Channeling 2014
5-10 October 2014 *Capri-Naples, Italy*

AWAKE: The Proton Driven Plasma Wakefield Acceleration Experiment at CERN

Alexey Petrenko
on behalf of the AWAKE Collaboration

Outline

- Motivation
- AWAKE at CERN
- AWAKE Experimental Layout: 1^{st} Phase
- AWAKE Experimental Layout: 2^{nd} Phase
- Experimental Facility at CERN
- Planning
- Next Steps
- Summary

What is the AWAKE experiment?

- 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: 14 Institutes world-wide:

Motivation

- Accelerating field of today's RF cavities is **limited to <100 MV/m**
  - Several tens of kilometers for future linear colliders

- Plasma can sustain up to **three orders of magnitude higher gradient**
  - SLAC (2007): electron energy doubled from 42GeV to 85 GeV over 0.8 m → 52GV/m gradient
  - However to reach 1 TeV energy with 50 GeV drive beam will require 20 stages. Similar staging problem exists for laser-driven plasma wakefield accelerators.

Why protons?

- There are proton beams available at CERN with TeV scale energy per particle and huge total stored energy. For example:

LHC nominal beam parameters:
(2808 bunches)*(1.15e11 protons)*(7 TeV) = 360 MJ

Fully loaded A320 (80 t) at take-off speed (300 km/h) carries similar amount of kinetic energy (280 MJ).
(However the momentum of the airplane is ~ $c/v \sim 10^6$ times larger than the LHC beam momentum)

Single LHC proton bunch **(7 TeV, 1.2e11 protons)** carries **130 kJ**
Single SPS proton bunch **(0.4 TeV, 3e11 protons)** carries **19 kJ**
Single ILC electron bunch **(0.5 TeV, 2e10 e+/e-)** carries **1.6 kJ**

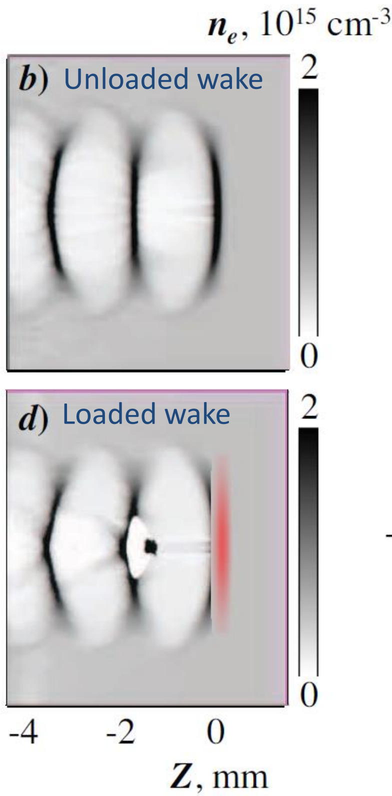
Using LHC beam as a driver it's possible to obtain TeV-level (e-/e+/muons) in a single stage!

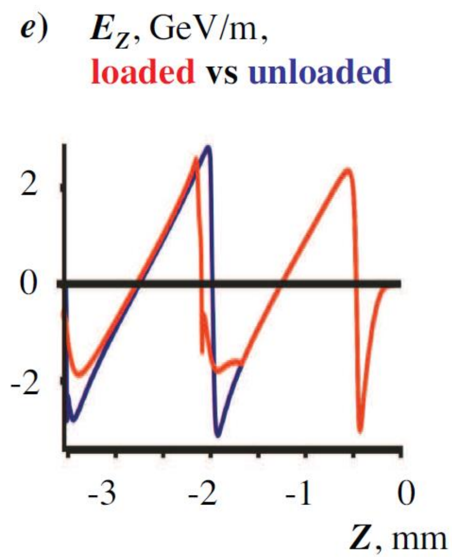
Motivation

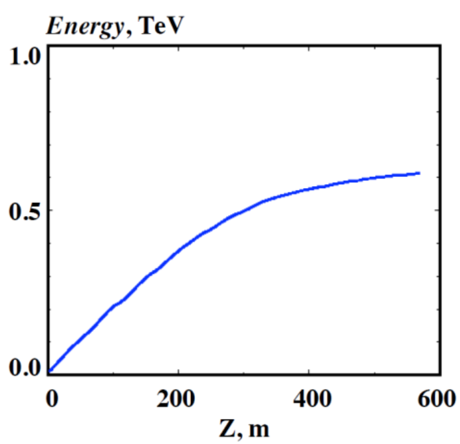
A. Caldwell, K. Lotov, A. Pukhov, F. Simon, Nature Physics (2009):

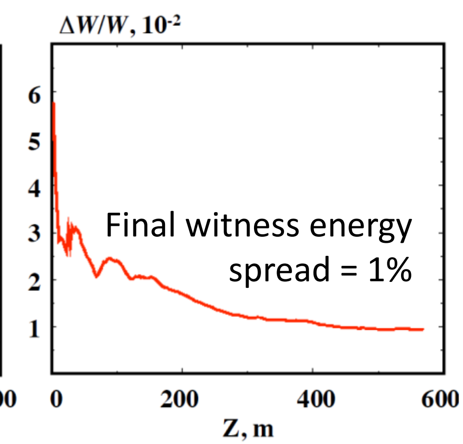
Proton bunch driver: 1 TeV, σ_z = **0.1 mm**

Witness bunch of $1.5 \cdot 10^{10}$ electrons









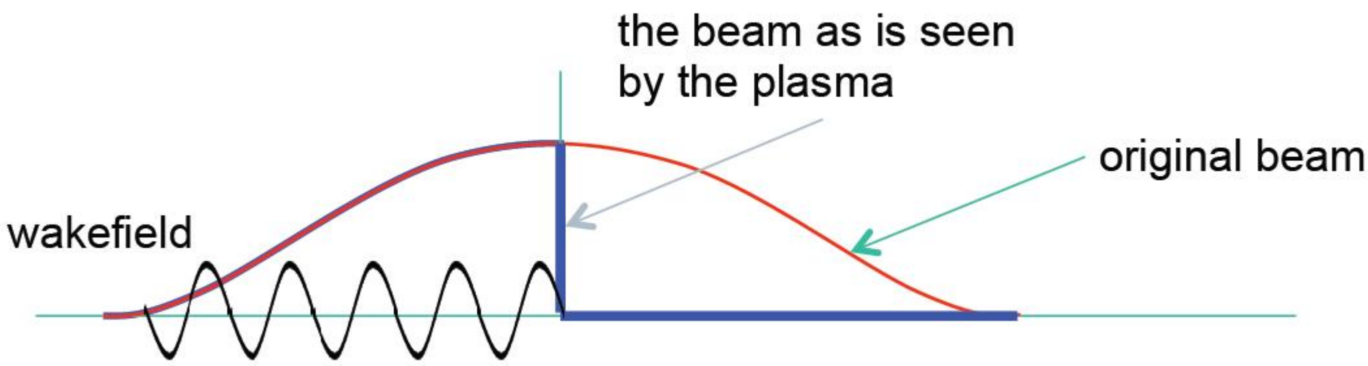
Unfortunately compressing 12 cm long LHC bunch down to σ_z = **0.1 mm** is very challenging and expensive (although technically possible).

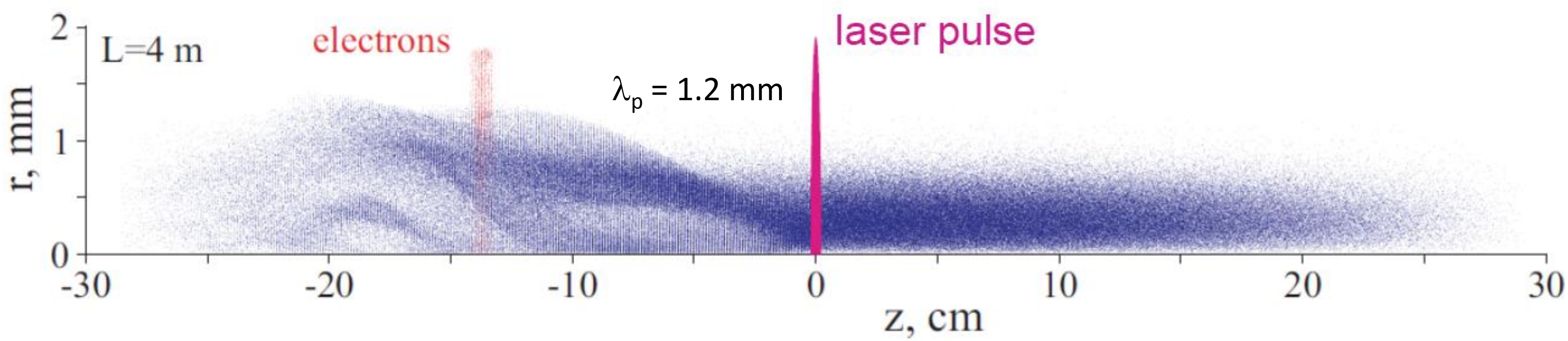
Motivation

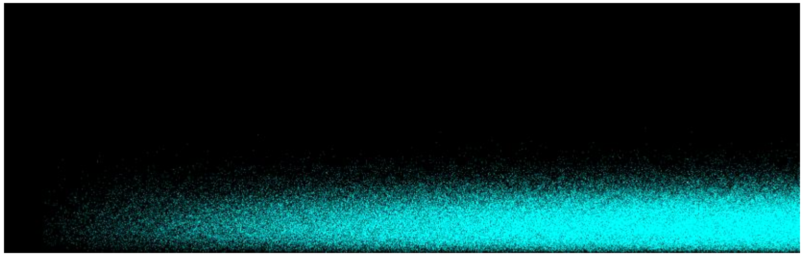
N. Kumar, A. Pukhov, K. Lotov, Phys. Rev. Letters (2010):

Self-modulation instability of a long proton bunch in plasma

(Very similar to Raman self-modulation of long laser pulses -- LWFA with long laser beams, before the invention of chirped pulse compression)

