The AWAKE Project at CERN and its Connections to CTF3

Edda Gschwendtner, CERN

Outline

- Motivation
- AWAKE at CERN
- AWAKE Experimental Layout: 1st Phase
- AWAKE Experimental Layout: 2nd Phase
- Experimental Facility at CERN
- Electron Source
- Summary

AWAKE

- AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment
  - Use SPS proton beam as drive beam
  - Inject electron beam as witness beam
- Proof-of-Principle Accelerator R&D experiment at CERN
  - First proton driven wakefield experiment worldwide
  - First beam expected in 2016
- AWAKE Collaboration: 14 Institutes world-wide

Motivation

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

- Plasma can sustain up to **three orders of magnitude much higher gradient**
  - SLAC (2007): electron energy doubled from 42GeV to 85 GeV over 0.8 m → 52GV/m gradient

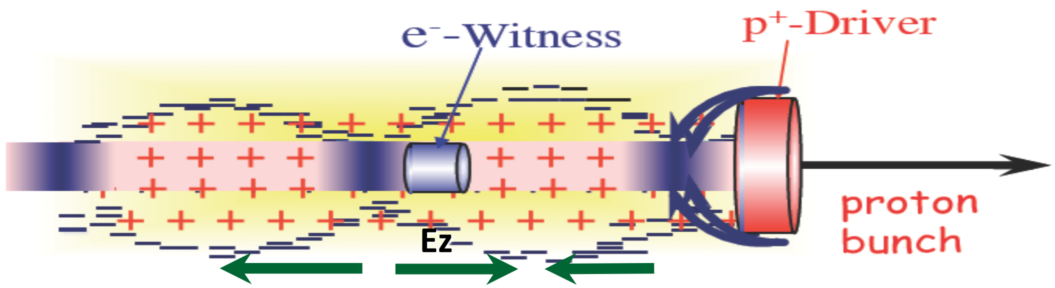
Why protons?

- Energy gain is limited by energy carried by the laser or electron drive beam (<100J) and the propagation length of the driver in the plasma (<1m).
  - **Staging** of large number of acceleration sections required to reach 1 TeV region.

- **Proton beam carry much higher energy**: 19kJ for 3E11 protons at 400 GeV/c.
  - Drives wakefields over much longer plasma length, only 1 plasma stage needed.

Simulations show that it is possible to gain 600 GeV in a single passage through a 450 m long plasma using a 1 TeV p+ bunch driver of 10e11 protons and an rms bunch length of 100 μm.

Motivation



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

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

- Plasma wave is excited by a relativistic particle bunch
- Space charge of drive beam displaces plasma electrons. → deceleration
- Plasma electrons attracted by plasma ions, and rush back on-axis → acceleration

→ plasma wavelength λ_p **=1mm**, (for typical plasma density of $n_p = 10^{15}\mathrm{cm}^{-3}$)

→ To excite large amplitude wakefields, **proton bunch length $\sigma_z \sim \lambda_p$ = 1mm**

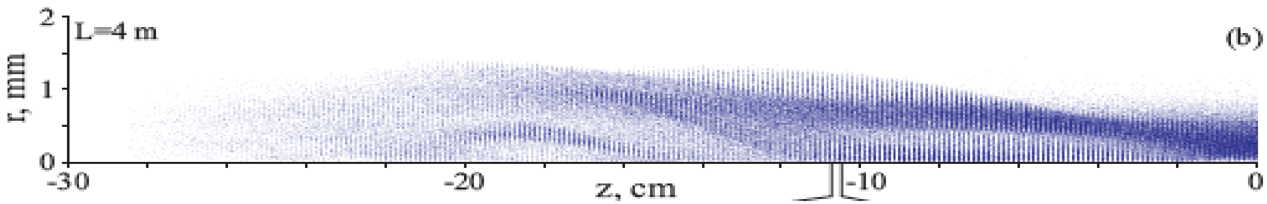
SPS beam: σ_z~12cm

→ Way out: Self-Modulation Instability (SMI):

Modulate long SPS bunch to produce a series of 'micro-bunches' in a plasma with a spacing of plasma wavelength λ_p.

