Horizons …

Allen Caldwell
Max-Planck-Institut für Physik

ICTS Workshop - November 16, 2022

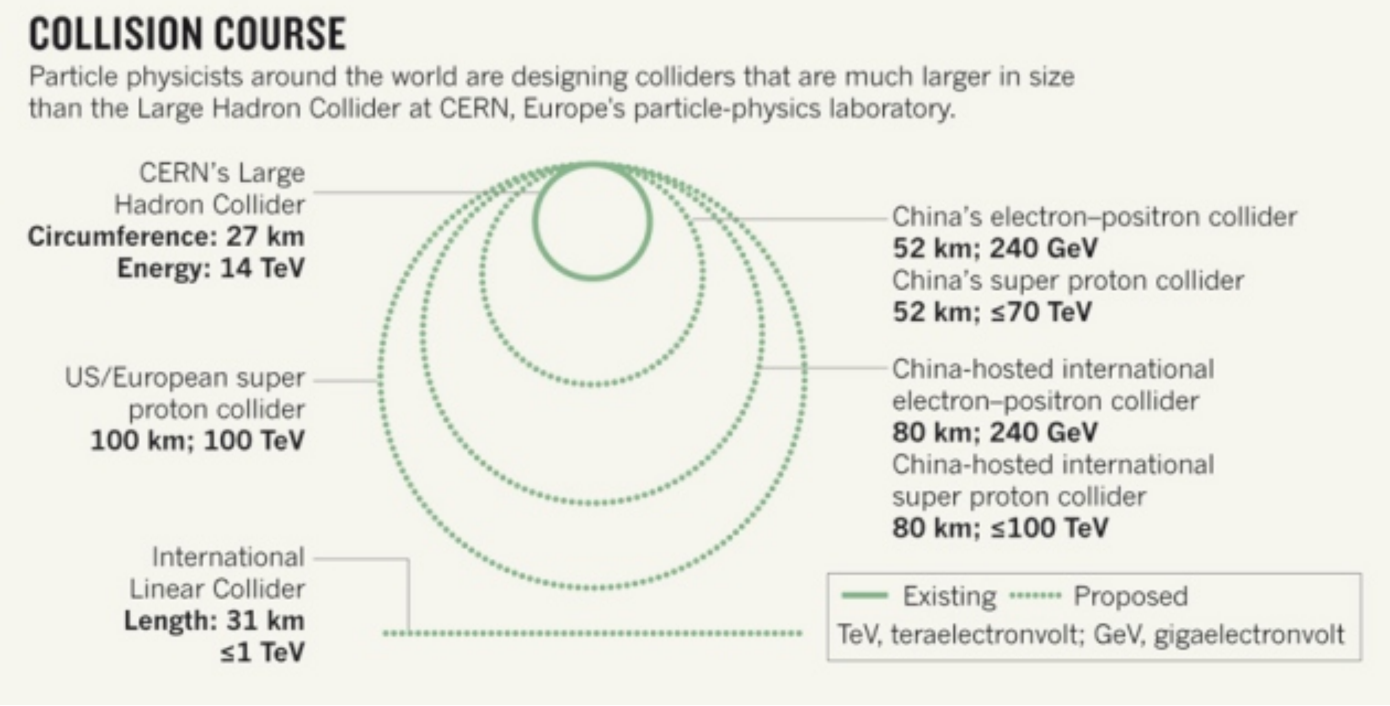
Even larger Accelerators ?

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.

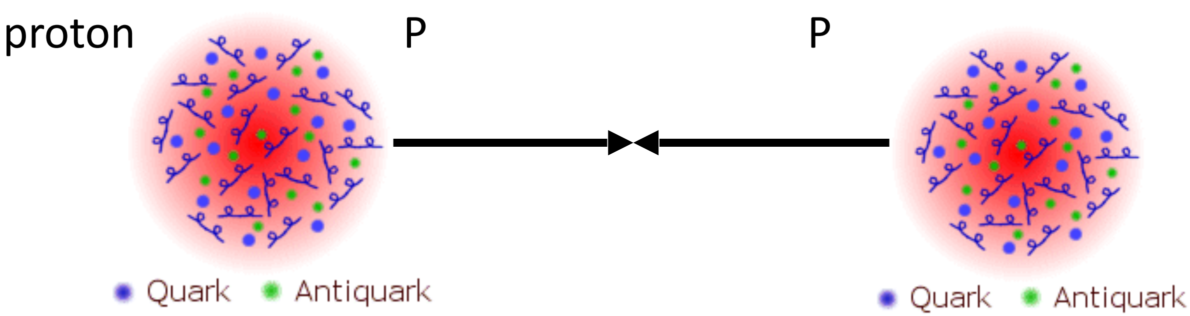
Energy limit of circular proton collider given by magnetic field strength.

$$P \propto B \cdot R$$

Energy gain relies in large part on magnet development



Linear Electron Collider or Muon Collider?

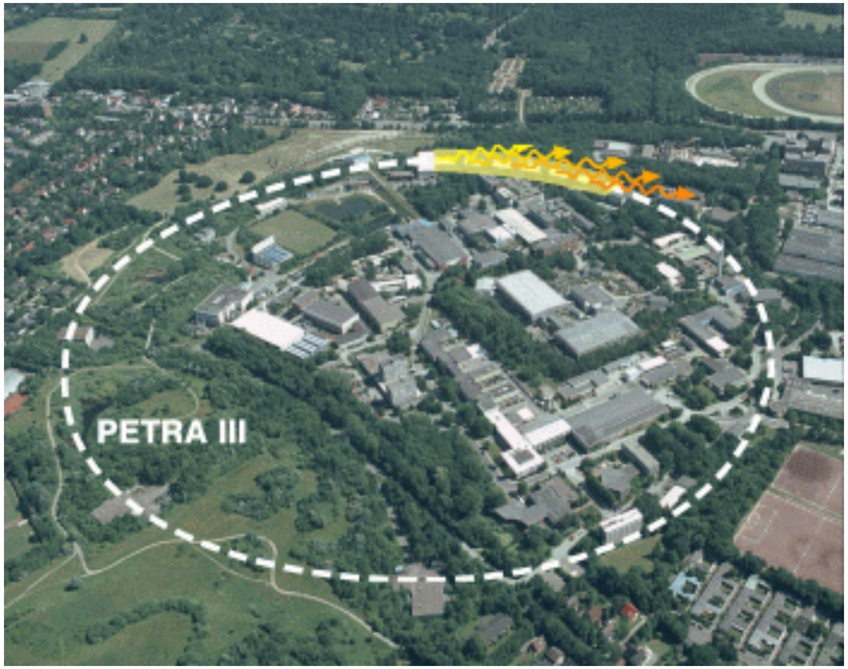


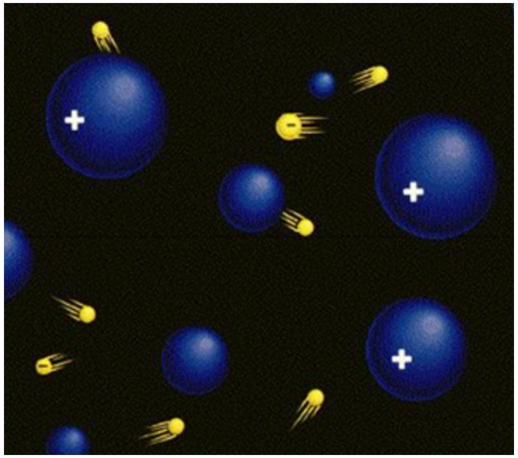
Leptons preferred: Collide point particles rather than complex objects

But, charged particles radiate energy when accelerated.

Power α $(E/m)^4$

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

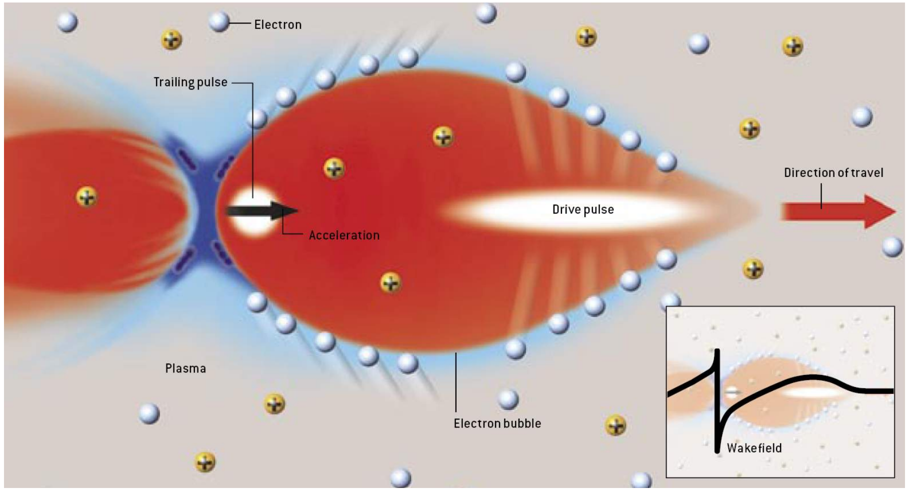




A plasma: collection of free positive and negative charges (ions and electrons). Material is already broken down. A plasma can therefore **sustain very high fields.**

E. Adli, Oslo

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:

