Accelerating Electrons with Protons
The AWAKE Project

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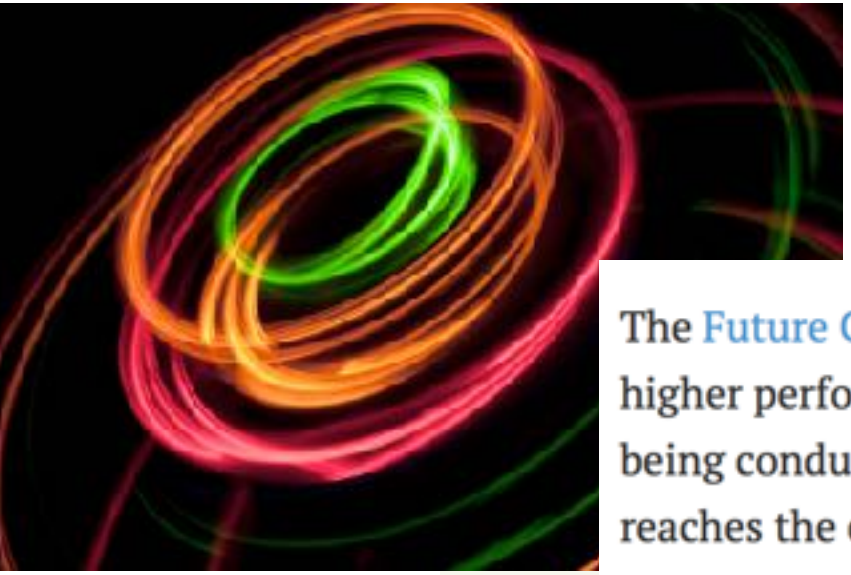
1. **How it works & challenges**
2. **The AWAKE project: evolution and current status**
3. **Long-term perspectives**

Humboldt-Kolleg. June 23-28, 2019 Kitzbühel

Even larger Accelerators ?

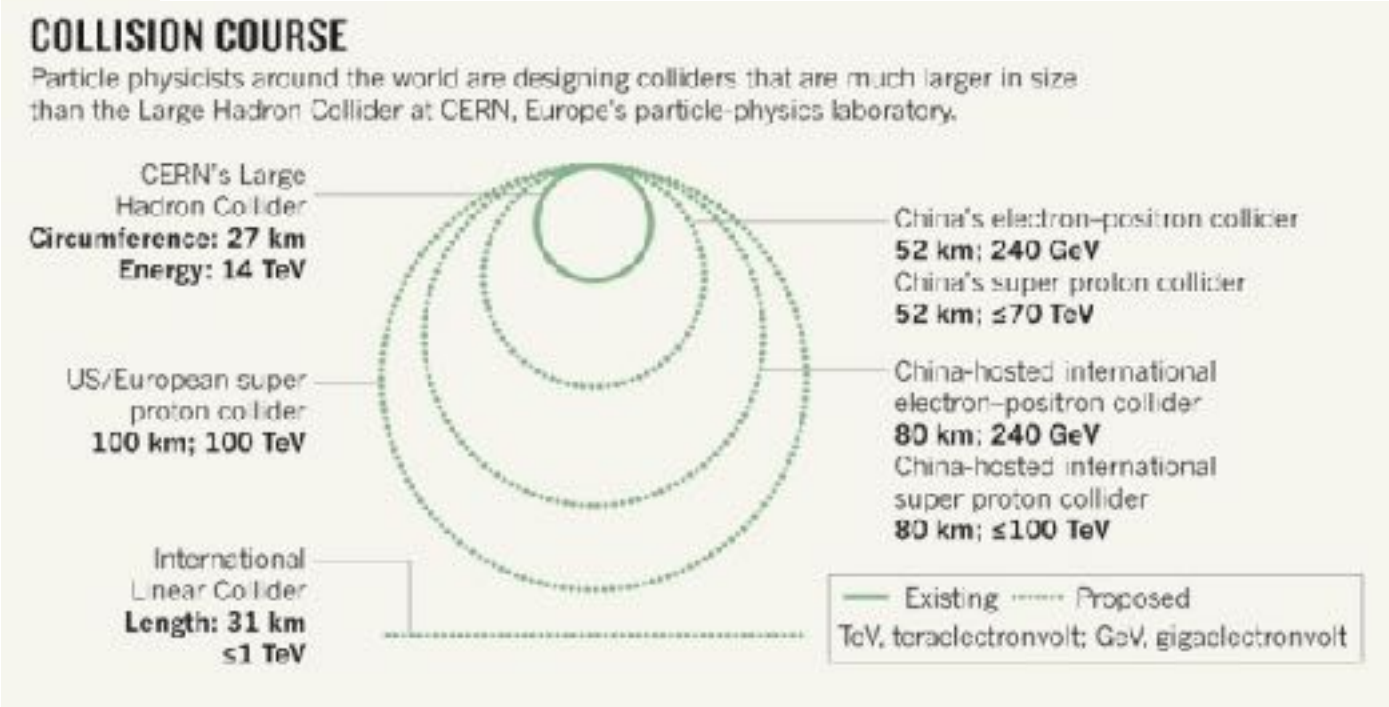


The Future Circular Collider Study (FCC) is developing designs for a higher performance particle collider to extend the research currently being conducted at the Large Hadron Collider (LHC), once the latter reaches the end of its lifespan.

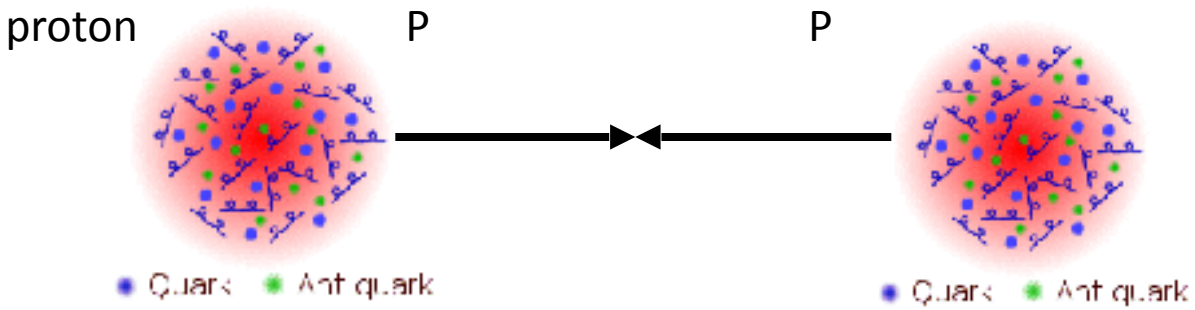
Energy limit of circular proton collider given by magnetic field strength.

$$P \propto B \cdot R$$

CERN aiming to double field strength of LHC magnets



Linear Electron Collider or Muon Collider?

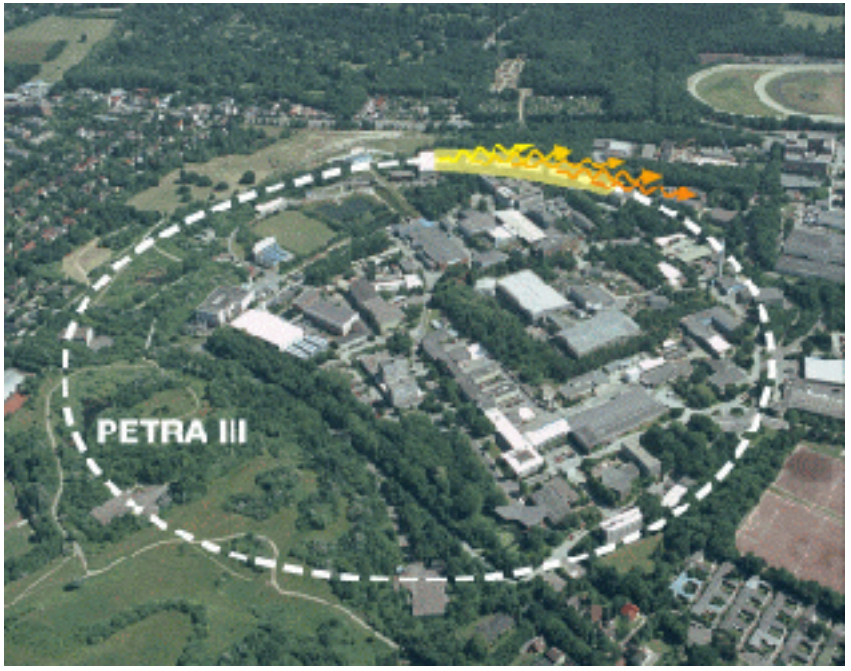


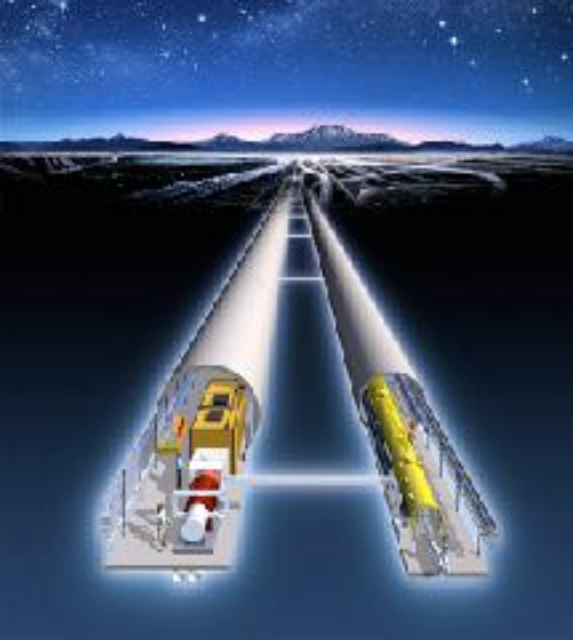
Leptons preferred:
Collide point particles rather than complex objects

But, charged particles radiate energy when accelerated.

