MAX-PLANCK-GESELLSCHAFT

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

AWAKE
A novel plasma wakefield acceleration experiment

Allen Caldwell
Max-Planck-Institut für Physik

1. **Motivation for plasma wakefield acceleration**
2. **How it works & challenges**
3. **The AWAKE project**
4. **Long-term perspectives**

AWAKE

The most important tool for this development was the particle accelerator

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 [illegible] 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}	[illegible]	[illegible]	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	[illegible]	[illegible]

FERMIONS

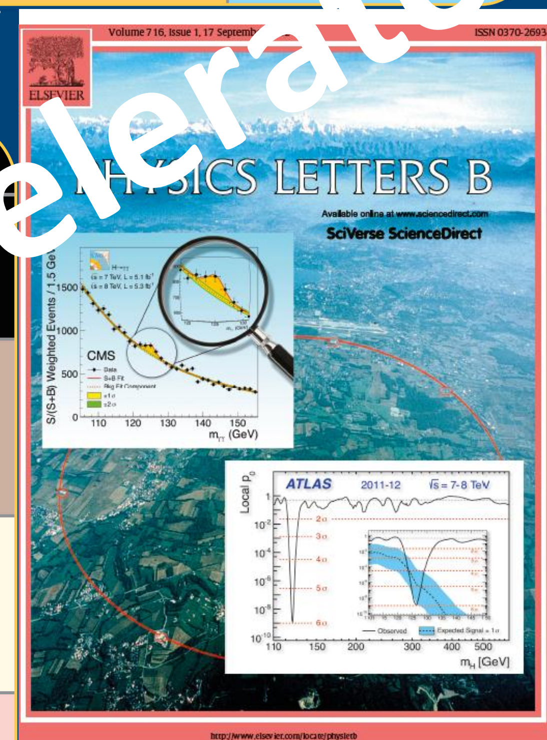
matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

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

Quarks spin = 1/2

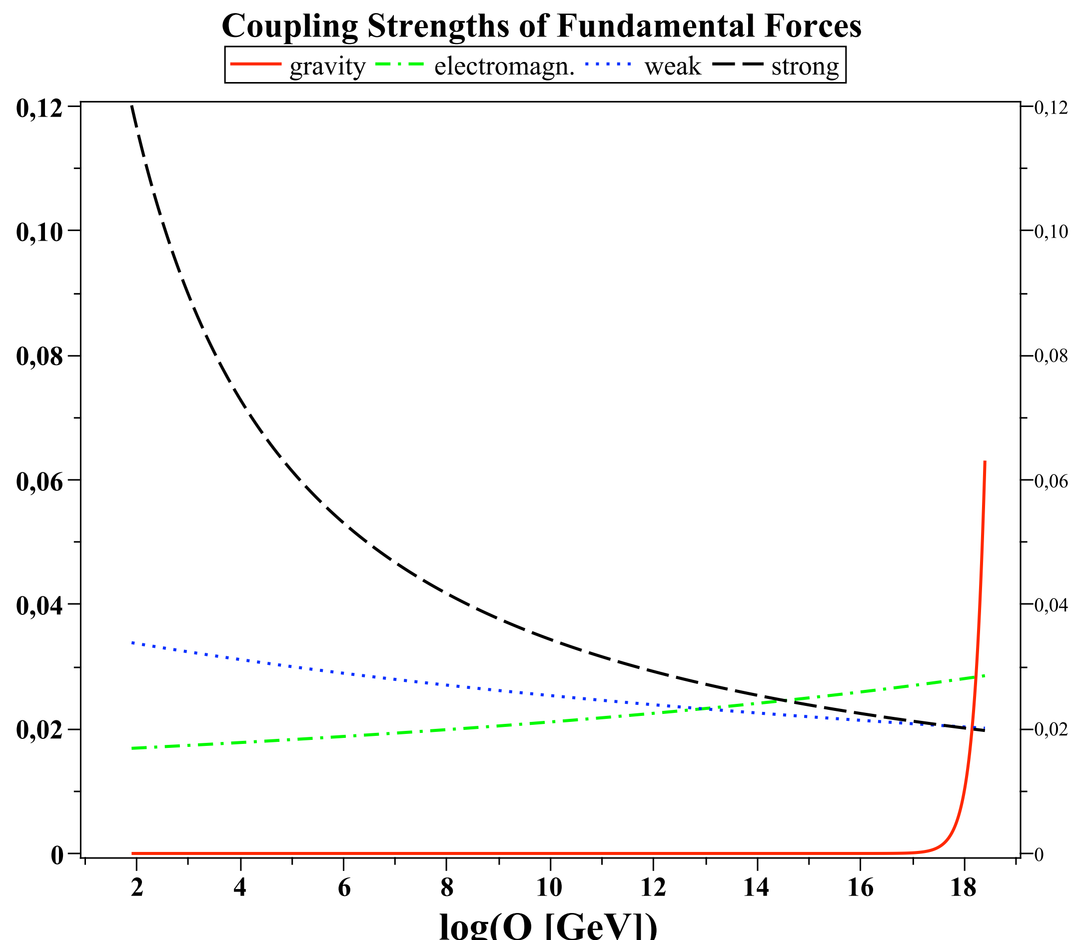
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	[illegible]	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3



Particle physicists are convinced there are more discoveries to come:

Many things not explained in the standard model:

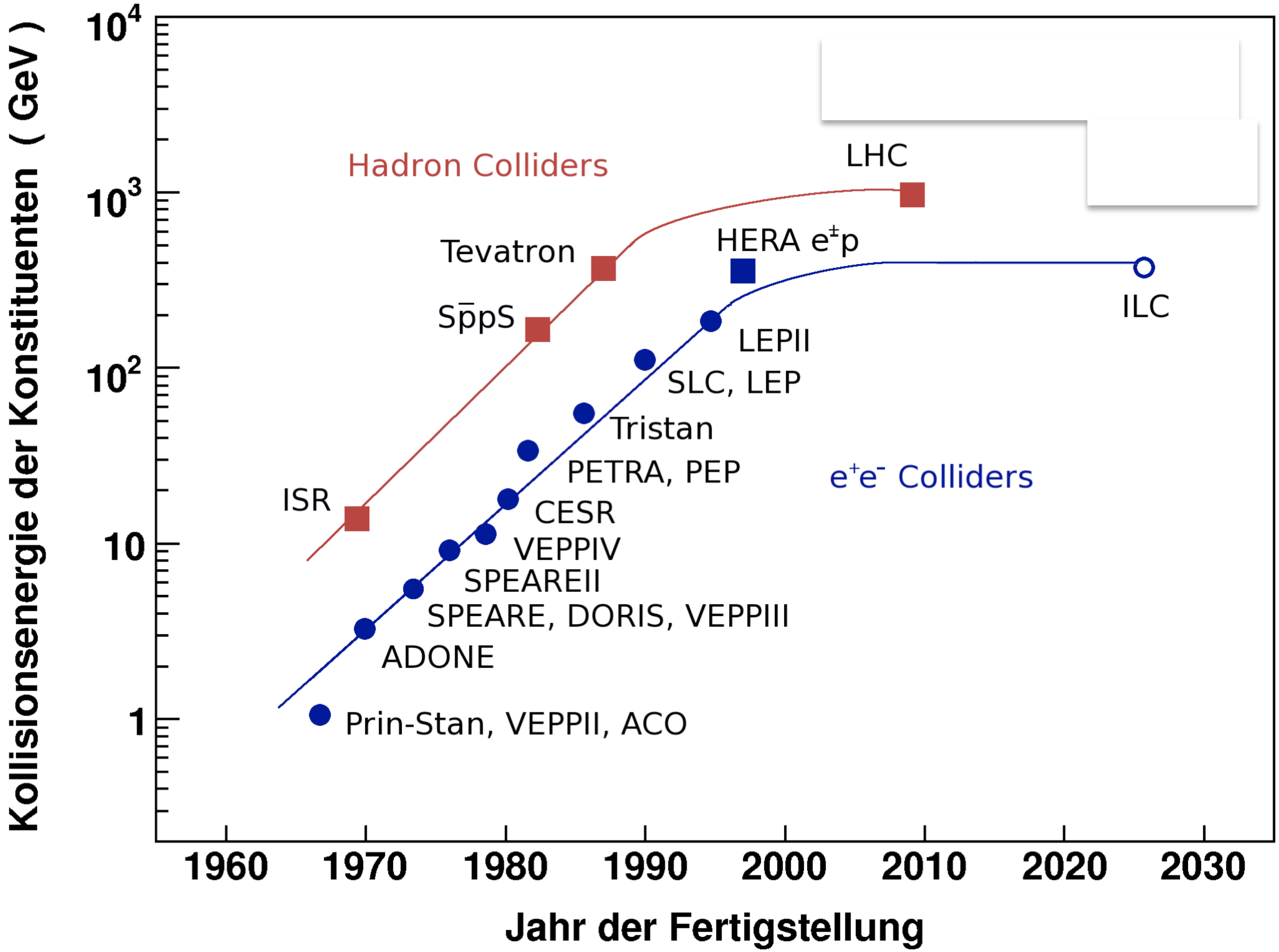
- why three families
- matter/antimatter imbalance
- neutrinos and neutrino mass
- hierarchy problem/unification
- dark matter
- dark energy
- …



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

New acceleration technology !

The Livingston plot shows a saturation …

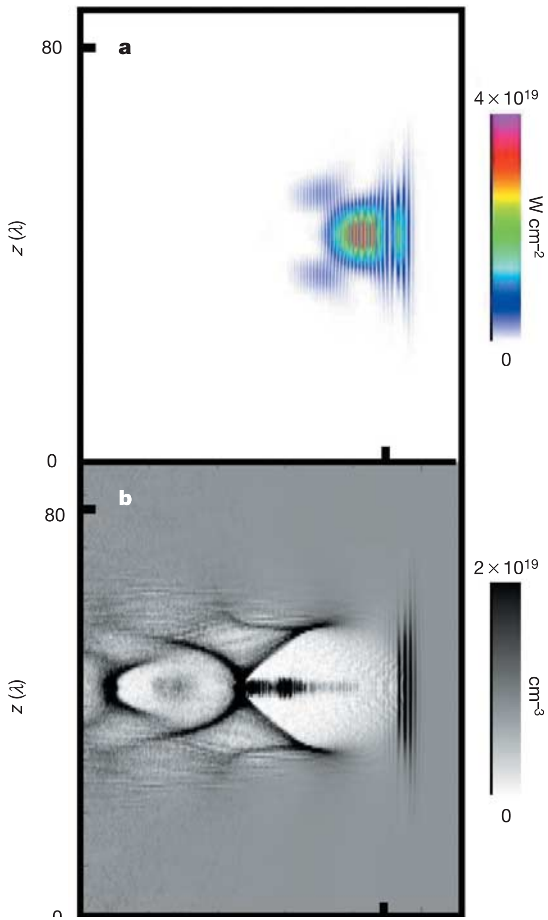


Practical limit for accelerators at the energy frontier: Project size and cost increasing with the energy ! New technology needed…

Plasma Wakefield Acceleration

Original Proposal: T. Tajima and J. W. Dawson, *Phys. Rev. Lett.* **43** (1979) 267.

