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Particle physics experiments using the novel AWAKE accelerator technology

Matthew Wing (UCL)

- Motivation and introduction to plasma wakefield acceleration
- Proton-driven plasma wakefield acceleration and the AWAKE experiment
- Results from AWAKE Run 1 and plans for AWAKE Run 2
- Application of AWAKE technology
  - Enabling the search for dark photons
  - Matter and the strong force (QCD) at the highest *ep* energies
- Summary

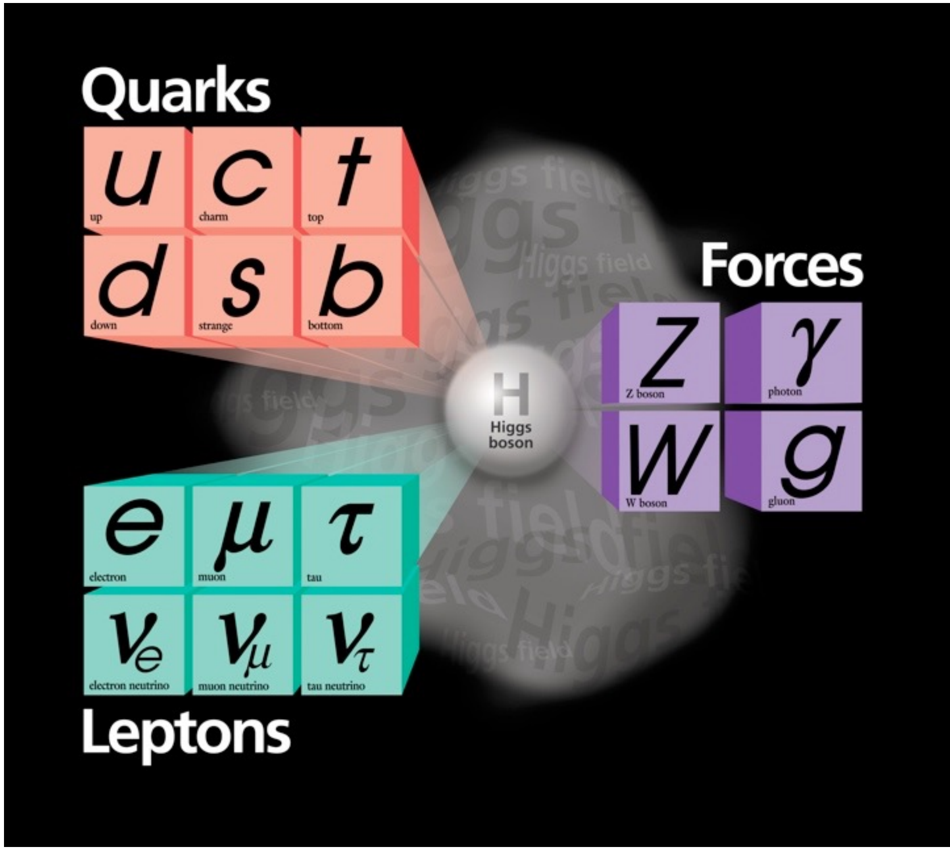
RAL Seminar — 11 August 2021

Motivation and introduction

Motivation: big questions in particle physics

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

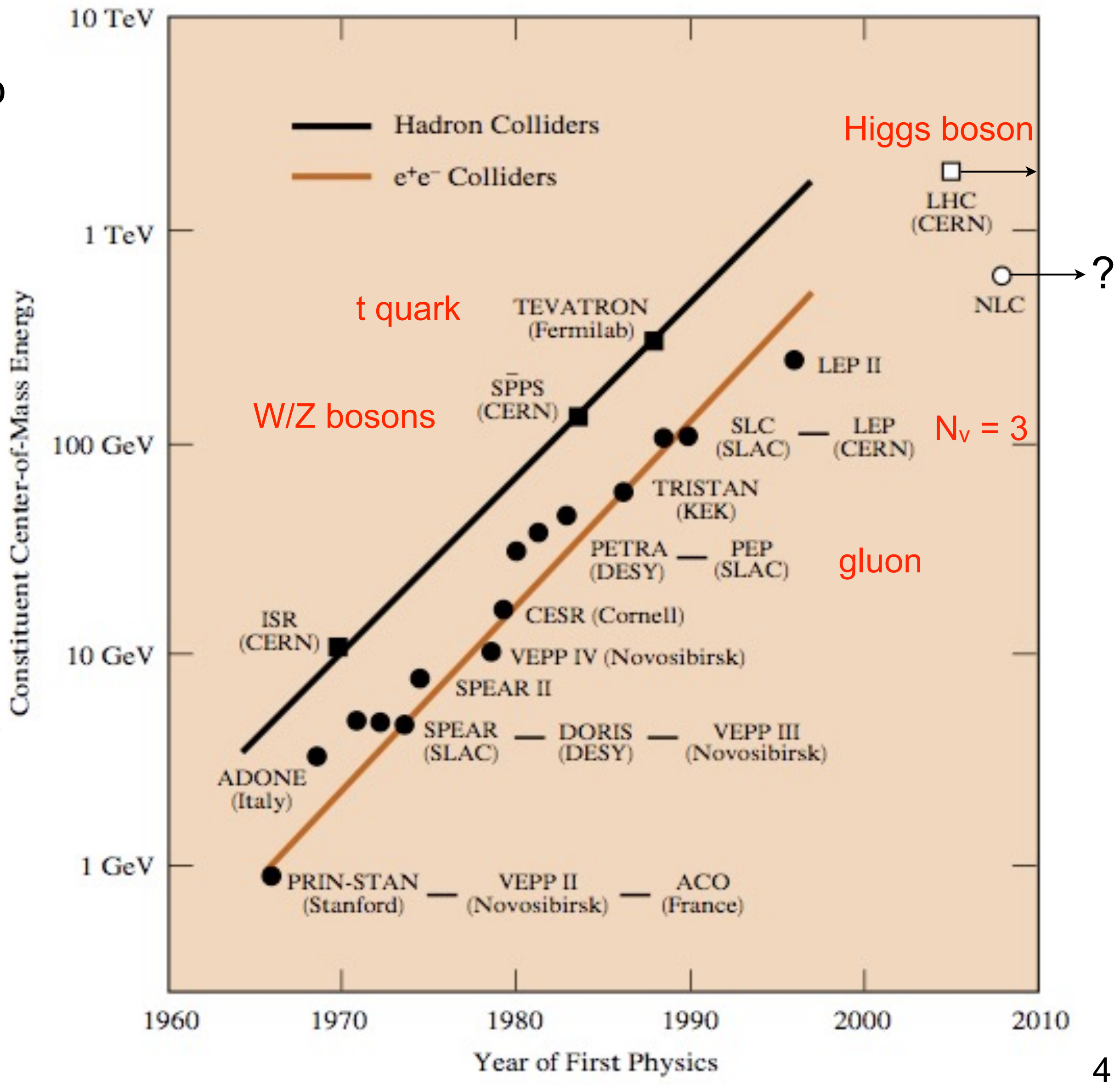
- a detailed understanding of the Higgs Boson/mechanism
- neutrinos and their masses
- why is there so much matter (vs anti-matter) ?
- why is there so little matter (*5%* of Universe) ?
- what is dark matter and dark energy ?
- why are there three families ?
- hierarchy problem; can we unify the forces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



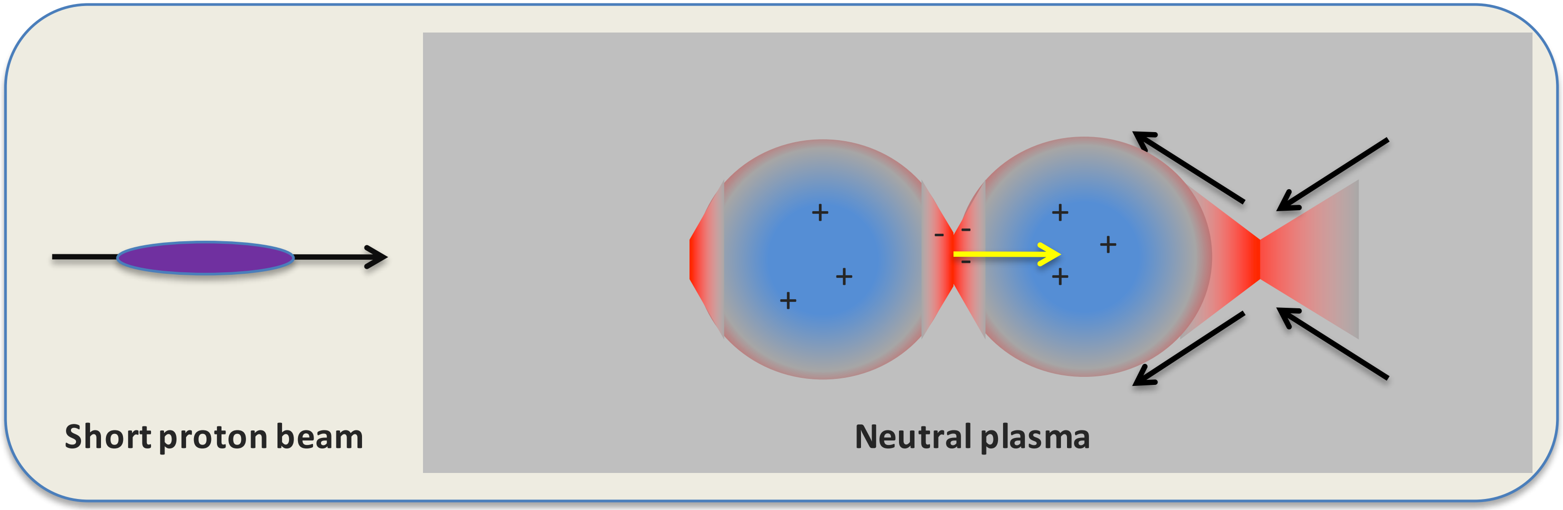
Plasma wakefield acceleration as a solution

- 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 :

  - Small energy spread;
  - 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 :

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

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

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

Relevant physical quantities :

- Oscillation frequency, 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

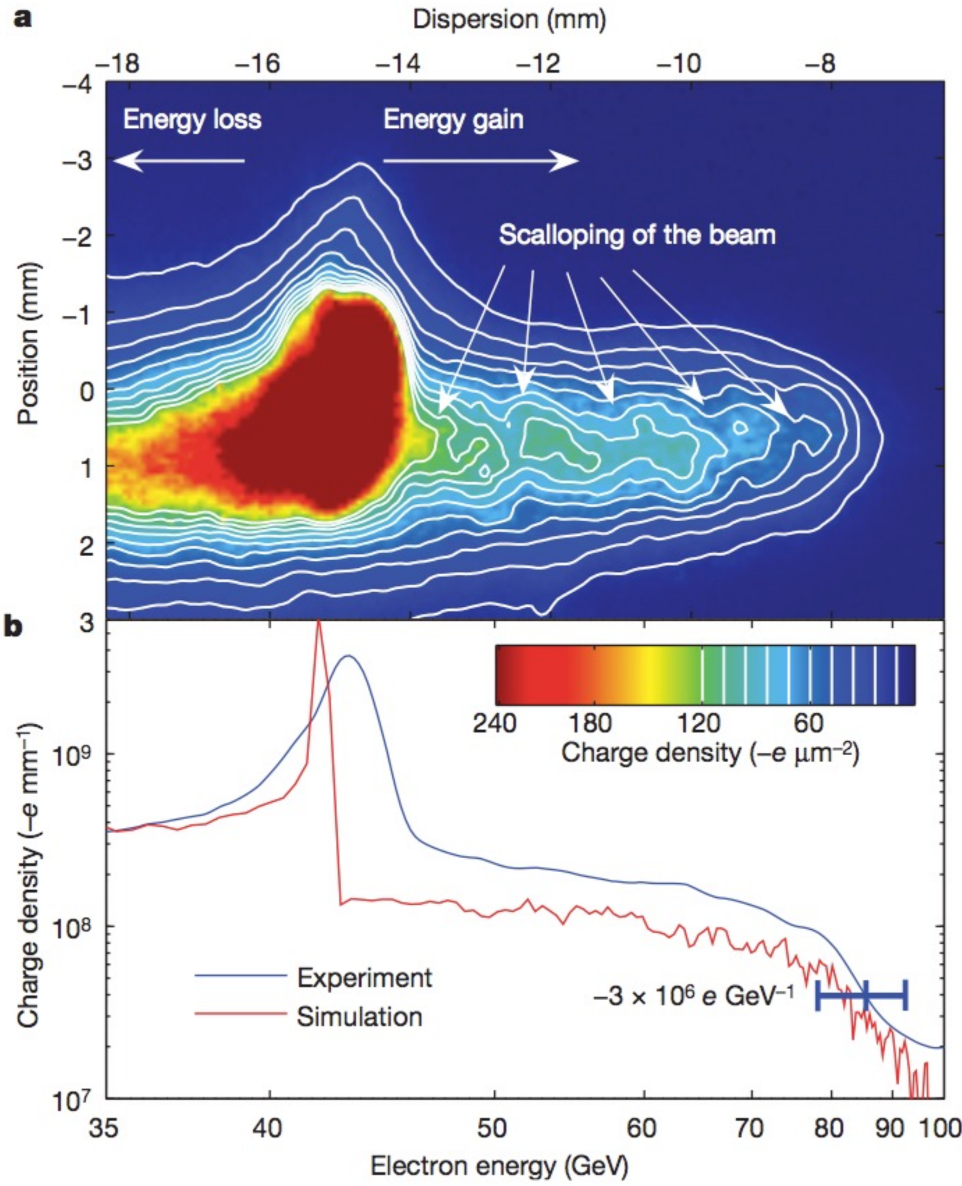
High gradients with :

- **Short drive beams**
- **Pulses with large number of particles**

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*.
  - - Recent success of *8 GeV* at BELLA*
- Experiments at SLAC§ used a particle (electron) beam :
  - - Initial energy $E_e = 42$ *GeV*
  - - Gradients up to ~ *52 GV/m*
  - - Energy doubled over ~ *1 m*
  - - Particles in head of beam ‘transferred’ energy to particles in tail
- Ongoing electron-driven projects at:
  - - FACET-II at SLAC
  - - FLASHForward at DESY



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* A.J. Gonsalves et al., PRL **122** (2019) 084801

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

Proton-driven plasma wakefield acceleration and the AWAKE experiment

Why protons ?

Lasers do not have enough energy :

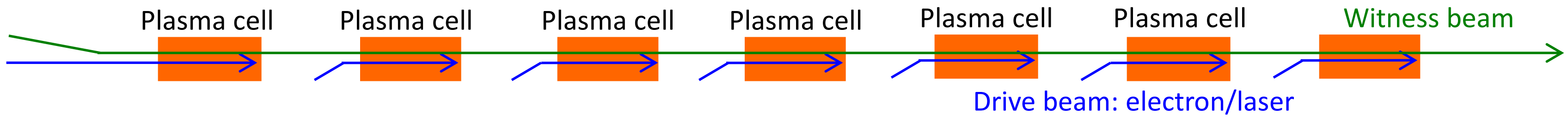
- Can not propagate long distances in plasma
- Can not accelerate electrons to high energy
- For high energy, need multiple stages.

Electrons also limited by initial energy :

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

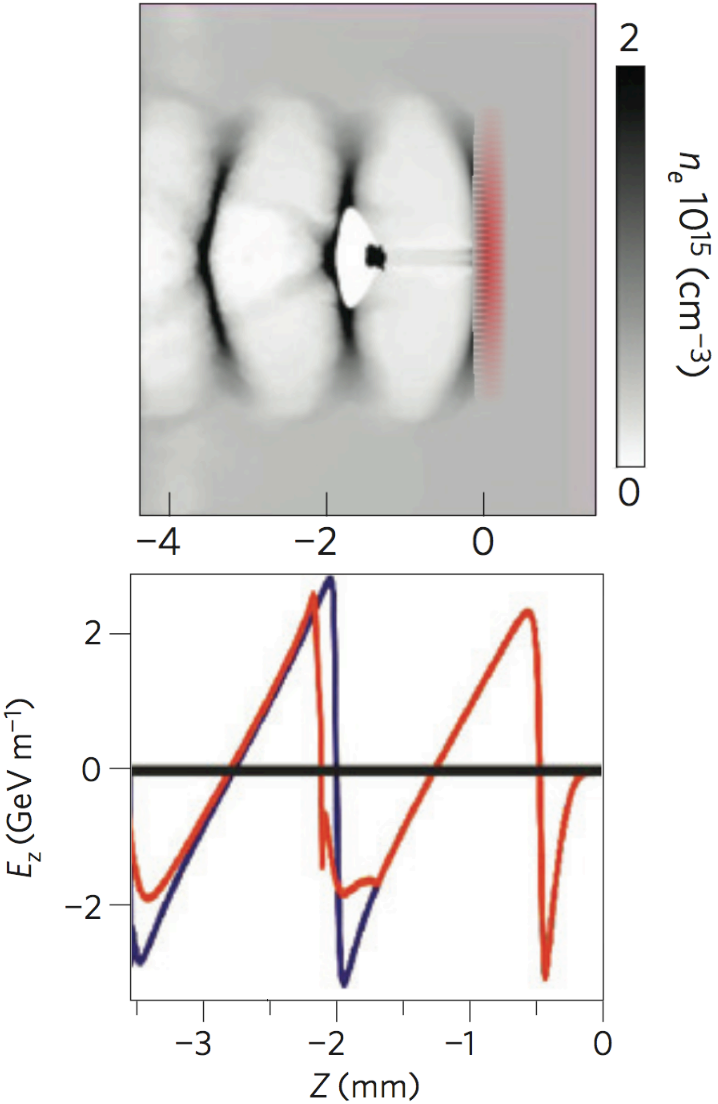
Proton beams at TeV scale and with high stored energy are around today : what about using protons ?

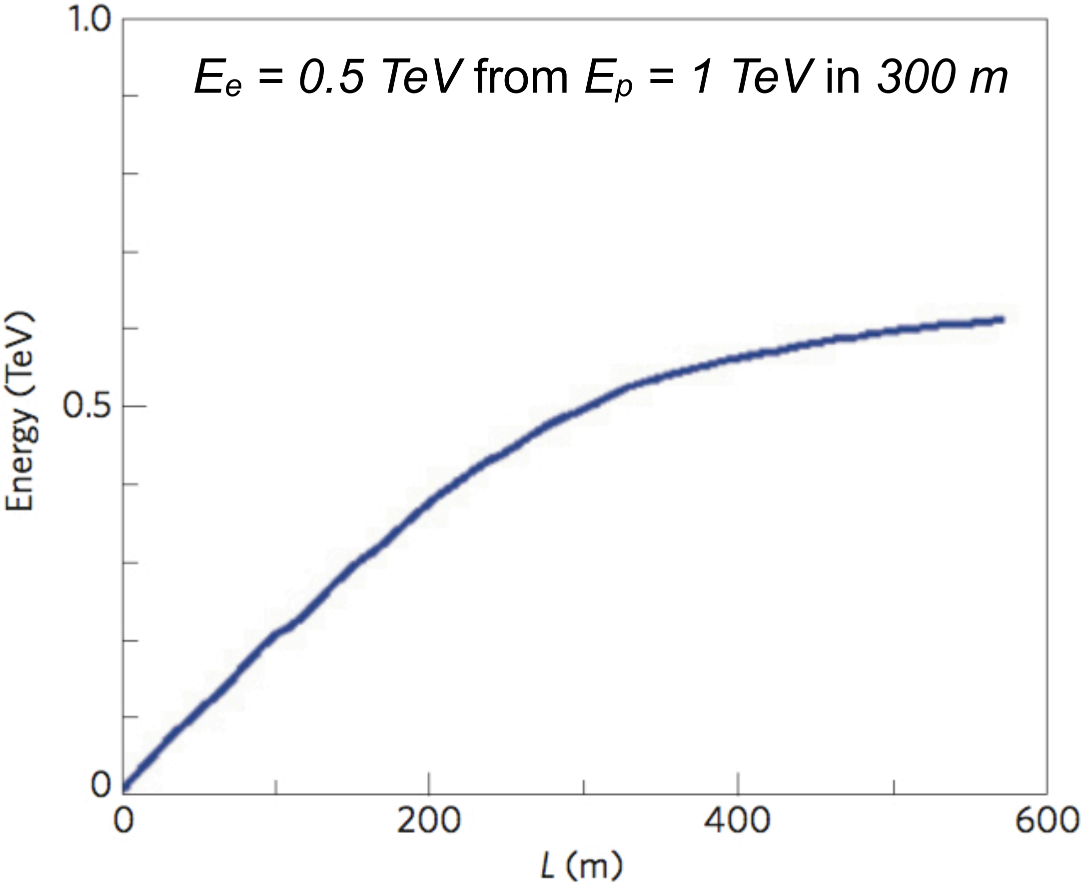
Laser/electron driver



Proton driver

Proton-driven plasma wakefield acceleration concept*




E_e = *0.5 TeV* from E_p = *1 TeV* in *300 m*

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

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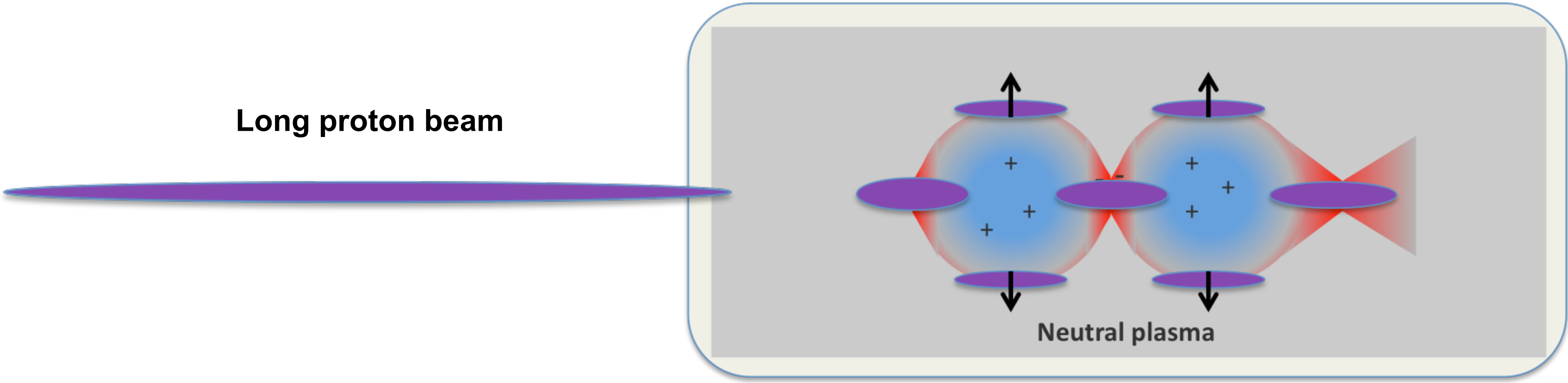
* A. Caldwell *et al.*, Nature Physics **5** (2009) 363.

Long proton bunches ?

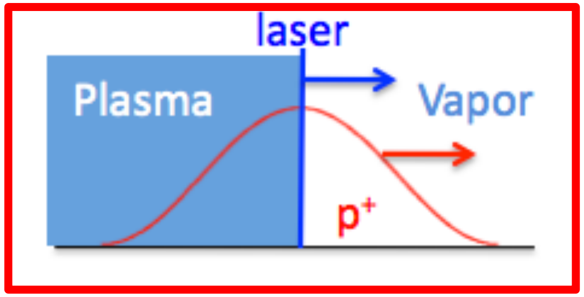
Use self-modulation where micro-bunches are generated by a transverse modulation of the bunch density.

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

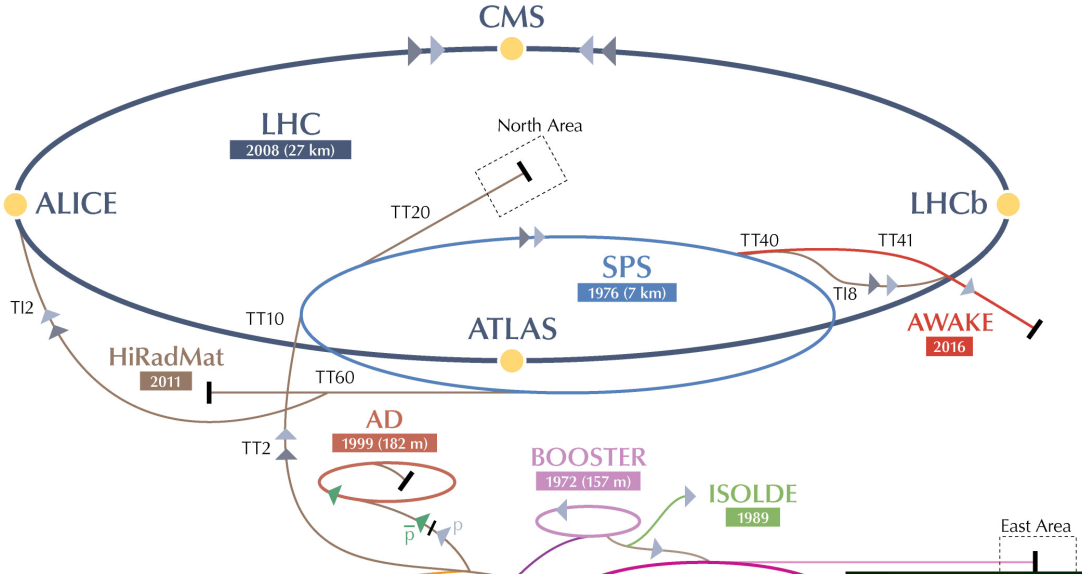


Self-modulated driver beam

- Micro-bunches are spaced 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.**



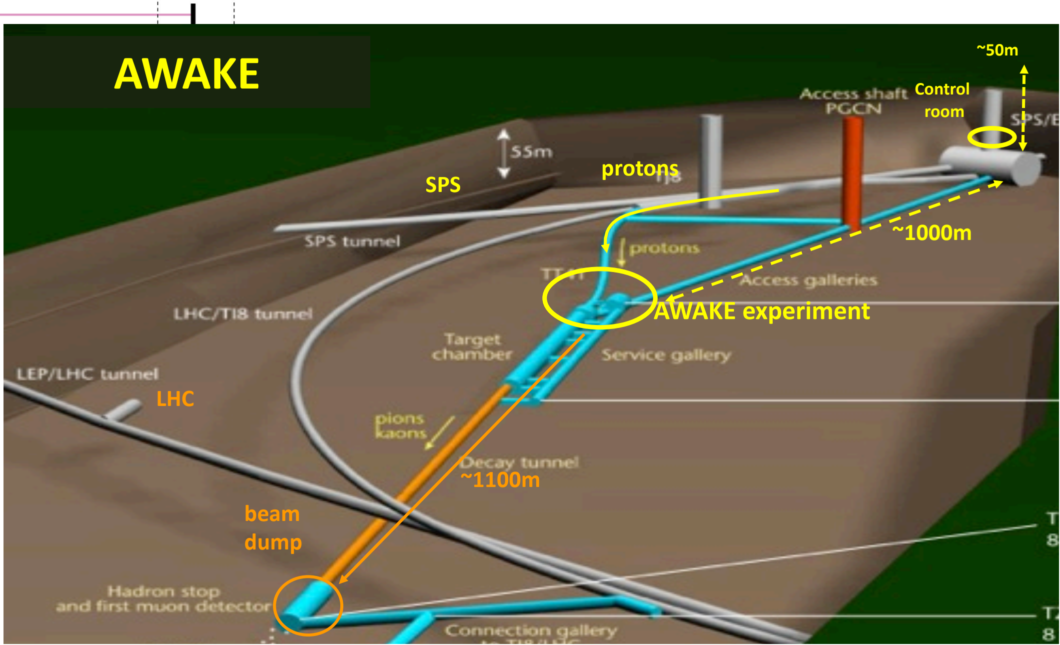
AWAKE experiment at CERN



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

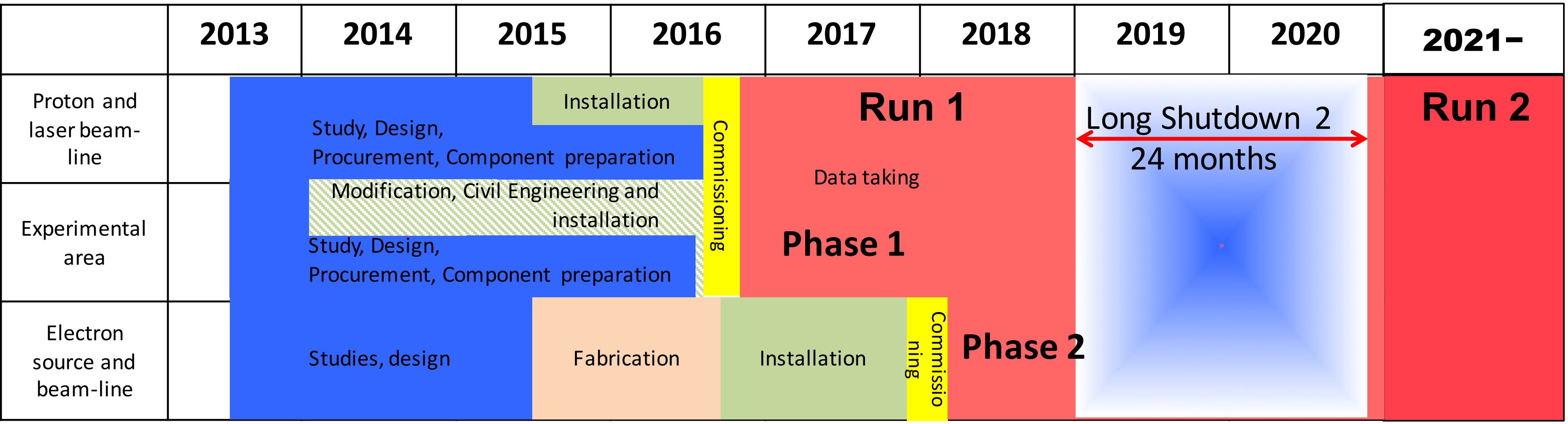
Advanced proton-driven plasma wakefield experiment.