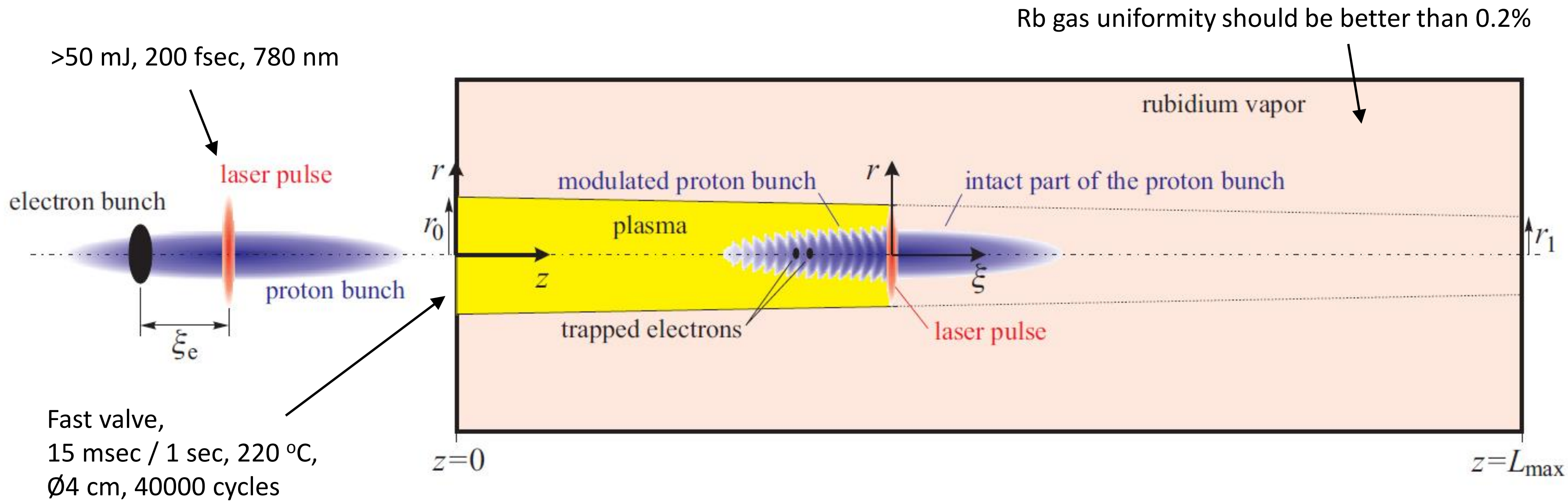






Self-modulated proton bunch resonantly driving plasma wakefields.

The AWAKE experiment configuration & baseline parameters:



Plasma density, n_0	$7 \times 10^{14}\,\mathrm{cm}^{-3}$
Plasma length, $L_{\max}$	10 m
Atomic weight of plasma ions, M_i	85.5
Plasma skin depth, $c/\omega_p \equiv k_p^{-1}$,	0.2 mm
Initial plasma radius, r_0,	1.5 mm
Final plasma radius, r_1,	1 mm
Wavebreaking field, $E_0 = mc\omega_p/e$,	2.54 GV/m
Proton bunch population, N_b	3×10^{11}
Proton bunch length, σ_{zb}	12 cm
Proton bunch radius, σ_{rb}	0.2 mm
Proton bunch energy, W_b	400 GeV

Proton bunch energy spread, δW_b	0.35%
Proton bunch normalized emittance, ϵ_{nb}	3.6 mm mrad
Proton bunch maximum density, n_{b0}	$4 \times 10^{12}\,\mathrm{cm}^{-3}$
Electron bunch population, N_e	1.25×10^9
Electron bunch length, σ_{ze}	1.2 mm
Electron bunch radius, σ_{re}	0.25 mm
Electron bunch energy, W_e	16 MeV
Electron bunch energy spread, δW_e	0.5%
Electron bunch normalized emittance, ϵ_{ne}	2 mm mrad
Electron bunch delay, ξ_e	16.4 cm

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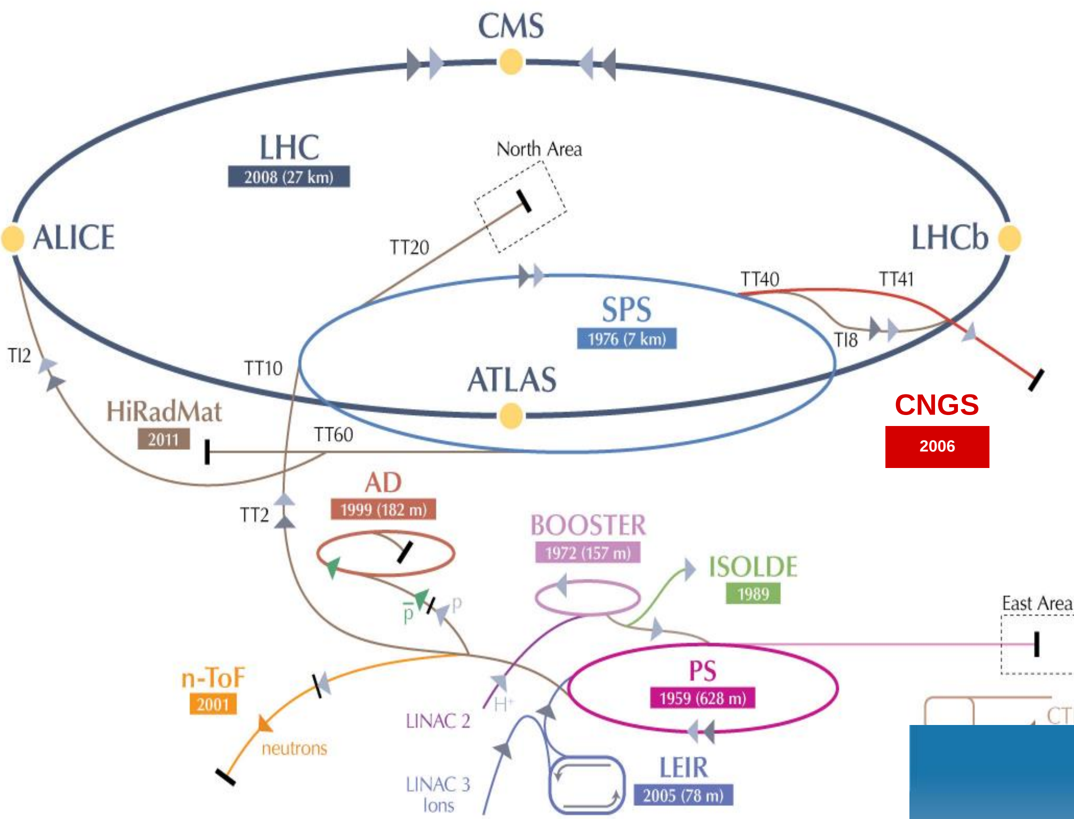
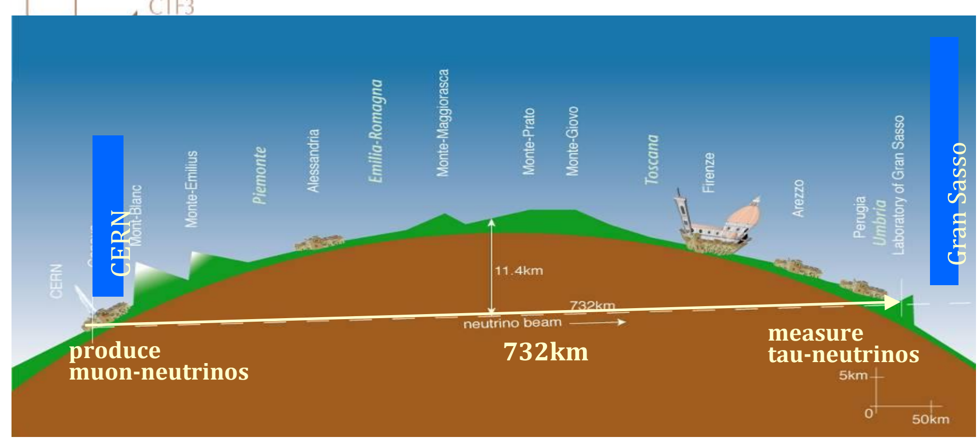
AWAKE at CERN



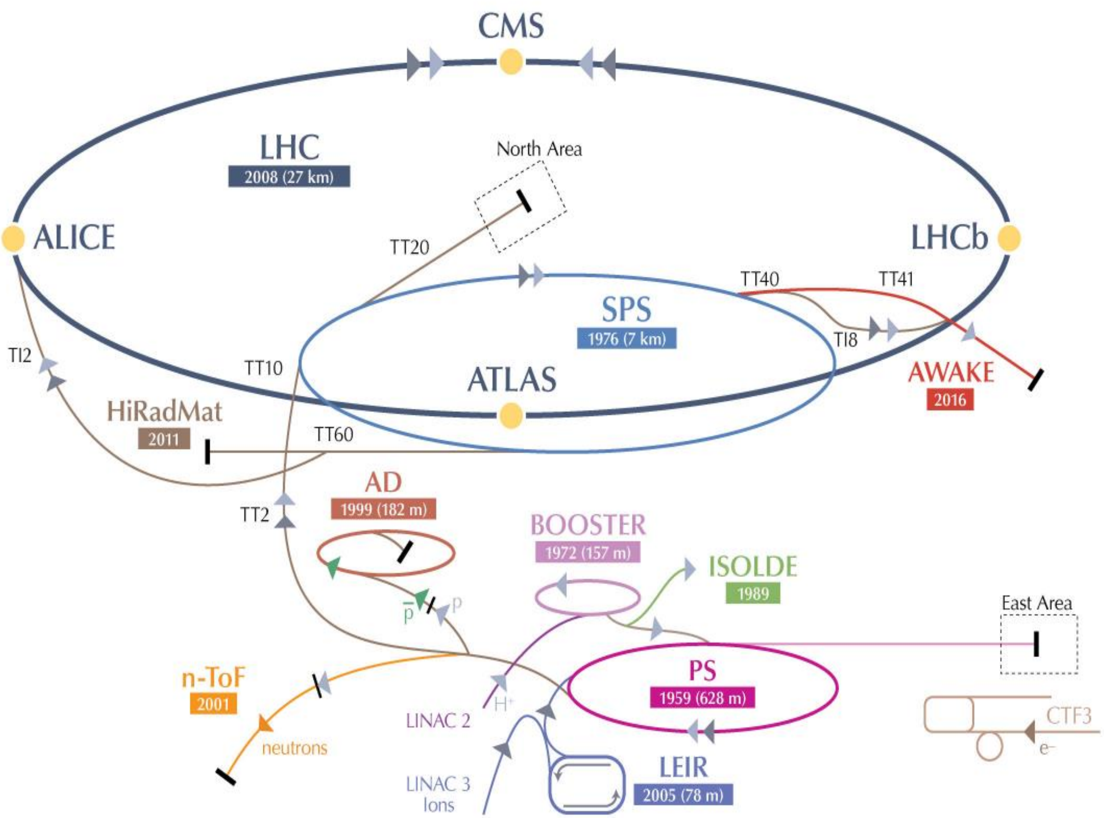
AWAKE in CNGS Facility (CERN Neutrinos to Gran Sasso)

CNGS physics program finished in 2012

- CNGS approved for 5 years: 2008 – 2012
- Expect ~8 tau-neutrinos, 4 published so far



