Accelerating Electrons with Protons
The AWAKE Project

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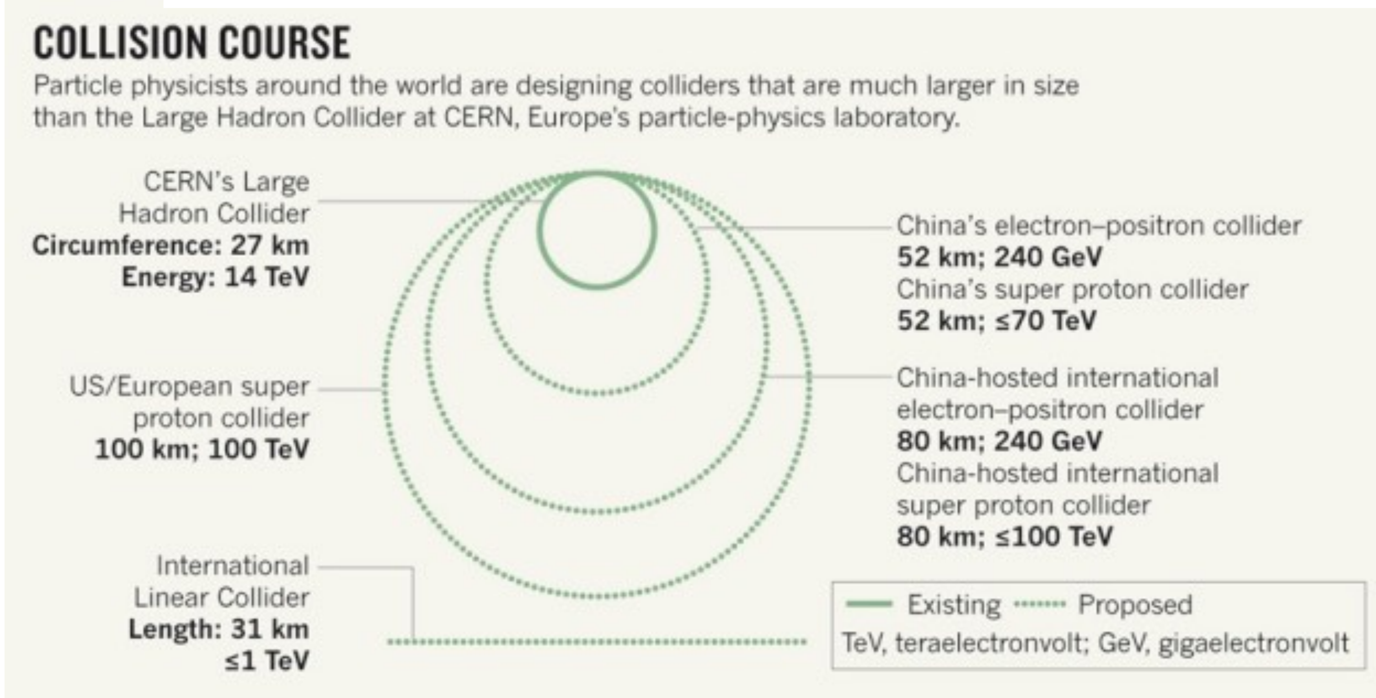
1. Motivation for plasma wakefield acceleration
2. How it works & challenges
3. The AWAKE project: evolution and current status
4. Long-term perspectives

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.

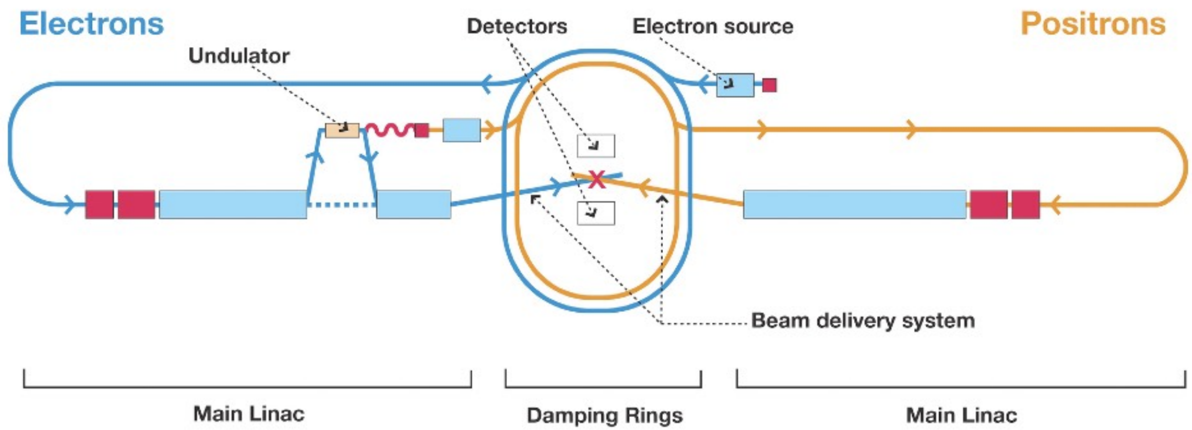
Energy limit of circular proton collider

$$P \propto B \cdot R$$



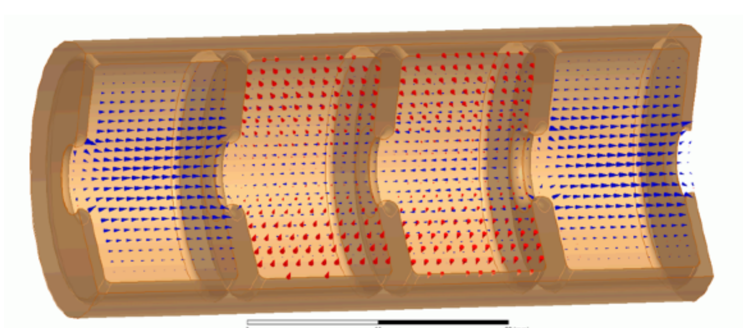
Linear Colliders are expensive with today's gradients

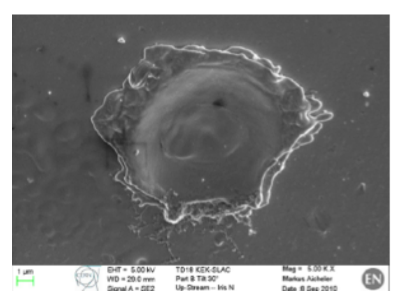
e^+e^- collisions at 500-1000 GeV

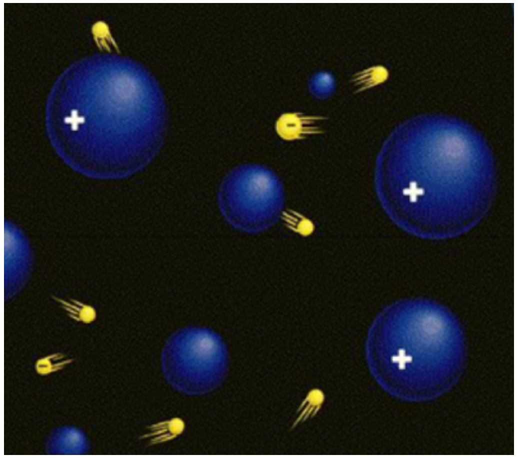


>30 km, > 10G$

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



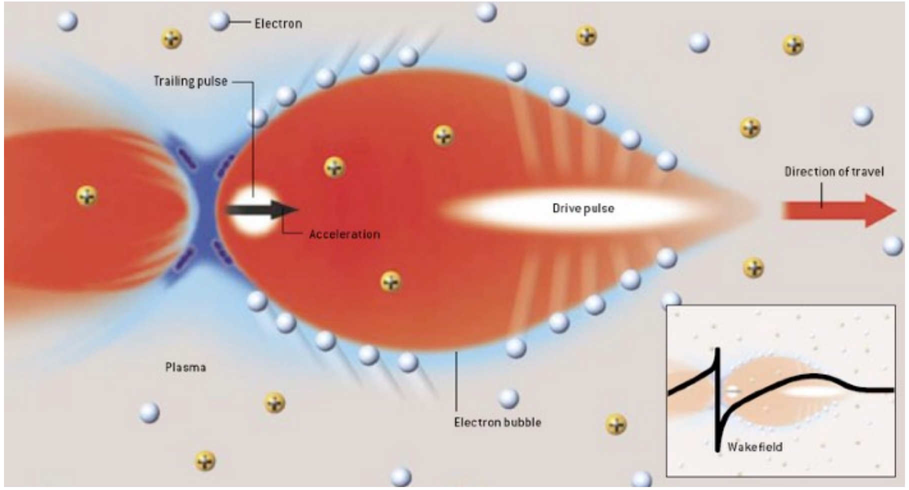




E. Adli, Oslo

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:

$$\omega_p^2 = \frac{4\pi n_p e^2}{m}$$

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

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)

Laser Wakefield Acceleration

Acceleration is ***DEPLETION-LIMITED***
i.e., the lasers do not have enough energy to accelerate a bunch of particles to very high energies

e.g.,

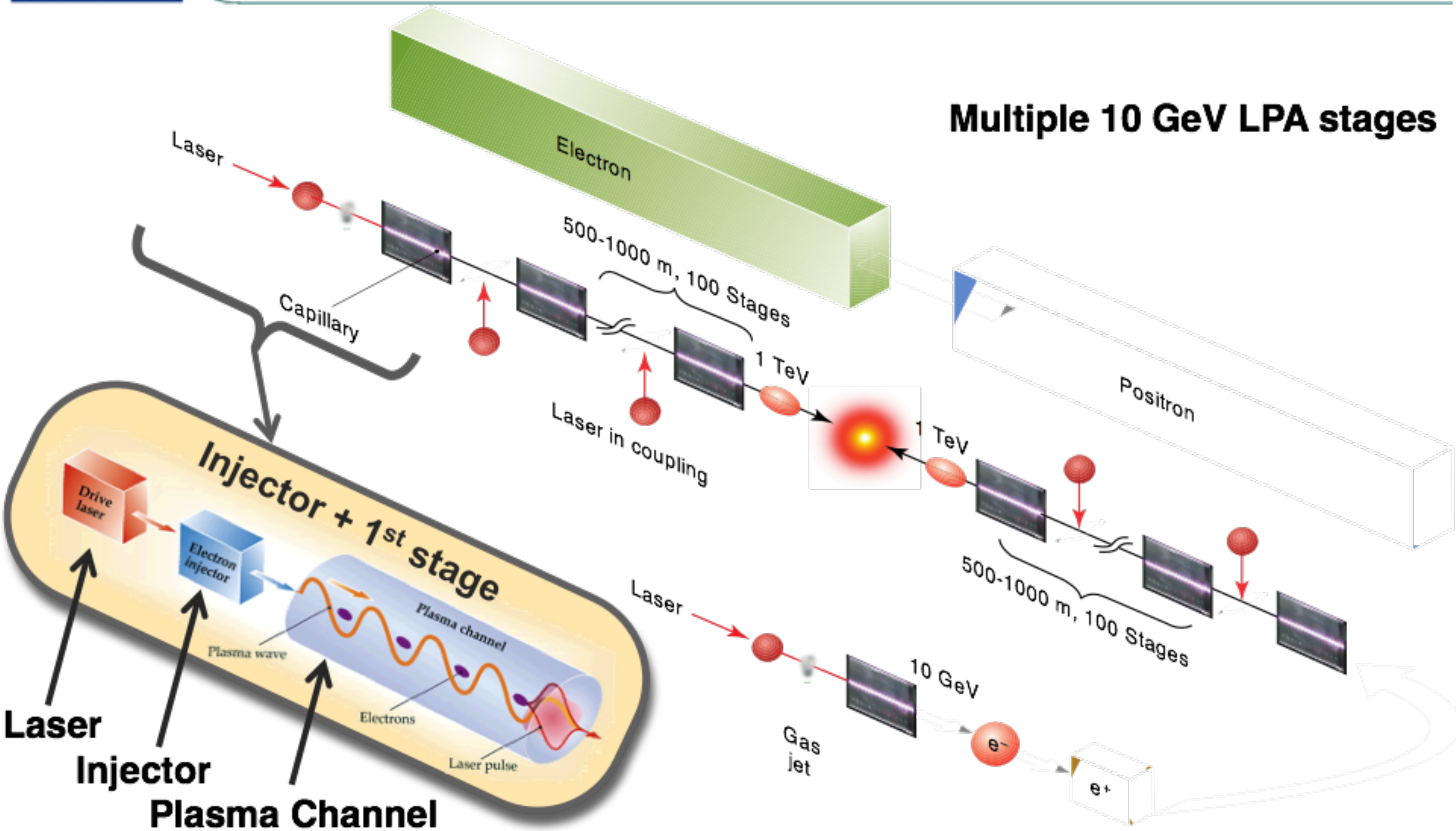
$$10^{10} \text{ electrons} \cdot 10^{12} \text{ eV} \cdot 1.6 \cdot 10^{-19} \text{ J/eV} = kJ$$

This is orders of magnitude larger than laser energy today[1].