Power α $(E/m)^4$

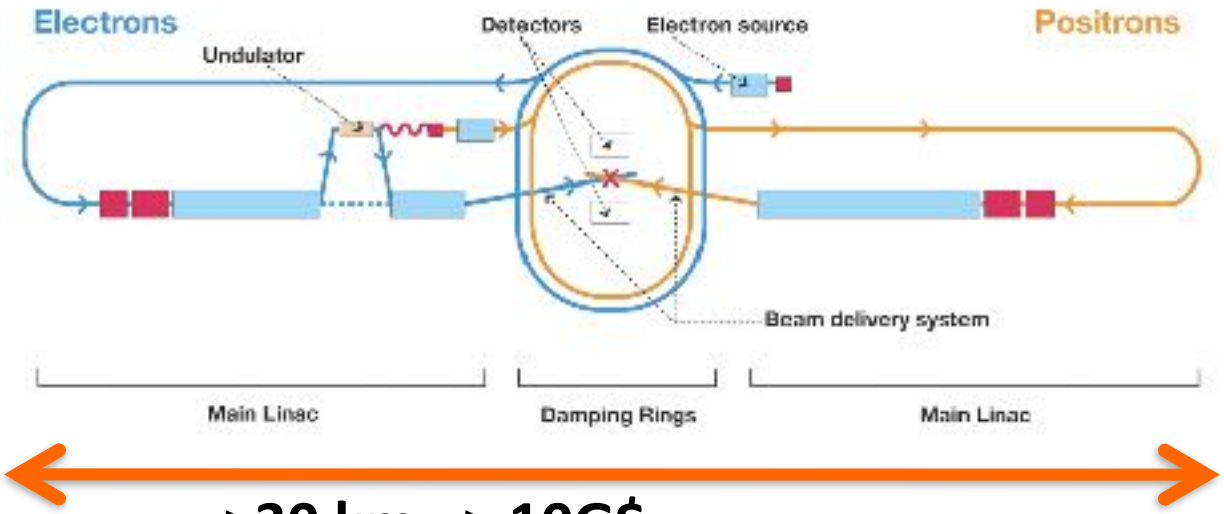
Need linear electron accelerator or m large (muon 200 heavier than electron)





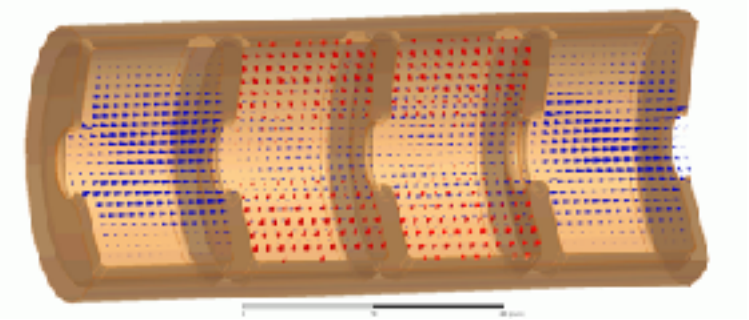
Linear Colliders are expensive with today's gradients

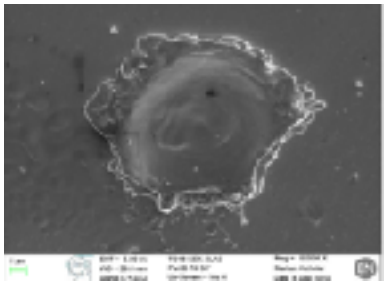
e^+e^- collisions at 500-1000 GeV

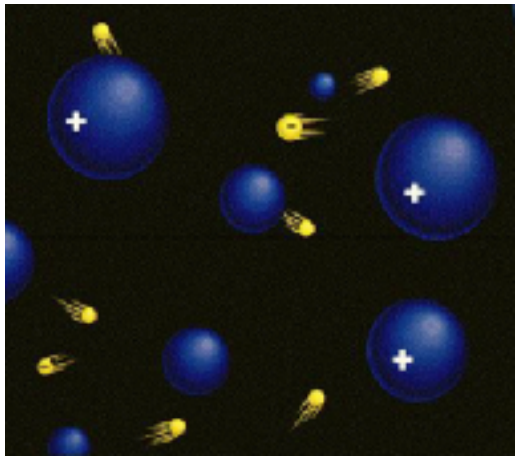


>30 km, > 10G$

In **metallic structures** surfaces break down if fields too high $\rightarrow$ electric discharges.
Current practical limit (CLIC): order of 100 MV/m accelerating field.



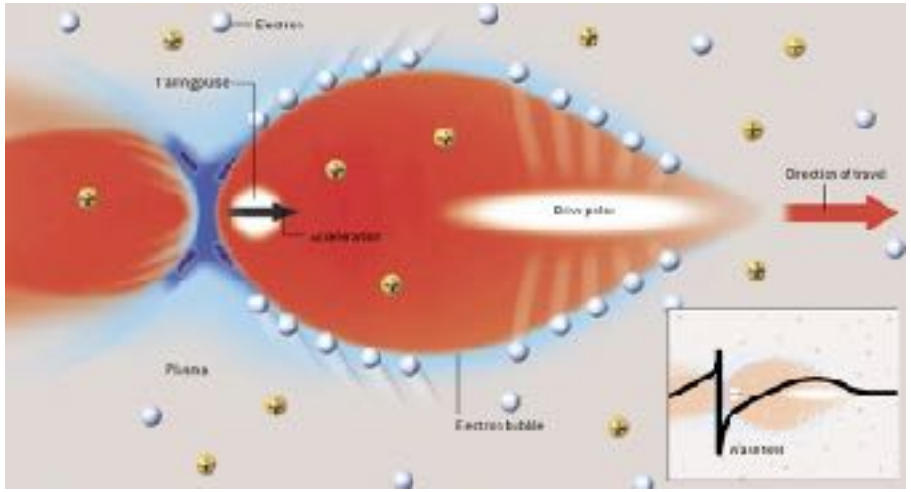




E. Adli, Oslo

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:

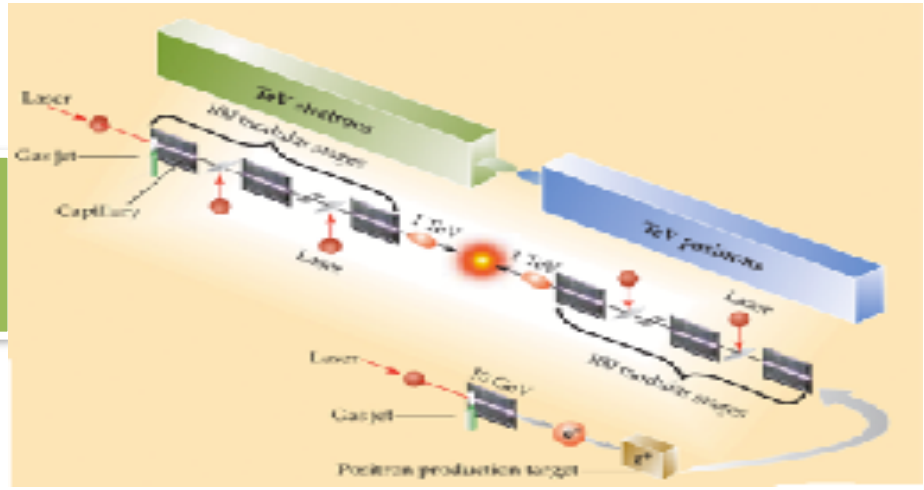
$$\omega_p^2 = \frac{4\pi n_p e^2}{m} \qquad \lambda_p = \frac{2\pi}{k_p} = 1mm\sqrt{\frac{1\cdot 10^{15}\ \mathrm{cm}^{-3}}{n_p}}$$

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)

Staging Concepts

Energy Budget:

Witness:
10^{10} particles @ 1 TeV ≈ few kJ

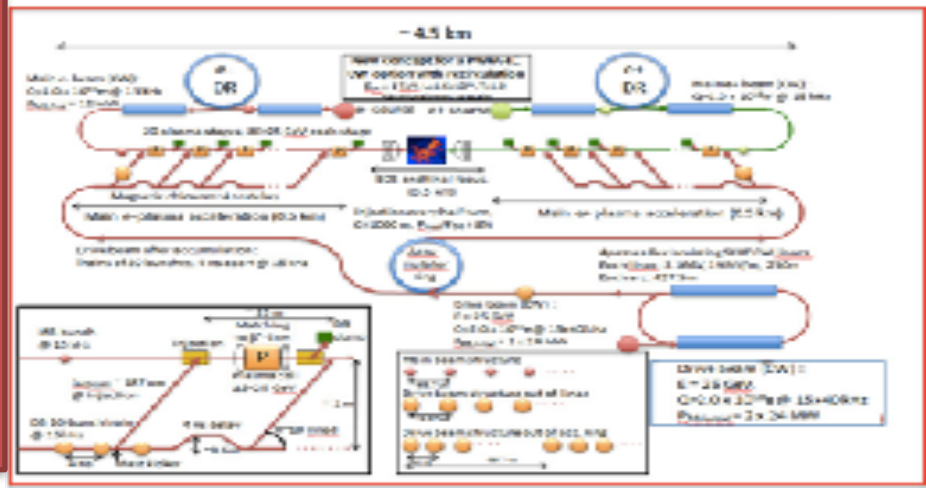


Leemans & Esarey, Phys. Today ***62 #3*** *(2009)*

Drivers:
PW lasers today, ~40 J/Pulse

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

SPS@CERN 20kJ/bunch
LHC@CERN 300 kJ/bunch

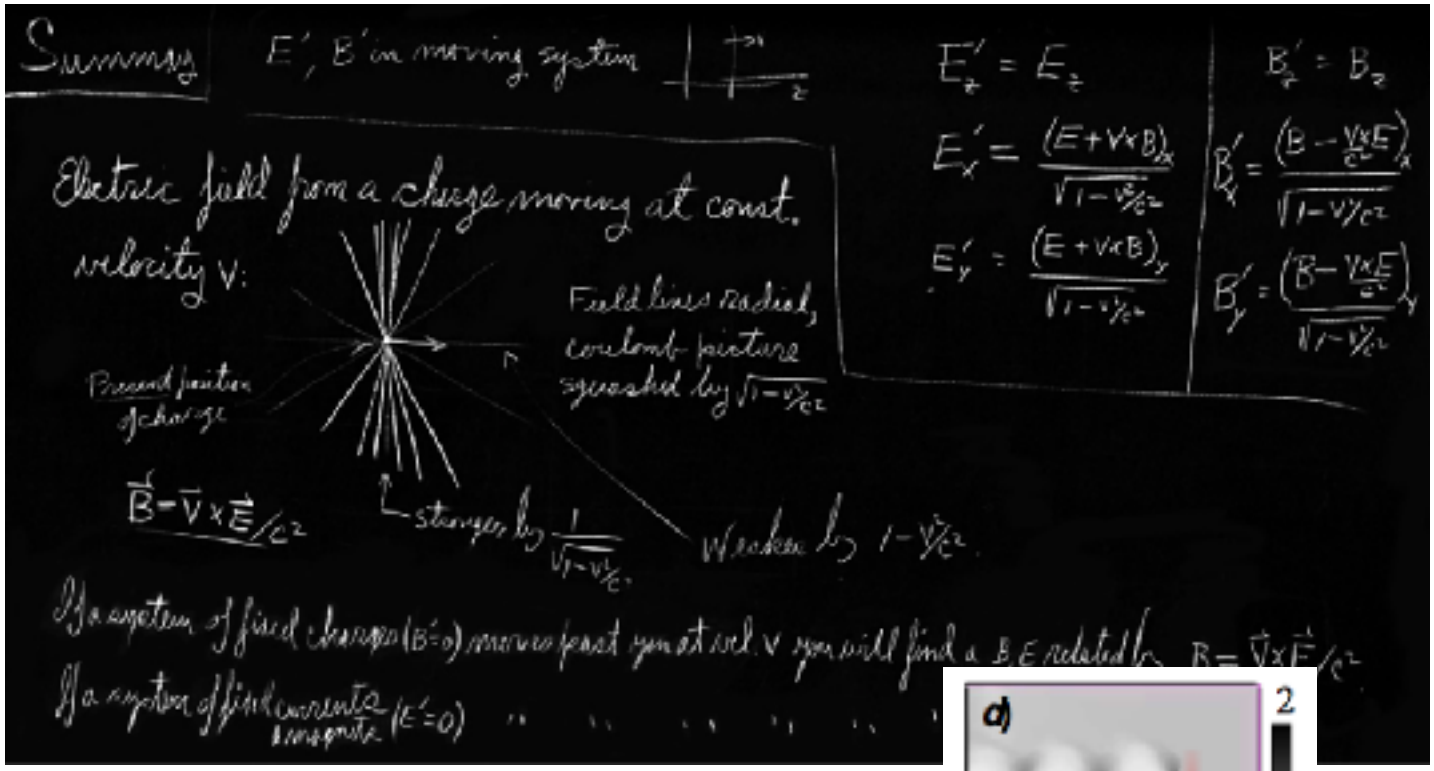


E. Adli et al. arXiv:1308.1145,2013

Basic Aspects

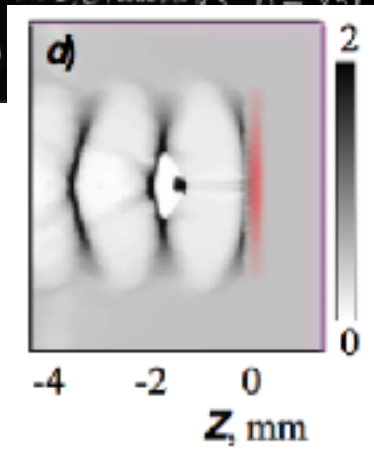
Small beam dimensions required !

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 $\sigma_z \approx 10 - 30$ cm



Basic Aspects

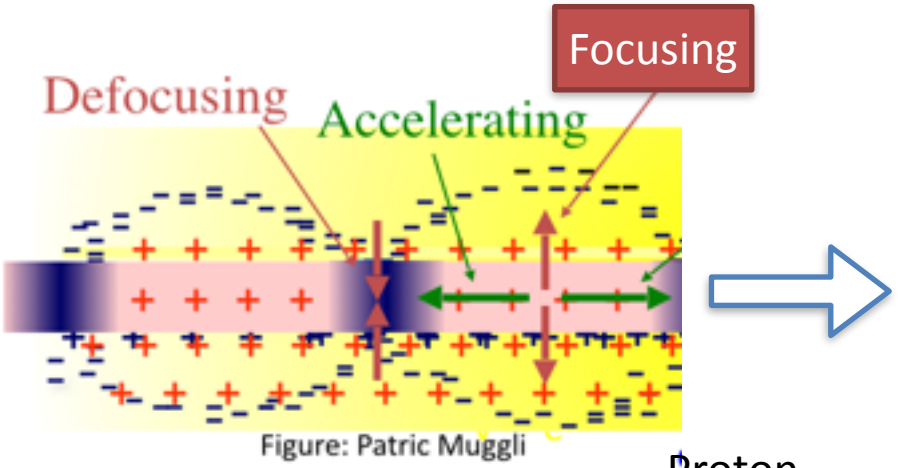


Figure: Patric Muggli

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

Electron

Proton

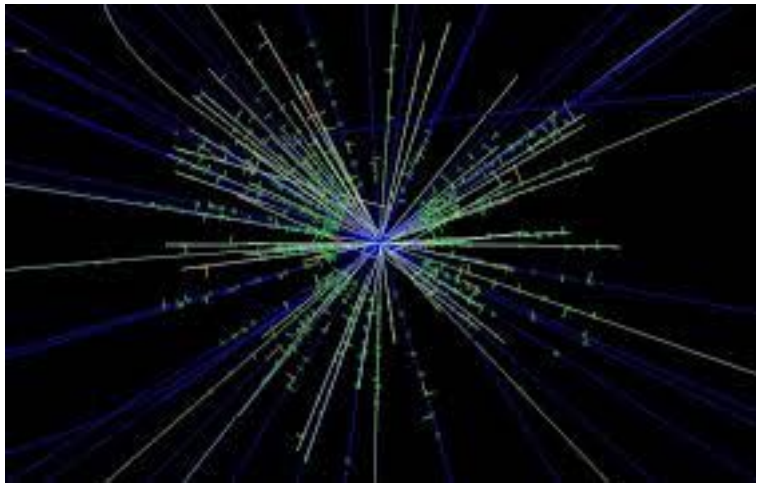
Do the electrons outrun the protons ?

Phase slippage (protons 2000 times heavier than electrons) ?

Basic Aspects

Proton (QCD) interactions ?

LHCb event display



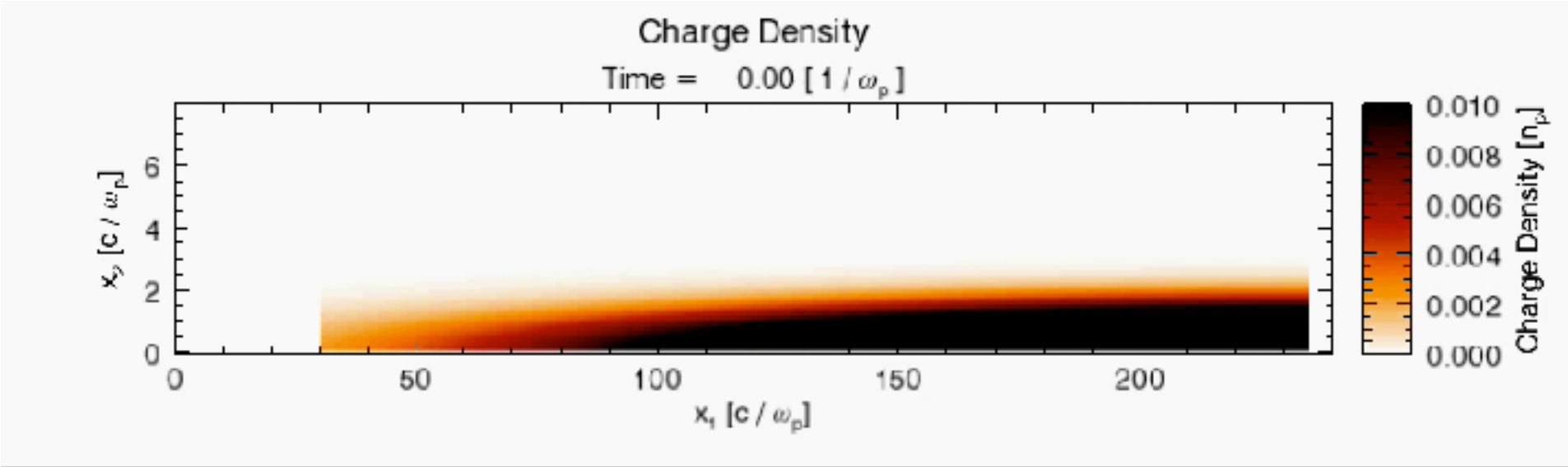
$$\lambda = \frac{1}{n\sigma} \qquad n = 1 \cdot 10^{15}\ \mathrm{cm}^{-3} \quad \Rightarrow \lambda > 1000\ \mathrm{km}$$

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.

