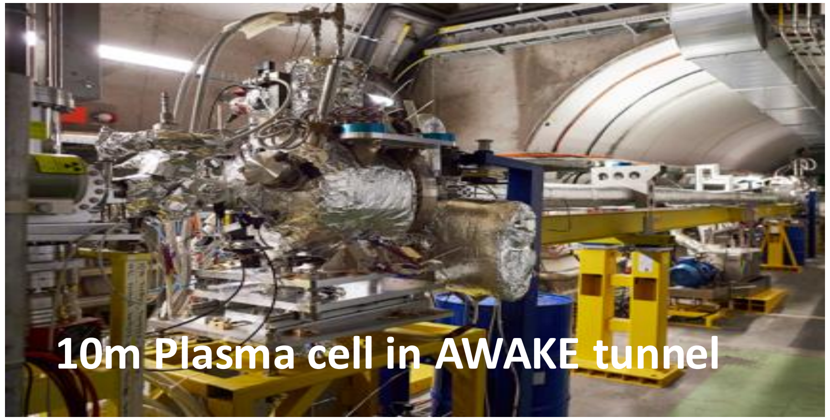
Key Ingredients of AWAKE





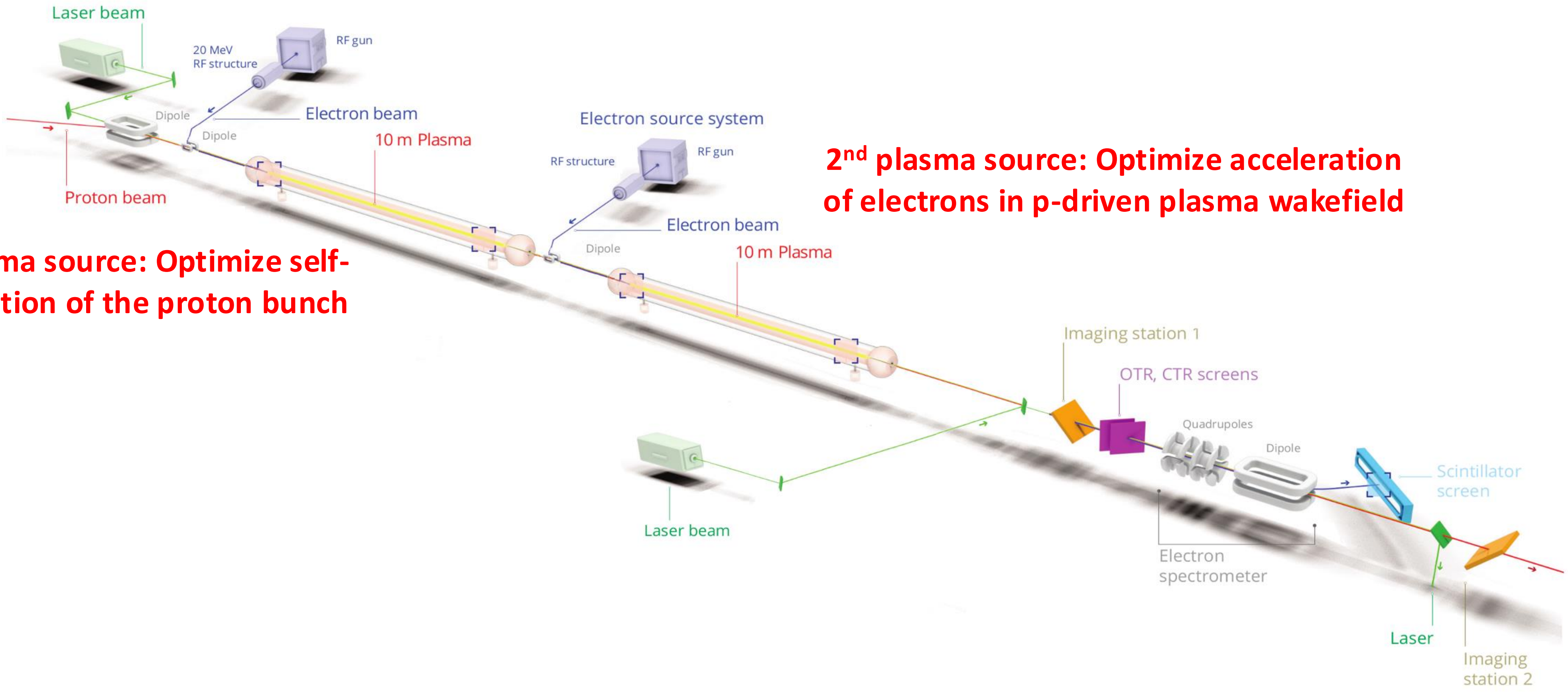






AWAKE Run 2 (2021 – 2033)

AWAKE Run 2 Goal: Accelerate an electron beam to **high energies (0.4 – 1 GeV/m)**, while controlling the electron **beam quality (2 - 30 mm mrad normalized emittance)** and demonstrate **scalable plasma source (several 10s meters)** technology.



2^{nd} plasma source: Optimize acceleration of electrons in p-driven plasma wakefield

