AWAKE Run 2 Preparation and Prospects for High Energy Electron Beams

Physics Beyond Collider Annual Workshop, 1 – 4 March 2021

Edda Gschwendtner, CERN, for the AWAKE Collaboration

Outline

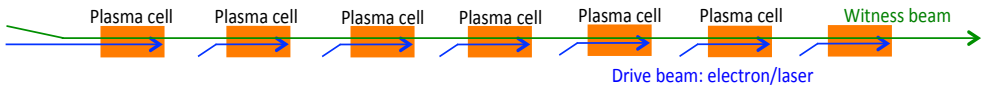
- Motivation
- AWAKE, The Advanced Wakefield Experiment
- AWAKE Run 2
- Particle Physics Applications
- Summary

Motivation – Acceleration to HEP Energies in PWA

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

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

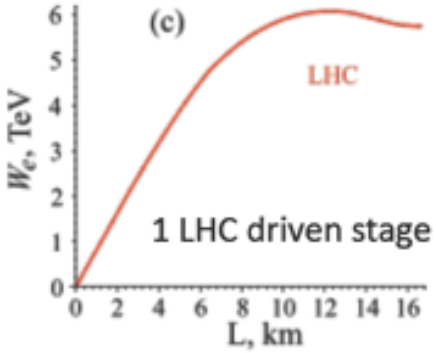
- **Electron/laser driven PWA**: need several stages
  - effective gradient reduced because of long sections between accelerating elements….



➔ Challenges: staging, matching, tolerances, driver technologies, efficiencies

- **Proton driven PWA**: large energy content in proton bunches → allows to consider single stage acceleration:
  - A single SPS/LHC bunch could produce an ILC bunch in a single PDWA stage.

➔ Challenges: long plasma sources , efficiency



*A. Caldwell and K. V. Lotov, Phys. Plasmas **18,** 103101 (2011)*

Motivation – Drive Beams in Plasma Wakefield Acceleration

In order to create plasma wakefields efficiently, the drive bunch length has to be short compared to the plasma wavelength. → Relatively easy for **Laser** and **Electron** bunches.

$$E_{acc} = 110 \ \frac{MV}{m} \ \frac{N/(2 \times 10^{10})}{(\sigma_z / 0.6mm)^2}$$

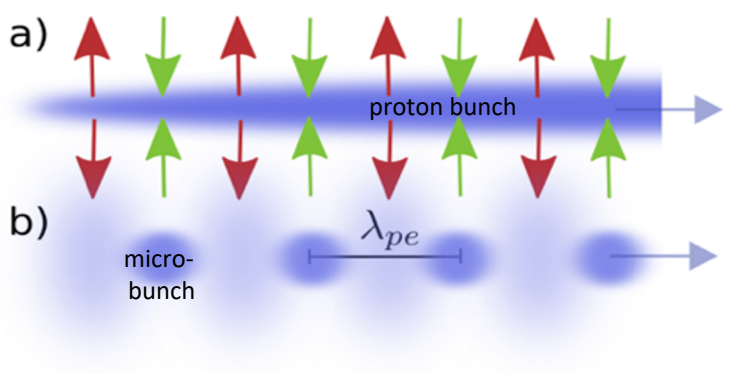
Proton beam as drive beam**:** CERN SPS proton bunch: very long! (σ_z = 12 cm) → much longer than plasma wavelength (λ = 1mm), but rely on self-modulation of the proton beam

Self-Modulation of a Long Proton Beam:

a) Bunch drives wakefields at the initial seed value when entering plasma.

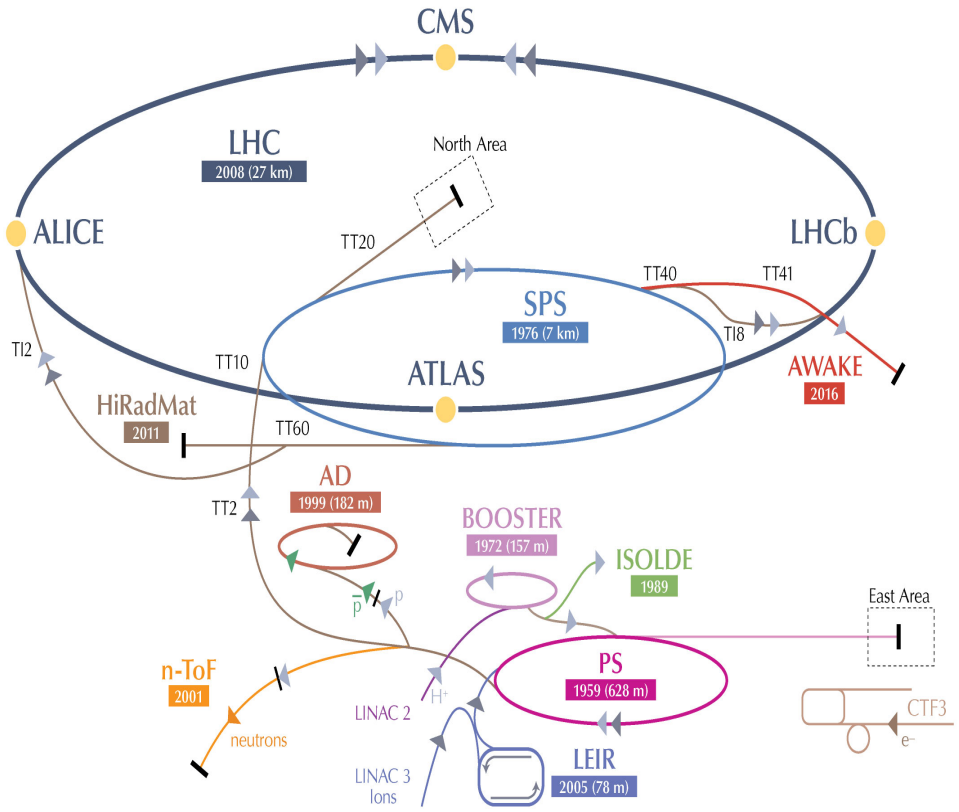
- **Initial wakefields act back** on the proton bunch itself. → On-axis density is modulated. → Contribution to the wakefields is $\propto n_b$.

b) Density modulation on-axis → **micro-bunches**. → separated by plasma wavelength λ_{pe} → drives wakefields resonantly.



→ AWAKE: Demonstration of Seeded Self-Modulation of the proton bunch

AWAKE at CERN



Advanced WAKEfield Experiment

- Proof-of-Principle Accelerator R&D experiment at CERN to study proton driven plasma wakefield acceleration.

- Collaboration of 22 institutes world-wide
- Approved in August 2013

AWAKE Run 1 (2016-2018):

✓ 1st milestone: Demonstrate seeded self-modulation of the proton bunch in plasma (2016/17)

✓ 2nd milestone: Demonstrate electron acceleration in plasma wakefield driven by a self-modulated proton bunch. (2018)

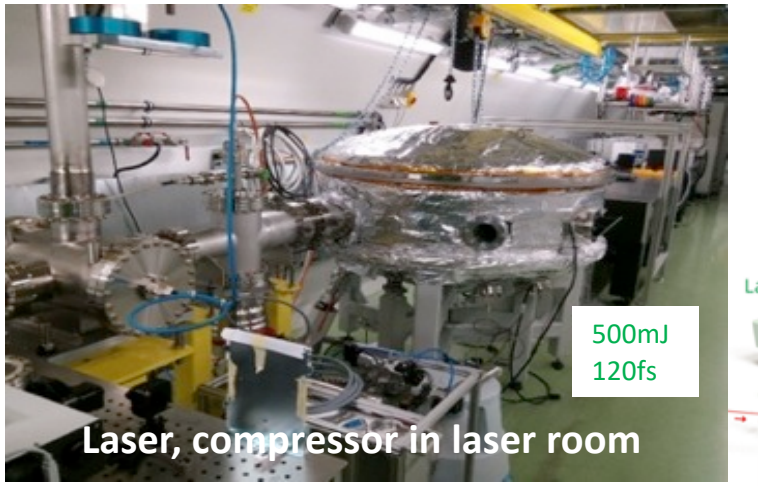
AWAKE Run 2 (starting 2021 - 2028):

