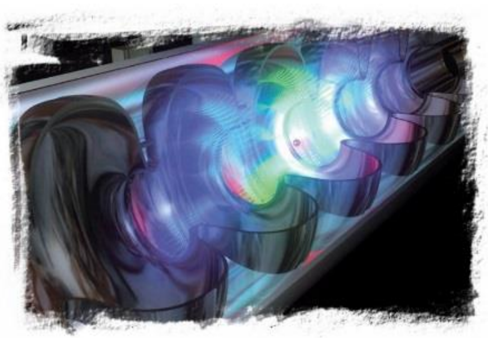
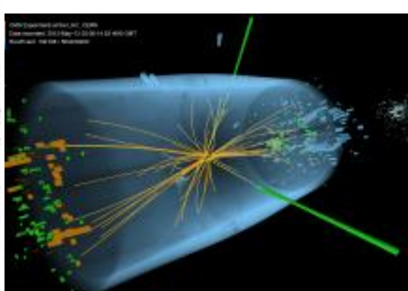
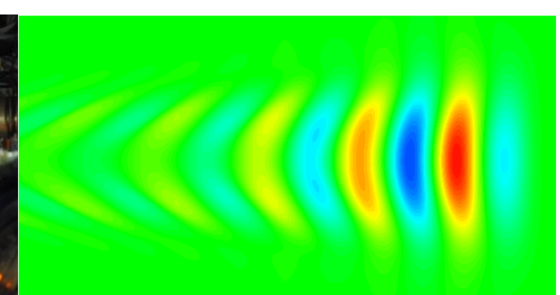
A Proton-driven Plasma Wakefield Experiment At CERN

Swapan Chattopadhyay

Laboratori Nazionali di Frascati , INFN Colloquium

6 July , 2016



OUTLINE

- Prologue
- Motivation for Plasma Wakefield acceleration
- Why Proton-driven?
- AWAKE Experiment and Global Collaboration
- AWAKE Experimental Set-up
- AWAKE Installation, Time-table and Phases
- Outlook

Acknowledgments

- **Allen Caldwell (MPI Munich, Germany)**

→ Spokesperson

- **Matthew Wing (UCL, UK)**

→ Deputy-Spokesperson

- **Edda Gschwendtner (CERN)**

→ Technical Project Leader

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Thanks to David Alessini, Massimo Ferrario, Marica Biagini (LNF/INFN)

And

Luigi Palumbo and Andrea Mostacci (Sapienza Univ. di Roma)

For the invitation!!!

Sir Humphrey Davy

"Nothing tends so much to the advancement of knowledge as the application of a new instrument"

from

Elements of Chemical Philosophy
(1812)

→ ***" High Energy Particle Beams and Colliders" are indeed "Grand Instruments of Science", playing a historically critical role in advancing our knowledge of elementary particles and forces***

Professor Victor F. Weisskopf

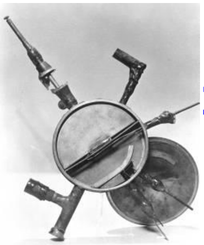
When I think about how we got into this small-scale region, I must say that the most important contributors have been the entire machine team --- I am reminded of the voyage of Columbus. There were those hardy ship builders, who knew not how far or where to or for how long the ships had to sail, but that they should withstand all tests of the unknown sea. These are our accelerator builders of today. Then we had those folks who jumped onto the ships and sailed away, landed at the first island they could reach and noted down everything they saw in great detail. These are our experimental colleagues. Finally there were those fellows so dear to us who stayed back in Madrid and told the expedition crew that they were going to land in India! .

" The Structure of Matter and Elementary Particles " **CERN (1978)**

Innovative Particle Accelerators of Ever Increasing Size and Cost in 20th – 21st Century

Nobel Trio: Walton, Rutherford, Cockcroft

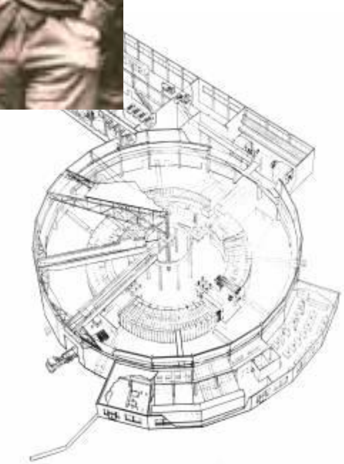
1m Cyclotron



10m Cockcroft-Walton

100m Wideröe Linac

~400m Bevatron



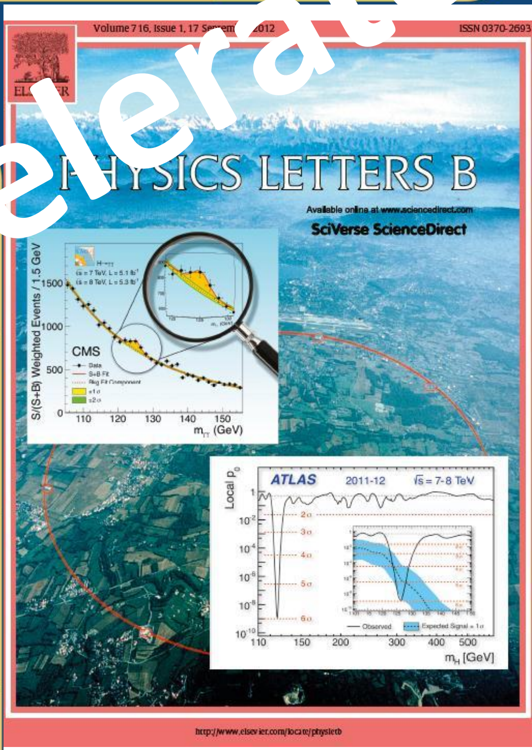
3km SLAC

10km Tevatron

27km LEP/LHC

100km FCC/ILC ??

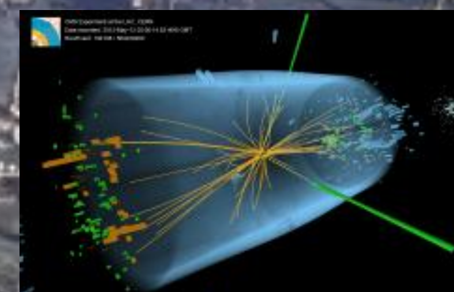
Particle Accelerators and Colliders have helped us piece together the entire Standard Model of Particles and Associated Ineteractions from Quarks to Leptons to Gauge Bosons



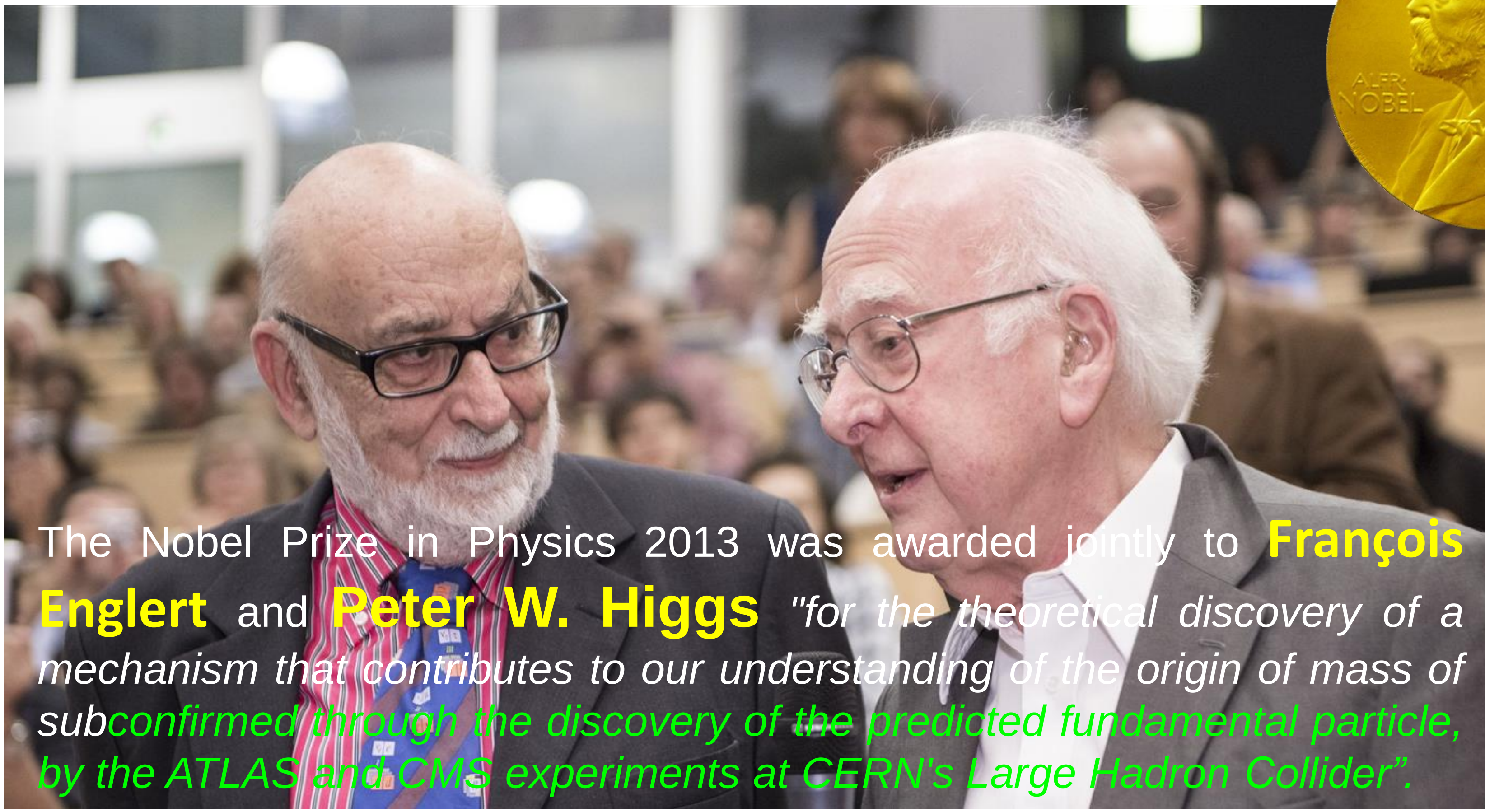
The most important tool for this development was the particle accelerator

TODAY'S HIGHEST ENERGY PARTICLE COLLIDER:
Large Hadron Collider at CERN, Geneva
→Enabled Major Discovery of the Early 21st century

HIGGS!



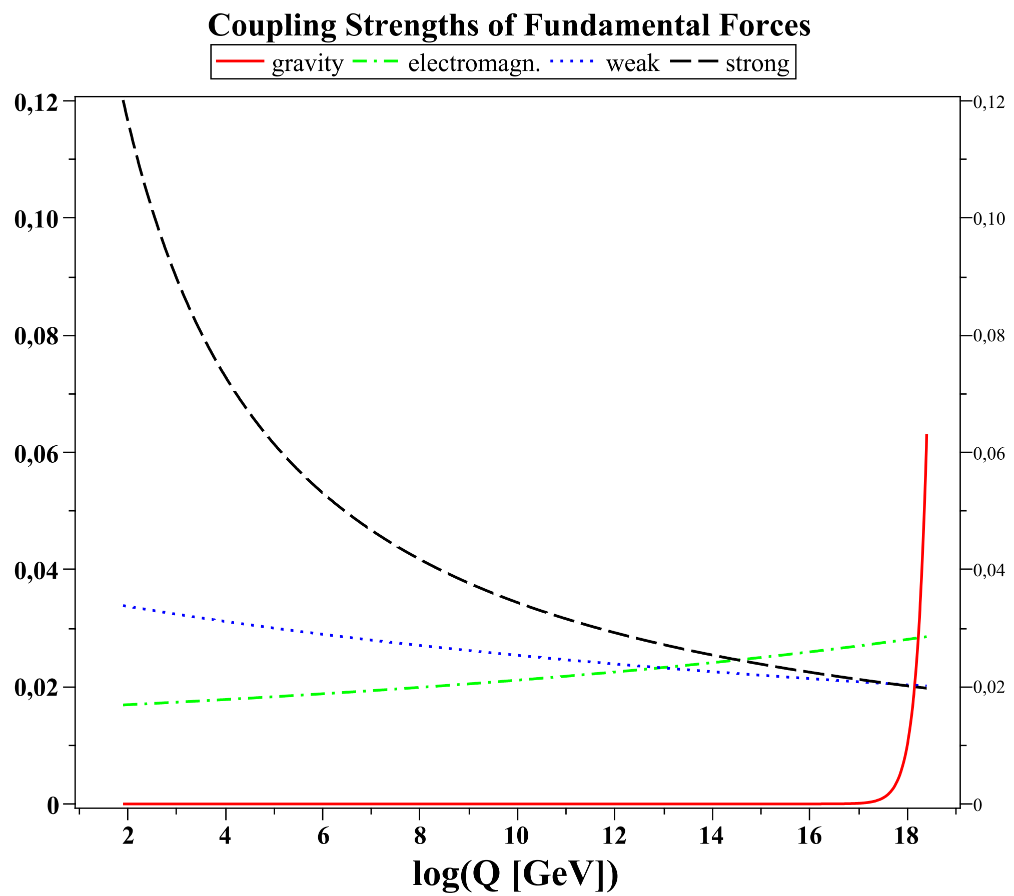
→ NEXT?



The Nobel Prize in Physics 2013 was awarded jointly to **François Englert** and **Peter W. Higgs** *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of sub**confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider”.***

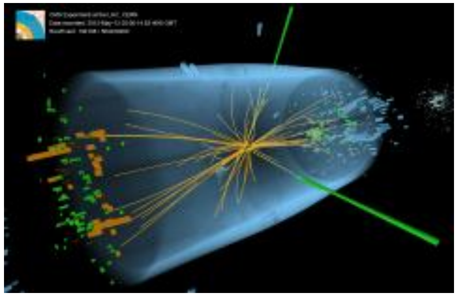
Particle physicists are convinced there are more discoveries to come: many things not explained in the standard model:

- why three families
- matter/antimatter imbalance
- neutrinos and neutrino masses
- hierarchy problem/unification
- dark matter, dark energy……
- Inflationary cosmology and connection with gravity



SCALES of FUTURE POSSIBILITIES IN PARTICLE PHYSICS: *Time, Effort, Cost*

LHC HIGGS?



ν Programme **I**
(~ $1B)

Muons **I**
(< $ 1 B)

Brighter LHC (<$1B) **I, E**

Even Larger Circular Colliders (FCC) **E (I)**
100 TeV pp / 400 GeV e+e-
(~$ 10 B - 40 B)
→ Other Colliders?

2010 2020 2030 2040 2050

Linear e+e- Collider **E (I)**
Options Higgs factory"
(~400 GeV)
(~ $10 B - $30 B)

Are their new ways to explore physics at higher energy scales in an earth-based laboratory environment in a manner acceptable fiscally, geo-politically and socially?

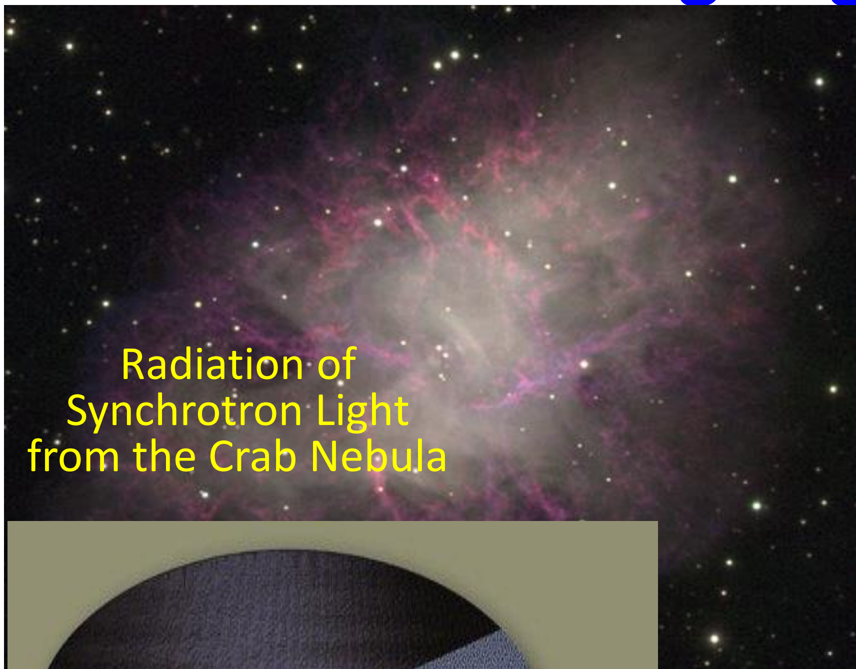
→ New cost-effective, compact acceleration technology !

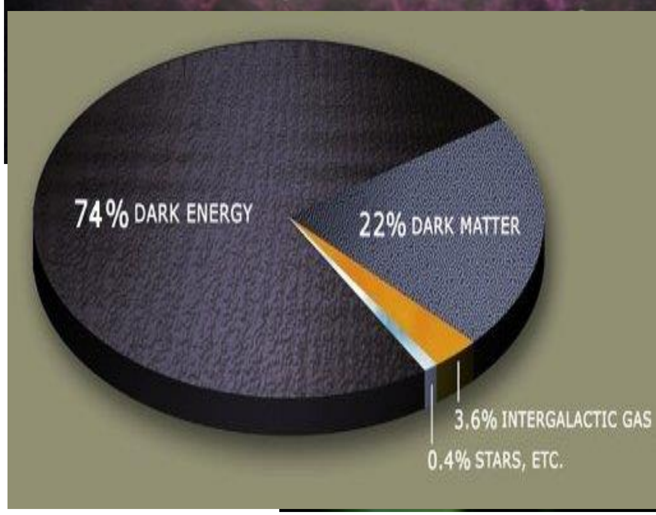
→ Focus of this talk, “speculative”, future promise depending on laboratory demonstration!!