1^{st} plasma source: Optimize self-modulation of the proton bunch

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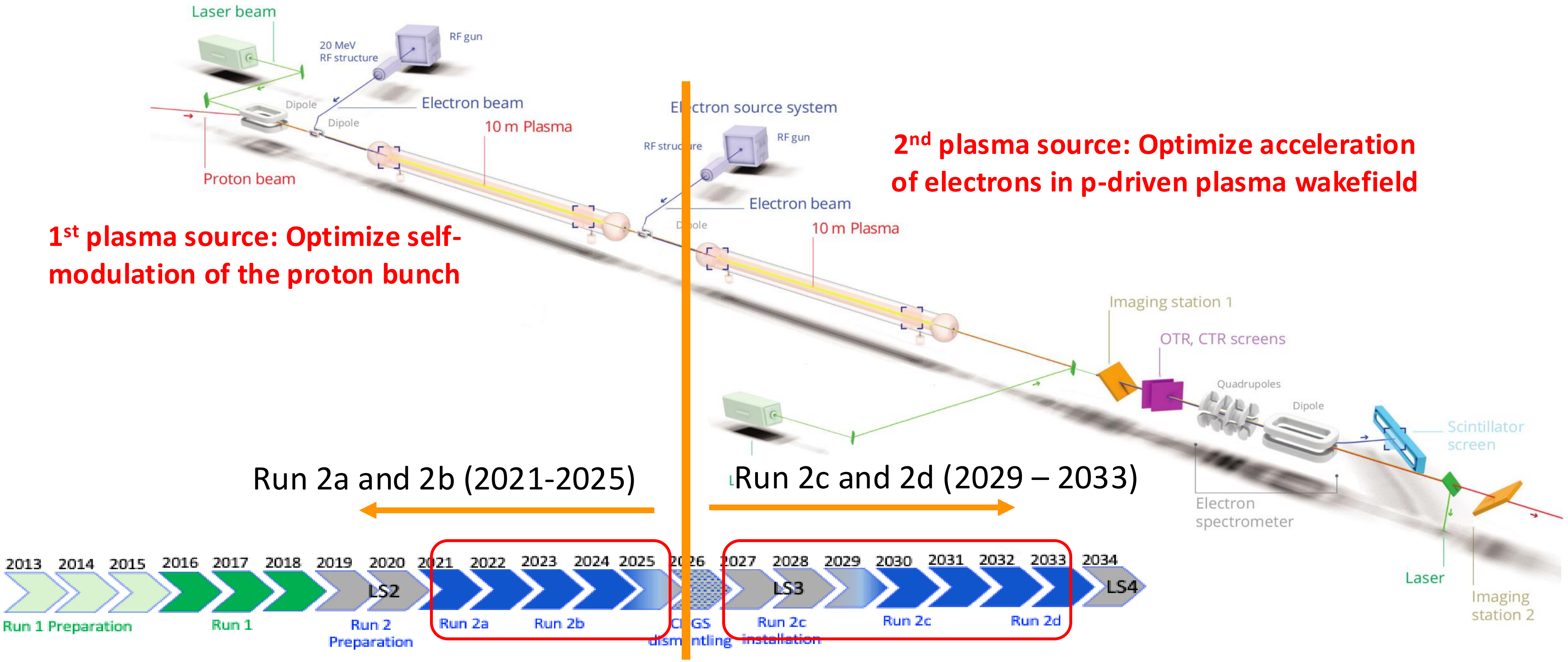
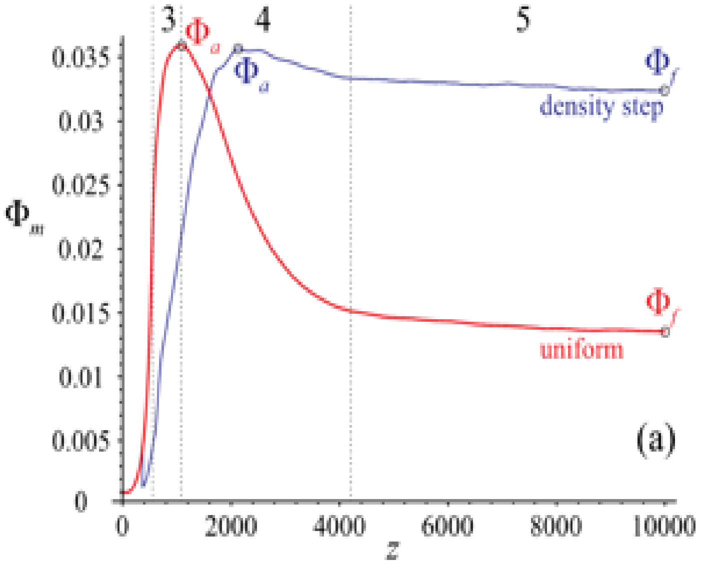


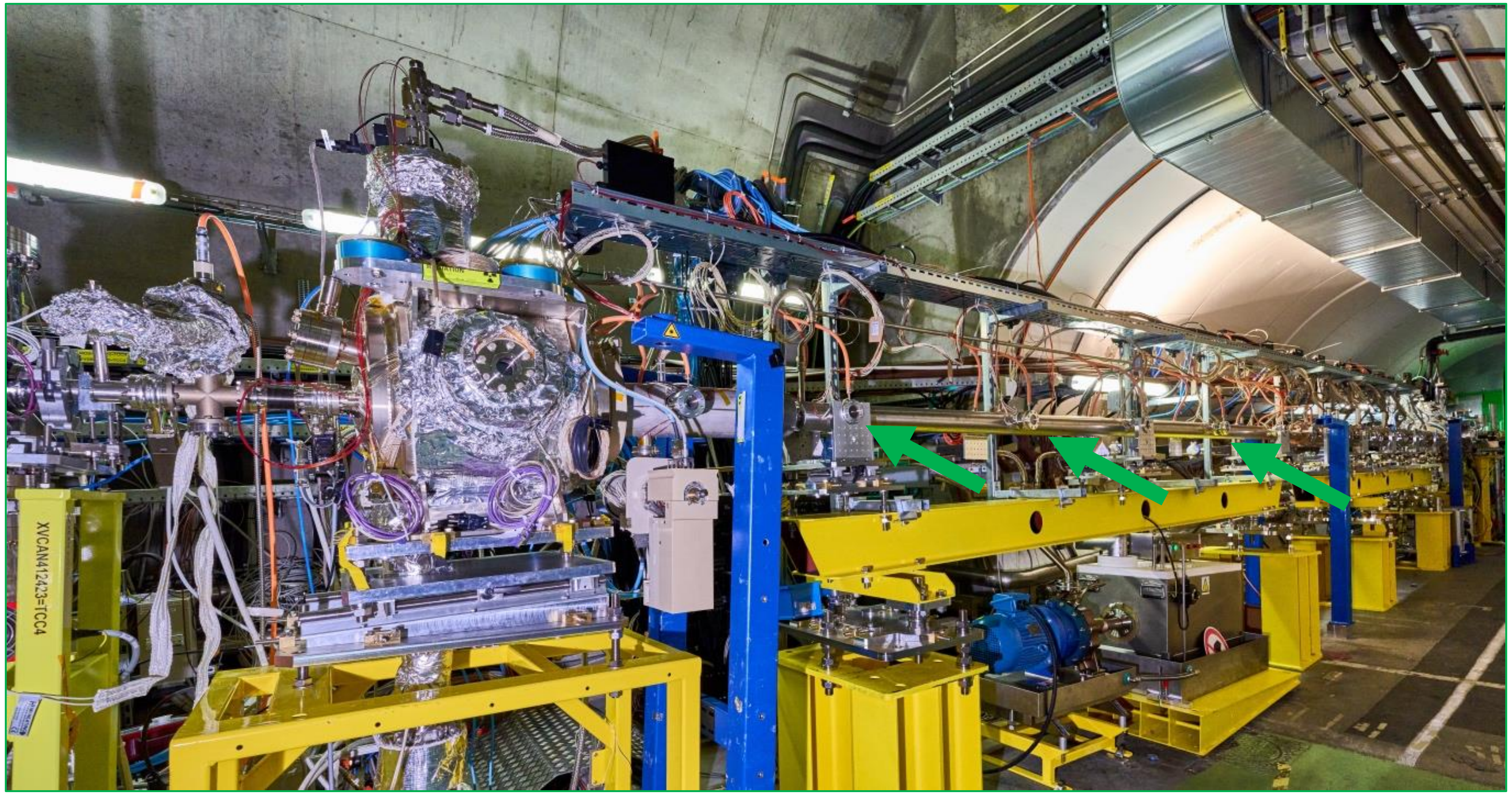
Run 2a,b – Stabilizing Large Wakefield Amplitudes

