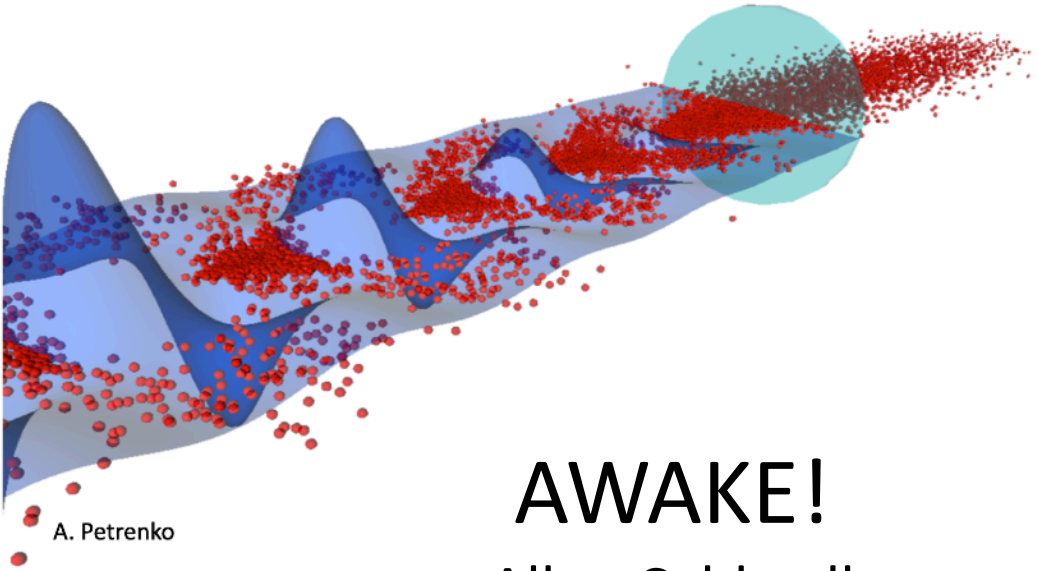
Swapan Chattopadhyay Symposium
April 30, 2021



AWAKE!

Allen Caldwell

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

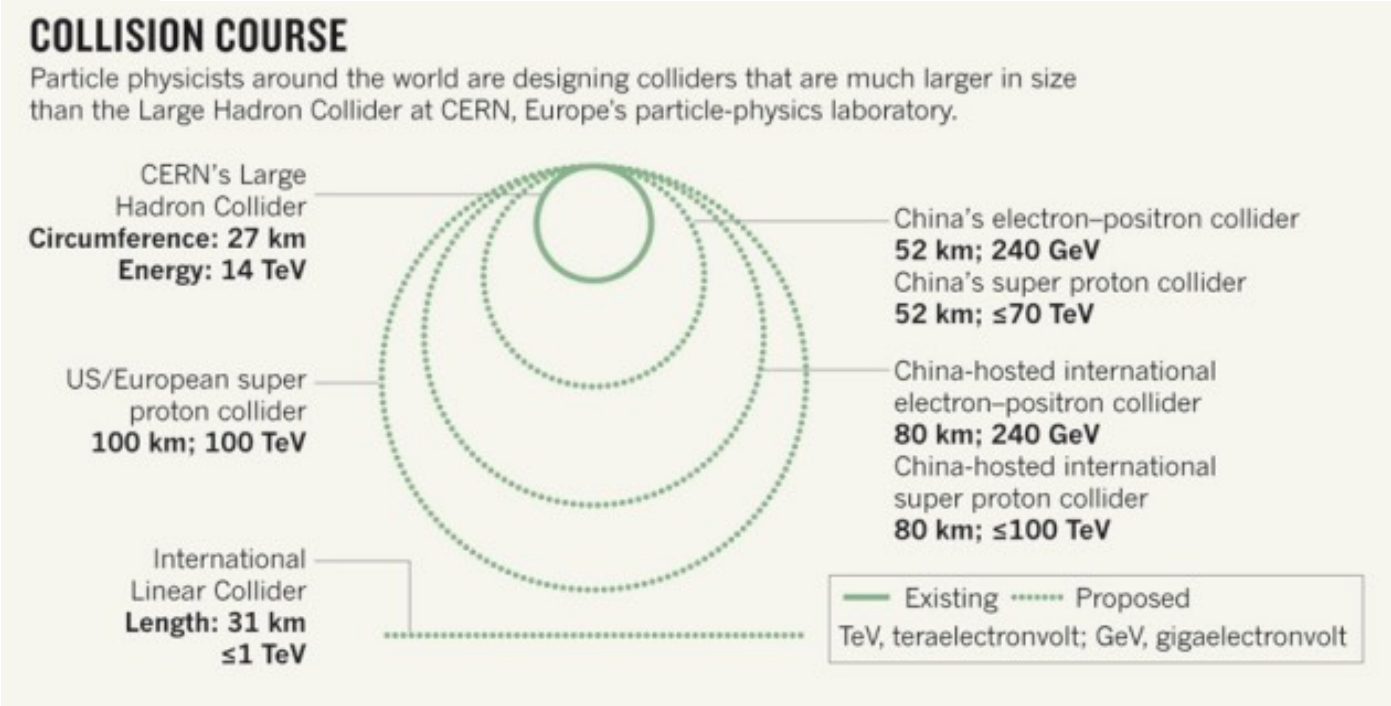
Even larger Accelerators ?

The Future Circular Collider Study (FCC) is developing designs for a higher performance particle collider to extend the research currently being conducted at the Large Hadron Collider (LHC), once the latter reaches the end of its lifespan.

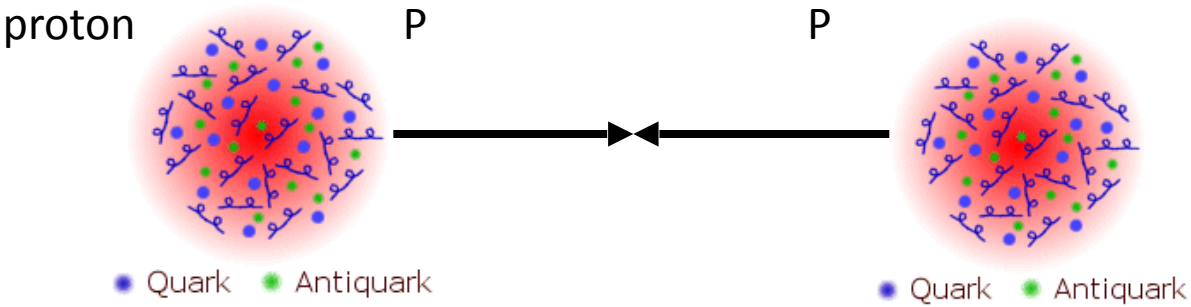
Energy limit of circular proton collider given by magnetic field strength.

$$P \propto B \cdot R$$

Energy gain relies in large part on magnet development



Linear Electron Collider or Muon Collider?

