

Acceleration of electrons in the plasma wakefield of a proton bunch at the AWAKE experiment

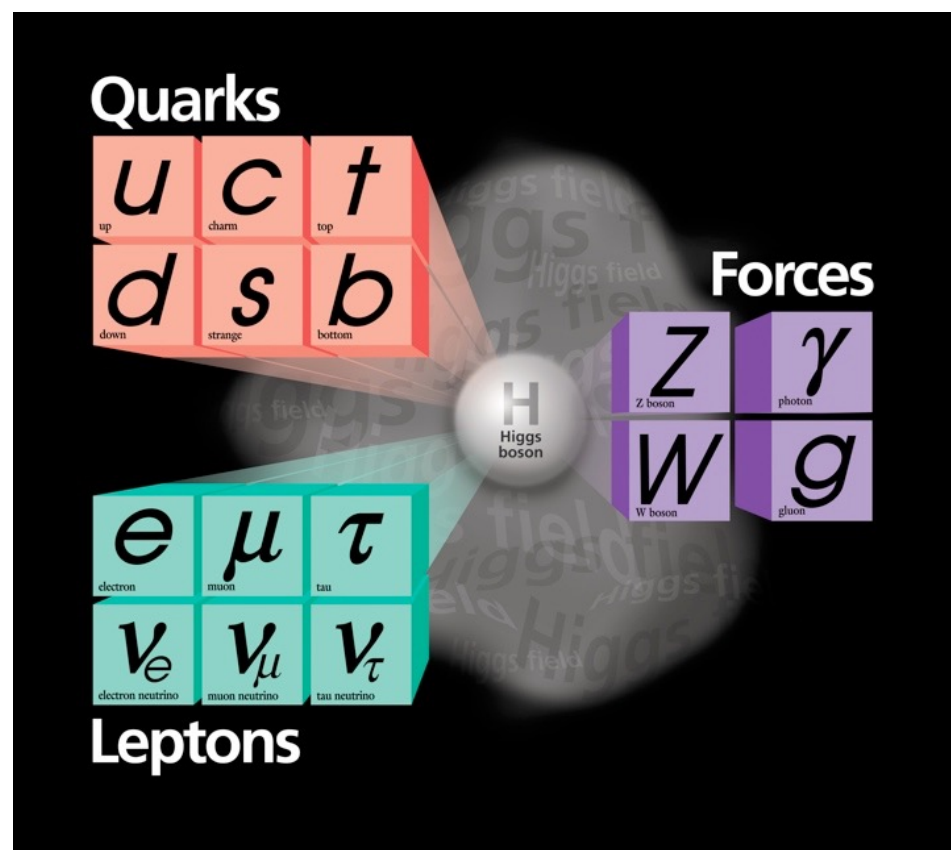
Matthew Wing (UCL / DESY)

- Motivation and introduction to plasma wakefield acceleration
- The AWAKE experiment
- AWAKE results
 - Establish self-modulation of proton bunch
 - Acceleration of electrons in wakefields
- AWAKE Run 2 and applications
- Summary

Motivation: big questions in particle physics

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

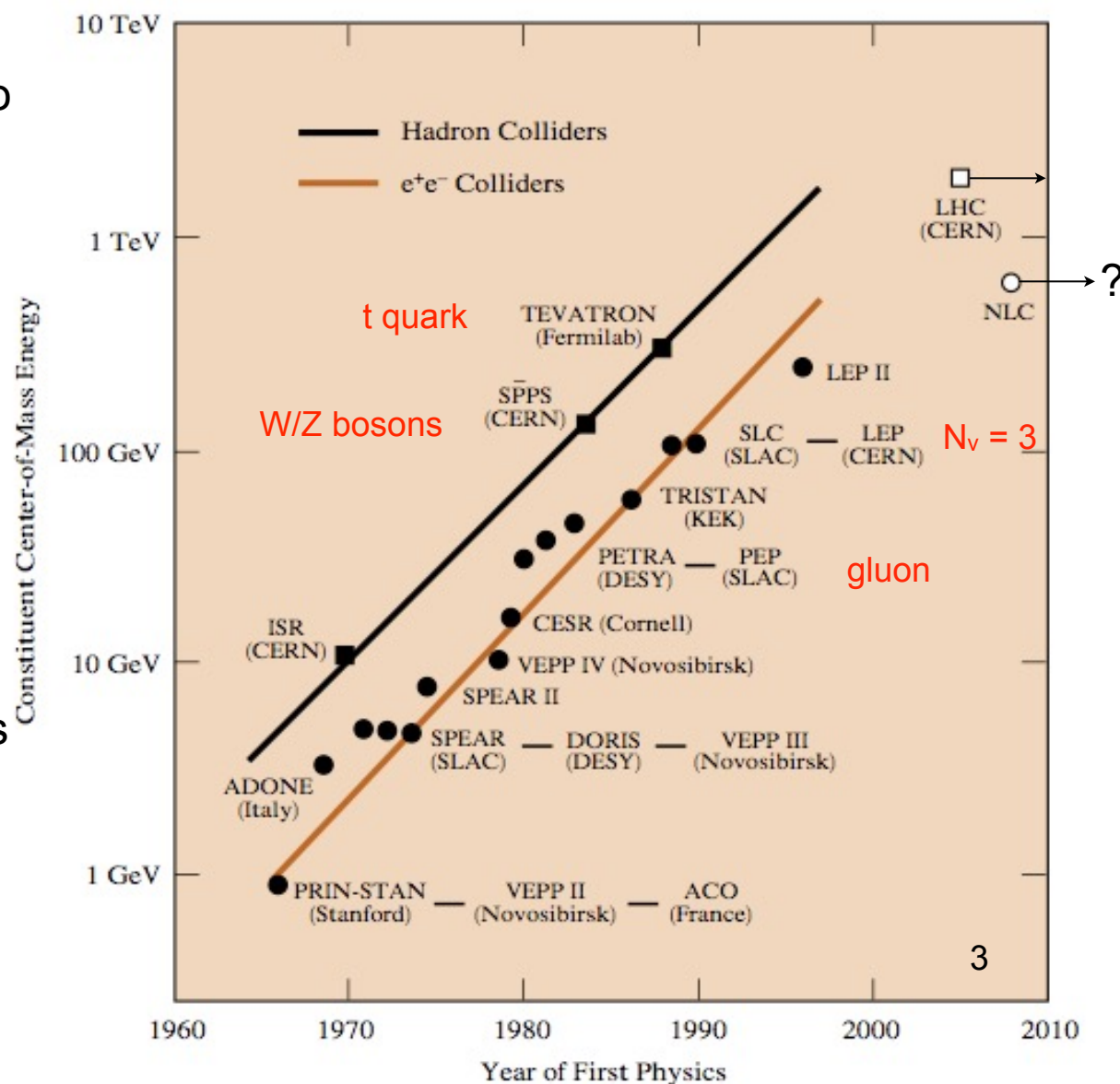
- a detailed understanding of the Higgs Boson/mechanism
- neutrinos and their masses
- why is there so much matter (vs anti-matter) ?
- why is there so little matter (5% of Universe) ?
- what is dark matter and dark energy ?
- why are there three families ?
- hierarchy problem; can we unify the forces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



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

Motivation: colliders

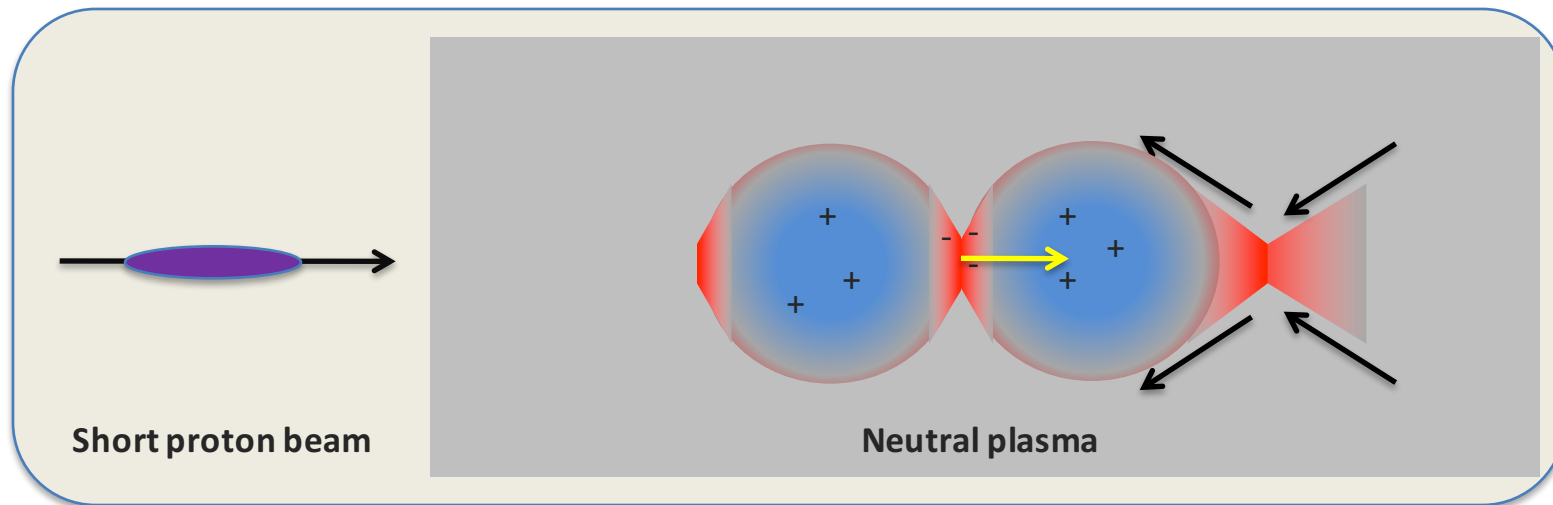
- The use of (large) accelerators has been crucial to advances in particle physics.
- Culmination in 27-*km* long LHC (*pp*); e.g. a future e^+e^- collider planned to be 30–50-*km* long.
- The high energy frontier is (very) expensive; can we reduce costs? Can we develop and use new technologies?
- Accelerators using RF cavities limited to ~ 100 MV/m; high energies \rightarrow 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*, but need :
 - High repetition rate and high number of particles per bunch;
 - Efficient and highly reproducible beam production;
 - Small beams sizes (potentially down to *nm* scale).
- 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* beams 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**

Plasma considerations

Based on linear fluid dynamics :

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

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

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

Relevant physical quantities :

- Oscillation frequency, ω_p
- Plasma wavelength, λ_p
- Accelerating gradient, E

where :

