The AWAKE Experiment in 2021: Performance and Preliminary Results on Electron-Seeding of Self-Modulation

Edda Gschwendtner, Livio Verra, Giovanni Zevi Della Porta, CERN, Geneva, Switzerland
Patric Muggli, MPP, Munich, Germany
For the AWAKE Collaboration

IPAC22

IPAC'22, Bangkok, Thailand, June 12 – 17, 2022

Outline

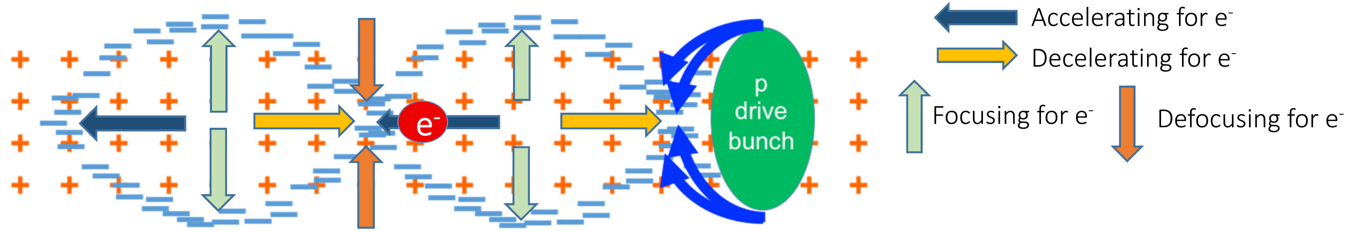
- Motivation
- The AWAKE Experiment
- Run 1 Results
- Program of Run 2
- Results of the First Phase of Run 2
- Summary

Plasma Wakefield Acceleration

Use a plasma to convert the transverse space charge force of a beam driver into a longitudinal electrical field in the plasma,
T. Tajima and J. Dawson, 1979

Drive beams:

laser, electrons, protons



Charged particle bunch traveling inside a plasma perturbs the plasma electron distribution

→ oscillation with $\omega_{pe} = \sqrt{\frac{n_{pe}e^2}{m_e\varepsilon_0}}$ $\lambda_{pe} = 2\pi \frac{c}{\omega_{pe}}$

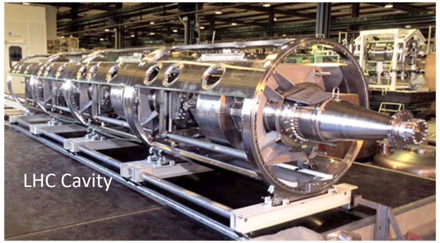
The plasma oscillation leads to a longitudinal accelerating field. The maximum accelerating field (wave-breaking field) is:

$$E_{WB} = 96 \frac{V}{m} \sqrt{n_{pe}}$$

Example: $n_{pe} = 7\times10^{14}\ cm^{-3}$ (AWAKE) → $E_{WB} = 2.5\ GV/m$
Example: $n_{pe} = 7\times10^{17}\ cm^{-3}$ → $E_{WB} = 80\ GV/m$

Conventional Acceleration

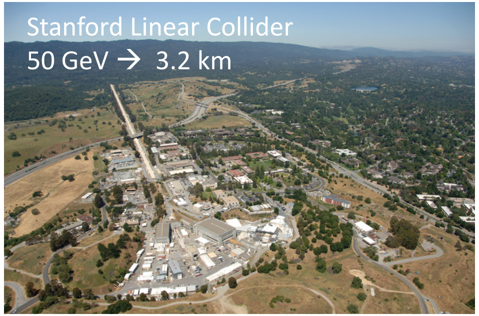
- Radiofrequency Cavities very successfully used in all accelerators in the last 100 years.
- Typical gradients:
  - LHC: 5 MV/m
  - ILC: 35 MV/m
  - CLIC: 100 MV/m
- However, accelerating fields are limited to <100 MV/m
  - In metallic structures, a too high field level leads to break down of surfaces, creating electric discharge.

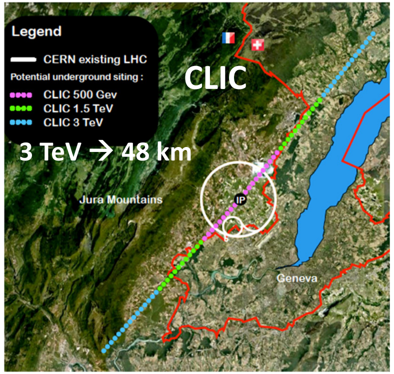


To reach high energies with conventional accelerators:

➔ several tens of kilometers for linear colliders

The **high gradient of plasma wakefield acceleration** makes this technology very interesting for reducing the size (and cost) for future linear colliders.



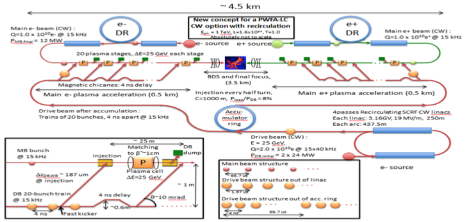


Energy Budget for High Energy Plasma Wakefield Accelerators

Drive beams:
Lasers: ~40 J/pulse
Electron drive beam: 30 J/bunch

→

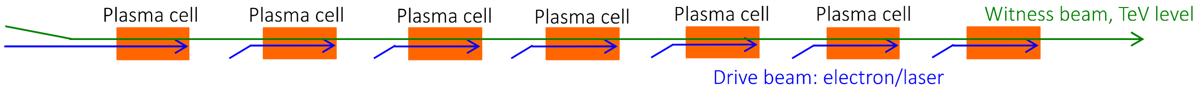
Witness beams:
Electrons: 10^{10} particles @ 1 TeV ~few kJ