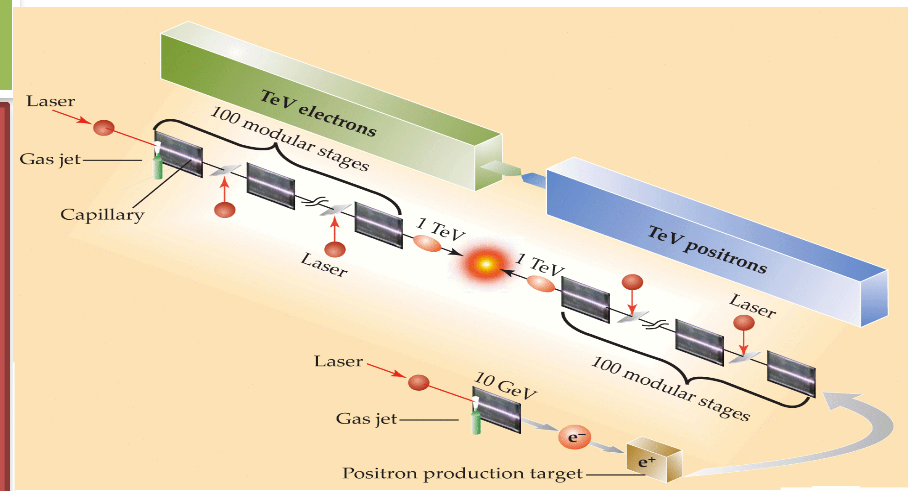
PW lasers today, ~40 J/Pulse

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

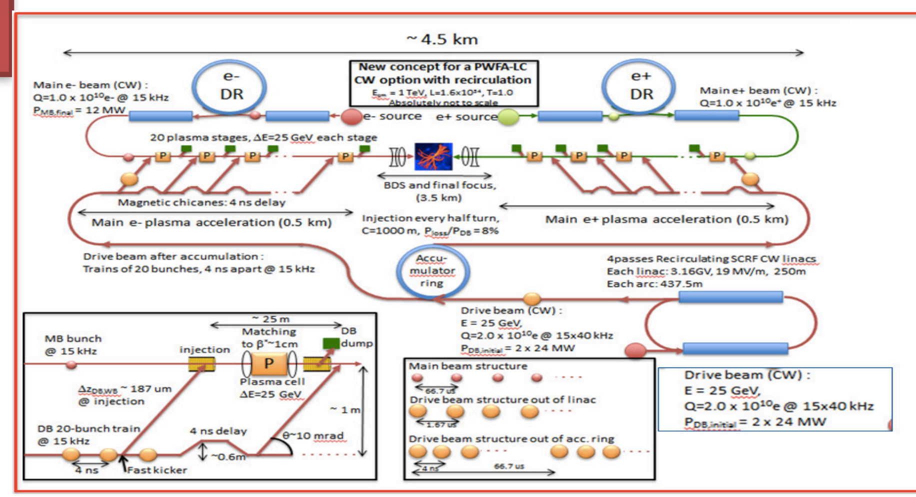
SPS@CERN 20kJ/bunch

LHC@CERN 300 kJ/bunch

Staging Concepts



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



E. Adli et al. arXiv:1308.1145,2013

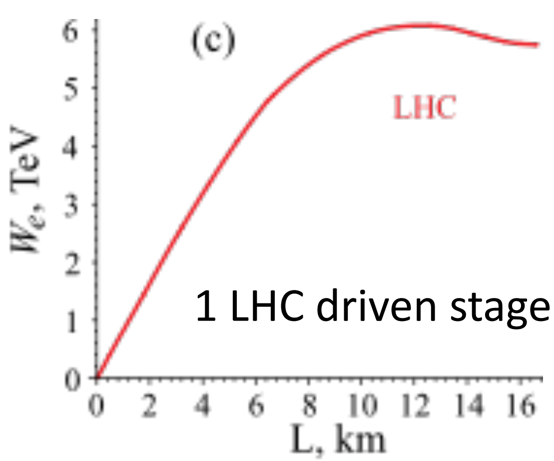
Dephasing

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

SPS: ~100m,

LHC: ~few km

FCC: ~ ∞



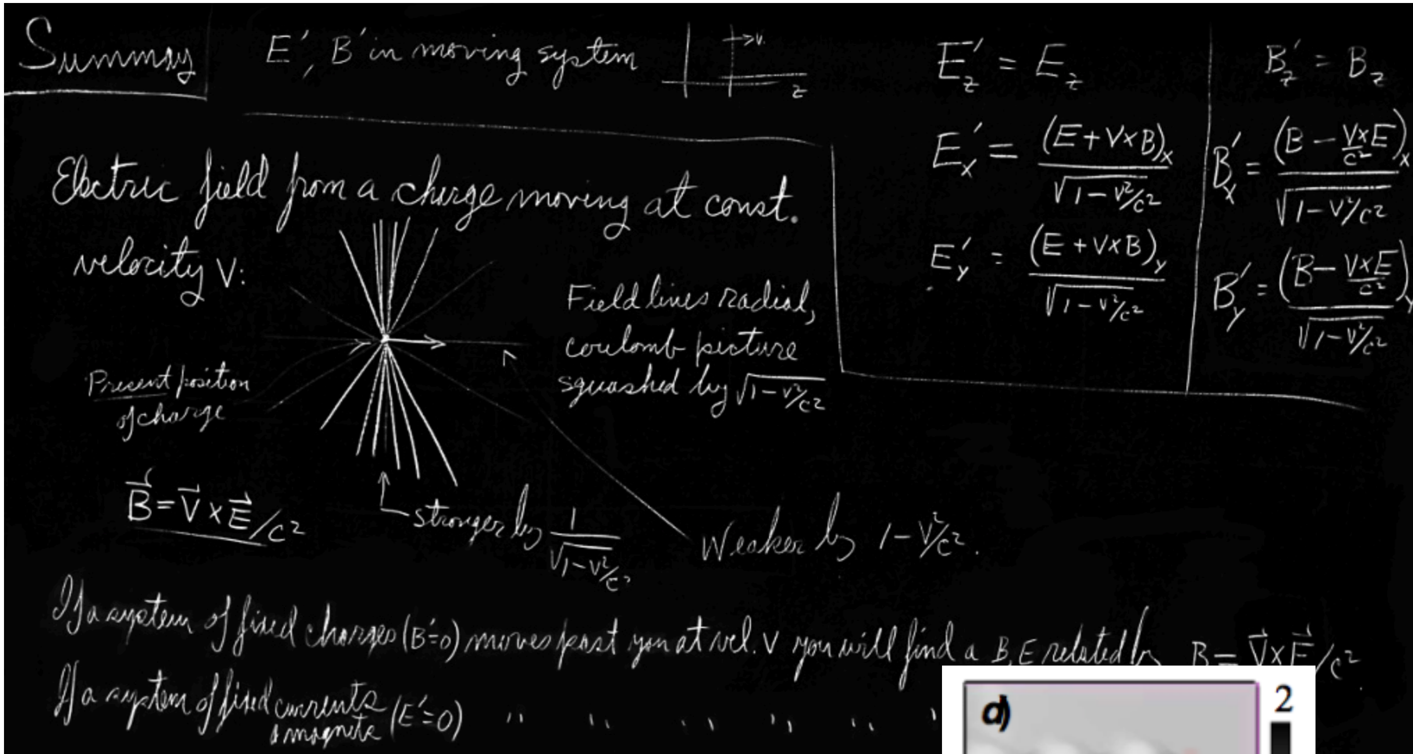
1 LHC driven stage

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

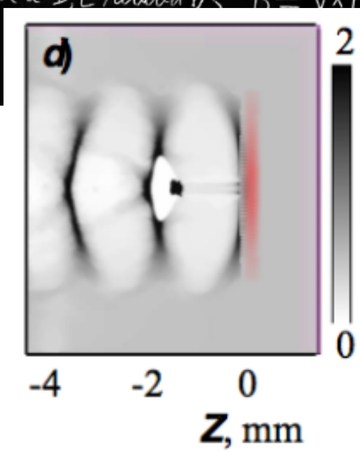
Basic Aspects

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

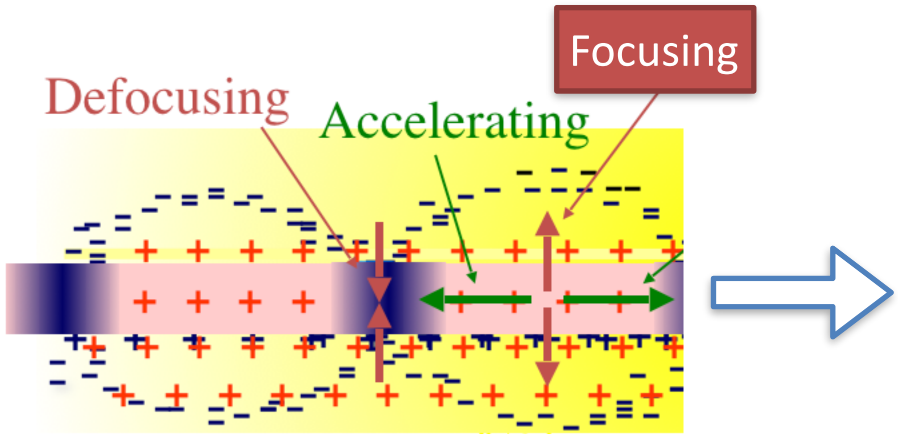


Figure: Patric Muggli

Proton

Electron

Do the electrons outrun the protons ?

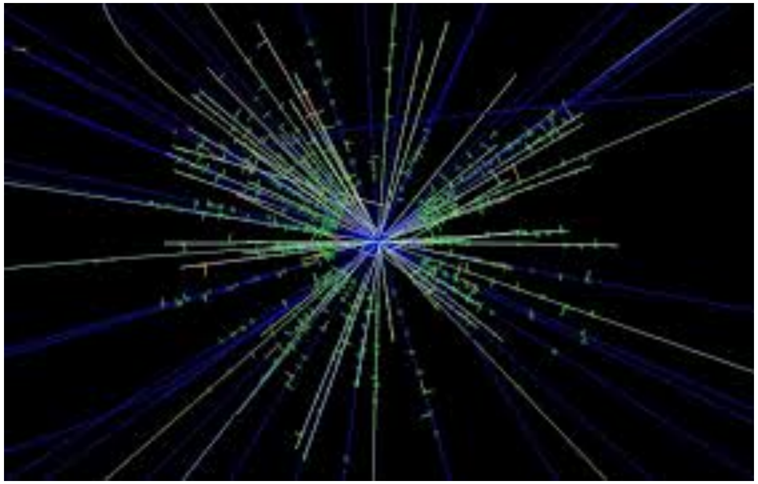
$$\delta \approx \frac{\pi L}{\lambda_p} \frac{1}{\gamma^2}$$

Phase slippage (protons 2000 times heavier than electrons) ?

