Proton beam self-modulation and electron acceleration in AWAKE experiment

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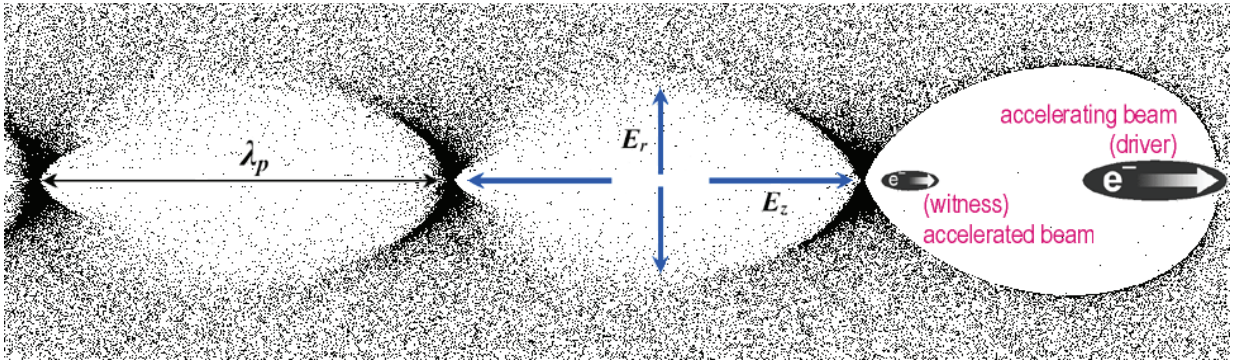
AWAKE Collaboration

AWAKE (Advanced proton driven plasma WAKEfield acceleration experiment) is the first experiment on plasma wakefield acceleration driven by a proton beam

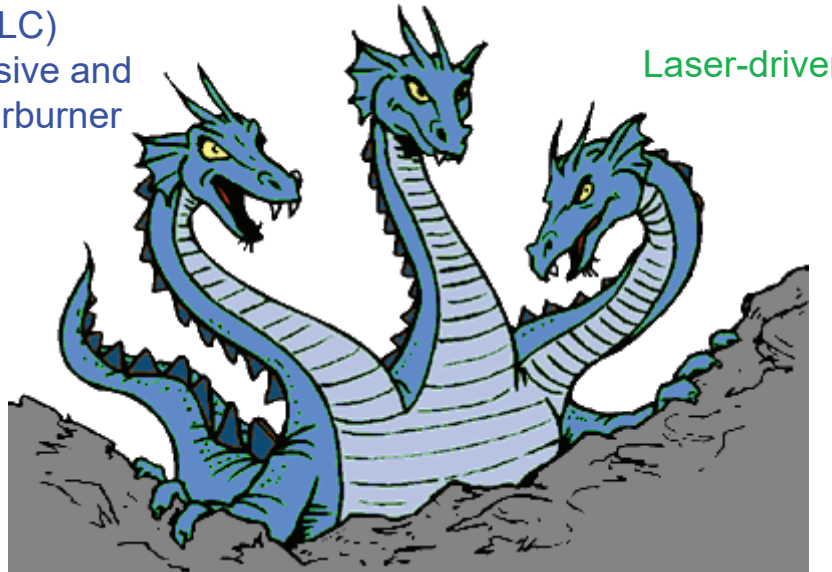
PWFA promises x100 higher acceleration rate, but has a great number of problems to solve on the way to real high-energy collider

One problem is related to the energy content of the accelerated bunch: ILC-like electron bunch has ~1 kJ at 250 GeV



Proton drivers: 20 kJ (SPS), >150kJ (LHC) drivers have enough energy in a single bunch to accelerate electrons to TeVs in a single plasma stage

Electron-driven: < 120 J (SLC) either many stages (expensive and complicated design) or afterburner (energy doubling after a conventional linac),



Laser-driven: < 50 J in the drive laser pulse, < 10 GeV/stage, many stages are needed for TeVs,

Compact radiation sources and electron injectors become the mainstream applications

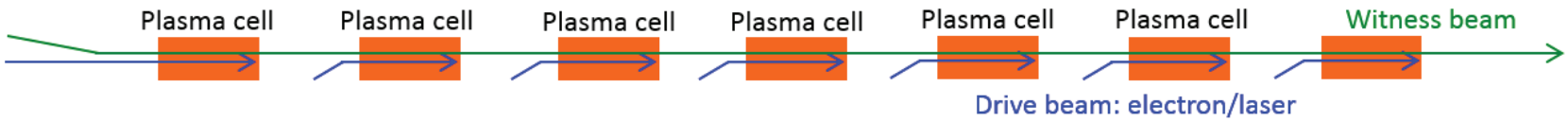
Why proton drivers?

Drive beams:
Lasers: ~40 J/pulse
Electron drive beam: 30 J/bunch
Proton drive beam: SPS 19kJ/bunch, LHC 300kJ/bunch

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

To reach TeV scale:

- **Electron/laser driven PWA**: need several stages (challenging tolerances, matching, etc…)
  - effective gradient reduced because of long sections between accelerating elements….



- **Proton drivers**: large energy content → could accelerate a full ILC-like e^--bunch (~1.6kJ) in a **single stage**

Seeded Self-Modulation (SSM) of the proton beam

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! ($\sigma_z \approx 7$ cm) → much longer than plasma wavelength ($\lambda_p \sim 1$mm)

Seeded Self-Modulation (N. Kumar, A. Pukhov, K. Lotov, PRL 104, 255003 (2010)):

Initial (seed) wakefields locked to the beam

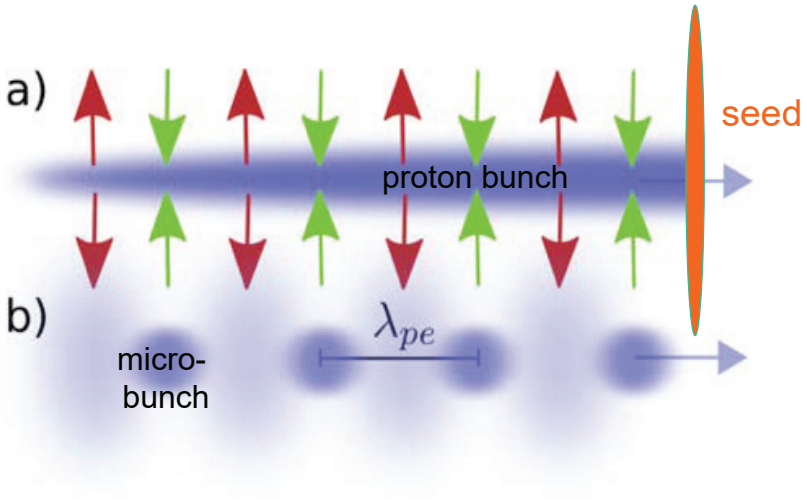
→ Initial wakefields act back on the proton bunch itself