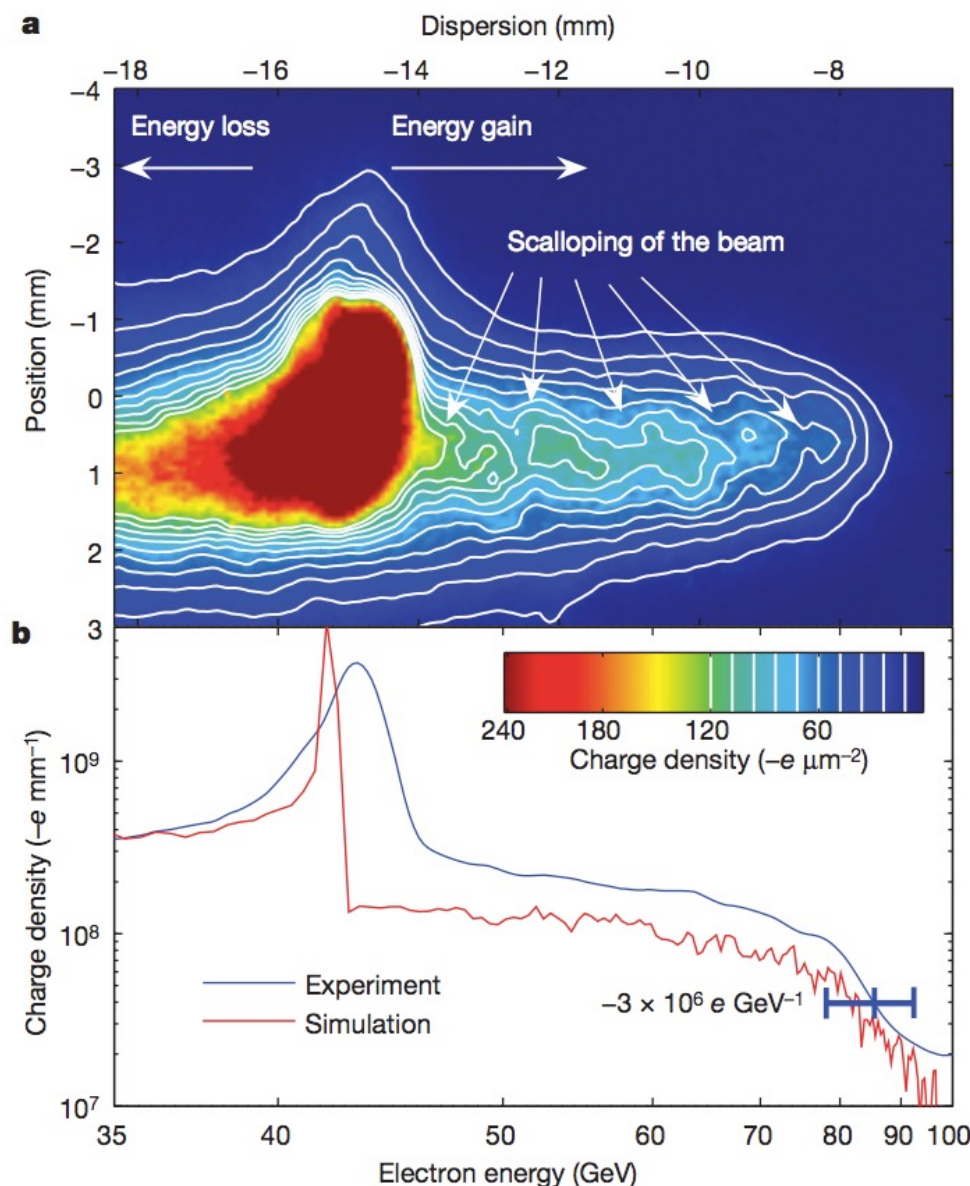
- n_p is the plasma density
- e is the electron charge
- ϵ_0 is the permittivity of free space
- m_e is the mass of electron
- N is the number of drive-beam particles
- σ_z is the drive-beam length

High gradients with :

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

Plasma wakefield experiments

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



Why protons ?

Lasers do not have enough energy :

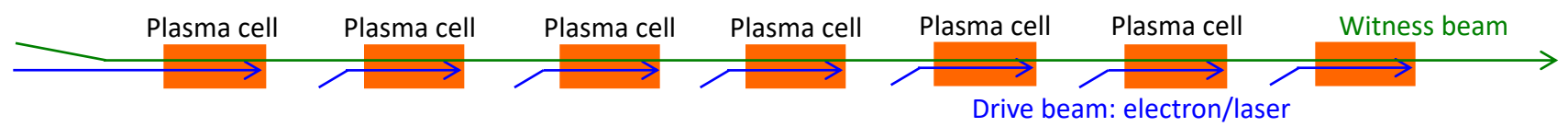
- Can not propagate long distances in plasma
- Can not accelerate electrons to high energy
- For high energy, need multiple stages.

Electrons also limited by initial energy and by the transformer ratio ($E^{witness}/E^{drive} < 2$:

- So many stages needed to accelerate to the TeV scale using known electron beams

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

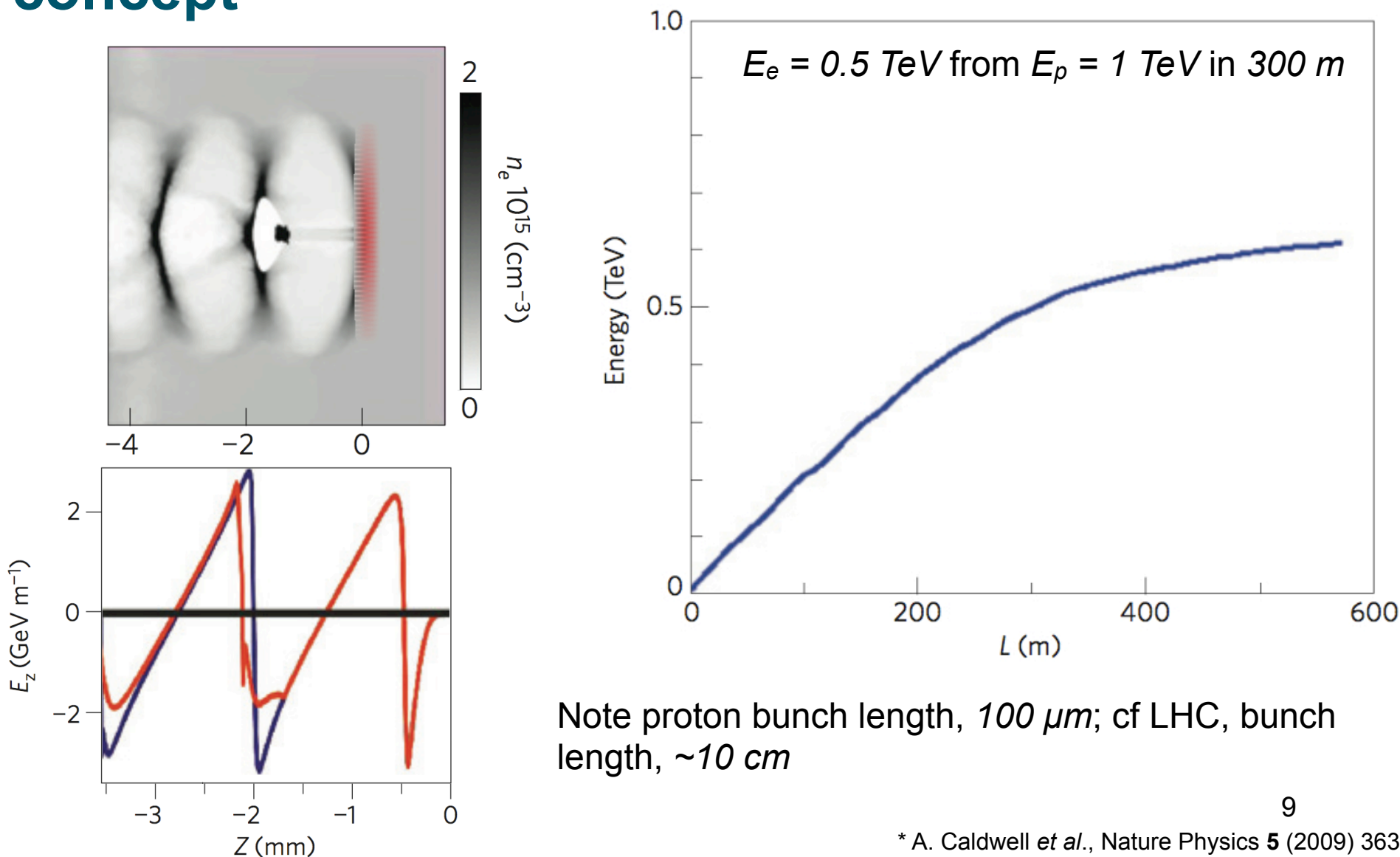
Laser/electron driver



Proton driver



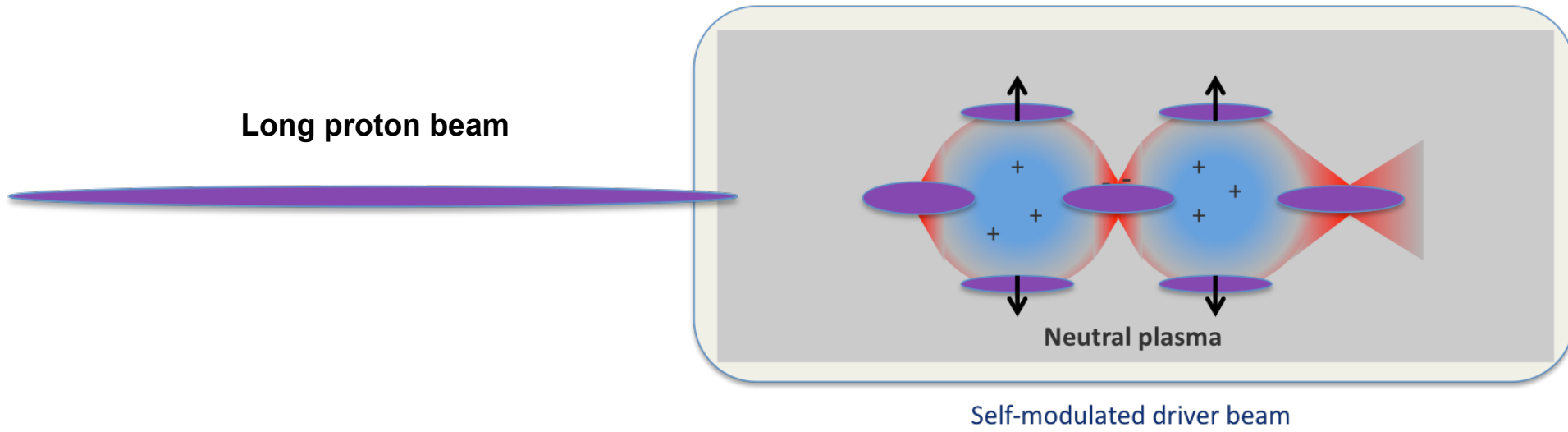
Proton-driven plasma wakefield acceleration concept*



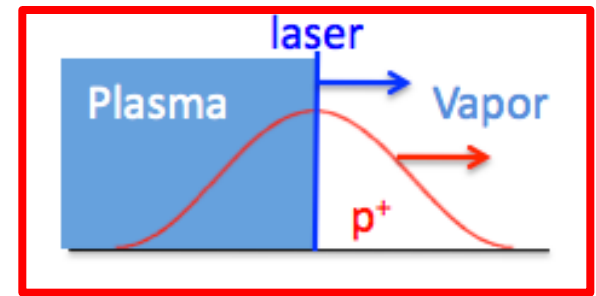
Long proton bunches ?

