AWAKE
Status and Prospects

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1. Motivation for proton-driven plasma wakefield acceleration
2. The AWAKE project
3. Long-term perspectives

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	[illegible]	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	[illegible]	60

The most important tool for this development was the particle accelerator

FERMIONS

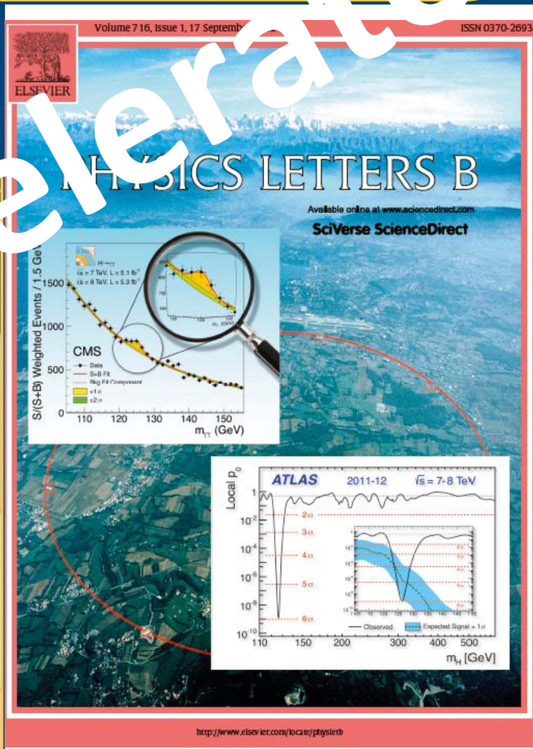
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	−1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	−1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	−1

Quarks spin = 1/2

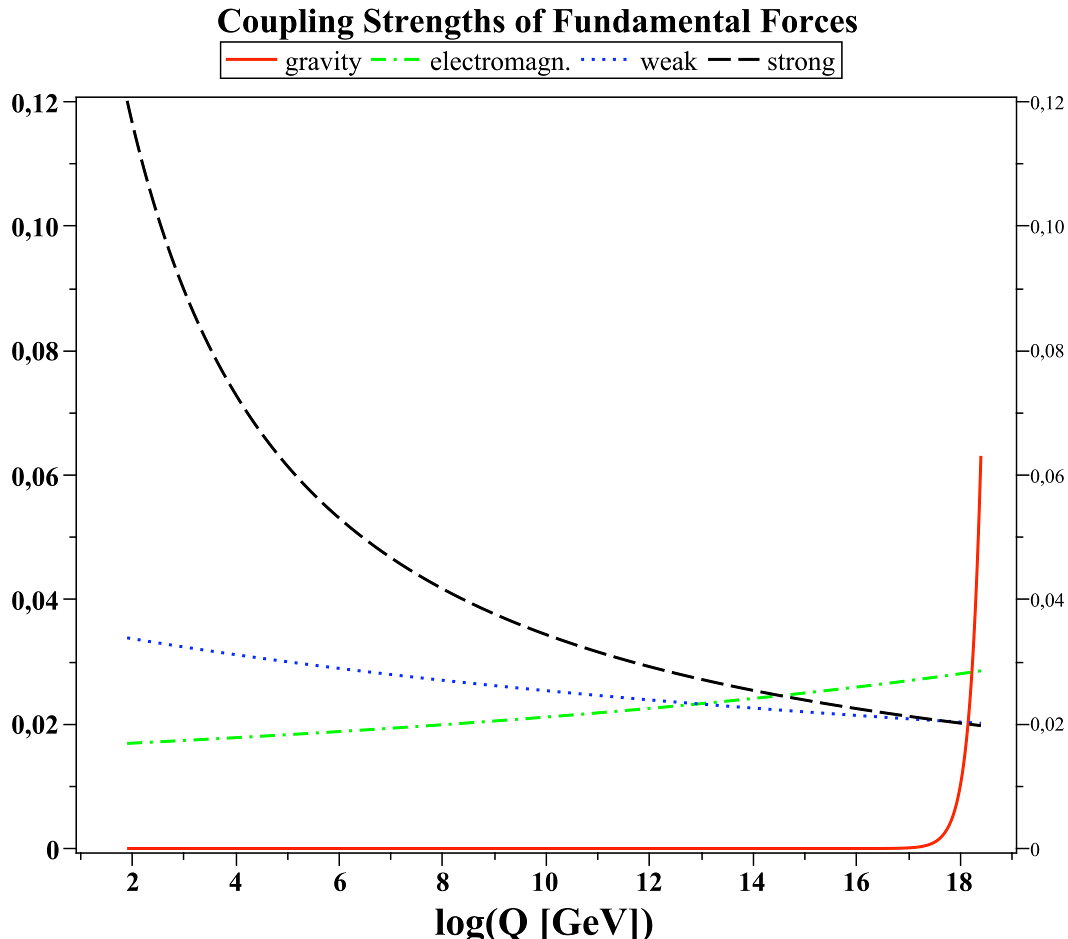
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	173	2/3
b bottom	4.2	−1/3



Particle physicists are convinced there are more discoveries to come:

Many things not explained in the standard model:

- why three families
- matter/antimatter imbalance
- neutrinos and neutrino mass
- hierarchy problem/unification
- dark matter
- dark energy
- …



Need to find ways to explore physics at higher energy scales in a laboratory environment.

New acceleration technology !

Proton Drivers for PWFA

Proton bunches as drivers of plasma wakefields are interesting because of the very large energy content of the proton bunches.

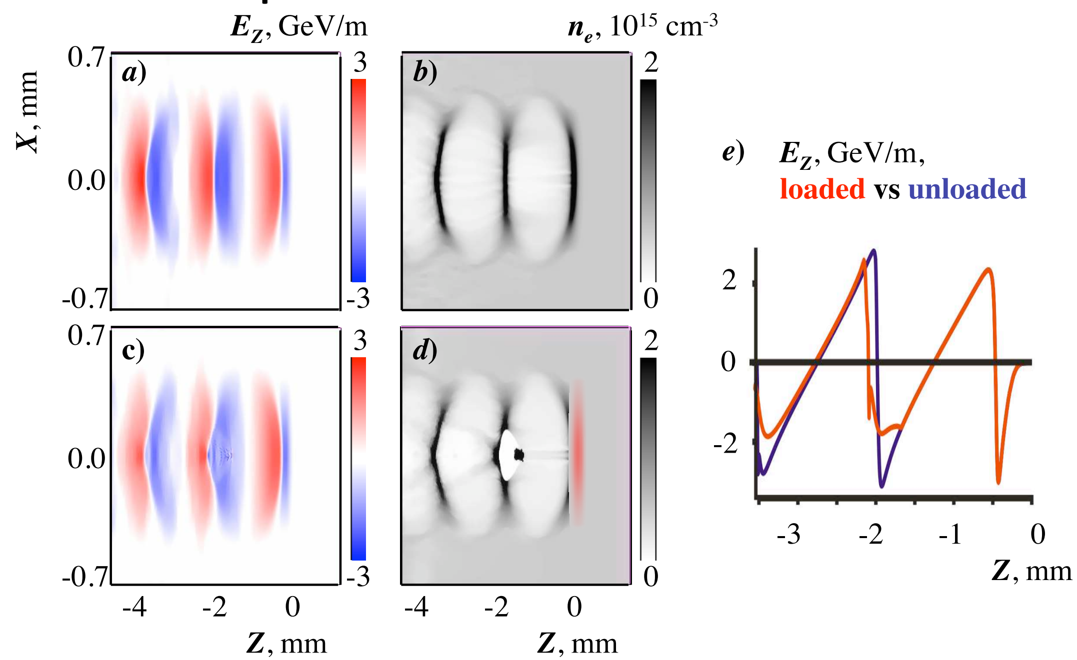
Drivers:

PW lasers today, ~40 J/Pulse

FACET, 30J/bunch

SPS 20kJ/bunch

LHC 300 kJ/bunch



Witness:

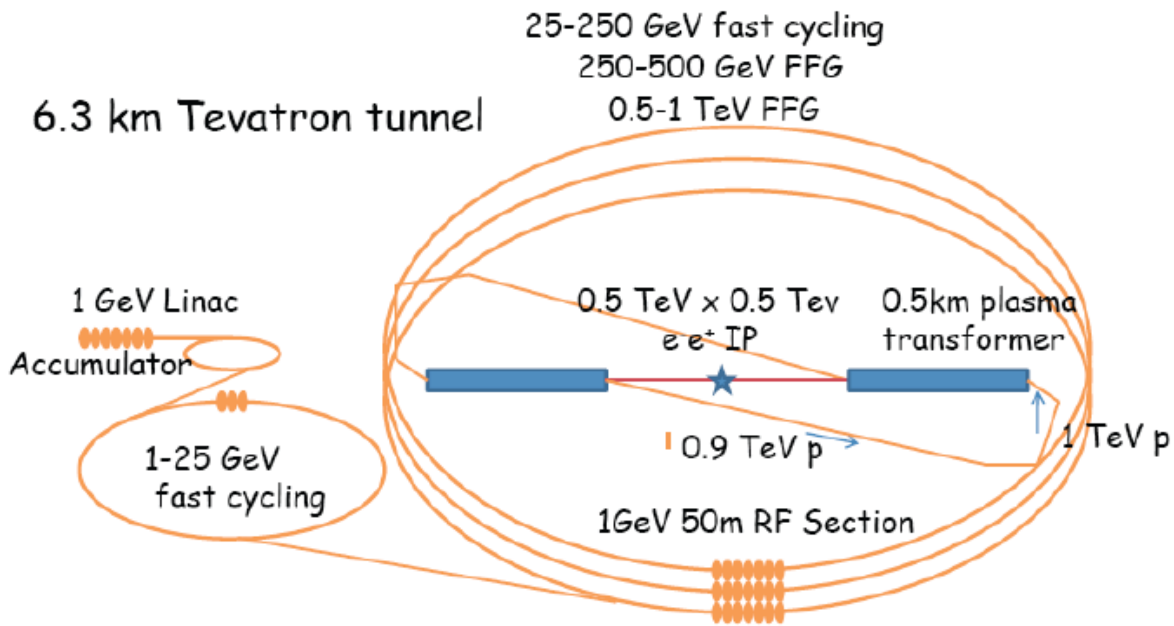
10^{10} particles @ 1 TeV ≈ few kJ

$$\lambda_p \approx 1 \text{ mm} \sqrt{\frac{1 \cdot 10^{15}\text{cm}^{-3}}{n_p}}$$

Energy content of driver allows to consider single stage acceleration

Ideal proton-driven PWPA accelerator

V. Yakimenko, BNL, T. Katsouleas, Duke



Wish list:

- high repetition rate
- Short proton bunches
- Diverse physics program: pp, ep, e^+e^-, $\mu^+ \mu^-$, ν beams