If use several lasers – need to have relative timing in the 10's of fs range, scheme for getting rid of spent laser beam, introducing new beam, etc …

[1] with useful repetition rate; i.e., not the NIF laser

Strawman Design of a TeV LPA Collider



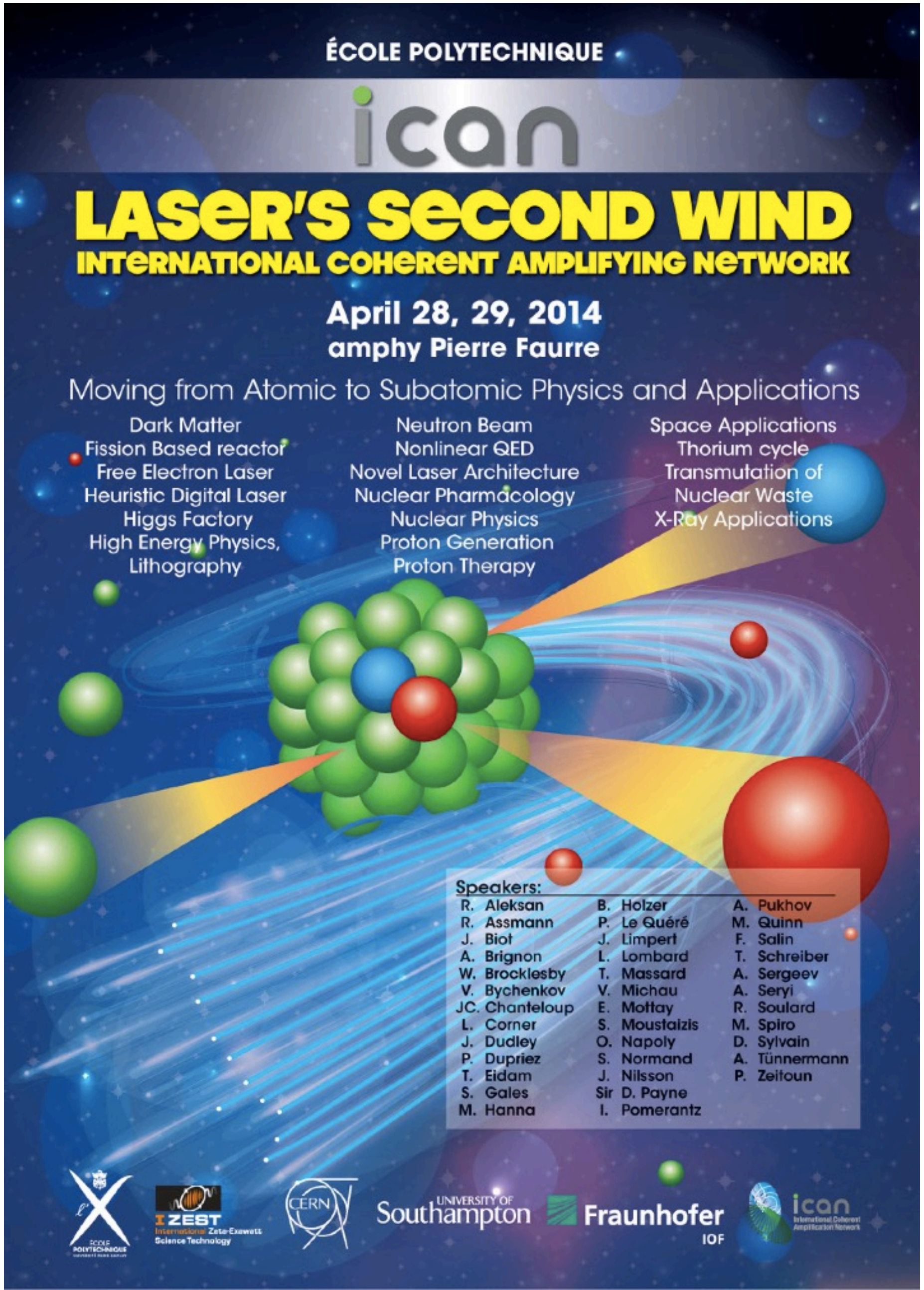
Leemans & Esarey, Physics Today, March 2009

Laser Wakefield Acceleration

The situation could change.

There are very interesting developments ongoing in the Laser community that could have great impact on a future Laser Driven PWA.

IZEST/ICAN – coherent amplification network. Many fiber lasers in phase could bring needed energy, rep rate and efficiency.



Electron driven PWA

50 GeV/m gradients have been demonstrated with electron beam drivers.

Are electrons the obvious drivers ???

There is a limit to the energy gain of a trailing bunch in the plasma:

$$R = \frac{\Delta T^{\text{witness}}}{\Delta T^{\text{drive}}} \leq 2 \quad \text{T is the kinetic energy}$$

(for longitudinally symmetric bunches).

See e.g. SLAC-PUB-3374, R.D. Ruth et al.

This means many stages required to produce a 1TeV electron beam from known electron beams (SLAC had 45 GeV)

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:

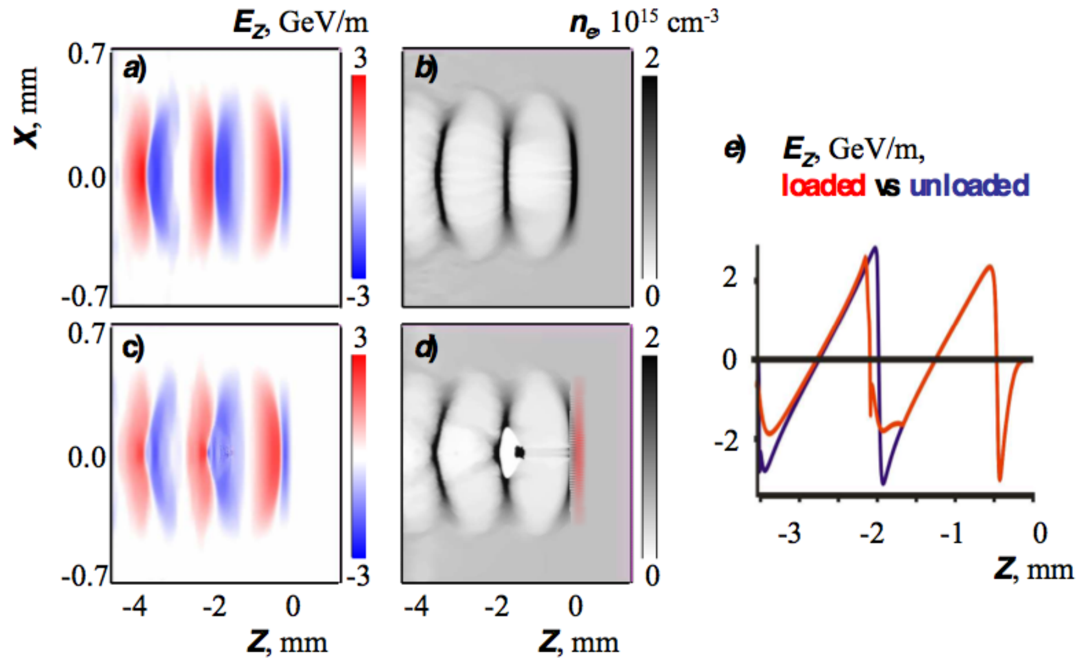
PW lasers today, ~40 J/Pulse

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

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

Witness:

10^{10} particles @ 1 TeV ≈ few kJ



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

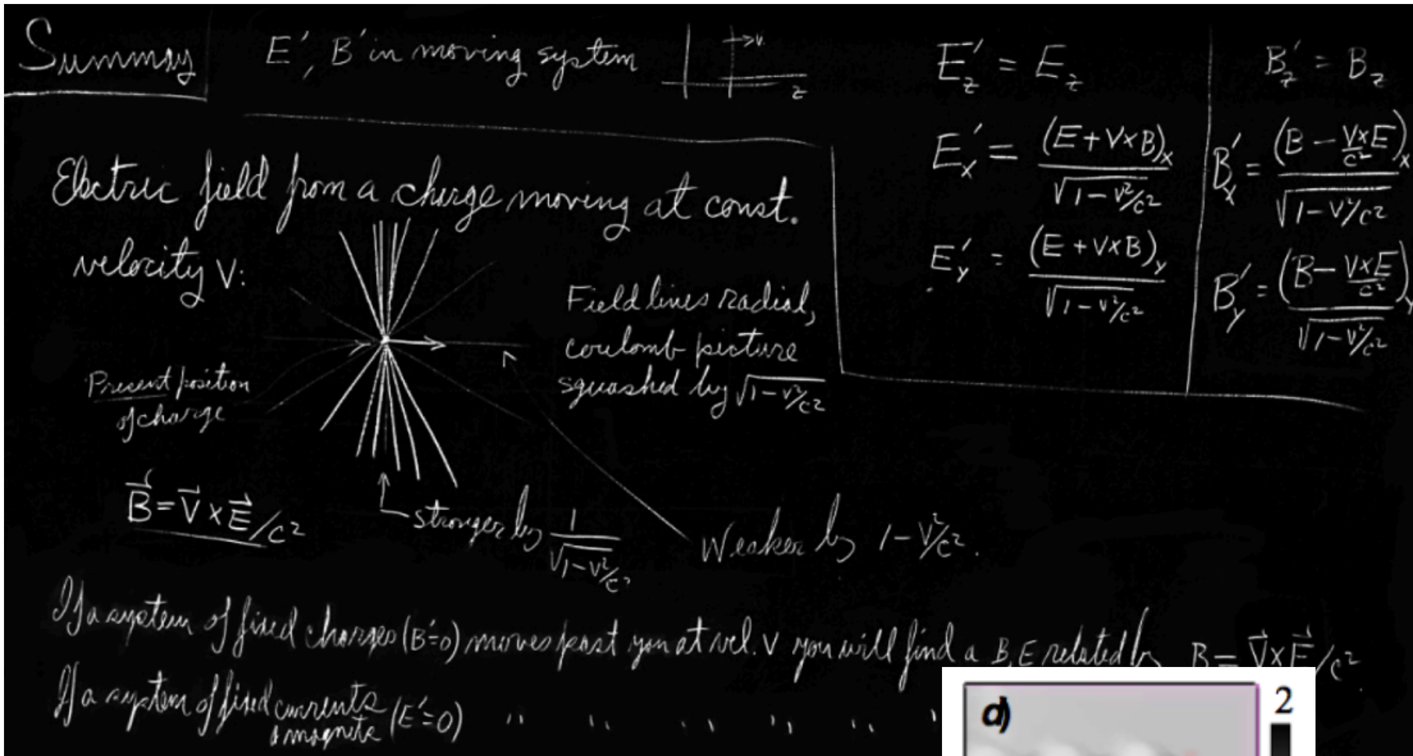
Energy content of driver allows to consider single stage acceleration

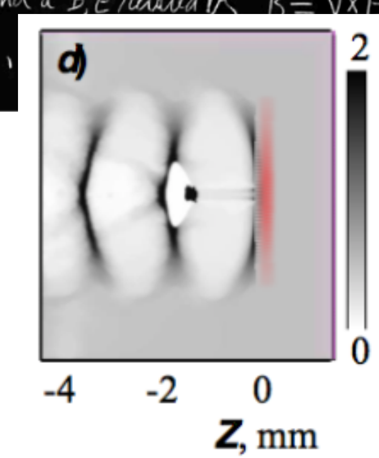
A. Caldwell, K. Lotov, A. Pukhov, F. Simon, Nature Physics 5, 363 (2009).