Figure from
J. Faure et al.,
Nature **43**



Plasma frequency depends only on density

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

$$k_p = \frac{\omega_p}{c}$$

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

Produce an accelerator with mm (or less) scale 'cavities'

100 GeV/m acceleration demonstrated !

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

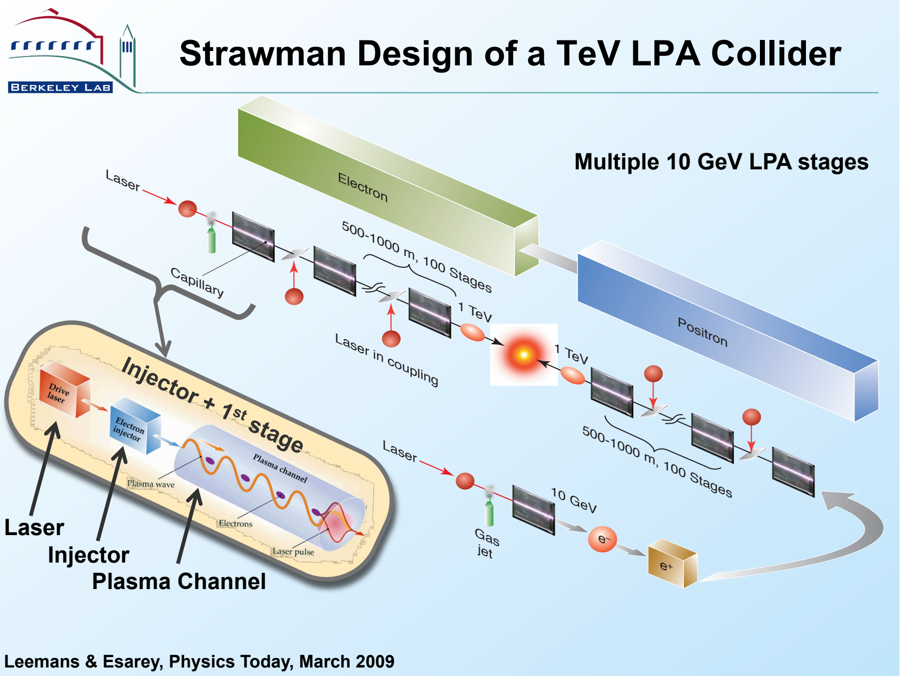
FACET, 30J/bunch

SPS 20kJ/bunch

LHC 300 kJ/bunch

Witness:

10^{10} particles @ 1 TeV ≈ few kJ



Energy content of driver allows to consider single stage acceleration

Basic Aspects

- Small beam dimensions required !

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

  - Need very short proton bunches for strong gradients. Today's proton beams have

$$\sigma_z \approx 10 - 30\ \mathrm{cm}$$

- Phase slippage (protons 2000 times heavier than electrons) ?

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

  - Few hundred meters acceleration stage possible for E_p=1 TeV and λ_p ≈ mm

Basic Aspects

- Longitudinal growth of driving bunch due to energy spread ?

$$d \approx 2 \frac{\Delta E}{E} \frac{L}{\gamma^2}$$

  - Few hundred meters possible for E_p=1 TeV, ΔE/E=0.1 with d≈100 μm

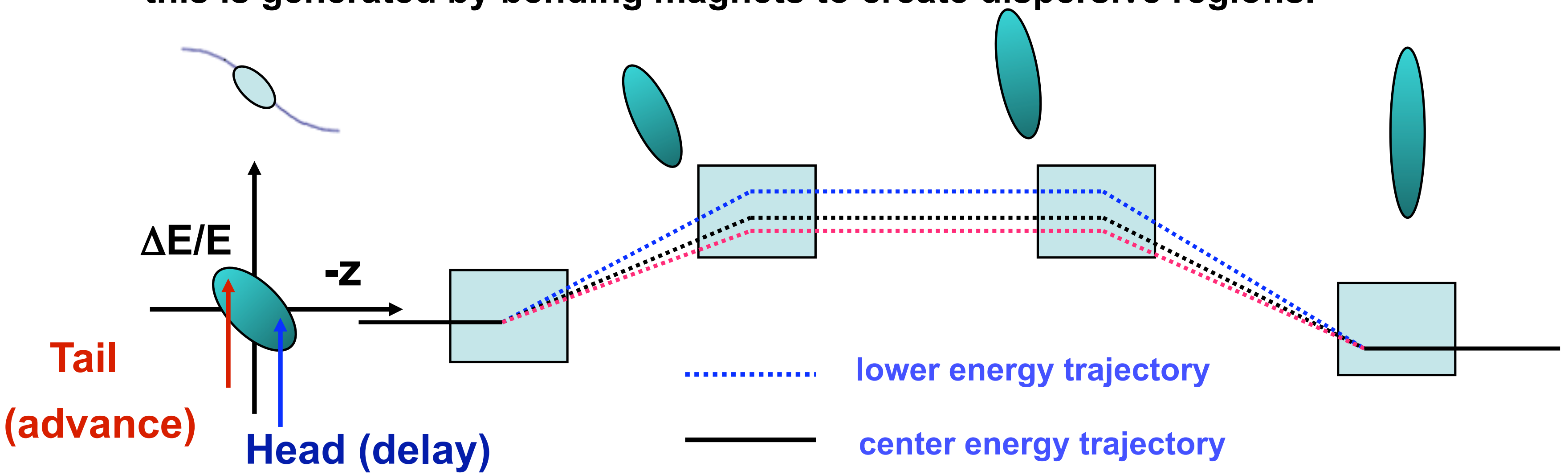
- Proton (QCD) interactions ?

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

Fundamental issue: proton bunch length

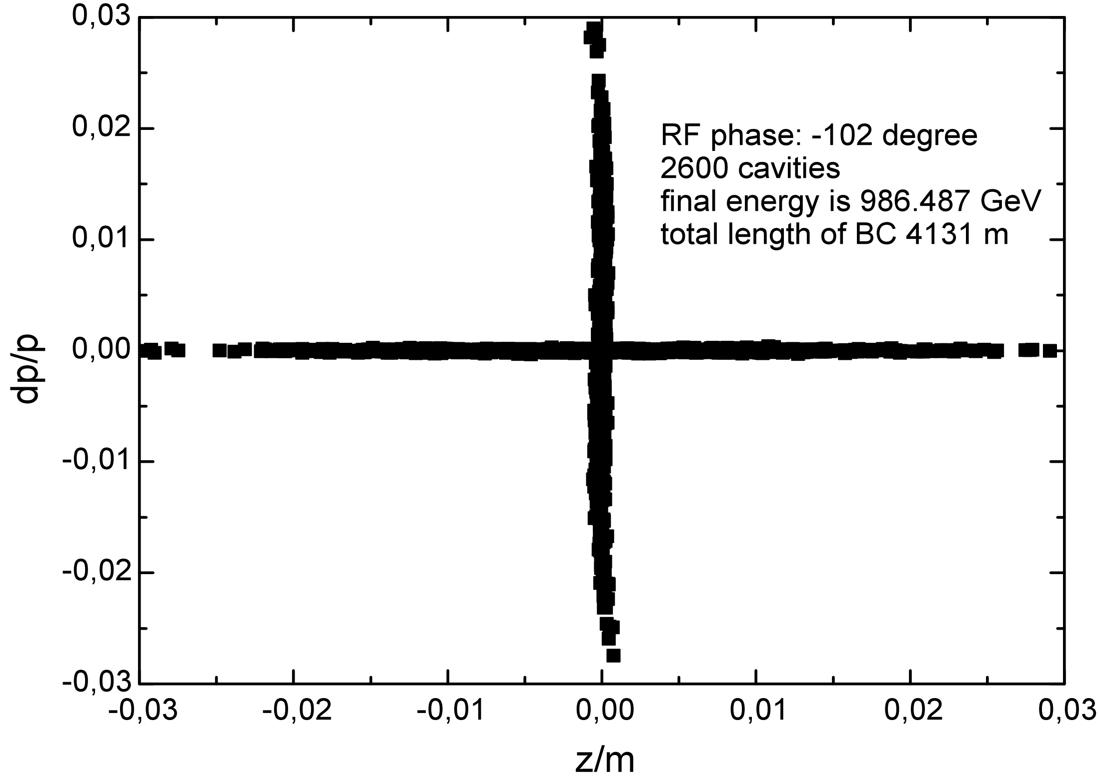
Magnetic bunch compression (BC)

- **Beam compression can be achieved:**
  (1) by introducing an energy-position correlation along the bunch with an RF section at zero-crossing of voltage
  (2) and passing beam through a region where path length is energy dependent: this is generated by bending magnets to create dispersive regions.



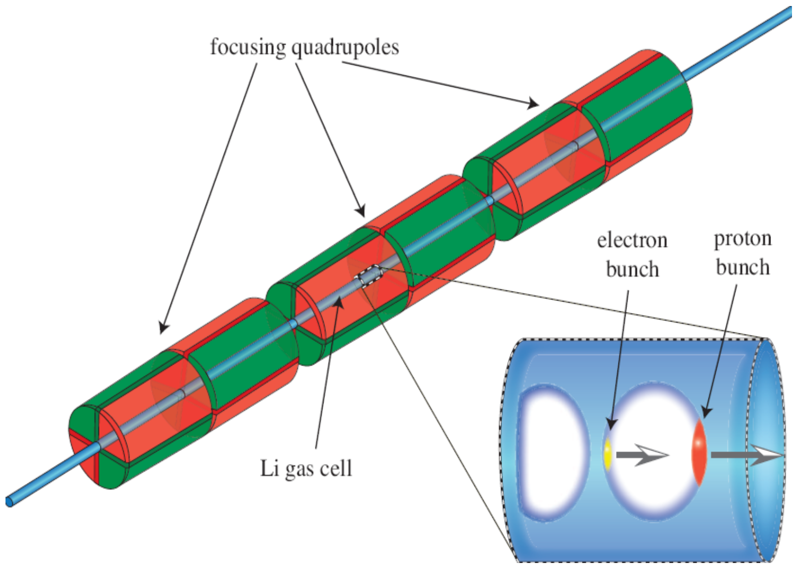
- **To compress a bunch longitudinally, trajectory in dispersive region must be shorter for tail of the bunch than it is for the head.**

