# Status and plans of the AWAKE experiment

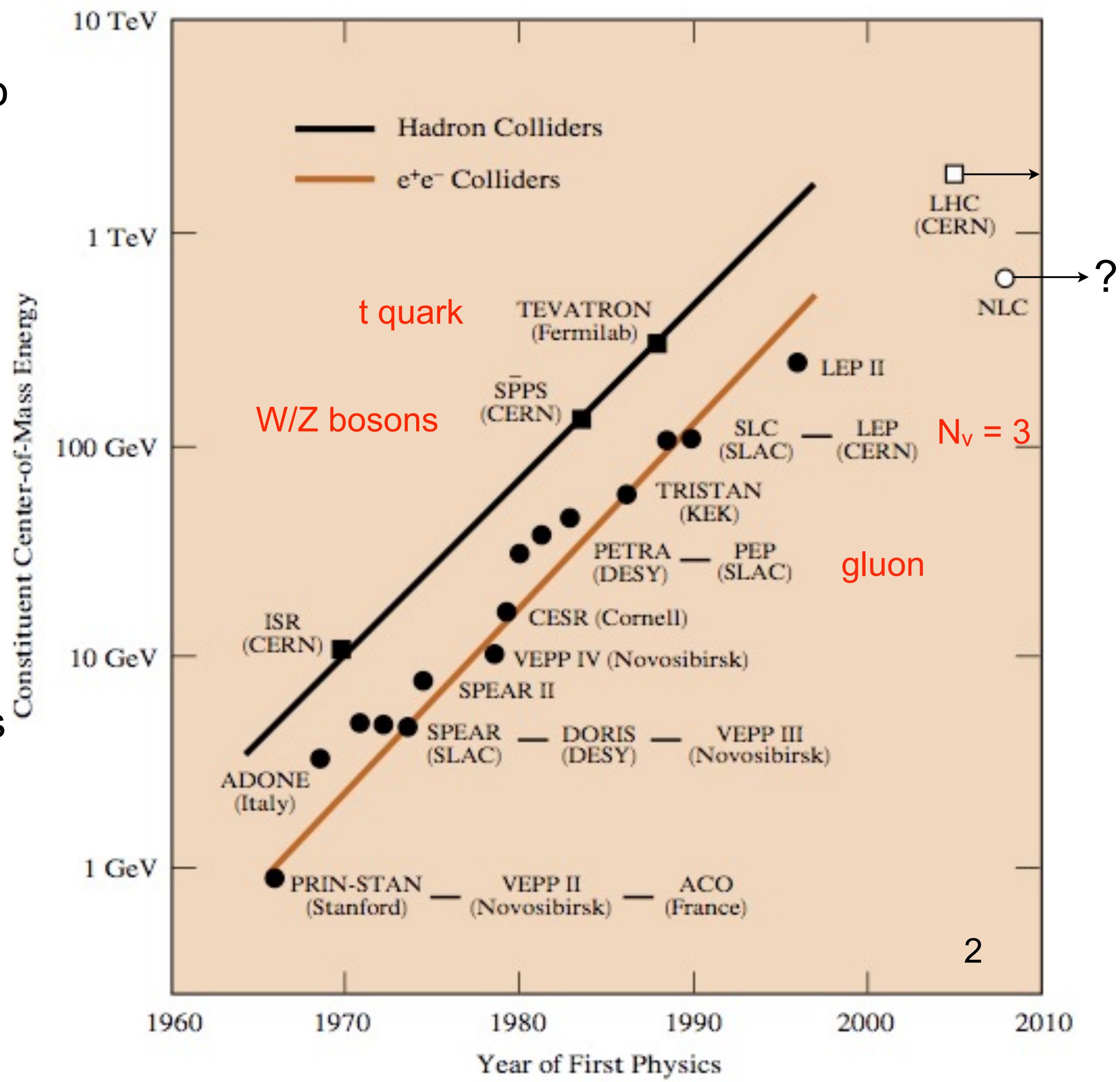
Matthew Wing (UCL)
on behalf of the AWAKE Collaboration

- Motivation and introduction to plasma wakefield acceleration
- The AWAKE experiment
- Selection of AWAKE results
  - Self-modulation of proton bunch
  - Acceleration of electrons in wakefields
- AWAKE plans
- Summary

CERN SPSC Annual Review — 16 October 2018

# Motivation: colliders

- The use of (large) accelerators has been crucial to advances in particle physics.
- Culmination in *27-km* long LHC (*pp*); e.g. a future *e⁺e⁻* collider planned to be *30–50-km* long.
- The high energy frontier is (very) expensive; can we reduce costs ? Can we develop and use new technologies ?
- Accelerators using RF cavities limited to *~100 MV/m*; high energies → long accelerators.
- The Livingston plot shows a saturation …



# Plasma wakefield acceleration as a solution

• Plasma wakefield acceleration is a promising scheme as a technique to realise shorter or higher energy accelerators in particle physics.

• Accelerating gradients achieved in the wakefield of a plasma are very high.

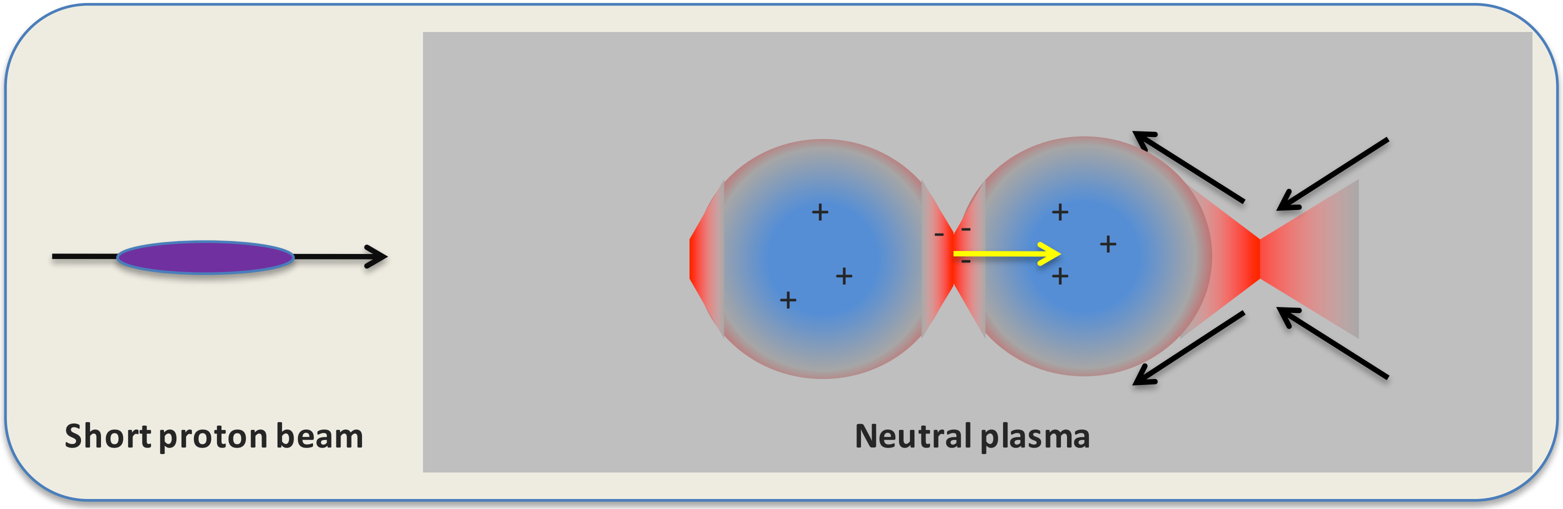
• Using lasers or electron bunches have achieved up to 3 orders of magnitude more than RF acceleration and up to *100 GV/m.*

• What about using proton bunches as the driver ?  Higher stored energy, ability to drive wakefields over long lengths.

• Proton-driven plasma wakefield acceleration is well-suited to high energy physics applications.

• Ultimate goal : can we have *TeV* electrons produced in an accelerator structure of a few *km* in length ?

# Plasma wakefield acceleration



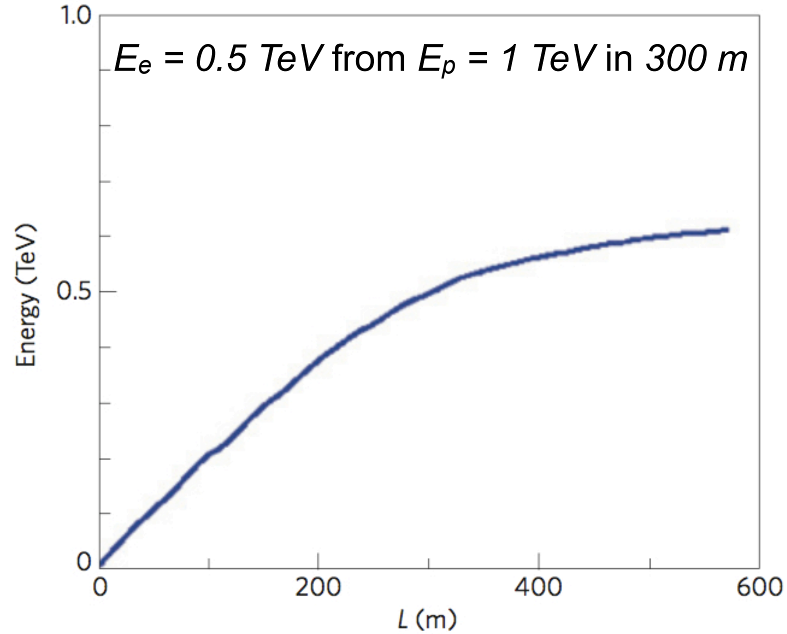

- Electrons ‘sucked in’ by proton bunch, continue across axis creating depletion region
- Oscillation of plasma electrons creates strong electric fields
- Longitudinal electric fields can accelerate particles in direction of proton bunch
- Transverse electric fields can focus particles
- **A ‘witness’ bunch of e.g. electrons placed appropriately can be accelerated by these strong fields**
- **High gradients with :**
  - **Short drive beams**
  - **Bunches with large number of particles**

# Why protons ?

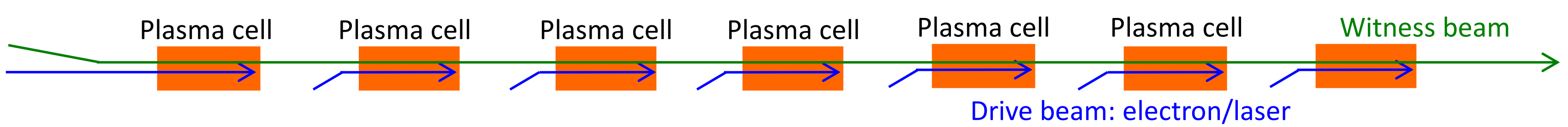
- Lasers and electron bunches do not have enough energy :
  - Can not propagate long distances in plasma
  - Can not accelerate electrons to high energy
  - For high energy, need multiple stages.

- Proton beams at TeV scale and with high stored energy are around today : what about using protons ?

A. Caldwell *et al.*, Nature Phys. **5** (2009) 363.




## Laser/electron driver

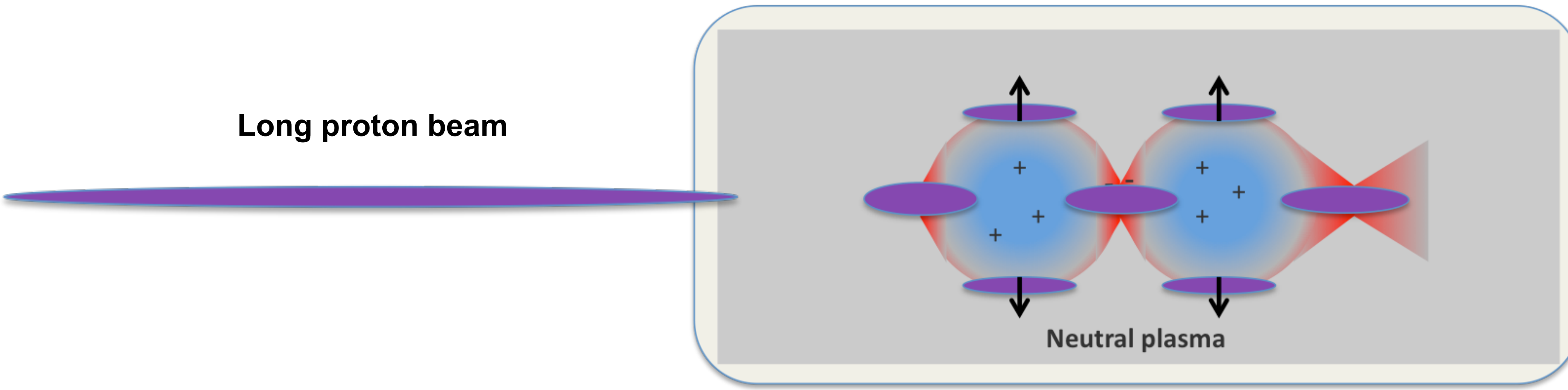



## Proton driver

# Long proton bunches ?

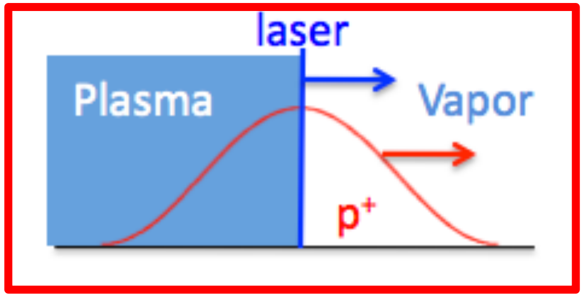
Use self-modulation where micro-bunches are generated by a transverse modulation of the bunch density.