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



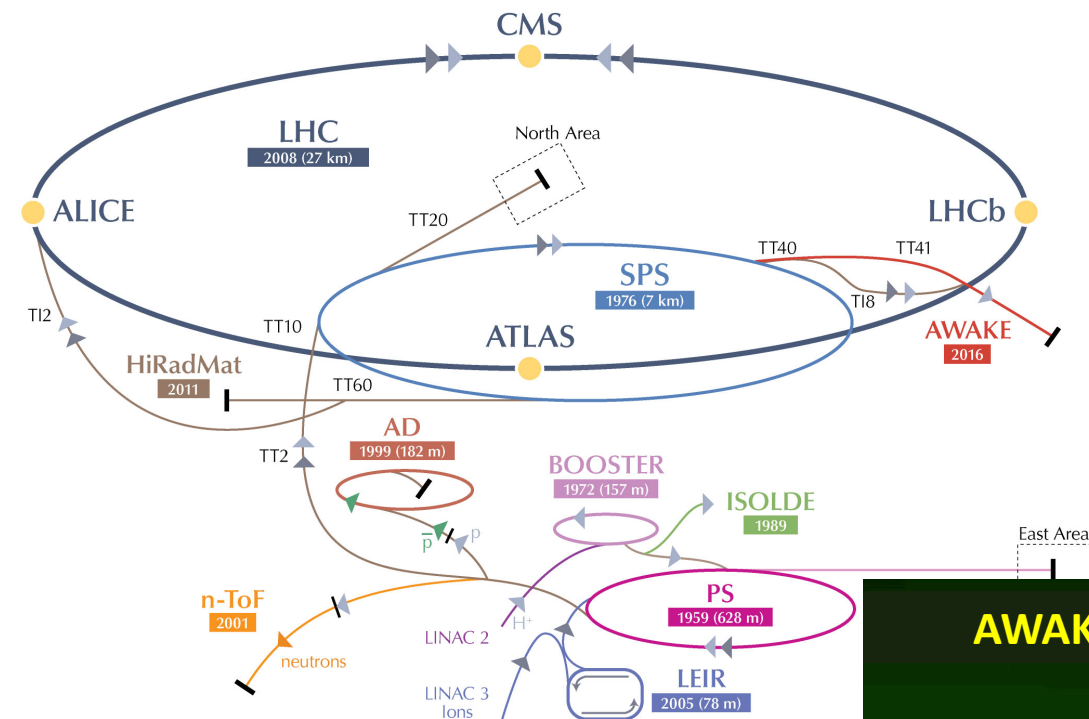
- Micro-bunches are spaced λ_p apart and have an increased charge density.
- Micro-bunches constructively reinforce to give large wakefields, GV/m .
- **Seeded self-modulation allows current beams to be used.**



The AWAKE experiment

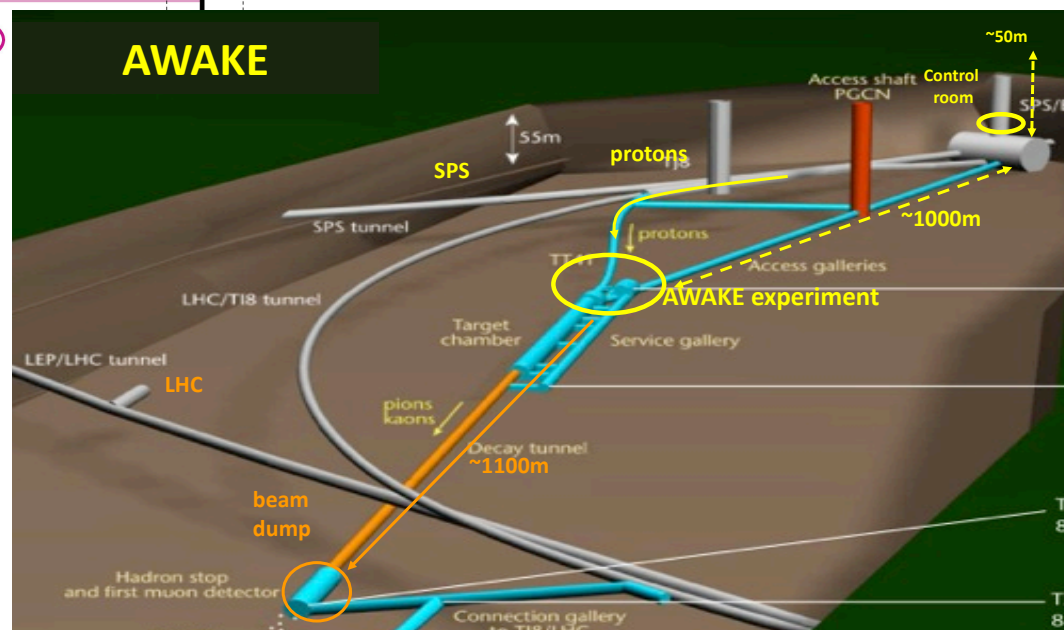
AWAKE experiment at CERN

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

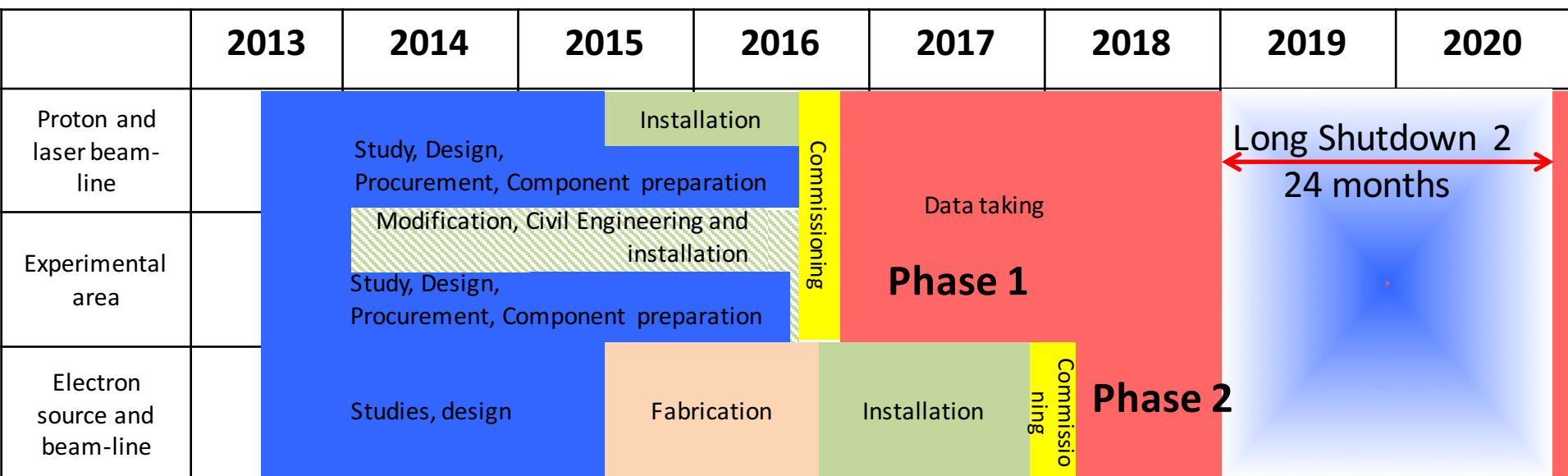


Advanced proton-driven plasma wakefield experiment.

Using 400 GeV SPS beam in former CNGS target area.

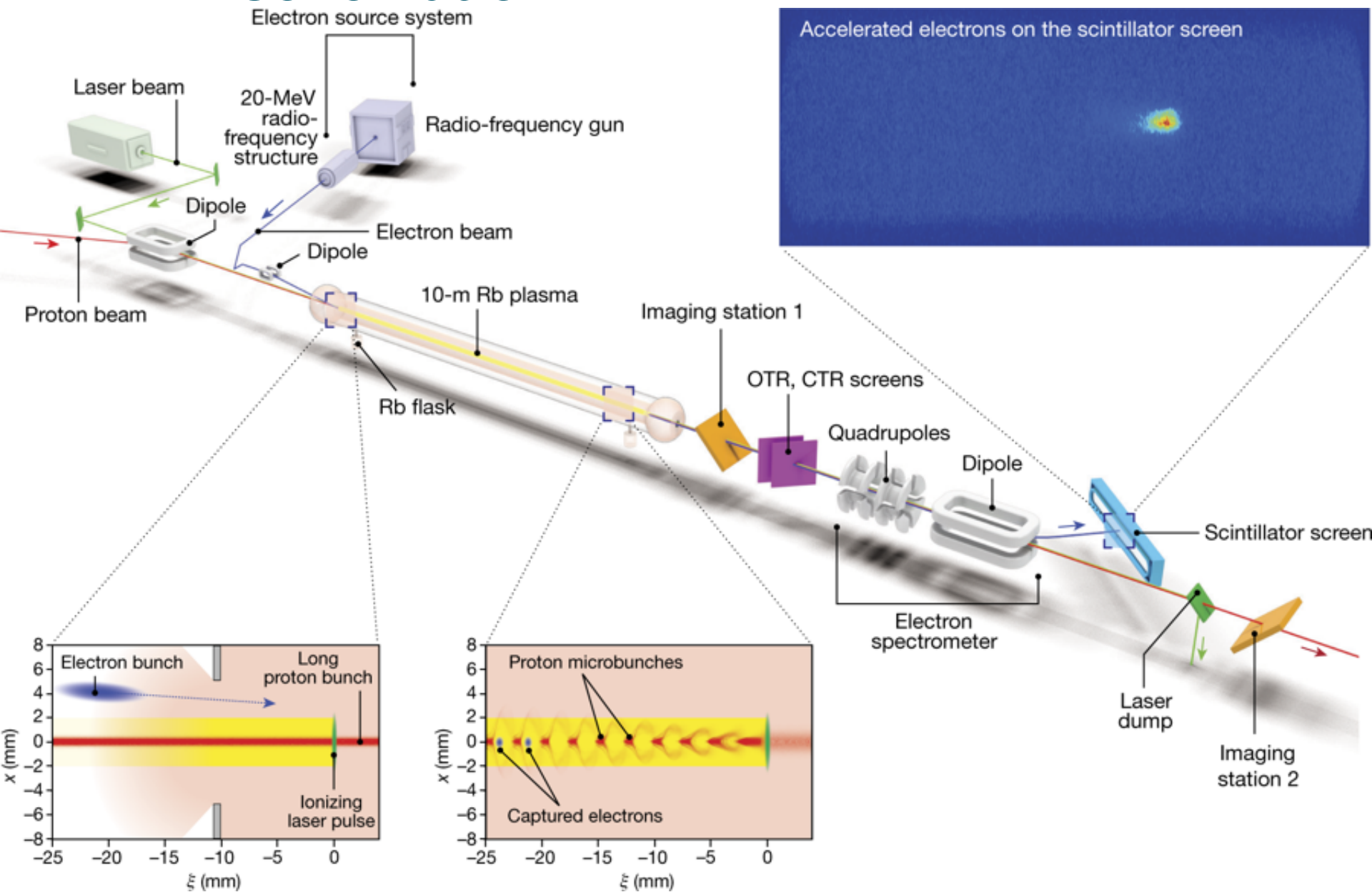


AWAKE physics and timeline



- 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

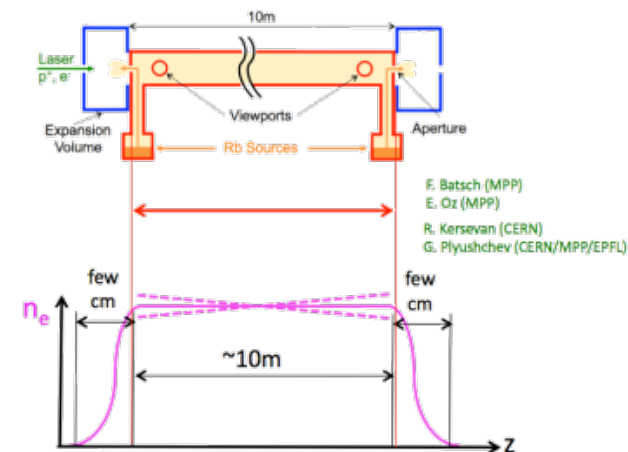
Parameter	Protons
Momentum (GeV)	400
Momentum spread (GeV)	0.14
Particles per bunch	3×10^{11}
Charge per bunch (nC)	48
Bunch length (mm)	120 (0.4 ns)
Norm. emittance (mm mrad)	3.5
Repetition rate (Hz)	1/30
Spot size at focal point (μm)	200 ± 20



