– Project Review –
an Advanced WAKefield Experiment

Max Planck Institute for Physics
09/12/2024

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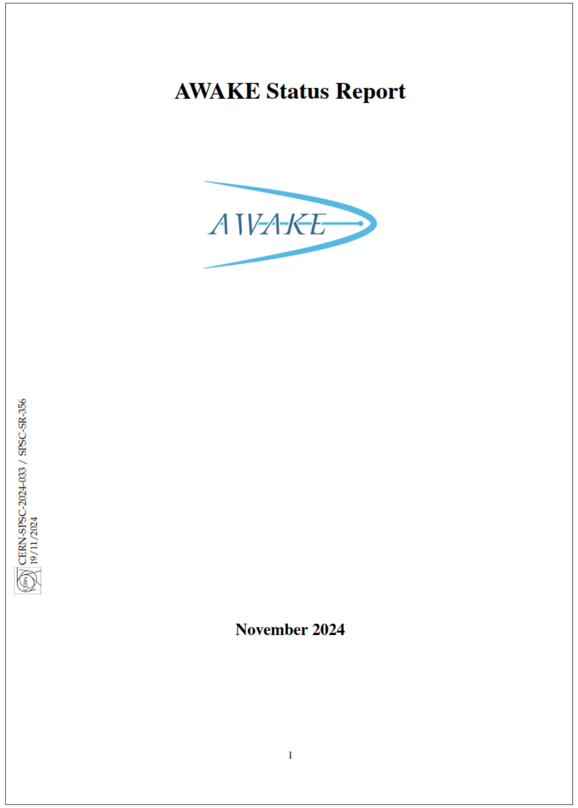
AWAKE Status Report

CERN-SPSC-2024-033 / SPSC-SR-356
19/11/2024

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https://cds.cern.ch/record/2917426/files/SPSC-SR-356.pdf

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- Recent Results
  - ➢ Plasma source upgrade
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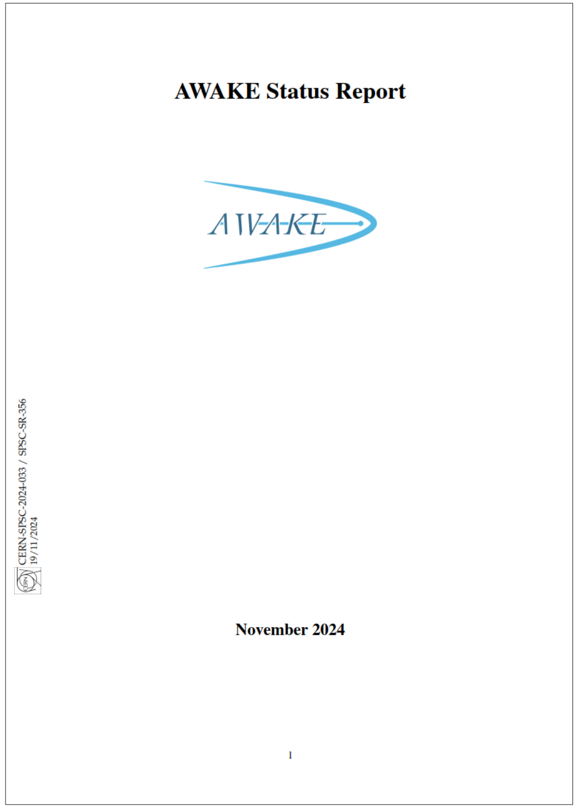
- Summary & Outlook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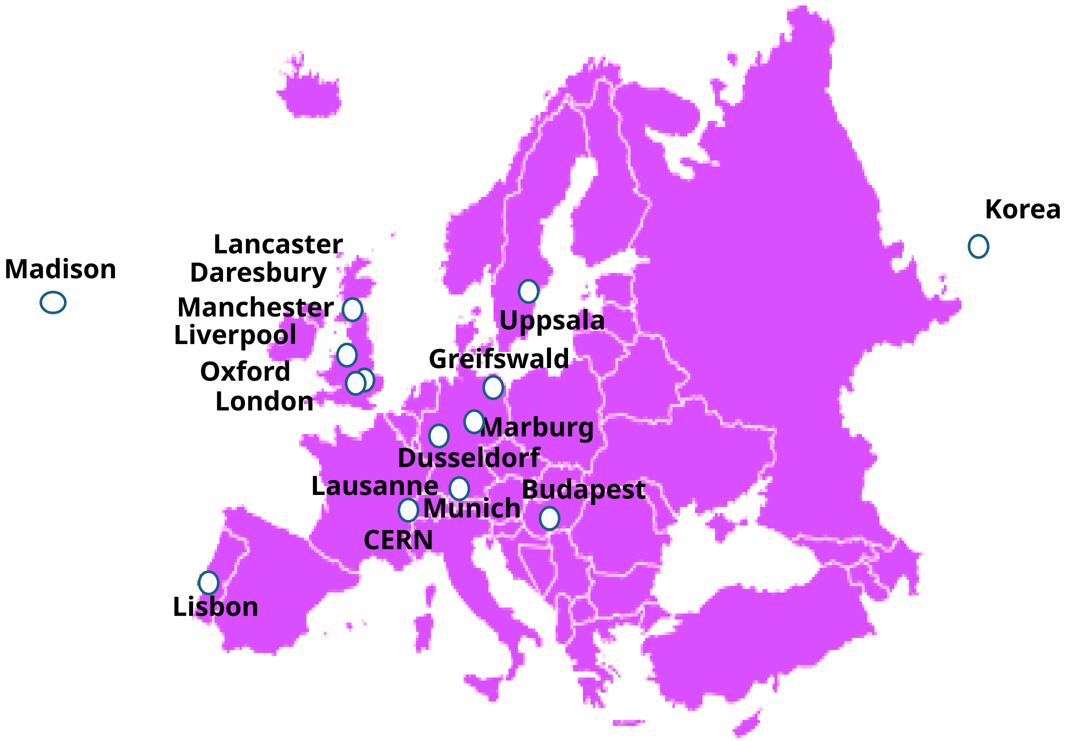
AWAKE Collaboration: 19 Institutes World-Wide

- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Oxford University, UK
- **Max Planck Institute for Physics, Munich, Germany**
- Max Planck Institute for Plasma Physics, Greifswald, Germany
- UCL, London, UK
- UNIST, Ulsan, Republic of Korea
- Philipps-Universität Marburg, Marburg, Germany
- Heinrich-Heine-University of Düsseldorf, Düsseldorf, Germany
- University of Liverpool, Liverpool, UK
- ISCTE - Instituto Universitéario de Lisboa, Portugal
- GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
- Ludwig-Maximilians-Universität, Munich, Germany
- University of Wisconsin, Madison, US
- Uppsala University, Sweden
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL, Lausanne, Switzerland

MPP – AWAKE, Future accelerator Group



AWAKE Team

Patric
Muggli

Allen
Caldwell

Post-Docs

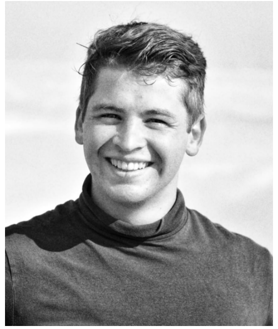
Michele
Bergamaschi

Lucas
Ranc

John
Farmer

PhD Candidates

Arthur
Clairembaud



Jan
Mezger

Master student

Jedd Page

Graduated PhD
Pablo Morales Guzmàn
Livio Verra → INFN
Tatiana Nechaeva → DESY

Acceleration of Charged Particles

Conventional accelerators:

RF accelerators have limited acceleration gradient because of RF cavities maximum field. The limit of the order of **100 MeV/m** due to electrical breakdown in resonant cavities

Plasma wakefields accelerators:

Use of plasma (ionized) as an accelerating medium overcomes the breakdown limits of the RF cavities and gradients above **1 up to 100 GeV/m** have been demonstrated

$$E_{WB} = \frac{m_e c}{e}\omega_{pe} \quad \text{where} \quad \omega_{pe} = \sqrt{\frac{n_{pe} e^2}{\epsilon_0 m_e}}$$