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

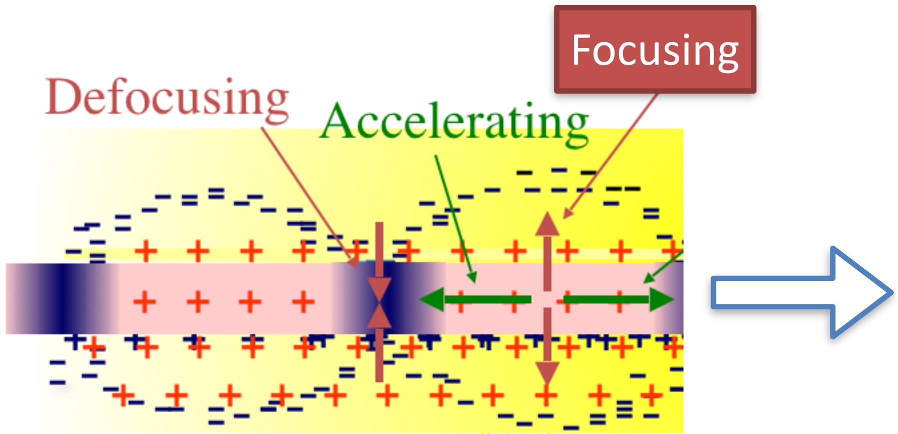


Figure: Patric Muggli

Proton

Electron

Do the electrons outrun the protons ?

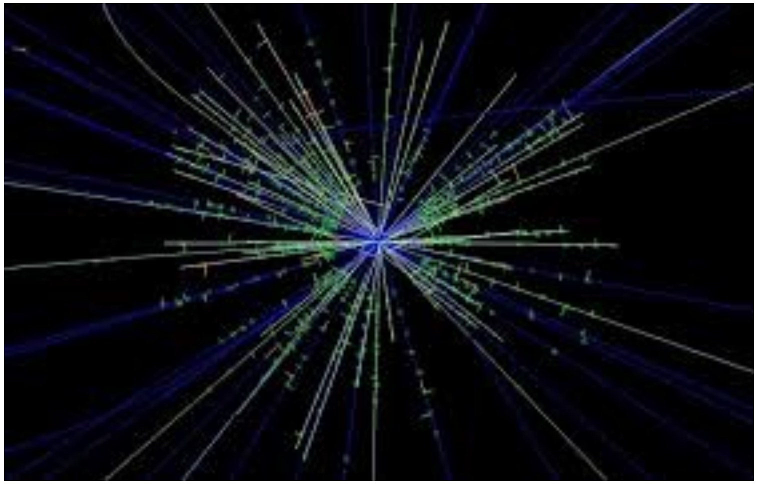
$$\delta \approx \frac{\pi L}{\lambda_p} \frac{1}{\gamma^2}$$

Phase slippage (protons 2000 times heavier than electrons) ?

Basic Aspects

Proton (QCD) interactions ?

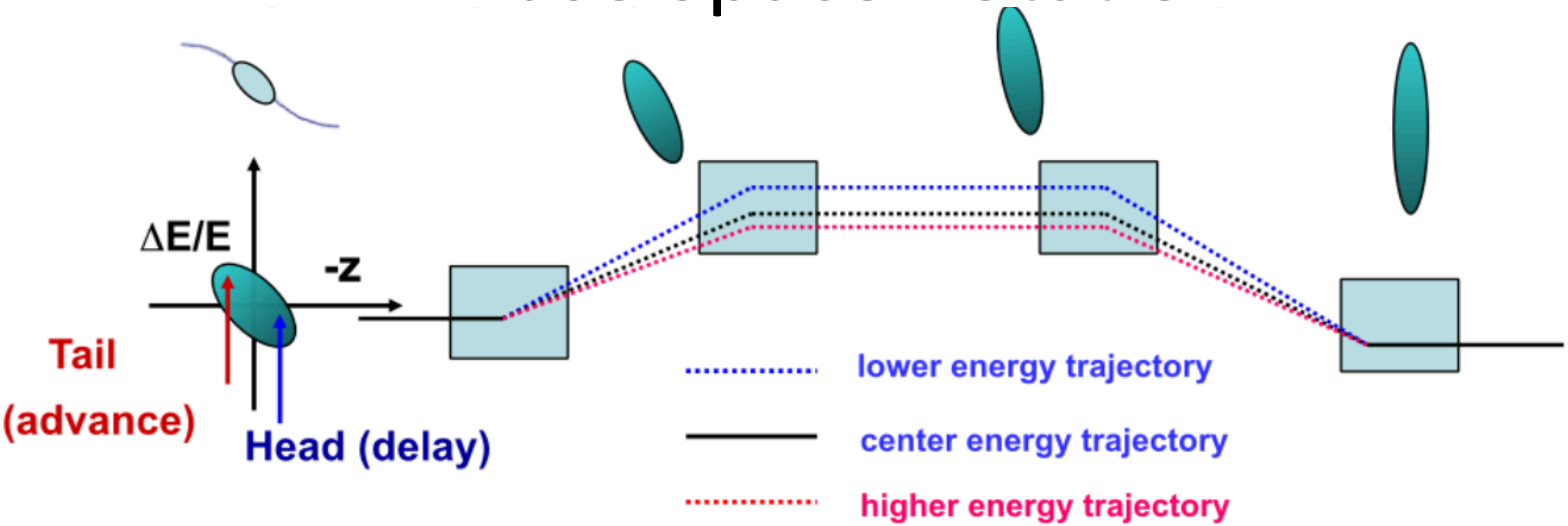
LHCb event display



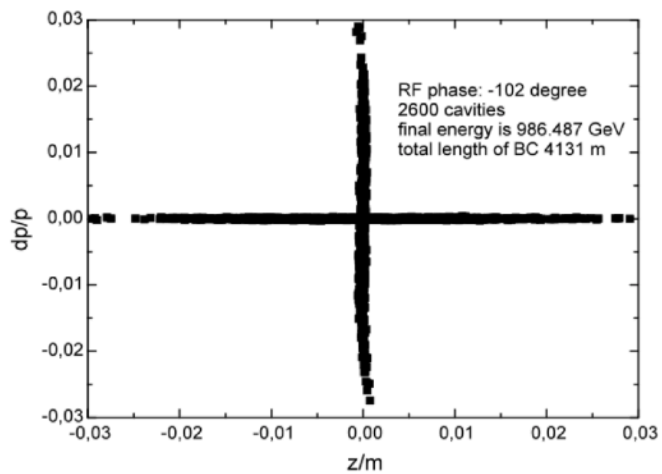
$$\lambda = \frac{1}{n\sigma} \quad n = 1 \cdot 10^{15}\ \mathrm{cm}^{-3} \quad \Rightarrow \lambda > 1000\ \mathrm{km}$$

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

Phase Space Rotation



- To compress a bunch longitudinally, trajectory in dispersive region must be shorter for tail of the bunch than it is for the head.



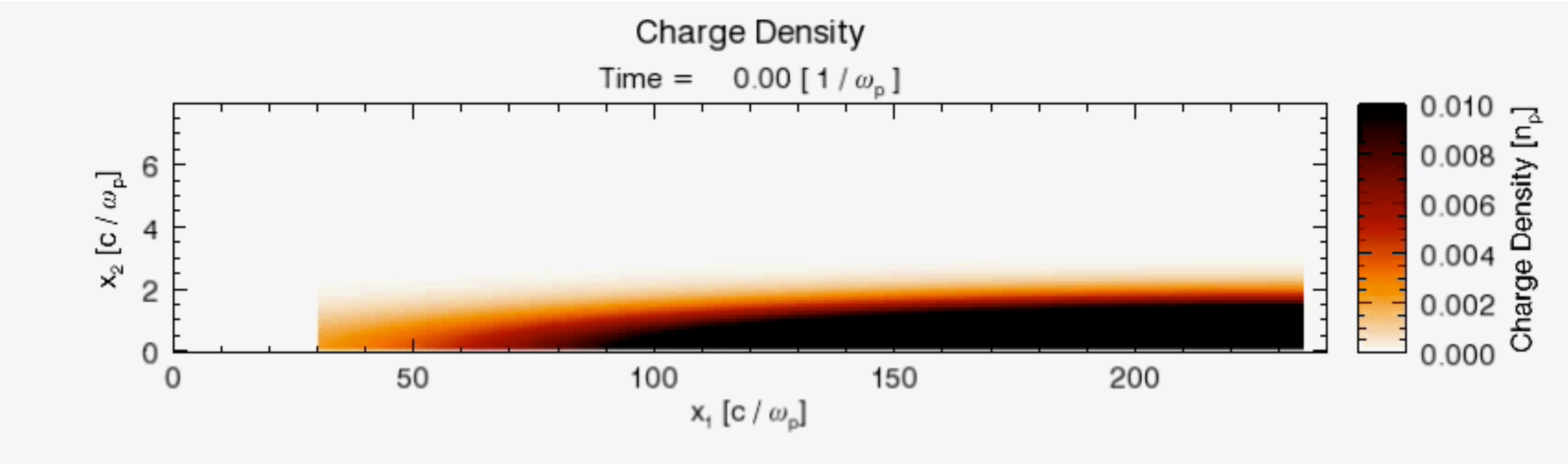
It works - but it takes a lot of space & expensive

See A. Caldwell, G. Xia et al., Preliminary study of proton driven plasma wakefield acceleration, Proceedings of PAC09, May 3-8, 2009, Vancouver, Canada

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)



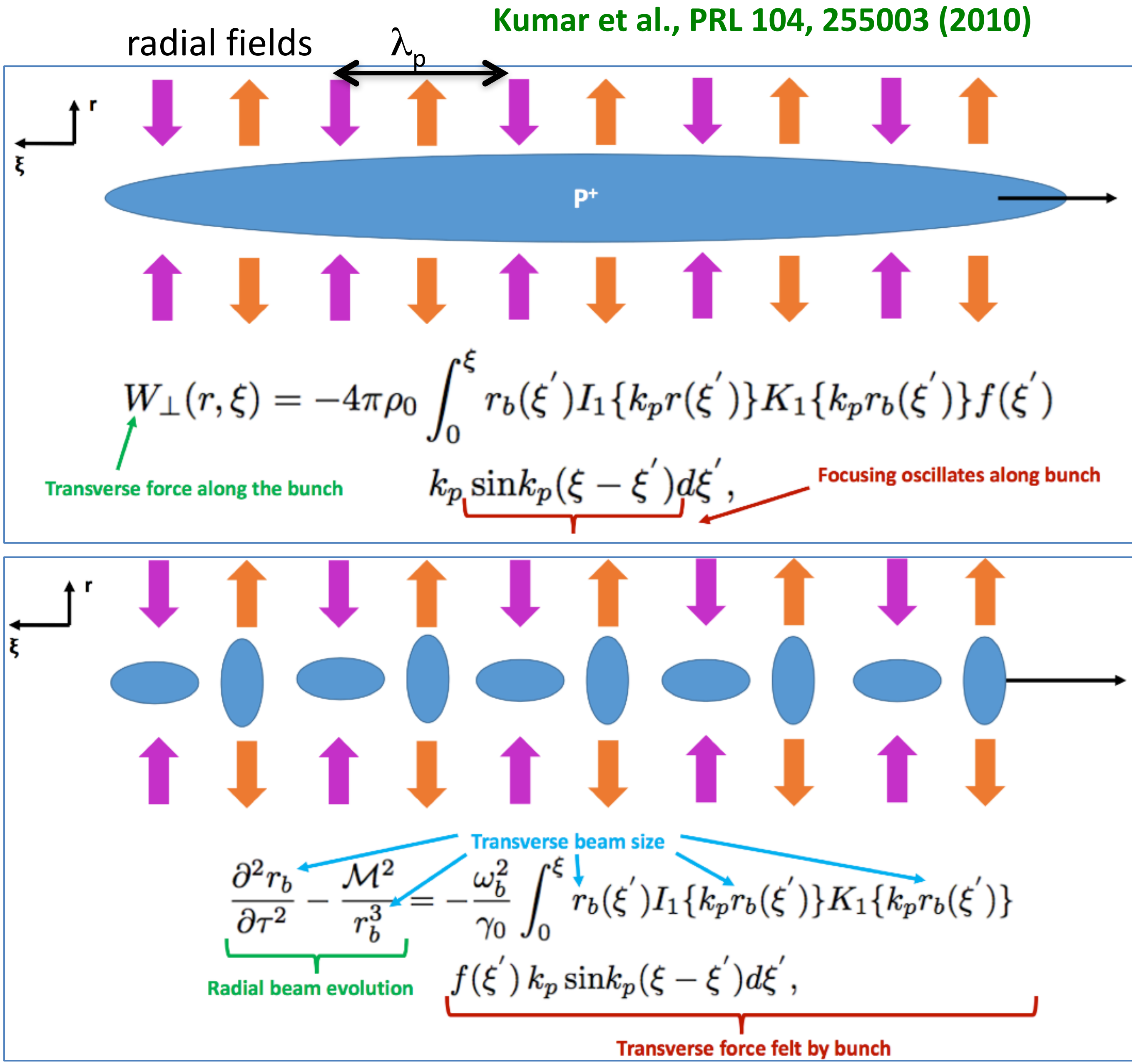
Propagation of a ‘cut’ proton bunch in a plasma. From Wei Lu, Tsinghua University

The self-modulation instability

The **radial fields** of the wake modulate the beam density, creating m**icrobunches** spaced at the plasma wavelength.

