High Energy Particle Accelerator Applications with the AWAKE-Scheme

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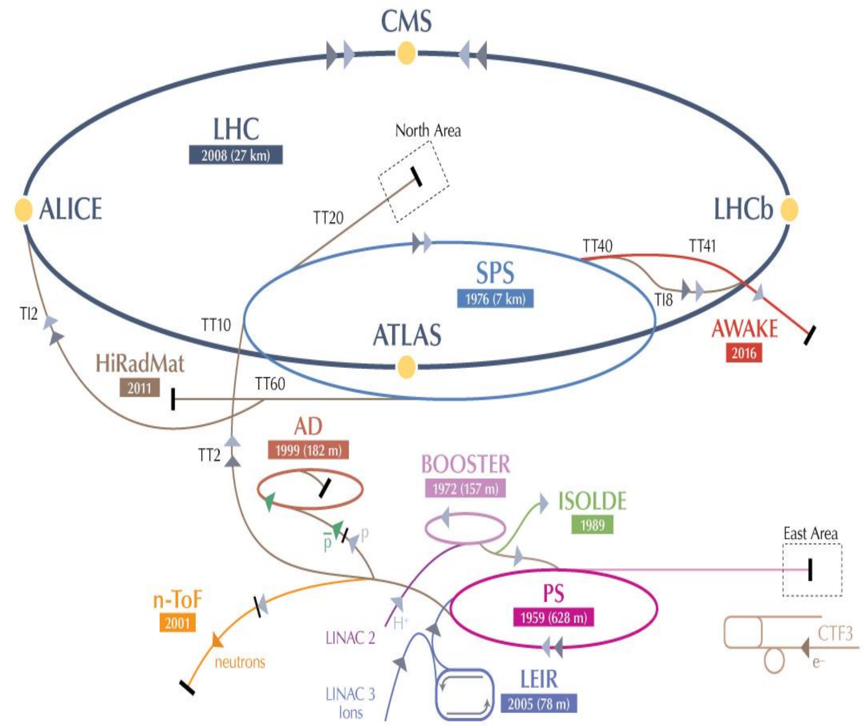
Outline

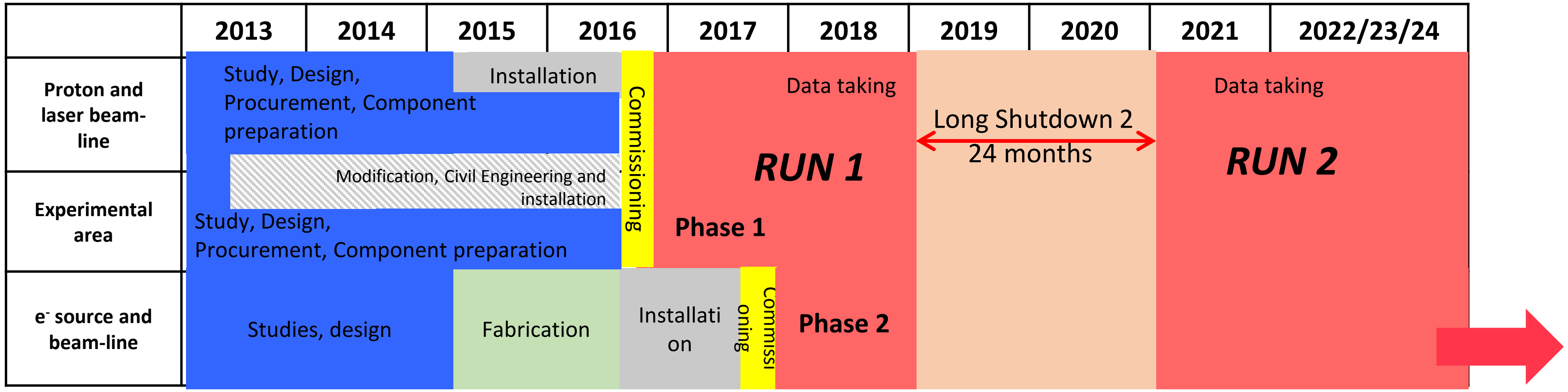
- AWAKE Run 1 Results
- AWAKE Run 2
- High Energy Physics Applications
  - Fixed Targets
  - Electron/proton or electron/ion collider
- Summary

Introduction



AWAKE: Advanced Proton driven Plasma Wakefield Experiment

- First facility that investigates the use of plasma wakefields driven by a proton beam to accelerate electrons to high energies at GeV level.
- Apply scheme to particle physics experiments leading to shorter or higher energy accelerators
- Collaboration of 18 institutes and 2 associate members.
- Approved in 2013
- First beam in 2016

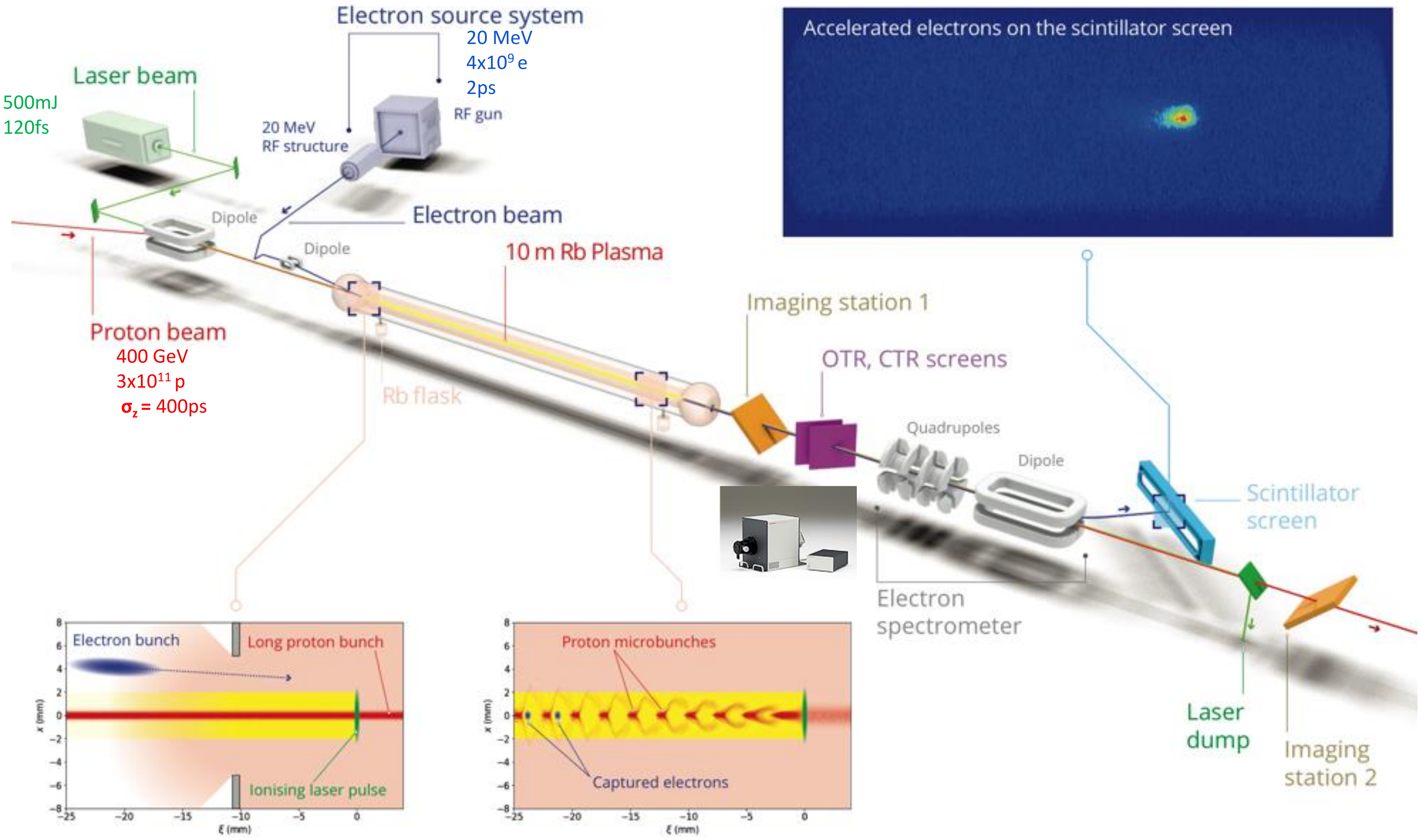


Run 1 – until LS2 of the LHC.

