Recent highlights and plans of the AWAKE experiment

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Outline

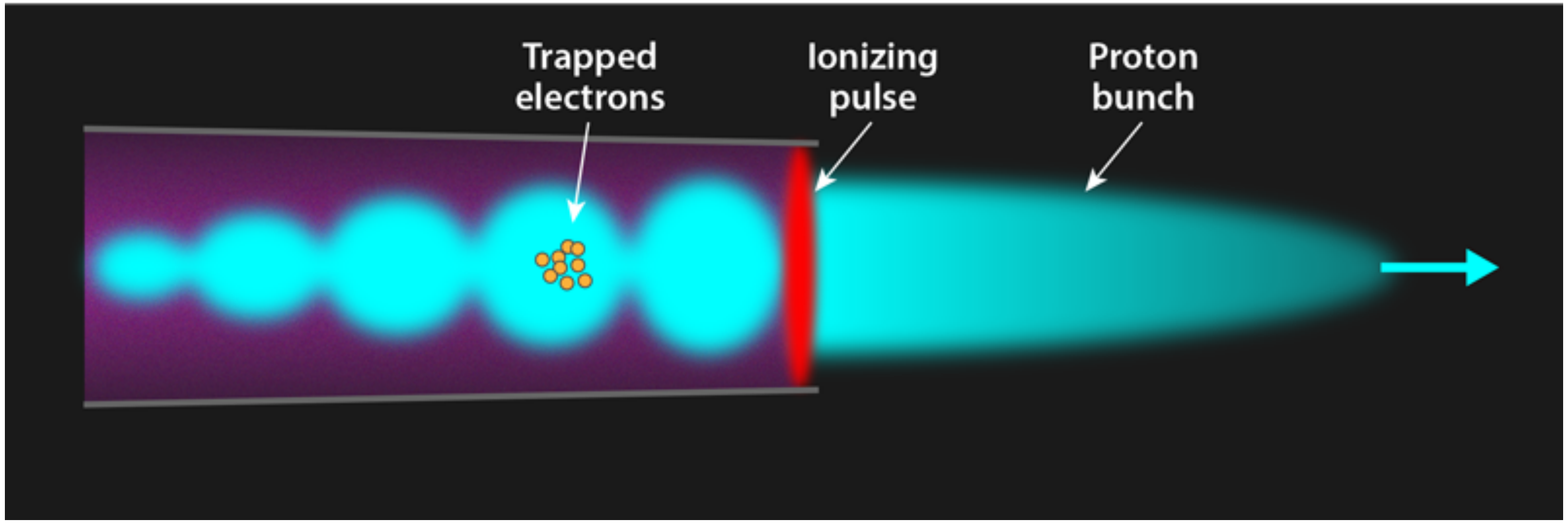
- The principle behind AWAKE
- Run 1 (2016-2018): setup and experimental results
- Run 2 (2021+): goals and milestones
- Beyond Run 2: applications to high-energy particle physics

Plasma wakefield acceleration, with a proton driver

1) **Laser** ionizes gas, forming **plasma**

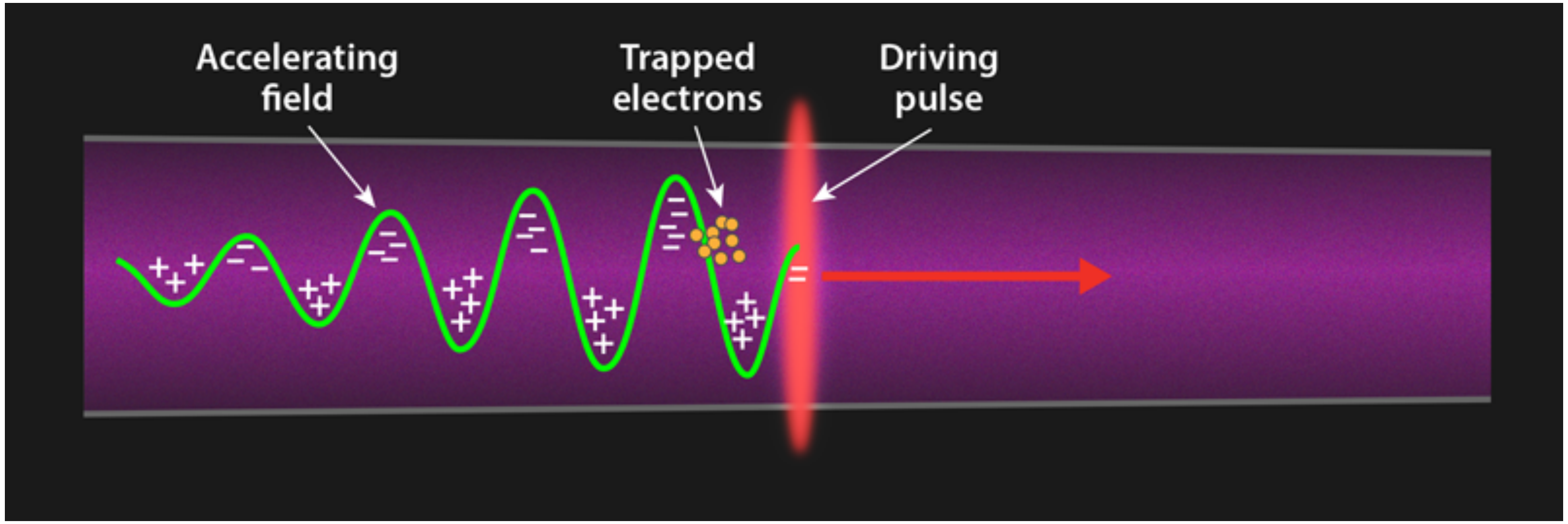
2) **Proton bunch** generates **wakefields** in the plasma, at its resonant frequency

3) **Micro-bunches form**, since plasma wavelength is smaller than proton bunch



APS/Alan Stonebraker

4) Proton **micro-bunches** act coherently to generate **wakefields** which **accelerate and focus electrons**



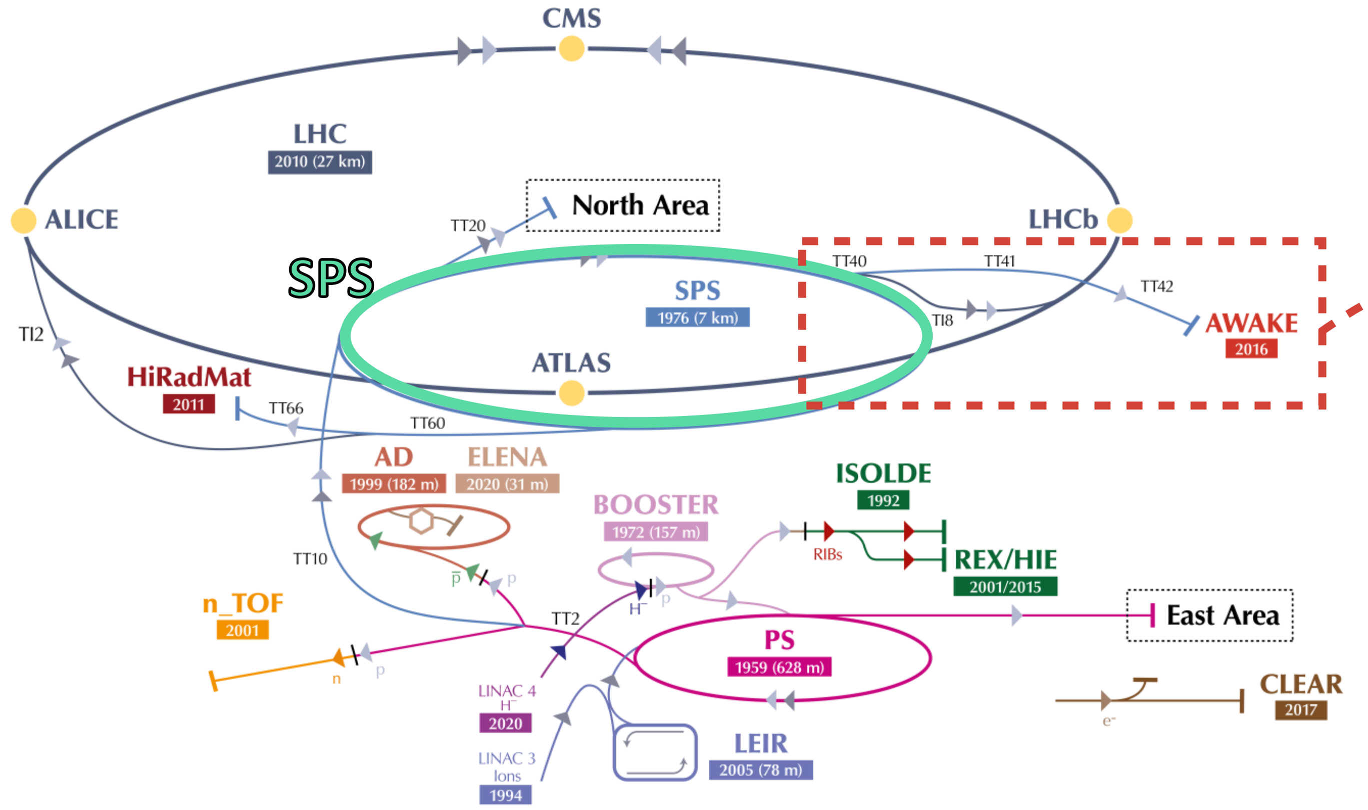
Plasma wakefield acceleration, with a proton driver