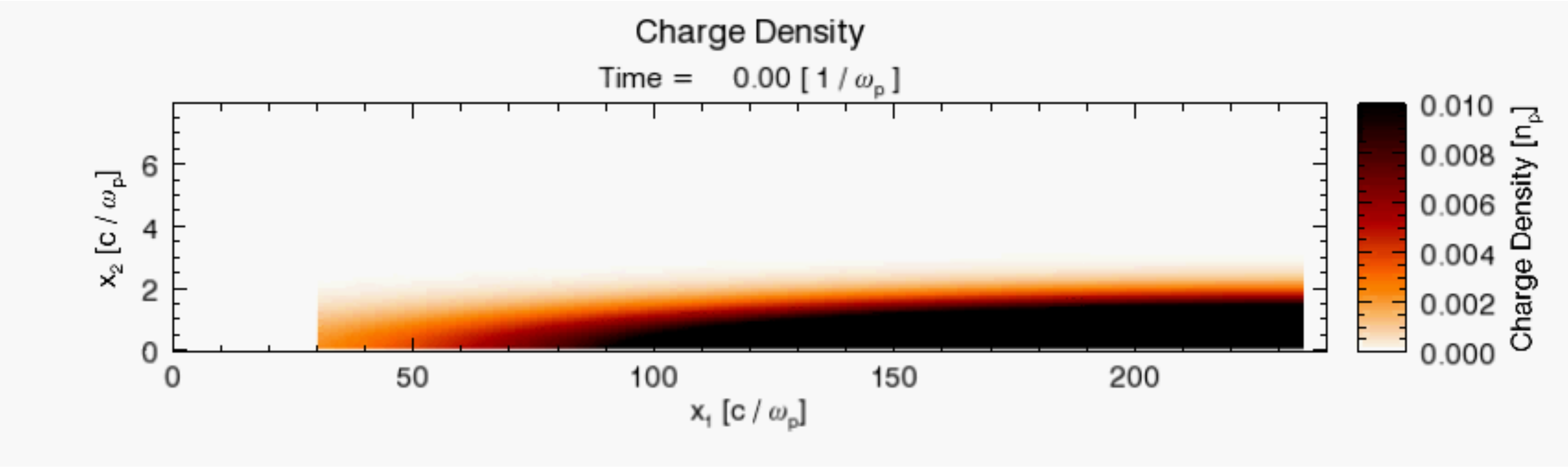
Exciting option, but needs design from scratch. What about existing machines ?

Self-modulation Instability

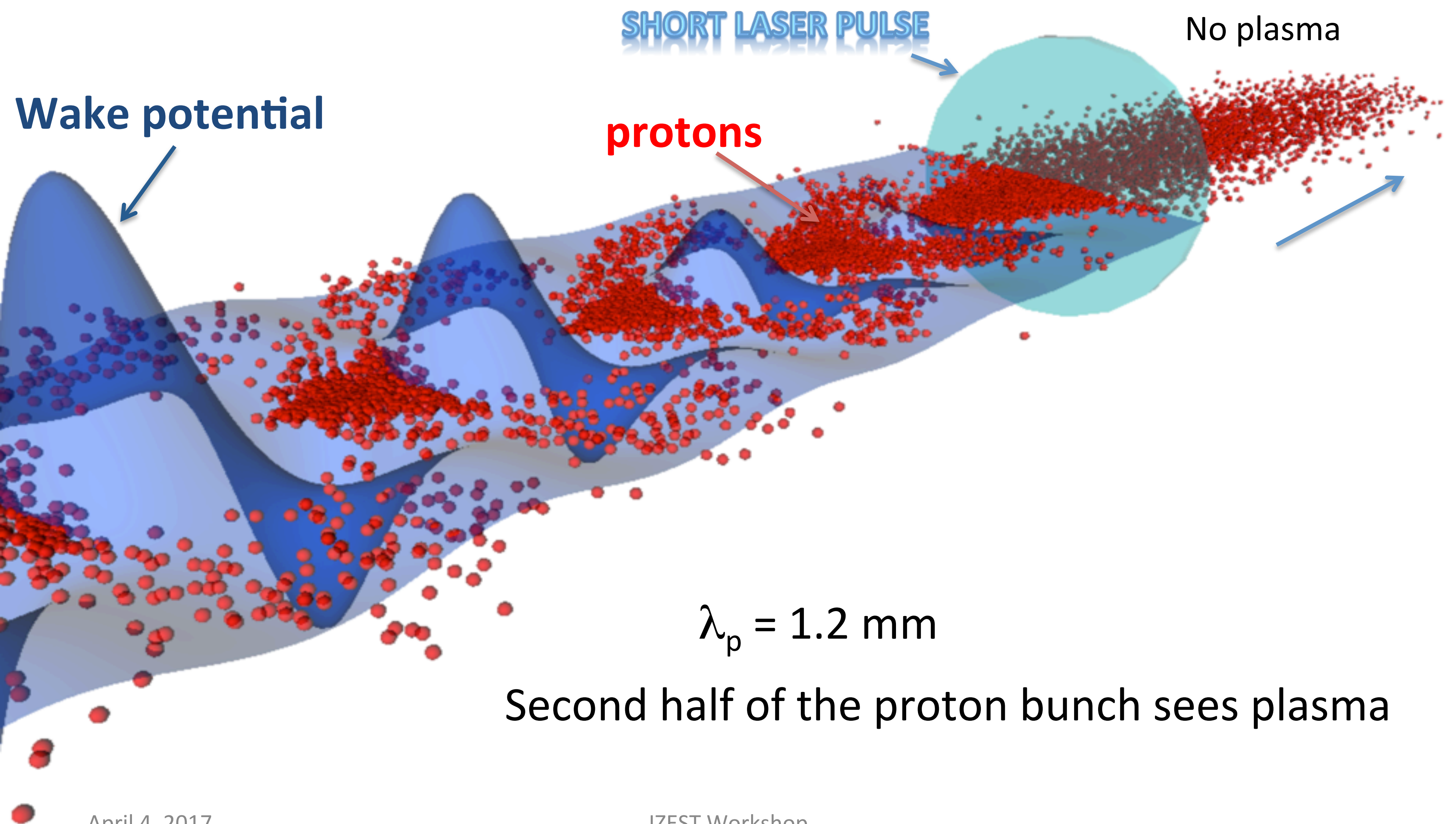
$$E_{z,\max} \approx 2\ \mathrm{GeV/m} \cdot \left(\frac{N_b}{10^{10}}\right) \cdot \left(\frac{100\ \mu\mathrm{m}}{\sigma_z}\right)^2$$

Need very short proton bunches for strong gradients. Today's proton beams have $\sigma_z \approx 10 - 30\ \mathrm{cm}$

Microbunches are generated by a transverse modulation of the bunch density (transverse two-stream instability). The microbunches are naturally spaced at the plasma wavelength, and act constructively to generate a strong plasma wake. Investigated both numerically and analytically.



Seeded self-modulation instability of a long proton bunch in plasma

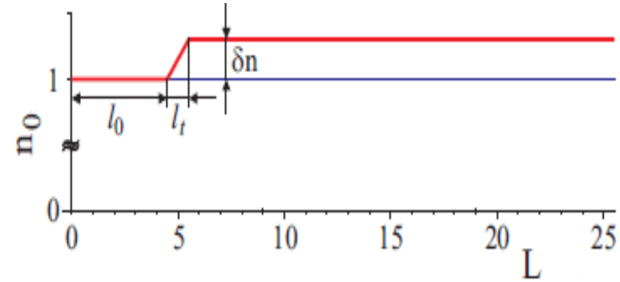


λ_p = 1.2 mm

Second half of the proton bunch sees plasma

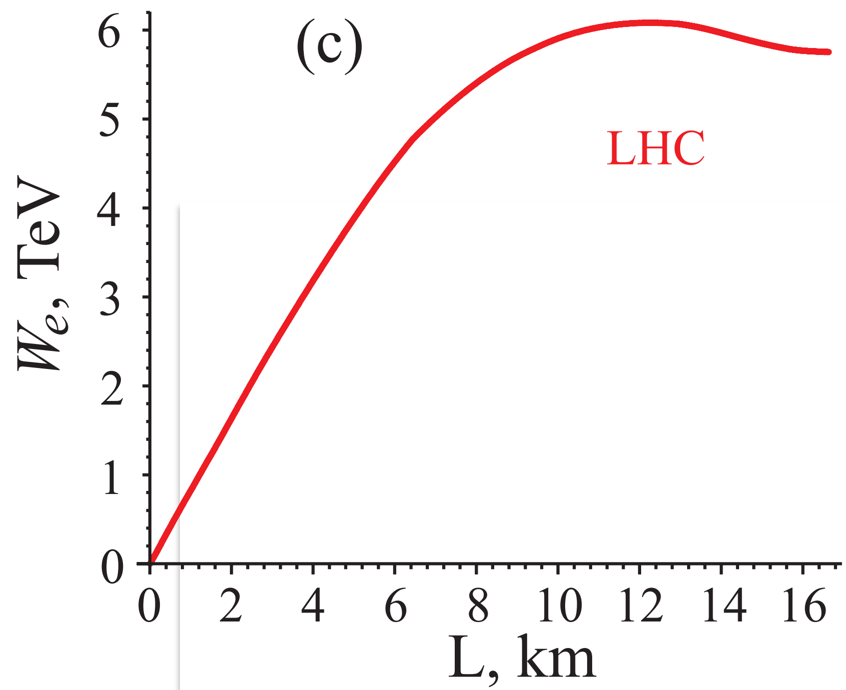
Freezing the Modulation

control of the wave phase by the plasma density profile



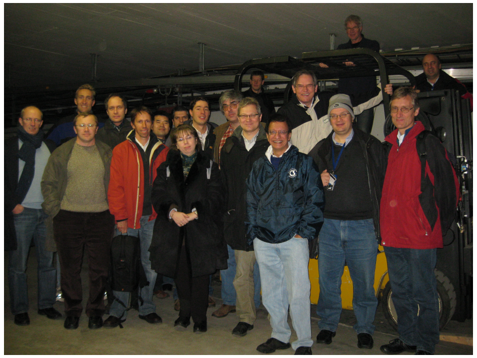
E_e= 6 TeV reached in simulations with modulated LHC beam

A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)



History

2009 driven

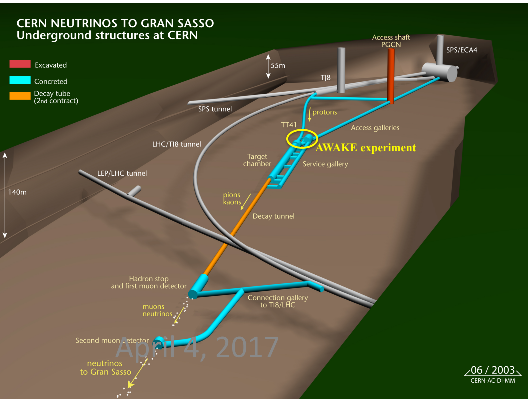


First workshop at CERN to discuss potential of proton-PWA.

2011 June meeting of the SPSC – Letter of Intent to perform experiment (TT4/5 area).

2012 June meeting in Lisbon – AWAKE Collaboration officially formed

2013 April meeting of the SPSC – Design Report. Use CNGS area



Significant reduction in cost from re-using existing facility !
Positive recommendation from SPSC.
Approval from Research Board August 2013.

Experimental program started end 2016.

