Results of Awake Run 1 and Plans for Run 2 Towards HEP Applications

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AWAKE

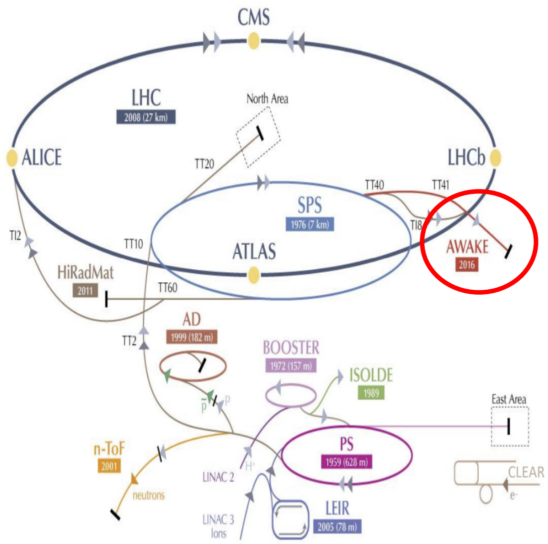
MAX-PLANCK-INSTITUT FÜR PHYSIK

CERN

Contents

AWAKE Advanced WAKefield Experiment

Plasma wakefield experiment at CERN



Collaboration of 23 institute worldwide :
Max-Planck-Institut für Physik is one of the key contributor

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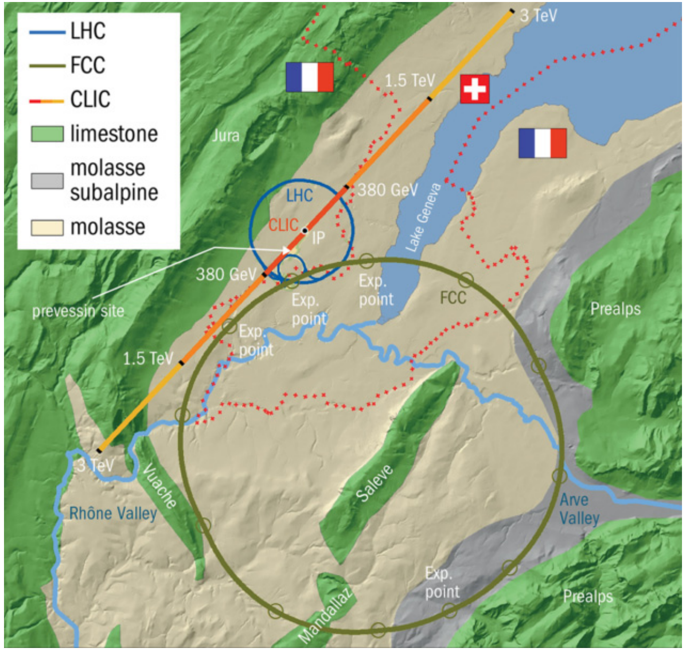
Plasma wakefield acceleration

High Energy physics requires ultra-relativistic accelerated particles



Maximum energy delivered to the particle is limited by:

- acceleration gradient mainly for linear accelerator
- bending dipole field in circular accelerator (hadron)
- synchrotron radiation losses in circular accelerator (electrons)
- maximum accelerator (tunnel) size

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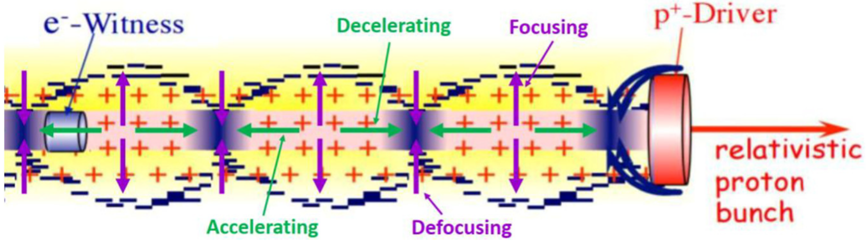
Plasma wakefield acceleration

Classics accelerators have limited acceleration gradient based on RF cavities limited accelerator gradient. The limit of the order of 100 MV/m due to electrical breakdown in the cavities

Use of plasma as it is already ionized i.e. conductor and gradients above 100 GV/m have been demonstrated

Plasma wakefield acceleration

A laser pulse or a charged particle that travel inside the plasma can induce a modulation of the plasma electron density that sustains longitudinal and transverse field which are called **wakefield**



Wakefield can be used to accelerate particles

At AWAKE we use proton bunch from the SPS as driver and electron bunch witness externally injected

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Why a proton Plasma Wakefield Accelerator?

PW laser ≈ 40J/Pulse

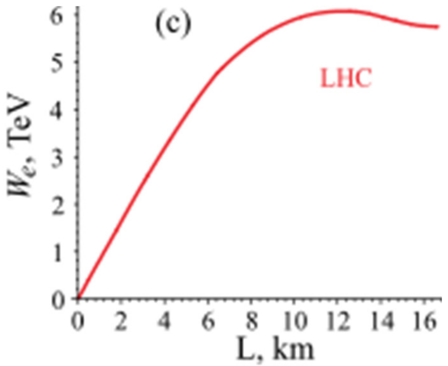
FACET (electron PWFA) ≈ 30J/Pulse

SPS 19 kJ/bunch
LHC 112kJ/bunch
} High energy gain in a single plasma stage

TeV in km ≈ GV/m

100 μm long p^+ bunch driver

Energy gain LHC bunch



A. Caldwell, & K. Lotov, (2011). Plasma wakefield acceleration with a modulated proton bunch, *Physics of Plasmas*, *18*(10), 103101

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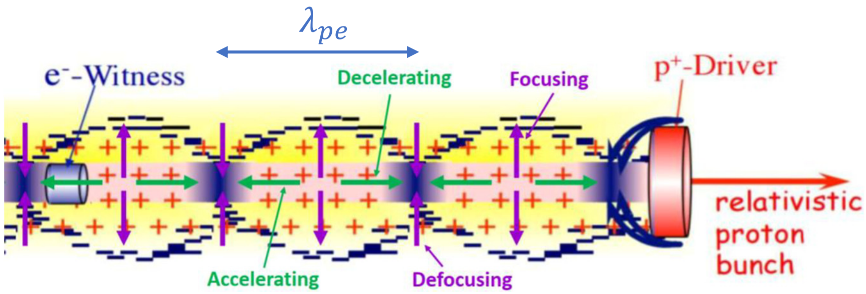
To efficiently drive wakefield the proton bunch should have: $\sigma_r \approx \frac{\lambda_{pe}}{2\pi} \quad \sigma_z \approx \frac{\lambda_{pe}}{2\pi}$



For SPS:

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

$$\sigma_r \approx 200\ \mu m \ \Rightarrow n_e \approx 7 \cdot 10^{14} cm^{-3}$$

$$\sigma_z \approx 7\ cm \ \gg \lambda_{pe}$$

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The SPS proton bunch length places an upper limit on the plasma densities and corresponding accelerating fields that can be driven by these single bunches, i.e., E_{wb}= 37–75 MV/m when $\sigma_z/(c/\omega_{pe}) \approx \sqrt{2}$

The process of Self-Modulation (SM) was proposed in * to drive E_{wb}= 1 GV/m. This is needed to drive efficiently wakefield, proton microbunches are formed and the self modulated proton bunch resonantly excite large wakefield.