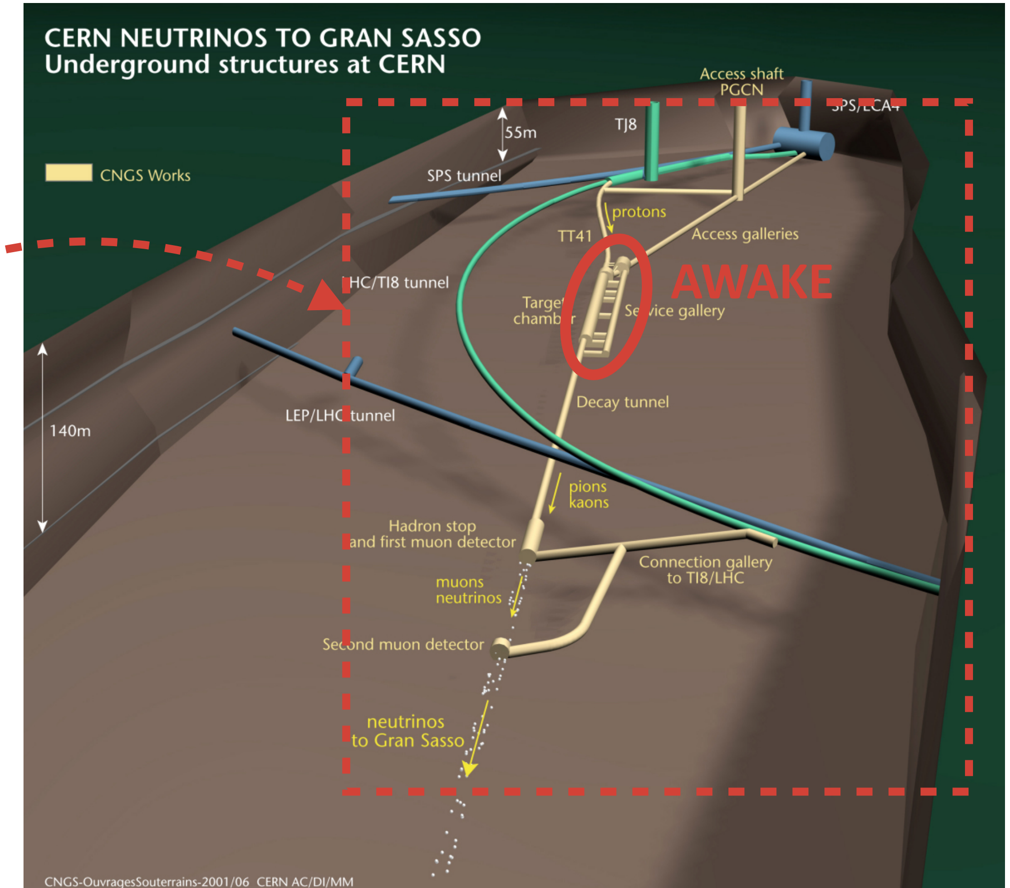
- Why plasma instead of a (superconducting) RF cavity?
  - **Higher fields**: can sustain more MV/m, leading to shorter accelerators
  - **Self-focusing**: plasma provides focusing fields, as well as accelerating

- Why protons, instead of electrons or lasers, to load the wakefields in the plasma?
  - **Highest stored energy per bunch** (SPS and LHC : 20 and 300 kJ/bunch)
  - Can use **existing proton beams** to reach the **energy frontier with electrons**!
  - **No need for "staging"** of multiple small accelerators, since $E_p >> E_e$

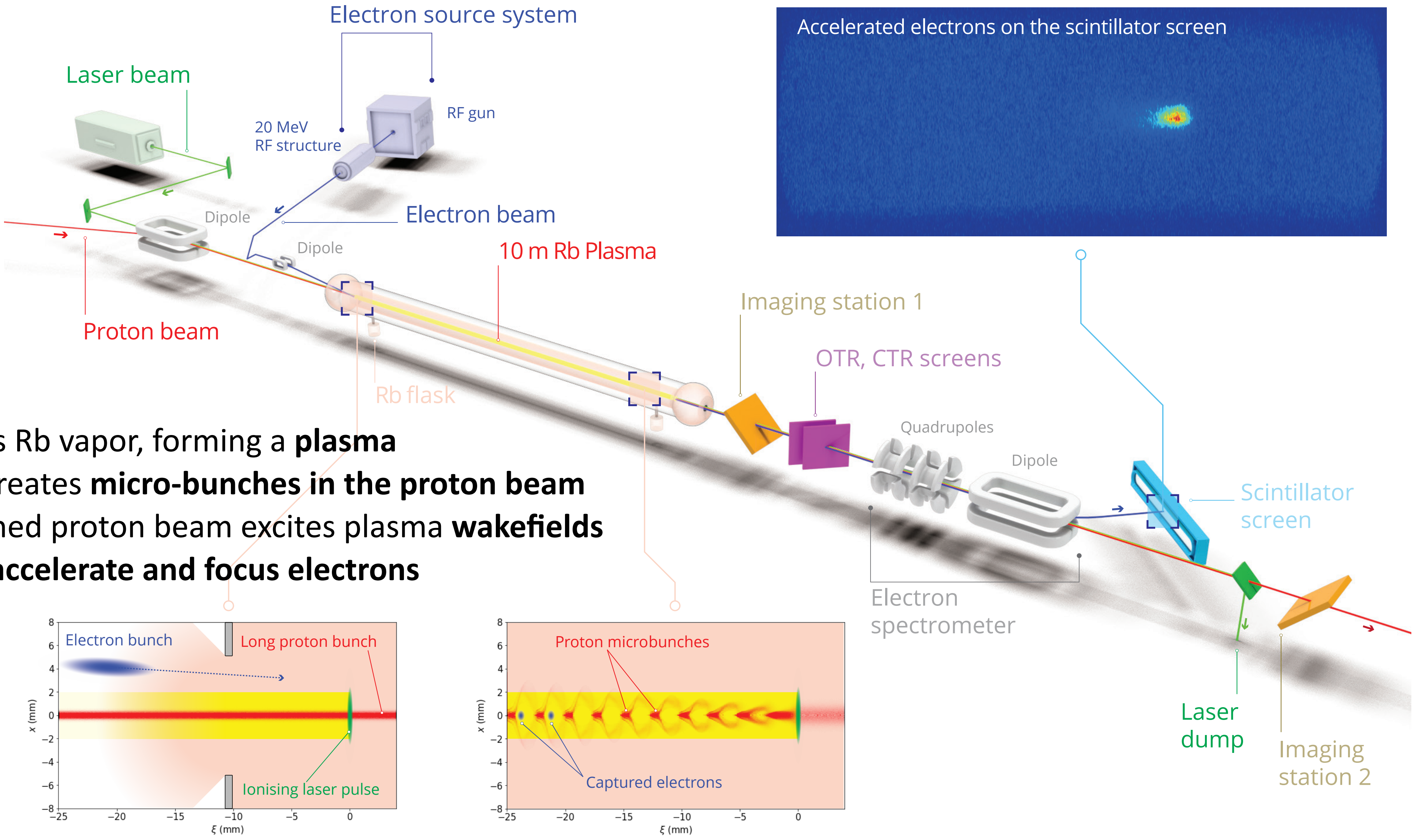
AWAKE at CERN

- AWAKE: **A**dvanced Proton Driven Plasma **Wake**field Acceleration Experiment
  - Proof of principle R&D experiment to study proton driven acceleration
  - 22 institutes, >100 people. Approved in 2013, electron acceleration in 2018