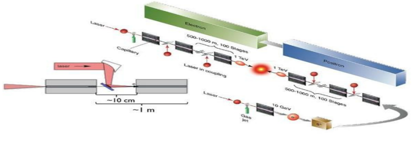


E. Adli *et. al.*,arXiv:1308.1145 [physics.acc-ph]

To reach TeV scale: Electron/laser driven PWA: need several stages

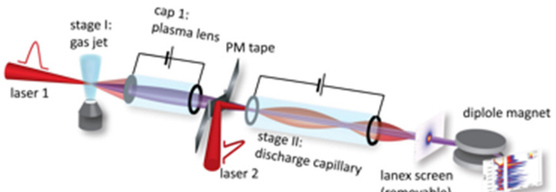
➔ challenging wrt to relative timing, tolerances, matching.





C. B. Schroeder *et. al*. Phys. Rev. ST Accel. Beams **13**, 101301

Multistage coupling of 2 independent laser-plasma accelerators demonstrated at 100 MeVs level.



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

Why Proton Bunch Driver?

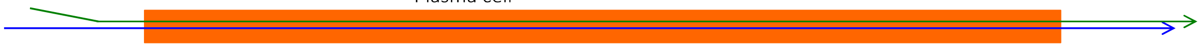
Proton drive beams:
SPS 19kJ/pulse
LHC 300kJ/pulse

→

Witness beams:
Electrons: 10^{10} particles @ 1 TeV ~few kJ

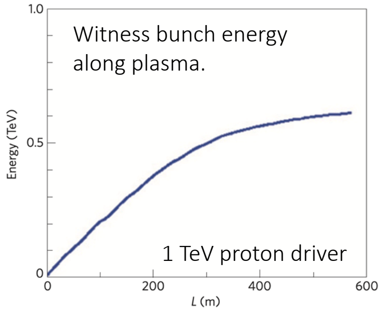
Proton drivers: large energy content in proton bunches

→ allows to consider single stage acceleration



With existing proton beams the energy frontier with electrons can be reached!

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



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

→ First applications in mid-term future: fixed target experiments with modest requirements!

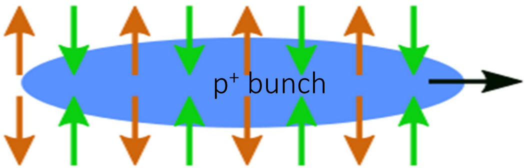
Self-Modulation of the Proton Beam

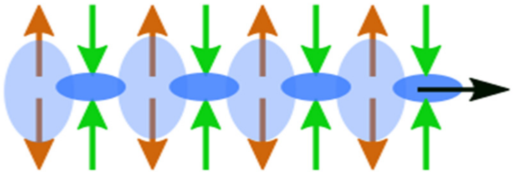
In order to create plasma wakefields efficiently, the drive bunch length has to be in the order of the plasma wavelength.

CERN SPS proton bunch: very long! (σ_z = 7 cm) → much longer than plasma wavelength (λ = 1mm, in AWAKE)

Self-Modulation Instability:

N. Kumar, A. Pukhov, K. Lotov, PRL 104, 255003 (2010)





Initial transverse wakefields

Periodic focusing/defocusing fields

Radial bunch and plasma density modulation

Stronger wakefields

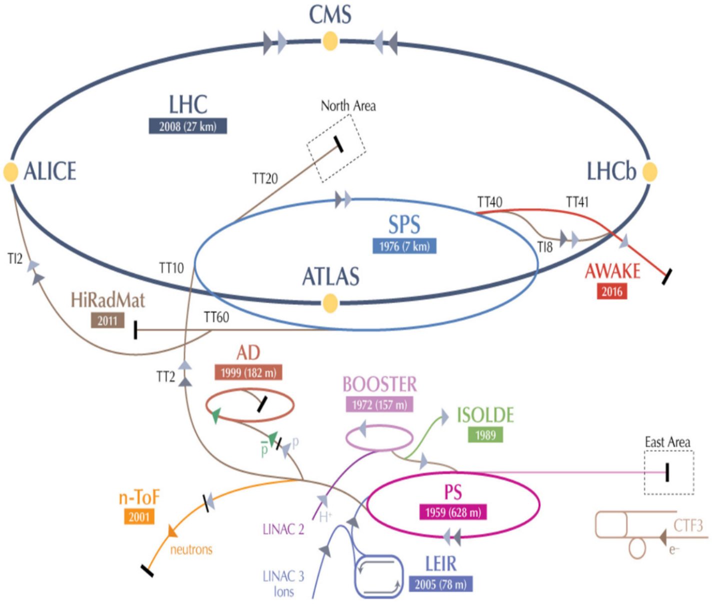
Full modulation

Density modulation on-axis → micro-bunches.

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

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

AWAKE at CERN



Advanced WAKEfield Experiment: Proof-of-Principle Accelerator R&D experiment at CERN to study proton driven plasma wakefield acceleration. Collaboration of 23 institutes world-wide.