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


2013 2014 2015 2016 2017 2018 2019 2020 2021–

Proton and laser beam-line

Experimental area

Electron source and beam-line

Installation

Study, Design, Procurement, Component preparation

Modification, Civil Engineering and installation

Study, Design, Procurement, Component preparation

Commissioning

Studies, design

Fabrication

Installation

Commissioning

Run 1

Data taking

Phase 1

Phase 2

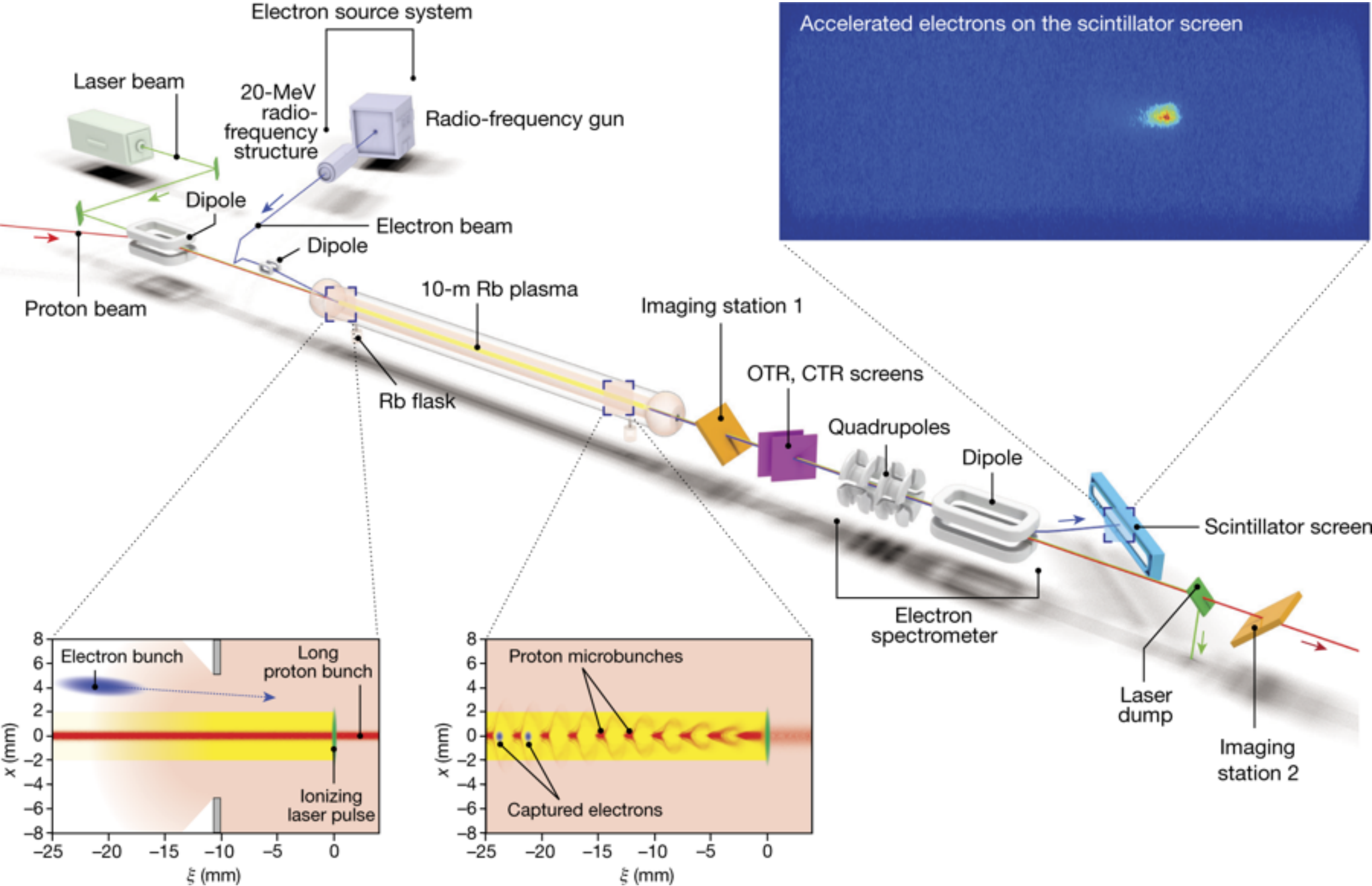
Long Shutdown 2

24 months

Run 2

- 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−].
- Then HEP applications …

AWAKE schematic



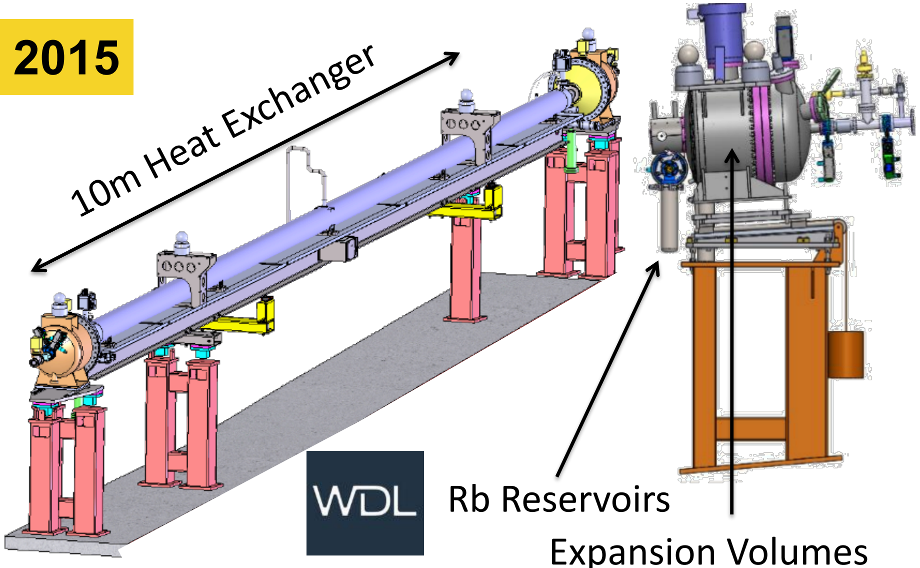
AWAKE proton beam

Parameter	Protons
Momentum (GeV)	400
Momentum spread (GeV)	0.14
Particles per bunch	3×10^{11}
Charge per bunch (nC)	48
Bunch length (cm)	6–12 (0.4 ns)
Norm. emittance (mm mrad)	3.5
Repetition rate (Hz)	1/30
Spot size at focal point (μm)	200 ± 20

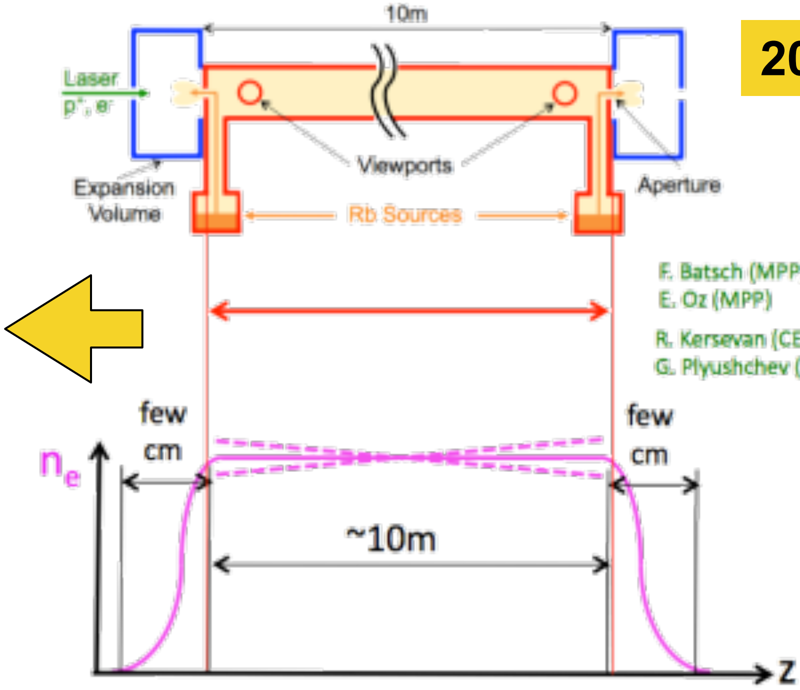

750 m proton beam line

AWAKE plasma cell

2015

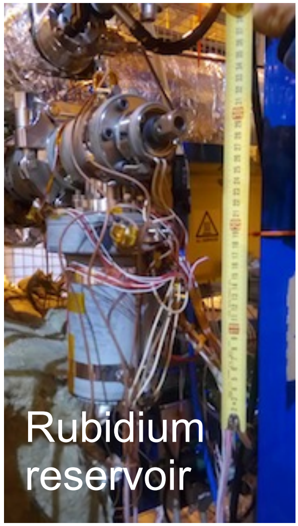


2014



F. Batsch (MPP)
E. Oz (MPP)
R. Kersevan (CERN)
G. Plyushchev (CERN/MPP/EPFL)


Rubidium


Rubidium reservoir


Plasma source in AWAKE

2016

AWAKE plasma cell requirements

The physics goals and technological feasibility place constraints on the plasma cell:

- Length, $L \sim 10\ m$.
- Radius, r_p, larger than three proton bunch rms radii or $\sim 1\ mm$.
- Density, n_e, in the range $10^{14} - 10^{15}\ cm^{-3}$.
- Density uniformity, $\delta n_e/n_e$ of order 0.2% or better.
- Reproducible density.
- Gas/vapour easy to ionise.
- Allow for seeding of self-modulation.
- High-Z element to avoid background plasma ion motion.

A rubidium vapour source held at about $200\ ^oC$ with default density $7 \times 10^{14}\ cm^{-3}$ ($\lambda_p \sim 1.2\ mm$) chosen.

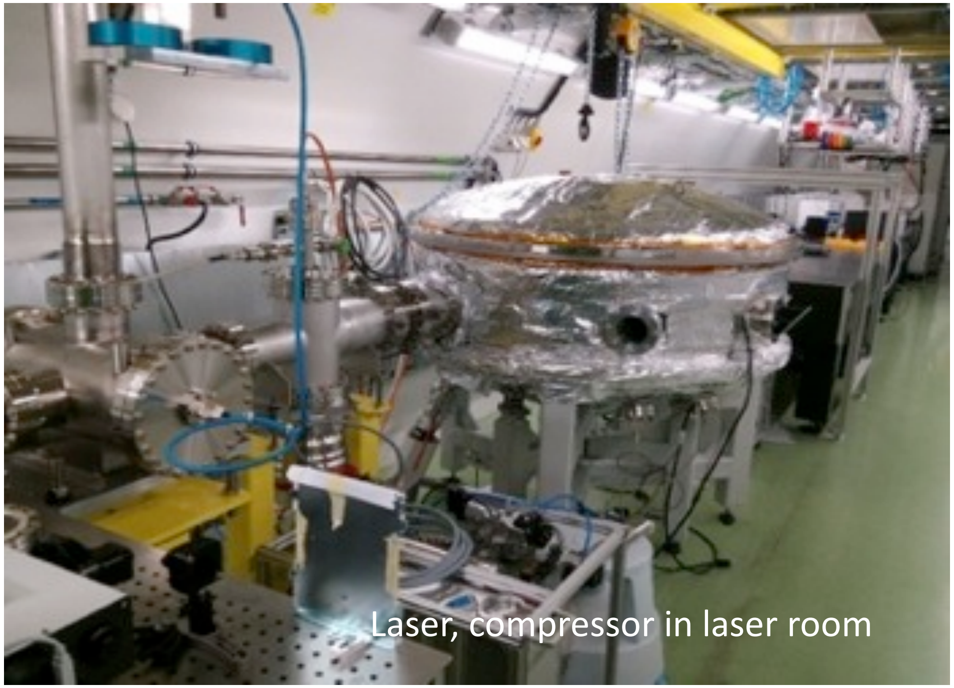
E. Öz, F. Batsch and P. Muggli, IPAC2014 Proc., p.1522;
E. Öz and P. Muggli, Nucl. Instrum. Meth. **A 740** (2014) 197.

Laser

Ti:sapphire laser needed for:

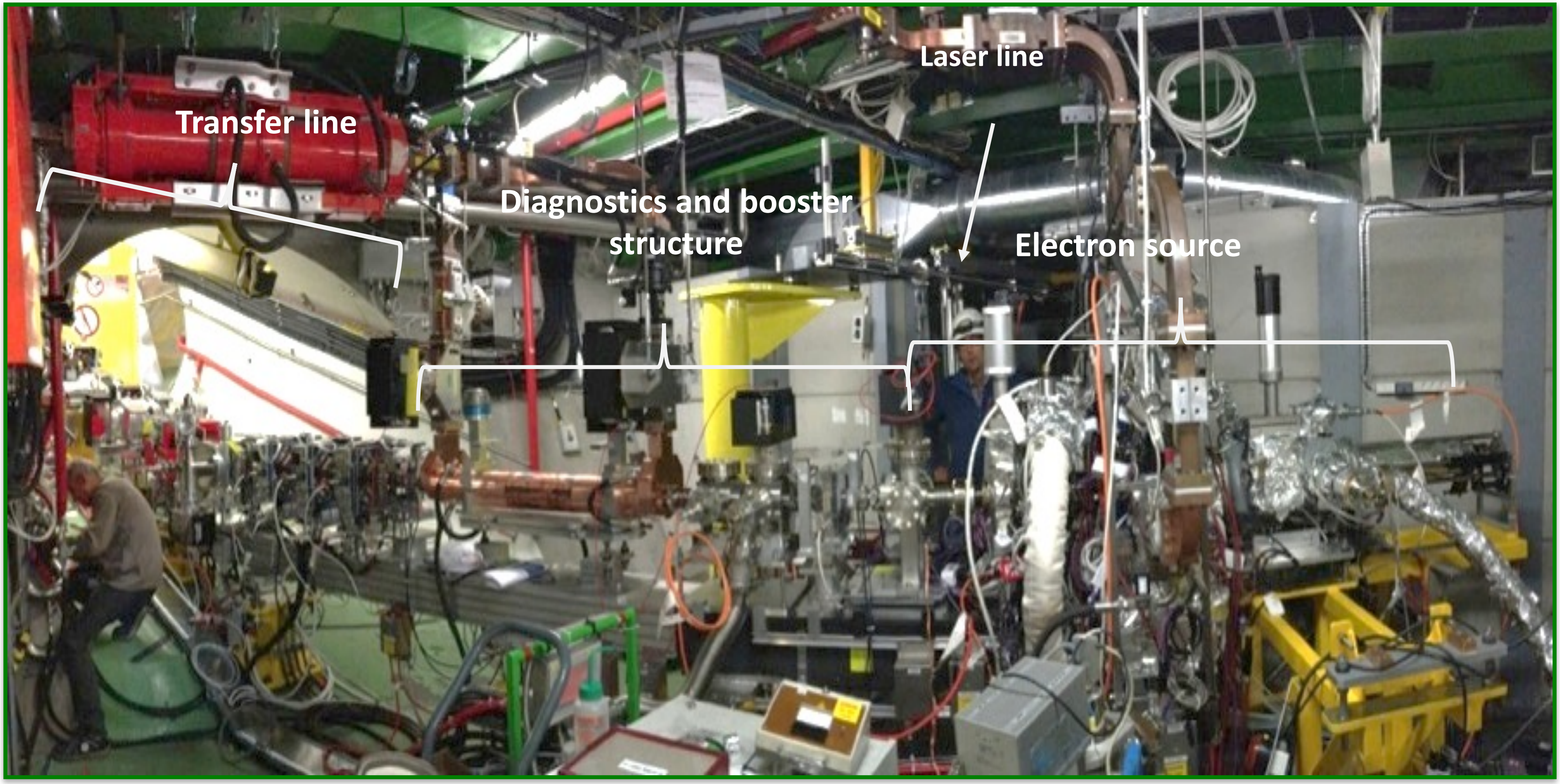
- Ionising vapour and seeding self-modulation in plasma.
- Diagnostic beam line.
- Beam to electron source.

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



Laser, compressor in laser room

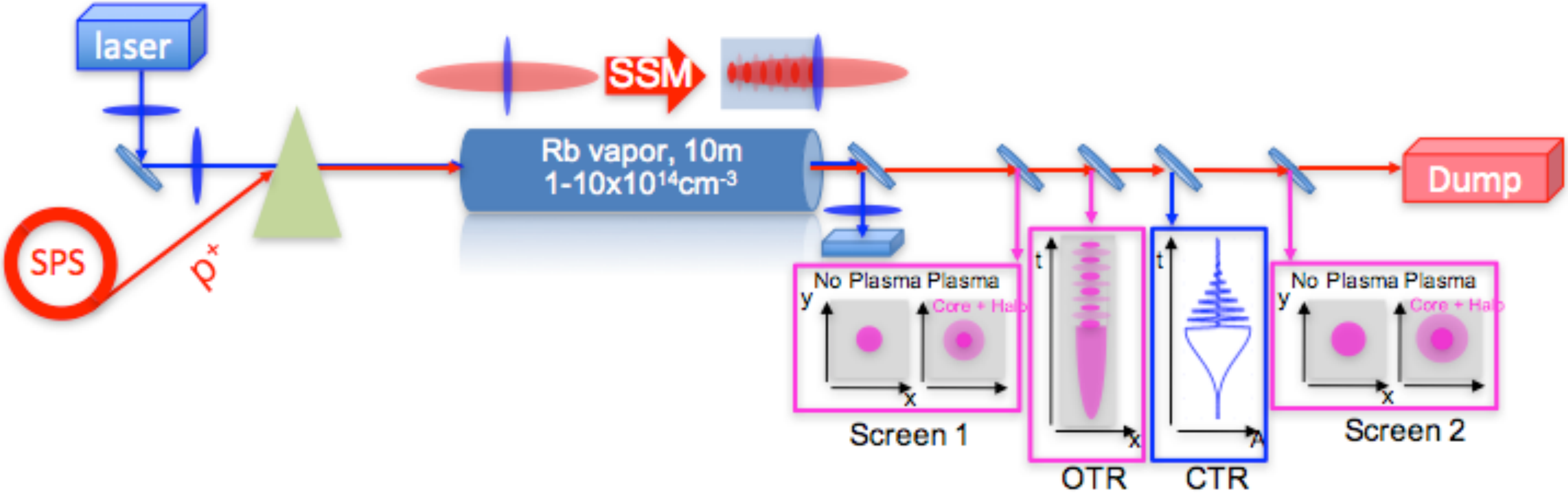
Electron beam



- Electron bunch up to ~650 pC, σ ~ 4 ps
- Produced at 5.5 MeV
- Accelerated up to 20 MeV
- 18 m beam line to plasma cell

Results from AWAKE Run 1 and plans for AWAKE Run 2

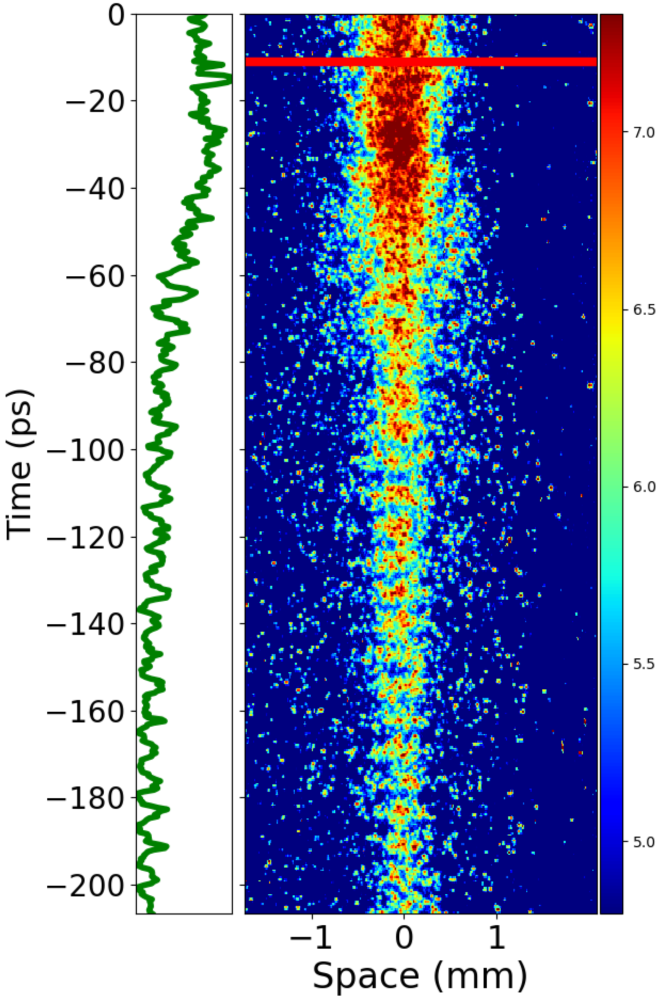
Proton micro-bunching

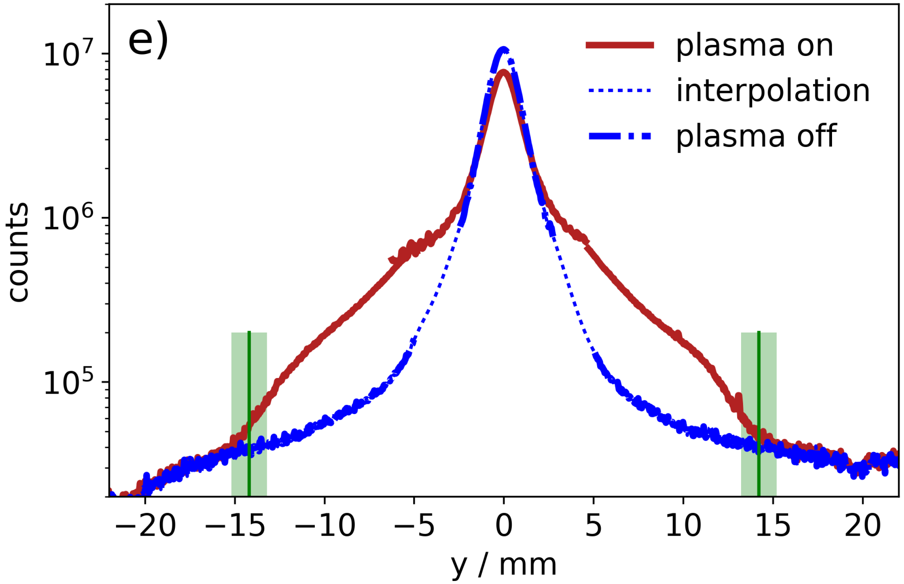


- Started with physics in Q4/2016 and continued through 2017−8.
- Various beam diagnostics to characterise proton beam and its modulation
  - Indirect measurement using two screens to measure transverse profile.
  - Direct measurements of modulation, i.e. micro-bunch structure through measuring transition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

Proton bunch modulation

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



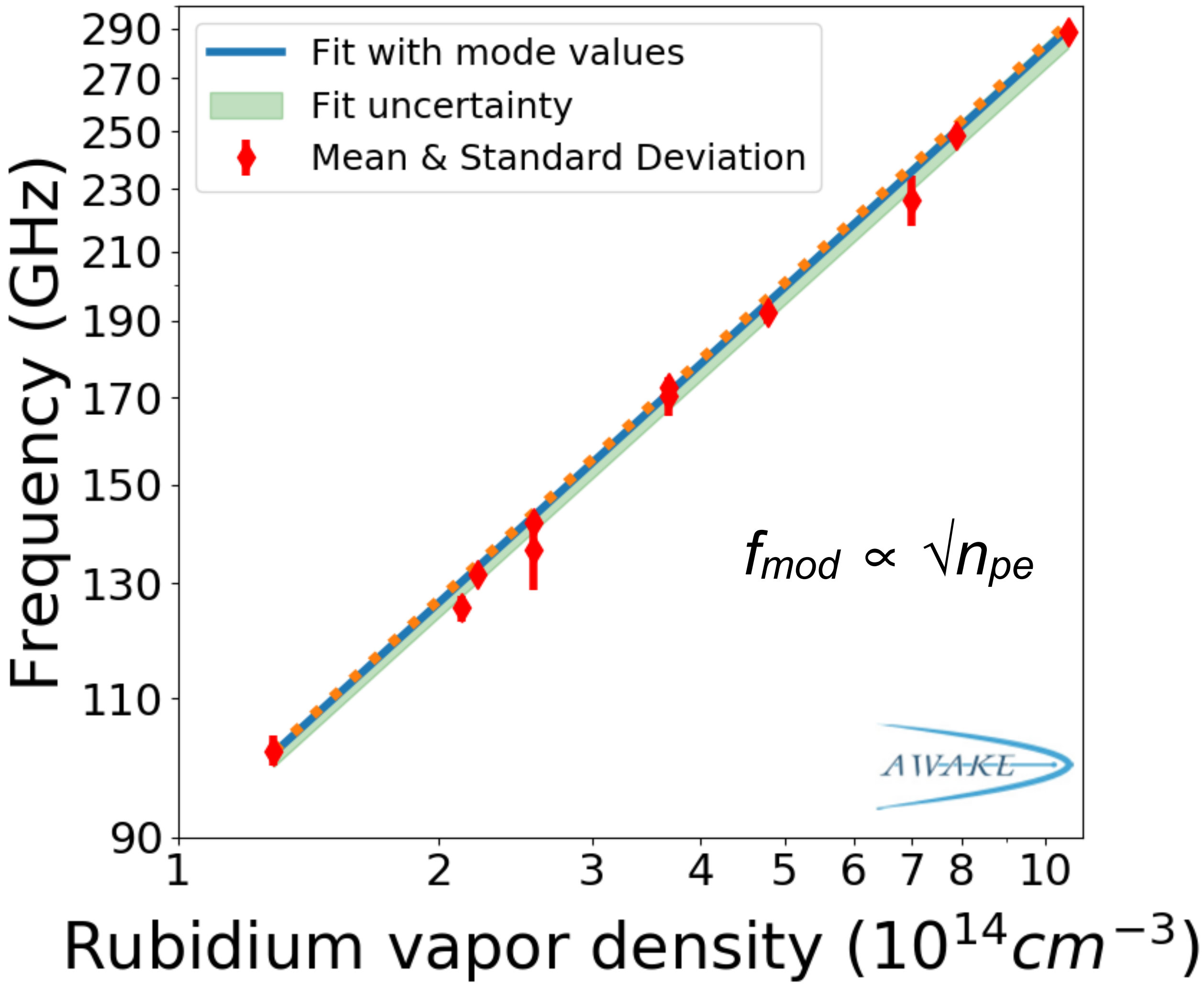


- Clear micro-bunching of proton beam.
- Spacing consistent with plasma wavelength.
- Reproducible, with a constant phase and stable event-by-event.
- This shows that we observe and understand seeded self-modulation.
- **This is crucial for injection of electrons which will happen at a given point.**

M. Turner et al. (AWAKE Coll.), “Experimental observation of plasma wakefield growth driven by the seeded self-modulation of a proton bunch”, *Phys. Rev. Lett.* **122** (2019) 054801.

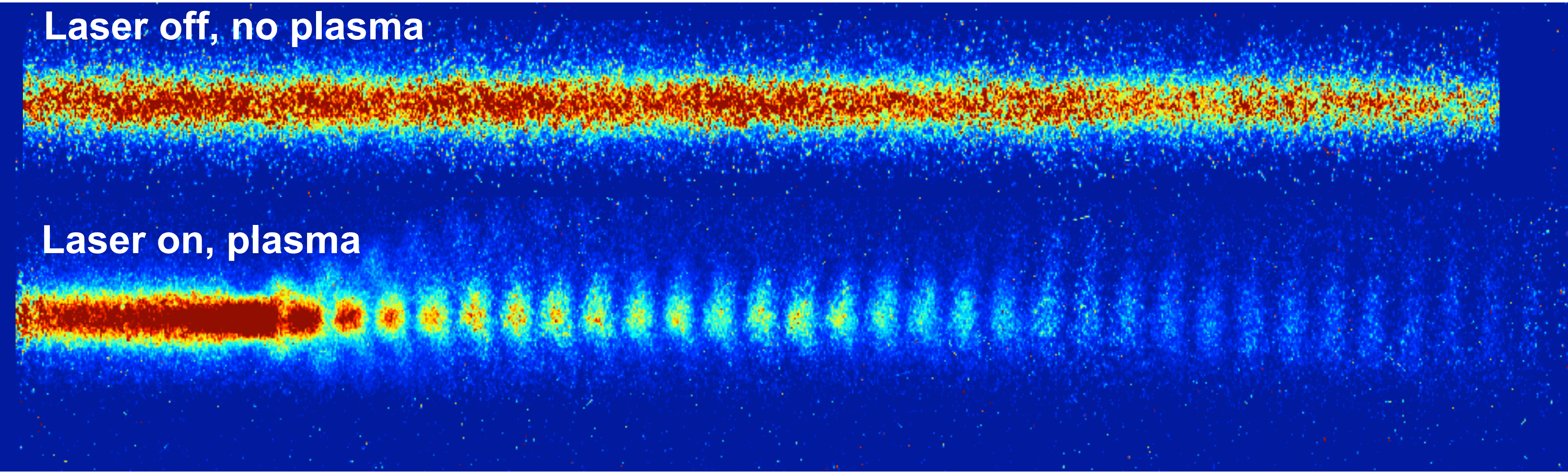
E. Adli et al. (AWAKE Coll.), “Experimental observation of proton bunch modulation in a plasma at varying plasma densities”, *Phys. Rev. Lett.* **122** (2019) 054802.