After LS2 – proposing Run 2 of AWAKE (during Run 3 of LHC)

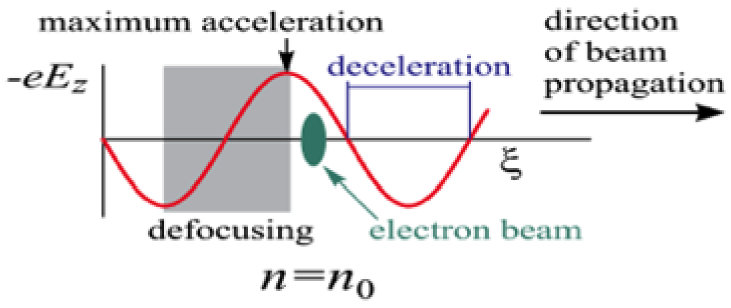
After Run 2: kick off particle physics driven applications

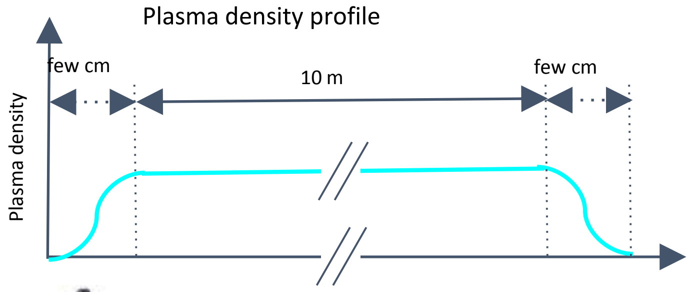
AWAKE Experiment

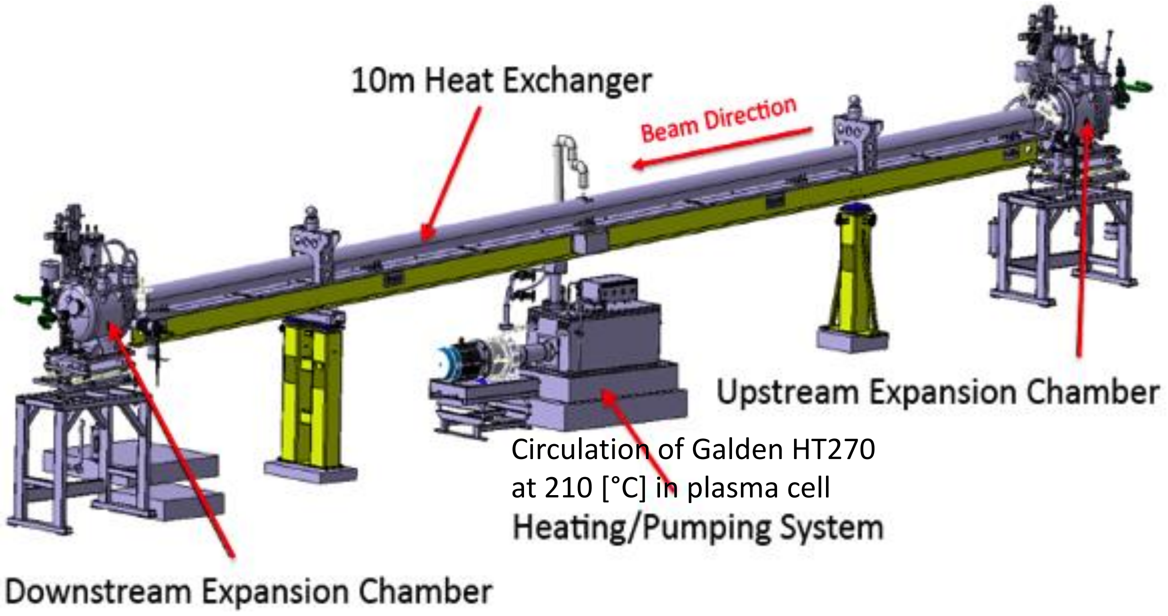


AWAKE Plasma Cell

- **10 m long**, 4 cm diameter
- Rubidium vapor, field ionization threshold ~10^{12} W/cm^2
- Density adjustable from 10^{14} – 10^{15} cm^{-3} ➔ **7x 10^{14} cm^{-3}**
- Requirements:
  - **density uniformity better than 0.2%**
    - Fluid-heated system (~220 deg)
    - Complex control system: 79 Temperature probes, valves
  - **Transition between plasma and vacuum as sharp as possible**