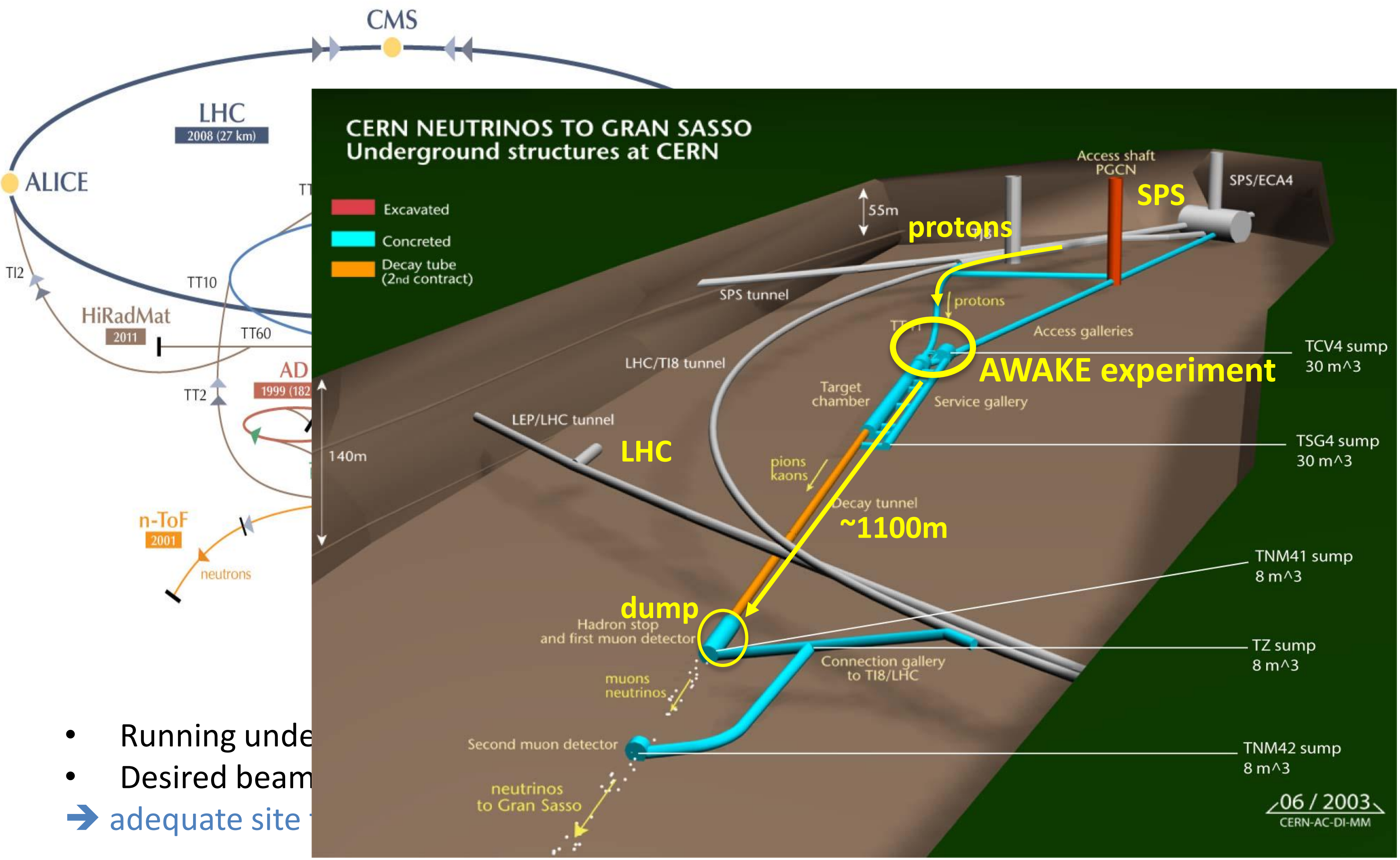
AWAKE at CERN



- Running underground facility
- Desired beam parameters

➔ adequate site for AWAKE

AWAKE at CERN



- Running unde
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➔ adequate site

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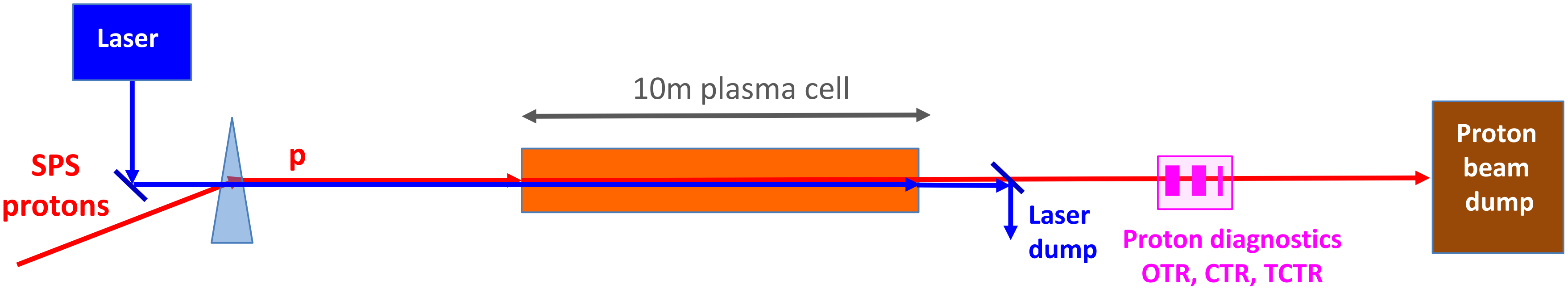
AWAKE Experimental Layout: 1st Phase

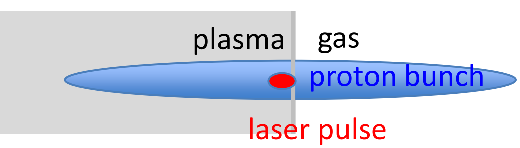
- Perform **benchmark experiments using proton bunches** to drive wakefields for the first time ever.
- Understand **the physics of self-modulation instability** processes in plasma.



→ SPS proton bunch experiences **Self-Modulation Instability** (SMI) in the plasma.

→ **Laser ionizes** the plasma and **seeds the SMI** in a controlled way.

→ 10 m long plasma cell**: Rubidium vapor** source, $n_e = 7 \times 10^{14}$ cm^{-3}.

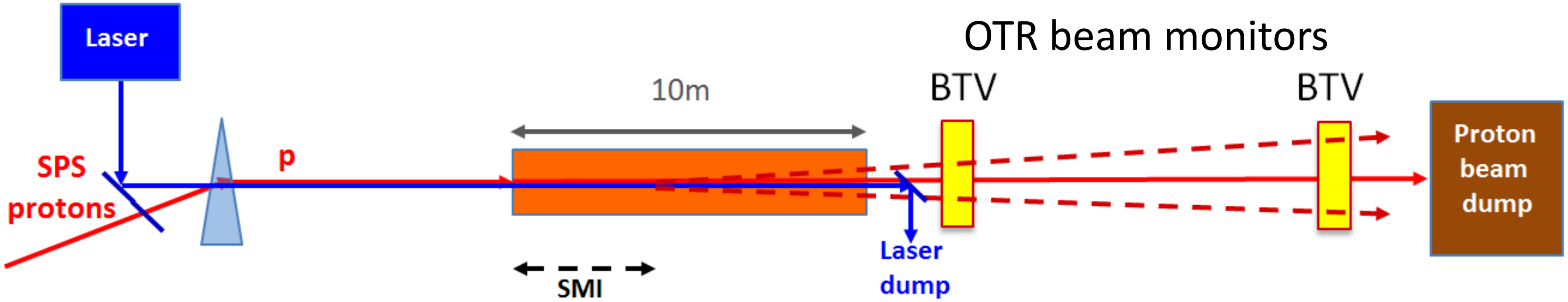


Proton Beam	
Momentum	**400 GeV/c**
Protons/bunch	**$3 \cdot 10^{11}$**
Bunch extraction frequency	**1/30 Hz**
Bunch length	**σ_z = 0.4 ns (12 cm)**
Bunch size at plasma entrance	**$\sigma^*_{x,y}$ = 200 μm**
Normalized emittance (r.m.s.)	3.5 mm mrad
Relative energy spread	$\Delta p/p$ = 0.35%
Beta function	$\beta^*_x = \beta^*_y$ = 4.9m
Dispersion	$D^*_x = D^*_y$ = 0

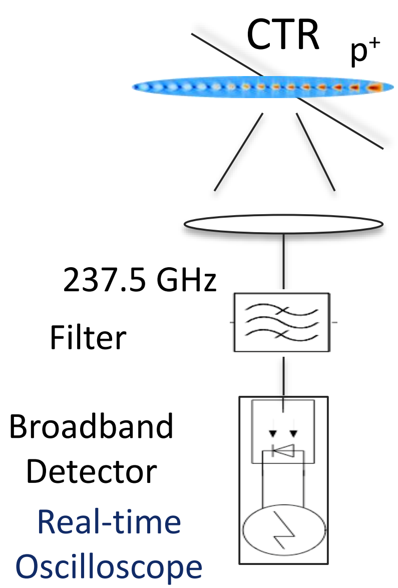
Laser Beam	
Laser type	Fiber Ti:Sapphire
Pulse wavelength	λ_0 = 780 nm
Pulse length (FWHM)	200 fs
Pulse energy (after compr.)	**450 mJ**
Laser power	2 TW
Focused laser size	**$\sigma_{x,y}$ = 1 mm**
Energy stability	±1.5% r.m.s.
Repetition rate	10 Hz

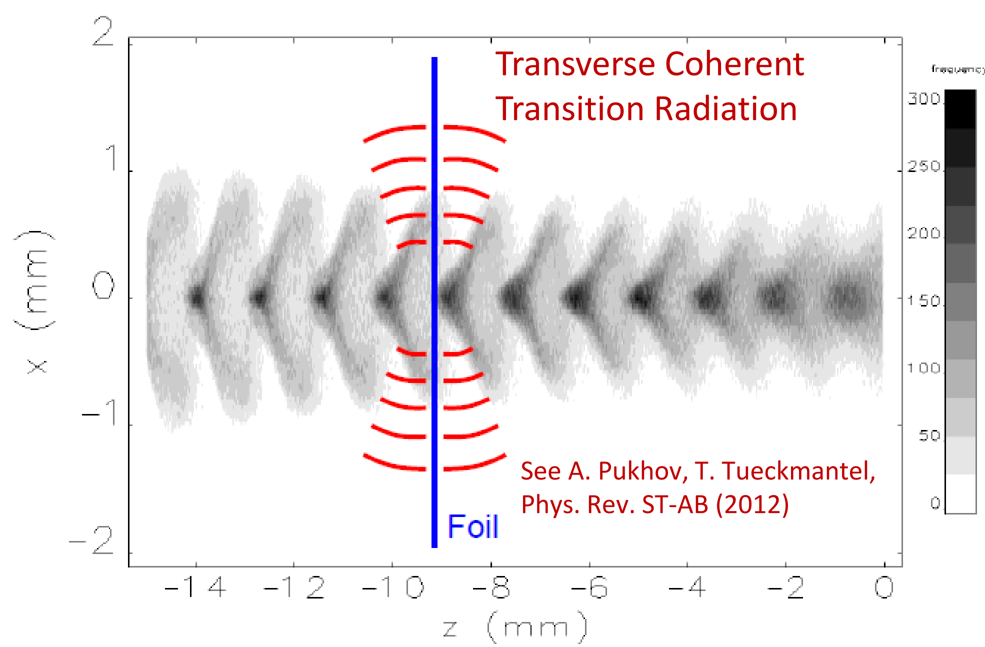
Self-Modulation-Instability Diagnostics

Measure the **characteristics of the proton** beam after propagating through the plasma cell.