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




Self-modulated driver beam

- Micro-bunches are spaced $\lambda_p$ apart and have an increased charge density.
- Micro-bunches constructively reinforce to give large wakefields, *GV/m*.
- **Seeded self-modulation allows current beams to be used.**



# The AWAKE experiment

# AWAKE Collaboration

18+4 institutes worldwide

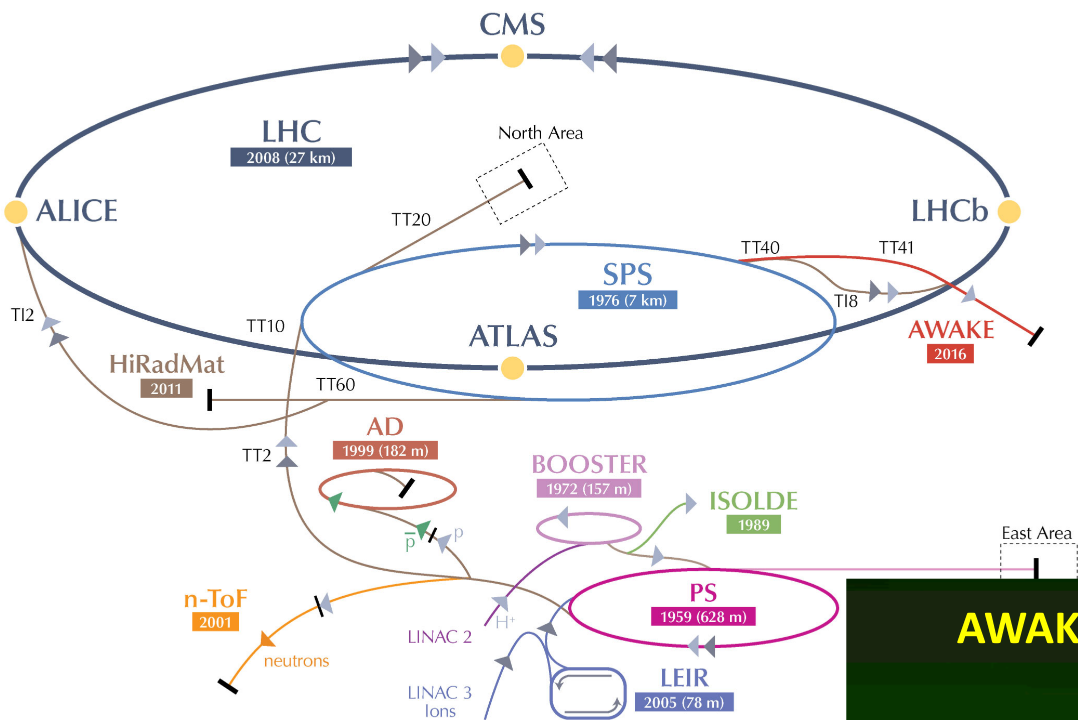
**Collaboration members:**

- 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

**Associate members:**

- University of Wisconsin, Madison, US
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL
- Xi’an Jiaotong University, China

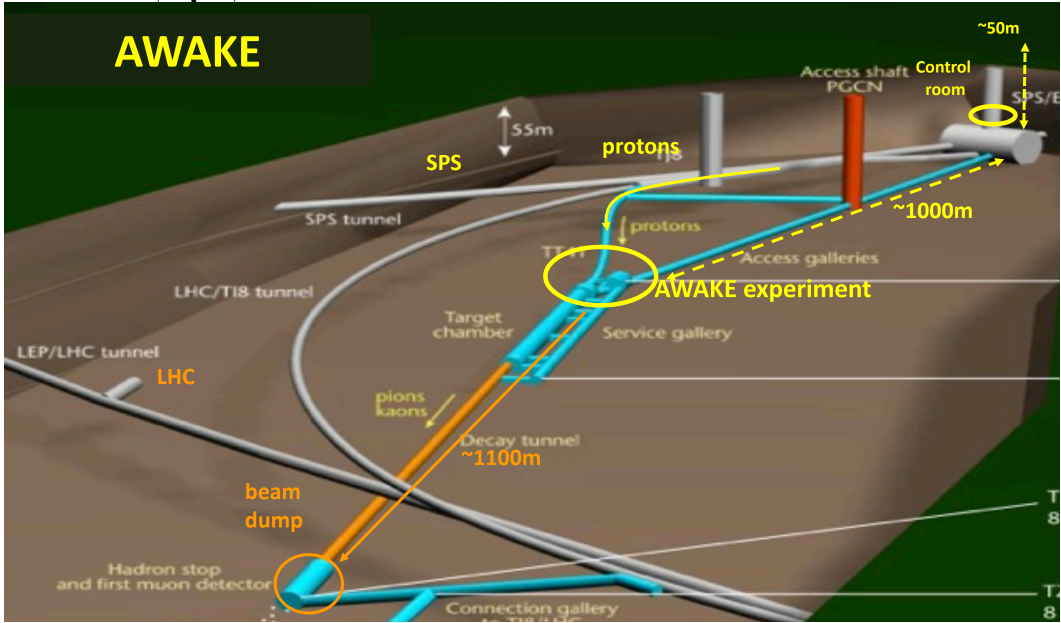
# AWAKE experiment at CERN




Demonstrate for the first time proton-driven plasma wakefield acceleration.

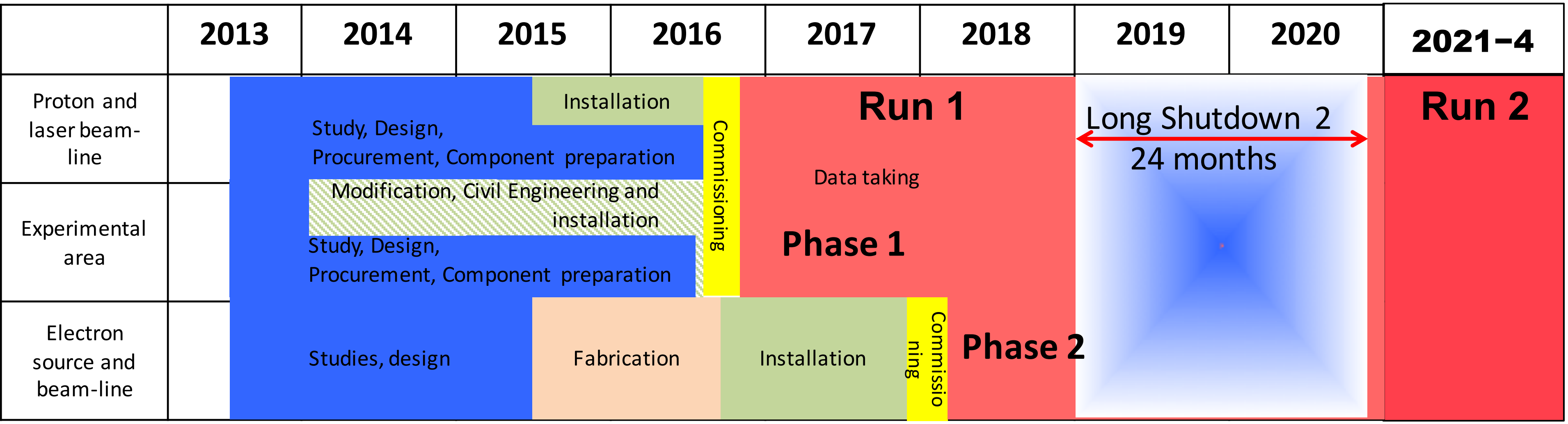
Advanced proton-driven plasma wakefield experiment.

Using *400 GeV* SPS beam in former CNGS target area.



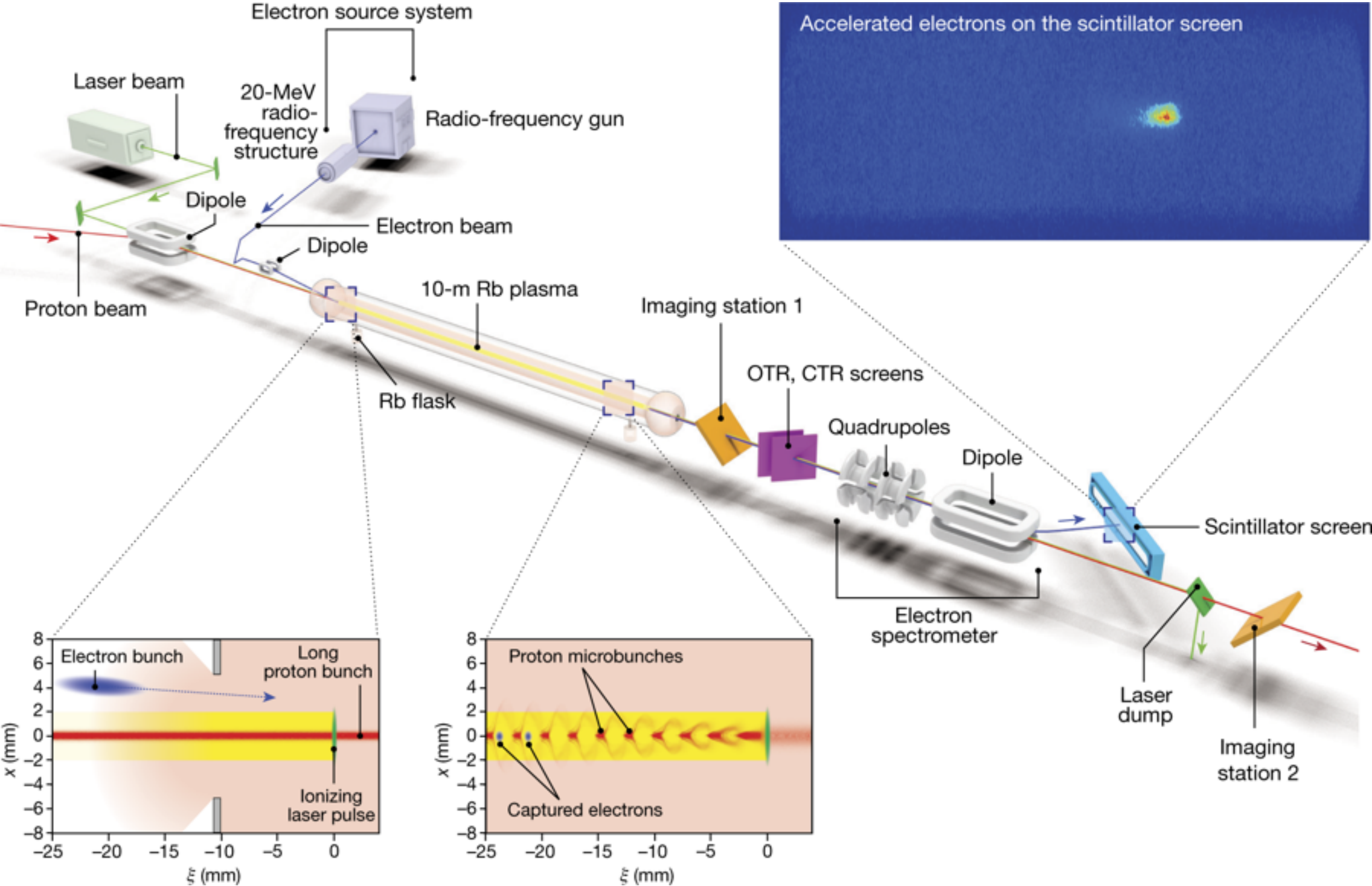

AWAKE Coll., Plasma Phys. Control. Fusion **56** (2014) 084013; Nucl. Instrum. Meth. **A 829** (2016) 3; Nucl. Instrum. Meth. **A 829** (2016) 76.

# AWAKE physics and timeline




- AWAKE was approved as a CERN project in August 2013.
- Demonstrate and understand self-modulation of long proton bunch [2016−8].
- Sample high-gradient wakefields with electron bunch and accelerate to *O*(GeV) [2018].
- AWAKE Run 2 [2021−4].

# AWAKE schematic



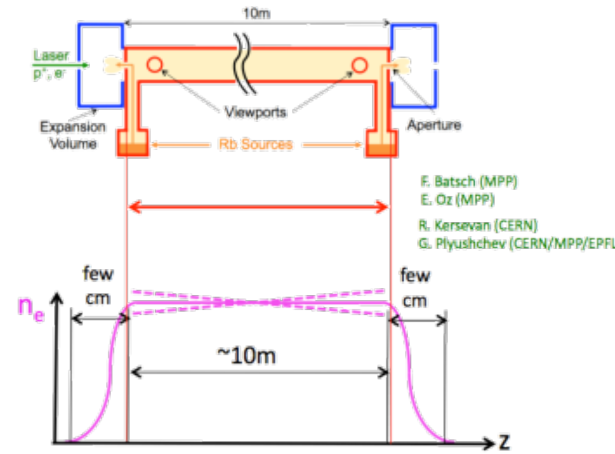
# AWAKE proton beam

| Parameter | Protons |
|---|---|
| Momentum (GeV) | 400 |
| Momentum spread (GeV) | 0.14 |
| Particles per bunch | $3 \times 10^{11}$ |
| Charge per bunch (nC) | 48 |
| Bunch length (mm) | 120 (0.4 ns) |
| Norm. emittance (mm mrad) | 3.5 |
| Repetition rate (Hz) | 1/30 |
| Spot size at focal point (μm) | 200 ± 20 |


750 m proton beam line

# AWAKE plasma cell

- 10 m long, 4 cm diameter
- Rubidium vapour, field ionisation threshold ~$10^{12}$ W/cm$^2$
- Density adjustable $10^{14} - 10^{15}$ cm$^{-3}$.
- System heated to about 220 C, need density uniformity of better than 0.2%.




**Plasma cell has been stable and reliable with uniform density.**

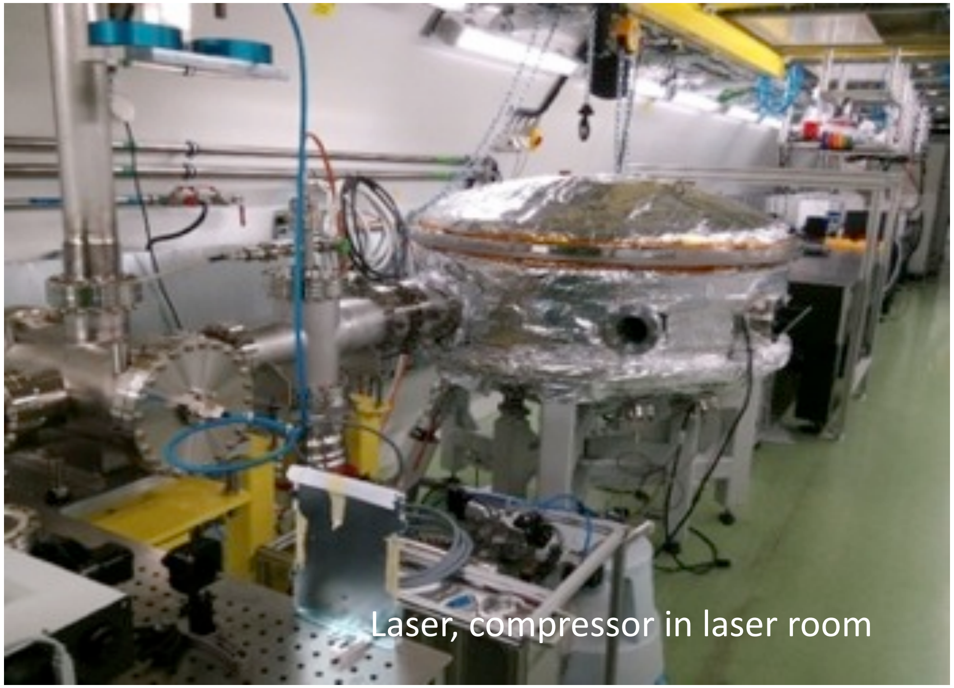
# Laser

Ti:sapphire laser needed for:

- Ionising vapour and seeding self-modulation in plasma.
- Diagnostic beam line.
- Beam to electron source.