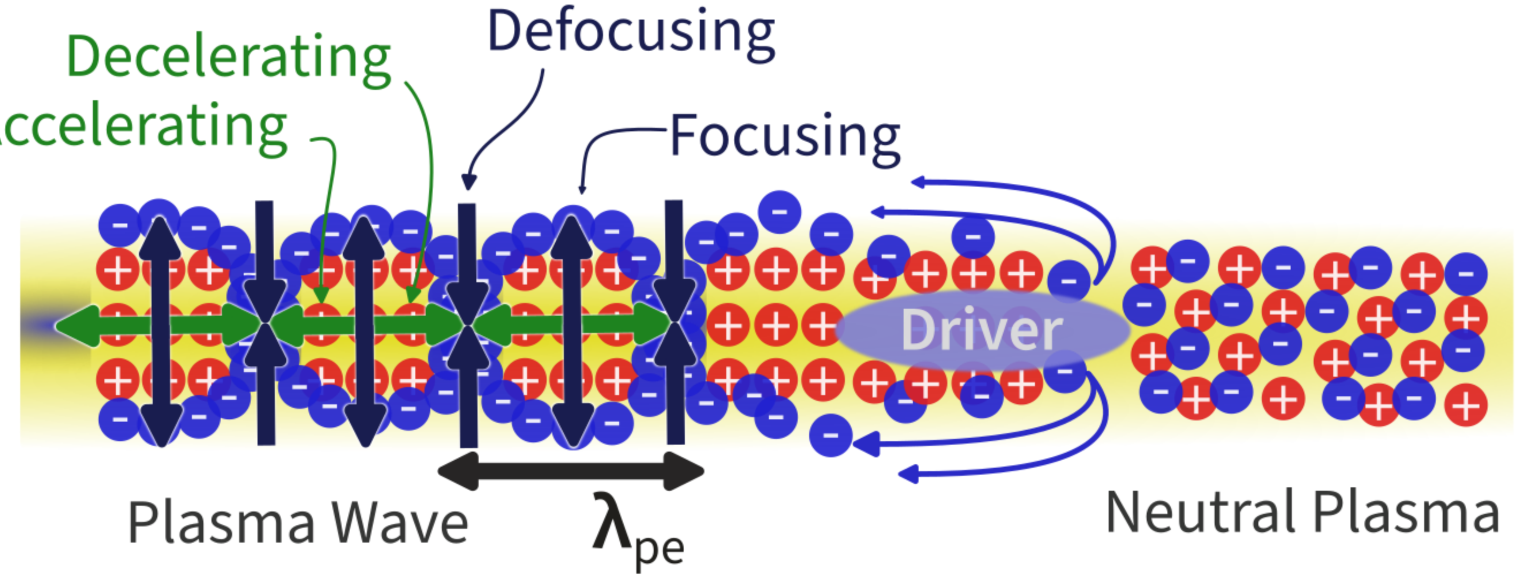
scale

$$\mathrm{E}_{WB} \propto 100\sqrt{n_{pe}}$$

$$\mathrm{n}_{pe} \approx 10^{14} - 10^{18} cm^{-3}$$

Plasma Wakefield Acceleration

- A **driver** can be
  - ultra-short, high-intensity **laser pulse**,
  - short relativistic **bunch of - or + charged particles**
- The driver generates a **radial transverse force**
  - Expel or / Attract — plasma electrons
  - **→ Leads to a periodic e- oscillation**
  - **→ Wakefields**



- To drive wakefields **E >> 1 GV/m** ; Need the driver
  - Longitudinal size σ_t **smaller than** λ_{pe} plasma wavelength
  - Transverse size σ_r **smaller than** k_{pe} 1/(plasma skin depth)

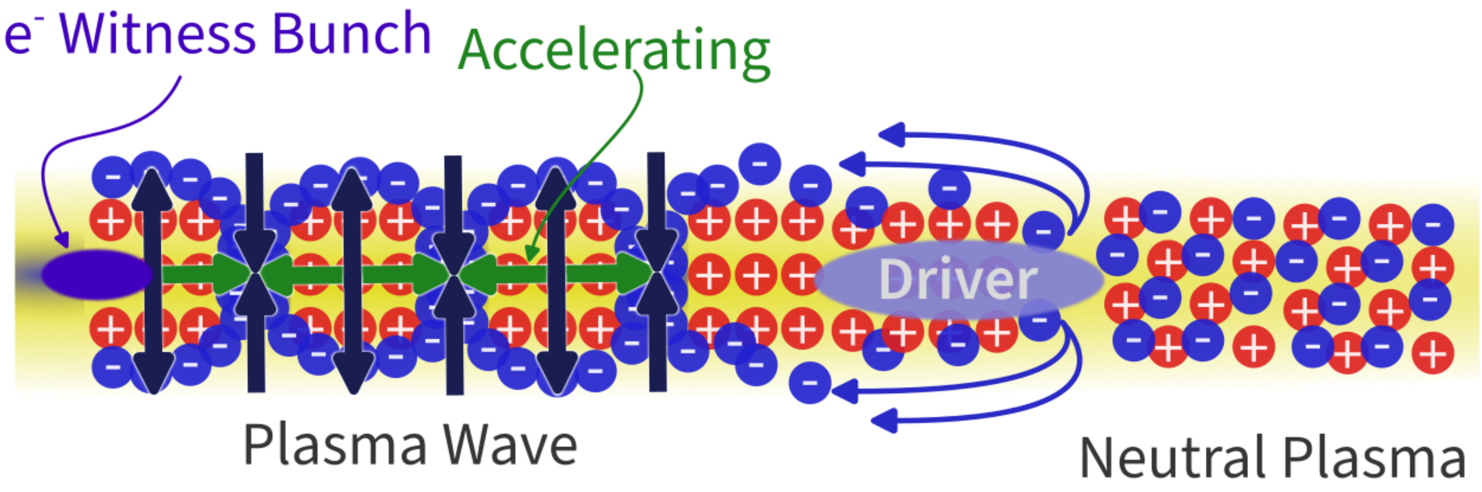
$$\sigma_t \sim 4\ ps\ (\leq \lambda_{pe} = 2\pi c/\omega_{pe} \sim 1 - 3\ mm)$$

$$\sigma_r \leq \frac{c}{\omega_{pe}} \simeq 200\ \mu m$$

$$\rightarrow E_{WB} \propto \frac{1}{\sigma_t}$$

Plasma Wakefield Acceleration

The **Driver** travels in the plasma to **induce** a modulation of the plasma electron density that sustains longitudinal and transverse fields which are called **wakefields**



>1 GV/m wakefield can be used to accelerate particles

AWAKE:

- CERN SPS proton bunch as driver of wakefields
- Accelerate externally injected electron witness bunch ~MeV to GeV

$$E_{WB} \propto \frac{1}{\sigma_t}$$

$$\mathrm{E}_{WB} \propto 100\sqrt{n_{pe}}$$

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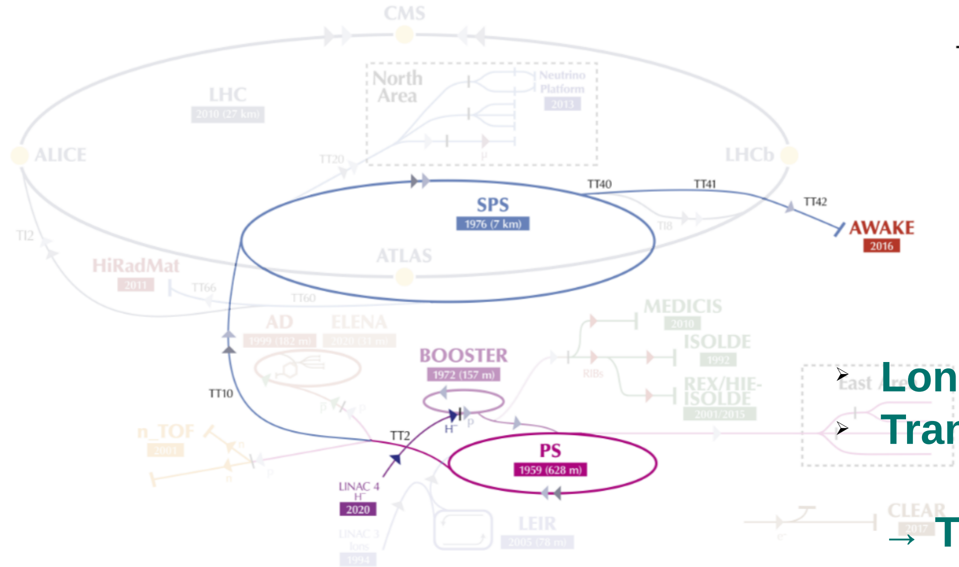
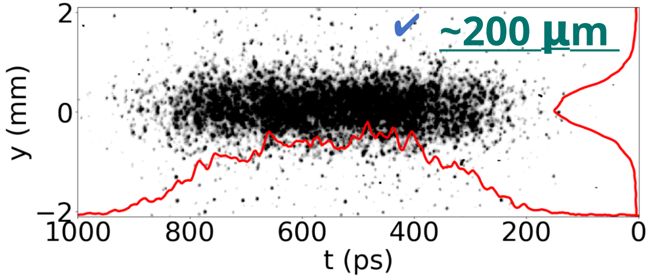
AWAKE is a Plasma Wakefield Acceleration experiment using a **proton driver**

CERN Synchrotron SPS as Driver (400 GeV):