AWAKE Run 1 (2016-2018):

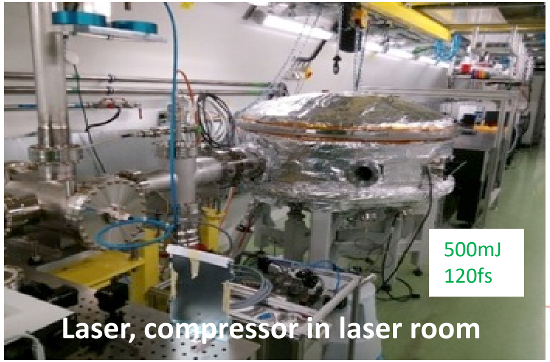
- ✓ 1st milestone: Demonstrated seeded self-modulation of the proton bunch in plasma (2016/17)
- ✓ 2nd milestone: Demonstrated electron acceleration in plasma wakefield driven by a self-modulated proton bunch. (2018)

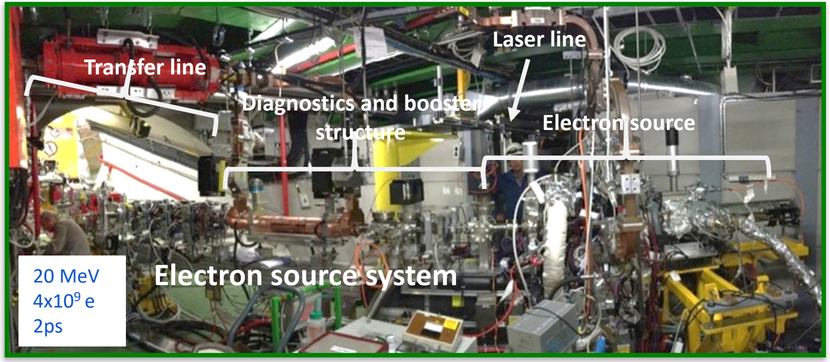
AWAKE Run 2 (2021 – ~2029):

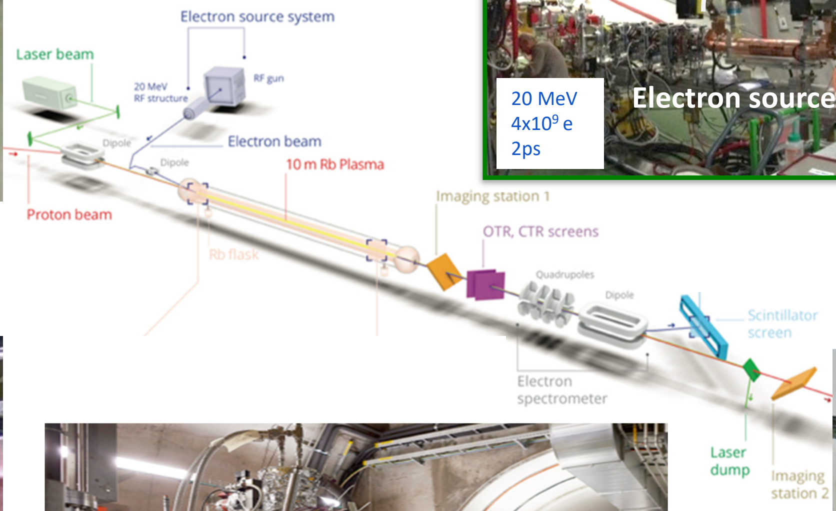
Accelerate an electron beam to high energies (gradient of 0.5-1GV/m) while preserving the electron beam quality and demonstrate scalable plasma source technology.

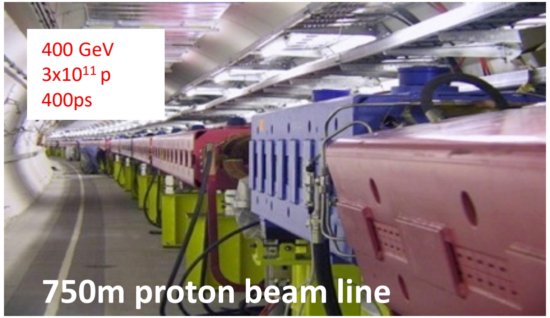
Once AWAKE Run 2 demonstrated: **First application of the AWAKE-like technology:** Particle physics experiments for e.g. dark photon search.