Self-modulation of proton bunch



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

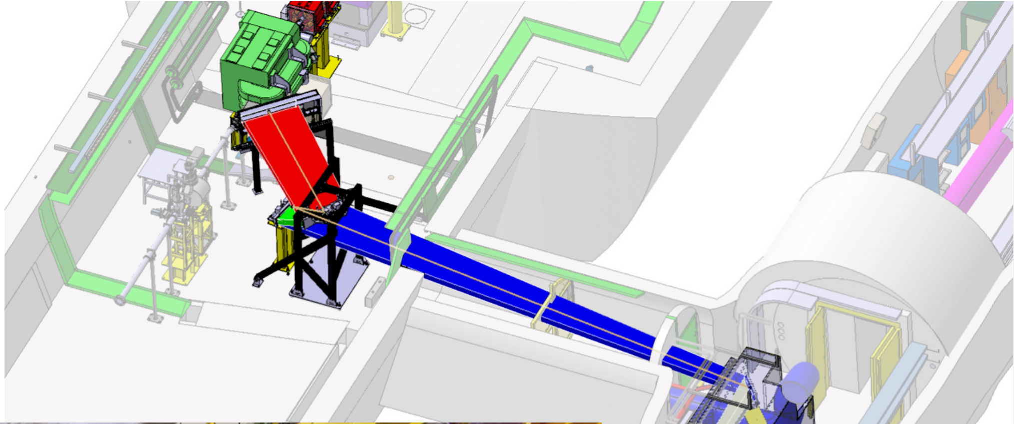
Direct measurement using OTR – reproducibility



- Micro-bunches present over a long time-scale from seed point.
- They are reproducible, with a constant phase and stable event-by-event.
- This shows that we observe and understand seeded self-modulation.
- **This is crucial for injection of electrons which will happen at a given point.**

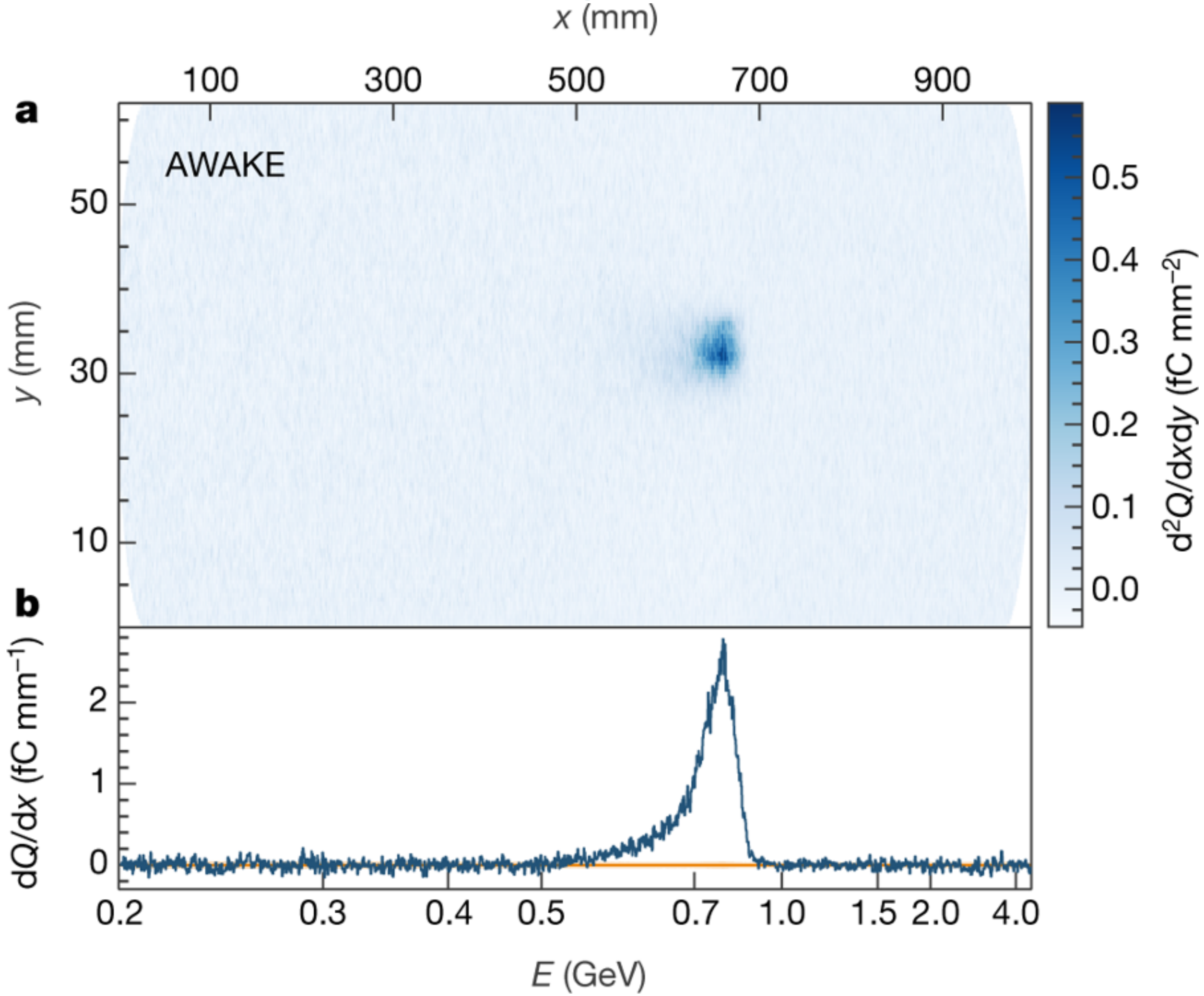
F. Batsch et al. (AWAKE Coll.), “Transition between instability and seeded self-modulation of a relativistic particle bunch in plasma”, PRL **126** (2021) 164802.

AWAKE spectrometer

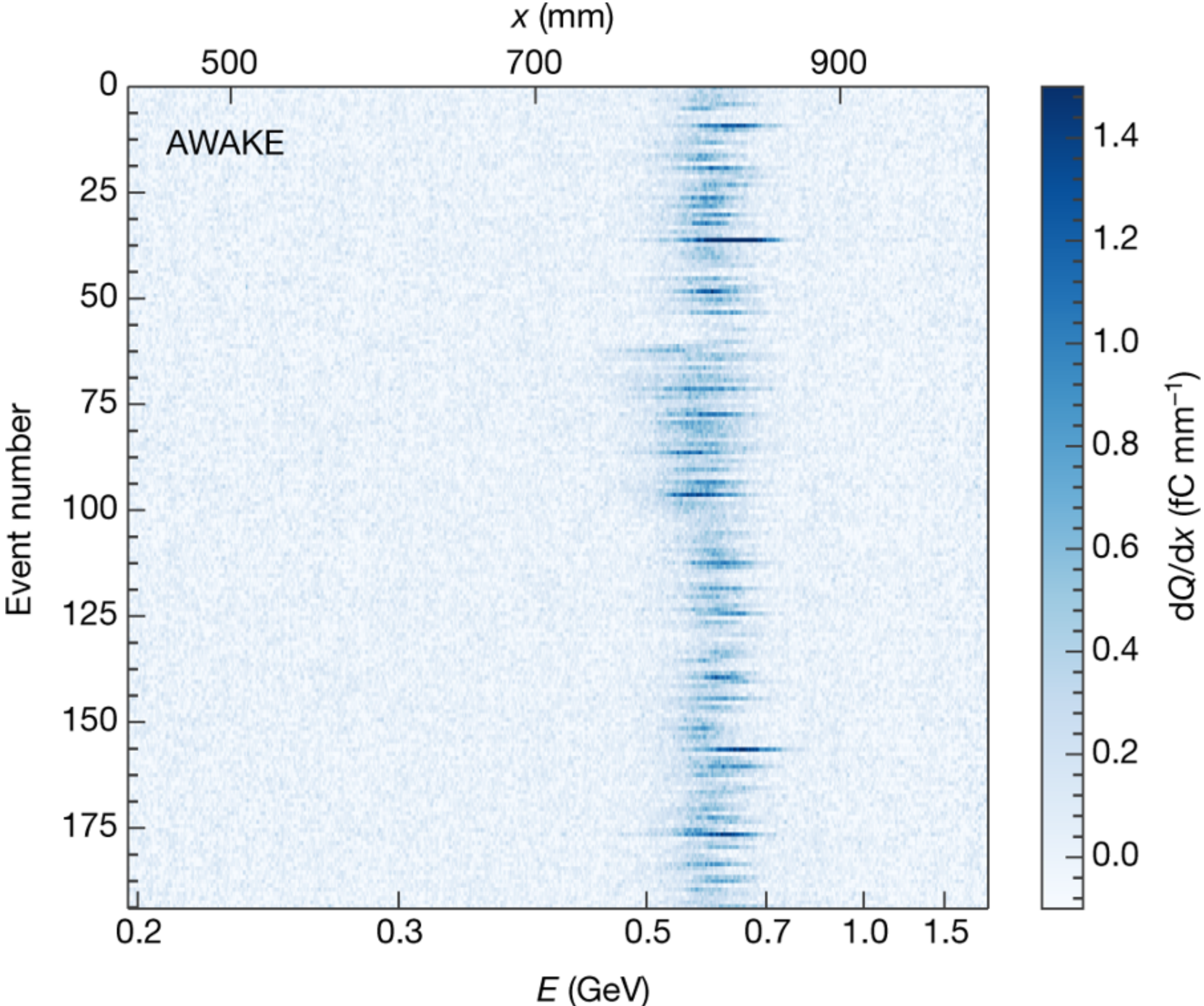


J. Bauche et al., “A magnetic spectrometer to measure electron bunches accelerated at AWAKE”, NIM **A940** (2019) 103.

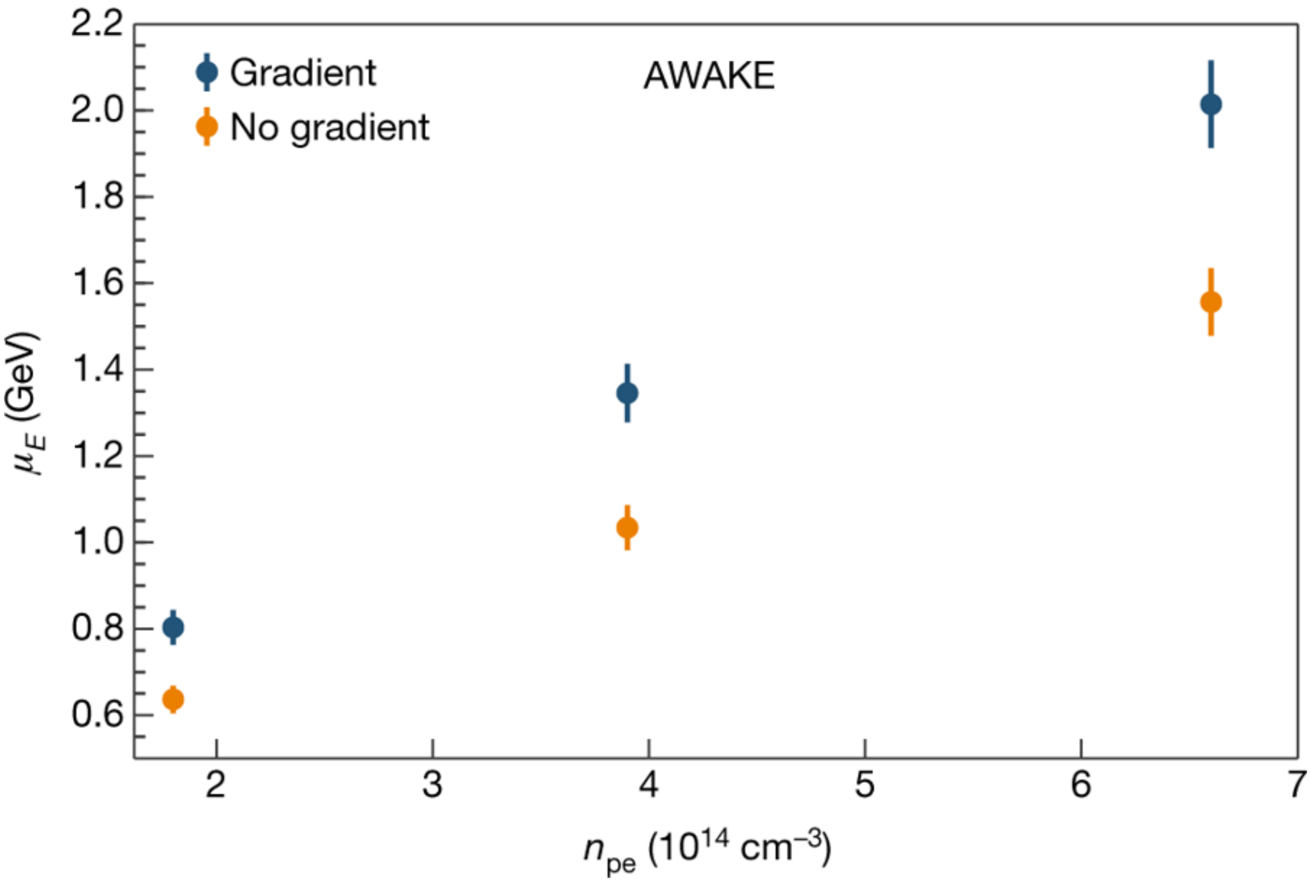
Electron acceleration signal



Electron acceleration reproducibility



Electron acceleration energy dependence



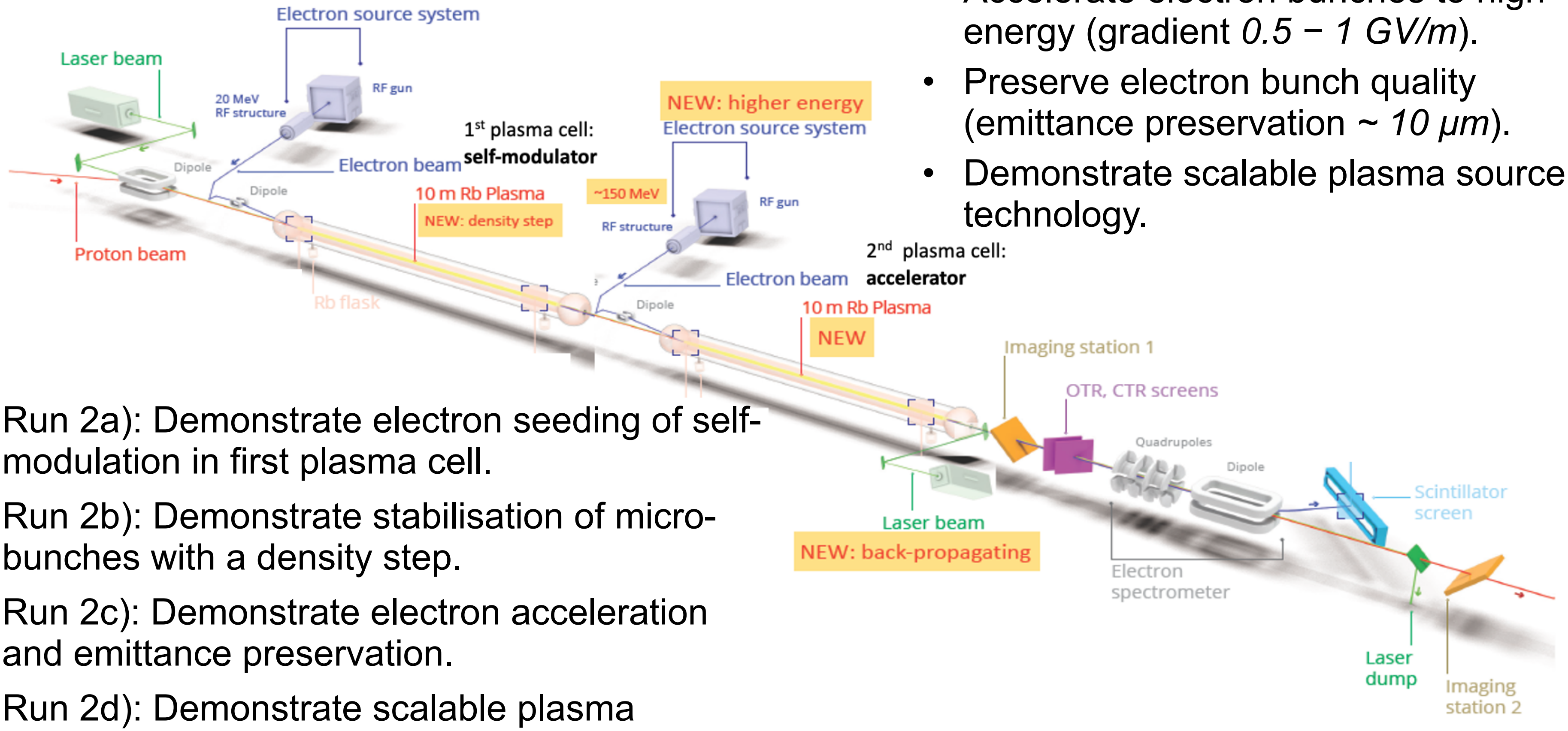
- Acceleration to *2 GeV* is a great achievement.
- Simulation/theory predicted similar energy gains.
- Experiment not optimised for electron injection.
- Accelerated charge *O(pC)* is low; have since achieved up to *~100 pC*.

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

AWAKE Run 2

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

- Accelerate electron bunches to high energy (gradient *0.5 − 1 GV/m*).
- Preserve electron bunch quality (emittance preservation ~ *10 μm*).
- Demonstrate scalable plasma source technology.



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

- **Then applications to particle physics experiments by end of decade**
  - Are there experiments that require an electron beam of *O(50 GeV)* ?
  - Using the LHC beam as a driver, *TeV* electron beams are possible.

Applying AWAKE technology

- Plasma wakefield acceleration in general aims to produce new 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, e.g. 200 GeV electrons from SPS proton driver[#].
  - ‣ Having high bunch charge looks possible.
  - ‣ Emittance and beam size need to be demonstrated, but look promising.
  - \- 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 as well as pursuing R&D for the ultimate machine.
- There are not many high energy electron beams out there:
  - ➡ Secondary SPS electron beam (up to ~*100 GeV*), but with low intensity.
  - ➡ High intensity, but E_e ~ *20 GeV* for FELs.

[#] K. Lotov and P. Tuev, "Ultimate plasma wakefield acceleration with 400 GeV proton driver", arXiv:2105.10140.

HEP applications

Considered applications with electron bunches:

- $E_e \sim 50$ GeV, wakefields driven by SPS protons; higher now looks possible.
- $E_e \sim$ TeV, wakefields driven by LHC protons.

Possible ideas are:

- Accelerator or detector test facility.
- Injector for e.g. EIC.
- Fixed-target/beam-dump experiments for deep inelastic scattering or dark-photon searches.
- Non-linear QED in electron−laser collisions.
- TeV-scale electron−proton colliders, $E_e = 50$ GeV up to $E_e = 3$ TeV.
- Booster in conjunction with conventional accelerator.

Other possible ideas:

- Accelerate muons (rather than electrons) to high energy.
- Heavy ions as the driver.
- …

A. Caldwell et al., arXiv:1812.11164.
W. Bartmann et al., CERN-PBC-REPORT-2018-005.
M. Wing, *Phil. Trans. R. Soc. A* **377** (2019) 20180185.

Enabling the search for dark photons

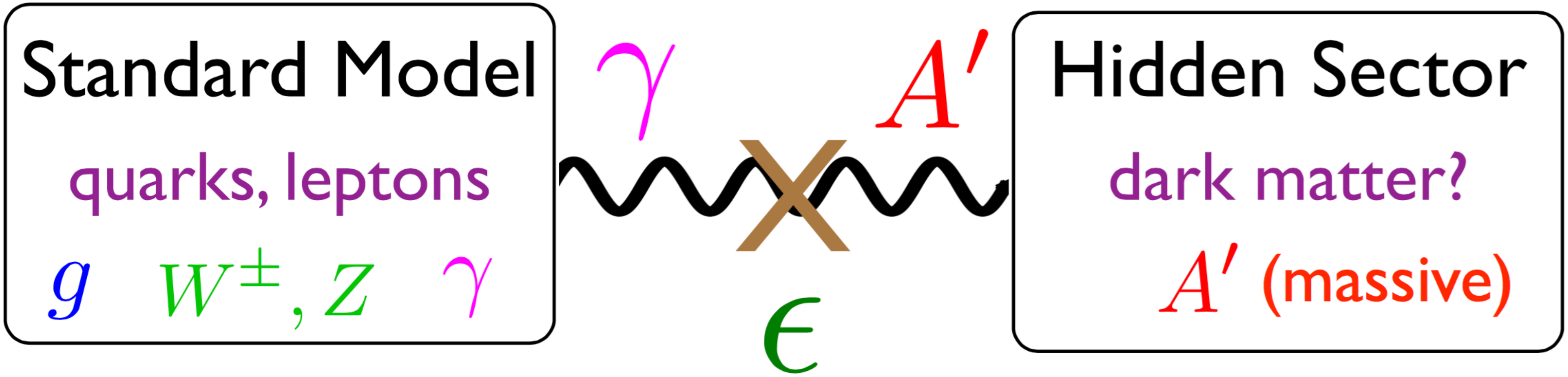
The hidden / dark sector

- Baryonic (ordinary) matter constitutes ~*5%* of known matter.
    - What is the nature of dark matter ? Why can we not see the dominant constituent of the Universe ?
- The LHC (and previous high energy colliders) have found no dark matter candidates so far.
- LHC to continue the search for heavy new particles such as those within supersymmetry.
- Also direct detection experiments looking for recoil from WIMPs
- There are models which postulate light (*GeV* and below) new particles which could be candidates for dark matter.
- There could be a dark sector which couples to ordinary matter via gravity and possibly other very weak forces.

Dark photons

A light vector boson, the “dark photon”, *A′*, results from a spontaneously broken new gauge symmetry, $U(1)_D$.

The *A′* kinetically mixes with the photon and couples primarily to the electromagnetic current with strength, εe



Standard Model

quarks, leptons

$g \quad W^{\pm}, Z \quad \gamma$

γ

A'

ϵ

Hidden Sector

dark matter?

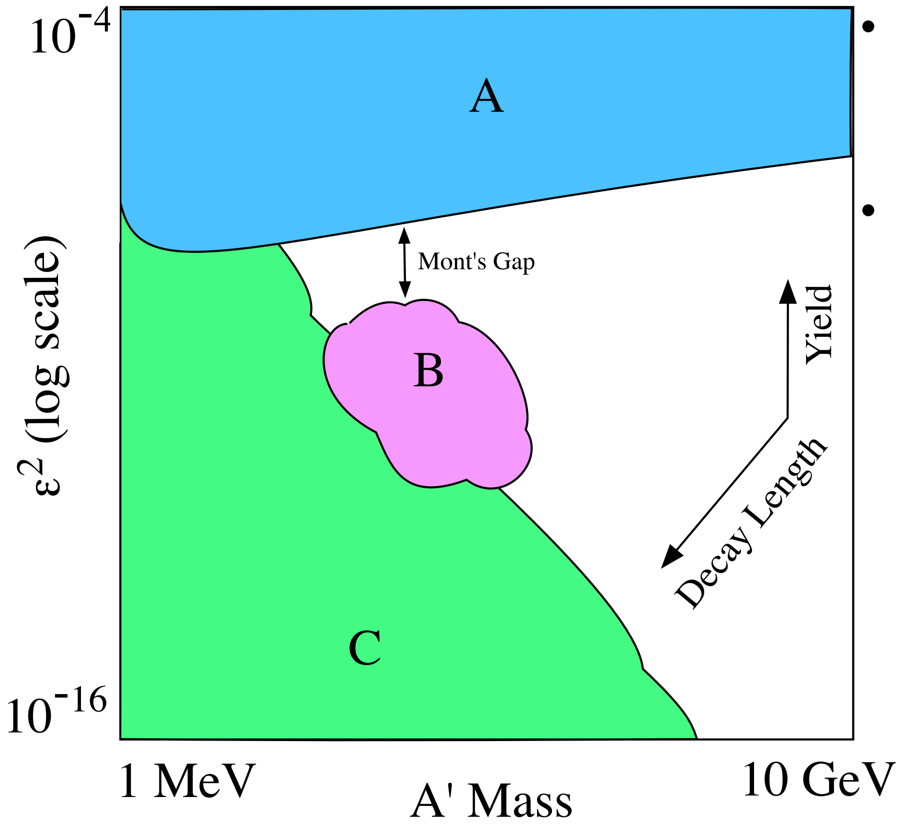
A' (massive)

$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

Growing field of experiments with many running or starting or proposed at JLab, SLAC, INFN, Mainz, etc.

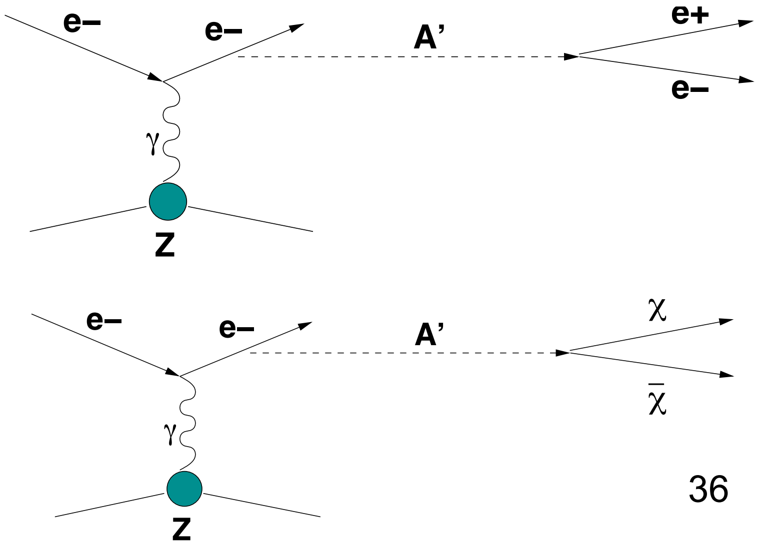
Search for dark photons

- Several ways to look for dark photons:
  - A: bump-hunting, e.g. $e^+e^- \rightarrow \gamma A'$
  - B: displaced vertices, short decay lengths
  - C: displaced vertices, long decay lengths



J. Alexander et al., arXiv:1608.08632

- Search for dark photons, *A′*, up to (and beyond) *GeV* mass scale via their production in a light-shining-through-a-wall type experiment.
- Use high energy electrons for beam-dump and/ or fixed-target experiments.

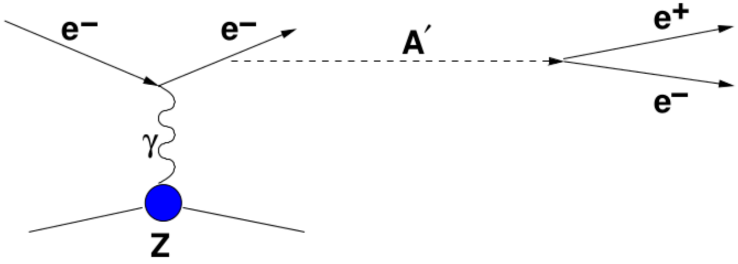


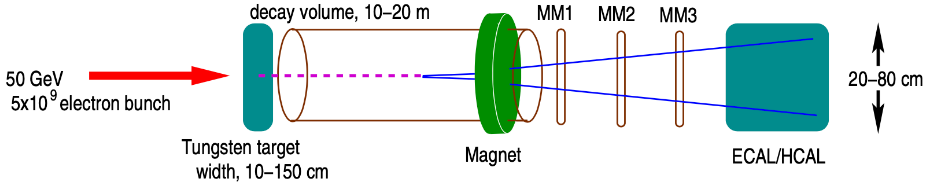
Electrons on target

Similar to NA64 experiment @CERN using ~100 GeV electrons from SPS secondaries.

Propose to use electrons accelerated by AWAKE to 50 GeV+

AWAKE would provide bunches, so beam-dump experiment.





NA64 will receive about $10^{6}\ e^{-}/spill$ or $2 \times 10^{5}\ e^{-}/s$ from SPS secondary beam

➡ $N_e \sim 10^{12}\ e^{-}$ for 3 months running.

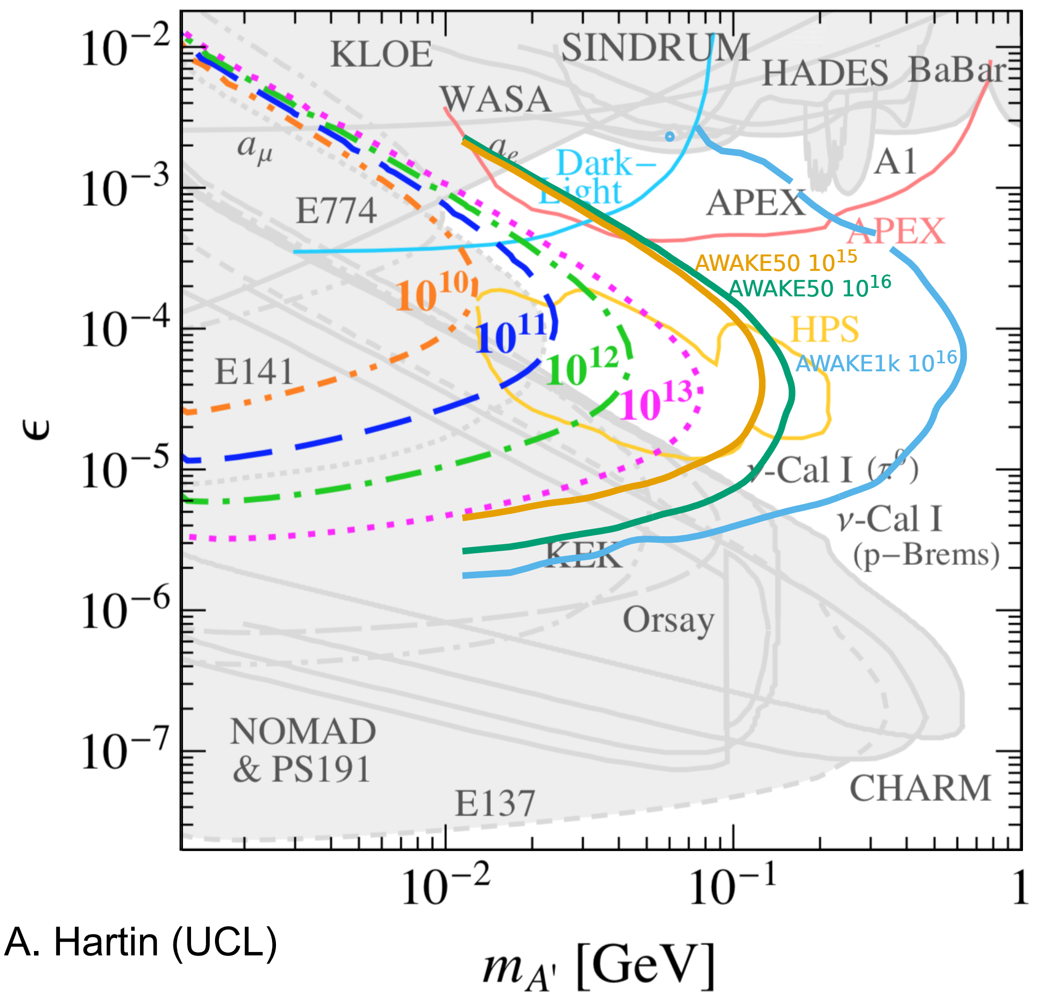
AWAKE-like beam with bunches of $10^{9}\ e^{-}$ every (SPS cycle time of) ~ $5\ s$ or $2 \times 10^{8}\ e^{-}/s$ *(1000* × higher than NA64/SPS secondary beam*)*

➡ $N_e \sim 10^{15}\ e^{-}$ for 3 months running.