→ Bunch radius and on-axis density are modulated

→ Stronger wakefields → Stronger modulation

→ Micro-bunches separated by plasma wavelength λ_p

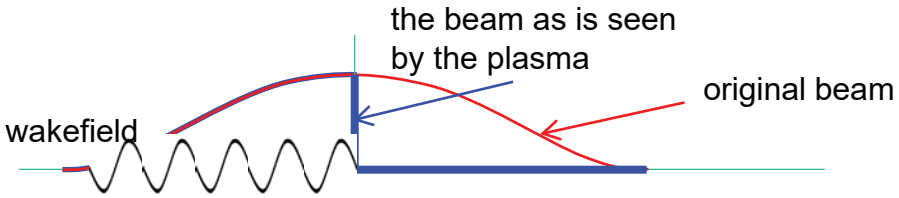
→ Resonant wakefield drive

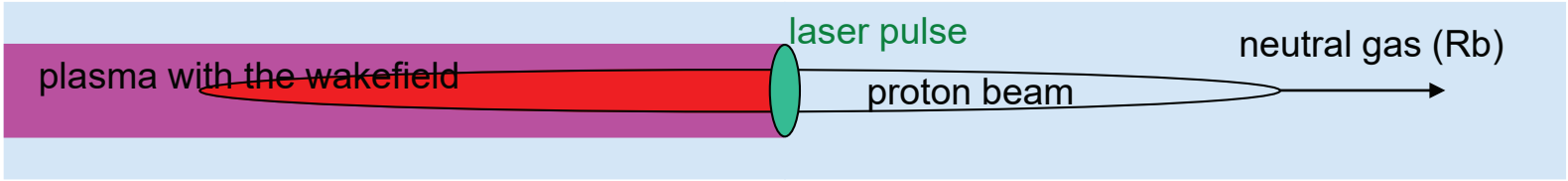


AWAKE: Seeding of the instability by

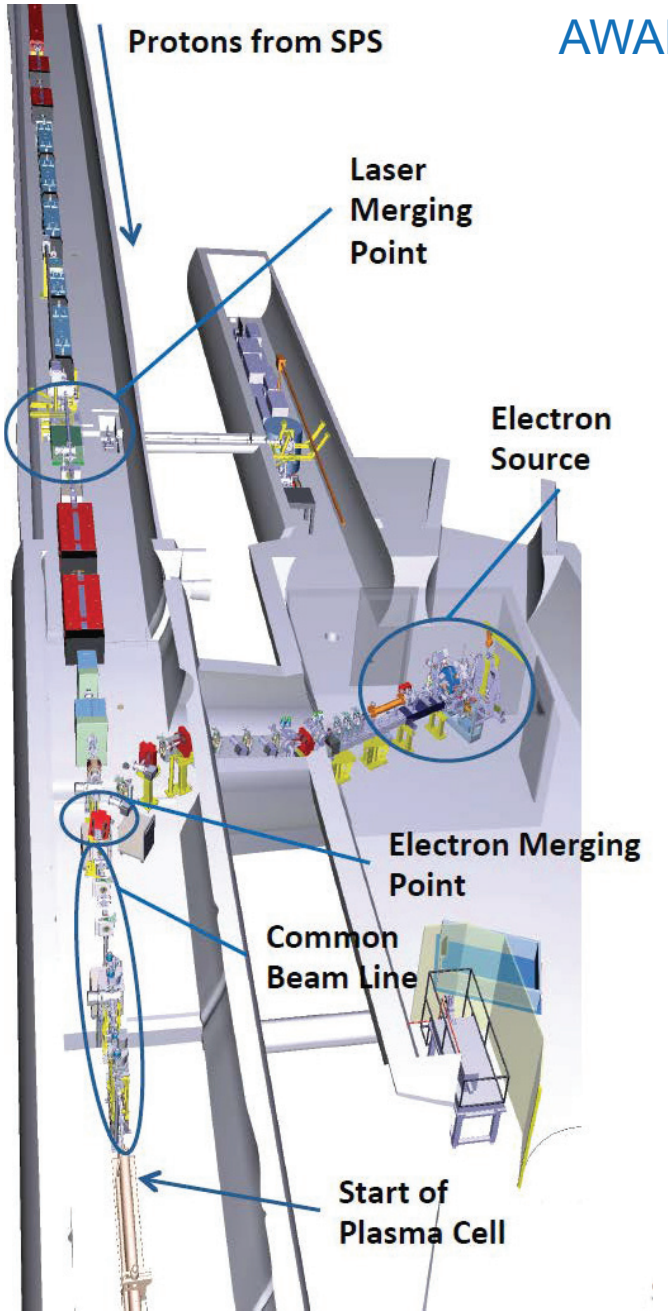
- Placing a **laser** close to the center of the proton bunch
- Laser ionizes vapour to produce plasma
- Sharp start of beam/plasma interaction