AWAKE

- AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment
  - Use SPS proton beam as drive beam (Single bunch 3e11 protons at 400 GeV)
  - Inject electron beam as witness beam

- Proof-of-Principle Accelerator R&D experiment at CERN
  - First proton driven plasma wakefield experiment worldwide
  - First beam expected in 2016

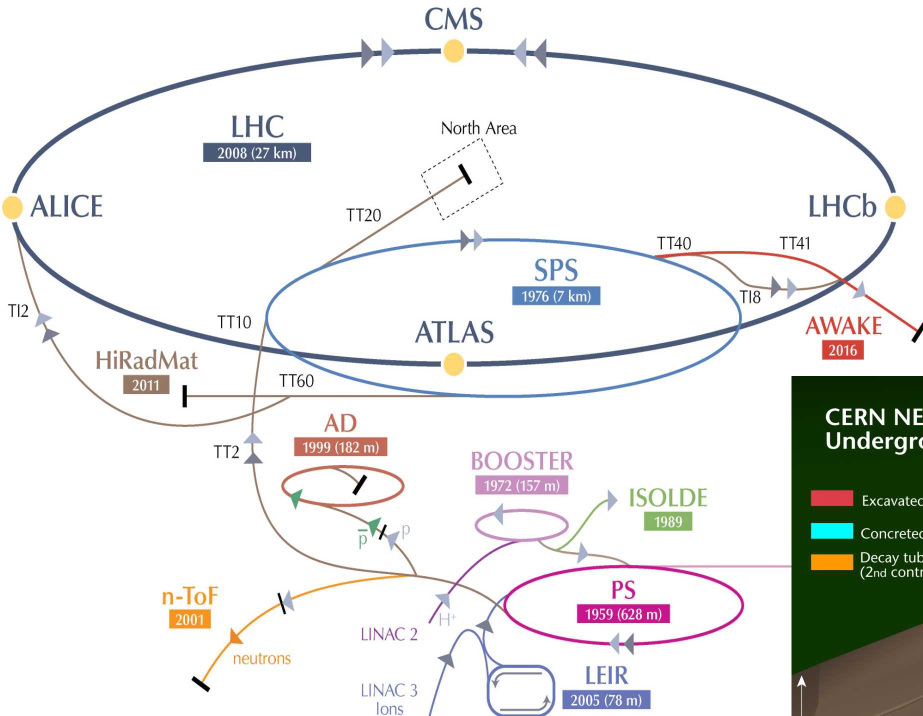
- AWAKE Collaboration: 16 Institutes world-wide:

John Adams Institute for Accelerator Science,
Budker Institute of Nuclear Physics & Novosibirsk State University
CERN
Cockroft Institute
DESY
Heinrich Heine University, Düsseldorf
Instituto Superior Tecnico
Imperial College
Ludwig Maximilian University
Max Planck Institute for Physics
Max Planck Institute for Plasma Physics
Rutherford Appleton Laboratory
TRIUMF
University College London
Univesity of Oslo
University of Strathclyde

+ 3 Associate members:

Swiss Plasma Center, EPFL
Wigner Institute, Hungary
UNIST, Korea

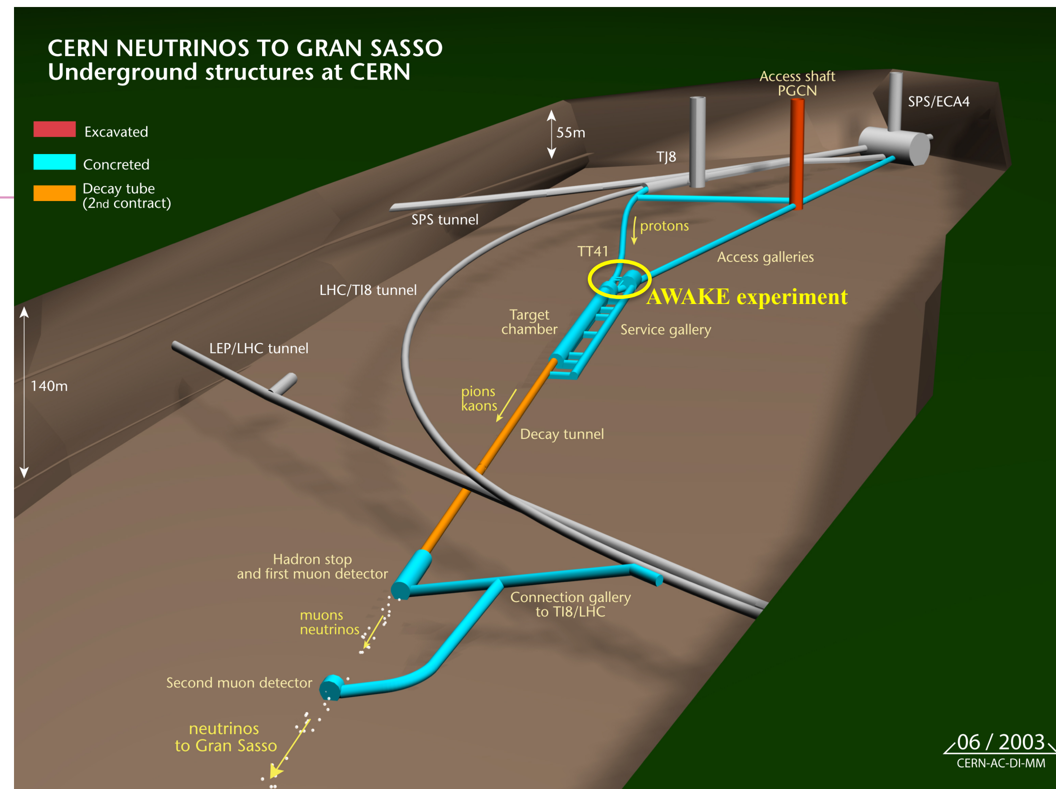
AWAKE at CERN



AWAKE is installed in

CNGS Facility (CERN Neutrinos to Gran Sasso)

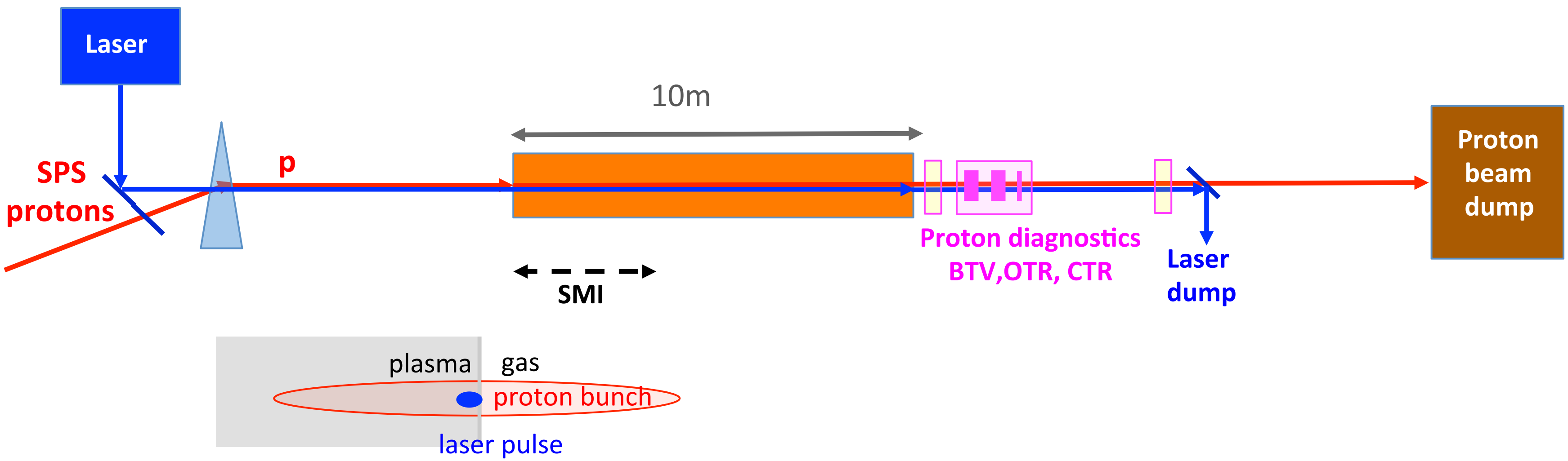
→ CNGS physics program finished in 2012



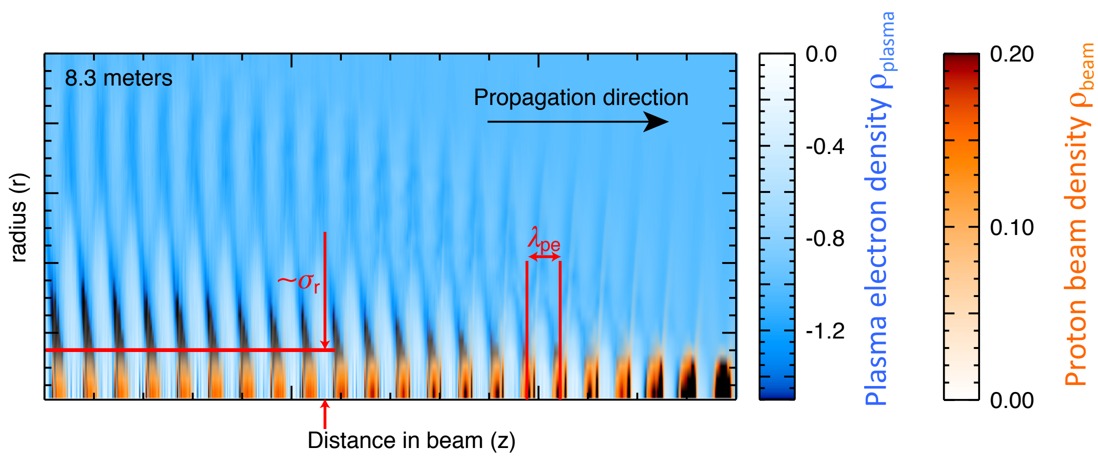
A. Caldwell et al., "Path to AWAKE: Evolution of the concept", Nucl. Instrum. Meth. A829 (2016) 3-16; E. Gschwendtner et al. [AWAKE Collaboration], "AWAKE, The Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN," Nucl. Instrum. Meth. A829, 76 (2016).

AWAKE: Experimental Program

Phase 1: Understand **the physics of self-modulation instability.**

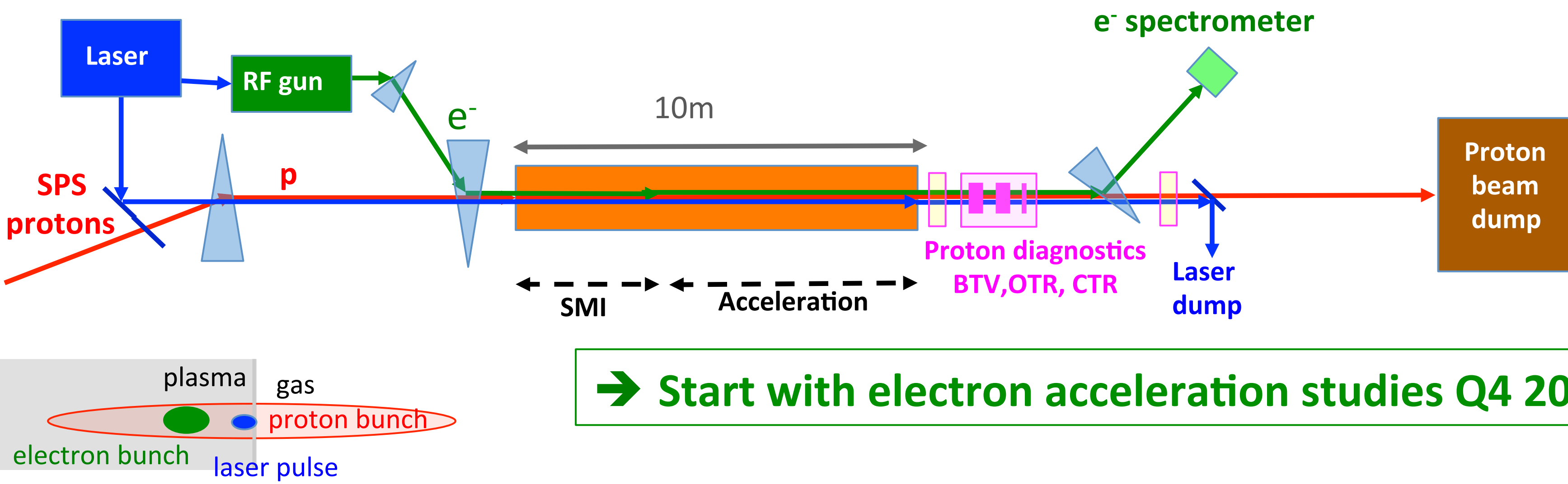


Self-modulated proton bunch resonantly driving plasma wakefields.