Self-Modulation Instability (SMI)

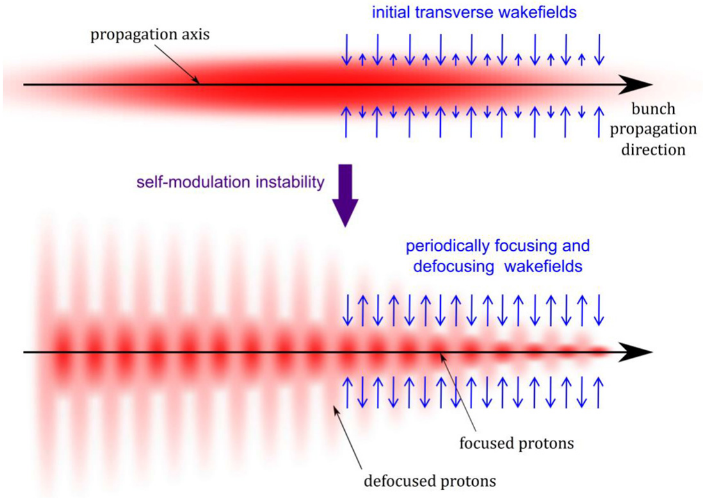


Image from F. Batch *PhD thesis*

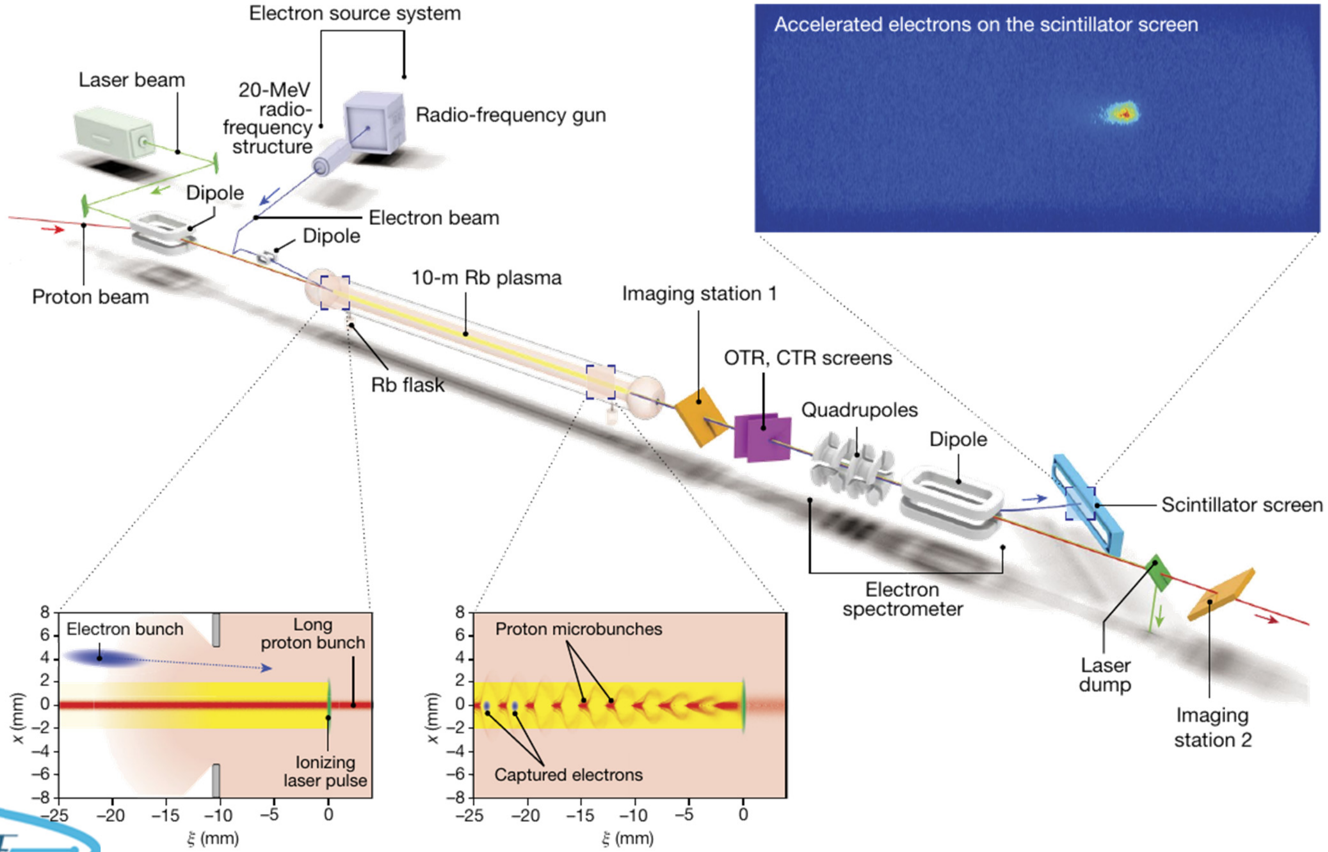
* N. Kumar, A. Pukhov, and K. Lotov, *Phys. Rev. Lett.* 104, 255003 (2010)

AWAKE Run 1 (2016-2018)

Awake Run 1 goals:

1. Demonstrate and study the seeded self-modulation (SSM) of the long SPS proton bunch in a dense plasma: $\sigma_z \gg \lambda_{pe} \approx {n_e}^{-1/2}$
2. Accelerate externally injected electrons to the GeV energy level

AWAKE Run 1 (2016-2018)