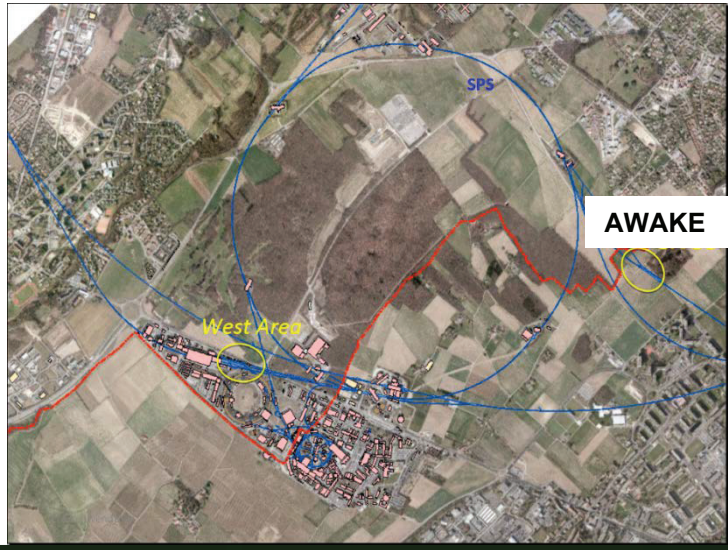
→ Seeding with ionization front

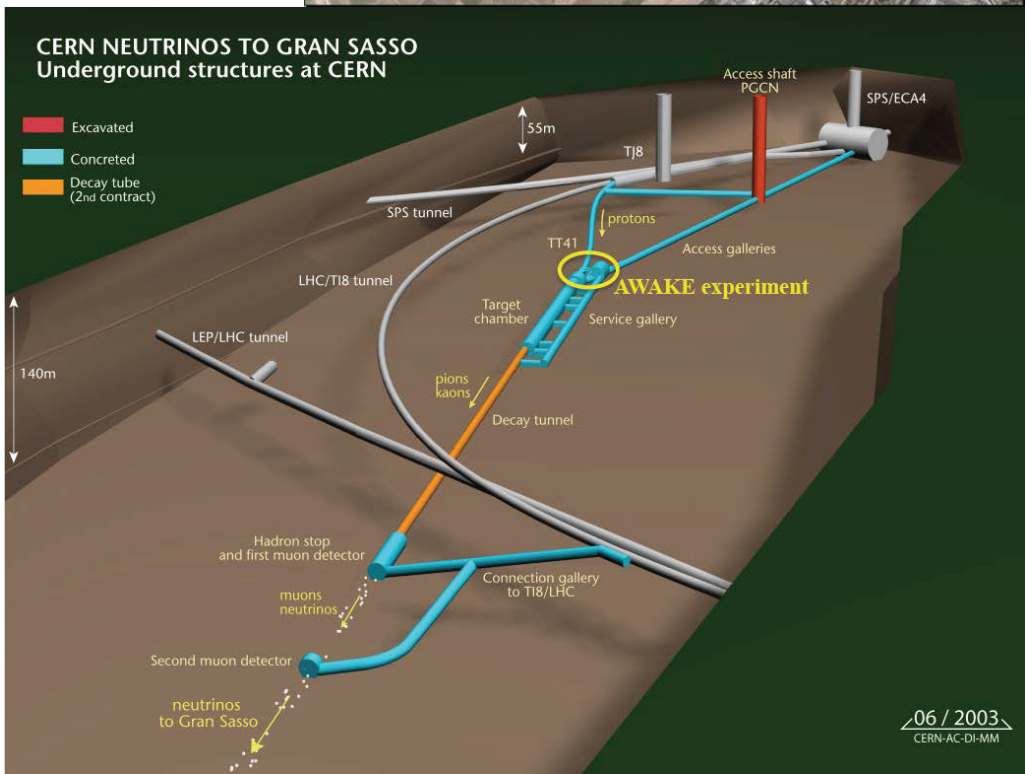




AWAKE experiment







AWAKE Collaboration: 18+3 Institutes world-wide

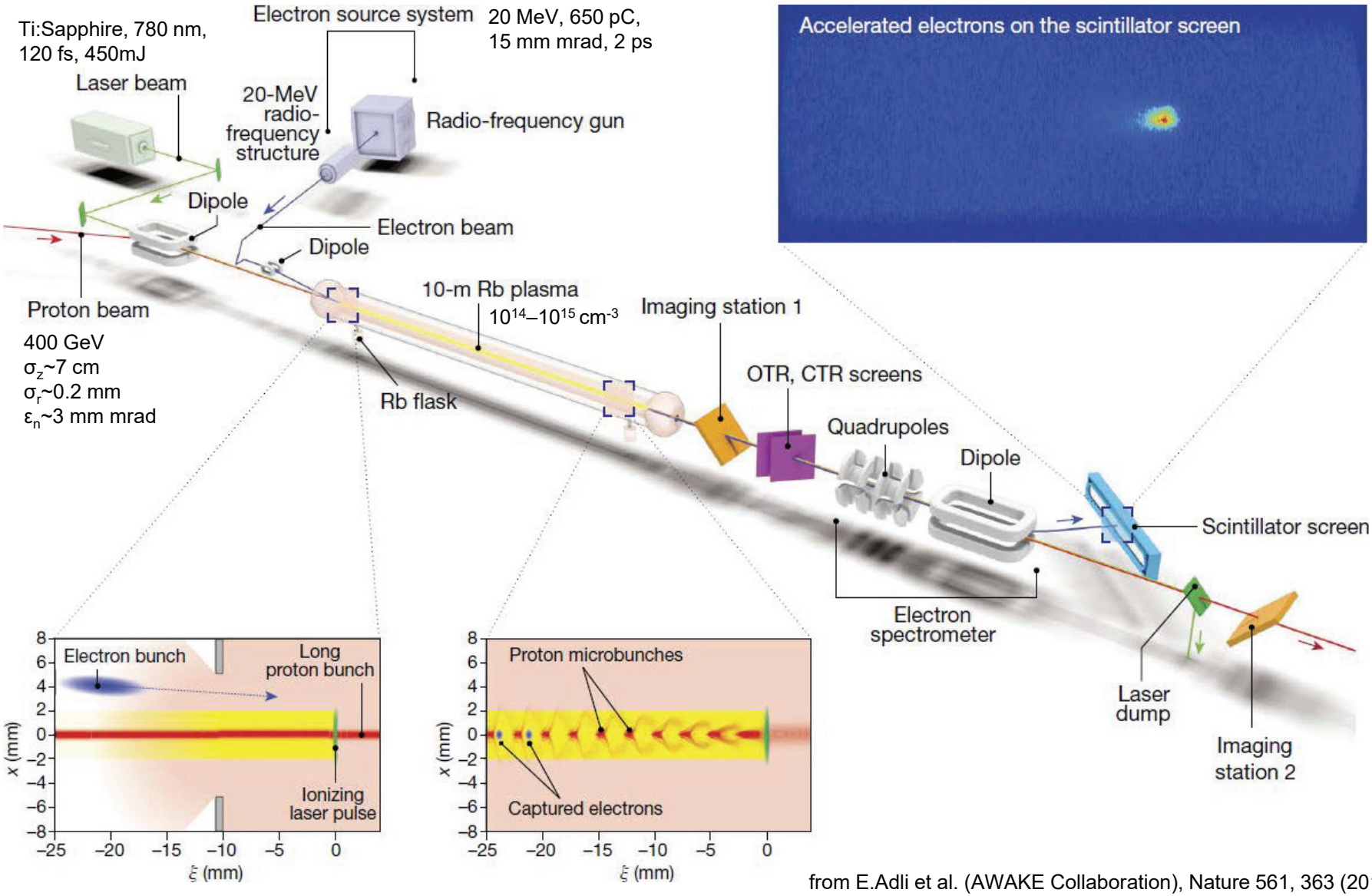
Collaboration members:

- University of Oslo, Oslo, Norway
- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, 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
- Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
- Novosibirsk State University, Novosibirsk, Russia
- GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
- TRIUMF, Vancouver, Canada
- Ludwig-Maximilians-Universität, Munich, Germany

Associated members:

- University of Wisconsin, Madison, US
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL

Layout of the AWAKE experiment



from E.Adli et al. (AWAKE Collaboration), Nature 561, 363 (2018)