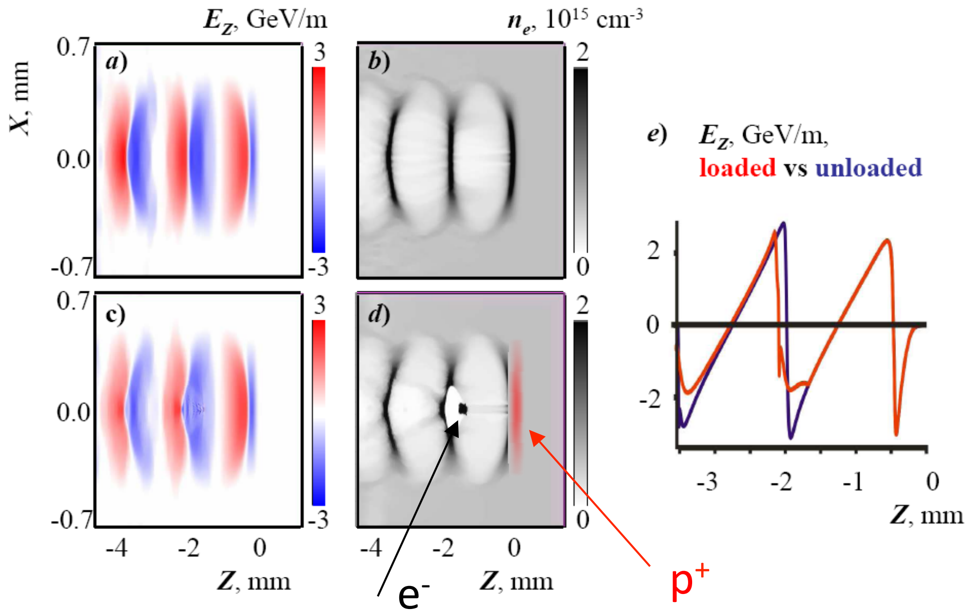
Phase space of beam



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

Simulation Results





Drive beam: p^+

E=1 TeV, $N_p=10^{11}$

σ_z=100 µm,σ_r=0.43 mm

σ_θ=0.03 mrad, ΔE/E=10%

Witness beam: e^-

E_0=10 GeV, $N_e=1.5\times10^{10}$

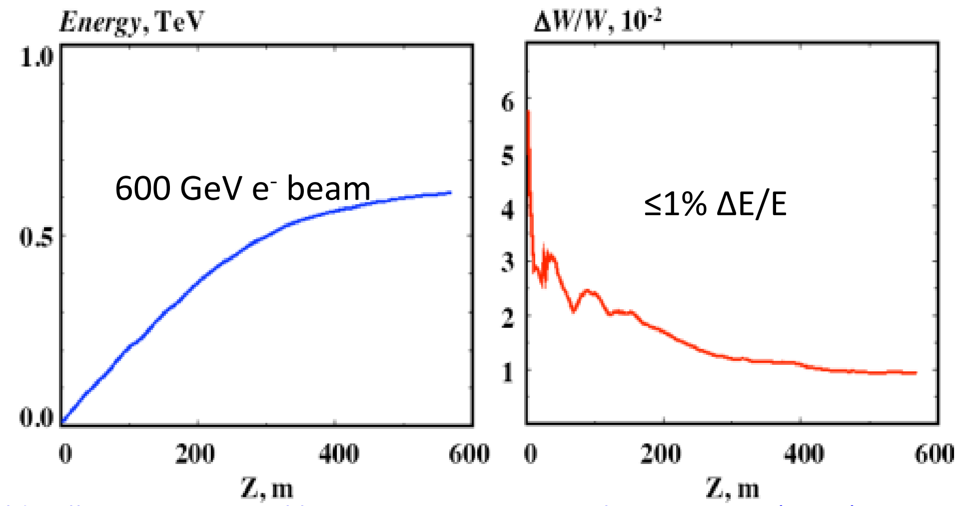
Plasma: Li^+

$n_p=6\times10^{14}cm^{-3}$

External magnetic field:

Field gradient: 1000 T/m

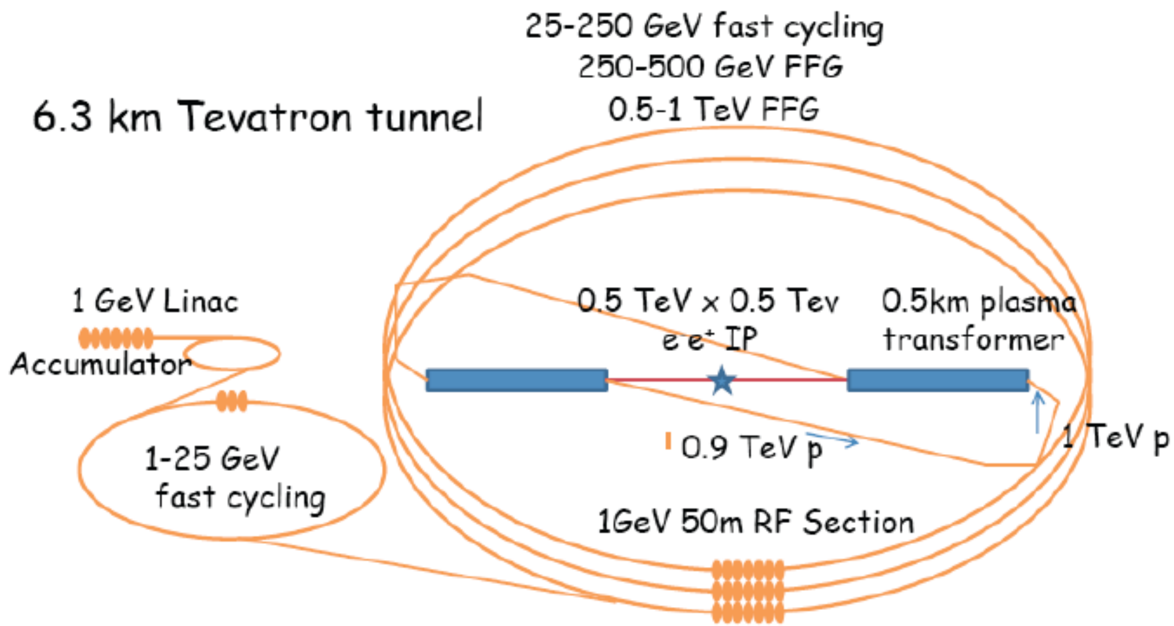
Magnet length: 0.7 m



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

Ideal proton-driven PWPA accelerator

V. Yakimenko, BNL, T. Katsouleas, Duke



Wish list:

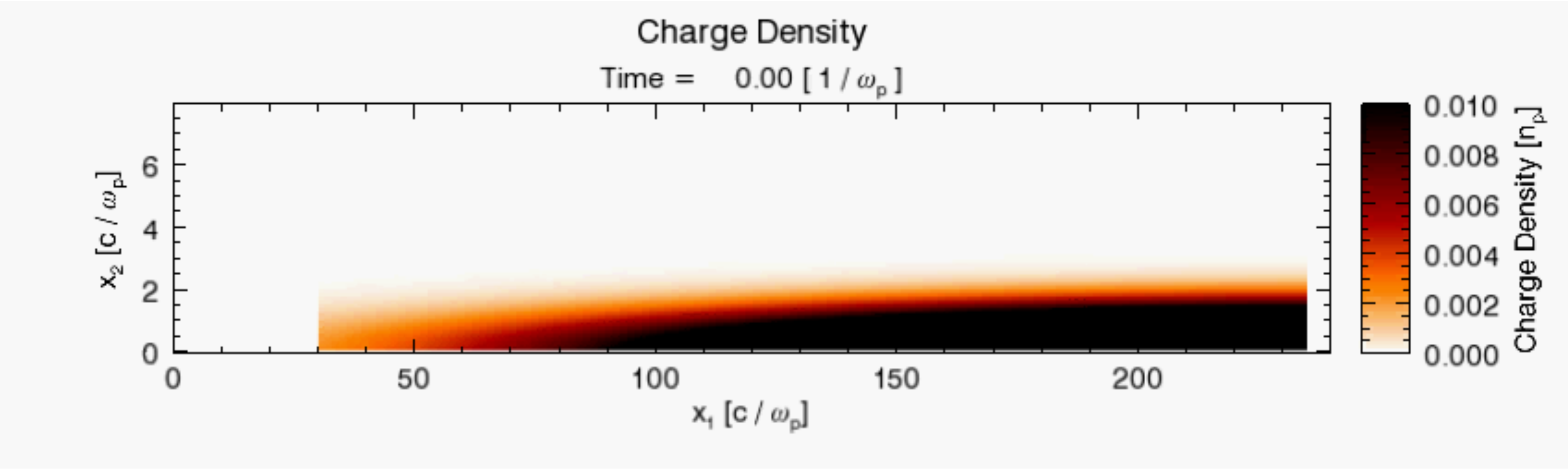
- high repetition rate
- Short proton bunches
- Diverse physics program: pp, ep, e^+e^-, $\mu^+ \mu^-$, ν beams

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

Modulated Proton Beam

The 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.

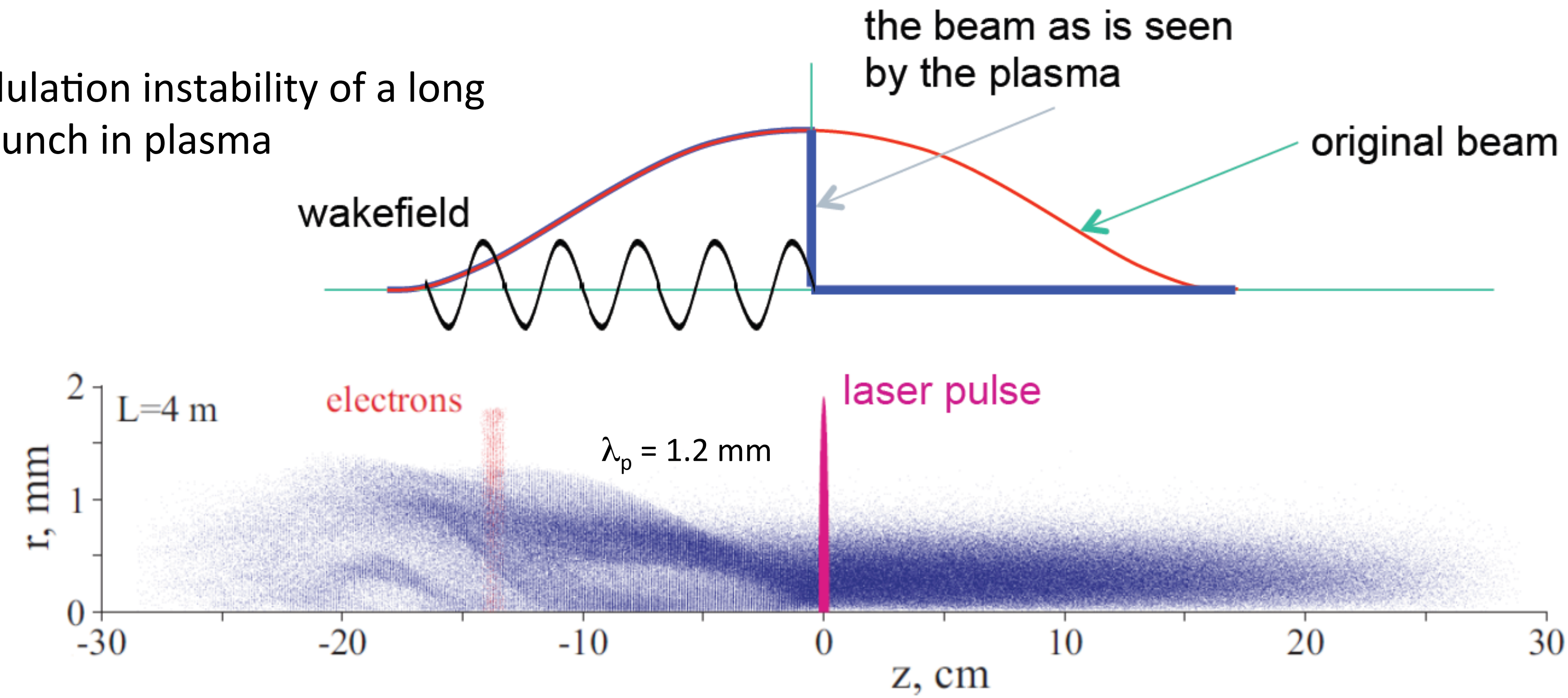
N. Kumar, A. Pukhov, and K. V. Lotov, Phys. Rev. Lett. **104**, 255003 (2010)