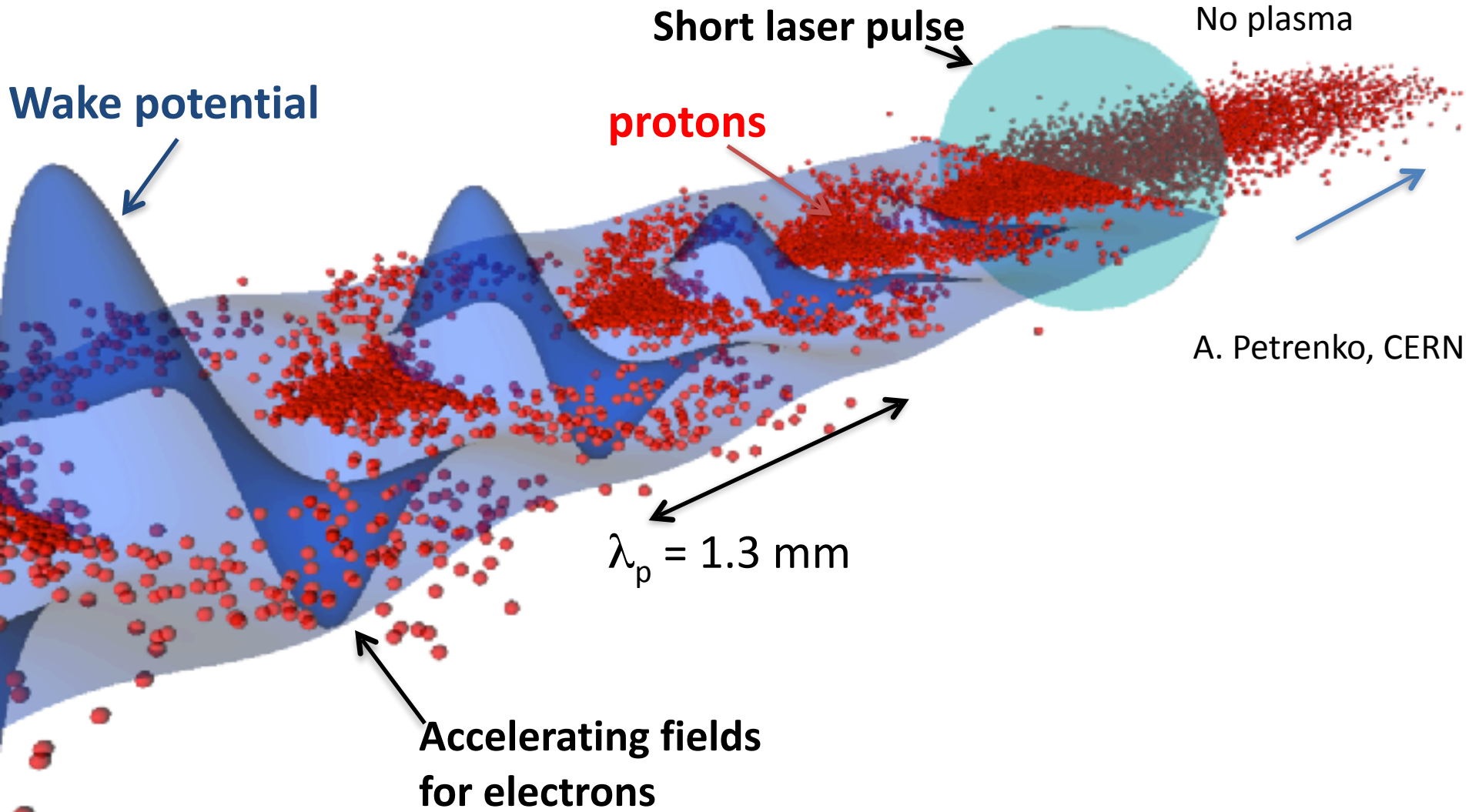
N. Kumar, A. Pukhov, and K. V. Lotov, Phys. Rev. Lett. **104**, 255003 (2010)



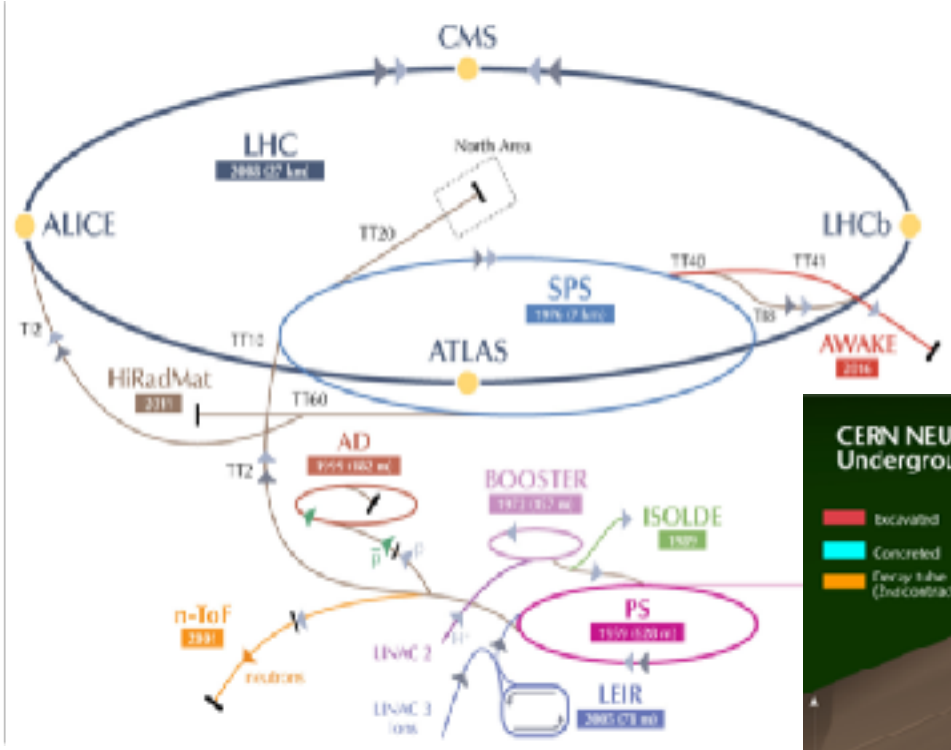
Propagation of a ‘cut’ proton bunch in a plasma. From Wei Lu, Tsinghua University

Seeded self-modulation

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



AWAKE at CERN



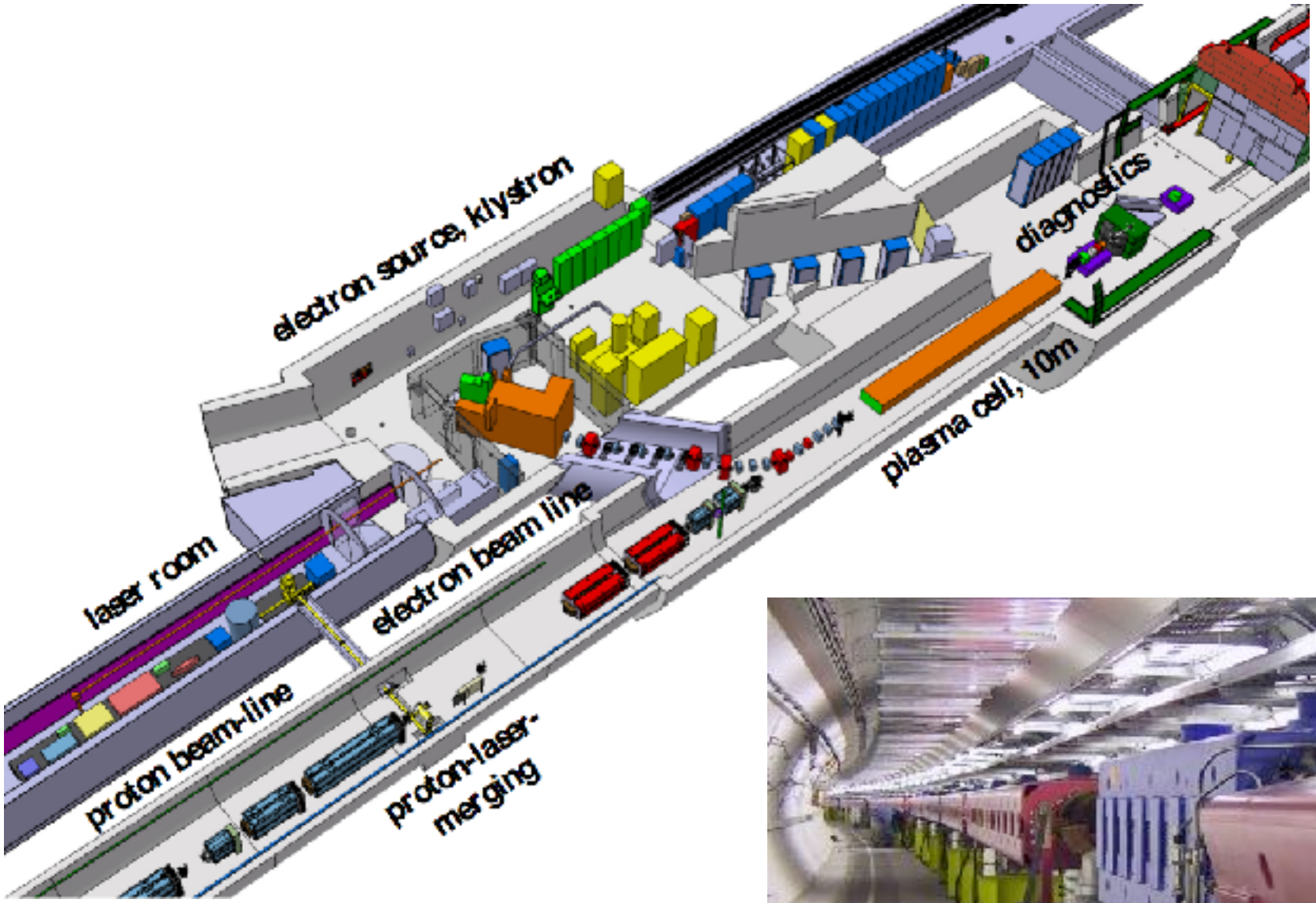
AWAKE is installed in

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).