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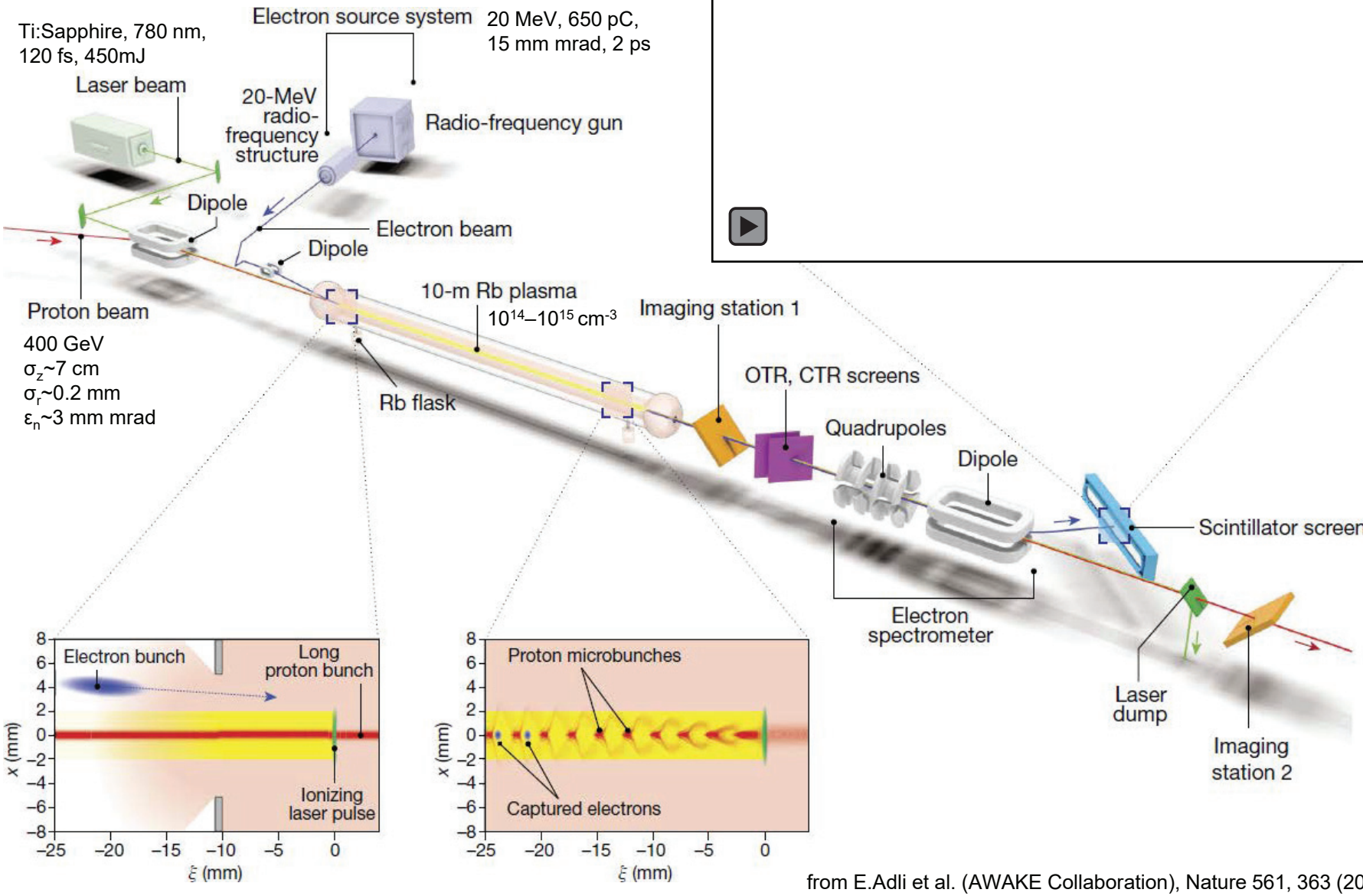

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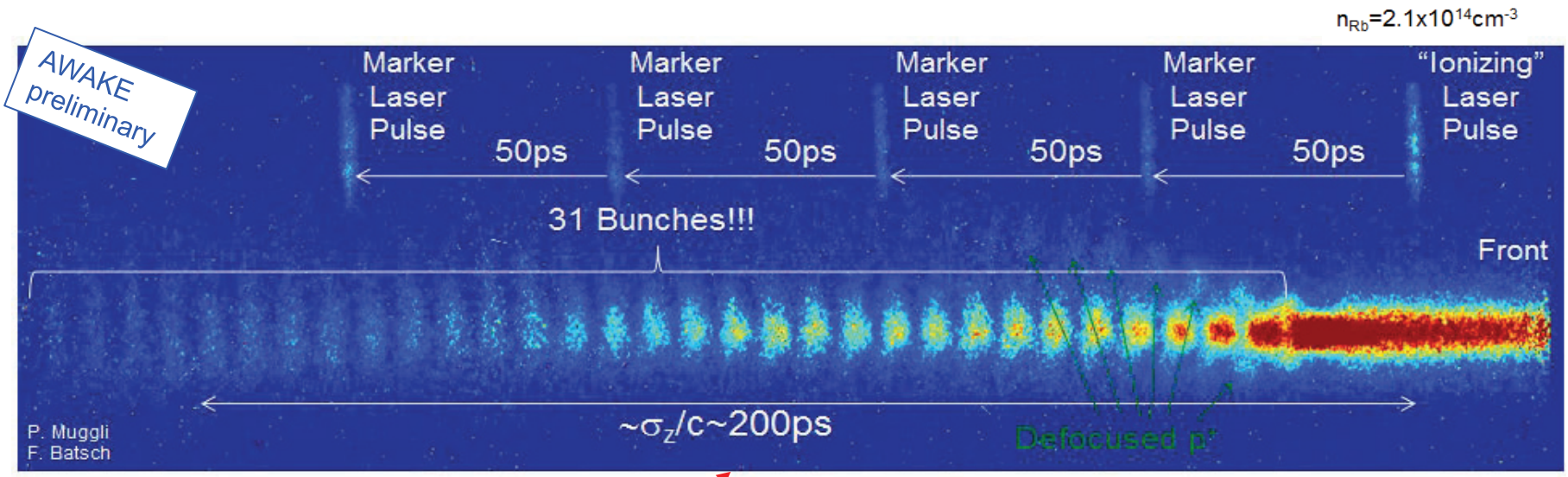
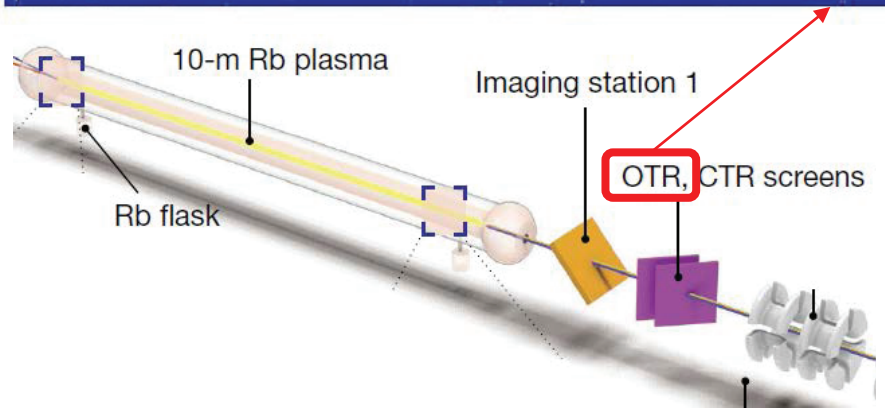
Results: Direct Seeded Self-Modulation Measurement