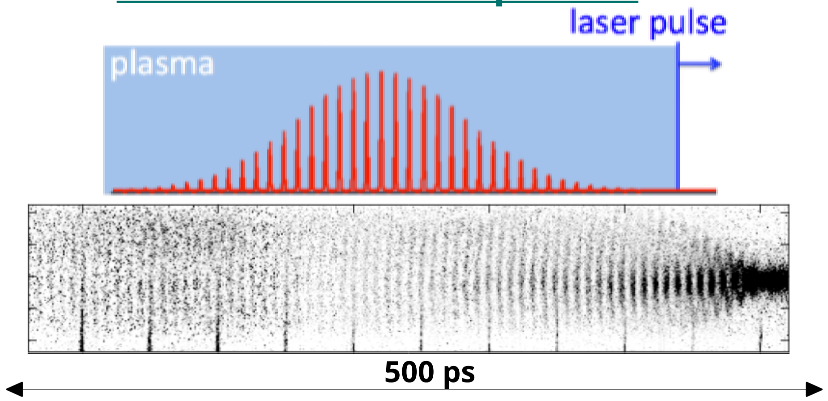


Time resolved measurement



✗ 200 ps (6 cm)
(>> 4 ps ~ mm)

Self-Modulation in plasma



- **Long p+ bunch** propagating in plasma is **subject** to **Self-Modulation** (SM) instability.
- **Transform** driver bunch into a **train of shorter bunches** with a periodicity λ_{pe}.

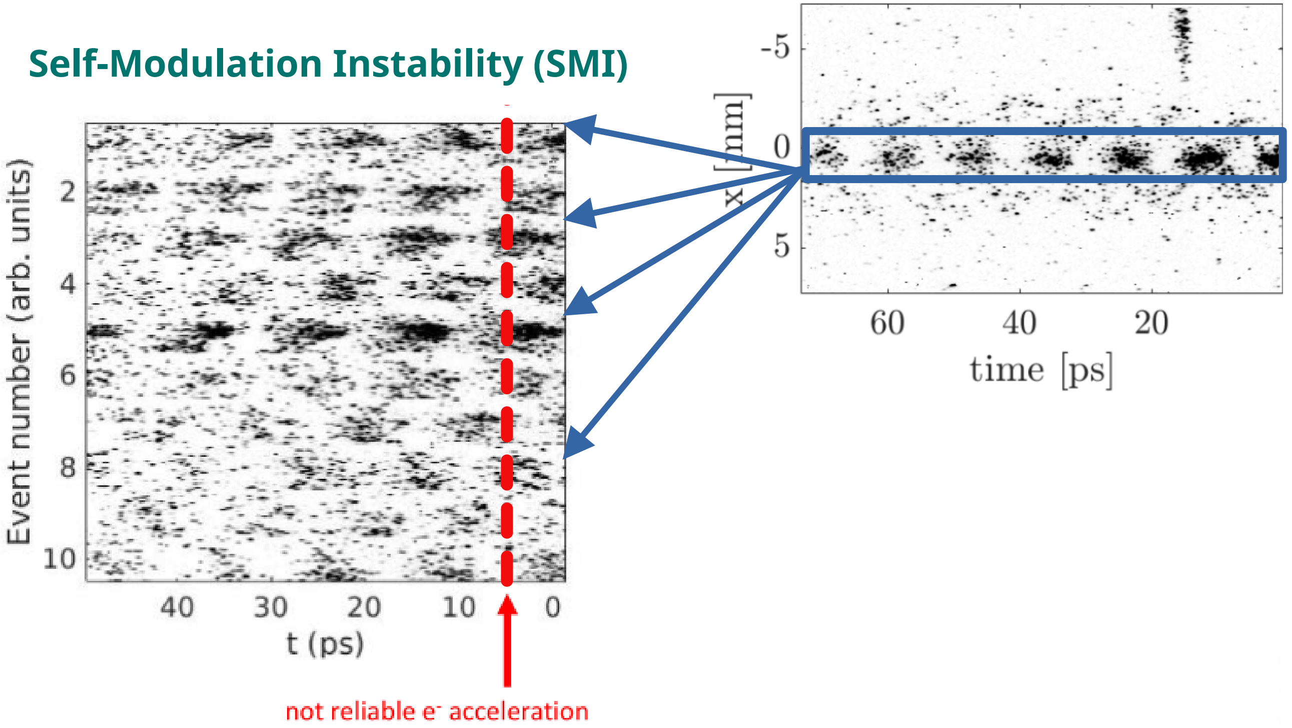
→ **The micro-bunch train can then resonantly excite large amplitude wakefields.**

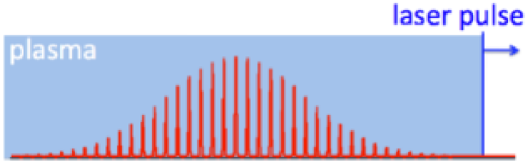
AWAKE is a Plasma Wakefield Acceleration experiment using a **proton driver**

Controlled Self Modulation (SM) → Seed

- Relative **phase** of the wakefields control
- Deterministic **injection to accelerate** a witness bunch

Self-Modulation Instability (SMI)





AWAKE is a Plasma Wakefield Acceleration experiment using a **proton driver**

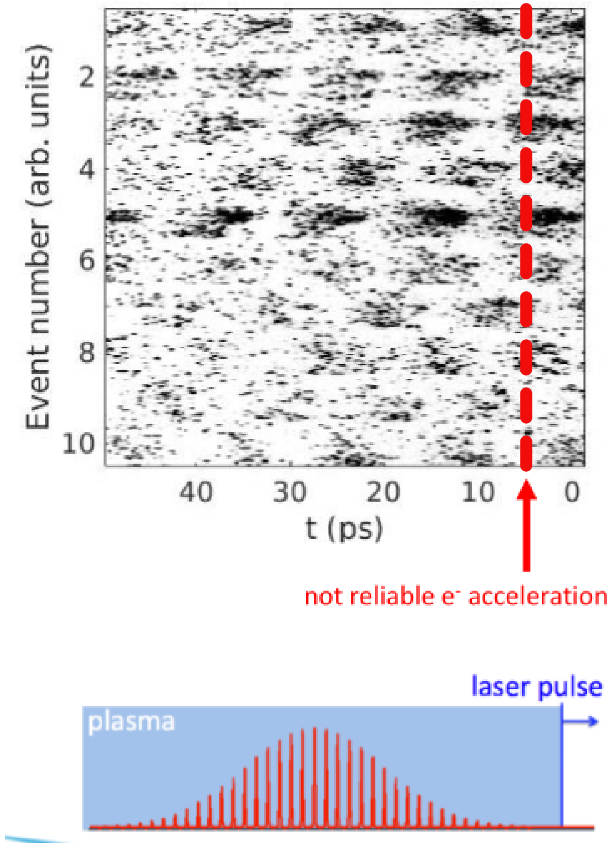
Controlled Self Modulation (SM) → Seed

- Relative **phase** of the wakefields control
- Deterministic **injection to accelerate** a witness bunch

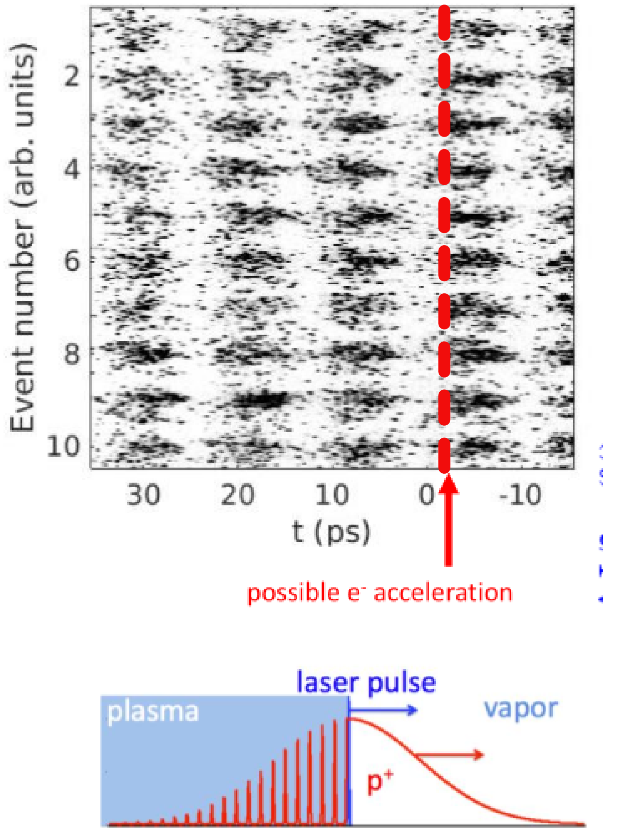
AWAKE has recently demonstrated [1] that the SM process does indeed transform a long proton bunch ($\sigma_t > 200$ ps) into a train of micro-bunches with period $2\pi/\omega_{pe}$ (<10 ps)