→ Strong self-modulation effect of proton beam due to transverse wakefield in plasma

→ Starts from any perturbation and grows exponentially until fully modulated and saturated.

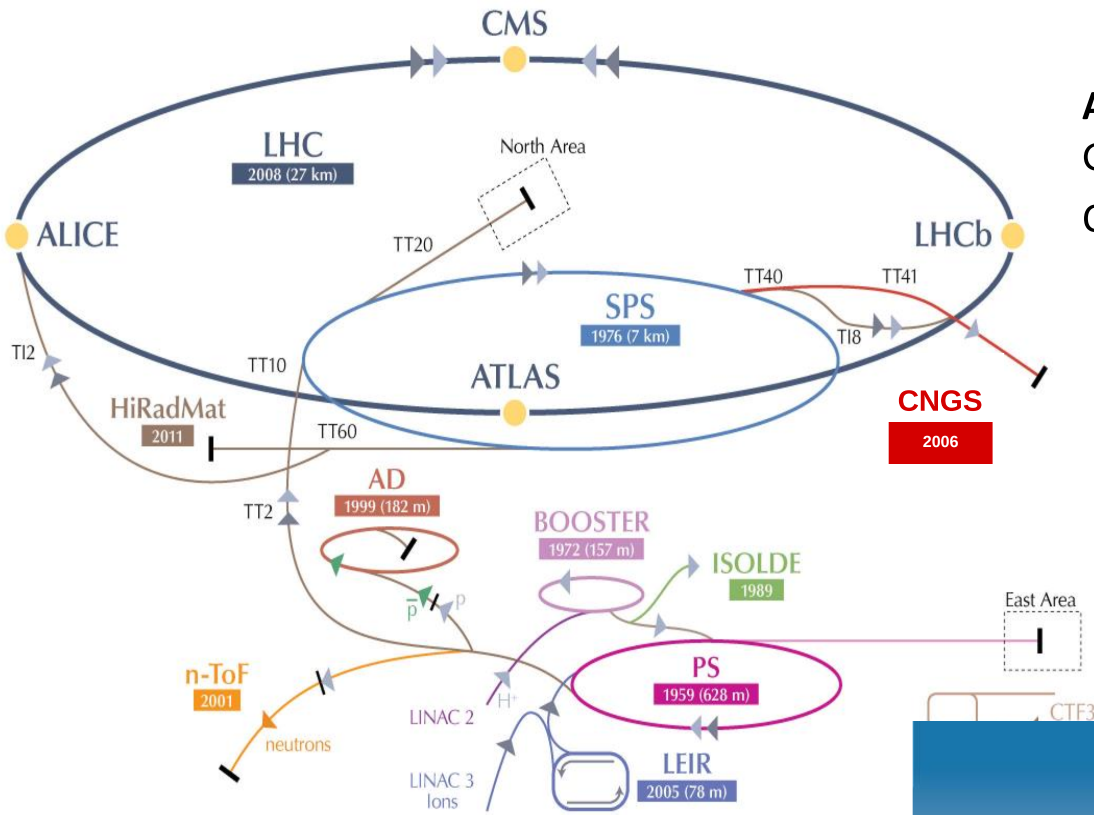


→ Immediate use of CERN SPS beam

Outline

- Motivation
- AWAKE at CERN
- AWAKE Experimental Layout: 1st Phase
- AWAKE Experimental Layout: 2nd Phase
- AWAKE Experimental Facility at CERN
- Electron Source
- Summary