750 m proton beam line

AWAKE plasma cell

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

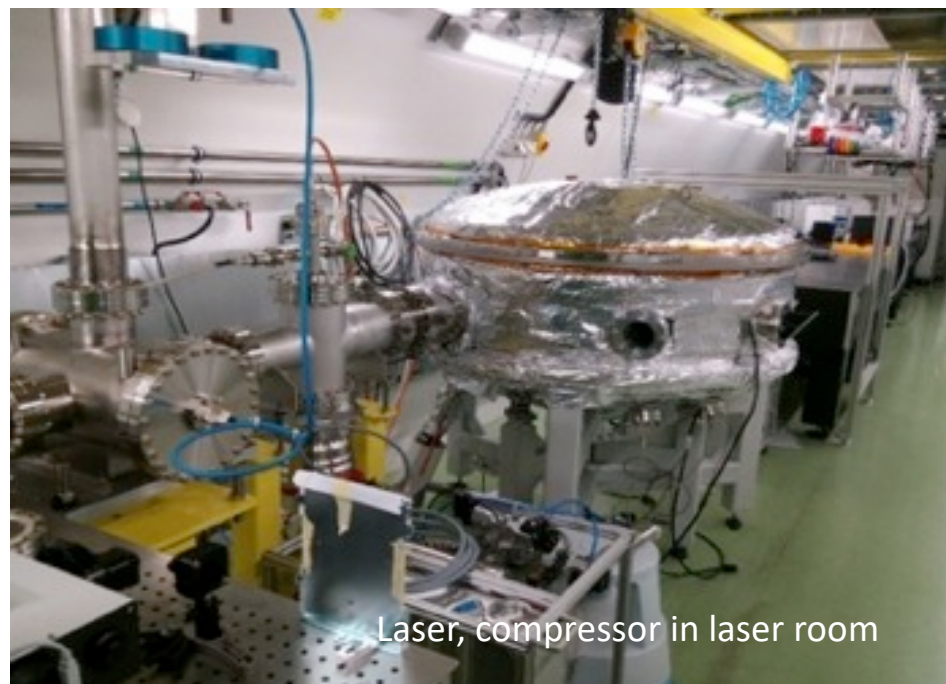


Laser

Ti:sapphire laser needed for:

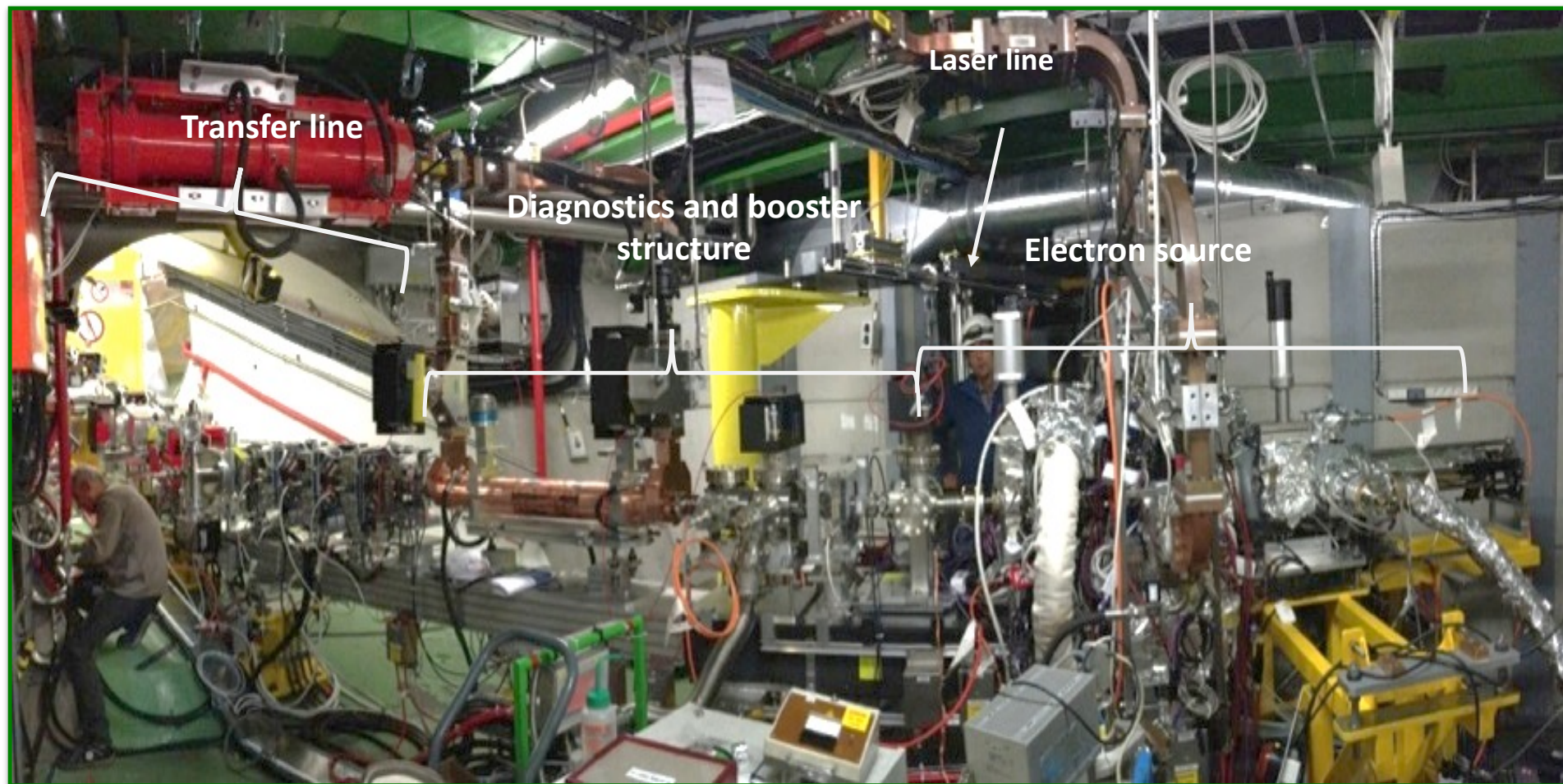
- Ionising vapour and seeding self-modulation in plasma.
- Diagnostic beam line.
- Beam to electron source.

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



Laser, compressor in laser room

Electron beam

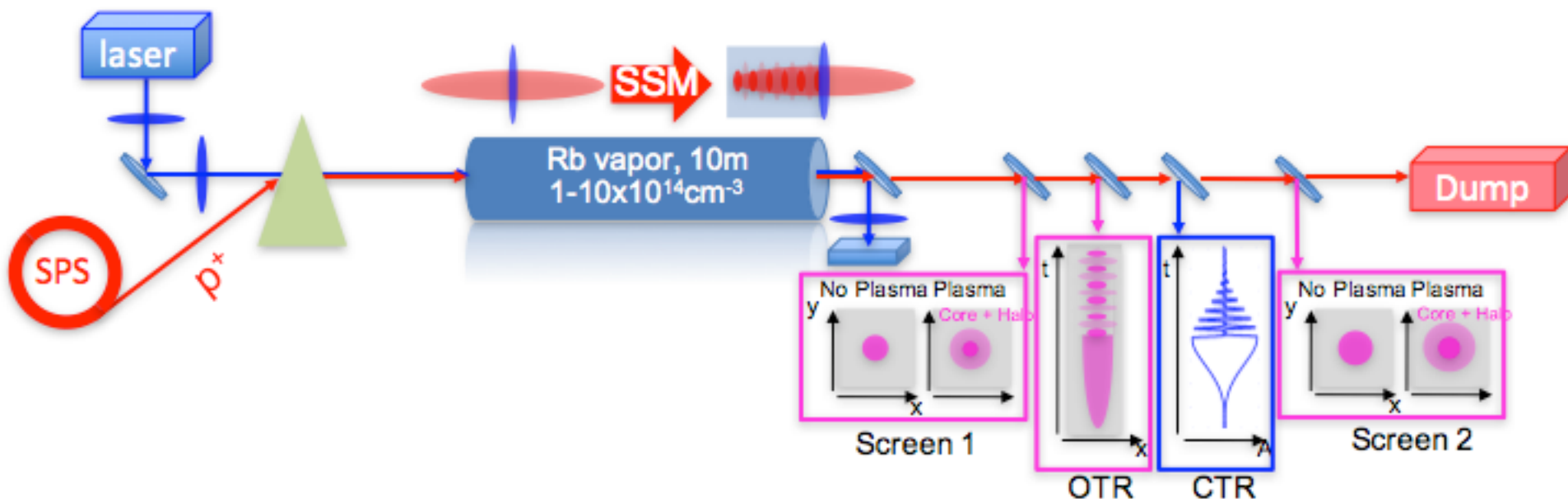


- Electron bunch of ~ 650 pC, $\sigma \sim 2$ ps
- Accelerated up to 20 MeV
- Produced at 5.5 MeV
- 18 m beam line to plasma cell

Self-modulation of proton bunch

Proton micro-bunching

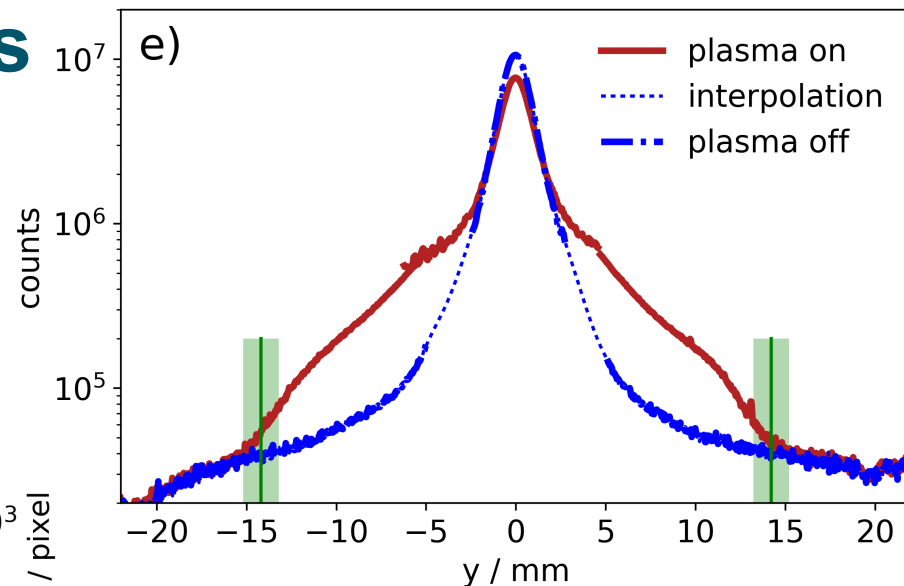
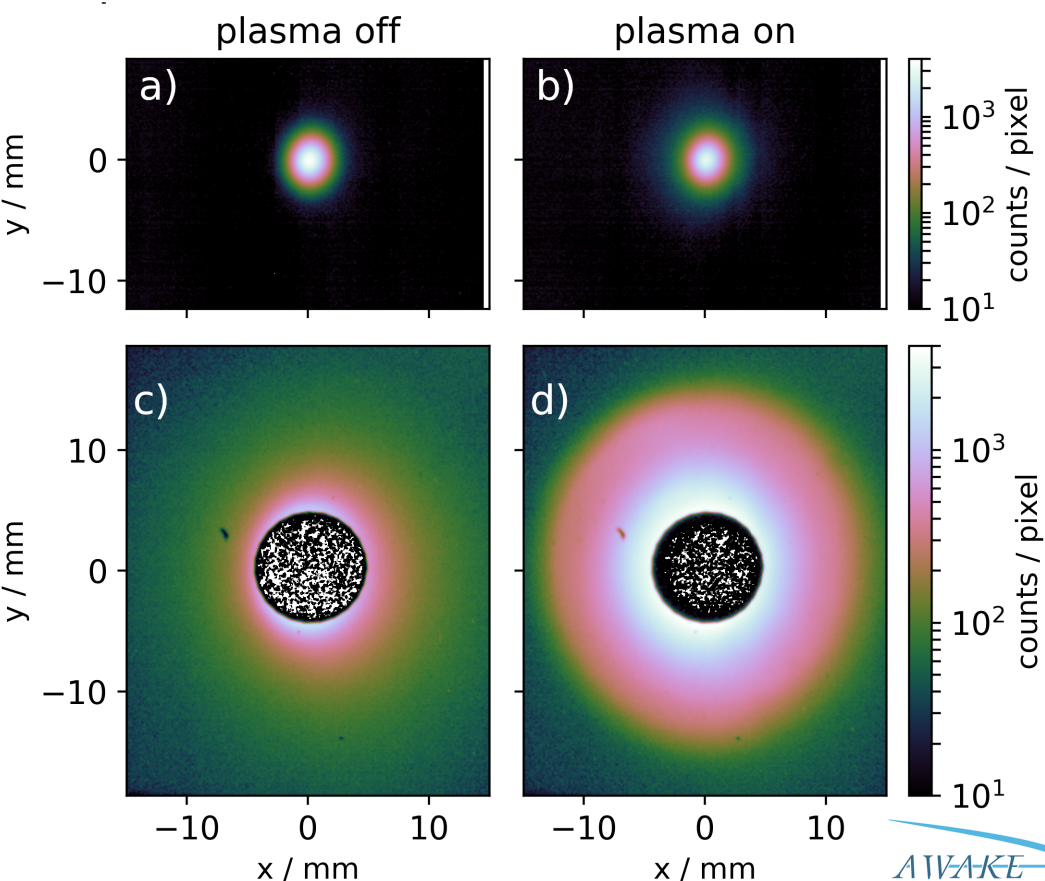
Phase 1: understand the physics of self-modulation process in plasma



- 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.