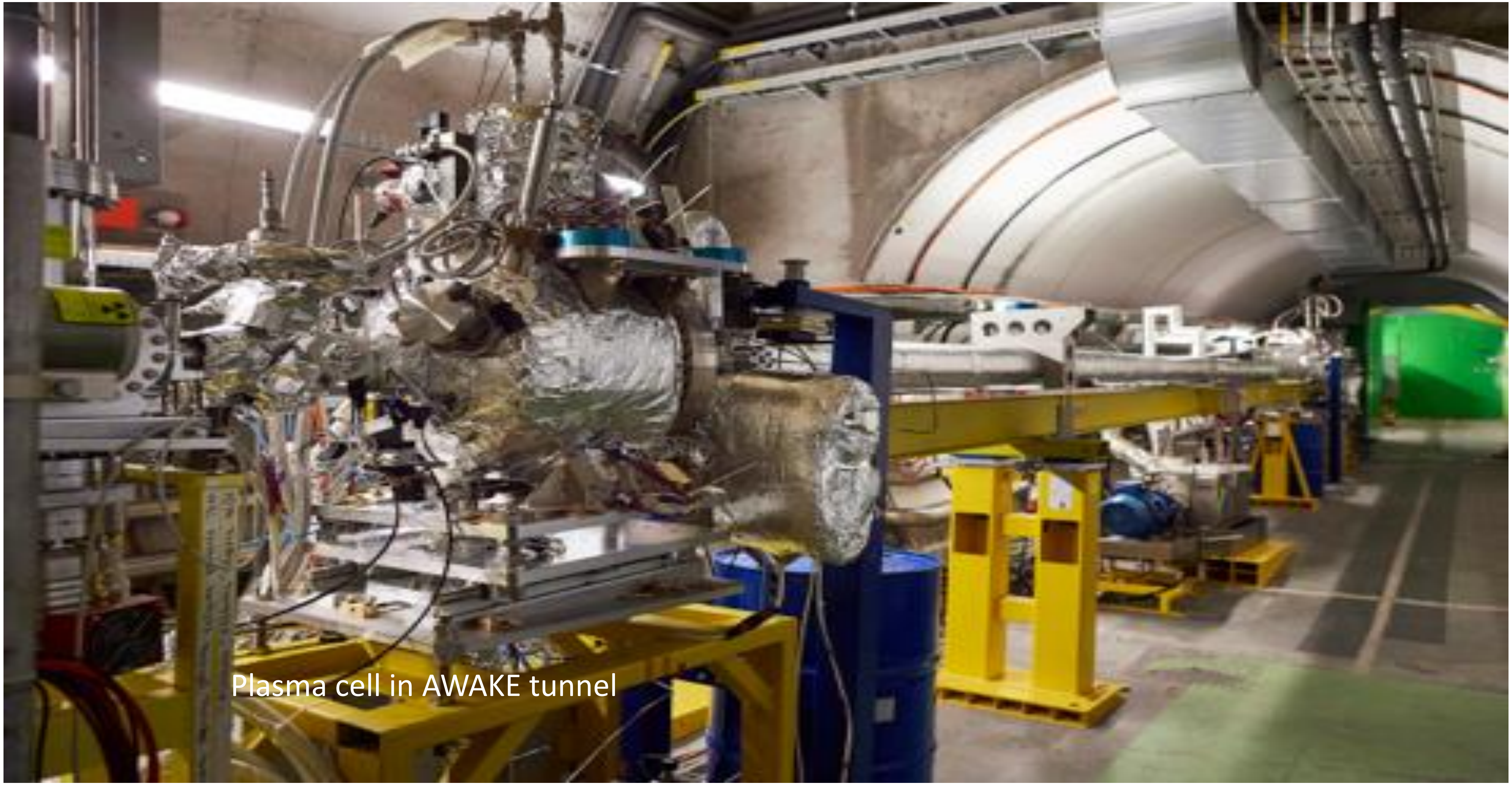






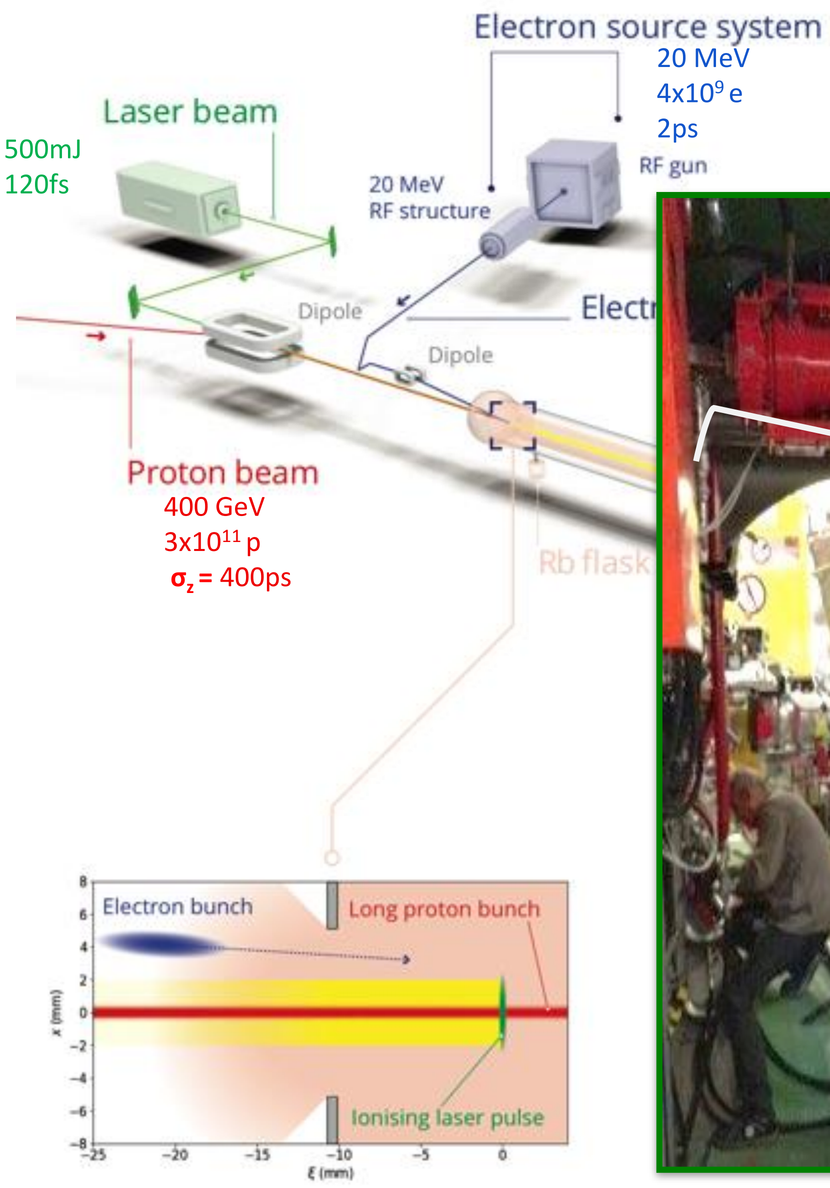
E. Öz et al., NIM A 740(11), 197 (2014)
E. Öz et al., NIM A829, 321 (2016)
F. Batsch et al., NIM A, 909, 359 (2018)