Introducing a density step in the plasma cell
➔ stabilization of the micro-bunches
➔ Increased wakefield amplitudes after SSM saturation



K. V. Lotov, Physics of Plasmas 22, 103110 (2015)
*K. V. Lotov and P. V. Tuev 2021 PPFC **63 125027***

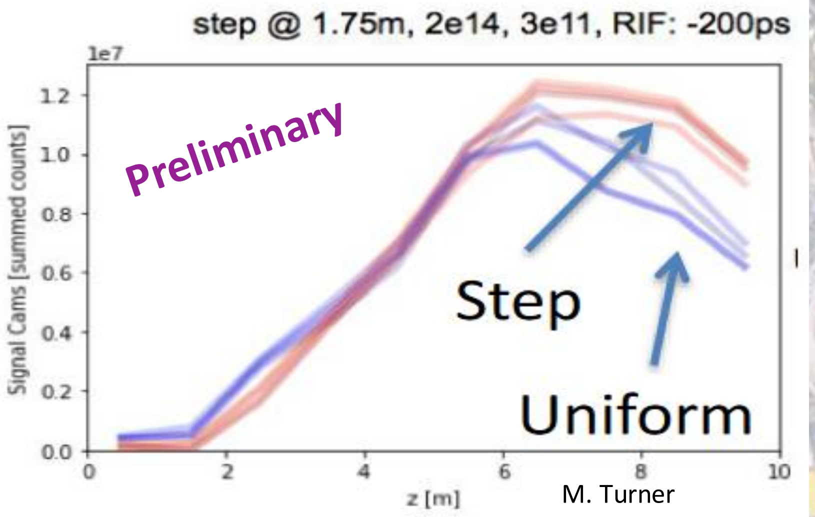
New Rubidium vapour source with density step installed in 2023



- Length: ~ 10 m, independent electrical heater of 50 cm from 0.25 to 4.75 m, Step height up to ±10%
- 10 diagnostic viewport ➔ to measure light emitted by wakefields dissipating after the passage of the proton bunch

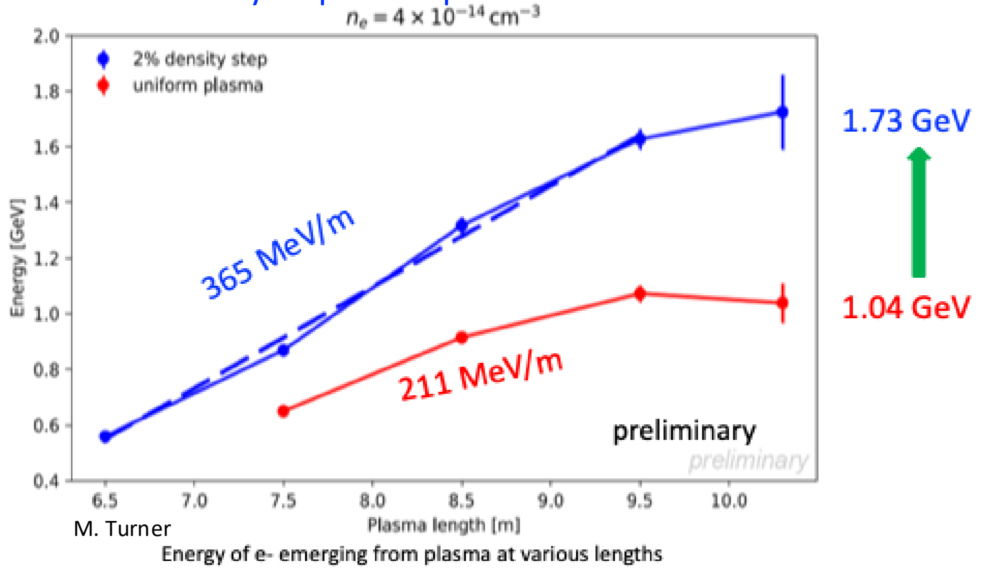
Run 2b - Stabilizing Large Wakefield Amplitudes

Wakefield light



Accelerated electrons

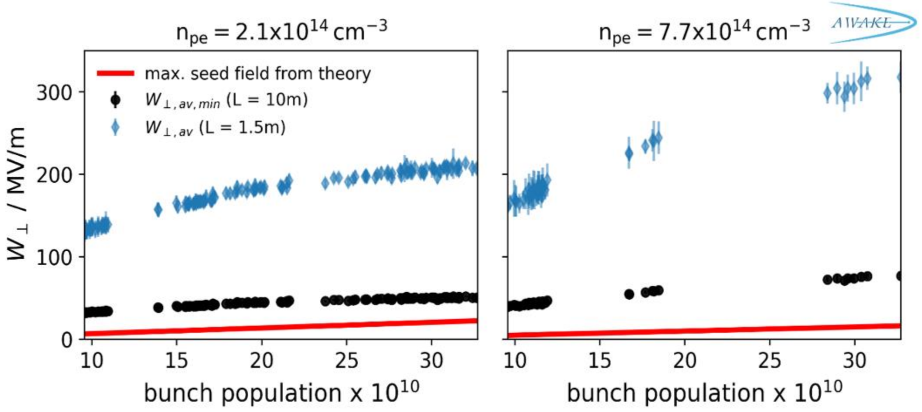
Effect of density step in the plasma source