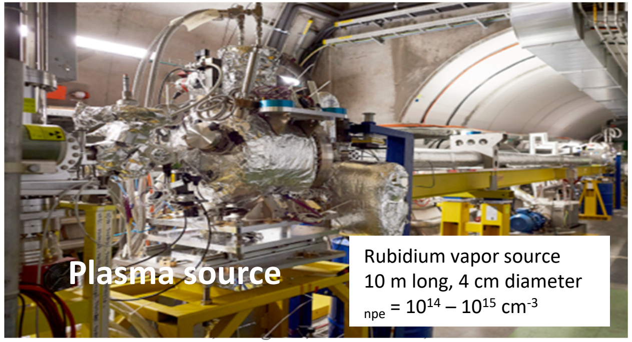
Key Ingredients of AWAKE







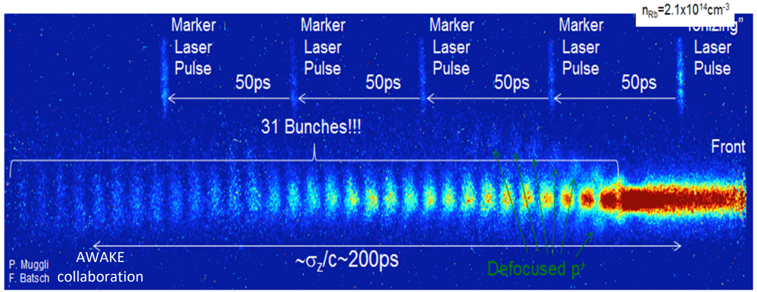




Results AWAKE Run 1

→ 1st AWAKE Milestone

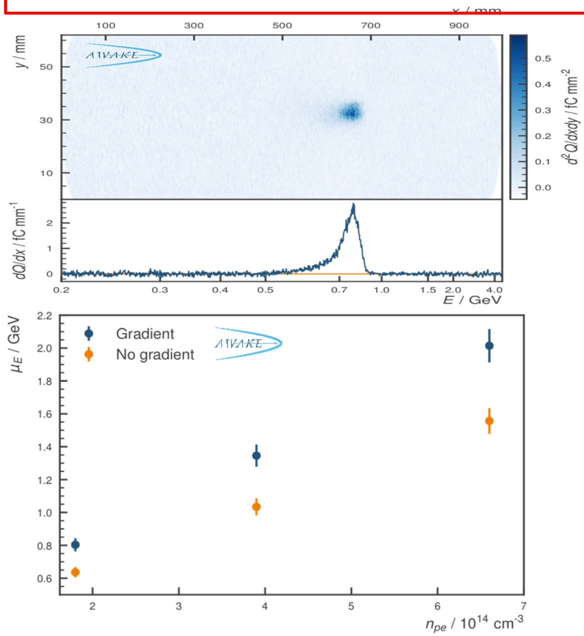
- Phase stable and reproducible self-modulation of the proton bunches.
- Micro-bunches present over long time scale from seed point.



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), Phys. Rev. Lett. 126, 164802 (2021).

→ 2nd AWAKE Milestone

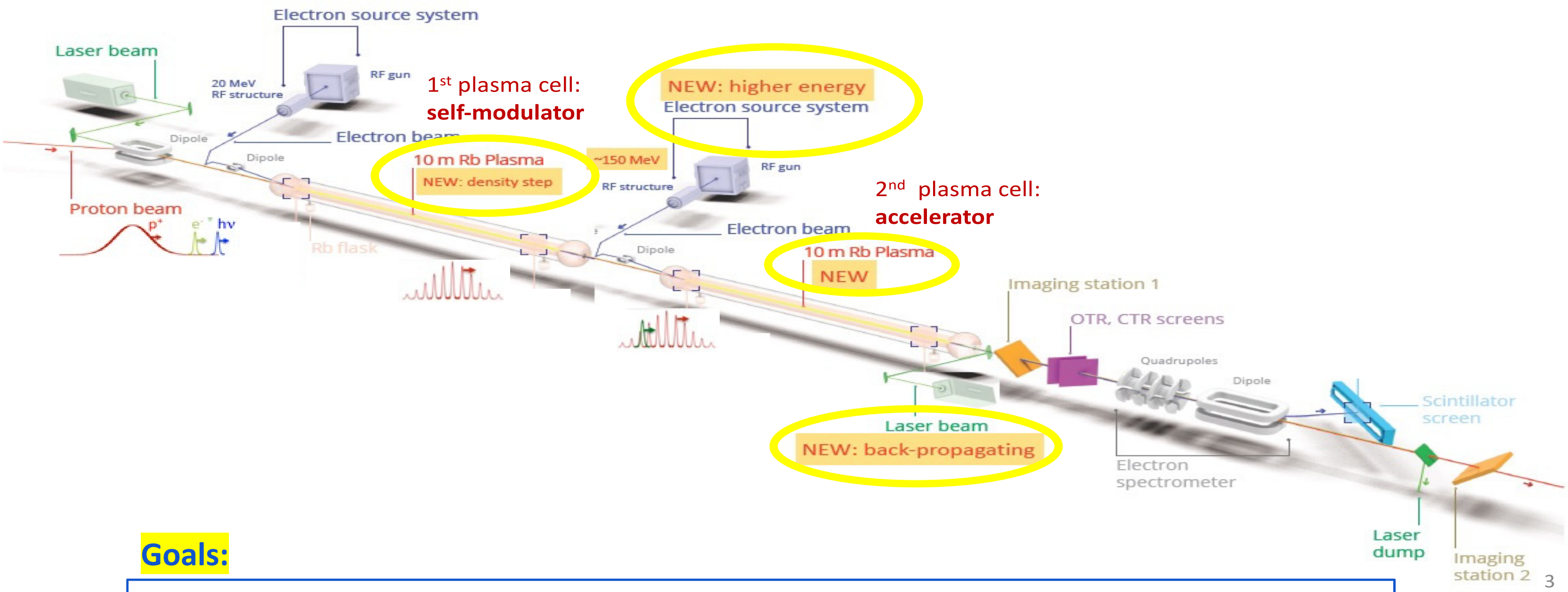
- Acceleration from 18 MeV to 2 GeV.
- Charge capture up to 100pC (~20%).



AWAKE Collaboration, Nature 561, 363 (2018)

AWAKE Run 2

- ➔ Demonstrate possibility to use AWAKE scheme for high energy physics applications in mid-term future!
- ➔ Start 2021, program goes beyond CERN Long Shutdown 3 (2027+)!