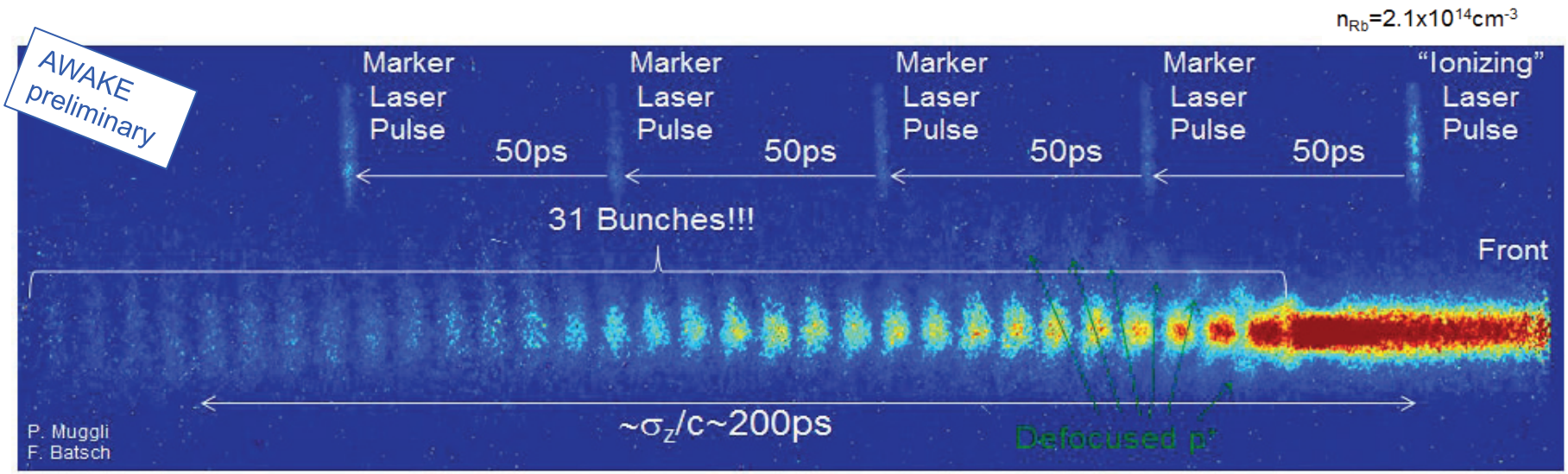
- Density modulation at the ps-scale visible
- Effect starts at laser timing → SM seeding
- Micro-bunches present over long time scale from seed point
- Reproducibility of the μ-bunch process against bunch parameters variation
- Phase stability essential for e^- external injection.

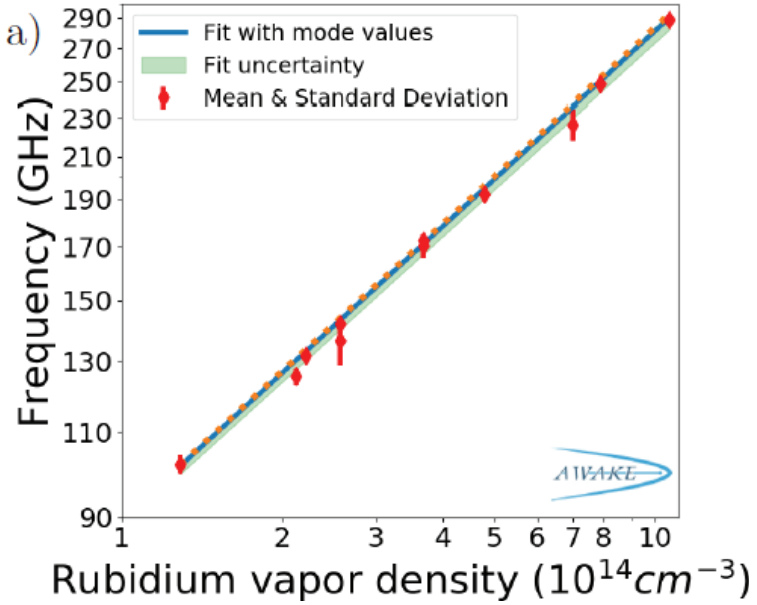
Longitudinal structure of self-modulated proton bunch:

→ Image OTR light onto the slit of a streak camera.

→ Time resolved measurement.

Results: Direct Seeded Self-Modulation Measurement

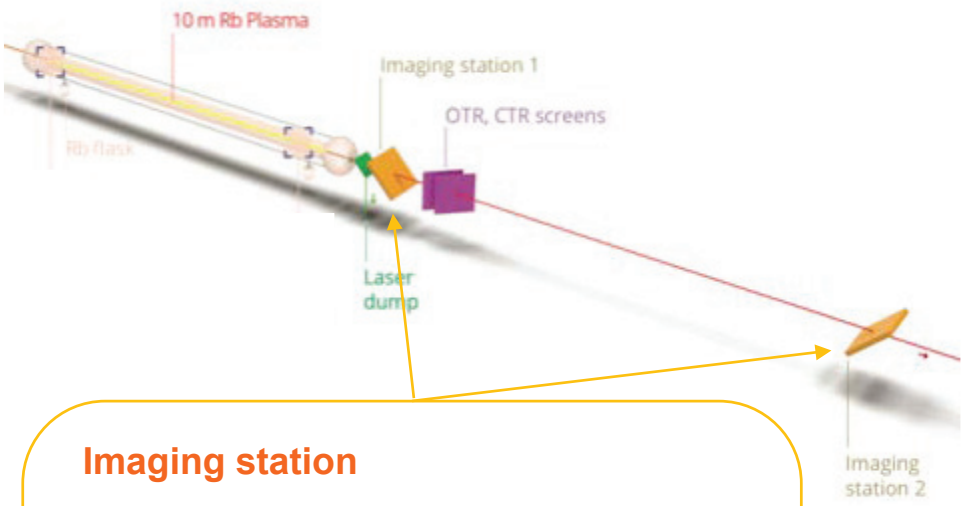




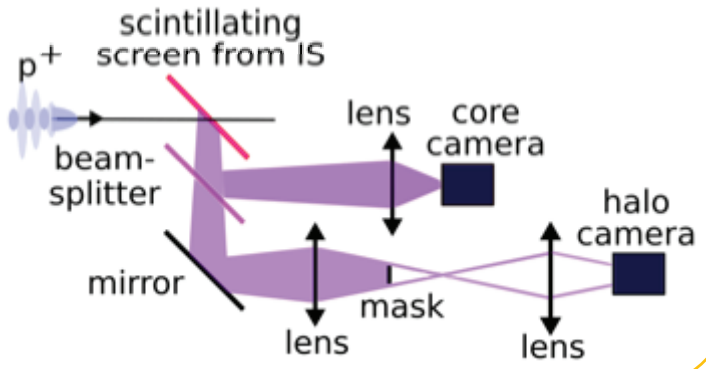
- Microbunch frequency corresponds to the plasma frequency of single-ionized Rubidium

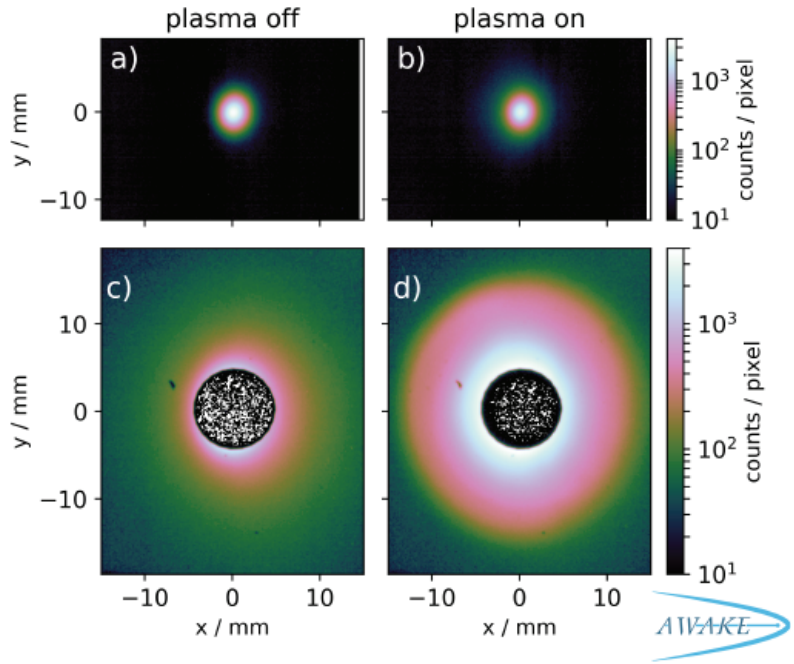
from E.Adli et al. (AWAKE Collaboration), arXiv:1809.04478 (2018)