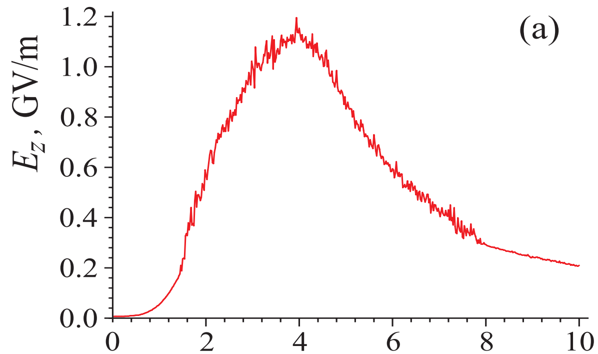


AWAKE Experimental Program

- Phase 1: Understand **the physics of self-modulation instability**.
- Phase 2: **Probe the accelerating wakefields** with externally injected electrons.



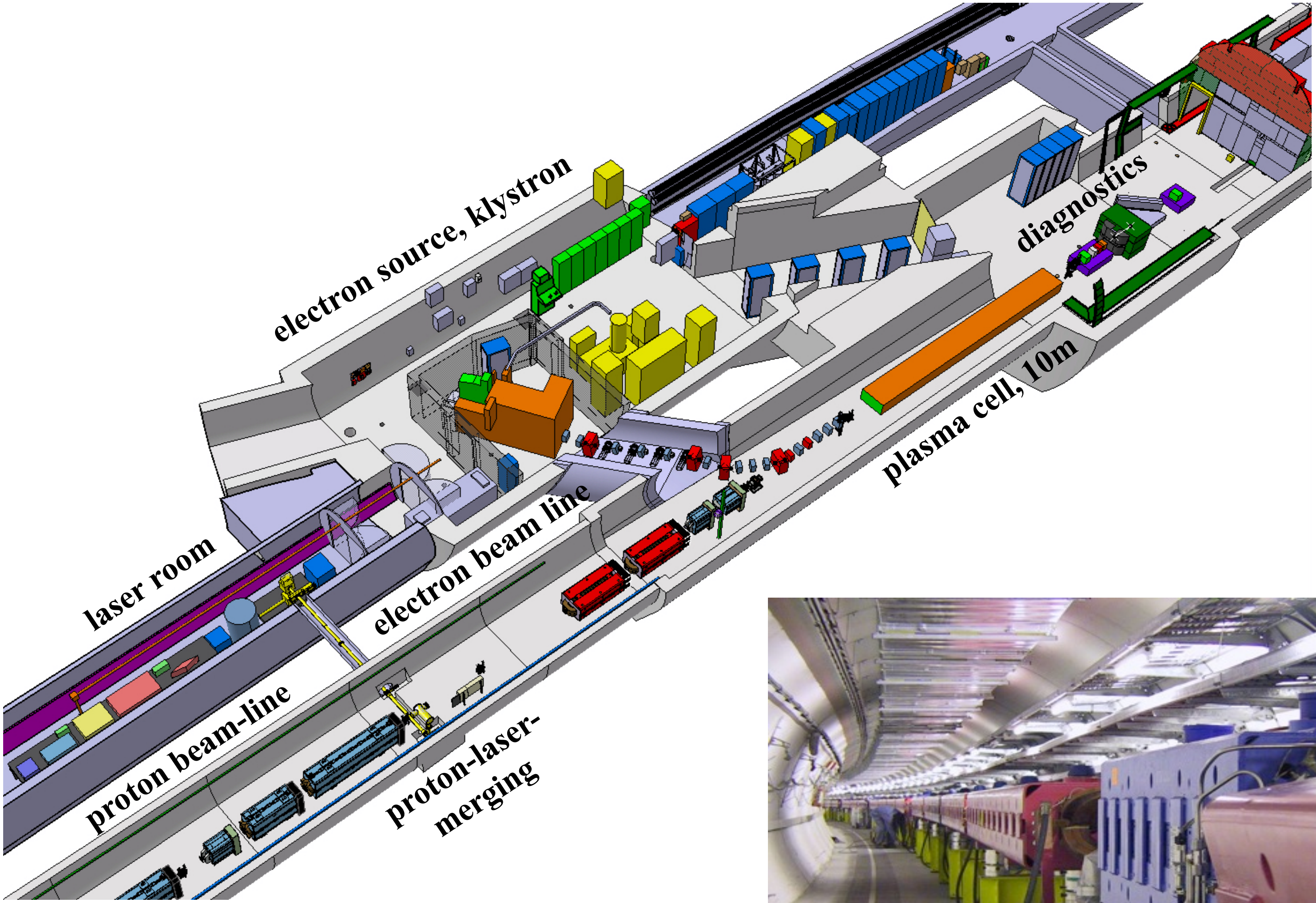
➔ **Start with electron acceleration studies Q4 2017**



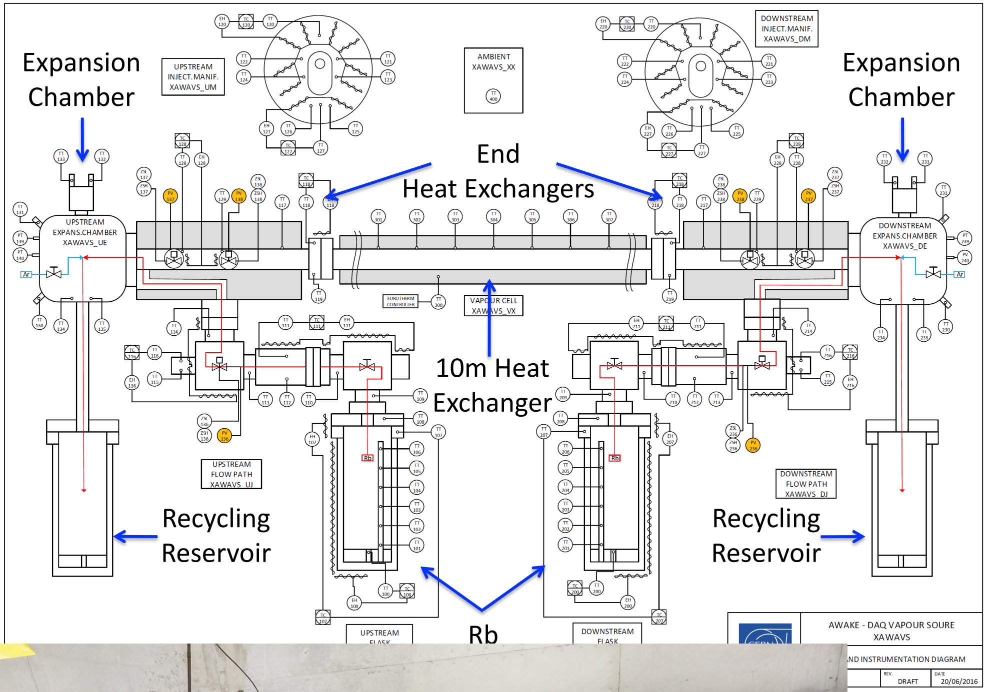
Demonstrate GeV scale gradients with proton driven wakefields.

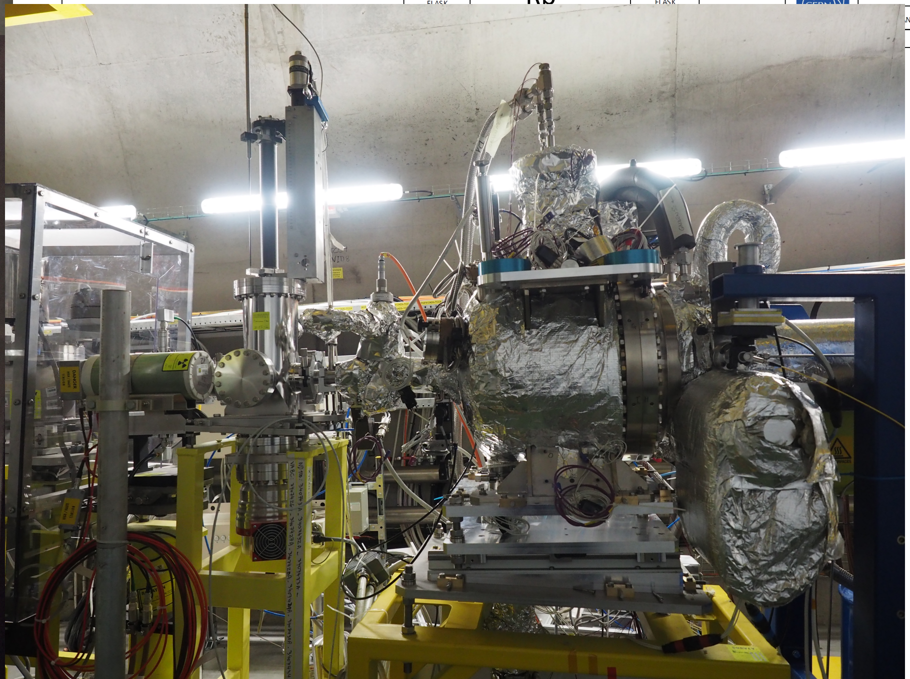
Maximum amplitude of the **accelerating field E_z** as a function of position along the plasma. Saturation of the SMI at ~4m.