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

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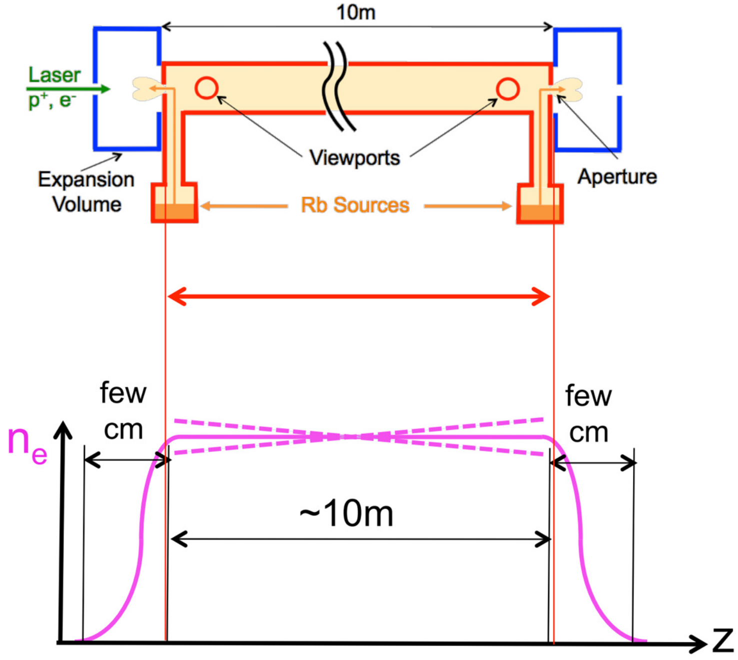
AWAKE Run 1 (2016-2018)

Rubidium vapor source

- $10^{14} \leq n_e \leq 10^{15} cm^{-3}$
- $\Delta n_e / n_e \leq 0.2\%$
- Few cm n_e ramp

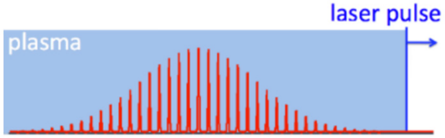
Laser → Field Ionization

- $n_e = n_{Rb}$
- Same for n_{Rb}
- $r_p > 1\ mm$

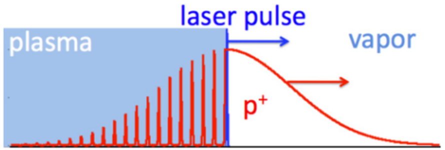


P. Muggli Awake Collaboration meeting 04/01/2019

Pre-formed plasma



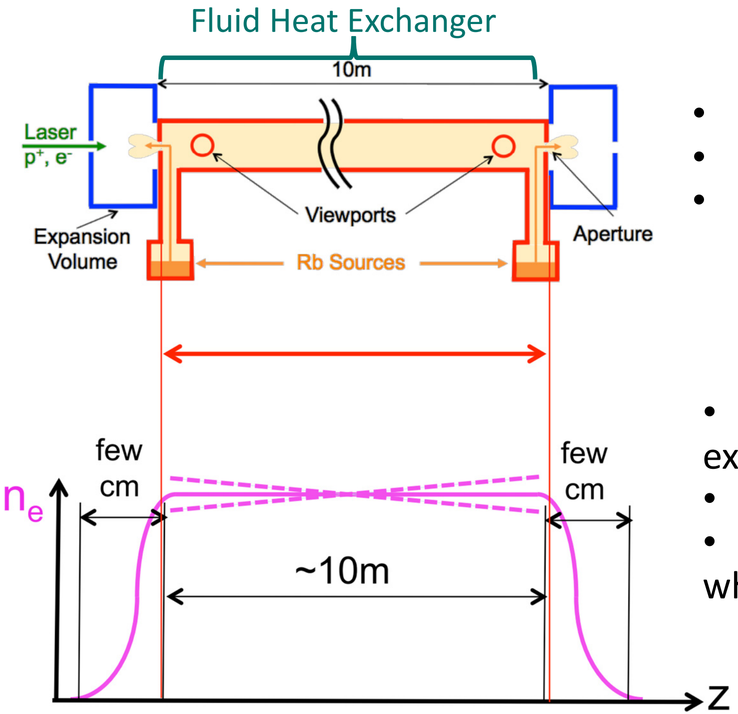
Partial Plasma



G. Plyushchev, R. Kersevan, A. Petrenko, and P. Muggli, A rubidium vapor source for a plasma source for AWAKE, *J. Phys. D* 51, 025203 (2017)
E. Öz and P. Muggli, A novel Rb vapor plasma source for plasma wakefield accelerators, *Nucl. Instrum. Methods Phys. Res., Sect. A* 740, 197 (2014)

AWAKE Run 1 (2016-2018)

Rubidium vapor source



- Impose very uniform T: $\delta n_{Rb}/n_{Rb} = \delta T/T \leq 0.2\%$
- $160 \leq T \leq 220^{o}C$ for $10^{14} \leq n_e \leq 10^{15} cm^{-3}$
- Control n_{Rb} gradient with Rb source T

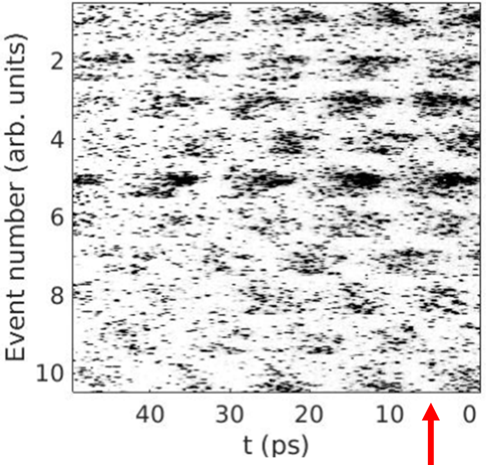
- Rb vapor expands into vacuum and sticks to cold walls of expansion volumes: short ramp
- Scale lengths ~ diameter aperture: 1cm
- n_{Rb} Rb measured at both end with $< 0.2\%$ accuracy using white light interferometry

P. Muggli Awake Collaboration meeting 04/01/2019

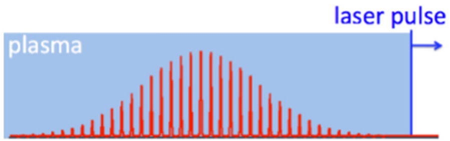
G. Plyushchev, R. Kersevan, A. Petrenko, and P. Muggli, A rubidium vapor source for a plasma source for AWAKE, *J. Phys. D* 51, 025203 (2017)
E. Öz and P. Muggli, A novel Rb vapor plasma source for plasma wakefield accelerators, *Nucl. Instrum. Methods Phys. Res., Sect. A* 740, 197 (2014)

AWAKE Run 1 (2016-2018)

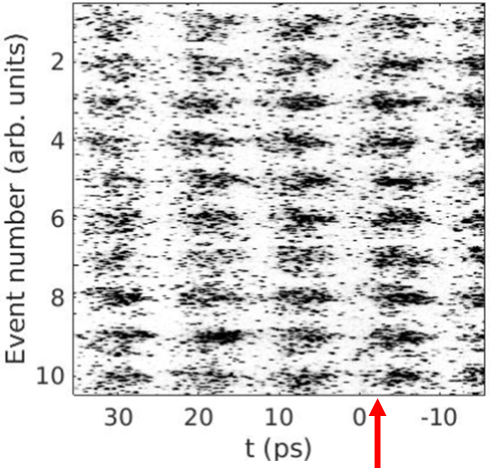
Self-Modulation Instabilities (SMI)



