The Program of AWAKE towards High-Energy Electrons for Particle Physics Experiments

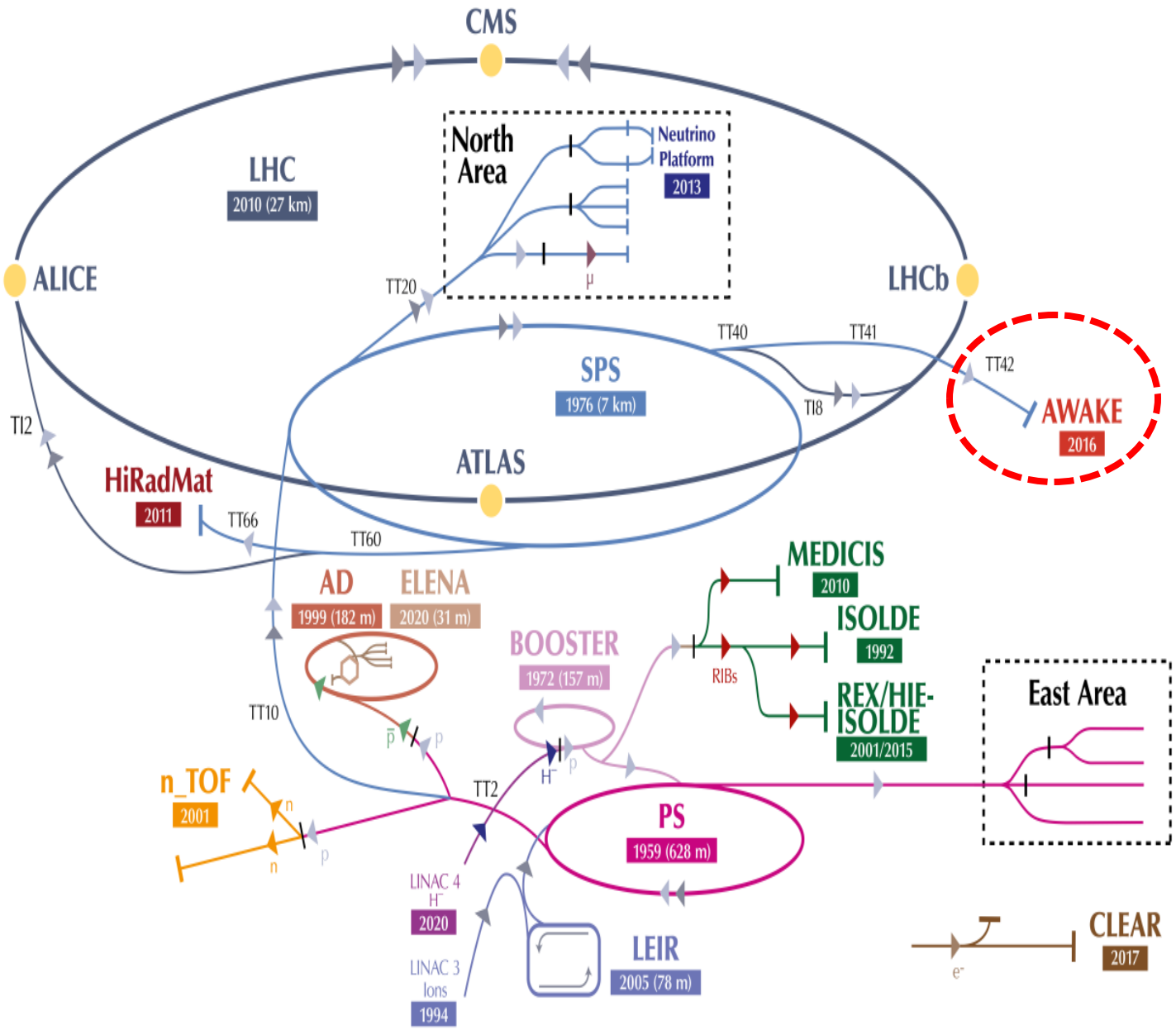
Edda Gschwendtner, CERN
for the AWAKE Collaboration

EAAC2025, 21 – 27 September 2025, Elba

AWAKE at CERN

Advanced WAKEfield Experiment

- → Accelerator R&D experiment.
- → 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.

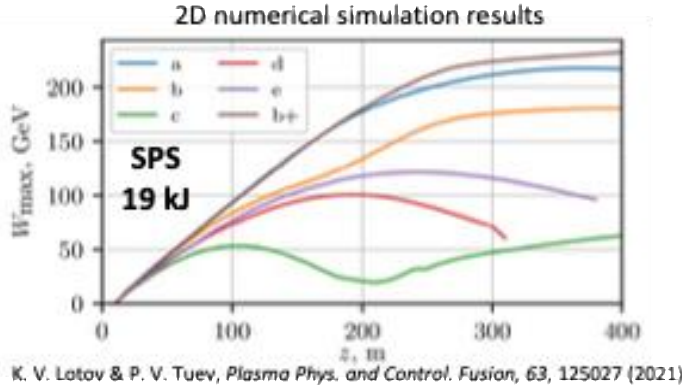
AWAKE is an International Collaboration

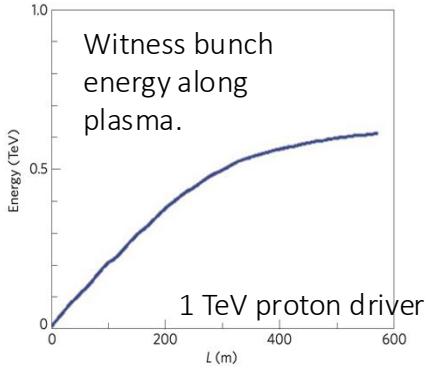
Strong commitment from 19 institutes

Towards Higher Energies

Proton bunch driver: ➔ single plasma cell

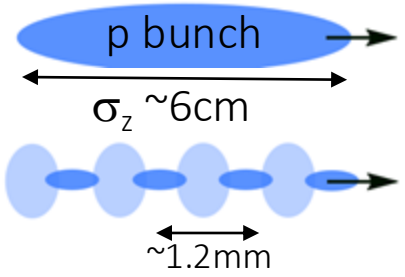
~SPS 19 kJ/bunch, LHC 112 kJ/bunch

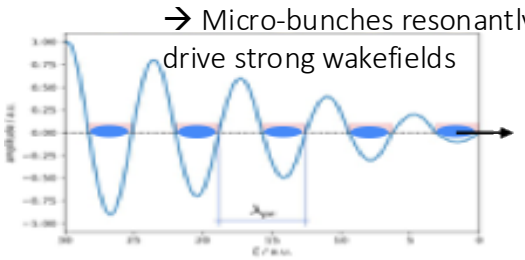




A. Caldwell et al., Nature Phys. **5**, 363–367 (2009)

➔ Rely on self-modulation of the proton-bunch





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

AWAKE Clear Timeline towards Applications

AWAKE addresses key challenges relevant for the entire plasma-based accelerator community:
➔ quality, emittance control, energy spread, external injection, plasma source developments, …

Transition from proof-of-concept towards applications.