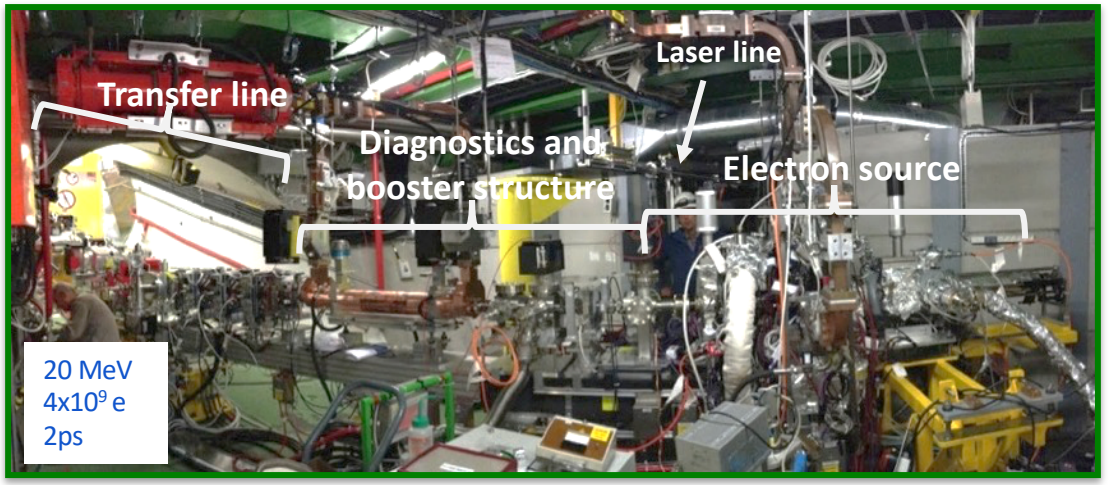
Accelerate an electron beam to high energies (gradient of 0.5-1GV/m) while preserving the electron beam quality and demonstrate scalable plasma source technology.

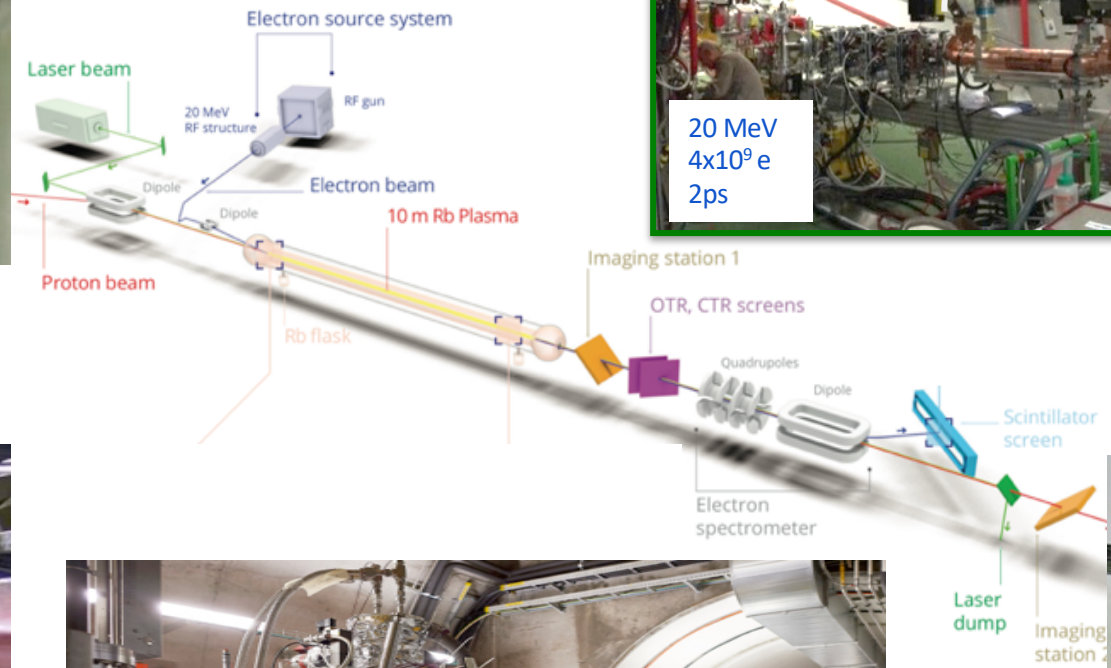
After 2028: First application of the AWAKE-like technology:

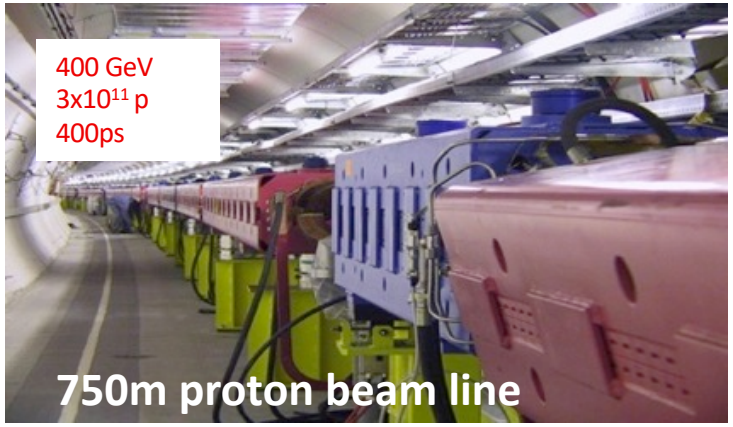
Once AWAKE Run 2 demonstrated: fixed target experiments for e.g. dark photon search.