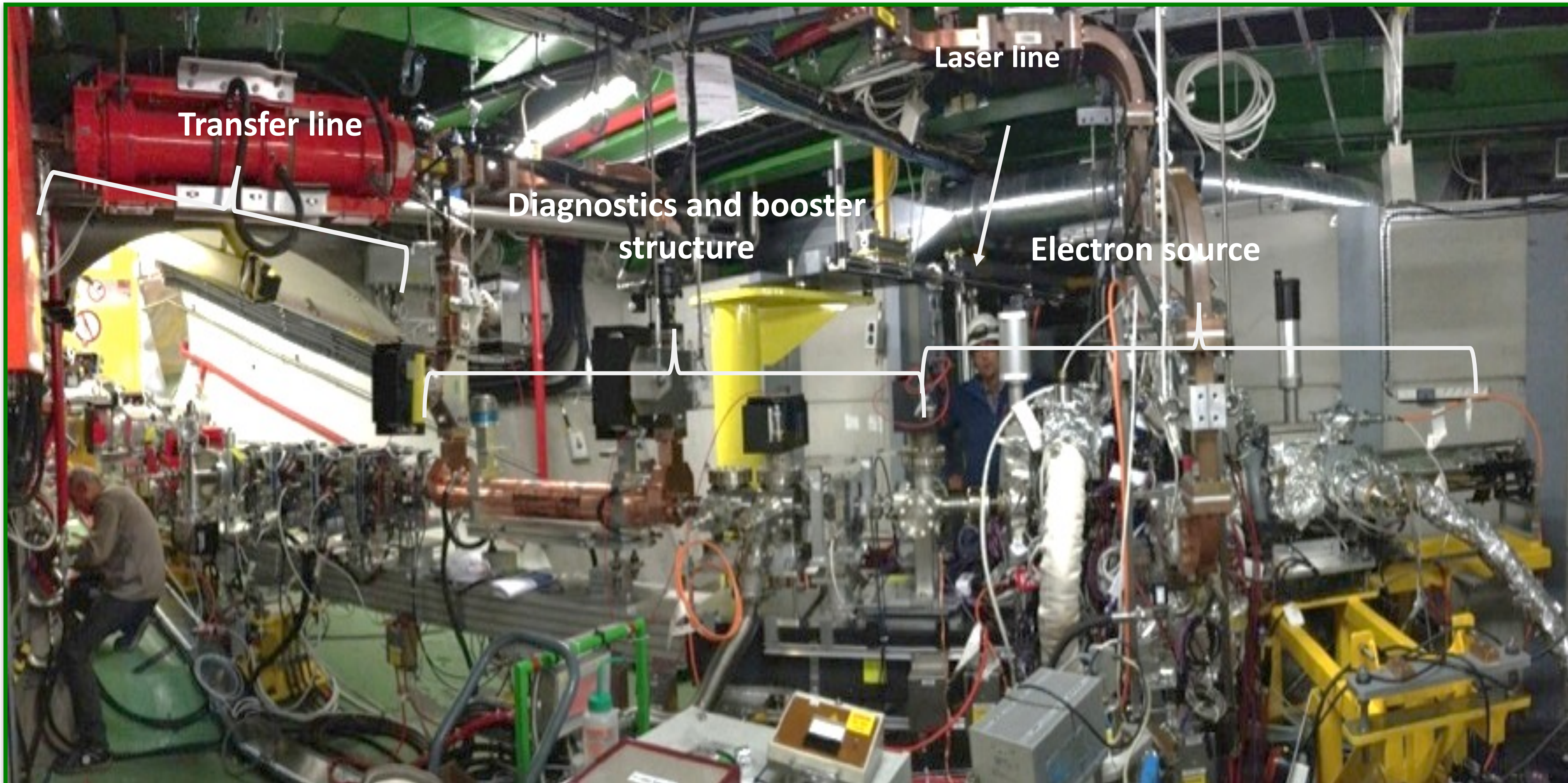
| Parameter | Value |
|---|---|
| Central wavelength (nm) | 780 |
| Pulse length (fs) | 120 |
| Maximum energy (mJ) | 450 |
| Focused size (mm) | 1 |

**Performance of laser through 2018 generally very good.**



Laser, compressor in laser room

# Electron beam

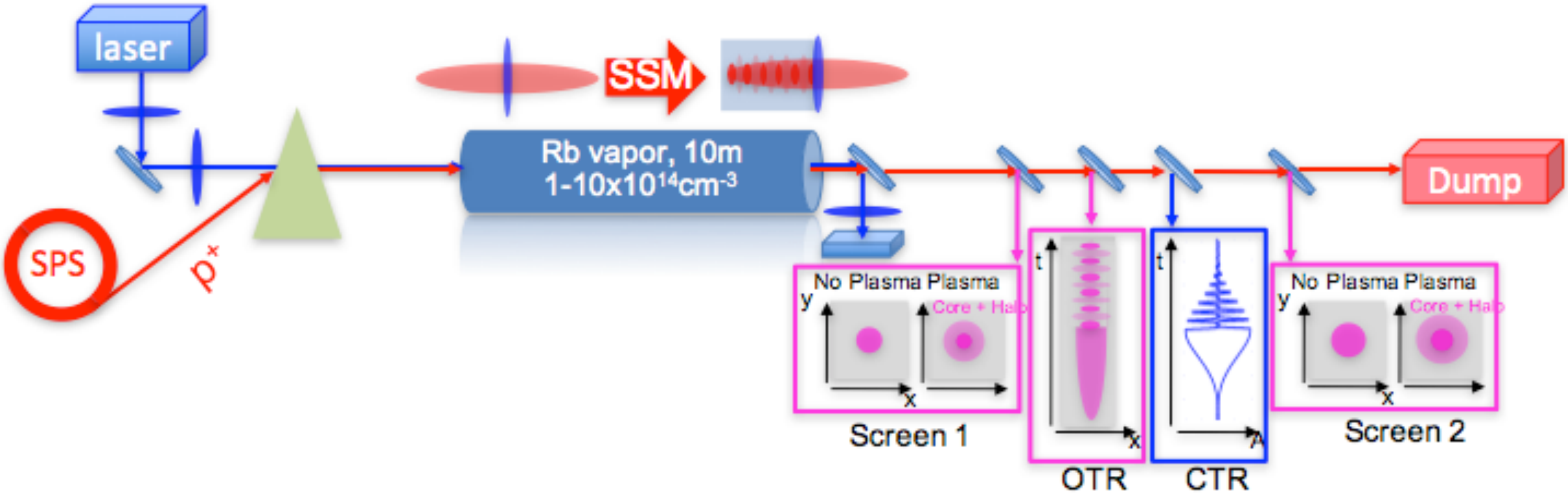



- Electron bunch of ~650 pC, σ ~ 2 ps
- Produced at 5.5 MeV
- Accelerated up to 20 MeV
- 18 m beam line to plasma cell

# Self-modulation of proton bunch

# Proton micro-bunching

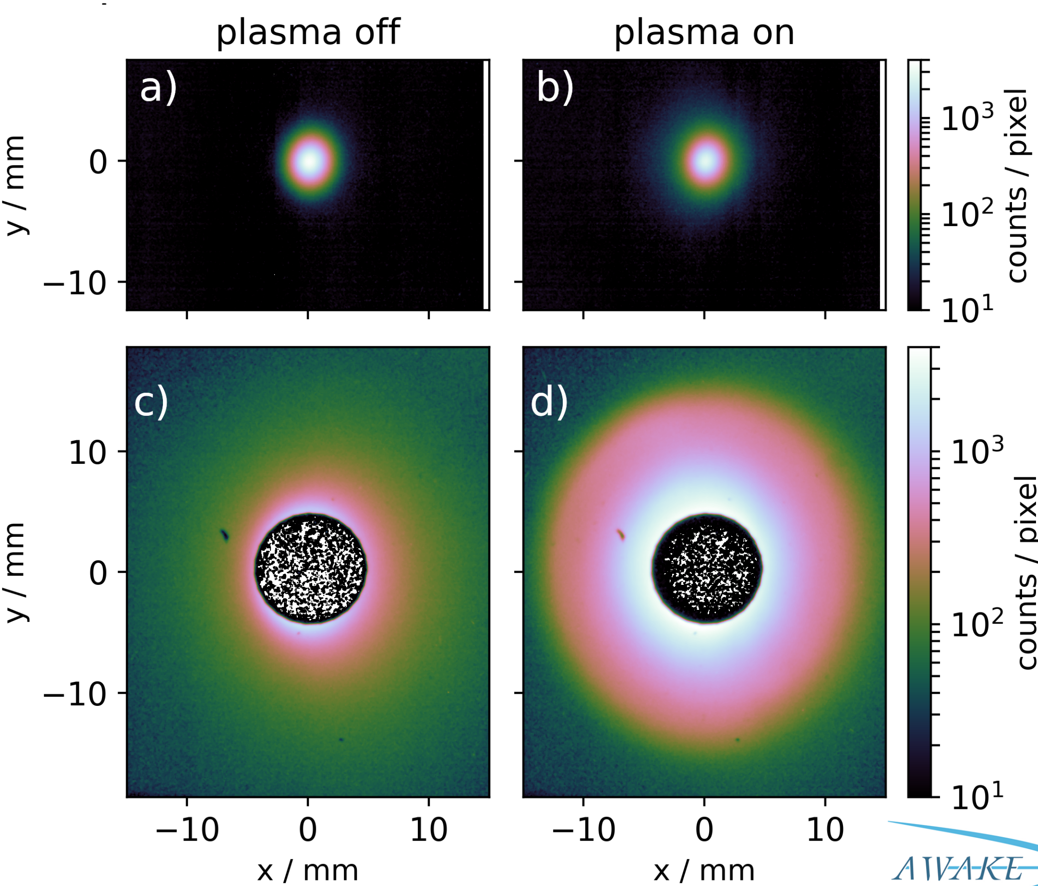
**Phase 1: understand the physics of self-modulation process in plasma**

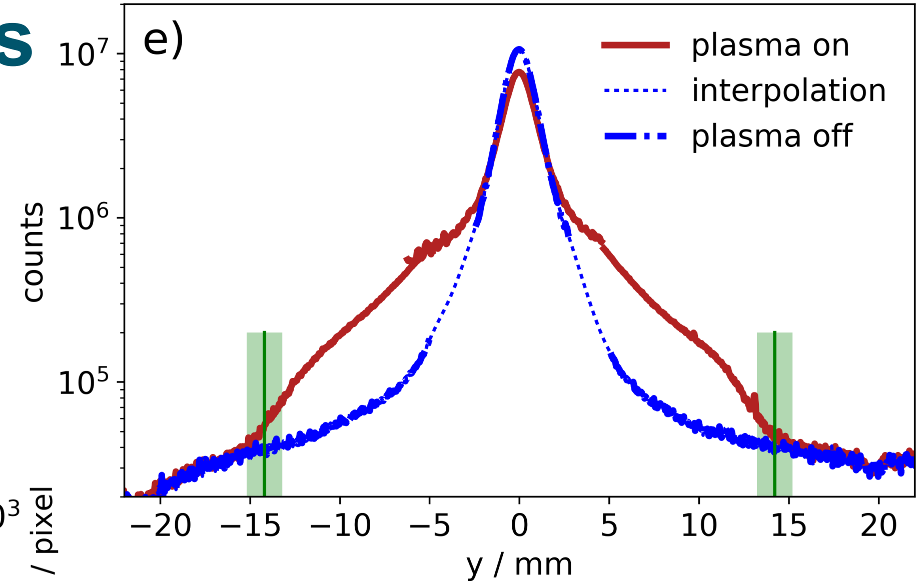



- Started with physics in Q4/2016 and continued through 2017−8.
- Various beam diagnostics to characterise proton beam and its modulation
  - Indirect measurement using two screens to measure transverse profile.
  - Direct measurements of modulation, i.e. micro-bunch structure through measuring transition radiation.