Optimizing the proton bunch self-modulation

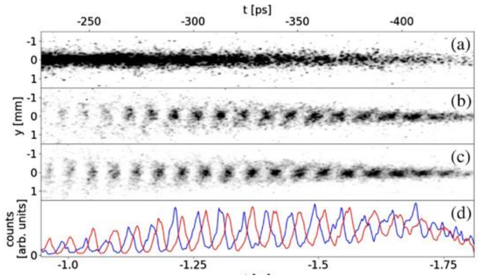
Other Scientific Results

Wakefield growth due to SM



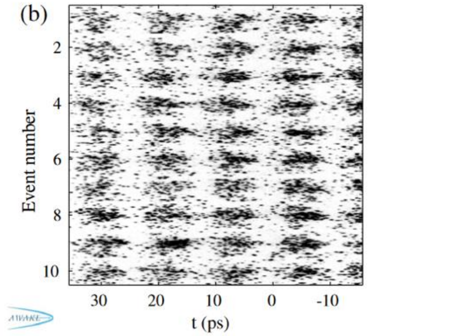
M. Turner et al. (AWAKE Collaboration), 'Phys. Rev. Lett. 122, 054801 (2019).

Seeding with electron bunch



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

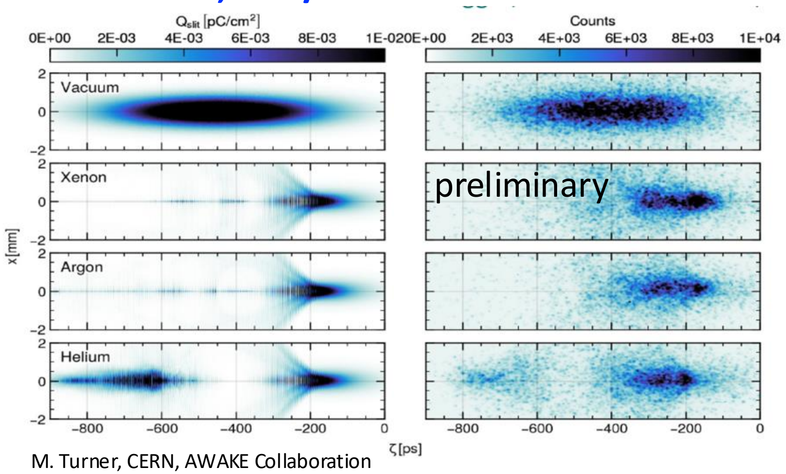
Seeding with relativ. ionization front



F. Batsch, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Lett. 126, 164802 (2021).

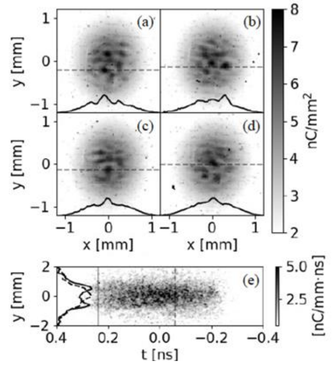
- ✓ **All milestones achieved – plus additional ones.**
  - ✓ **Relevant studies for general plasma wakefield acceleration concepts.**
- ✓ **Investing in young researchers.**
- ✓ **Many thesis and publications.**