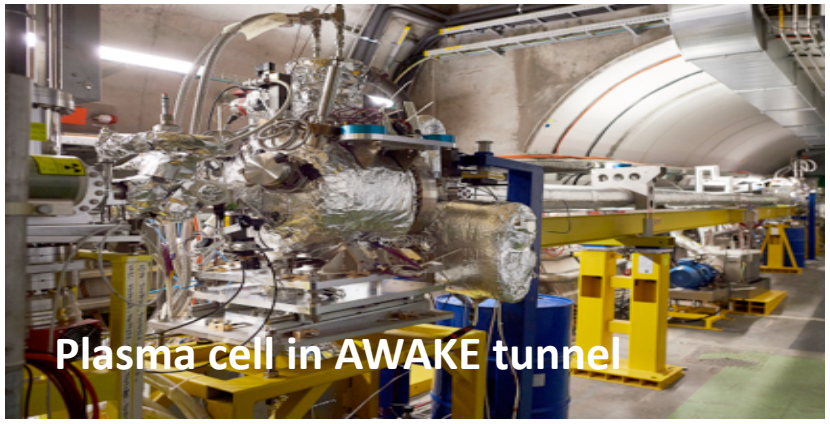
Key Ingredients of AWAKE





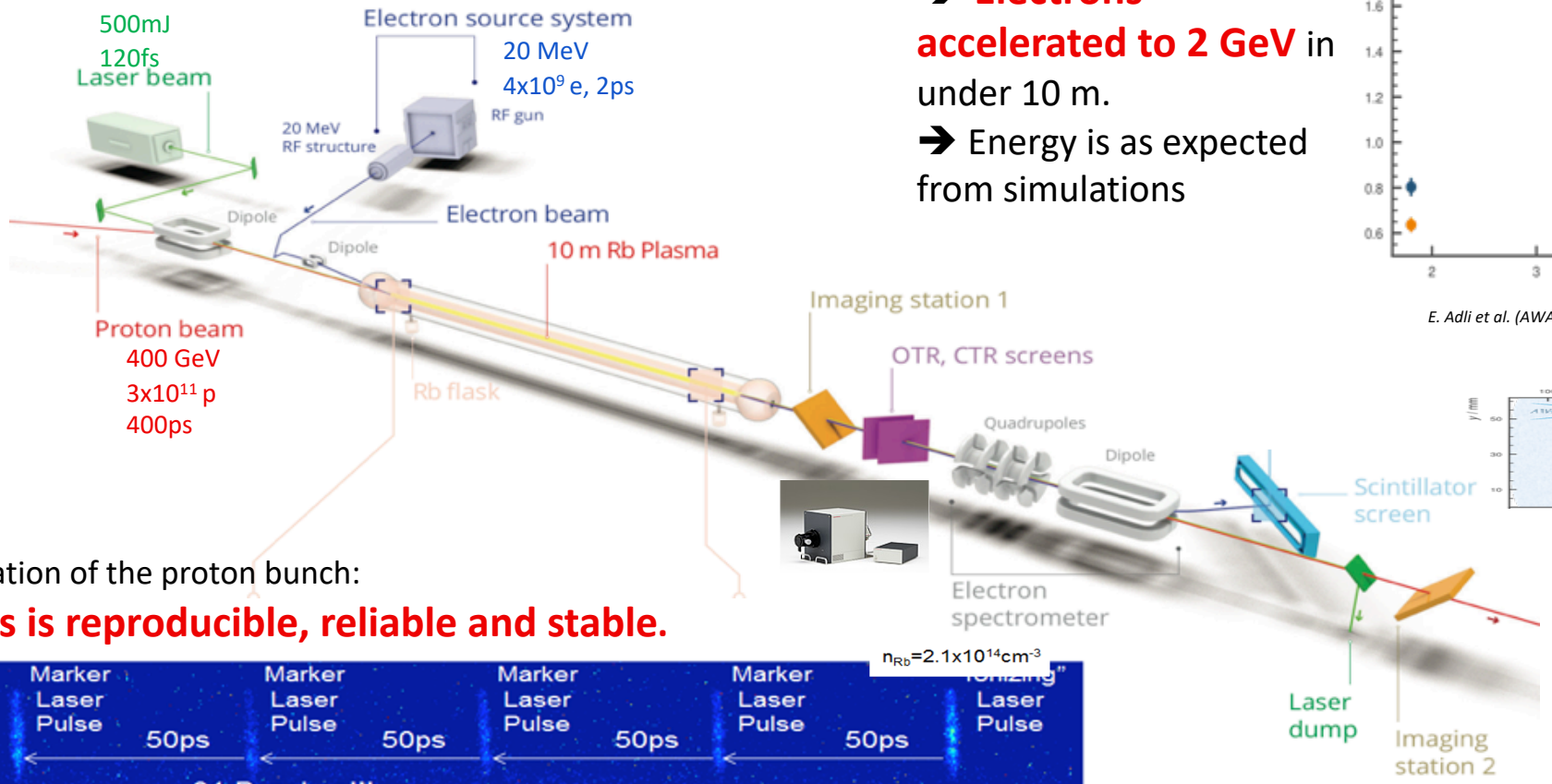






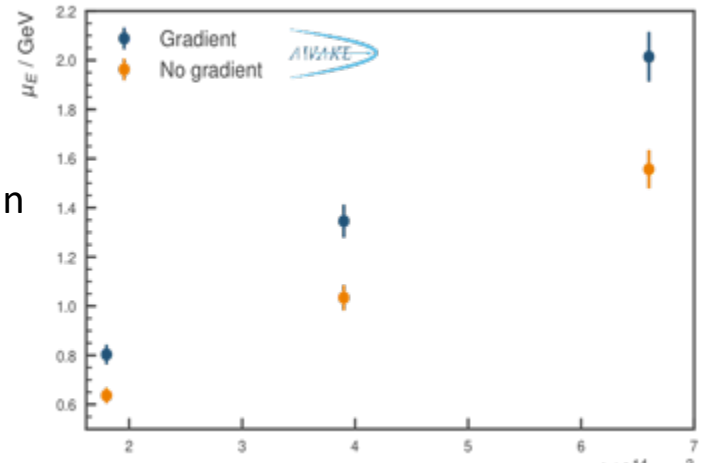
AWAKE Run 1

AWAKE has demonstrated during Run 1 (2016-2018) that the seeded self-modulation is a reliable and robust process and that electrons can be accelerated with high gradients.

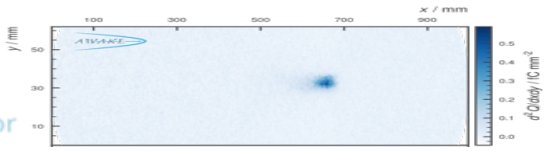


➔ **Electrons accelerated to 2 GeV** in under 10 m.

➔ Energy is as expected from simulations

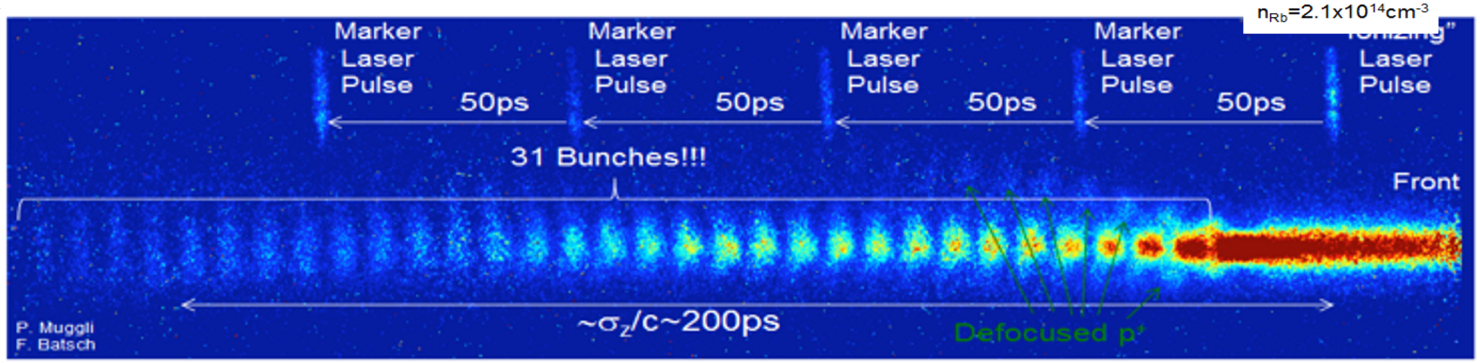


E. Adli et al. (AWAKE Collaboration), ***Nature 561****, 363–367 (2018)*



Seeded self-modulation of the proton bunch:

➔ **SSM process is reproducible, reliable and stable.**



E. Adil et al. (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).

AWAKE Run 2

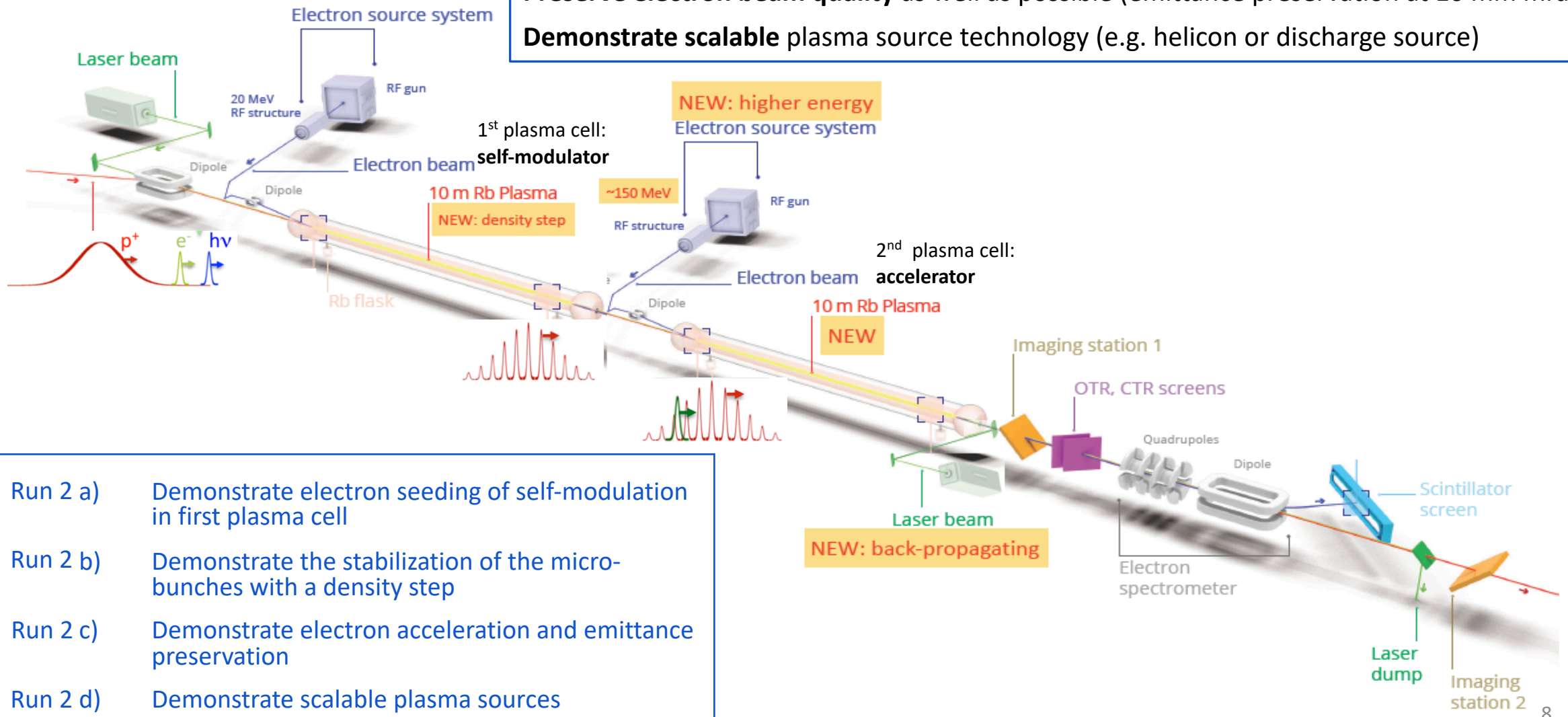
➔ Demonstrate possibility to use AWAKE scheme for high energy physics applications in mid-term future!

Goals:

Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)

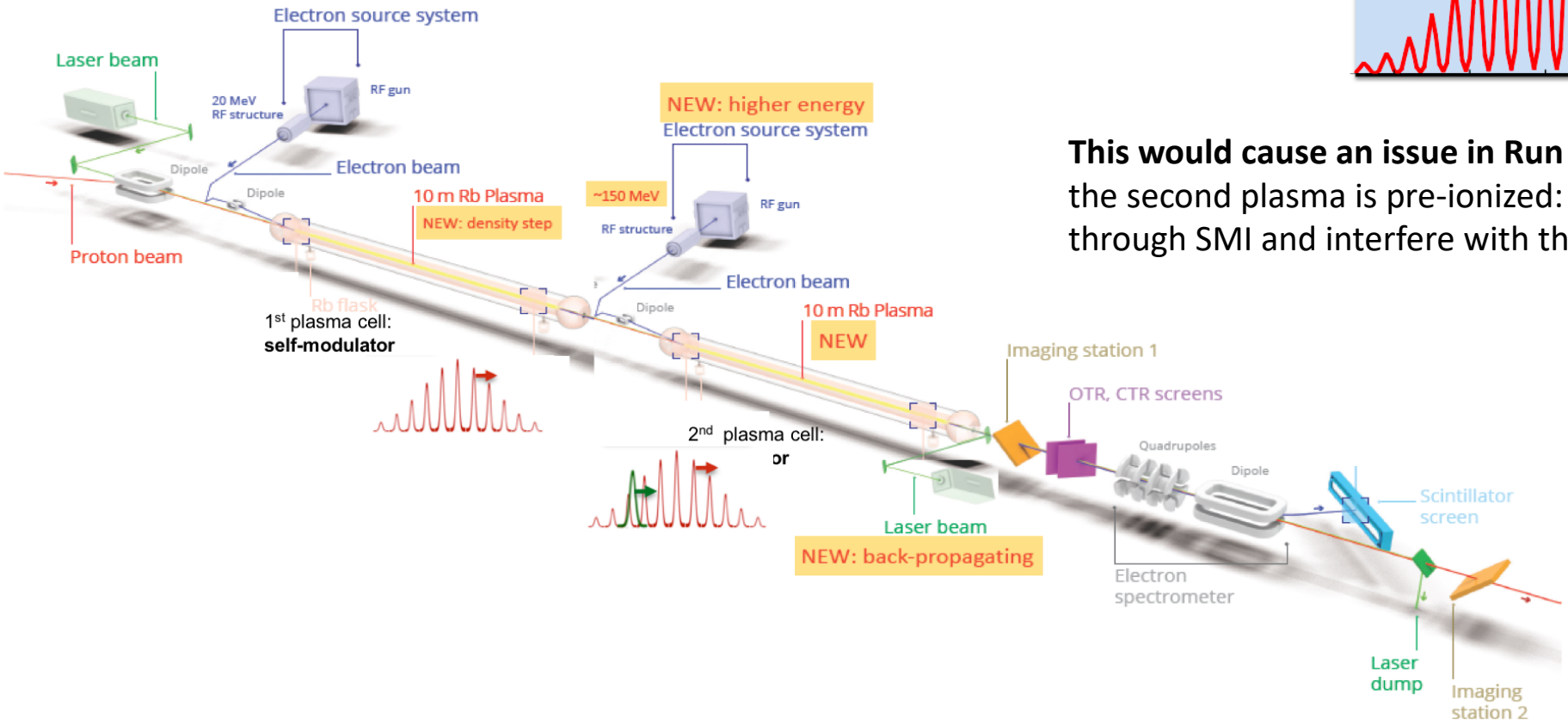
Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)

Demonstrate scalable plasma source technology (e.g. helicon or discharge source)

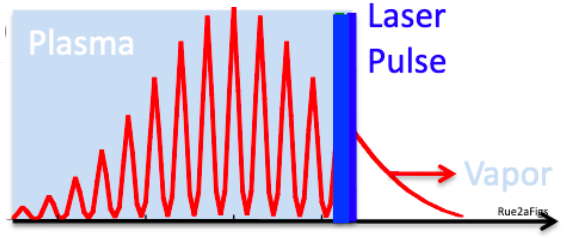


Run 2 a)	Demonstrate electron seeding of self-modulation in first plasma cell
Run 2 b)	Demonstrate the stabilization of the micro-bunches with a density step
Run 2 c)	Demonstrate electron acceleration and emittance preservation
Run 2 d)	Demonstrate scalable plasma sources