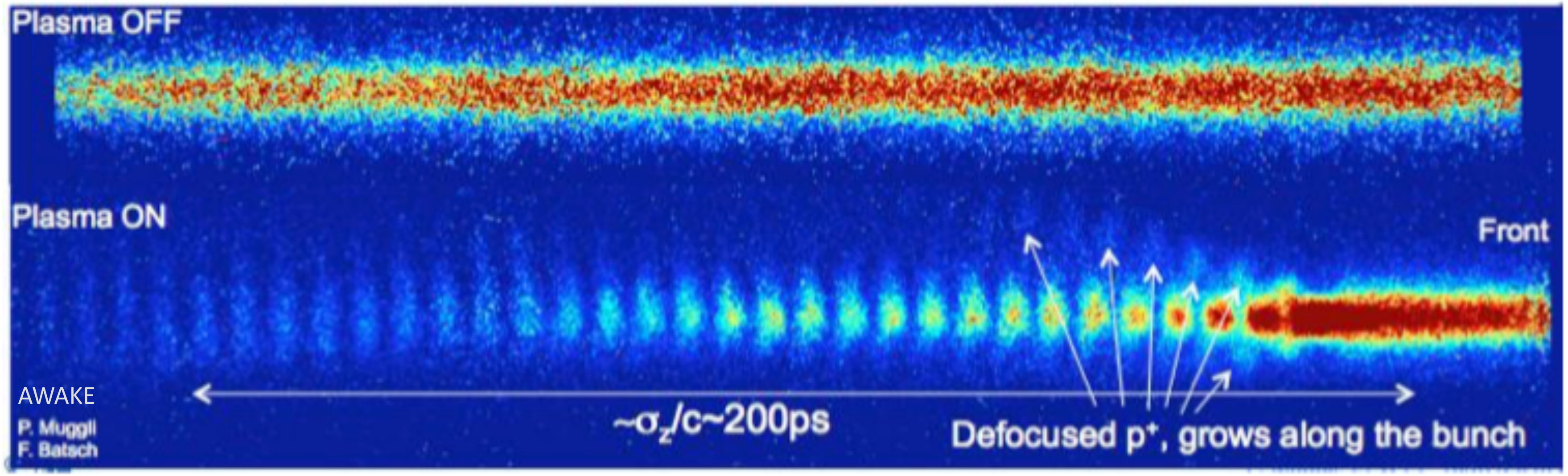
Experimental setup

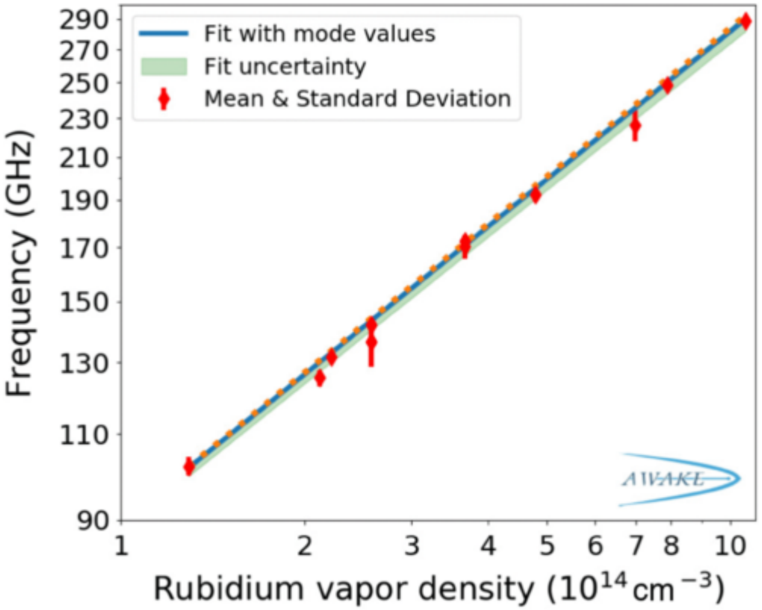


1) **Laser** ionizes Rb vapor, forming a **plasma**
2) Rb plasma creates **micro-bunches in the proton beam**
3) Micro-bunched proton beam excites plasma **wakefields**
4) Wakefields **accelerate and focus electrons**

AWAKE Run 1: Milestone #1

- 2016/2017: SELF-MODULATION
  - First seeded self-modulation of a high energy proton bunch in plasma
  - Phase-stability and reproducibility are essential for electron acceleration!

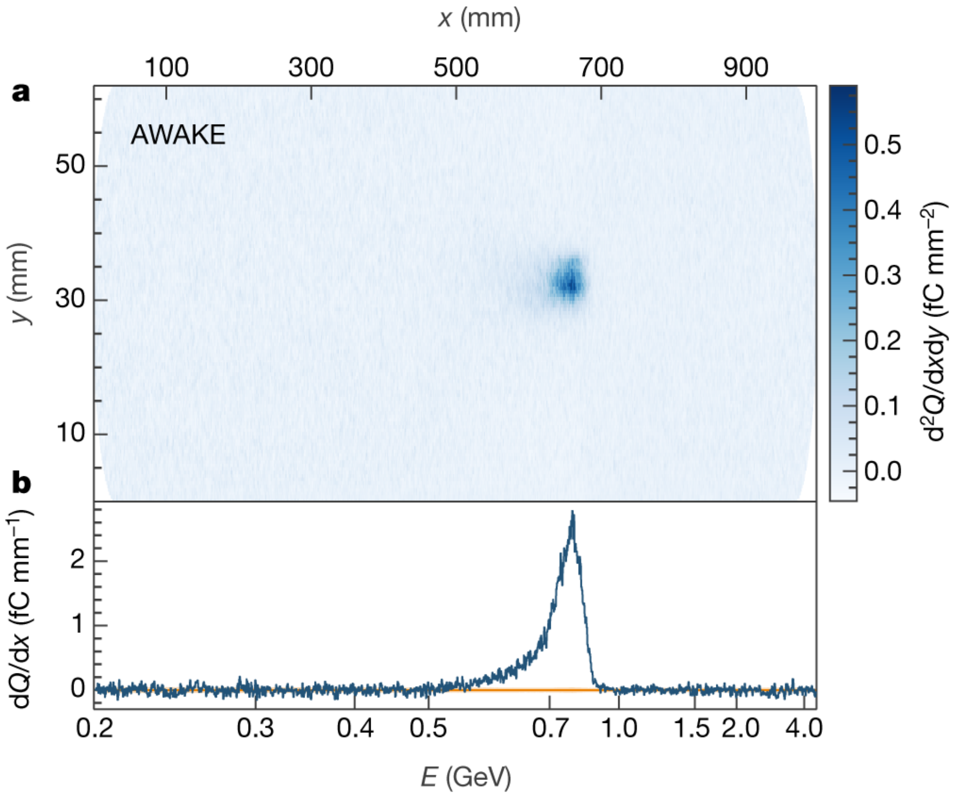


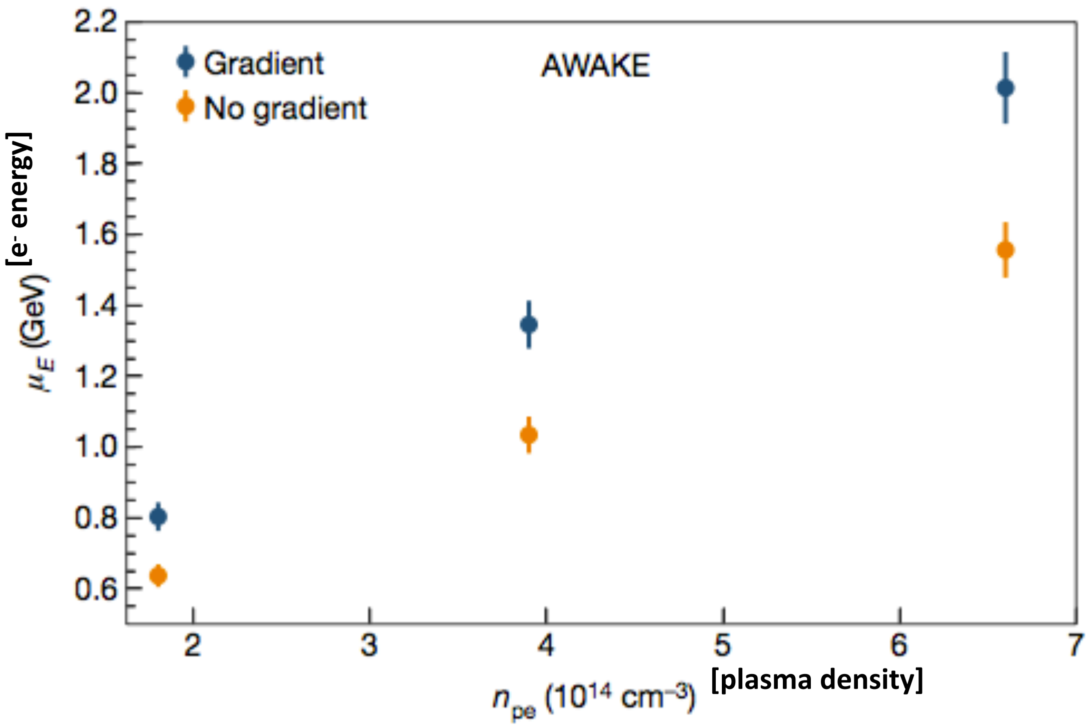


Phys. Rev. Lett. 122 (2019) 054801, 054802

AWAKE Run 1: Milestone #2

- 2018: ACCELERATION (from 19 MeV to 2GeV)
  - Inject e⁻ and accelerate to GeV in the wakefield driven by the SPS protons
  - Maximum accelerated charge ~100 pC (~20% of injected)