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

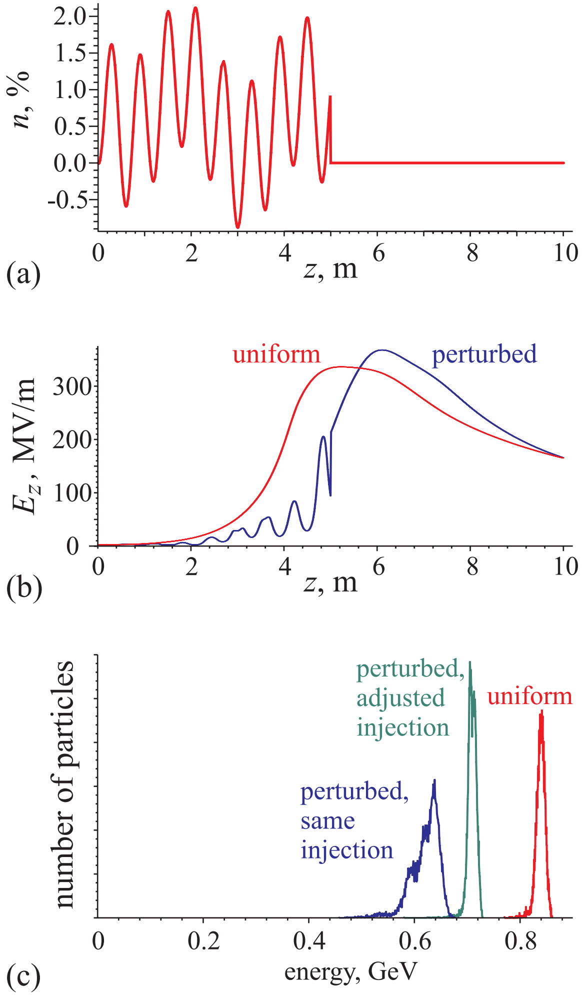
Modulated Proton Bunch

Self-modulation instability of a long proton bunch in plasma



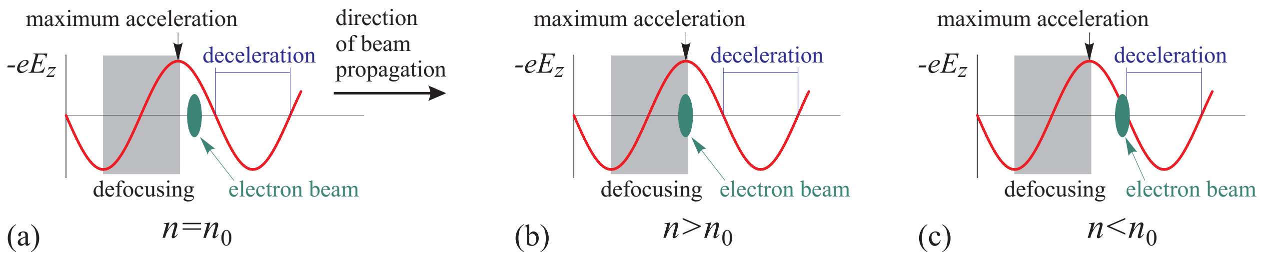
Self-modulated proton bunch resonantly driving plasma wakefields.

Plasma Uniformity



Nonuniformities can be tolerated in the modulation stage

But are dangerous for electron trapping and acceleration.

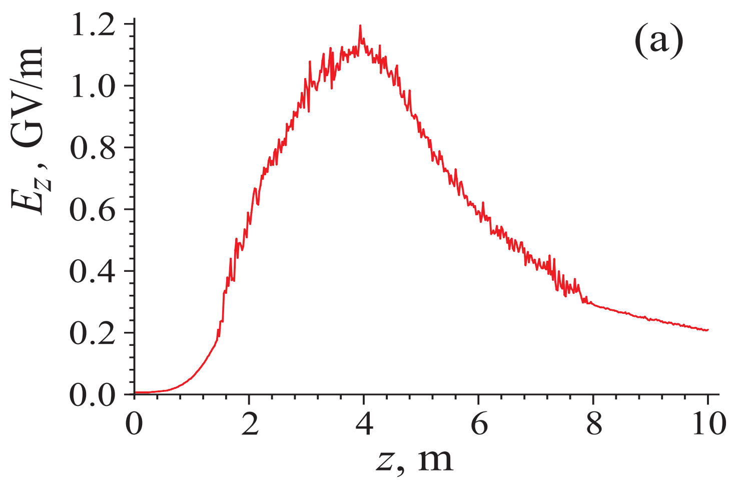


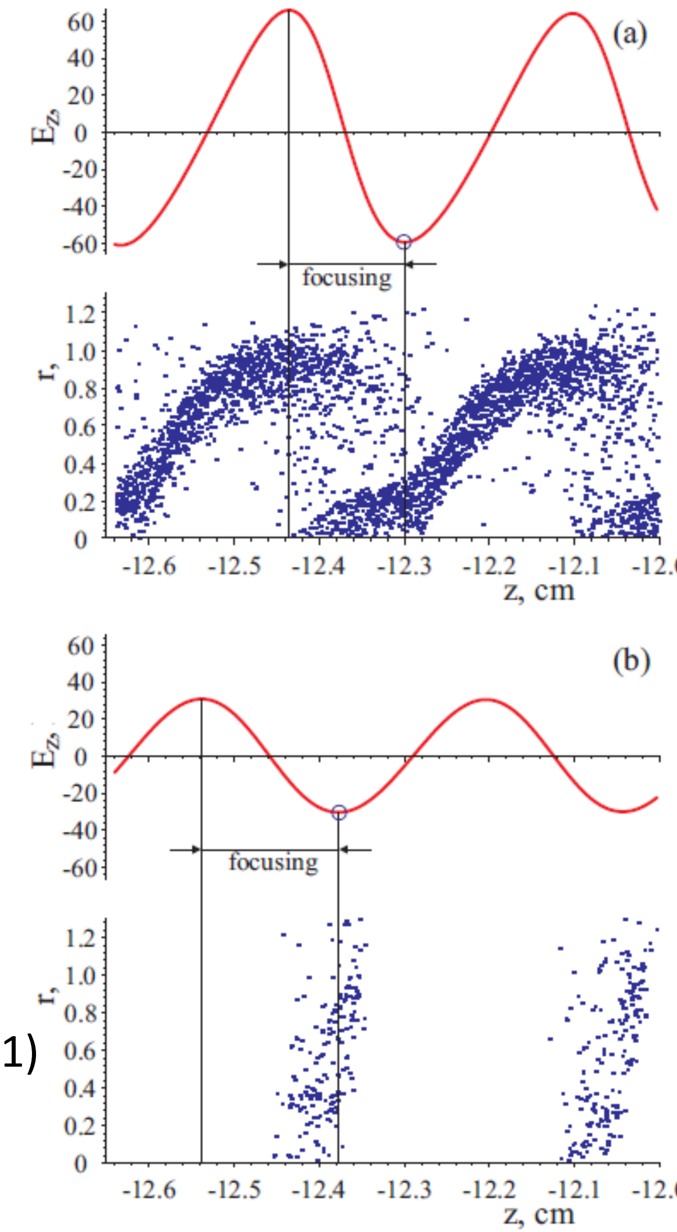
$$\delta n_{\max} \approx \frac{0.25}{N_{\text{periods}}}$$

But smooth gradients can be tolerated …

Lotov, Pukhov, Caldwell, Phys. of Plasmas, **20**, 013102 (2013)

Freezing the Modulation





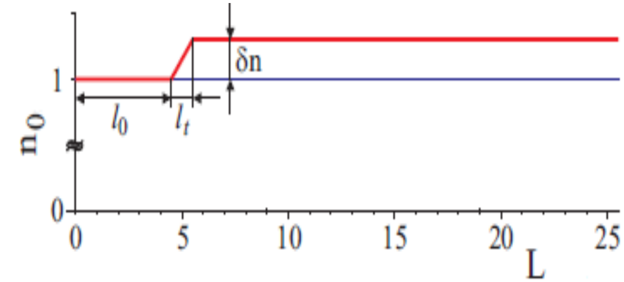
... wakefield amplitude quickly drops after the beam gets modulated.

Reason: defocusing regions keep on moving along the beam and destroys the bunches.

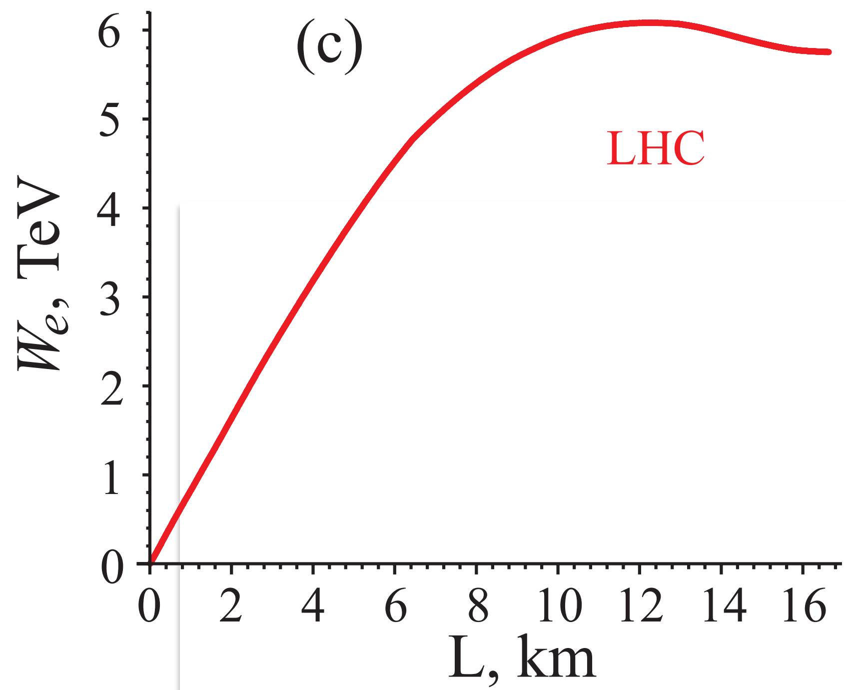
A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

Freezing the Modulation

Remedy: control of the wave phase by the plasma density profile



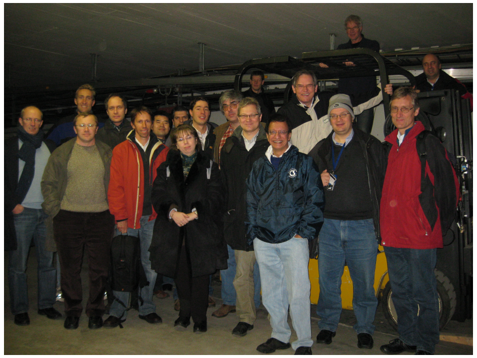
E_e= 6 TeV reached in simulations with modulated LHC beam



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

History

2009 driven

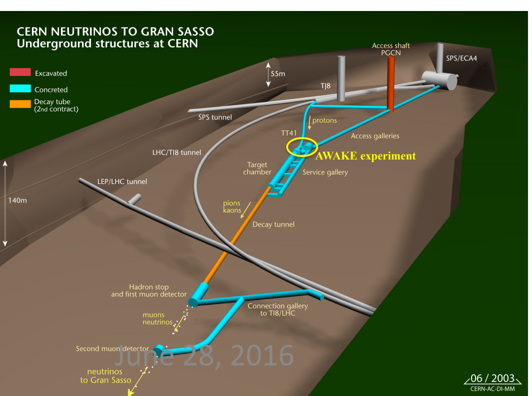


First workshop at CERN to discuss potential of proton-PWA.