[1] AWAKE collaboration,
Acceleration of electrons in the plasma wakefield of a proton bunch,
Nature 561, 363–367 (**2018**)

Self-Modulation Instability (SMI)



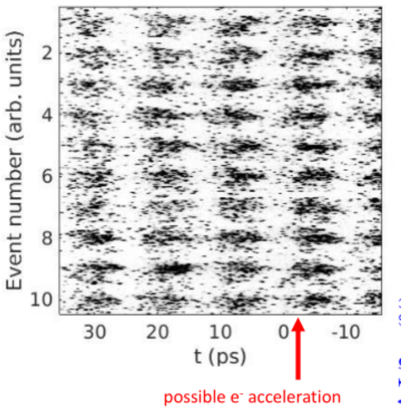
Seeded Self-Modulation (SSM)

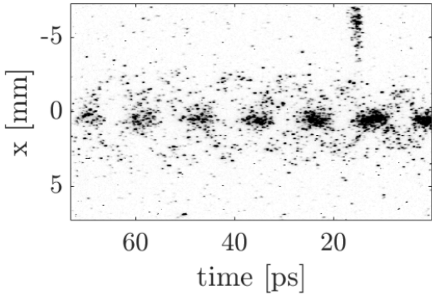


Acceleration Towards a (scalable) Accelerator

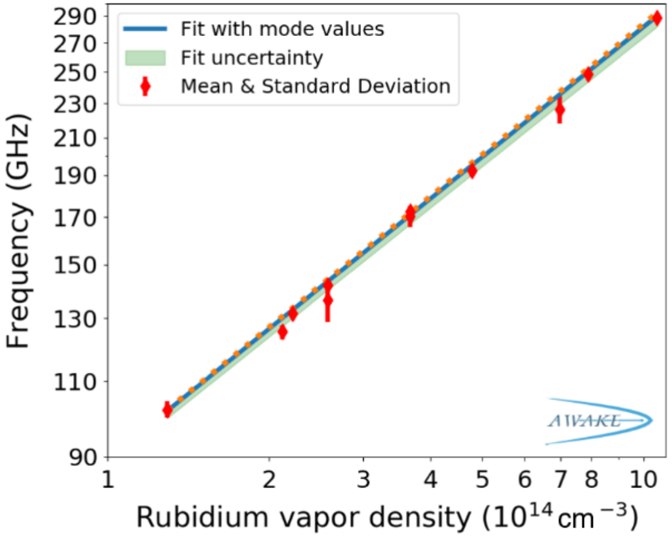
✅ ➢ **AWAKE Run 1 → Demonstrate and study the seeded self-modulation**

Seeded Self-Modulation (SSM)

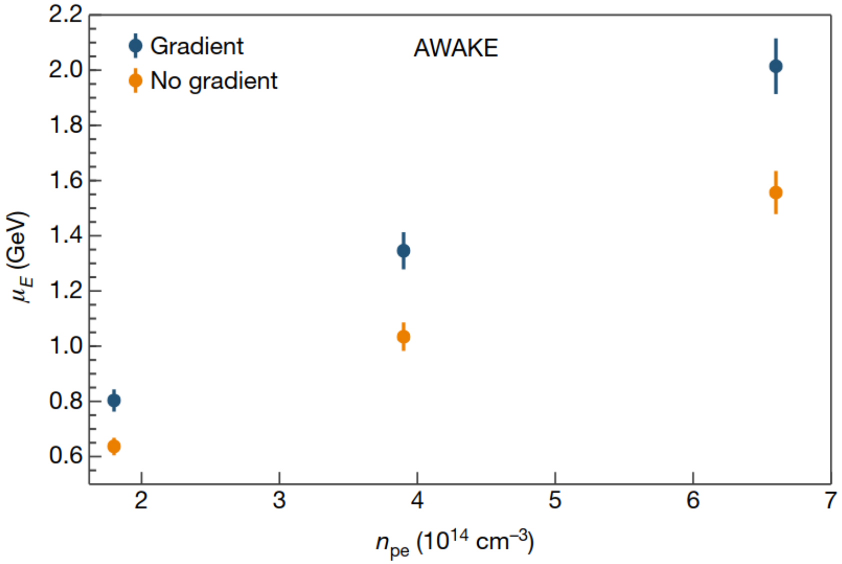




$$f_{mod} = f_{pe} \propto \sqrt{n_{pe}}$$



19 MeV => 2 GeV



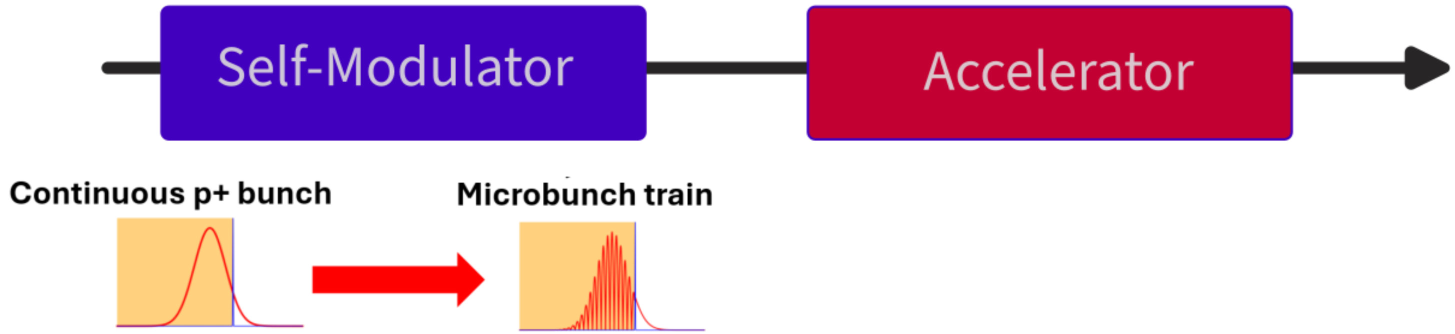
AWAKE collaboration,
Acceleration of electrons in the plasma wakefield of a proton bunch, Nature 561, 363–367 (**2018**)

Bachmann, A. M., & Muggli, P. (2020). JACoW: Beam Diagnostics in the Advanced Plasma Wakefield Experiment AWAKE.

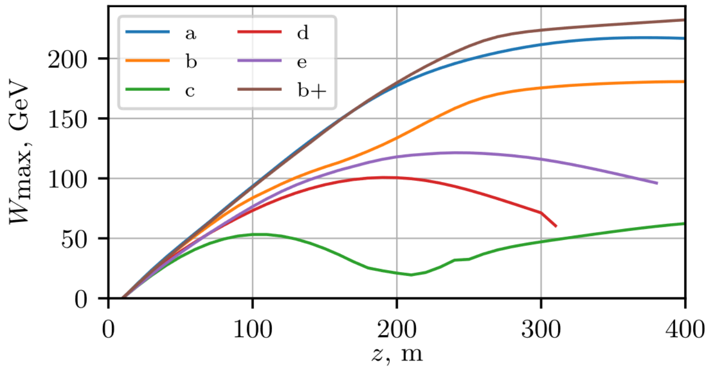
Acceleration Towards a (scalable) Accelerator

- ✅ ➢ **AWAKE Run 1 → Demonstrate and study the seeded self-modulation**
- now ➢ **AWAKE Run 2: → Transition from proof-of-principle to applications**

200 GeV in 200 m



2D numerical simulation results



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

- **Possible first applications for particle physics experiments with 50-200 GeV electron bunches**

Acceleration Towards a (scalable) Accelerator

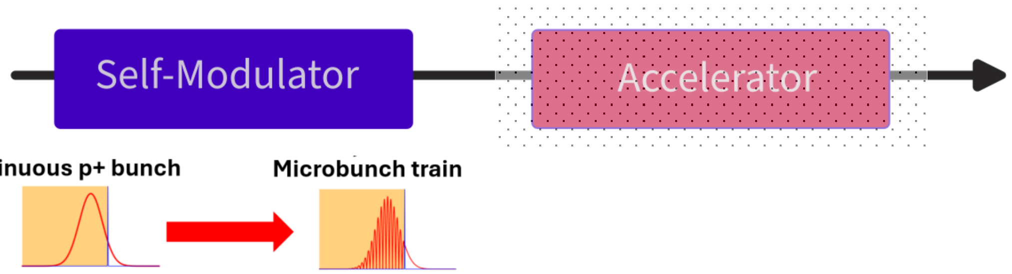
- ✓ ➢ **AWAKE Run 1 → Demonstrate and study the seeded self-modulation**
- now ➢ **AWAKE Run 2: → Transition from proof-of-principle to applications**

Run 2 in 4 phases:

- ✓ **Run 2a:** Demonstrate the **seeding** of the self-modulation of the entire proton bunch with an **electron bunch**
- ✓ **Run 2b: Maintain large wakefield amplitudes** over long plasma distances by introducing a **step** in the plasma density