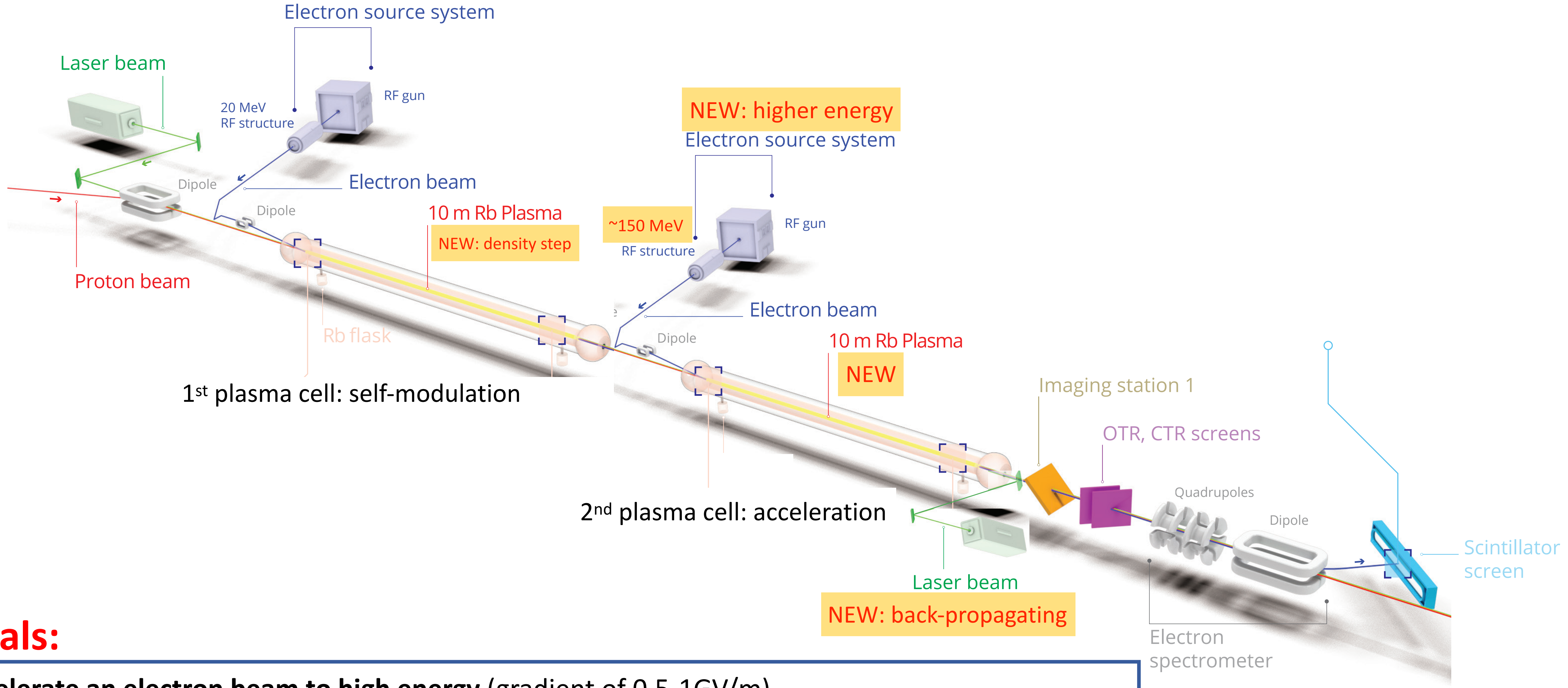
Nature 561, 363 (2018)

AWAKE Run 1: … and a broad scientific output

- Exploring the large parameter space allowed by AWAKE
  - Characterize experimental setup (laser, e^- beam, diagnostics)
  - Understand how self-modulation starts and grows
  - Optimize charge and energy in electron acceleration

- Recent output (2018-2020)
  - ≥ 10 peer-reviewed journal papers
  - ≥ 30 conference presentations/proceedings
  - and more papers in preparation

The next step: AWAKE Run 2



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)

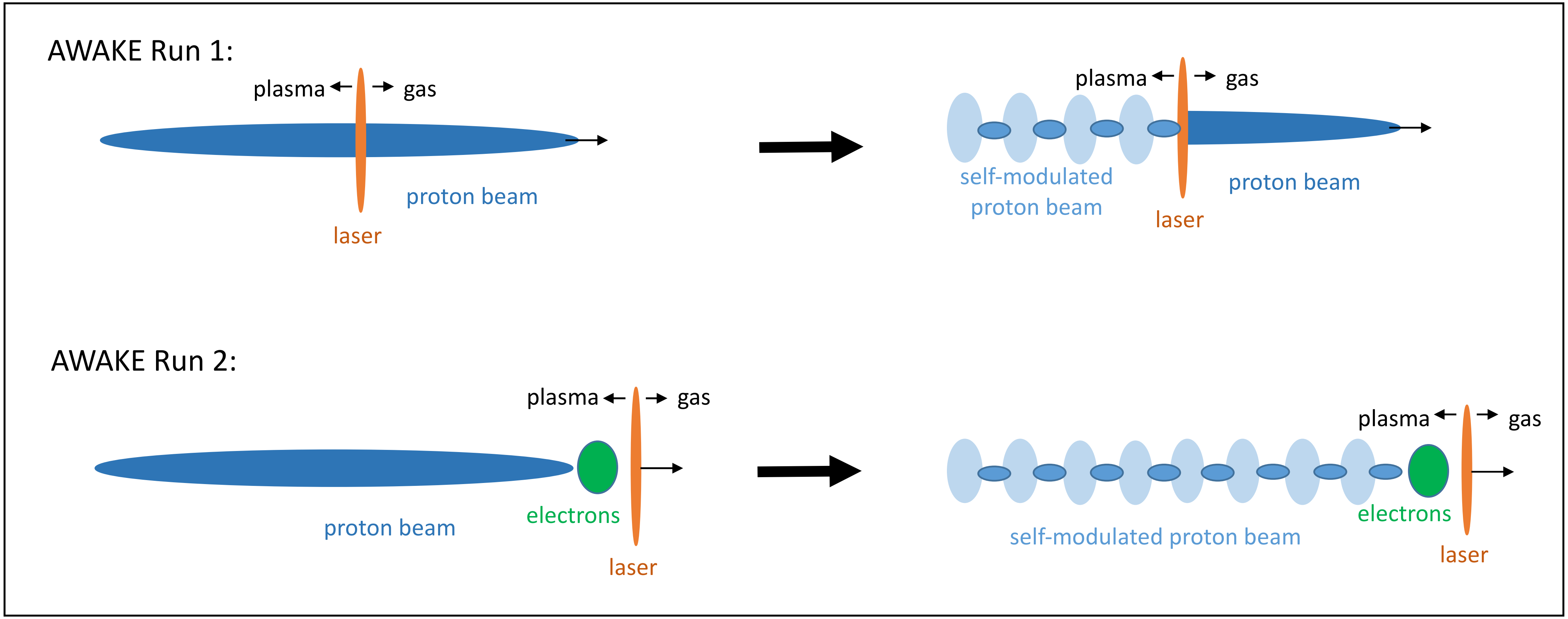
Demonstrate scalable plasma source technology (up to 100 m of plasma)

AWAKE Run 2: milestones

1. Demonstrate electron seeding of self-modulation in 1st plasma cell
   - Need self-modulation of the entire proton bunch
2. Demonstrate the stabilization of the micro-bunches with a density step in 1st plasma cell
   - Show levelling of strong acceleration field
3. Demonstrate electron acceleration and emittance preservation in 2nd plasma cell
   - Simultaneous energy gain and good emittance
4. Develop scalable plasma sources
   - Current method (laser ionization) cannot support O(100) m plasma cells

AWAKE Run 2: milestones

1. Demonstrate electron seeding of self-modulation in 1st plasma cell
   - Need self-modulation of the entire proton bunch before entering 2nd cell, to prevent the head of the proton beam from disrupting the wakefields

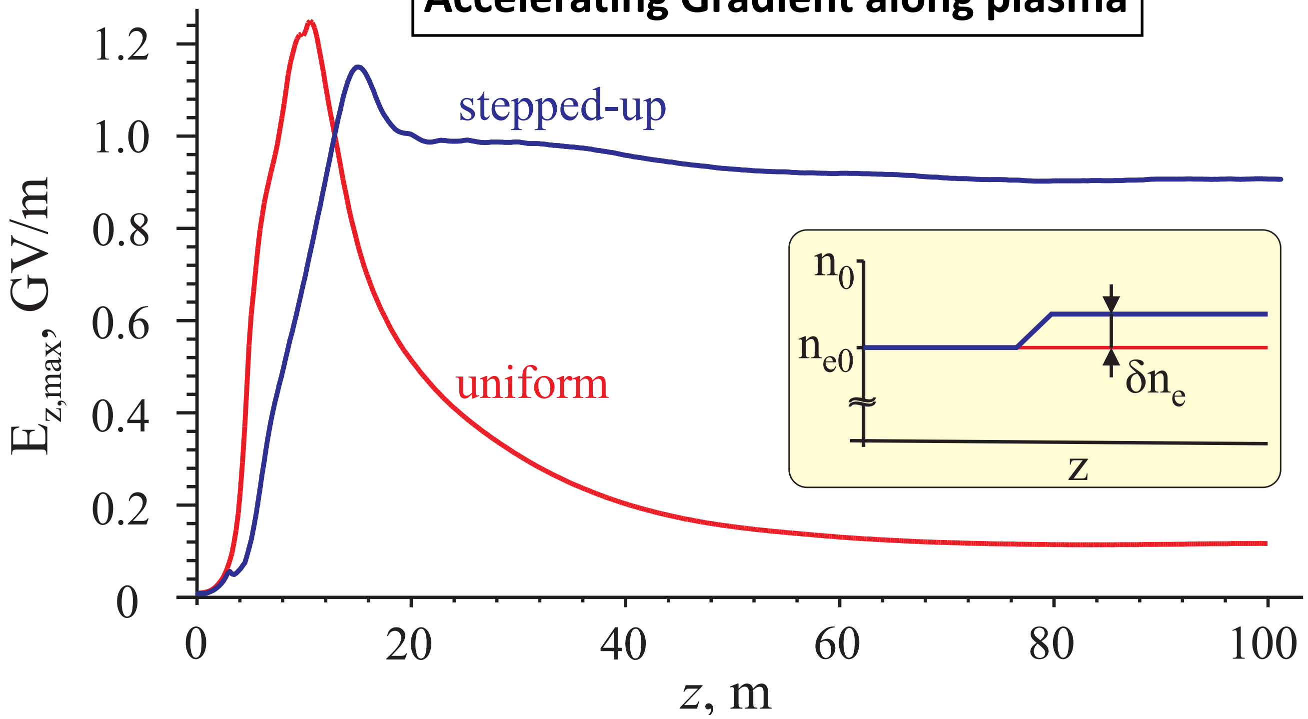


AWAKE Run 2: milestones

2. Demonstrate the **stabilization** of the micro-bunches with a **density step in 1st plasma cell**

- Self-modulation can eventually destroy the beam, due to phase shifting
- Simulations show we can "freeze" the micro-bunching process by accurately choosing the plasma density profile