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.

Plan – start experimental program 2016.

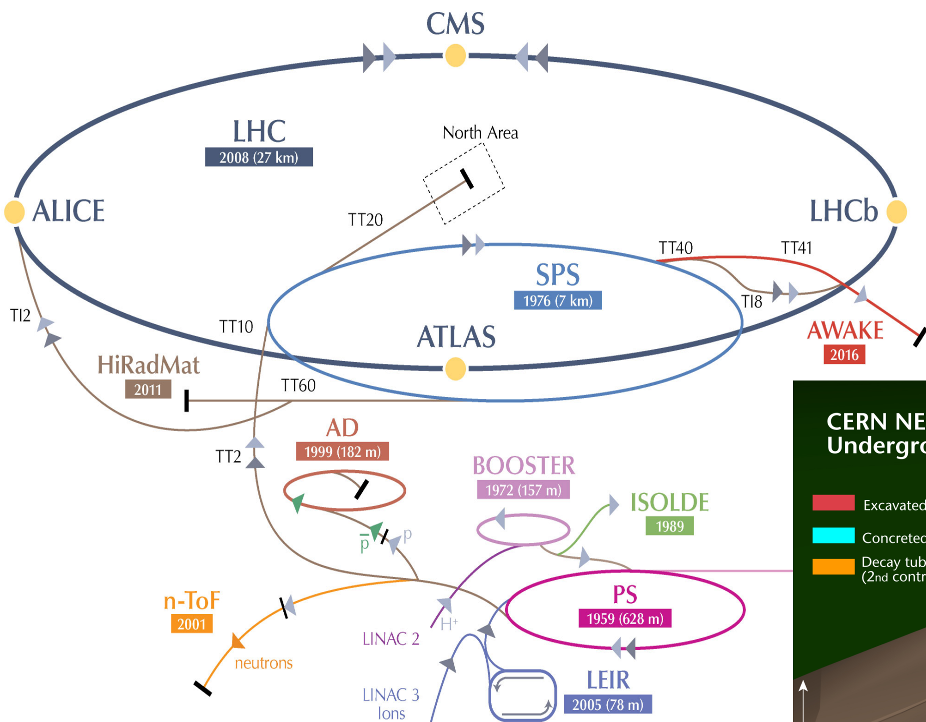
AWAKE

- 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

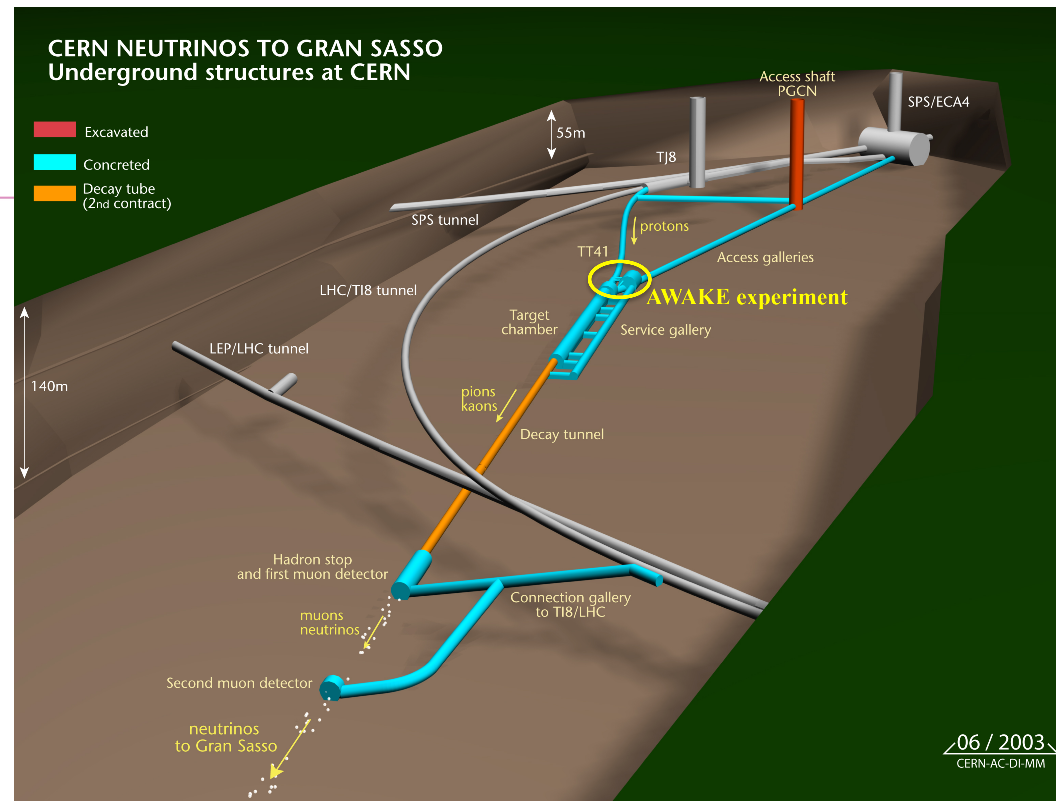
AWAKE at CERN



AWAKE is installed in

CNGS Facility (CERN Neutrinos to Gran Sasso)

→ CNGS physics program finished in 2012

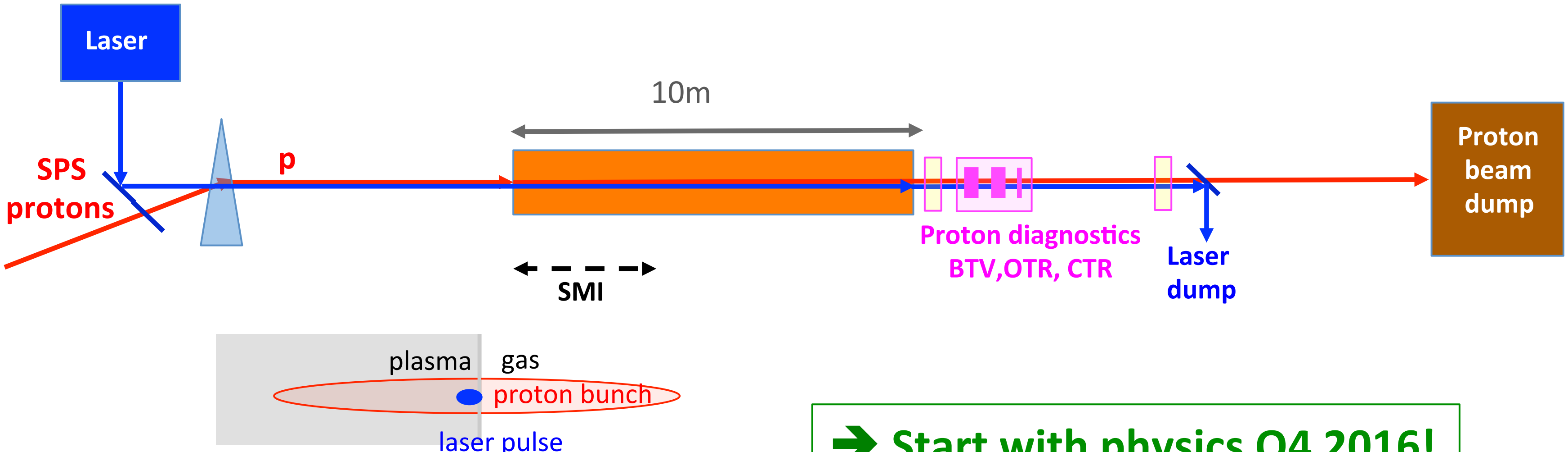


Proton-driven plasma wakefield acceleration: a path to the future of high-energy particle physics

R Assmann et al.,
Plasma Physics and Controlled Fusion
Vol 56, Number 8

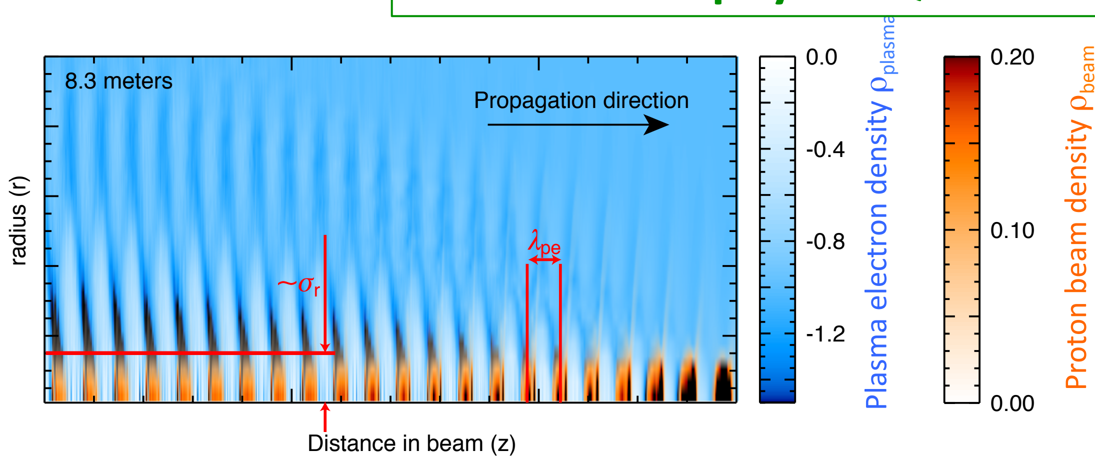
AWAKE: Experimental Program

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



➔ Start with physics Q4 2016!

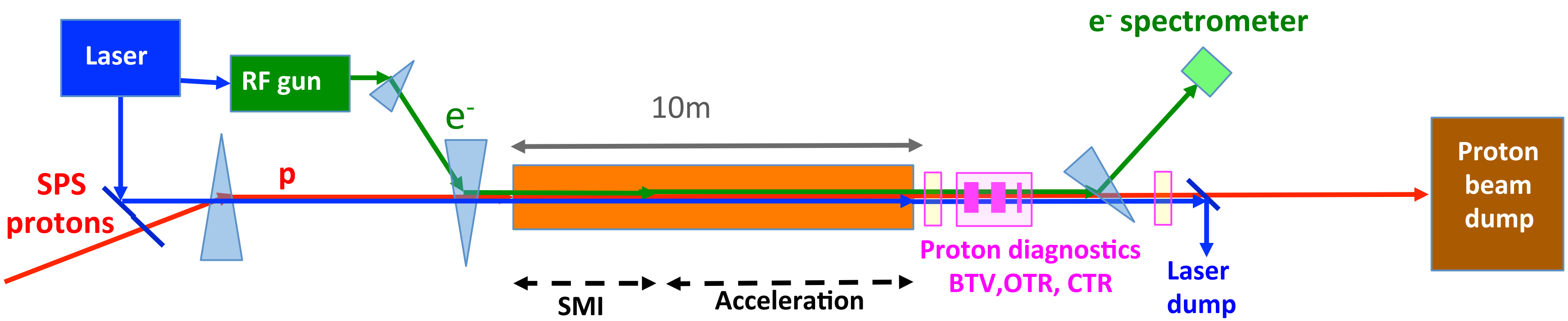
Self-modulated proton bunch resonantly driving plasma wakefields.