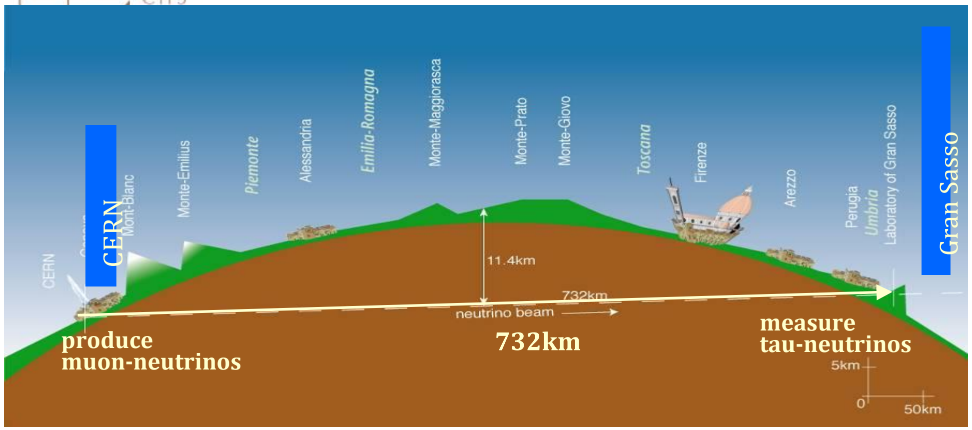
AWAKE at CERN



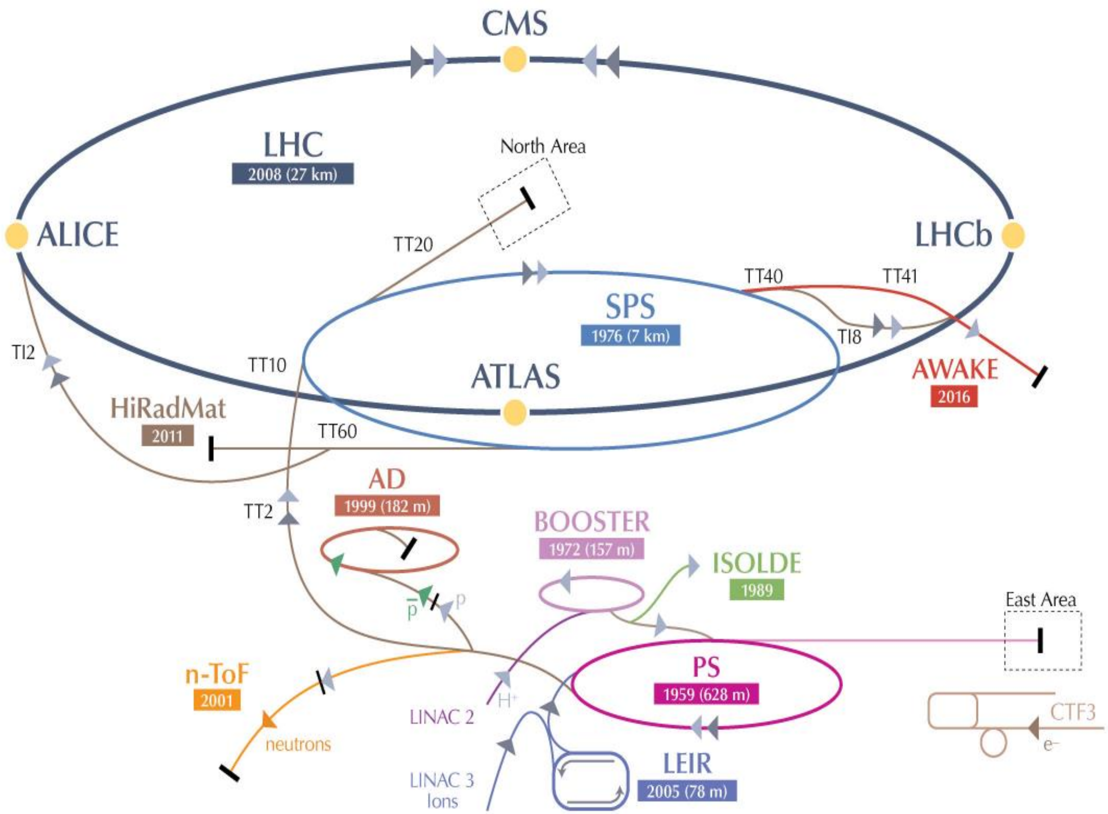
AWAKE in CNGS Facility (CERN Neutrinos to Gran Sasso)