AWAKE Experiment until Today

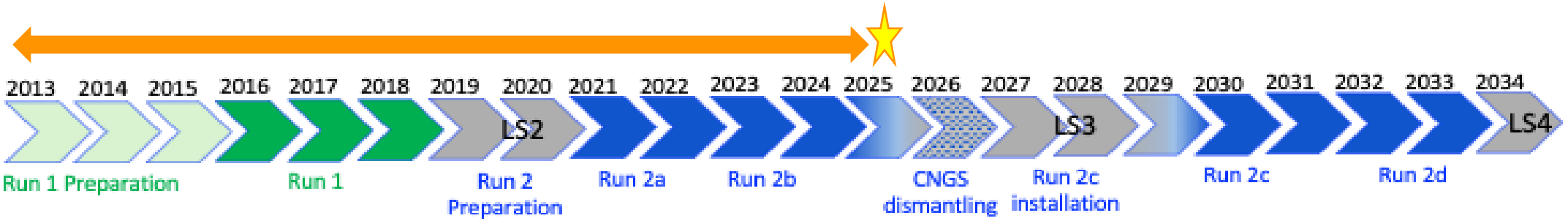
RUN 1 (2016-2018)

p+ self-modulation

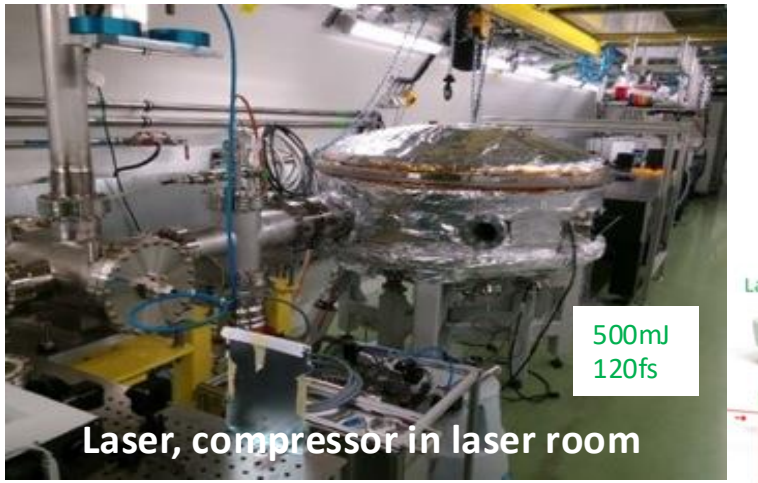
2 GeV e- acceleration

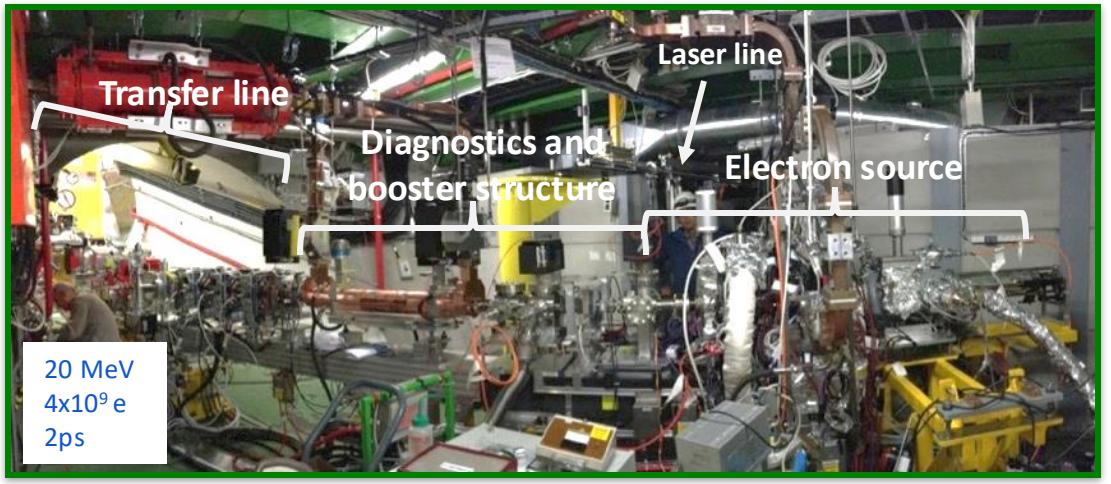
RUN 2 (2021-2033)

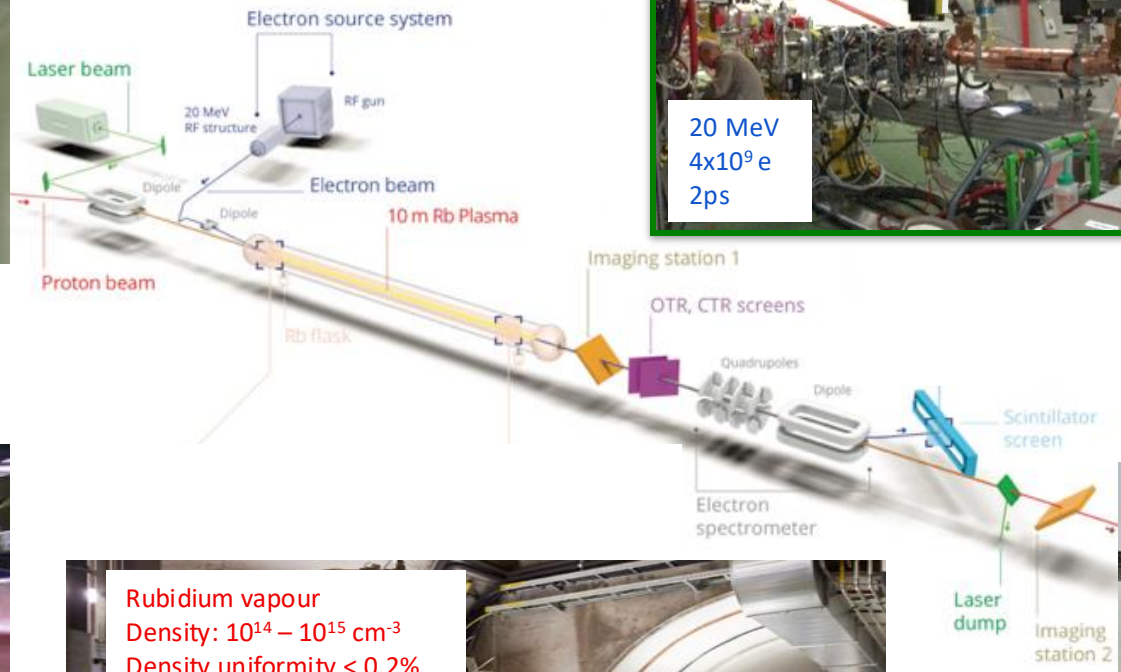
e- acceleration to several GeV,
beam quality control, scalability