- Optical Transition Radiation (OTR):
  - Time-resolve bunch radius variation with streak-camera (~100fs resolution)
  - Measure relative phasing of laser pulse, proton bunch and electron bunch
- Coherent Transition Radiation (CTR) and Transverse Coherent Transition Radiation (TCTR)
  - High frequency (~f_p = 237.5 GHz)
  - Broadband detection scheme (500 GHz)





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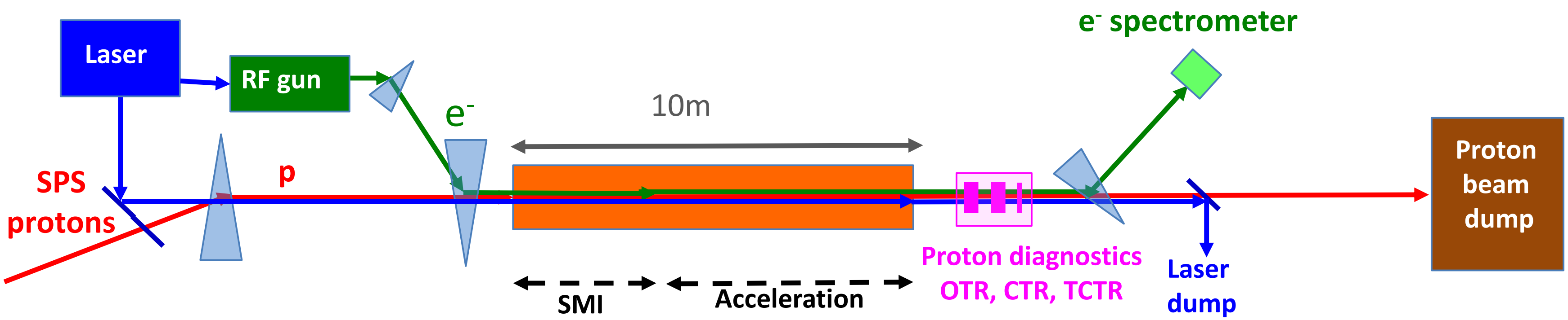
AWAKE Experimental Layout: 2nd Phase

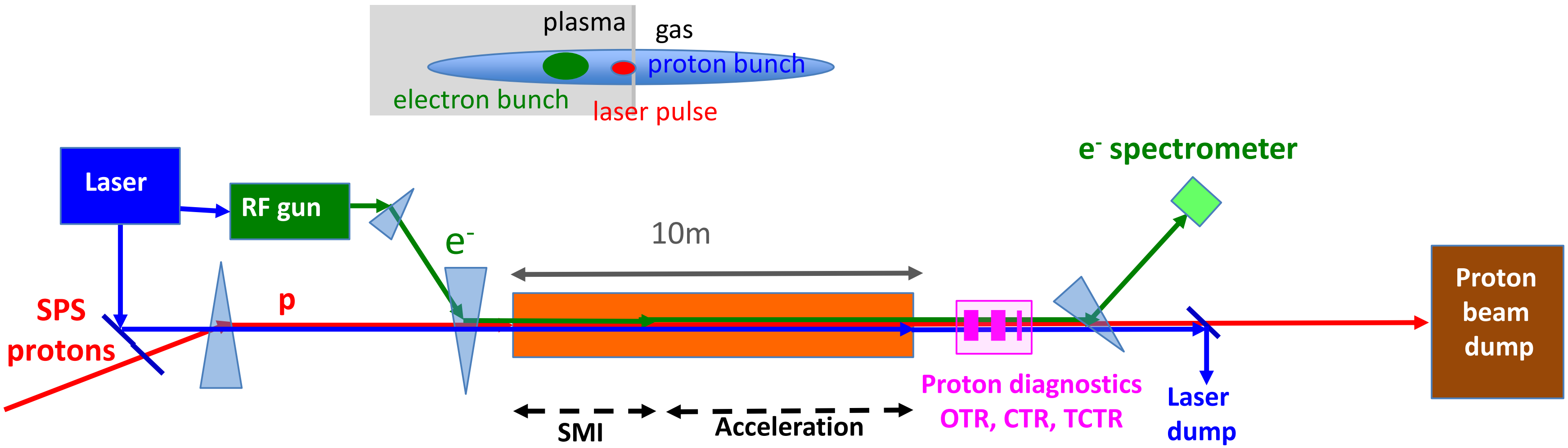
- **Probe the accelerating wakefields with externally injected electrons**, including energy spectrum measurements for different injection and plasma parameters.



Electron beam	
Momentum	**16 MeV/c**
Electrons/bunch (bunch charge)	**1.2 E9 (0.2 nC)**
Bunch length	**σ_z =4ps (1.2mm)**
Bunch size at focus	**$\sigma^*_{x,y}$ = 250 μm**
Normalized emittance (r.m.s.)	2 mm mrad
Relative energy spread	$\Delta p/p$ = 0.5%
Beta function	$\beta^*_x = \beta^*_y = 0.4$ m
Dispersion	$D^*_x = D^*_y = 0$

Laser beam for electron source	
Laser type	Ti:Sapphire Centaurus
Pulse wavelength	λ_0 = 260 nm
Pulse length	10 ps
Pulse energy (after compr.)	50 μJ
Electron source cathode	Copper
Quantum efficiency	3.00 E-5
Energy stability	±2.5% r.m.s.

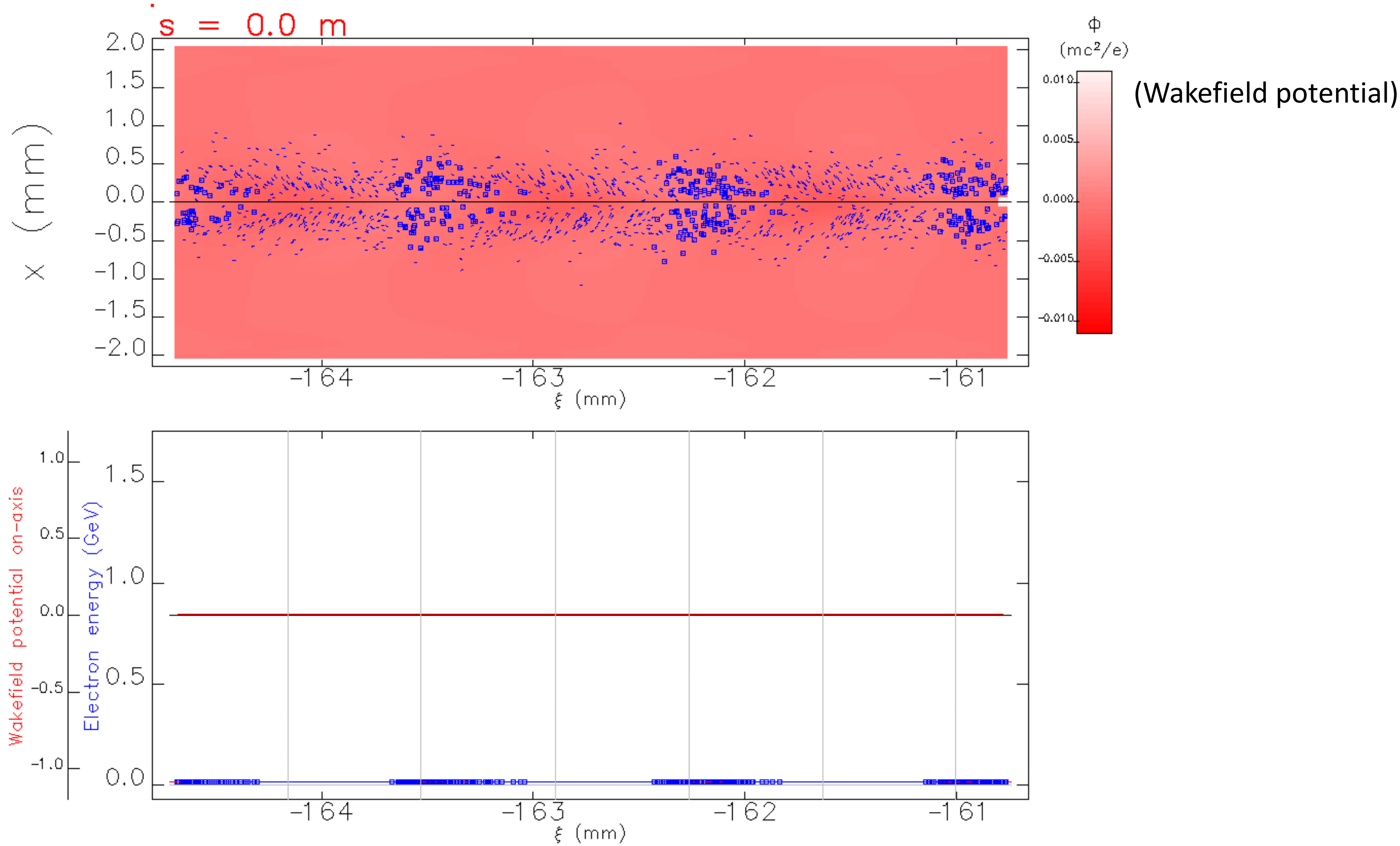
AWAKE Experimental Layout: 2nd Phase



- Laser and electron beam synchronized at the **< 1 ps level**.
- **Electron bunch is externally injected** into the plasma cell, on-axis and collinearly with the proton and laser beam.
- **On-axis injection** point is upstream the plasma cell.