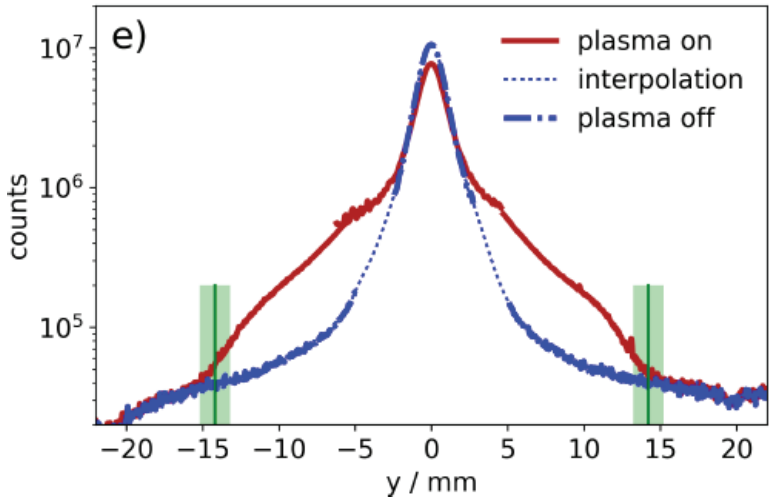
Results: Indirect Seeded Self-Modulation Measurement



Imaging station







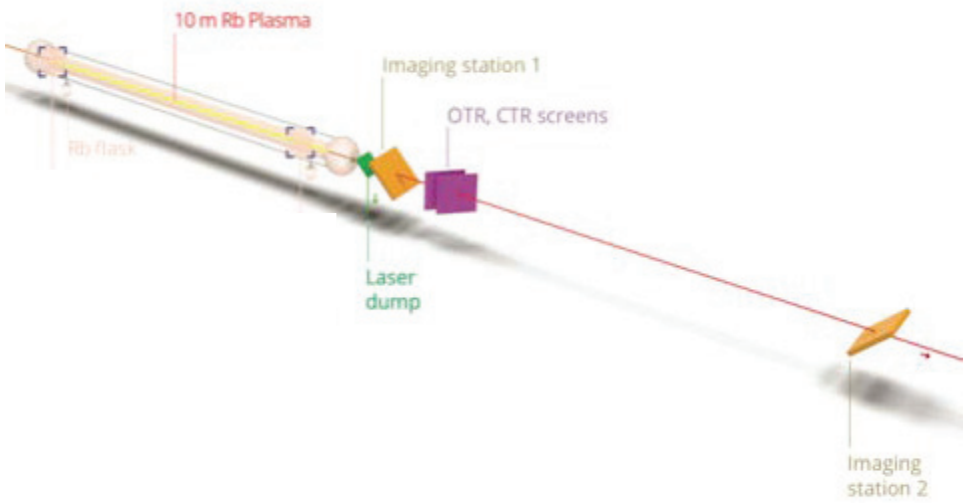
Time integrated transverse bunch distribution:

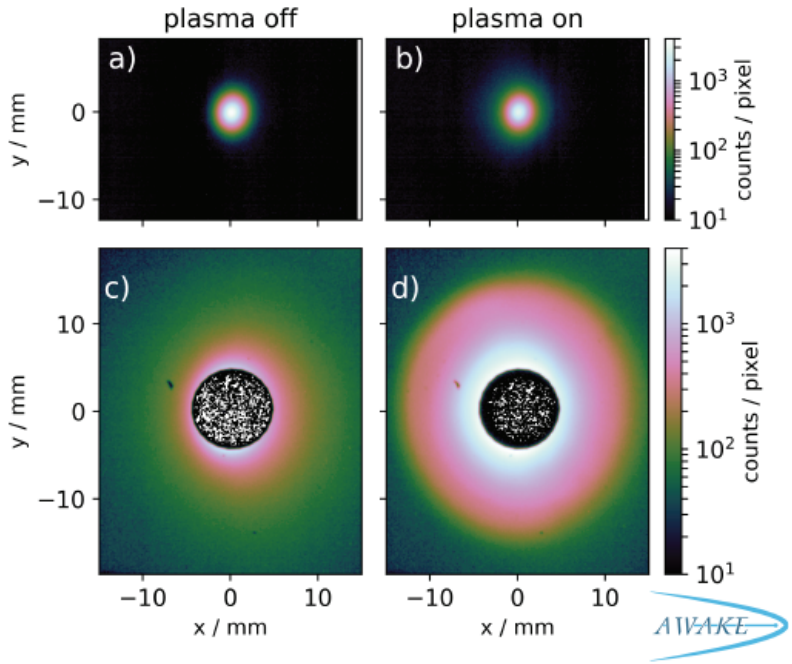
→ Image protons defocused by the strong plasma wakefields

→ Scintillation light from screen measured with digital camera.

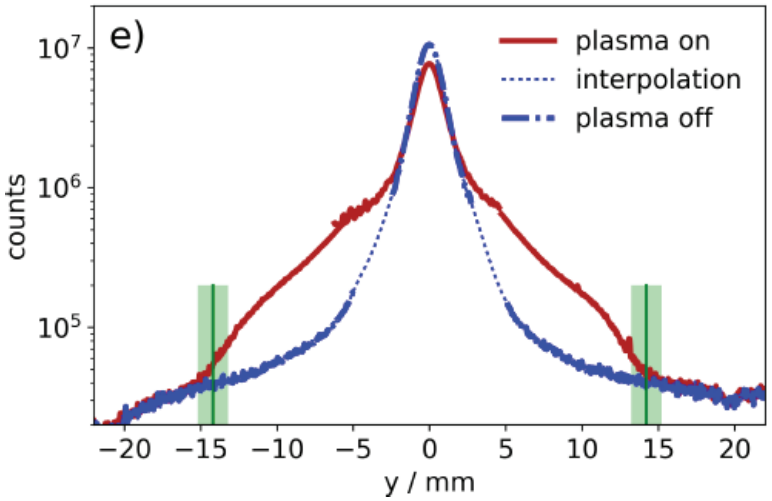
from M.Turner et al. (AWAKE Collaboration), arXiv:1809. 01191 (2018)