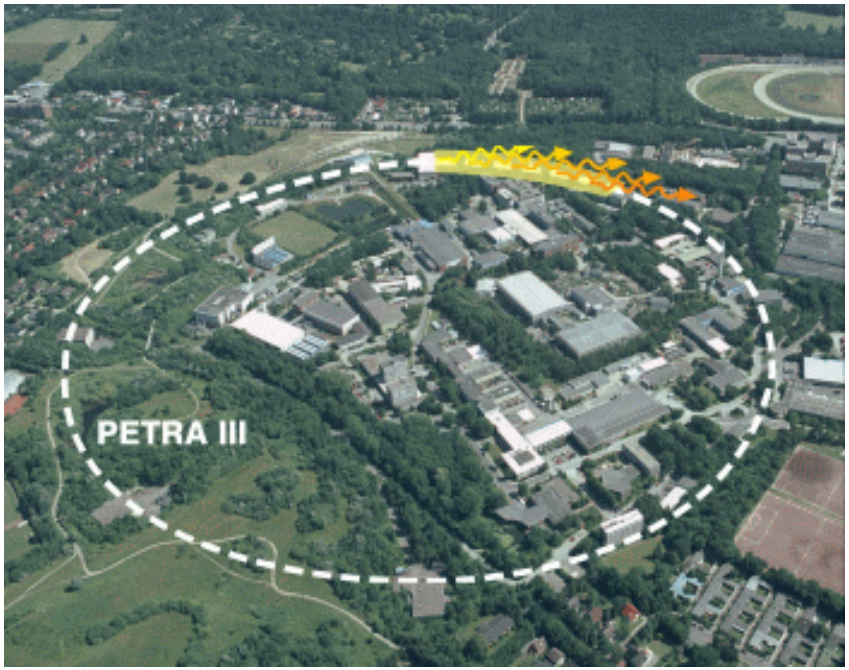


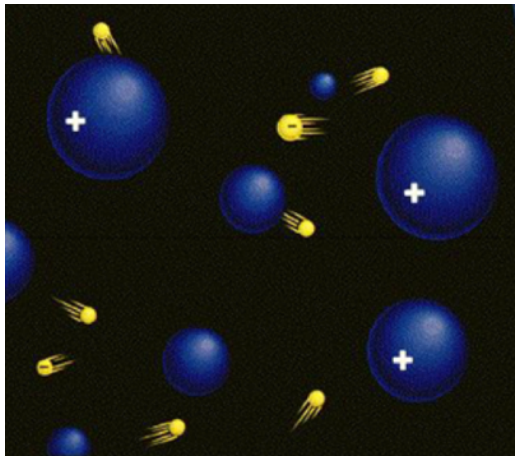
Leptons preferred: Collide point particles rather than complex objects

But, charged particles radiate energy when accelerated.

Power α $(E/m)^4$

Need linear electron accelerator or m large (muon 200 heavier than electron)

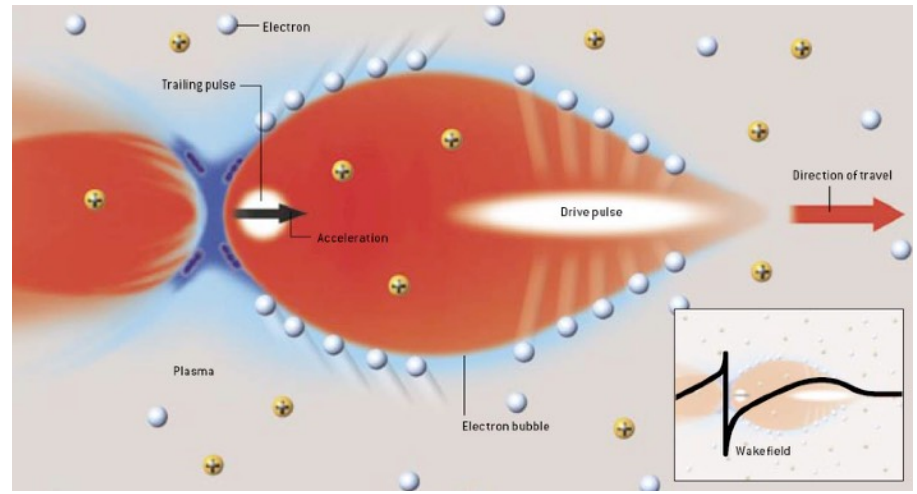




E. Adli, Oslo

A plasma: collection of free positive and negative charges (ions and electrons). Material is already broken down. A plasma can therefore **sustain very high fields.**

C. Joshi, UCLA



An intense **particle beam**, or intense **laser beam**, can be used to drive the plasma electrons.

Plasma frequency depends only on density:

$$\omega_p^2 = \frac{4\pi n_p e^2}{m} \qquad \lambda_p = \frac{2\pi}{k_p} = 1mm\sqrt{\frac{1\cdot 10^{15}\ \mathrm{cm}^{-3}}{n_p}}$$

Ideas of **~100 GV/m** electric fields in plasma, using 10^{18} W/cm^2 lasers: 1979 **T.Tajima and J.M.Dawson** (UCLA), Laser Electron Accelerator, Phys. Rev. Lett. 43, 267–270 (1979).
Using partice beams as drivers: P. **Chen et al**. Phys. Rev. Lett. 54, 693–696 (1985)

Introduction

Energy Budget:

Witness:

10^{10} particles @ 1 TeV ≈ few kJ

Drivers:

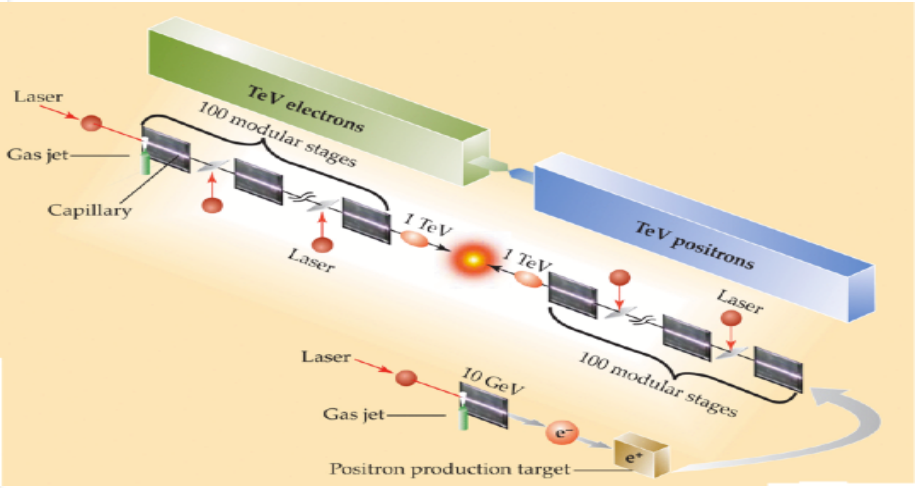
PW lasers today, ~40 J/Pulse

FACET (e beam, SLAC), 30J/bunch

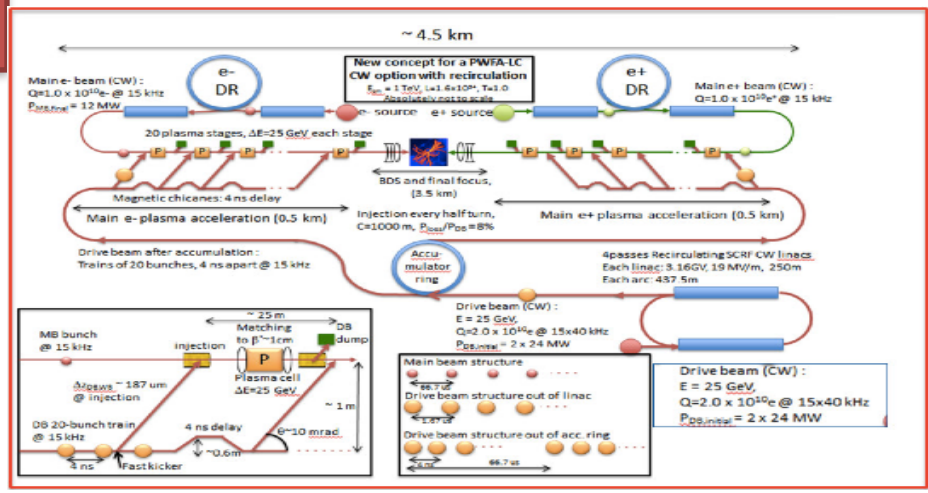
SPS@CERN 20kJ/bunch

LHC@CERN 300 kJ/bunch

Staging Concepts



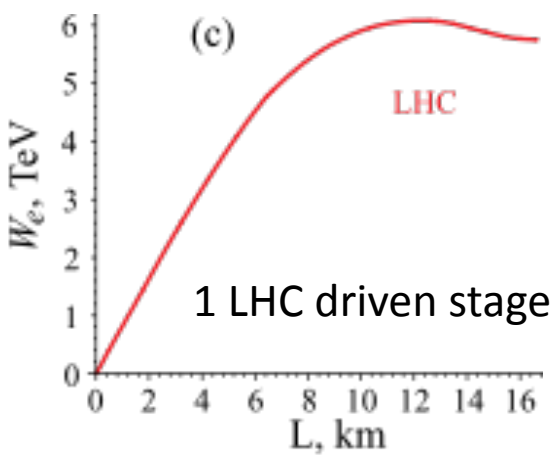
Leemans & Esarey, Phys. Today ***62 #3*** *(2009)*