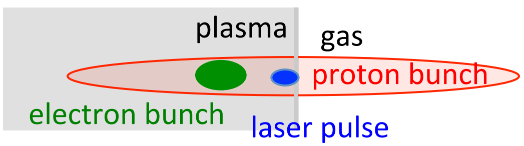


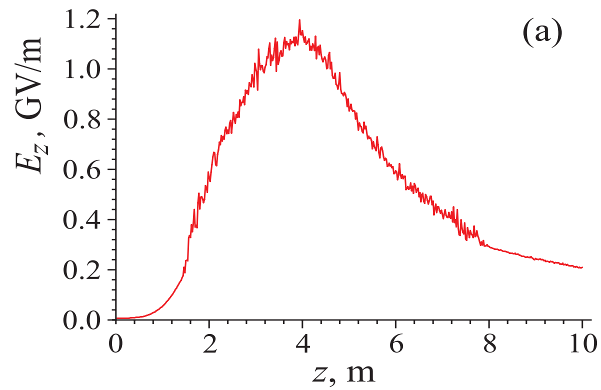
J. Vieira et al PoP 19063105 (2012)

AWAKE Experimental Program

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



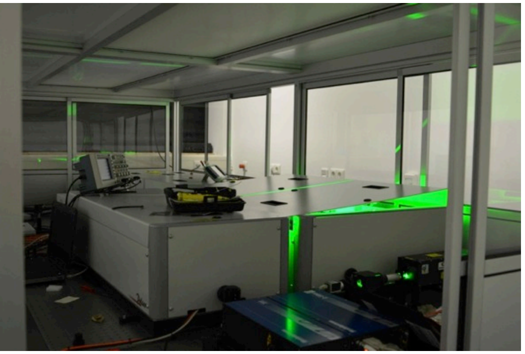


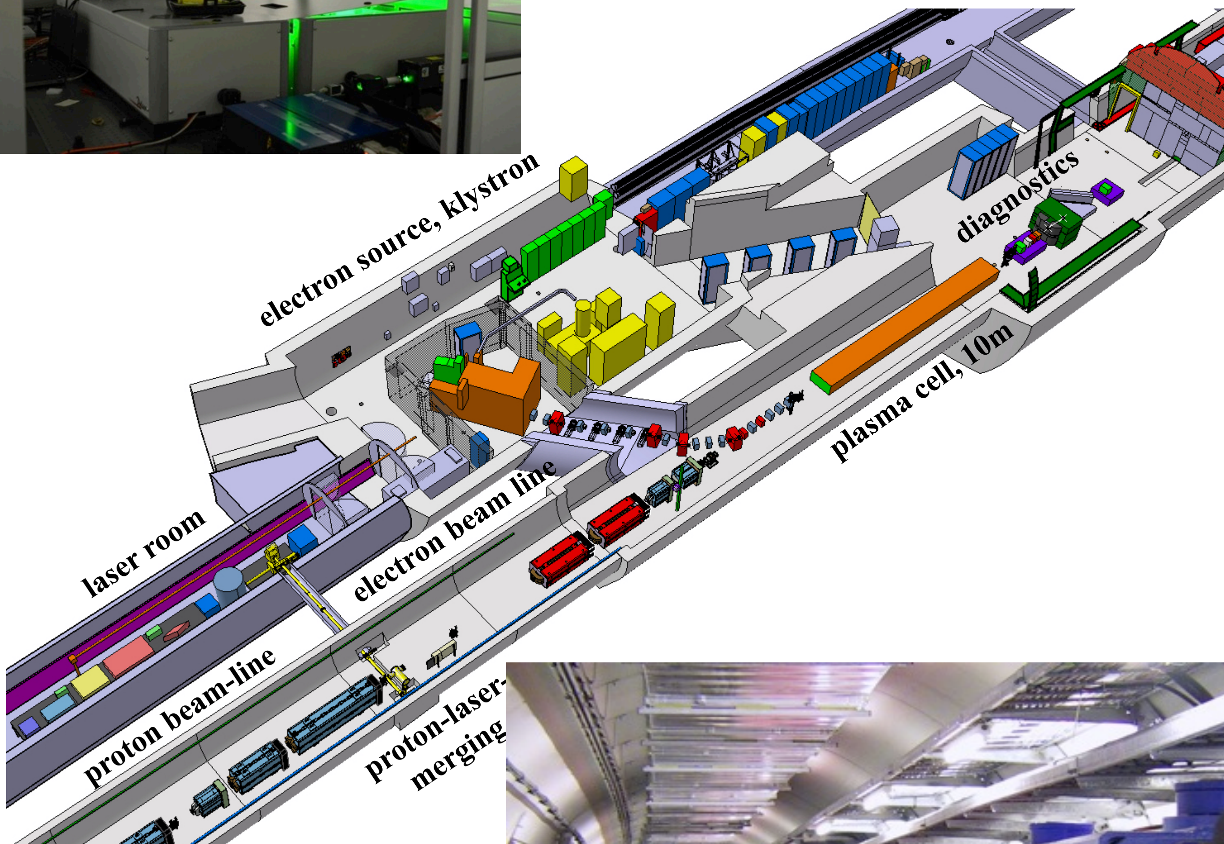


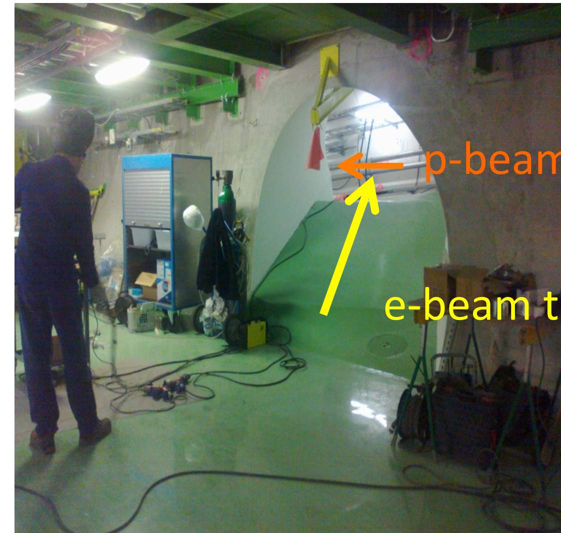
Demonstrate GeV scale gradients with proton driven wakefields.

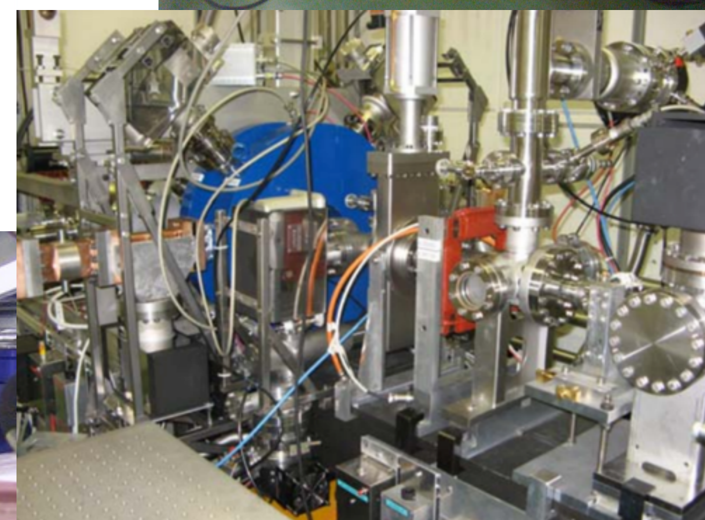
Maximum amplitude of the **accelerating field E_z** as a function of position along the plasma. Saturation of the SMI at ~4m.

AWAKE Overview

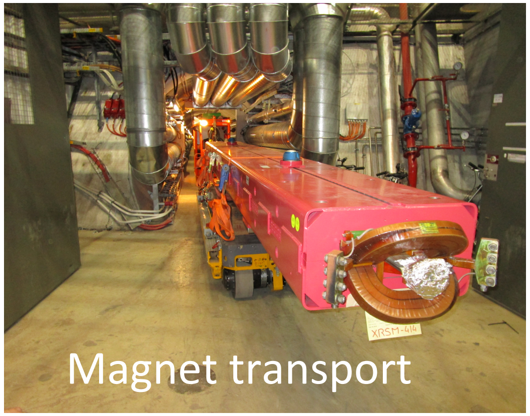


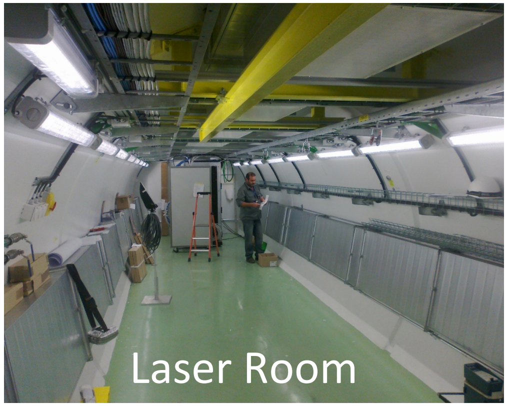






AWAKE Preparations





Particle Physics Application

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.

VHEeP: A very high energy electron–proton collider based on proton-driven plasma wakefield acceleration

Allen Caldwell (MPI)
Matthew Wing (UCL/DESY/Univ. Hamburg)

- Introduction
- Accelerator based on plasma wakefield acceleration
- Physics in very high energy *eP* collisions
- Summary and outlook