Basic Aspects

Proton (QCD) interactions ?

LHCb event display



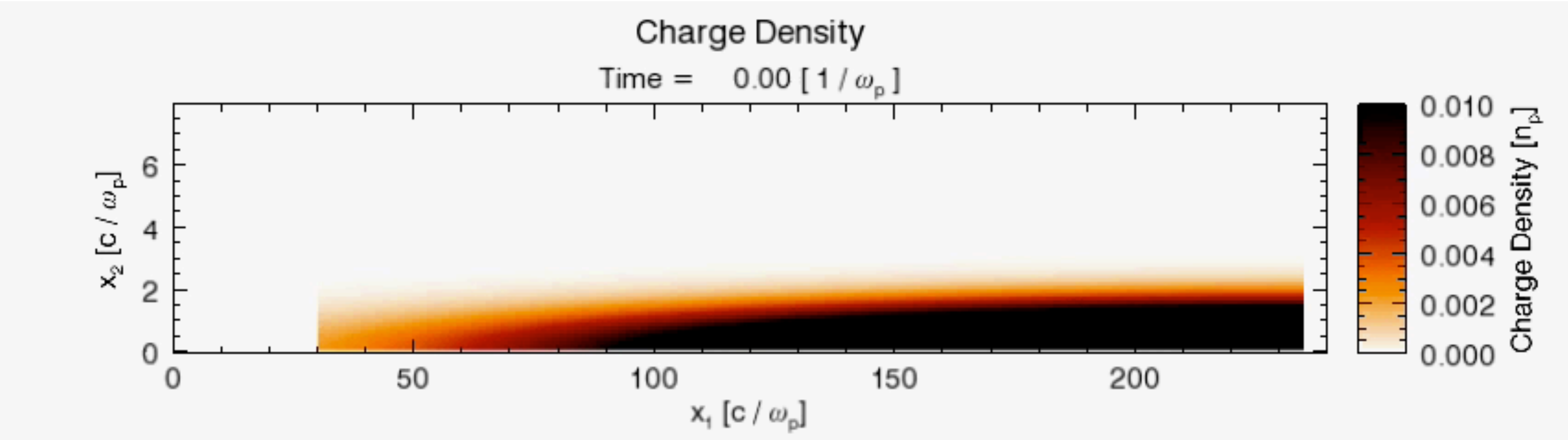
$$\lambda = \frac{1}{n\sigma} \quad n = 1 \cdot 10^{15}\ \mathrm{cm}^{-3} \quad \Rightarrow \lambda > 1000\ \mathrm{km}$$

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.

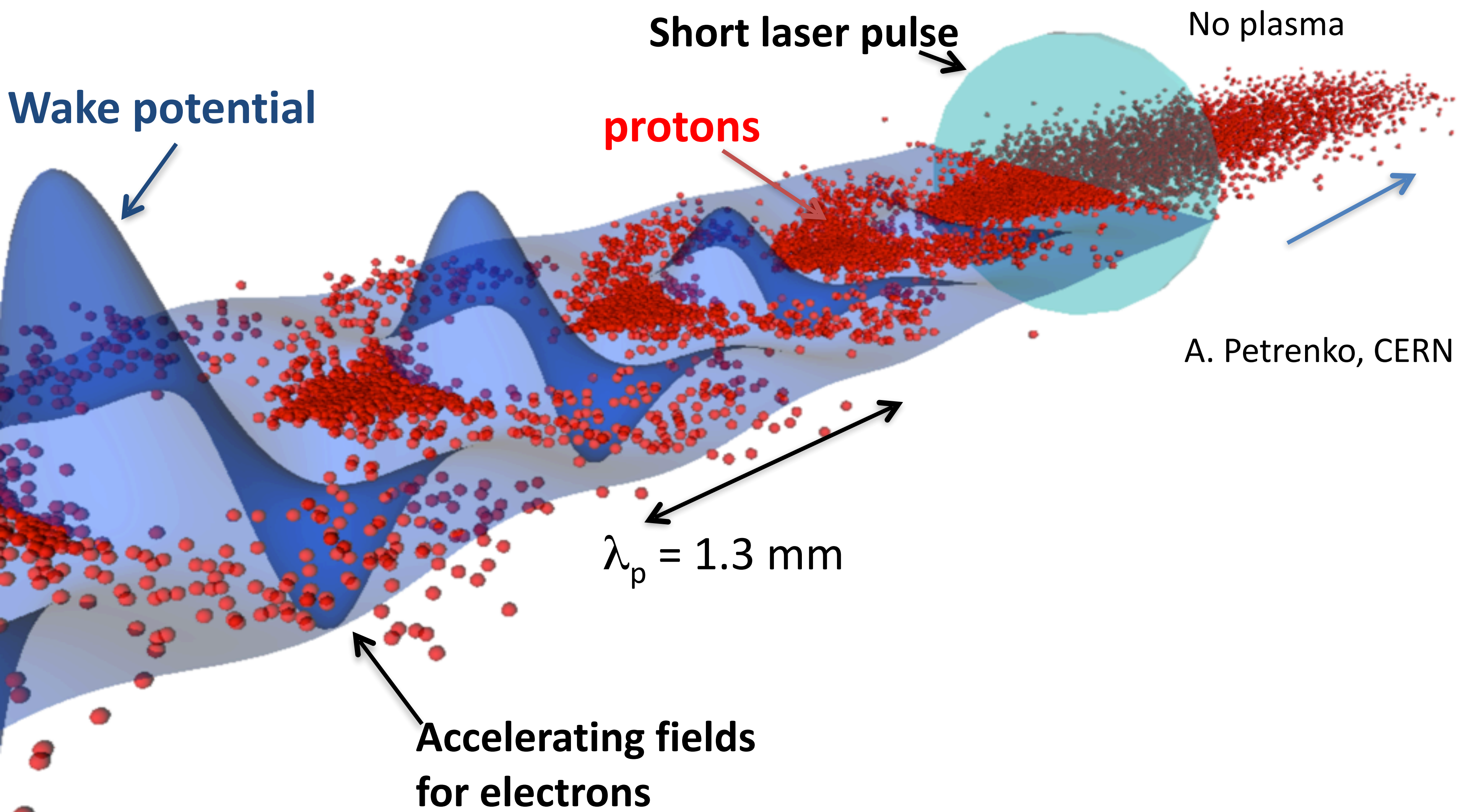
N. Kumar, A. Pukhov, and K. V. Lotov, Phys. Rev. Lett. **104**, 255003 (2010)



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

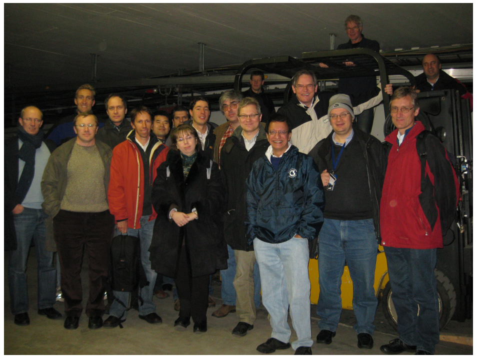
Seeded self-modulation

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



History

2009 driven

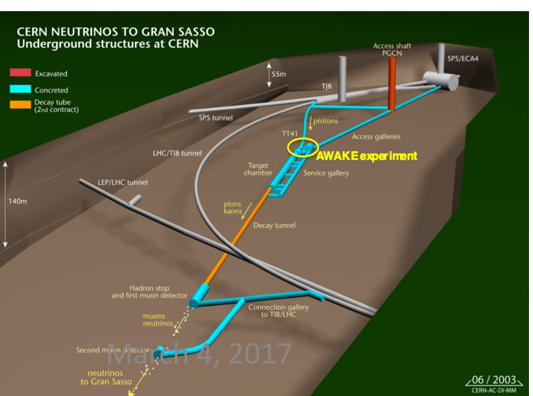


First workshop at CERN to discuss potential of proton-driven PWA.

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

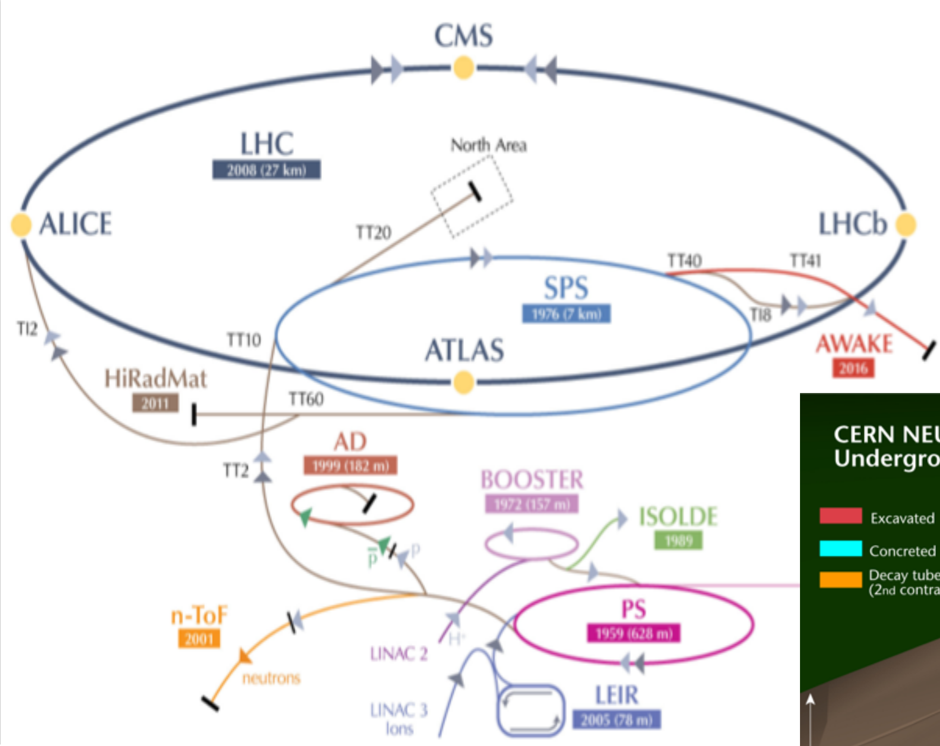
AWAKE Collaboration: 22 Institutes world-wide:

- 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

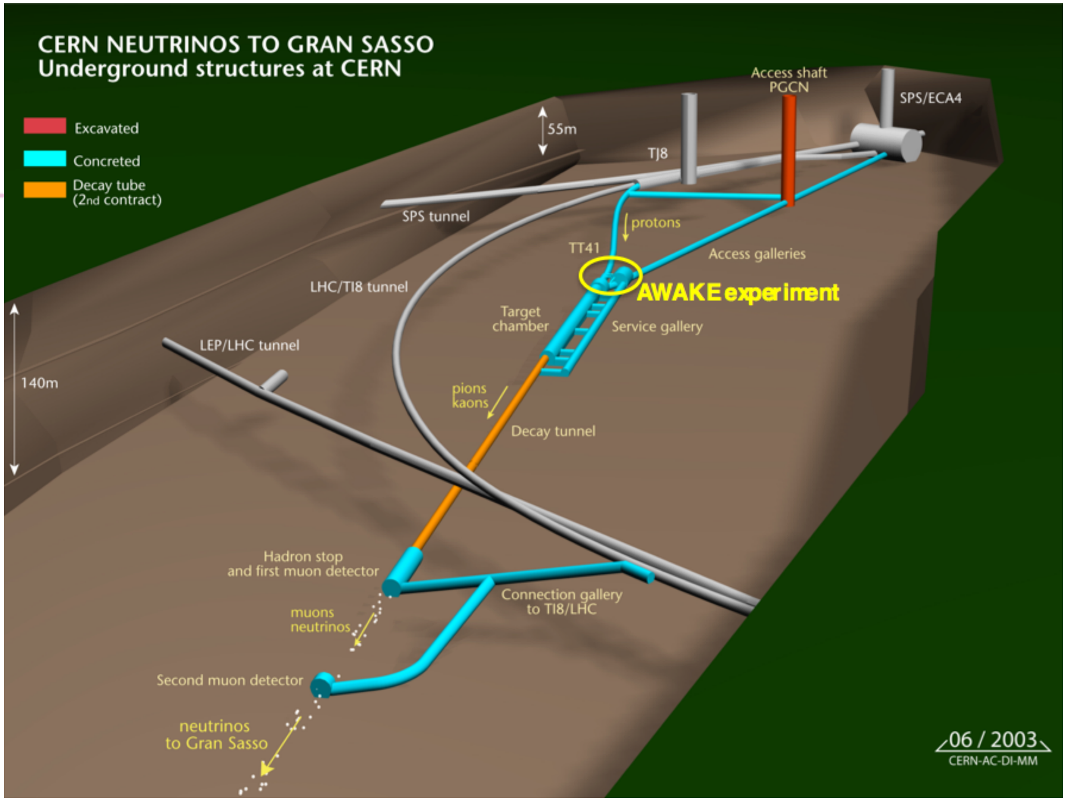
AWAKE at CERN



AWAKE is installed in

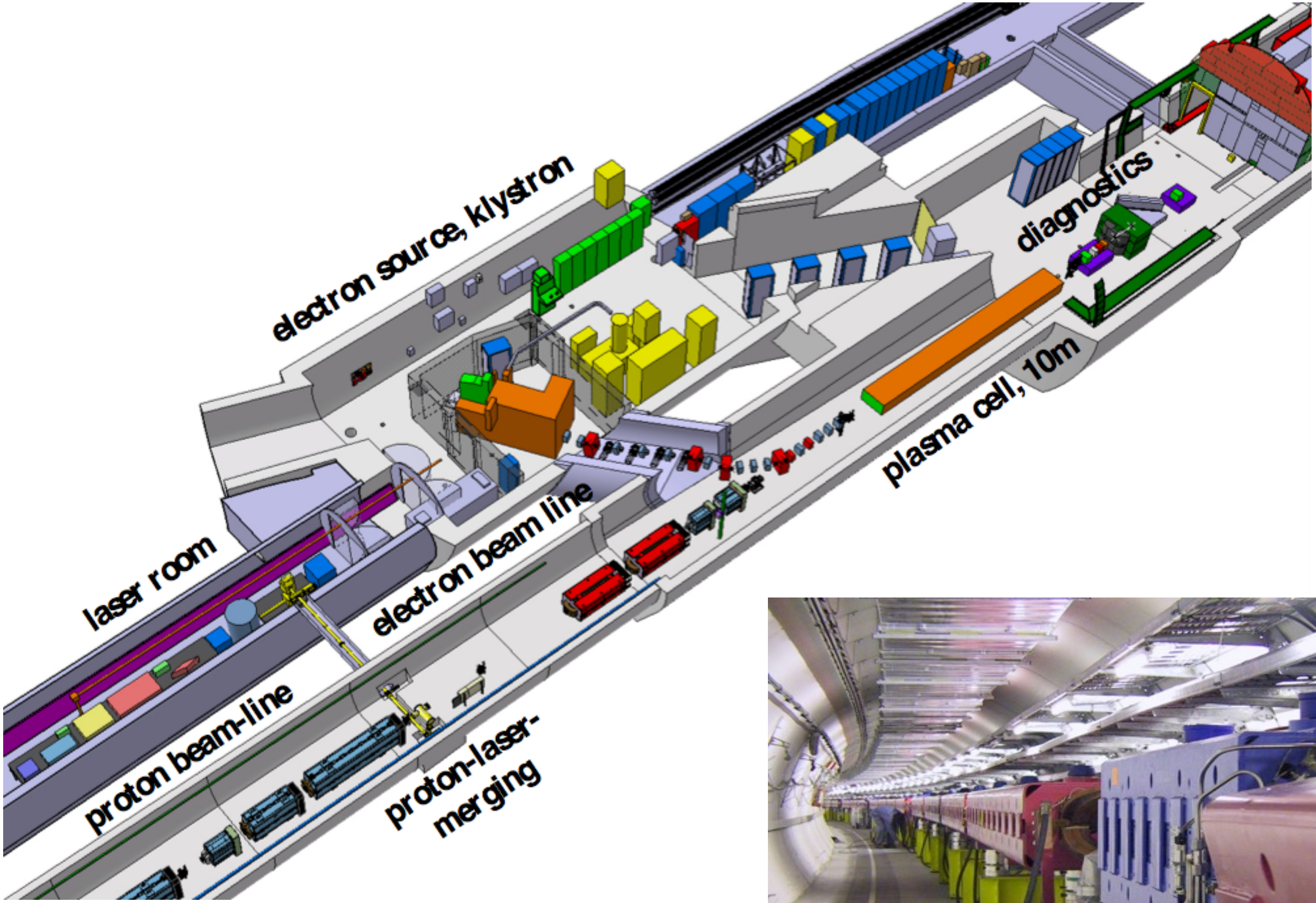
CNGS Facility (CERN Neutrinos to Gran Sasso)

→ 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).