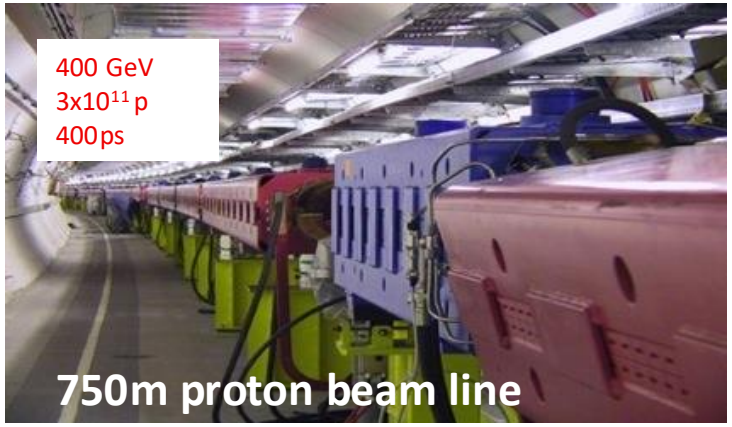


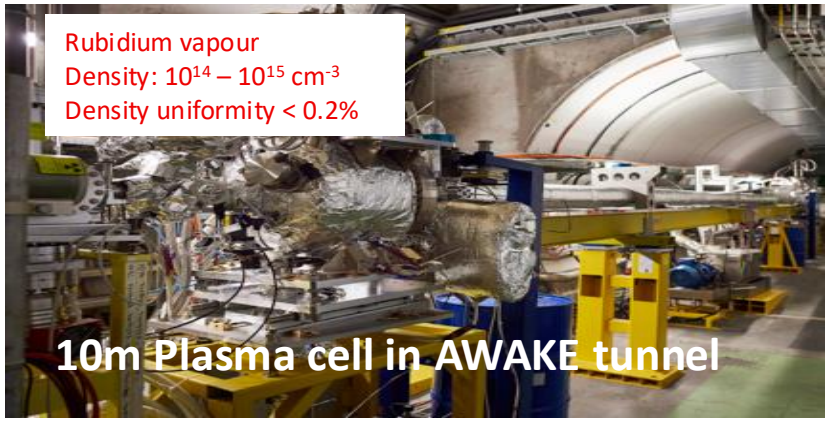
Key Ingredients of AWAKE





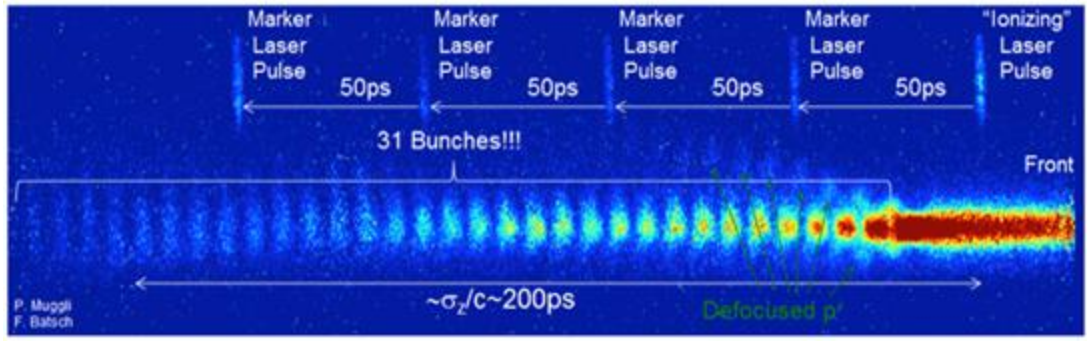




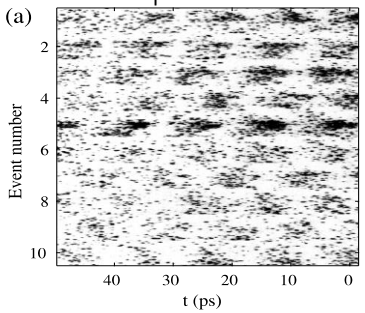


Proof-of-Principle Results

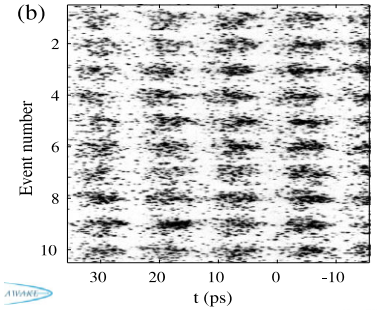
Seeded self-modulation of the proton bunch



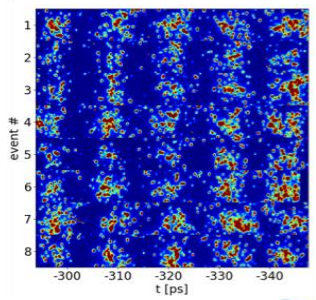
Unseeded: phase not reproducible



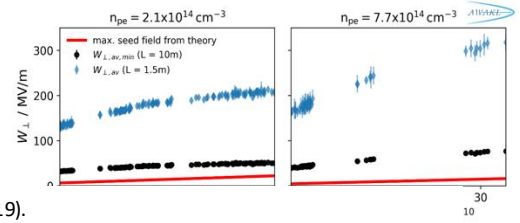
Seeded with laser ionization front



Seeded with e- beam

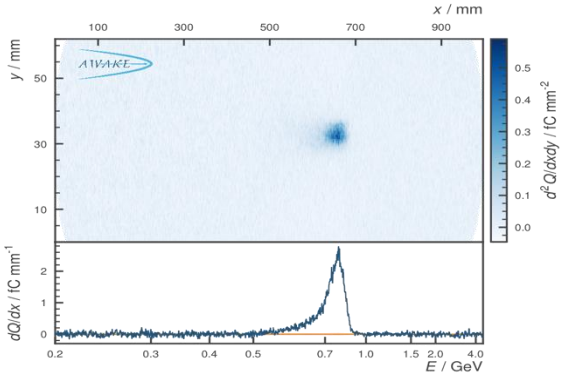


→ Phase stability of the SM
→ Reproducible SM
→ Wakefield growth due to SM

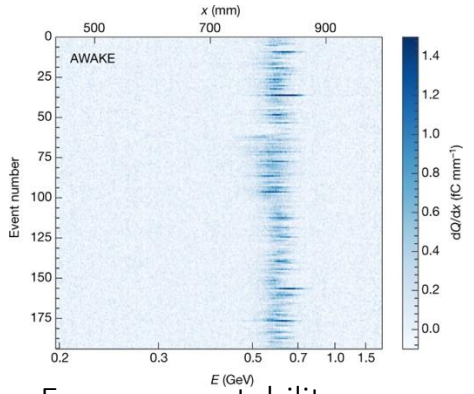


AWAKE Collaboration, Phys. Rev. Lett. 122, 054802 (2019).
M. Turner et al. (AWAKE Collaboration), Phys. Rev. Lett. 122, 054801 (2019).
M. Turner, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Accel. Beams 23, 081302 (2020)
F. Braunmueller, T. Nechaeva et al. (AWAKE Collaboration), Phys. Rev. Lett. 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)
L. Verra et al. (AWAKE Collaboration), Phys. Rev. Lett, 129, 024802 (2022)

Electron acceleration

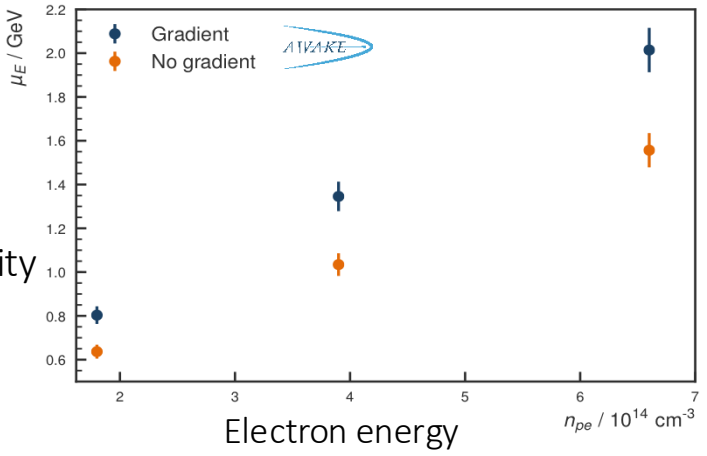


Electron spectrometer signal



Energy repeatability

Increased electron energy gain
→ with increasing plasma density
→ with plasma density gradient