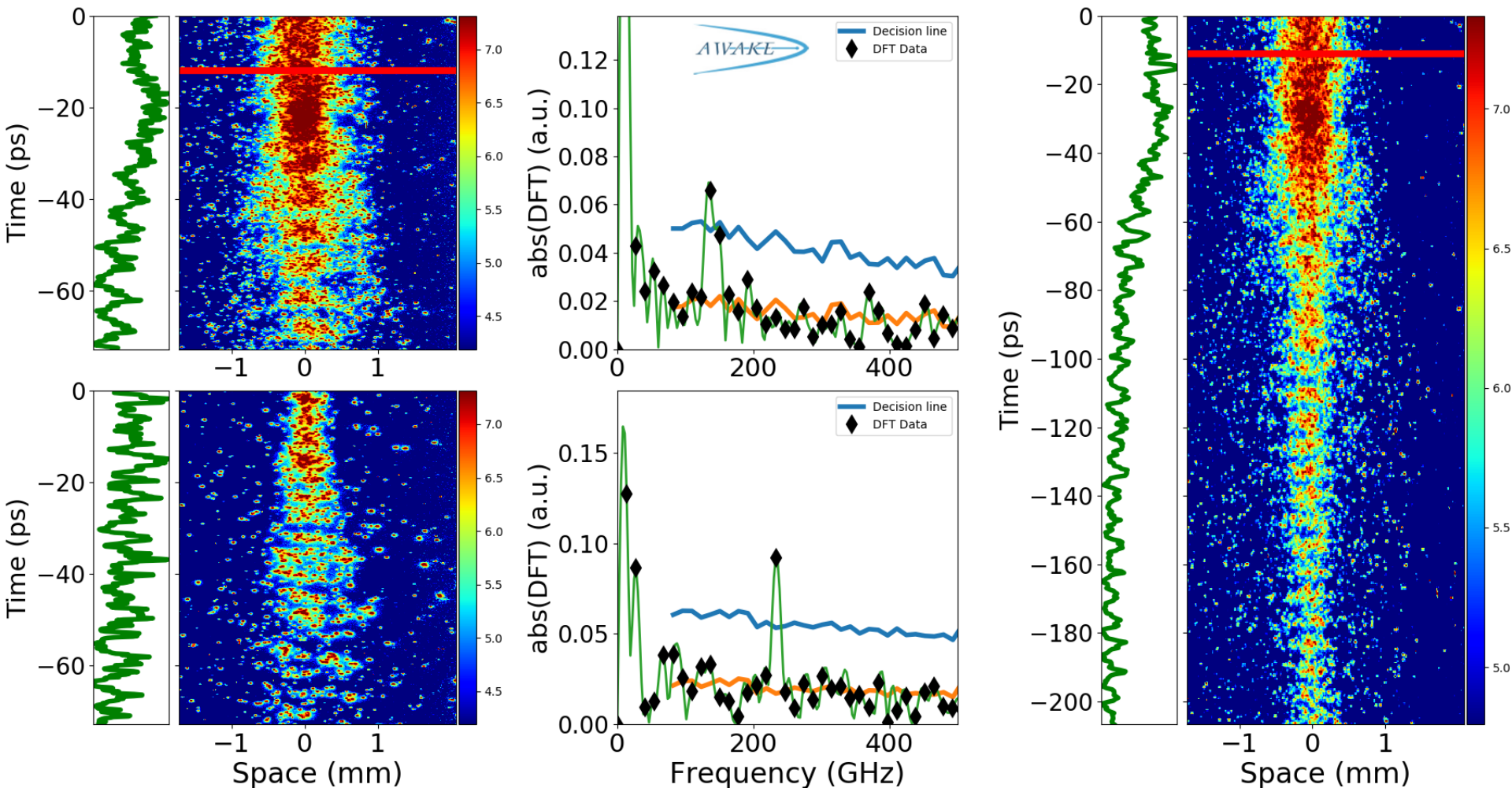
Beam halo measurements

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

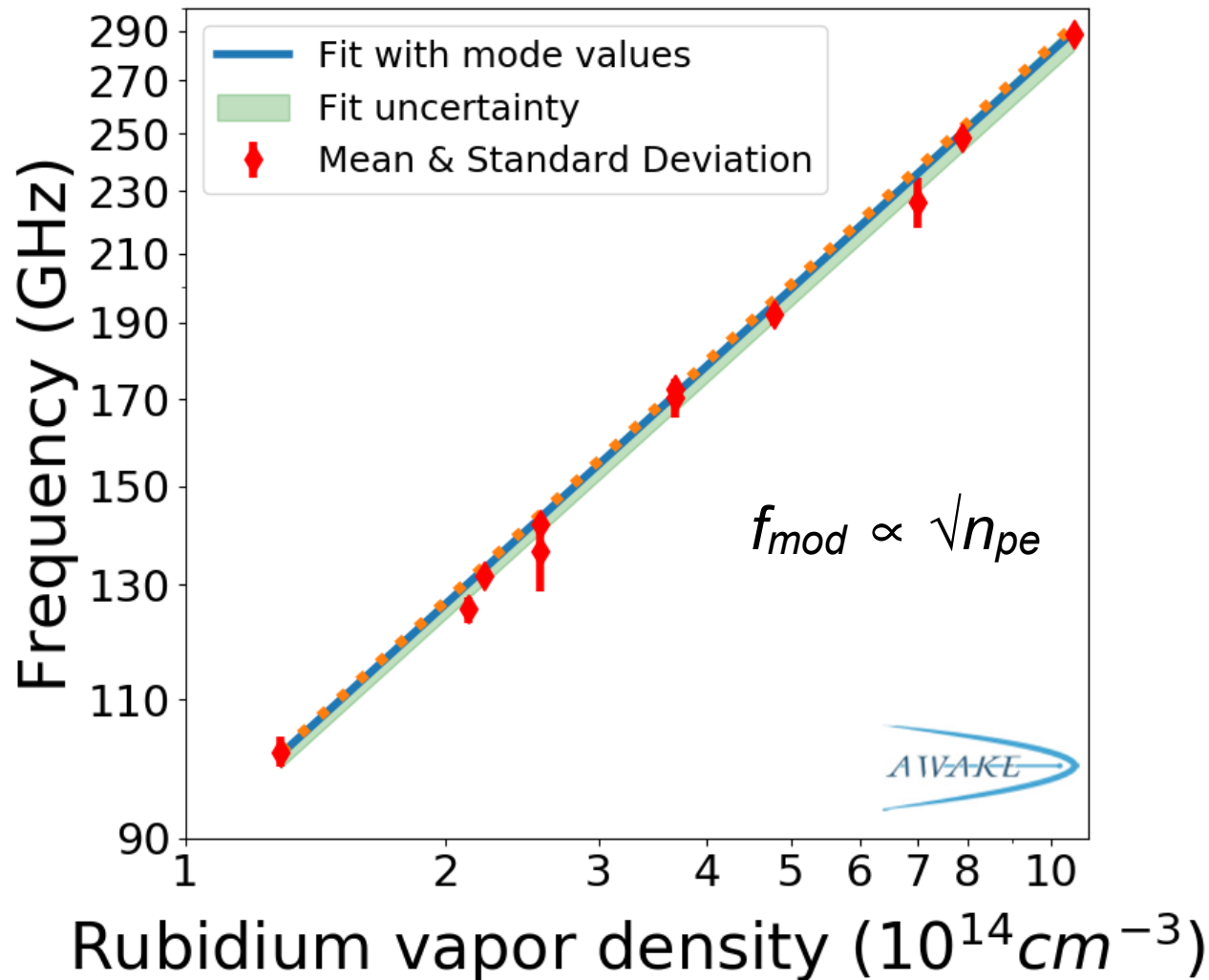


AWAKE Coll., M. Turner et al. "Experimental observation of plasma wakefield growth driven by the seeded self-modulation of a proton bunch", arXiv:1809.01191, submitted to *Phys. Rev. Lett.*