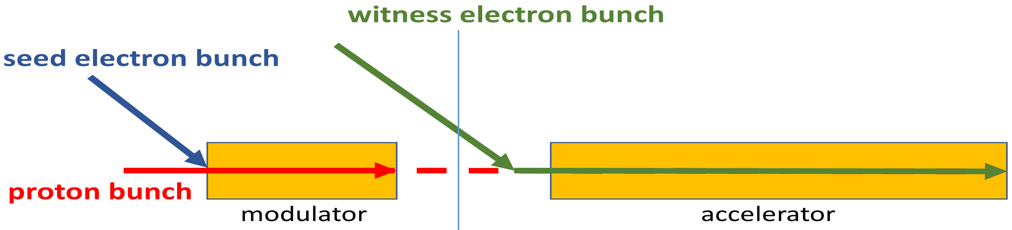


Goals:

Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)
Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)
Demonstrate scalable plasma source technology (e.g. helicon prototype)

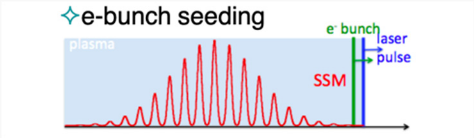
AWAKE Run 2 – Program Phases

Optimize self-modulation of the proton bunch



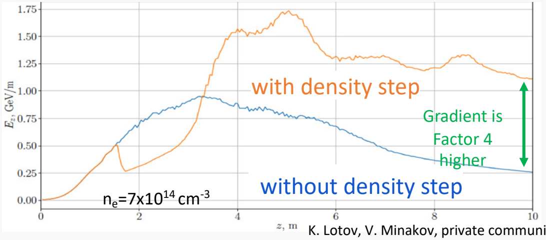
Optimize acceleration of electrons in p-driven plasma wakefield

AWAKE Run 2a: self-modulation of entire p-bunch seeded with an e-bunch



AWAKE Run 2b: stabilization of the micro-bunches with a density step in the plasma cell and maintain high gradient

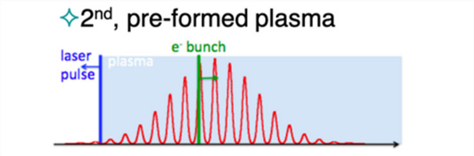
Gradient in 1st plasma source (self-modulator)



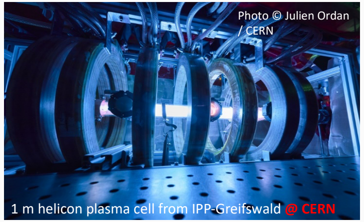
K. Lotov, V. Minakov, private communication

AWAKE Run 2c: electron acceleration and emittance control

2nd electron source, 150MeV, 200fs



AWAKE Run 2d: scalable plasma sources



➔ Program for next ~10 years

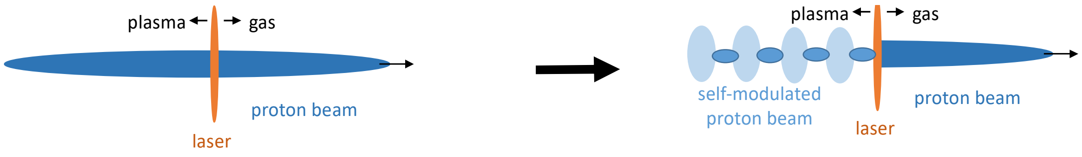
AWAKE Run 2a – Electron Bunch Seeding

‘Seeding’ the proton bunch self-modulation is required for reproducible acceleration

- Only electrons injected at a precise phase of the micro-bunch train can accelerate and remain focused
- Actively seeding the self-modulation allows phase-reproducible micro-bunch trains

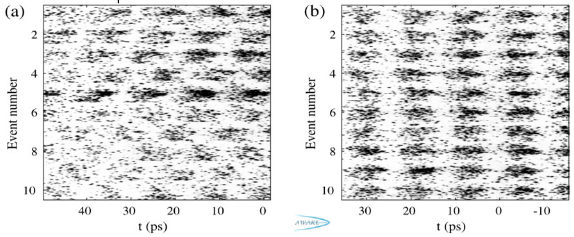
AWAKE Run 1: self-modulation seeded by a laser ionization front (i.e. the plasma starts in the middle of the proton bunch)

- The head of the proton bunch remains unmodulated



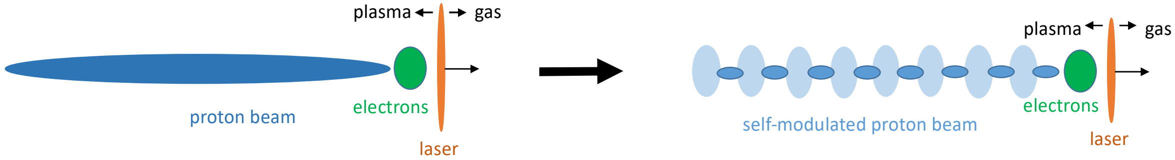
Unseeded: phase not reproducible

Seeded with laser ionization front



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

- → prevents the bunch head from modulating at a different phase and affecting the wakefields

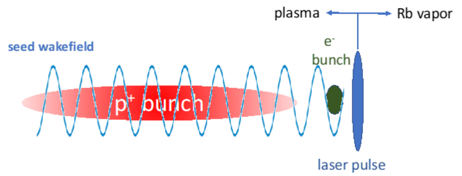


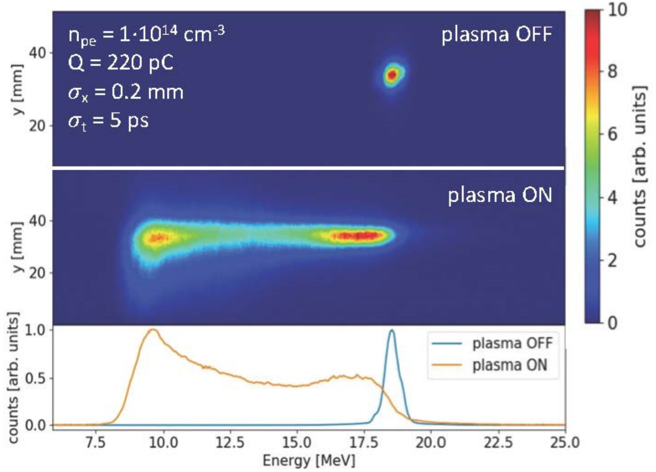
➔ Primary goal of Run 2a
➔ Can be done in existing AWAKE experiment