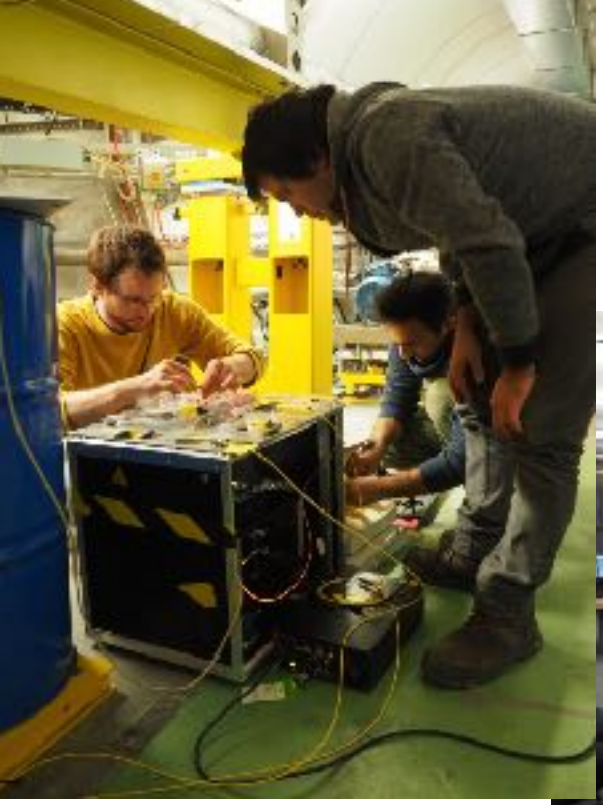
AWAKE Overview

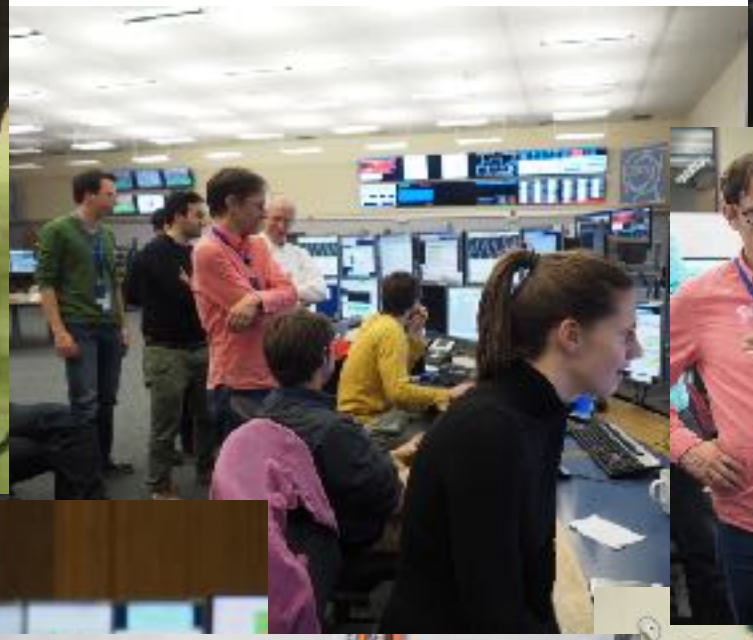


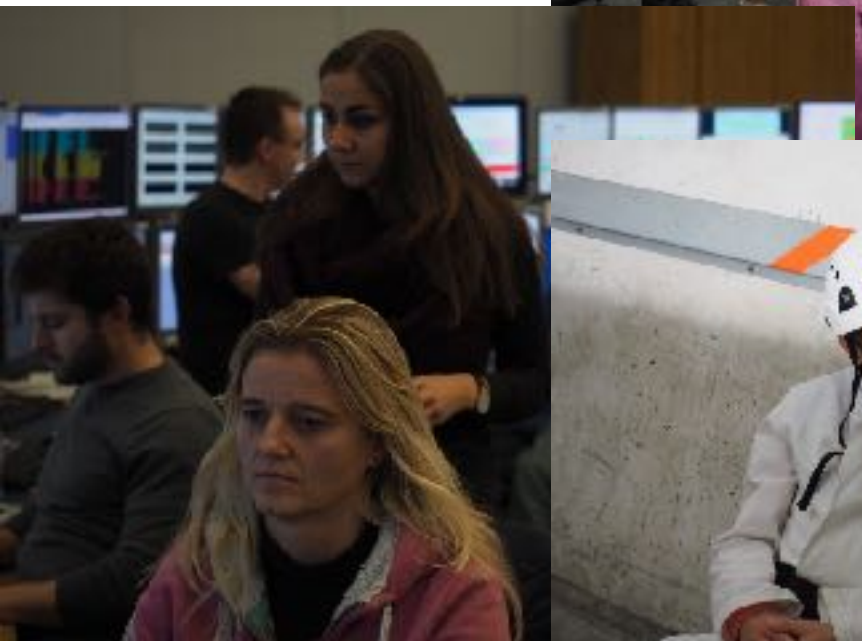
AWAKE Overview

First Run

December 9-12, 2016

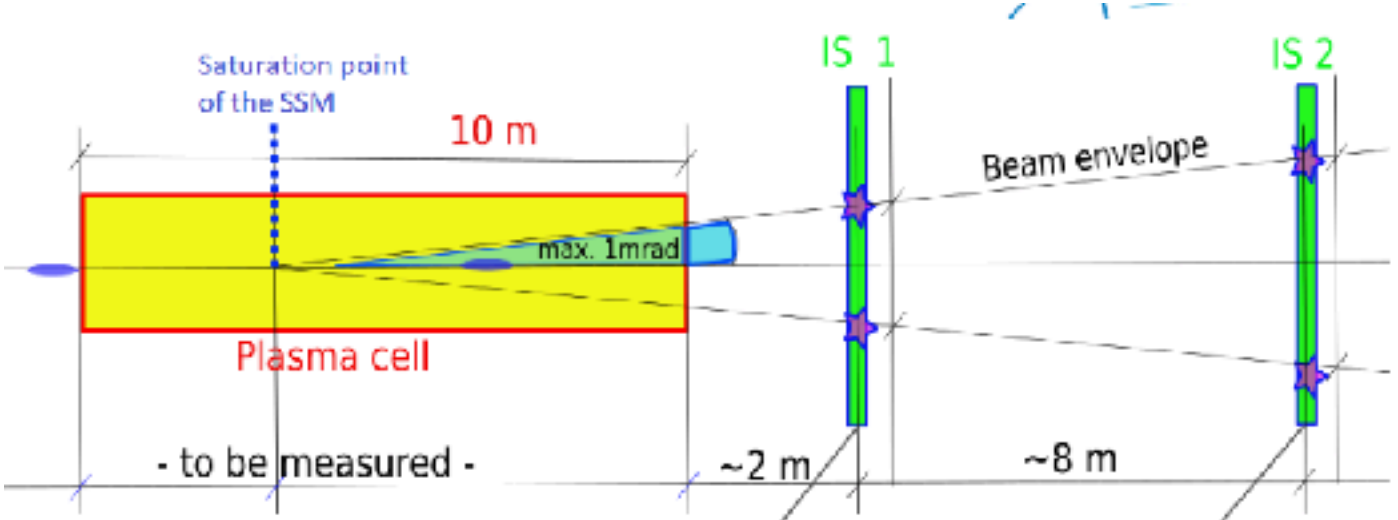


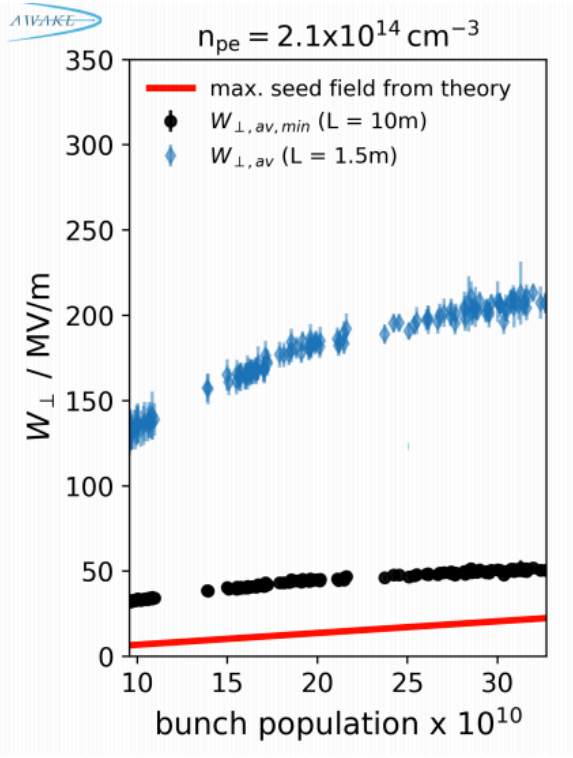




AWAKE

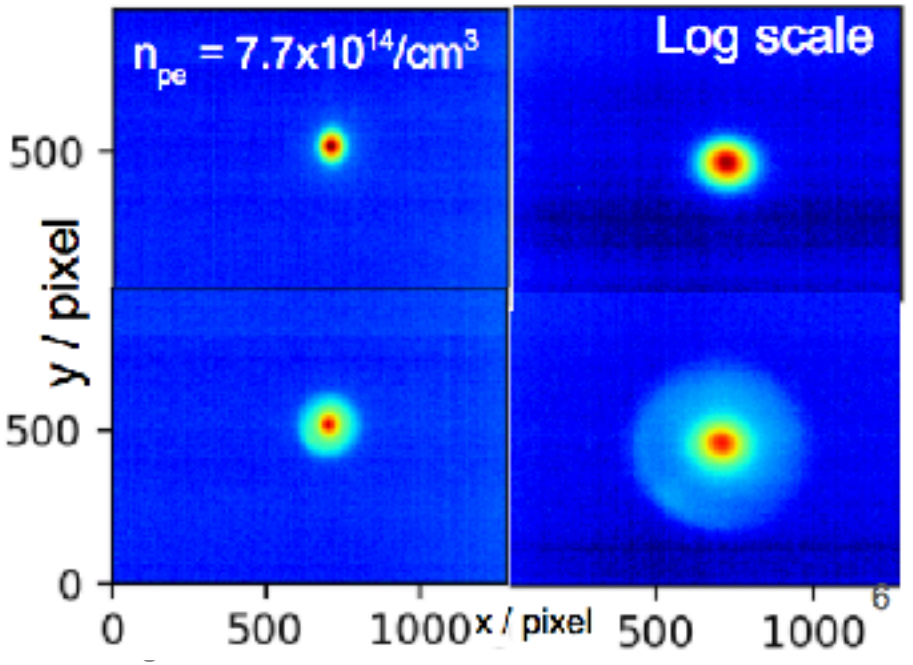
Tranverse Modulation - expanding proton bunches