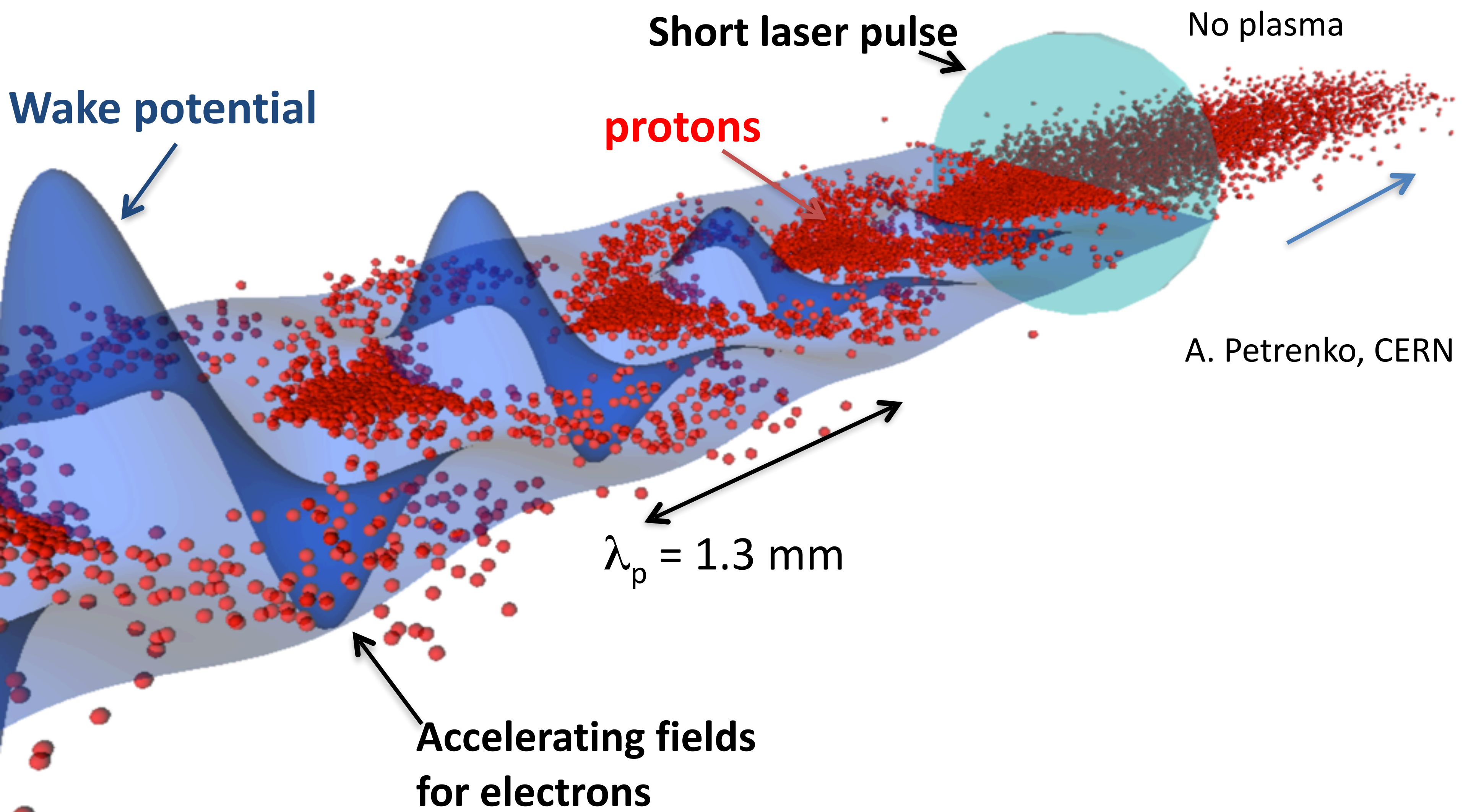
The microbunches leads to **resonant build-up** of strong wake fields (of order GV/m).

Graphics: E. Adli, Olso



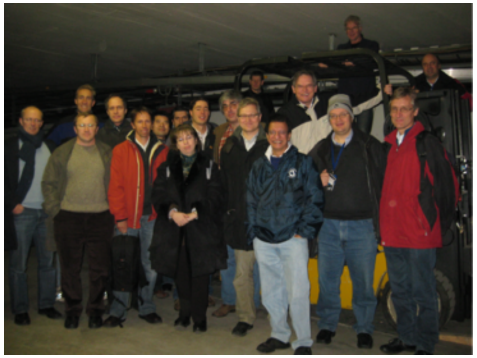
Seeded self-modulation

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

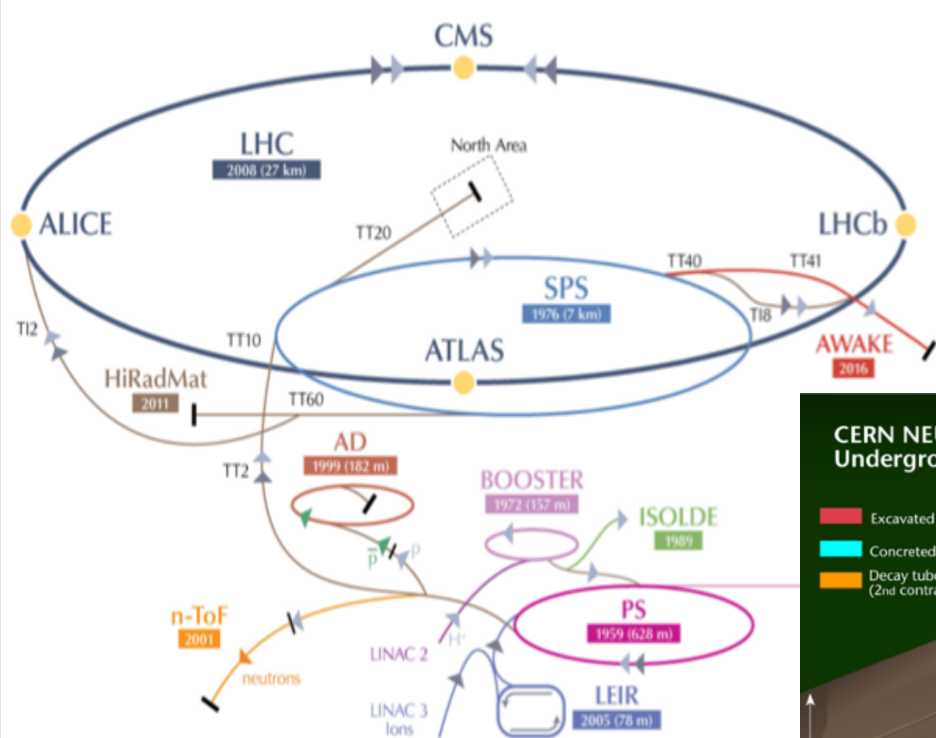
- AWAKE Collaboration: 16 Institutes world-wide:

John Adams Institute for Accelerator Science
Budker INP & Novosibirsk State University
CERN
Cockcroft Institute
Heinrich Heine University, Düsseldorf
Instituto Superior Tecnico, Lisbon
Imperial College
UNIST, Korea
Ludwig Maximilian University
Philipps-Universität Marburg
Max Planck Institute for Physics
Max Planck Institute for Plasma Physics
Rutherford Appleton Laboratory
TRIUMF
University College London
University of Oslo

+ 3 Associate members:

Swiss Plasma Center, EPFL
Wigner Institute, Hungary
University of Wisconsin

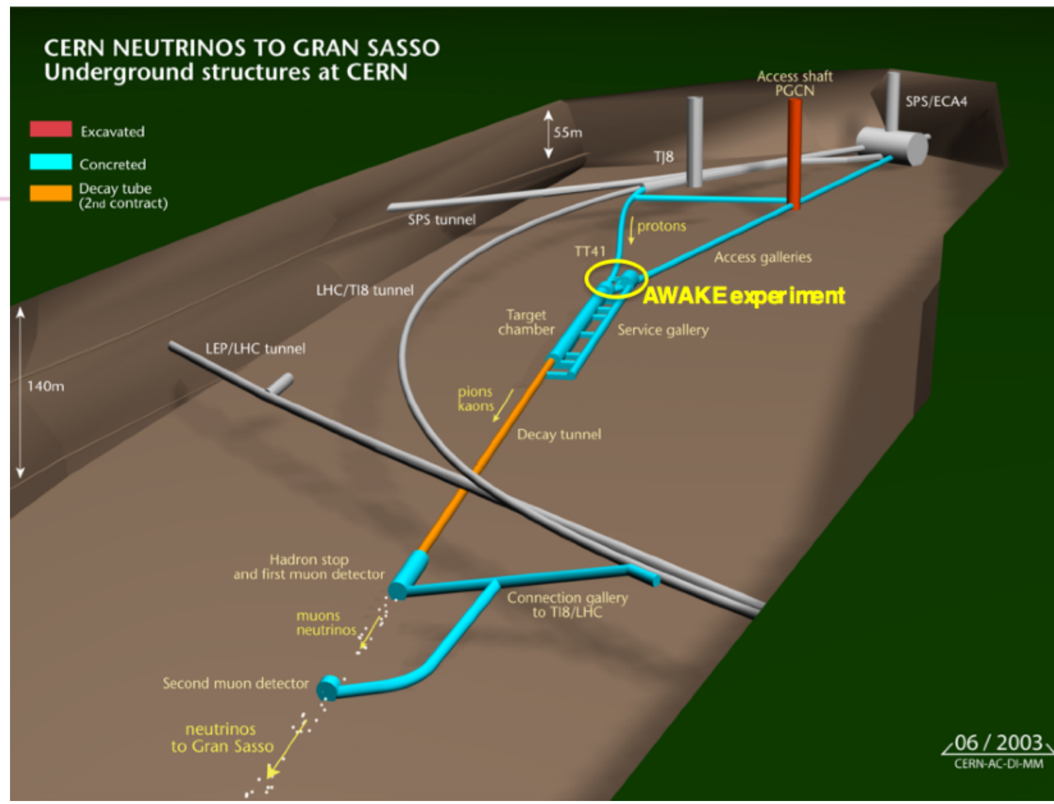
AWAKE at CERN



AWAKE is installed in

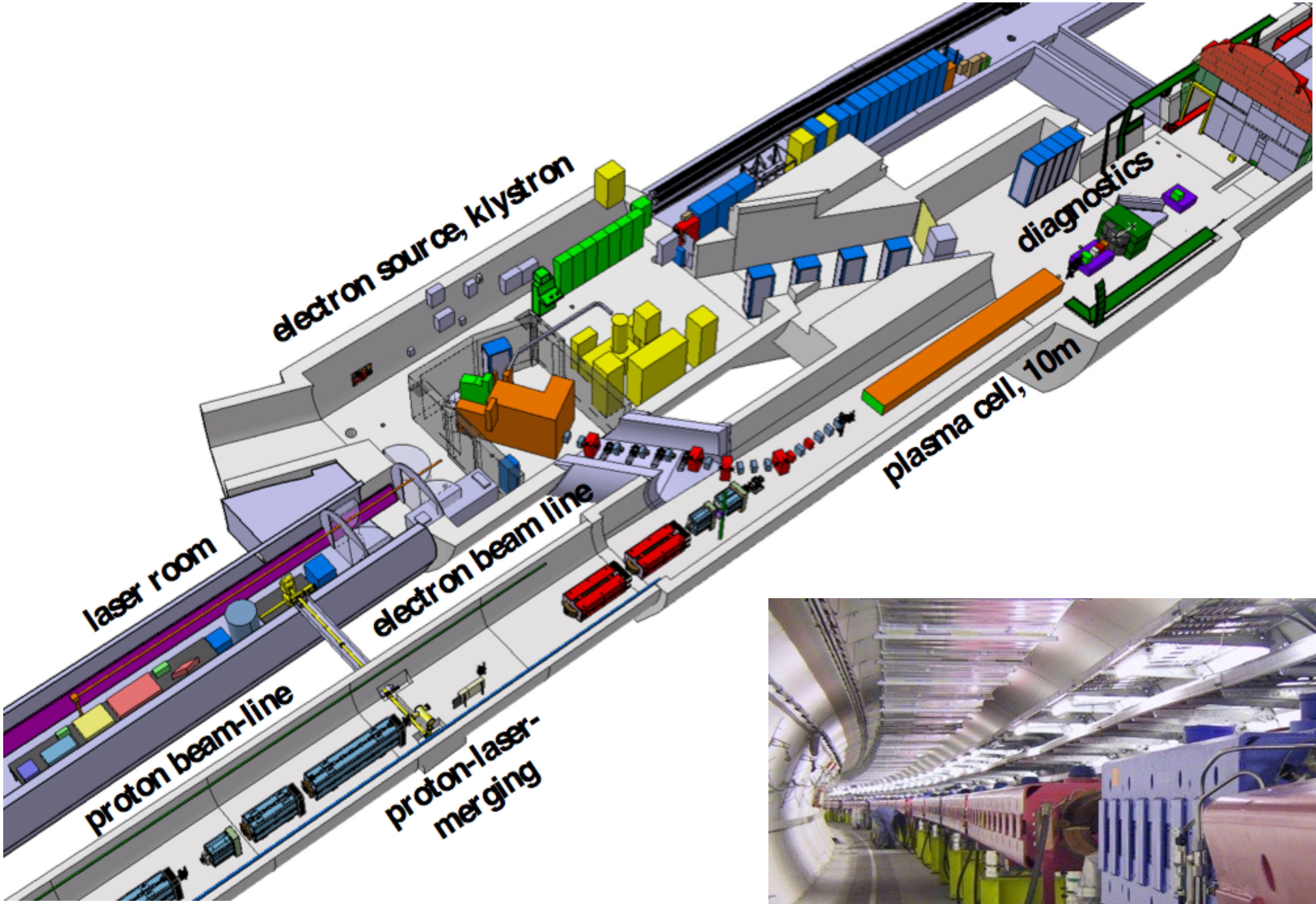
CNGS Facility (CERN Neutrinos to Gran Sasso)

→ CNGS physics program finished in 2012



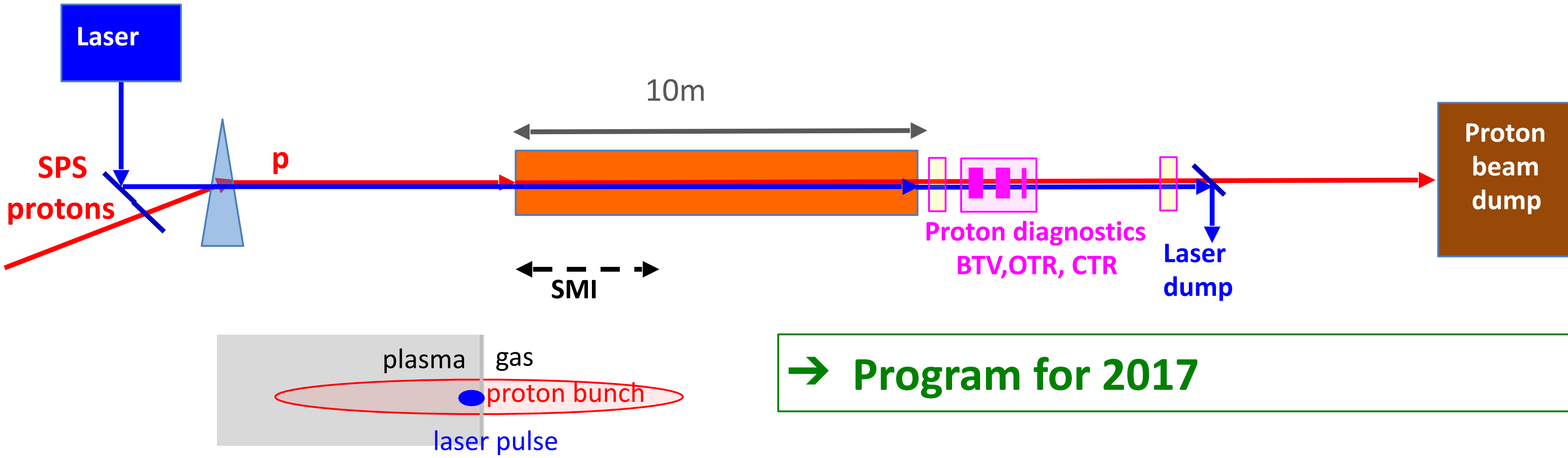
A. Caldwell et al., "Path to AWAKE: Evolution of the concept", Nucl. Instrum. Meth. A829 (2016) 3-16; E. Gschwendtner et al. [AWAKE Collaboration], "AWAKE, The Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN," Nucl. Instrum. Meth. A829, 76 (2016).

AWAKE Overview



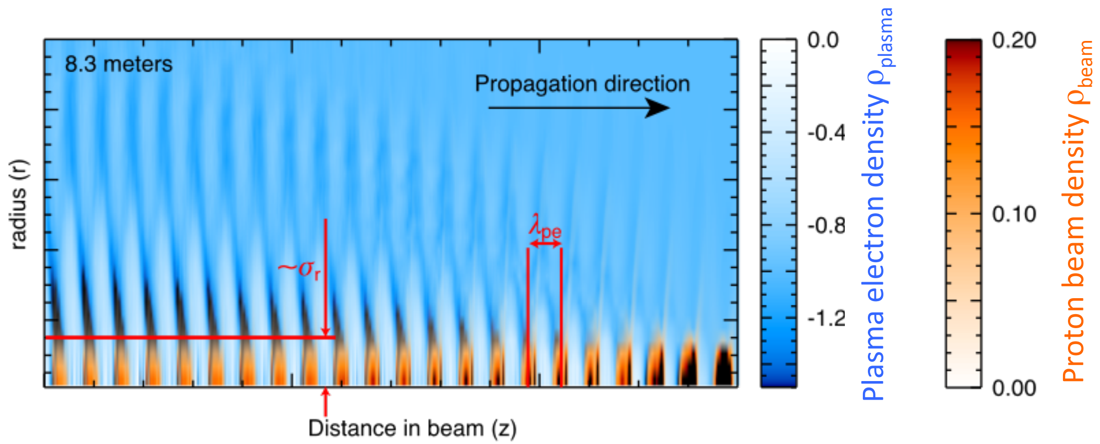
AWAKE: Experimental Program

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

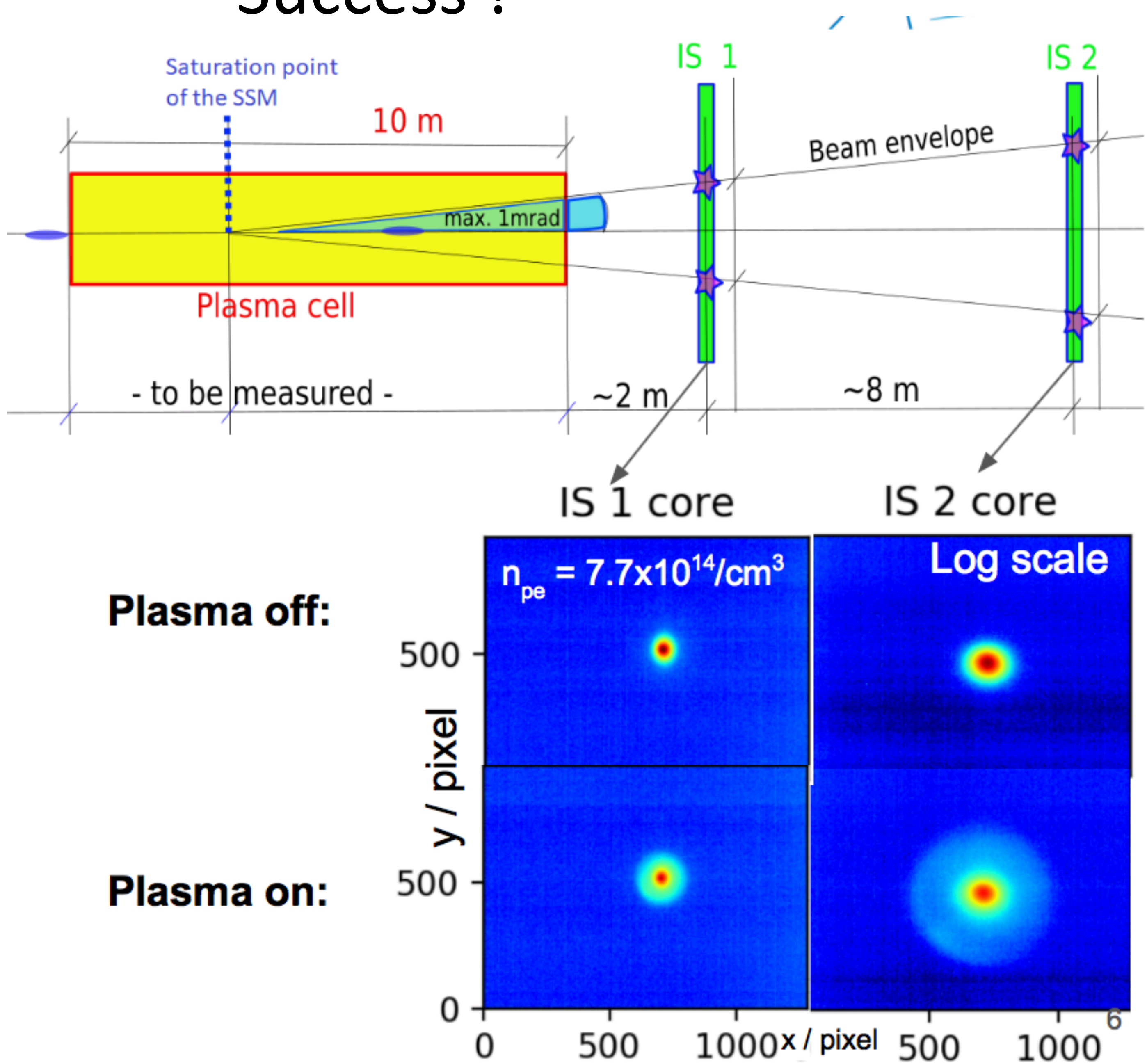


→ **Program for 2017**

Self-modulated proton bunch resonantly driving plasma wakefields.