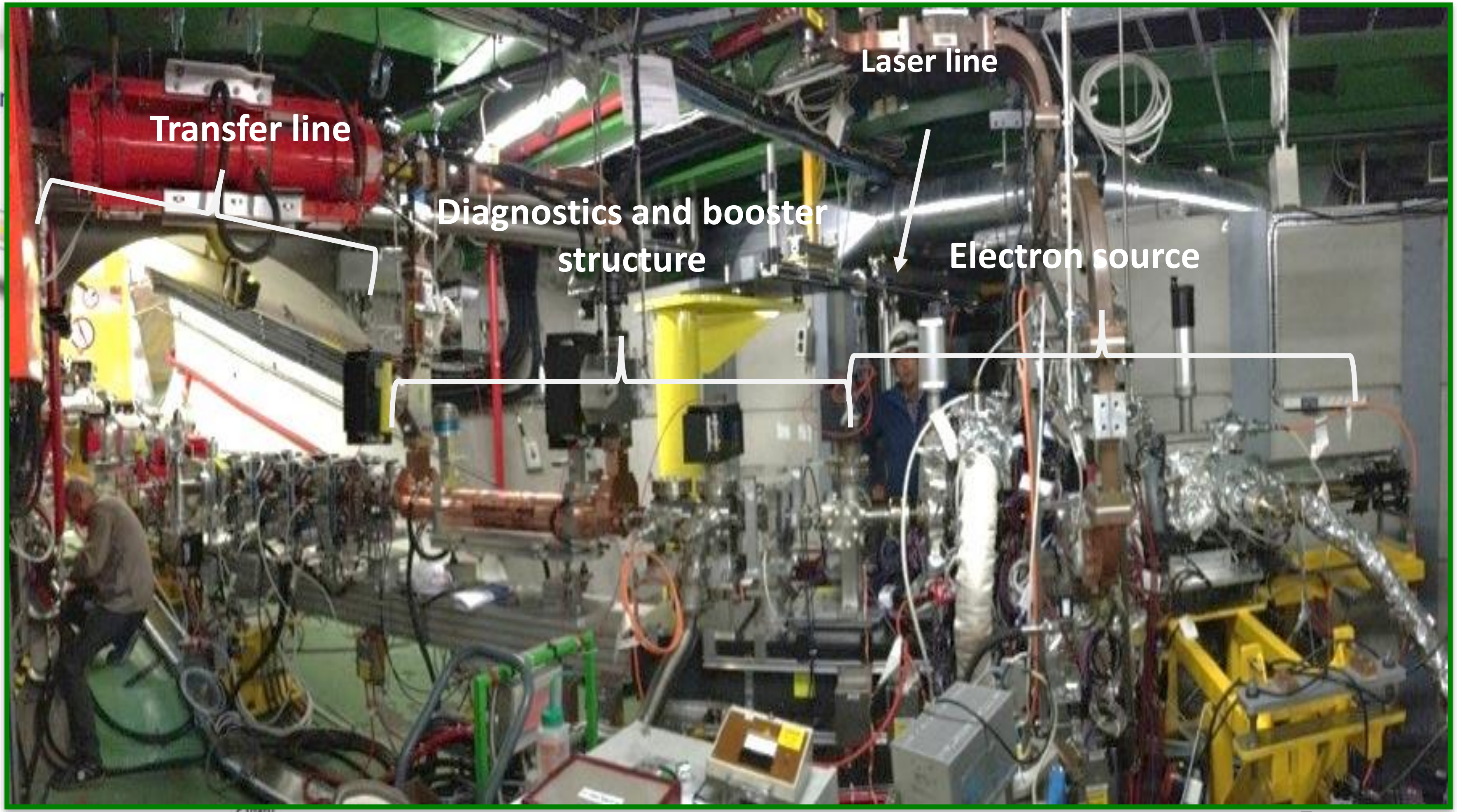
AWAKE Plasma Cell



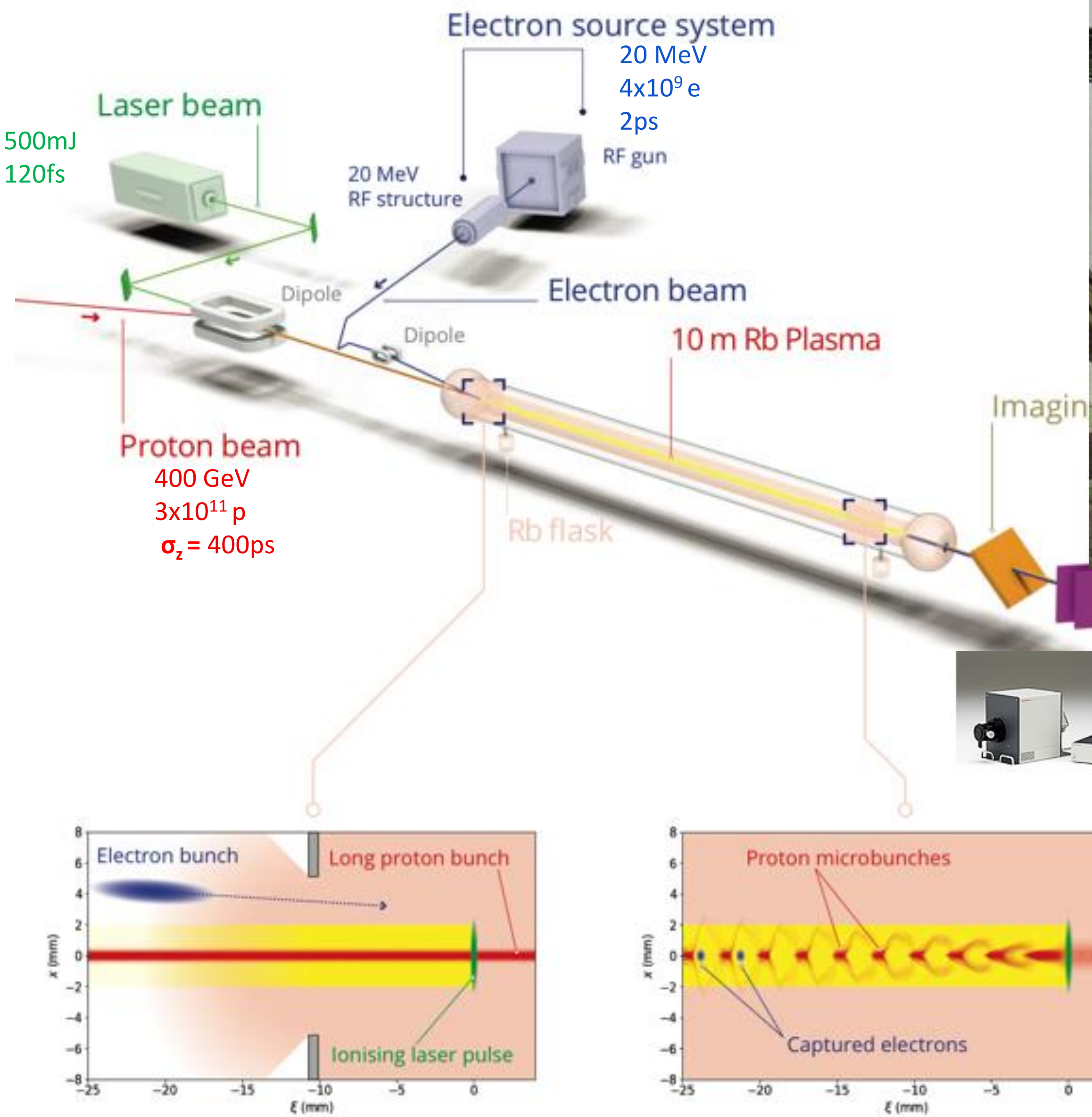
Plasma cell in AWAKE tunnel

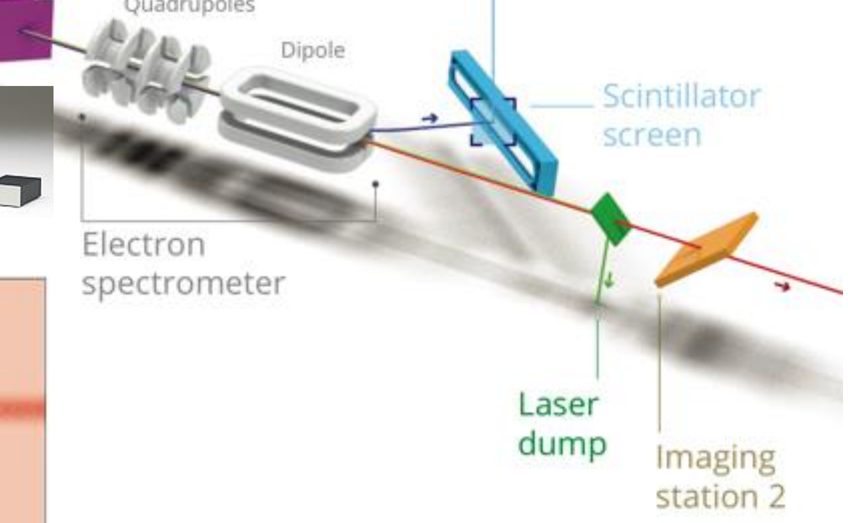
AWAKE Experiment



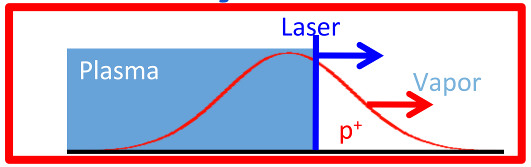


AWAKE Experiment

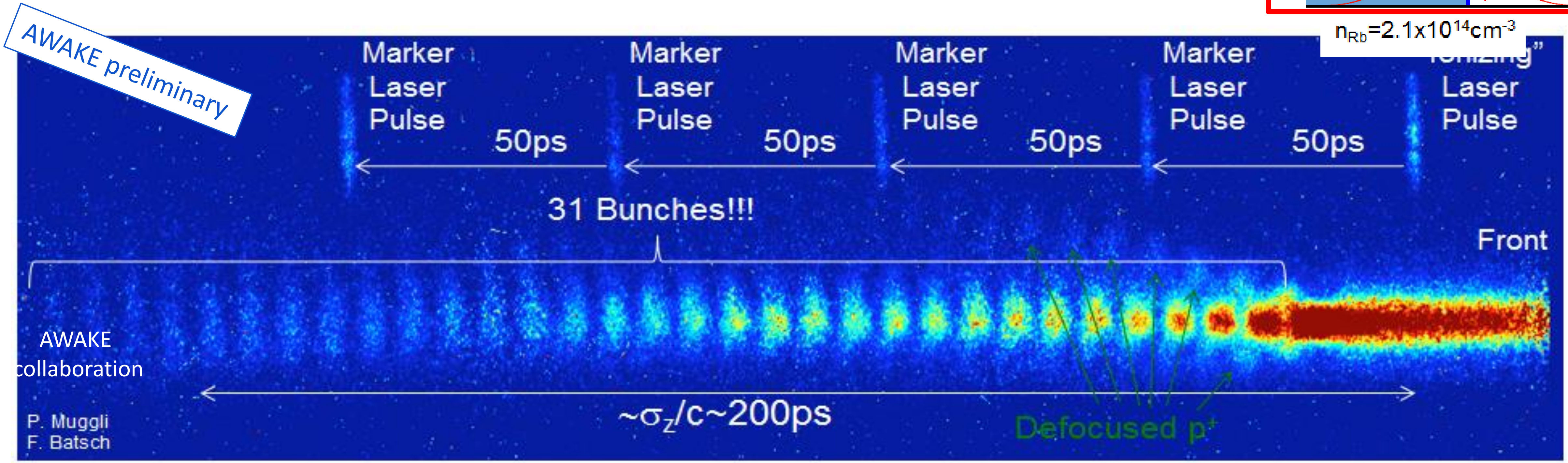




Results: Direct Seeded Self-Modulation Measurement, 2018



$n_{Rb}=2.1x10^{14}cm^{-3}$



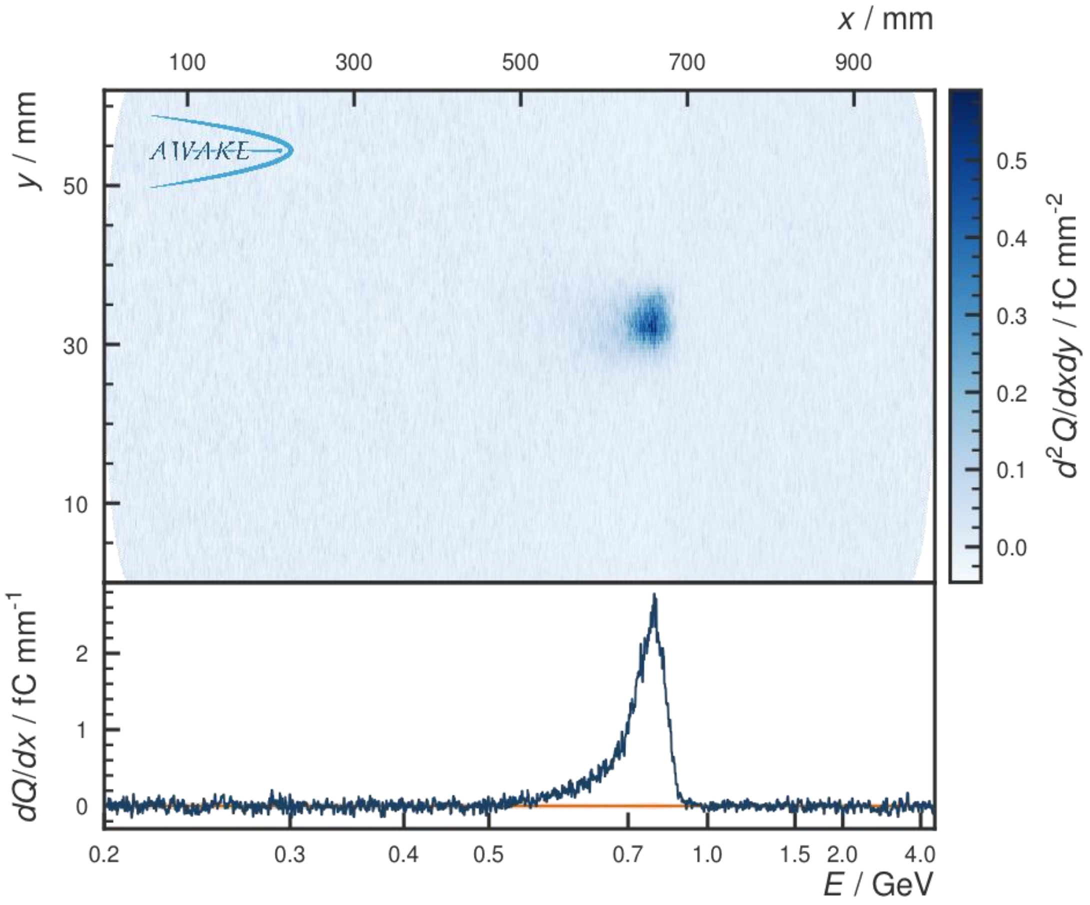
- Effect starts at laser timing → **SM seeding**
- **Density modulation** at the ps-scale visible
- Micro-bunches **present over long time scale** from seed point
- **Reproducibility** of the μ-bunch process against bunch parameters variation
- **Phase stability** essential for e^- external injection.