Run 2a: Demonstrate Electron Seeding of Self-Modulation in First Plasma Cell



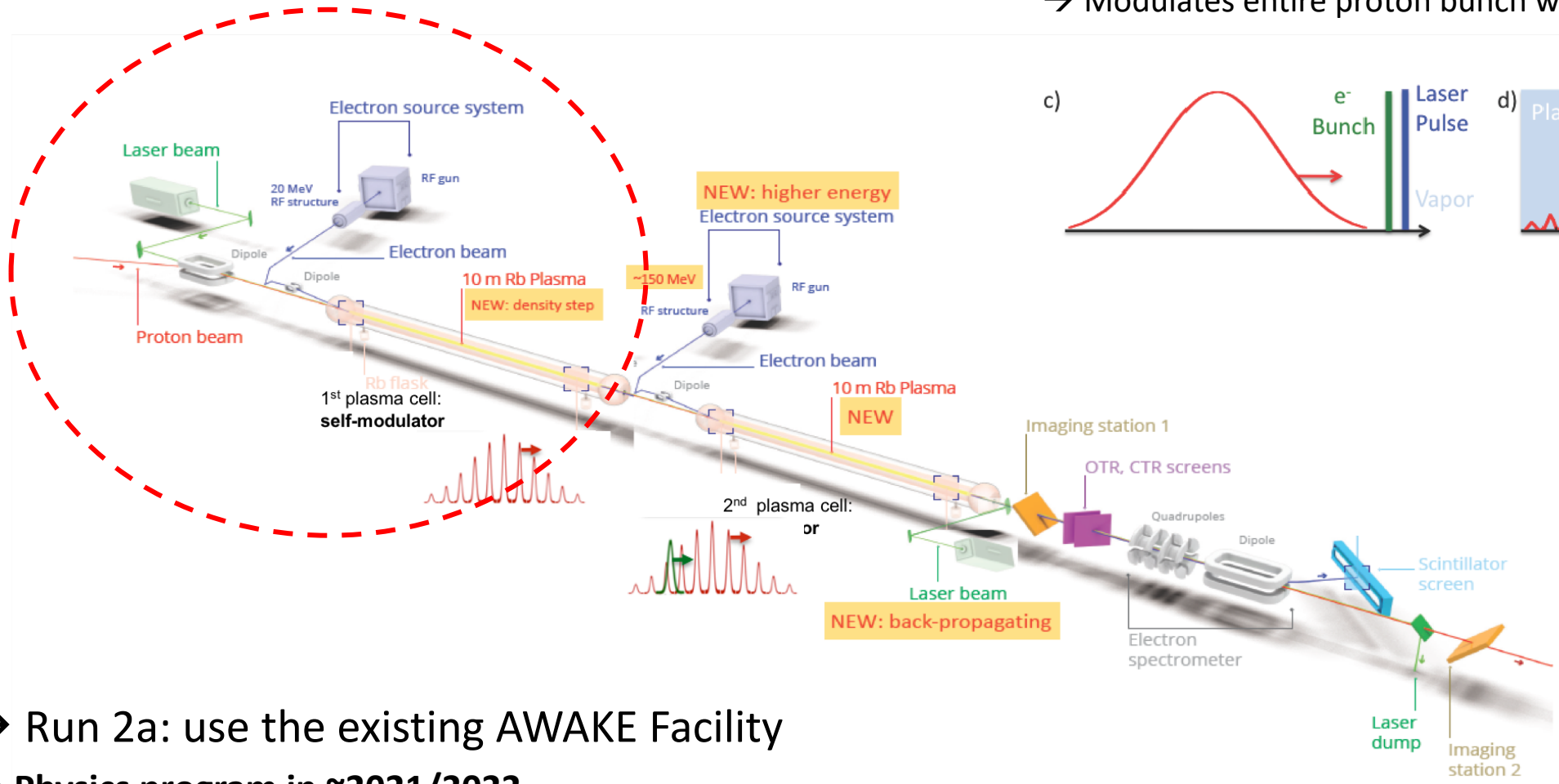
AWAKE Run 1:
Laser Ionization Front seeding



This would cause an issue in Run 2c:
the second plasma is pre-ionized: front of the bunch can go through SMI and interfere with the SSM-ed back of the bunch

Run 2a: Demonstrate Electron Seeding of Self-Modulation in First Plasma Cell

AWAKE Run 2: Electron bunch seeding:
→ Modulates entire proton bunch with phase reproducibility

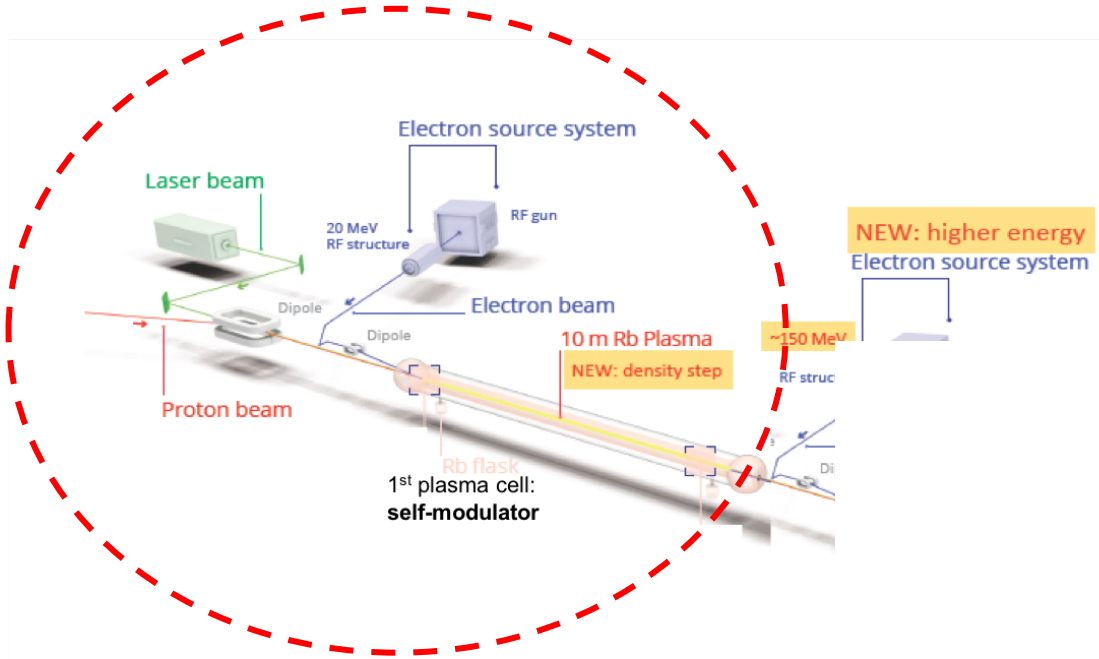


→ Run 2a: use the existing AWAKE Facility

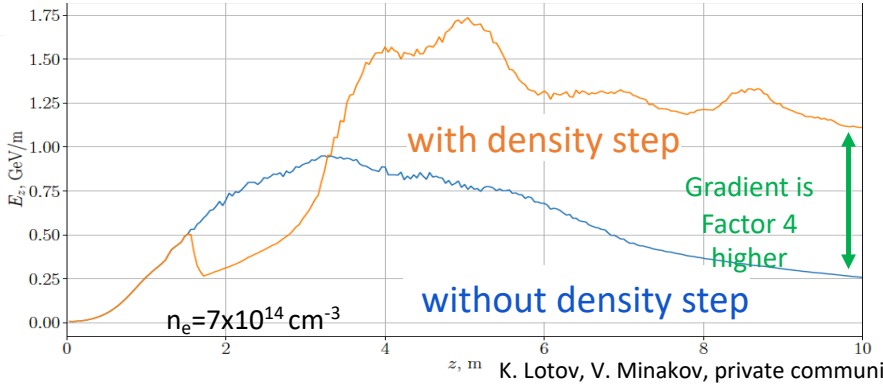
→ **Physics program in ~2021/2022**

Run 2b: Demonstrate Stabilization of Micro-Bunches with a Density Step

- In constant plasma, wakefield amplitude decreases after saturation.
- In a plasma with density step within the SM grow: wakefield amplitude **maintains larger** after saturation.