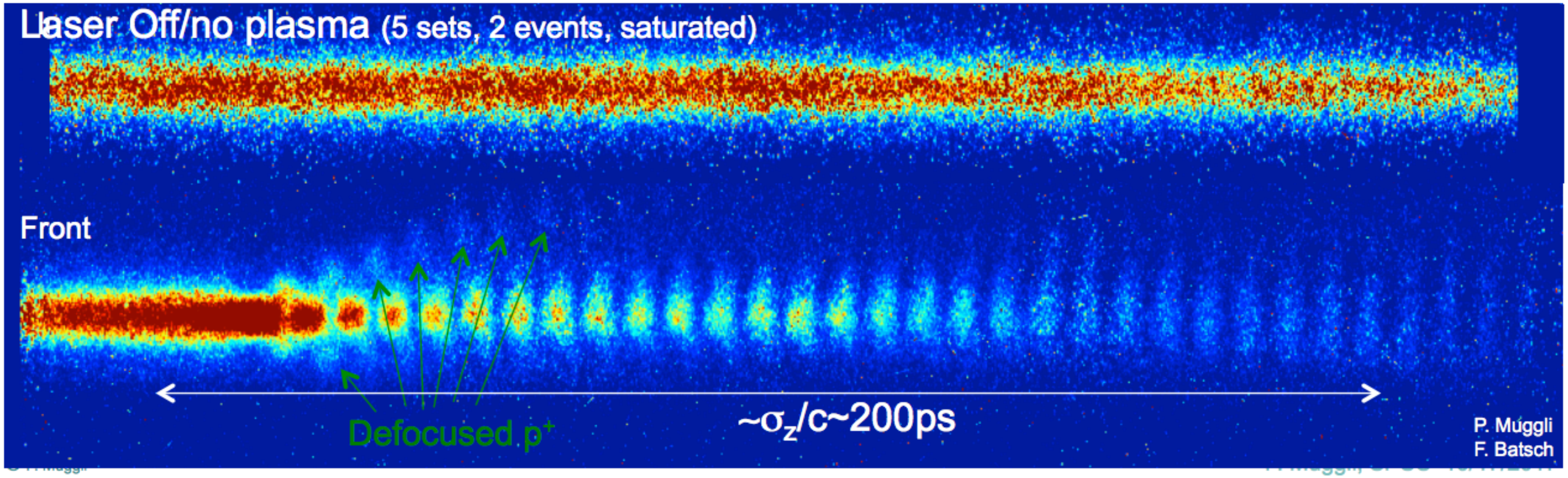
Success !



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

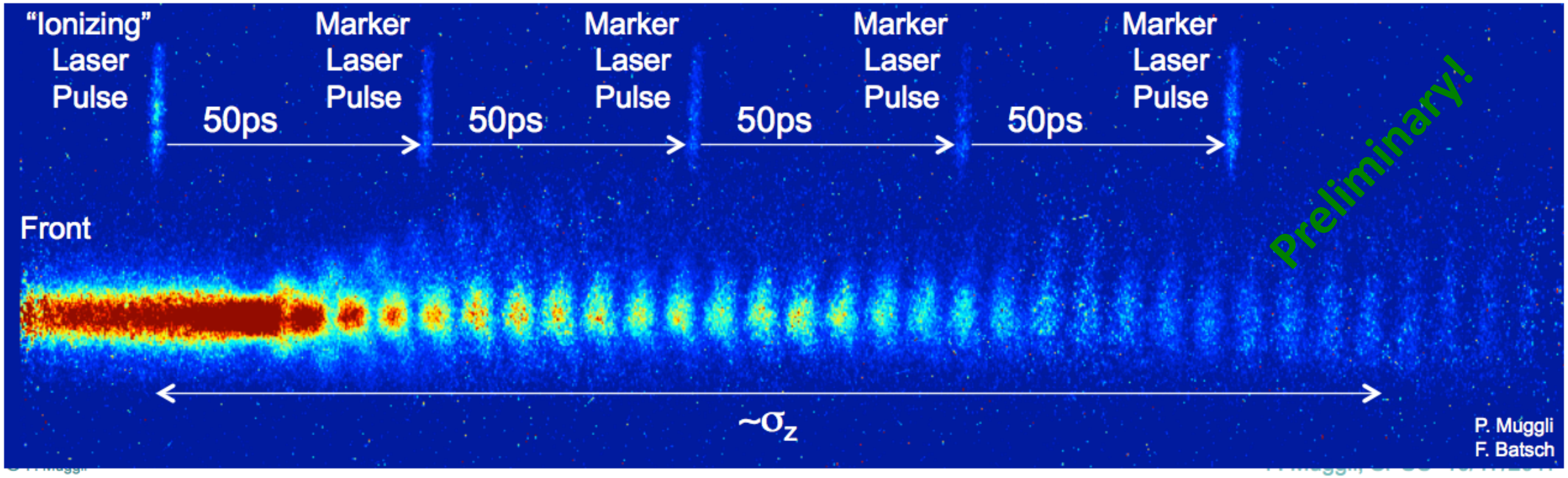
Observation of Seeded SMI

Streak camera Images



Streak camera Images

10 events each

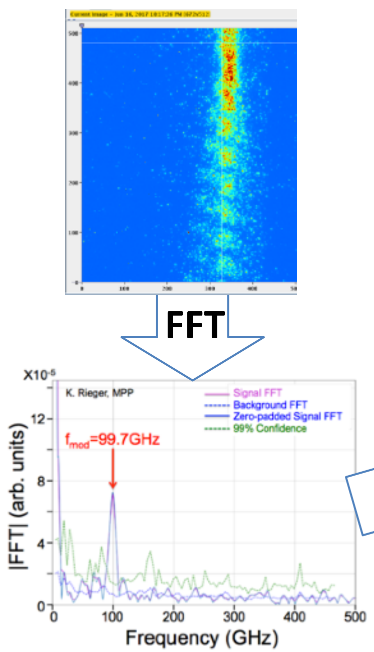


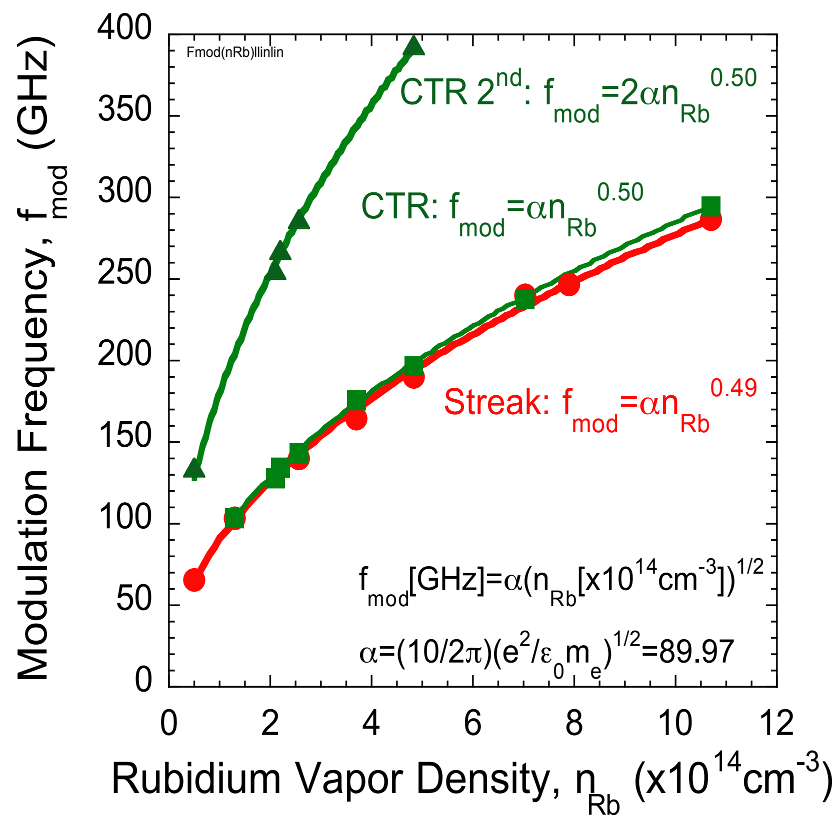
Summary of OTR and CTR results

Preliminary!

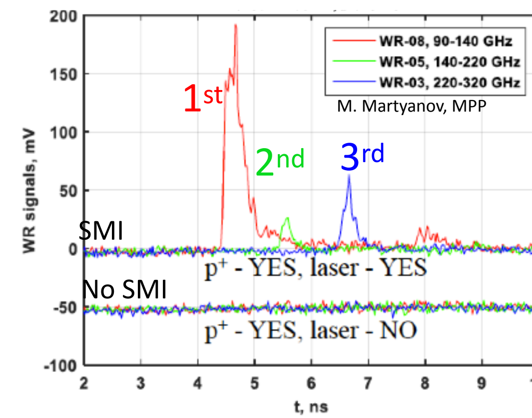
K. Rieger
M. Martyanov,
F. Braunmueller, MPP