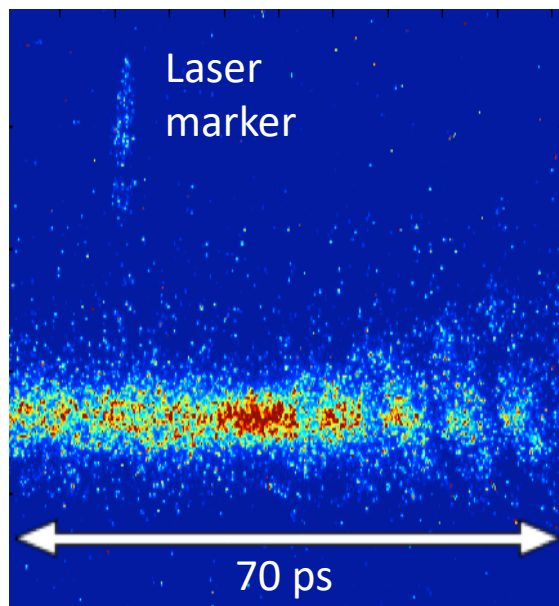
Self-modulation of proton bunch



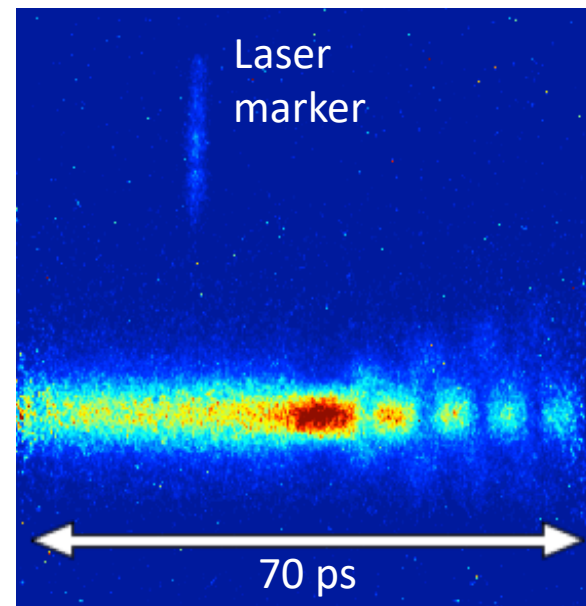
Self-modulation of proton bunch



Direct measurement using OTR – reproducibility



1 → 10 events

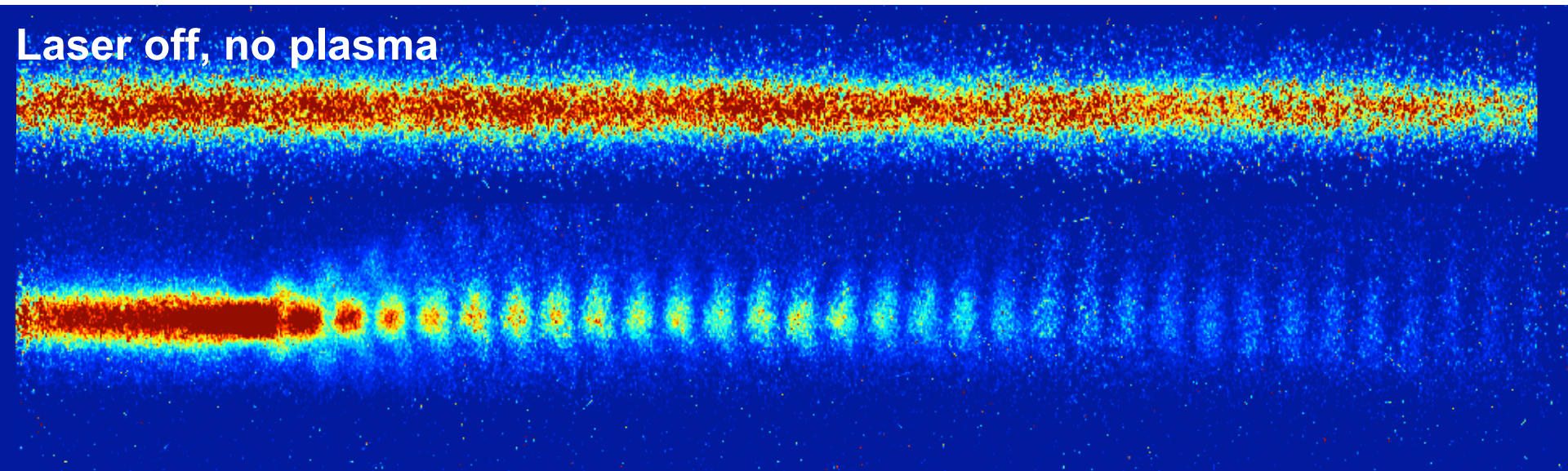


- Streak camera image from single event.
- What about multiple events ?

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

Direct measurement of self-modulation

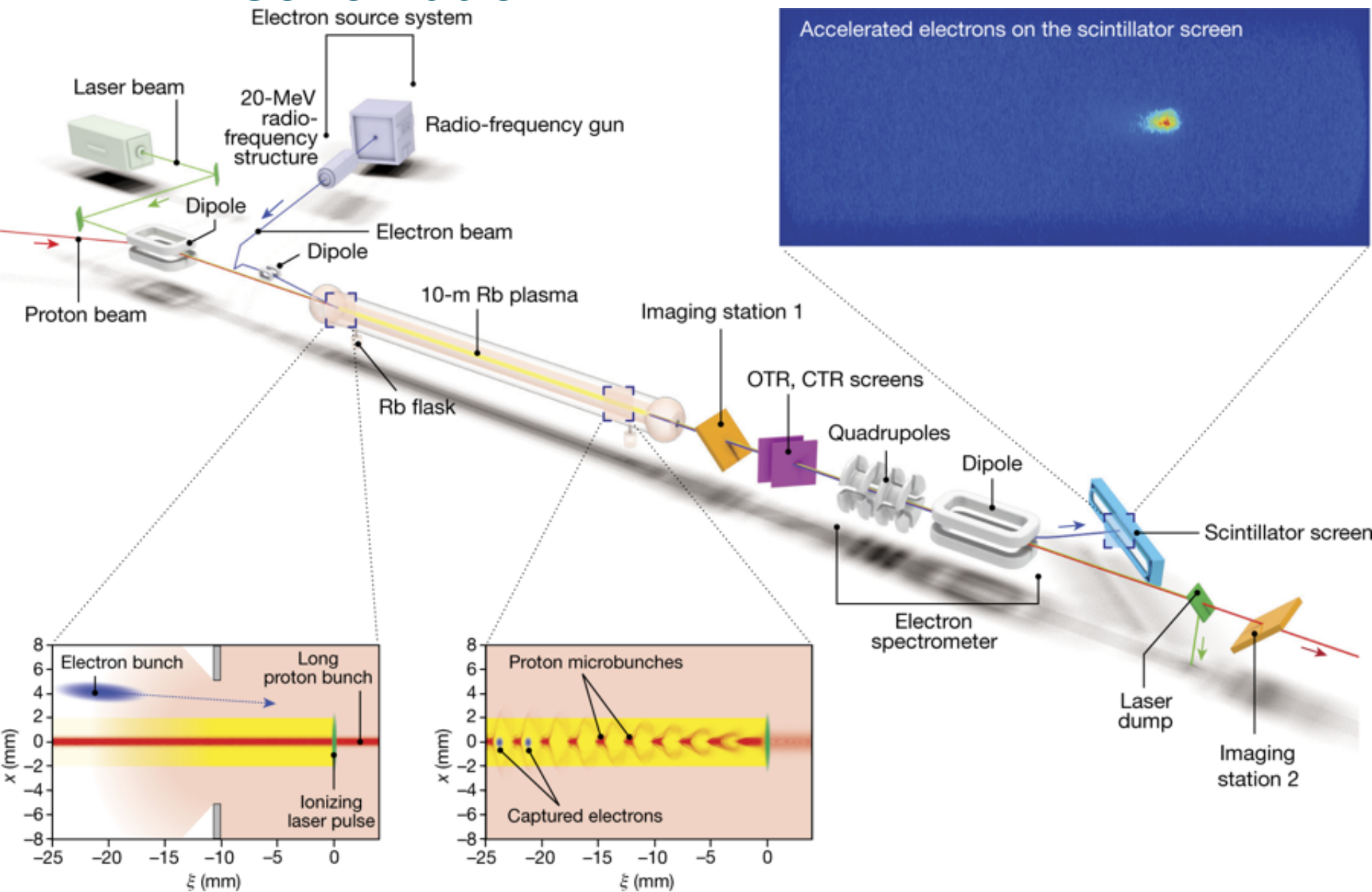
Laser off, no plasma



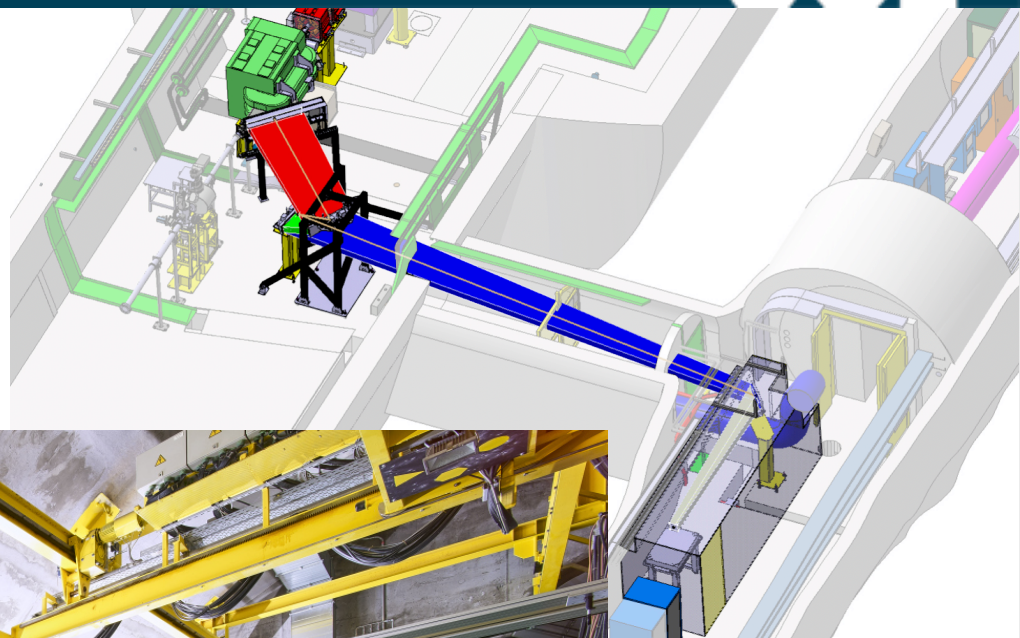
- Events stitched together.
- Clear modulation of the proton bunch.
- Highly reproducible phase between the bunches (and events).
- Crucial for injection of electrons.

Electron acceleration

AWAKE schematic

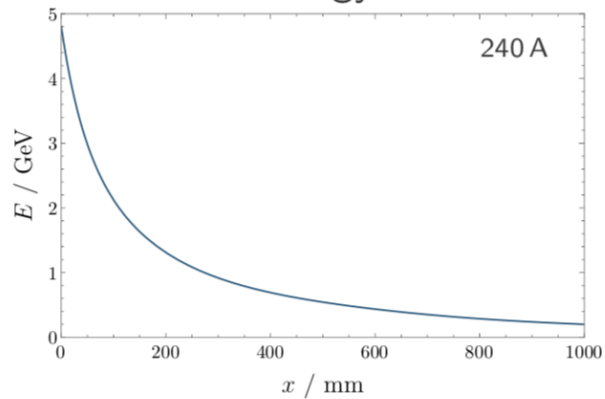


AWAKE spectrometer

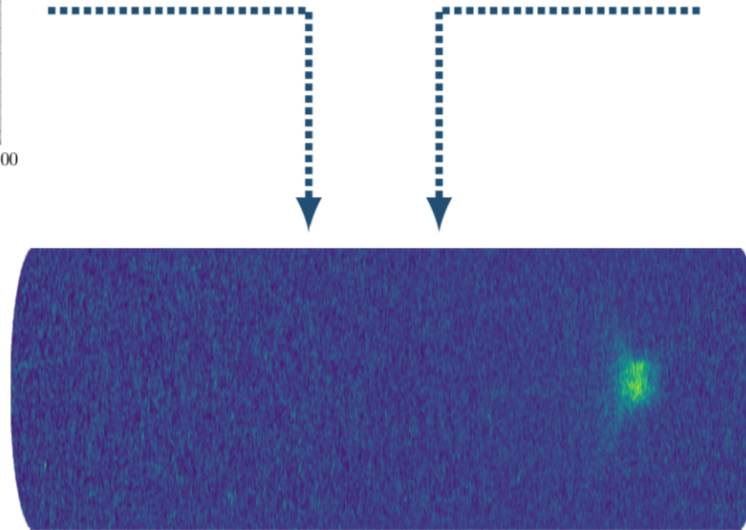
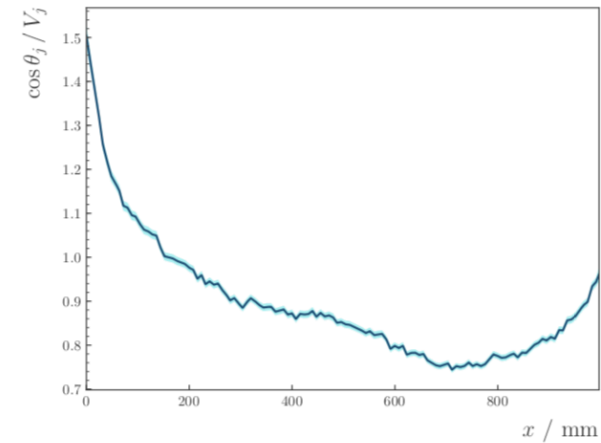