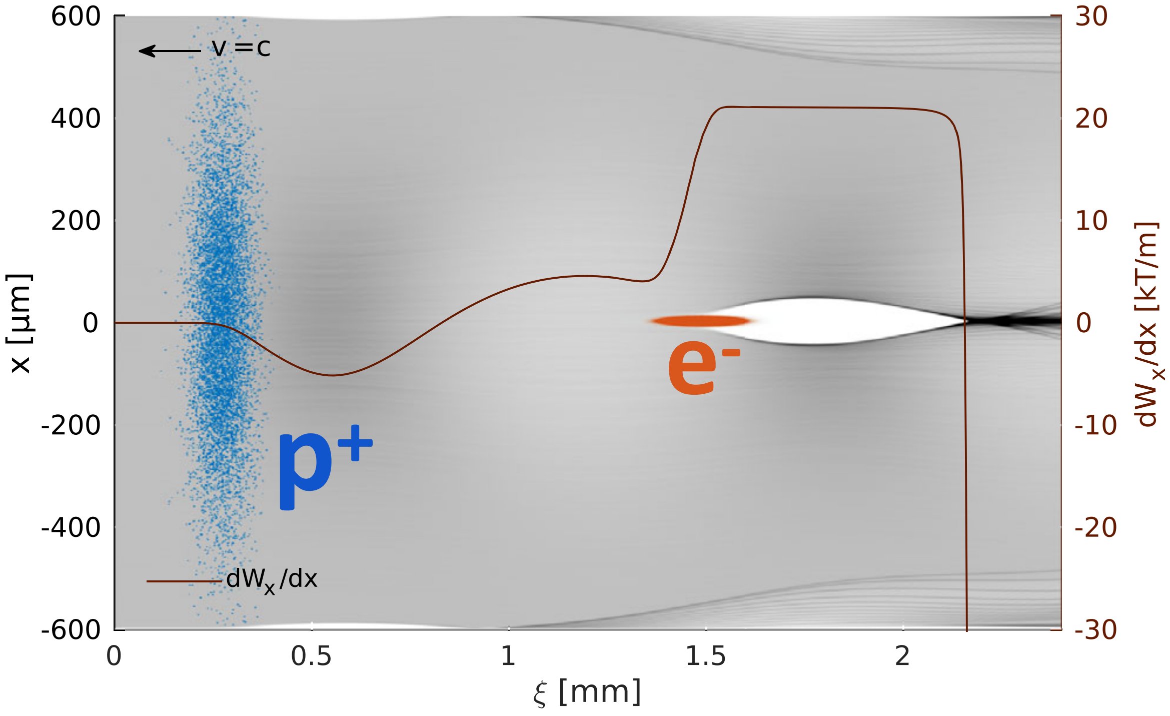
Accelerating Gradient along plasma

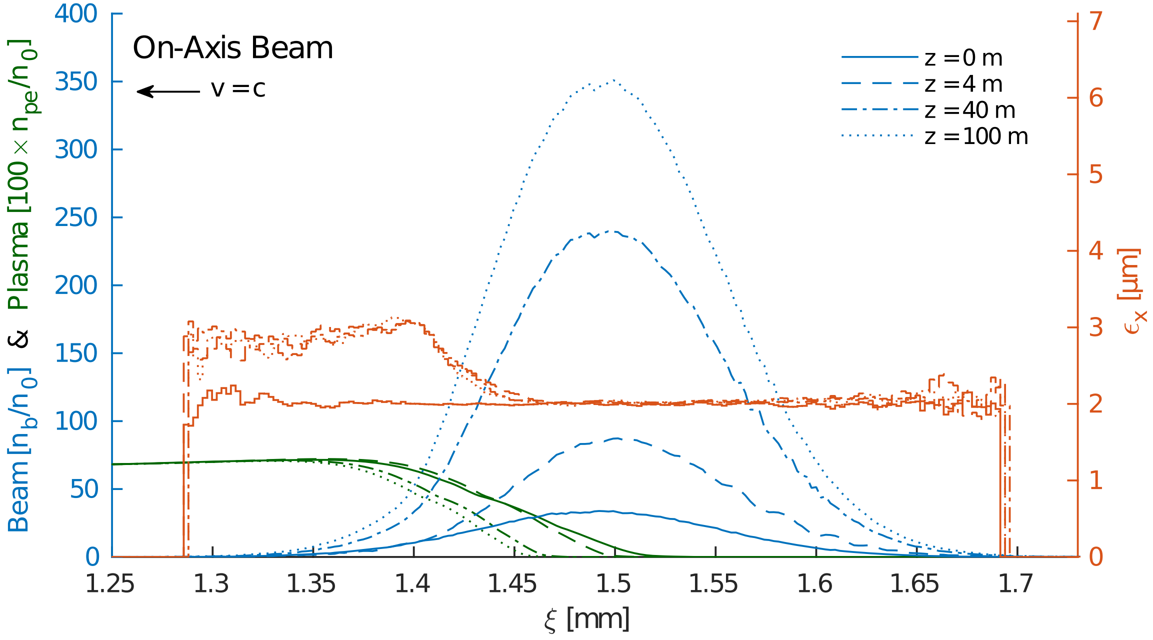


[A. Caldwell et al, *Nucl.Instrum.Meth.A* 829 (2016) 3-16]

AWAKE Run 2: milestones

3. Demonstrate electron acceleration and emittance preservation in 2nd plasma cell
   - 1: **Match e- beam** transverse properties to the plasma entrance: preserve emittance
   - 2: **Blow out regime** (e- density >> Rb density): **linear focusing, ε preservation**
   - 3: **Beam loading**: tune the charge/position of e- beam to reach **small δE/E**



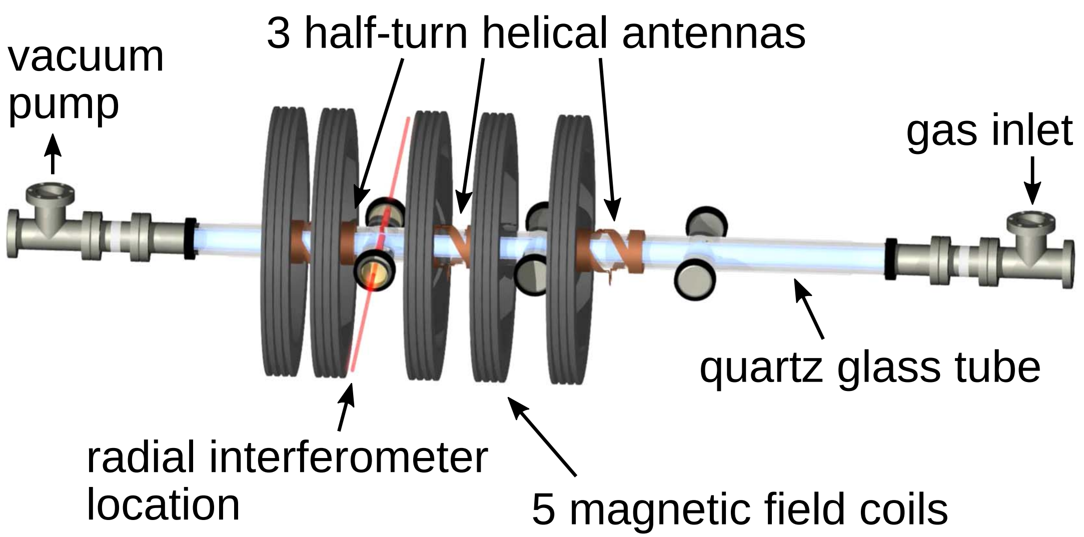


[V. K. Berglyd Olsen, E. Adli, P. Muggli, Phys. Rev. Accel. Beams 21, 011301 (2018)]