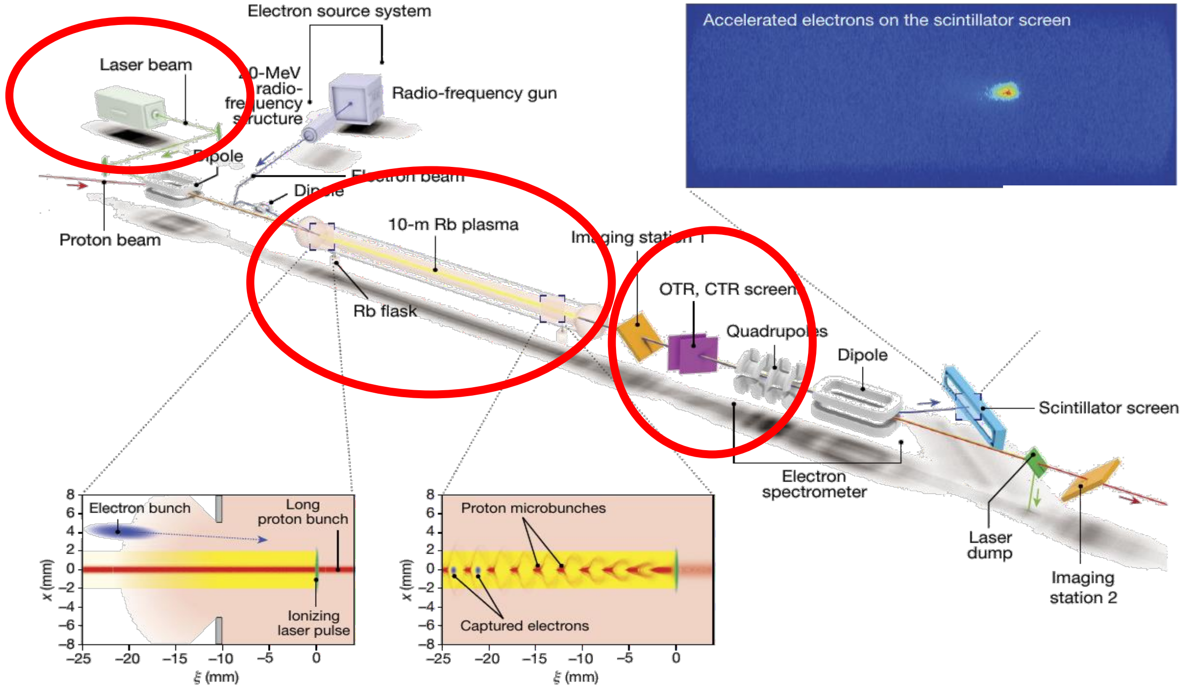
- 2029 **Run 2c *:** Demonstrate electron acceleration and **emittance control** of externally injected electrons
- 2032 **Run 2d *:** Development of **scalable plasma** sources to 100s meters length with sub-% level plasma density uniformity.

Current Layout and Contributions of MPP



Acceleration using:
- 10 m long Rubidium vapor source
- Ionized using TW-class Ti:Sapphire laser
- 19 MeV electon RF Gun

Diagnostics:
- Imaging screens
- Transition Radiation (OTR / CTR) screens
- Scintillators screen
- Streak cameras
- Interferometers
- ...



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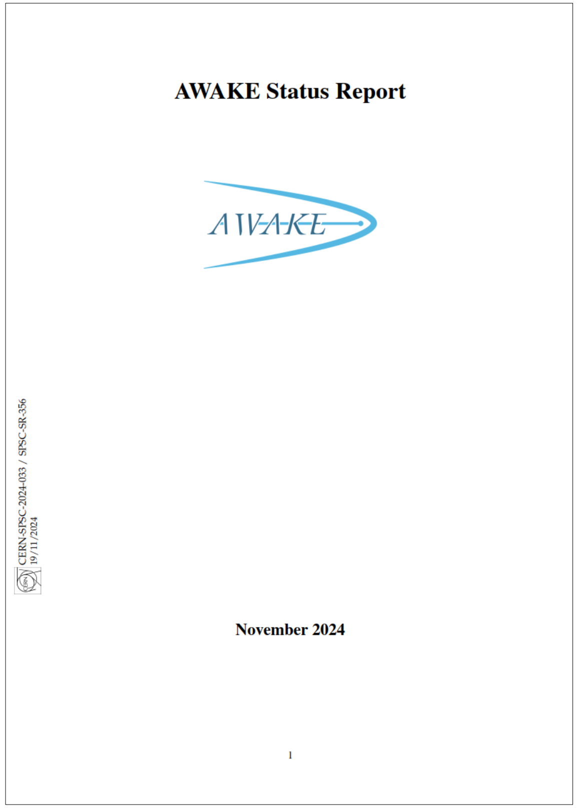
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Acceleration Towards a (scalable) Accelerator

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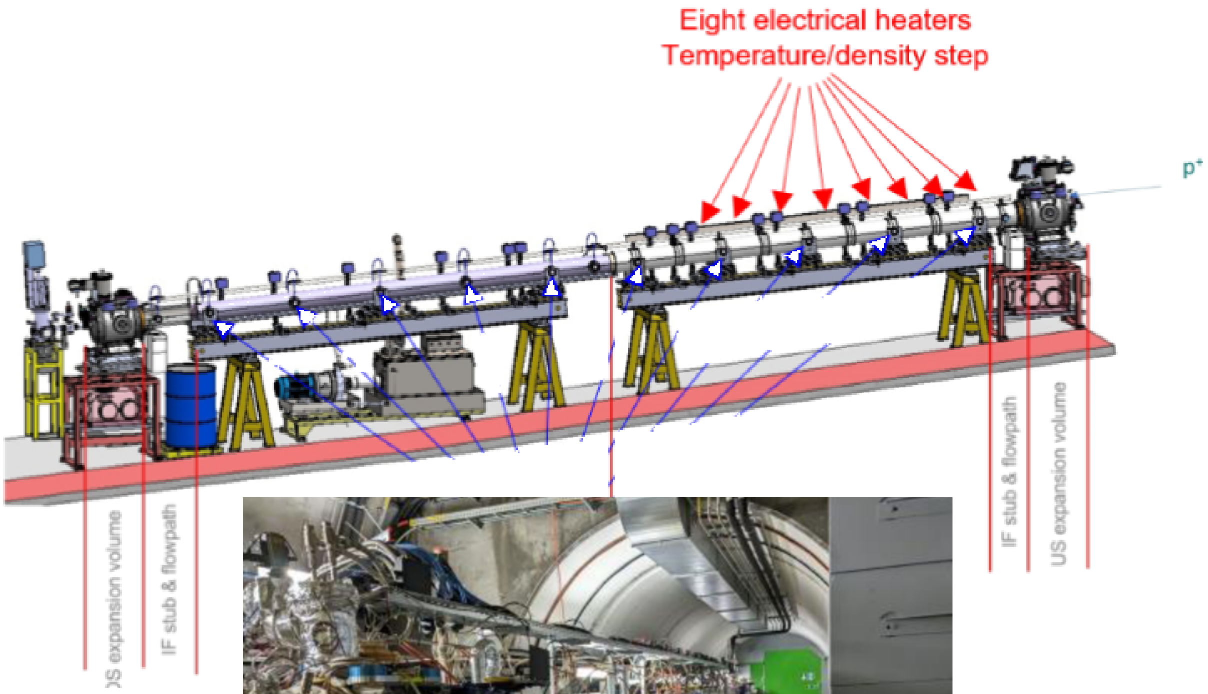
Plasma Source Upgrade

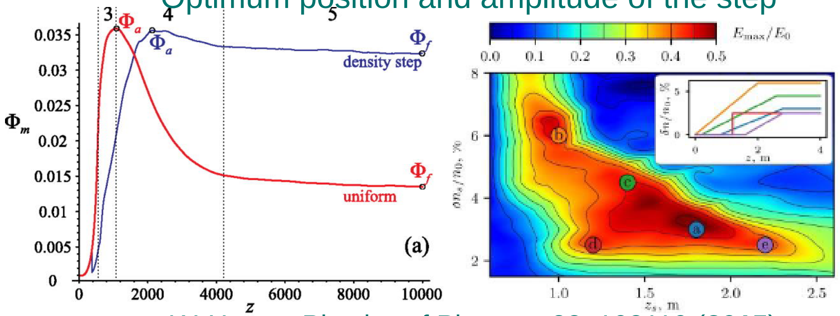


Impose temperature/plasma density step

- ➔ Explore the effect of a plasma density on
  - micro-bunch train
  - bunch halo
  - plasma light from dissipation of wakefields
  - Energy gain
  - Hosing
  - …