# Beam halo measurements

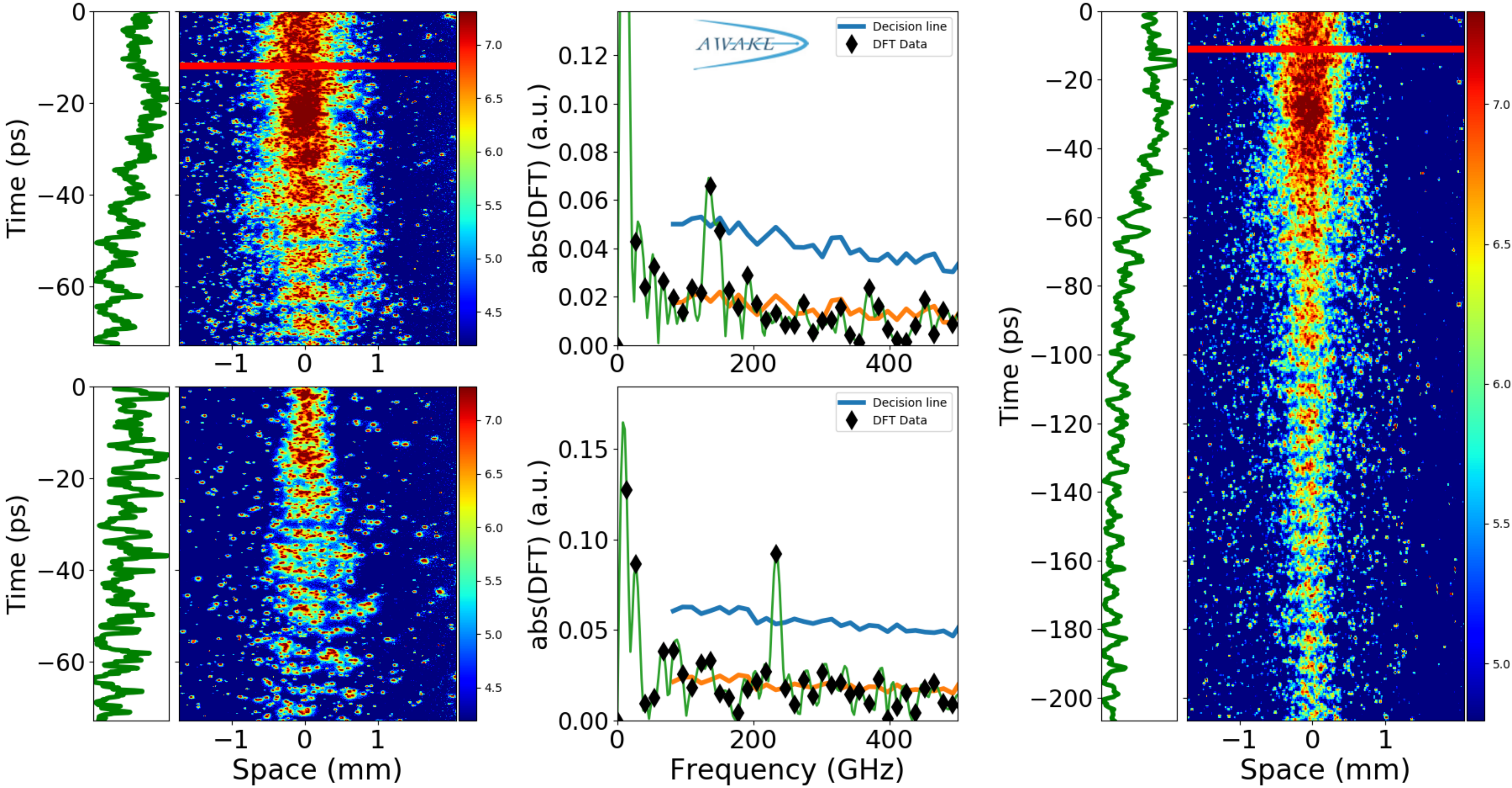
- Clear defocusing of proton bunch.
- Effect shows presence of strong transverse electric fields.



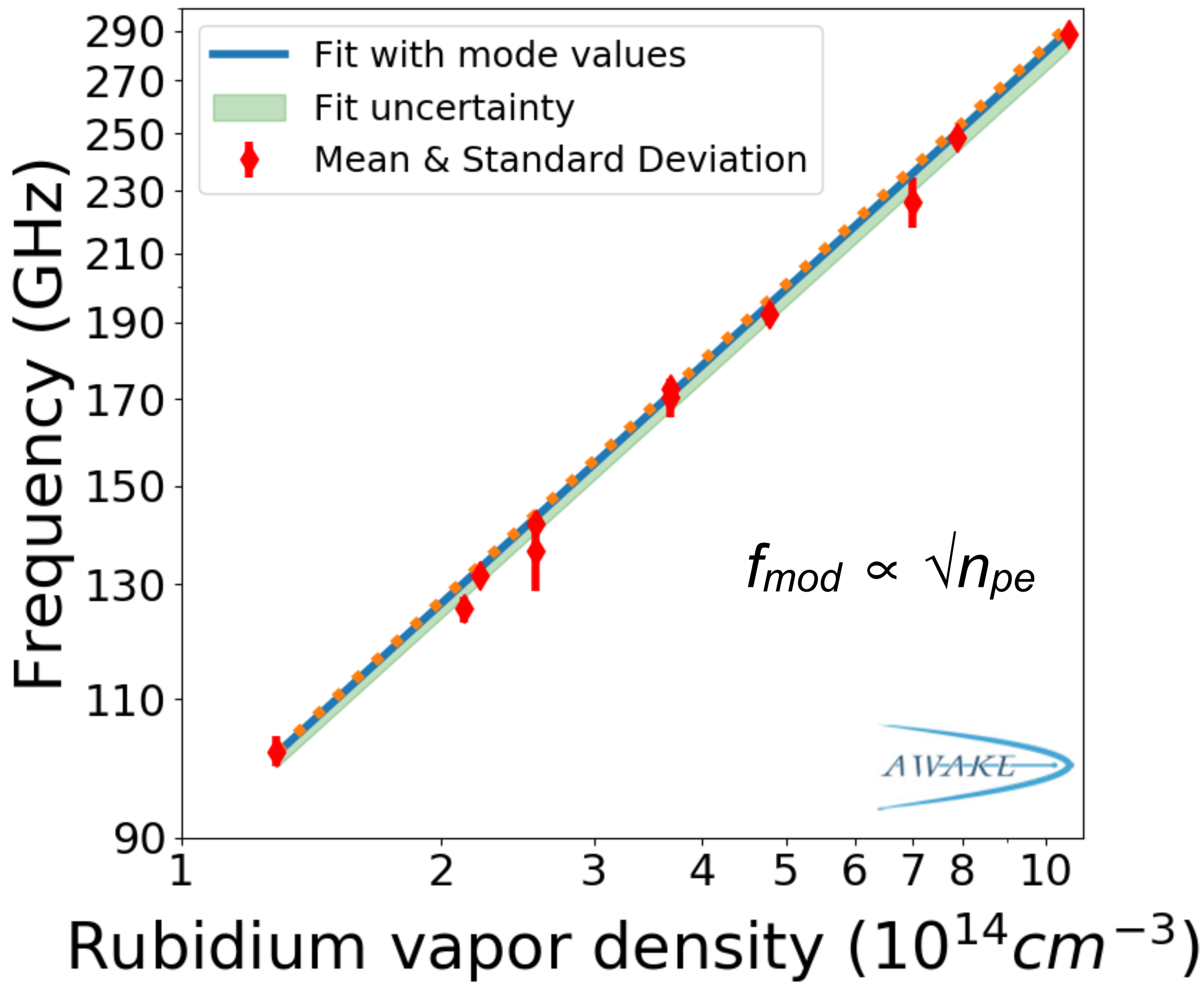

AWAKE Coll., M. Turner et al. “Experimental observation of plasma wakefield growth driven by the seeded self-modulation of a proton bunch”, arXiv:1809.01191, submitted to *Phys. Rev. Lett.*

# Self-modulation of proton bunch




AWAKE Coll., E. Adli et al., “Experimental observation of proton bunch modulation in a plasma at varying plasma densities”, arXiv:1809.04478, submitted to *Phys. Rev. Lett.*