Electron energy

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

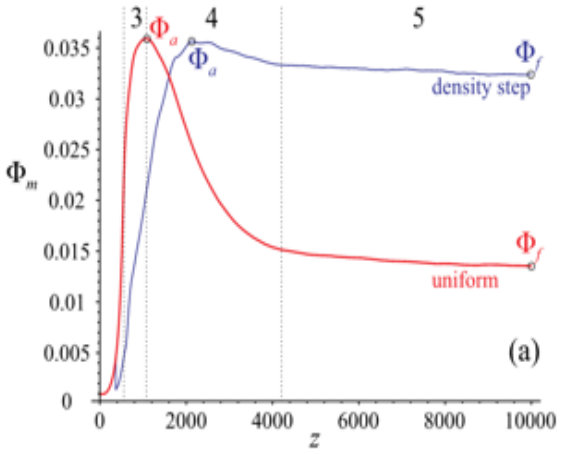
New Plasma Source with Density Step

Stabilising large wakefield amplitudes

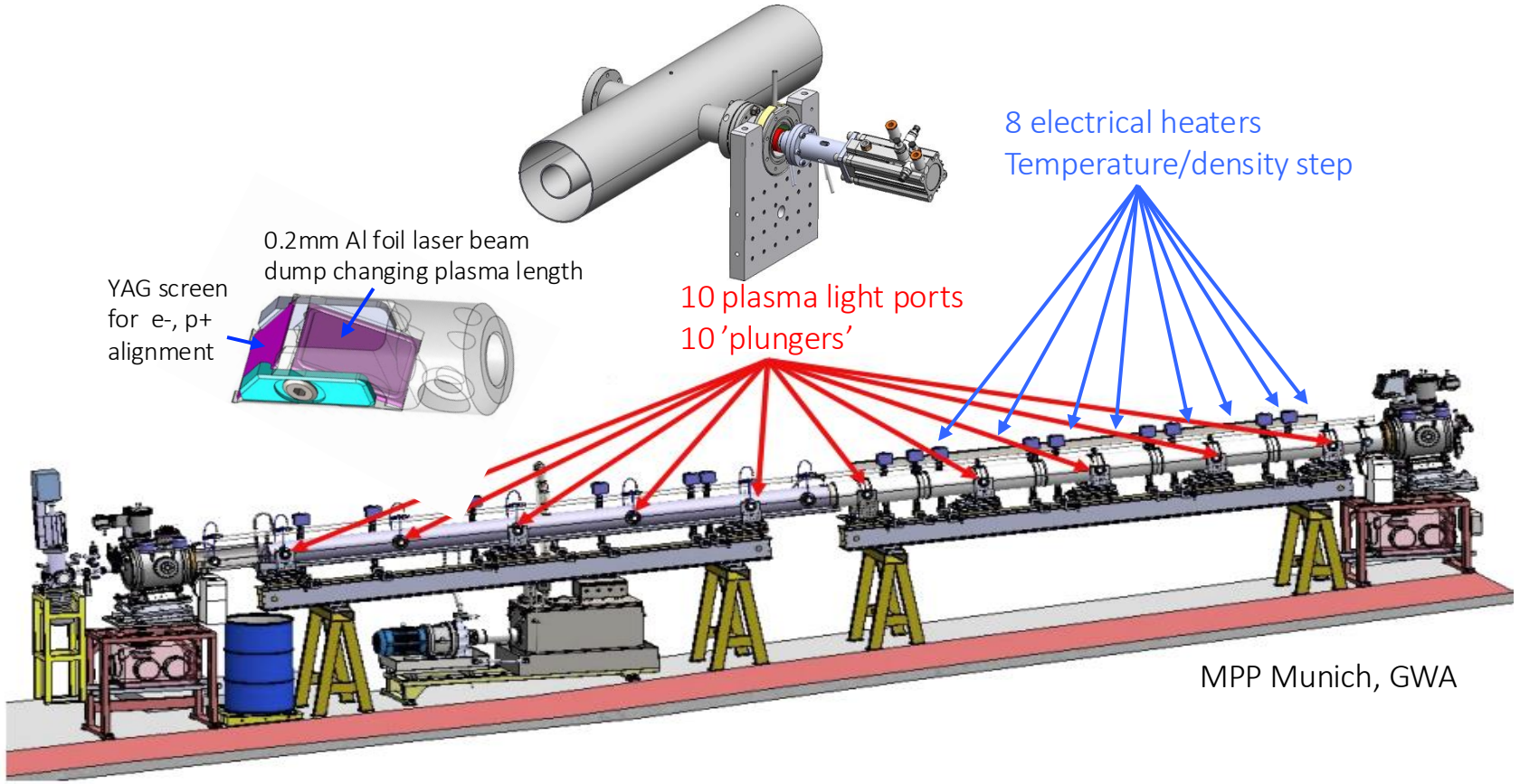
M. Bergamaschi, Talk, PS1, Wed

➔New plasma source: density step and change of plasma length

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

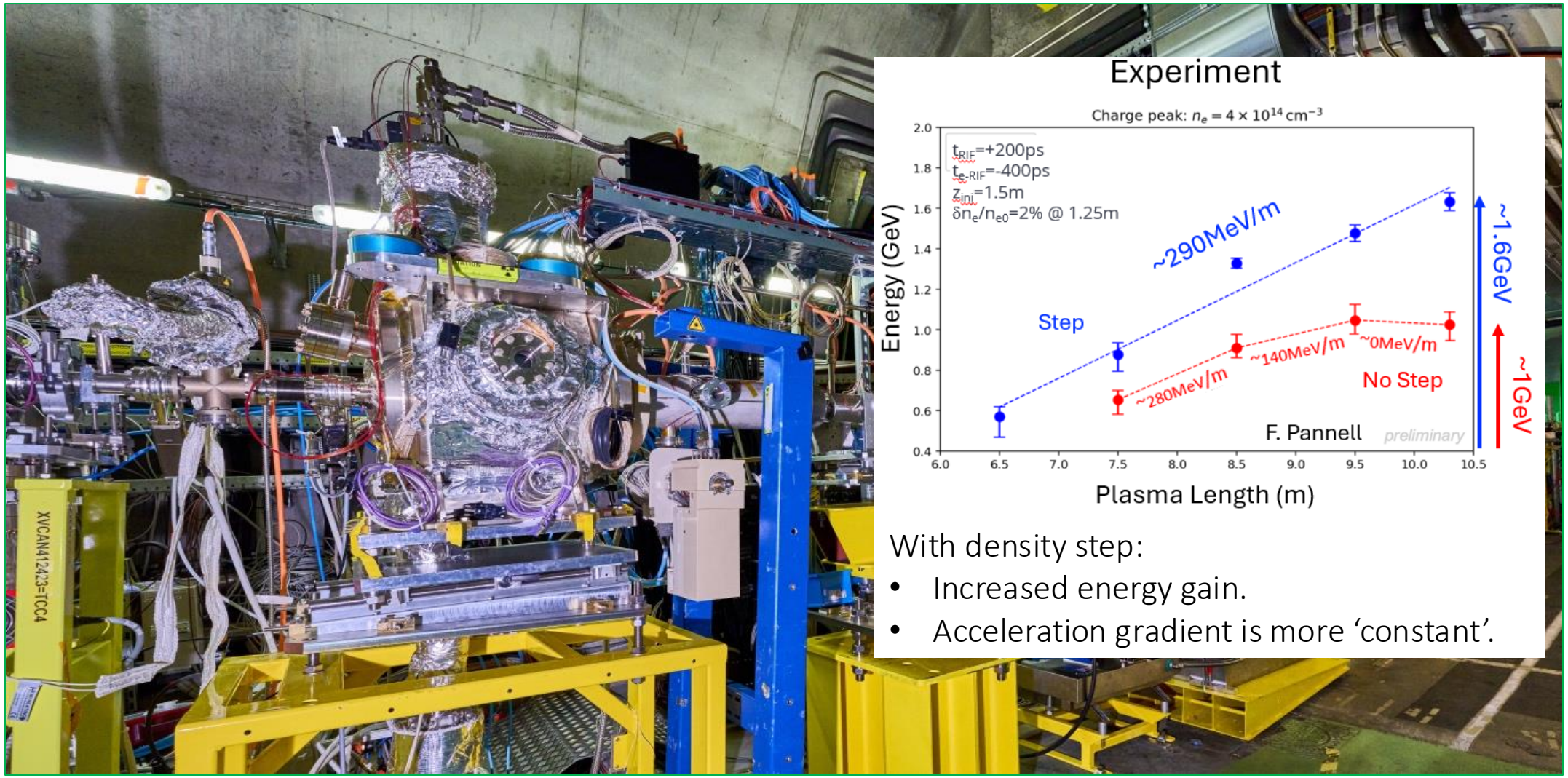


K. V. Lotov, Physics of Plasmas 22, 103110 (2015)
K. V. Lotov and P. V. Tuev 2021 PPFC ***63 125027***



- Independent electrical heater of 50 cm from 0.25 to 4.75 m, Step height up to ±10%
- 10 diagnostic viewport ➔ measure light emitted by wakefields dissipating after passage of the p+ bunch
- 10 plungers from 0.5m to 10.3m

New Plasma Source with Density Step - Results

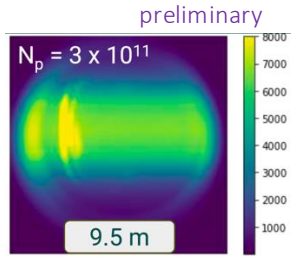


With density step:

- Increased energy gain.
- Acceleration gradient is more ‘constant’.