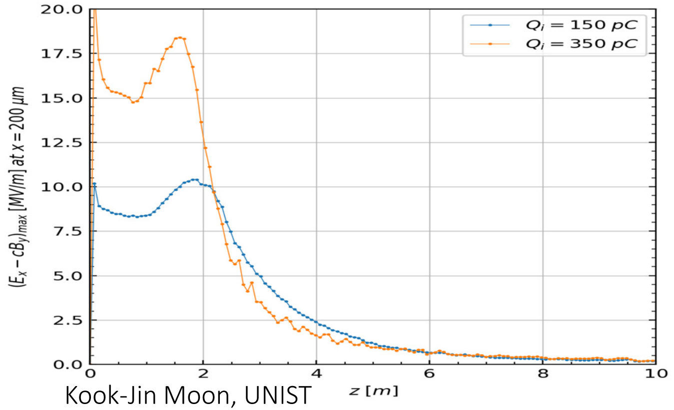
AWAKE Run 2a – Performance

Use the electron bunch from AWAKE Run 1 to seed the wakefields.

First check: electrons in plasma (without protons):

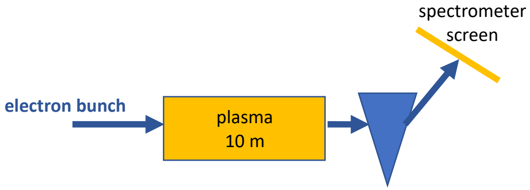






Kook-Jin Moon, UNIST

FBPIC simulation parameters: $n_{pe} = 2{\cdot}10^{14}$ cm^{-3}, σ_x = 0.2 mm

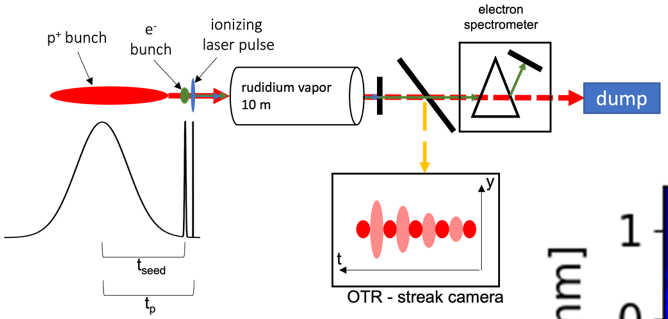


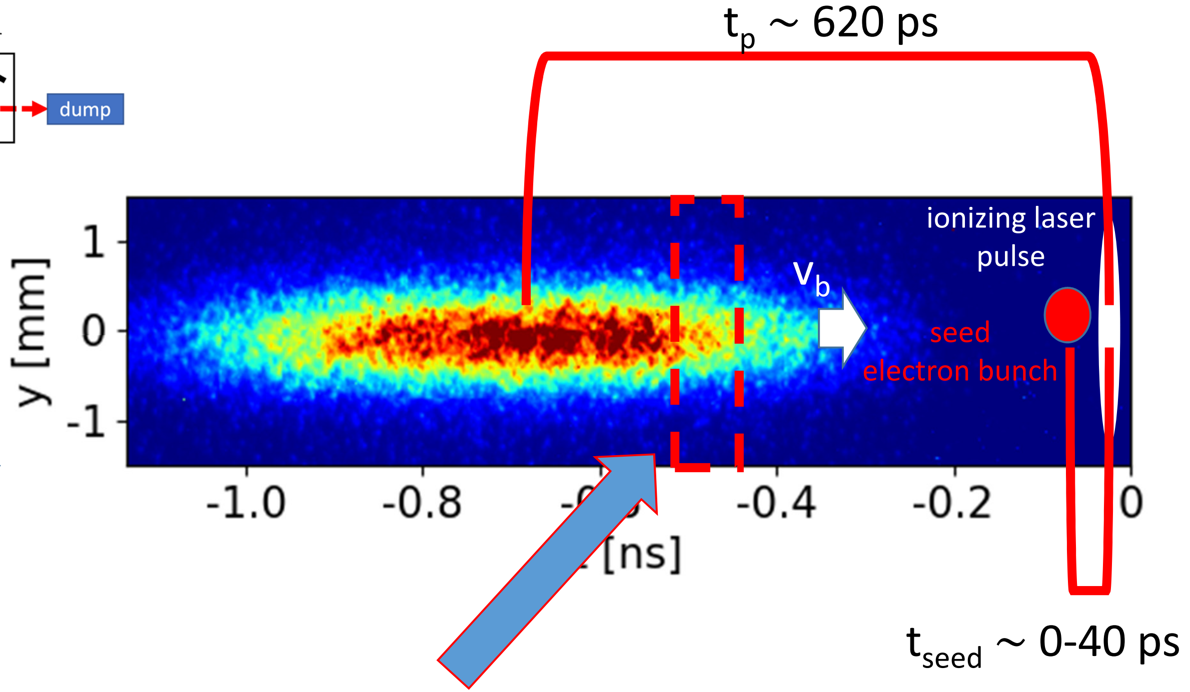
Seeding relies on transverse wakefields generated by electron bunch in the first meters of plasma

- Size: electron bunch pinches transversally in the first few cm and remains small for several meters
- Wakefield: while the e⁻ bunch is small, large wakefields are sustained for the first two meters

L. Verra et al., Seeding of proton bunch self-modulation by an electron bunch in plasma, EuroPhysics Conference Abstracts 45A, P3.2011 (2021).