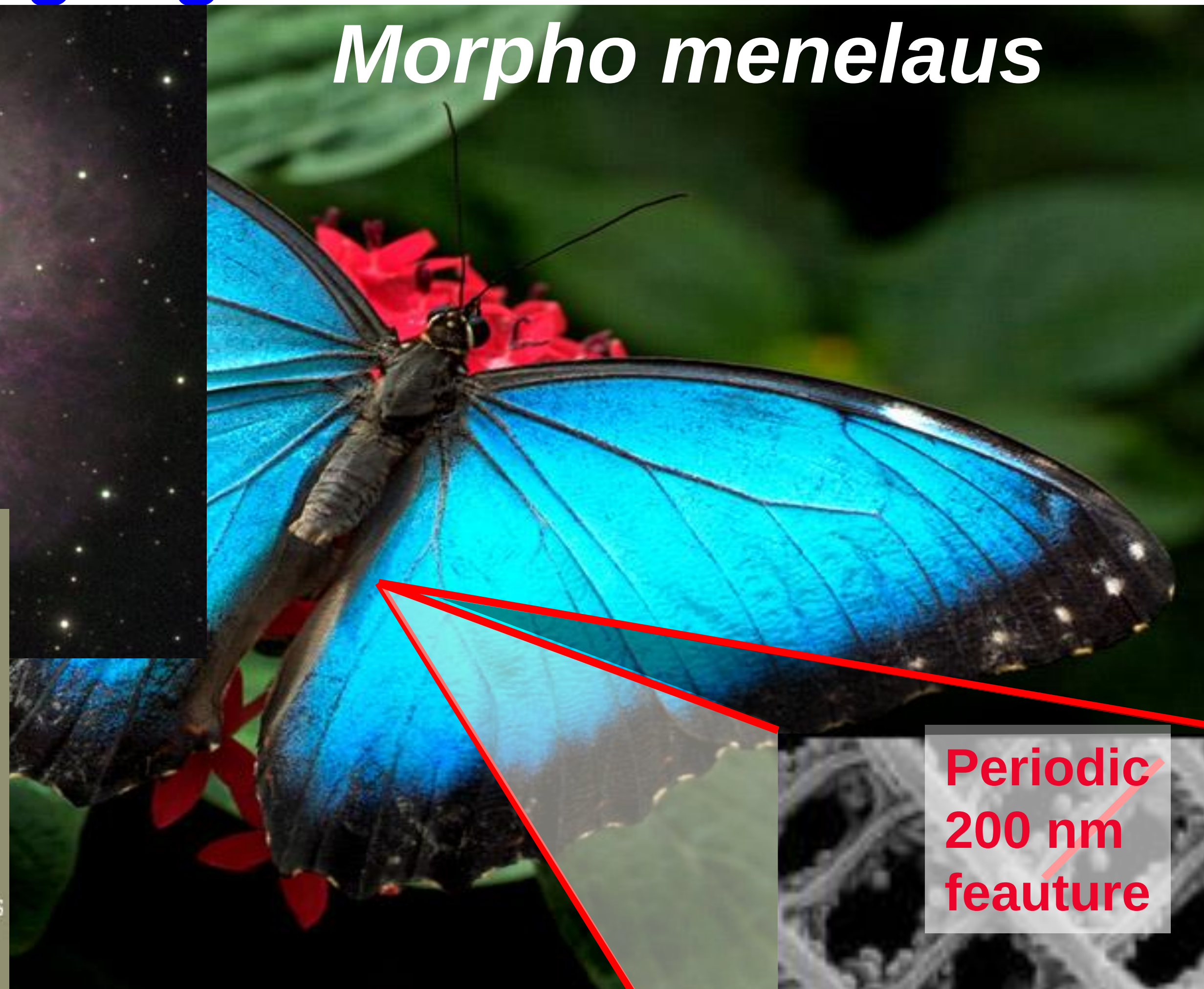
→ Alternative technologies as laboratory-based “precision” probes to “sense” very “weak” effects e.g. BSM, the “Dark Universe”: exploring the energy frontier without colliders but exploiting collider technologies augmented by emerging “Quantum Sensors” technologies : cavities, high magnetic fields and vacuum, lasers, atomic beam interferometers, qubit-sensing of photons, etc.

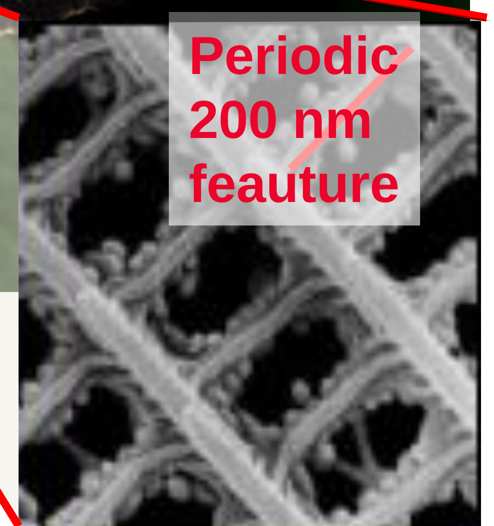
→ Promising but needing implementation!! Focus of yesterday’s talk at Sapienza Univ. di Roma and INFN Rome

Accelerators in Space and in Nature……
Amazing Light and Particles!









The inverse of Acceleration (energy gain) is Radiation (energy loss) and vice-versa:

Detection of faint Radiation ← ---------------- → *Acceleration of High Energy Particles*

"Reciprocity"

ACCELERATOR OPTIONS for Far Future:

Creating artificial periodic structures for rapid and efficient acceleration

- **New Materials**

  Dielectrics

  Photonic structures and Metamaterials

- **Plasmas**

  Laser Driven

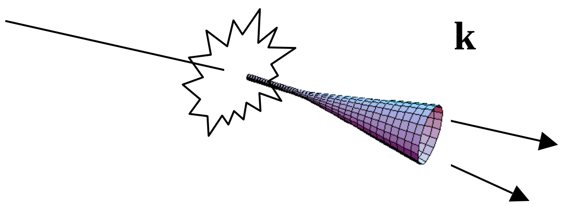
  Electron Beam Driven

  Proton Beam Driven

A bit of Digression:
Superposition, Acceleration and Radiation

- Superposition with Radiation
- Linear Acceleration and Deceleration
- Fundamental limit to acceleration from radiation

Superposition and Radiation of beam



p_i

k

$$E_s(t, r) = \sum e_s\left(t - \tau_i, \vec{r} - \vec{r}_i\right)$$

$$E_s\left(\omega, \vec{k}\right) = e_s\left(\omega, \vec{k}\right) \sum e^{i\vec{k}\vec{r}_i - i\omega\tau_i}$$

If

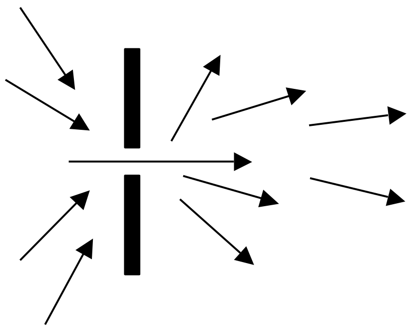
$$k a \theta << 1 \qquad a << d_c$$

Incoherent radiation $\omega\,\tau_b >> 1$ — **amplitude** $E_s(\omega,\theta) \sim N^{1/2}$

Bunch length >> radiation wavelength — **intensity** $\sim |Es(\omega,\theta)|^2 \sim N$

Coherent radiation $\omega\,\tau_b << 1$ — **amplitude** $E_s(\omega,\theta) \sim N$

Bunch length << radiation wavelength — **intensity** $\sim |Es(\omega,\theta)|^2 \sim N^2$



Linear acceleration/ deceleration

If in the far field region one has fields from an external source and fields from spontaneous emission from particles

$$\mathbf{E} = \mathbf{E}_{ex}(\omega,\theta) + \mathbf{e}_s(\omega,\theta)$$

$$\mathcal{E} \sim \int |E_{ex}(\omega,\theta) + e_s(\omega,\theta)|^2 \, d\Omega \, d\omega$$

$$\mathcal{E} = \mathcal{E}_{ex} + \mathcal{E}_s + 2\eta\sqrt{\mathcal{E}_{ex}\mathcal{E}_s}\,\mathrm{Cos}\varphi$$

$$\boxed{\begin{aligned} E(\omega) &\sim \int_{-\infty}^{\infty} E(t)\, e^{i\omega t}\, dt \\ E(0) &\sim \int_{-\infty}^{\infty} E(t)\, dt \equiv 0 \end{aligned}}$$

where η is the overlap of external and spontaneous fields

Acceleration/ deceleration linear with external field always is interference of spontaneous radiation with external field.

The charge must be able to radiate in the mode that we want to use for accelerating it.

FUNDAMENTAL THEOREM of ACCELERATION and DECELERATION

For optimal acceleration/deceleration, linear or otherwise in $\vec{E}_{ext}$, there must be optimal overlap of 'acceleration' mode $\vec{E}_{ext}(\omega, \vec{k})$ with 'radiation' mode $\vec{e}_s(\omega, \vec{k})$. The particles are accelerated if the coherent radiation loss is less than the energy gain, leading to the restriction:

$$\boxed{N \lesssim (|\vec{E}_{ext}|/e)\, \lambdabar^2}$$

on the number of particles in a bunch that can be effectively accelerated before losses start to dominate, leading to deceleration ($\lambdabar \equiv \lambda/2\pi$ is the reduced wavelength of accelerating mode).

ACCELERATOR OPTIONS for Far Future:

Creating artificial periodic structures for rapid and efficient acceleration

- **New Materials**

  Dielectrics

  Photonic structures and Metamaterials

- **Plasmas**

  Laser Driven

  Electron Beam Driven

  Proton Beam Driven

Dielectrics, Photonics and Metamaterials

ISSUES AND QUESTIONS:

Gradient : <0.3-1 GeV/m (?) – (barely) NOT sufficient for compact very high energy colliders but can be explored for low intensity, low energy 'accelerator-on-a-chip'

Staging: VERY inefficient to stack acceleration modules

Cost : Unknown, probably prohibitive from laser power, efficiency structure integrity and clean-room logistics

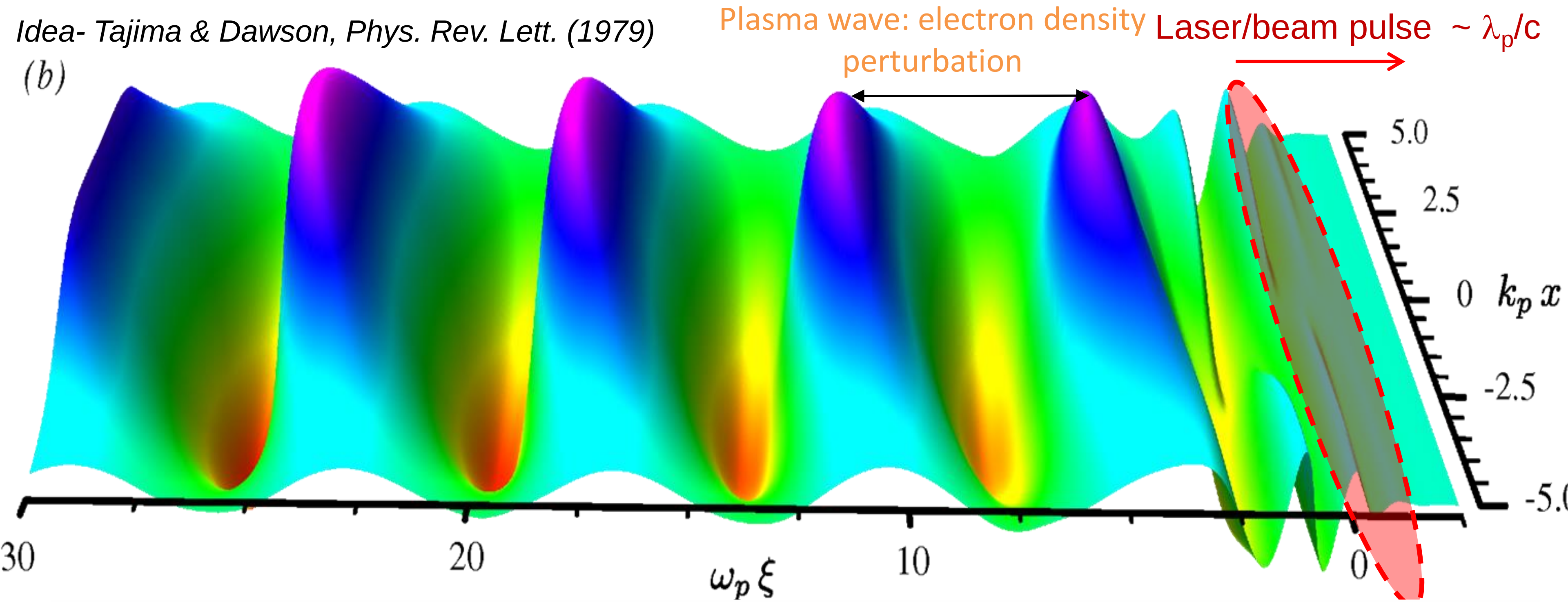
Power : 430 MW for 3 TeV (est.)!

Luminosity : Very low!! (many issues, dE/E)

NB - at >1 TeV electrons radiate even in a linear collider!

Plasma Waves

Idea- Tajima & Dawson, Phys. Rev. Lett. (1979)



$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Option A:
Short intense e-/e+/p bunch
10^{18}cm^{-3}, 100 GV/m, λ_p~30µm

Option B:
Short intense laser pulse
~10^{17}cm^{-3}, 30 GV/m, λ_p~100µm

Plasmas: Laser Driven Wakefield

ISSUES AND QUESTIONS:

Gradient : <10-100 GV/m – **Sufficient for compact colliders!**

Staging : VERY difficult at relativistic energies

Efficiency : Lasers are still very inefficient, more than an order of magnitude less efficient than RF Sources: **Need R&D on fiber lasers, power combining,….! Many decades away.**

Cost and Power : Prohibitive today!

Luminosity : **Unknown but probably very low!**

Beam Physics: Scattering, luminosity, positrons,…?????

Plasmas: Electron Beam Driven Wakefield

ISSUES AND QUESTIONS:

Gradient : <10-100 GV/m – **Sufficient for compact colliders**

Staging and Transformer Ratio (TR): $[(2-3)]^{\mathbf{n}}$

→ requiring too many inefficient stages

→ Pulse shaping to improve TR a challenge!

Cost : Unknown but probably very high as requires conventional electron beam linear accelerator infrastructure as driver!!!

Power : OK with the after-burner concept!

Luminosity : too low, L_0 x e (-n)!! And all the Beam Physics issues scattering, positrons,..??

Plasmas: Proton Beam Driven Wakefield

ISSUES AND QUESTIONS:

Gradient : <10-100 GV/m – **Sufficient for compact colliders!**

Staging and Transformer Ratio: OK, requiring only one or two stages (transform 100-200 kilojoules of multiple TeV proton beams into TeV class electron beams!).

Cost : Unknown but depends on existing TeV-class proton beam infrastructure (e.g CERN!)

Power : OK with availability of 1-10 TeV proton beams

Luminosity : **Unknown! Positron plus beam stability?**

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: **Peta-Watt lasers today : ~40 J/Pulse**

FACET facility @SLAC: ~ 30 J/bunch

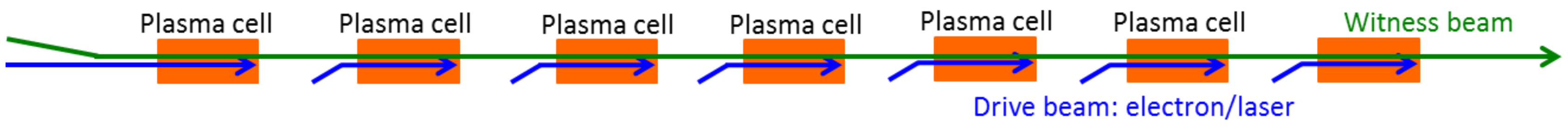
SPS: ~ 20 kJ/bunch !!
LHC: ~ 300 kJ/bunch !!

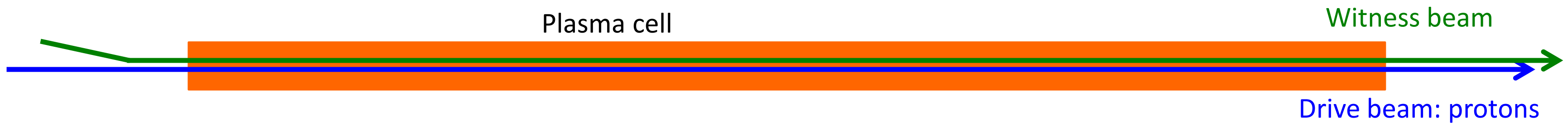
WITNESS ACCELERATED BUNCH REQUIREMENT:

10^{10} electrons @ 1 TeV ≈ few kJ

Energy content of driver allows to consider single stage acceleration !!!

Multiple Stage Laser-driven and/or Electron Beam-driven Plasma Wakefield Accelerator
vs.
Single Stage Proton-driven Plasma Wakefield Accelerator





In Summary: Motivation for PDPWA

- Laser-plasma wakefield acceleration has made great advances producing GeV class electron beams in compact setting;

- Electron beam-driven plasma wakefield acceleration has also shown high gradients and energy-doubling of 42 GeV to 85 GeV in a single pass;

- However, both have limitations: laser-plasma approach being limited by the multiple staging needed for reaching high energies relevant for particle physics, while electron beam-plasma approach being limited by the energy of the drive beam and maximum possible “transformer ratio”;

- Proton beams such as in the 7 TeV LHC carry significant stored energy (>140 kilojoules per pulse) that can be transformed into a TeV class electron beam using a plasma channel as the wakefield transformer. Hence using a proton driver is the best option for particle physics ; can we model the interaction?