Ion motion, Sim/Meas



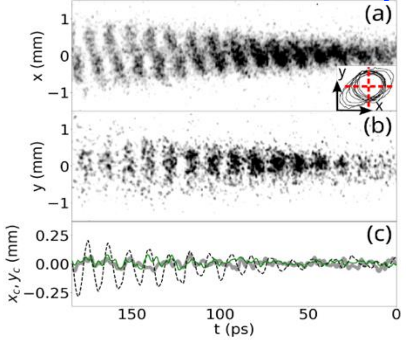
M. Turner, CERN, AWAKE Collaboration

Filamentation instability



L. Verra, et al. (AWAKE Collaboration), Phys. Rev. E 109, 055203 (2024).

Beam-hose instability



T. Nechaeva, et al. (AWAKE Collaboration), Phys. Rev. Lett. 132, 075001 (2024).

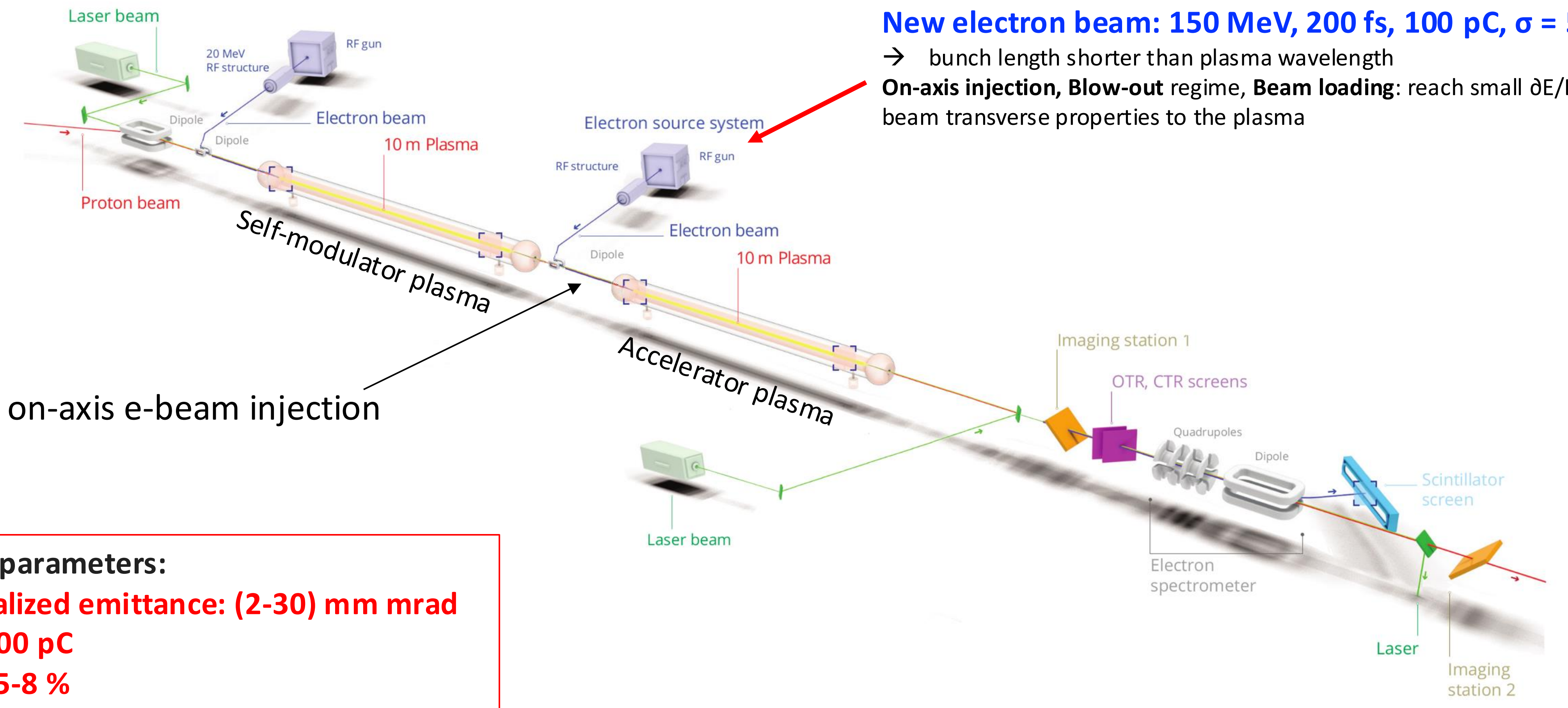
AWAKE Run 2c – Start in 2029 after LS3

Demonstrate electron acceleration and emittance control of externally injected electrons.

New electron beam: 150 MeV, 200 fs, 100 pC, σ = 5.75 µm

→ bunch length shorter than plasma wavelength

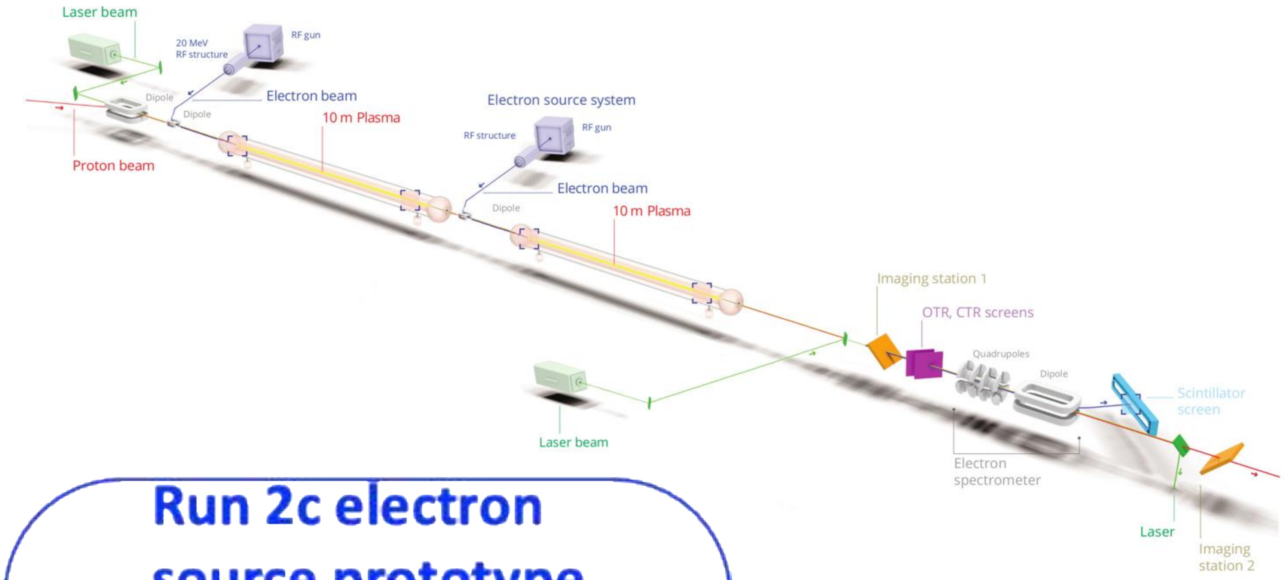
On-axis injection, Blow-out regime, **Beam loading**: reach small ∂E/E, **Match** electron beam transverse properties to the plasma



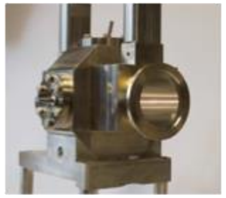
Expected parameters:

- **Normalized emittance: (2-30) mm mrad**
- **Q_e = 100 pC**
- **dE/E: 5-8 %**
- **Run 2c: E ~ 4-10 GeV in 10 m**