New Plasma Source with Density Step – Other Results

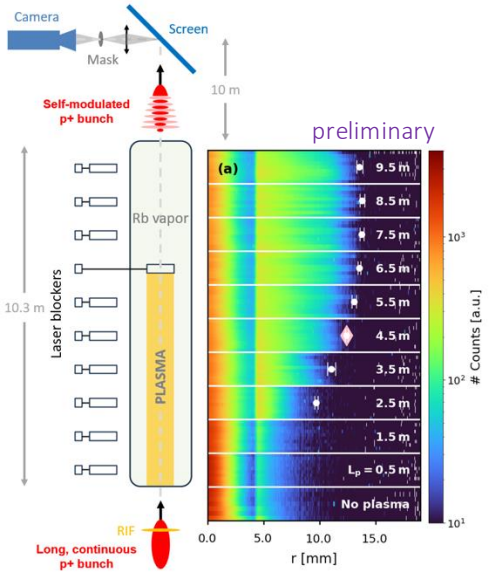
Light emission of dissipating wakefields



Investigate longitudinal evolution of wakefields

J. Mezger, Poster Tue

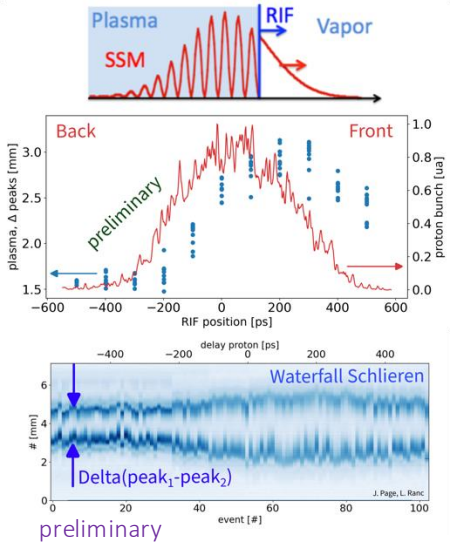
Saturation length of the self-modulation instability



Radial slice of transverse distribution of bunch at screen for different L_p.

A.Clairembaud, Poster Wed

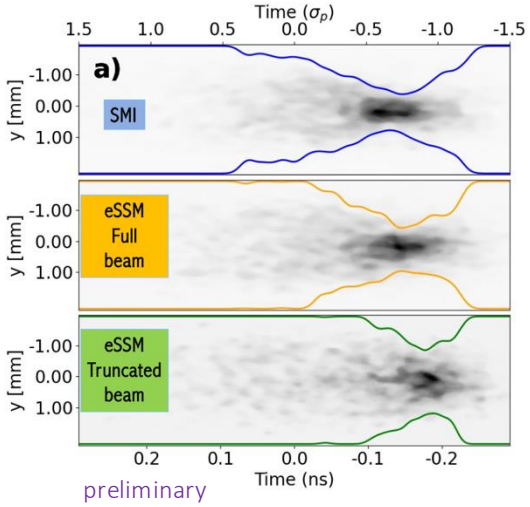
Plasma Radius



Schlieren Imaging diagnostic to determine in-situ the plasma transv. size. → Plasma transverse size in presence of wakefields (RIF Scan).

L. Ranc, Talk, PS8, Thu

Electron beam seeding at $7x10^{14}$ cm^{-3}

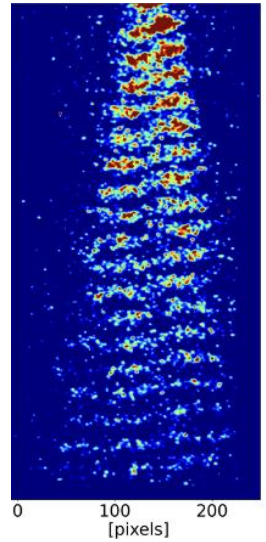


Using a truncated electron beam suggests stronger self-modulation seeding.

N. Van Gils, Poster, Mon

Beam-hose instability

9.5m preliminary



Growth of the instability along the plasma.

M. Bergamaschi, Talk, PS1, Thu

New Plasma Source with Density Step – Other Results

Light emission of dissipating wakefields

Investigate longitudinal evolution of wakefields

J. Mezger, Poster Tue

Saturation length of the self-modulation instability

Radial s… distribu… differen…

A…

Plasma Radius

Electron beam seeding at 7x10^{14} cm^{-3}

…tron beam …modulation

…ster, Mon

Beam-hose instability

9.5m preliminary

Growth of the instability along the plasma.

M. Bergamaschi, Talk, PS1, Thu

Thanks to a great team!

AWAKE: What's Next?

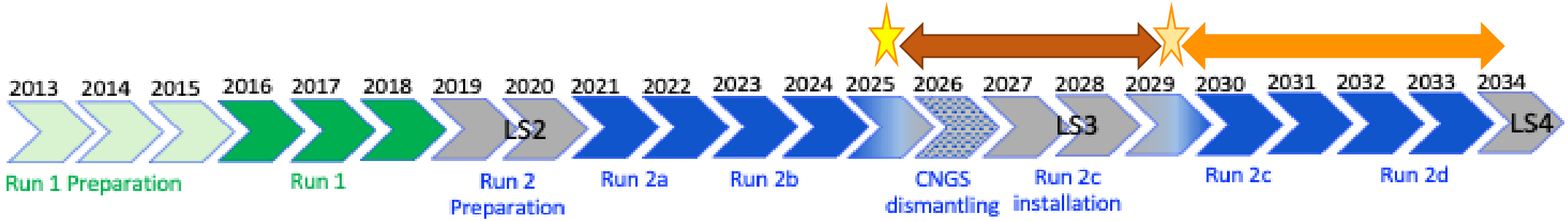
RUN 1 (2016-2018)