Proton-driven Plasma Wakefield Acceleration

Short beam enters plasma

Free e- pulled towards beam

e- reach beam, and overshoot

Ion region is left behind beam

e- pulled back towards axis by ions

‘bubble’ structure formed

High electric fields created

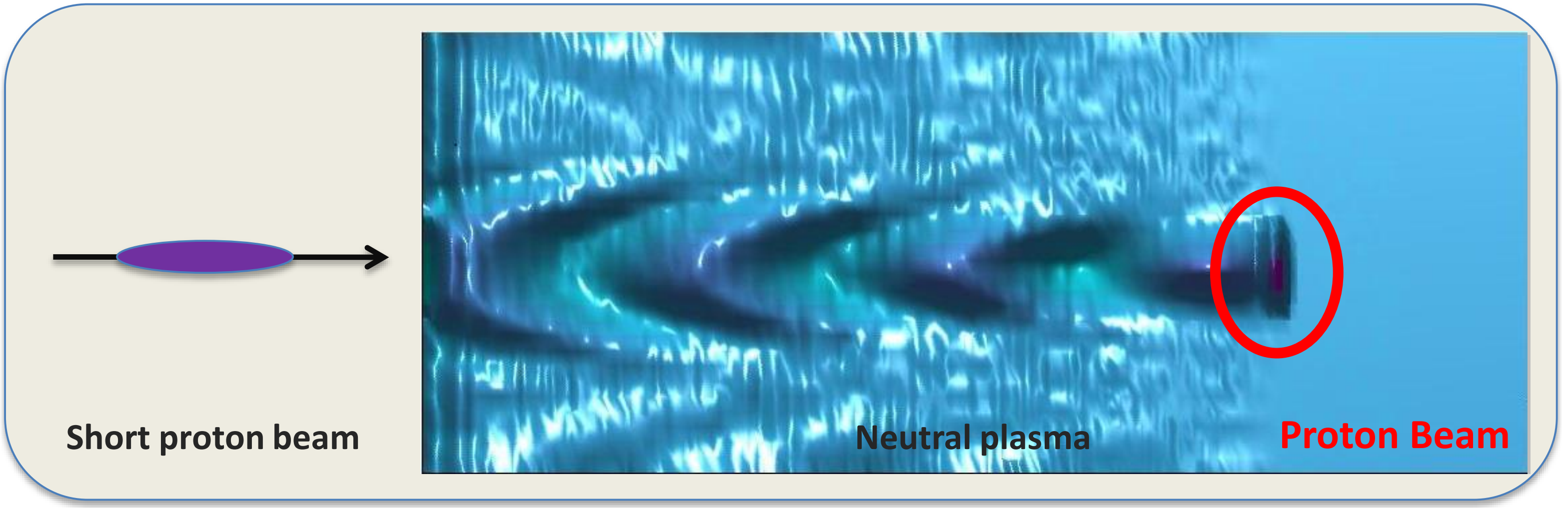
Many ‘bubbles’ trail beam

Inject e- into bubble to accelerate them

Here is a simulation of the cartoon (electric field plotted)

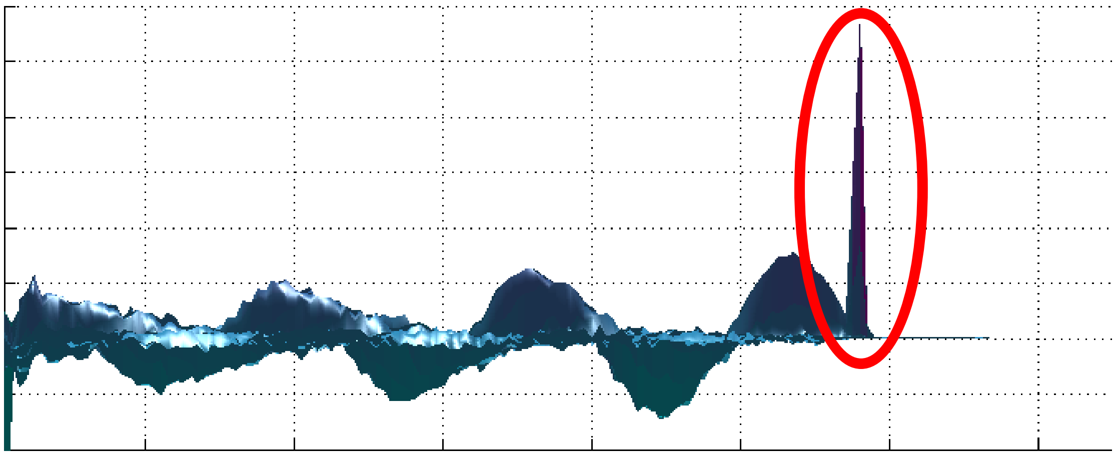
The side view shows how the ‘bubbles’ Get noisier further behind the beam

Circled is the electric field of the proton beam driving the wakefield

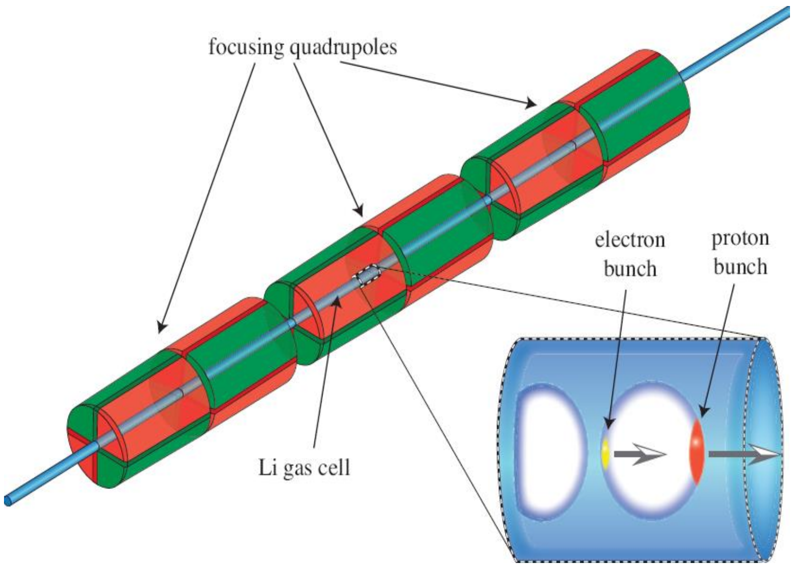


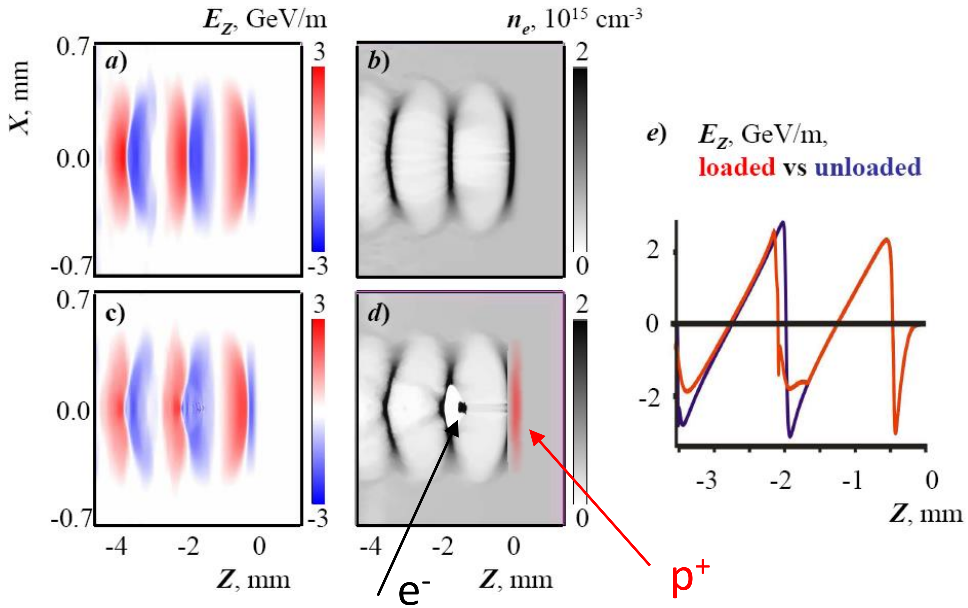
Can also drive wakefields with:

- Electrons
- Photons
- Positrons
- Muons (in principle)



Simulation Results: E_e = 0.6 TeV from E_p = 1 TeV in 500 m





Drive beam: p^+

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

$\sigma_z=100$ µm, $\sigma_r=0.43$ mm

$\sigma_\theta=0.03$ mrad, $\Delta E/E=10\%$

Witness beam: e^-

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

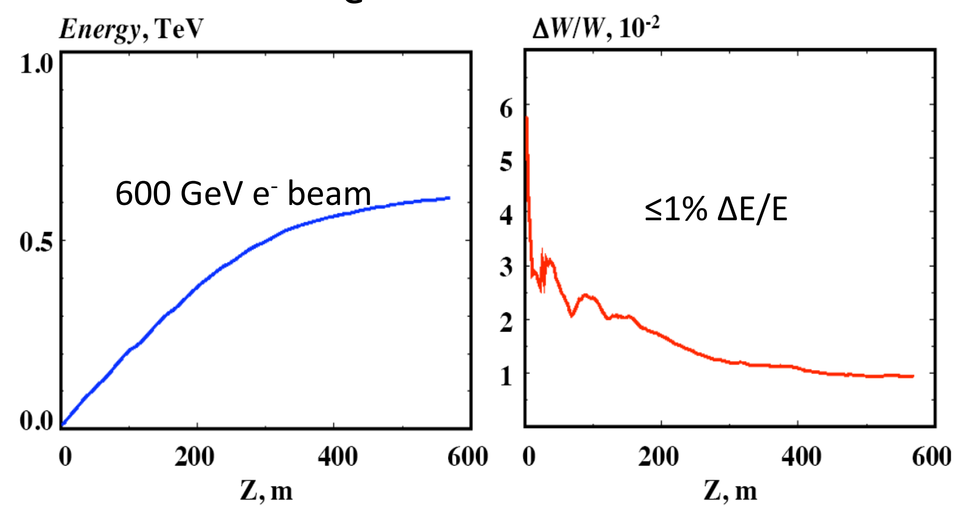
Plasma: Li^+

$n_p=6\times10^{14}$ 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).

Simulation points to Promise and Challenge!!

PROMISE:

- **Proton-driven plasma wakefield acceleration (PD-PWFA) can accelerate electron bunch to the energy frontier (TeV) in a single stage, while the transverse electric fields focus the accelerating bunch;**

CHALLENGE:

- **This requires ultra-short proton beams not yet achievable in practice: typical proton beams are 'nanoseconds' long, not 'pico-seconds' short!**

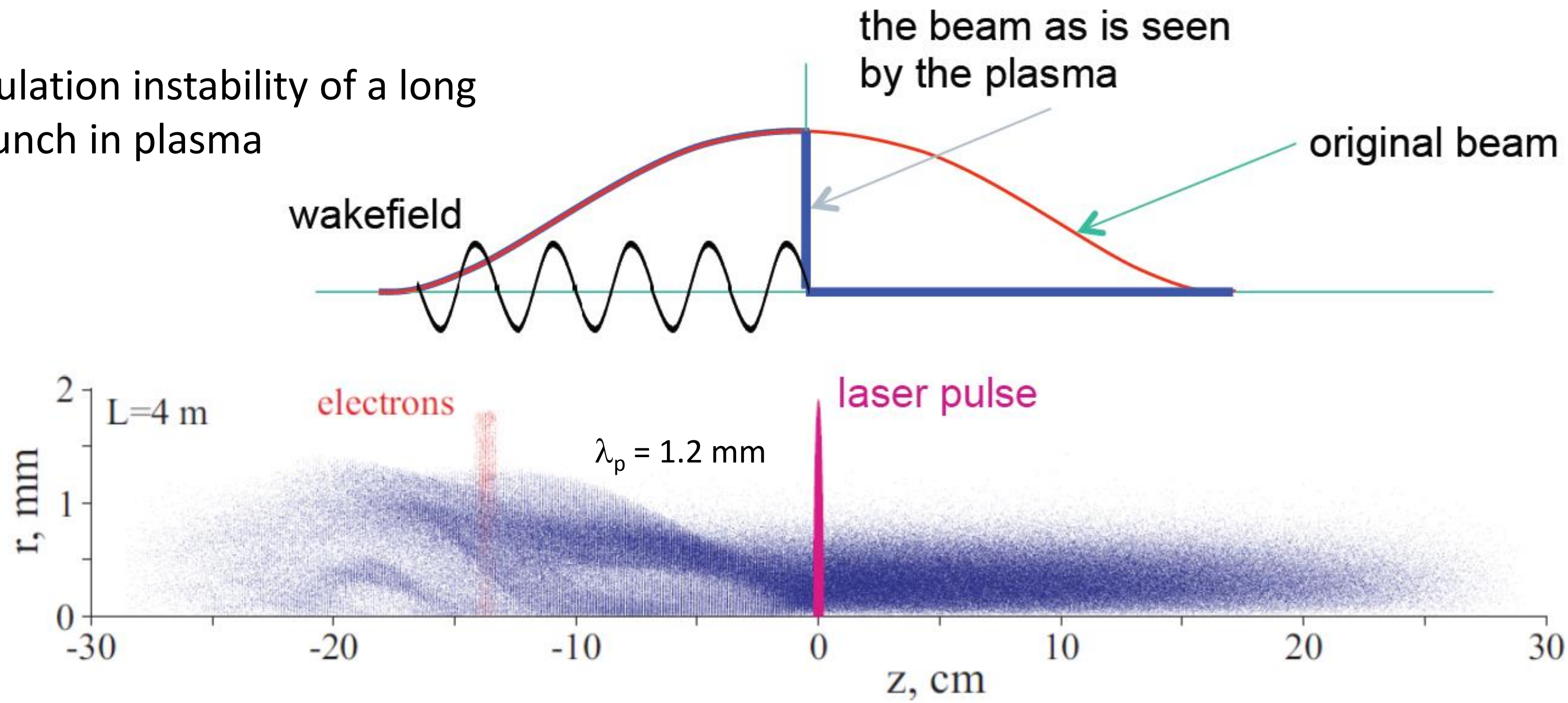
COMPROMISE for Proof-of Principle Demonstration:

- **Compromise can be reached by using plasma-modulated protons beams as a driver exploiting SMI (Self-Modulation Instability)**

Modulated Proton Beam

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

Self-modulation instability of a long proton bunch in plasma



Self-modulated proton bunch resonantly driving plasma wakefields.

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.

The Self-Modulation Instability

Affects long drive beams.

Long beam enters plasma

Free e- pulled towards proton beam

E- overshoot the proton beam

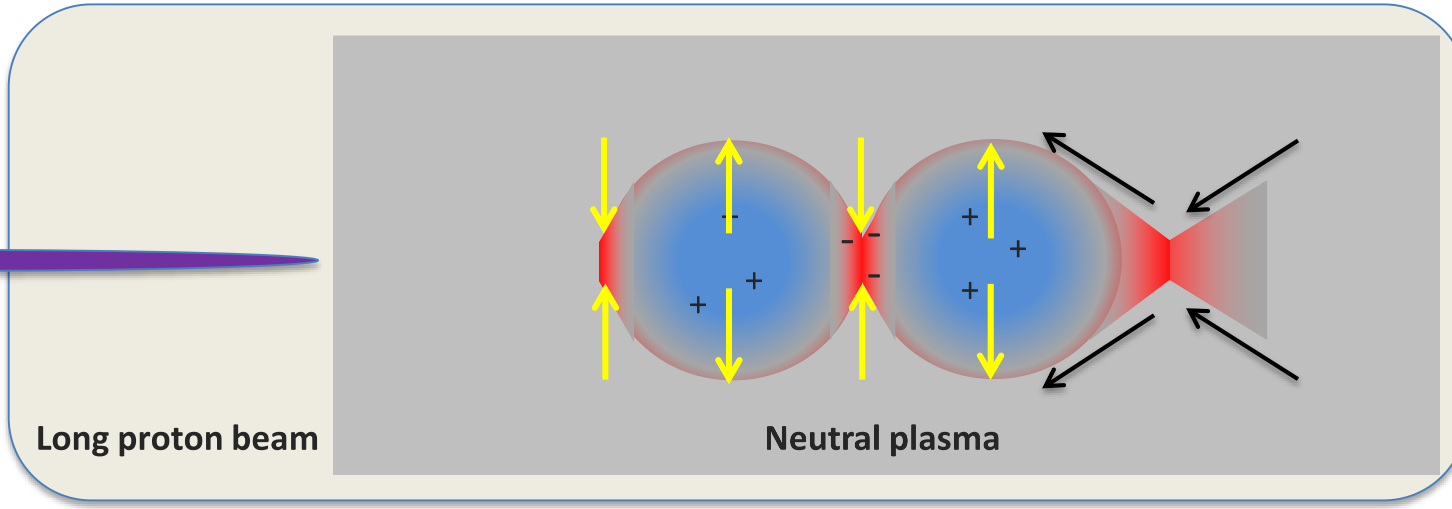
Ion region left behind head of proton beam

E- pulled back on axis by ions Impinge on proton beam

Weak wakefield co-propagates with beam

Ion regions force beam protons away

E- regions focus beam and keep on axis

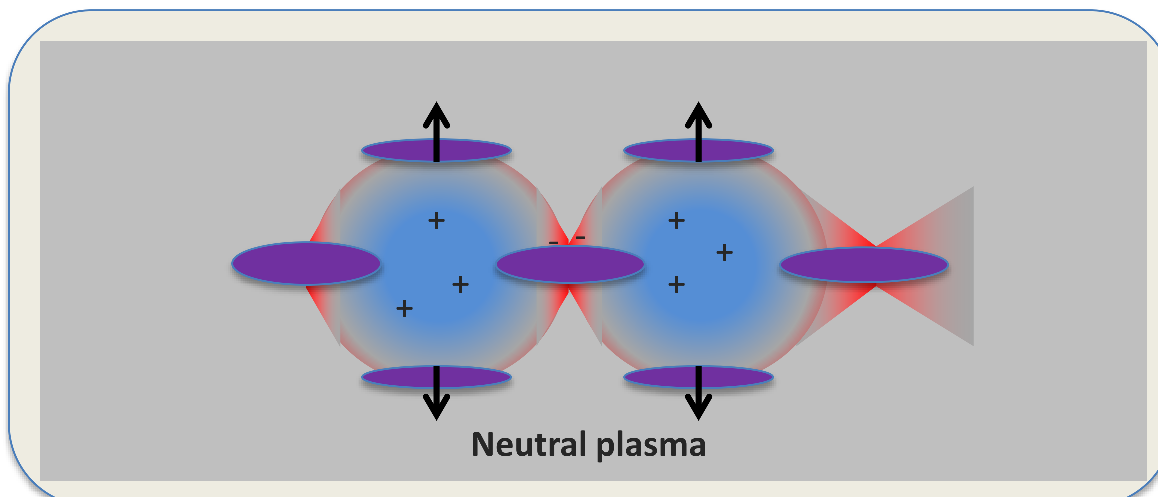


After some time, half the proton beam is discarded, leaving micro-bunches

- Microbunches are spaced λ_p apart.
- Charge density increased.
- Micro bunch lengths are much closer to the ideal driver length of:

$$\sigma_{ideal} = \lambda_p / \pi\sqrt{2}$$

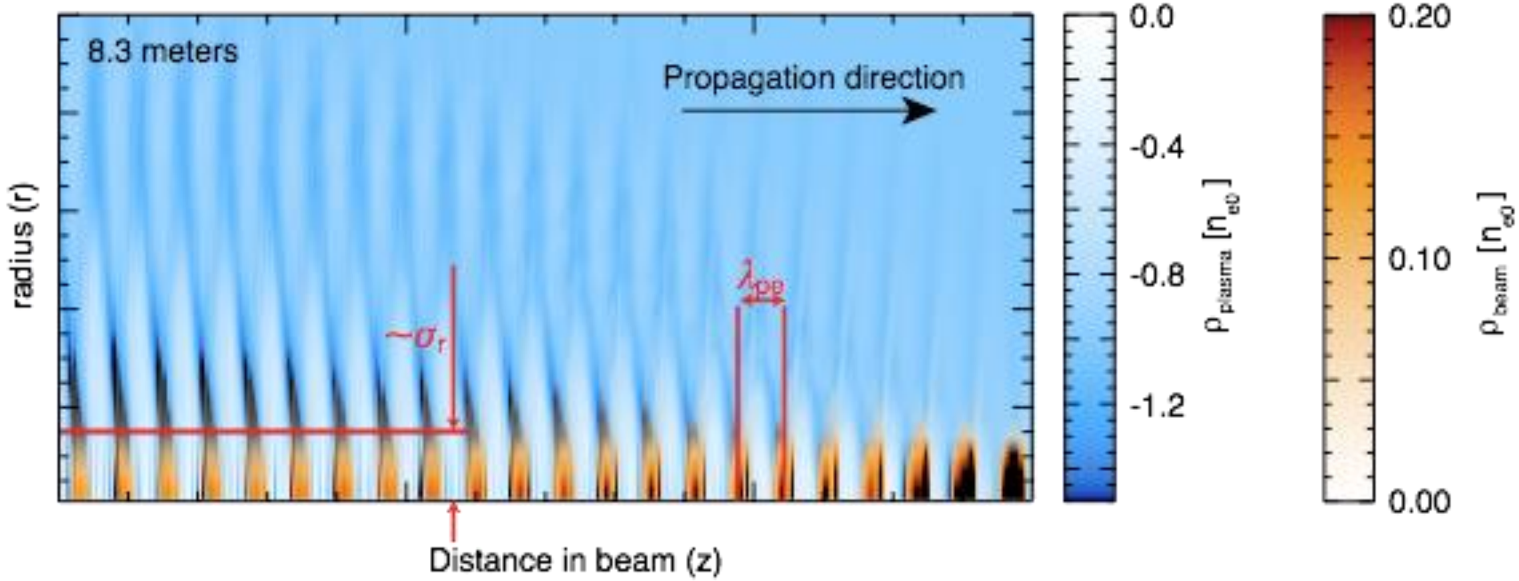
These properties then allow the modulated beam to drive a wakefield much more effectively.