CNGS physics program finished in 2012

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



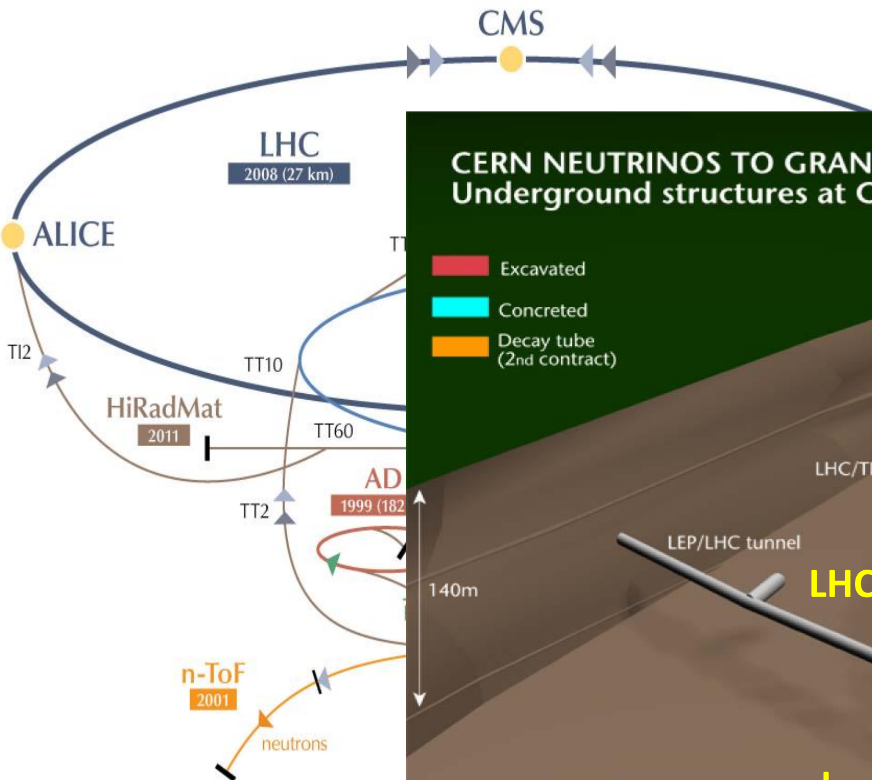
AWAKE at CERN

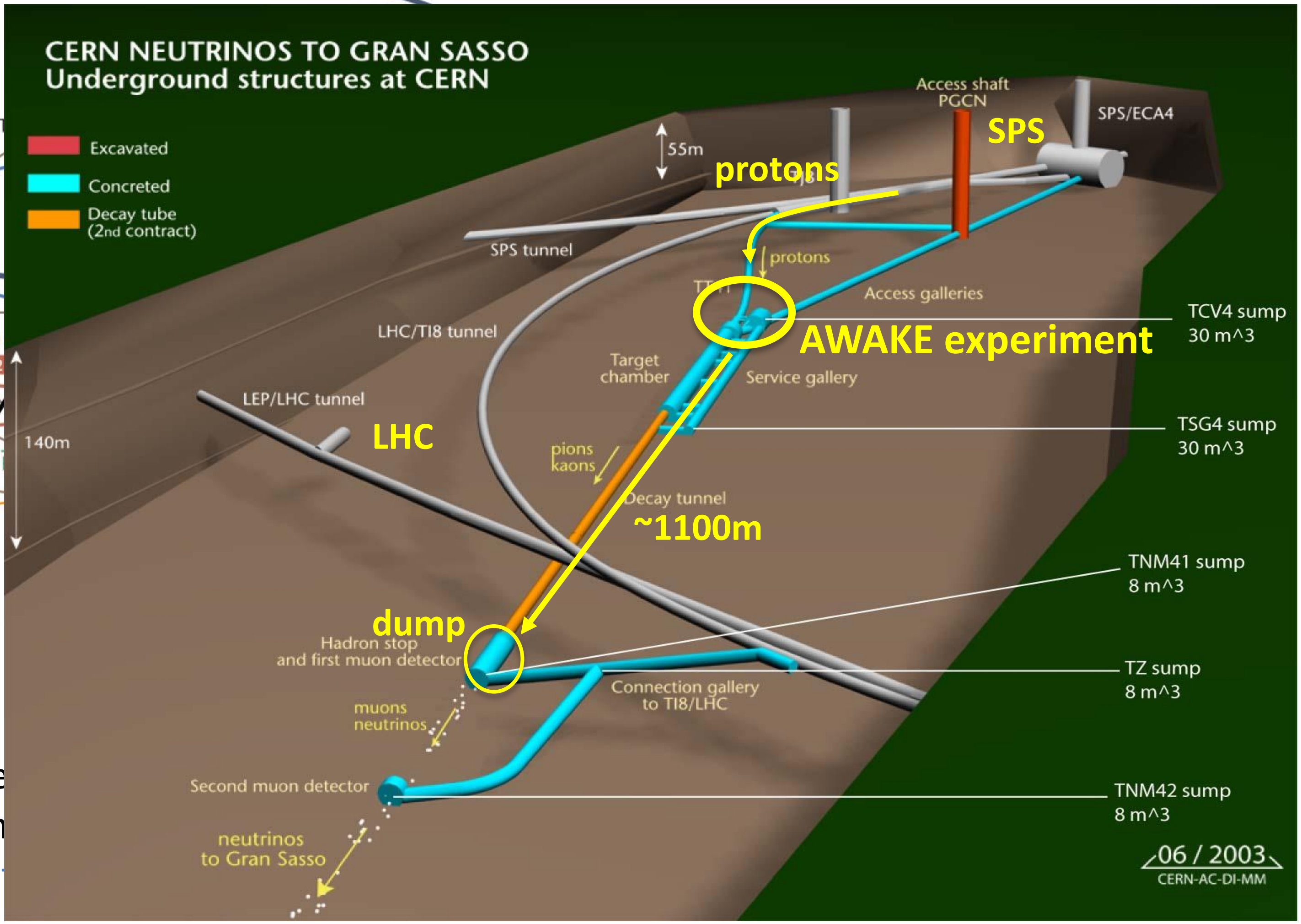


- Running underground facility
- Desired beam parameters

➔ adequate site for AWAKE