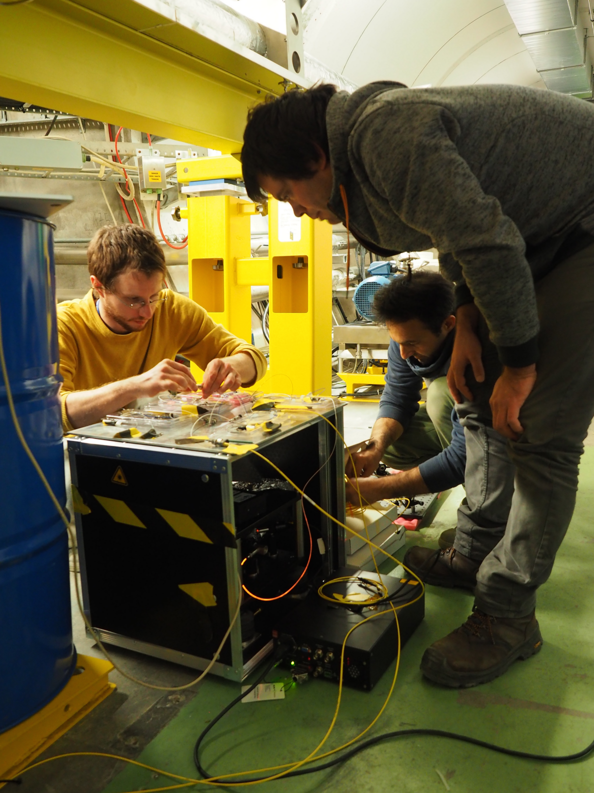
AWAKE Overview



AWAKE Overview

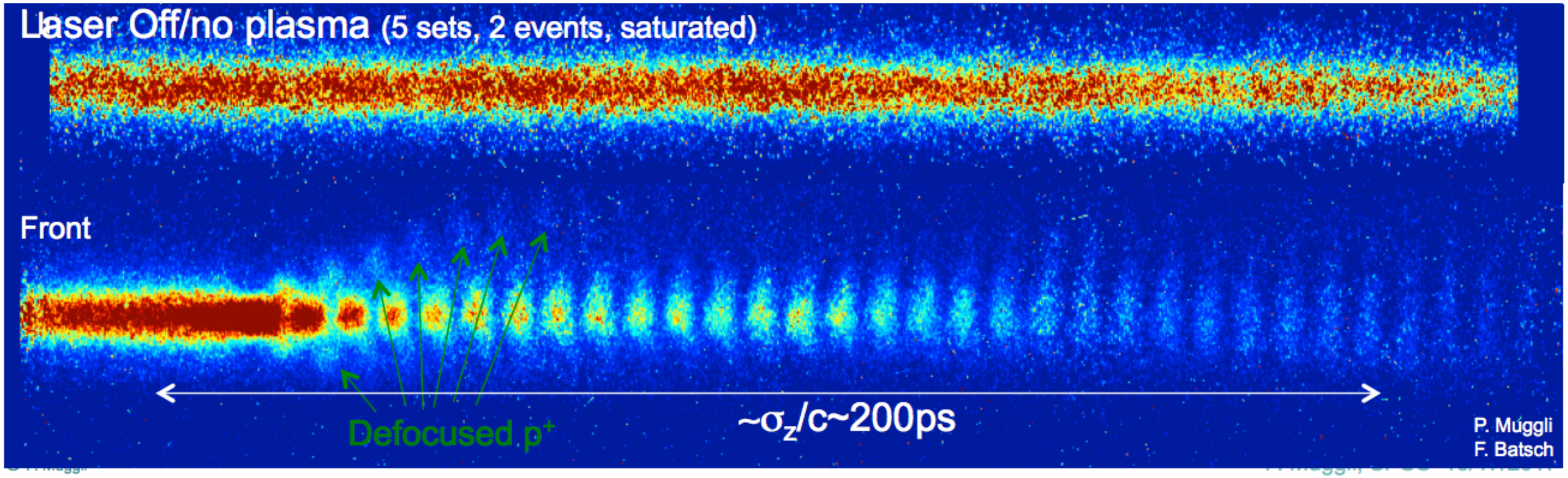
First Run

December 9-12, 2016



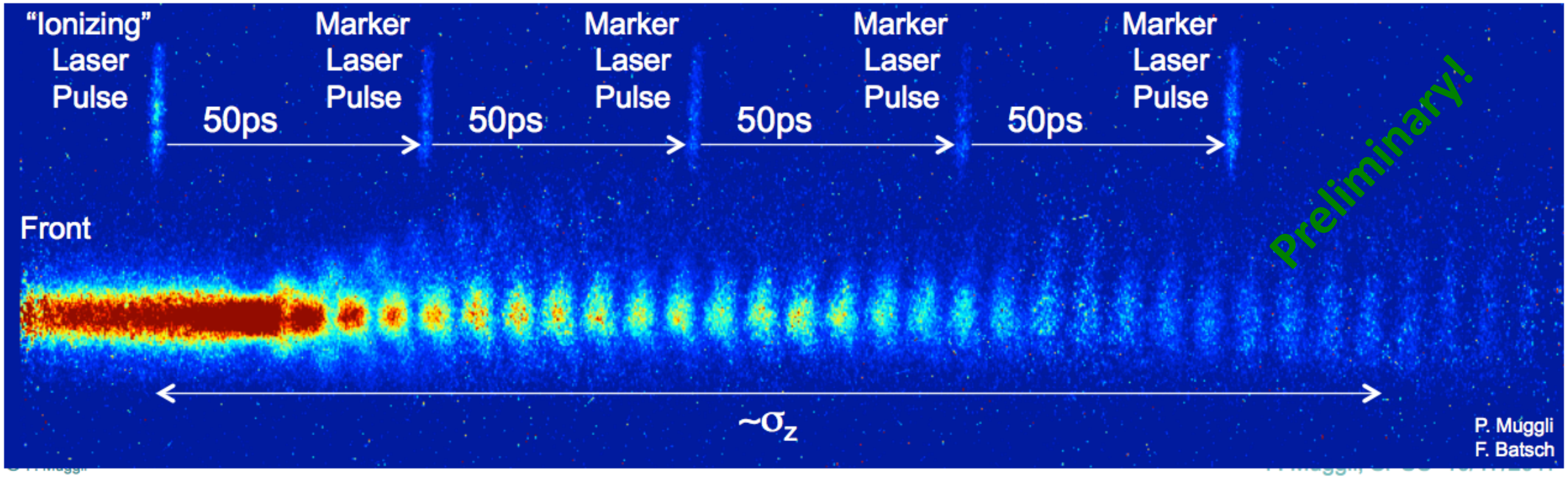
Observation of Seeded SMI

Streak camera Images



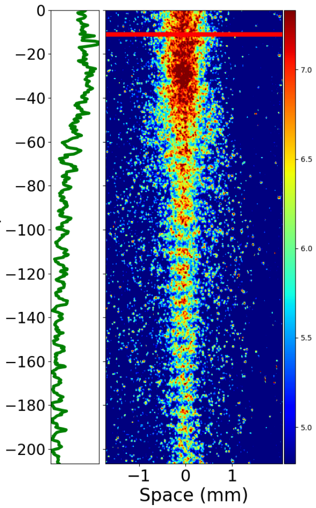
Streak camera Images

10 events each

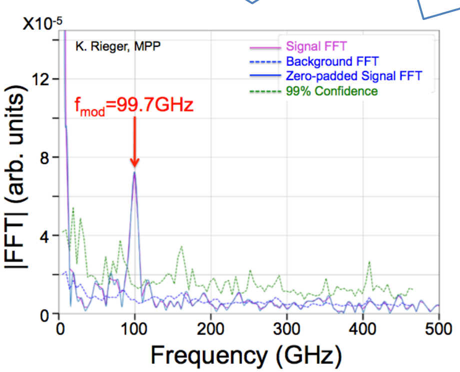


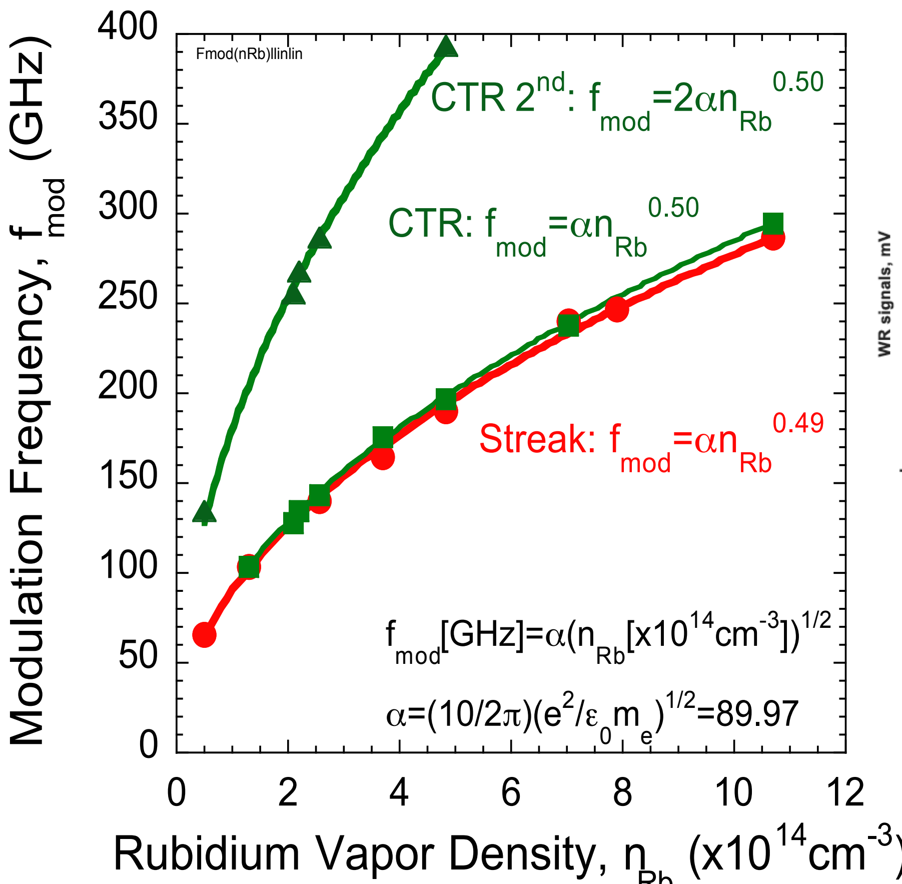
AWAKE

Modulation at the expected frequency

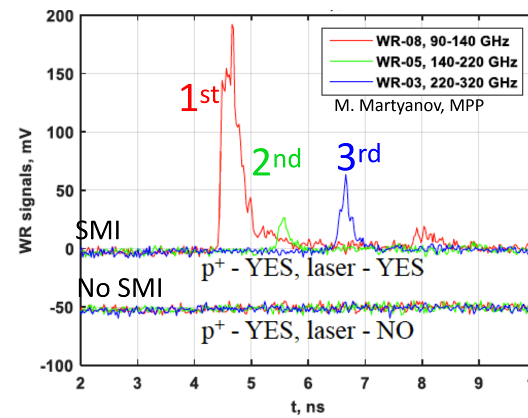


FFT





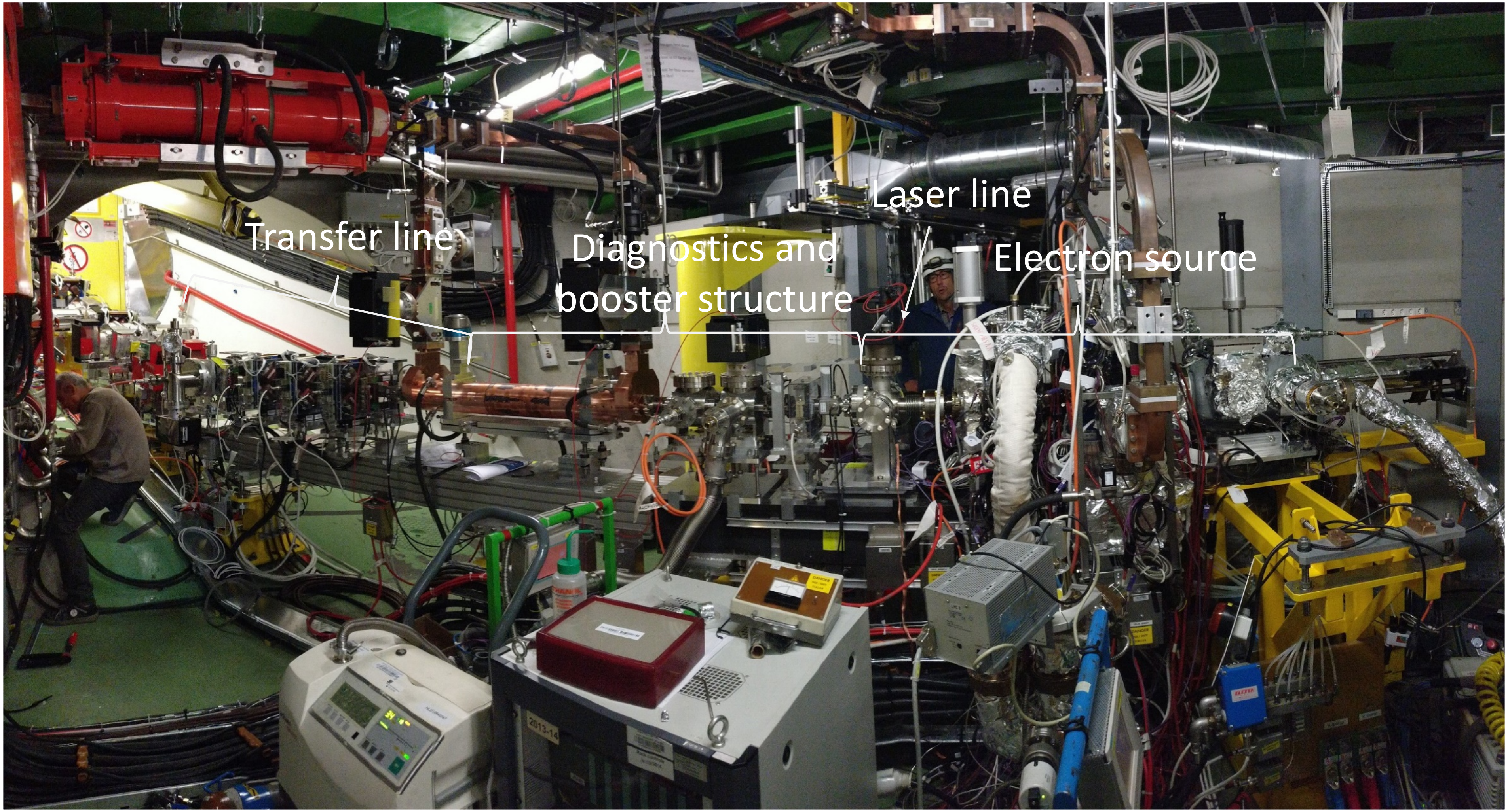
CTR



→ 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)

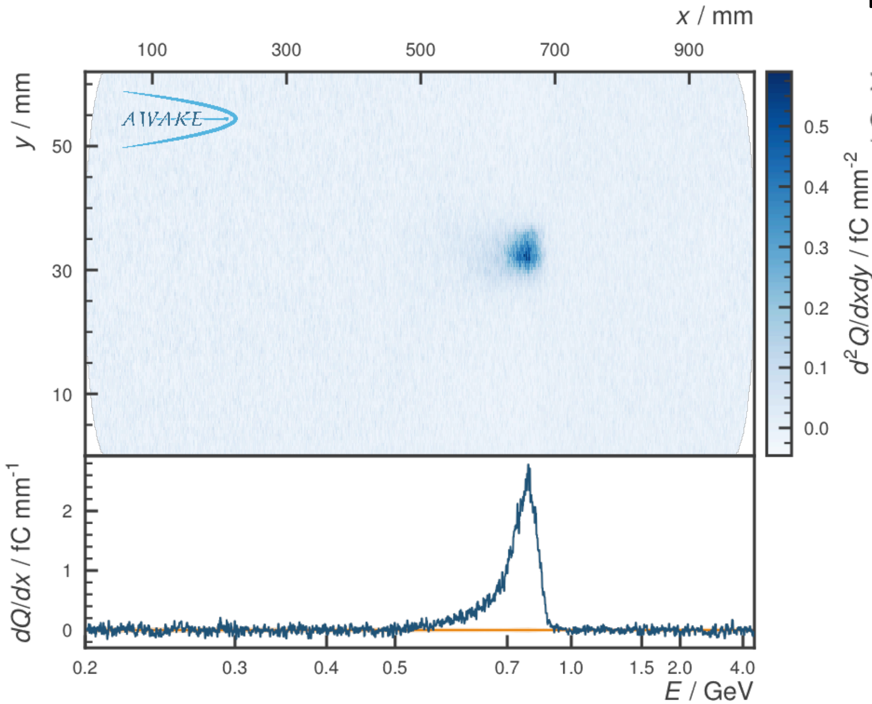
Electron Line

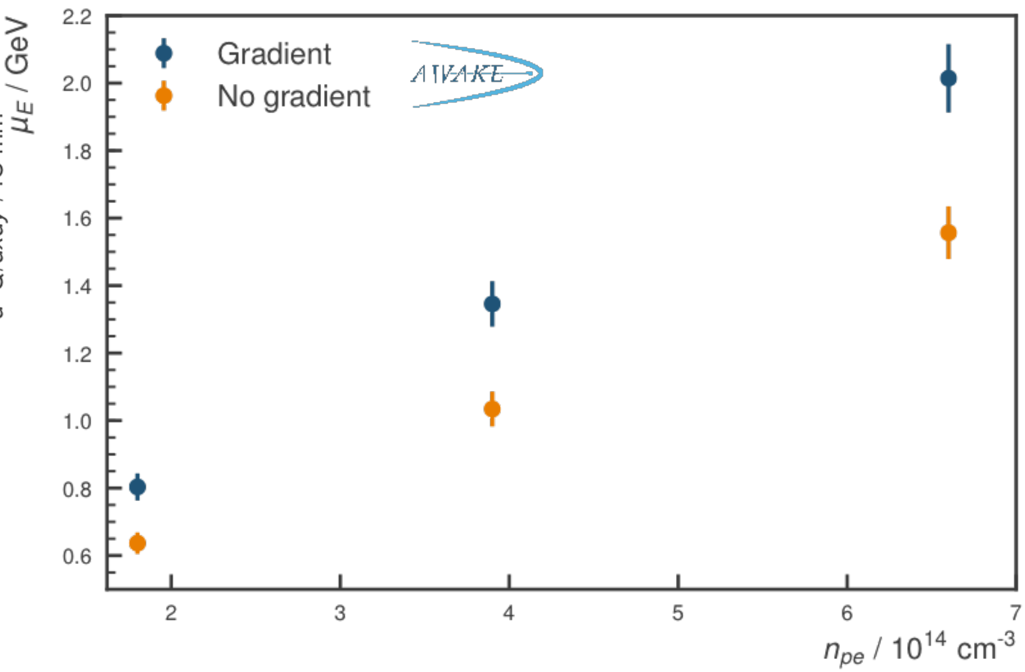


AWAKE

Electron Acceleration Results

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