OTR





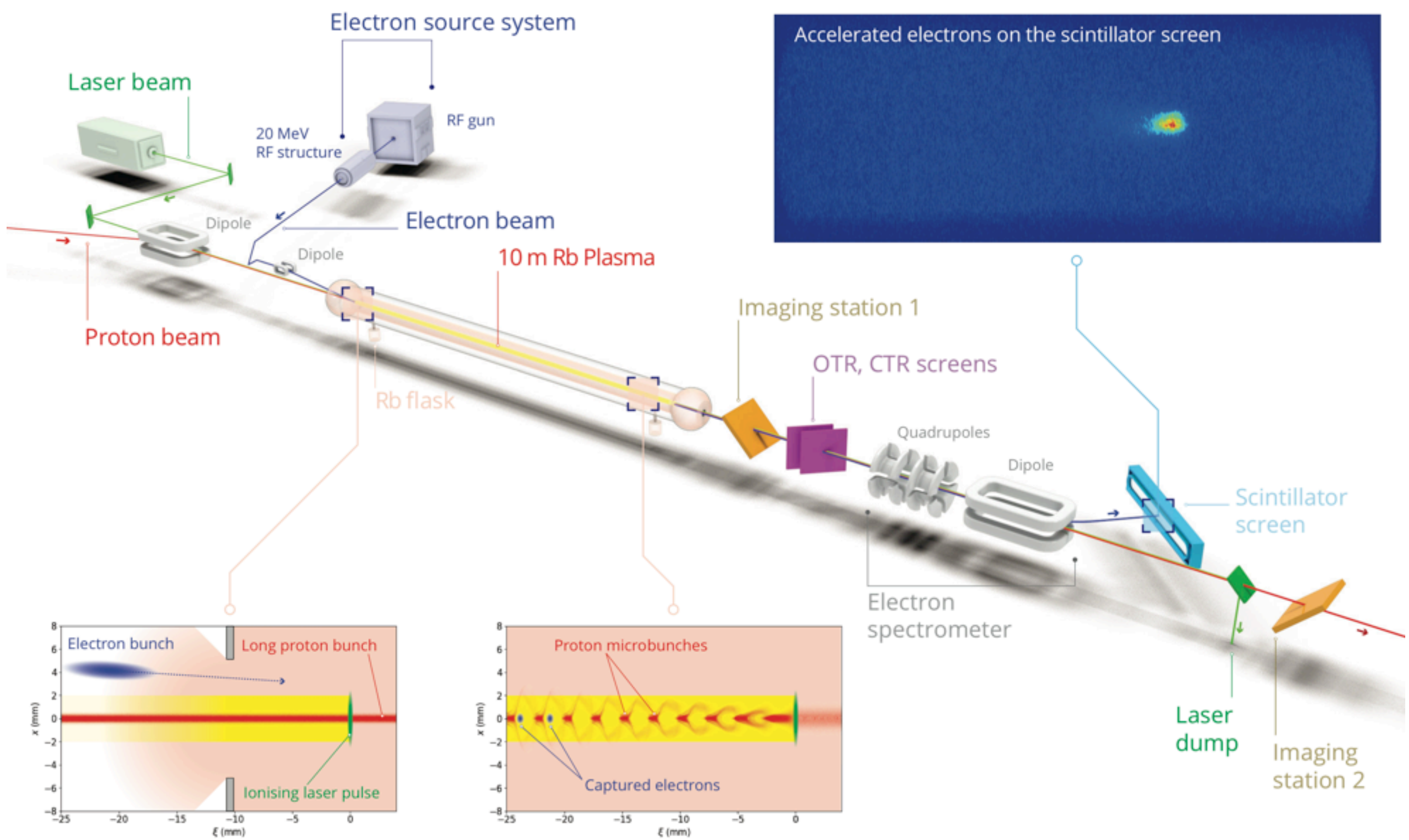
CTR



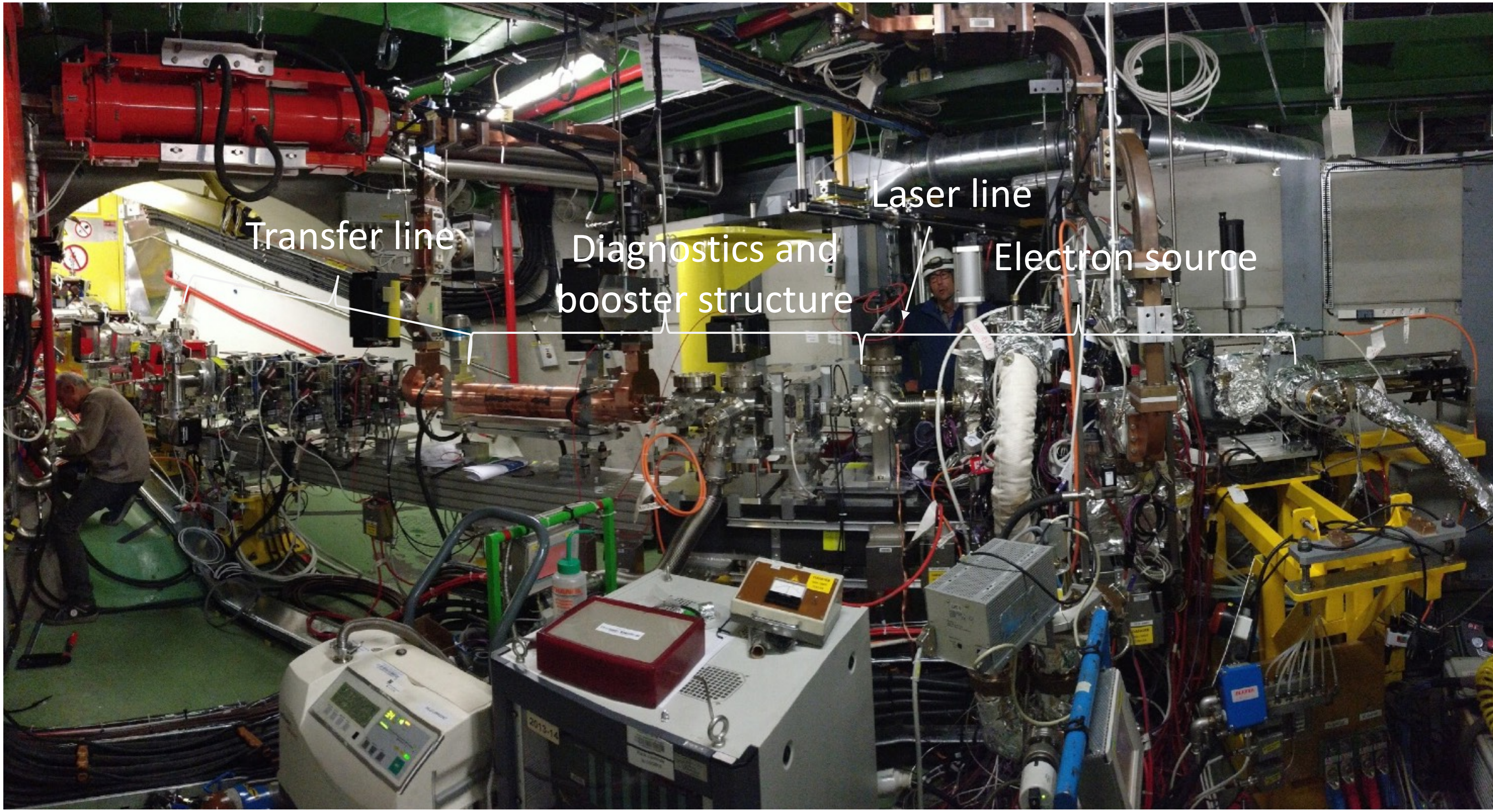
→ both OTR and CTR based measurements fit very well to predicted modulation frequency, for a range of plasma densities.

AWAKE Experimental Program

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



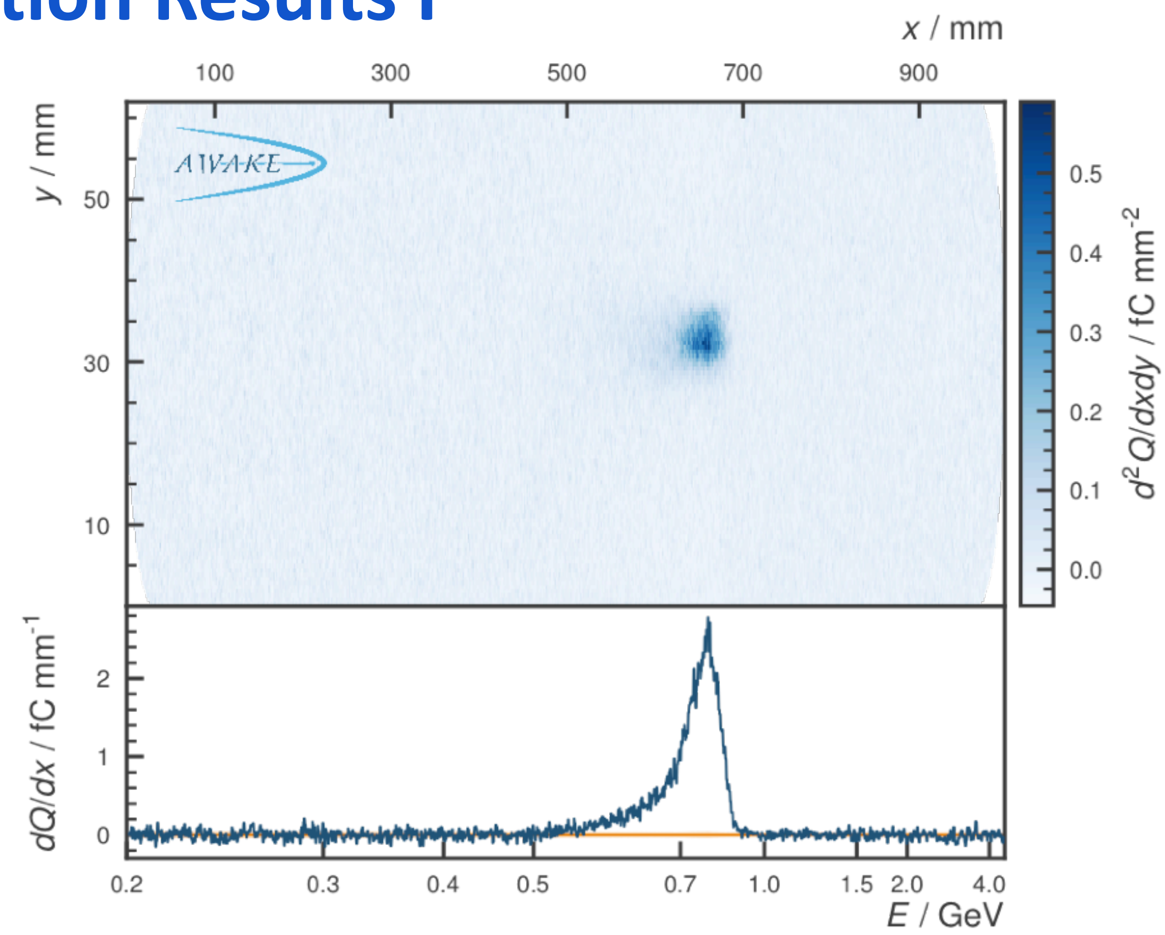
Electron Line



Electron Acceleration Results I

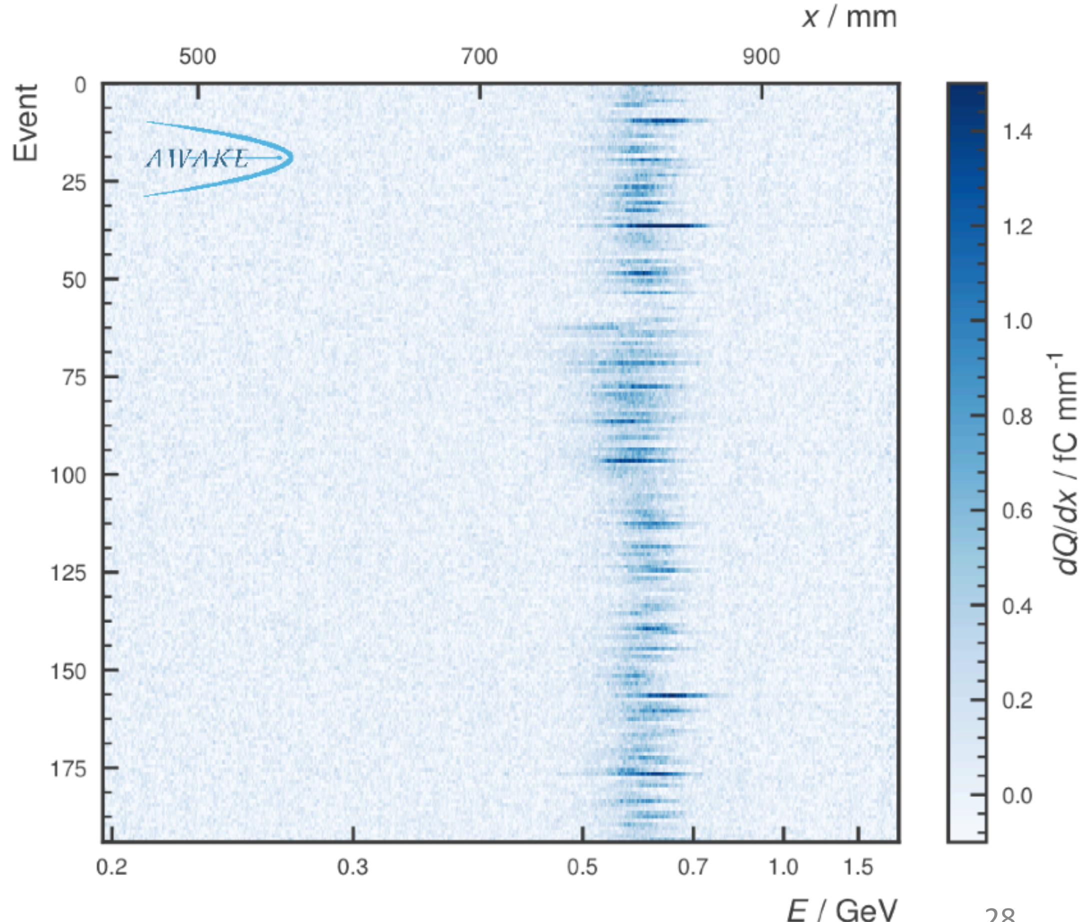
Event **at n_{pe} =1.8 x 10^{14} cm^{-3} with 5%/10m** density gradient.

- Acceleration to **800 MeV**.
- Energy is **dependent on n_{pe}** and on the **gradient.**
- **Accelerated bunch charge** of 0.2pC → Capture efficiency not yet optimized.