p+ self-modulation

2 GeV e- acceleration

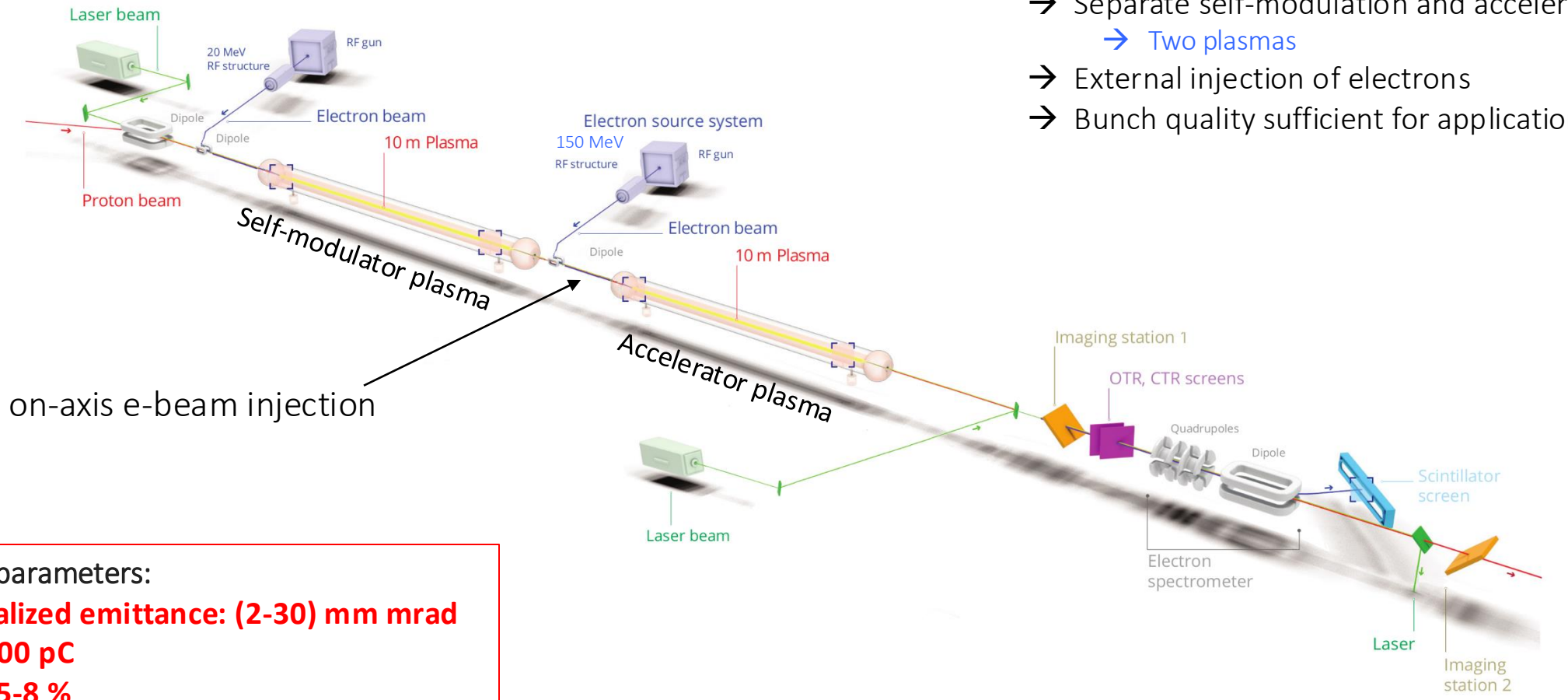
RUN 2 (2021-2033)

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



Next: Two Plasma Sources – Electron Beam Quality

Demonstrate electron acceleration and emittance control of externally injected electrons.



- → Separate self-modulation and acceleration
  - → Two plasmas
- → External injection of electrons
- → Bunch quality sufficient for applications

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**

➔ Start with physics program in 2029 after LS3

Getting Ready for Run 2c: CNGS Target Area Dismantling

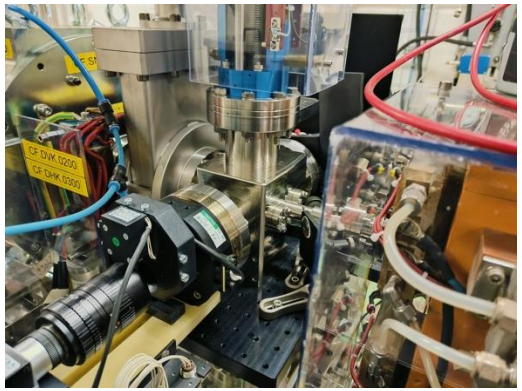
600 m^3 equipment (including 500 m^3 shielding blocks) up to 20 mSv/hr

New surface building for the storage of CNGS concrete shielding blocks to reuse at CERN.

→ Dismantling: 2025/2026

Getting Ready: Design, Integration and Installation

New e-source prototype
in CTF2 → commissioned



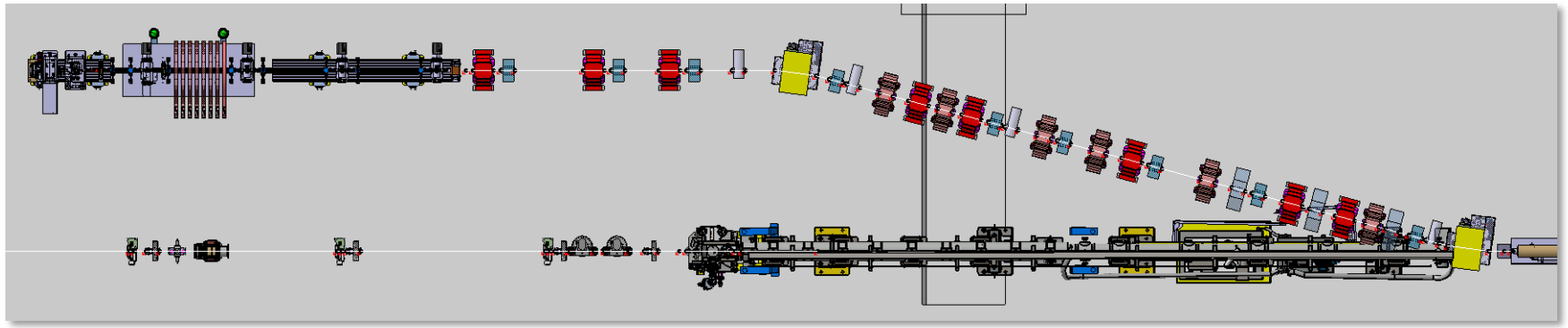
S. Doebert, Talk, PS2, Mon

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

E. Belli, Talk, PS4, Mon

→ bunch length shorter than plasma wavelength, $\varepsilon_{\mathrm{norm}\,(x,y)}$ = 2mm mrad

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



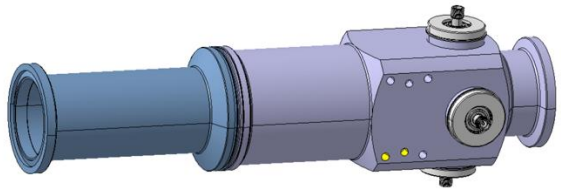
→ Position of beam line elements well defined.

→ Design and integration of services ongoing.

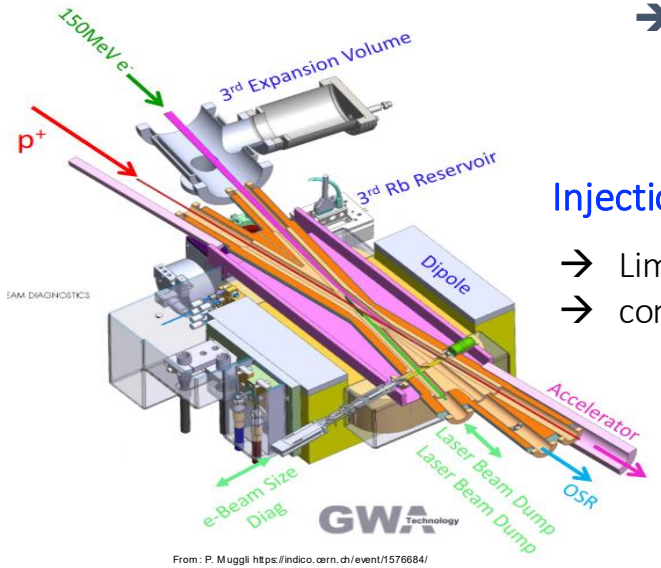
Improved instrumentation

→ High resolution BPMs (10µm) and beam screens (1µm)