Electron acceleration in a proton-driven plasma wakefield works !

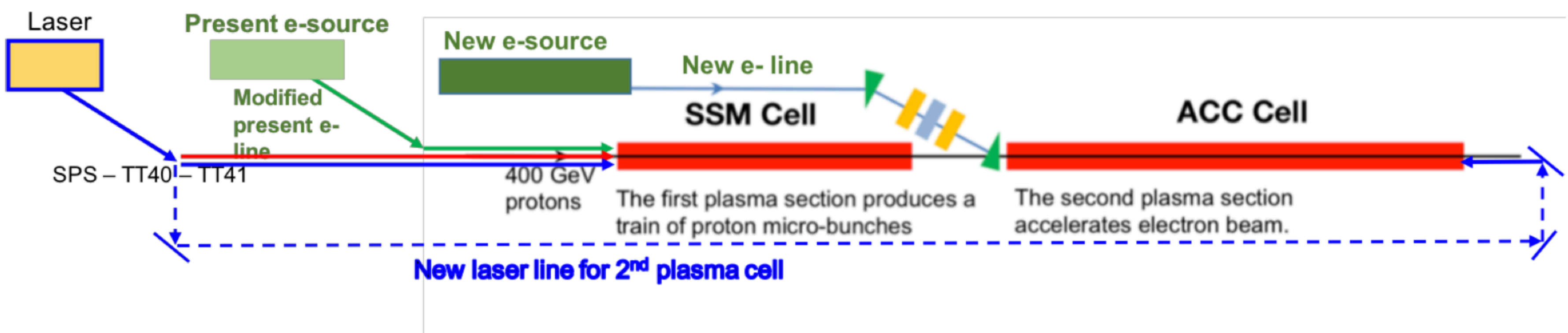
With todays existing proton bunches via seeded self-modulation!

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



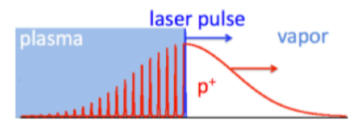
Four phases:
- seeding the SSM with an electron bunch
- plasma cell with density step to freeze the modulation structure
- inject electrons & accelerate without emittance blowup
- implement scalable plasma cell technologies

Run 2a

LASER

Seeding with electrons allows to use the full proton bunch (with laser seeding, need to seed inside the proton bunch).

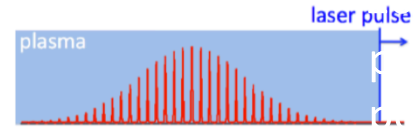
"Seeding":



SSM

Avoids possible complication with instability developing in unmodulated region.