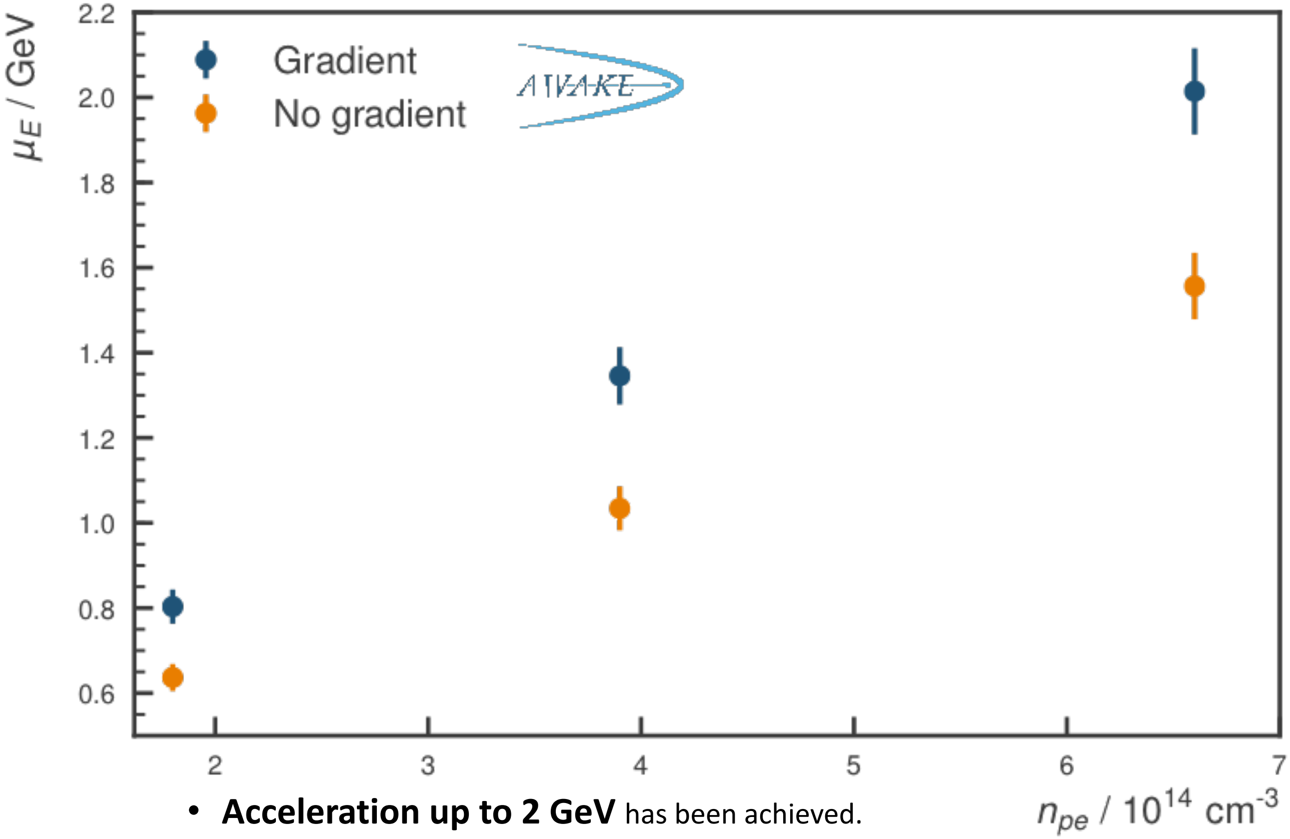


Electron Acceleration Results II

- **Consecutive electron injection** events at n_{pe} = 1.8 x $10^{14}cm^{-3}$.
- **Quadrupole scan** performed over this period.
- **Stability** crucial for further development.



Electron Acceleration Results III

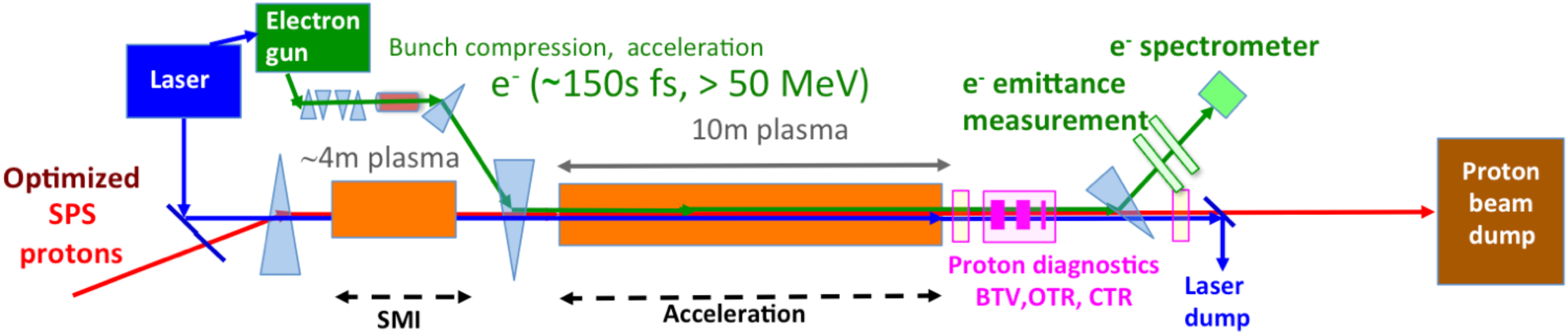


- **Acceleration up to 2 GeV** has been achieved.
- Charge capture decreases with plasma density n_{pe}.

Run II (2021-2024)

Goals:

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

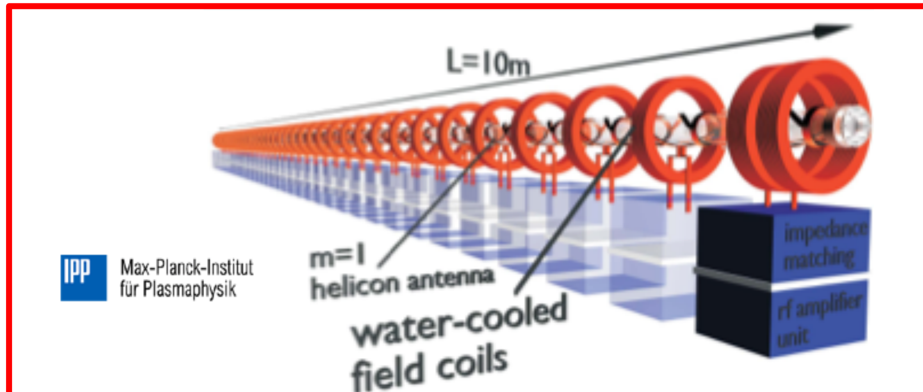


Require:

- 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 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

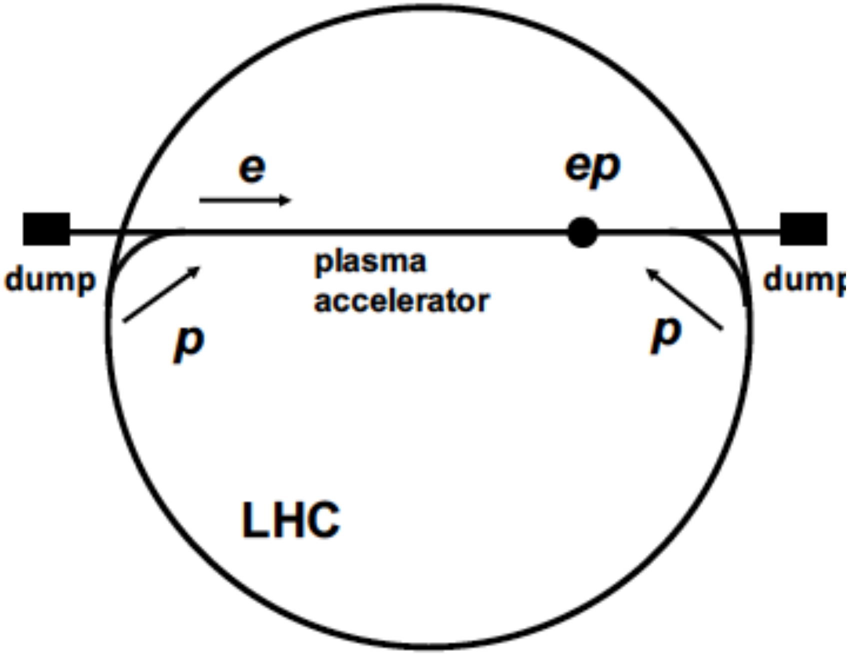
Are there fundamental particle physics topics for high energy but low luminosity colliders ?

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.

VHEeP

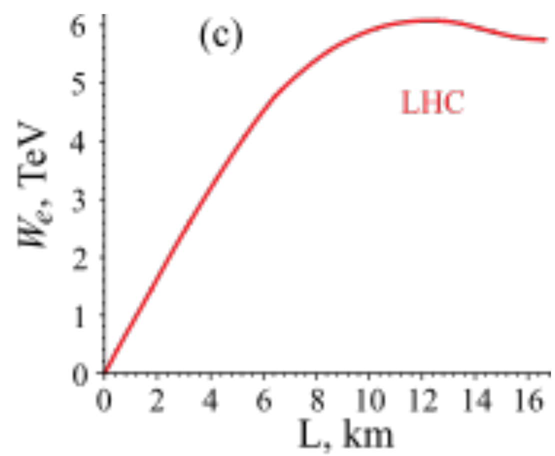
(Very High Energy electron-Proton collider)



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



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

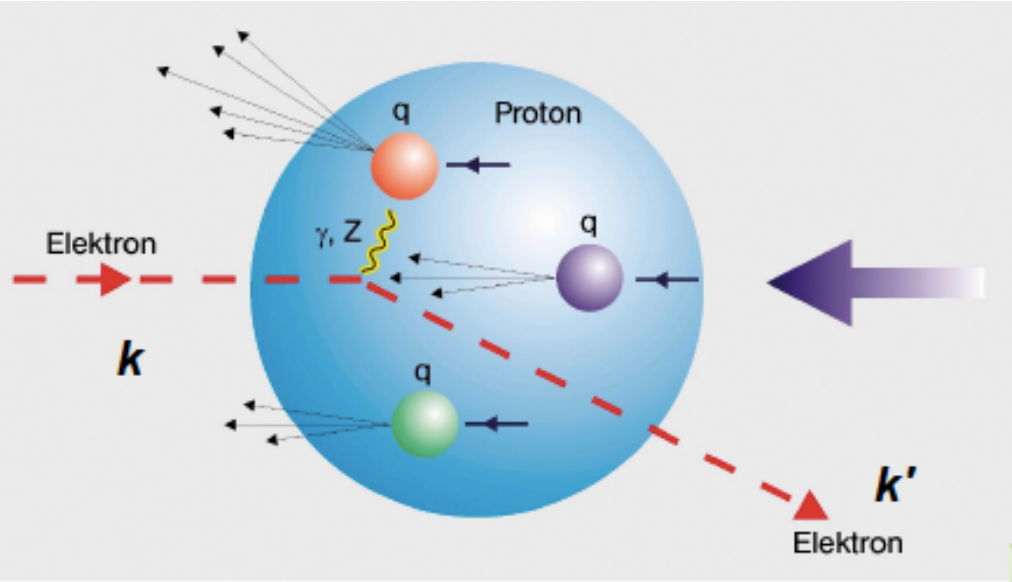
VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

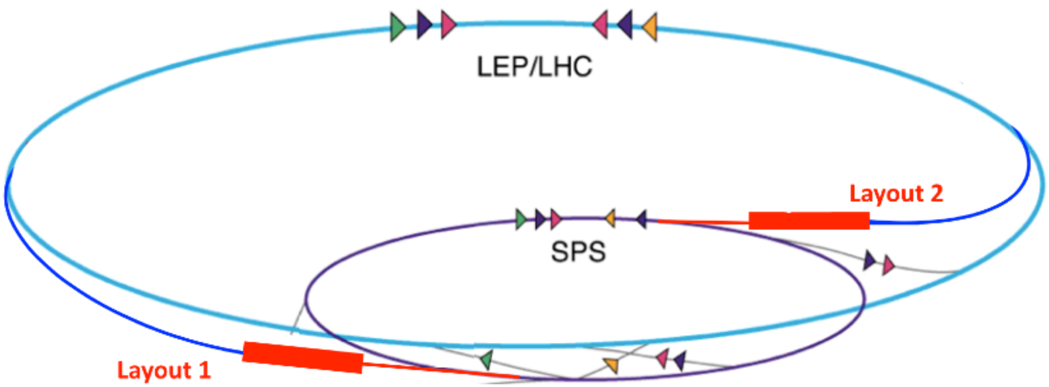
A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

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}.

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.