AWAKE at CERN





- Running unde
- Desired beam

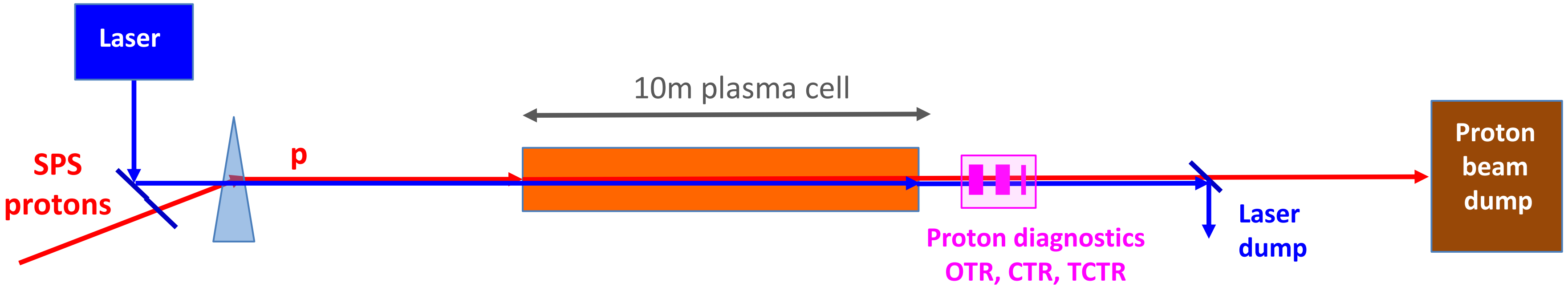
➔ adequate site

Outline

- Motivation
- AWAKE at CERN
- AWAKE Experimental Layout: 1st Phase
- AWAKE Experimental Layout: 2nd Phase
- AWAKE Experimental Facility at CERN
- Electron Source
- Summary