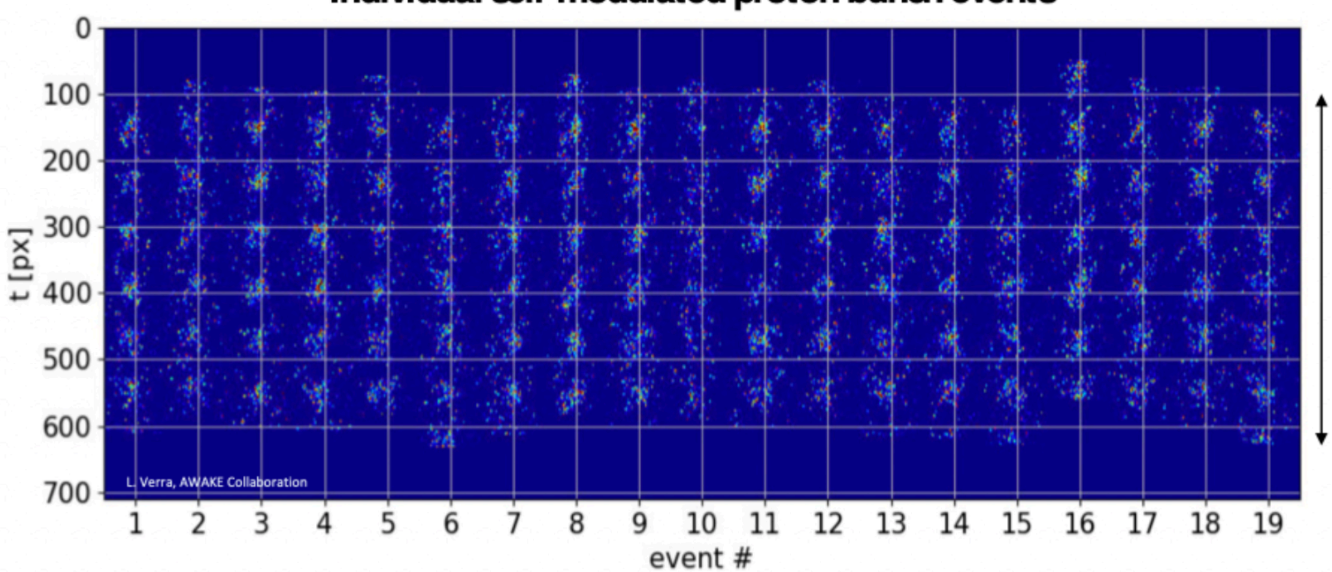
"No seeding":



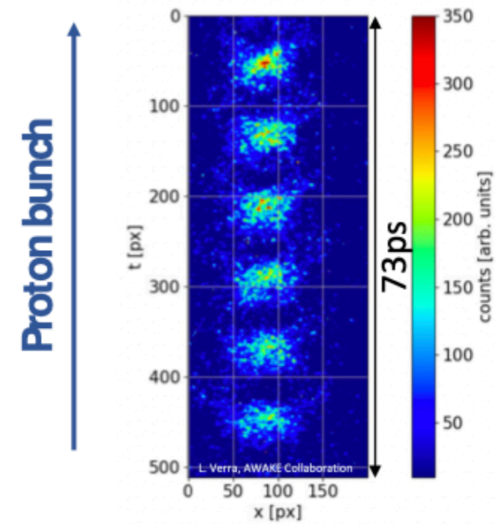
SMI

Electron bunch

Individual self-modulated proton bunch events



Summed events (19)

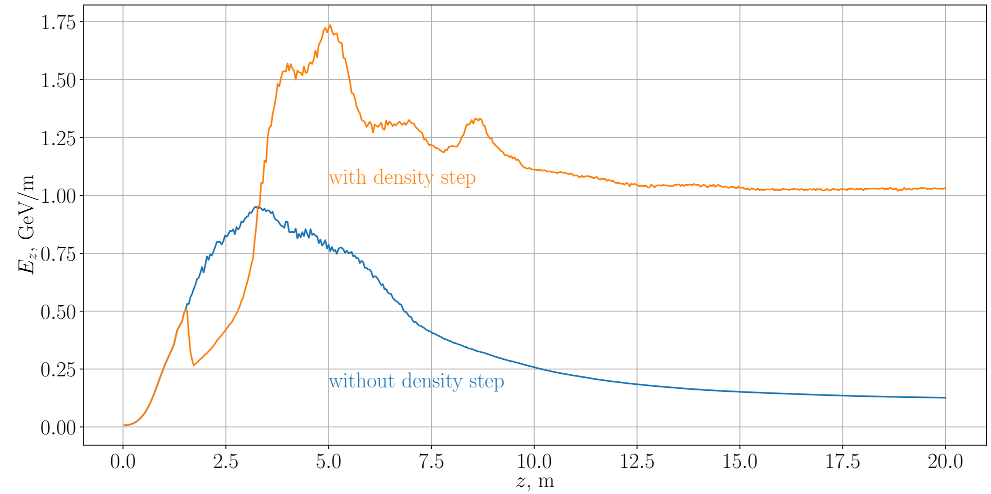


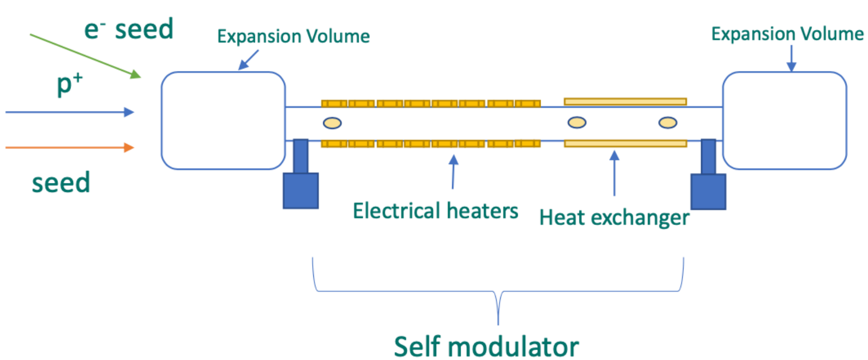
It works! 2022 will be used to study in detail under different parameter regimes + many other important studies (hosing, …)

Run 2b

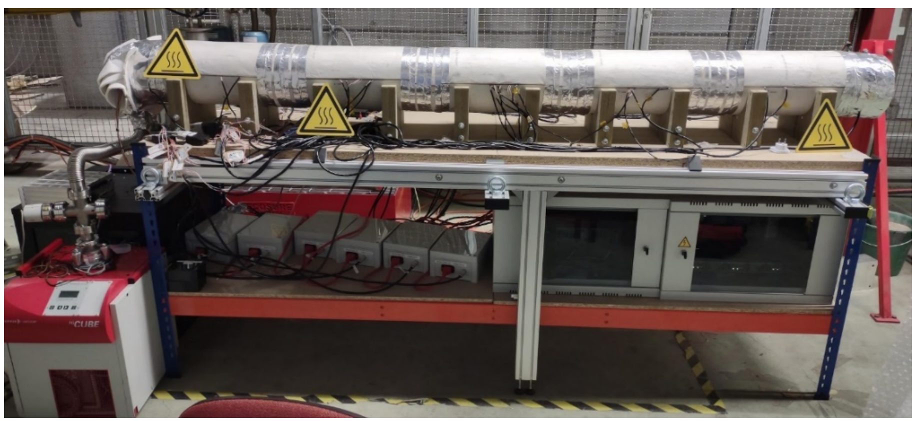
Density step in the plasma will allow us to keep strong accelerating fields over long distances

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





Prototype: electrically heated sections

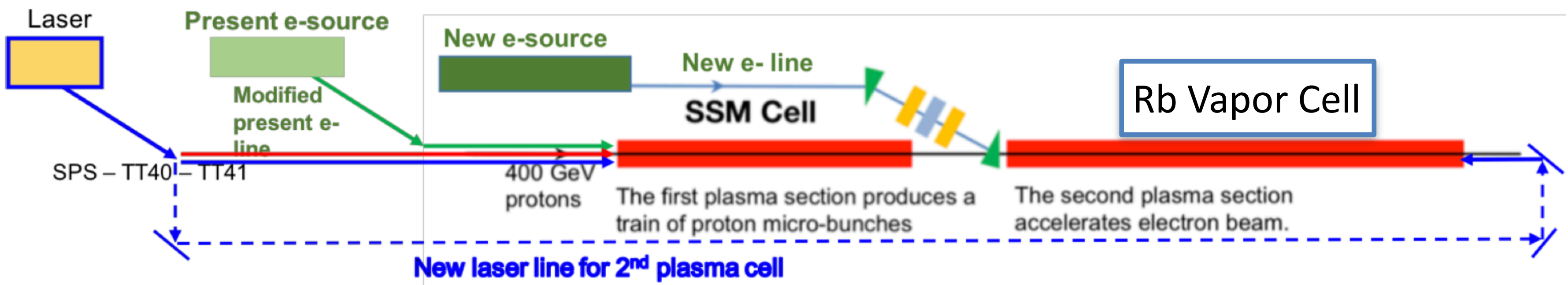


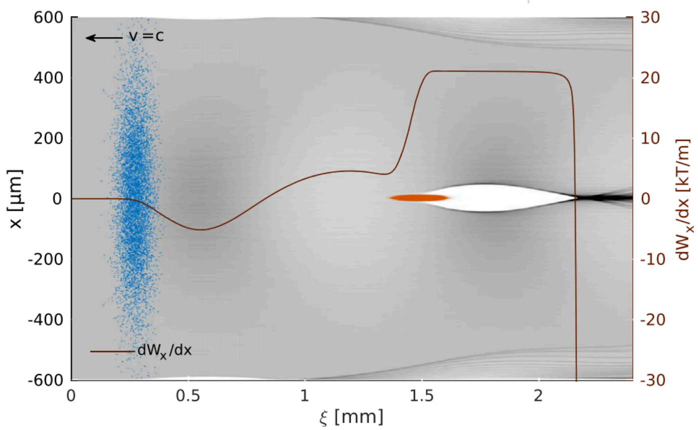
Strong field Diagnostics: plasma light, plasma density modulation, electron energy, …