→ Emittance measurements, bunch length



M. Moreira, Talk, PS4, Mon



Injection region

→ Limited space

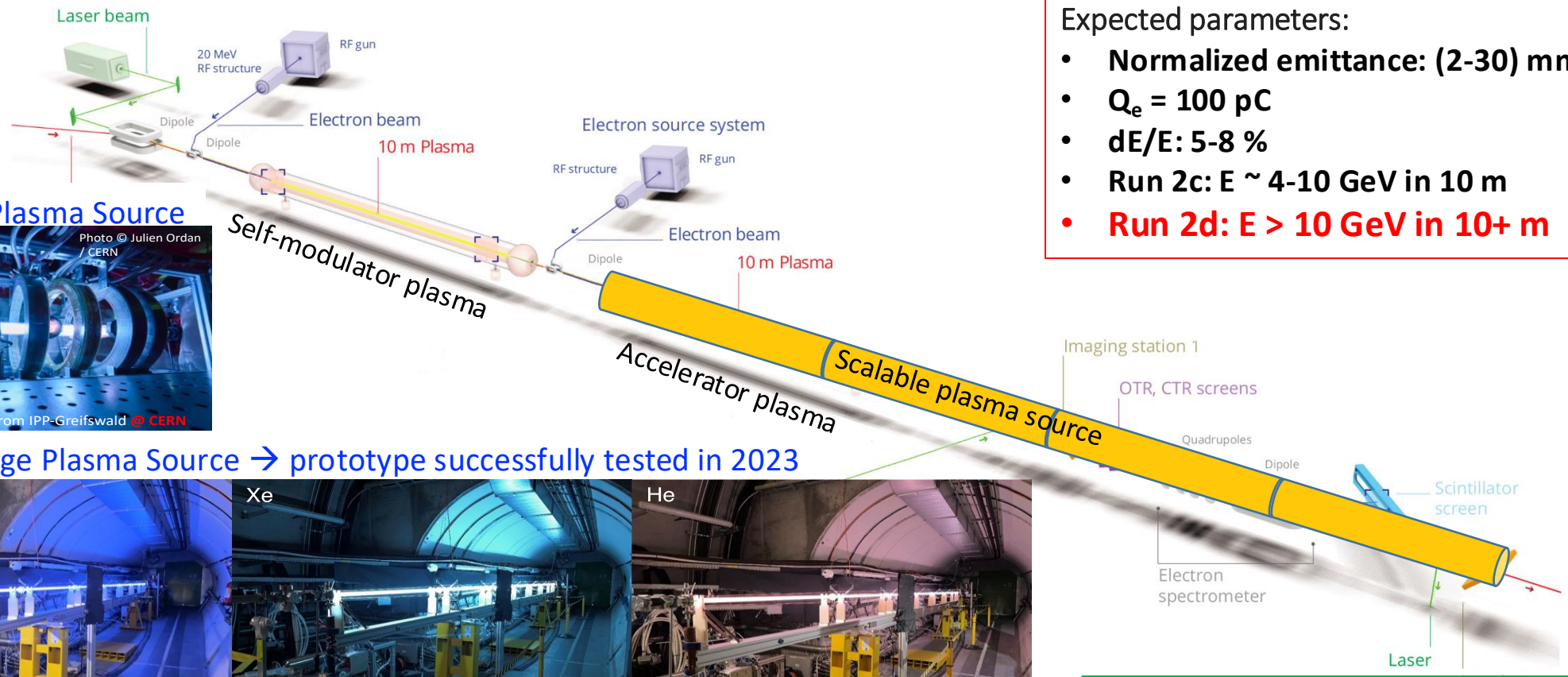
→ components with custom design

→ Installation: 2027/2028

→ Physics Run starts in 2029

Next, Next: Scalable Plasma Sources – Demonstrate Scalability

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



1m Helicon Plasma Source

10m Discharge Plasma Source → prototype successfully tested in 2023

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**

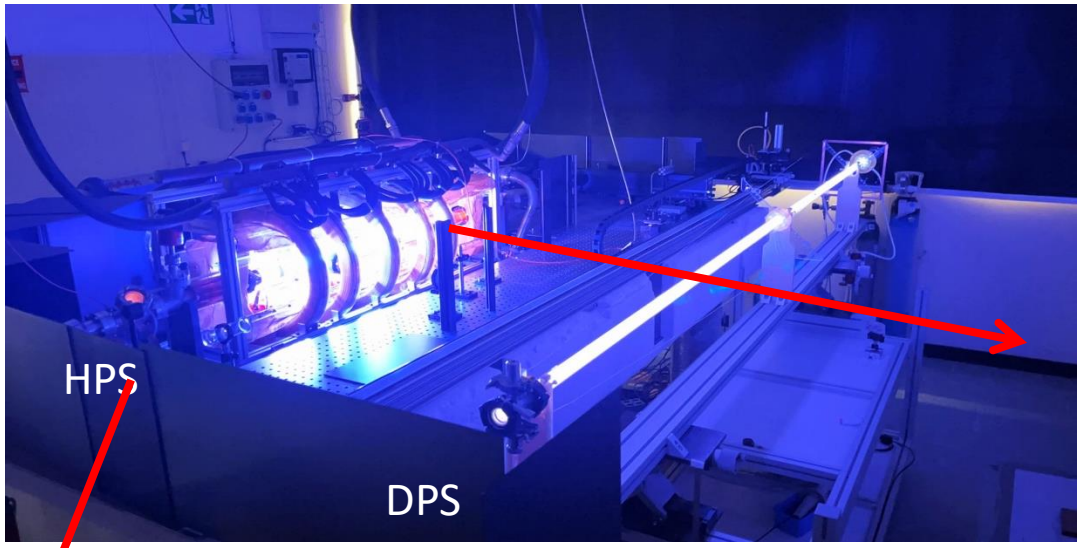
→ Scalability demonstration: 2032/2033

Experimental observation of the motion of ions in a resonantly driven plasma wakefied accelerator
M. Turner et al. (AWAKE Collaboration), PRL 134, 155001, 2025

Scalable Plasma Sources R&D Results:
→ First Longitudinal Density Profiles Using Thomson Scattering

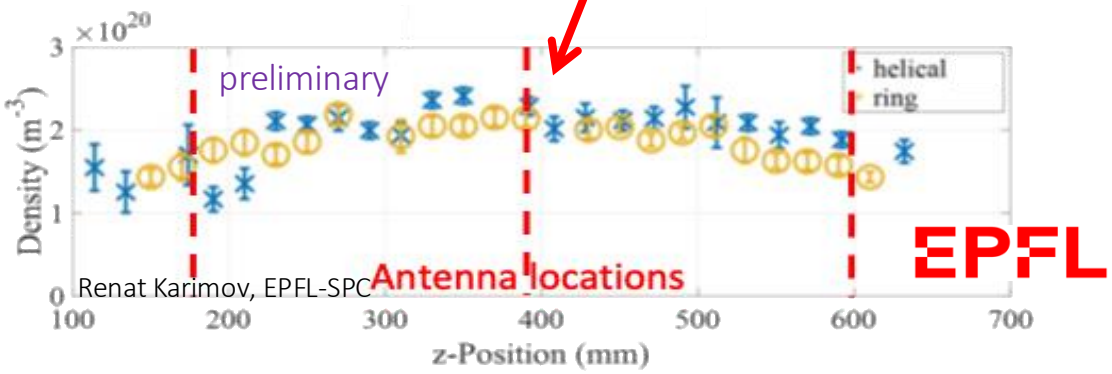
A. Sublet, Talk, PS1, Wed

Technical challenge: achieve 0.25% plasma uniformity and be able to measure it.
So far, ~ 6% measured uniformity, at the limit of diagnostic capability!
→ focus on plasma diagnostics and source design optimization.