AWAKE Run 2c Design, Prototyping, Installation



Beam instrumentation

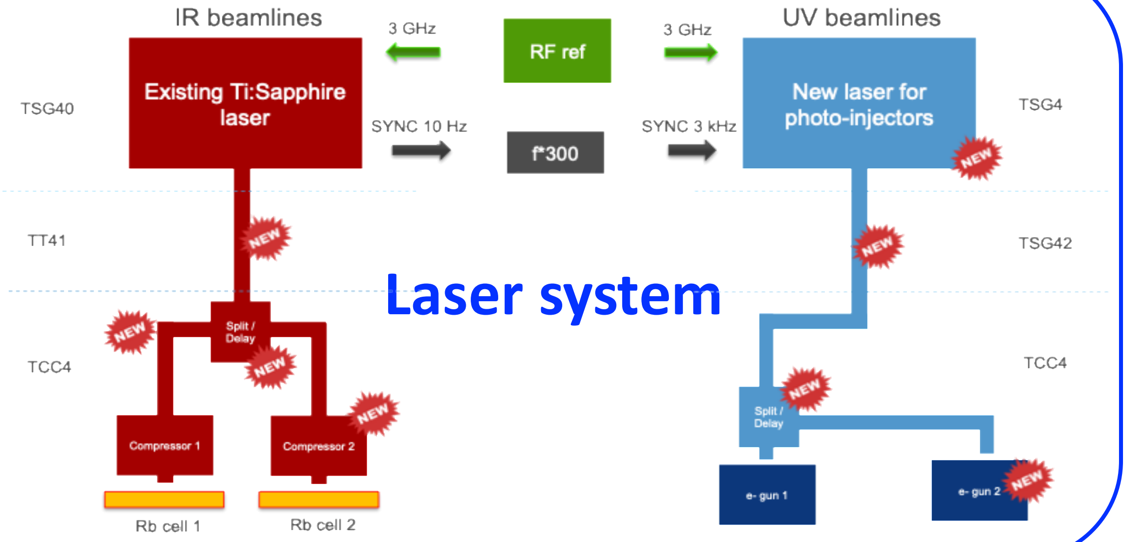


BPMs 10 μm resolution

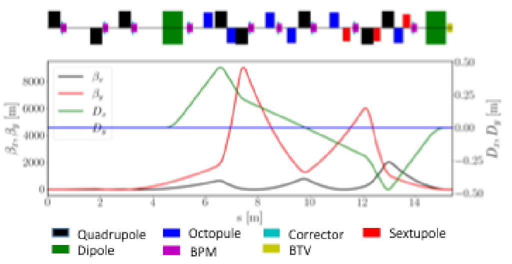
Run 2c electron source prototype

S-band e-gun (INFN) with
X-band accelerator (CLIC/CLEAR)

Laser system



150 MeV beamline

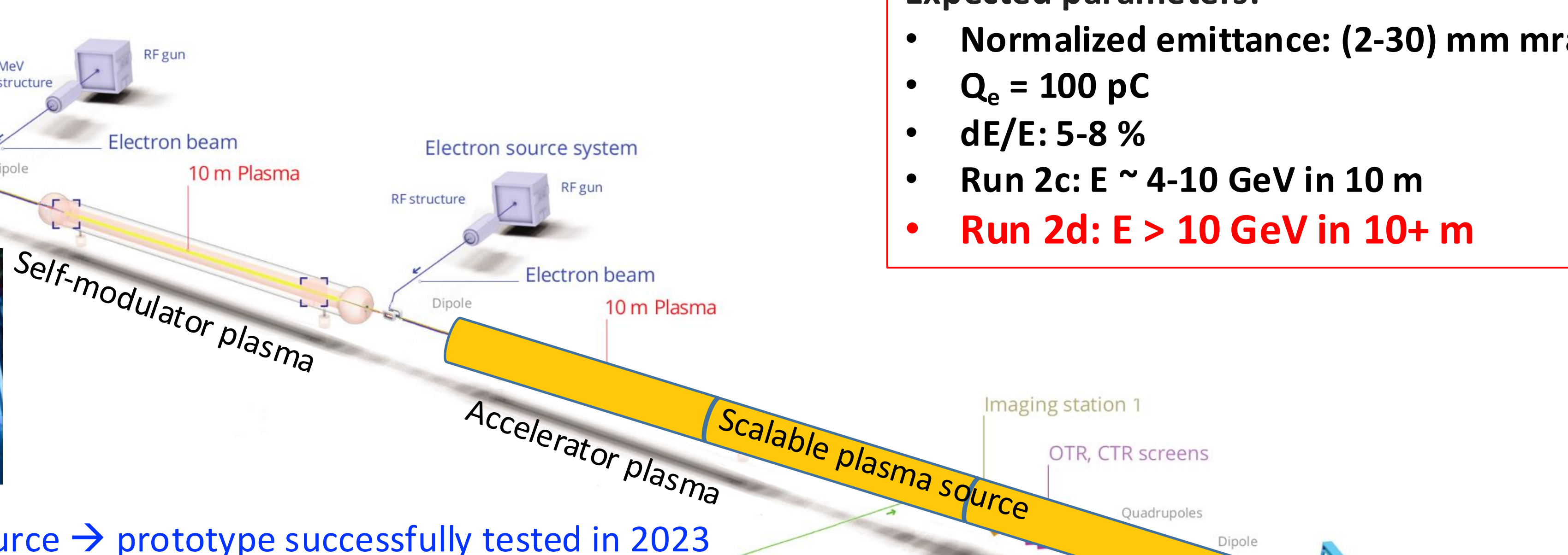


AWAKE Run 2d (2032/33) – Scalability

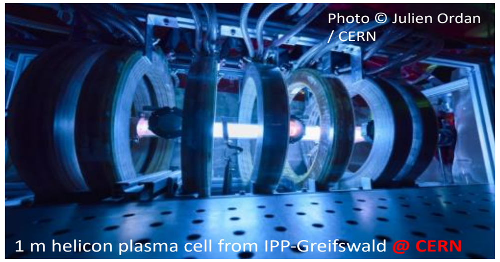
Development of scalable plasma sources to 100s meters length with sub-% level plasma density uniformity

Expected parameters:

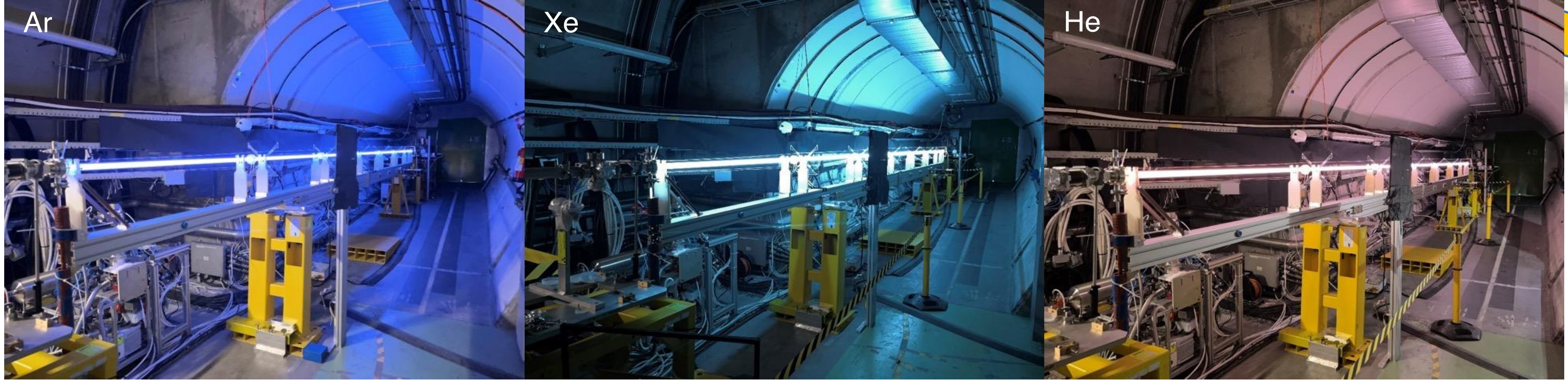
- Normalized emittance: (2-30) mm mrad
- Q_e = 100 pC
- dE/E: 5-8 %
- Run 2c: E ~ 4-10 GeV in 10 m
- **Run 2d: E > 10 GeV in 10+ m**