Numerical simulation

- Amplitude of wakefields larger w/ plasma density step
- Optimum position and amplitude of the step

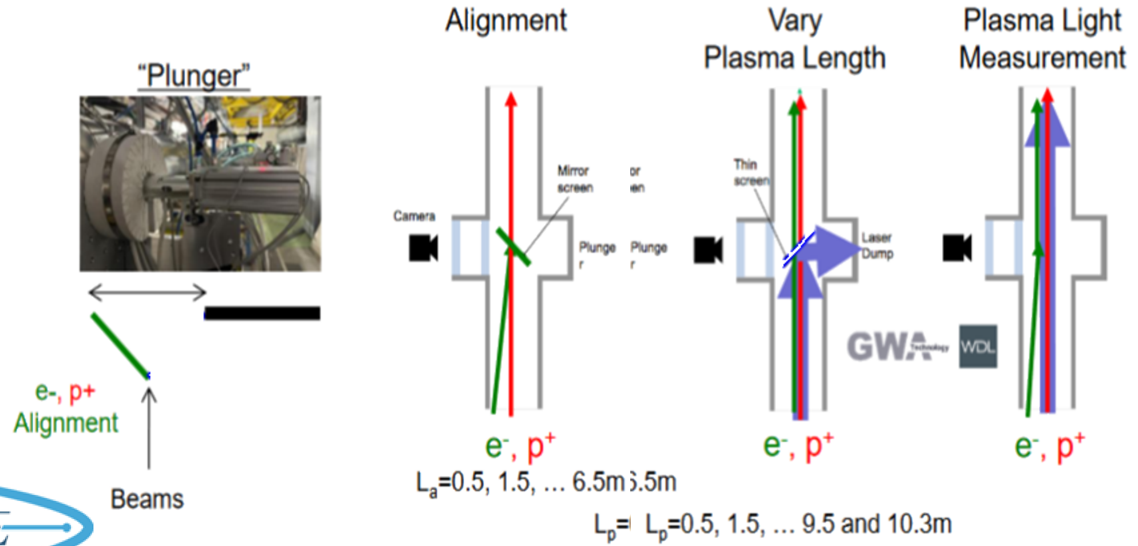


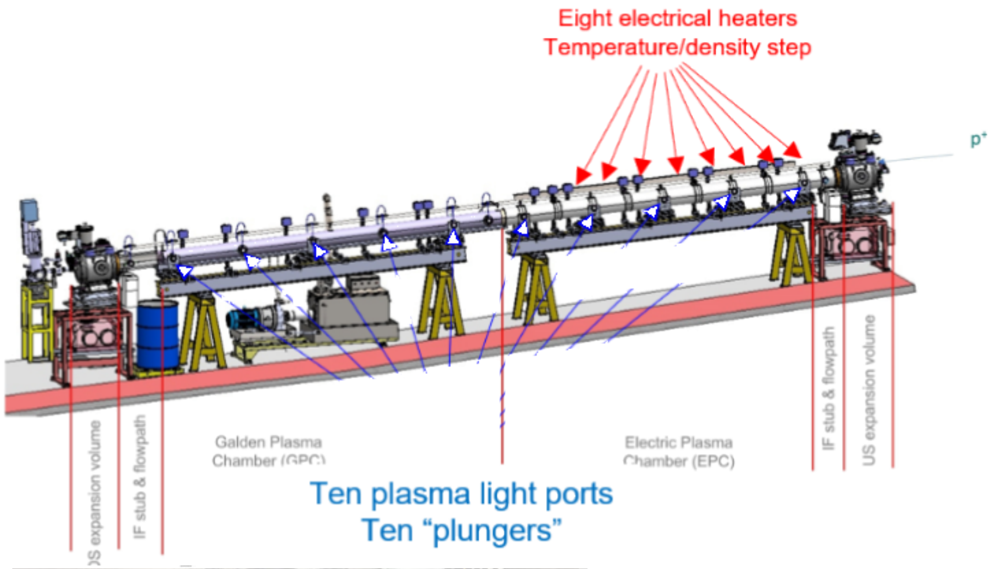
K V Lotov, Physics of Plasmas 22, 103110 (**2015**)
K V Lotov and P V Tuev PPFC 63 125027 (**2021**)

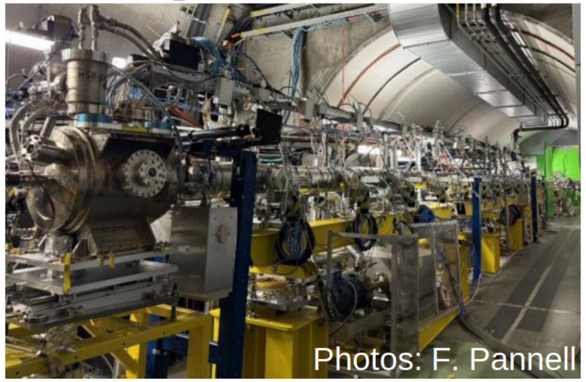
Plasma Source Upgrade, Plungers Installation

Plungers installed and **commissioned on schedule** in June 2024:

- **Align e^- and p^+ beams** inside plasma source for :
  - Acceleration, side injection
  - e^- Seeding of Self-Modulation (e^- SSM)
  - e^- Seeding of hosing
- **Vary plasma length** to perform:
  - **Acceleration gradient** measurements
  - Growth of the wakefields
  - Growth of hosing





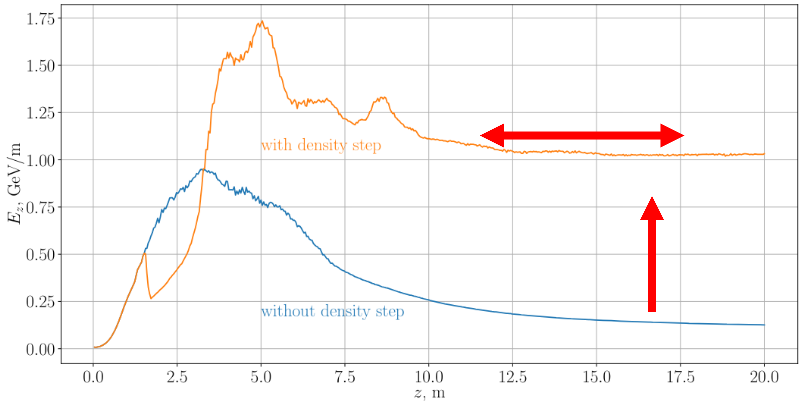


Plasma Density Step

Increases energy gain, constant acceleration gradient

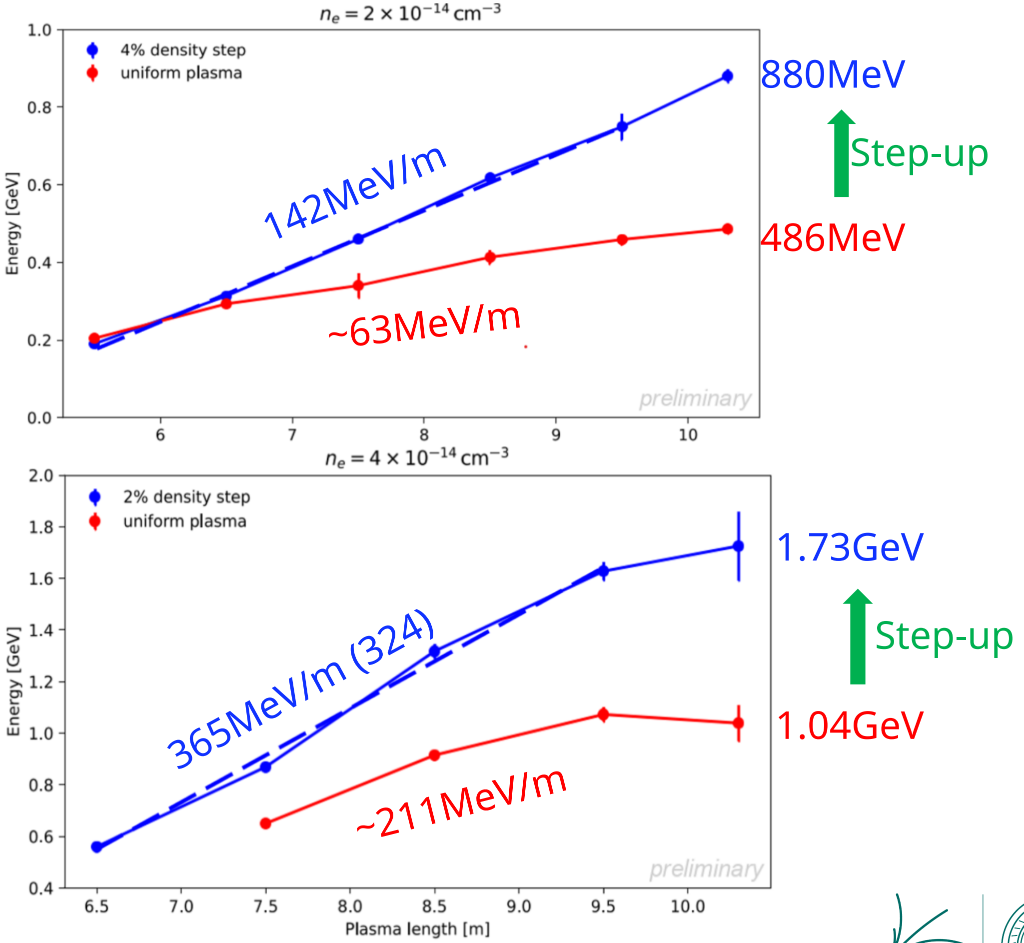
Plasma density (up) step to **make E_z** and **acceleration constant past the SM saturation point**

n_{e0}=7x10^{14}cm^{-3}



AWAKE status report 2024, https://cds.cern.ch/record/2917426/files/SPSC-SR-356.pdf