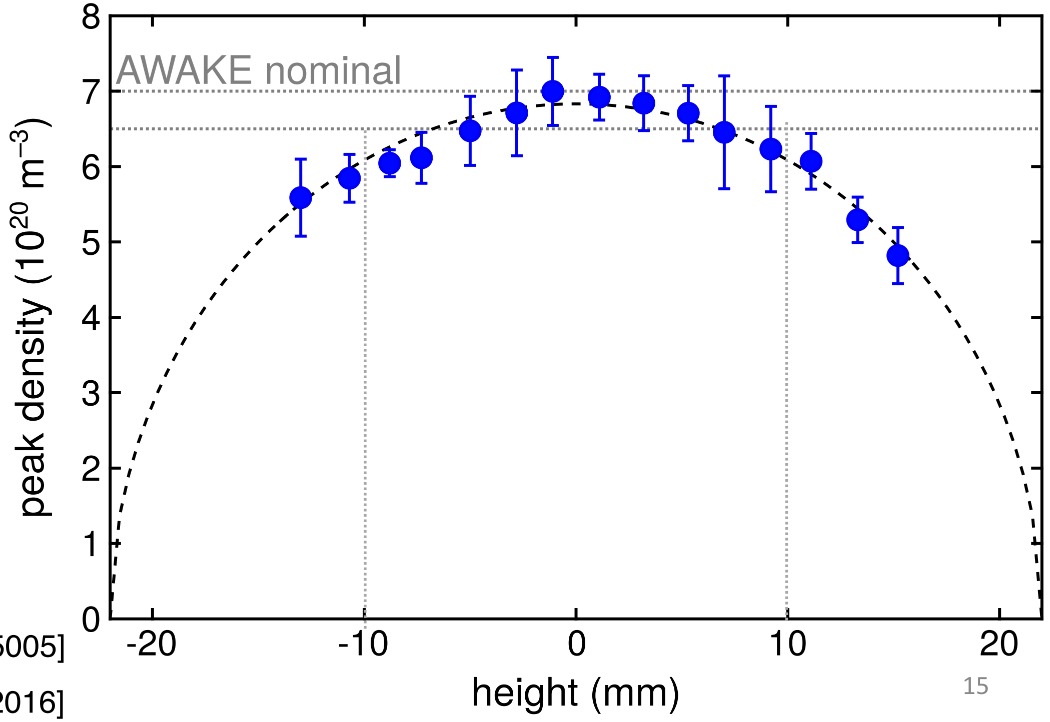
AWAKE Run 2: milestones

4. Develop scalable plasma sources
   - Current method (laser ionization) cannot support O(100) m plasma cells
   - 'Helicon': low-frequency EM wave generated by RF antennas
   - 'Discharge': high-current arc in plasma

Helicon design



Helicon results: profile/density/timing in line with AWAKE requirements



[B Buttenschön *et al* 2018 *Plasma Phys. Control. Fusion* **60** 075005]

[N. C. Lopes, Z. Najmudin, et al. CALIFES Workshop 2016]

Roadmap for Particle Physics Applications

- The AWAKE scheme can provide **high-energy (> 50 GeV) high-charge electron bunches**
  - Switch from R&D to particle physics experiments!

- Step 1: produce e^- bunches for fixed target experiments (standalone, least stringent)
  - Build upon AWAKE Run 2, extend plasma from 10 m to ~100 m
  - Physics: dark photons, strong-field QED, …

- Step 2: re-inject electron beam for e-p (or e-ion) collisions
  - Move AWAKE on a transfer line feeding back into the LHC, use SPS or LHC protons
  - Physics: explore proton/ion structure, pγ cross section, leptoquarks, …

- And beyond: e^+e^-, polarized beams, muons, …

Active participation in Physics Beyond Colliders workshop and European Strategy Update

- arXiv:1812.11164, arXiv:1812.08550, CERN-PBC-REPORT-2018-005 and 007

Step 1: produce e⁻ bunches for fixed target experiments

- Fixed target requirements: energy & flux important, relaxed emittance
  - Simulations show parameter ranges for SPS-based beams
  - Energy and electrons on target competitive with state-of-the-art

proton energy	plasma length	electron energy	electron charge
400 GeV	50 m	33 GeV	107 pC
400 GeV	100 m	54 GeV	134 pC
450 GeV	130 m	70 GeV	134 pC

Parameter	AWAKE-upgrade-type	HL-LHC-type
Proton energy E_p (GeV)	400	450
Number of protons per bunch N_p	3×10^{11}	2.3×10^{11}
Longitudinal bunch size protons σ_z (cm)	6	7.55
Transverse bunch size protons σ_r (μm)	200	100
Proton bunches per cycle n_p	8	320
Cycle length (s)	6	20
SPS supercycle length (s)	40	40
Electrons per cycle N_e	2×10^9	5×10^9
Number of electrons on target per 12 weeks run	4.1×10^{15}	2×10^{17}

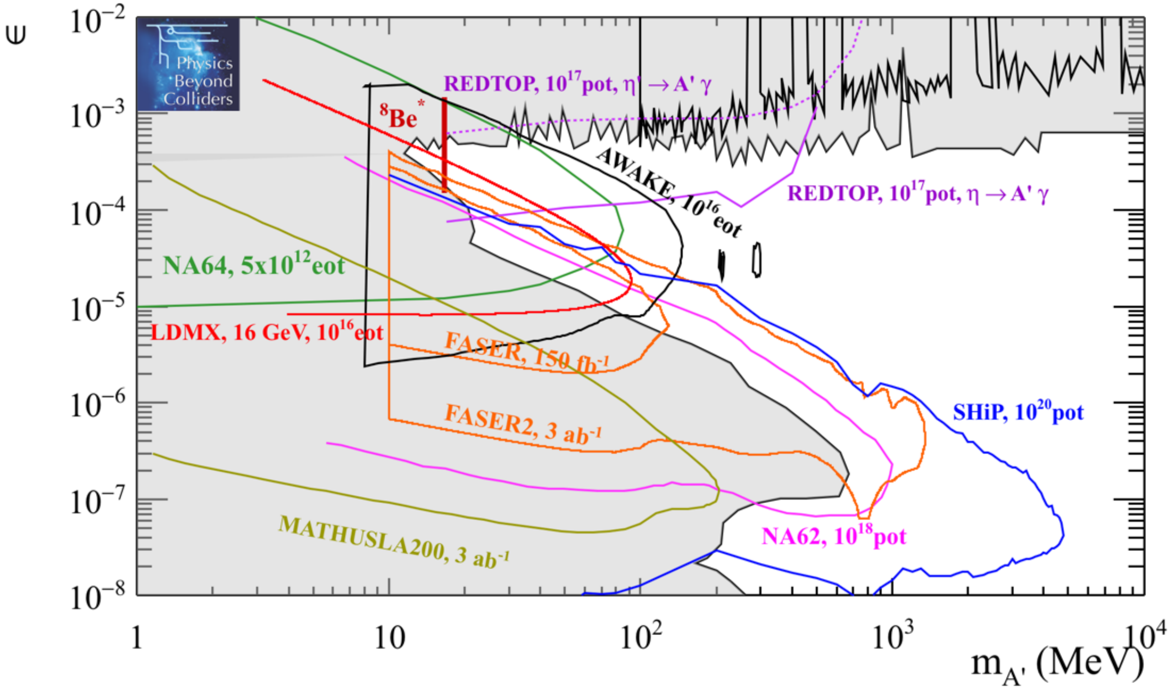
* Assumes a 12 week experimental period with a 70% SPS duty cycle.

Reference: NA64 experiment @ CERN
- 100 GeV
- 3×10^{12} electrons for entire lifetime

Step 1: produce e⁻ bunches for fixed target experiments

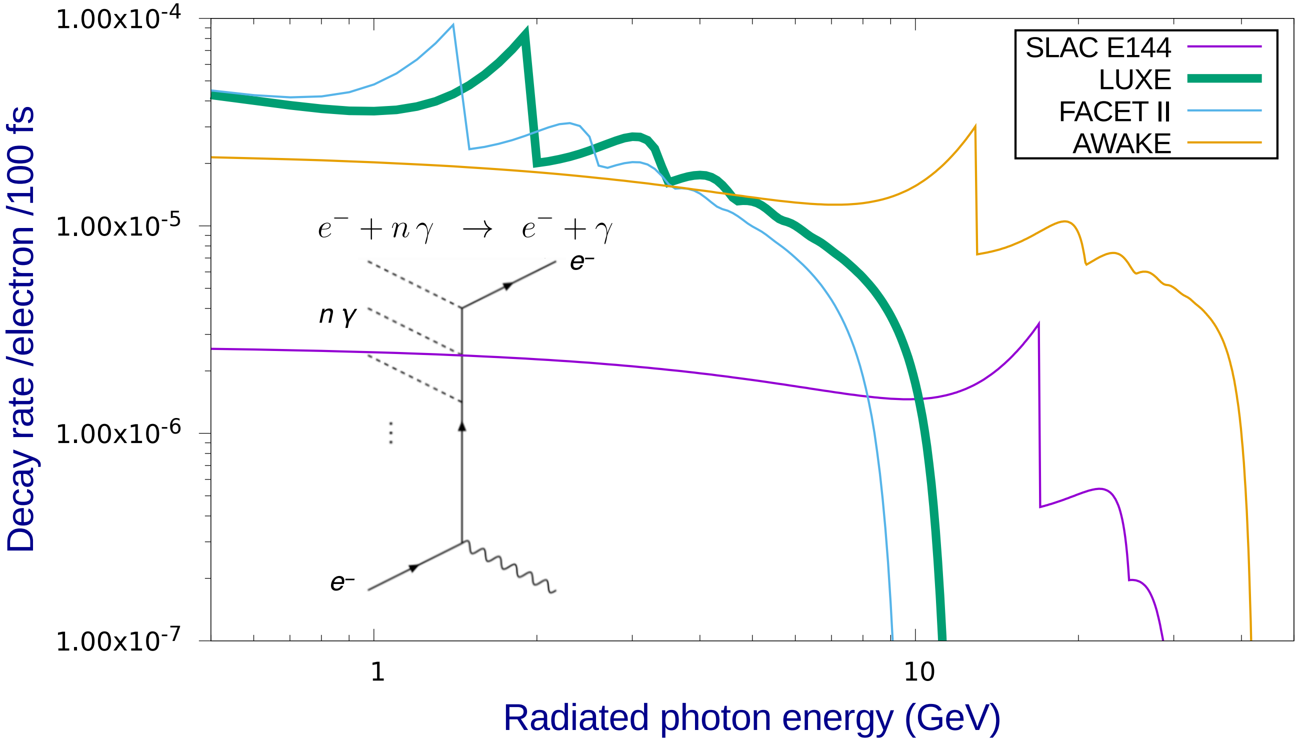
- Significant extension in physics reach using an AWAKE-like electron beam