AWAKE Overview



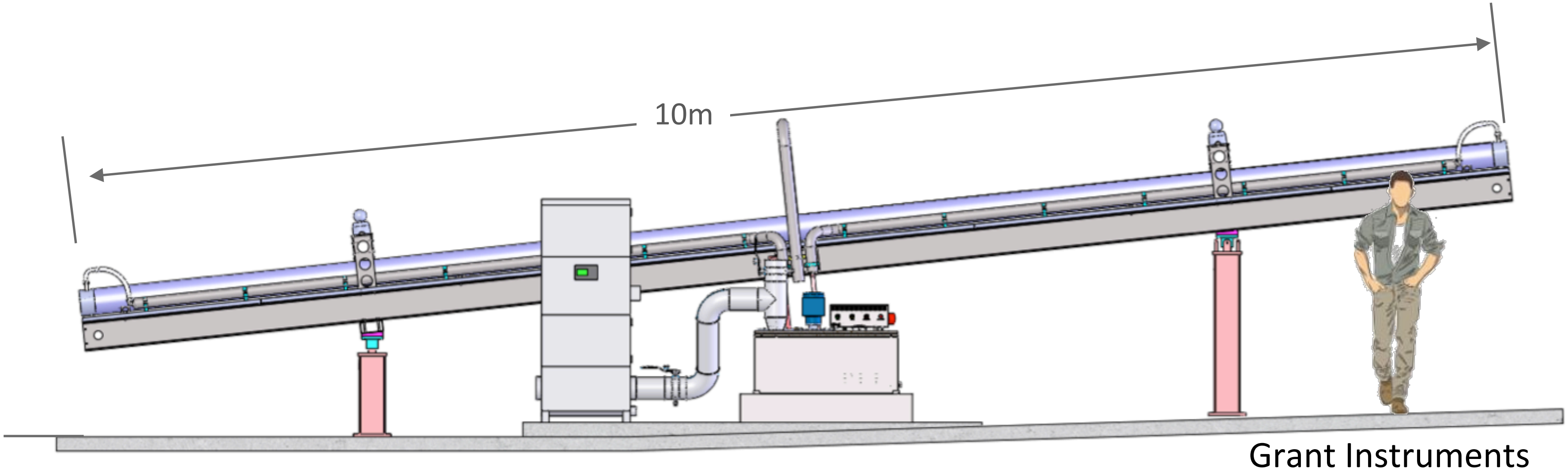
AWAKE Overview





AWAKE: Plasma Source

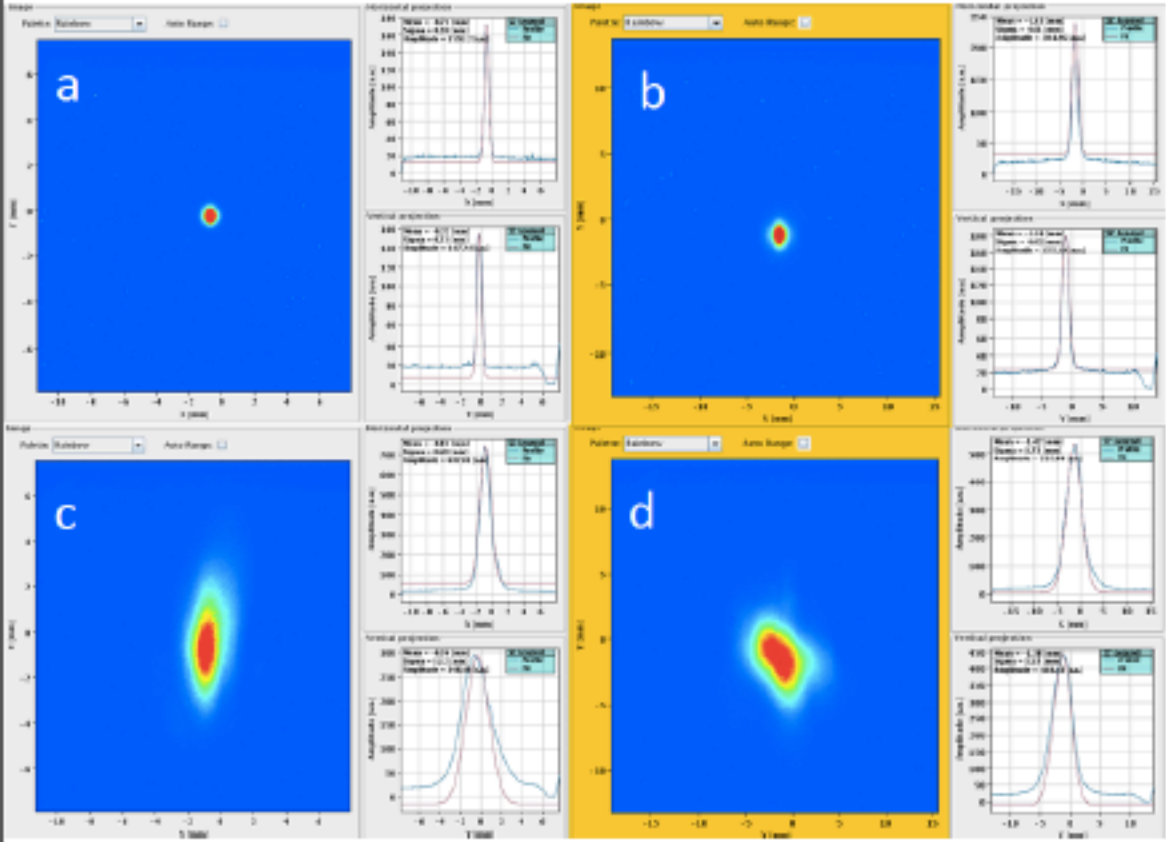
- Density adjustable from **$10^{14} – 10^{15}$ cm^{-3}**
- 10 m long, 4 cm diameter
- Plasma formed by field ionization of Rb
  - Ionization potential Φ_{Rb} = 4.177eV
  - above intensity threshold (I_{ioniz} = 1.7 x 10^{12}W/cm^2) 100% is ionized.
- Plasma density = vapor density
- System is oil-heated: 150˚ to 200˚ C
  - → keep temperature uniformity
  - → Keep density uniformity



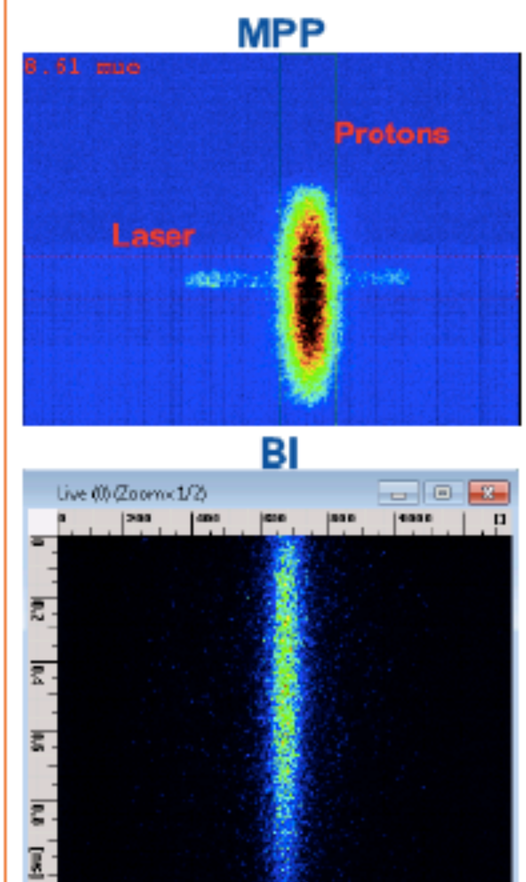
Grant Instruments

Commissioning

Proton & laser beam commissioning run September 2016

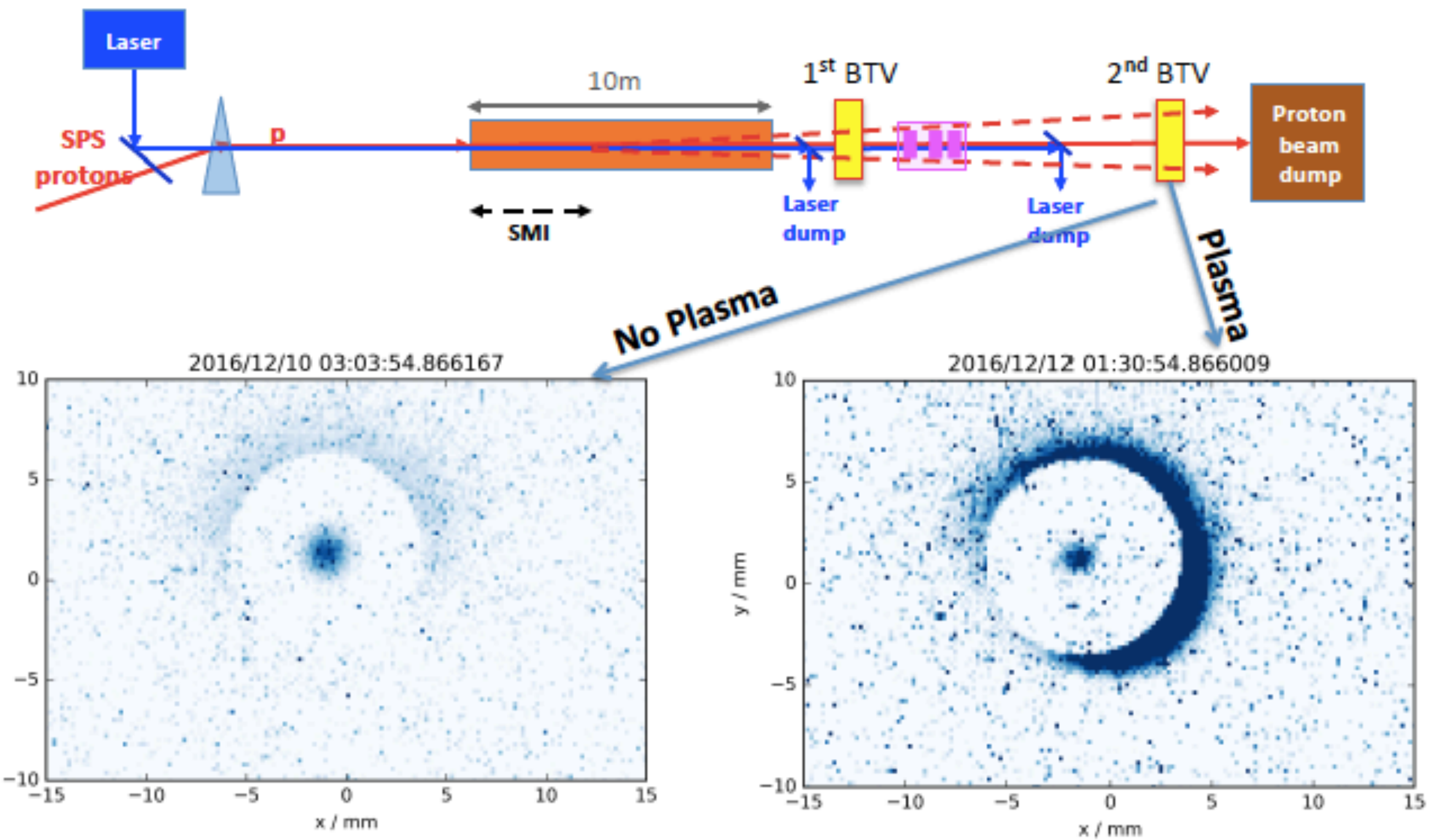


Spatial and temporal overlap of the proton and laser beams achieved.



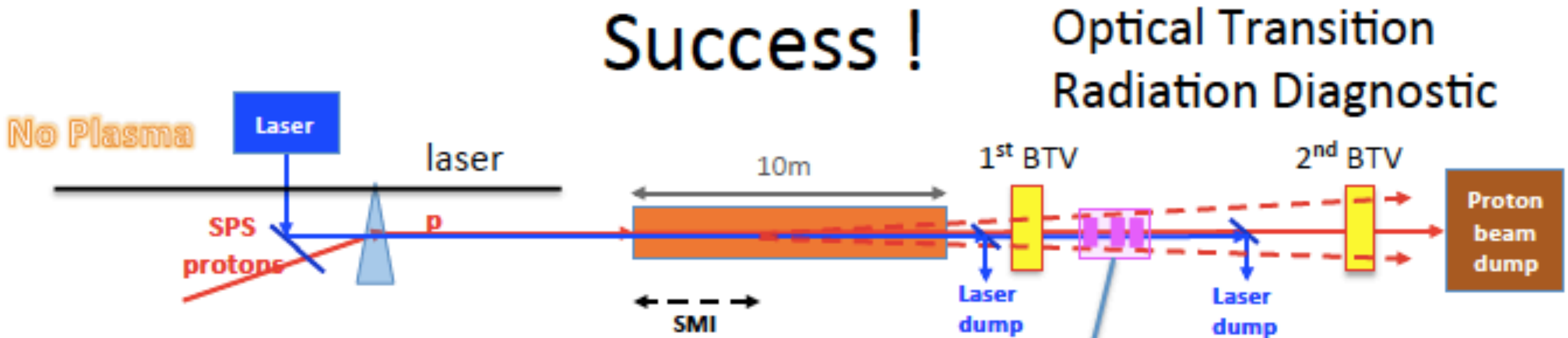
Beam properties (size, jitter, etc. as expected)

Success !