1m Helicon Plasma Source



10m Discharge Plasma Source → prototype successfully tested in 2023



Outline

- Introduction to plasma wakefield acceleration and state-of-the-art
- AWAKE
- Examples of R&D efforts towards applications and colliders within the Particle Physics Planning Exercises

Applications of AWAKE Technology

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

First applications to high energy physics for 50 GeV beam:

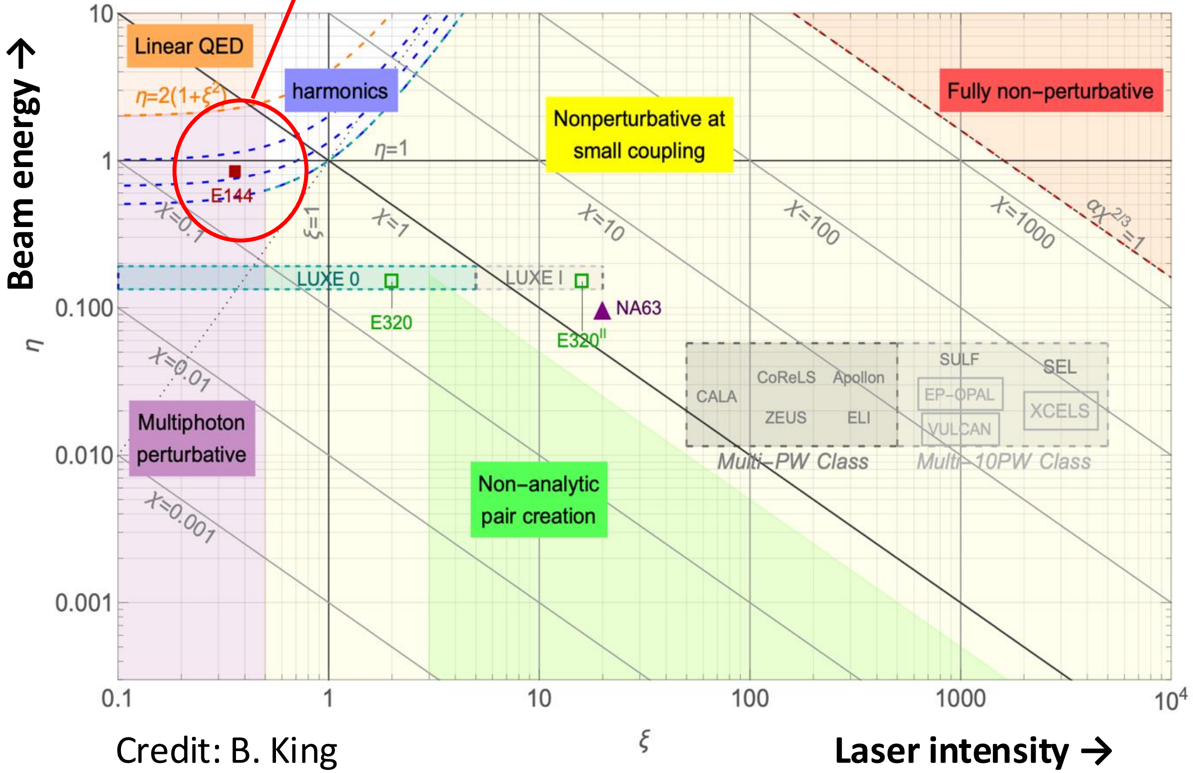
- → Use for collider, e.g. ***ep* collider**, which would be like a **low-luminosity** LHeC.
- → **Beam-dump experiments** to e.g. search for dark photons.
- → **Interaction with high-power laser to investigate strong-field QED.**

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.

High energy, ~50 GeV

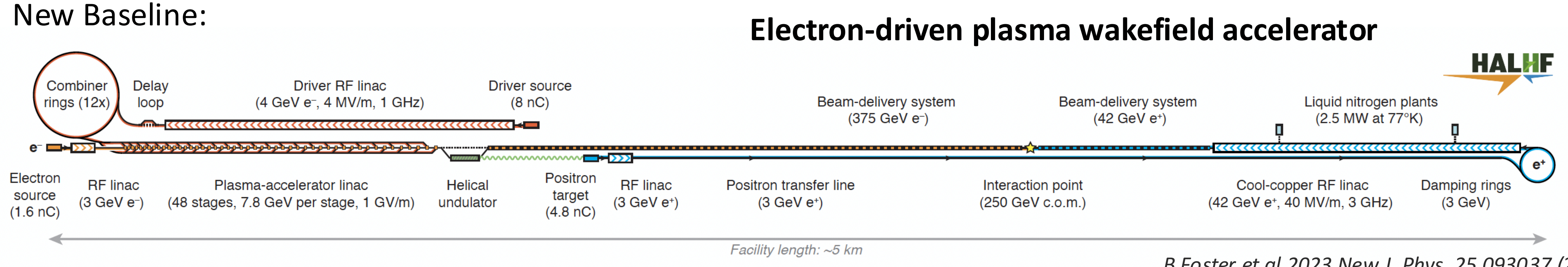
Nonlinear Breit–Wheeler



Credit: B. King

Higgs Factory Based on Plasma Wakefields - HALHF

New Baseline:



B Foster et al 2023 New J. Phys. 25 093037 (2023)