AWAKE Run 2a – Experimental and Timing Setup





electron bunch:

- Q = 220 pC
- ε_N ~ 1 µm
- σ_r = 0.2 mm
- σ_t ~5 ps
- E = 19 MeV

proton bunch:

- N_p =1-3 $\cdot 10^{11}$
- σ_r = 0.1 – 0.2 mm
- ε_N ~ 1.5-3.5 µm
- σ_t ~250 ps
- p = 400 GeV/c

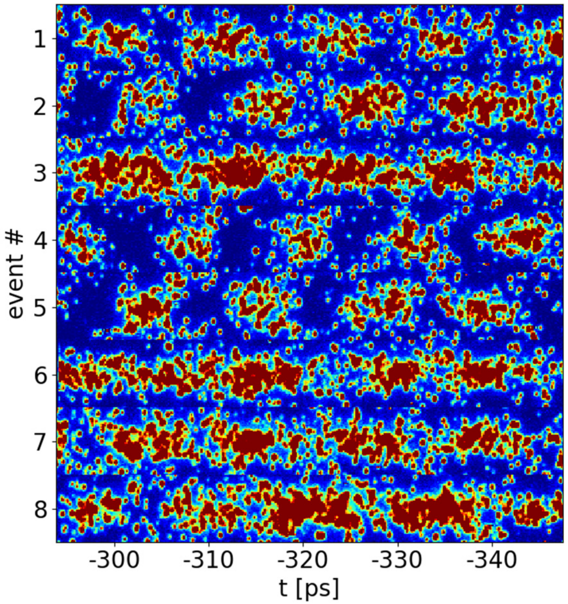
plasma:
$n_{pe} = 1 \cdot 10^{14}$ cm^{-3}

To prove that the electron bunch seeds SM:
→ study the time structure of the microbunch train at the ps time scale

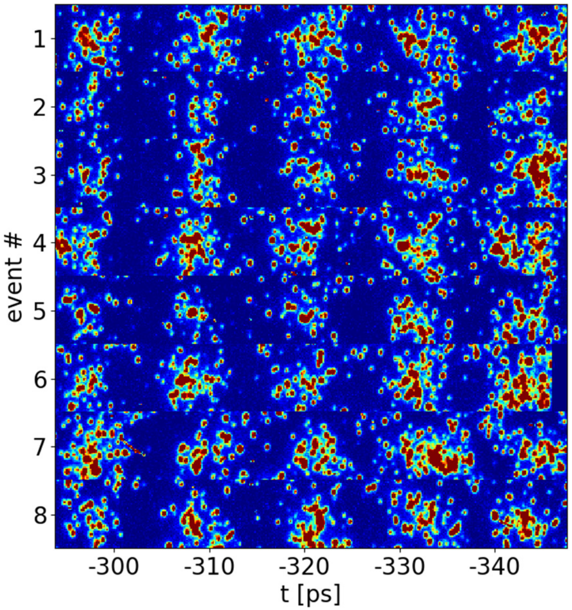
Electron Bunch Seeding – Timing Reproducibility

Waterfall plots of single-event images

No e^- bunch → SMI



with e^- bunch → seeded SM



v_b

The microbunches appear at the same time t_μ along the bunch event after event

Self-Modulation of the proton bunch is seeded by the electron bunch!

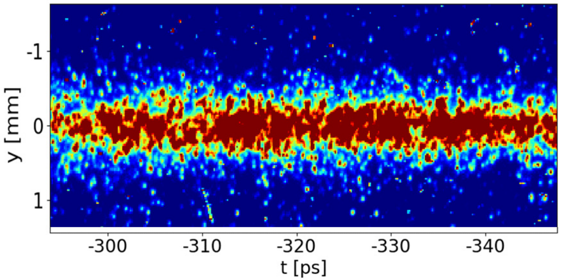
$N_p = 2.5 \cdot 10^{11}$ (Q_p=40.8nc)
73 ps streak camera window

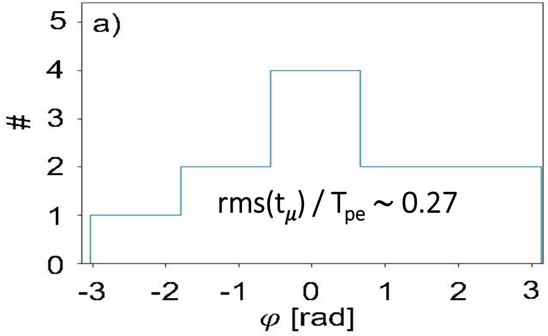
electron bunch charge Q_e = 250 pC
$n_{pe} = 1 \cdot 10^{14}\ cm^{-3}$
→ f_{pe} = 89.7 GHz, T_{pe} = 11.1 ps