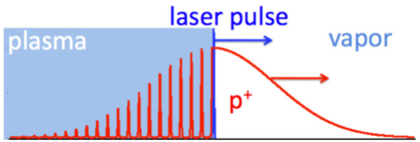
not reproducible, cannot inject e^- with same phase event to event

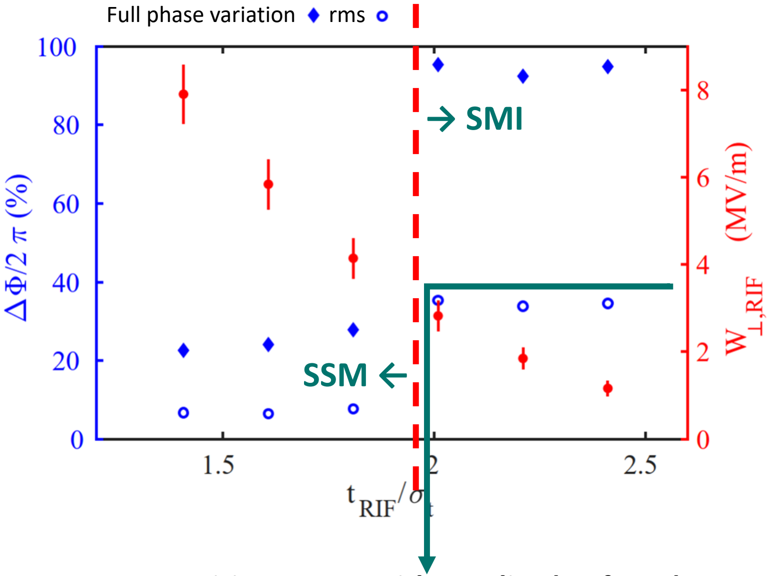


Seeded Self-Modulation (SSM)



possible e^- acceleration





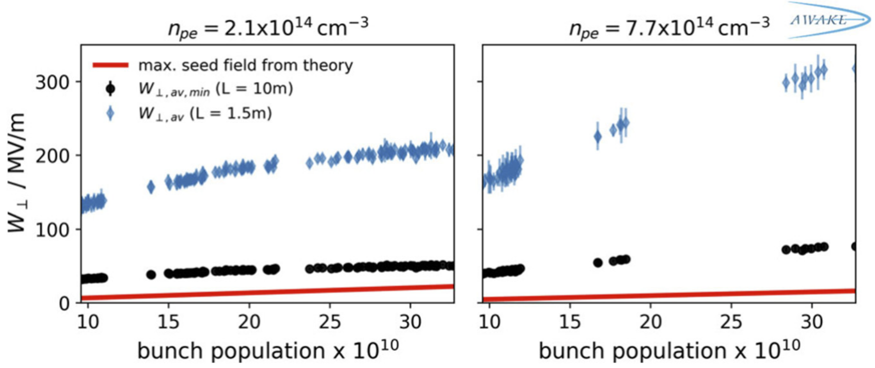
Transition occurs with amplitude of seed wakefields > 2.8-4.0 MV/m

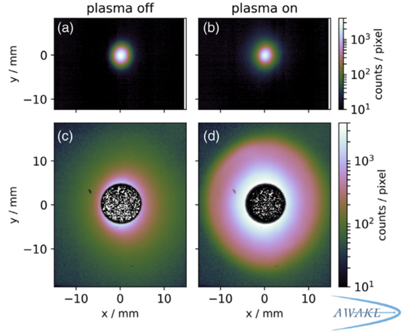
F. Batsch et al., *Phys. Rev. Lett.* 126, 164802, 2021

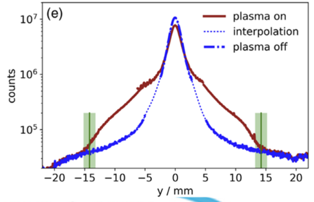
AWAKE Run 1 (2016-2018)

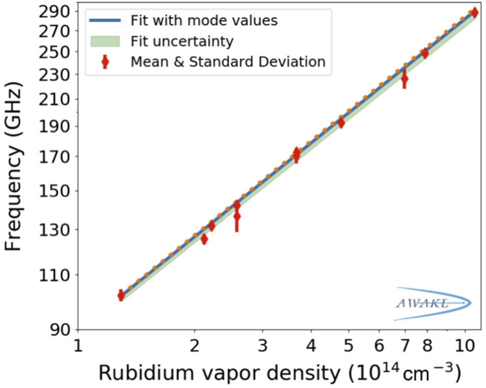
Self-Modulation

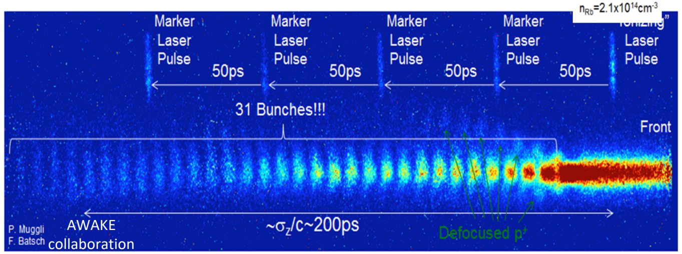
- Self-Modulation grows along the plasma and the bunch, with Wakefields ⊥≈ 100's MeV
- Self-Modulation frequency is the plasma electron frequency
- Micro-bunches present over long time scale from seed point
- Phase stable and reproducible self-modulation of the proton bunches