Will assume that an AWAKE-like beam could provide an **effective upgrade** to the NA64 experiment, increasing the intensity by a factor of *1000*.

Different beam energies or higher intensities (e.g. bunch charge, SPS cycle time) may be possible, but are not considered in this talk.

Limits on dark photons, $A' \rightarrow e^+ e^-$ channel



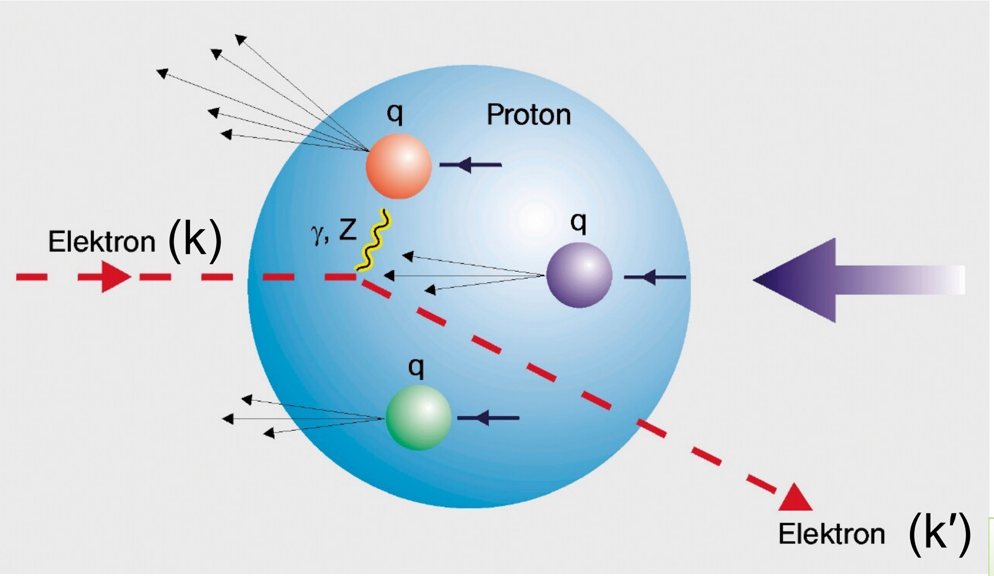
- For $10^{10} - 10^{13}$ electrons on target with NA64.
- For 10^{16} electrons on target with AWAKE-like beam.
- Using an AWAKE-like beam would extend sensitivity further:
  - around $\varepsilon \sim 10^{-3} - 10^{-5}$.
  - to high masses ~ *0.1 GeV*.
- A *1 TeV* goes to even higher masses:
  - similar ε values.
  - approaching *1 GeV*.
  - beyond any other planned experiments.

Recent simulations, with 200 GeV, would have sensitivity in between those shown.

A. Caldwell et al., arXiv:1812.11164
M. Wing, *Phil. Trans. R. Soc. A* **377** (2019) 20180185.

Matter and the strong force at the highest energies

High energy electron−proton collisions



Energy scale or resolution,
$Q^2 = -(k-k')^2$

Parton momentum fraction, x

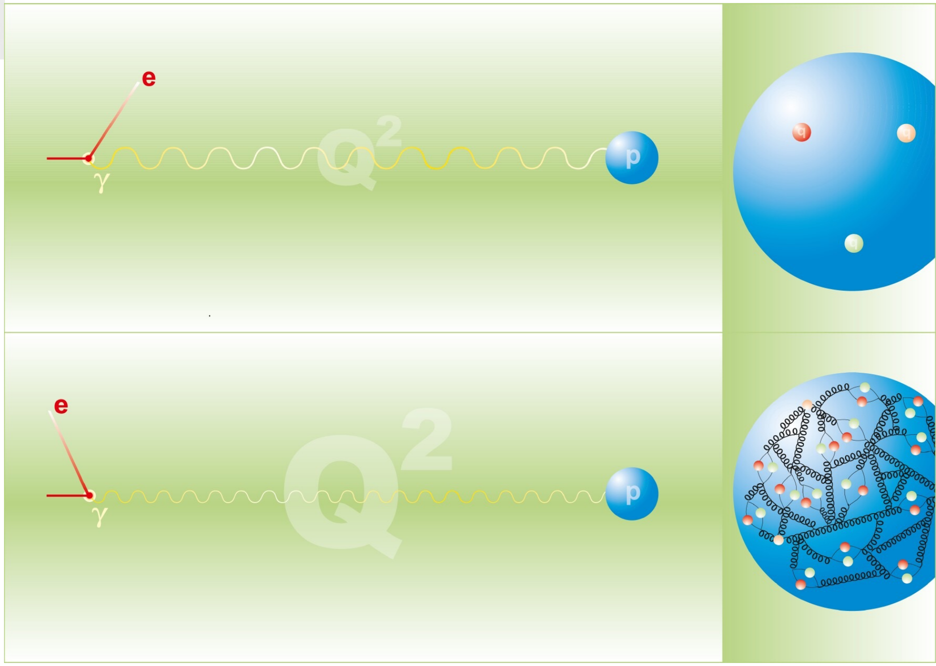
Understand hadronic cross sections as a function of these variables.

Deep inelastic scattering is the way to study the structure of matter.

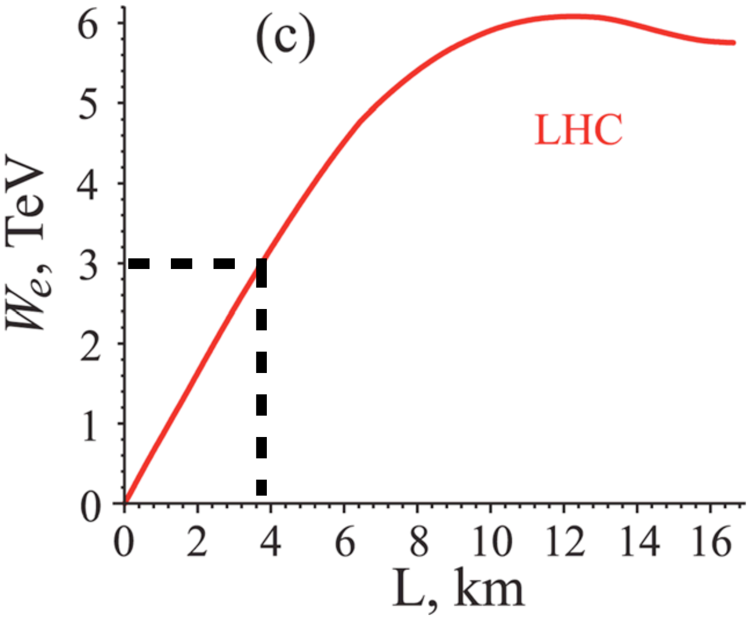
When does the complex structure “level out” or “saturate” ?

Tells us a lot about the strong force: parton interactions, α_s, etc.

Is there further partonic substructure ?



Very high energy electron–proton collisions, VHEeP



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

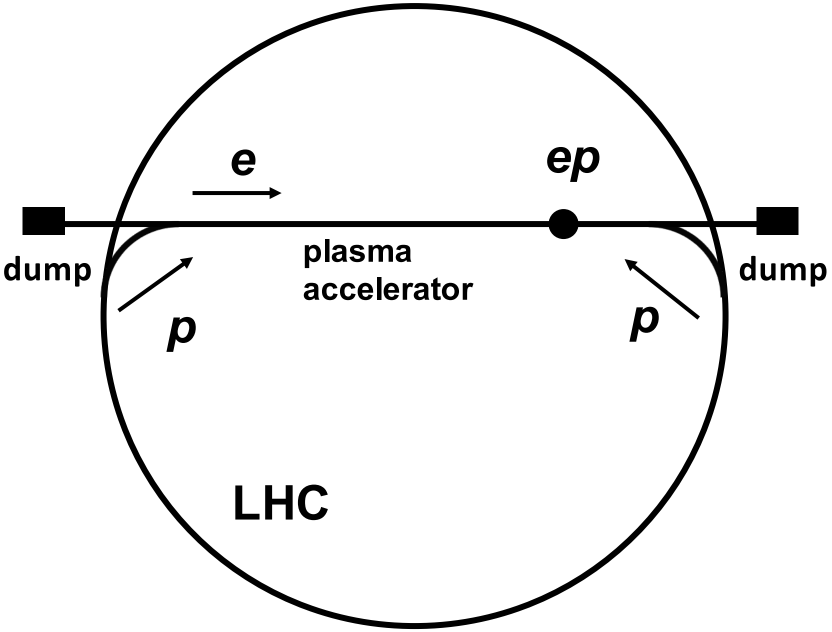
- What about very high energies in a completely new kinematic regime ?
- Choose E_e = *3 TeV* as a baseline for a new collider with E_p = *7 TeV* ⇒ $\sqrt{s}$ **= 9 TeV**.
- Acceleration of electrons in under *4 km*.
- Can vary the energy.
- Centre-of-mass energy ×30 higher than HERA.
- Reach in (high) Q^2 and (low) Bjorken *x* extended by ×1000 compared to HERA.

Idea presented at various workshops and published*. Also had a workshop to expand particle physics case:

https://indico.mpp.mpg.de/event/5222/overview

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

Plasma wakefield accelerator



$$\mathcal{L} \sim \frac{f \cdot N_e \cdot N_P}{4\pi\,\sigma_x \cdot \sigma_y}$$
$$\sim 4 \times 10^{28}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

For few × 10^7 s, have 1 pb^{-1} / year of running.

Other schemes to increase this value ?

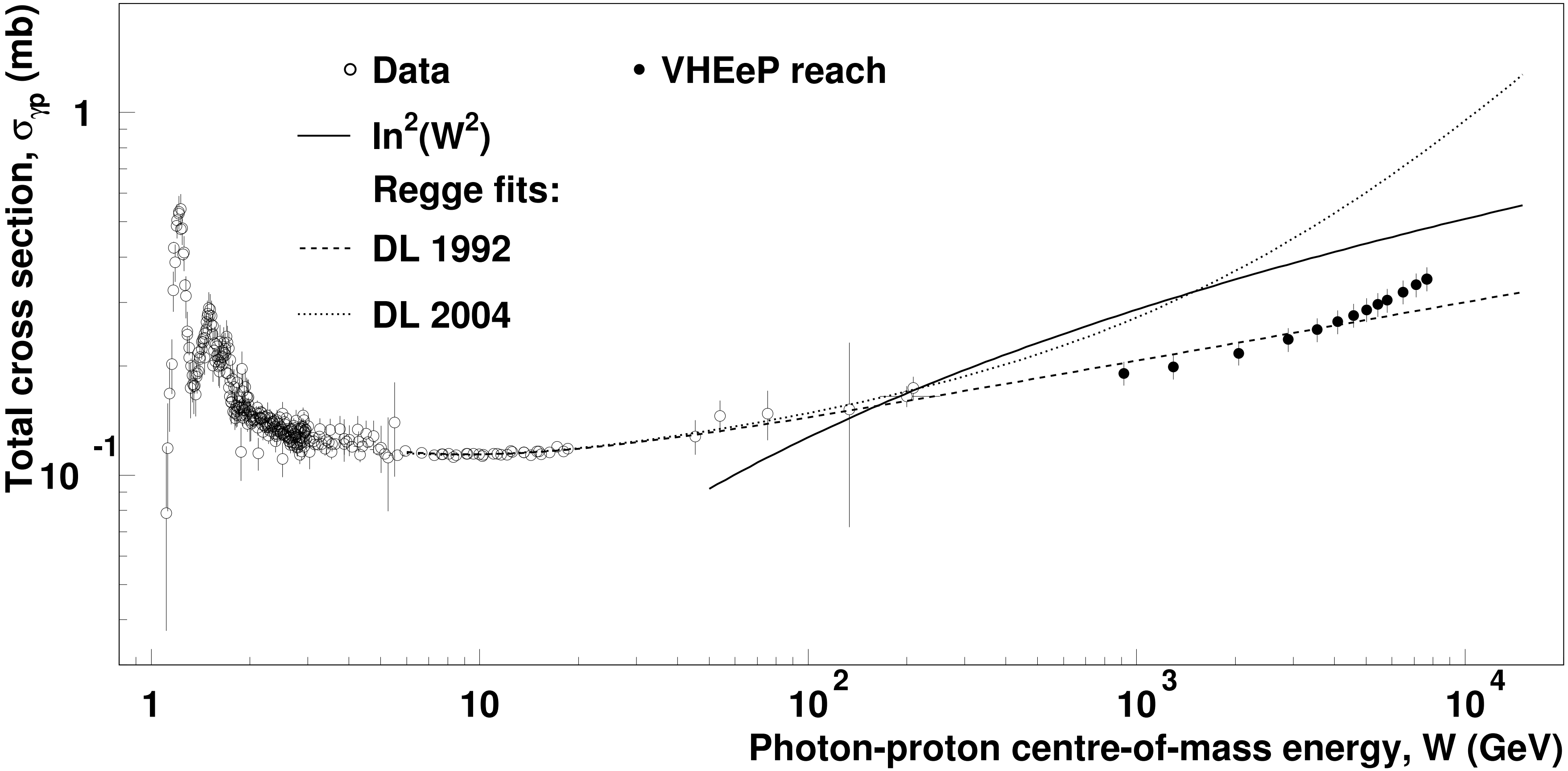
- Emphasis on using current infrastructure, i.e. LHC beam with minimum modifications.
- Overall layout works in powerpoint.
- Need high gradient magnets to bend protons into the LHC ring.
- One proton beam used for electron acceleration to then collider with other proton beam.
- High energies achievable and can vary electron beam energy.
- What about luminosity ?
- Assume
  - *~3000* bunches every *30 mins* ⇒ $f \sim 2$ Hz.
  - $N_p \sim 4 \times 10^{11}$, $N_e \sim 1 \times 10^{11}$
  - $\sigma \sim 4\ \mu m$

Physics case for very high energy, but moderate (*10−100* $\mathbf{pb^{-1}}$) luminosities.

Physics at VHEeP

- Cross sections at very low *x* and observation/evidence for saturation. Completely different kind of proton structure.
- Measure total *γP* cross section at high energies and also at many different energies; relation to cosmic-ray physics.
- Vector meson production and its relation to the above.
- Beyond the Standard Model physics; contact interactions, e.g. radius of quark and electron; search for leptoquarks.
- Proton and photon structure, and *eA* scattering. Also related to saturation and low *x*.
- Tests of QCD, measurements of strong coupling, etc.. I.e. all usual QCD measurements can and should be done too in a new kinematic regime.
- Relation of QCD and gravity ?
- …

Total photon–proton cross section

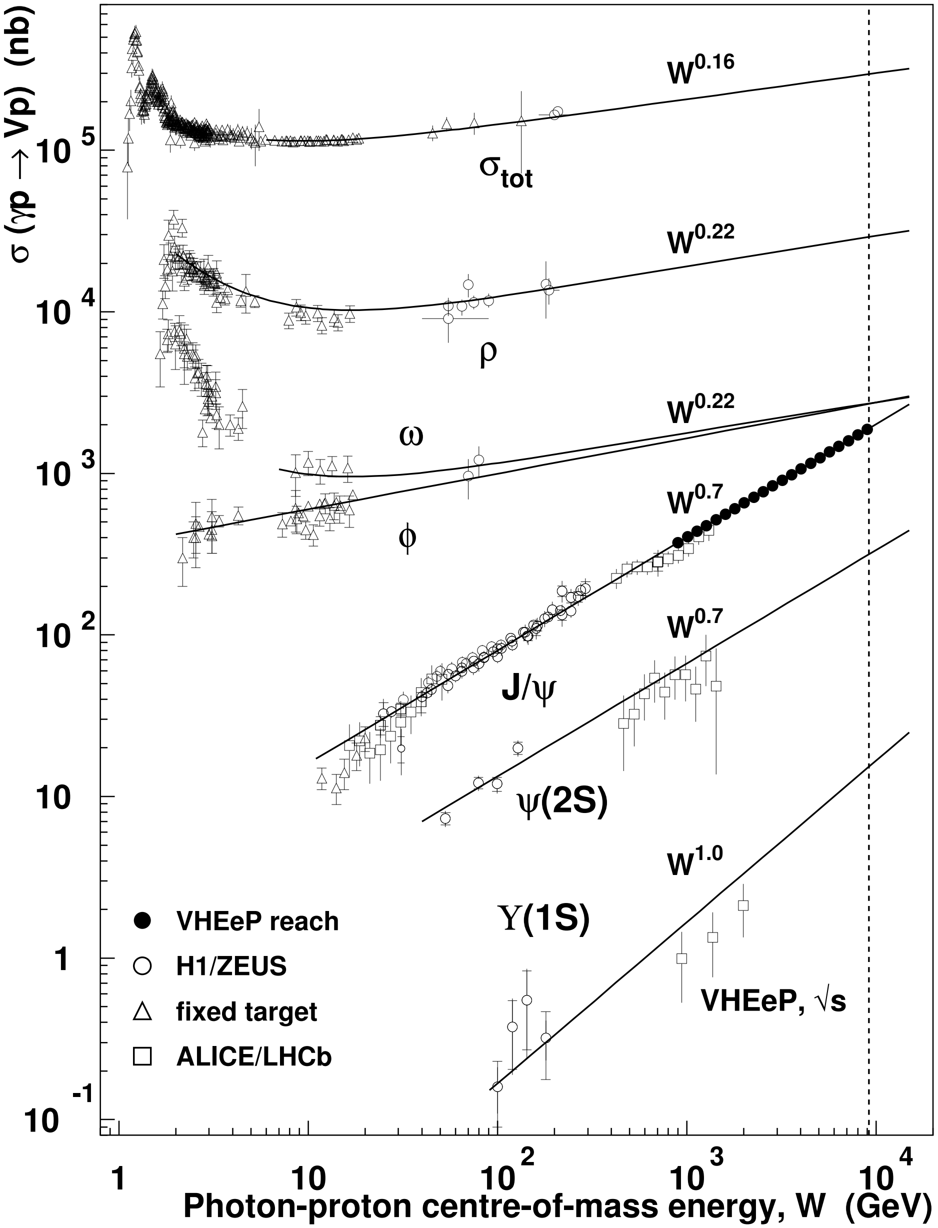


Energy dependence of hadronic cross sections poorly understood.

- Multiple measurements can be made with low luminosities.
- When does the cross section stop rising ?
- Relation to cosmic-ray physics.
- **Great example of where you really gain with energy.**

Equivalent to a 20 PeV photon on a fixed target.

Vector meson cross sections



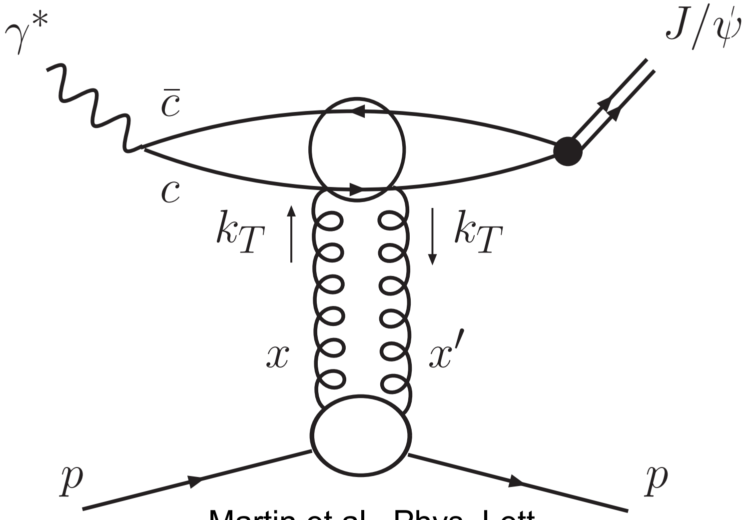
Strong rise with energy related to gluon density at low *x*.

Can measure all particles within the same experiment.

Comparison with fixed-target, HERA and LHCb data—large lever in energy.

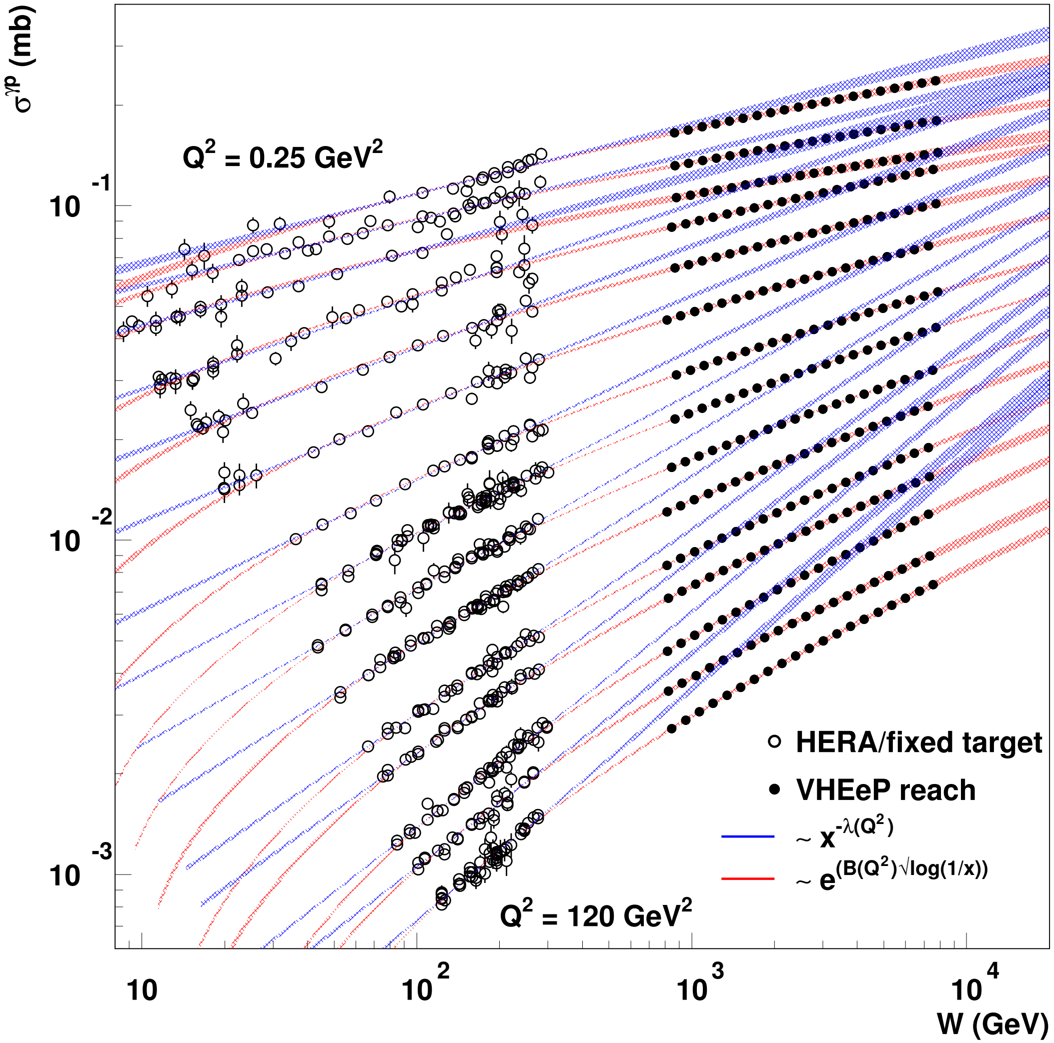
At VHEeP energies, *σ(J/ψ)* > *σ(φ)* !

Onset of saturation ?



Martin et al., Phys. Lett. **B 662** (2008) 252

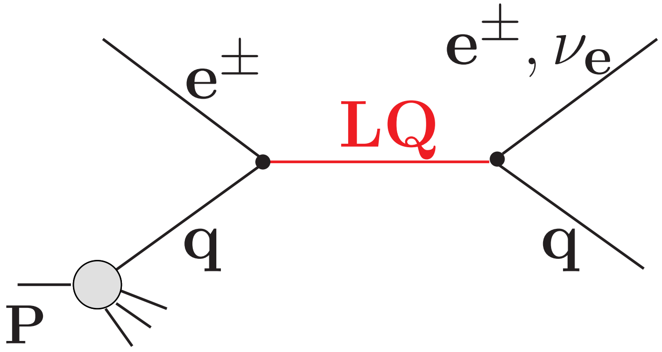
Virtual-photon−proton cross section



- Cross sections for all Q^2 are rising; again luminosity not an issue, will have huge number of events.
- Depending on the form, fits cross; physics does not make sense.
- Different forms deviate significantly from each other.
- VHEeP has reach to investigate this region and different behaviour of the cross sections.
- Can measure lower Q^2, i.e. lower x and higher *W.*
- Unique information on form of hadronic cross sections at high energy.

VHEeP will explore a region of QCD where we have no idea what is happening.

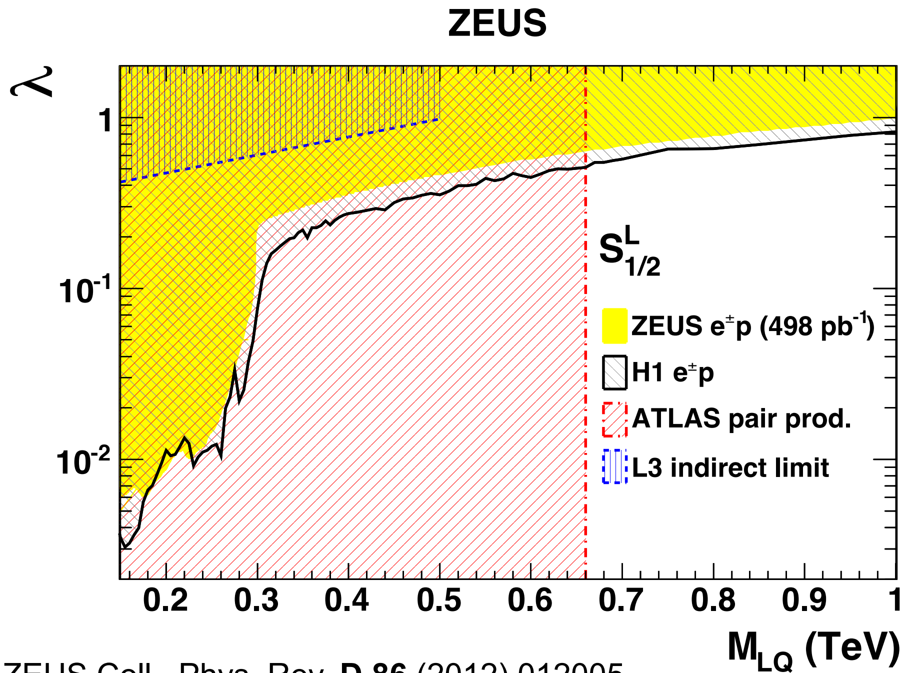
Leptoquark production



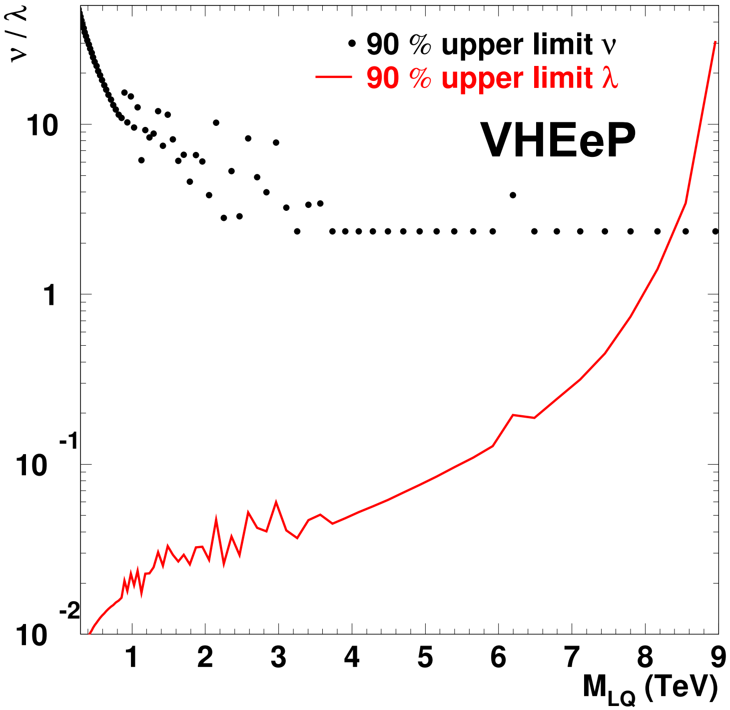
Electron–proton colliders are the ideal machine to look for leptoquarks.

s-channel resonance production possible up to √*s*.

Reach of LHC currently about *1 TeV*, to increase to *2 − 3 TeV*.