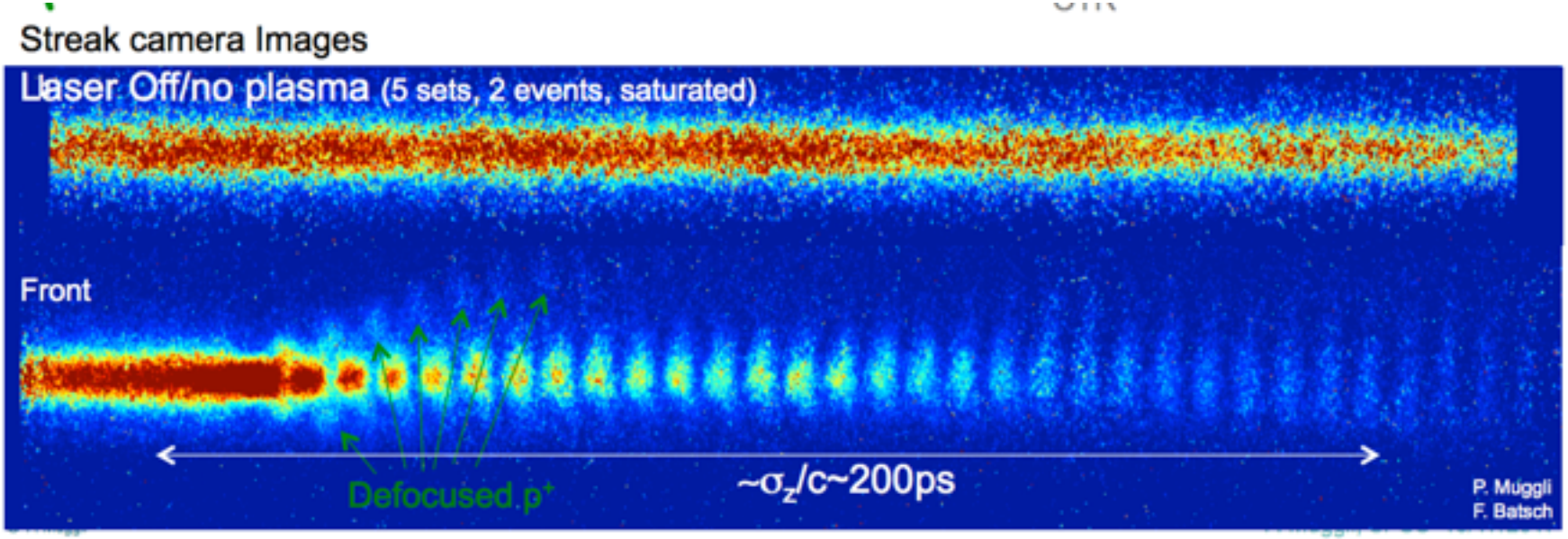
Plasma off:

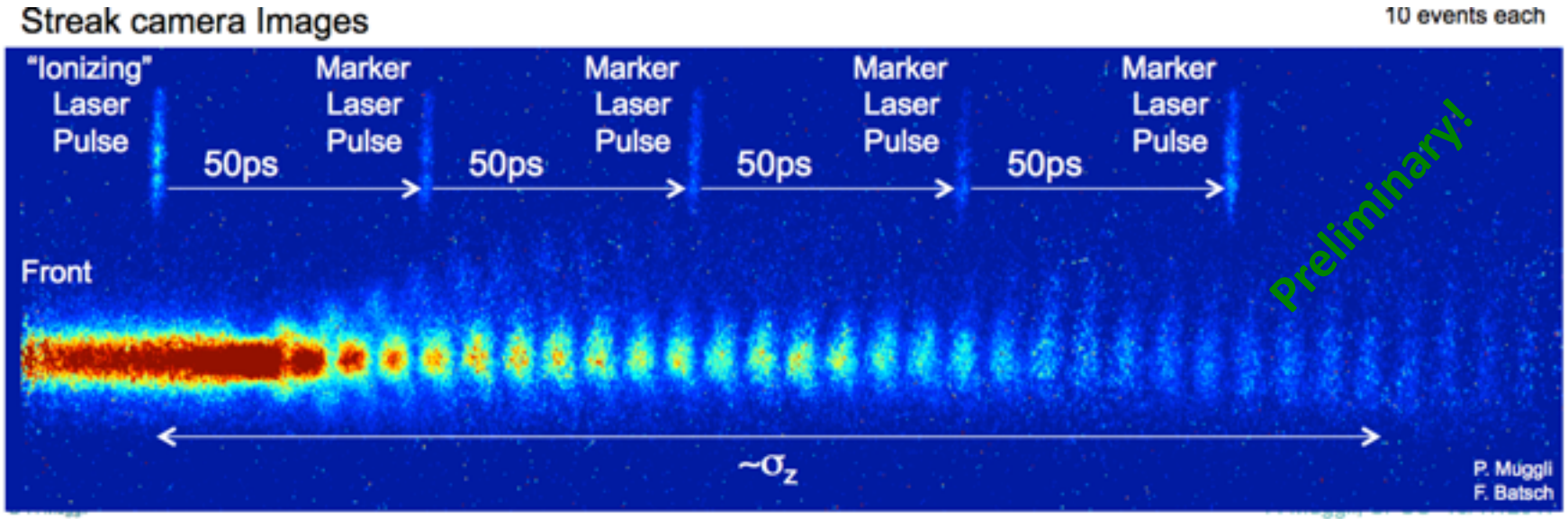
Plasma on:



M. Turner et al., (AWAKE Collaboration) PRL **122**, 054801 (2019)

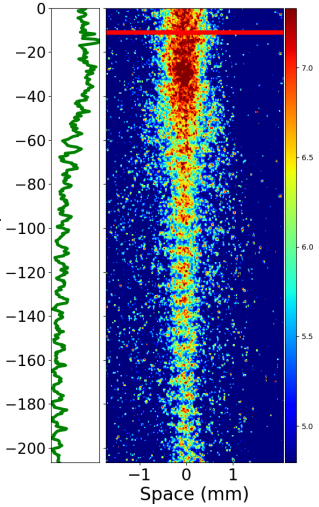
Observation of Seeded SMI



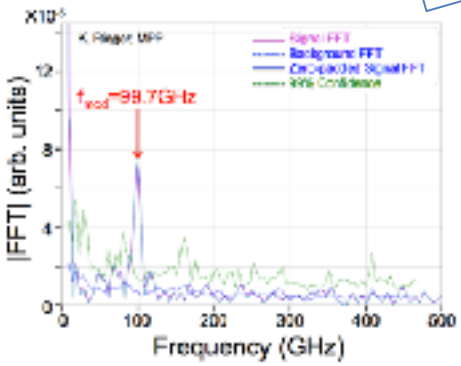


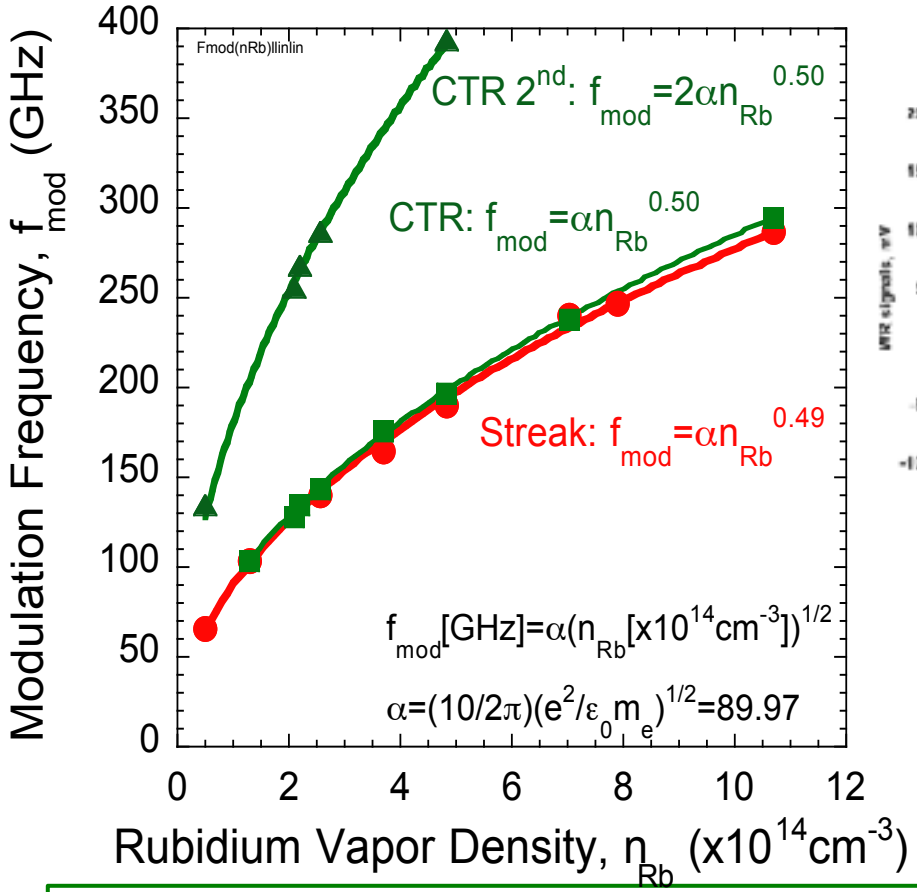
AWAKE

Modulation at the expected frequency

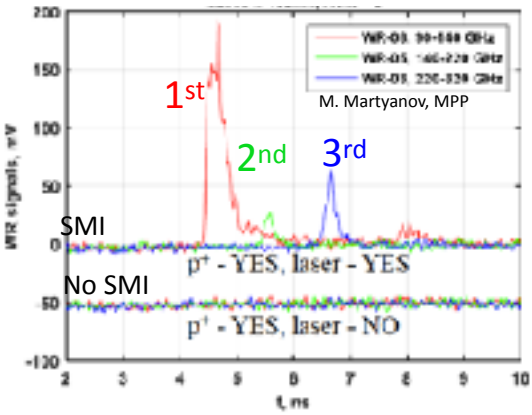


FFT





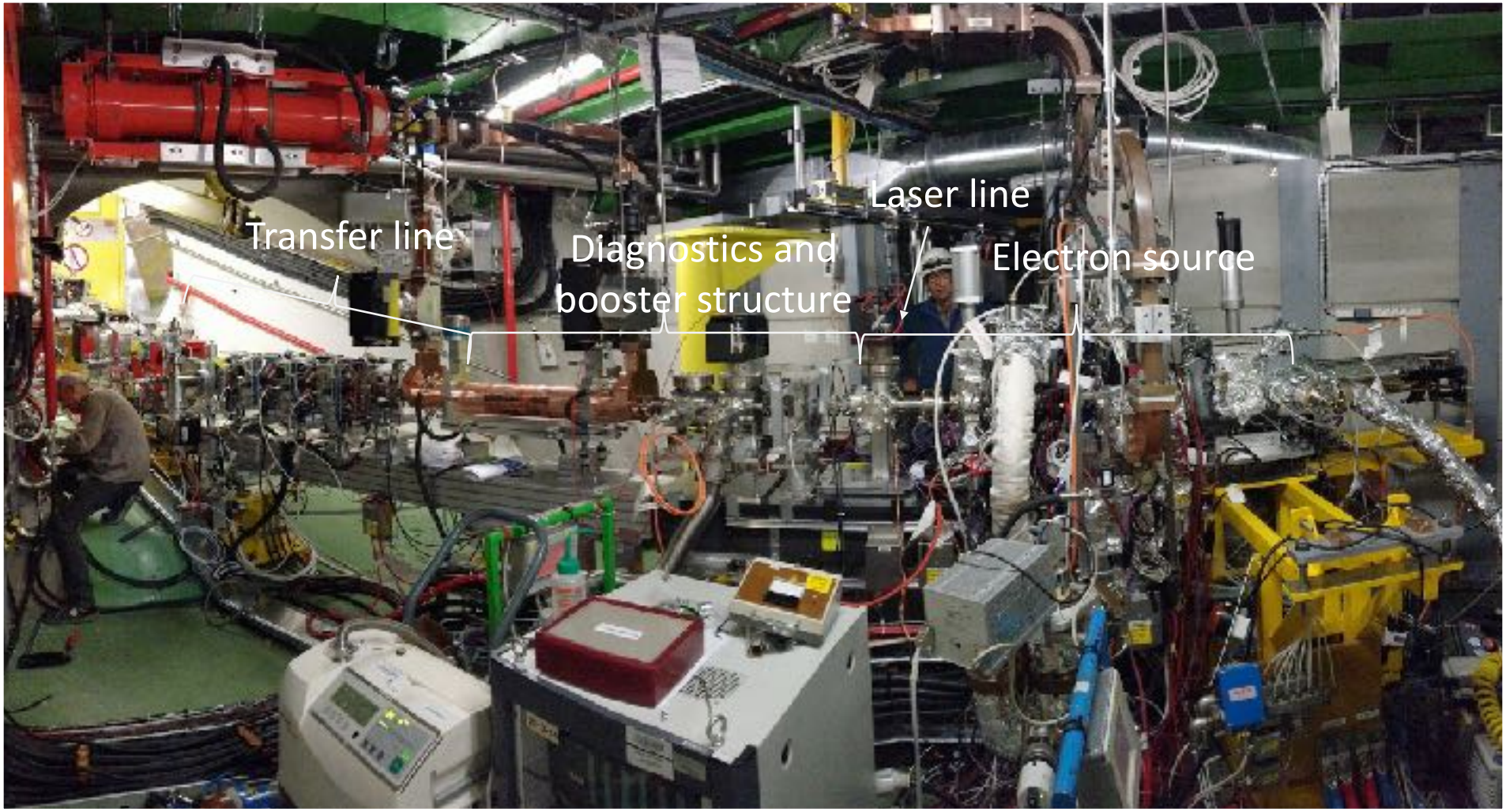
CTR



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

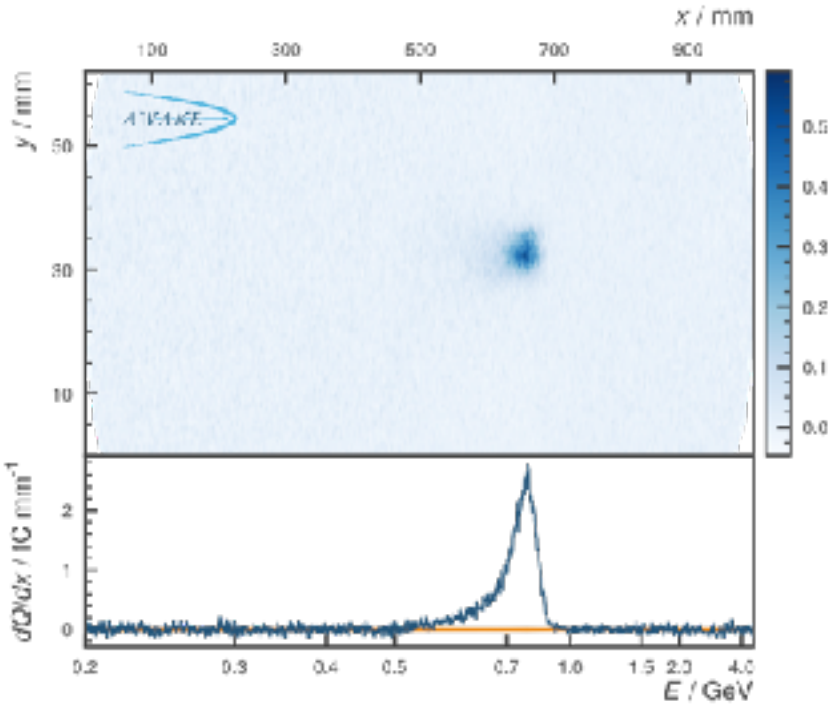
E. Adli et al.,(AWAKE Collaboration), PRL **122**, 054802 (2019)

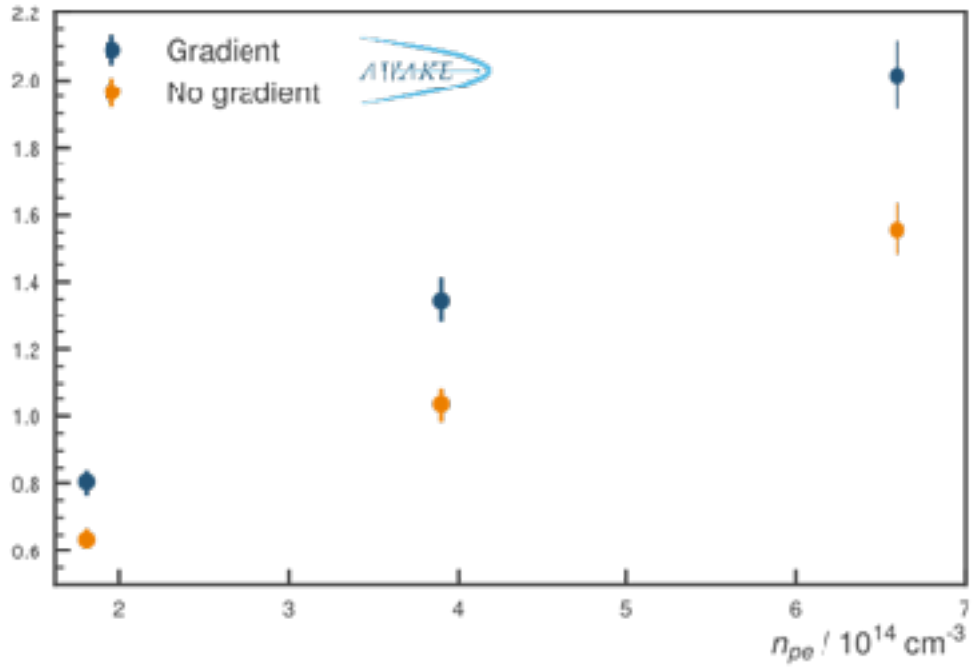
Electron Line



AWAKE

Electron Acceleration Results





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

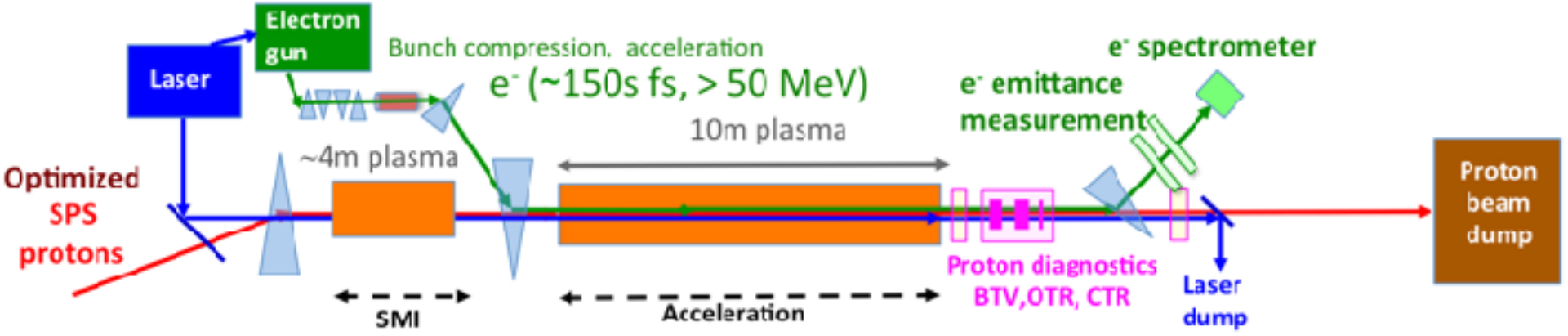
Electron acceleration in a proton-driven plasma wakefield works !