Results: Indirect Seeded Self-Modulation Measurement



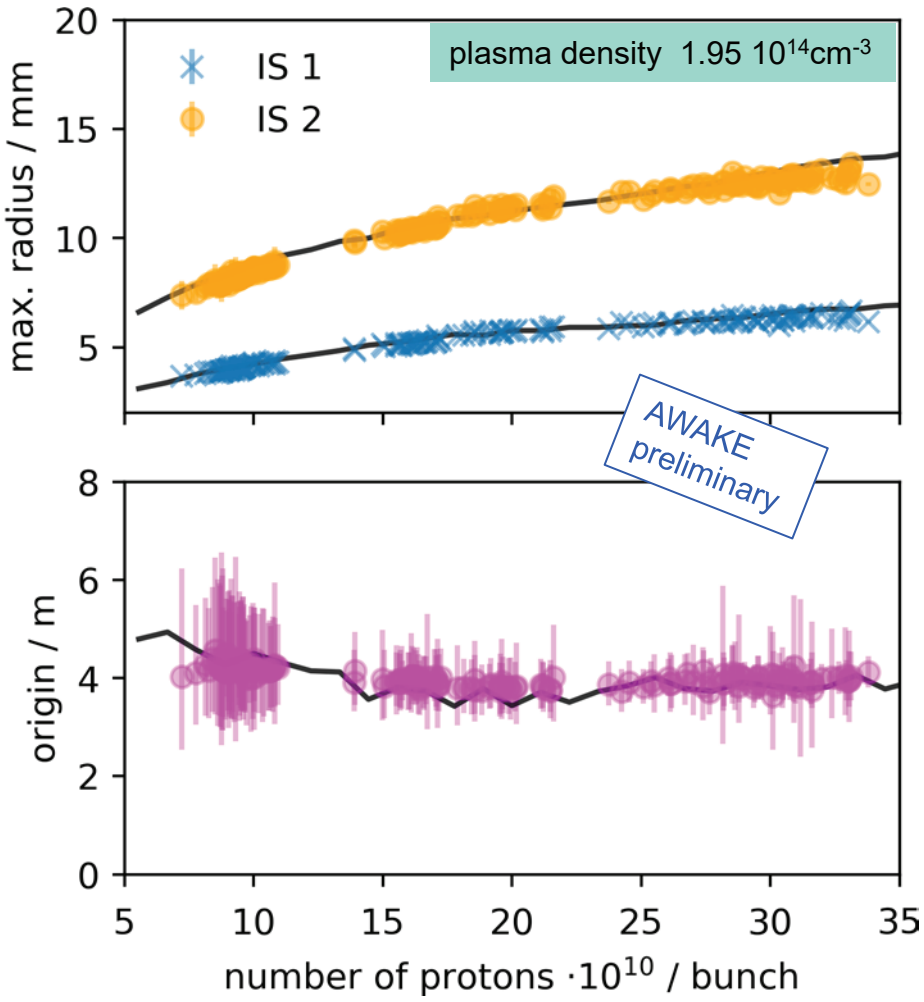


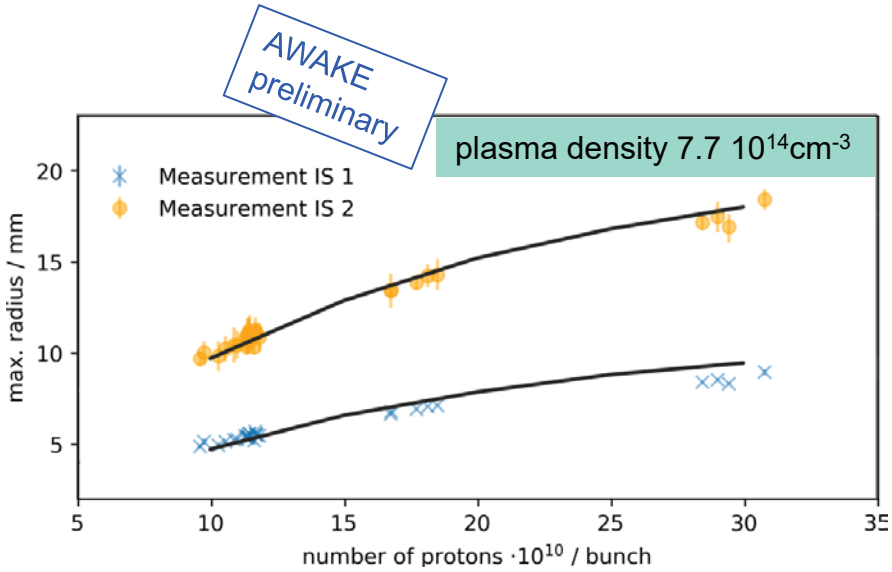
- Protons are defocused by the transverse wakefield (SSM) and form a halo
- Proton density in core decreases, proton density at large radii increases (appearance of halo).
- Halo symmetric ⇒ no hose instability.



from M.Turner et al. (AWAKE Collaboration), arXiv:1809. 01191 (2018)