Gradient in 1st plasma source (self-modulator)

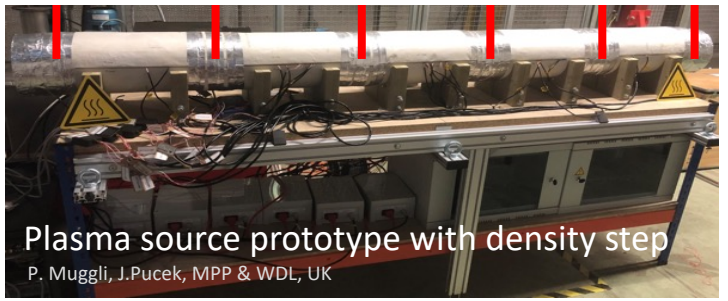


K. Lotov, V. Minakov, private communication

Installation:

➔ new plasma source with density step capability

➔ novel plasma diagnostics to allow measurement of plasma 'wave' directly



station 2

➔ Run 2b: use the existing AWAKE Facility

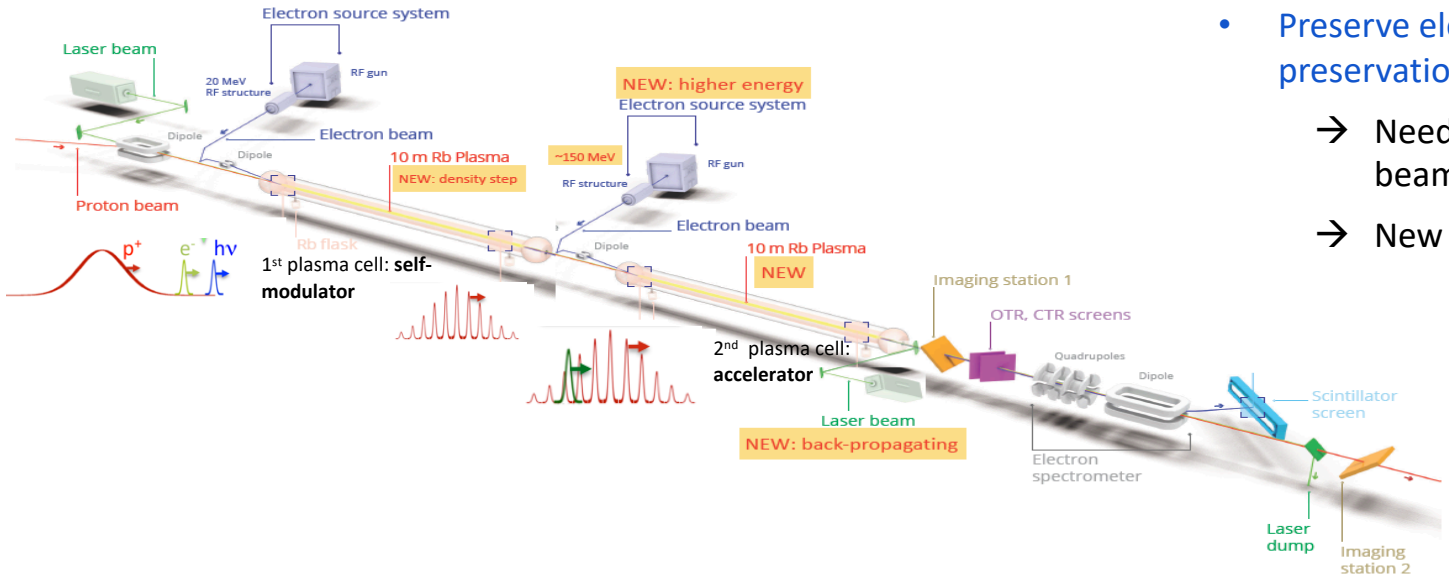
➔ **Physics program in ~2023/2024**

Run 2c: Demonstrate Electron Acceleration and Emittance Preservation

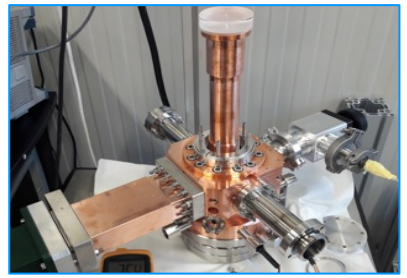
To house the full length of the Run 2 experiment, **the AWAKE area must be extended** into the former CNGS target area (radioactive!)

- New electron source and beam line
- New plasma cell (ACC cell)
- New laser to 2nd plasma cell
- New diagnostics
- *Expand the experimental area (CNGS dismantling)*

Run 2c: Demonstrate Electron Acceleration and Emittance Preservation



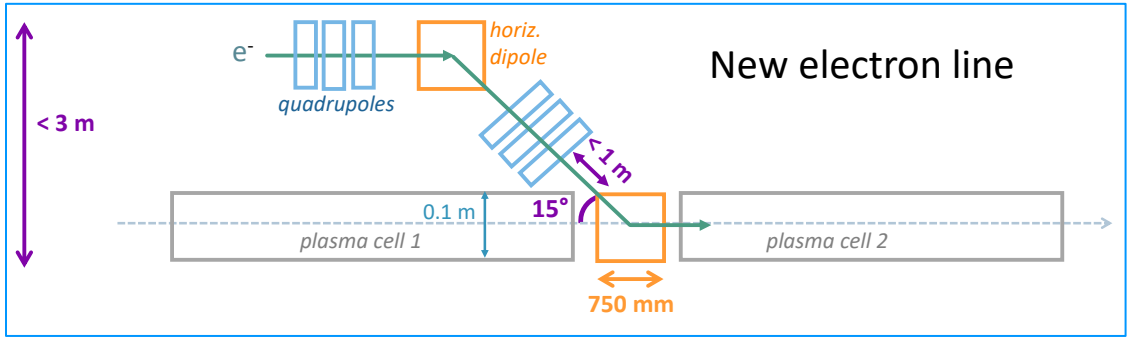
- Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)
- Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)
  - → Need to work in blow-out regime (→ linear focusing) and do beam-loading (→ small ∂E/E)
  - → New electron beam:150 MeV, 200 fs, 100 pC, σ = 5.75 µm



E-gun assembly at INFN

➔ **Area extension and installation: 2025/26**

➔ **Physics program: 2026/27/28**



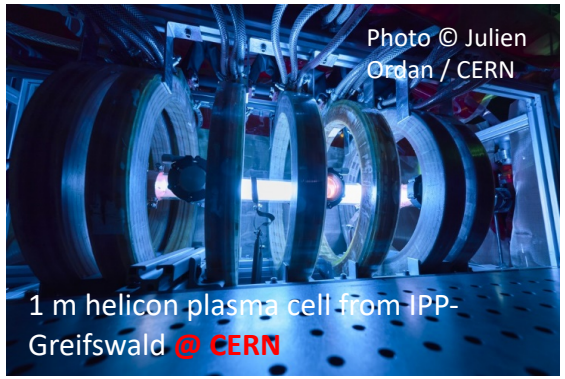
Run 2d) Demonstrate Scalable Plasma Sources

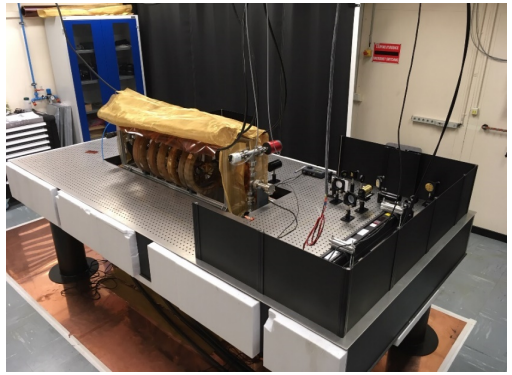
Today: Laboratory developments in dedicated plasma lab at CERN

Aim: Propose a design for a scalable, several meter-long plasma cell for Run 2d).

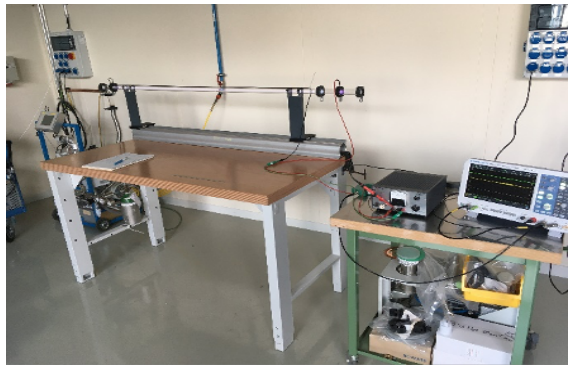
- → Study uniformity and scalability at CERN.
- → Use new diagnostics to understand features of plasma.