Dark photon search (NA64-like)



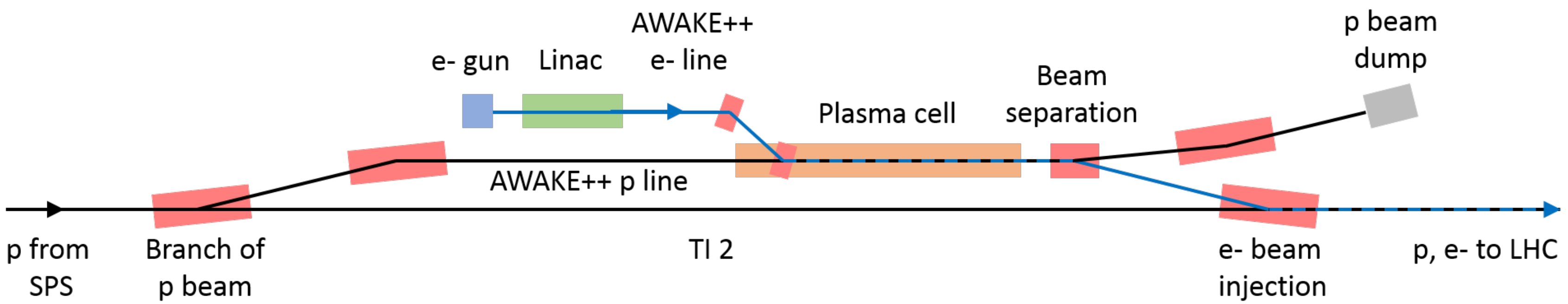
[CERN-PBC-REPORT-2018-007]

Strong-field QED tests (e⁻/laser interactions)



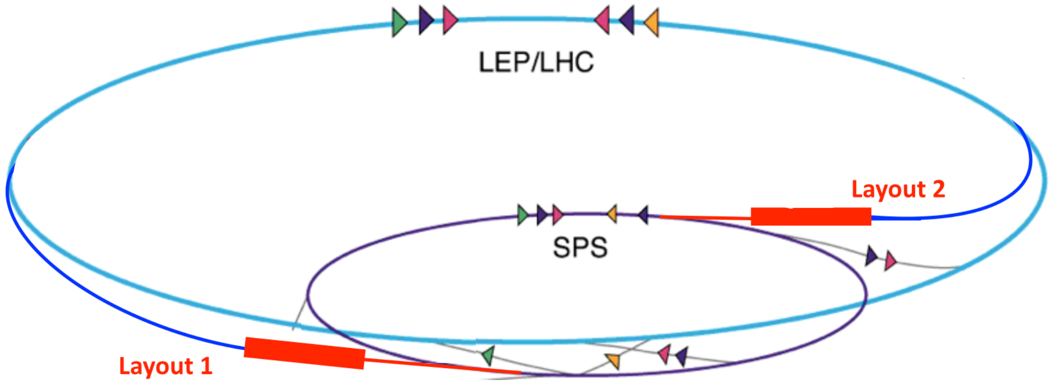
[A. Hartin, IJMP A33 1830011 (2018), M. Altarelli et al. arXiv:1905.00059]

Step 2: re-inject electron beam for e-p (or e-ion) collisions



PEPIC: √s = 1.3 TeV, SPS-driven

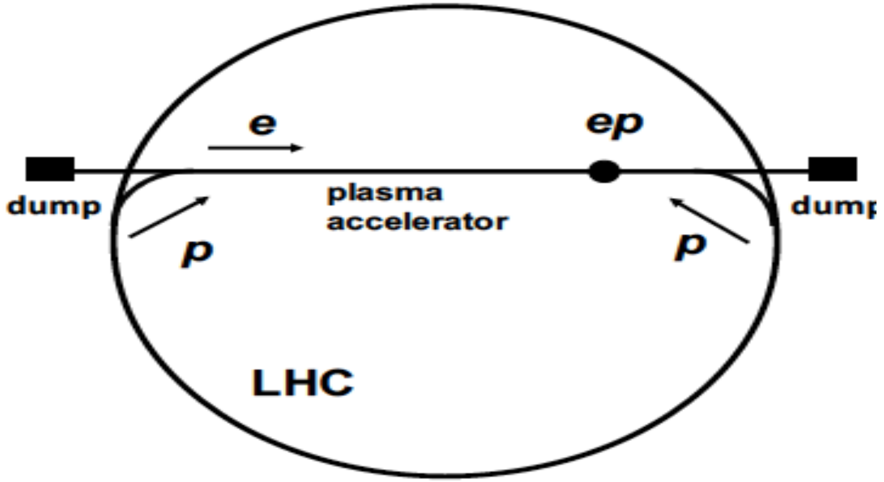
(Plasma electron-proton/ion collider)



G. Xia et al., Nucl. Instrum. Meth. A 740 (2014) 173.

VHeP: √s = 9 TeV (LHC-driven)

(Very high energy eP collider)



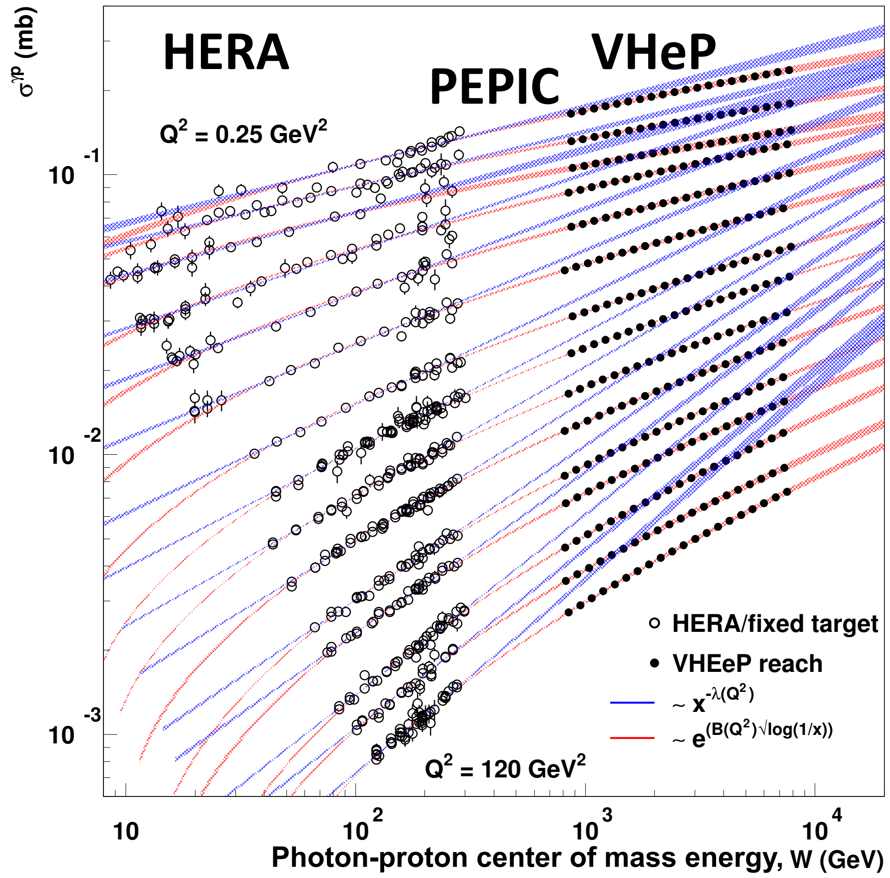
VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

Beyond CERN: RHIC-EIC proposal for 18 GeV electron beam [J. Chappel et al, *PoS* DIS2019 (2019) 219]

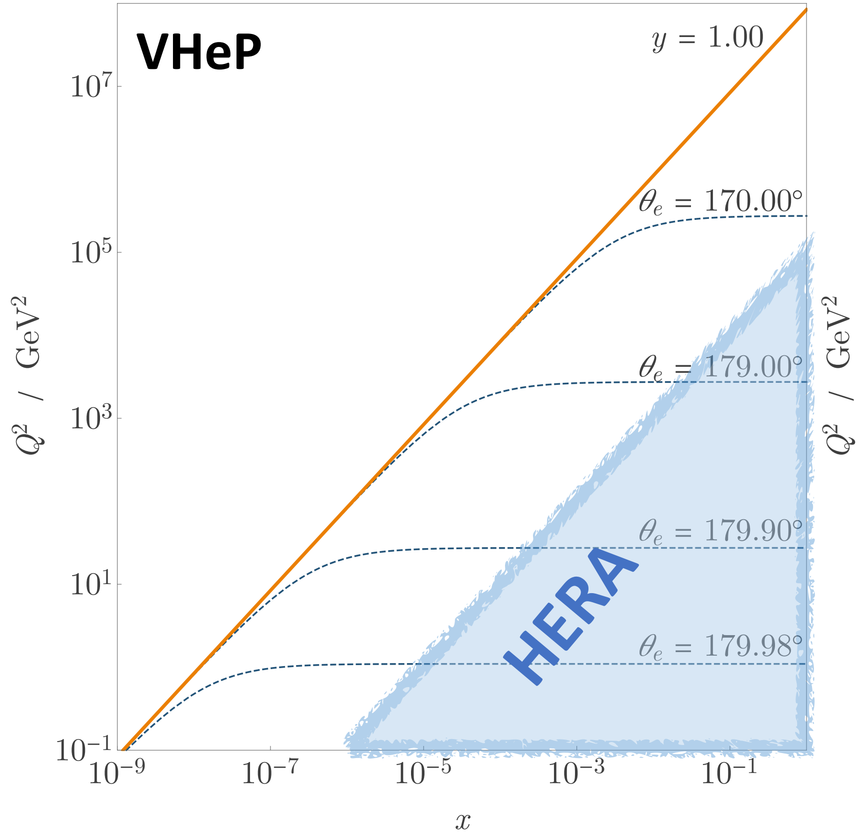
Step 2: re-inject electron beam for e-p (or e-ion) collisions

- New energy regime for Deep Inelastic Scattering

Test scaling laws at high c.m.e.