AWAKE Collaboration, 'Experimental observation of proton bunch modulation in a plasma, at varying plasma densities'. **Phys. Rev. Lett. 122, 054802 (2019).**

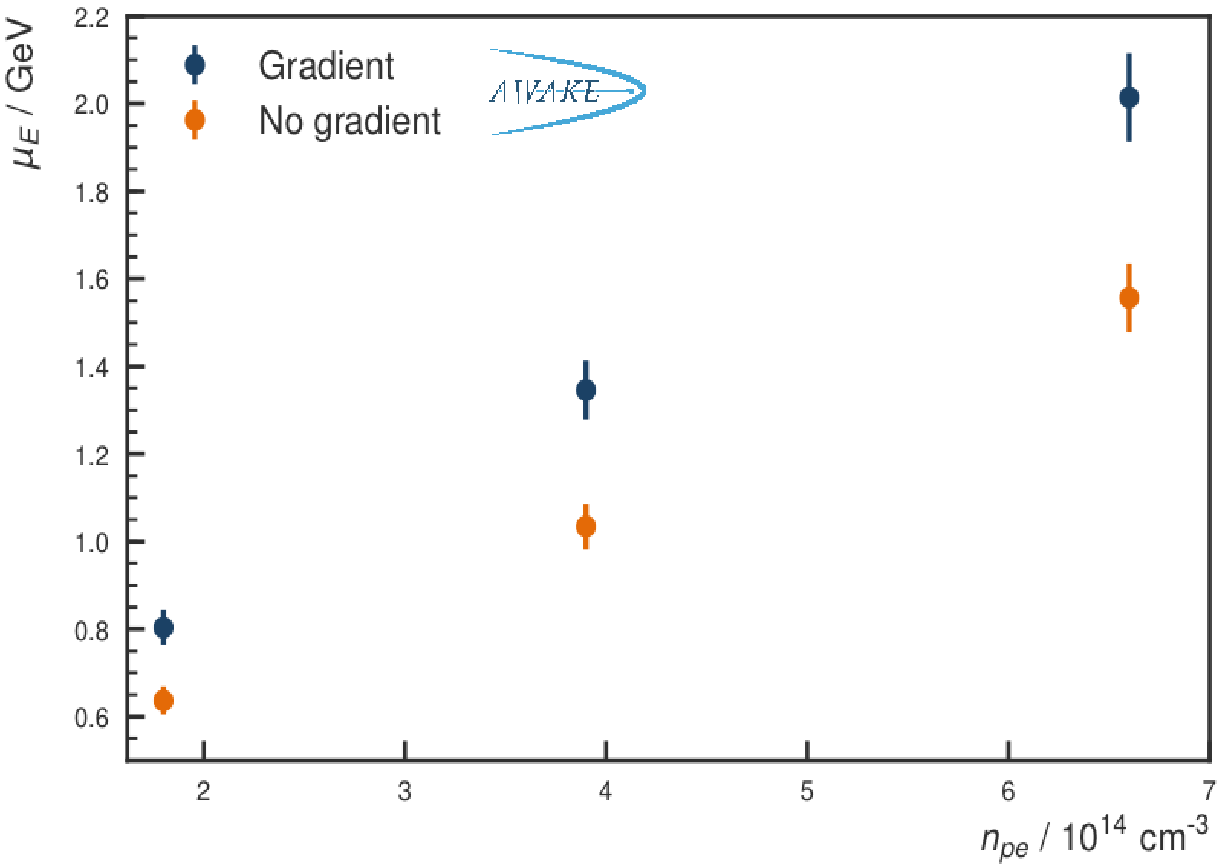
M. Turner et al. (AWAKE Collaboration), 'Experimental observation of plasma wakefield growth by the seeded self-modulation of a proton bunch', **PRL, 122, 054801 (2019).**

Electron Acceleration Results, 2018

Results from **May 2018 Run**



Event **at n_{pe} =1.8 x 10^{14} cm^{-3} with 5%/10m** density gradient.



➔ **Acceleration up to 2 GeV** has been achieved.

AWAKE Collaboration, Nature, doi:10.1038/s41586-018-0485-4 (2018)

What’s Next?

AWAKE Run 2

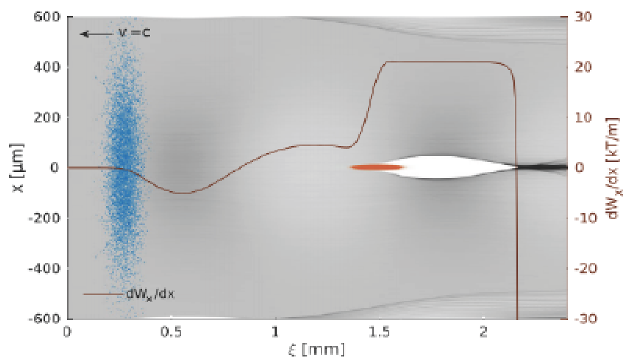
➔**Accelerate an electron beam to high energy** (gradient of 0.5-1GV/m)

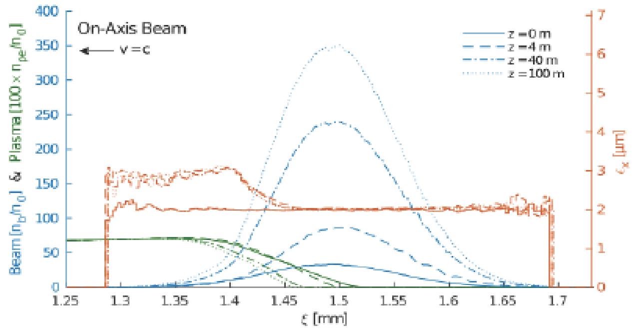
➔**Preserve electron beam quality** as well as possible (emittance preservation at 10 mm mrad level)

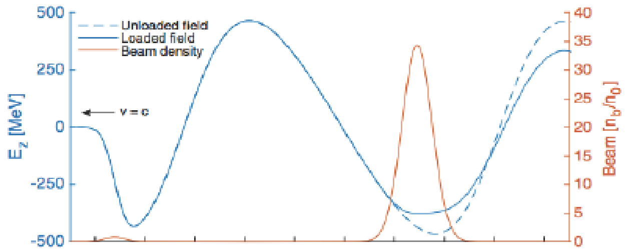
➔**Demonstrate scalability** of the AWAKE concept (R&D plasma sources)

✧Acceleration of an externally injected e⁻ bunch with small final ε and ΔE/E @ GeV

OLSEN, ADLI, and MUGGLI PHYS. REV. ACCEL. BEAMS **21,** 011301 (2018)







<u>Typical parameters</u>:

σ_z=60μm

σ_r=5.25μm

(matched for ε_N=2mm-mrad, n_e=7x10^{14}cm^{-3}, ~$\varepsilon_N^{1/4}$)

Q=100pC

Blow-out and beam loading

~73% charge with $\Delta\varepsilon_N/\varepsilon_N$<5%, ΔE/E~%

✧Challenging parameters to produce with low energy particles (σ_r,σ_z)

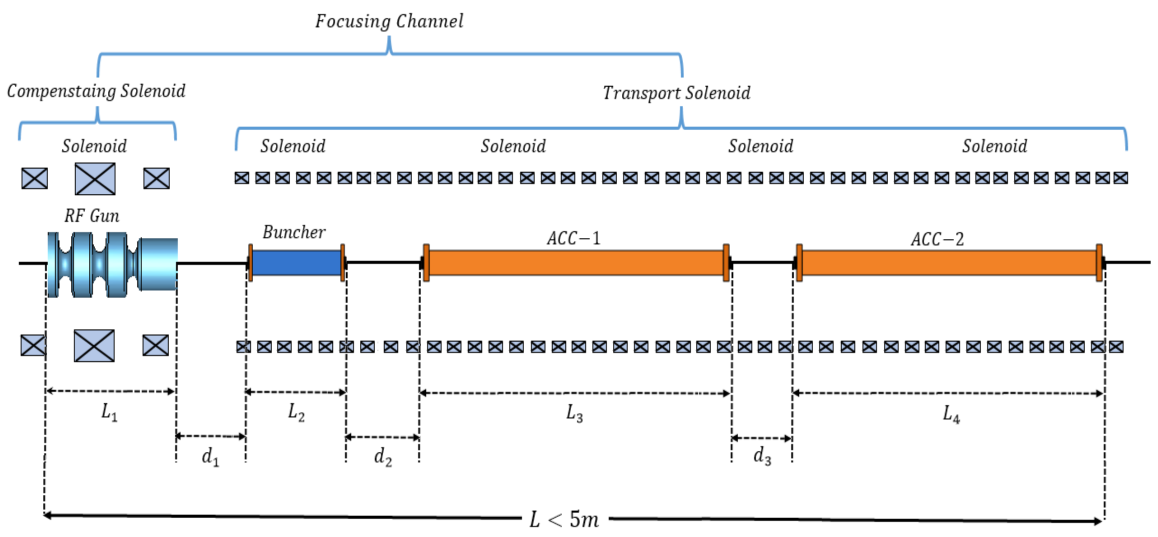
✧Challenging to measure (σ_r)

- AWAKE Run 1: Proof-of-Concept
- AWAKE Run 2: Propose for after CERN Long Shutdown 2: Accelerate electron beam to high energy while preserving beam quality so that it can be used for first physics application.