Self-modulated driver beam

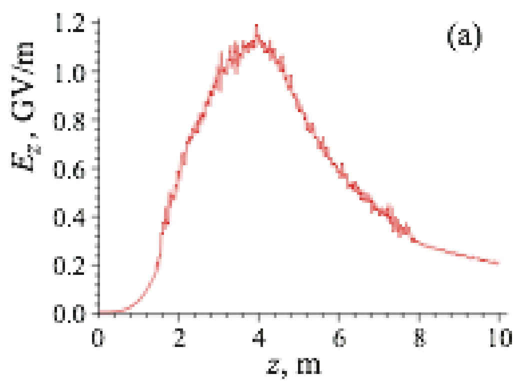
- http://www.cern.ch/awake

Proton-beam modulation

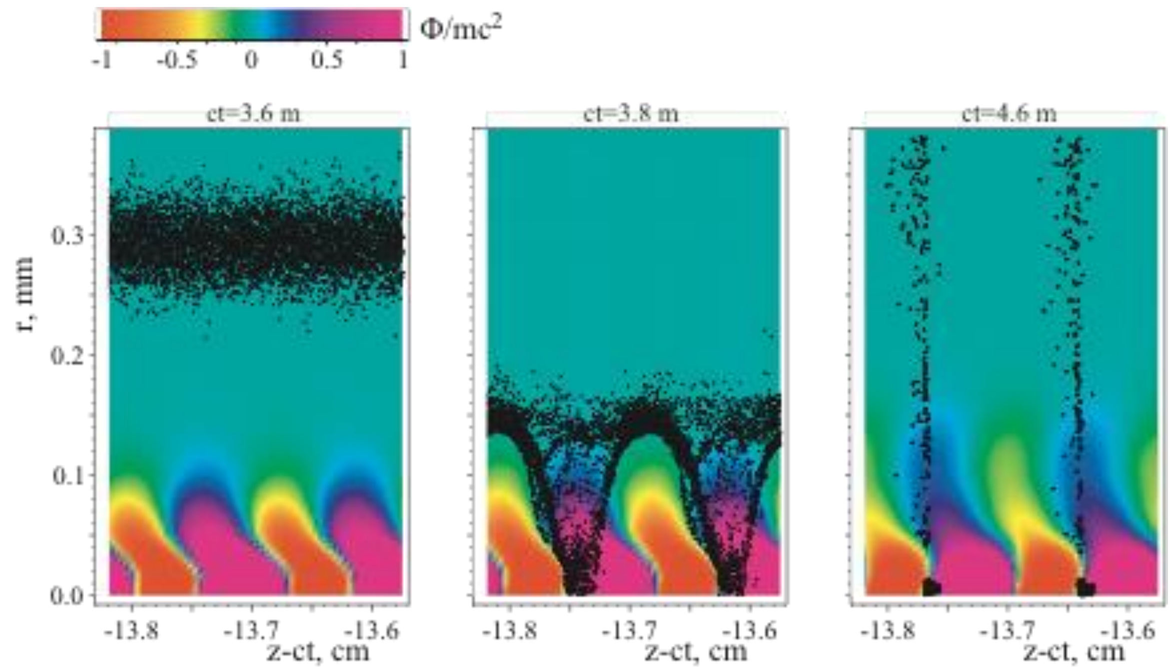


CERN SPS proton beam

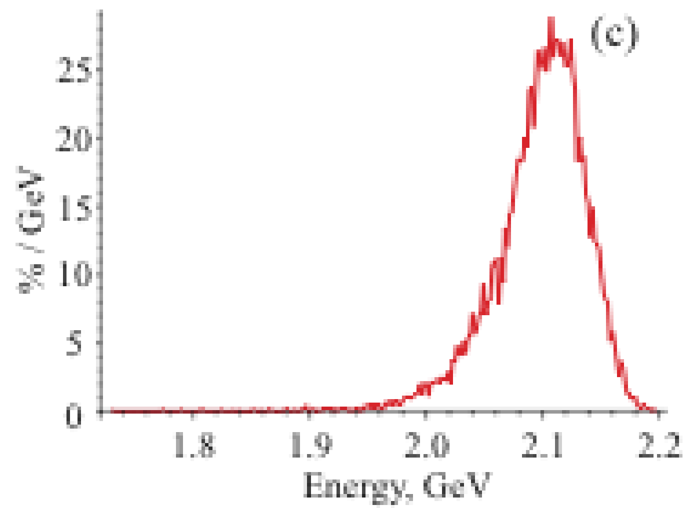
Proton bunch population, N_b	3×10^{11}
Proton bunch length, σ_z	12 cm
Proton bunch radius, σ_r	0.02 cm
Proton energy, W_b	400 GeV
Proton bunch relative energy spread, $\delta W_b/W_b$	0.35%
Proton bunch normalized emittance, ϵ_{bn}	3.5 mm mrad



Injection of witness electrons



Electron bunch population, N_e	1.25×10^9
Electron bunch length, σ_{ze}	0.25 cm
Electron bunch radius at injection point, σ_{re}	0.02 cm
Electron energy, W_e	16 MeV
Electron bunch normalized emittance, ϵ_{en}	2 mm mrad
Injection angle for electron beam, ϕ	9 mrad
Injection delay relative to the laser pulse, ξ_0	13.6 cm
Intersection of beam trajectories, z_0	3.9 m



An international collaboration (AWAKE) has been set up for experimental study of proton-driven PWFA using SPS beam.

AWAKE Collaboration

Spokesperson: Prof. Allen Caldwell, MPI, Munich(Germany)

Deputy Spokesperson: Prof. Matthew Wing, UCL (UK)

Technical Project Manager: Dr. Edda Gschwendner (CERN)

A fully approved CERN project; on their Medium-Term Plan and significant funding

AWAKE Collaboration: 16 Institutes world-wide:

Budker Institute of Nuclear Physics & Novosibirsk State University
CERN
Cockcroft Institute
DESY
Heinrich Heine University, Düsseldorf
Instituto Superior Tecnico
John Adams Institute
Imperial College
Ludwig Maximilian University
Max Planck Institute for Physics
Max Planck Institute for Plasma Physics
Rutherford Appleton Laboratory
TRIUMF
University College London
University of Oslo
University of Strathclyde

Requests under consideration:
Ulsan National Institute of Science and Technology (UNIST), Korea
Wigner Institute, Budapest
Swiss Plasma Center group of EPFL
Northern Illinois University, USA

Further groups have also expressed their interest to join AWAKE.

New since 2014 SPSC report

In the News

CERN Accelerating science

CERN

TEDxCERN

x = independently organized TED event

Videos | Speakers | Attend | Programme | Interactive story | Participate

Edda Gschwendtner

Edda Gschwendtner, physicist, is the project leader of CERN's plasma wakefield ac

Süddeutsche Zeitung

Presseartikel

Ritt auf der Plasma-Welle

Teilchenphysiker haben ein Problem

The Economist | World politics | Business & finance | Economics | Science & technology | Cultu

Particle physics

A new awakening?

Accelerators are getting bigger and more expensive. There may be a way to make them smaller and cheaper

Jan 31st 2015 | From the print edition

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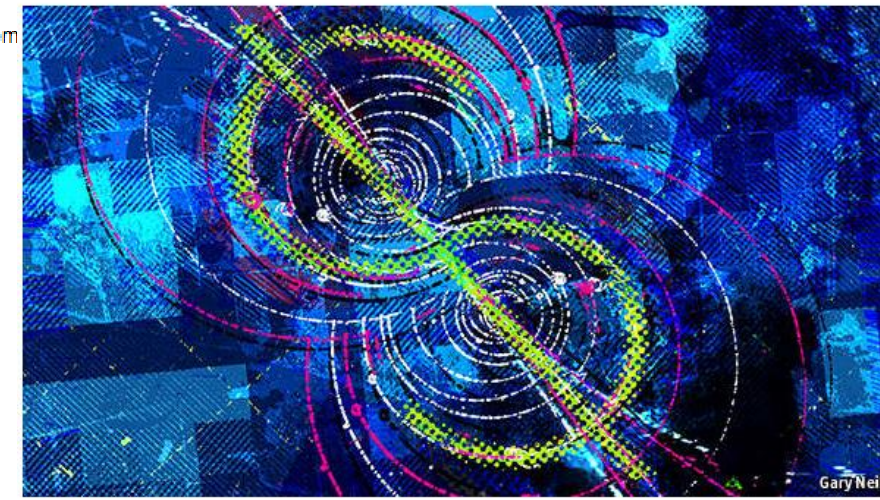

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Archive > Volume 526 > Issue 7572 > News > Article

NATURE | NEWS

CERN prepares to test revolutionary mini-accelerator

Machines that 'surf' particles on electric fiel

Elizabeth Gibney

07 October 2015

AWAKE: Platz 5 der SPIEGEL Bestsellerliste DVD (TV & Hobby)

SPIEGEL ONLINE KULTUR

Just kidding – but there was a Spiegel article!

AWAKE reports

CERN COURIER

Feb 24, 2010

Workshop pushes proton-driven plasma wakefield acceleration

PPA09

PPA09, a workshop held at CERN on proton-driven plasma wakefield acceleration, has launched discussions about a first demonstration experiment using a proton beam. Steve Myers, CERN's director for Accelerators and Technology, opened the event and described its underlying motivation. Reaching higher-energy collisions for future particle-physics experiments beyond the LHC requires a novel accelerator technology, and "shooting a high-energy proton beam into a plasma" could be a promising first step. The workshop, which brought together participants from Germany, Russia, Switzerland, the UK and the US, was supported by the EuCARD AccNet accelerator-science network (**CERN Courier November 2009 p16**).

AWAKE: to high energies in a single leap

Proton-driven plasma wakefield acceleration could accelerate electrons to the terascale in a single plasma stage. The AWAKE project is set to verify this novel technique using proton beams at CERN.

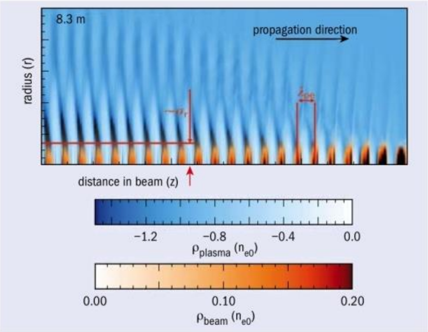

Fig. 1. Simulation of a self-modulated proton bunch resonantly driving plasma wakefields sustained by the plasma-density perturbation. The plasma density is shown increasing from white to blue and the proton density increasing from yellow to dark red.

To complement the results that will come from the LHC at CERN, the particle-physics community is looking for options for future lepton colliders at the tera-electron-volt energy scale. These will need to be huge circular or linear colliders. With the accelerating gradients of today's RF cavities or microwave technology limited to about 100 MV/m, the length of the linear machines would be tens of kilometres. However, plasma can sustain much higher gradients and the idea of harnessing them in plasma wakefield acceleration is gathering momentum. One attractive idea is to use a high-energy proton beam as the driver of a wakefield in a single plasma section.

J. Plasma Physics: page 1 of 7.
doi:10.1017/S0022377812000086

A proposed demonstration of an experiment of proton-driven plasma wakefield acceleration based on CERN SPS

G. XIA[1], R. ASSMANN[2], R. A. FONSECA[3], C. HUANG[4], W. MORI[5], L. O. SILVA[3], J. VIEIRA[3], F. ZIMMERMANN[2] and P. MUGGLI[1]
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[2]CERN, Geneva, Switzerland
[3]GoLP/Instituto de Plasmas e Fusao Nuclear-Laboratório Associado, IST, Lisboa, Portugal
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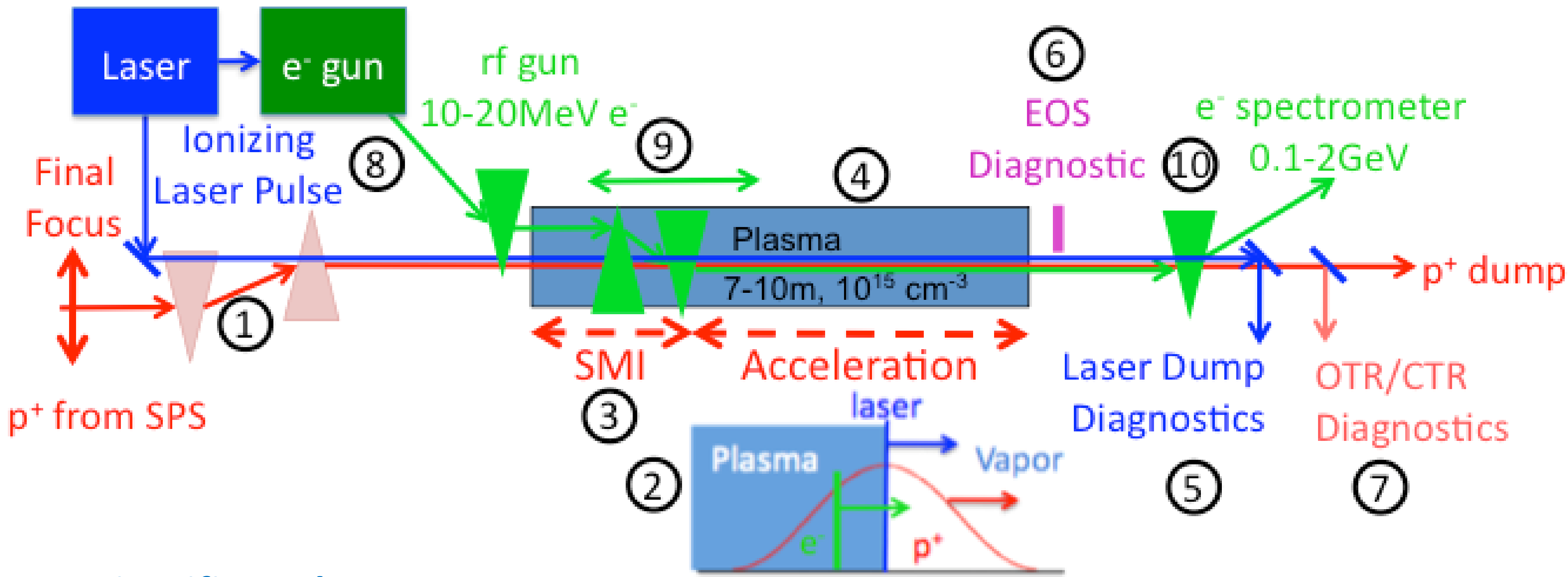
(Received 20 September 2011; accepted 2 January 2012)

AWAKE schematic



Scientific goals

1. Demonstrate self-modulation effect of a long proton bunch and realize 1 GeV electron energy gain with a ~10 m plasma;
2. Develop and test the diagnostic equipments for the first and later experiments;
3. Benchmark data against simulation results;
4. Provide inputs for future experiment for 100 GeV energy gain in 100 m plasma.

AWAKE Experimental Program

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

AWAKE Experimental Program

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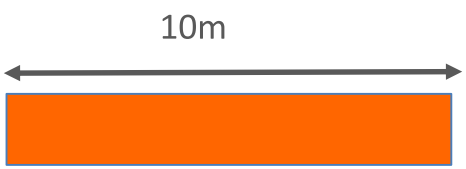

Plasma cell

→ Rb vapour source

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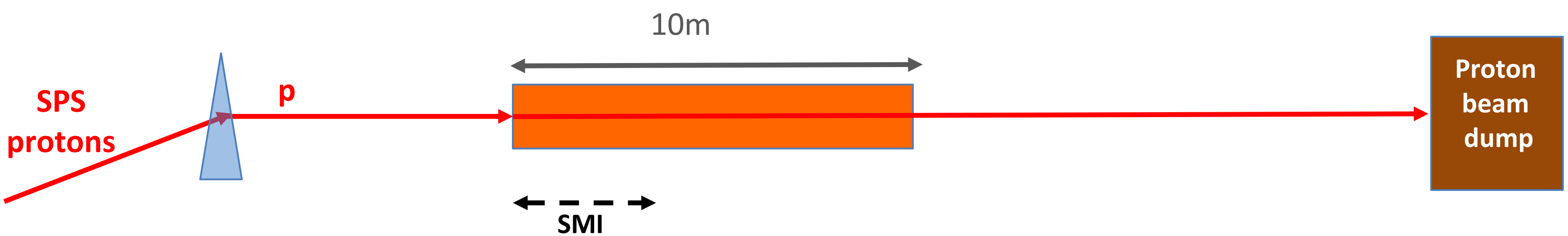

Plasma cell

→ Rb vapour source

Proton beam

→ drives the plasma wakefield + undergoes self-modulation instability.