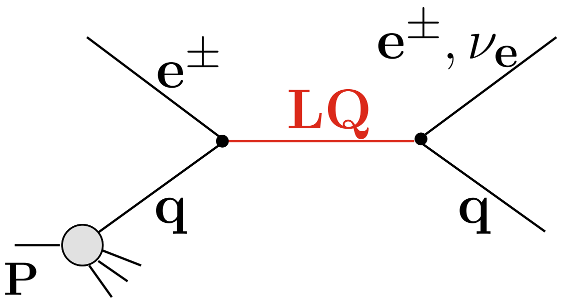


Higher c.m.e. —> larger cross sections, higher photon Q^2 , lower parton x w.r.t. HERA

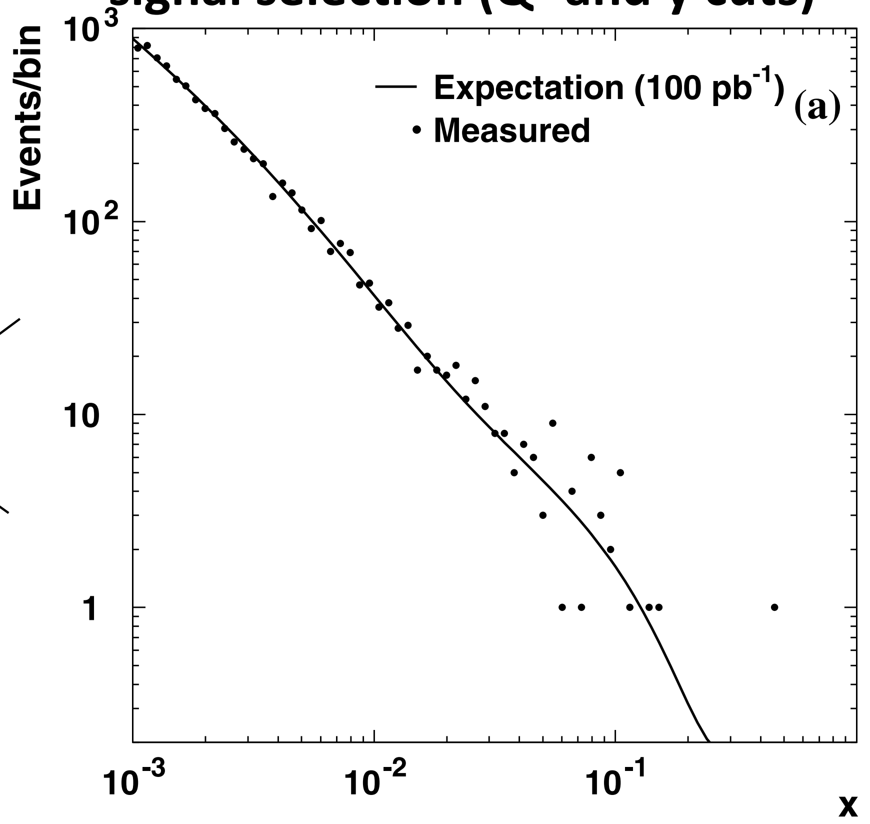


Step 2: re-inject electron beam for e-p (or e-ion) collisions

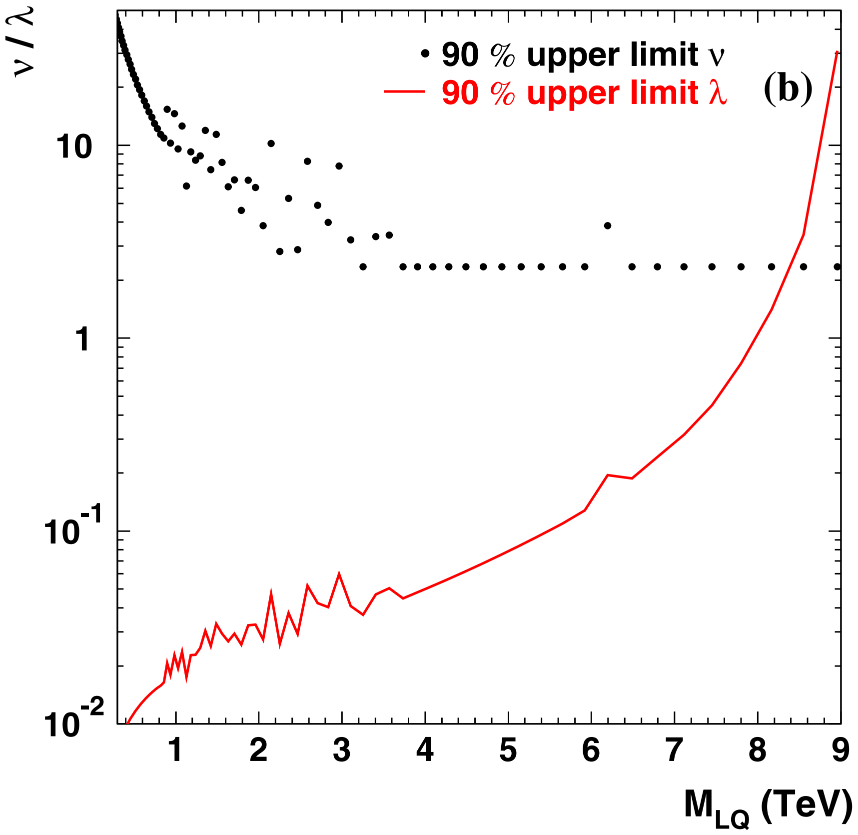
- New energy regime for Leptoquark searches



Expected $N^{background}$ events after signal selection (Q^2 and y cuts)



Upper limit on N^{signal} events ν and coupling λ



VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

Conclusions

- AWAKE Run 1 proved that we can accelerate electrons using protons
  - self modulation of a long proton beam is the key
- AWAKE Run 2 aims at higher energy and beam quality
  - and scalable plasma sources up to 100 m
- Next: from accelerator R&D to particle physics experiments
  - Explored a few examples for fixed target and electron-proton collisions
  - Still many open opportunities (ion-driven acceleration, muon acceleration, …)

Backup

Some recent papers (2019, 2020)

- Experimental setup
  - A magnetic spectrometer to measure electron bunches accelerated at AWAKE, Nucl. Instrum. Methods Phys. Res., A 940 (2019) 103-108
  - Commissioning of the electron injector for the AWAKE experiment, Nucl. Instrum. Methods Phys. Res., A 953 (2020) 163194
  - Electron Beam Characterization with Beam Loss Monitors in AWAKE, Phys. Rev. Accel. Beams. 23 (2020) 032803
  - Online Multi-Objective Particle Accelerator Optimization of the AWAKE Electron Beam Line for Simultaneous Emittance and Orbit Control, AIP Adv. 10 (2020) 055320
- Understanding self-modulation
  - **Experimental observation of proton bunch modulation in a plasma, at varying plasma densities, Phys. Rev. Lett. 122 (2019) 054802**
  - Experimental observation of plasma wakefield growth driven by the seeded self-modulation of a proton bunch, Phys. Rev. Lett. 122, 054802 (2019)
  - Evolution of a plasma column measured through modulation of a high-energy proton beam, arXiv:2006.09991
- Understanding electron acceleration
  - **Acceleration of electrons in the plasma wakefield of a proton bunch, Nature 561, 363 (2018)**
  - Transformer ratio saturation in a beam-driven wakefield accelerator, Phys. Plasmas 22 (2015) 123113
  - Experimental Study of Wakefields Driven by a Self-Modulating Proton Bunch in Plasma, accepted Phys. Rev. Accel. Beams, arXiv:2005.05277
- Looking into the future
  - Emittance preservation of an electron beam in a loaded quasilinear plasma wakefield, Phys. Rev. Accel. Beams 21, 011301
  - Particle physics applications of the AWAKE acceleration scheme, CERN-PBC-REPORT-2018-004 (European Strategy Input)
  - AWAKE++: The AWAKE Acceleration Scheme for New Particle Physics Experiments at CERN, CERN-PBC-REPORT-2018-005 (European Strategy Input)
  - AWAKE: On the path to particle physics applications, arXiv:1812.08550 (European Strategy Input)
- And many more conference proceedings and analyses in progress