E. Adli et al. arXiv:1308.1145,2013

Dephasing

$$\delta \approx \frac{\pi L}{\lambda_p} \frac{1}{\gamma^2}$$



SPS: ~100m,

LHC: ~few km

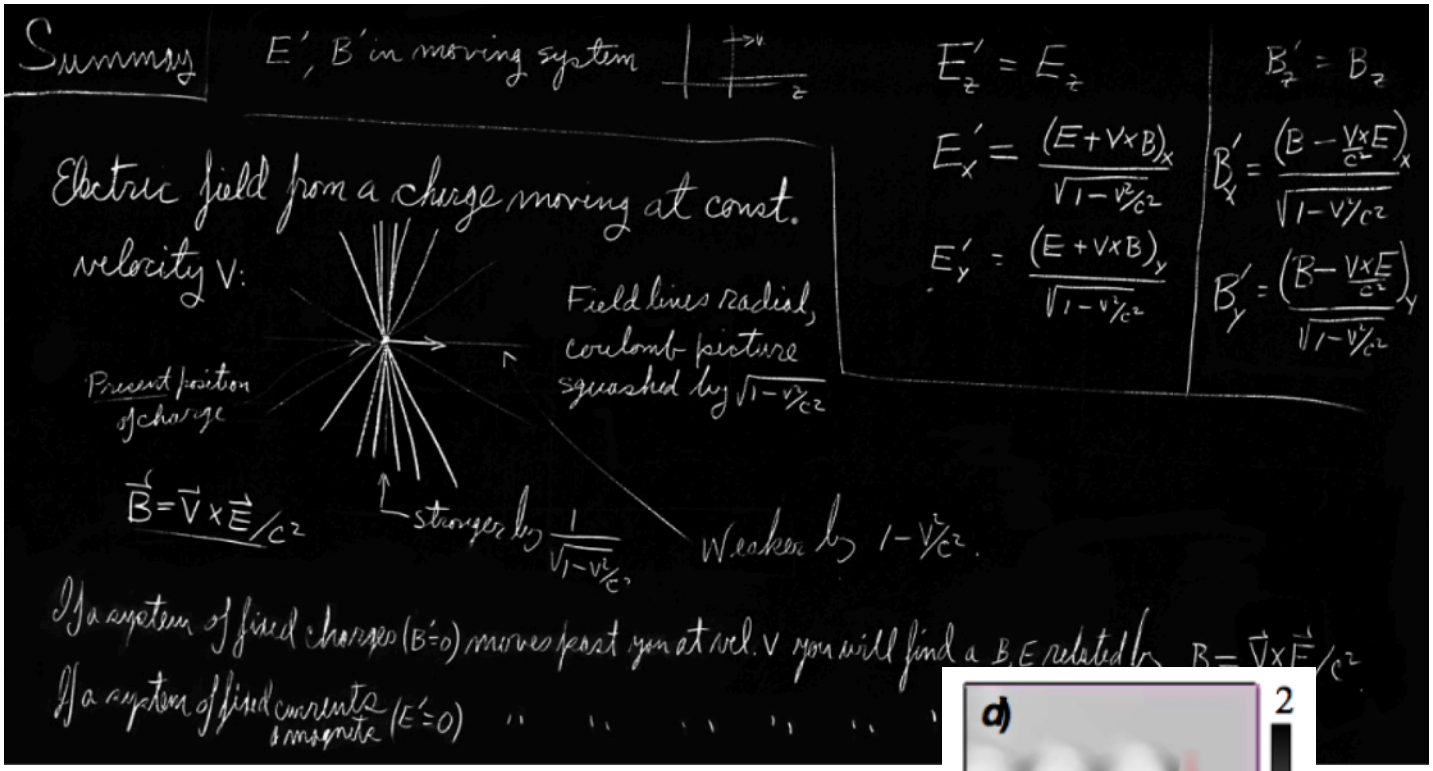
FCC: ~ ∞

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

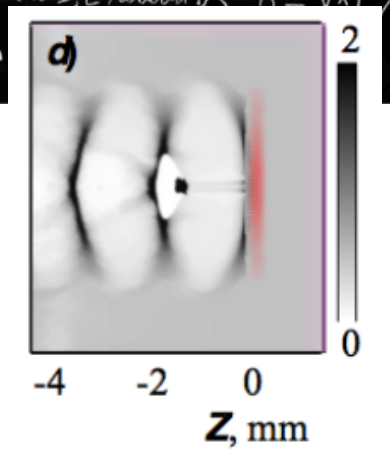
Basic Aspects

Small beam dimensions required !

Feynman Lectures, CalTech



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



Today's proton beams have $\sigma_z \approx 10 - 30\ \mathrm{cm}$

Basic Aspects

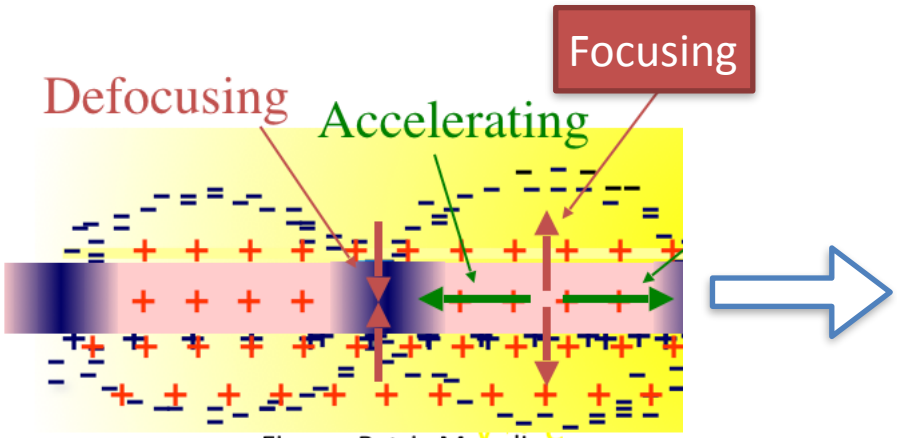
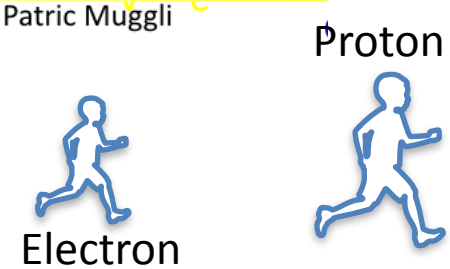


Figure: Patric Muggli



Do the electrons outrun the protons ?

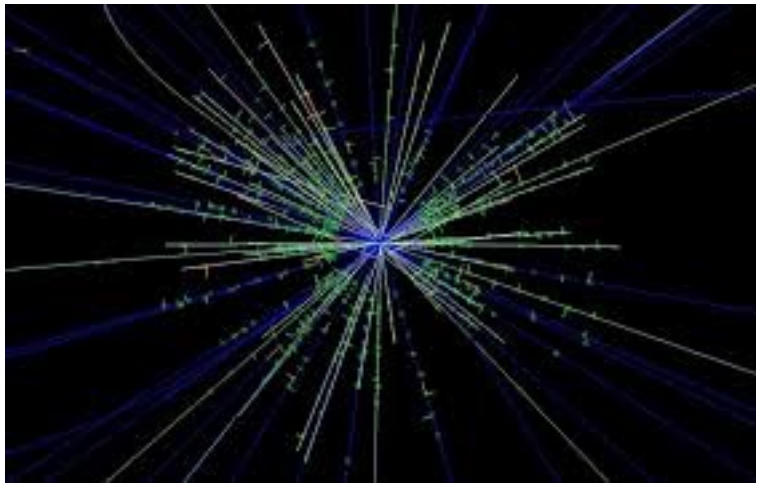
$$\delta \approx \frac{\pi L}{\lambda_p} \frac{1}{\gamma^2}$$

Phase slippage (protons 2000 times heavier than electrons) ?

Basic Aspects

Proton (QCD) interactions ?