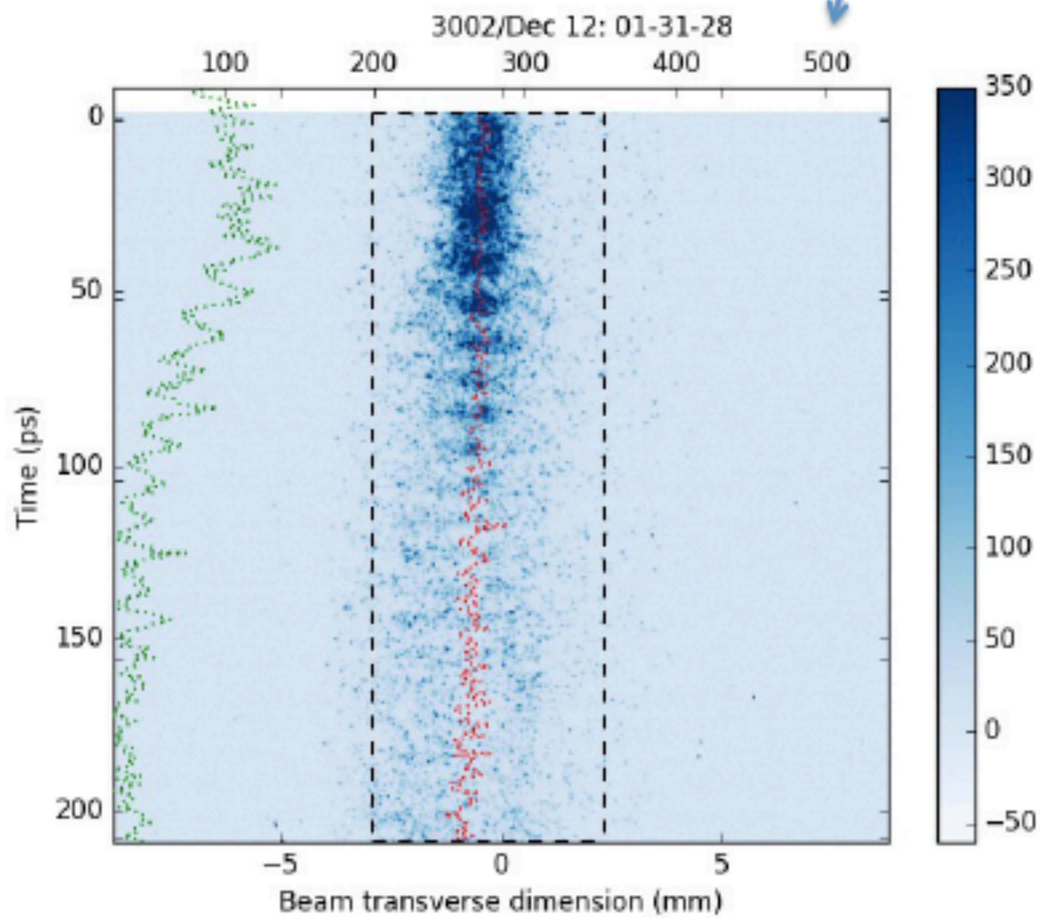


Clearly see the transverse blow-up of the proton beam. Only possible with very strong electric fields !

Success !



Modulation visible in streak camera data



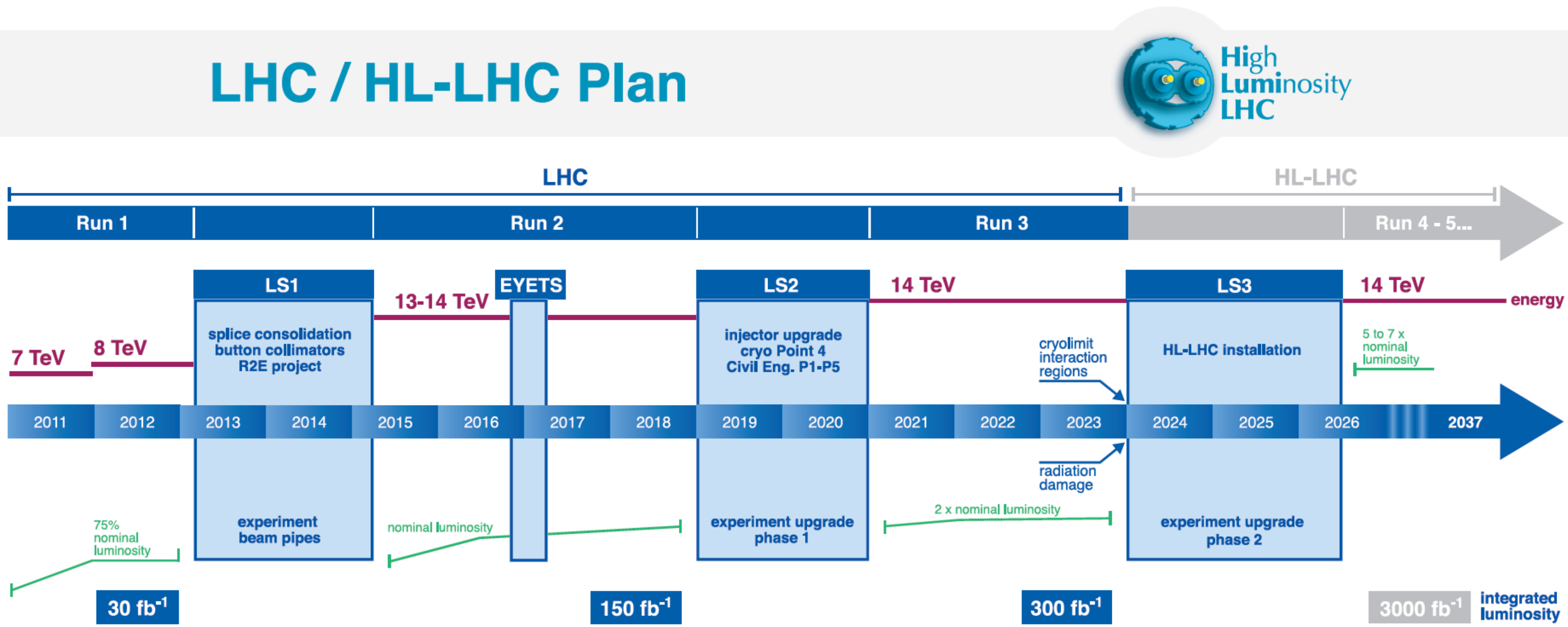
AWAKE Run Team

Schedule

AWAKE Planning for Run I (until LS2 of the LHC) is clearly defined (see Edda's talk).

After LS2 – proposing Run II of AWAKE (during Run 3 of LHC). It is critical that we make full use of this time slot in order to allow physics applications of AWAKE in a timely way. Otherwise, risk loss of momentum.

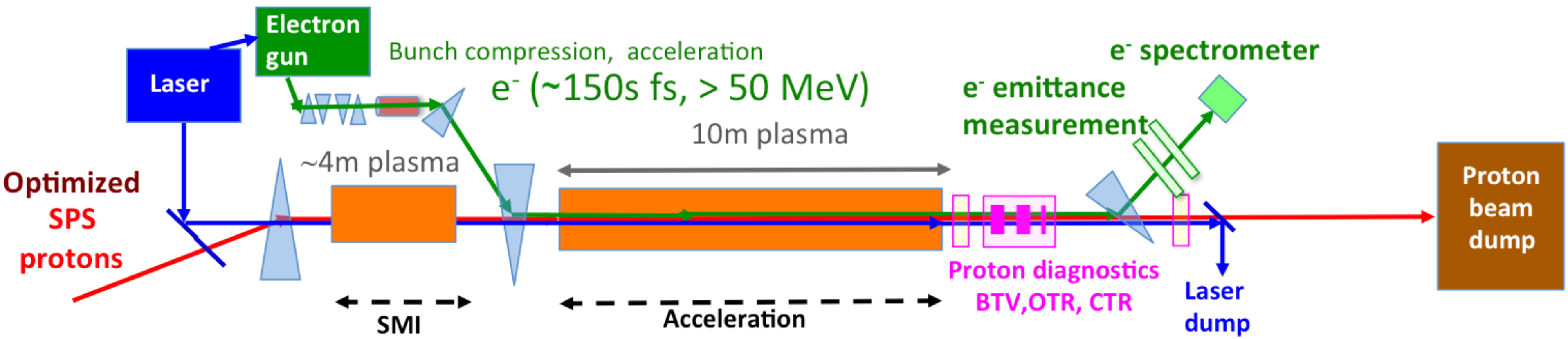
Goal: after Run II of AWAKE – first particle physics driven applications !



Run II

Goals:

- stable acceleration of bunch of electrons with high gradients over long distances
- 'good' electron bunch emittance at plasma exit



Require:

- Compressed proton beam in SPS
- Short electron bunch with higher energy for loading wakefield
- Density step in plasma for freezing modulation
- Alternative plasma cell developments

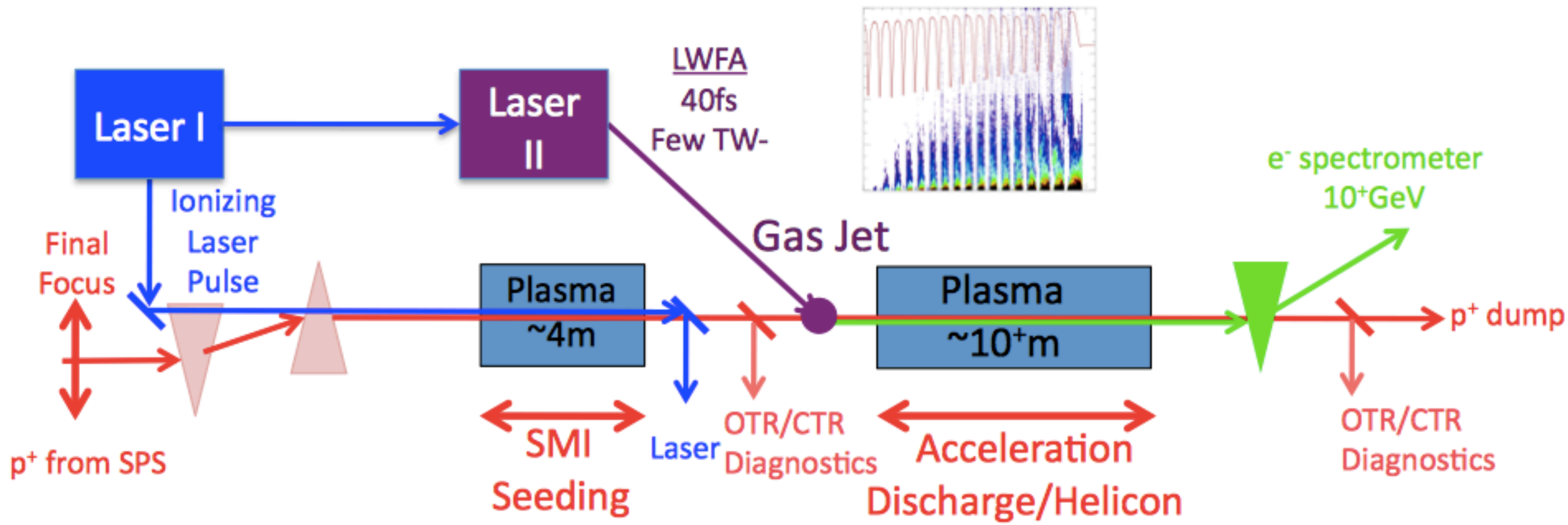
Preliminary Run 2 electron beam parameters