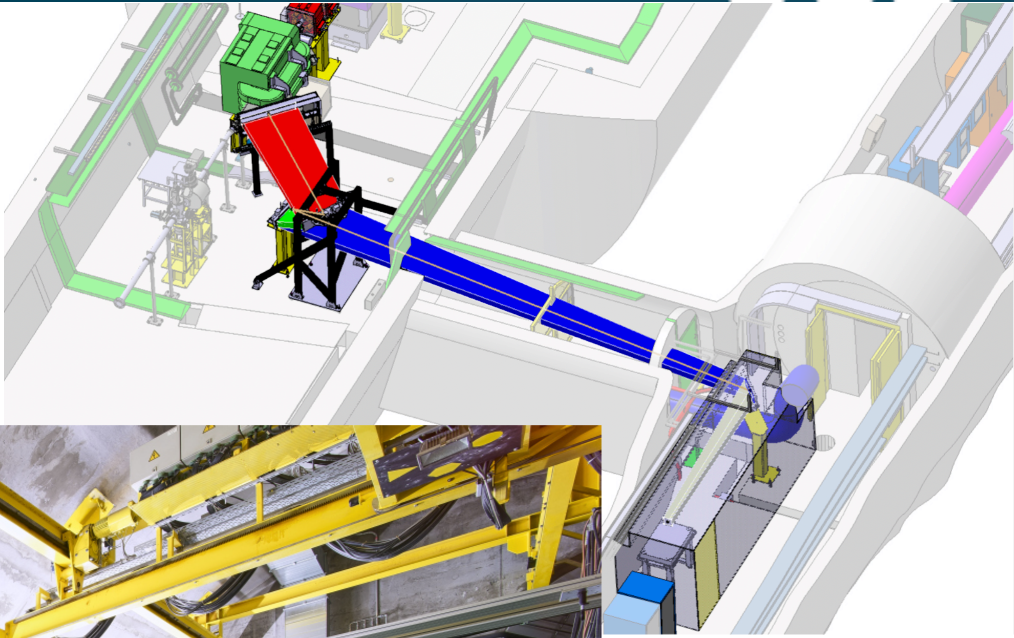
# Self-modulation of proton bunch



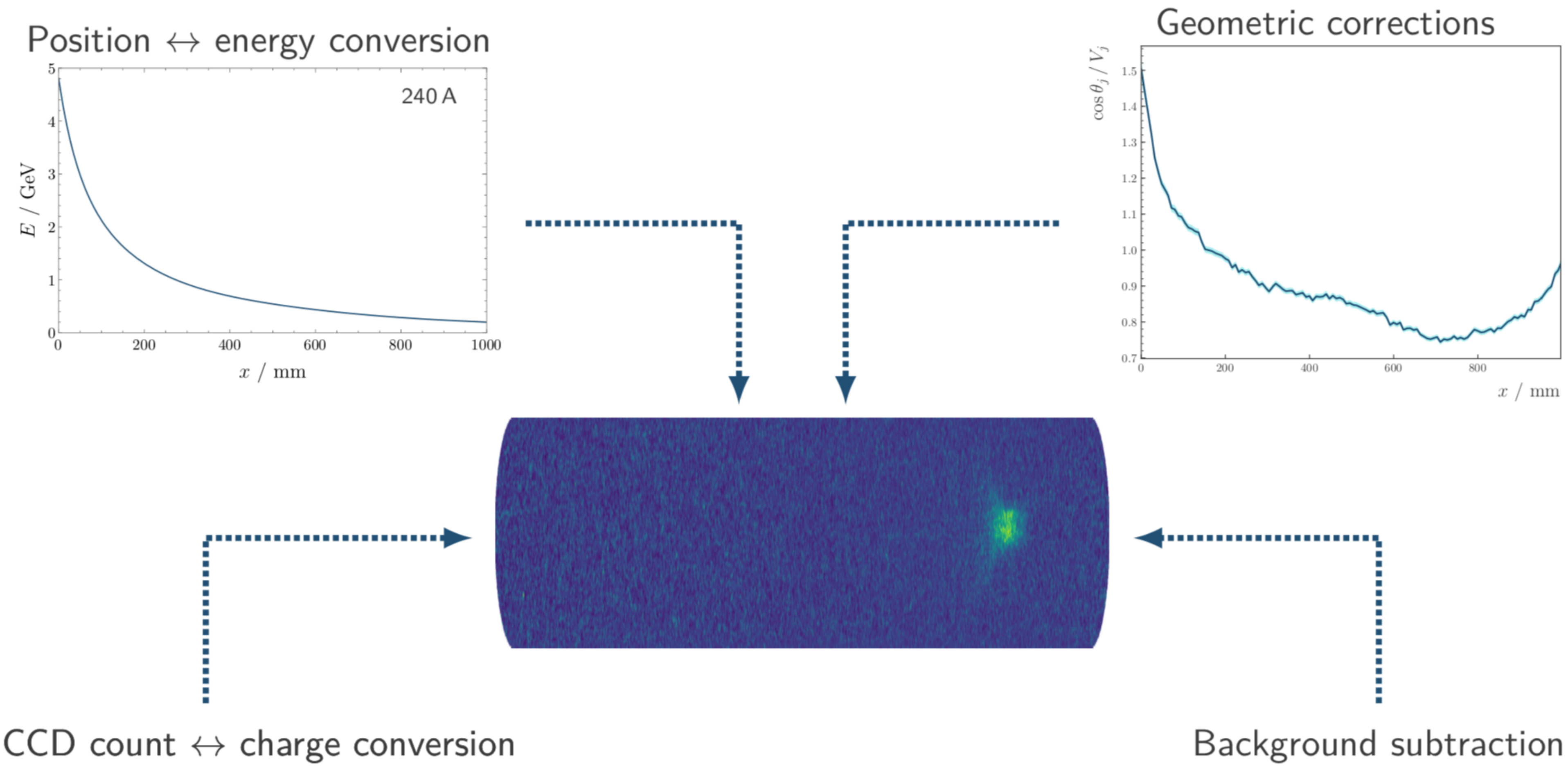

**Seeded self-modulation frequency dependency on plasma density scales with expected square root of density.**

# Electron acceleration

# AWAKE spectrometer

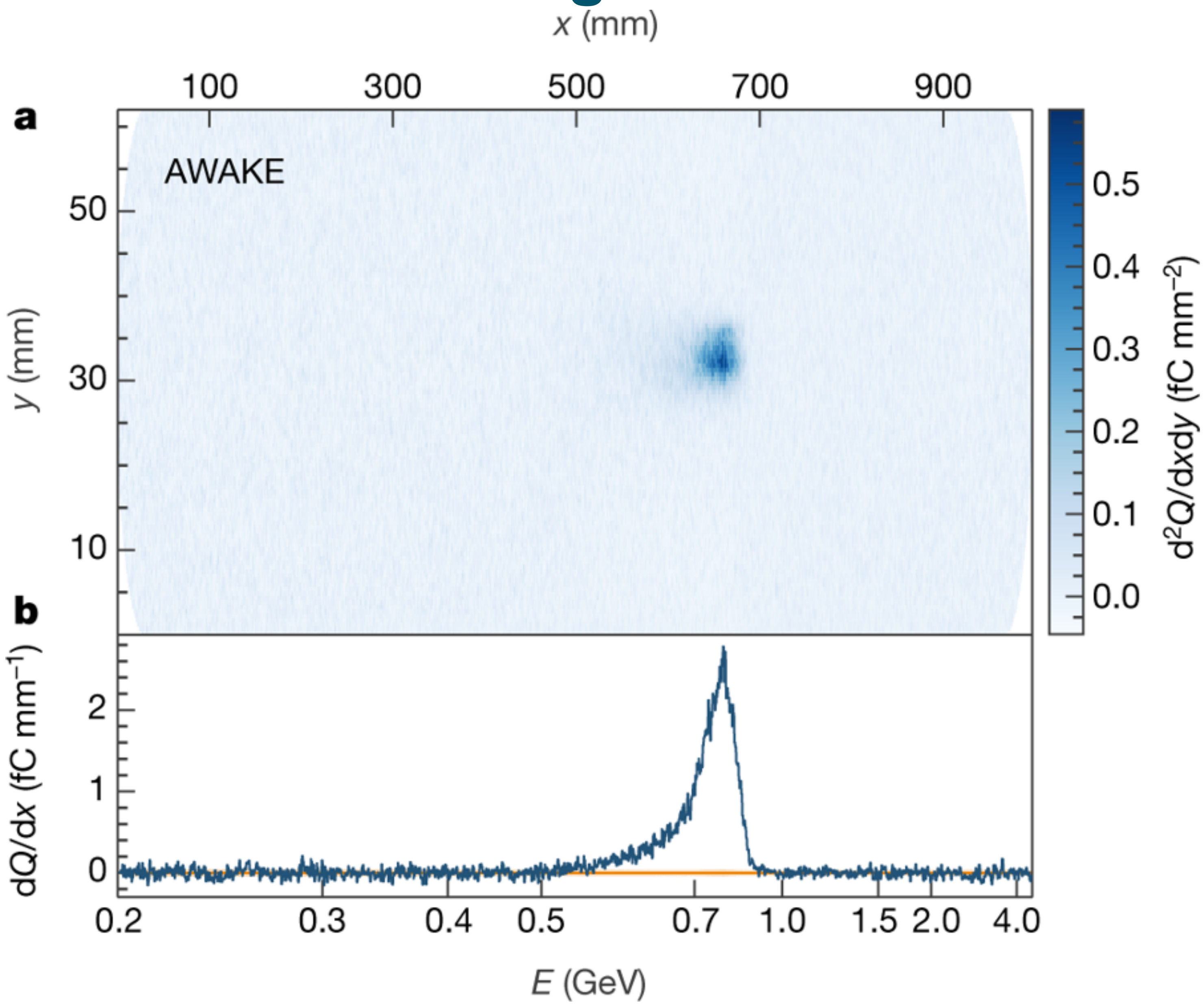


# Spectrometer analysis

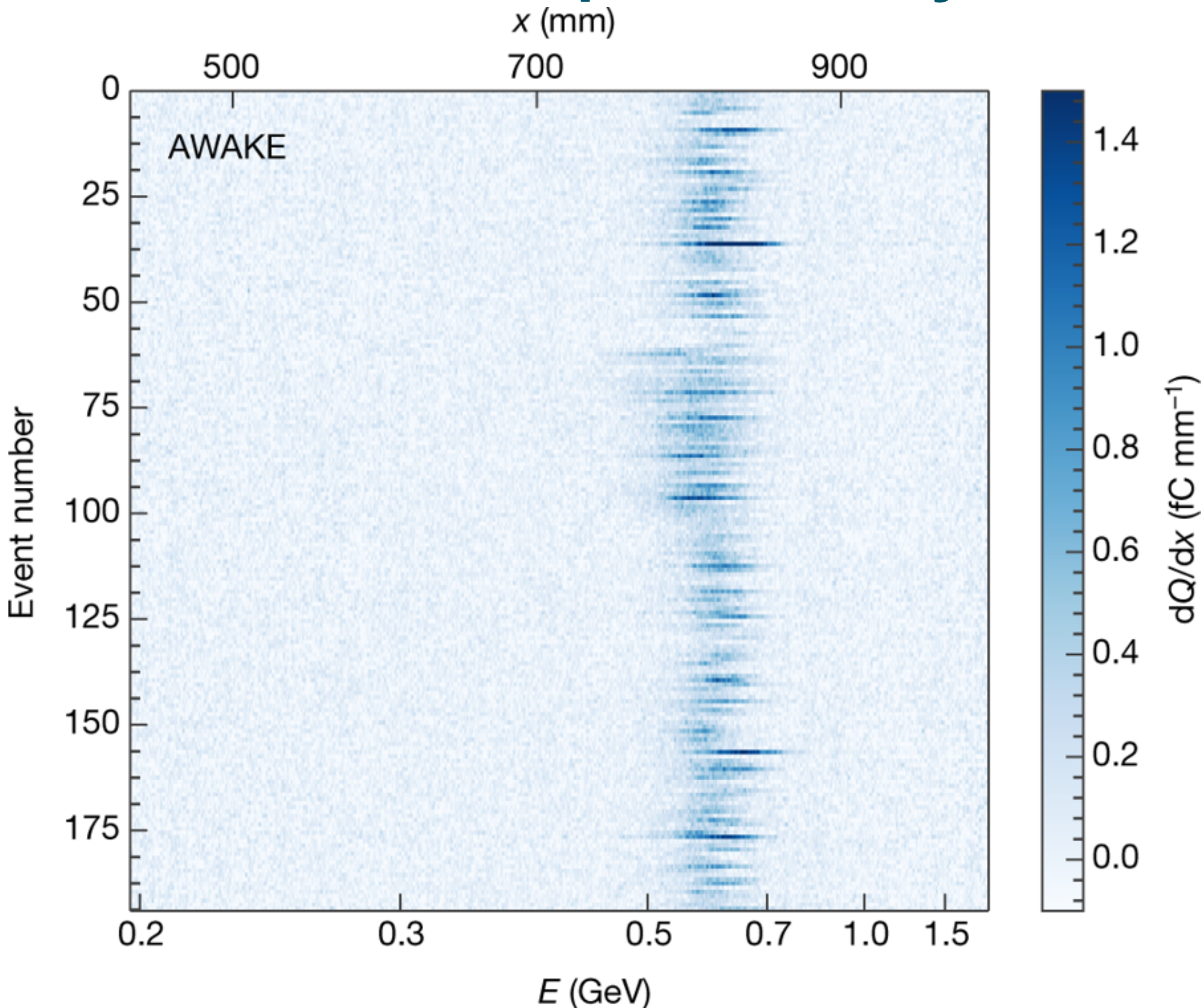



AWAKE Coll., E. Adli et al., “Acceleration of electrons in the plasma wakefield of a proton bunch”, arXiv:1808.09759, *Nature* **561** (2018) 363.

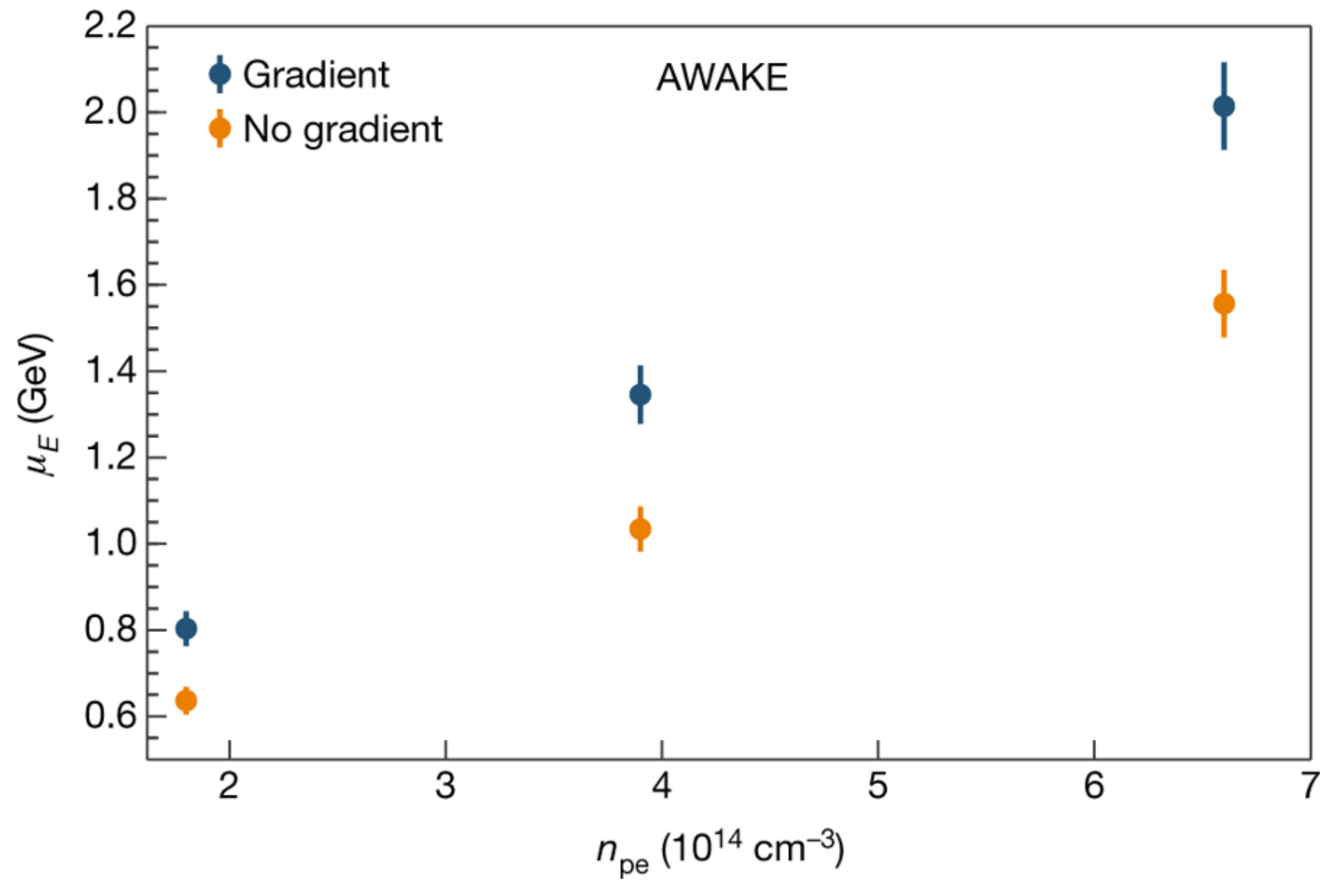
# Electron acceleration signal



# Electron acceleration reproducibility



# Electron acceleration energy dependence

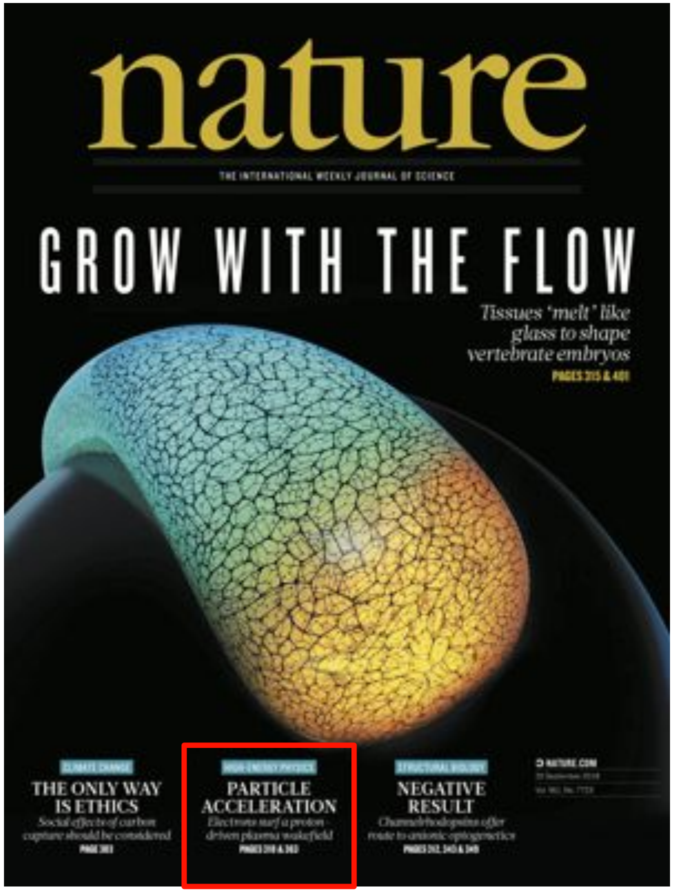



- Acceleration to 2 GeV is a great achievement..
- Simulation/theory predicted similar energy gains.
- Experiment not optimised for electron injection.
- Accelerated charge (~0.25 pC) is low; looking at ways to increase.

# Electron acceleration paper

- Data taken on 26 May.
- Submitted to Nature on 22 June.
- Accepted by Nature on 14 August.
- Published online on 29 August.
- In print on 20 September.

- Significant media attention appearing in the regular press as well as scientific press.




"*And once again, thanks ever so much for coming to us with this paper… it is one that we are exceptionally proud to have published!*", *Nature* Physical Sciences Editor.

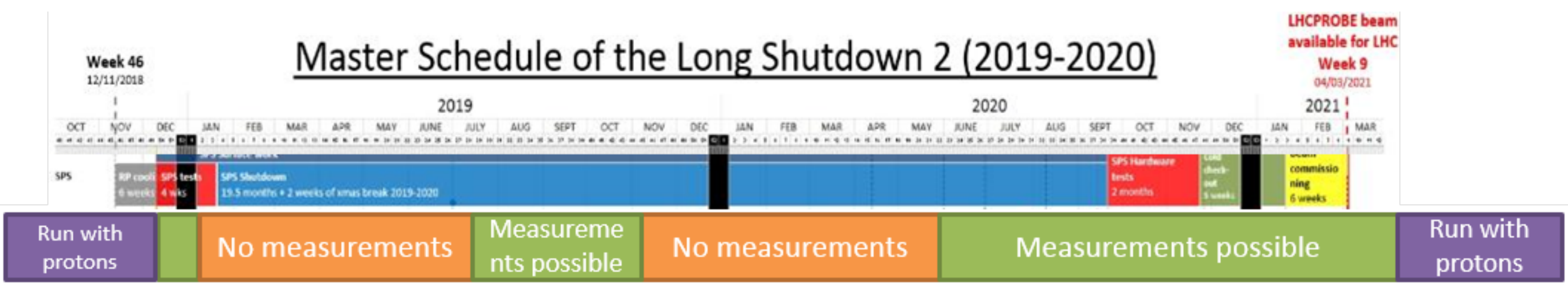
# AWAKE data taking 2018

- Two initial major milestones of AWAKE Run 1 achieved:
  ✓ Demonstration of self-modulation of proton bunch
  ✓ Acceleration of electrons in wakefields created by proton micro-bunches
- Since acceleration of electrons, have had two further data-taking periods and embarking on final data taking for AWAKE Run 1 until mid-November.
- Have many new measurements:
  - Stability of modulation process, i.e. constant phase and other investigations of seeded self-modulation.
  - Energy dependence of accelerated electrons on initial conditions such as electron bunch injection angle, electron bunch delay, etc..
- Analyses ongoing; more results and papers to come.