AWAKE Experimental Layout: 2nd Phase

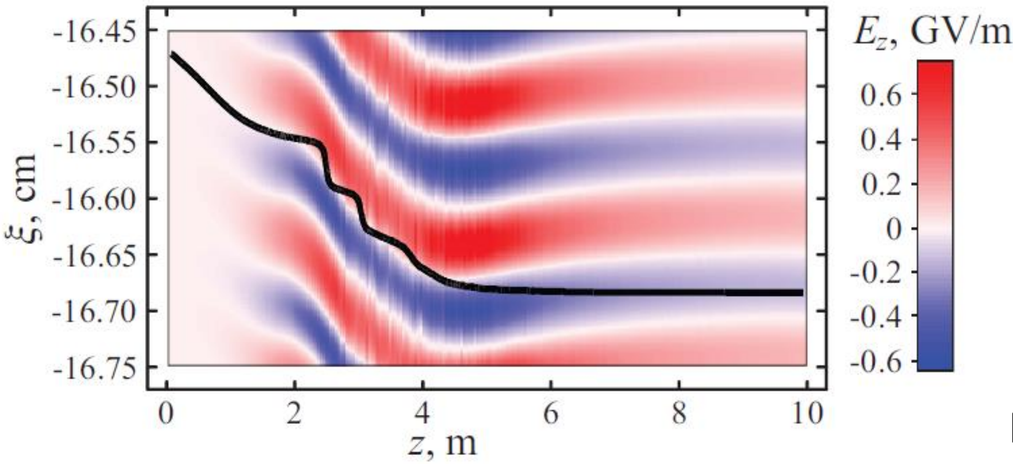
On-axis injection: animation of electron trapping and acceleration

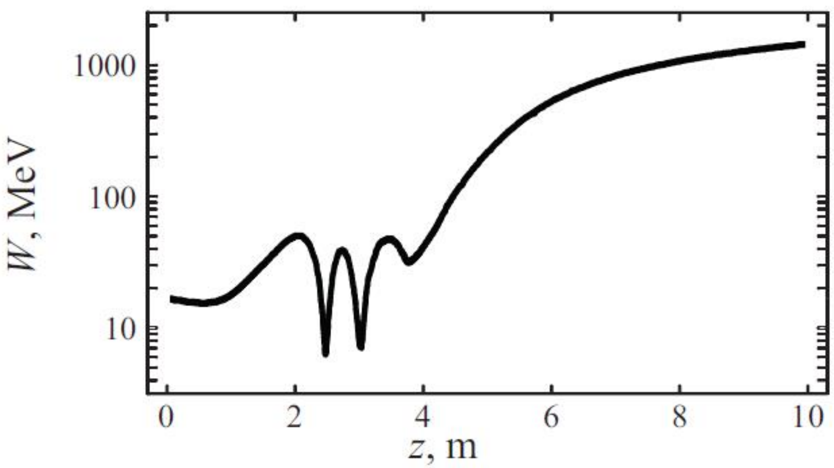


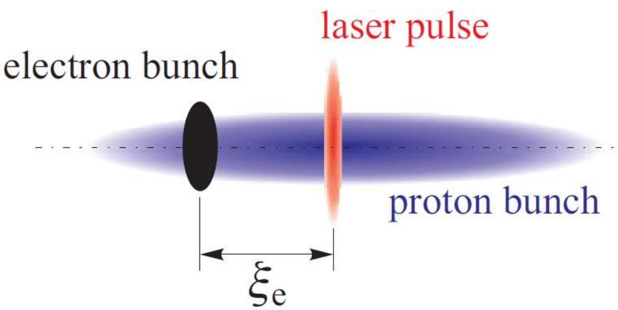
- Electrons are trapped from the very beginning by the wakefield of seed perturbation
- Trapped electrons make several synchrotron oscillations in their potential wells
- After z=4 m the wakefield moves forward in the light velocity frame

The baseline AWAKE accelerated electron beam:

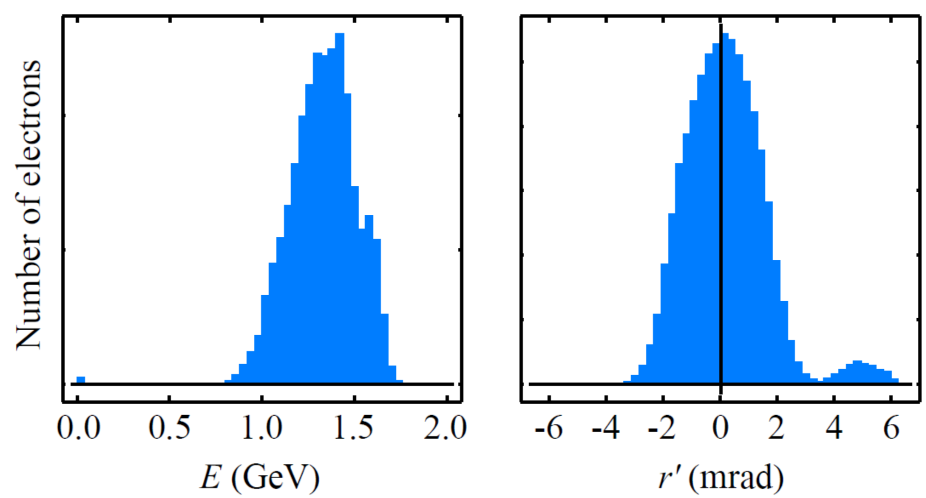
Typical trajectory of accelerated electron:







Final energy & angle distributions in e-beam:



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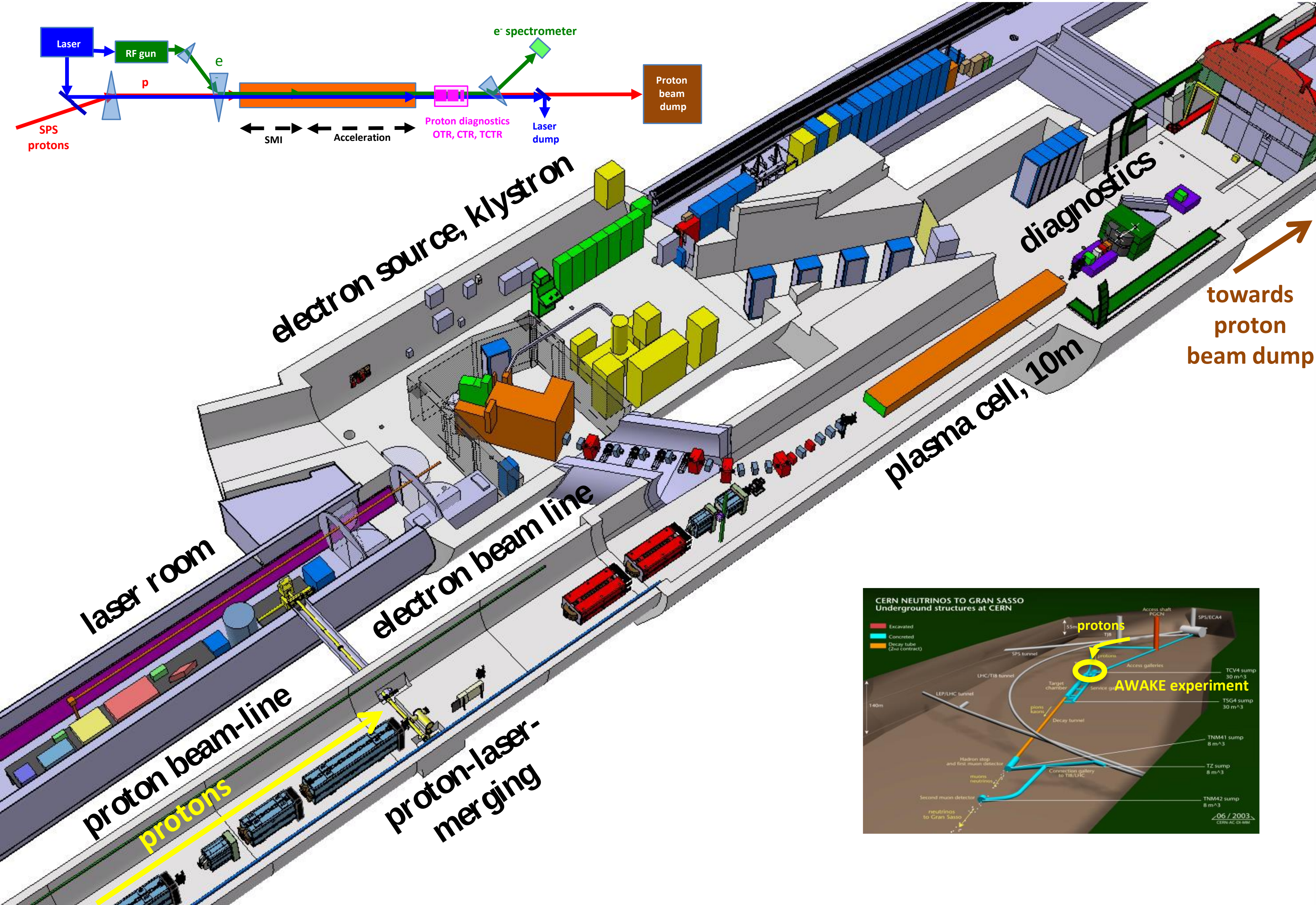
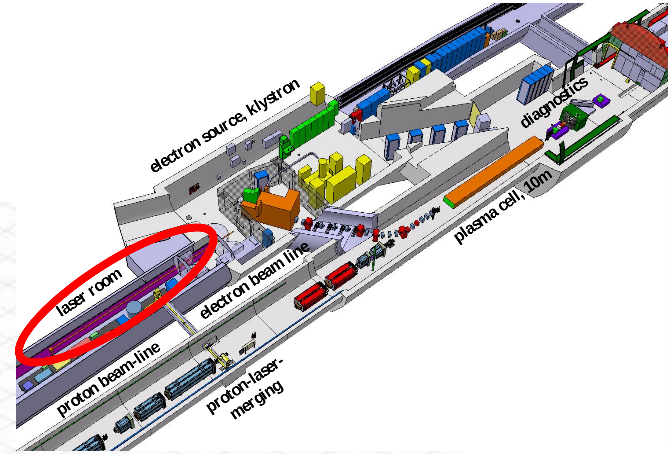
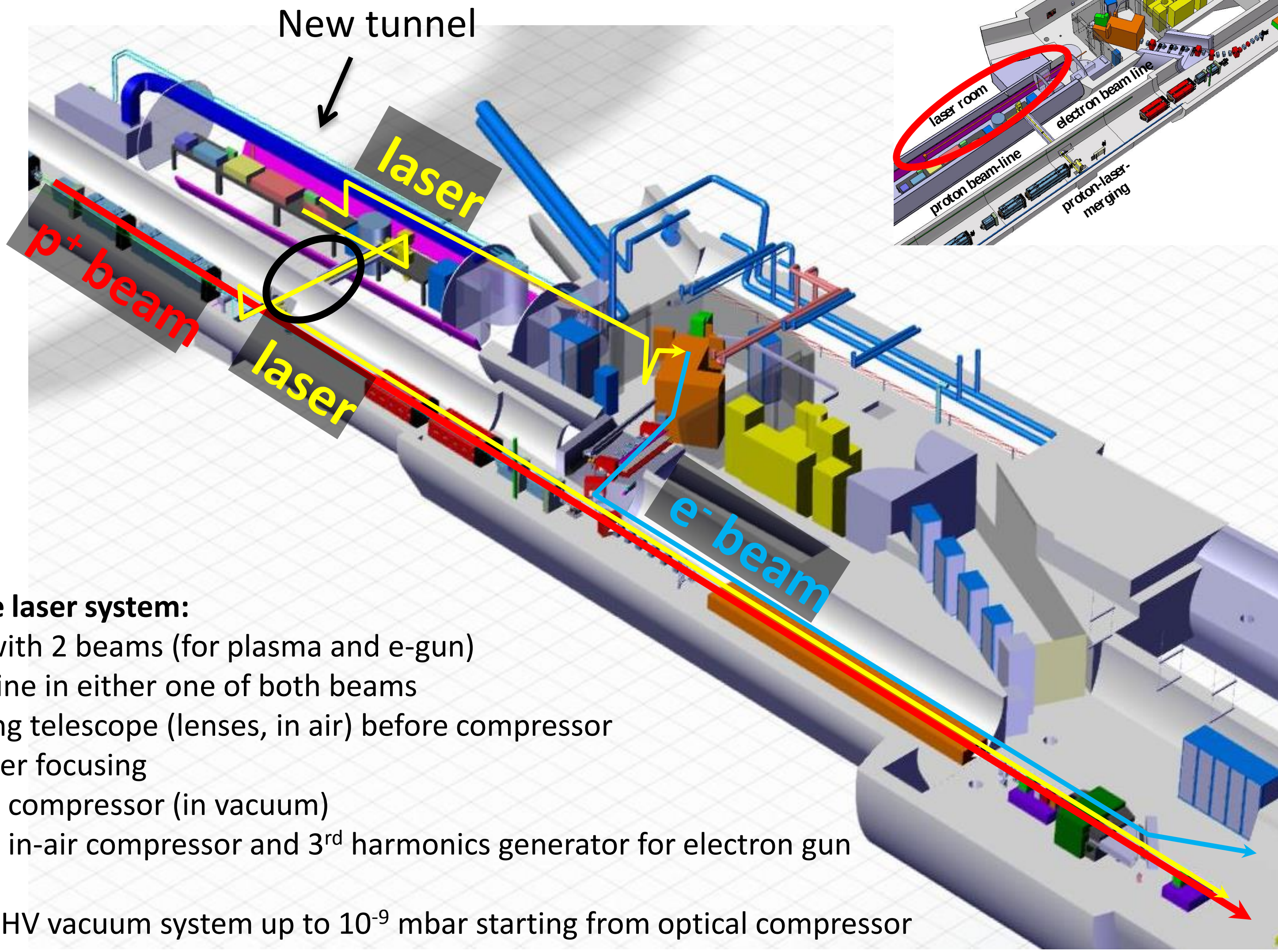
AWAKE Experimental Facility at CERN