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

Run II

Electron Injectors:

- **S-band gun**: cannot provide parameters in available space (bunch length, peak current)
- **X-band gun**: interesting technology, 50 MeV electrons in few meter. Expensive to "re-develop" a new gun.
- **LWFA** :

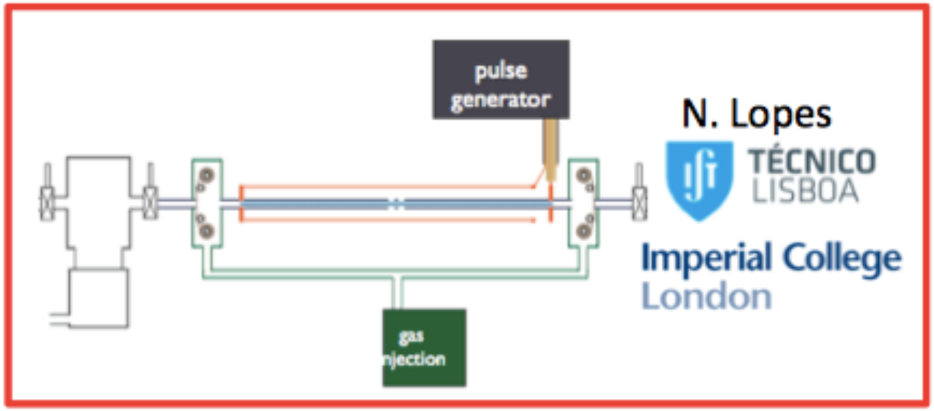


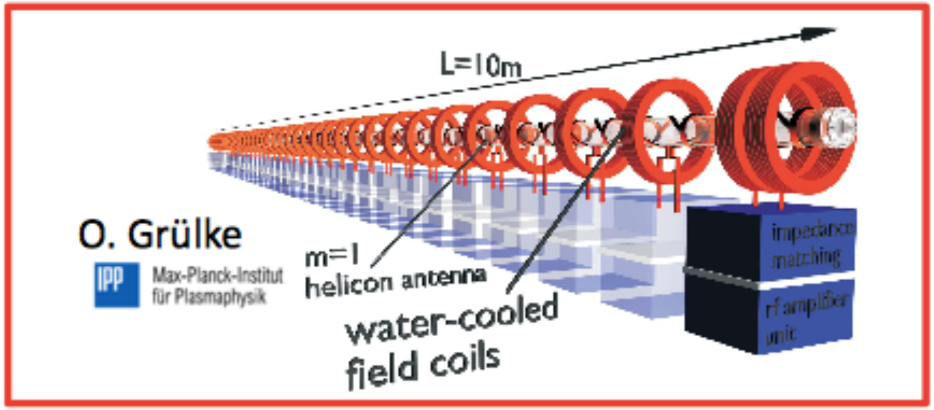
- **Ionization injection** : preliminary studies – fields need to be strong; still in linear regime ?

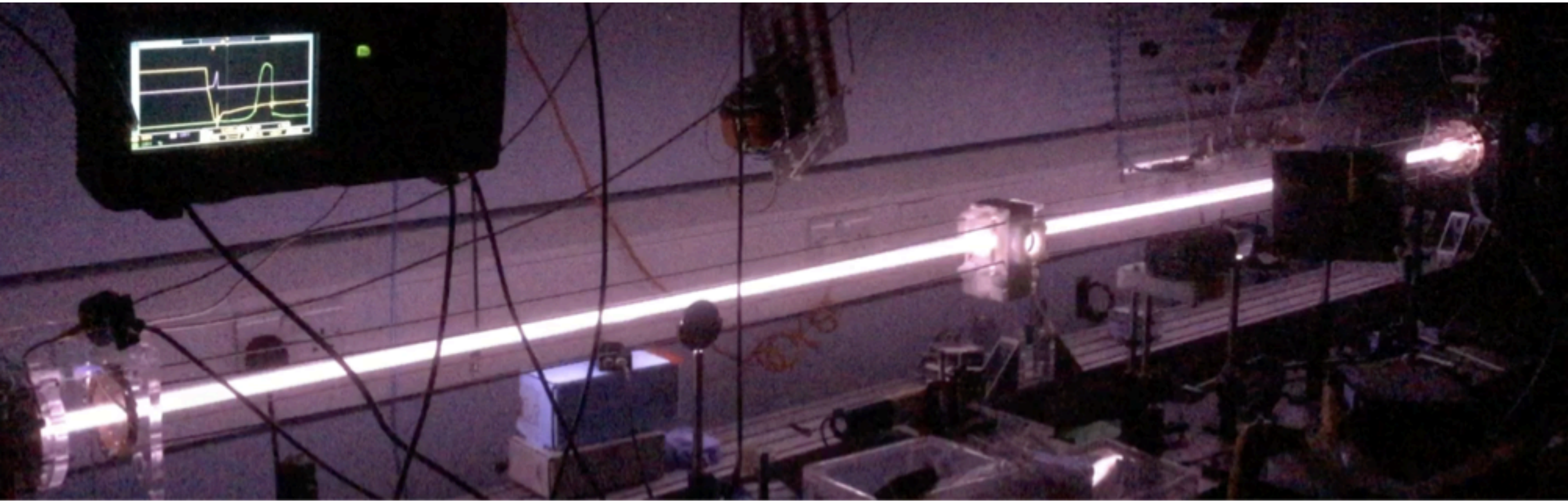
Run II

Scalable Plasma sources :

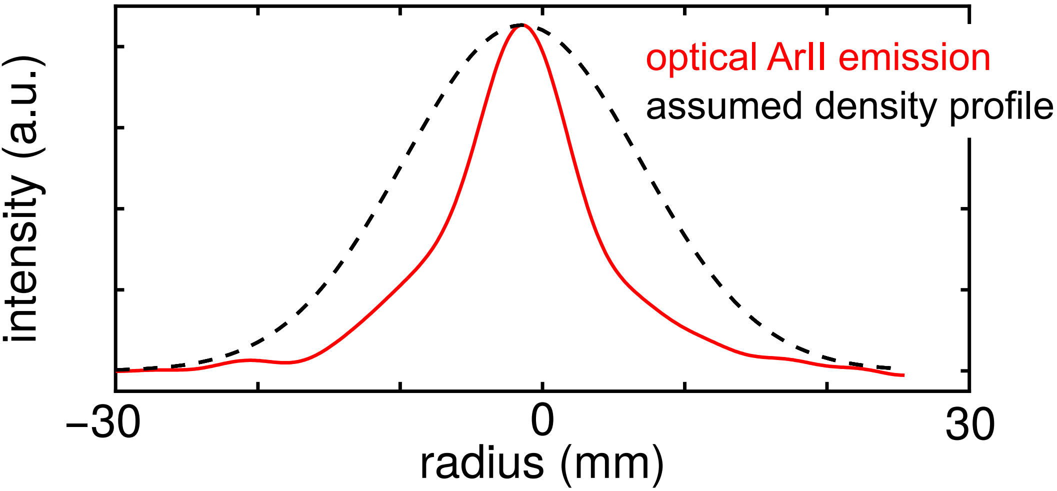
- CERN-MPP-SPC **helicon initiative**
- **Discharge source technology,** 10 m cell, is being further developed at UCL.

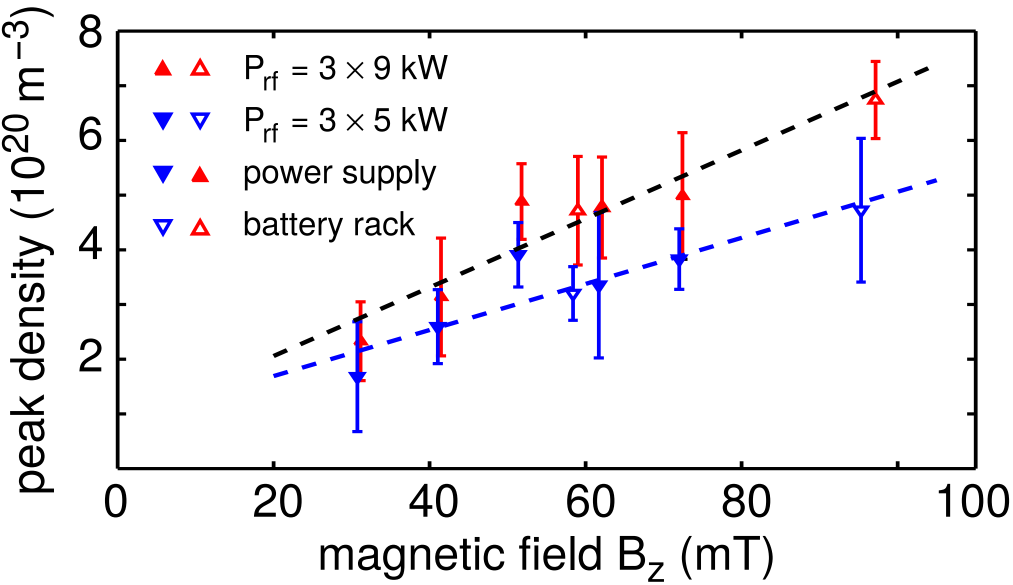






Helicon cell





1m prototype in regular operation (B. Buttenschön, O. Grülke, IPP Greifswald)

Target density achieved

Uniformity under study.

New effort CERN - IPP – SPC @CERN under consideration

Particle Physics Perspectives

Started considering:

- **Physics with a high energy electron beam**
  - E.g., search for dark photons

- **Physics with an electron-proton or electron-ion collider**
  - Low luminosity version of LHeC
  - Very high energy electron-proton, electron-ion collider

Are there fundamental particle physics topics for high energy but low luminosity colliders ?

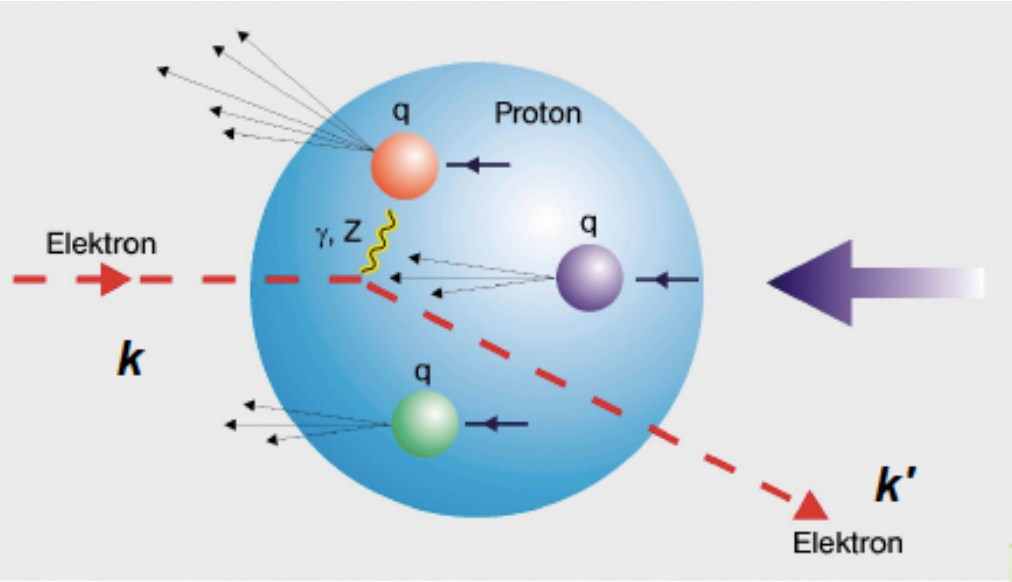
I believe – yes ! Particle physicists will be interested in going to much higher energies, even if the luminosity is low.