LHCb event display



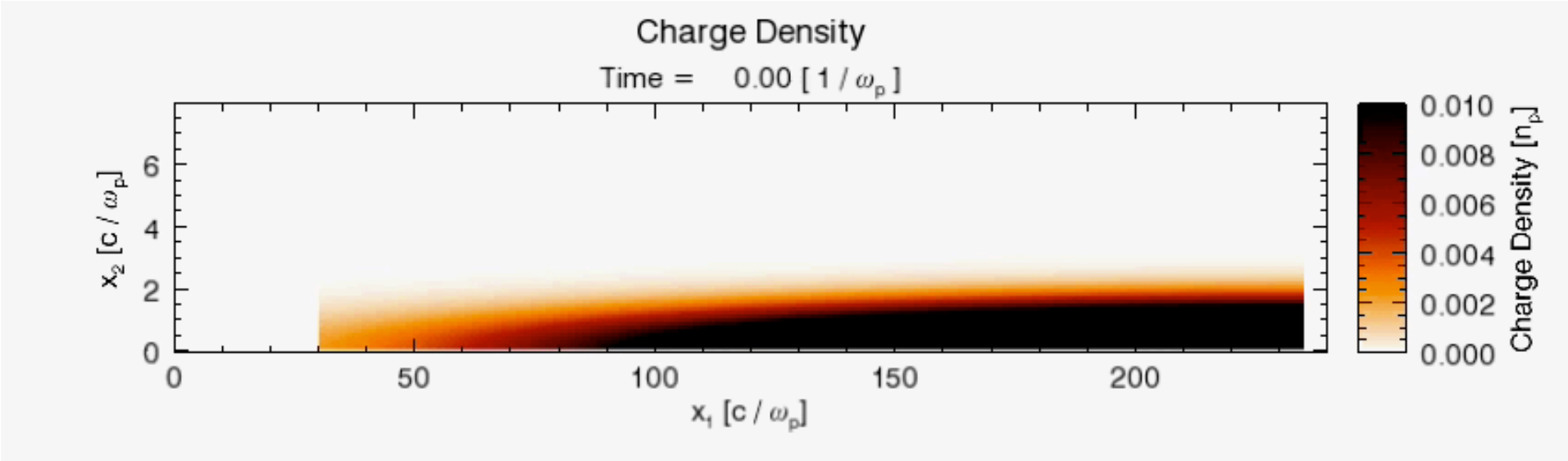
$$\lambda = \frac{1}{n\sigma} \qquad n = 1 \cdot 10^{15}\ \mathrm{cm}^{-3} \quad \Rightarrow \lambda > 1000\ \mathrm{km}$$

Fundamental issue: **proton bunch length**. Can we squeeze the protons together to increase the electric field strength & plasma Wakefield ?

Modulated Proton Beam

Solution ! microbunches are generated by the interaction between the bunch and the plasma. The microbunches are naturally spaced at the plasma wavelength, and act constructively to generate a strong plasma wake. Investigated both numerically and analytically.

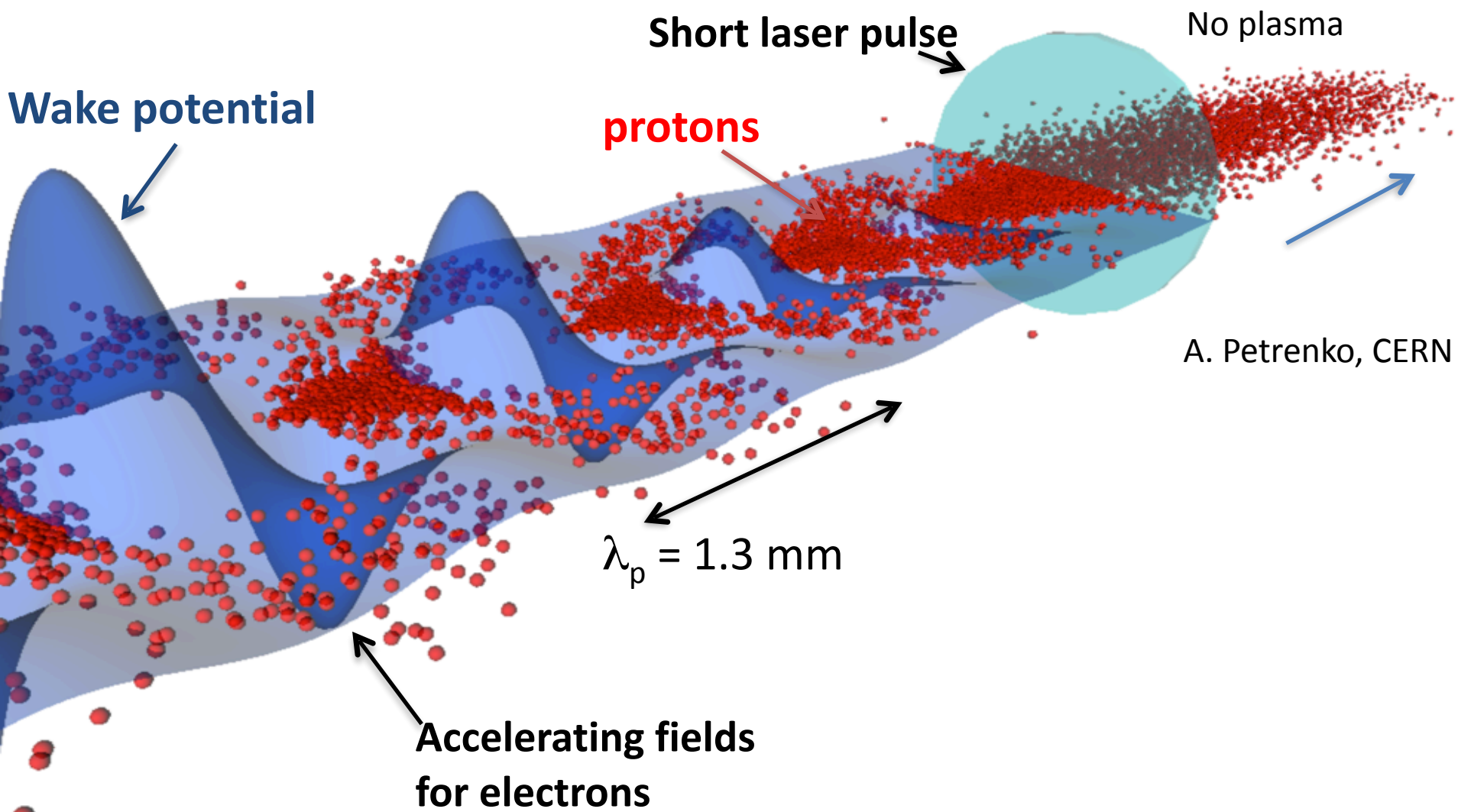
N. Kumar, A. Pukhov, and K. V. Lotov, Phys. Rev. Lett. **104**, 255003 (2010)



Propagation of a 'cut' proton bunch in a plasma. From Wei Lu, Tsinghua University

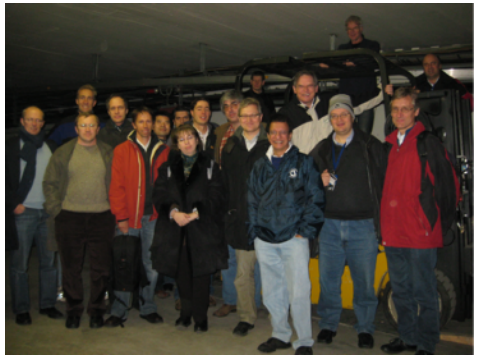
Seeded self-modulation

The self-modulation can be seeded by a sharp start of the beam (or beam-plasma interaction).



History

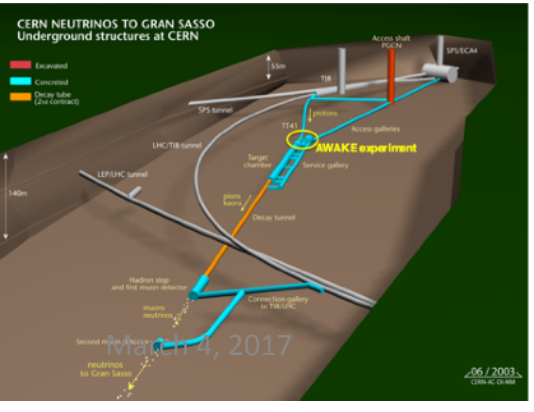
2009 First workshop at CERN to discuss potential of proton-driven PWA.