# AWAKE plans

# Immediate plans

- Have one more (4-week) data-taking period from now until mid-Nov when CERN proton running stops until 2021.
  - More understanding of electron injection
  - Further investigate energy dependence on conditions of the experiment
  - Try to increase charge capture and study dependencies
  - Measure the emittance of the accelerated electron bunch
  - Investigation of modulation process
- Run with partially stripped ions in Nov/Dec this year, as tool for in-situ calibration of spectrometer.  Request support of SPSC.
- Measurements during LS2 with plasma, laser and electrons. Request support of SPSC.

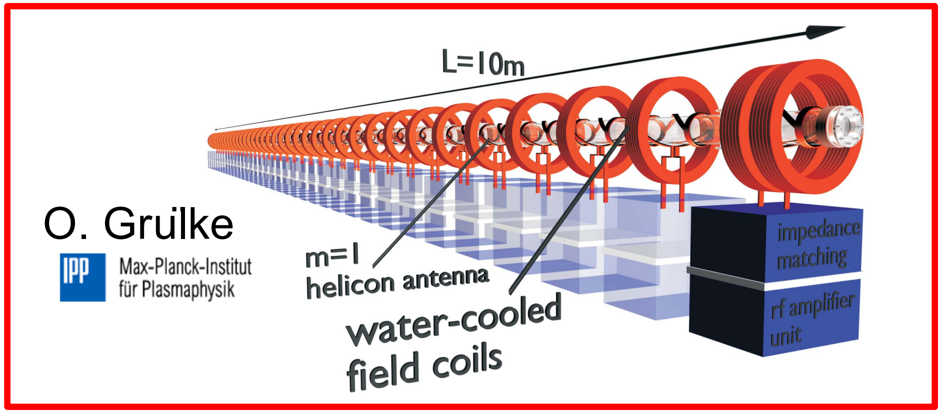


# AWAKE Run 2

- Preparing AWAKE Run 2, after CERN LS2 and before LS3, 2021–4.
  - Accelerate electron bunch to higher energies.
  - Demonstrate beam quality preservation.
  - Demonstrate scalability of plasma sources.
- Meeting these goals could lead to applications for high energy physics experiments.

Preliminary Run 2 electron beam parameters

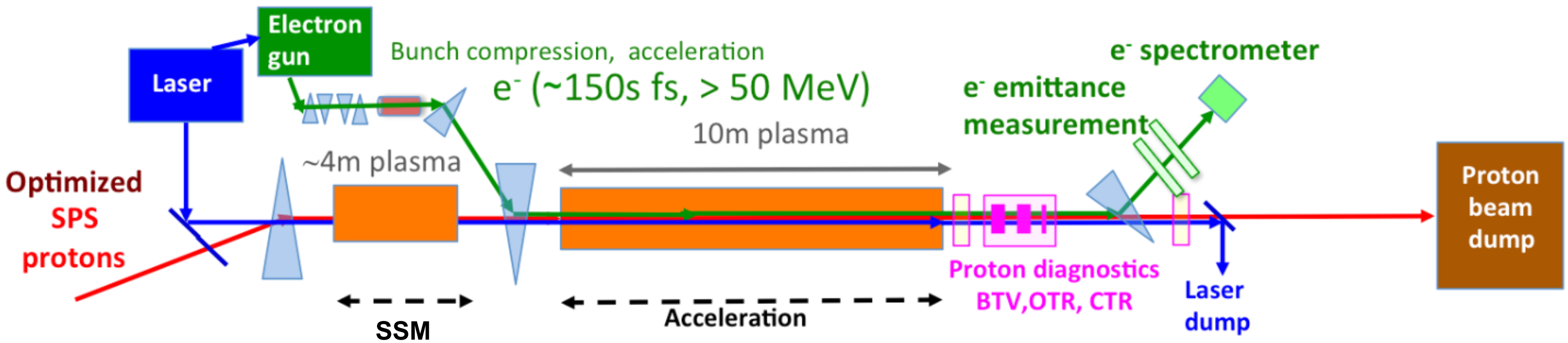
| Parameter | Value |
|---|---|
| Acc. gradient | >0.5 GV/m |
| Energy gain | 10 GeV |
| Injection energy | $\gtrsim$ 50 MeV |
| Bunch length, rms | 40–60 $\mu$m (120–180 fs) |
| Peak current | 200–400 A |
| Bunch charge | 67–200 pC |
| Final energy spread, rms | few % |
| Final emittance | $\lesssim$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




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

# AWAKE Run 2

- First phase of Run 2 with upgraded electron source, plasma source, diagnostics, etc.
- Development of scalable plasma sources (helicon, discharge) based at CERN.
- High-energy electron witness beam to come in a second stage of Run 2.
- Run 2 will be optimised for electron injection and acceleration.




- Will be seeking approval of AWAKE Run 2:
  - Submit proposal with physics, resources required, etc.
  - Anticipate a Cost and Schedule Review to follow.

**To submit Run 2 proposal in 2019**

# Summary

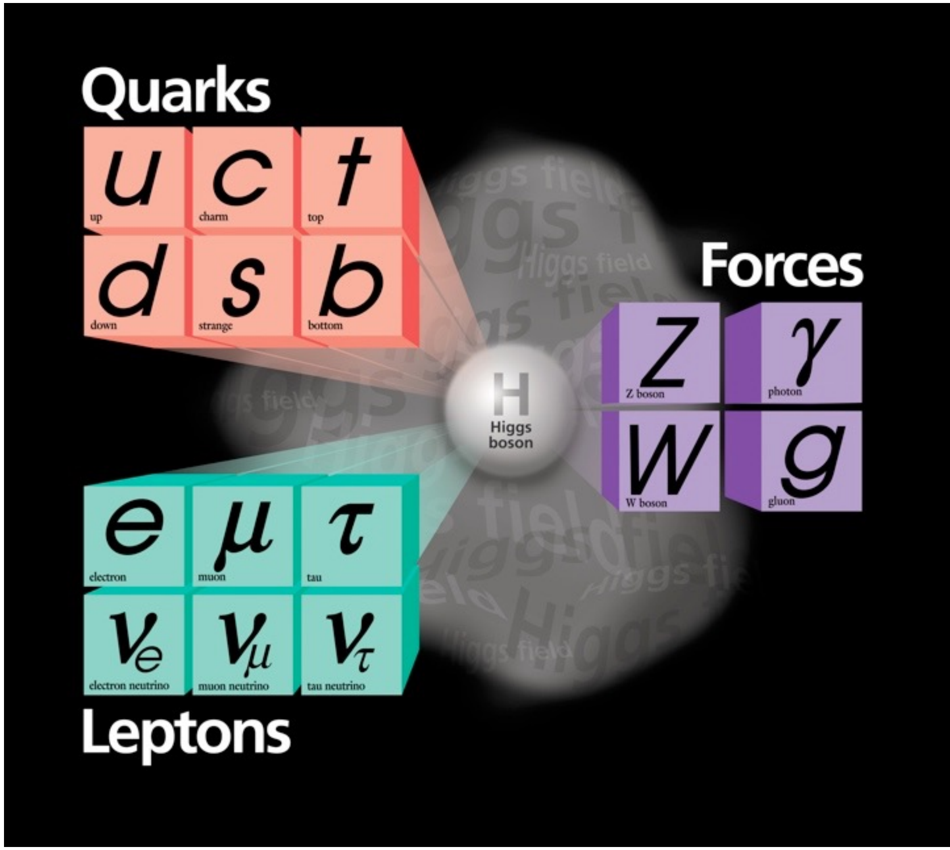
- AWAKE has demonstrated proton-driven plasma wakefield acceleration for the first time:
  - Clear modulation of long proton bunch which then drives wakefields.
  - Externally injected electron bunches sample wakefields and accelerated up to 2 GeV in 10 m of plasma.
  - Reproducibility looks promising.
- More data to be taken and investigation of process in 2018.
- Developing a Run 2 programme for 2021−4.

# Back-up

# Motivation: big questions in particle physics

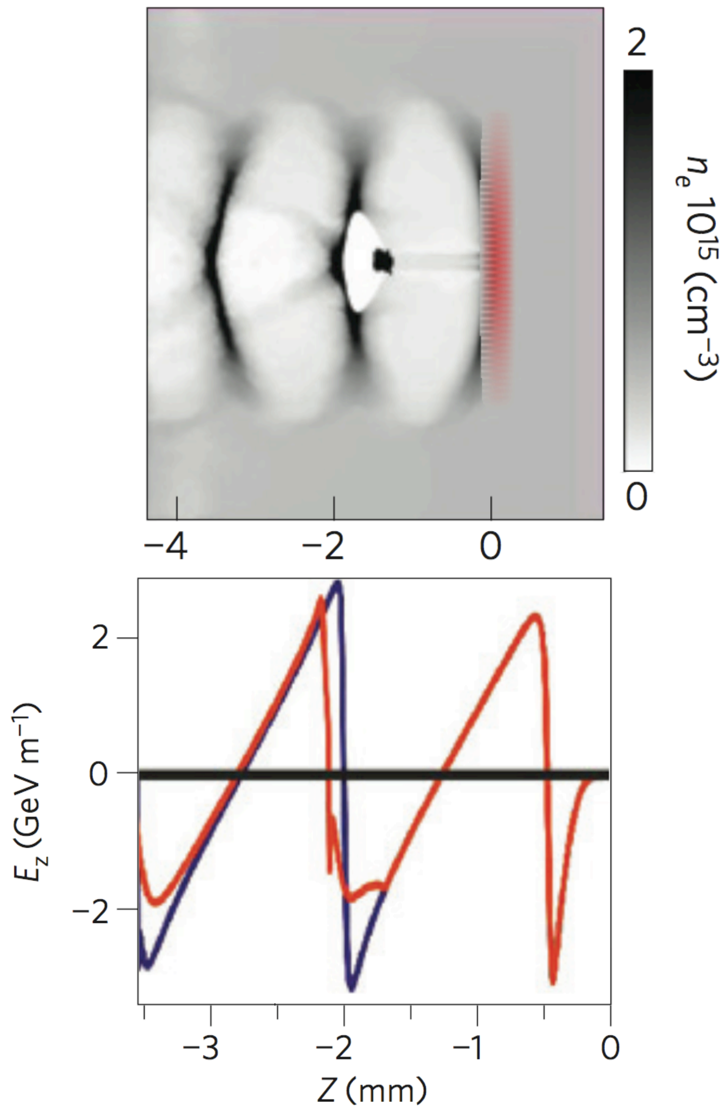
The Standard Model is amazingly successful, but some things remain unexplained :

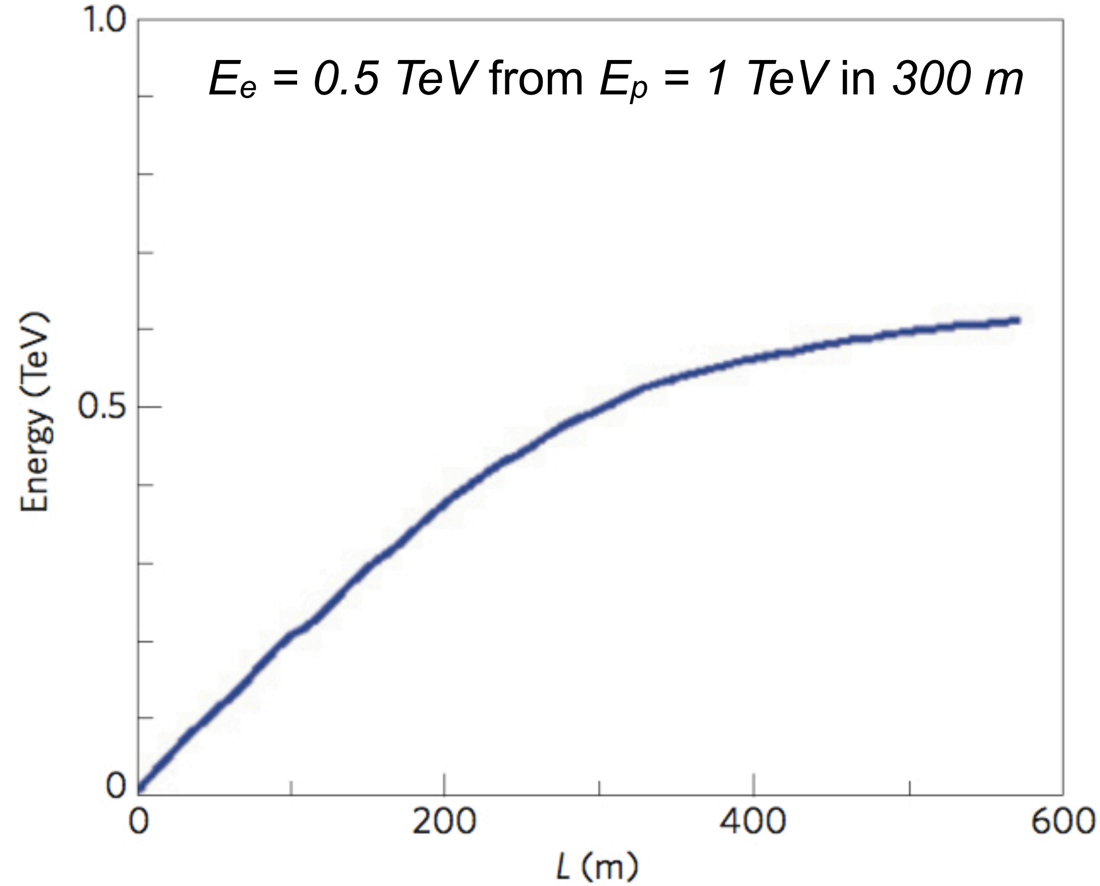
- a detailed understanding of the Higgs Boson/mechanism
- neutrinos and their masses
- why is there so much matter (vs anti-matter) ?
- why is there so little matter (*5%* of Universe) ?
- what is dark matter and dark energy ?
- why are there three families ?
- hierarchy problem; can we unify the forces ?
- what is the fundamental structure of matter ?
- …




**Colliders and use of high energy particle beams will be key to solving some of these questions**

# Proton-driven plasma wakefield acceleration concept*




Note proton bunch length, *100 μm*; cf LHC, bunch length, *~10 cm*



* A. Caldwell *et al.*, Nature Physics **5** (2009) 363.