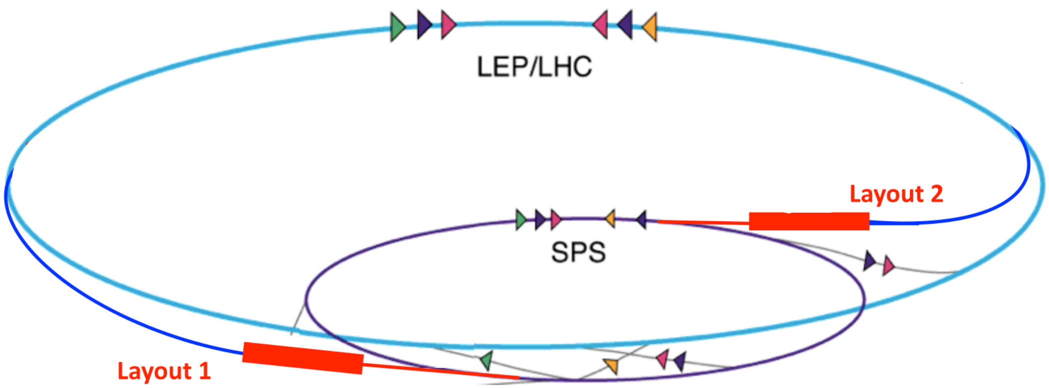
In general – start investigating the particle physics potential of an AWAKE-like acceleration scheme.

LHeC-like

Focus on QCD:

- Large cross sections – low luminosity (HERA level) enough
- Many open physics questions !
- Consider high energy ep collider with Ee up to O(50 GeV), colliding with LHC proton; e.g. Ee = 10 GeV, Ep = 7 TeV, √s = 530 GeV already exceeds HERA cm energy.





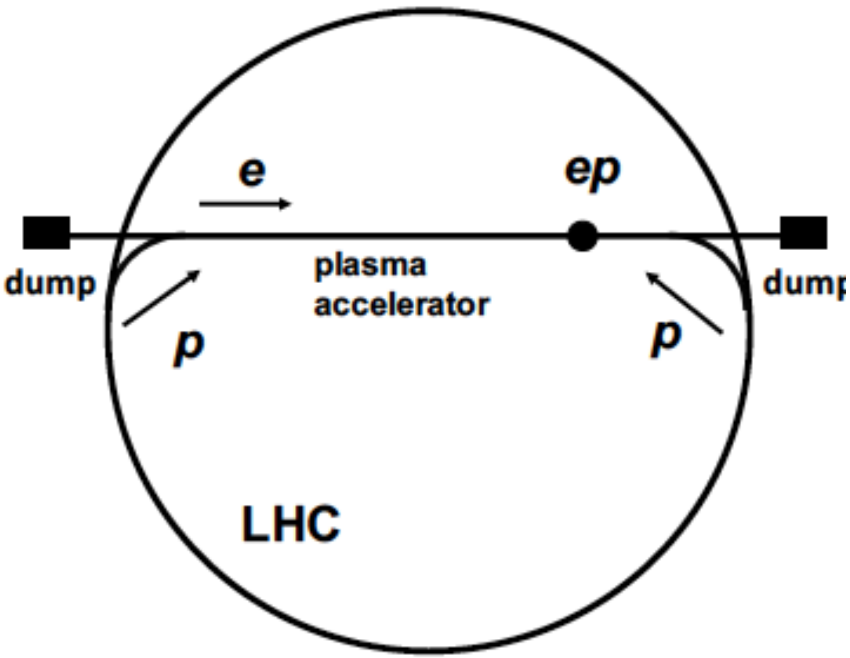
G. Xia et al., Nucl. Instrum. Meth. A 740 (2014) 173.

Create ~50 GeV beam within 50–100 m of plasma driven by SPS protons and have an LHeC-type experiment.

Clear difference is that luminosity currently expected to be $< 10^{30}$ cm^{-2} s^{-1}.

VHEeP

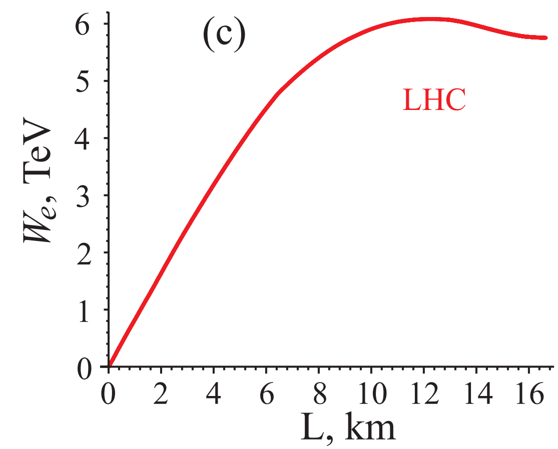
(Very High Energy electron-Proton collider)



One proton beam used for electron acceleration to then collide with other proton beam

Luminosity ~ $10^{28} - 10^{29}$ cm^{-2} s^{-1} gives ~ 1 pb−1 per year.

Electron energy from wakefield acceleration by LHC bunch



A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

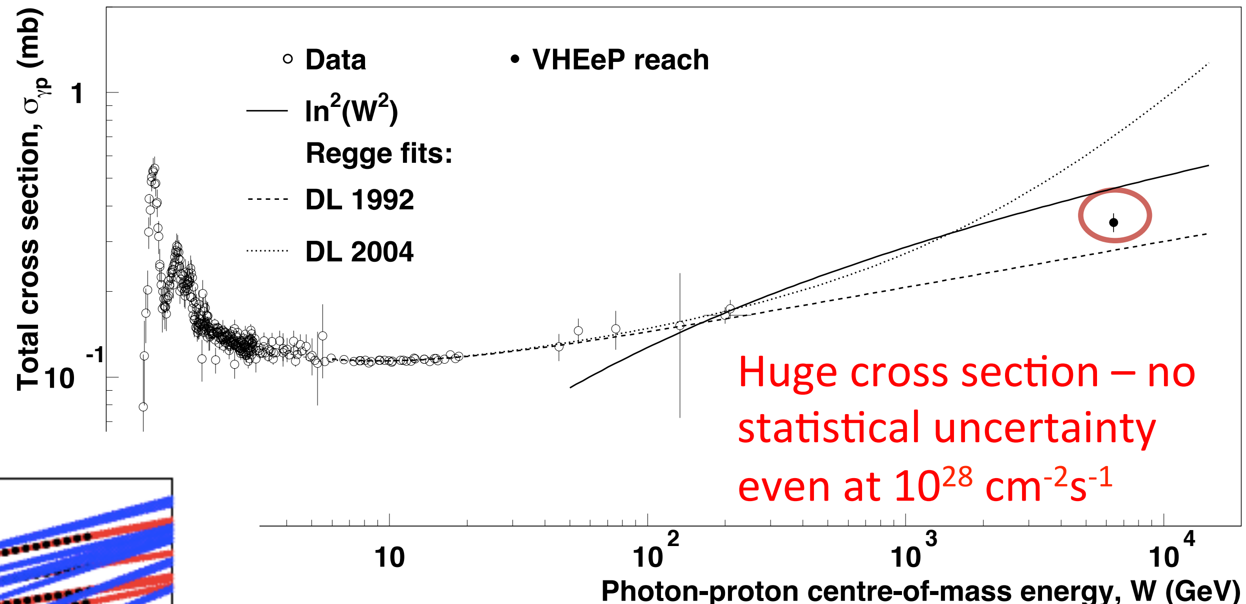
Choose E_e = 3 TeV as a baseline for a new collider with E_P = 7 TeV yields $\sqrt{s}$ = 9 TeV. Can vary.

- Centre-of-mass energy ~30 higher than HERA.
- Reach in (high) Q^2 and (low) Bjorken x extended by ~1000 compared to HERA.
- Opens new physics perspectives

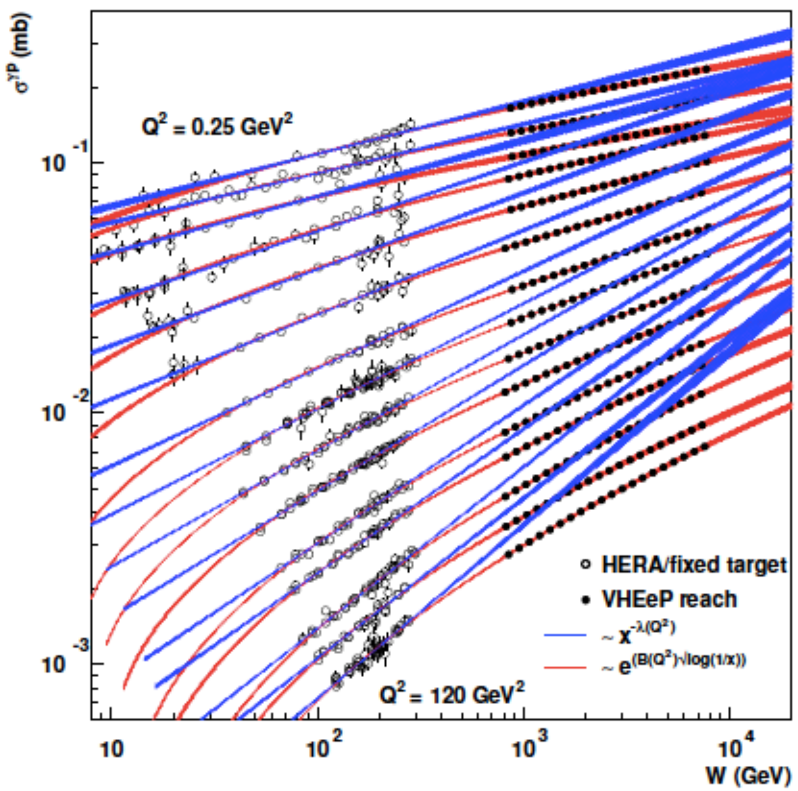
VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

Physics Reach

Total photoproduction cross section – energy dependence ? Fundamental physics question, impact on cosmic ray physics



Huge cross section – no statistical uncertainty even at 10^{28} $cm^{-2}s^{-1}$



Virtual photon cross section – observation of saturation of parton densities ? Would provide information on the fundamental structure of the QCD vacuum.

+ BSM physics such as Leptoquarks, quark substructure, etc.

Summary

Proton-driven plasma wakefield acceleration interesting because of large energy content of driver.

Modulation process means existing proton machines can be used.

Goal for AWAKE run I: demonstrate modulation process and proton-driven acceleration of electrons before LS2 of the LHC. **First data show the modulation – now need to study in detail !**

Run II proposal developing: goals are demonstration of stable acceleration and good electron bunch properties.

Long term prospects for proton-driven PWA exciting ! Starting to develop particle physics program that could be pursued with an AWAKE-like beam.