Electron Bunch Seeding – Timing Reproducibility

Average of 10 events

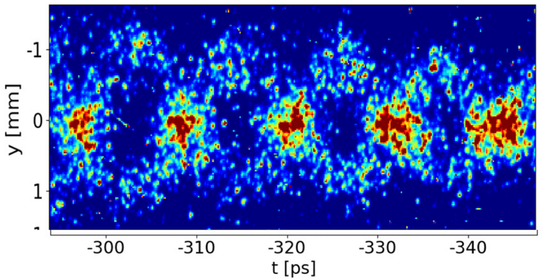
No e^- bunch → SMI

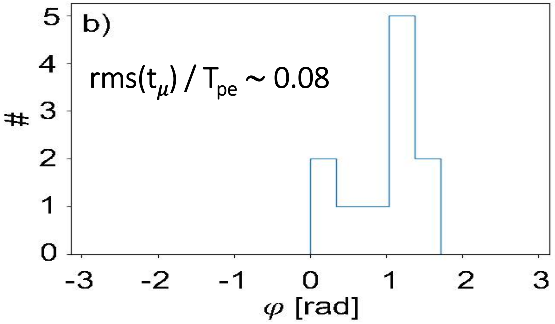




N_p = 2.5·10^{11} (Q_p=40.8nc)
73 ps streak camera window

With e^- bunch → seeded SM





electron bunch charge Q_e = 250 pC
n_{pe} = 1·10^{14} cm^{-3}
→ f_{pe} = 89.7 GHz, T_{pe} = 11.1 ps

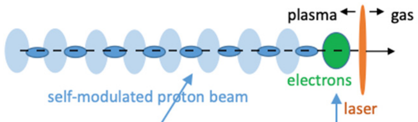
V_b

The microbunches appear at the same time t_μ along the bunch event after event

Self-Modulation of the proton bunch is seeded by the electron bunch!

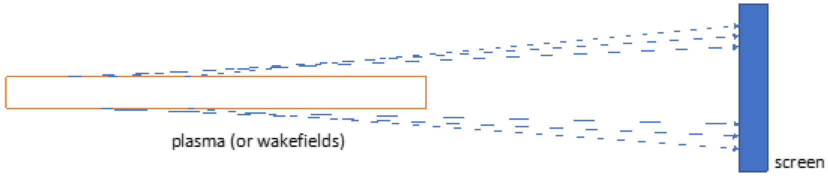
Electron Bunch Seeding – Self-Modulation Growth and Growth Rate

Understanding the seeding and growth of the self-modulation



scan *proton* bunch *charge*

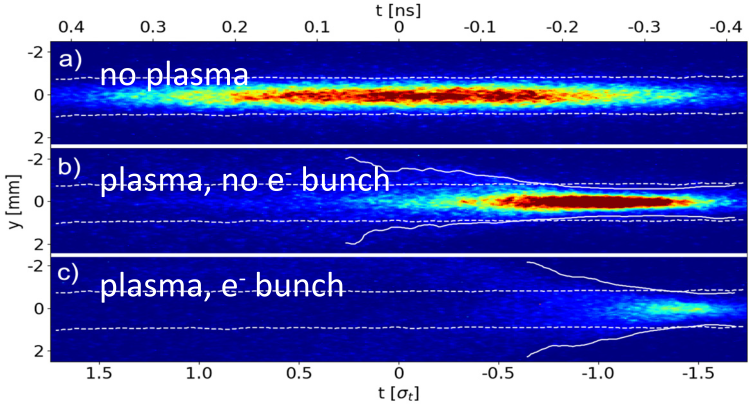
scan *electron* bunch *charge*

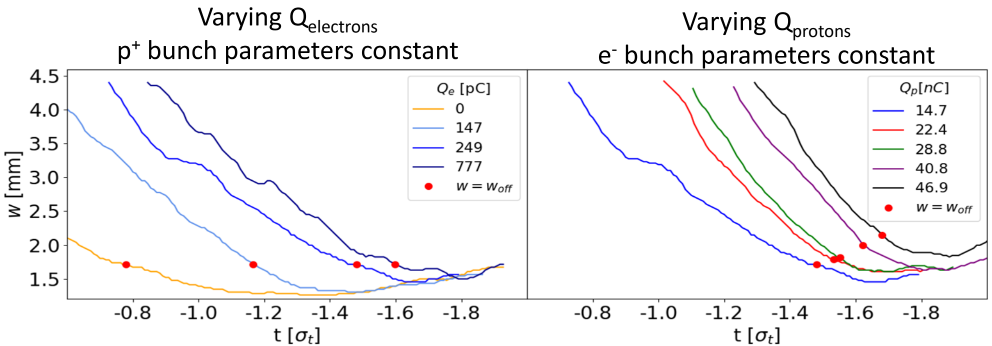


Defocused protons leave the plasma before SM reaches saturation

→ propagate with straight trajectory

→ their position at a screens gives information on the amplitude of the wakefields in the first meters of propagation





Key results accepted for publication in Phys. Rev. Lett: L. Verra et al. (AWAKE Collaboration), *Controlled Growth of the Self-Modulation of a Relativistic Proton Bunch in Plasma*, [arXiv:2203.13752]

Summary

→**AWAKE is a unique plasma wakefield acceleration experiment** using proton bunches to drive plasma wakefields.

- → Proton-driven plasma wakefield acceleration interesting because of large energy content of driver.
- → The Self-Modulation process means existing proton machines can be used.

→**AWAKE Run 1 met all expectations**: First time demonstration of proton driven plasma wakefield acceleration of externally injected electrons.

→**AWAKE Run 2 aims** to achieve high-charge bunches of electrons accelerated to high energy, about 10 GeV, while maintaining beam quality through the plasma and showing that the process is scalable.

→**First phase of AWAKE Run 2 was very successful**:

- → The **electron bunch seeds the self-modulation** of the entire proton bunch
- → **Allows to control** instability and inject the witness beam in a controlled way.

→**AWAKE Run 2 has a clear plan** towards an accelerator for particle physics.

Once AWAKE Run 2 demonstrated: First application of the AWAKE-like technology already in the mid-term future:

- → Use the AWAKE scheme for particle physics applications such as fixed target experiments for dark photon searches (modest requirements on the emittance) and also for future electron-proton or electron-ion colliders.