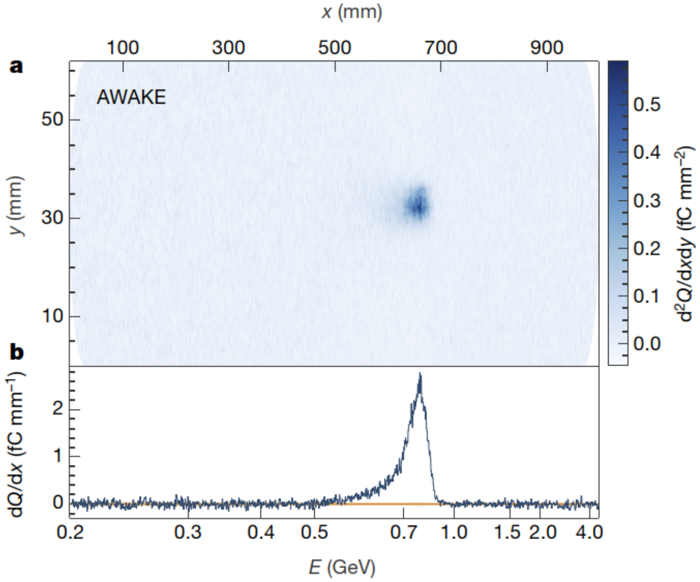


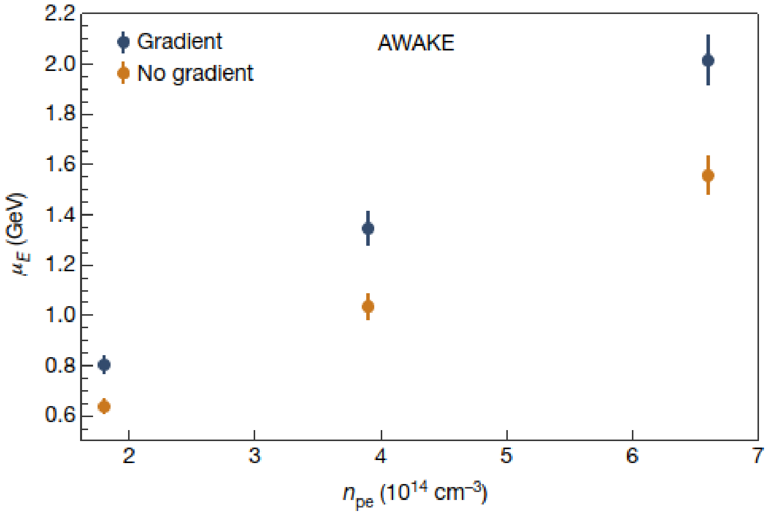
M. Turner et al. (AWAKE Collaboration), *Phys. Rev. Lett.* 122, 054801 2019
AWAKE Collaboration, *Phys. Rev. Lett*. 122, 054802, 2019
F. Batsch et al. (AWAKE Collaboration), *Phys. Rev. Lett.* 126, 164802, 2021

AWAKE Run 1 (2016-2018)

Acceleration

- Acceleration of externally injected electrons from 18MeV to 2GeV
- Longitudinal Wakefield of the order of 100s MeV





AWAKE Collaboration, *Nature* 561, 363, 2018

AWAKE Run 2 (2021-)

Awake Run 2 :

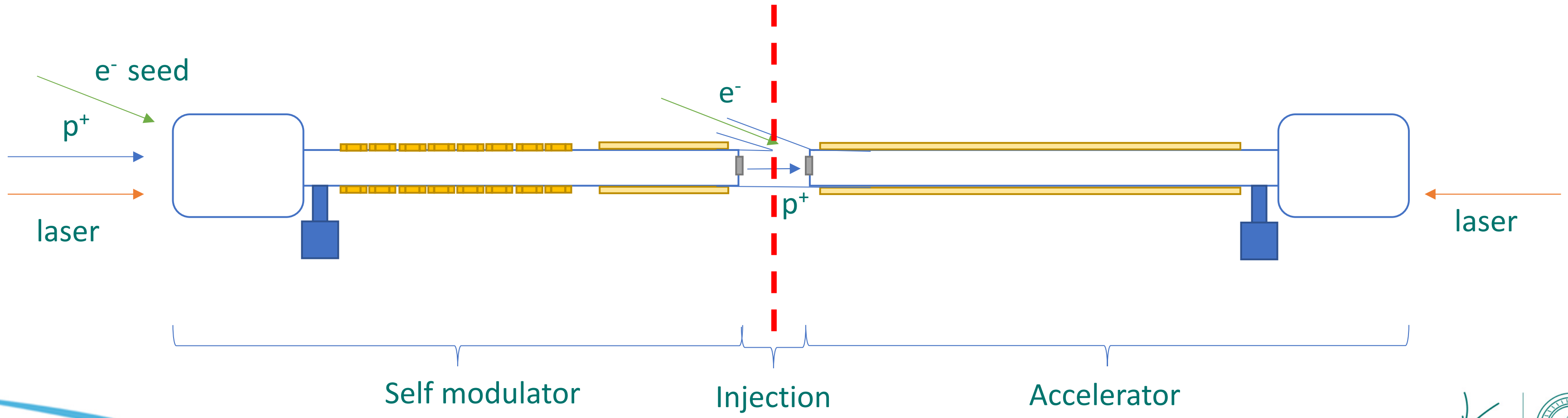
From Acceleration to Accelerator

- Demonstrate acceleration of externally injected electron bunch (100 pC)
- Preserve electron beam quality
- Plasma source scalability and acceleration

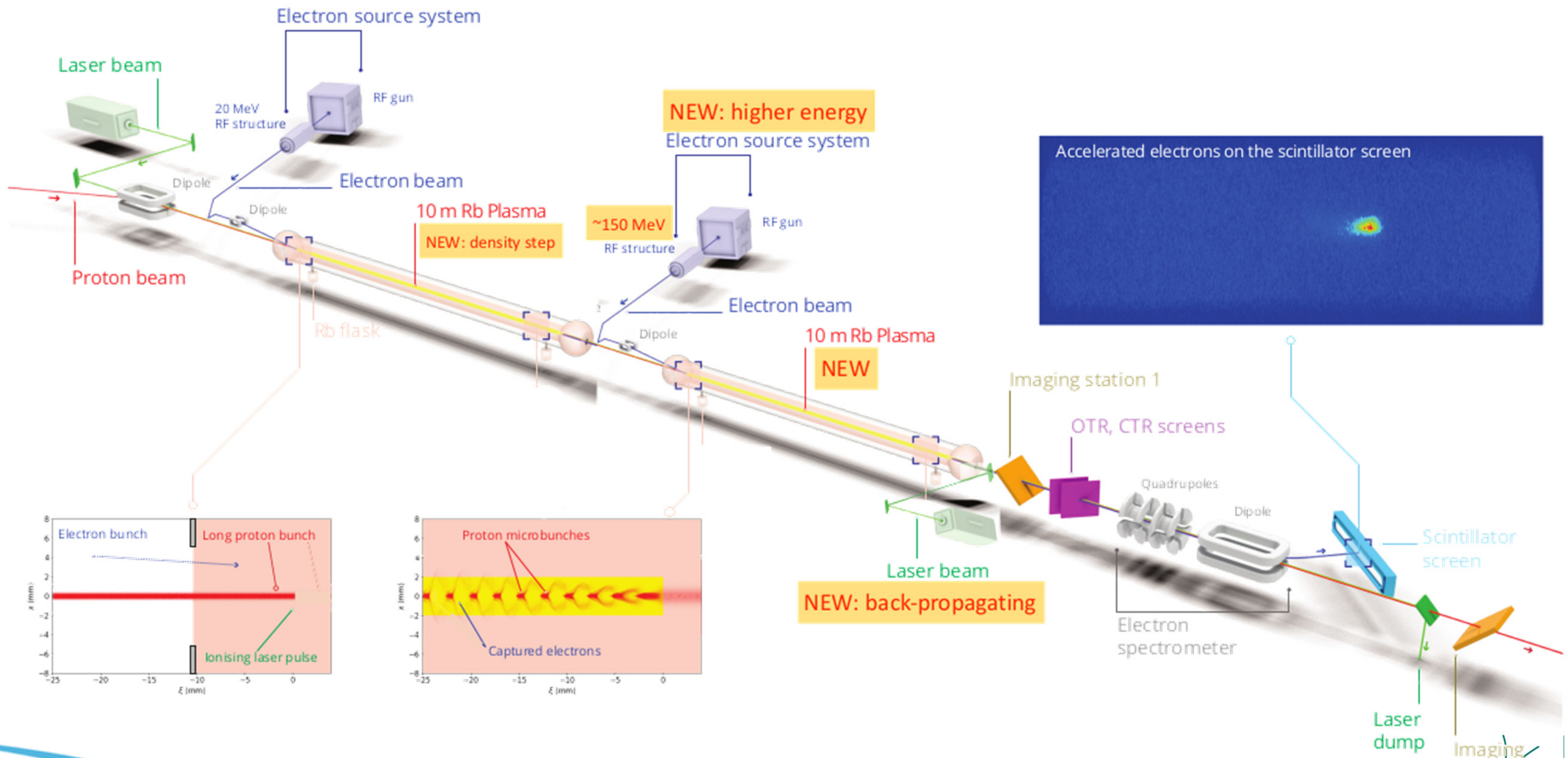
AWAKE Run 2 (2021-)