AWAKE Run 2

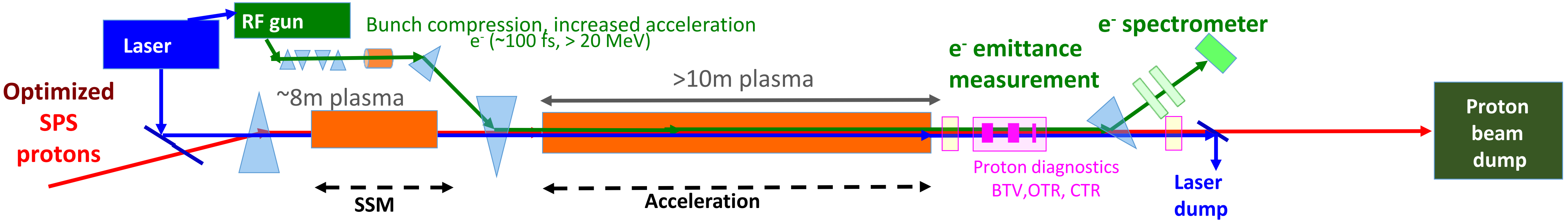
Proposing Run 2 for 2021 after CERN Long Shutdown 2

Proposal: X-band electron source



Preliminary Run 2 electron beam parameters

Parameter	Value
Acc. gradient	>0.5 GV/m
Energy gain	10 GeV
Injection energy	$\gtrsim$ 50 MeV
Bunch length, rms	40–60 μm (120–180 fs)
Peak current	200–400 A
Bunch charge	67–200 pC
Final energy spread, rms	few %
Final emittance	$\lesssim$ 10 μm



E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008)

First Applications

After AWAKE Run 2 and after LS3: get ready for first applications:

Use bunches from SPS with 3.5 E11 protons every ~5sec, electron beam of up to O (50GeV).

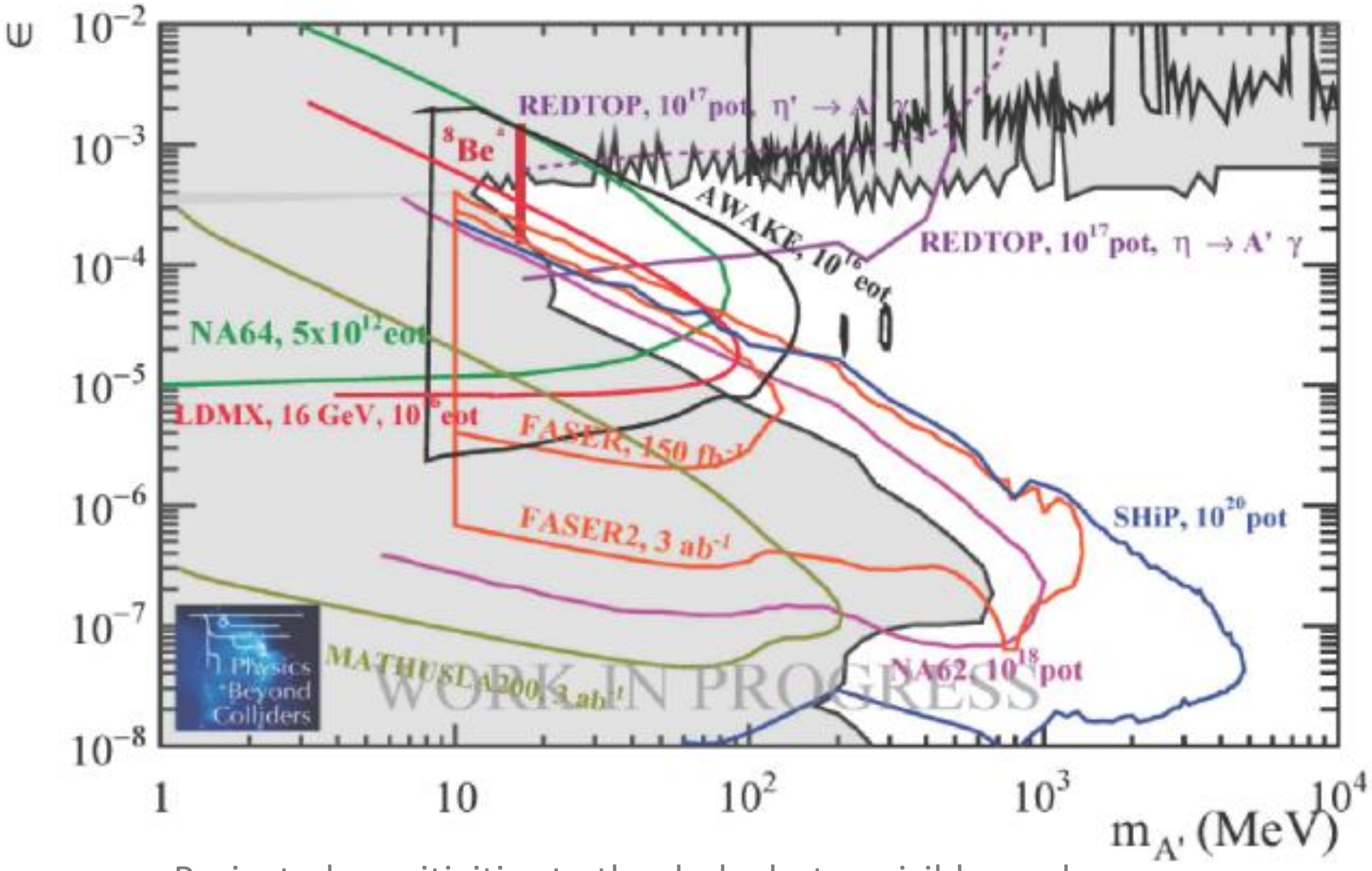
→Fixed target test facility

→Collide with LHC protons/ions

Application: Fixed Target Experiments

→ **Fixed target test facility**: Use bunches from SPS with 3.5 E11 protons every ~5sec,
→ electron beam of up to O (50GeV), **3 orders of magnitude increase in electrons**

→ deep inelastic scattering, non-linear QED, **search for dark photons a la NA64**



Projected sensitivities to the dark photon visible mode

NA64 invisible-like experiment requires tagging of single electrons
→ not compatible with AWAKE time structure

Investigate **visible mode A' → e^+e^-**
→ **fixed target experiment** → compatible with AWAKE time structure

Application: Fixed Target Experiments

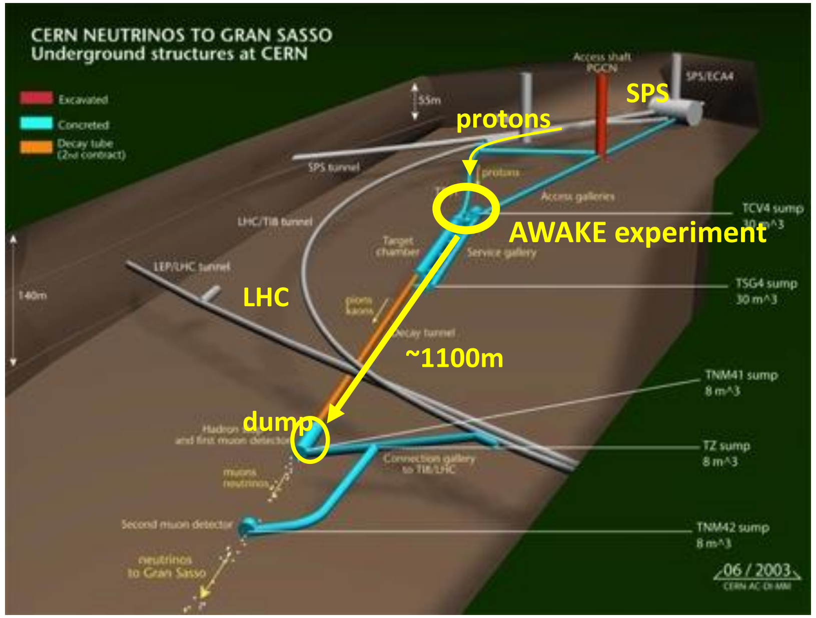
→ **Fixed target test facility**: Use bunches from SPS with 3.5 E11 protons every ~5sec,
→ electron beam of up to O (50GeV), **3 orders of magnitude increase in electrons**

→ deep inelastic scattering, non-linear QED, **search for dark photons a la NA64**

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}

NA64 experiment: ~3×10^{12} electrons on target

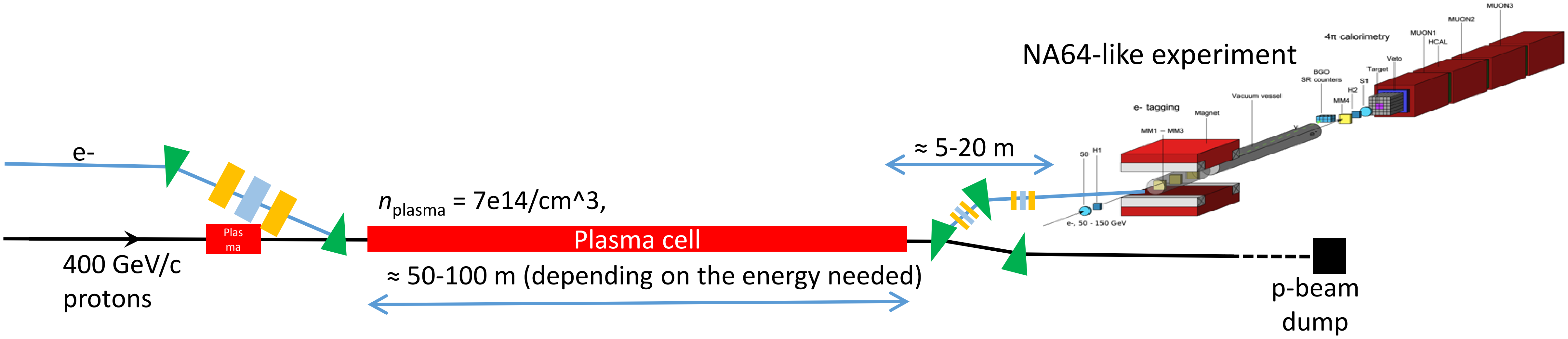
Application: Fixed Target Experiments



Install in the current AWAKE facility, empty old CERN Neutrinos to Gran Sasso Area