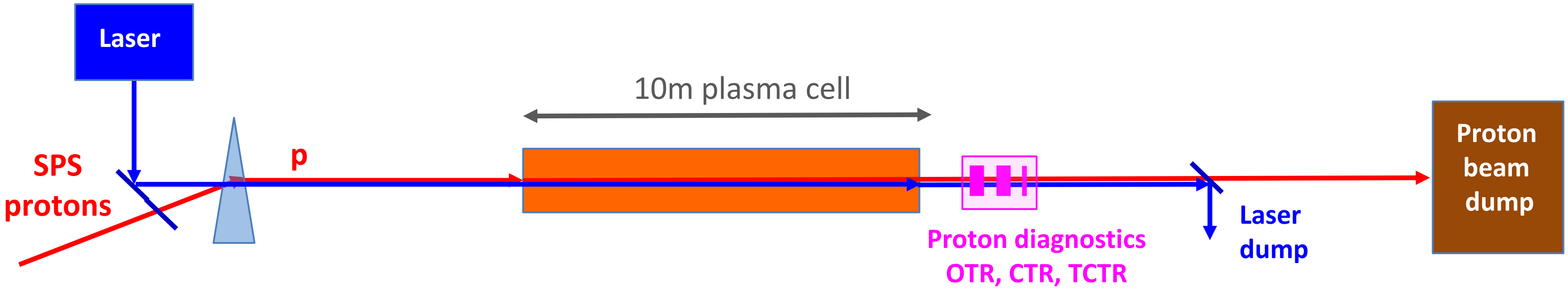
AWAKE Experimental Layout: 1st Phase

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



AWAKE Experimental Layout: 1st Phase

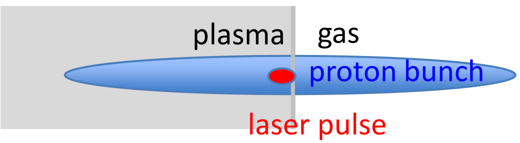
- Perform **benchmark experiments using proton bunches** to drive wakefields for the first time ever.
- Understand **the physics of self-modulation instability** processes in plasma.



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

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

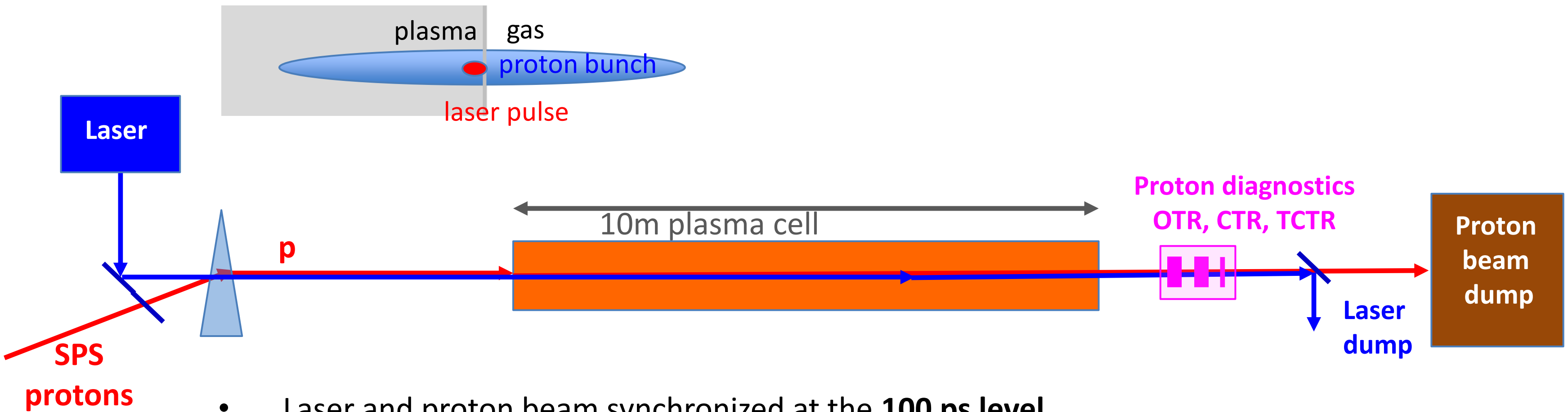
→ 10 m long plasma cell**: Rubidium vapor** source, $n_e = 7\times10^{14}\ cm^{-3}$.