- **Clear increase in final energy** (L_p=10.3m): 1.04 → 1.73GeV
- **Clear increase in accelerating gradient:** ~211 → 365MeV/m



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Dependency of saturation length on plasma density

Growth of the Wakefields

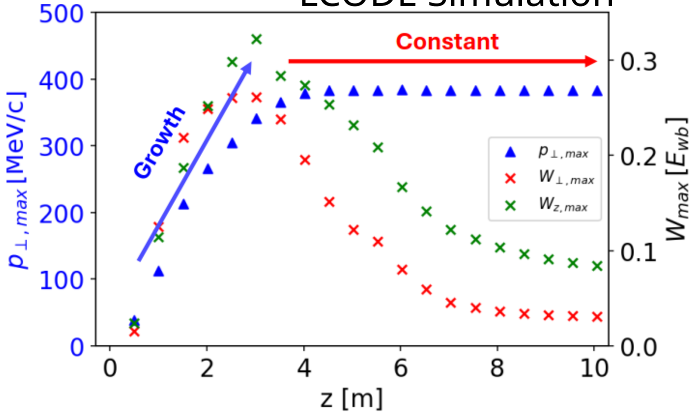
SM saturates in less than 10m

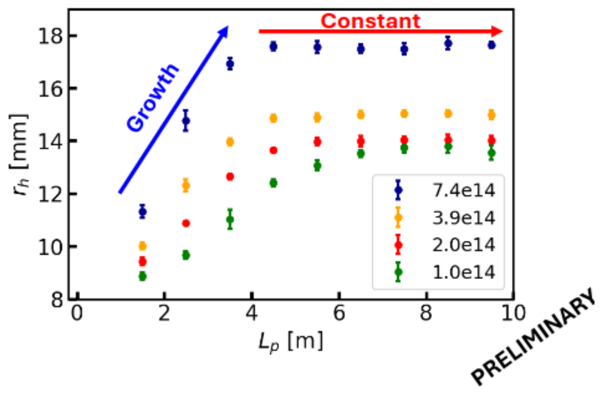
=> Self-modulator for Run 2c

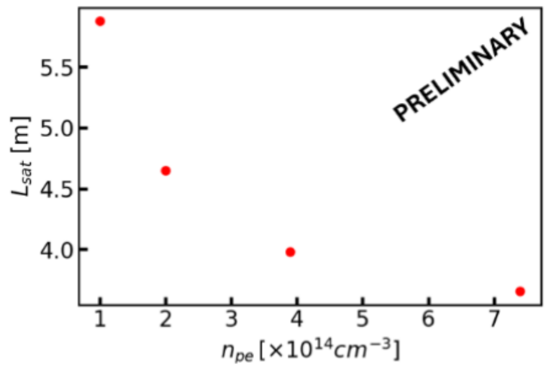
1) SM µB formation → W
2) µB fully formed
3) SM vs W → Halo

Transverse momentum

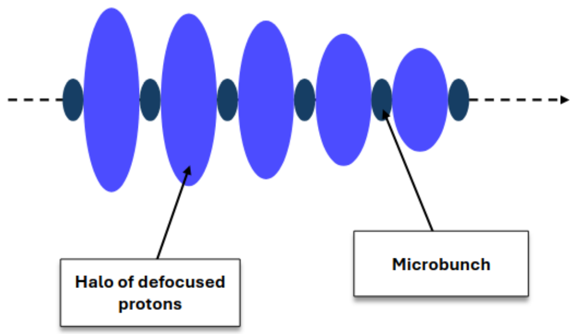
LCODE Simulation

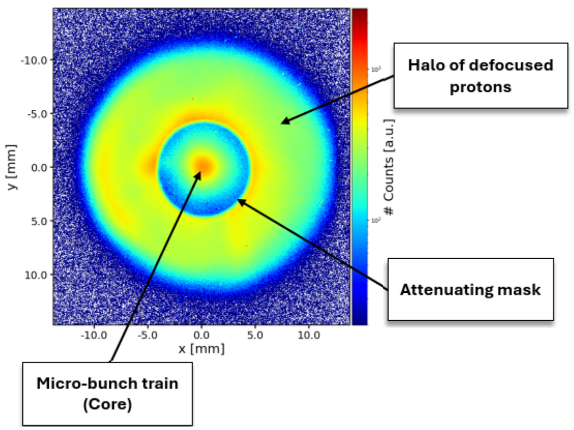


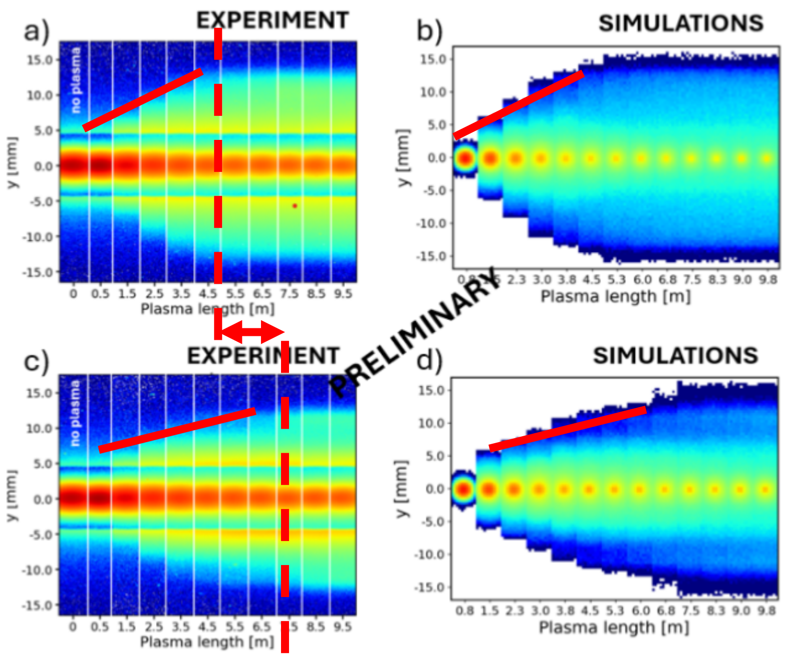




Halo radius shows Self-Modulation saturation length







Constant density plasma

$N_b = 3 \times 10^{11}$

$n_{pe} = 2 \times 10^{14}$/cc

RIF +100ps

Plasma with density step

$N_b = 3 \times 10^{11}$

$n_{pe} = 2 \times 10^{14}$/cc

RIF +100ps

4% step

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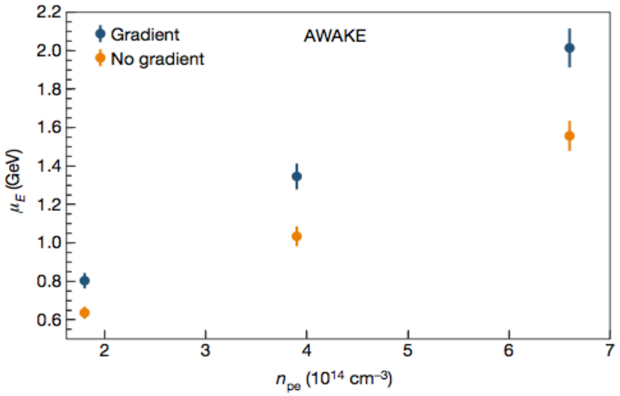
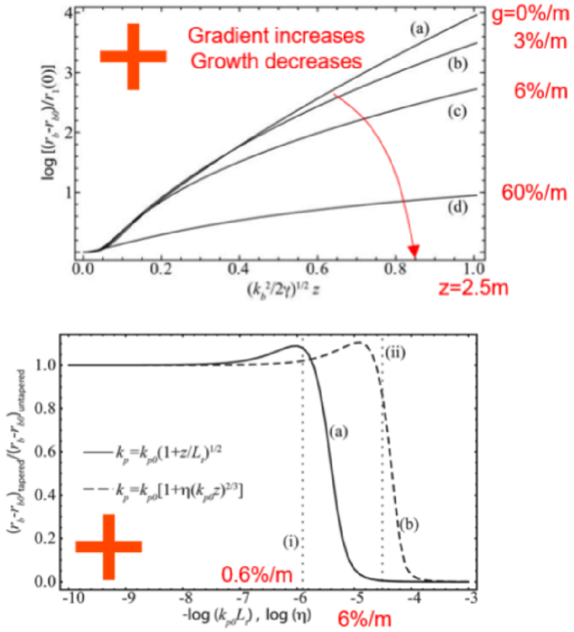
Effect of Density Gradient on Seeded Self-Modulation