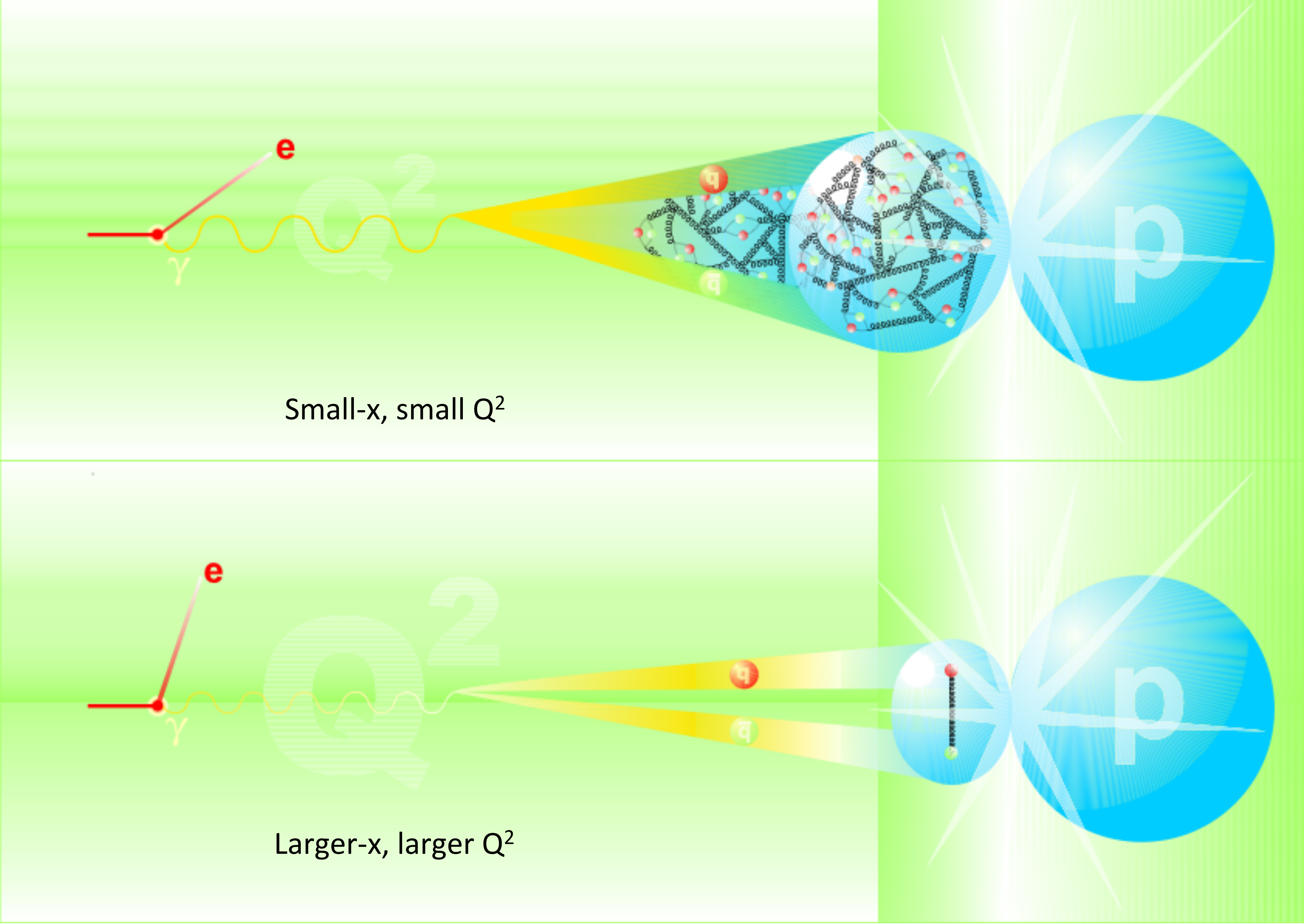
DIS 2015 Workshop — 28 April 2015

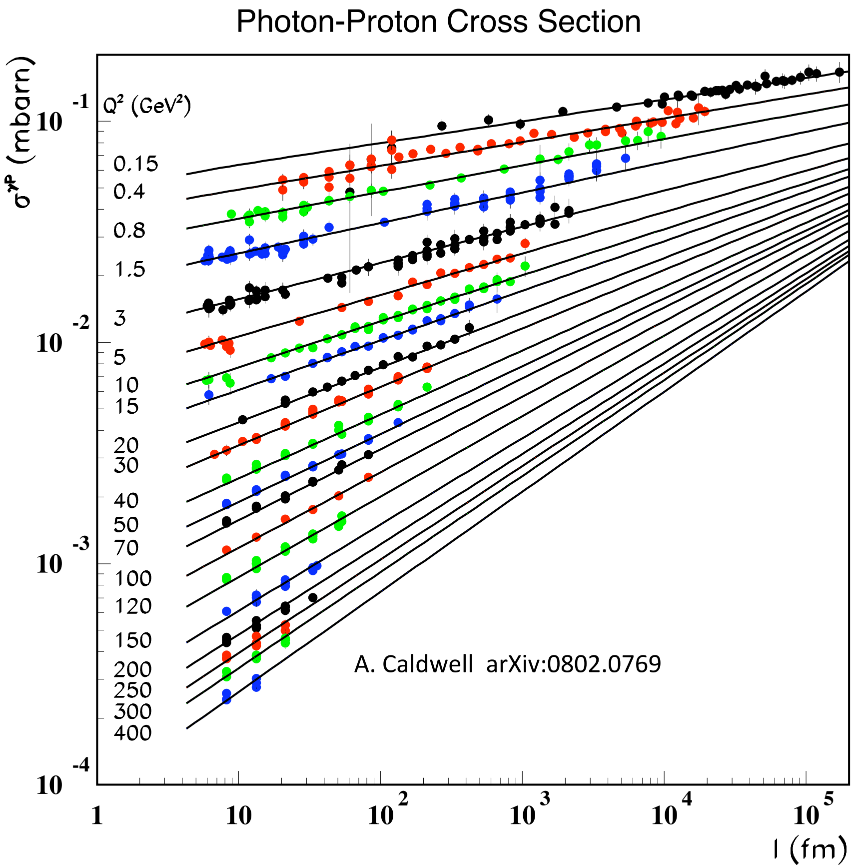
Electron Proton Scattering in the Proton Rest Frame

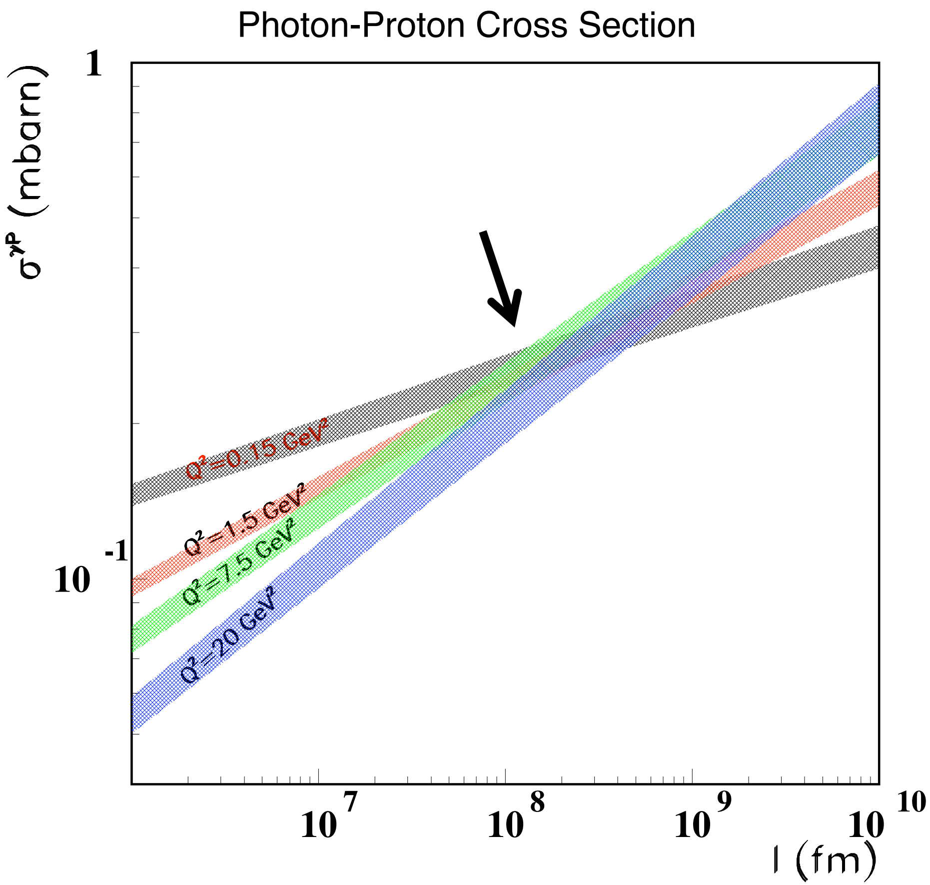
$$\Delta E_\gamma = \sqrt{P_\gamma^2 + M_X{}^2} - \sqrt{P_\gamma^2 + q^2} \approx \frac{Q^2}{E_\gamma} \qquad M_X = Q$$

$$E_\gamma = W^2/2M_P \qquad \Delta E_\gamma \approx \frac{2M_P Q^2}{W^2} \qquad l \approx \frac{0.2\,fm}{2M_P x}$$

So, small-x means long-lived photon fluctuations (not proton structure)


e
γ
Q2
q
p
Small-x, small Q2
e
γ
Q2
q
p
Larger-x, larger Q2

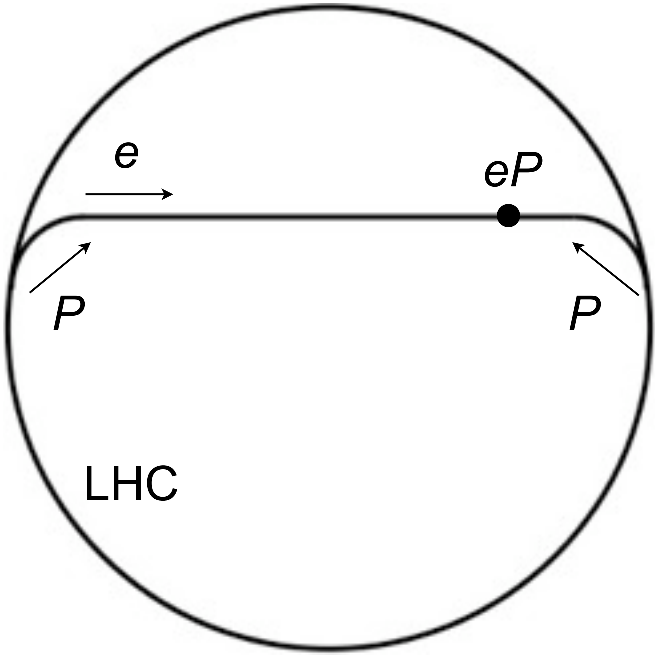




Increase of the photon-proton cross section with coherence length.

Cross sections increasing with energy -> do not require large luminosity to probe this physics.

Plasma wakefield accelerator



$$\mathcal{L} = f \frac{N_e \cdot N_p}{4\pi\sigma_x \cdot \sigma_y}$$

$$\approx 5 \cdot 10^{28} \mathrm{cm}^{-2} \mathrm{s}^{-1}$$

- Emphasis on using current infrastructure, i.e. LHC beam with minimum modifications.
- Overall layout works in powerpoint.
- Need high gradient magnets to bend protons into the LHC ring.
- One proton beam used for electron acceleration to then collider with other proton beam.
- High energies achievable and can vary electron beam energy.
- What about luminosity ?
- Assume
  - *~3000* bunches every *30 mins*, gives $f \sim 2$ Hz.
  - $N_p \sim 4 \times 10^{11}$, $N_e \sim 1 \times 10^{11}$
  - $\sigma \sim 4\ \mu m$

Summary

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

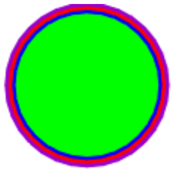
Modulation process means existing proton machines can be used

Goal for AWAKE: demonstrate modulation process and proton-driven acceleration of electrons before LS2 of the LHC

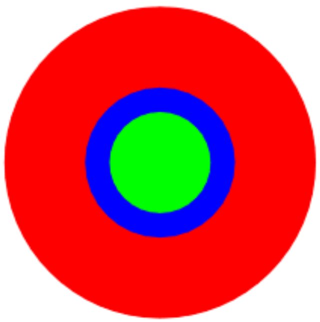
Long term prospects for proton-driven PWA exciting !