Helicon plasma cell → wave heated plasma: 1 m helicon plasma source

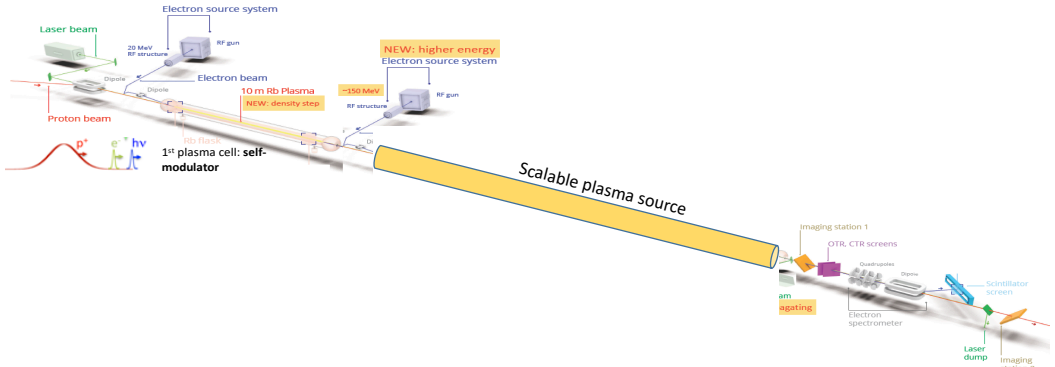




Discharge plasma source → high current arc plasma: 1.6 m long prototype cell setup at CERN



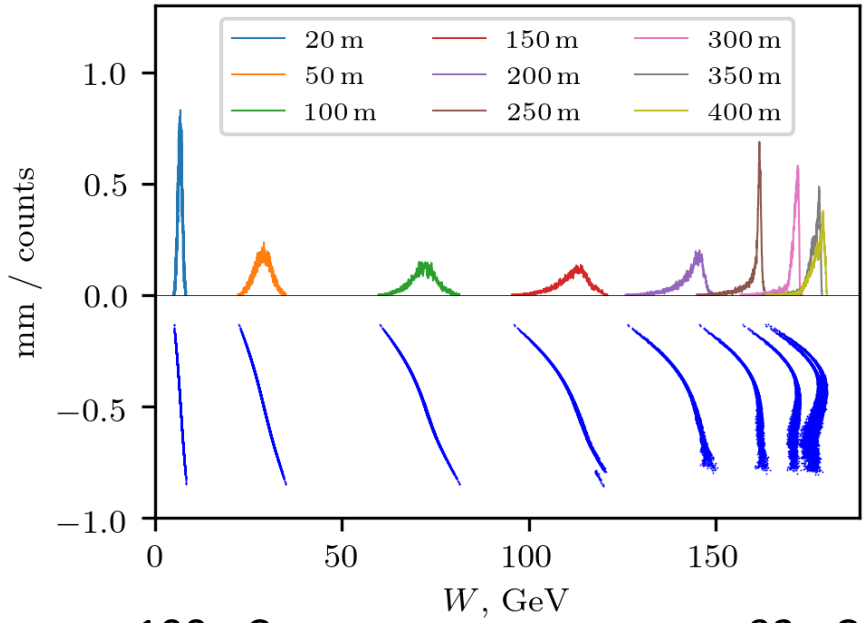
CERN, IPP Greifswald, SPC Lausanne, Univ. Wisconsin, IST Lisbon, Imperial College



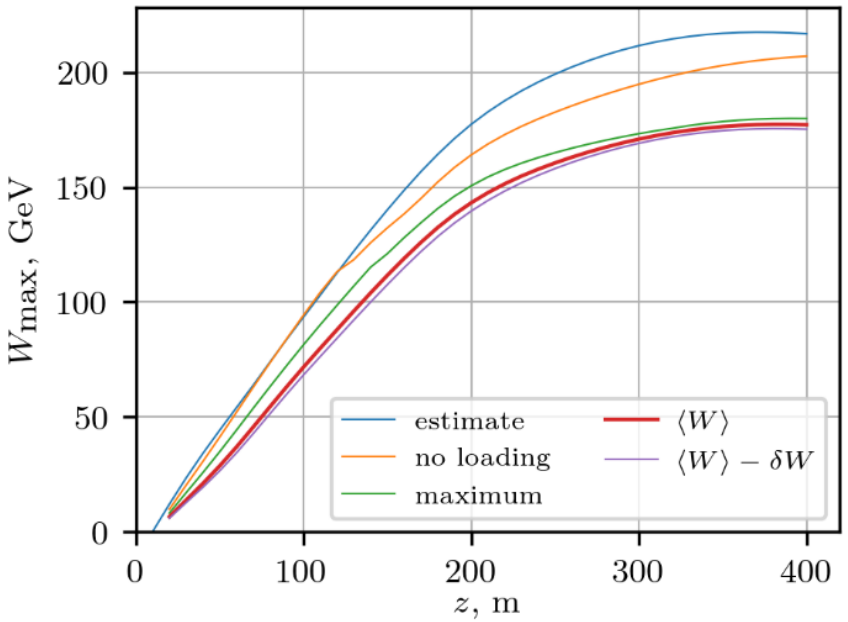
Final Goal:
Use this technology to build a 50-100m long plasmas source and use it for **first applications (~2029)**

Electron Beam Parameters for Applications

- Baseline in previous PBC meetings: 33 GeV after 50 m, 10^9 electrons on target, ~2% energy resolution
- Latest Results show that we can increase the energy up to 200 GeV, 10^9 electrons, ~1% energy resolution after ~300 m.



100 pC 93 pC



Final rms energy spread ~ 1%

Preliminary results, further optimization is possible!

K. Lotov, AWAKE Physics Board, 5.3.2021

Particle Physics Applications

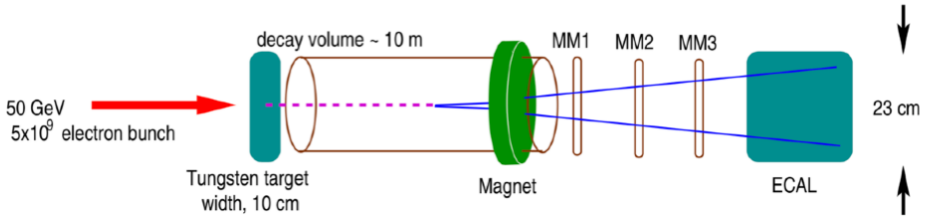
Beam Dump Experiment:

Search for dark photons 50 GeV electrons and 12 weeks of data taking period → 10^{16} electrons on target.

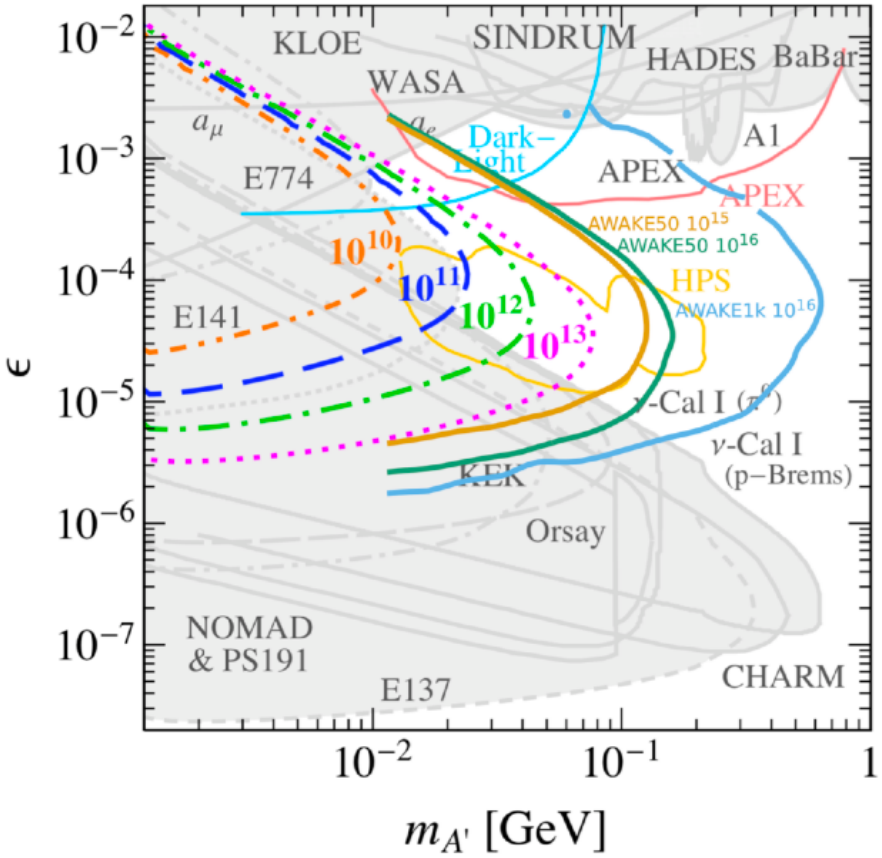
→ Decay of dark photon into visible particles (e.g. e+/e-)

→Energy and flux is important

→Relaxed parameters for emittance



Experimental conditions modeled on NA64 experiment.