ZEUS Coll., Phys. Rev. **D 86** (2012) 012005



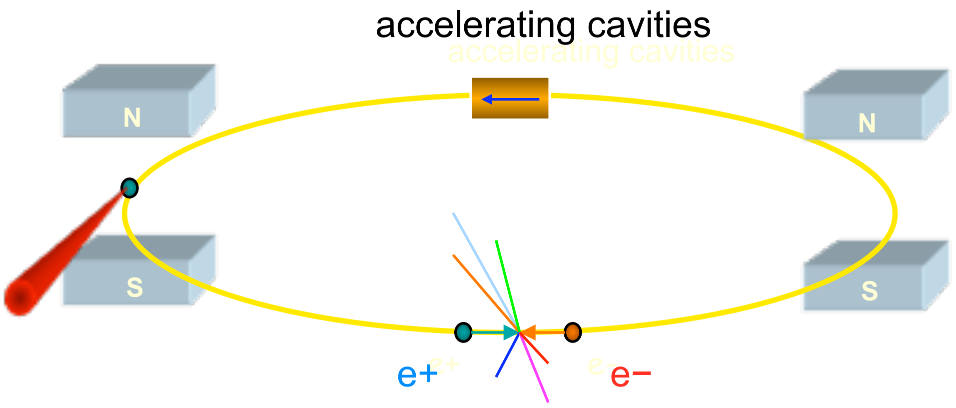
Sensitivity depends mostly on √*s* and VHEeP = 30 × HERA

Summary and discussion

- Plasma wakefield acceleration could be a technology of the future for particle physics experiments.
- The AWAKE collaboration has an exciting programme of R&D aiming to develop a **useable accelerator technology**.
- Have started to consider **realistic** applications to novel particle physics experiments:
    - **Fixed-target/beam-dump experiments in particular those sensitive to dark photons.**
    - **Electron–proton collider up to very high energies.**
- Work continues studying boundary conditions / possibilities from physics, technical and integration side, e.g. repetition rate, tunnel space, etc..

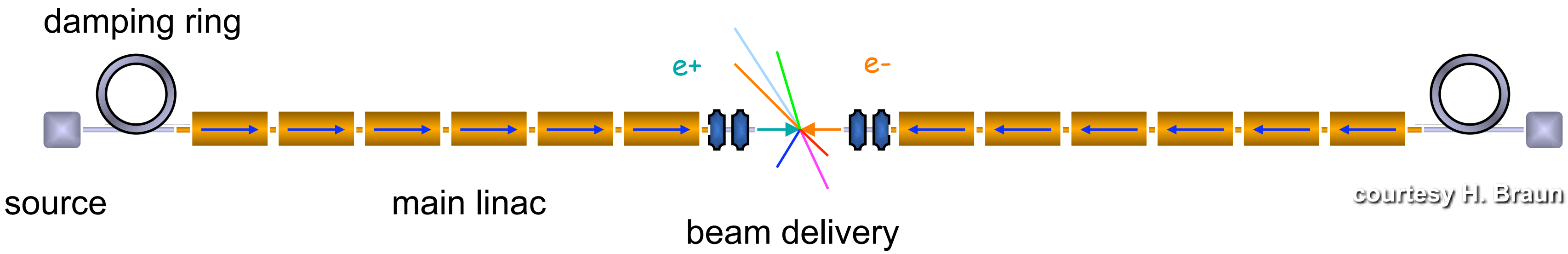
Back-up

Conventional accelerators



Circular colliders :

- Many magnets, few cavities so strong fields needed;
- High synchrotron radiation;
- High repetition rate leads to high luminosity.



courtesy H. Braun

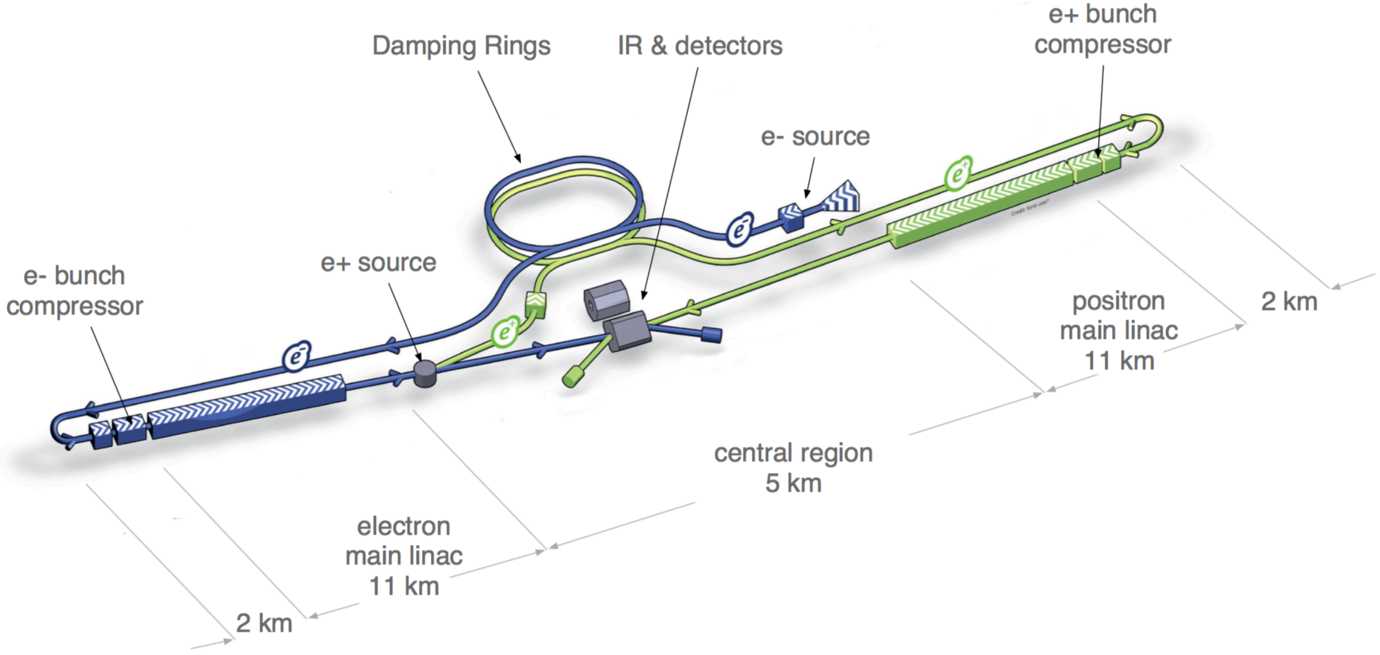
Linear colliders :

- Few magnets, many cavities so efficient RF power production needed;
- Single pass so need small cross section for high luminosity and very high beam quality;
- The higher the gradient, the shorter the linac.

Proposed linear accelerators

- Few magnets, many cavities so efficient RF power production needed;
- Single pass so need small cross section for high luminosity and very high beam quality;
- The higher the gradient, the shorter the linac.

Parameter	ILC	CLIC
E_{CM} (TeV)	0.1–1	0.4–3
Bunch separation (ns)	369	0.5
No. particles/bunch	2×10^{10}	4×10^{9}
No. bunches/train	2625	312
Repetition rate (Hz)	5	50
Accelerating gradient (MV/m)	31.5	100
Beam size (nm^2)	640 × 5.7	40 × 1



Plasma wakefield acceleration applications

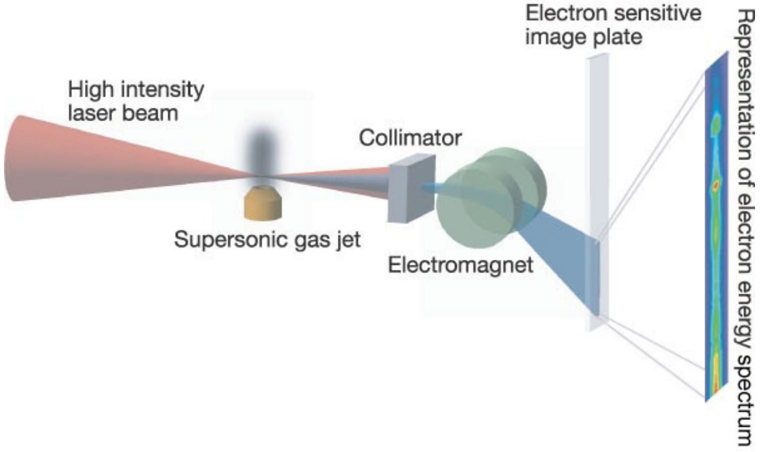
Plasma wakefield acceleration could have applications in many areas of science and industry where accelerators are needed.

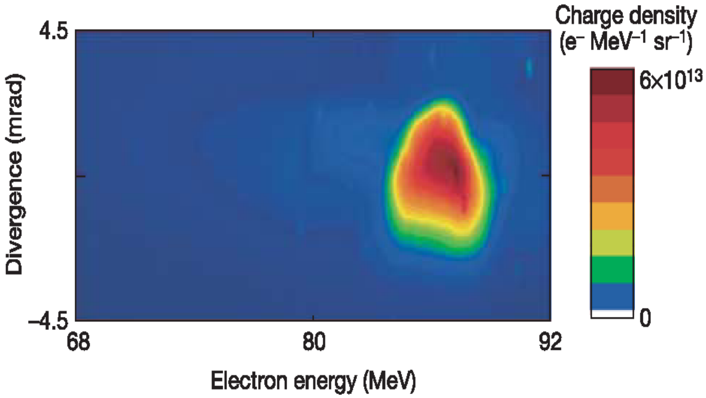
- Miniaturisation and ‘table-top’ accelerators
- E.g. medical applications, XFELs, etc.

Will here focus on general principles and successes of plasma wakefield acceleration but with definite focus on its application to high energy physics.

First laser-driven plasma wakefield experiments

2004 result: *10 TW* laser, *mm* scale plasma






30 September 2004

International weekly journal of science

nature

Dream beam

The dawn of compact particle accelerators

Disease control Europe plays catch-up

Protein folding Escape from the ribosome

The Earth's hum Sounds of air and sea

Human ancestry One from all and all from one

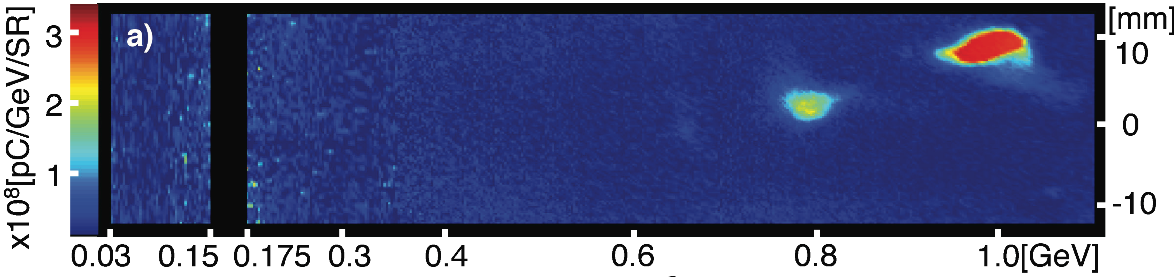
technology feature RNA interference

~ *100 MeV* beams.

S. Mangles et al., Nature **431** (2004) 535
C.G.R. Geddes et al., Nature **431** (2004) 538
J. Faure et al., Nature **431** (2004) 541

2006 result: *40 TW* laser, *cm* scale plasma

First *GeV* beams.



W.P. Leemans et al., Nature Phys. **2** (2006) 696
K. Nakamura et al., Phys. Plasmas **14** (2007) 056708

Accelerator based on laser plasma wakefield acceleration

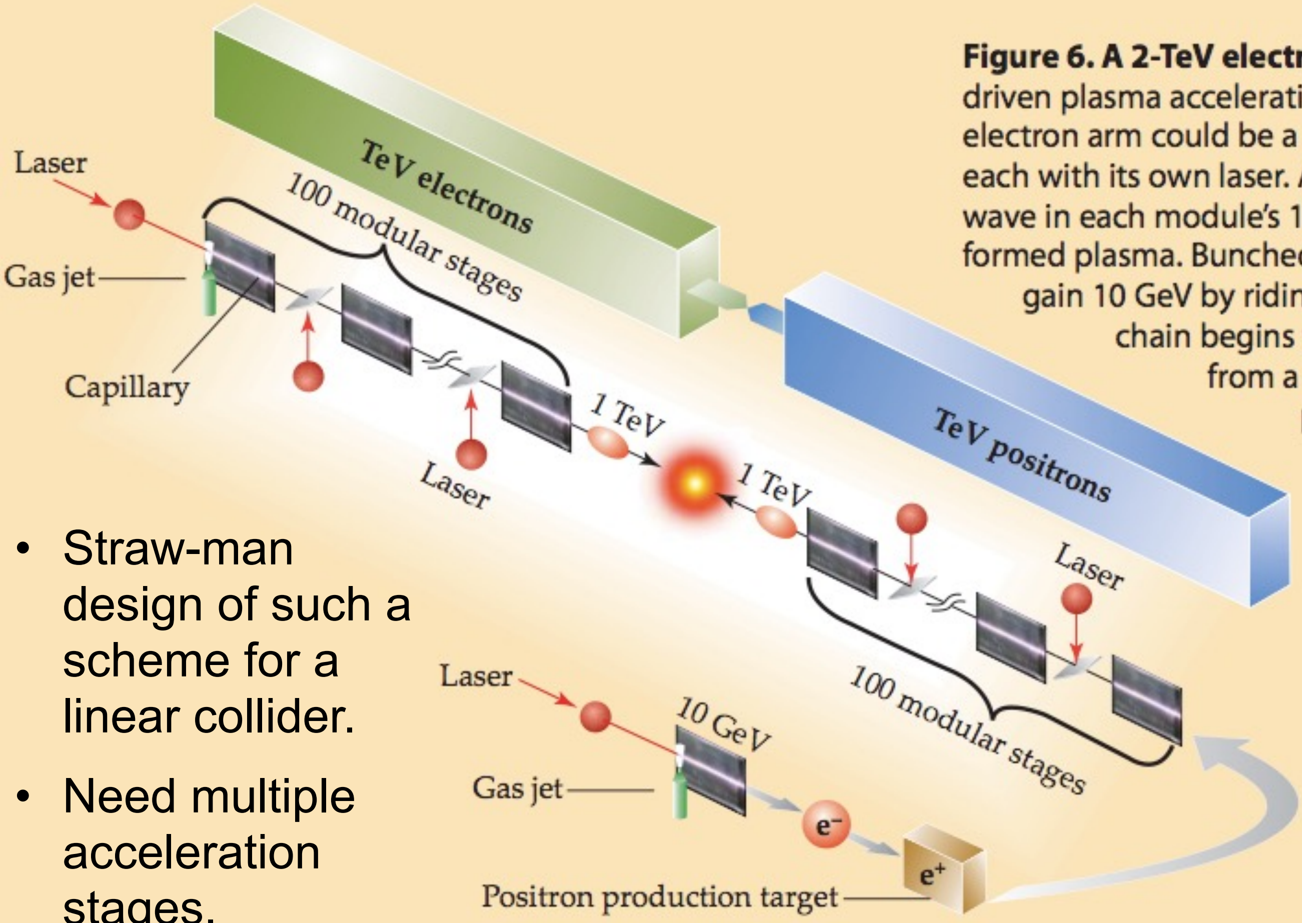


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of preformed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

W. Leemans, E. Esarey, Physics Today, March 2009

- Straw-man design of such a scheme for a linear collider.
- Need multiple acceleration stages.
- Acceleration using 100 stages of *10 GeV* each.
- Assume laser with high repetition rate, *O(10) kHz.*

Scaling in laser-driven plasma experiments

Energy gain limited by laser energy depletion

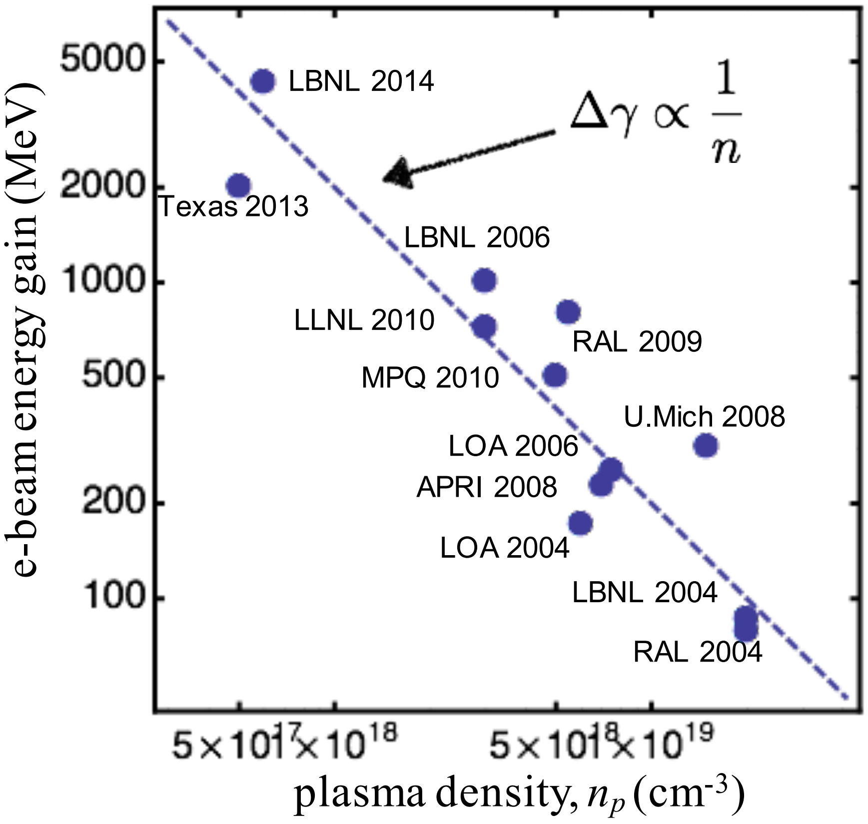
- Depletion length: $L_D \propto n^{-3/2}$
- Accelerating gradient: $E \propto n^{1/2}$
- Energy gain: $W \propto n^{-1}$

Staging is necessary to reach high energies

Example for a single stage

$W \sim 1$ GeV		$W \sim 10$ GeV
$n \sim 10^{18}$ cm^{-3}		$n \sim 10^{17}$ cm^{-3}
$L_D \sim 3$ cm	⟶	$L_D \sim 1$ m
$U_{laser} \sim 1$ J		$U_{laser} \sim 40$ J
$P_{laser} \sim 100$ TW		$P_{laser} \sim 1$ PW

LPA Experiments (single stage)



E. Esarey, LCWS2015

Latest results from BELLA laser, LBNL

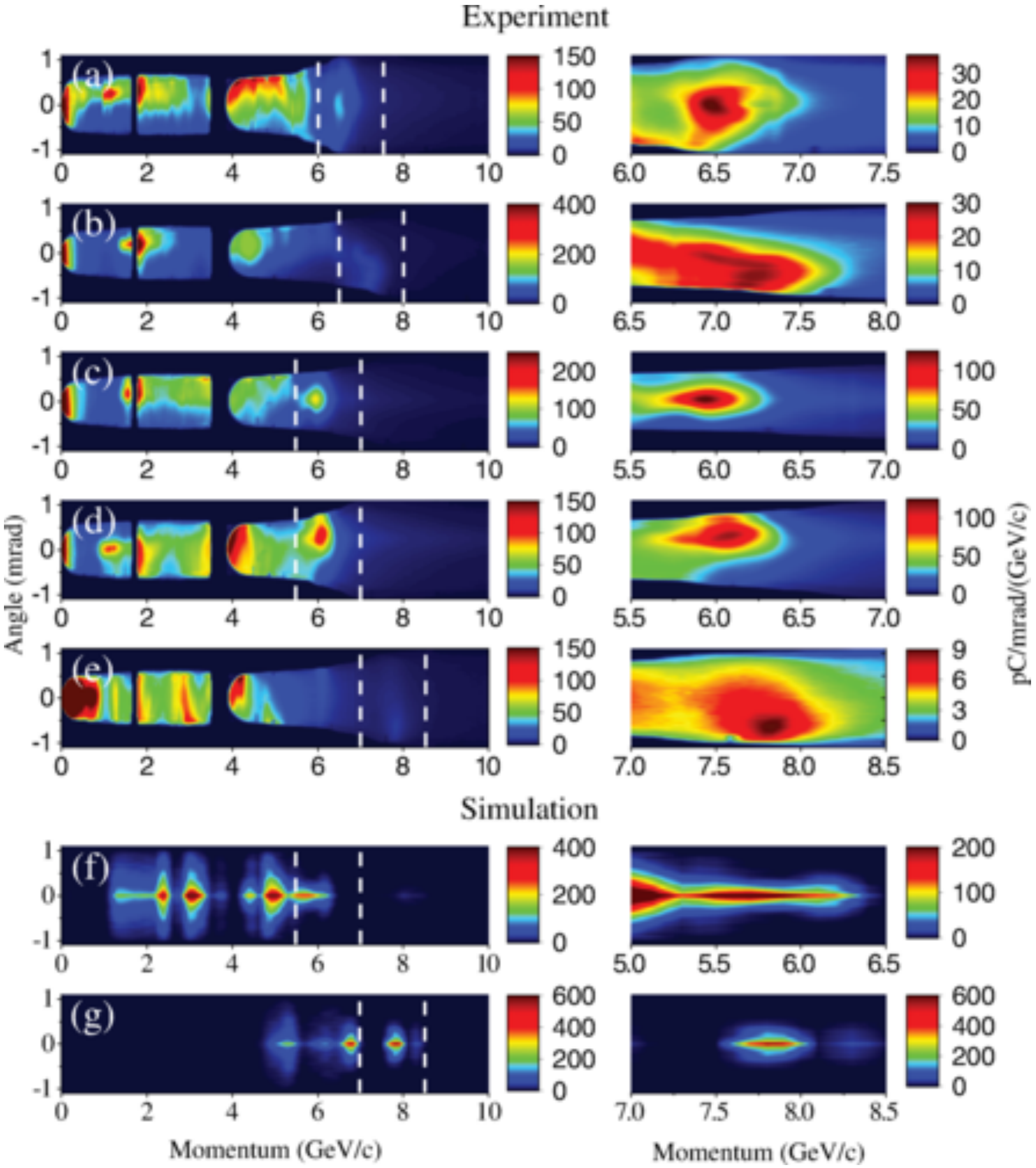
Using a *0.85 PW* laser pulse and *20 cm* plasma:

- ***E = 7.8 GeV***, *Q = 5 pC*
- *E = 6 GeV, Q = 62 pC*

Beating previous record of *4.2 GeV*

Simulations described the results

- Goal to achieve *10 GeV* bunches at BELLA.
- Investigate using two stages.
- Can then envisage multiple *10 GeV* stages for high energies, although staging is a major challenge …



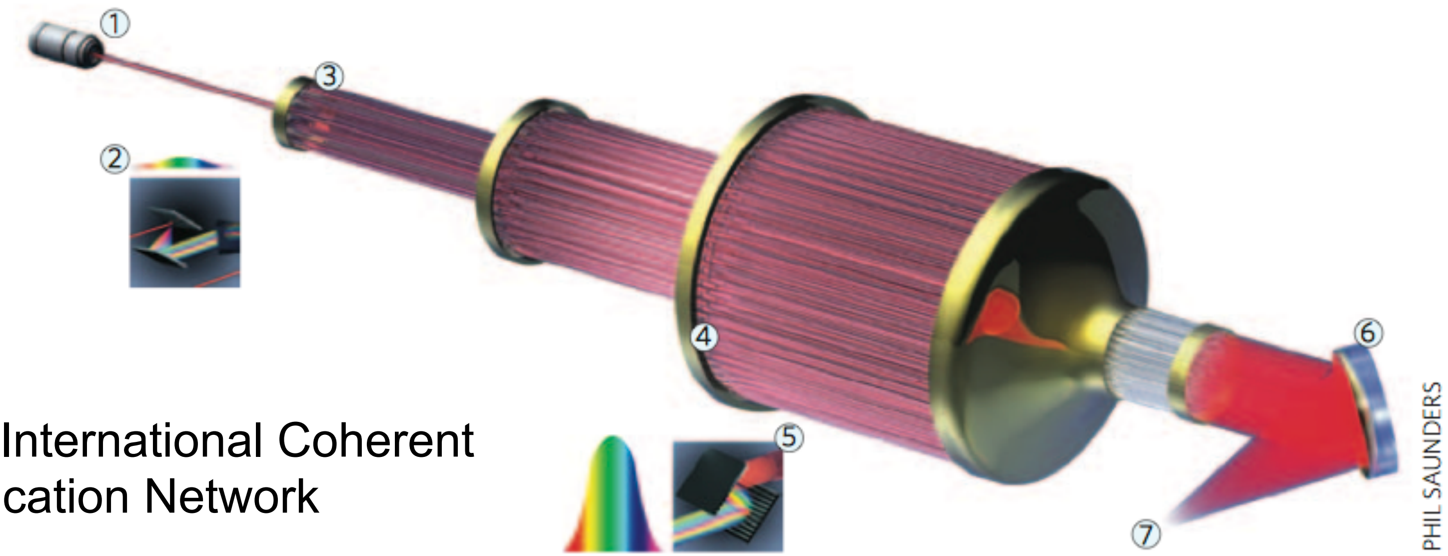
A.J. Gonsalves et al., Phys. Rev. Lett. **122** (2019) 084801.

Combining laser fibres

Coherent combination of diode-pumped fibre lasers could lead to high-power, high-efficiency lasers.

Repetition rates of *O(10) kHz*

Challenge: need to combine ~ 10^4 fibre lasers



ICAN: International Coherent Amplification Network

Figure 1 | Principle of a coherent amplifier network. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of ~10 kHz (7).

G. Mourou et al., Nature Photonics **7** (2013) 258

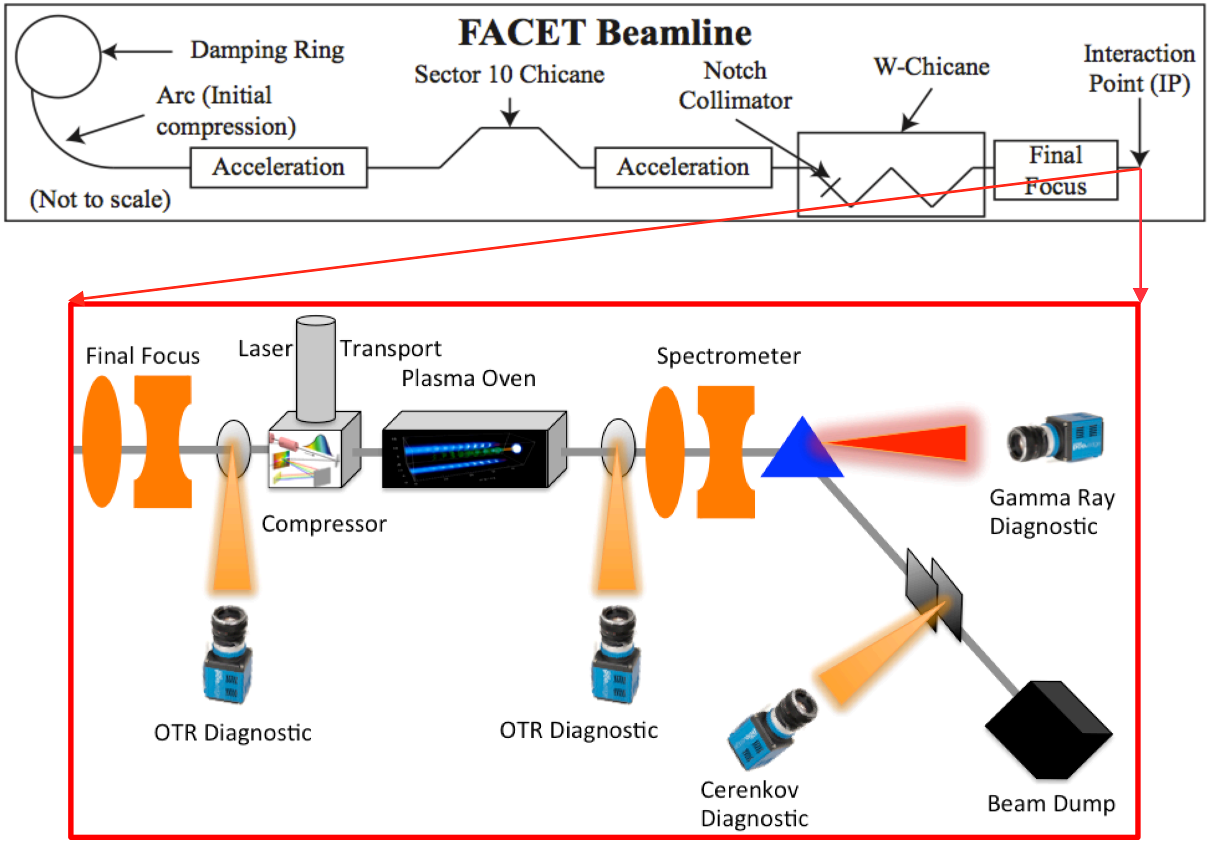
FACET project at SLAC

Facility for Advanced Accelerator Experimental Tests at SLAC was a five-year programme by SLAC, UCLA, University of Oslo and Ecole Polytechnique to investigate:

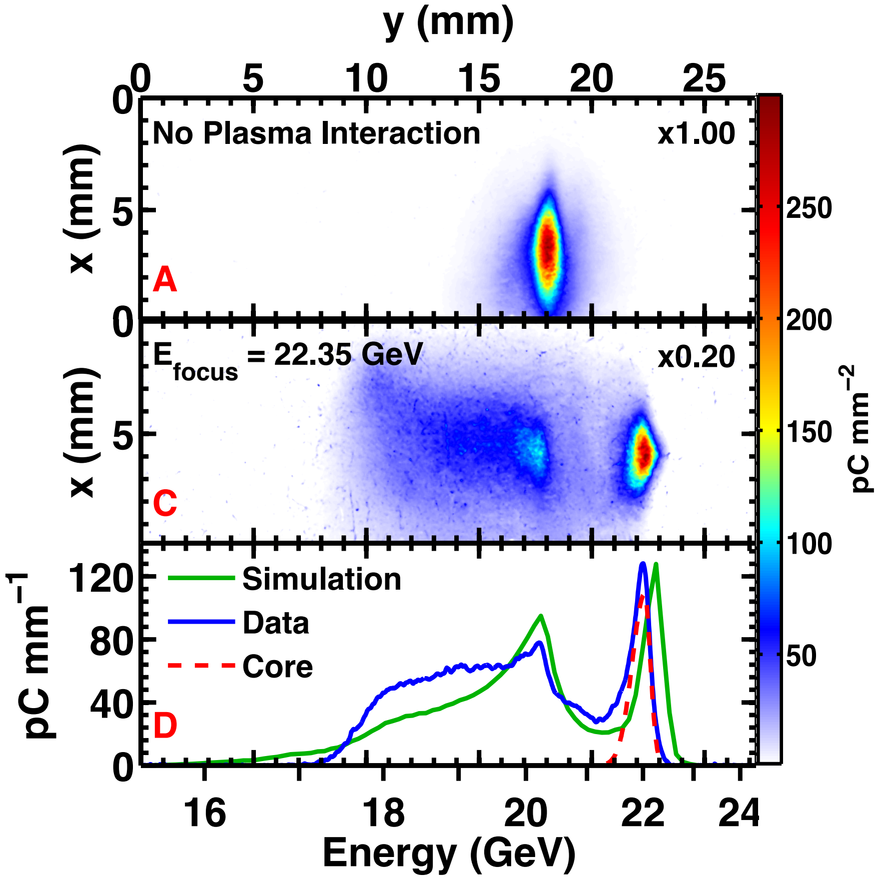
- Two-bunch experiments: acceleration of a witness bunch.
- Metre-scale plasmas
- High gradients
- Low energy spread
- High efficiency
- Acceleration with e^+
- Emittance preservation

Electron or positron bunch:

- $E = 20\ GeV$
- $Q = 3\ nC$
- $\sigma_{z,r} = 20\ \mu m$
- $\varepsilon \sim 100\ \mu m$

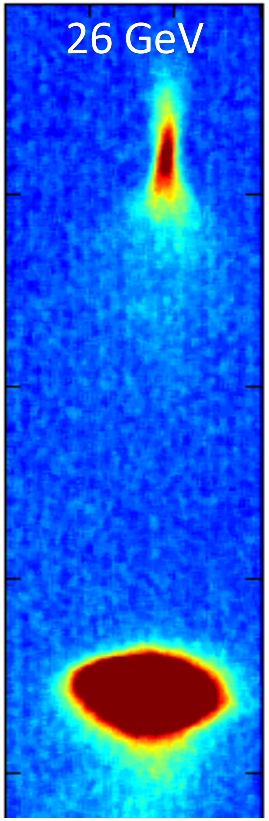


FACET two-bunch results



- *1.7 GeV* energy gain in *30 cm* of Li vapour plasma.
- 2% energy spread.
- Accelerated bunch has charge ~ *70 pC*
- Up to *30%* wake-to-bunch energy transfer efficiency (mean *18%*).
- *6 GeV* energy gain in *1.3 m* of plasma.