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

AWAKE

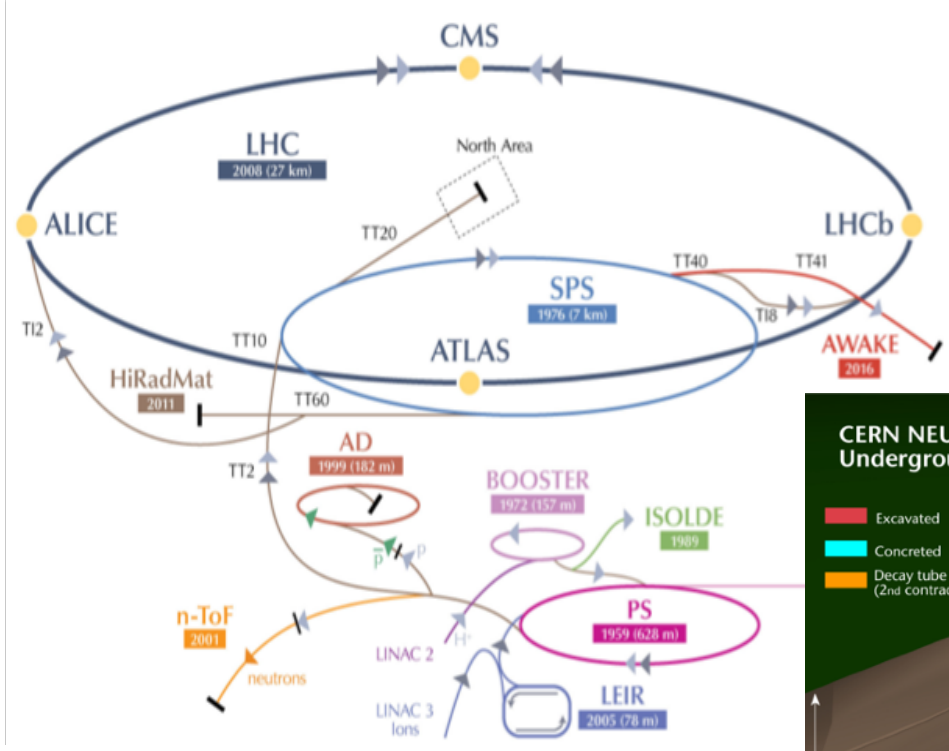
AWAKE Collaboration: 22 Institutes world-wide:

- University of Oslo, Oslo, Norway
- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Oxford University, UK
- Max Planck Institute for Physics, Munich, Germany
- Max Planck Institute for Plasma Physics, Greifswald, Germany
- UCL, London, UK
- UNIST, Ulsan, Republic of Korea
- Philipps-Universität Marburg, Marburg, Germany
- Heinrich-Heine-University of Düsseldorf, Düsseldorf, Germany
- University of Liverpool, Liverpool, UK
- ISCTE - Instituto Universitéario de Lisboa, Portugal
- Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
- Novosibirsk State University, Novosibirsk, Russia
- GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
- TRIUMF, Vancouver, Canada
- Ludwig-Maximilians-Universität, Munich, Germany
- University of Wisconsin, Madison, US
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL, Lausanne, Switzerland

+ 2 associate members:

Jena University
University of Texas

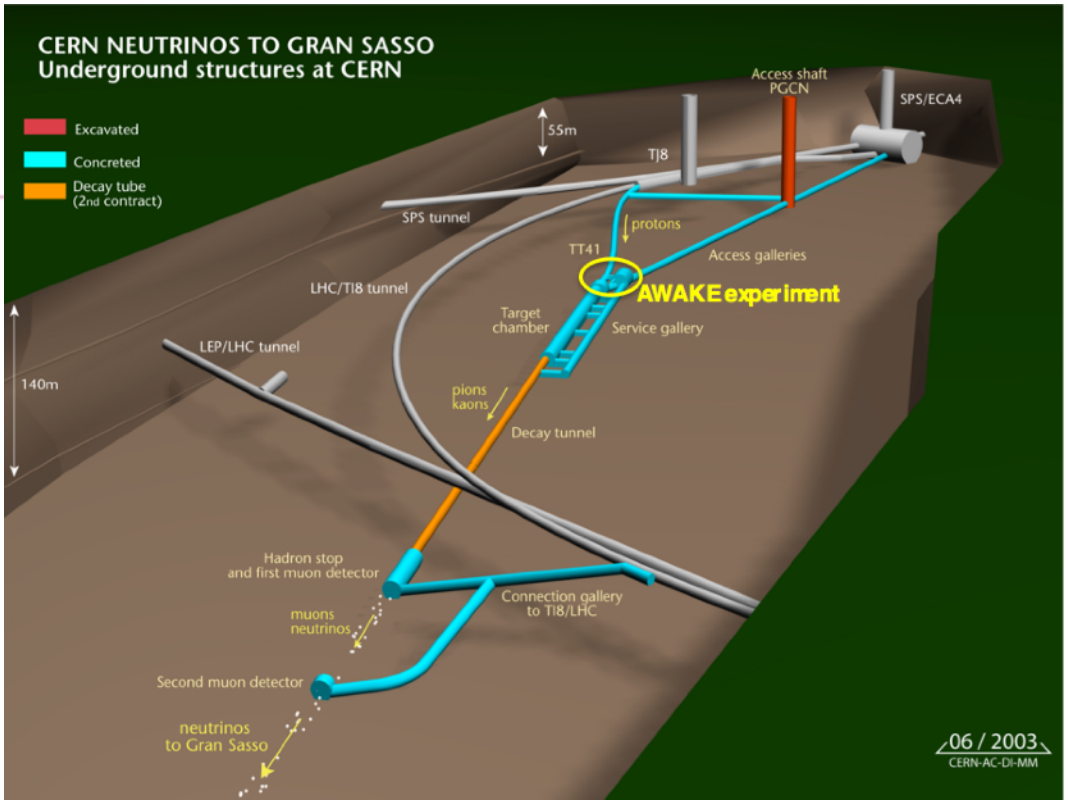
AWAKE at CERN



AWAKE is installed in

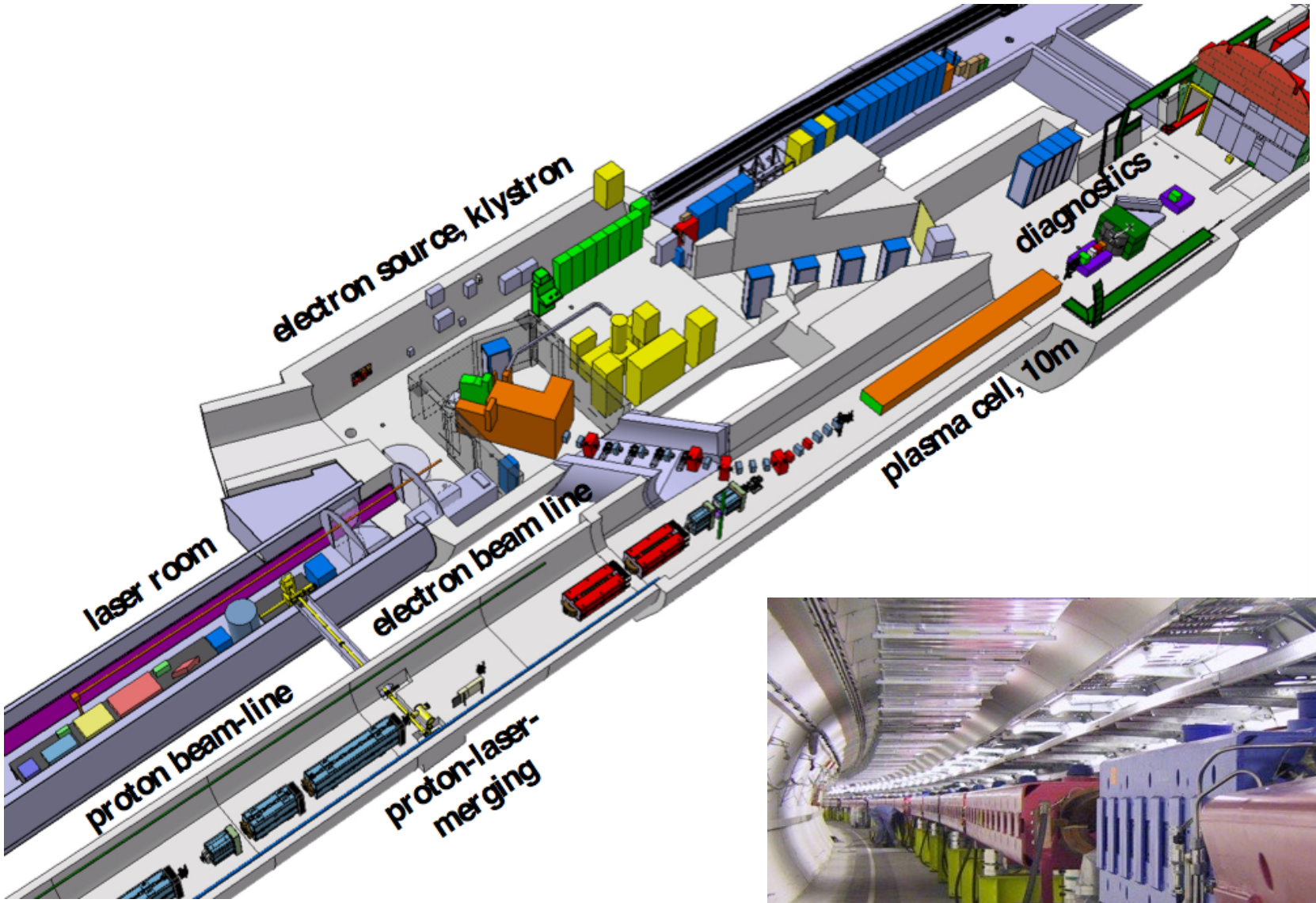
CNGS Facility (CERN Neutrinos to Gran Sasso)