Updated layout

- **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: ~1 x 10^{34} cm^{-2} s^{-1}**
- Length: 5 km
- Technology choice: CLIC (power soure) + PWFA (transformer) + cool copper technology (positrons)
- PWFA Stages: 48 stages, 1 GV/m gradient, higher driver charge 5x10^{10} (8nC), higher transformer ratio T=2

- ➔ **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

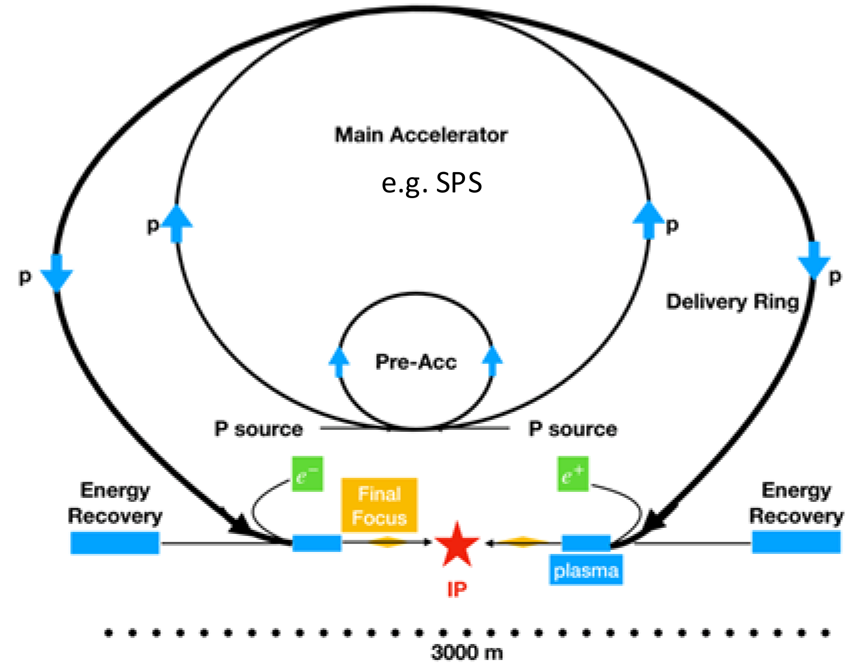
Proton-driven plasma wakefield accelerator

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 x 10^{34} cm^{-2} s^{-1}**

- Proton drive bunches from fast cycling synchrotron (HTS magnets) or FFAG to reach competitive luminosity.
- Short proton driver (σ_z =150 μm); 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)*

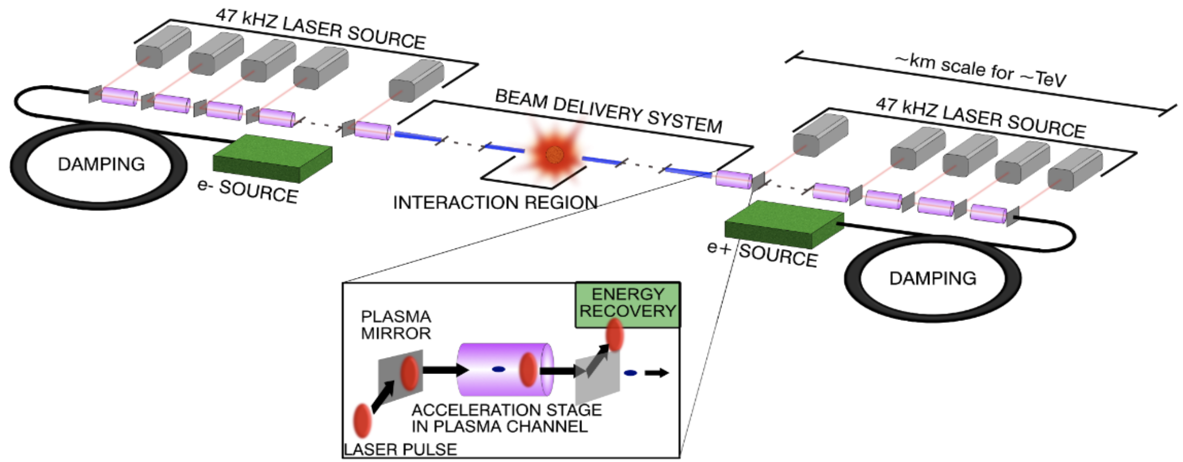
Key challenges: Short (sub-mm) driver, high (kHz) rep rate, positron acceleration in plasma.
Fewer challenges for e−p/e−A collider or asymmetric scheme.

→ These are exploratory studies

10 TeV pCM Collider

Call from the 2023 P5 Report:
Design of a **10 TeV parton-center-of-mass (pCM) collider based on wakefield accelerator (WFA) technology**.

Charge: "… wakefield concepts for a collider are in the early stages of development. A critical next step is the **delivery of an end-to-end design concept, including cost scales, with self-consistent parameters throughout**…"



Laser-plasma LC: C.B.Schroeder et al., 2023, JINST 18 T06001, arXiv:2203.08366

- → First meetings starting now.
- → Working groups organized in connection with collider components.
- → Final design report to be delivered in 2028.

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

ALEGRO, led by ICFA-ANA panel on Advanced Novel Accelerators: foster and trigger advanced LC related activities, provide framework to amplify international collaboration, organize workshops, contribute to interantional strategies, support all major projects.

Summary

- Plasma wakefield acceleration is an exciting and growing field with many encouraging results and a huge potential. Acceleration with more than 50 GeV/m gradients have been achieved.

- AWAKE is a key technology driver for plasma wakefield acceleration exploiting unique possibilities of the CERN injector complex and adding to the diversity of CERN experiments.

- Coordinated R&D programs towards colliders take shape within the Particle Physics planning exercises
    - Proposals for large scale applications of plasma wakefield acceleration follow two main lines: Proton driven, staged laser/electron driven.
    - Intermediate applications included user facilities for FELs, fixed-target experiments, SFQED studies,…
    - Concepts on plasma based Higgs factories such as HALHF and ALiVE are studied.
    - A 10 TeV pCM collider design study is underway.

Many thanks for the valuable input from

Allen Caldwell, John Farmer, Massimo Ferrario, Spencer Gessner, Carl Lindstrøm, Patric Muggli, Marlene Turner, Matthew Wing.