With todays existing proton bunches via seeded self-modulation!

Run II (2021-2024) - design study in preparation

Goals:

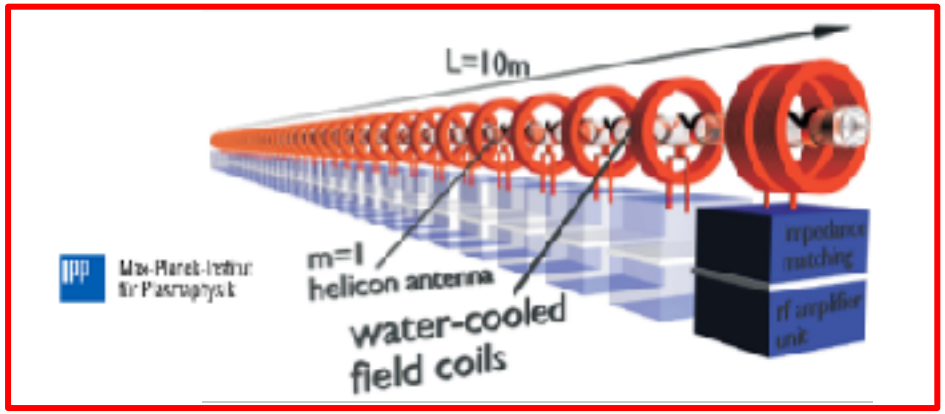
- stable acceleration of bunch of electrons with high gradients over long distances
- 'good' electron bunch emittance at plasma exit



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

O. Grülke, IPP
O. Schmitz, Wisconsin



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

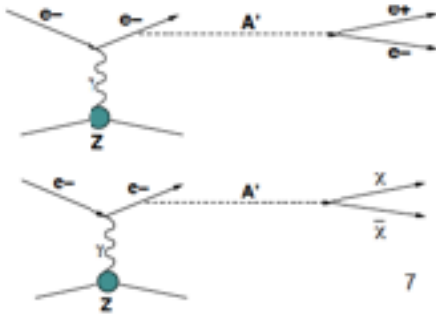
New energy regime means new physics sensitivity even at low luminosities !

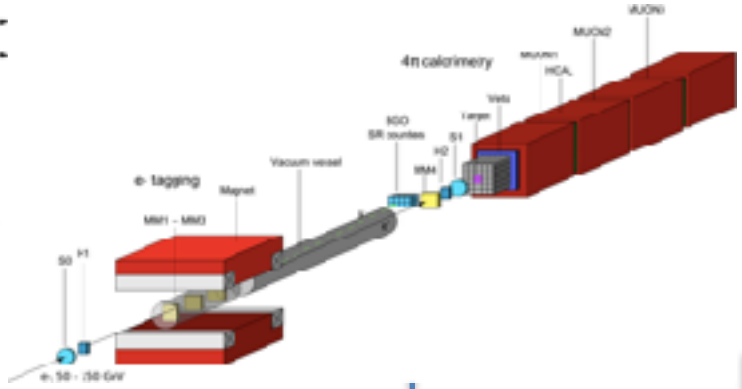
- **To be evaluated:**
  - AWAKE-like scheme with ions
  - acceleration of muons in LEMMA scheme
  - AWAKE-like scheme with FCC

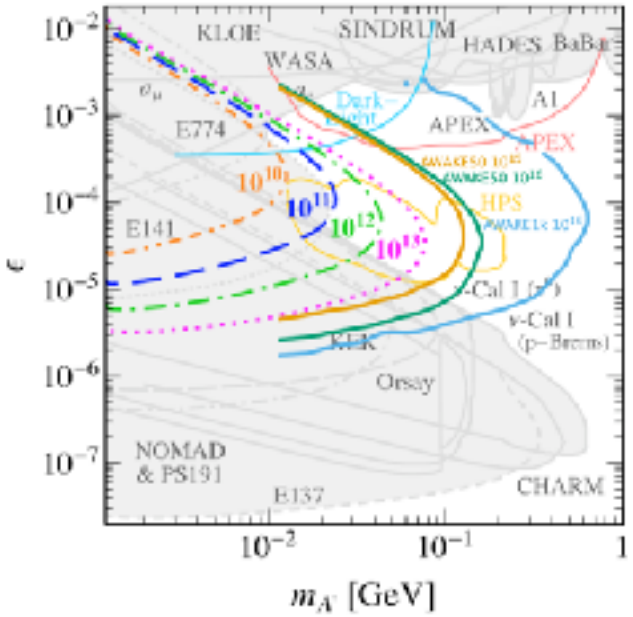
We have just started to evaluate the particle physics potential of plasma acceleration. Need creative thinking !

Dark Photon Search

NA64-like experiment with parameters that could become available with AWAKE-like acceleration of electrons using the SPS proton bunches

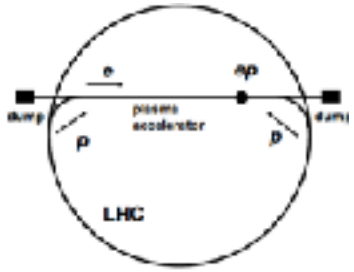


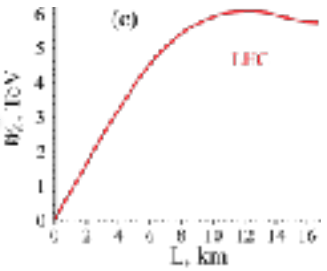




Fixed Target

LHC Driver





$$E_{\mathrm{CM}} = \sqrt{2M_P E_e} = 75\ \mathrm{GeV}$$

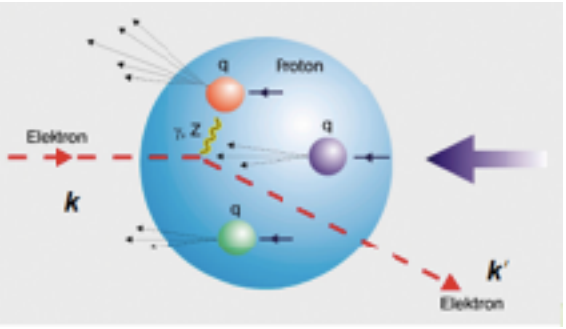
Compass: ~20 GeV

EIC: 15-140 GeV

n, UCL

Deep Inelastic Scattering

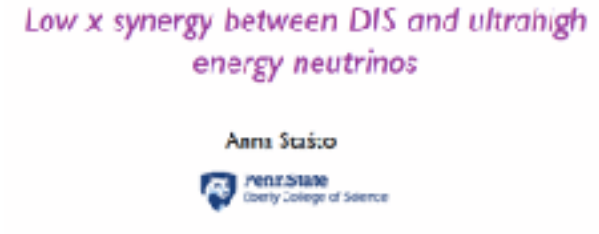
Topics: VHEeP Workshop, Munich 2017

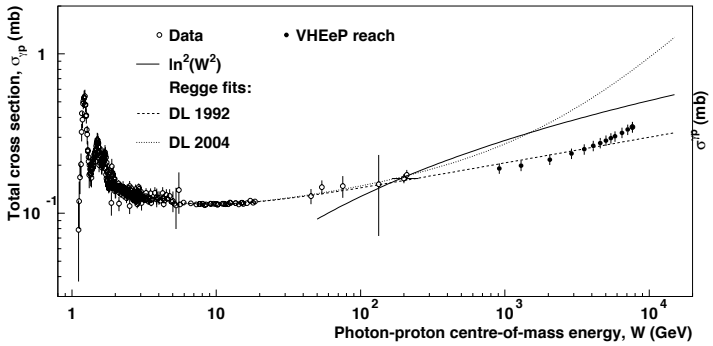


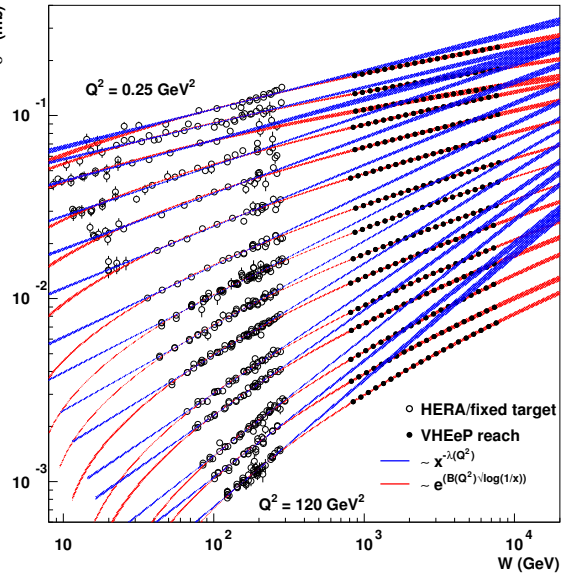
Focus on QCD:

- Large cross sections – low luminosity (HERA level) enough
- Many open physics questions !
- Matching proton beam sizes means normalized emittance 10-100 mm-mrad

real & virtual photon cross sections







protons grow with energy, similarly to black holes … connections between QCD & gravity ?

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 (done) and proton-driven acceleration of electrons before LS2 of the LHC (done).

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.