→ LHC-type proton beam, 400 GeV/c, 3E11 protons/bunch, σ = 400 ps long

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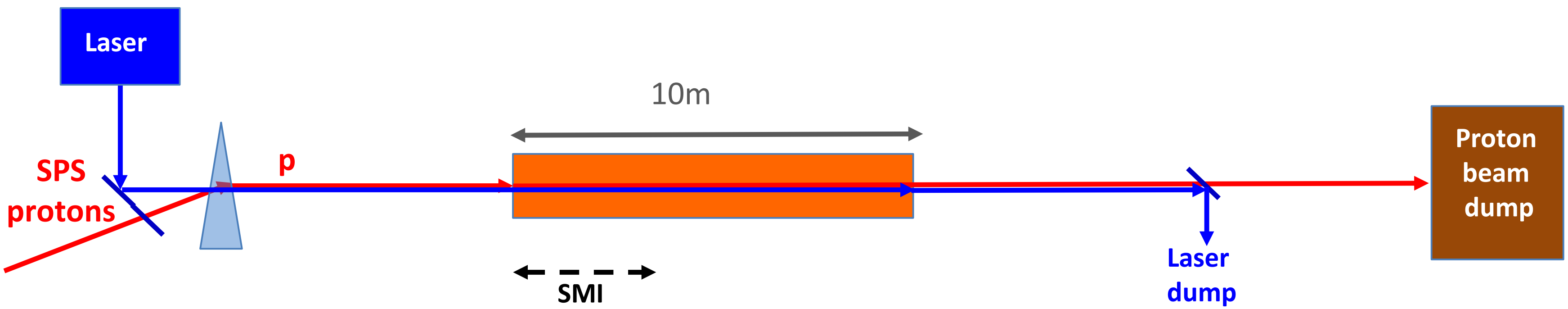

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Laser beam:

→ ionizes the plasma + seeds the self-modulation instability of the proton beam.

→ 4.5 TW laser, 100 fs

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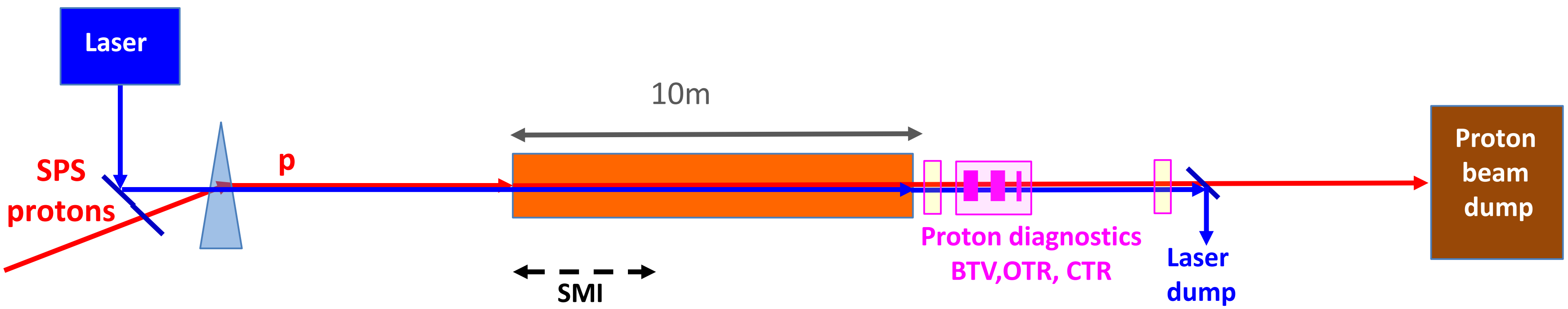

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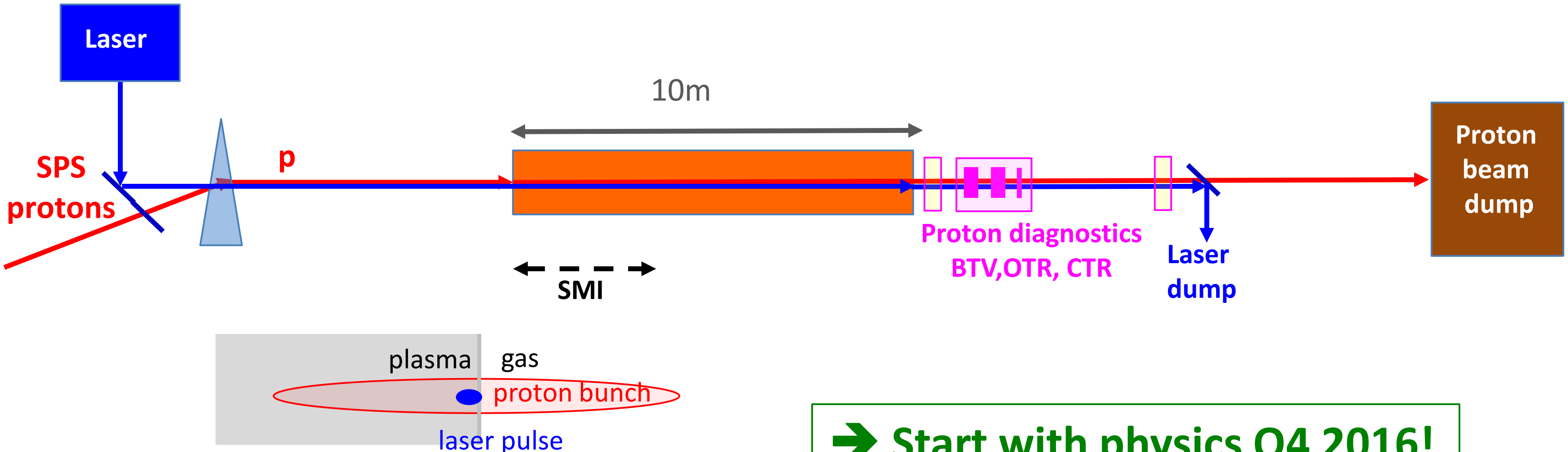
Diagnostics

→ BTVs, OTR, CTR

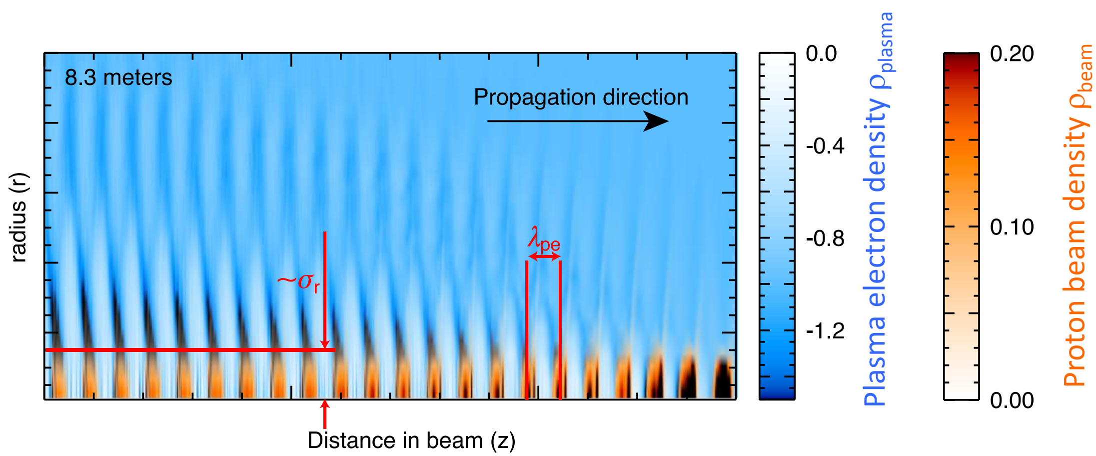
AWAKE: Experimental Program

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



➔ Start with physics Q4 2016!

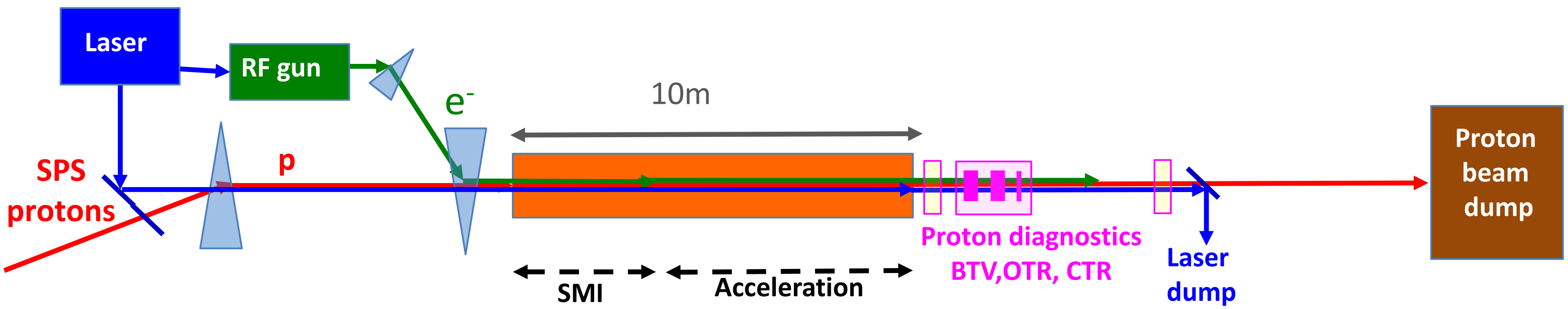
Self-modulated proton bunch resonantly driving plasma wakefields.



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.



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→ BTVs, OTR, CTR

Electron source and beam

→ Witness beam to 'surf' on the wakefield and get accelerated

→ 16 MeV/c, 1.2 E9 electrons/ bunch, σ = 4ps long

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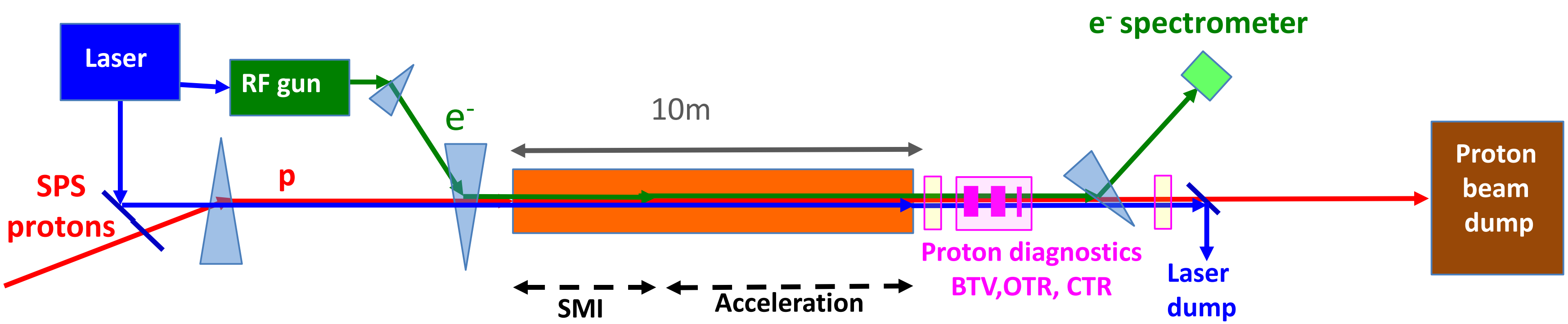

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Electron spectrometer system

AWAKE Experimental Program

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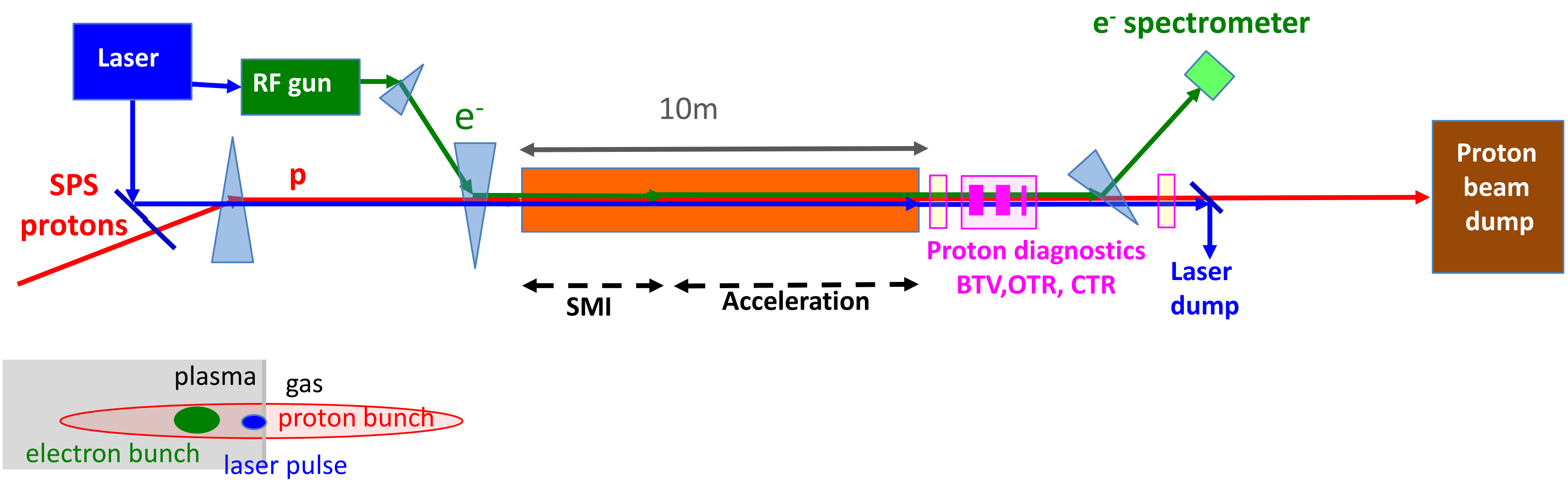
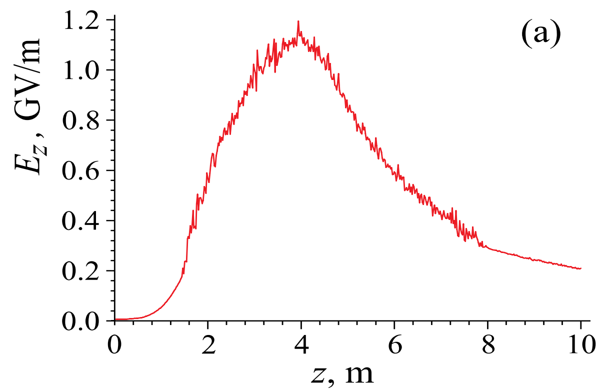
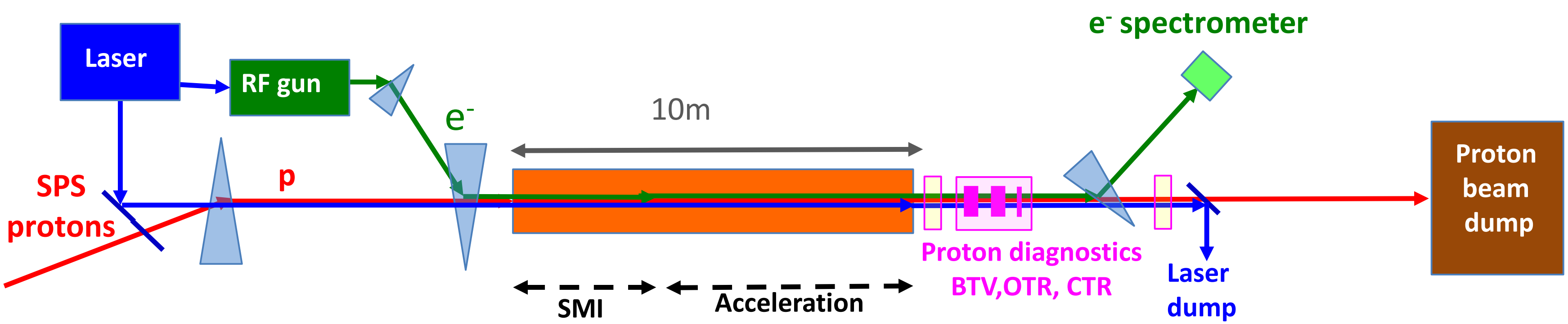


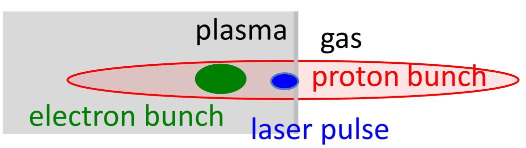


Maximum amplitude of the **accelerating field E_z** as a function of position along the plasma. Saturation of the SMI at ~4m.