→ 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).

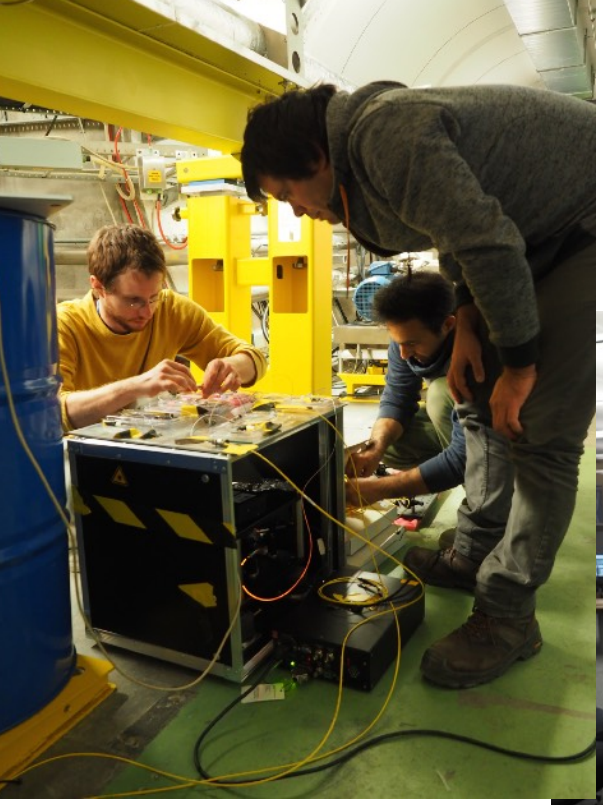
AWAKE Overview



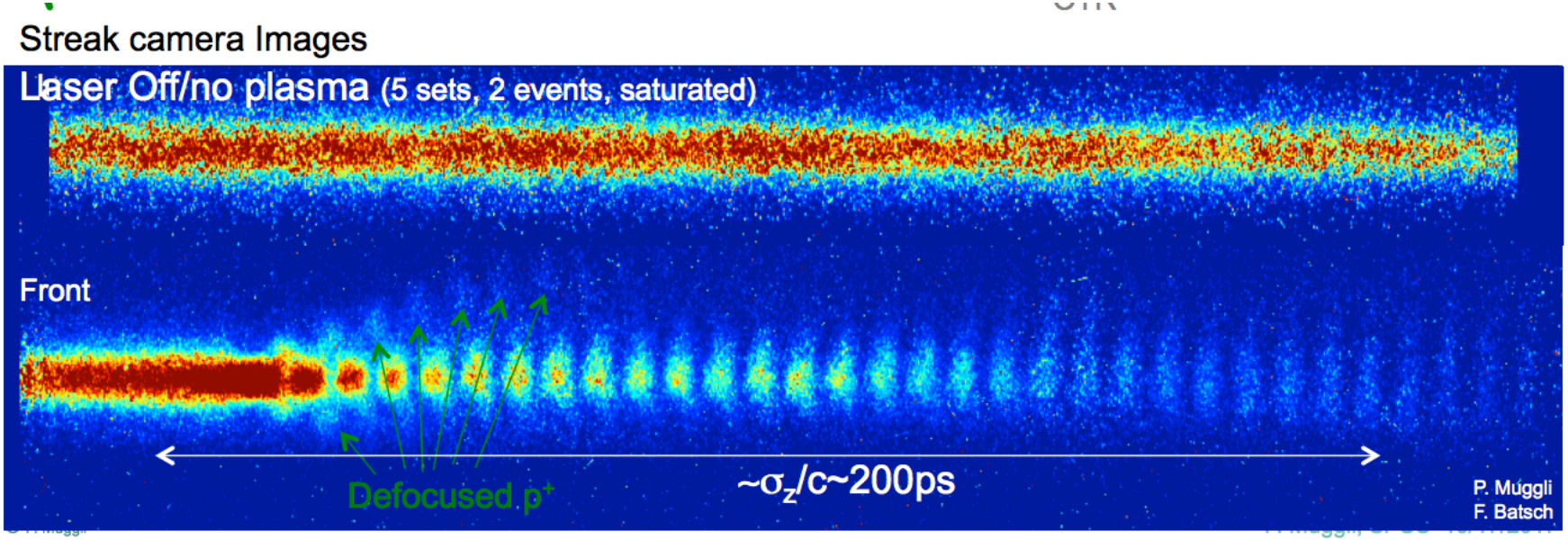
AWAKE Overview

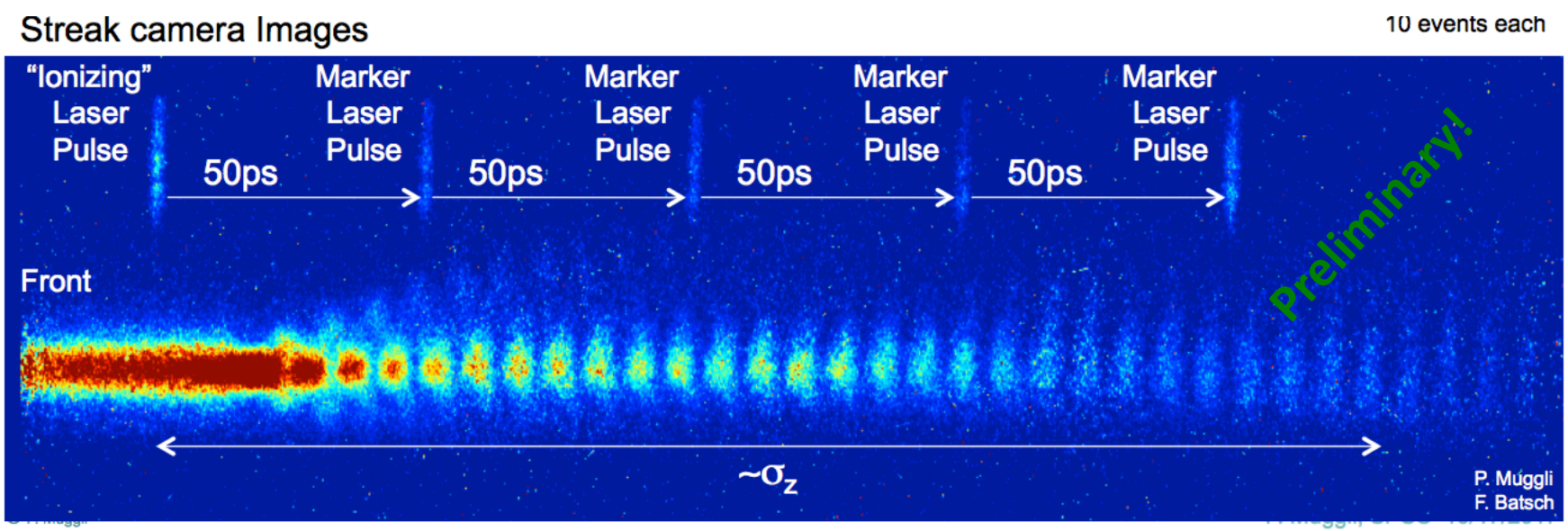
First Run

December 9-12, 2016



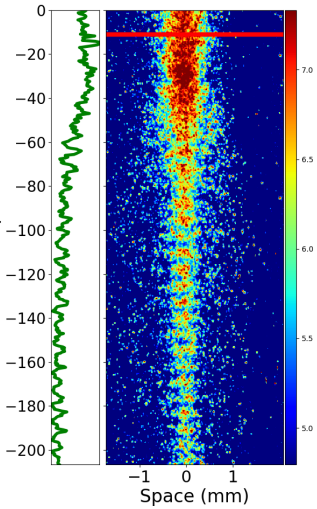
Observation of Seeded SMI