Laser System



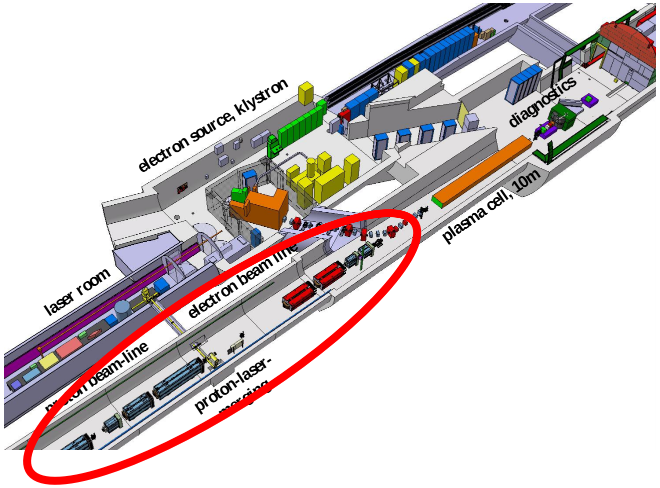


Ti: Sapphire laser system:

- Laser with 2 beams (for plasma and e-gun)
- Delay line in either one of both beams
- Focusing telescope (lenses, in air) before compressor
- 35 meter focusing
- Optical compressor (in vacuum)
- Optical in-air compressor and 3rd harmonics generator for electron gun

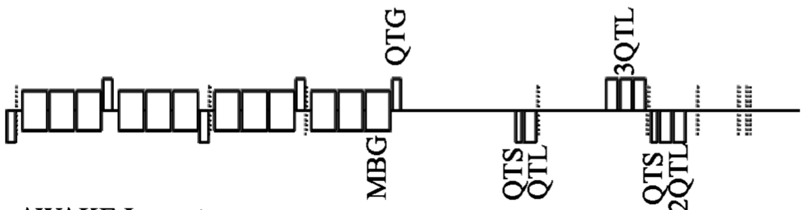
Complete UHV vacuum system up to 10^{-9} mbar starting from optical compressor

Proton Beam Line

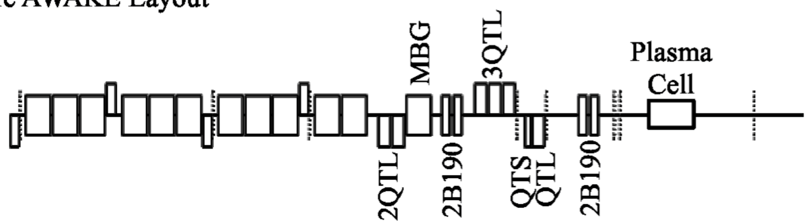


Change of the proton beam line only in the **downstream part (~80m)**

Present CNGS Layout (end of the line)

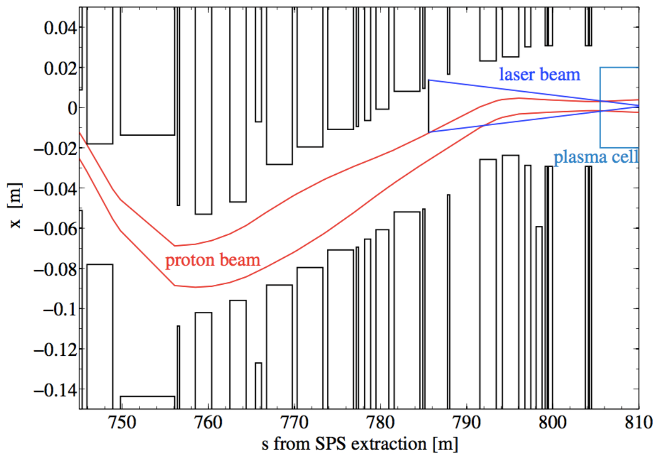


Future AWAKE Layout



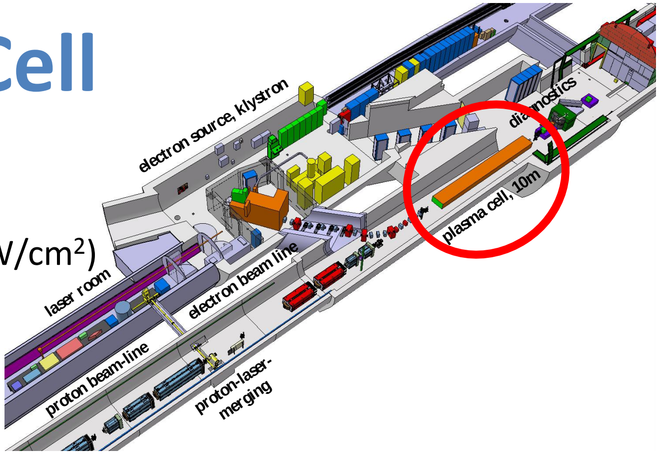
→ **Displace existing magnets** of the final focusing to fulfill optics requirements at plasma cell

→ Move existing dipole and **4 additional dipoles** to create a **chicane for the laser mirror** integration.



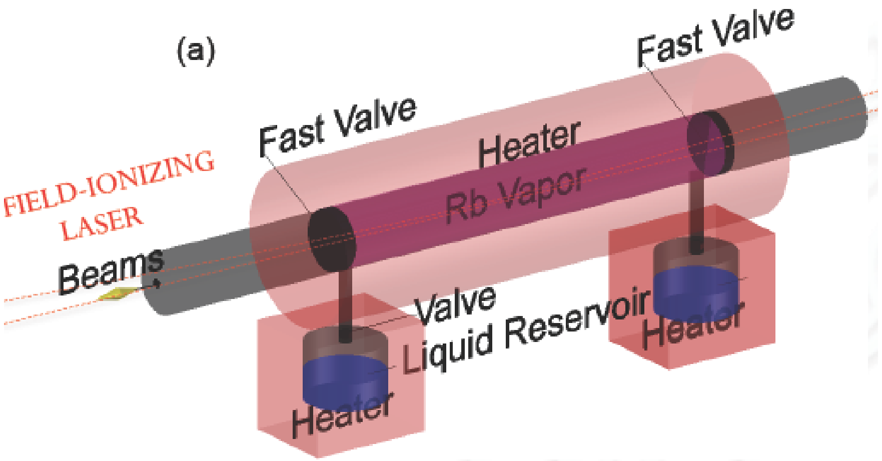
Laser-proton merging 20m upstream the plasma cell

Rubidium Vapour Plasma Cell

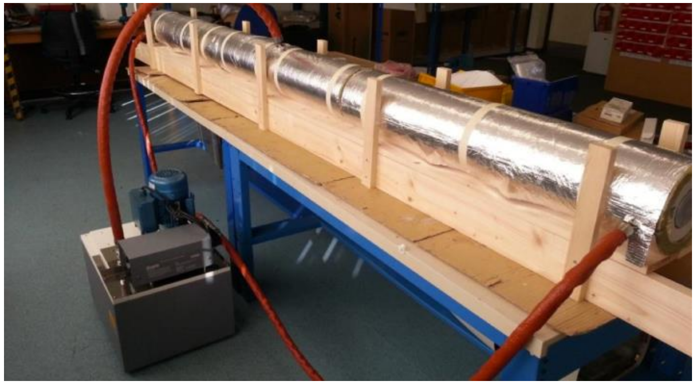


- Density adjustable from **10^{14} – 10^{15} cm^{-3}**
- 10 m long, 4 cm diameter
- Plasma formed by **field ionization of Rb vapour** using laser pulse (~1.7 10^{12} W/cm^2)
- System is oil-heated → keep temperature uniformity ➔ density uniformity