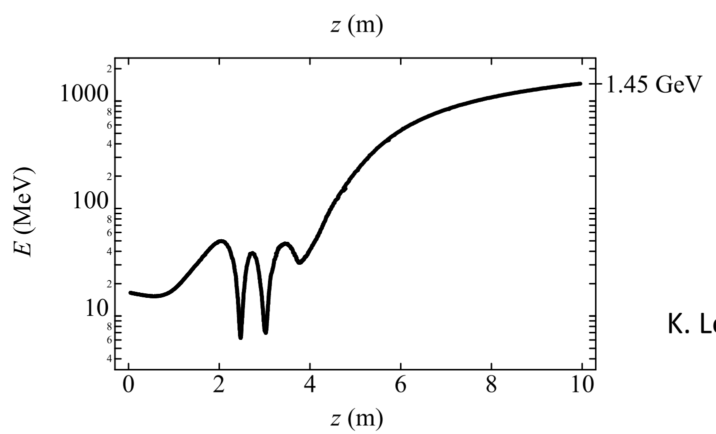
AWAKE Experimental Program

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





➔ **Start with physics Q4 2017!**



K. Lotov et al., arXiv: 1408.4448

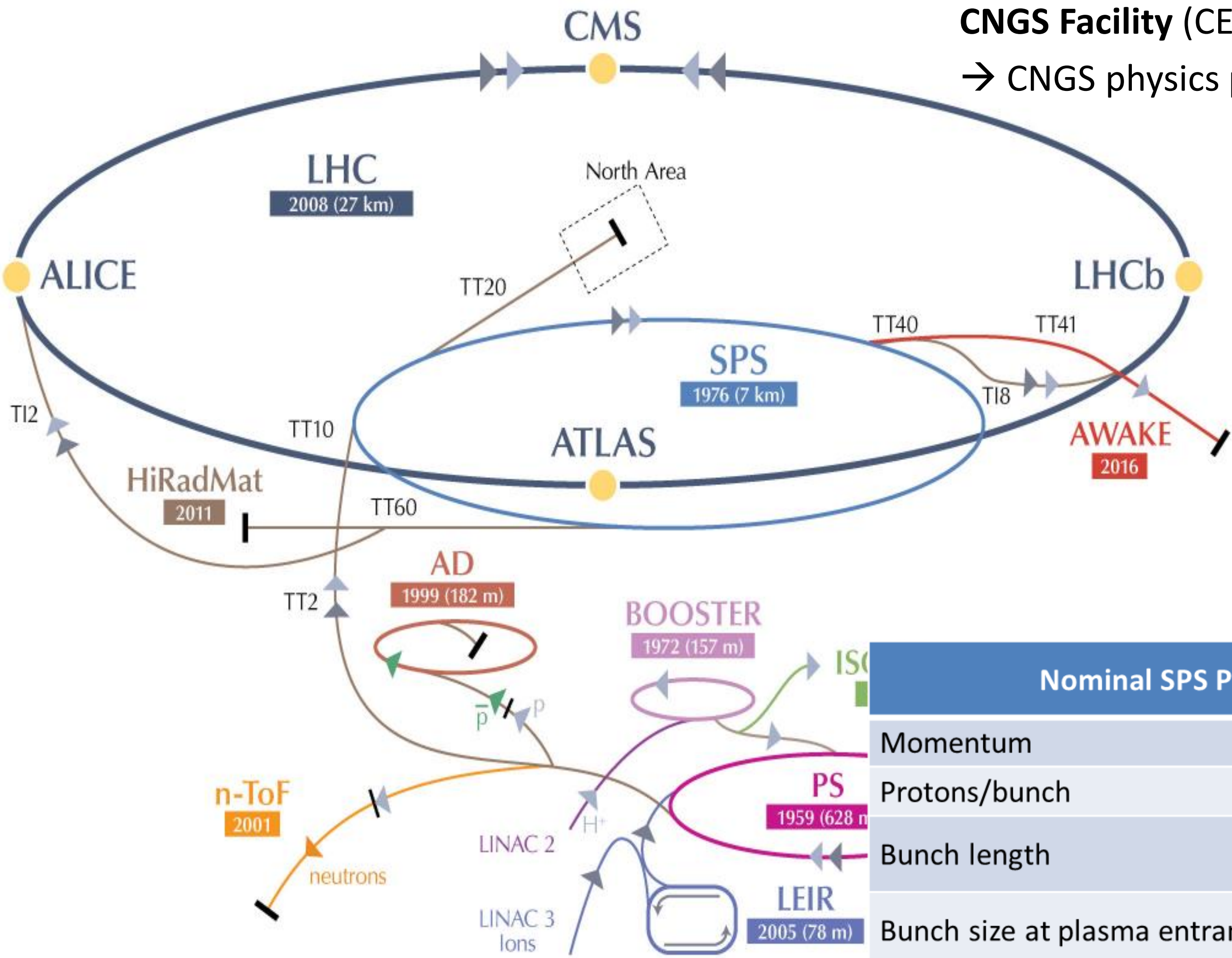
Energy of the electrons gained along the 10 m long plasma cell.

AWAKE at CERN

AWAKE is installed in

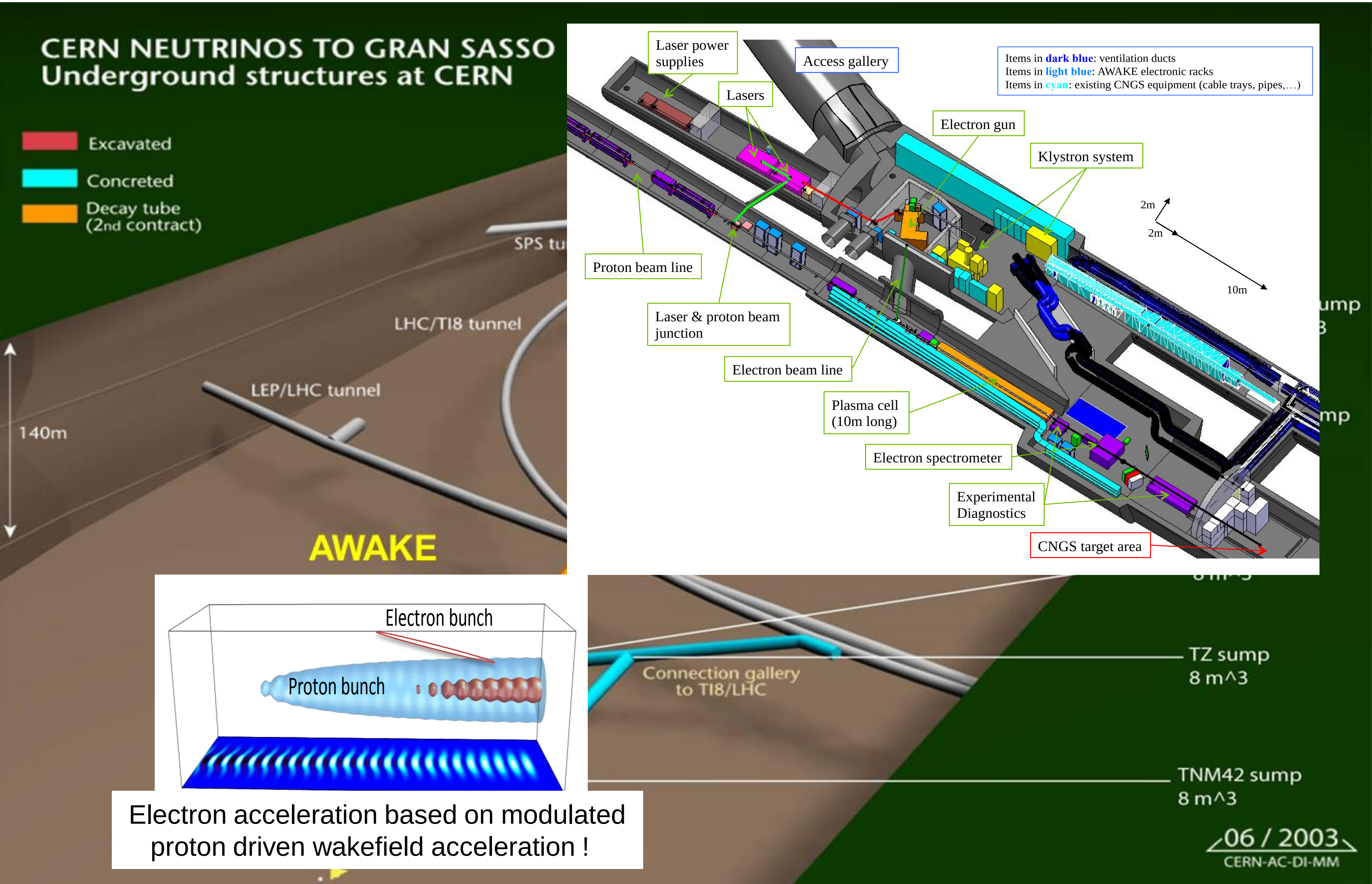
CNGS Facility (CERN Neutrinos to Gran Sasso)

→ CNGS physics program finished in 2012



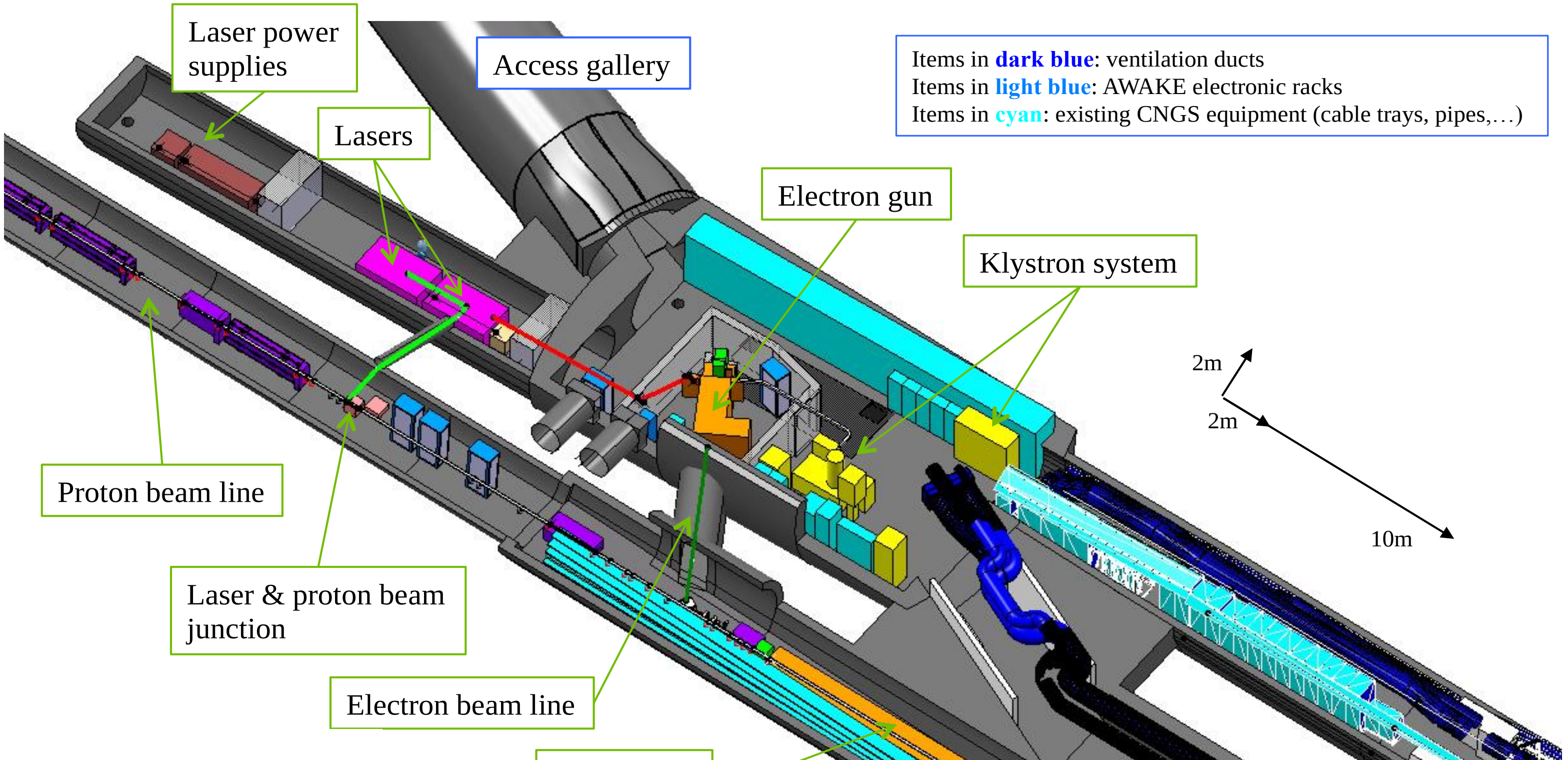
Nominal SPS Proton Beam Parameters	
Momentum	400 GeV/c
Protons/bunch	$3\ 10^{11}$
Bunch length	σ_z = 0.4 ns (12 cm)
Bunch size at plasma entrance	$\sigma^*_{x,y}$ = 200 μm
Normalized emittance (r.m.s.)	3.5 mm mrad
Relative energy spread	$\Delta p/p$ = 0.35%

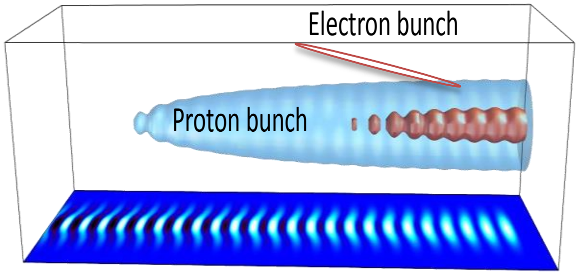
Proton Driven Plasma Wakefield Acceleration



Electron acceleration based on modulated proton driven wakefield acceleration !

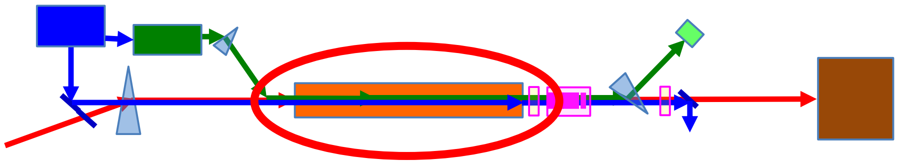
Layout of AWAKE experiment





Electron acceleration based on modulated proton driven wakefield acceleration !

Plasma Source: Rubidium Vapor Source developed simultaneously at MPI Munich, MPI Garching and Imperial College

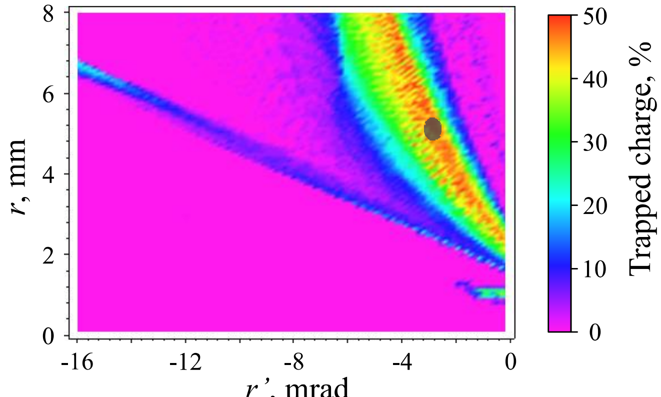


- Density adjustable from **10^{14} – 10^{15} cm^{-3}**
- 10 m long, 4 cm diameter
- Plasma density = vapor density
- System is oil-heated: 150˚ to 200˚ C
  → keep temperature uniformity
  → Keep density uniformity

Required:
$\Delta n/n = \Delta T/T \leq 0.002$

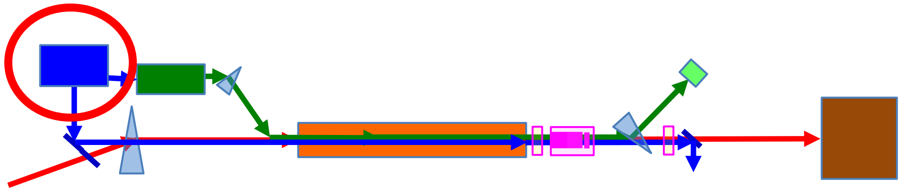
10 m long plasma cell prototype in the AWAKE test area at CERN

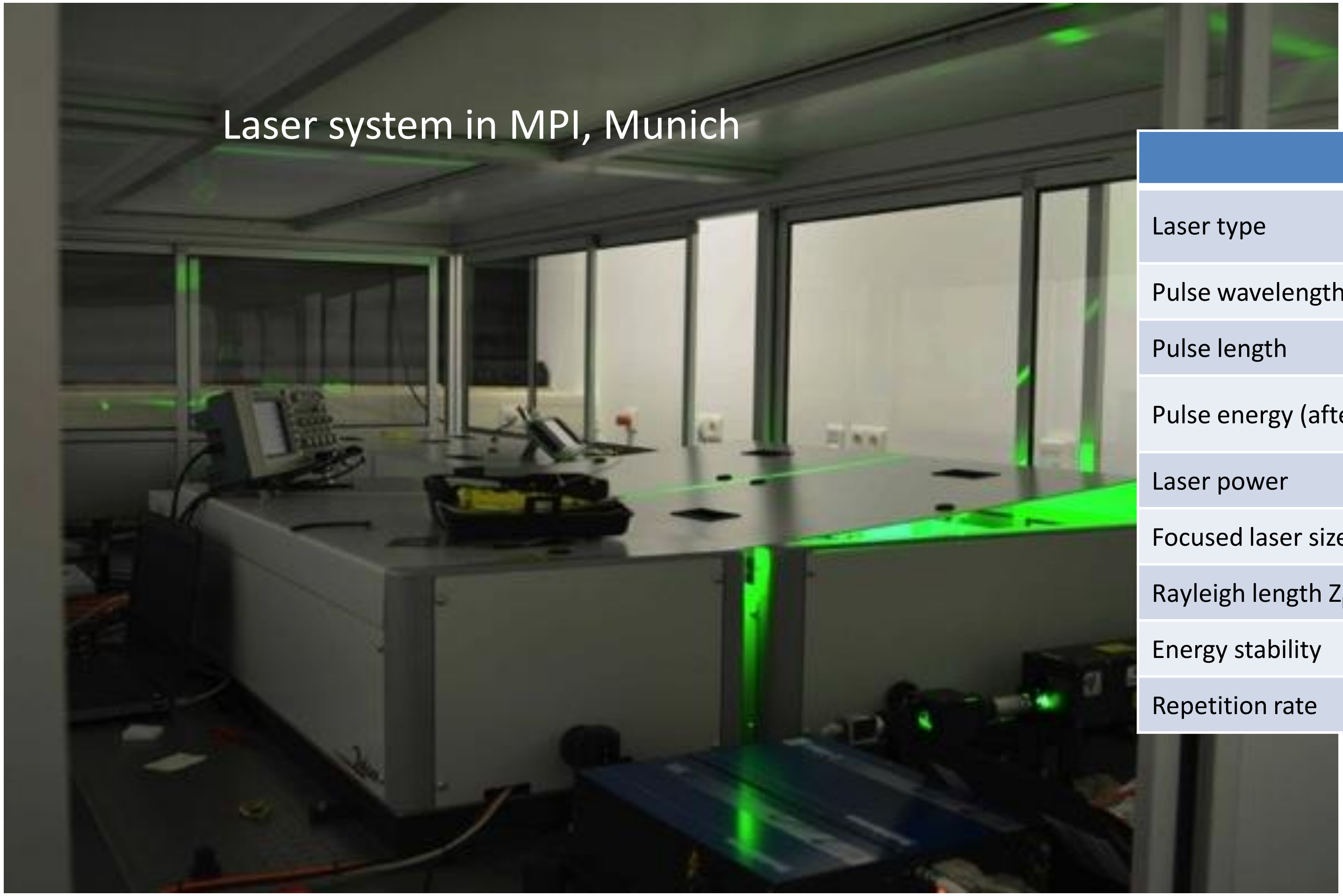
E. Öz, P. Muggli, NIM 740 (2014) 197.