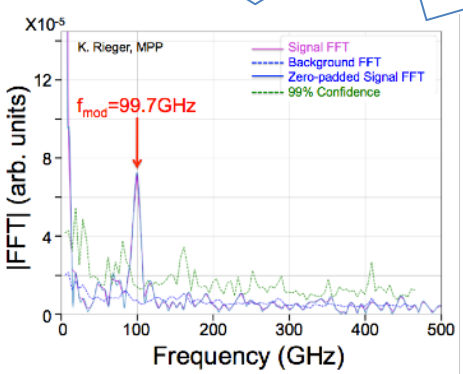


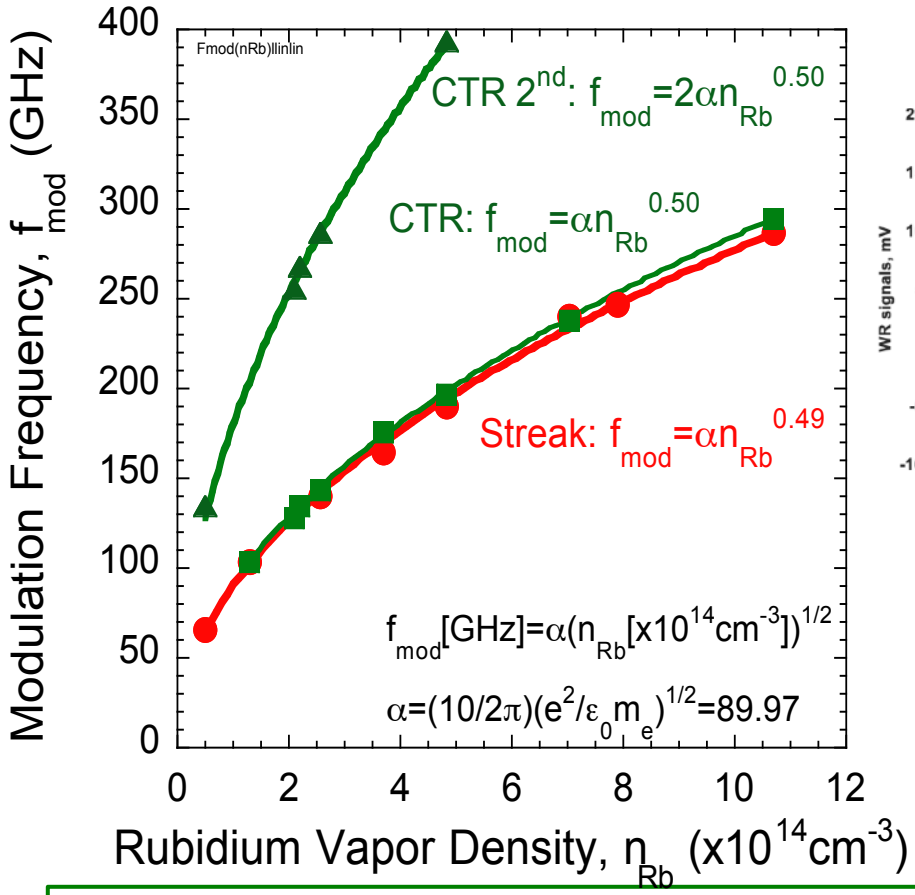
AWAKE

Modulation at the expected frequency

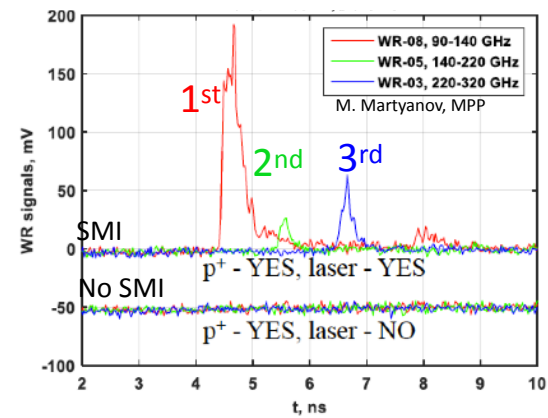


FFT





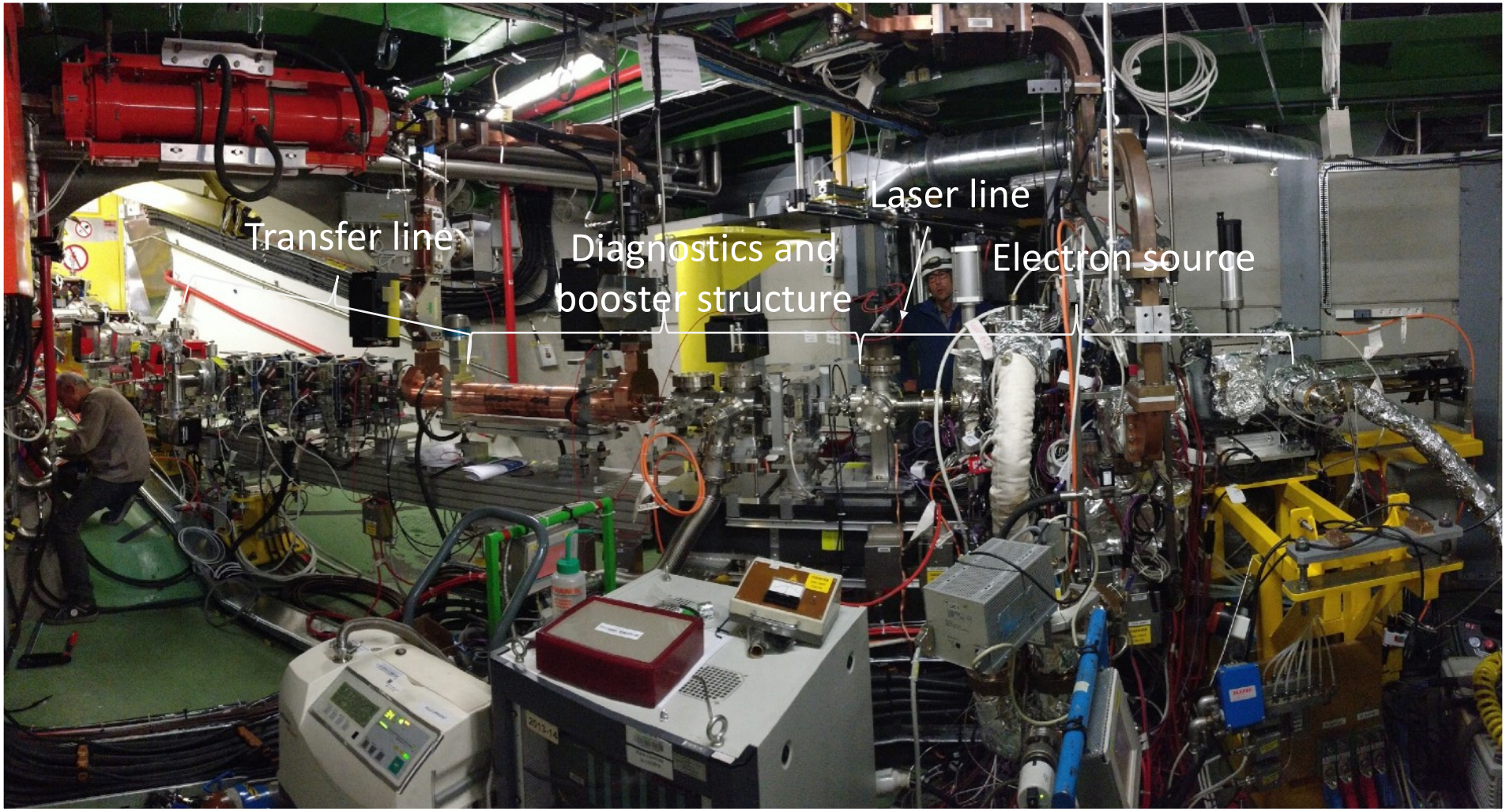
CTR



→ both OTR and CTR based measurements fit very well to predicted modulation frequency, for a range of plasma densities.