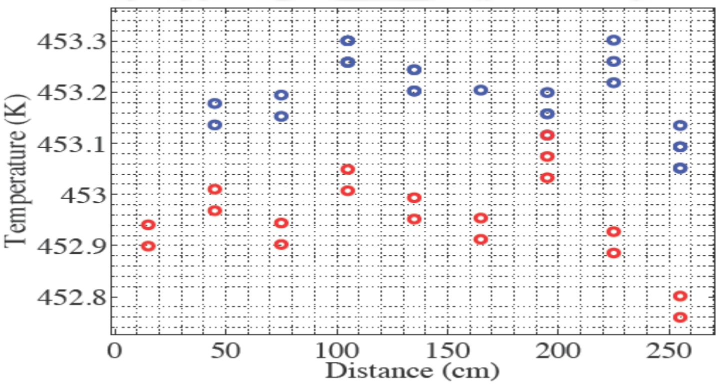
$\Delta n/n = \Delta T/T \leq 0.002$



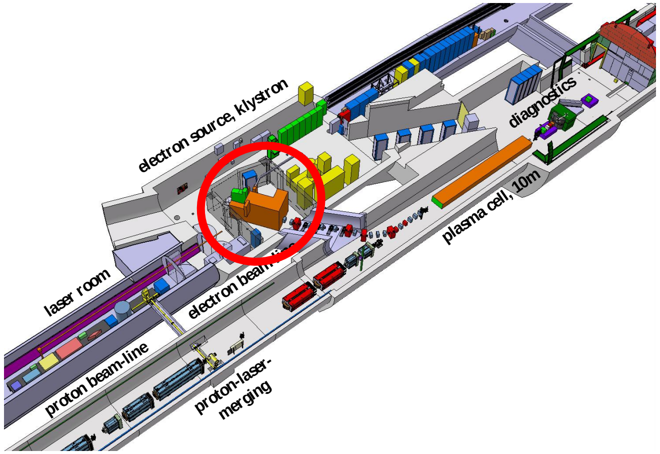
3m prototype



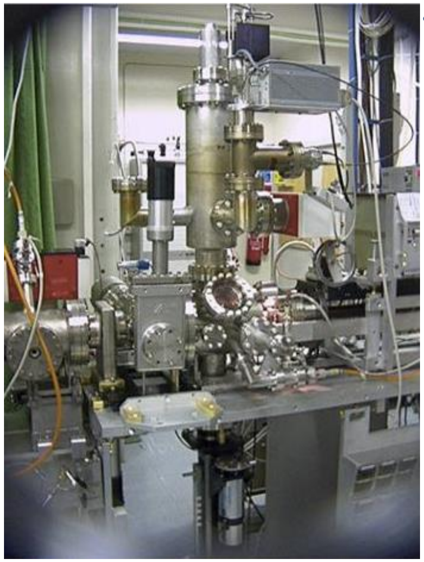
Temperature profiles along the heat exchanger
Measurements **remain < ± 0.1 K**

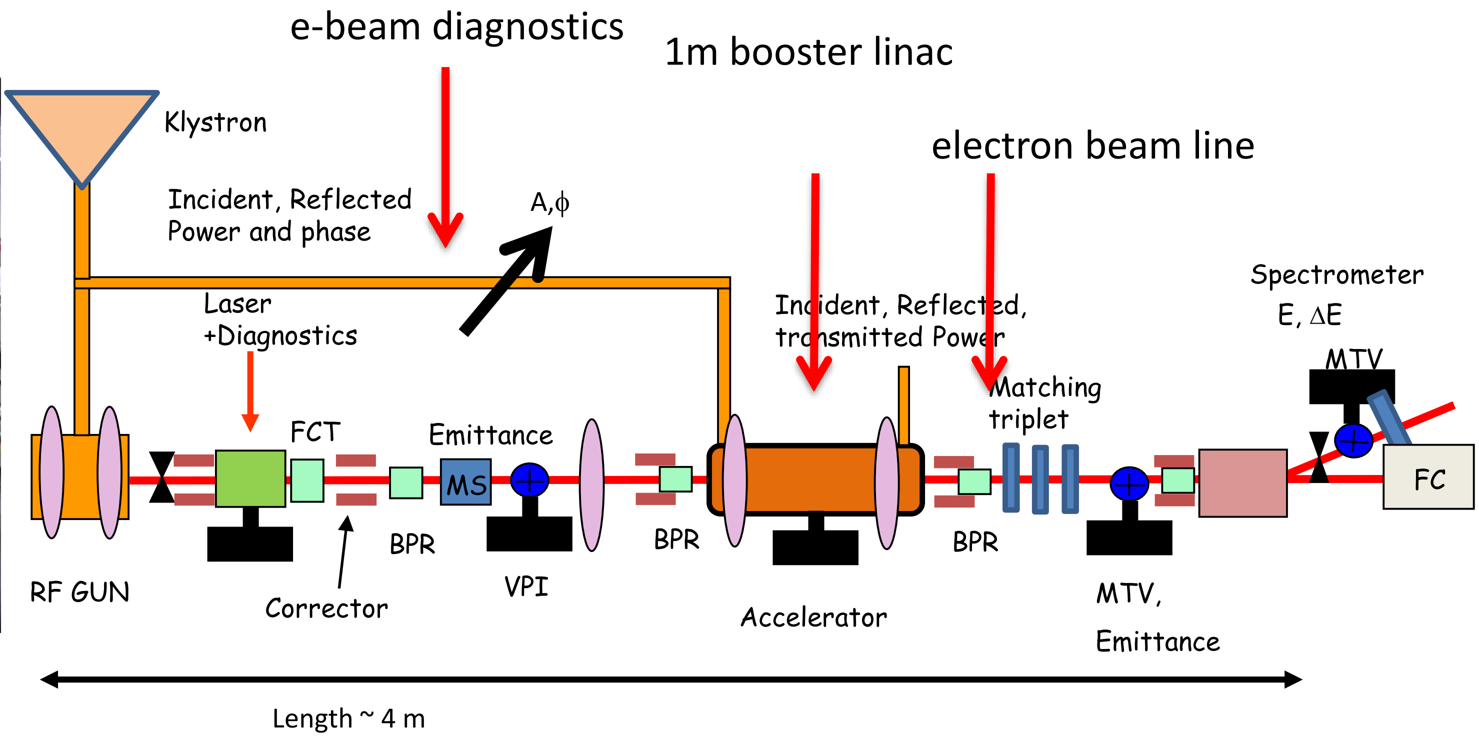


Electron – Source

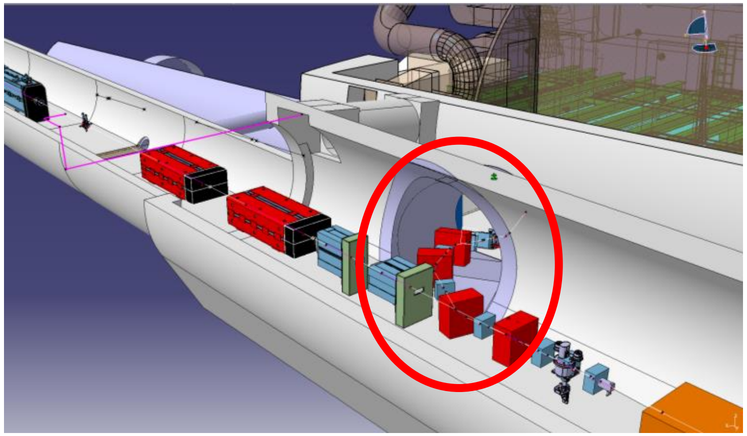


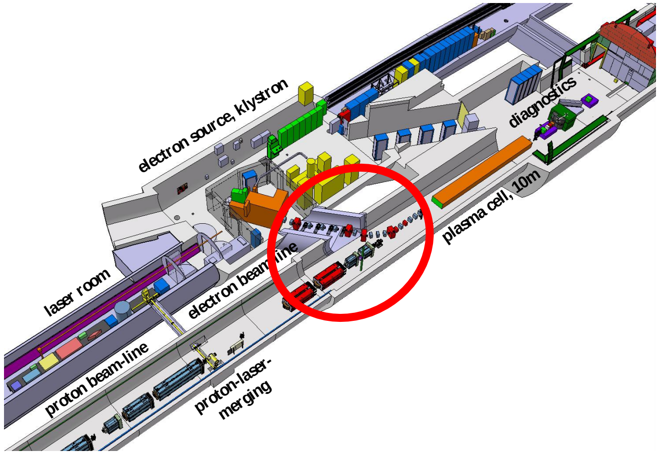
- Baseline:
  - Photo injector (**PHIN**) from CTF2 at CERN (5 MeV electrons)
  - Klystron and modulator from CTF3
  - Booster from Cockcroft/Lancaster 5 MeV→ 20 MeV
- Optimize and test performance of complex system.
  - use as test area after 2015.





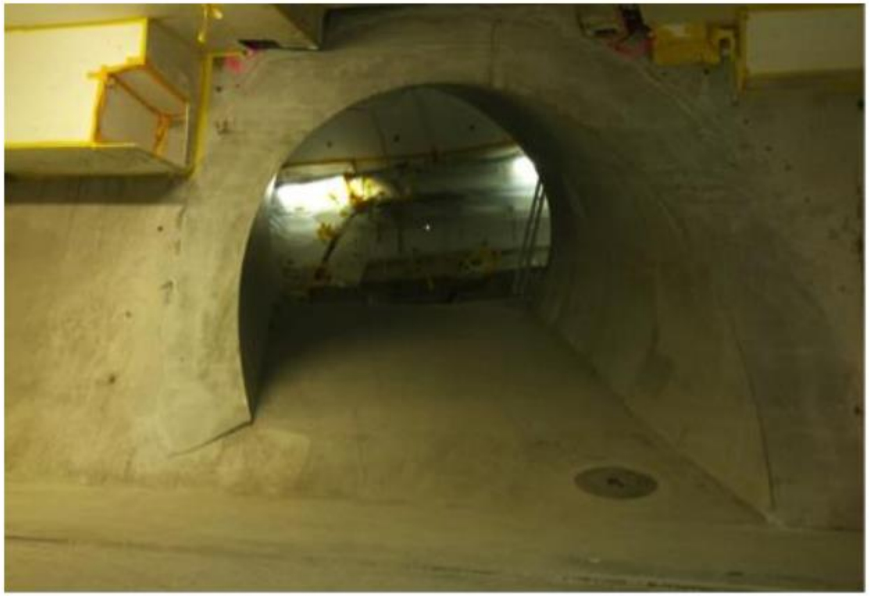
Electron Beam Line





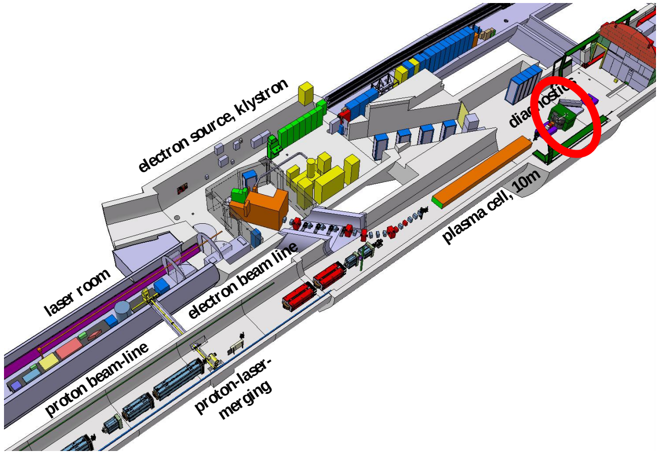
About two months ago:

Now:

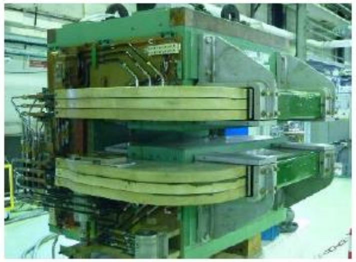


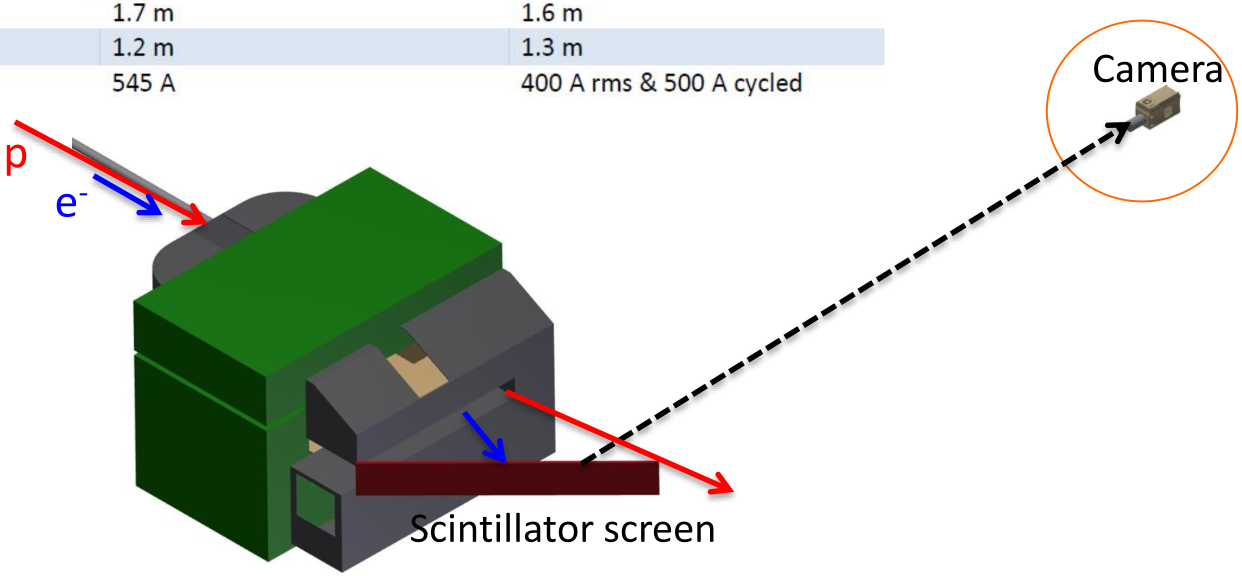
Laser tunnel has been excavated recently also.

Electron Spectrometer



- Measure **peak energy and energy spread** of electrons.
- Spectrometer magnet separates electrons from proton beam-line.
- Dispersed electron impact on scintillator screen.
- Resulting light collected with intensified CCD camera.

Photo		
Weight	15 t	8.5 t
Power consumption	60 kW	15 kW rms & 24 kW cycled
Integrated field (B*L)	1.9 T*m	1.3 T*m rms & 1.6 T*m cycled
Max. magnetic field	1.65 T	1.2 T rms & 1.5 T cycled
Horizontal aperture	52 cm	32 cm
Vertical aperture	11 cm	8 cm
Iron length	1 m	1 m
Total length	1.7 m	1.6 m
Total width	1.2 m	1.3 m
Current	545 A	400 A rms & 500 A cycled



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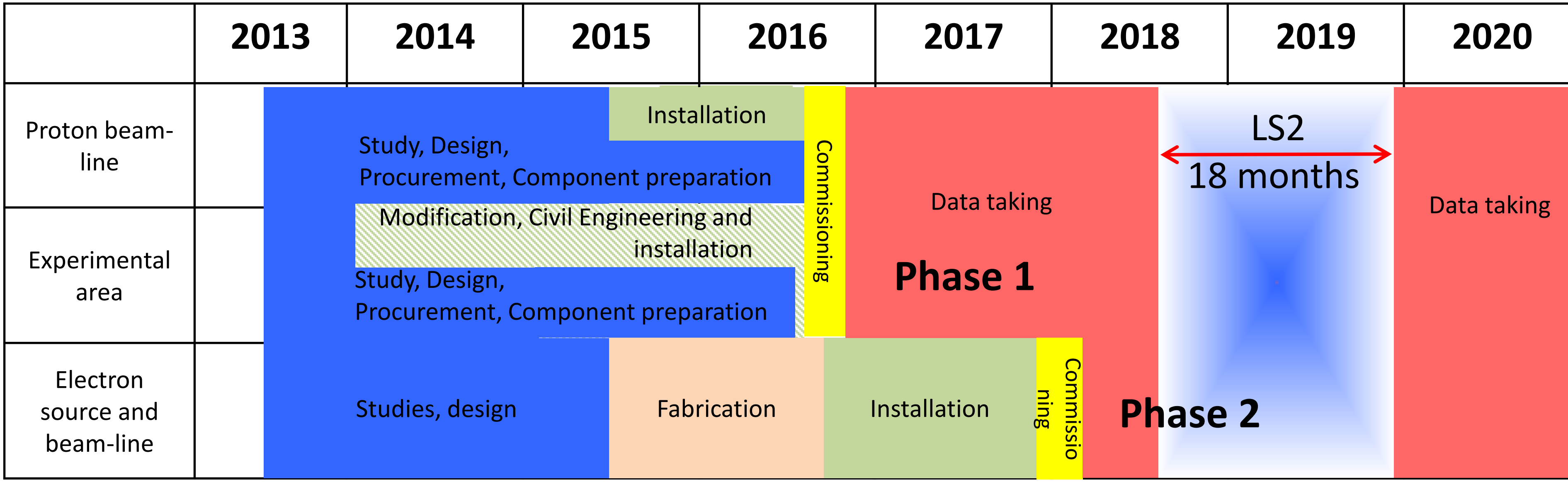
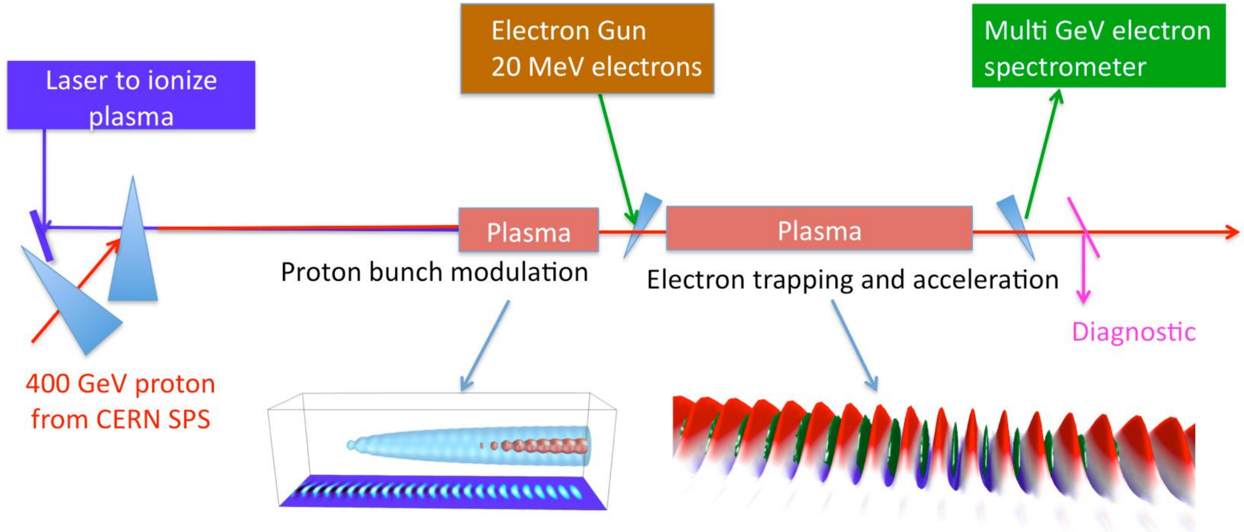


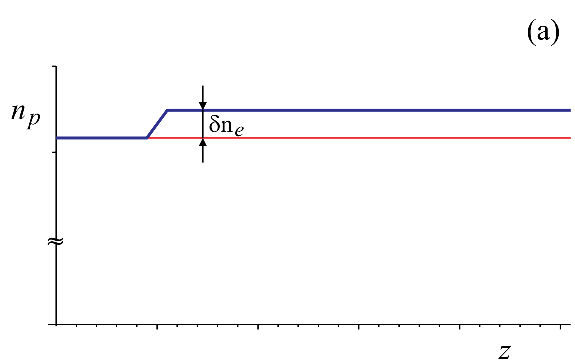
- AWAKE was approved in August 2013
- **1st Phase:** First proton and laser beam in 2016
- **2nd Phase:** first electron beam in 2017
- Physics program for 3 – 4 years

Run-scenario	Nominal
Number of run-periods/year	**4**
Length of run-period	**2 weeks**
Total number of beam shots/year (100% efficiency)	**162000**
Total number of protons/year	**4.86×10^{16} p**
Initial experimental program	**3 – 4 years**

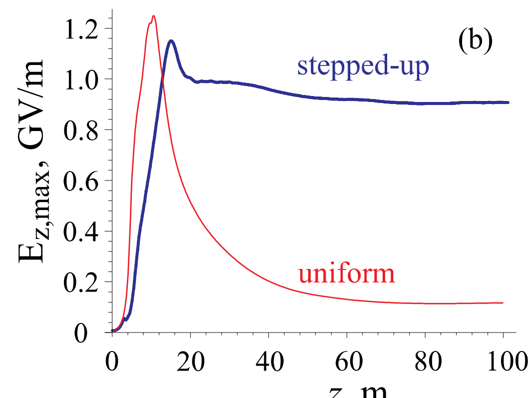
Next Steps



- **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



Plasma density profile



Maximum wakefield amplitude

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

Summary

- AWAKE is proof-of-principle accelerator R&D experiment currently being built at CERN.
  - First proton-driven wakefield acceleration experiment
  - The experiment opens a pathway towards plasma-based TeV lepton collider.
  - 400 GeV SPS proton beam as drive beam
  - 10-20 MeV electrons as witness beam
  - 2 TW laser beam for plasma ionization and seeding of the SMI
- AWAKE program
  - **Study the physics of self-modulation instability** as a function of plasma and proton beam parameters (1^{st} Phase, 2016)
  - **Probe the longitudinal accelerating wakefields** with externally injected electrons (2^{nd} Phase, 2017-2018)
  - **Develop long scalable and uniform plasma** cells, production of **shorter electron and proton bunches** (2020)

Many thanks to all members of the AWAKE collaboration, especially to Allen Caldwell and Edda Gschwendtner!