Laser

- Laser intensity must exceed ionization intensity at the plasma end (L=10m) over a plasma radius of r > 3σ = 600 μm.



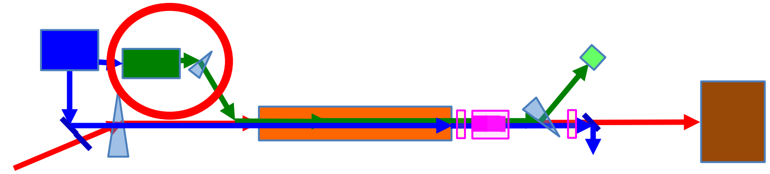


Laser Beam	
Laser type	Fiber Ti:Sapphire
Pulse wavelength	λ_0 = 780 nm
Pulse length	100-120 fs
Pulse energy (after compr.)	**450 mJ**
Laser power	**4.5 TW**
Focused laser size	$\sigma_{x,y}$ **= 1 mm**
Rayleigh length Z_R	5 m
Energy stability	±1.5% r.m.s.
Repetition rate	10 Hz

Laser will be moved to CERN in February 2016

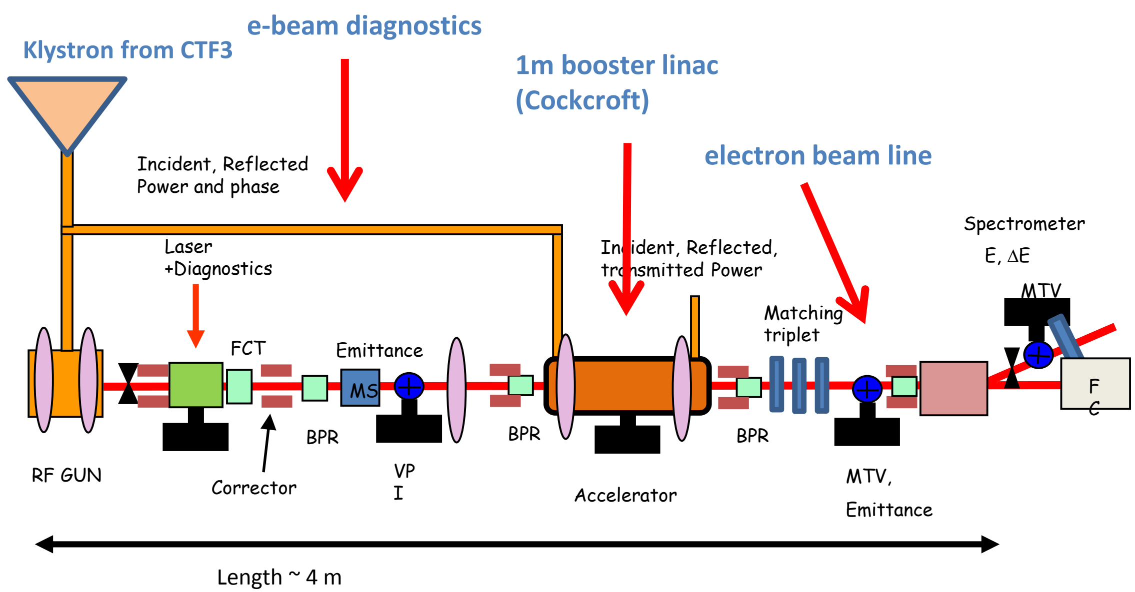
Electron Witness Beam – Electron Source

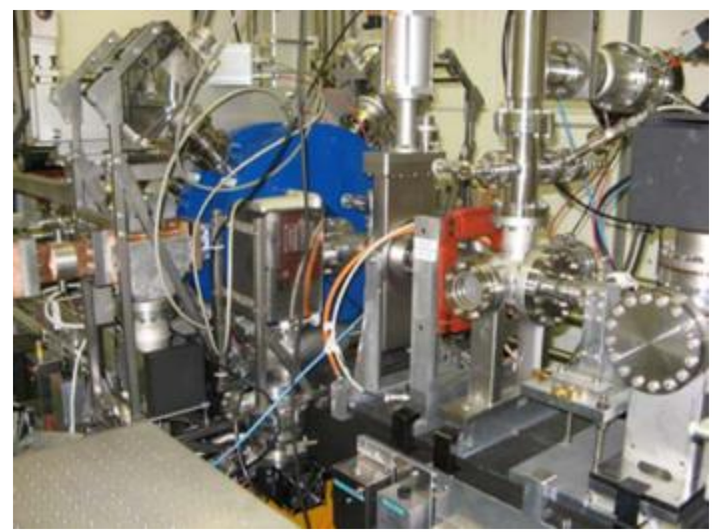
Electron beam for AWAKE	Baseline	Range for upgrade phase
Momentum	16 MeV/c	10-20 MeV
Electrons/bunch (bunch charge)	1.25 E9	0.6 – 6.25 E9
Bunch charge	0.2 nC	0.1 – 1 nC
Bunch length	σ_z =4ps (1.2mm)	0.3 – 10 ps
Bunch size at focus	$\sigma^*_{x,y}$ = 250 μm	0.25 – 1mm
Normalized emittance (r.m.s.)	2 mm mrad	0.5 – 5 mm mrad
Relative energy spread	Δp/p = 0.5%	<0.5%



PHIN Photo-injector for CTF3/CLIC:

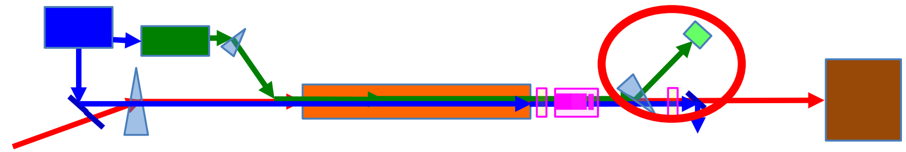
→ **Program will stop end 2015** ➔ Fits to requirements ➔ used for AWAKE



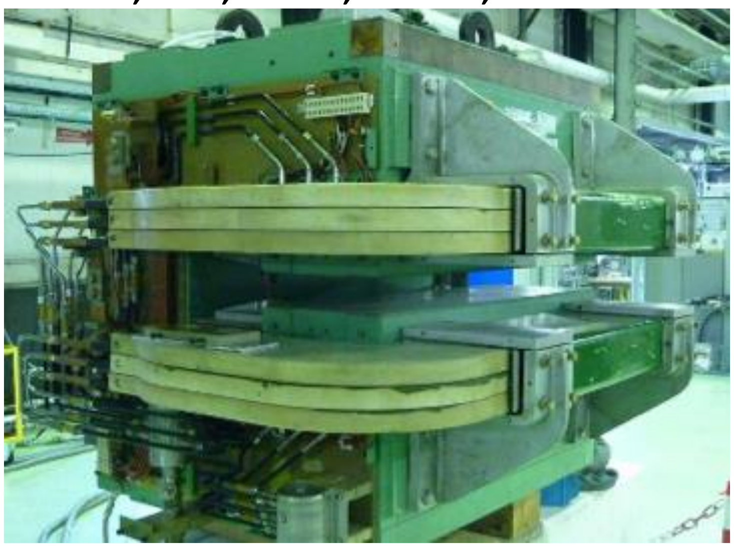


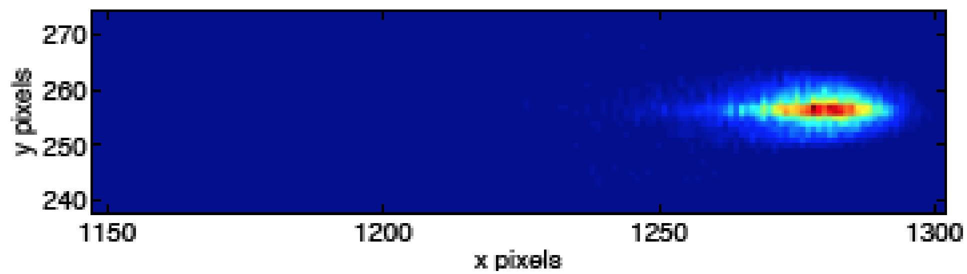
Electron Witness Beam Acceleration Diagnostics

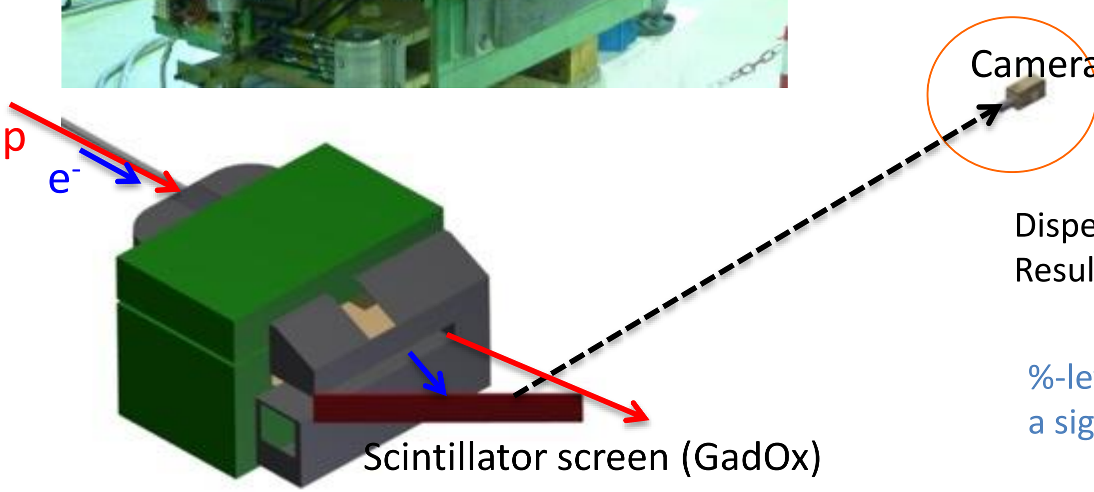
Probe the accelerating wakefields with externally injected electrons → Electron spectrometer



8.5 ton, 1.2 T, 1.3 Tm, L=1.6 m, W=1.3 m



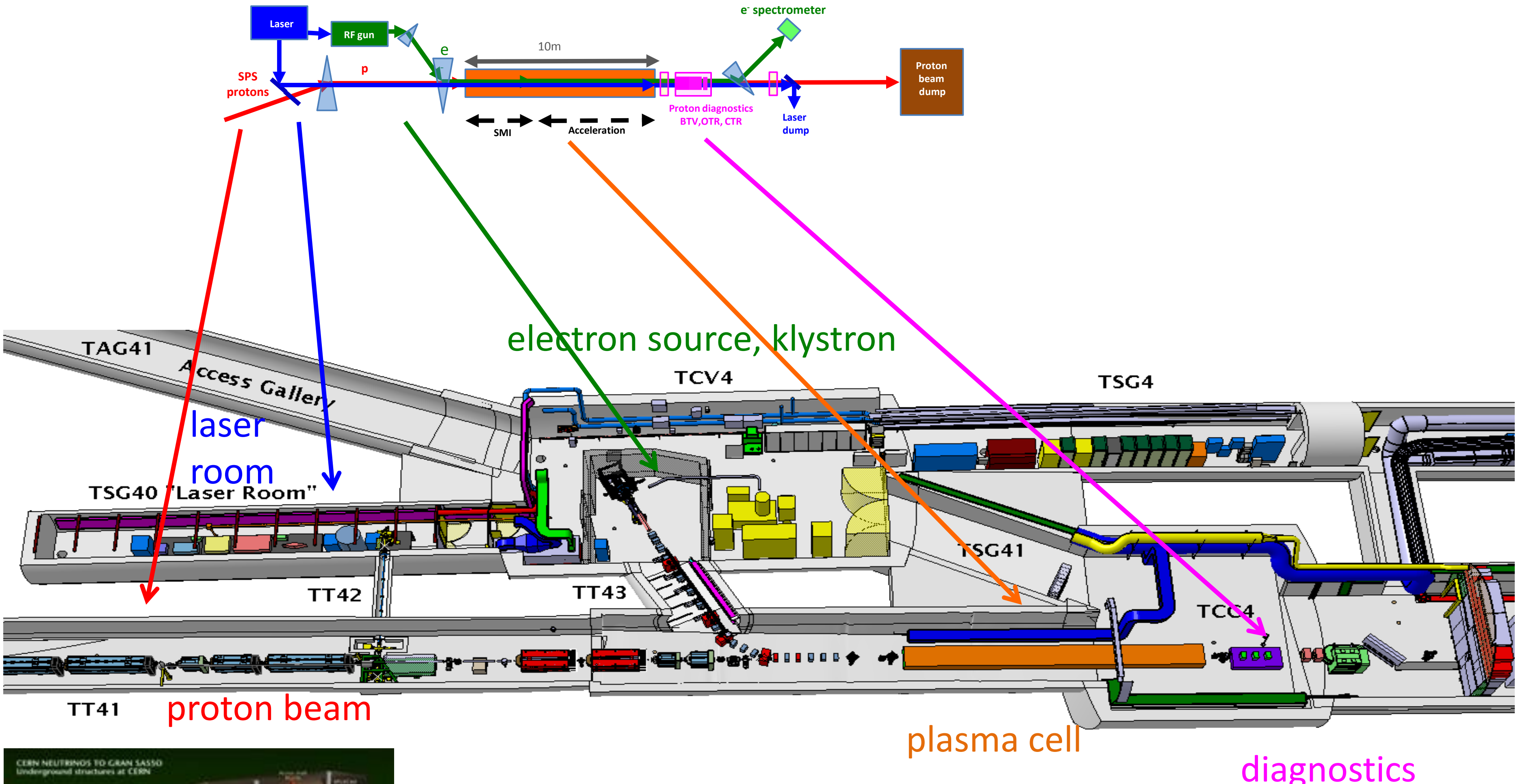


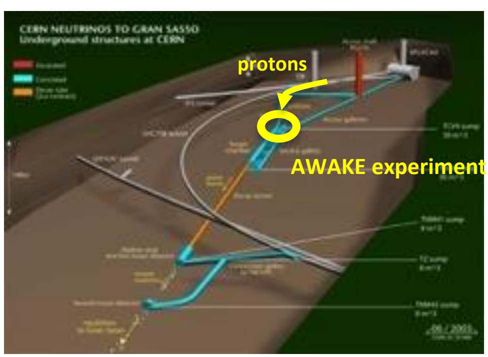


Dispersed electron impact on scintillator screen.
Resulting light collected with intensified CCD camera.

%-level energy resolution can be achieved with a signal to noise ratio larger than 1000:1

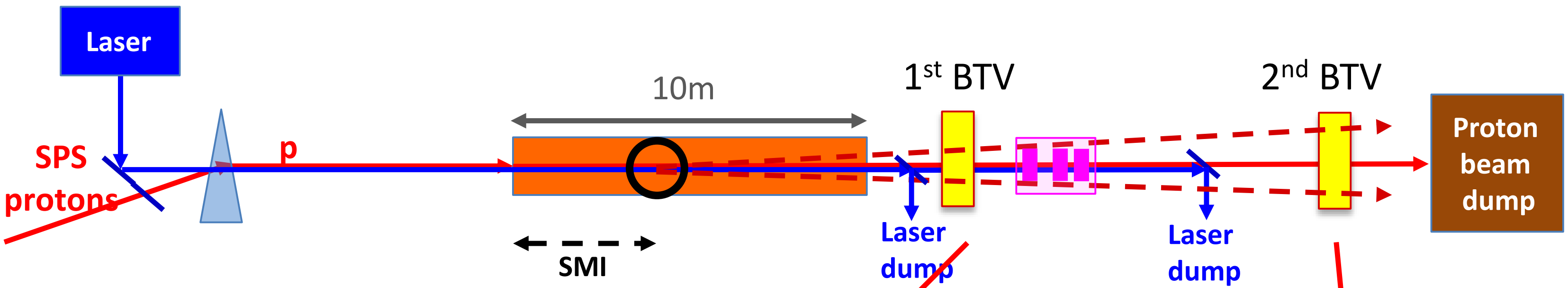
AWAKE Experimental Facility





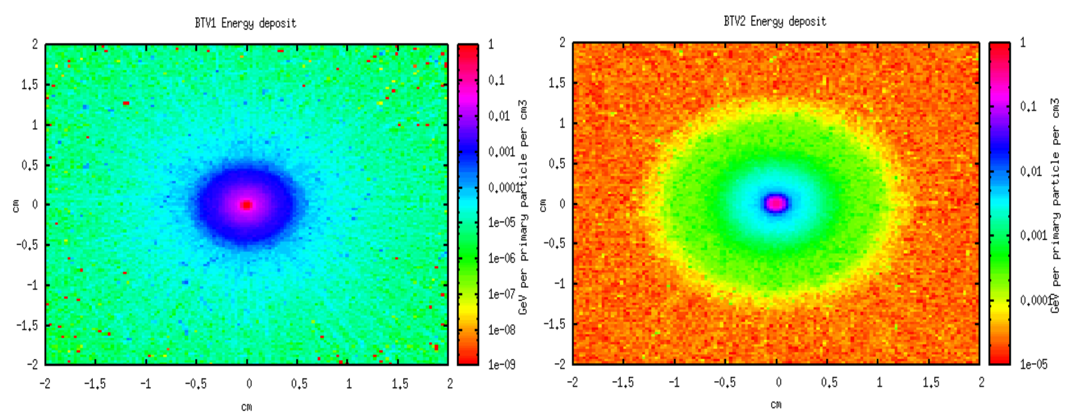
Diagnostics: Indirect Measurement of SMI

SMI causes angular divergence of the proton beam ofthe order of ~1 mrad.
→ Measure bunch profile at two different scintillator screens at a distance of ~8m.