1.3 m plasma

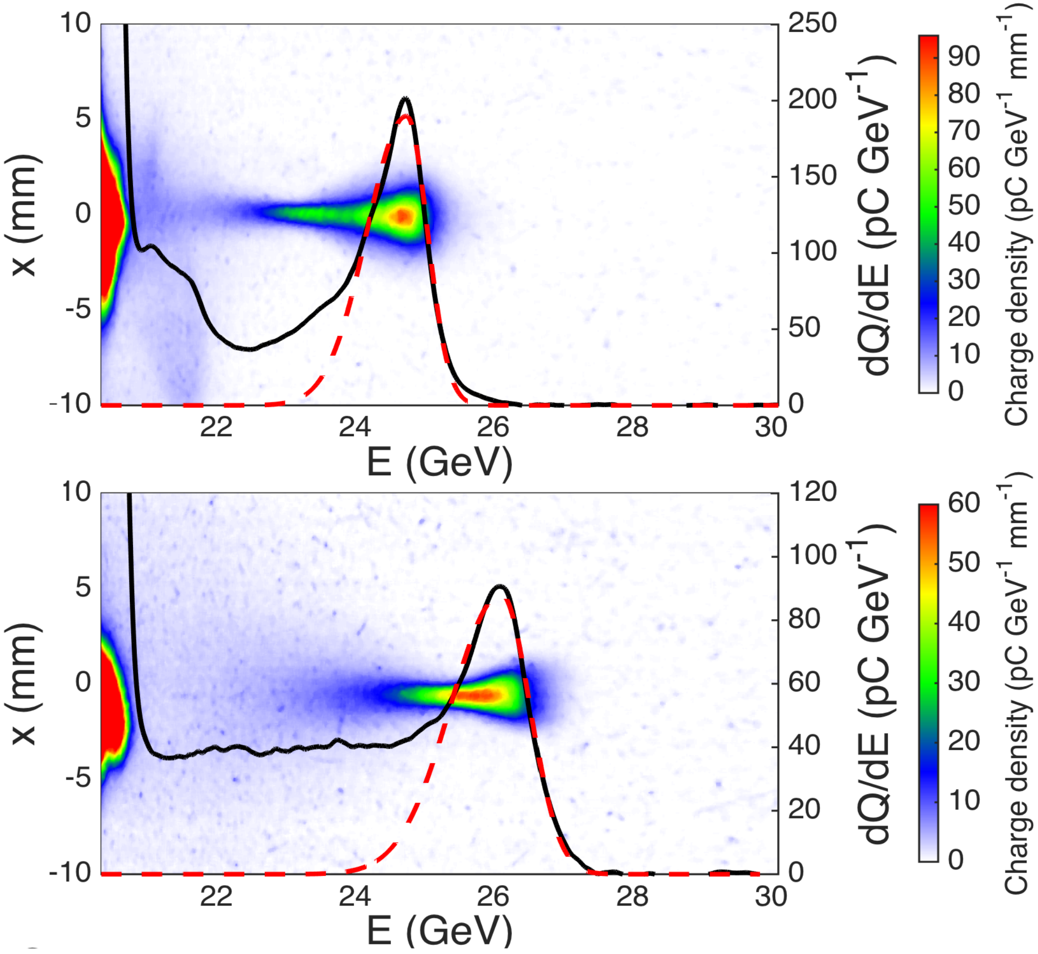


2014

M. Litos et al., Nature **515** (2014) 92

FACET positron acceleration

- Energy gains of about *5 GeV* over *1.3 m* of plasma.
- Energy spread about *2%*.
- *30%* energy efficiency from wake.
- Charge of up to *200 pC*.
- Note this is single-bunch running.
- Application to 'afterburner' for high energy positrons.



S. Corde et al., Nature **524** (2015) 442

FACET-II programme aims to:

- Have higher energy acceleration
- Higher charge
- Lower energy spread
- Investigate positrons as well as electrons

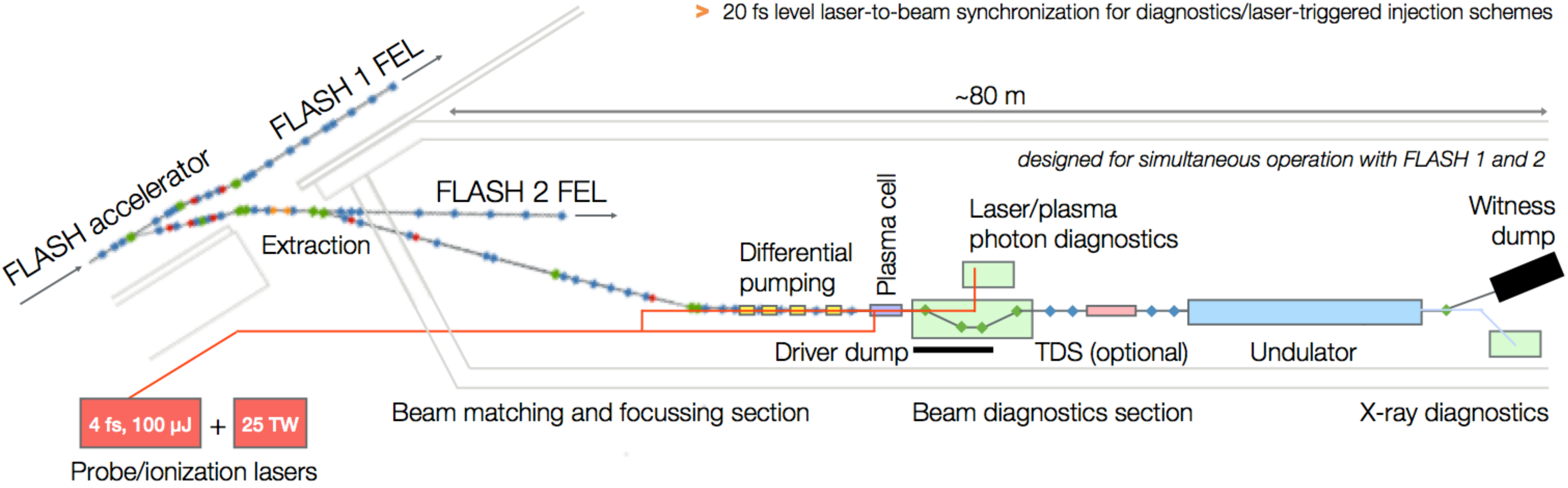
FLASHForward▸▸

Future-oriented wakefield-accelerator research and development at FLASH

Conceptual design concluded,
technical design in progress,
experiments to start in 2016, run for 4 years+

FLASH capabilities of particular interest for plasma-wakefield studies

- FEL-quality driver beam at 1.25 GeV, post-compression for ~10 kA level peak current
- variable longitudinal beam shape (e.g. triangular)
- 20 fs level laser-to-beam synchronization for diagnostics/laser-triggered injection schemes


FLASH accelerator
FLASH 1 FEL
FLASH 2 FEL
Extraction
~80 m
designed for simultaneous operation with FLASH 1 and 2
Differential pumping
Plasma cell
Laser/plasma photon diagnostics
Witness dump
Driver dump
TDS (optional)
Undulator
4 fs, 100 μJ + **25 TW**
Probe/ionization lasers
Beam matching and focussing section
Beam diagnostics section
X-ray diagnostics

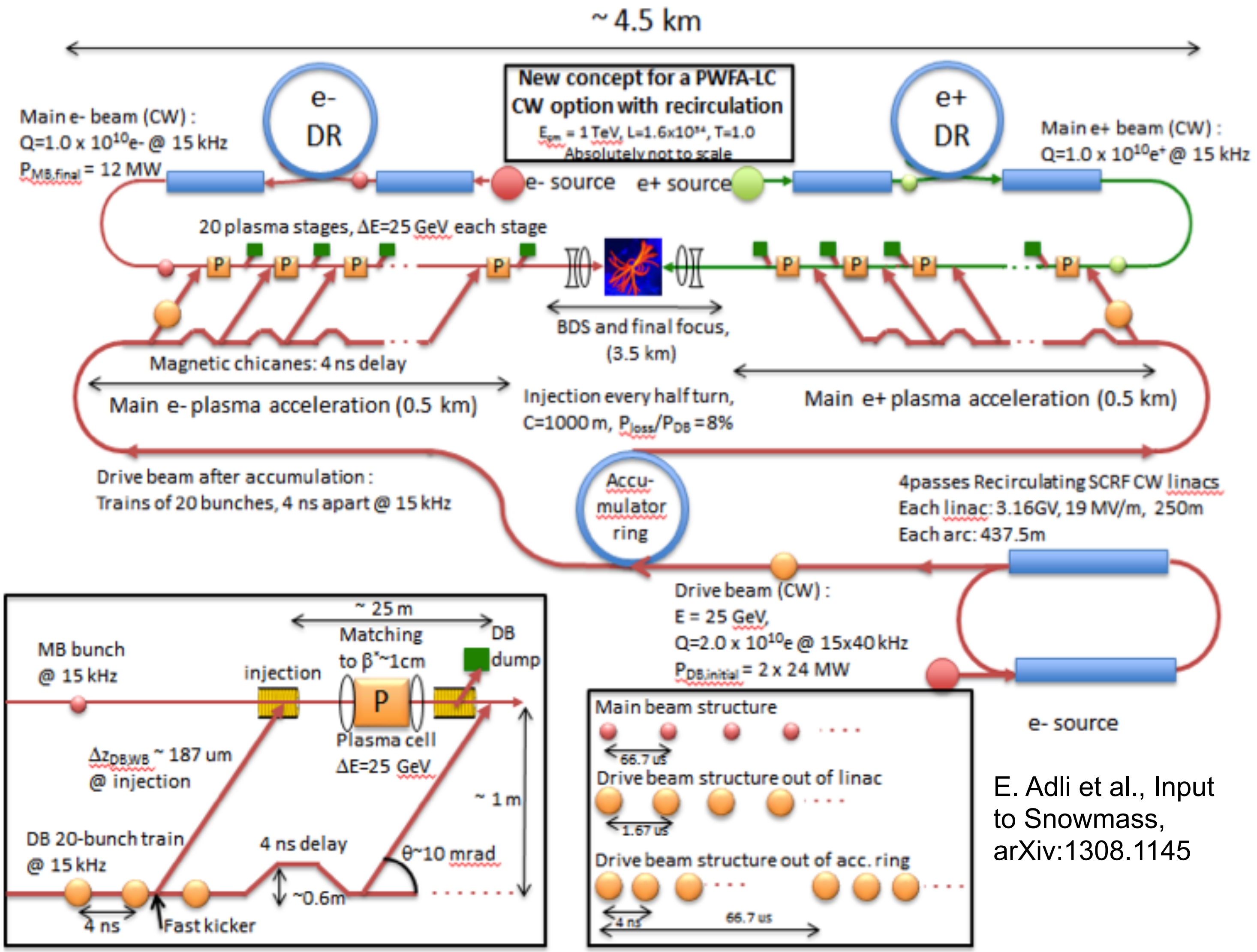
Contact Jens Osterhoff
jens.osterhoff@desy.de
for more details

Main objectives:

- demonstration of novel beam injection schemes for unprecedented quality from a plasma with *> 2.5 GeV, ~fs duration, ~100 nm norm. emittance, > kA currents, ~‰ uncorrelated energy spread*
- the application of these beams in undulators to test feasibility of FEL gain
- investigation of stability of and control over plasma-accelerated beams

e^+e^- collider based on beam-driven plasma wakefield acceleration

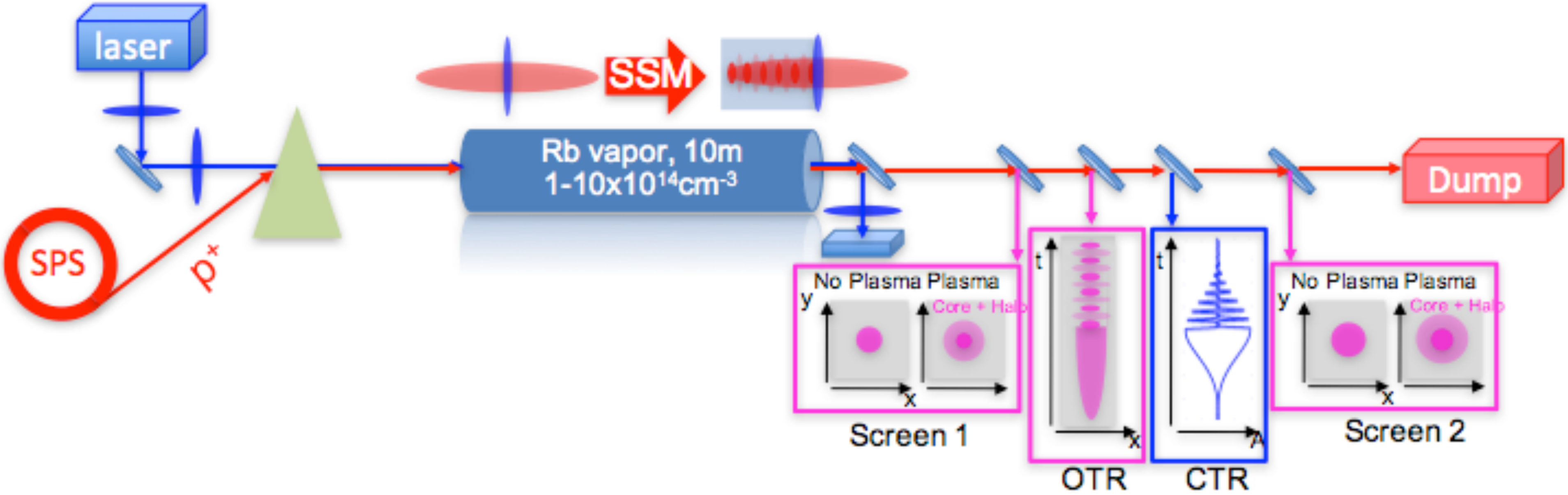
- Straw-man design of such a scheme for a linear collider.
- Need multiple acceleration stages.
- Acceleration to *500 GeV* over *0.5 km.*



E. Adli et al., Input to Snowmass, arXiv:1308.1145

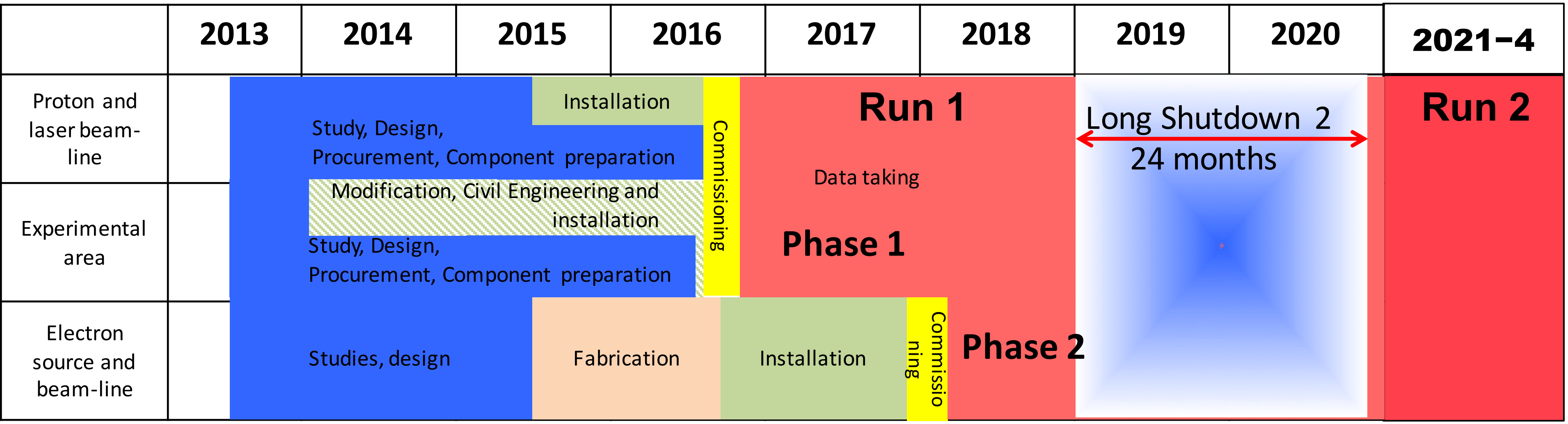
Proton micro-bunching

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.

AWAKE physics and timeline



2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021−4

Proton and laser beam-line

Experimental area

Electron source and beam-line

Installation

Study, Design, Procurement, Component preparation

Modification, Civil Engineering and installation

Study, Design, Procurement, Component preparation

Commissioning

Studies, design

Fabrication

Installation

Commissioning

Run 1

Data taking

Phase 1

Phase 2

Long Shutdown 2

24 months

Run 2

- 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].
- Then HEP applications …

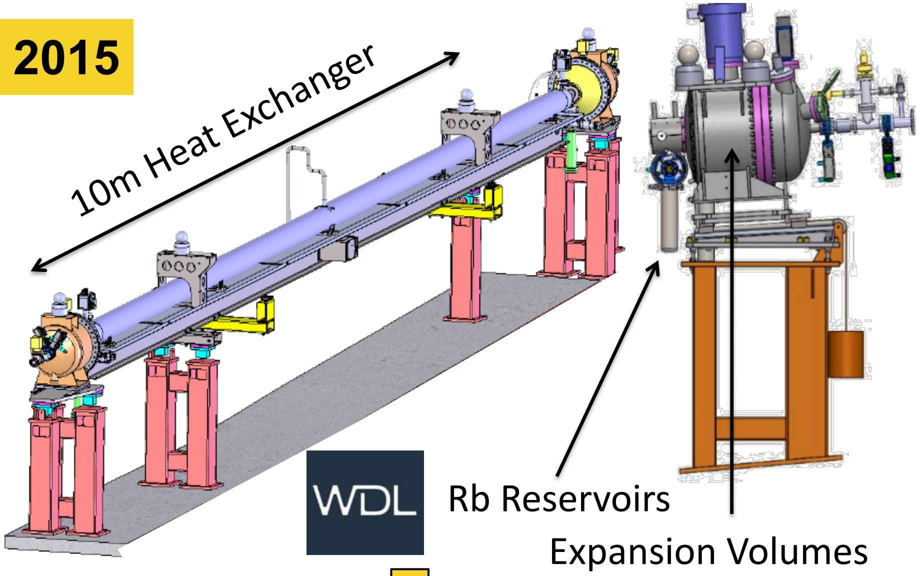
AWAKE proton beam

Parameter	Protons
Momentum (GeV)	400
Momentum spread (GeV)	0.14
Particles per bunch	3×10^{11}
Charge per bunch (nC)	48
Bunch length (cm)	6–12 (0.4 ns)
Norm. emittance (mm mrad)	3.5
Repetition rate (Hz)	1/30
Spot size at focal point (μm)	200 ± 20

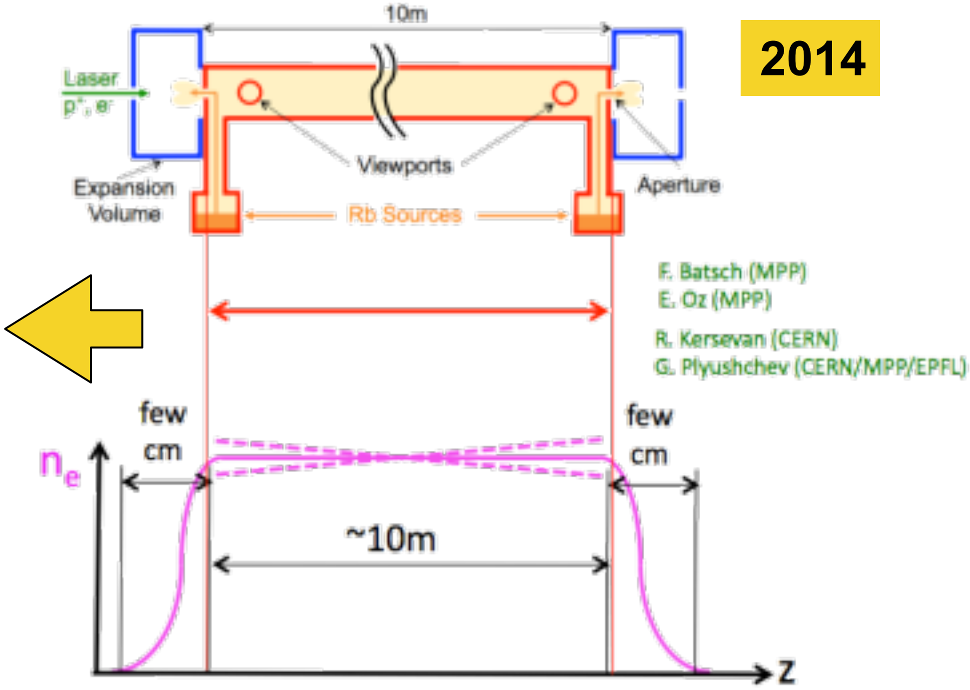

750 m proton beam line

AWAKE plasma cell

2015

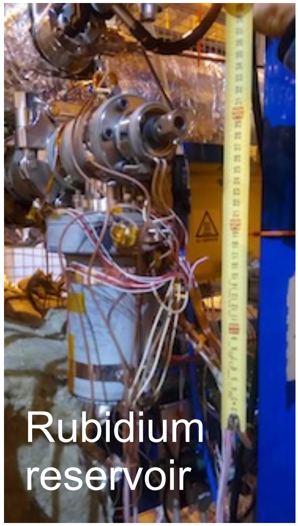


2014



F. Batsch (MPP)
E. Oz (MPP)
R. Kersevan (CERN)
G. Plyushchev (CERN/MPP/EPFL)


Rubidium


Rubidium reservoir


Plasma source in AWAKE

2016

AWAKE plasma cell requirements

The physics goals and technological feasibility place constraints on the plasma cell:

- Length, $L \sim 10\ m$.
- Radius, r_p, larger than three proton bunch rms radii or $\sim 1\ mm$.
- Density, n_e, in the range $10^{14} - 10^{15}\ cm^{-3}$.
- Density uniformity, $\delta n_e/n_e$ of order 0.2% or better.
- Reproducible density.
- Gas/vapour easy to ionise.
- Allow for seeding of self-modulation.
- High-Z element to avoid background plasma ion motion.

A rubidium vapour source held at about $200\ ^oC$ with default density $7 \times 10^{14}\ cm^{-3}$ ($\lambda_p \sim 1.2\ mm$) chosen.

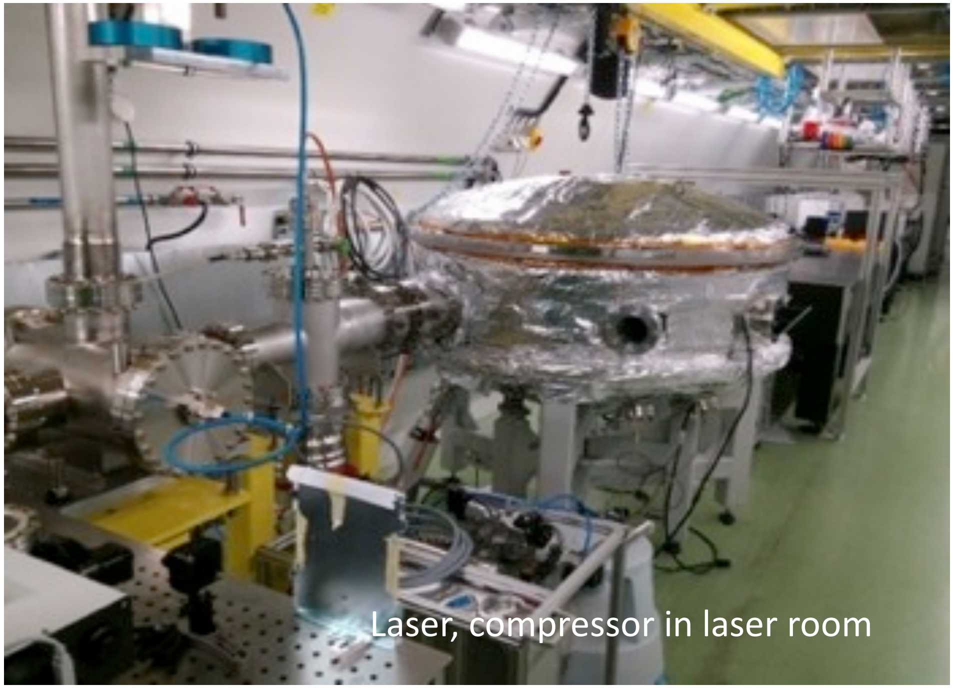
E. Öz, F. Batsch and P. Muggli, IPAC2014 Proc., p.1522;
E. Öz and P. Muggli, Nucl. Instrum. Meth. **A 740** (2014) 197.

Laser

Ti:sapphire laser needed for:

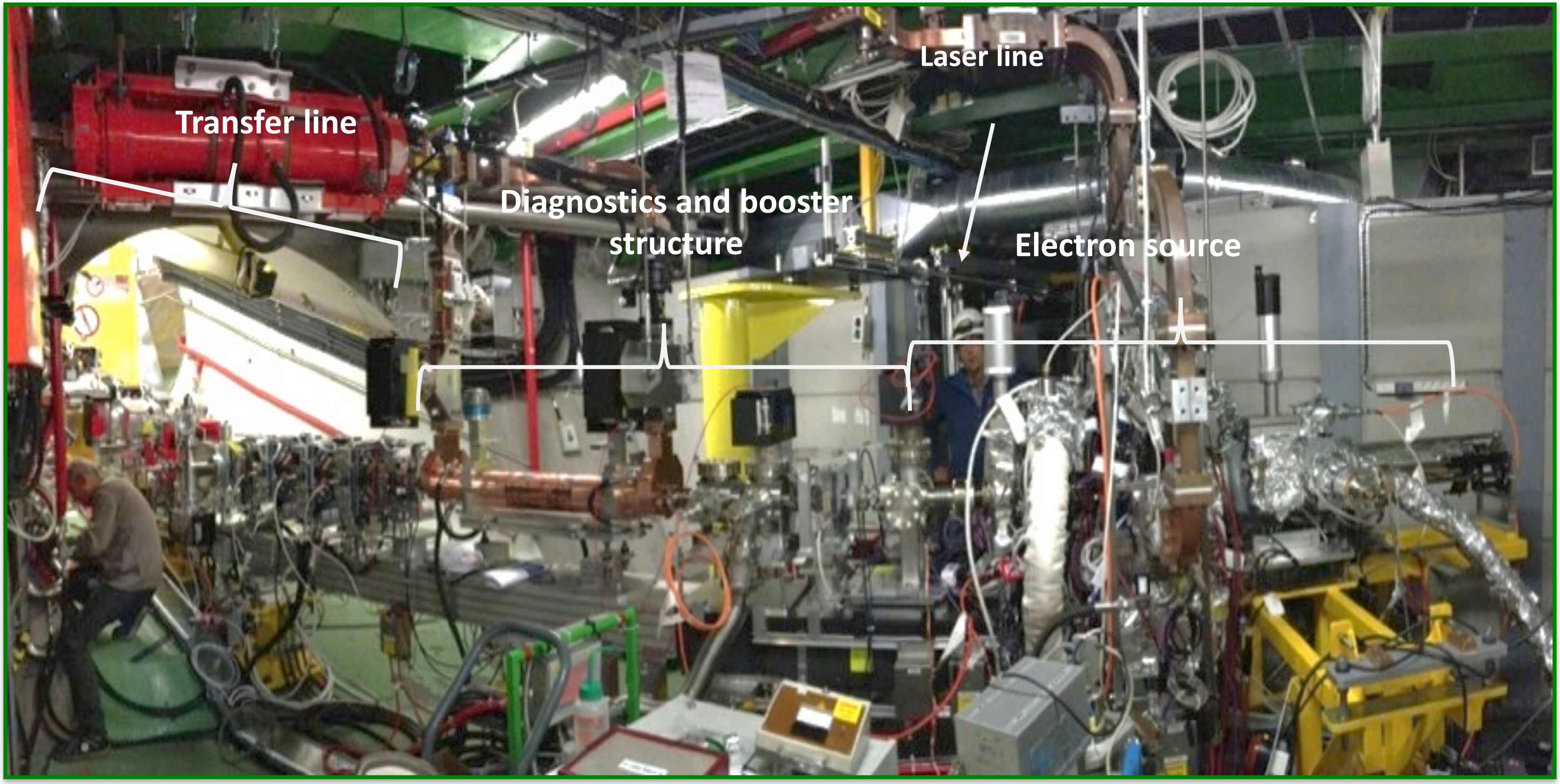
- Ionising vapour and seeding self-modulation in plasma.
- Diagnostic beam line.
- Beam to electron source.