1 m Helicon Plasma Source (HPS)

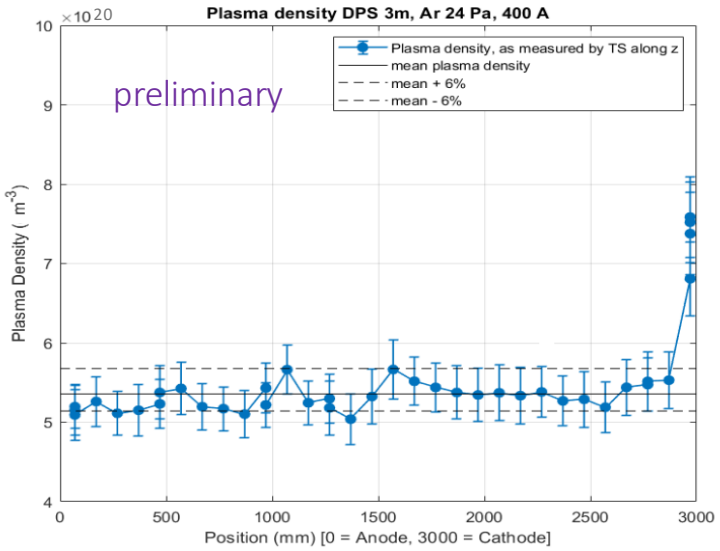
uniformity ± <11 %



Renat Karimov, EPFL-SPC

3 m Discharge Plasma Source (DPS)

uniformity ± 6%

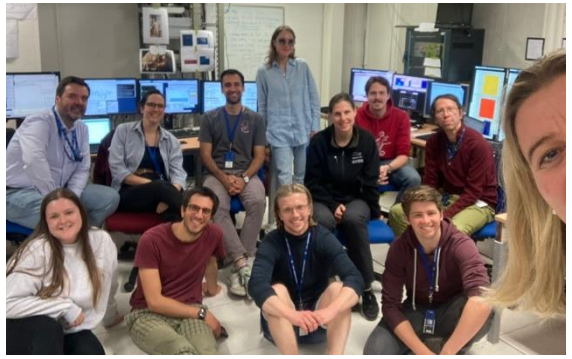


Carolina Amoedo, CERN/IST

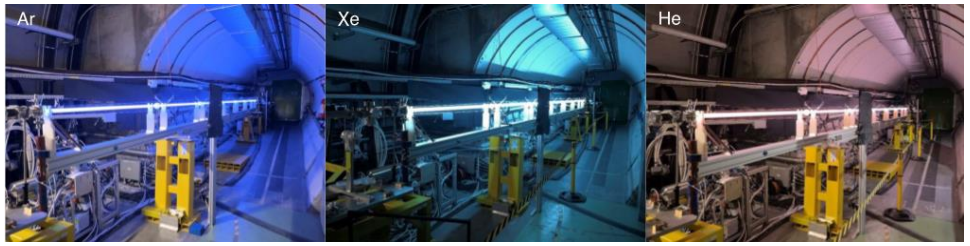
C. Almoedo, Poster, Tue

Synergies with Other Major Projects

- AWAKE is a novel accelerator in a real accelerator environment
  - Commissioning and operation of complex experiment.



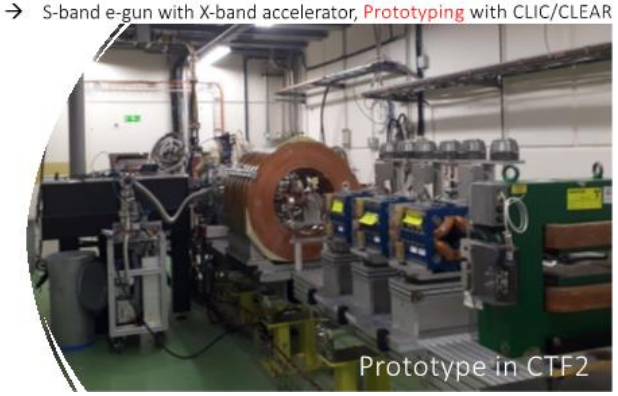
- HALHF, ALIVE, Higgs factories
  - Long, uniform, well-controlled plasma sources.
  - External injection → staging.
  - Proton-driven wakefields.
  - Understanding of beam-plasma instabilitites.
  - Development and validation of simulation tools.



- FCC-ee, CLIC
  - Experts on electron acceleration and operation are trained on AWAKE.

- CLEAR, CTF2
  - Development of new RF photo-injector.
  - Development/test of electron beam diagnostics.
  - Maintaining electron gun and beam line expertise.

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



First Applications

Applications of AWAKE Technology

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

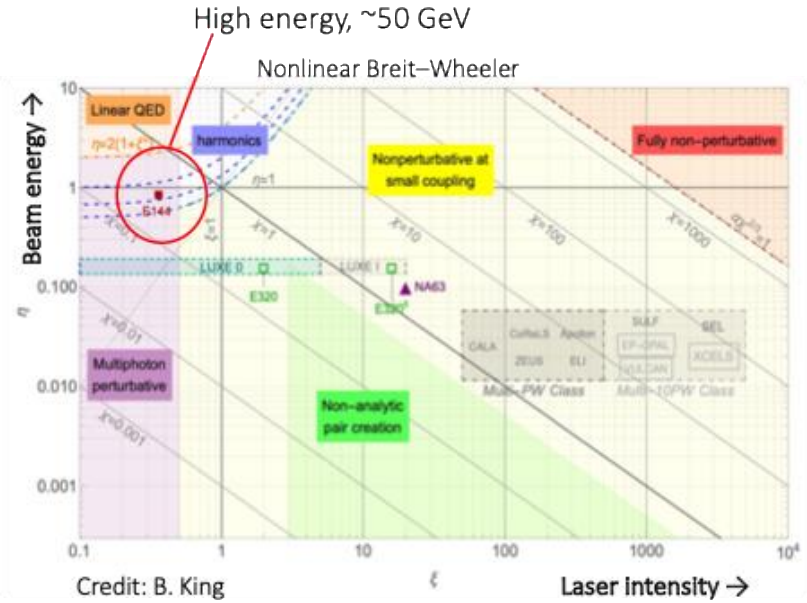
First applications to high energy physics for 50 GeV beam:

→ 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**

→ Investigate new region with high energy, currently no competitors, only modest laser needed, with increasing laser power probe more phase space



Higgs Factory based on plasma wakefields – ALIVE

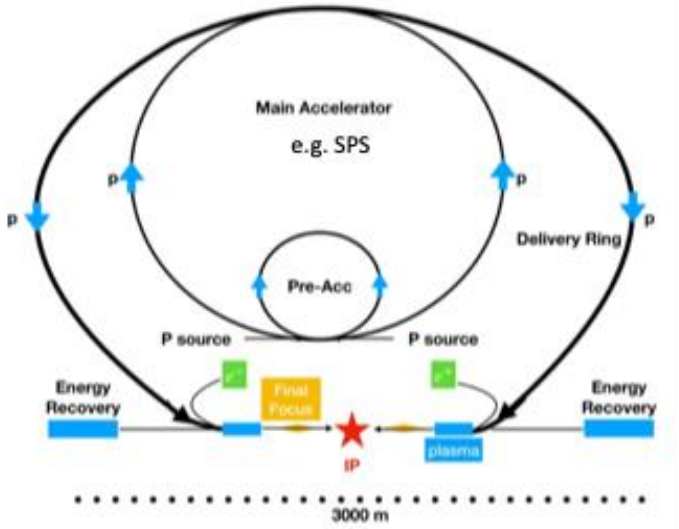
Collision energy: 250 (125 + 125) GeV, with upgrade to TeV range

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 (s_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)*

→ Still many challenges

A. Pukhov, Talk, PS9, Wed

Summary

- AWAKE is a high-profile accelerator R&D experiment and has achieved significant scientific and technological progress.
  - All milestones achieved: processes of self-modulation, instabilities, electron acceleration, etc. well understood.
  - Developed self-modulator plasma source, scalable plasma source prototypes.
  - Exploit the unique possibilities of the CERN accelerator complex and adding to the diversity of the CERN program.

- AWAKE addresses many challenges common to all plasma-based accelerators.

- AWAKE has a clear program for Run 2 until 2034 and towards first applications.
  - Major upgrades are underway for physics start in 2029, when proton beam is back.
  - Demonstrate high-quality acceleration of electrons to high energies using scalable plasma source.
  - Propose first particle physics experiments.


AWAKE