E. Adli et al.,(AWAKE Collaboration), PRL **122**, 054802 (2019)

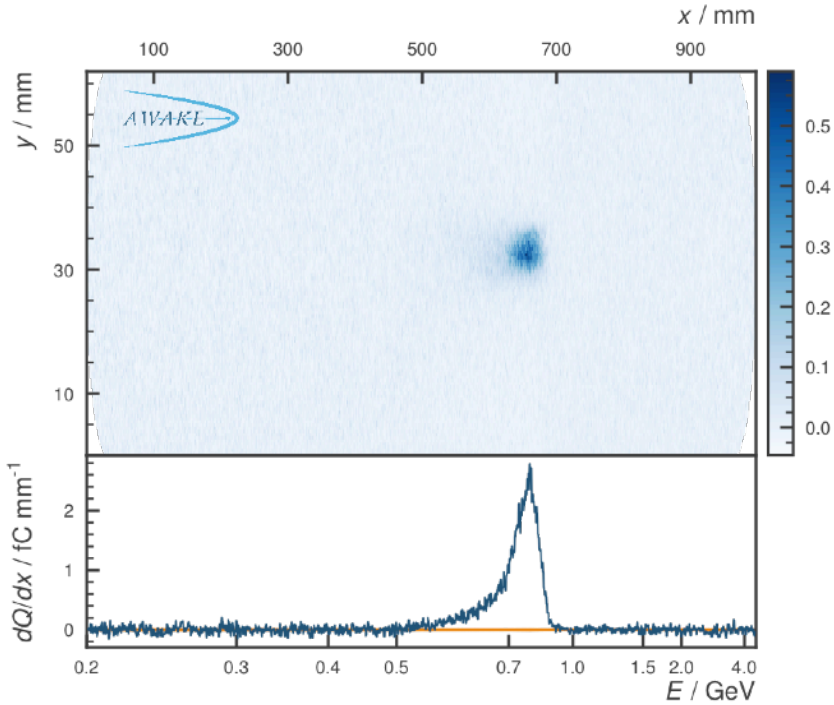
Electron Line

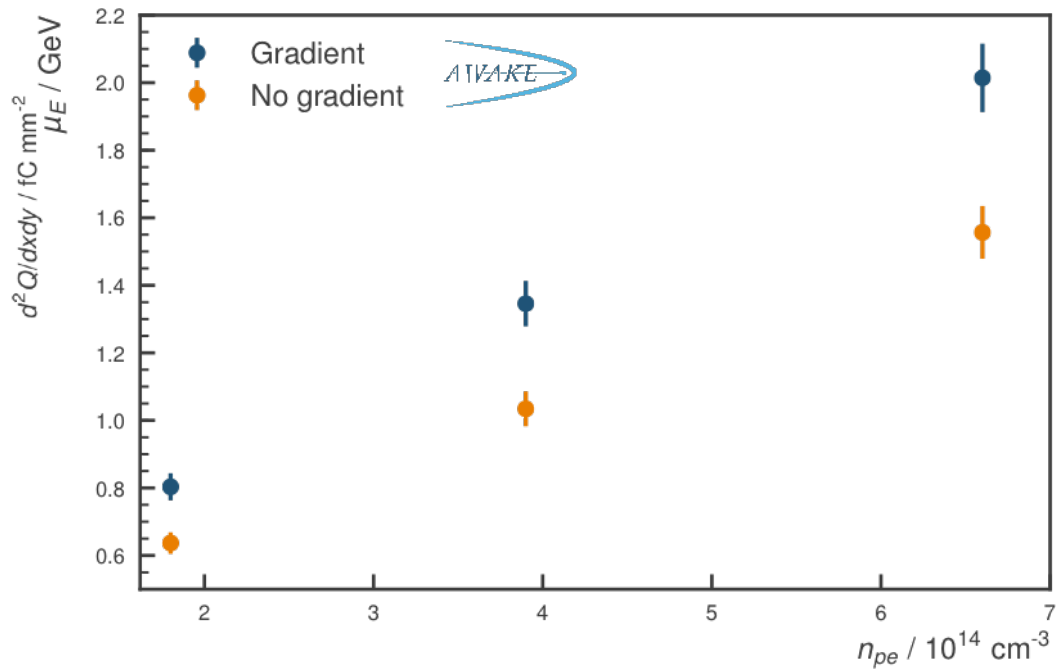


AWAKE

Electron Acceleration Results

E. Adli et al., AWAKE Collaboration, Nature **561,** 363 (2018)





Electron acceleration in a proton-driven plasma wakefield works !

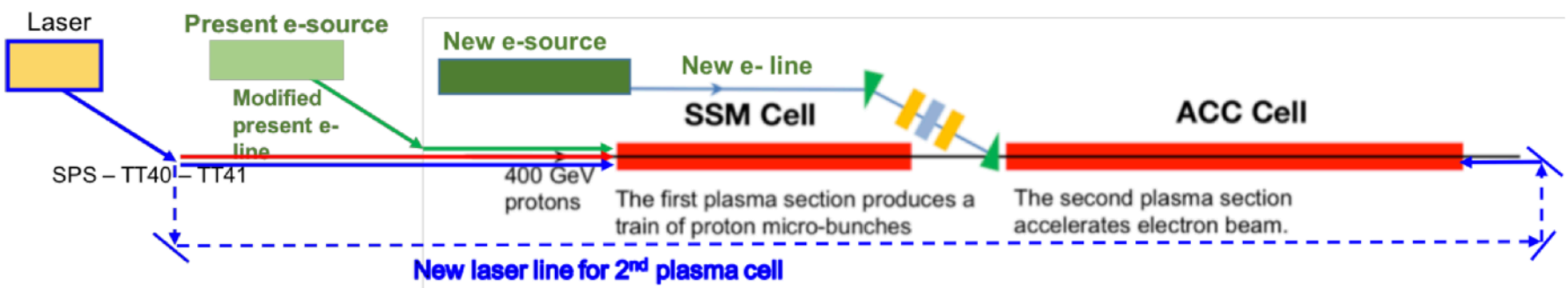
With todays existing proton bunches via seeded self-modulation!

Note: we are accelerating 10 times more charge than previously thought
Maximum accelerated charge ~100 pC (~20% of injected)

Run 2 (2021-)

Goals:
stable acceleration of bunch of electrons with high gradients over long distances
'good' electron bunch emittance at plasma exit
Be prepared to start particle physics experiment after Run 2

Baseline design



Four phases:
- seeding the SSM with an electron bunch
- plasma cell with density step to freeze the modulation structure
- inject electrons & accelerate without emittance blowup
- implement scalable plasma cell technologies

Particle Physics Applications

- **Physics with a high energy electron beam**
  - search for dark photons in beam dump experiments
  - Fixed target experiments in new energy regime

Energy & Flux important - luminosity determined by target properties. Much more relaxed parameters for plasma accelerator

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

New energy regime means new physics sensitivity even at low luminosities !

- **To be evaluated:**
  - AWAKE-like scheme with ions
  - acceleration of muons in LEMMA scheme
  - AWAKE-like scheme with FCC

We have just started to evaluate the particle physics potential of plasma acceleration. Need creative thinking !

Swapan and AWAKE

As Director of the Cockcroft Institute, Swapan was instrumental in building up the UK contribution to AWAKE. UK groups have been key to the success of AWAKE, contributing the spectrometer system as well as many beam line diagnostics. Thank you for this!

Swapan also put me in contact with magnet experts when we first started thinking about the MADMAX Axion search experiment. Now have a thriving Collaboration! Thanks for this too!

And thanks for the enjoyable conversations that we have had, often over collaboration dinners. They were always inspiring!