Program phases:

- **Seeding** proton bunch modulation with an **electron bunch** (**2a**) — 2021-2022
- **Plasma with density step** to stop the evolution of the modulation (**2b**) — 2023-2024
- Inject electrons & accelerate with emittance preservetion (**2c**) — After LHC LS3
- Implement scalable plasma source technologies (**2d**) — After LHC LS3

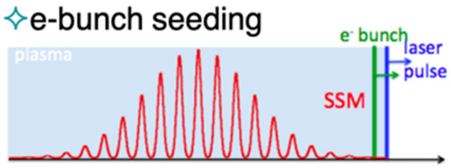


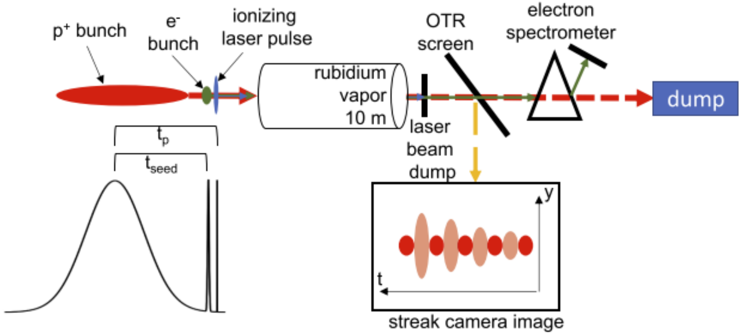
AWAKE Run 2 (2021-)

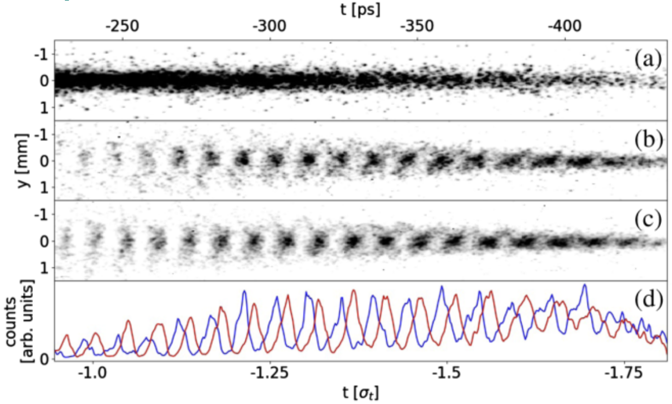


AWAKE Run 2a (2021-2022)

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







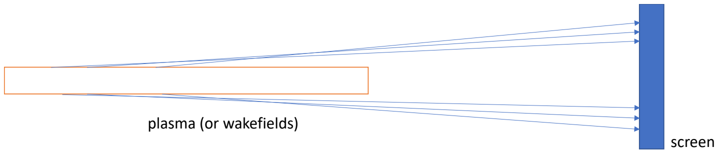
(a) No plasma, incoming proton bunch
(b) Sum of 10 events: microbunches appear at the same time along the bunch event after event
(c) Sum of 10 events with e-bunch delayed of 6.7ps: microbunches delayed
(d) Projection of (b) and (c)

Self-Modulation of the proton bunch is seeded and controlled with the electron bunch !

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

AWAKE Run 2a (2021-2022)

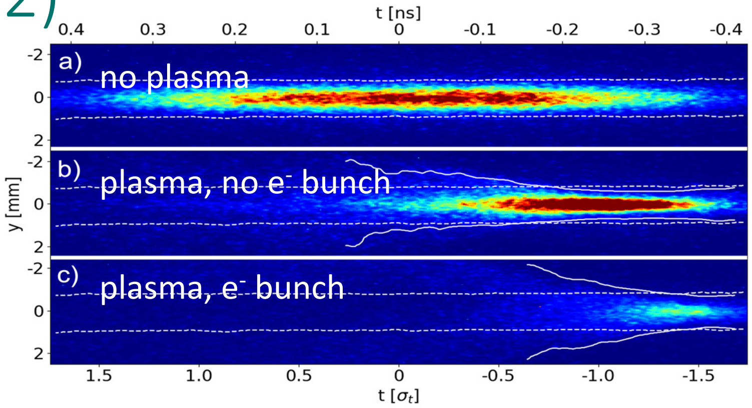
Studying the seeding and growth of the self-modulation