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



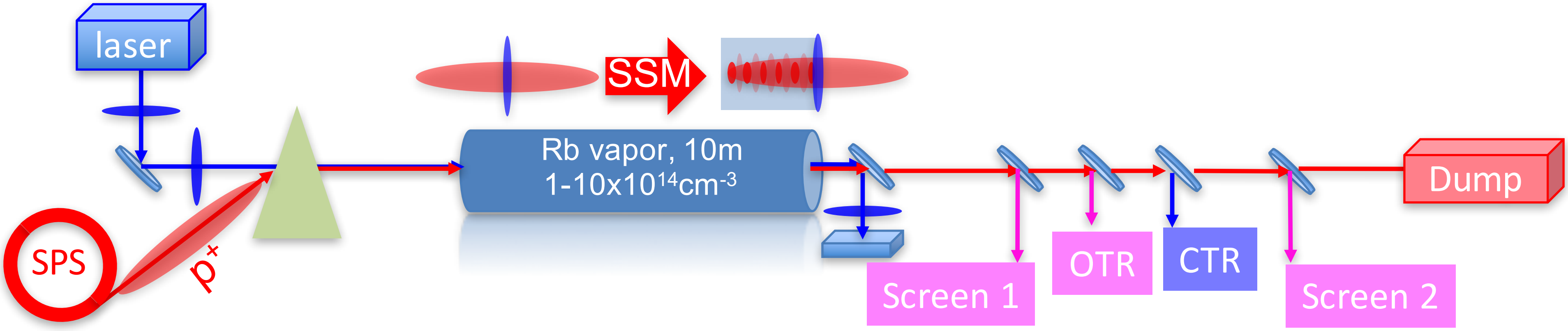
Laser, compressor in laser room

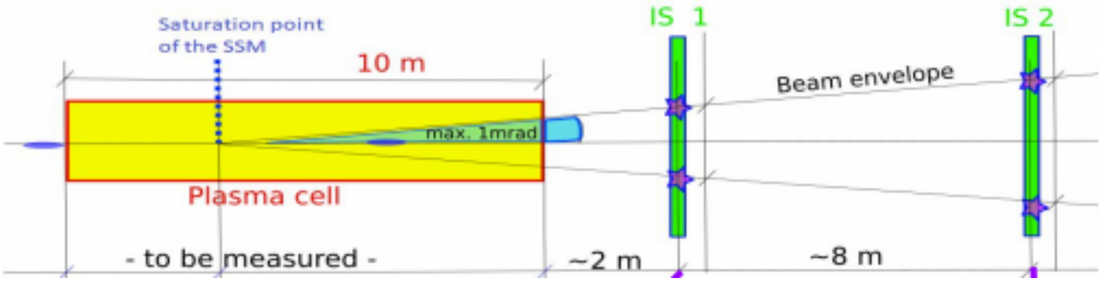
Electron beam



- Electron bunch up to ~650 pC, σ ~ 4 ps
- Produced at 5.5 MeV
- Accelerated up to 20 MeV
- 18 m beam line to plasma cell

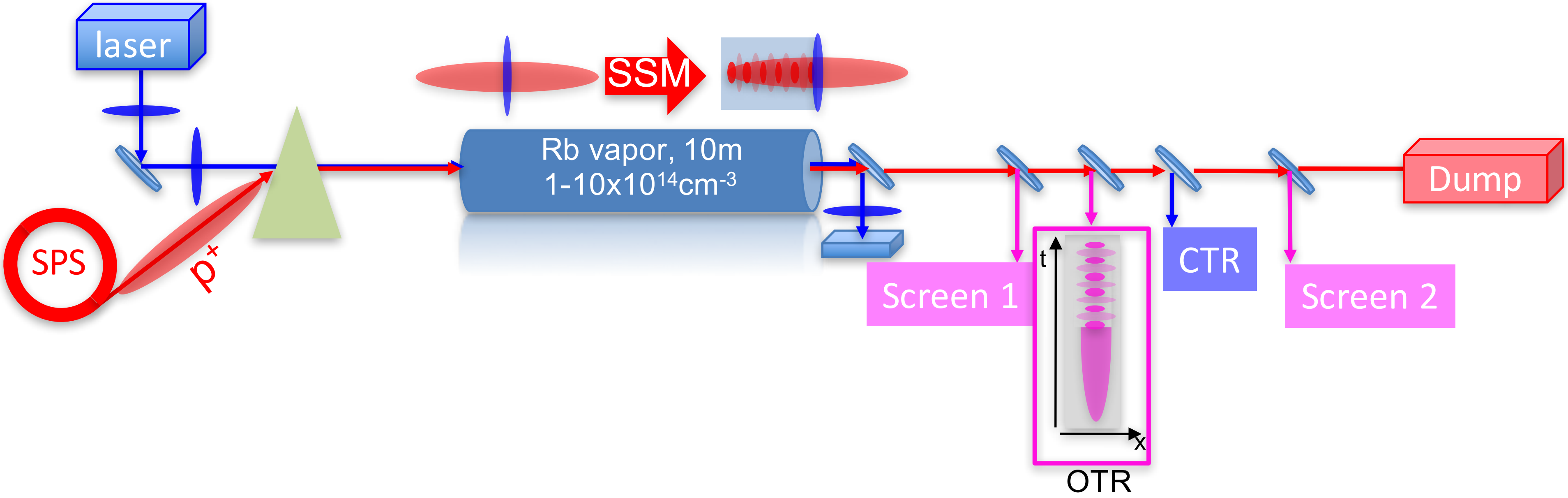
Two-screen indirect measurement





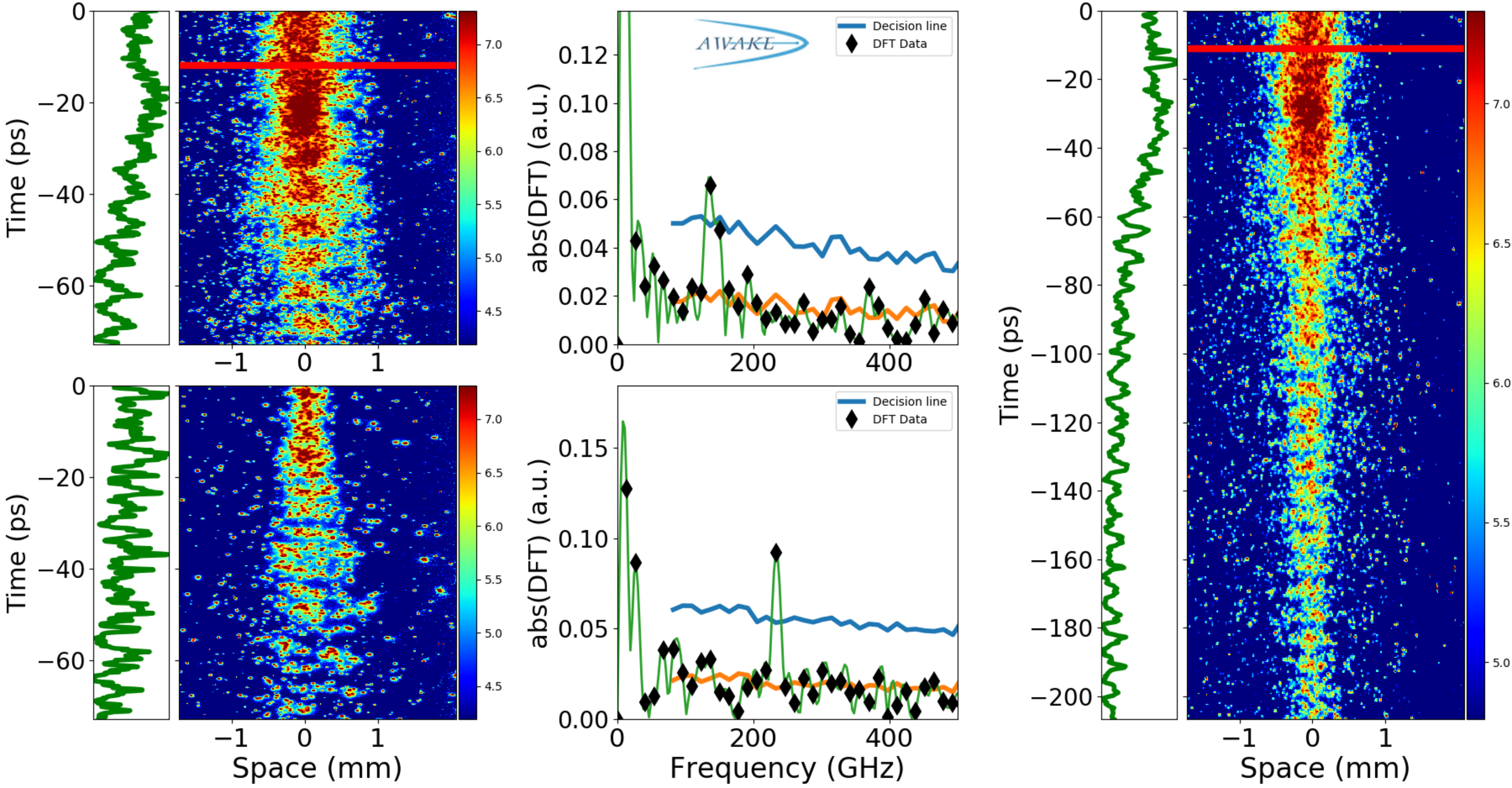
- Look for transverse development of proton beam on two screens:
  - Take images when plasma is off (“normal” propagation of proton beam).
  - Take images when plasma is on (and affected by plasma wakefields).

Direct measurement using optical transition radiation (OTR)



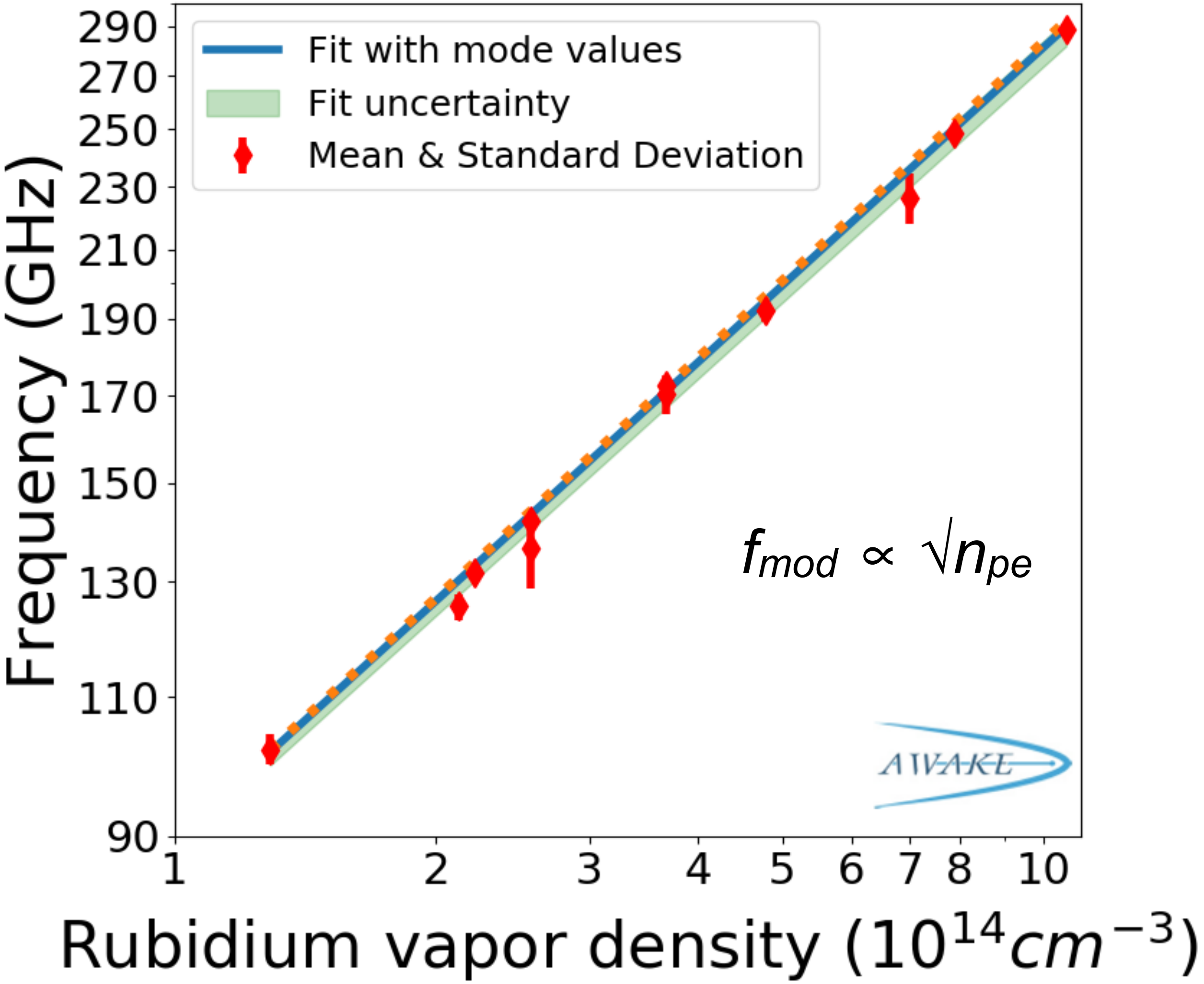
- Transition radiation occurs when charged particles pass through a boundary between two media.
- Place (alumnium) foil in the proton beam and measure optical (OTR) and measure emitted photons with a streak camera.
    - A streak camera measures the temporal characteristics of a light pulse.
    - Expect to see large light output for micro-bunched protons and lower light output in between.

Self-modulation of proton bunch



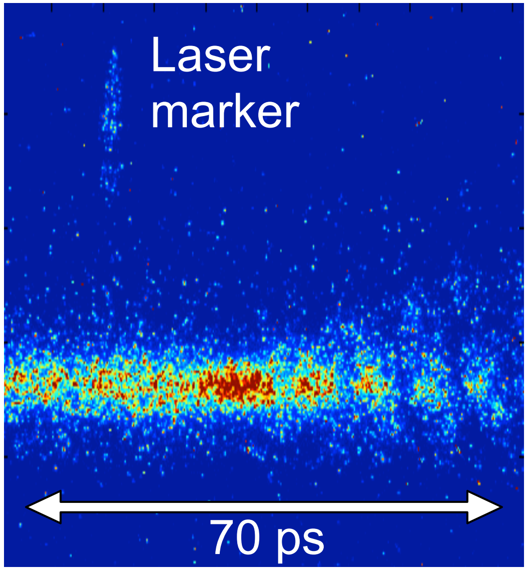
E. Adli et al. (AWAKE Coll.), “Experimental observation of proton bunch modulation in a plasma at varying plasma densities”, *Phys. Rev. Lett.* **122** (2019) 054802.

Self-modulation of proton bunch

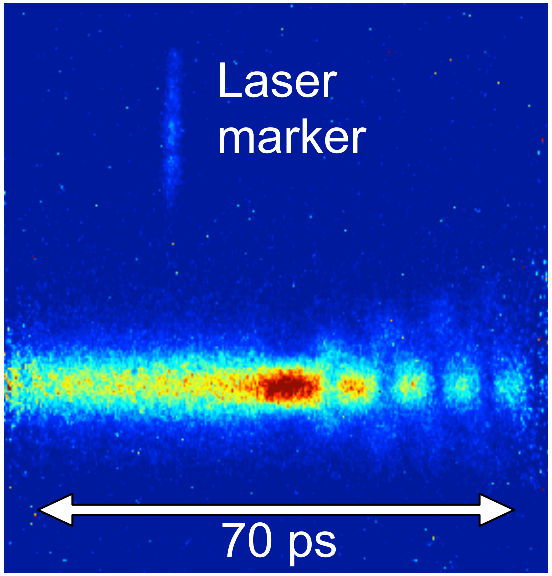


Seeded self-modulation frequency dependency on plasma density scales with expected square root of density.

Direct measurement using OTR – reproducibility



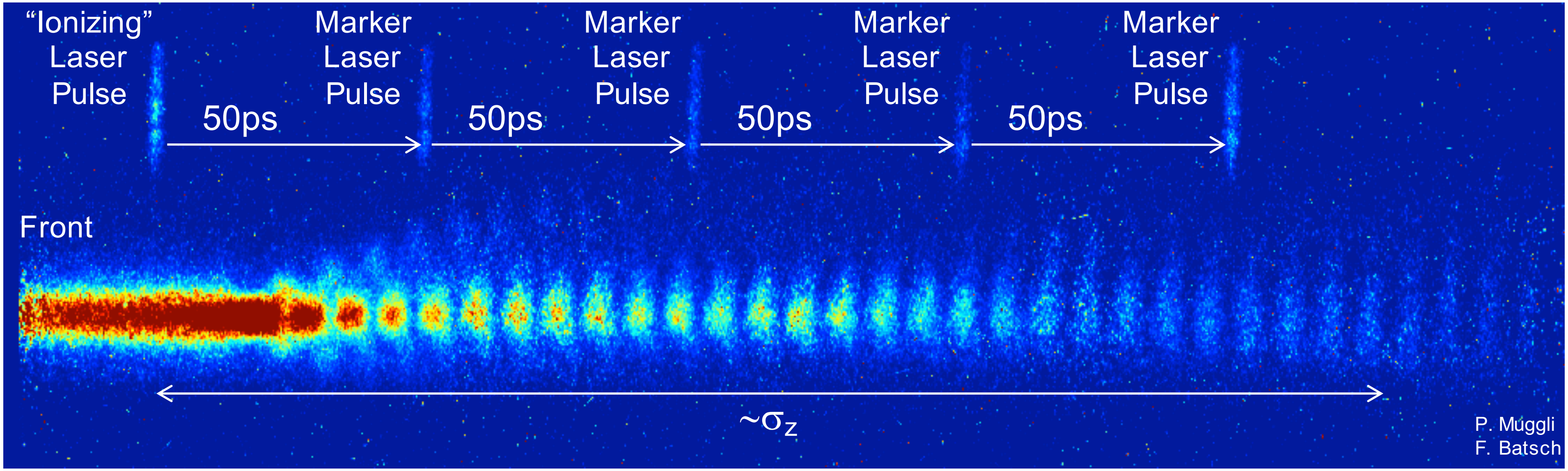
1 event → 10 events



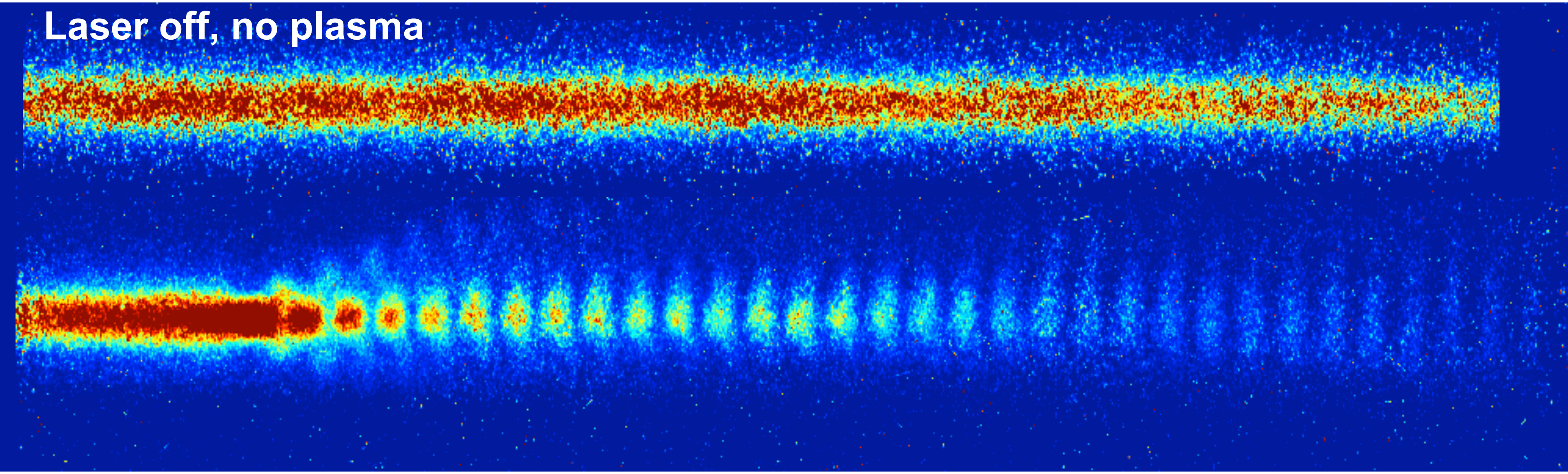
- Streak camera image from single event
- What about multiple events ?

- 10 consecutive events aligned to laser marker
- Image looks nicer !
- **Bunches add and align.**
- **Modulation fixed wrt seed.**

Direct measurement using OTR – reproducibility



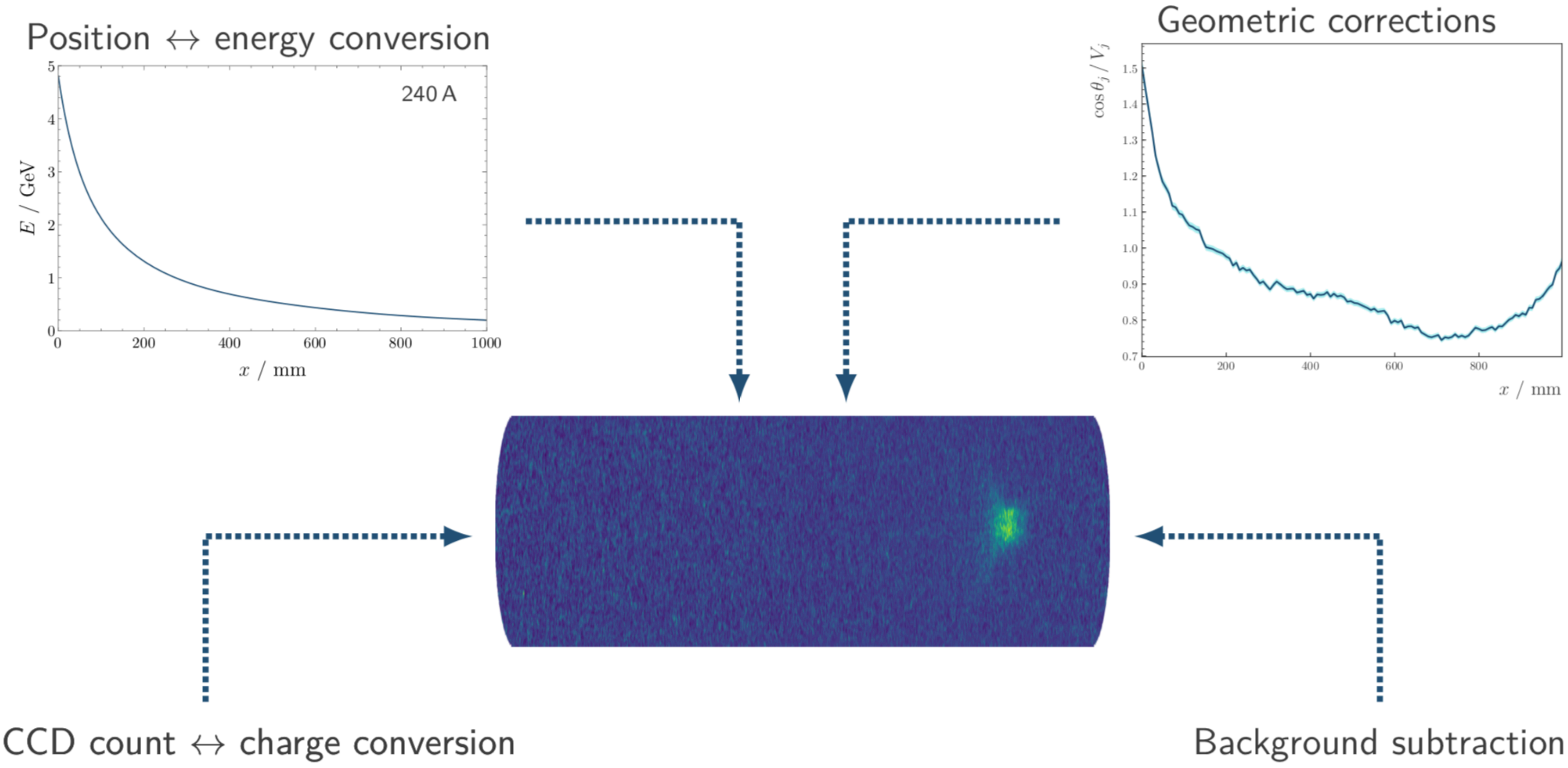
P. Muggli
F. Batsch



Stable proton micro-bunches

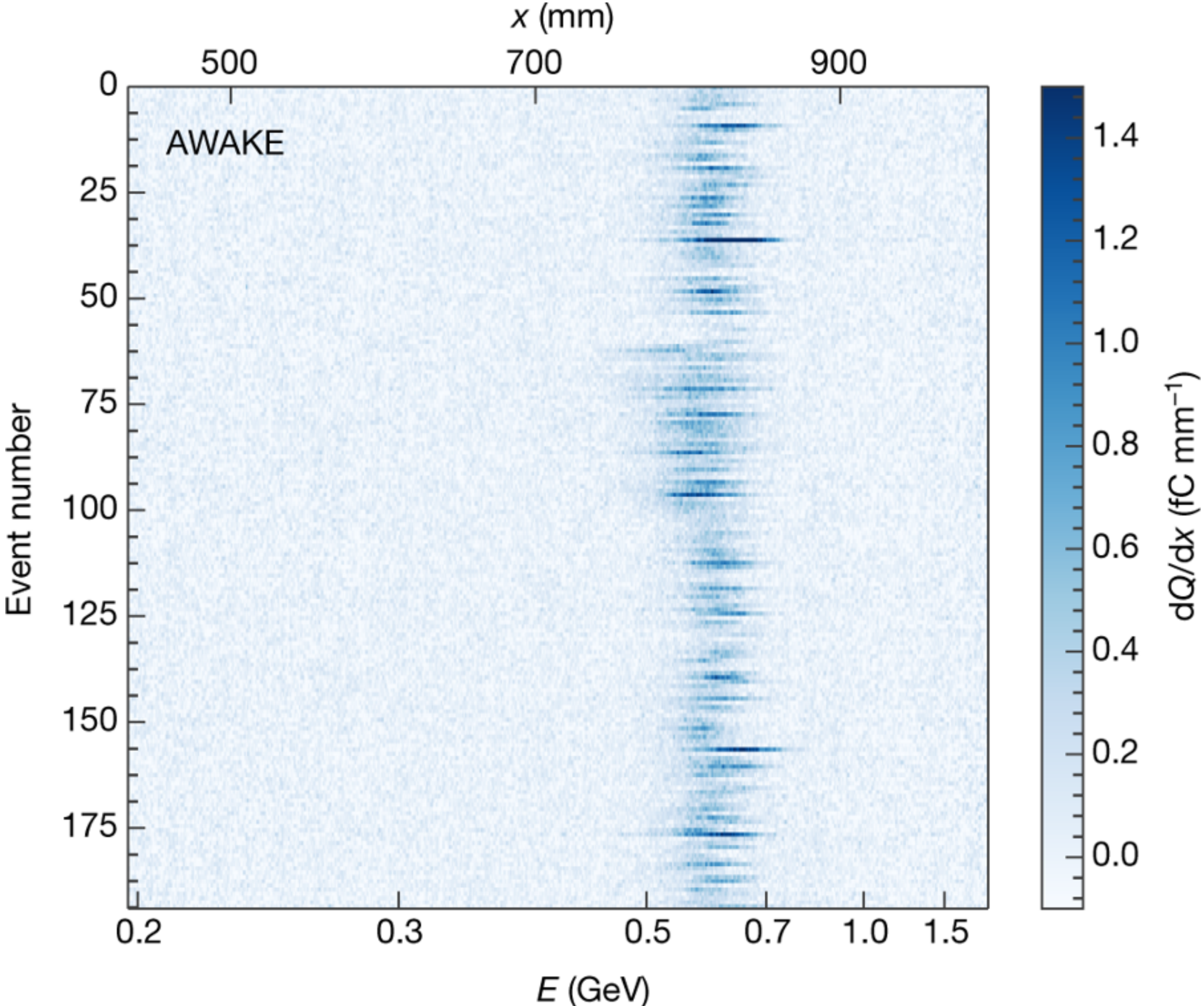
- Micro-bunches present over a long time-scale from seed point.
- They are reproducible, with a constant phase and stable event-by-event.
- This shows that we observe and understand seeded self-modulation.
- **This is crucial for injection of electrons which will happen at a given point.**

Spectrometer analysis



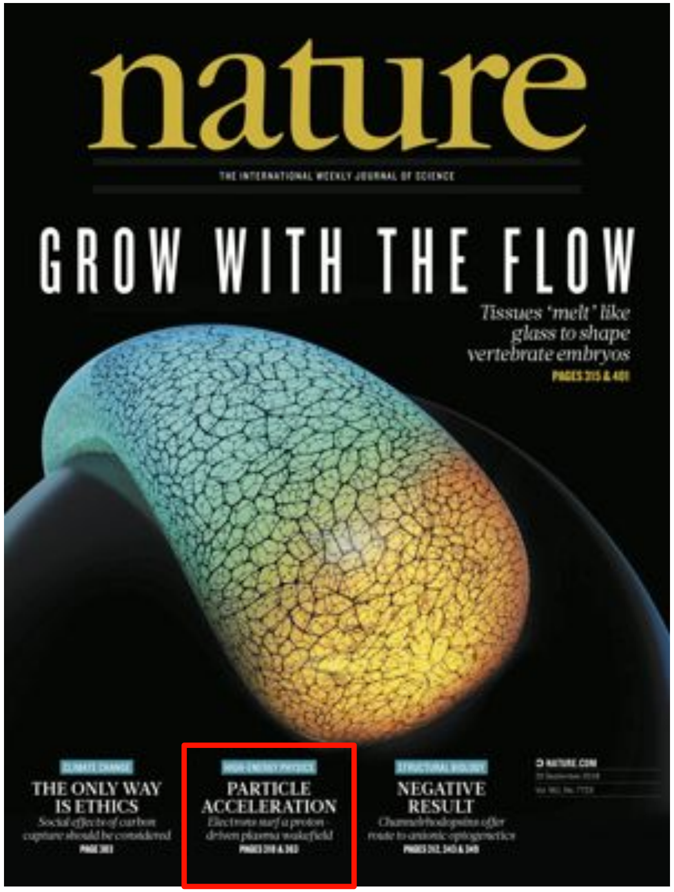
E. Adli et al. (AWAKE Coll.), "Acceleration of electrons in the plasma wakefield of a proton bunch", *Nature* **561** (2018) 363.