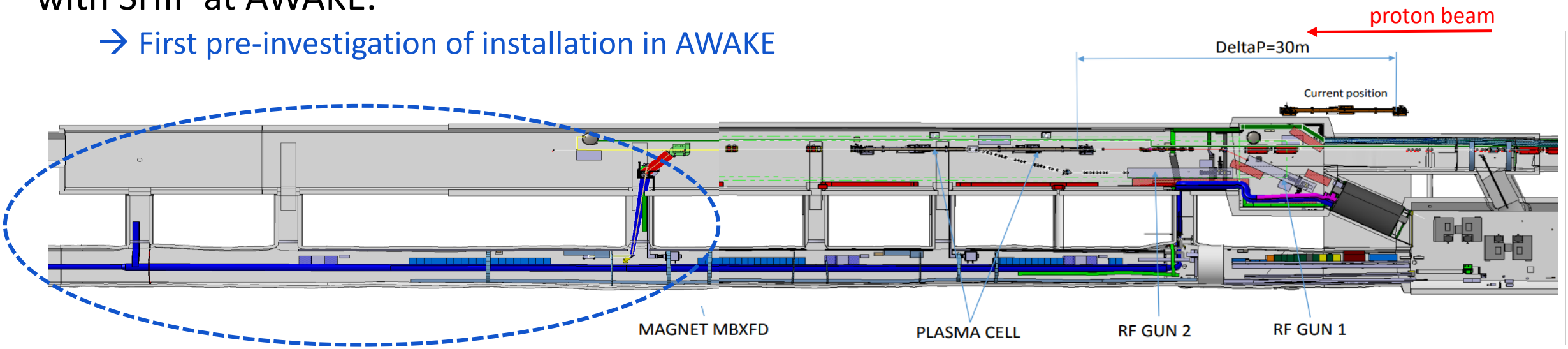


→ Extension of kinematic coverage for 50 GeV electrons and even more for 1 TeV electrons

Particle Physics Application

SHIP: Started discussions to investigate possibility for a beam dump experiment with SHIP at AWAKE.

→ First pre-investigation of installation in AWAKE

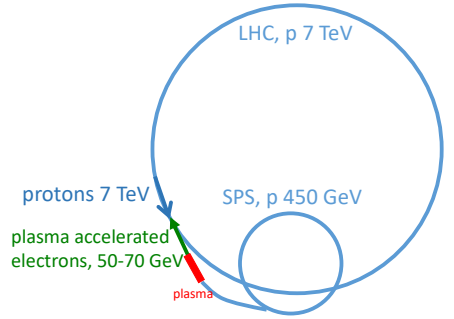


→ Need to further study aspects related to electron beam parameters: e.g. how to increase the intensity from 10^{16} by orders of magnitude (duty cycle, extraction mechanism, …)

Parameter	LIU-SPS
N_p	2.3×10^{11}
E_p (GeV)	450
$\sigma_{x,y}$ (μm)	100
σ_z (cm)	7.55
n_b (per SPS SC)	320
f_{rep} (Hz)	0.025
N_e	1×10^9
E_e (GeV)	65
Number of electrons on target per year	4.1×10^{16}

Particle Physics Applications

Electron-proton and electron-ion physics → Focus on QCD:

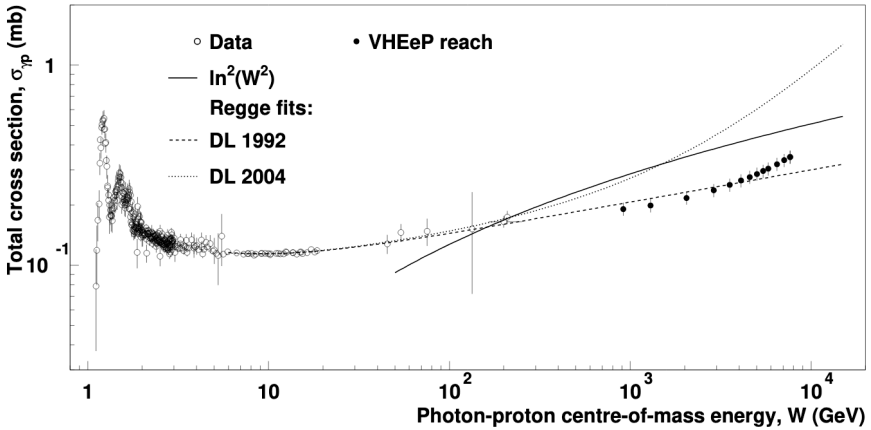


PEPIC: use the SPS to drive electron bunches to 50 GeV and collide with protons from LHC with 7 TeV
→ Modest luminosity → only interesting should the LHeC not go ahead.

VHEeP : use the LHC to drive electron bunches to 3 TeV and collide with protons from LHC with 7 TeV
→ Yields centre-of-mass energy of 9 TeV! Luminosity is relatively modest ~10^{28} – 10^{29} cm^{-2} s^{-1} , i.e. 1pb^{-1}/yr.
→ Reach in (high) Q^2 and (low) Bjorken x etended by ~1000 compared to HERA.

Energy dependence of hadronic cross-sections not understood and needs new experimetnal results.

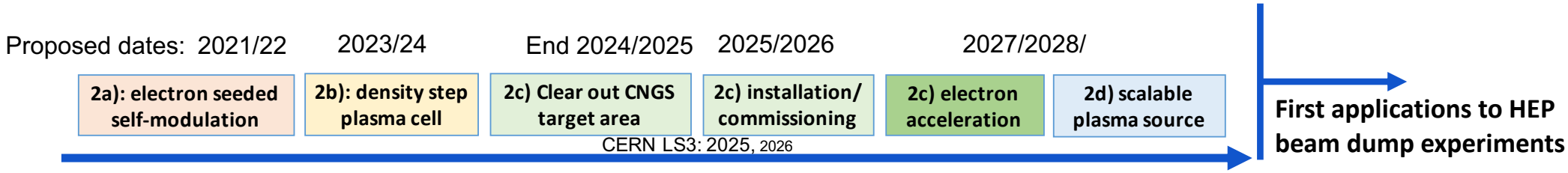
W=6TeV corresponds to ~20PeV photons on fixed target
→ Extends into regions of ultra-high energy cosmic rays!



Fixed target variants with these electron beams
Physics beyond Standard Model: e.g. search of new particles with both lepton and quark quantum numbers

Summary

AWAKE has a clear roadmap towards first applications for High-Energy Physics.



a) Demonstrate electron seeding of self-modulation in first plasma cell

b) Demonstrate the stabilization of the micro-bunches with a density step

c) Demonstrate **electron acceleration to high energies and emittance preservation**

d) Demonstrate scalable plasma sources

➔ First applications to beam dump experiments (e.g. dark photon search) with ~50 GeV electron beam.

➔ Baseline in previous PBC meetings: 33 GeV after 50m, 10^9 electrons on target, ~1% energy resolution

➔ But latest results show that we can increase the energy up to 200 GeV after ~300m!

➔ Opportunity to consider experimental requirements during AWAKE Run 2 area preparation

➔ Input welcome!