Spectrometer analysis

Position \leftrightarrow energy conversion



Geometric corrections

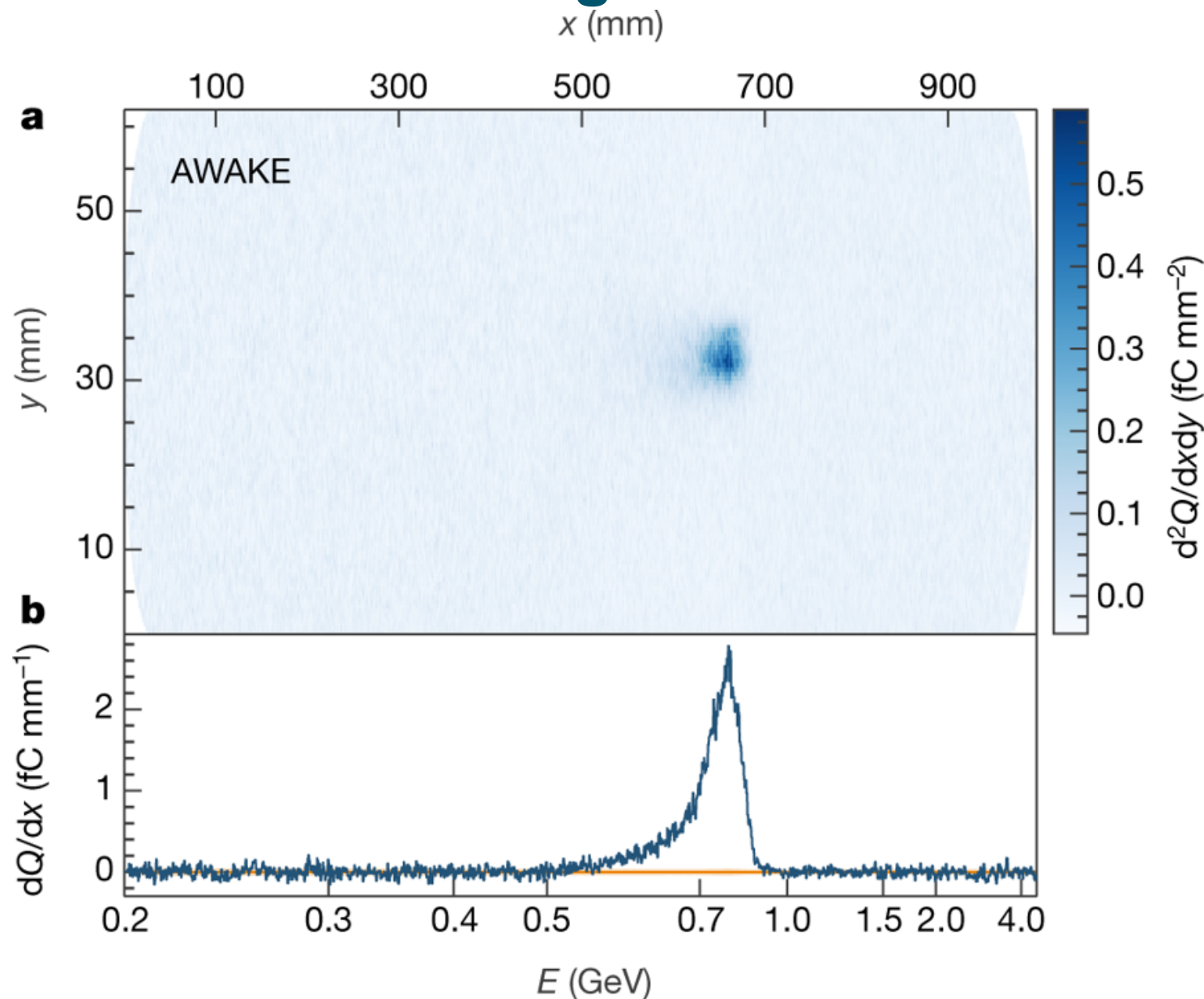


CCD count \leftrightarrow charge conversion

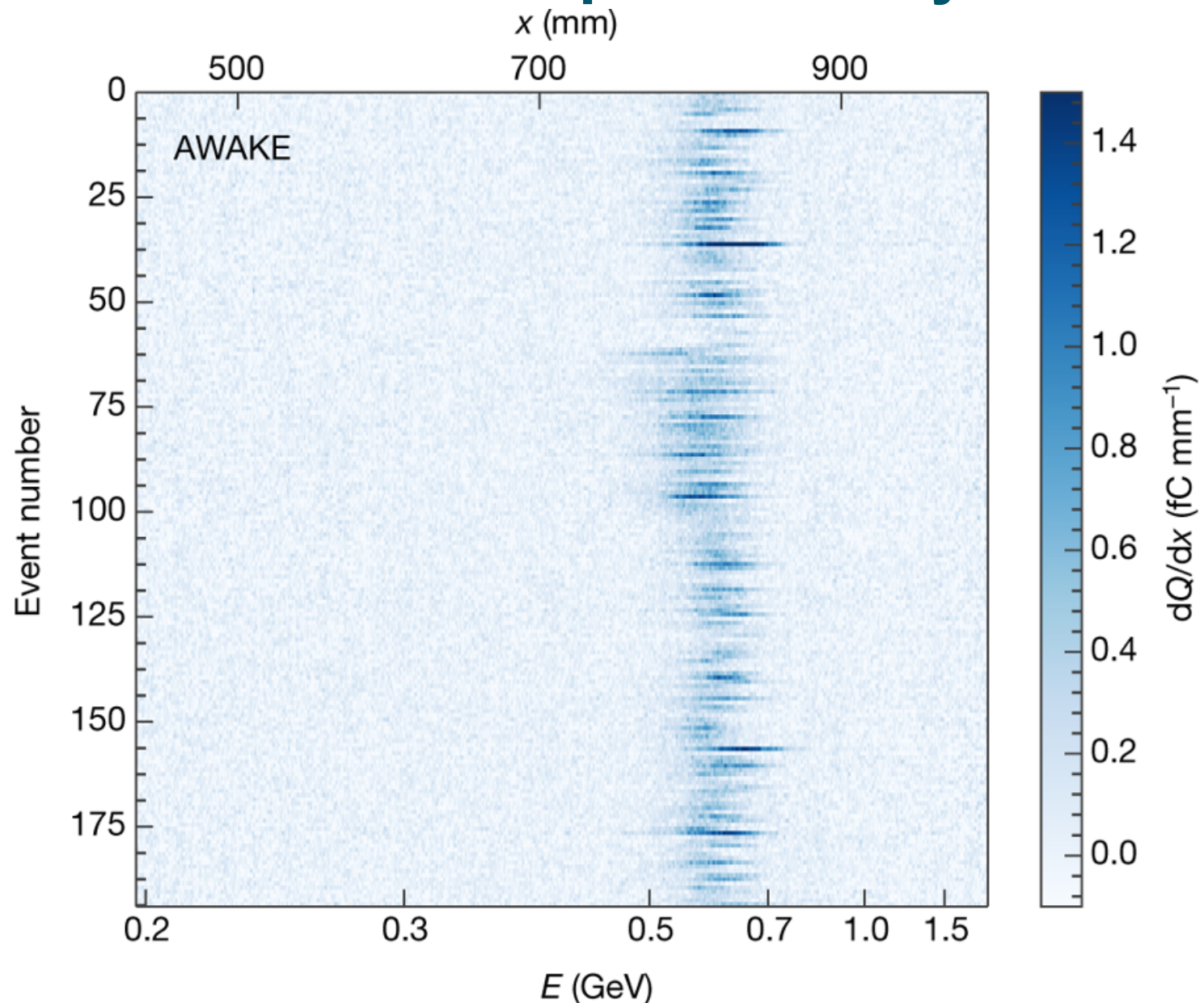
Background subtraction

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

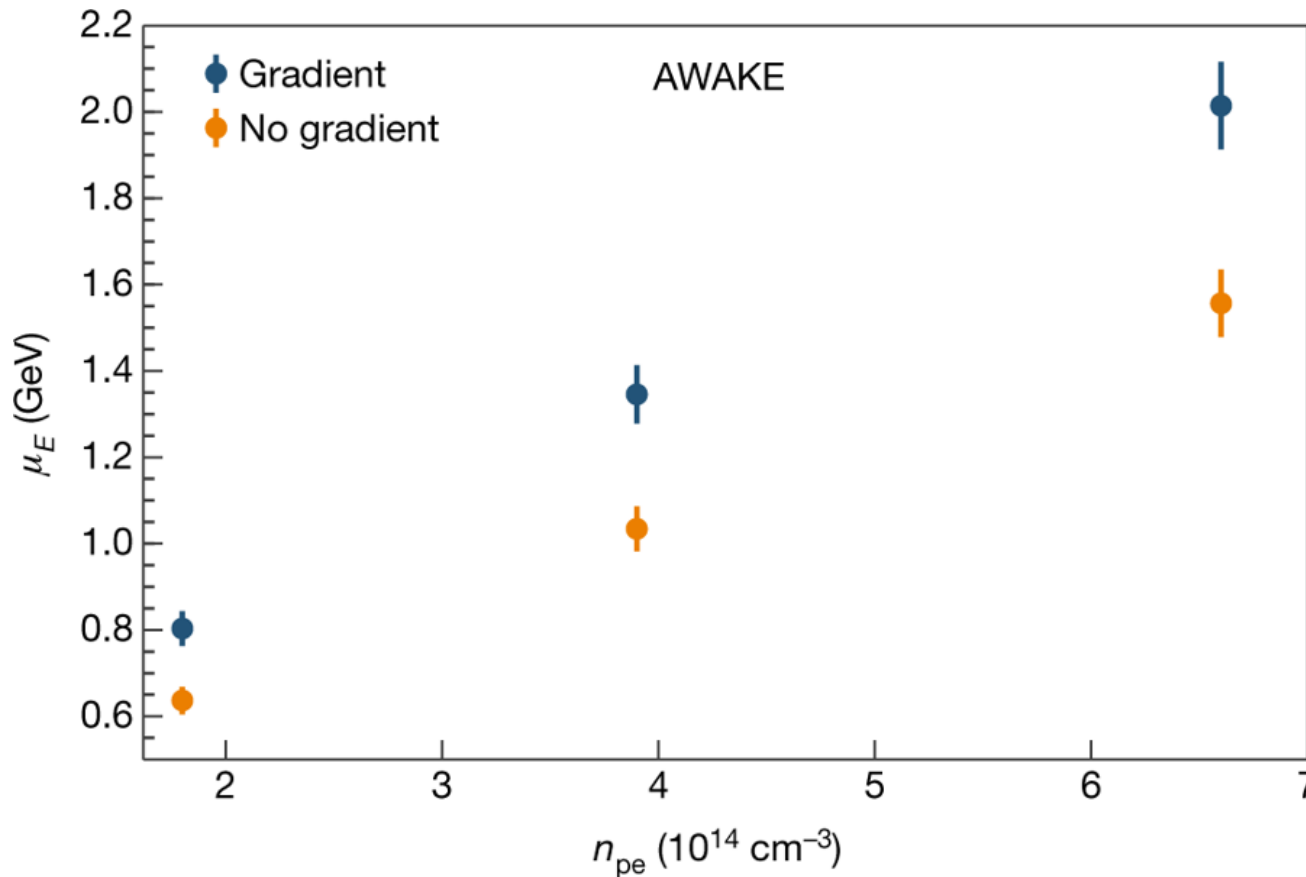
Electron acceleration signal



Electron acceleration reproducibility



Electron acceleration energy dependence



- Acceleration to 2 GeV is a great achievement; could go a bit higher.
- Simulation/theory predicted similar energy gains.
- Experiment not optimised for electron injection.
- Accelerated charge ($\sim 0.25 \text{ pC}$) 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.