# Plasma considerations

Based on linear fluid dynamics :

$$\omega_p = \sqrt{\frac{n_p\, e^2}{\epsilon_0\, m_e}}$$

$$\lambda_p \approx 1\,[\mathrm{mm}]\sqrt{\frac{10^{15}\,[\mathrm{cm}^{-3}]}{n_p}} \quad \text{or} \quad \approx \sqrt{2}\,\pi\,\sigma_z$$

$$E \approx 2\,[\mathrm{GV\,m^{-1}}]\left(\frac{N}{10^{10}}\right)\left(\frac{100\,[\mu\mathrm{m}]}{\sigma_z}\right)^2$$

Relevant physical quantities :

- Oscillation frequency, $\omega_p$
- Plasma wavelength, $\lambda_p$
- Accelerating gradient, $E$

where :

- $n_p$ is the plasma density
- $e$ is the electron charge
- $\varepsilon_0$ is the permittivity of free space
- $m_e$ is the mass of electron
- $N$ is the number of drive-beam particles
- $\sigma_z$ is the drive-beam length

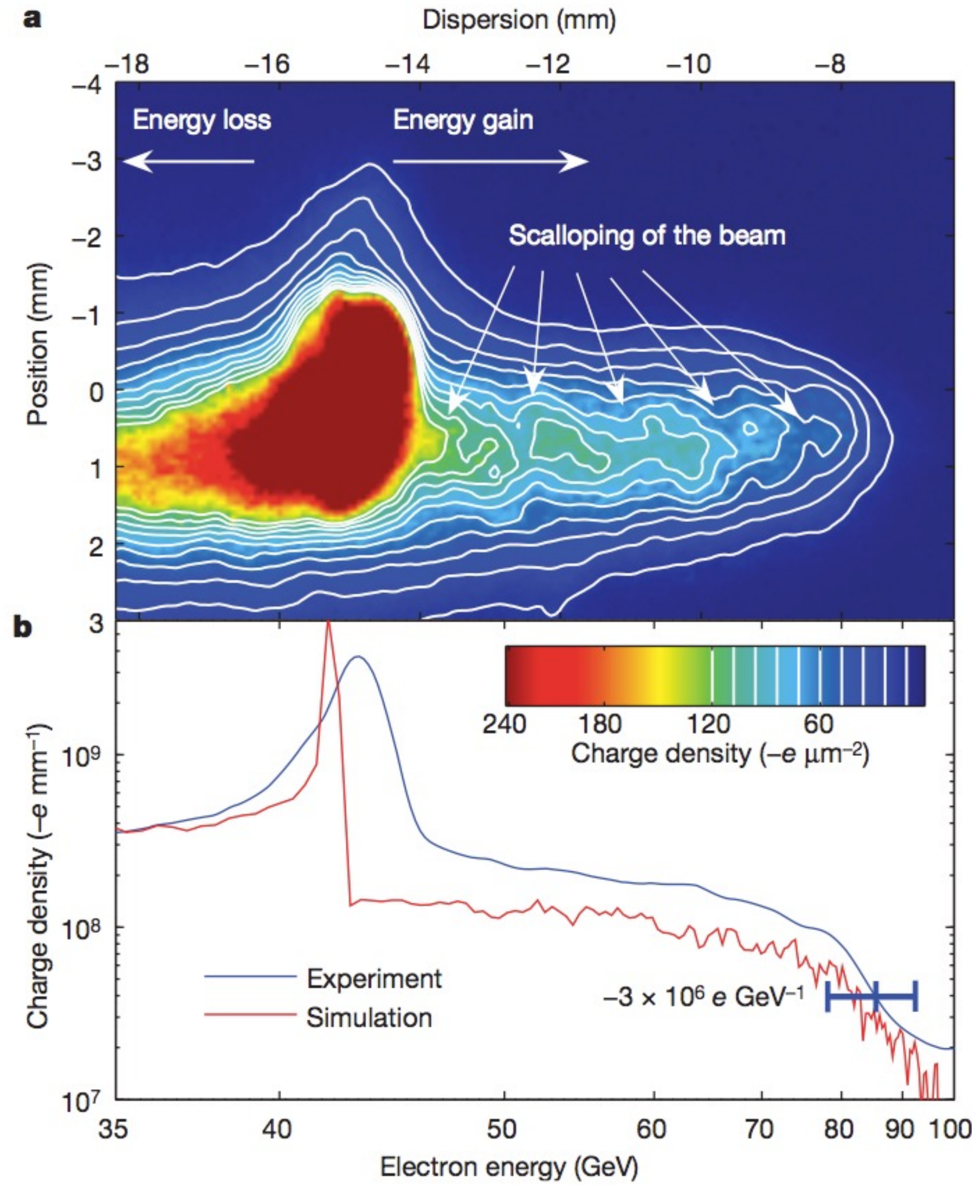
High gradients with :

- **Short drive beams** (and short plasma wavelength)
- **Pulses with large number of particles** (and high plasma density)

Plasma wakefield acceleration first proposed by T. Tajima and J.W. Dawson, Phys. Rev. Lett. **43** (1979) 267; use of particle beams proposed by P. Chen et al., Phys. Rev. Lett. **54** (1985) 693.

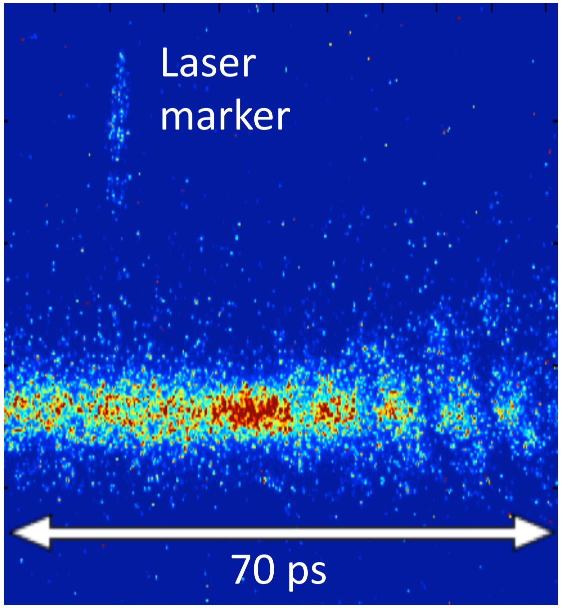
# Plasma wakefield experiments

- Pioneering work using a LASER to induce wakefields up to *100 GV/m*.
- Experiments at SLAC§ have used a particle (electron) beam :
  - Initial energy $E_e$ = *42 GeV*
  - Gradients up to ~ *52 GV/m*
  - Energy doubled over ~ *1 m*
  - Next stage, FACET(-II) project (http://facet.slac.stanford.edu)
- Have proton beams of much higher energy :
  - CERN : *450 GeV* and *6.5* (*7*) *TeV*
  - Can accelerate trailing electron bunch to high energy in one stage

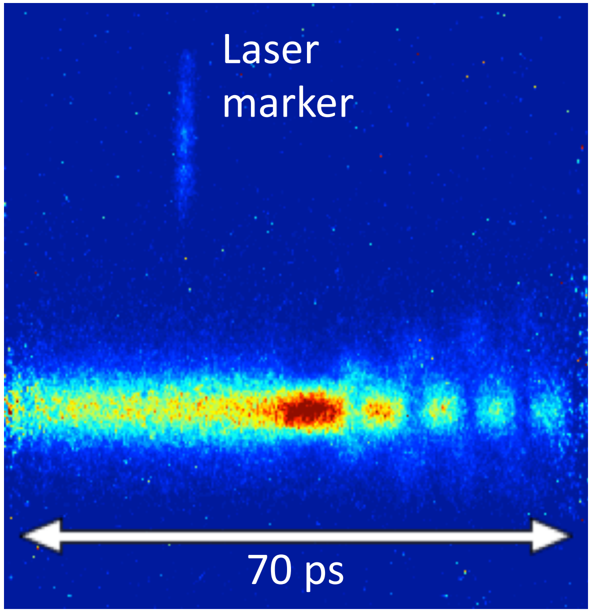



§ I. Blumenfeld et al., Nature **445** (2007) 741.

# Direct measurement using OTR – reproducibility



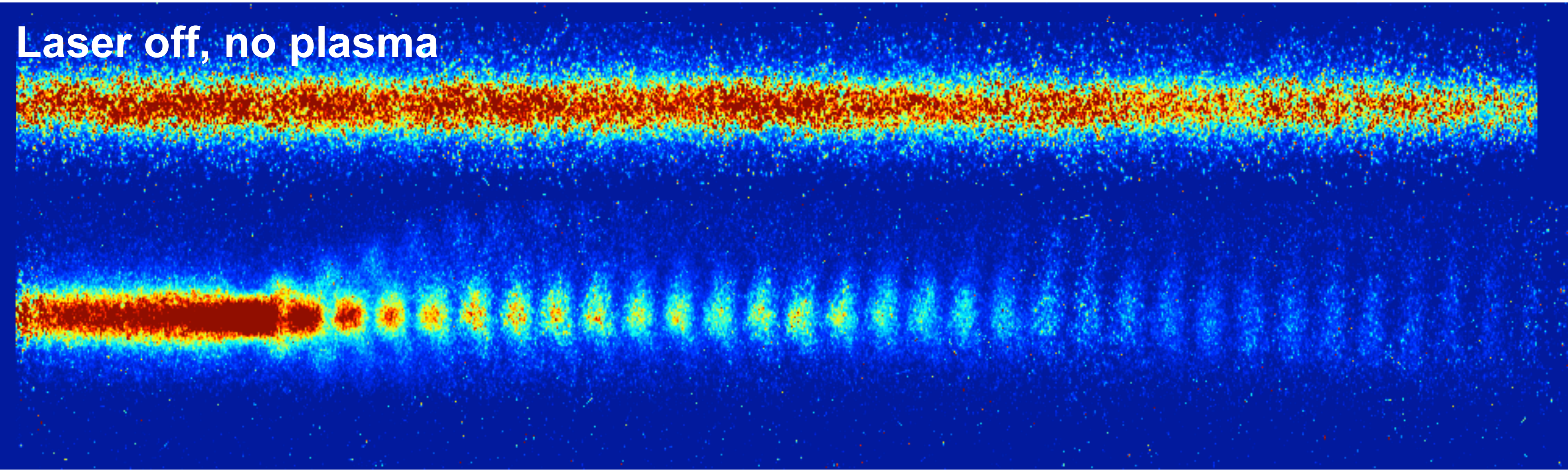

**1 → 10 events**




- Streak camera image from single event.
- What about multiple events ?

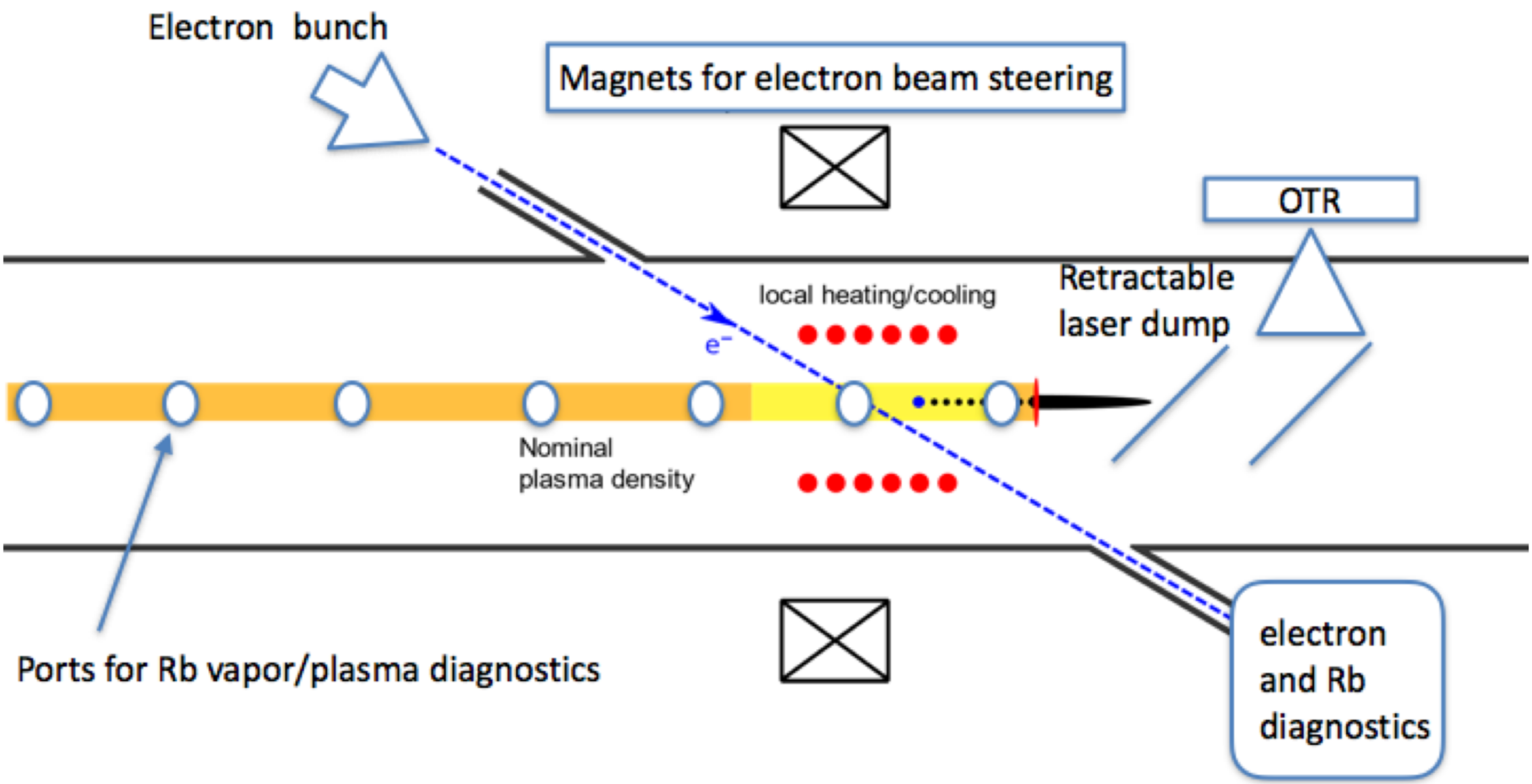
- 10 consecutive events.
- Image looks nicer.
- Bunches add and align.
- Modulation fixed wrt seed.