Meets specifications

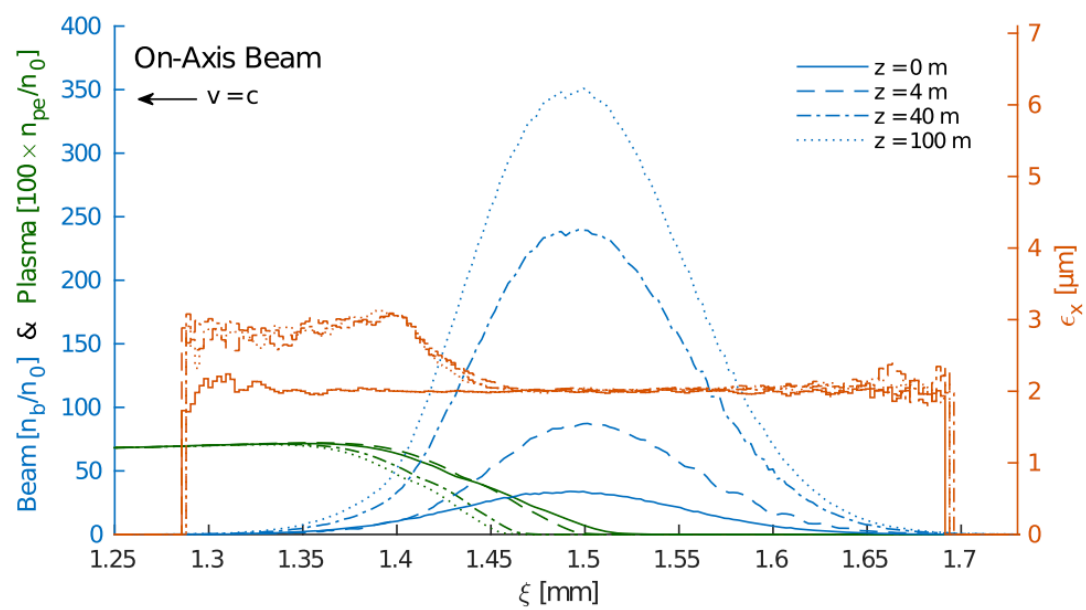
Run 2c

Baseline design





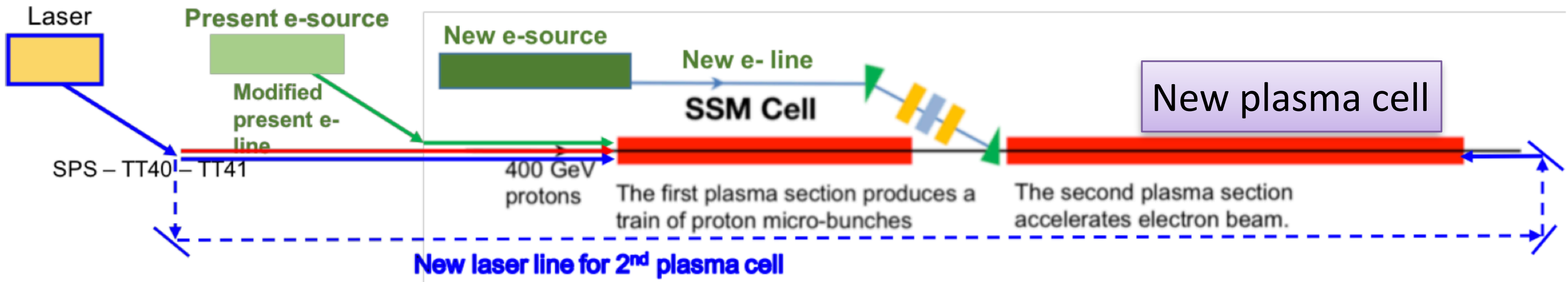
Compact electron bunch can create its own 'bubble'
emittance is preserved during acceleration



V.K. Berglyd Olsen, E. Adli and P. Muggli
Phys. Rev. Accel. Beams **21**, 011301

Run 2d

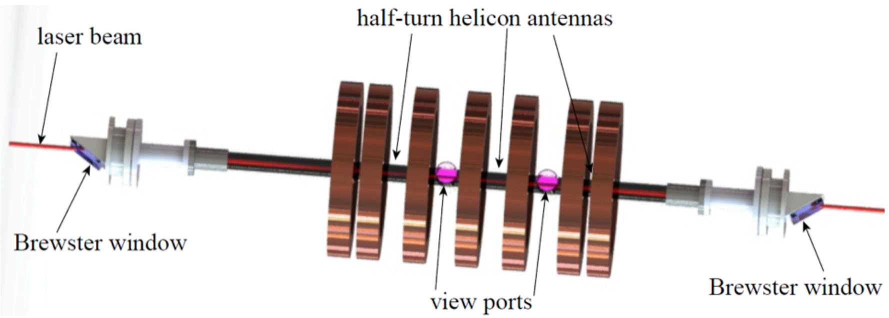
Baseline design



Density needed for AWAKE achieved at the IPP in Greifswald.

B Buttenschön et al 2018 Plasma Phys. Control. Fusion **60** 075005

Successful commissioning of helicon plasma source @ CERN



A suite of new diagnostics will be used to understand the features of the plasma.

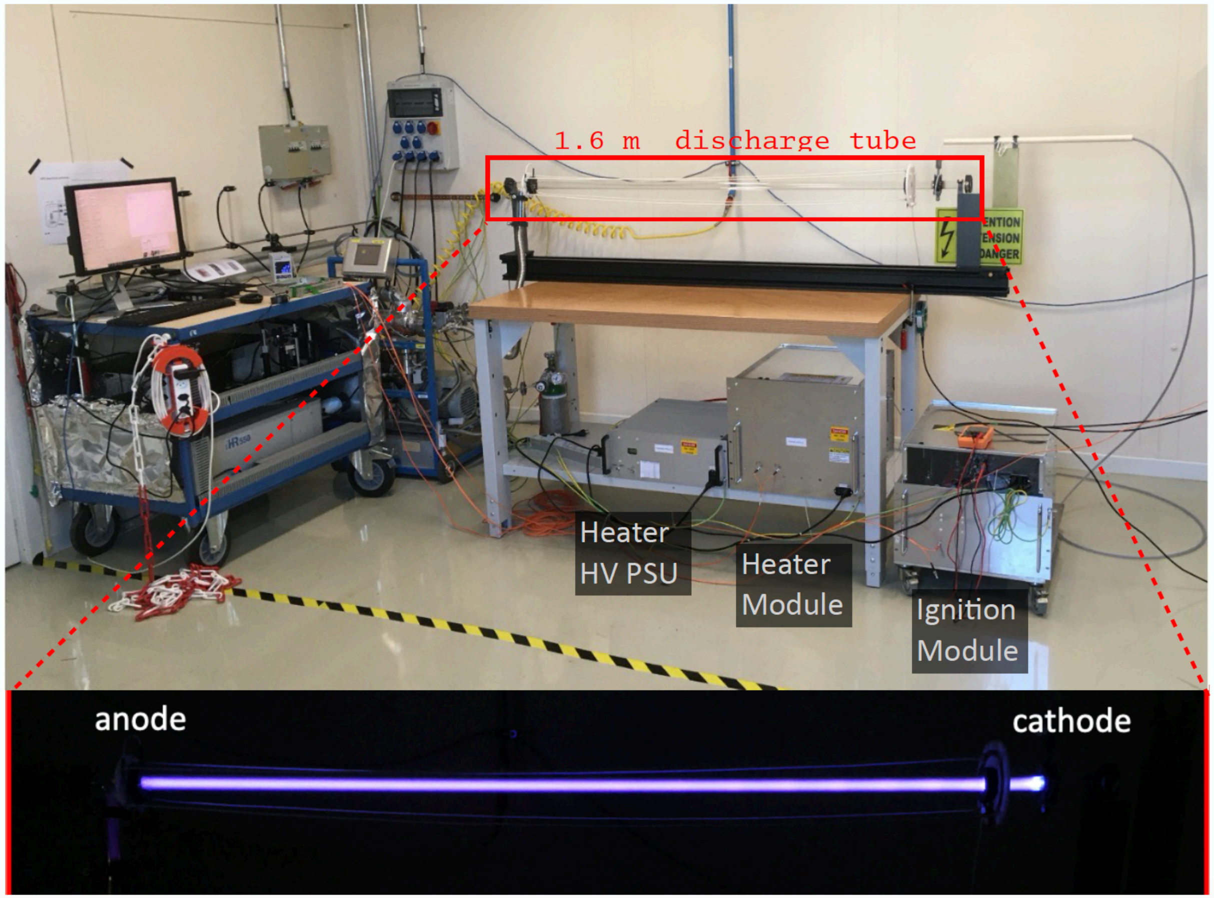
Here: Thomson Scattering concept (SPC)

Scalable, but uniformity needs to be demonstrated. Powering requirements costly.

Run 2d

Discharge plasma under study @ CERN, IST, IC

Ignition + heating CERN DPS lab setup



Much simpler & less expensive, but density, uniformity & scalability need to be demonstrated.

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 !

Summary

Goal for AWAKE run 1: demonstrate controllable modulation process (done) and proton-driven acceleration of electrons before LS2 of the LHC (done).

Run 2: goals are demonstration of stable acceleration and good electron bunch properties. We want to demonstrate possibility to use AWAKE scheme for particle physics applications in Run 2. Run 2a off to an excellent start.

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