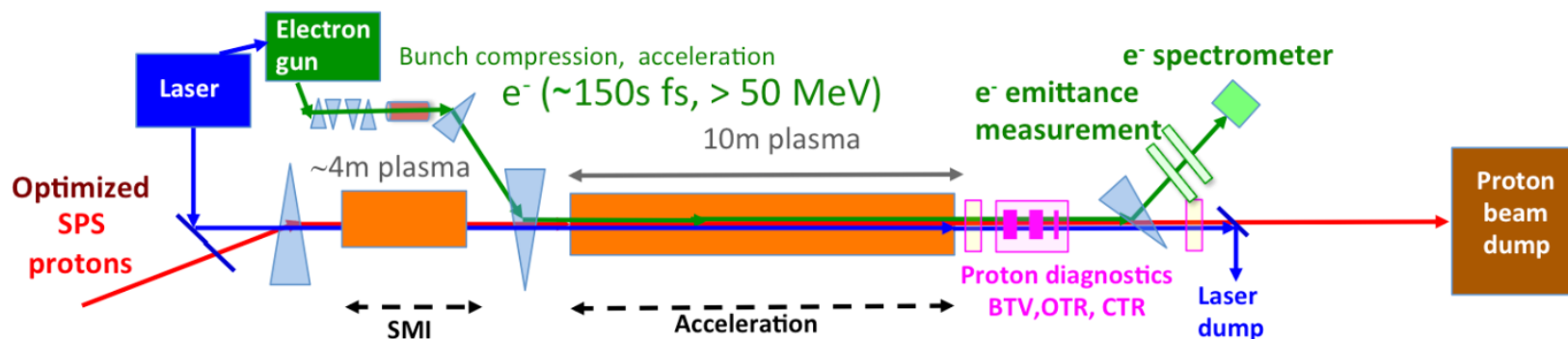
AWAKE plans

Immediate plans

- Have one more (4-week) data-taking period mid-Oct until mid-Nov when CERN proton running stops until 2021.
 - More understanding of electron injection
 - 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
- Work on design for Run 2.

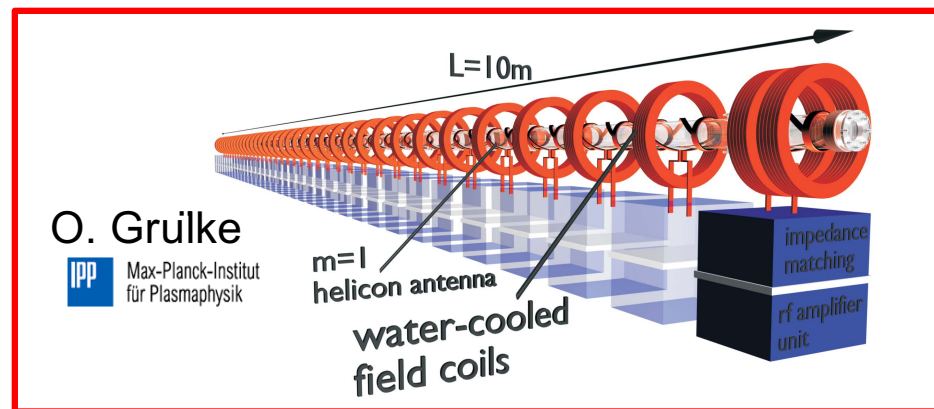
AWAKE Run 2

- 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.



Preliminary Run 2 electron beam parameters

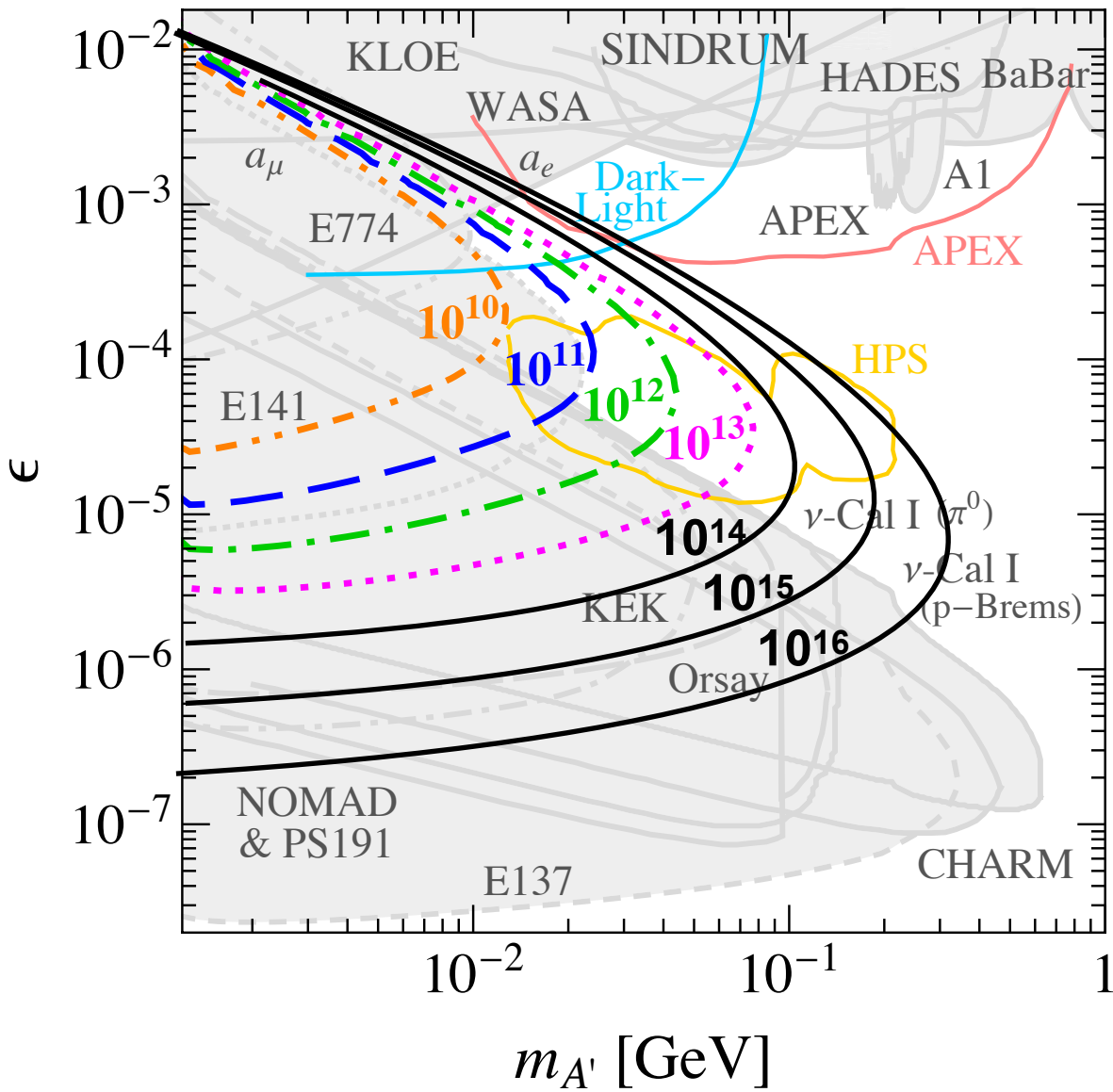
Parameter	Value
Acc. gradient	>0.5 GV/m
Energy gain	10 GeV
Injection energy	$\gtrsim 50$ MeV
Bunch length, rms	40–60 μm (120–180 fs)
Peak current	200–400 A
Bunch charge	67–200 pC
Final energy spread, rms	few %
Final emittance	$\lesssim 10$ μm



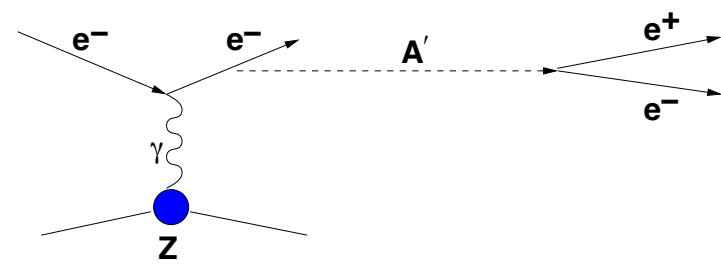
Applying AWAKE technology

- 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 $E_e \sim 20 \text{ GeV}$ for FELs.

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



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



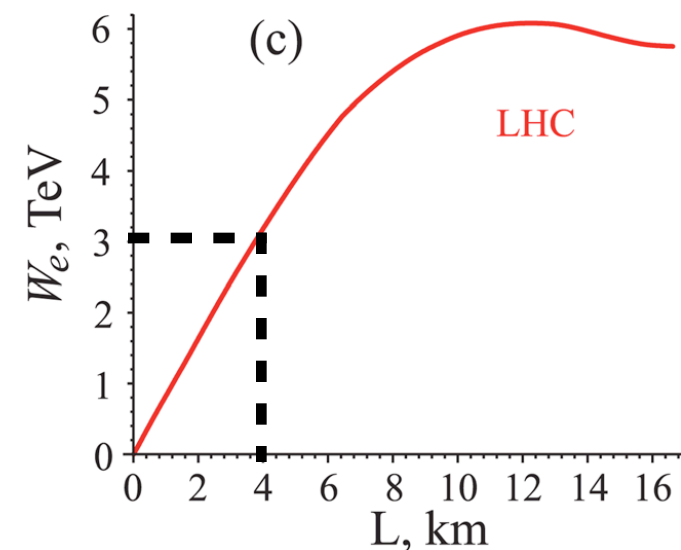
For $10^{10} - 10^{13}$ electrons on target with NA64.

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

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

Work ongoing...

Very high energy electron-proton collisions, VHEeP*



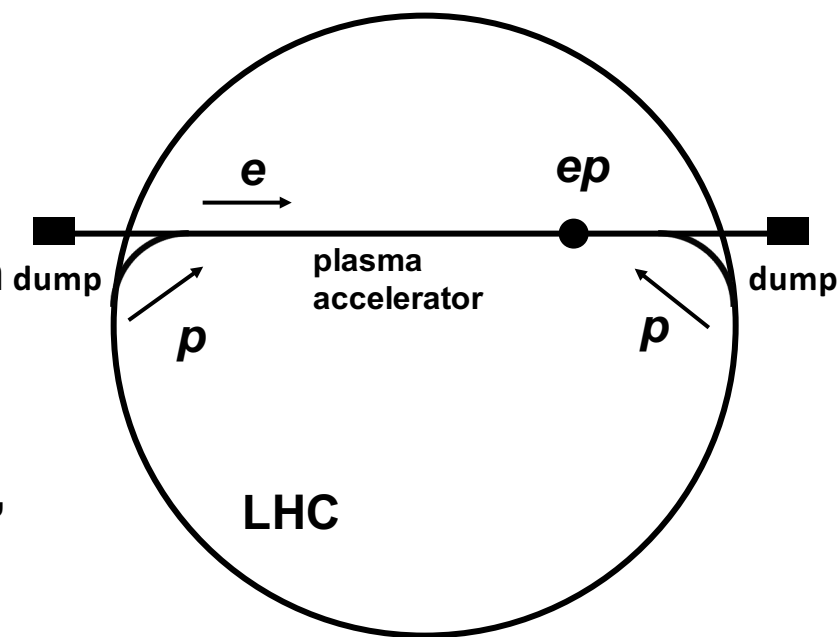
- What about very high energies in a completely new kinematic regime ?
- Choose $E_e = 3 \text{ TeV}$ as a baseline for a new collider with $E_p = 7 \text{ TeV} \Rightarrow \sqrt{s} = 9 \text{ TeV}$. Can vary.
 - Centre-of-mass energy $\times 30$ higher than HERA.
 - Reach in (high) Q^2 and (low) Bjorken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

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

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

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

More studies needed.



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.
 - Only a small amount of charge has been accelerated.
- More data to be taken and investigation of process in 2018.
- Developing a Run 2 programme for 2021–4.
- Aim to apply AWAKE technology to high energy physics experiments.

Back-up

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: $E_e \sim 50 \text{ GeV}$, 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 $\sqrt{s} = 9 \text{ TeV}$, $\times 30$ 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