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

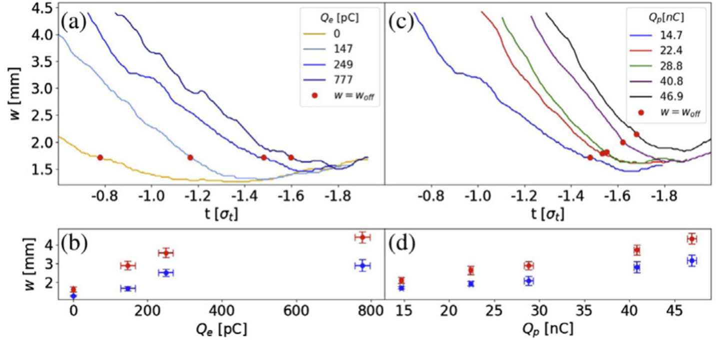


Varying Q_e

p^+ bunch parameters constant

Varying Q_p

e^- bunch parameters constant



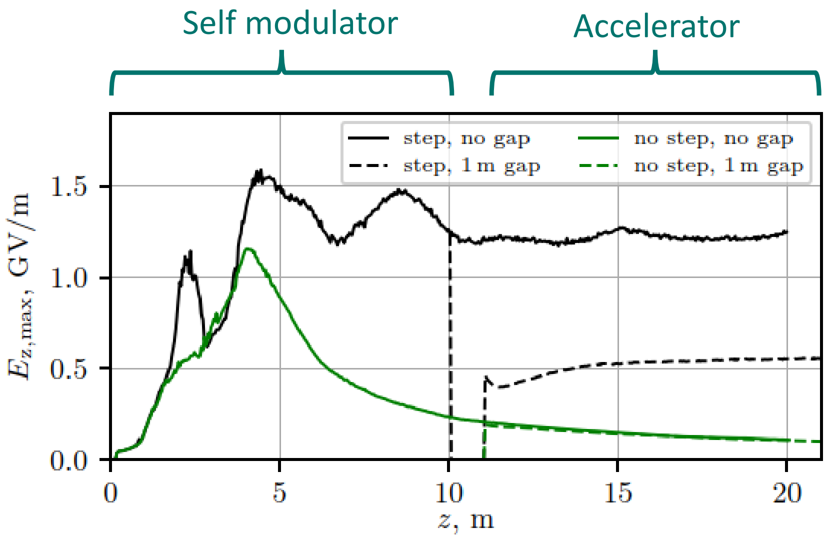
Growth of SM observed with increasing amplitude of the seed wakefields (Q_e)

And with increasing growth rate of SM (Q_p)

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

AWAKE Run 2b (2023-2024)

AWAKE Run 2b: stabilization of the wakefield with a density step in the plasma source and maintain high gradient



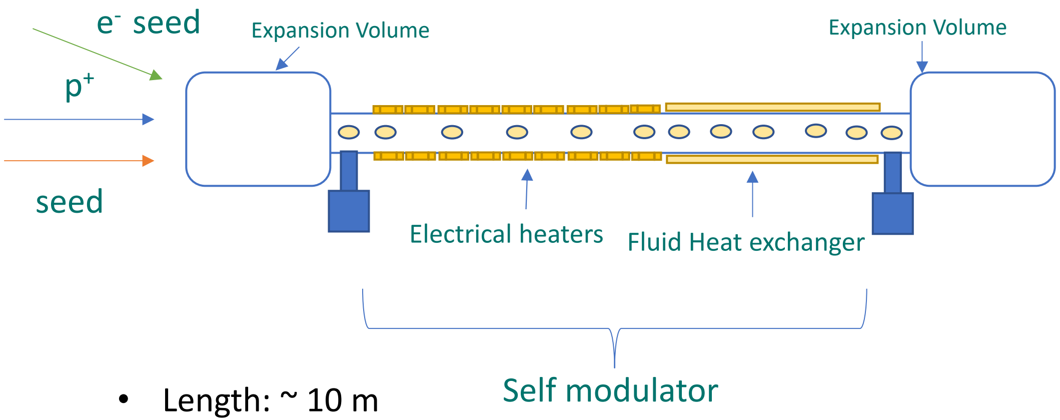
- With a density step in the selfmodulator, wakefields maintain a level close to saturation amplitude after the saturation
- Gap between two plasma reduces amplitude of wakefields in 2nd plasma (accelerator)-> gap length needs to be minimized

E. Gschwendtener et al. (AWAKE Collaboration), arXiv:2206.06040, accepted for publication in *Symmetry* MDPI

AWAKE Run 2b (2023-2024)

New vapor source with density step:

- Same requirements as Run 1 for Rb density uniformity and max value as for Run1 and Run 2a $\delta T\ ({}^{o}K)/T({}^{o}K) \approx 0.2\%$
- Additionally have to implement a "sharp" (tens of cm) step from 1% to 10% $\delta T\ ({}^{o}K)/T({}^{o}K)$ from 5 to 50°C

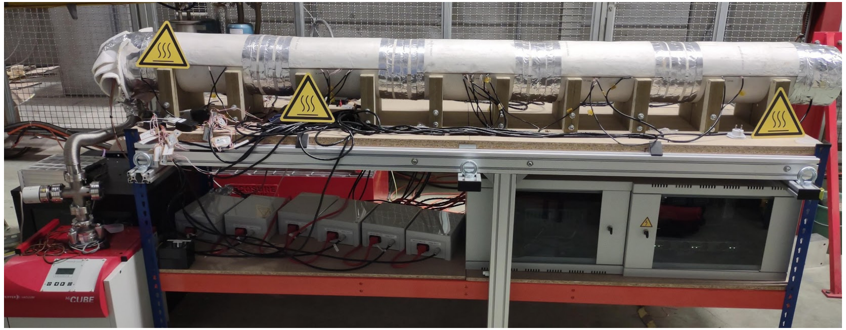


- Length: ~ 10 m
- Independent electrical heater of 50 cm from 0.25 to 4.75 meters
- 5.3m of fluid heated section
- Step height up to ±10%
- 10 diagnostic viewport, for plasma light + 3 for density diagnostic

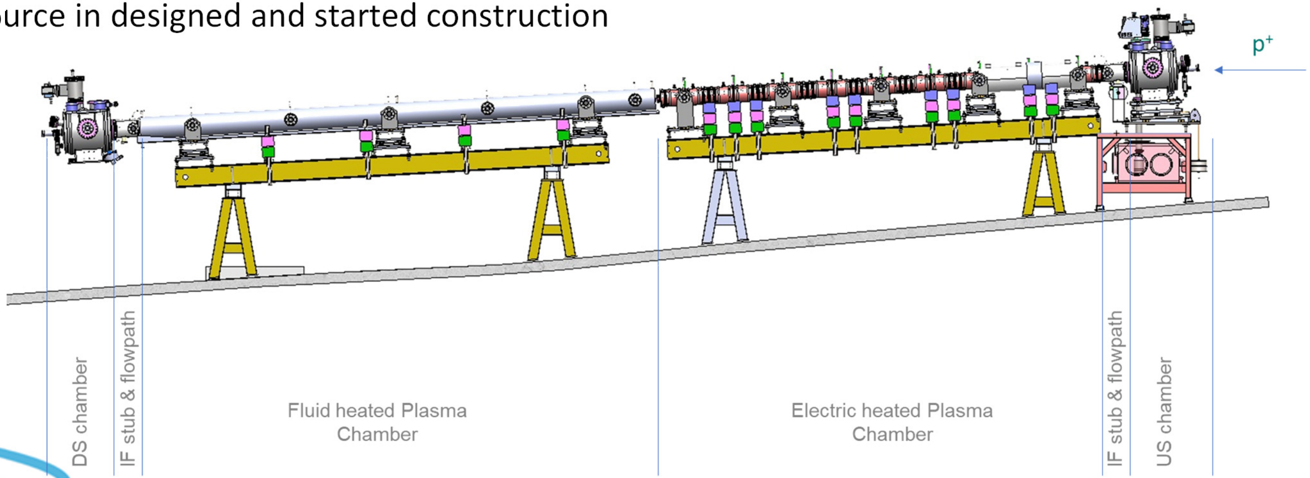
AWAKE Run 2b (2023-2024)