SM can be detuned and suppressed by (linear) density gradients

Acceleration results (Run 1)

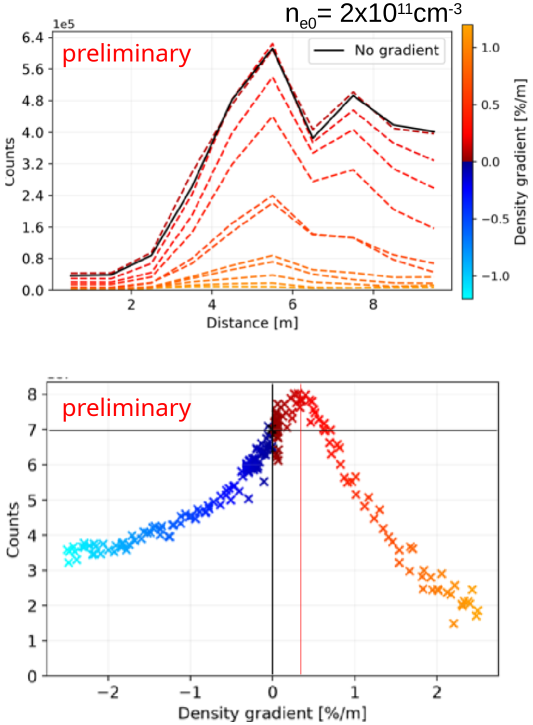


Theory predictions



C. B. Shroeder et al., *Phys. Plasmas* 19, 010703 (2012)

Plasma Light Measurements



- **Clear observation of SM suppression**: light, halo and time-resolved (not shown) diagnostics
- **Asymmetry** positive/negative gradients
- **Higher fields** with small positive gradient **consistent with higher energy gain observation**

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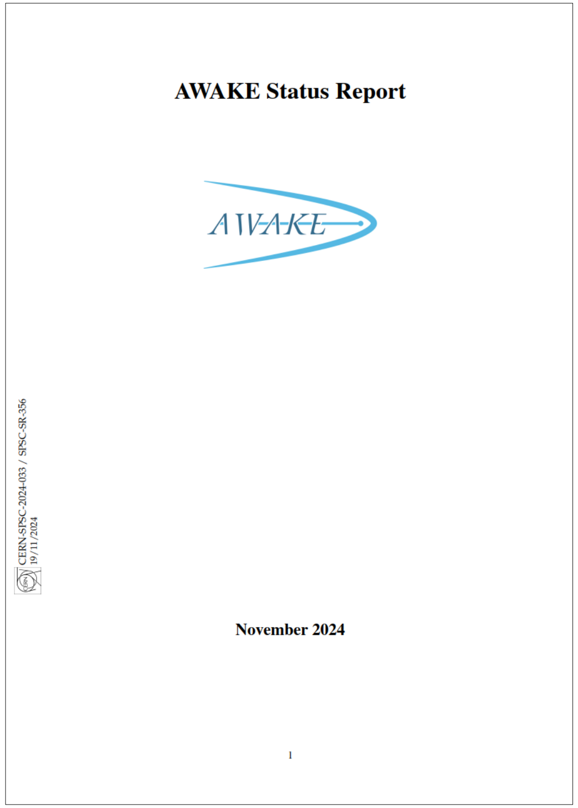
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Summary

- **AWAKE**
  - Plasma wakefield driven by a Self-Modulated proton bunch
  - Observed clear effect of density step
    - ✔ **Stabilization of accelerating gradient** at higher level
    - ✔ **Energy gain**
  - Growth of self-modulation & wakefields along plasma studies
  - Growth of hosing along plasma studies
  - **Successful data collection providing bases for publications and studies for preparation of AWAKE future steps**
- **Clear Scientific program**
  - Run 2b: plasma density step (→ 2023-25)
  - Run 2c: external injection of e-bunch in second plasma, quality (2028→)
  - Run 2d: operation with acceleration in scalable plasma source (2030→)
- **From acceleration to an accelerator → towards applications to particle physics in 2030's**
  - Dark photon searches
  - Non-linear QED in electron-photon collisions
  - …

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Beyond AWAKE → HEP + ALIVE

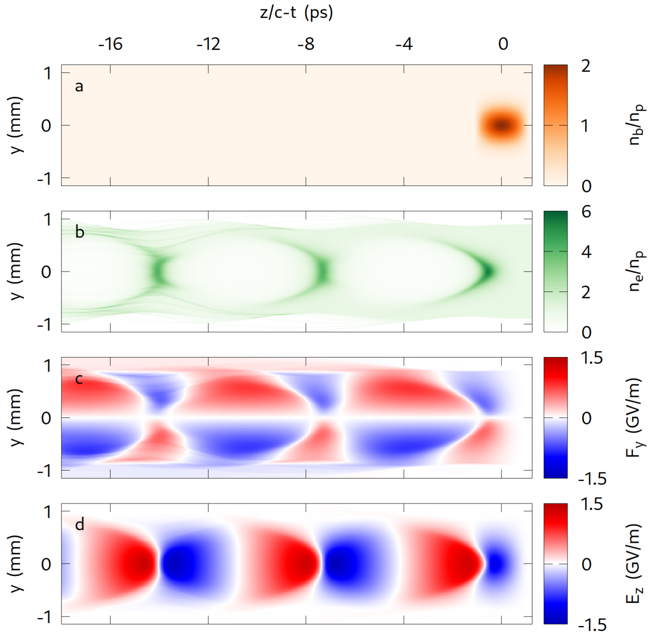
AWAKE approach will provide mid-term particle physics opportunities

Investigate:
• high repetition rate proton accelerator luminosity
• short proton bunches eases plasma requirements, more efficient use of protons

Longer-term:
• for collider applications, need scheme to reach interesting luminosity
• only fraction of protons in bunch contribute to generating useful wakefield - limiting energy efficiency
• long proton bunches susceptible to hosing instability. May limit full use of proton bunch
• acceleration of electrons using many micro bunches requires very uniform plasma

ALiVE

Advanced Linear accelerator for Very high Energies



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

Latest Publications

All time
Top Publication:
- (1) Nature
- (2) PRE
- (9) PRL
- (11) PRAB

- D.A. Cooke et al. (AWAKE Collaboration), Measurement of the emittance of accelerated electron bunches at the AWAKE experiment, arXiv:2411.08681 (2024)
- **M. Turner, et al. (AWAKE Collaboration), Experimental Observation of Motion of Ions in a Resonantly Driven Plasma Wakefield, arXiv:2406.16361 (2024) → PRL**
- **L. Verra, et al. (AWAKE Collaboration), Filamentation of a relativistic proton bunch in plasma, Phys. Rev. E 109, 055203 (2024)**
- **T. Nechaeva, et al. (AWAKE Collaboration), Hosing of a long relativistic particle bunch in plasma, Phys. Rev. Lett. 132, 075001 (2024)**
- C. Stollberg, et al., First Thomson scattering results from AWAKE's helicon plasma source, *Plasma Phys. Control. Fusion* 66 115011 (2024)
- H. Saberi, et al., Elevating electron energy gain and betatron x-ray emission in proton-driven wakefield acceleration, *Phys. Plasmas* 31, 093104 (2024)
- E. Walter, et al., Wakefield-driven filamentation of warm beams in plasma, Phys. Rev. E 110, 035208 (2024)
- **J. P. Farmer and G. Zevi Della Porta, Wakefield regeneration in a plasma accelerator, arXiv:2404.14175v1 (2024)**
- **J Farmer *et al* 2024, Preliminary investigation of a Higgs factory based on proton-driven plasma wakefield acceleration, *New J. Phys.* 26 113011 (2024)**
- **K. Oguzhan, et al. , A decomposition algorithm for streak camera data, *JINST* 19 P04005 (2024)**
- M. Martinez-Calderon, et al., Fabrication and rejuvenation of high quantum efficiency caesium telluride photocathodes for high brightness and high average current photoinjectors, Phys. Rev. Accel. Beams 27, 023401 (2024)
- E. Senes, et al., Selective electron beam sensing through coherent Cherenkov diffraction radiation, Phys. Rev. Research 6, 023278 (2024)

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