Electron acceleration reproducibility



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

- 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 three further data-taking periods.
- 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..
  - Increased charge capture and dependence on conditions.
- Analyses ongoing; more results and papers to come.

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.**

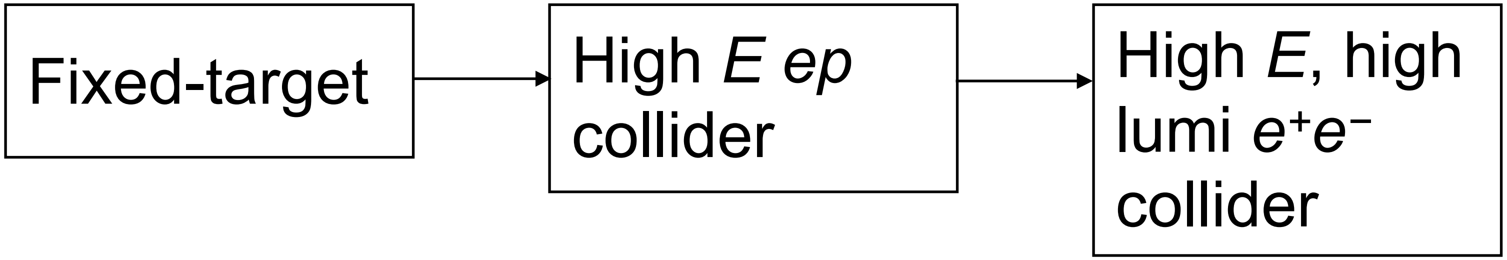
Possible particle physics experiments II

- **Search for dark photons à la NA64**
  - Consider beam-dump and counting experiments.
- **High energy electron−proton collider**
  - A low-luminosity LHeC-type experiment: $E_e \sim 50$ *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

Proton-driven plasma wakefield acceleration concept

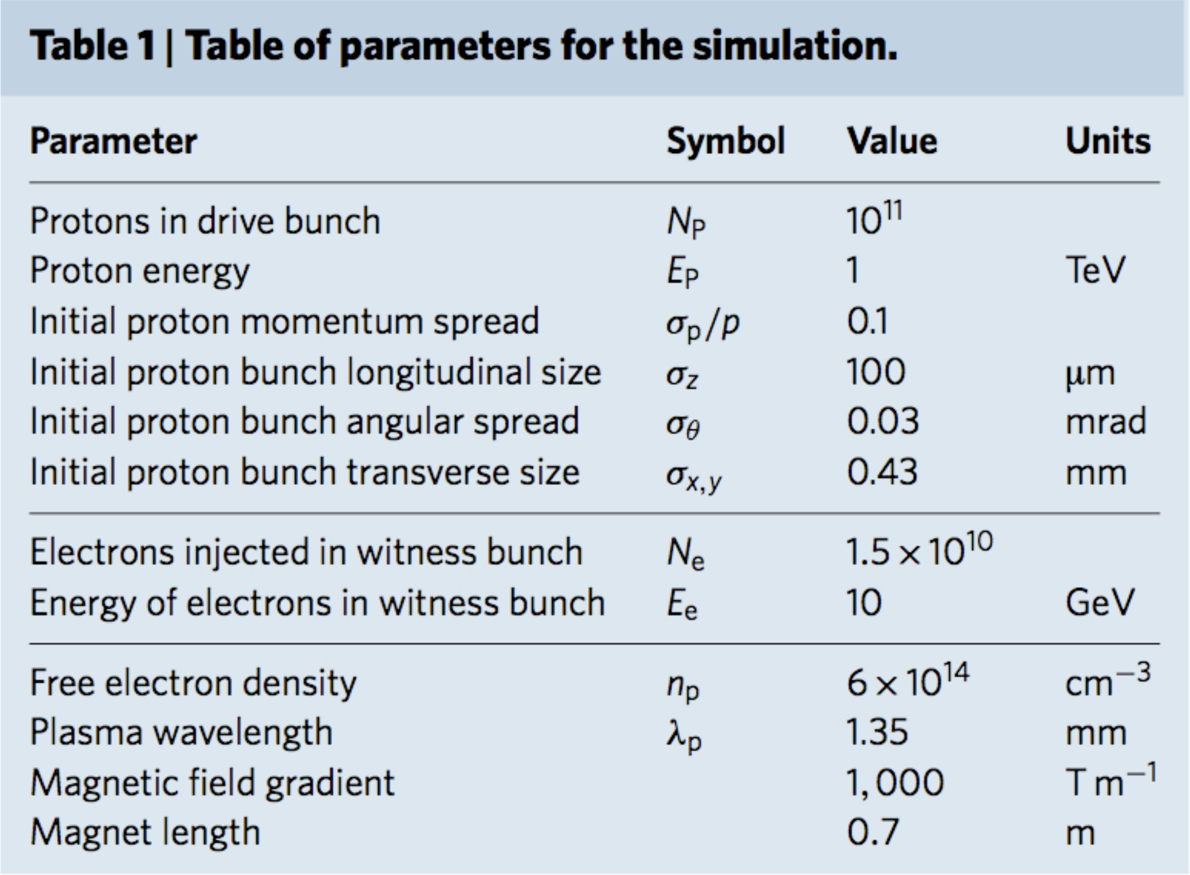


Table 1 | Table of parameters for the simulation.

Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_p/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons injected in witness bunch	N_e	1.5×10^{10}	
Energy of electrons in witness bunch	E_e	10	GeV
Free electron density	n_p	6×10^{14}	cm^{-3}
Plasma wavelength	λ_p	1.35	mm
Magnetic field gradient		1,000	$\mathrm{T\,m}^{-1}$
Magnet length		0.7	m

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

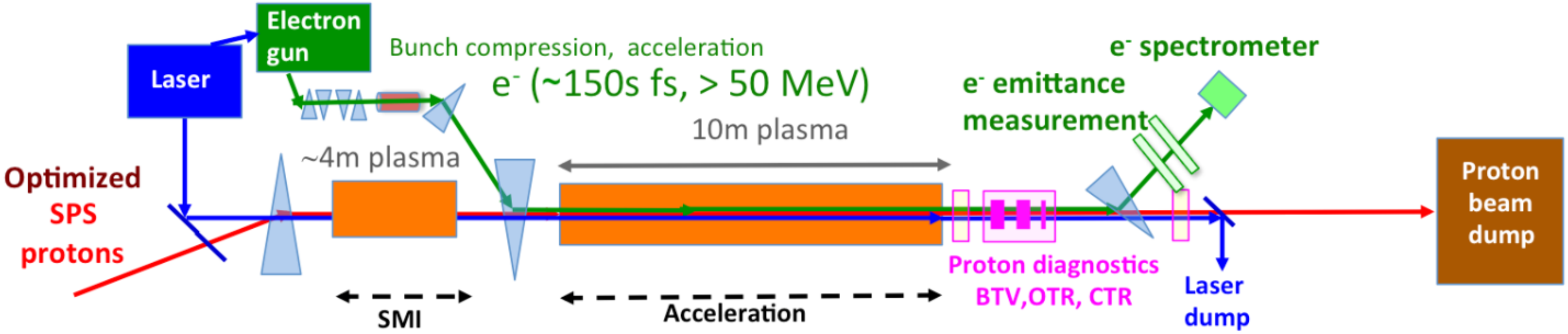
Proton beams @ CERN

Parameter	PS	SPS	**SPS Opt**	LHC
E (GeV)	24	400 (450)	**400**	6500 (7000)
N_p (10^{10})	13	11.5	**30**	11.5
$\Delta E/E$ (%)	0.05	0.03	**0.03**	0.01
σ_z (cm)	20	12	**12**	8
ε_N (mm·mrad)	2.4	3.6	**3.6**	3.5
σ_r (μm)	400	200	**200**	20

- SPS has high bunch energy and optimised for AWAKE with a higher bunch charge
- But the original proposal had a proton beam length of *100 μm* !

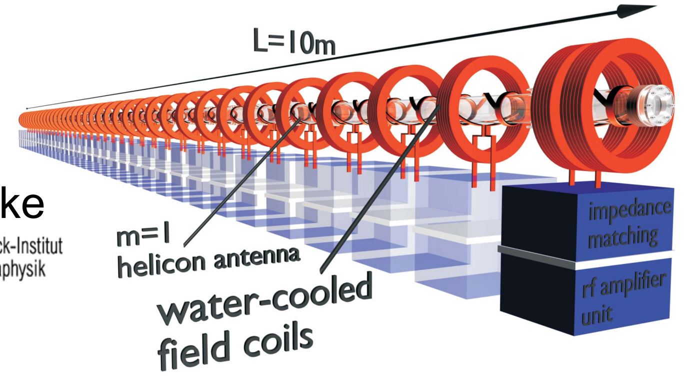
AWAKE Run 2

- 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



O. Grulke

IPP Max-Planck-Institut für Plasmaphysik

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

NA64 experimental programme

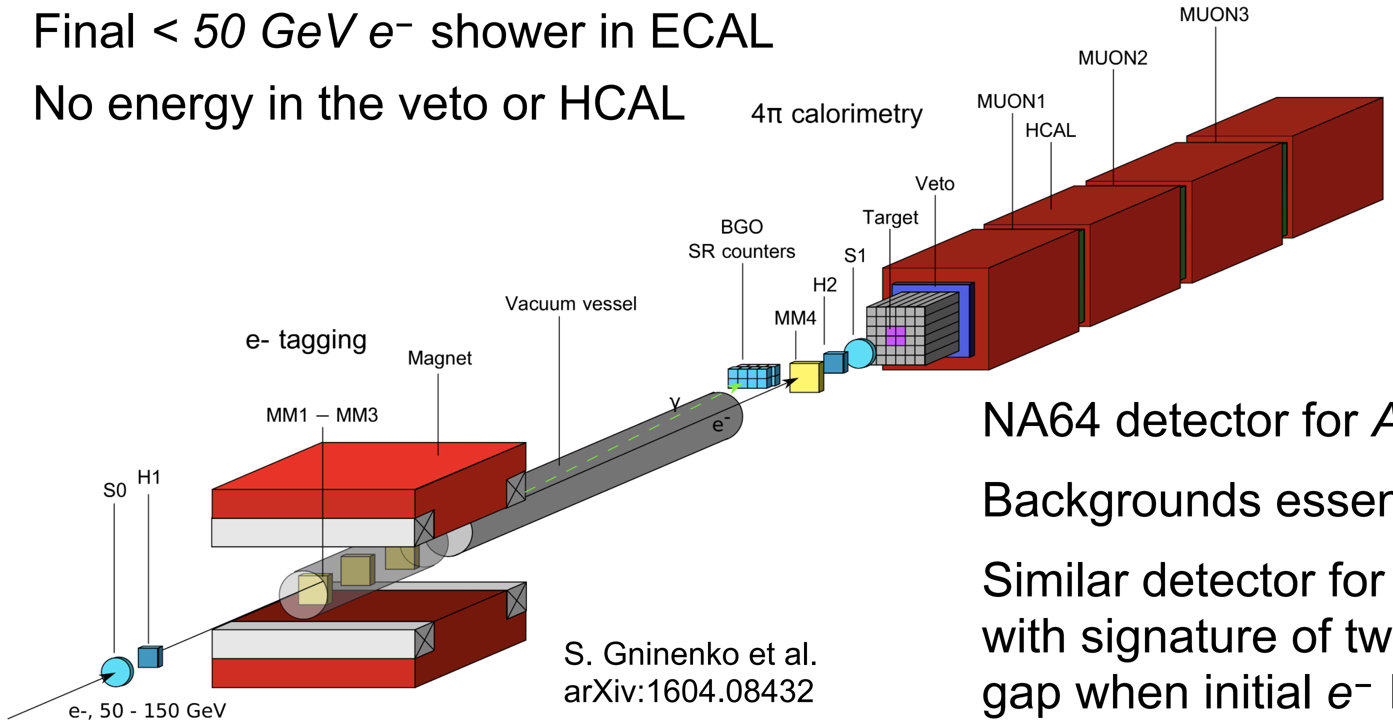
NA64 are an ongoing experiment searching for the dark sector. See various papers/ proposals from them.

Initial runs in SPS beam focusing on $A' \rightarrow$ *invisible* channel.

Also measuring $A' \rightarrow e^+ e^-$ channel.

Signature:

- Initial *100 GeV* e^- track
- Final < *50 GeV* e^- shower in ECAL
- No energy in the veto or HCAL



S. Gninenko et al.
arXiv:1604.08432

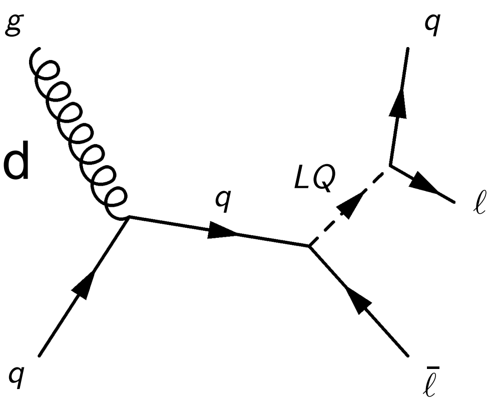
NA64 detector for $A' \rightarrow$ *invisible* channel.

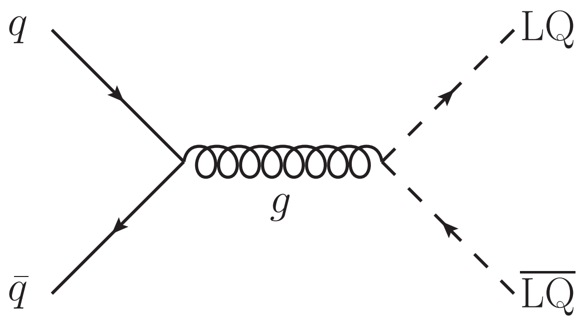
Backgrounds essentially zero.

Similar detector for $A' \rightarrow e^+ e^-$ channel with signature of two EM showers after gap when initial e^- hits target.

Leptoquark production at the LHC

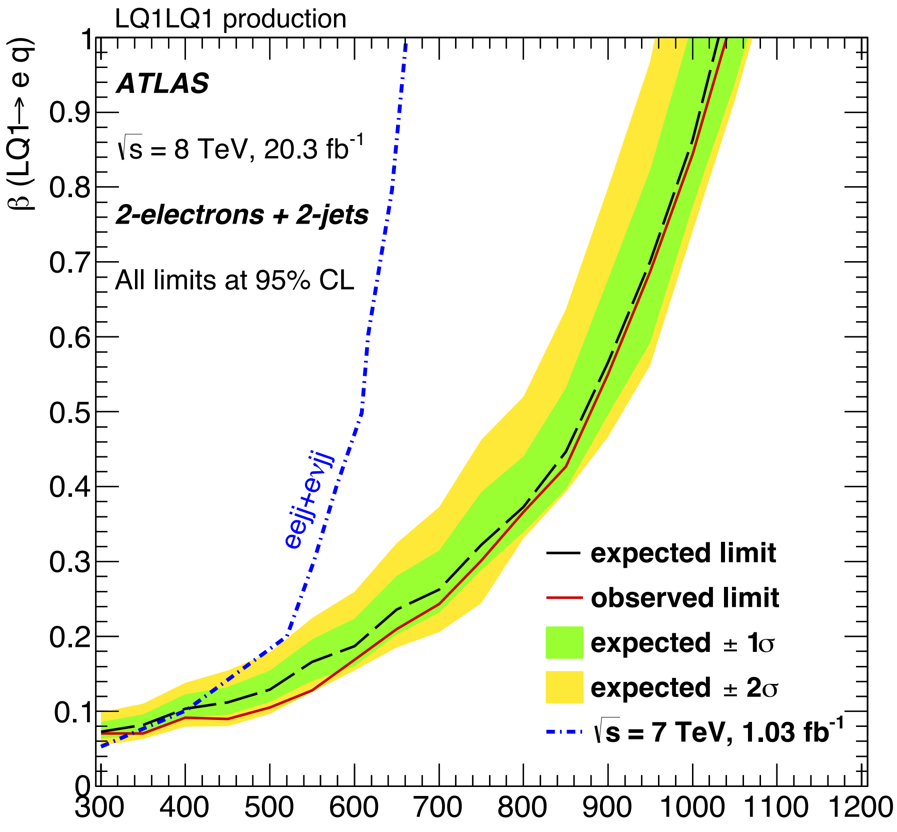
Can also be produced in *pp* singly or pair production





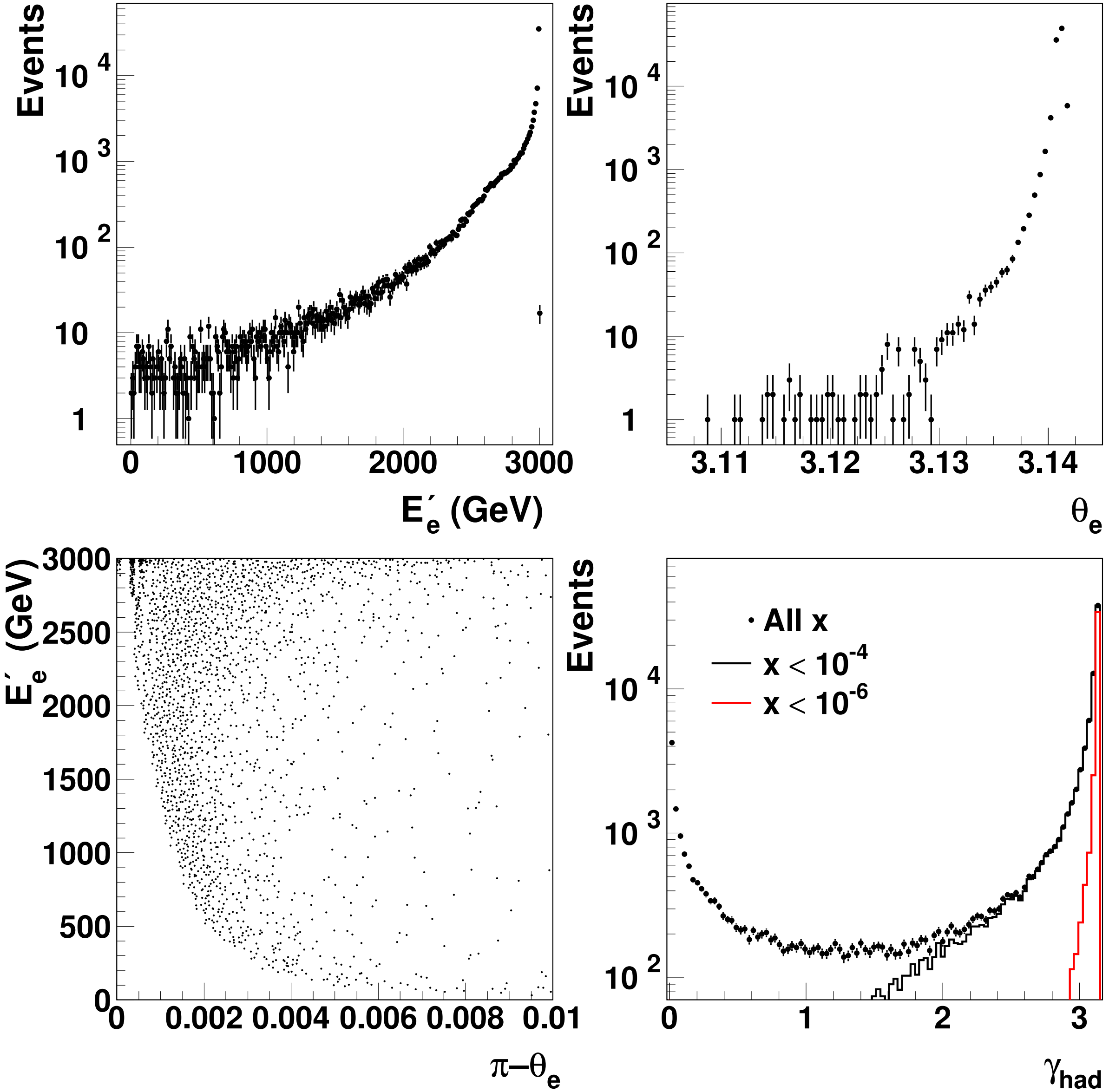
Reach of LHC currently about *1 TeV*, to increase to *2 − 3 TeV*.

Coupling dependent.



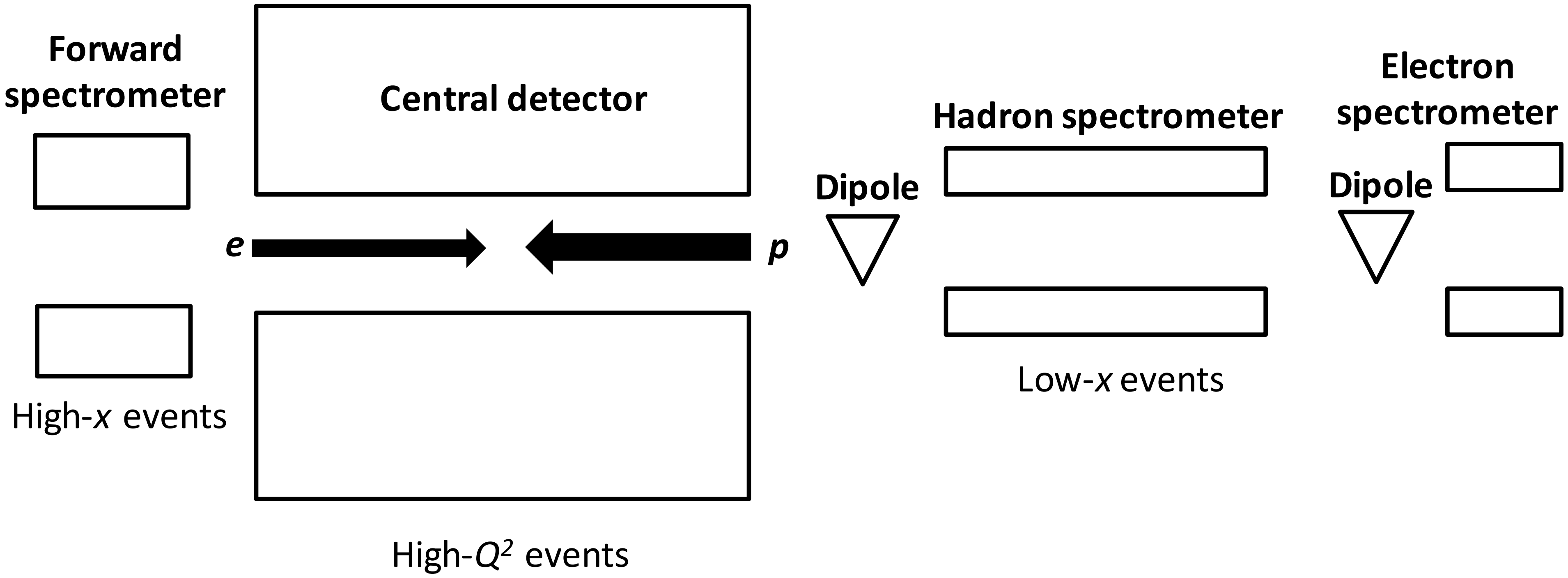
ATLAS Coll., Eur. Phys. J. **C 76** (2016) 1

Kinematics of the final state



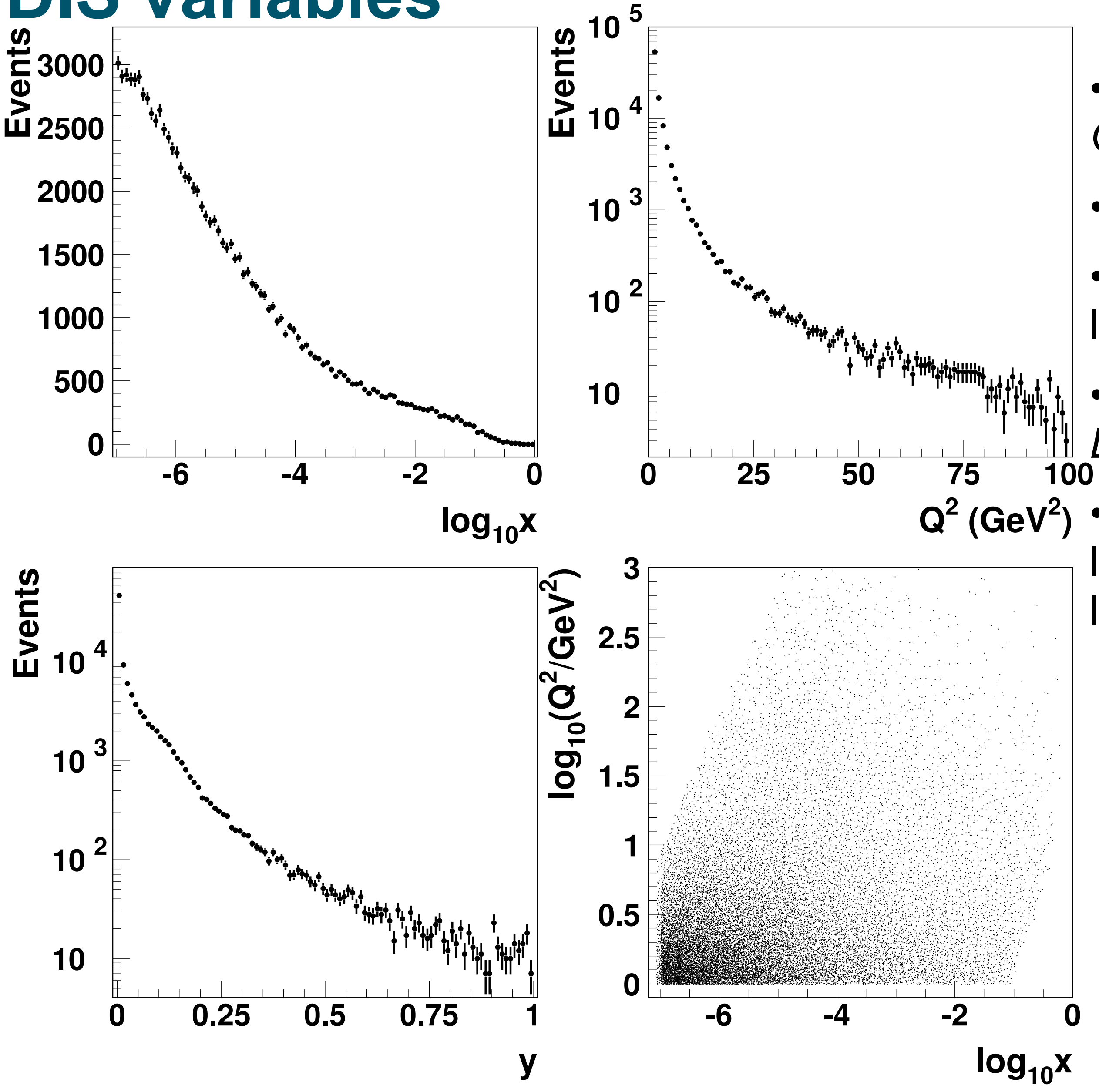
- Simulated events $Q^2 > 1\ GeV^2$ and $x > 10^{-7}$
- Test sample of $L \sim 0.01\ pb^{-1}$
- Kinematic peak at *3 TeV*, with electrons scattered at low angles.
- Hadronic activity in central region as well as forward and backward.
- Hadronic activity at low backward angles for low *x*.
- **Clear implications for the kind of detector needed.**

Sketch of detector



- Will need conventional central colliding-beam detector.
- **Will also need long arm of spectrometer detectors which will need to measure scattered electrons and hadronic final state at low *x* and high *x*.**

DIS variables



- Access down to $x \sim 10^{-8}$ for $Q^2 \sim 1$ GeV^2.
- Even lower x for lower Q^2.
- Plenty of data at low x and low Q^2 ($L \sim 0.01$ pb^{-1}).
- Can go to $Q^2 \sim 10^5$ GeV^2 for $L \sim 1$ pb^{-1}.
- Powerful experiment for low-*x* physics where luminosity less crucial.