Seeding the correct instability

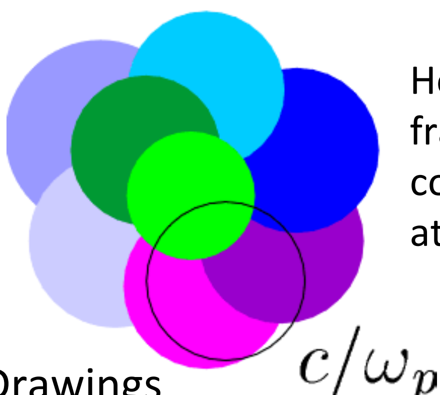
Spontaneous instability vs Seeded instability



Original beam
(front view)

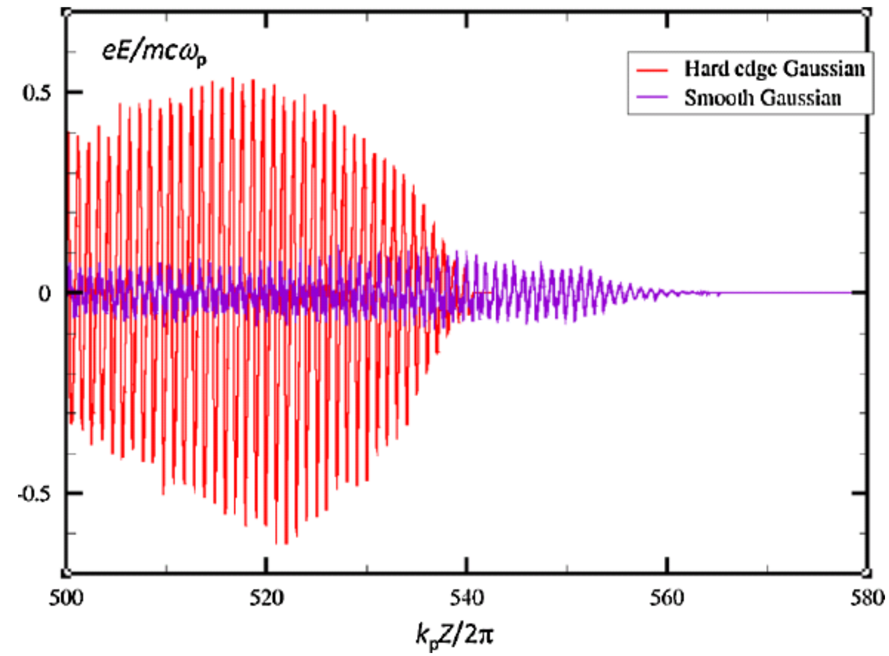


Axisymmetric mode
(half of the beam
contributes to on-axis
field excitation)



Hosing mode (small
fraction of the beam
contributes to the field
at a given point)

Drawings
from K. Lotov



Hosing Instability Suppression in
Self-Modulated Plasma Wakefields
J. Vieira, W. B. Mori, and P. Muggli
Phys. Rev. Lett. 112, 205001 (2014)

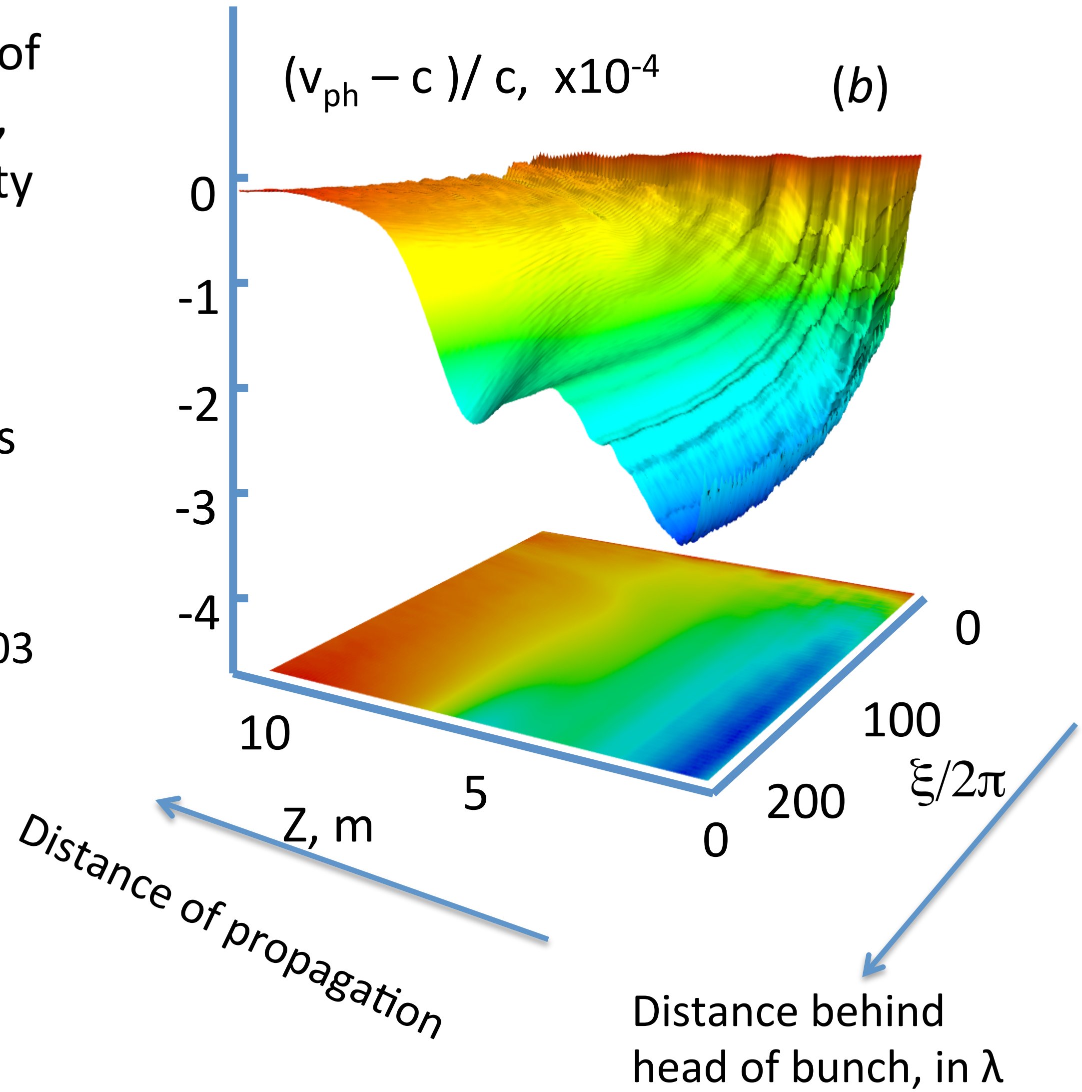
Need to avoid hosing to produce strong fields

Phase velocity of the wake

To optimize trapping & acceleration of electrons in the wake of the protons, should match the wake phase velocity to the electron velocity.

For best e-beam parameters, inject electrons after the phase velocity has stabilized.

Pukhov et al., Phys. Rev. Lett. **107**, 145003 (2011)



AWAKE: Plasma Source

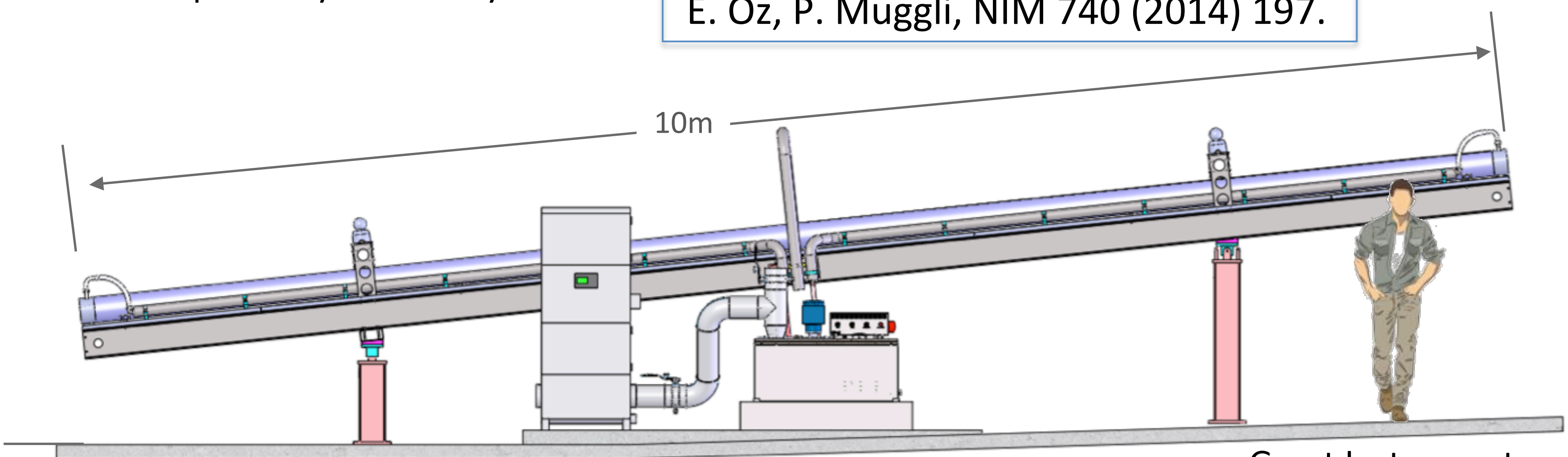
- Density adjustable from **$10^{14} – 10^{15}$ cm^{-3}**
- 10 m long, 4 cm diameter

- 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

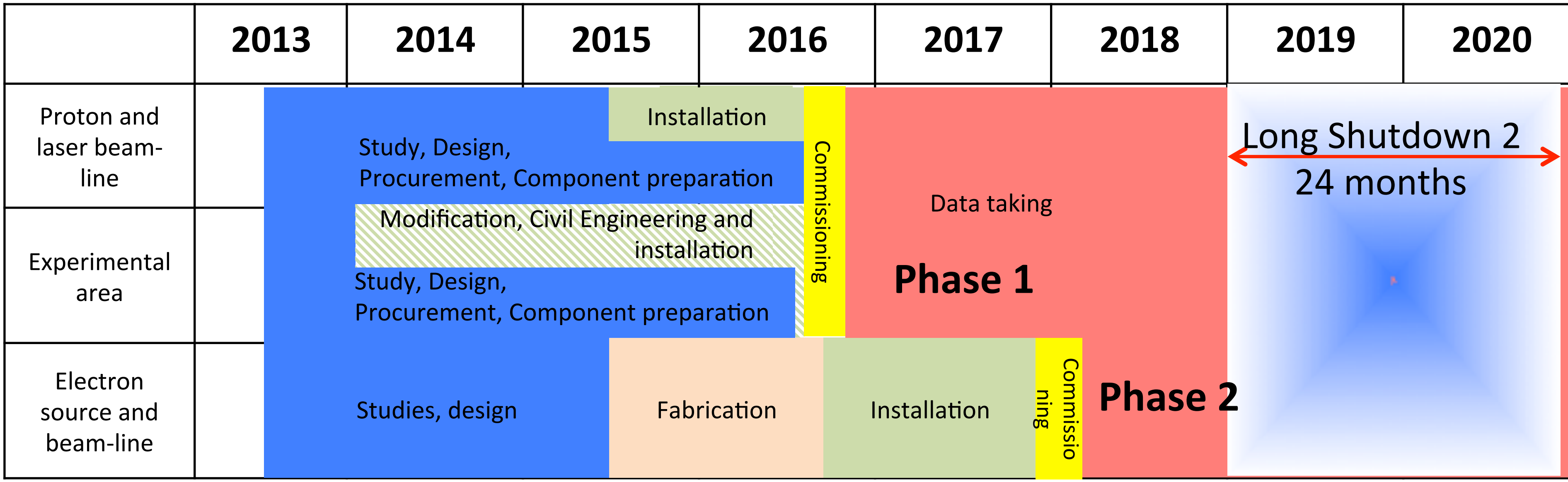
- System is oil-heated: 150˚ to 200˚ C
  → keep temperature uniformity
  → Keep density uniformity

E. Öz, P. Muggli, NIM 740 (2014) 197.



Grant Instruments

AWAKE Time Line



Continue data taking after LS2

- **1st Phase:**
  - Start in ~1 year
  - Demonstrate proton bunch modulation
- **2nd Phase:**
  - Start in ~2 years
  - Demonstrate electron acceleration with GeV/m scale gradients