# Direct measurement of self-modulation

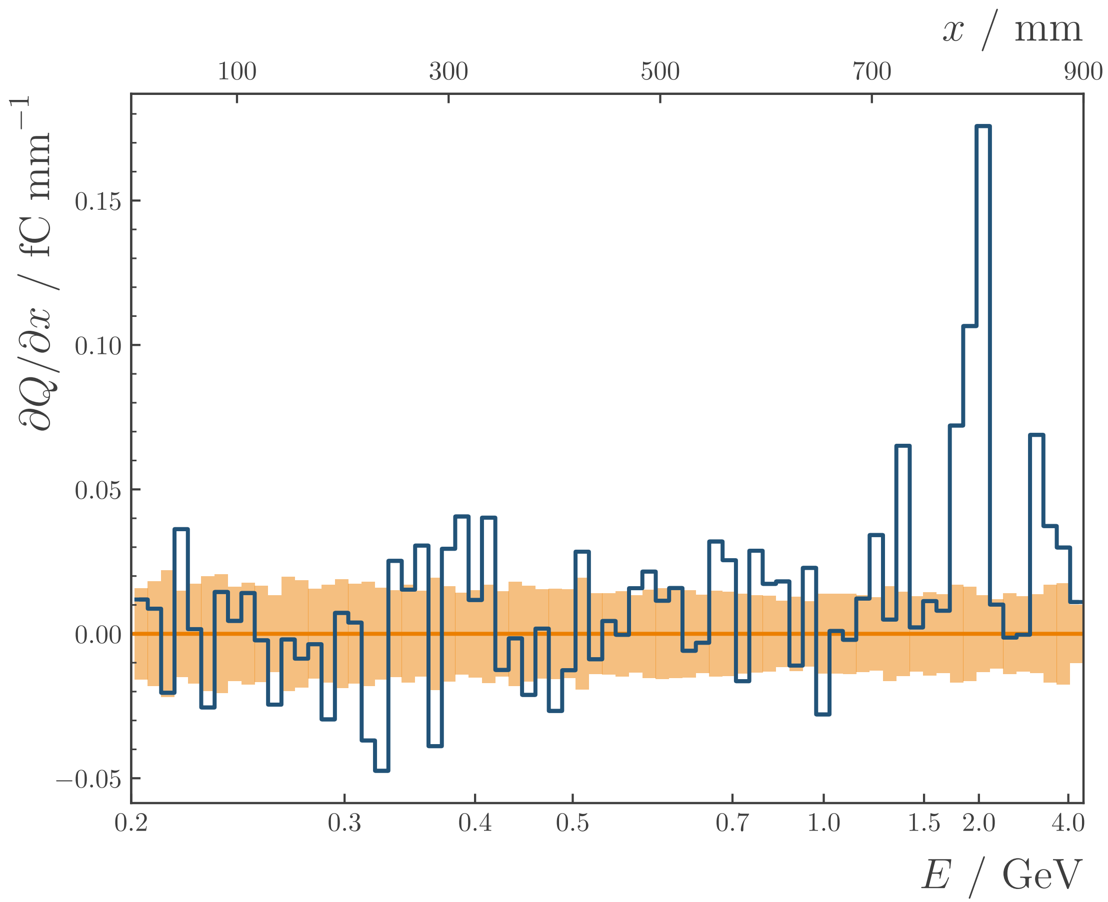



- Events stitched together.
- Clear modulation of the proton bunch.
- Highly reproducible phase between the bunches (and events).
- Crucial for injection of electrons.

# Possible AWAKE Run 2 layout



# 2 GeV peak



$x$ / mm
100
300
500
700
900
$\partial Q/\partial x$ / fC mm$^{-1}$
0.15
0.10
0.05
0.00
−0.05
0.2
0.3
0.4
0.5
0.7
1.0
1.5
2.0
4.0
$E$ / GeV

# Applying AWAKE technology

- Plasma wakefield acceleration in general aims to produce more efficient accelerators.
- The AWAKE scheme is focused on particle physics applications; higher energy and / or shorter accelerators.
- Compared to RF accelerators, with their rich history:
  - ✓ Pure energy gain looks possible.
  - ✓ Having high bunch charge looks possible.
  - ‣ Emittance and beam size need to be demonstrated.
  - \- Repetition frequency is still way behind RF accelerators.
  - \- Reproducibility is key and needs further work.
- The idea to build a high energy, high luminosity $e^+e^-$ collider as the first application is very ambitious.
- Should also consider applications with high energy and lower luminosity.
- There are not many high energy electron beams out there:
  - ➡ Secondary SPS electron beam, with low intensity.
  - ➡ High intensity, but $E_e \sim 20$ *GeV* for FELs.

# Possible particle physics experiments I

- Use of electron beam for test-beam campaigns.
  - Test-beam infrastructure for detector characterisation often over-subscribed.
  - Also accelerator test facility. Also not many world-wide.
  - Characteristics:
    - Variation of energy.
    - Provide pure electron beam.
    - Short bunches.
- Fixed-target experiments using electron beams, e.g. deep inelastic electron−proton scattering.
  - Measurements at high *x*, momentum fraction of struck parton in the proton, with higher statistics than previous experiments. Valuable for LHC physics.
  - Polarised beams and spin structure of the nucleon. The "proton spin crisis/puzzle" is still a big unresolved issue.
- **Investigation of strong-field QED at the Schwinger limit in electron−laser interactions.**

# Possible particle physics experiments II

- **Search for dark photons à la NA64**
  - Consider beam-dump and counting experiments.
- **High energy electron−proton collider**
  - A low-luminosity LHeC-type experiment: $E_e$ *~50 GeV,* beam within *50−100 m* of plasma driven by SPS protons; low luminosity, but much more compact.
  - A very high energy electron−proton (VHEeP) collider with $\sqrt{s}$ ***= 9 TeV,*** ×*30* higher than HERA. Developing physics programme.

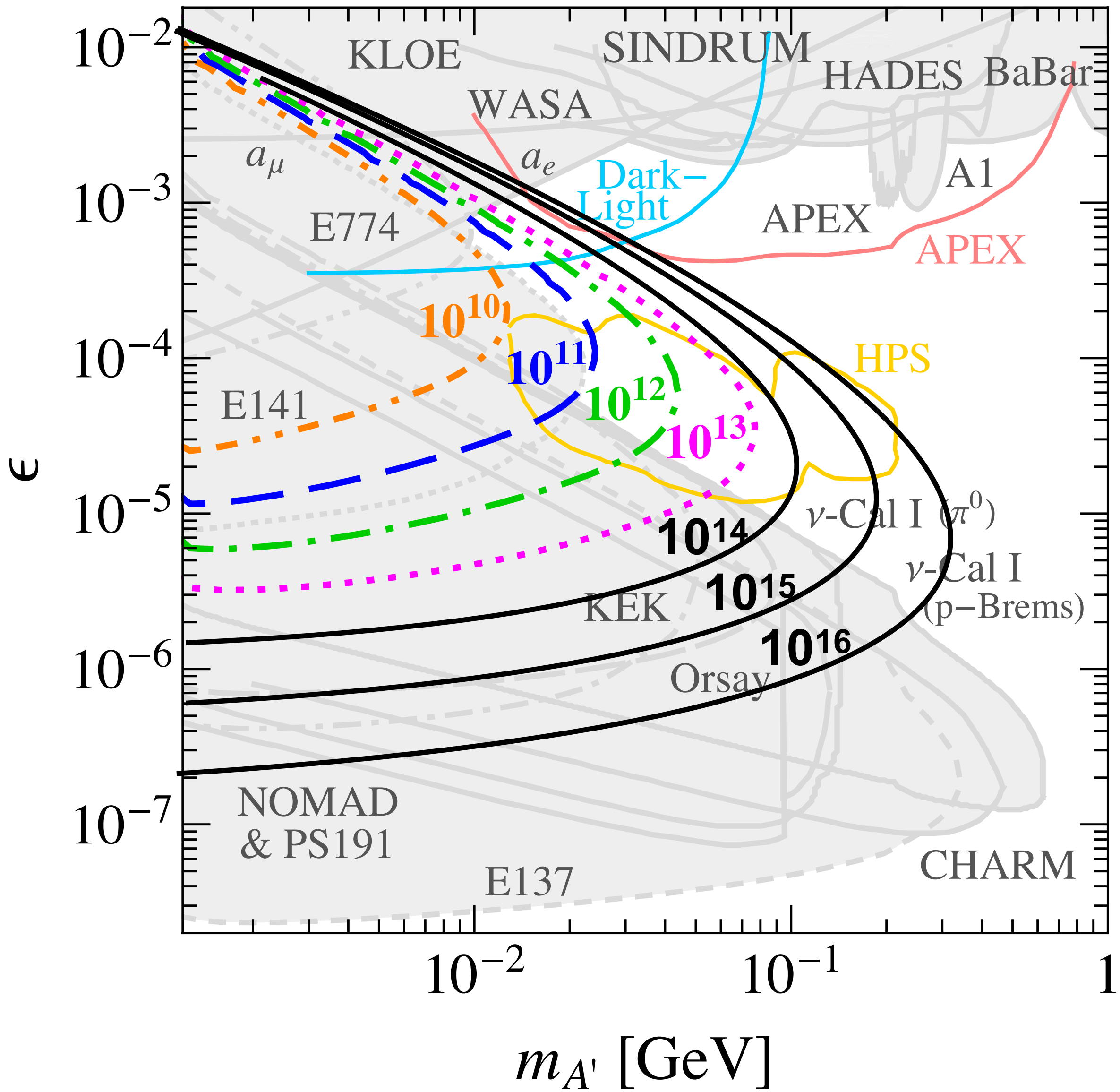
These experiments probe exciting areas of physics and will really profit from an AWAKE-like electron beam.

- **Demonstrate an accelerator technology also doing cutting-edge particle physics**

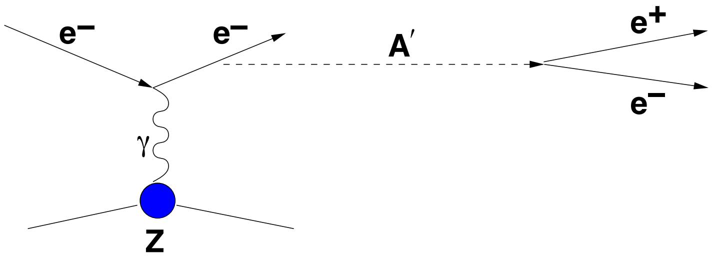
Using a new technology

Fixed-target → High *E ep* collider → High *E*, high lumi $e^+e^-$ collider

# Search for dark photons, $A' \rightarrow e^+e^-$ channel




An electron beam from AWAKE could be used to search for dark photons



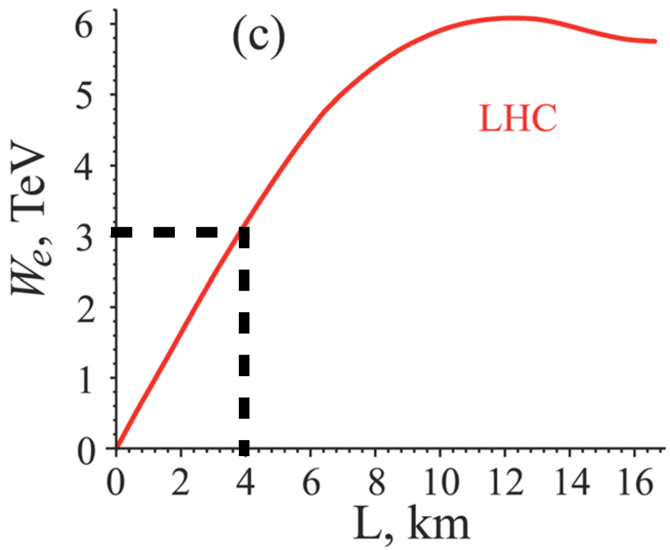

For $10^{10} - 10^{13}$ electrons on target with NA64.

For $10^{14} - 10^{16}$ electrons on target with AWAKE-like beam.

Using an AWAKE-like beam would extend sensitivity further around $\varepsilon \sim 10^{-5}$ beyond any current experiment.

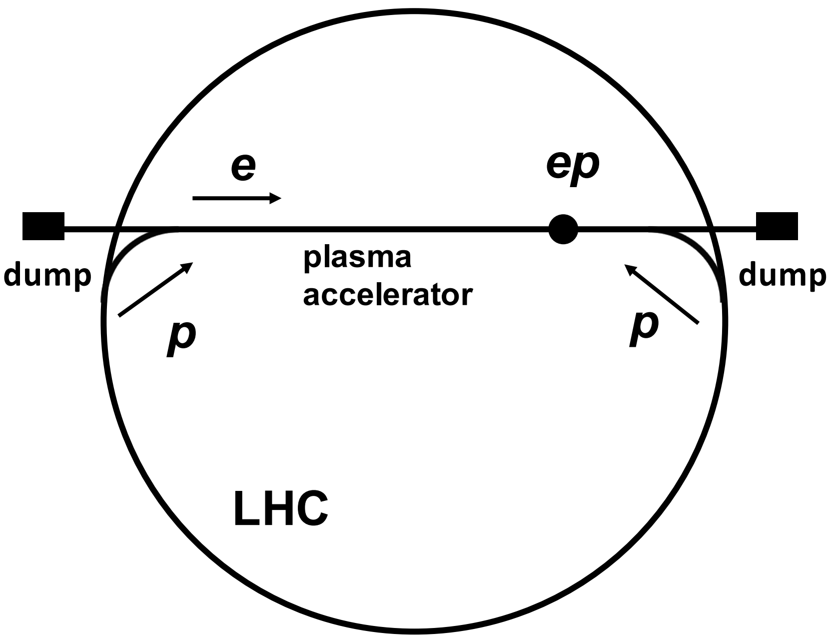
Work ongoing…

# Very high energy electron−proton collisions, VHEeP*




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

- What about very high energies in a completely new kinematic regime ?
- Choose $E_e$ = *3 TeV* as a baseline for a new collider with $E_P$ = *7 TeV* ⇒ $\sqrt{s}$ **= *9 TeV***. Can vary.
  - Centre-of-mass energy ×30 higher than HERA.
  - Reach in (high) $Q^2$ and (low) Bjorken *x* extended by ×1000 compared to HERA.




- Overall layout using current infrastructure.
- One proton beam used for electron acceleration to then collide with other proton beam
- Luminosity ~ $10^{29}$ $cm^{-2}s^{-1}$ or ~ 1 $pb^{-1}$ per year

**There is a physics case for very high energy, but moderate (*10−100 pb*$^{-1}$) luminosities.**

**More studies needed.**



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