Baseline scenario (based on AWAKE Run 2 parameters)

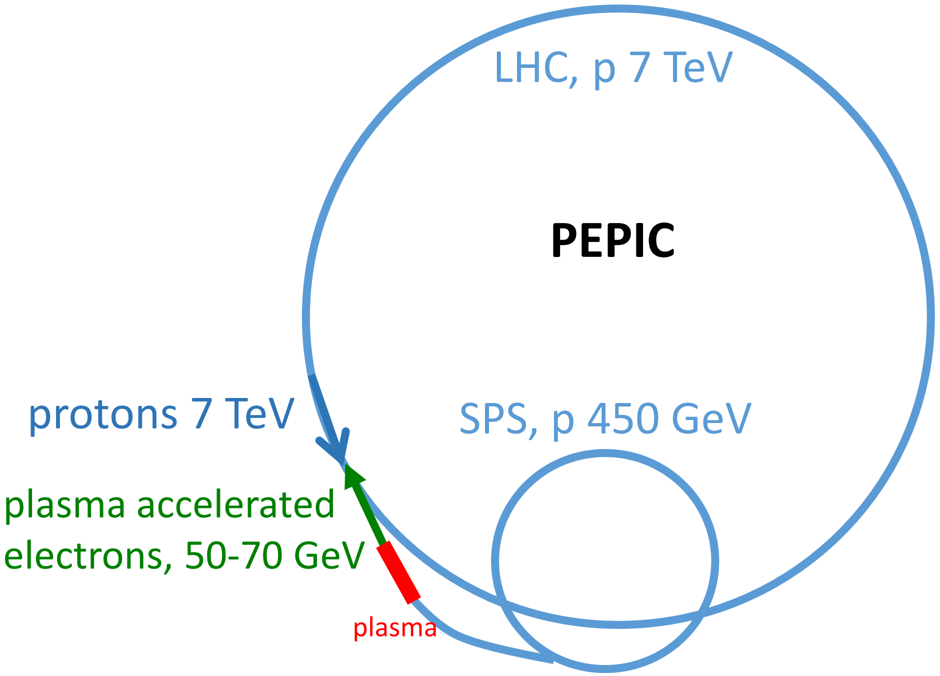
- **50 m** long plasma accelerator
- **33 GeV/c electrons**, **ΔE/E = 2%**, ~**100 pC**
- For 100 m accelerator: 53 GeV/c e, ΔE/E=2%, ~130 pC



Application: Colliders

Using **the SPS or the LHC beam as a driver**, TeV electron beams are possible → Electron/Proton or Ion Collider

- **PEPIC:** LHeC like collider: E_e up to O (70 GeV), colliding with LHC protons → exceeds HERA centre-of-mass energy

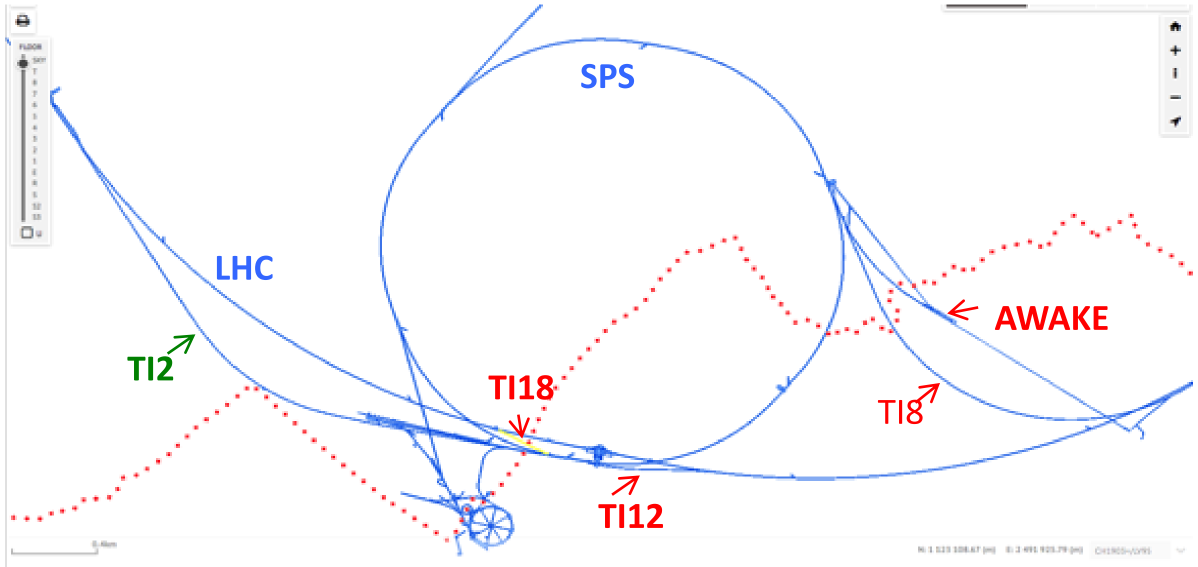


Luminosity << 10^{30} cm^{-2} s^{-1}
→ focus on QCD. → large cross-sections grow with energy → luminosity requirements modest

Possible Locations for PEPIC Plasma Acceleration Stage

- Possible locations for pe- collider experiment would be either ALICE or LHCb.

- Since p beam is produced in the SPS a natural location for the plasma cell(s) would be in one of the transfer tunnels from the SPS to the LHC:
  - TI 12 old e- TL from SPS to LEP: TI12: 275m straight section. Direction opposite to SPS direction.
  - TI 18 old e+ TL from SPS to LEP: 190m straight section. Bend inside SPS→ 4.7T. 40m height difference, slope of 15%.
  - TI 8 SPS -> LHC beam 2: TI8: filled with magnets, 230m straight section, smaller radius than LEP.
  - **TI 2 SPS -> LHC beam 1: TI2: 540m straight section. 18 empty half cells available.**