New vapor source with density step:

- Stand alone prototype electrically heated section tested at CERN in 2021 showing Flat profile 1°C ≈ $0.2\%\ \delta T\ (^{o}K)/T(^{o}K)$ and excellent reproducibility of 50°C Step



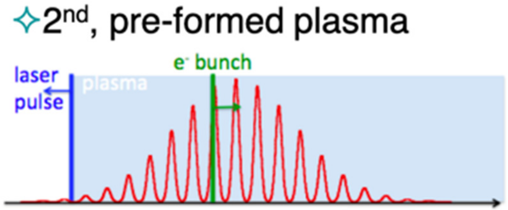
- New vapor source in designed and started construction



AWAKE Run 2c and 2d

AWAKE Run 2c: electron acceleration and emittance control

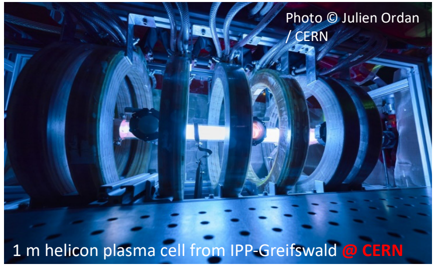
In Run 1, acceleration obtained with off-axis injection to avoid defocusing of the injected electrons in the density ramp at the entrance of the plasma. Un-modulated proton bunch drives transverse fields defocusing for injected electrons



Run 2, inject electrons on axis after the SM process has saturated
In 2nd plasma source

2nd electron source needed with bunch density n_{b0} must exceed the plasma electron density: $n_{b0} \gg n_{e0}$ to reach blow-out

AWAKE Run 2d: scalable plasma sources



Plasma source based on RB vapor limit distance to 10s of meter because of laser pulse depletion of the energy

AWAKE is developing other plasma sources that do not suffer from length limitations:

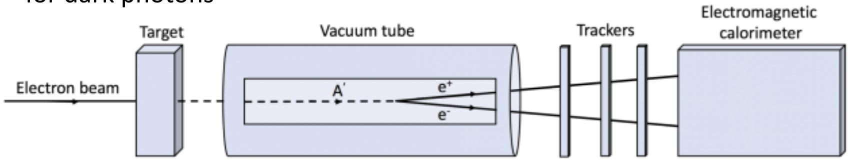
- direct-current electrical discharge in noble gases *
- helicon argon plasma **

* N.E. Torrado et al., Double pulse generator for unipolar discharges in long plasma tubes for the AWAKE experiment, Submitted for publication, 2022
** B. Buttenschön, N. Fahrenkamp and O. Grulke, A high power, high density helicon discharge for the plasma wakefield accelerator experiment AWAKE, *Plasma Phys. Control. Fusion* 60, 2018, 075005
E. Gschwendtener et al. (AWAKE Collaboration), arXiv:2206.06040, accepted for publication in *Symmetry* MDPI

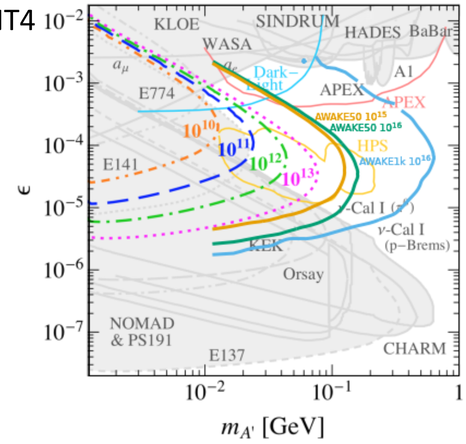
Particle physics application of AWAKE

A beam-dump experiment for dark photon searches

AWAKE acceleration scheme could enable an experiment to extend the search for dark photons



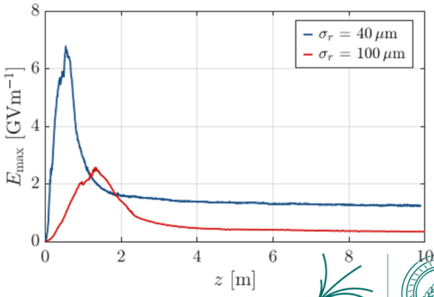
Sensitivity to coupling strength ε and mass, $m_{A'}$
Simulated with GEANT4



High energy electron–proton/ion colliders

Respect to high energy $e^+ e^-$ collider, in ep/eA collider low emittances are not needed (proton emittance dominated). With SPS p^+ driver 50 GeV e^-, centre-of-mass energy of 1 TeV but low Luminosity 1.5×10^{27} cm^{-2} s^{-1}
With LHC p^+ driver, centre-of-mass energy of 9 TeV, Low Luminosity $10^{28} - 10^{29}$ cm^{-2} s^{-1}

Longitudinal Wakefield evolution in 10m plasma
With EIC proton bunch parameters



BNL proton beams for a compact electron injector for a future electron–ion collider

Electron Ion Collider (EIC) is expected to collide electrons of up to 20 GeV with protons of up to 275 GeV at BNL

Investigation of strong-field QED in electron–laser collisions

e^- -laser collision rate limited by high power laser repetition rate ≈ 1Hz. AWAKE offer similar parameters

M. Wing, Particle physics experiments based on the AWAKE acceleration scheme, *Phil. Trans. R. Soc.* A. 377, 2019, 20180185
A. Caldwell et al., Particle physics applications of the AWAKE scheme, arXiv:1812.11164, 2018
A. Caldwell and M. Wing, VHEeP: A very high energy electron–proton collider, Eur. Phys. J. C 76, 2016, p.463.
E. Gschwendtener et al. (AWAKE Collaboration), arXiv:2206.06040, accepted for publication in *Symmetry* MDPI

Conclusion

- **AWAKE is a unique plasma wakefield acceleration experiment** making use of proton bunches to drive waakefield in plasma
  - ➢ **A large energy content** is carried by the proton driver
  - ➢ Self-Modulation process means that **existing proton machines can be used**
- **AWAKE Run 1 demonstred the self-modulation process** and **acceleration of externally injected electrons** of proton driven plasma wakefield
- **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**:

  Established **electron bunch seeding of the self-modulation** of the entire proton bunch
- **AWAKE Run 2 has a clear plan** towards an accelerator for particle physics. After demonstrating AWAKE Run 2 program, **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.

A big thank to the whole AWAKE collaboration

And thank you for your attention !