Measure saturation point of SMI

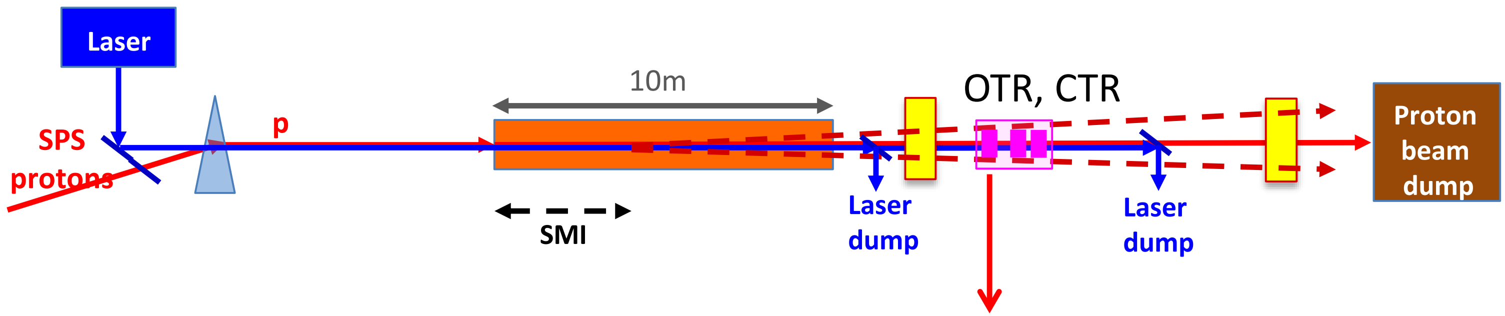
Growth of tails governed by the transverse fields in the plasma. Will give indication of strong plasma wakefields.

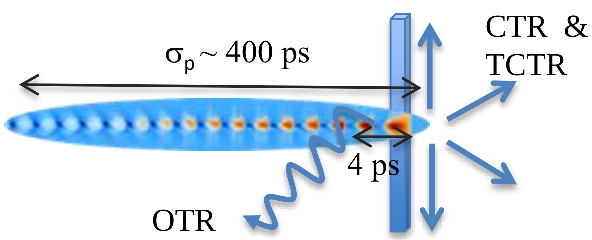


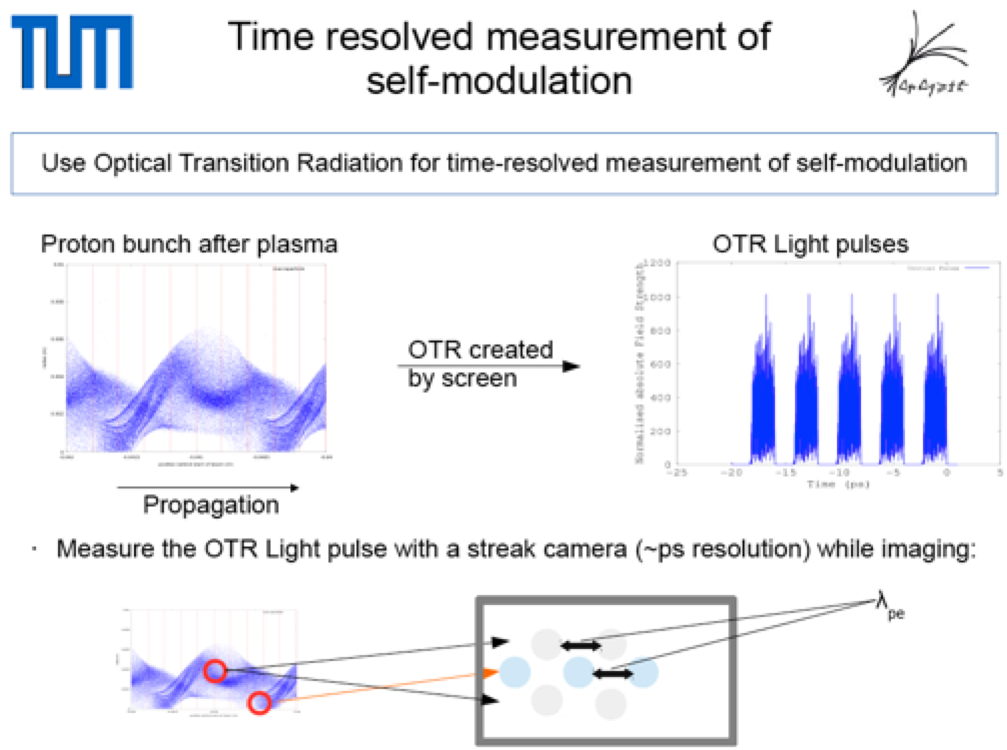
Diagnostics: Direct Measurement of SMI

→ transforming the charge distribution information into a radiation distribution using transition radiation

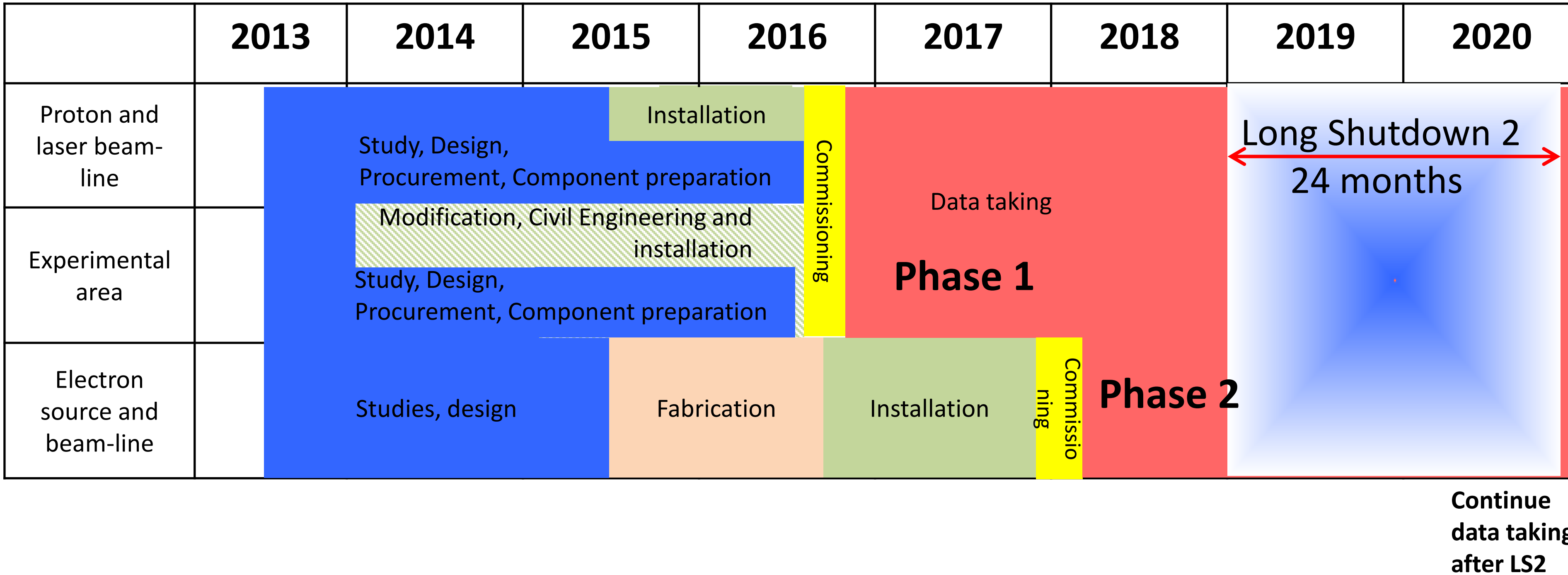
→ Measured radiation emitted by the bunch when traversing a dielectric interface or by directly sampling the bunch space charge field. → streak-camera.







AWAKE Time Line

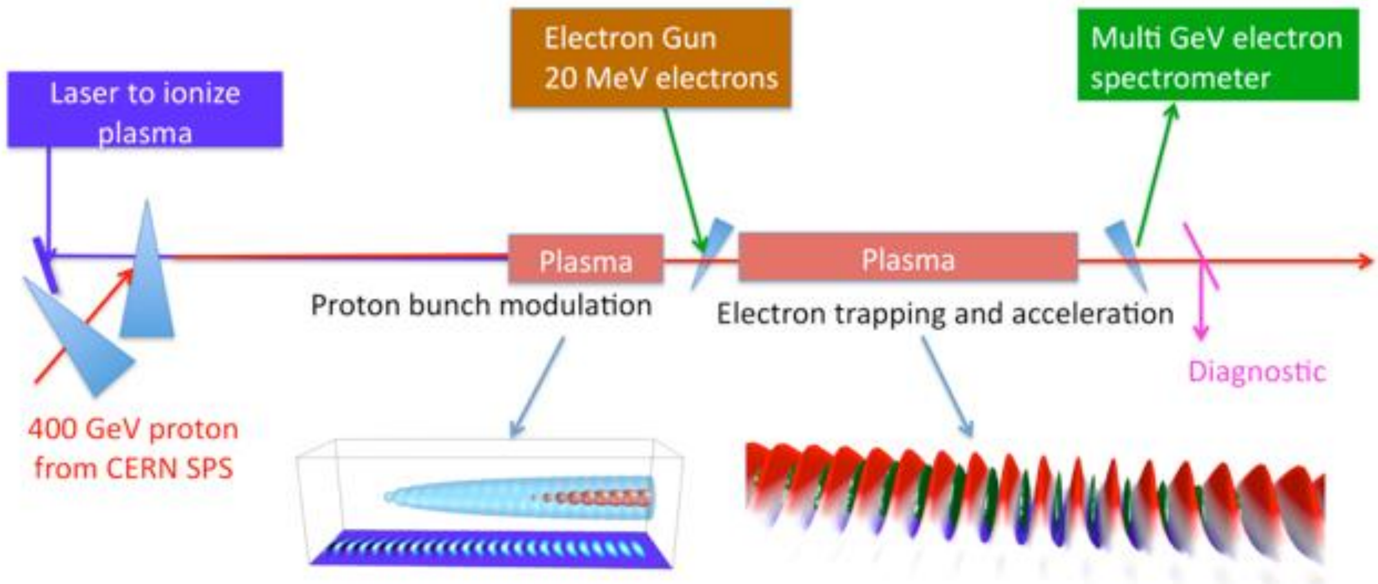


Run request:

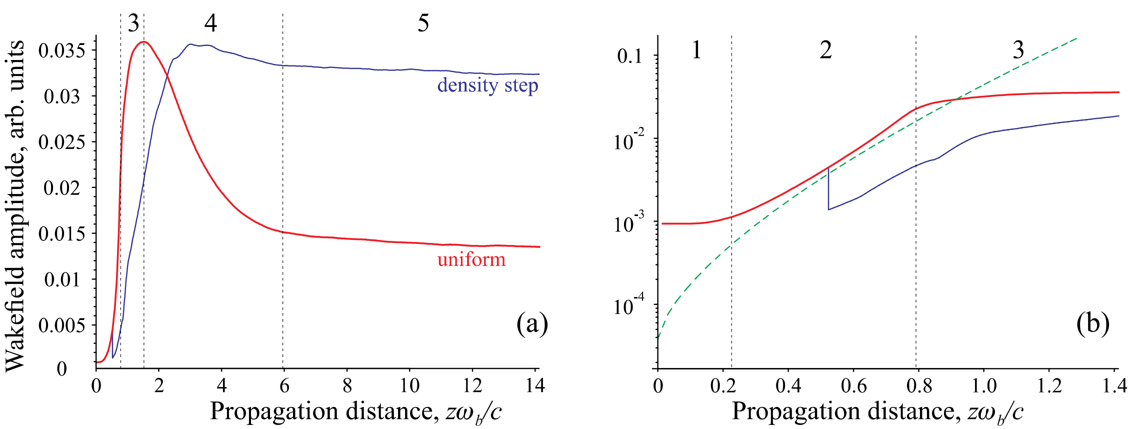
2016: equivalent of 4 weeks continuous running, but upon demand: 2.4 10^{16} protons
+ some running in the summer for proton beam commissioning

2017: equivalent of 8 weeks continuous running, but upon demand: 4.8 10^{16} protons

PHASE 3



- **Split-cell mode**: SMI in 1st plasma cell, acceleration in 2nd one.
- New scalable uniform plasma cells (helicon or discharge plasma cell)
- Step in the plasma density → maintains the peak gradient
- Need ultra-short electron bunches (~ 300fs) → bunch compression → Almost 100% capture efficiency



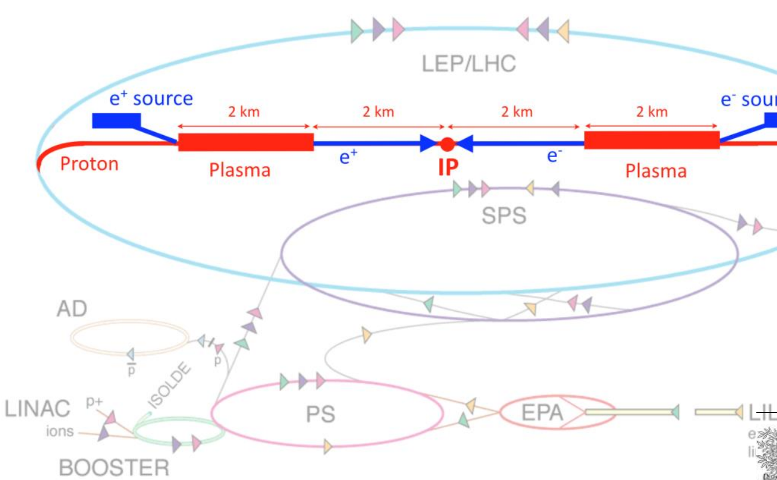
Density step physics better understood; expect to get electrons of few 10's of GeV using SPS drive beam.

Still far away from any collider scenario…..

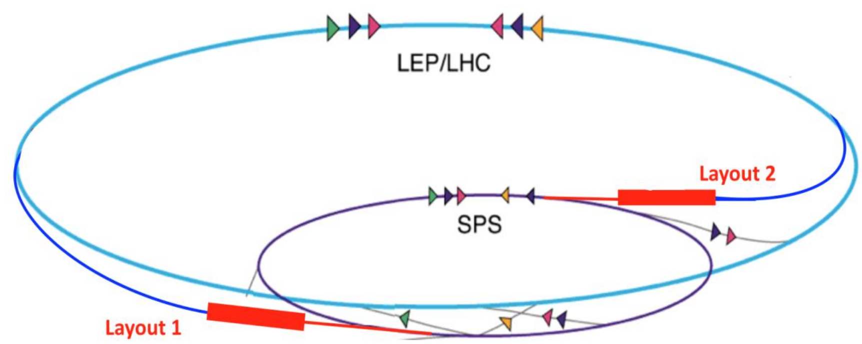
- Beam scattering in plasma → reduced luminosity
- Positron acceleration a problem in all scenarios, solutions being sought
- I am not advocating a plasma-based particle collider in the future but just pointing to a most promising and serious R&D to date at a laboratory with a major stake in energy frontier particle physics …CERN….!!!

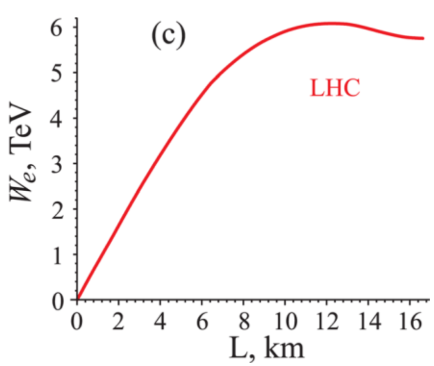
Future collider design

An e+ e- collider



An e-p collider





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Collider design issues based on proton-driven plasma wakefield acceleration

G. Xia [a,b,*], O. Mete [a,b], A. Aimidula [b,c], C.P. Welsch [b,c], S. Chattopadhyay [a,b,c], S. Mandry [d], M. Wing [d,e]

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[b] The Cockcroft Institute, Sci-Tech Daresbury, Daresbury, Warrington, United Kingdom
[c] The University of Liverpool, Liverpool, United Kingdom
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A R T I C L E I N F O

Keywords:
PDPWA
Colliders
Self-modulation instability
Dephasing

A B S T R A C T

Recent simulations have shown that a high-energy proton bunch can excite strong plasma wakefields and accelerate a bunch of electrons to the energy frontier in a single stage of acceleration. It therefore paves the way towards a compact future collider design using the proton beams from existing high-energy proton machines, e.g. Tevatron or the LHC. This paper addresses some key issues in designing a compact electron–positron linear collider and an electron–proton collider based on the existing CERN accelerator infrastructure.

“VHeP: A very High Energy electron-Proton Collider”, A. Caldwell and M. Wing, Proceedings of Science, September 2015
(talks about a 1 TeV electron against a 7 TeV proton collider)

“Path to AWAKE: Evolution of the Concept”, NIMA, November 2015

“Collider Design Issues based on Proton-driven Plasma Wakefield Acceleration”, NIMPR 2014

Summary

- AWAKE is the first proton-driven plasma wakefield acceleration in the world. It is also the first beam driven plasma wakefield acceleration experiment in Europe.

- AWAKE experiment will study the self modulated proton driven plasma wakefield acceleration; Proton beam from CNGS beam line will be used for the first experiment, expected in 2016.

- The first experiment goal is to demonstrate of 1 GeV electron energy gain @ 10 m plasma, 100 GeV @ 100 m plasma as the second step;

- The AWAKE experiment at CERN may shed light on a future e-e, e-p colliders.

Don't Bet on It

from Reader's Digest

AT THE END of every December, when Father Time's odometer is ready to click in another year, experts seem compelled to forecast what the coming year will bring. Economists read their econometric entrails and predict hard times or happy days accordingly; psychics announce that this is the year the San Andreas fault will pitch California into the sea. Well, before you believe any of this year's

predictions , consider these vintage prognostications:

—Octave Chanute, aviation pioneer, in 1904 : "The (flying) machine will eventually be fast ; they will be used in sport, but they are not to be thought of as commercial carriers."

—*The Literary Digest, 1889*: "The ordinary 'horseless carriage' is at present a luxury for the wealthy; and although its price will probably fall in the future, it will never come into as common use as the bicycle."

—Thomas Edison, on electricity in the home : "Just as certain as death, [George] Westinghouse will kill a customer within six months after he puts in a system of any size."

—Lt. Joseph C. Ives, Corps of Topographical Engineers, 1861, on the Grand Canyon: "[It] is, of course, altogether valueless .... Ours has been the first, and will doubtless be the last, party of whites to visit this profitless locality."

—Science Digest, August 1948: "Landing and moving around on the moon offers so many serious problems for human beings that it may take science another 200 years to lick them."

—Physicist and mathematician Lord Kelvin (1824-1907), who seemed to have a corner on the wrongheaded oneliner in his day: "X-rays are a hoax." "Aircraft flight is impossible." "Radio has no future."

-Paul Dickson, *The Future File* (Rawson Associates)

- http://www.cern.ch/awake