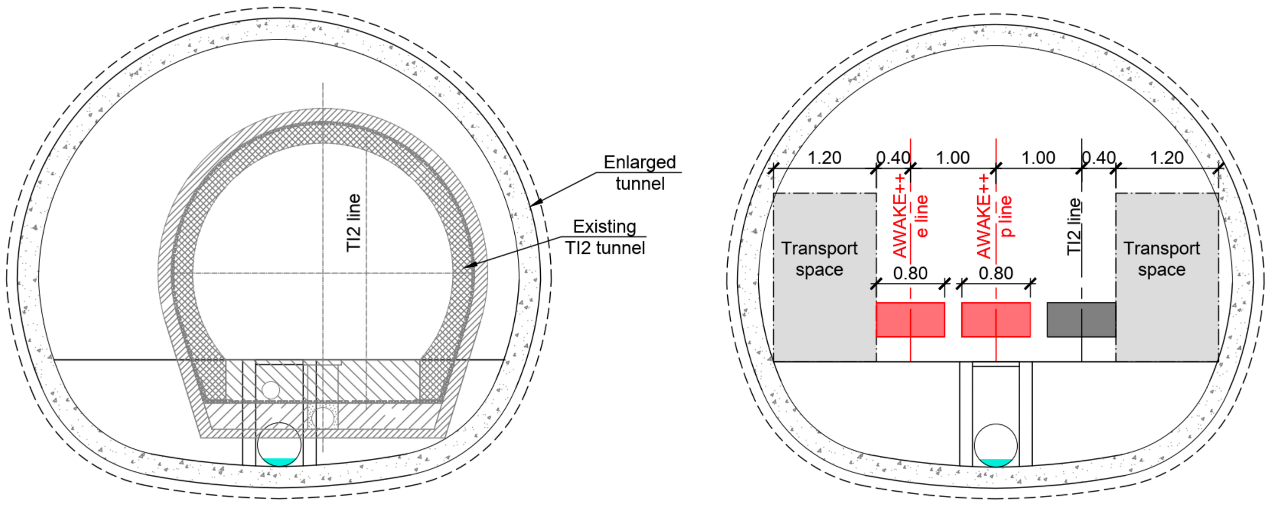


- LHC needs to stay fully operational as pp collider

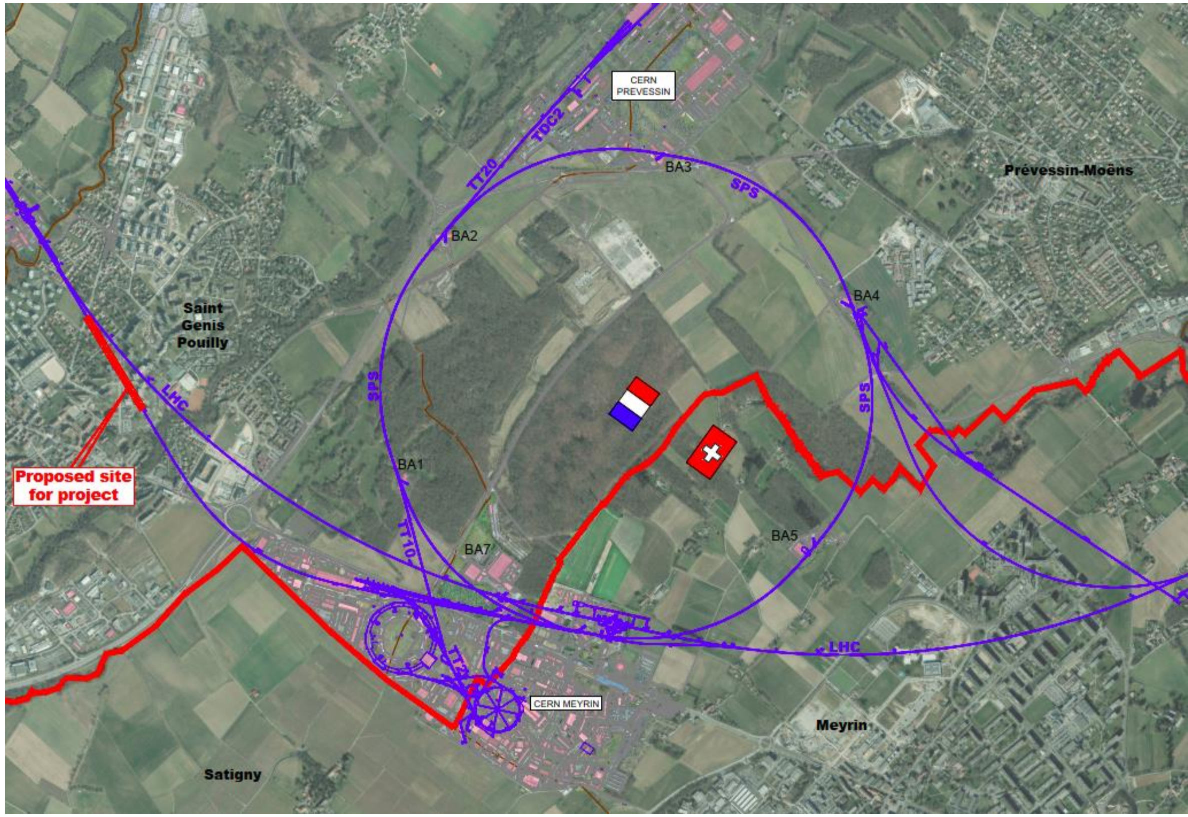
- PEPIC equipment needs to share space with existing equipment in LHC/TI2/TI8

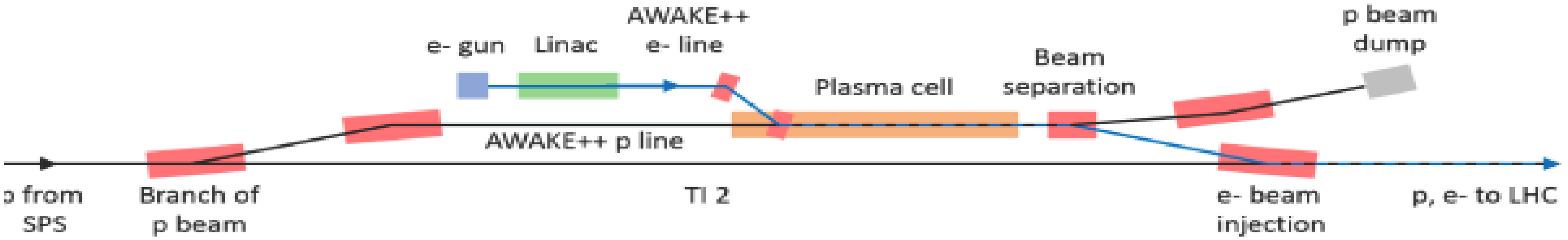
C. Hessler, CERN

PEPIC

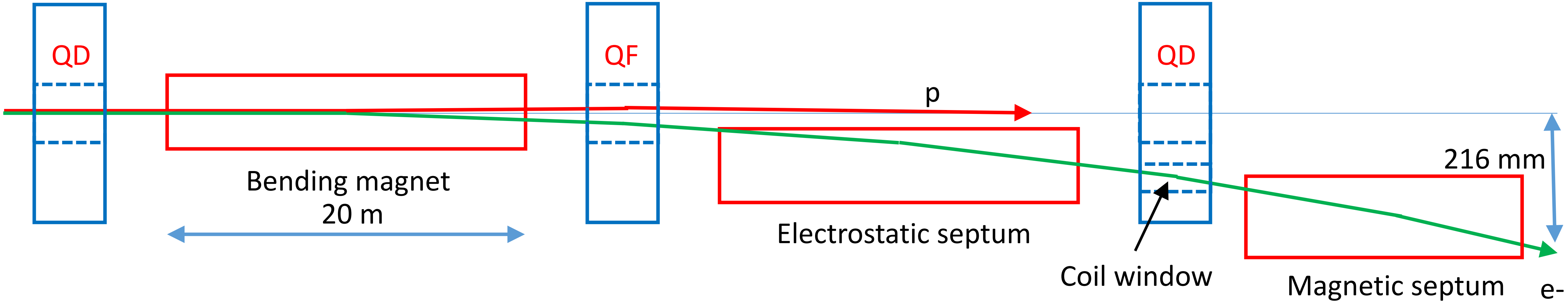


Exisiting and enlarged transfer tunnel





TI 2 Transfer Line for PEPIC



Proposal for separation scheme over multiple half cells

- Focussing quad for p is defocussing for e-
- Reduced energy loss for e- beam and reduced synchrotron radiation power.
- Reduced deflection of p beam. It might be able to transport p beam to TED.

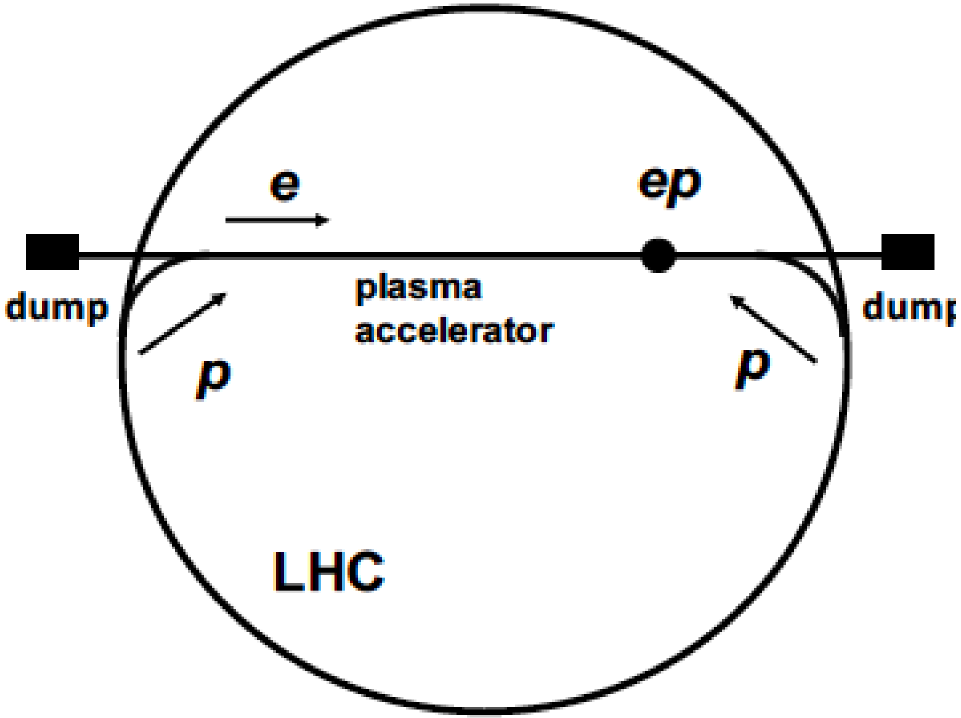
→ **To be further studied in detail**

C. Hessler, CERN

VHeP Collider

Using **the LHC beam as a driver**, TeV electron beams are possible → Electron/Proton or Electron/Ion Collider

- **VHPeC:** choose E_e = 3 TeV as a baseline and with E_P = 7 TeV yields $\sqrt{s}$ = 9 TeV. → CM ~30 higher than HERA. Luminosity ~ $10^{28} - 10^{29}$ cm^{-2} s^{-1} gives ~ 1 pb−1 per year. → Studies on achievable luminosity ongoing.
- Reach in high Q^2 and low Bjorken x extended by ~1000 compared to HERA.



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

Summary

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

→**AWAKE has for the first time demonstrated proton driven plasma wakefield acceleration of externally injected electrons.**

→AWAKE Run 1 was a proof-of-concept experiment. → Done!

→Aim of **AWAKE Run 2** starting 2021 after CERN's Long Shutdown 2 is 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 applications possible in nearer future: Use the AWAKE scheme for **particle physics applications** such as fixed target experiments for dark photon searches and also for future electron-proton or electron-ion colliders.