Results: Agreement with simulations

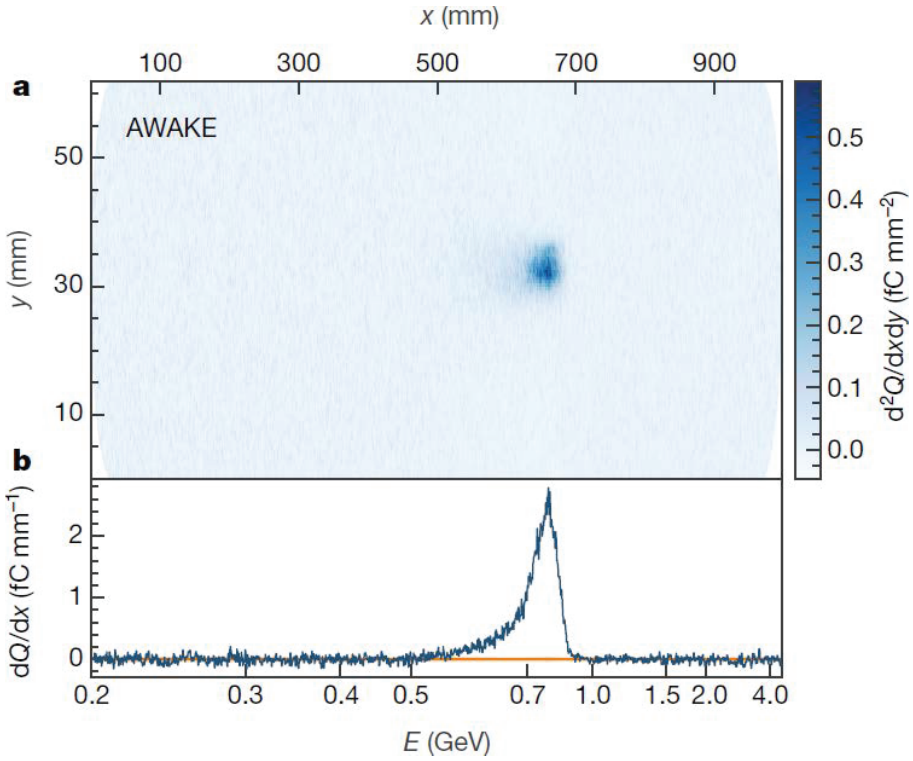


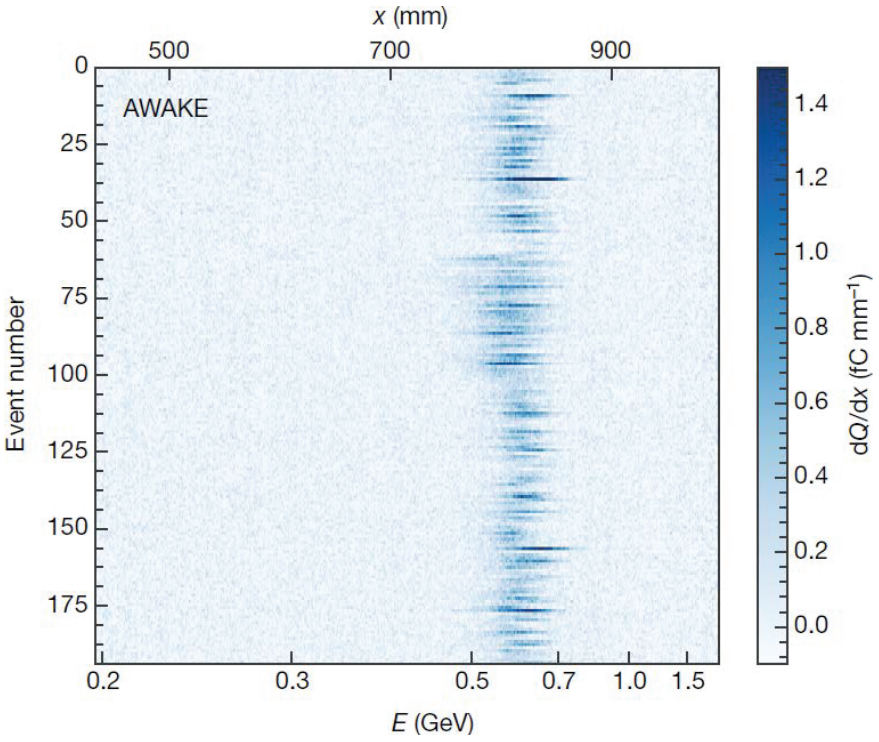


- Measurements of proton beam radius at imaging stations closely agree with simulations (LCODE) over a wide range of parameters
- Most defocused protons originate from z ≈ 4m

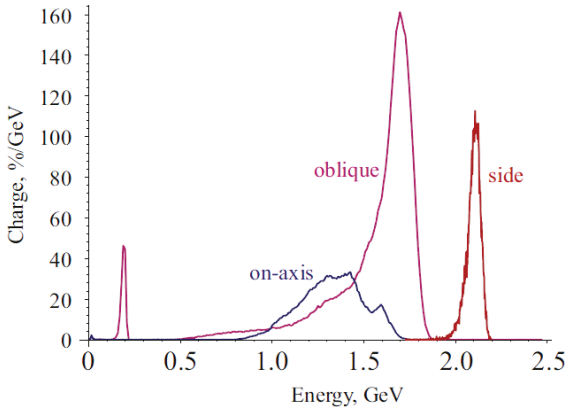
Results: Electron acceleration

from E.Adli et al. (AWAKE Collaboration), Nature 561, 363 (2018)





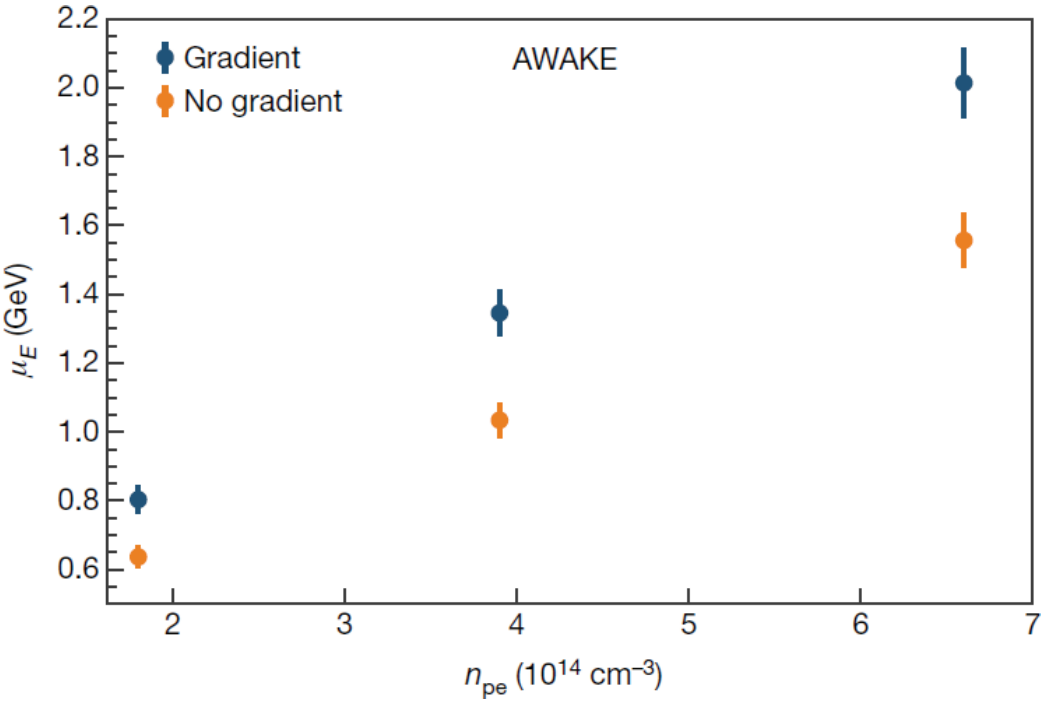
- Accelerated electrons are observed (and most clearly seen at low plasma density, 1.8 10^{14} cm^{-3})
- Energy spectrum is rather narrow (FWHM ≈ 17%) in spite of the fact that initial electron bunch is several wave periods long
- Energy spectrum shape is close to theoretical predictions
- Electron acceleration is reproducible



from A.Caldwell et al. (AWAKE Collaboration), NIMA 829, 3 (2016)

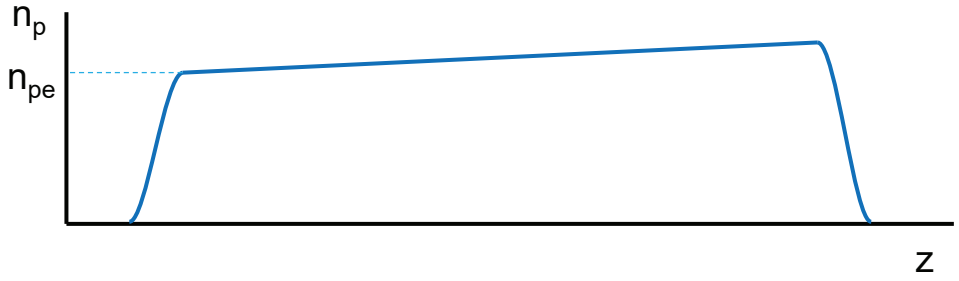
Results: Electron acceleration

from E.Adli et al. (AWAKE Collaboration), Nature 561, 363 (2018)



- Electron bunch energy almost linearly scales with plasma density and reach 2 GeV at 6.6 10^{14}cm^{-3}
- Positive plasma density gradient is favorable for acceleration

Plasma density profile (gradient case):



Summary

AWAKE achieved:

- Phase stable, reproducible Seeded Self-Modulation of the proton drive beam (2017)
- Agreement of theory and measurements
- Electron acceleration (2018)

Next steps:

- Accelerating an electron beam to higher energy
- Preserve electron beam quality as well as possible
- Demonstrate scalability of the AWAKE concept
- Theoretical studies of novel regimes

Thank you