Proton Beam	
Momentum	**400 GeV/c**
Protons/bunch	**$3\ 10^{11}$**
Bunch extraction frequency	**0.5 Hz** (ultimate: 0.14 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	$\beta^*_x = \beta^*_y = 4.9$m
Dispersion	$D^*_x = D^*_y = 0$

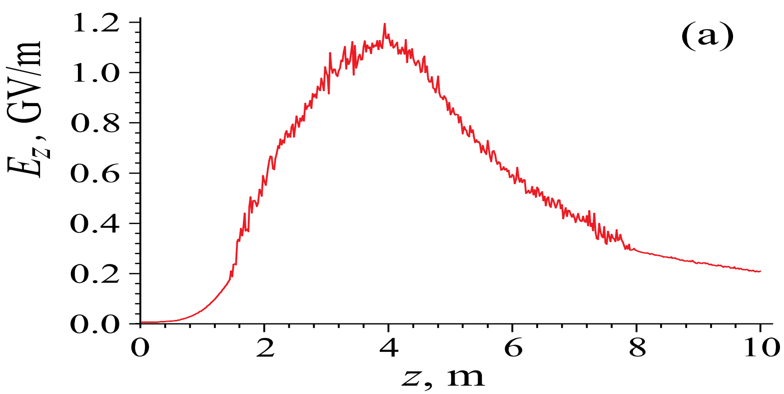
Laser Beam	
Laser type	Fiber Ti:Sapphire
Pulse wavelength	λ_0 = 780 nm
Pulse length	100-120 fs
Pulse energy (after compr.)	**450 mJ**
Laser power	2 TW
Focused laser size	**$\sigma_{x,y}$ = 1 mm**
Energy stability	±1.5% r.m.s.
Repetition rate	10 Hz

AWAKE Experimental Layout: 1st Phase

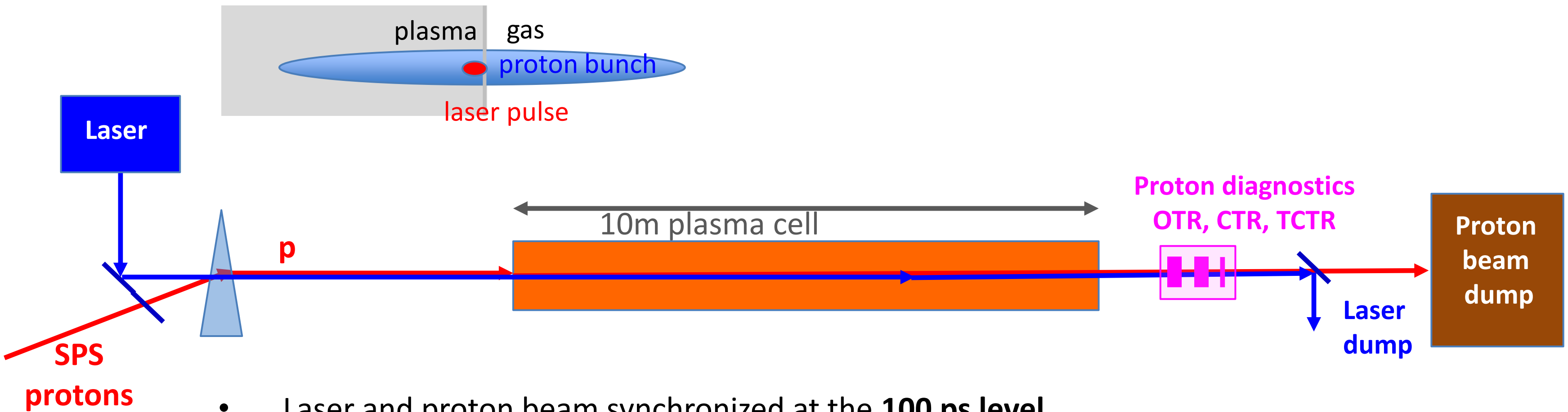


- Laser and proton beam synchronized at the **100 ps level**.
- Laser and proton beam **co-axial** over the full length of the plasma cell:
  - 100 μm and 15 μrad pointing accuracy
  - High resolution diagnostics to perform and monitor relative alignment
- Plasma density uniformity better than **0.2%**

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

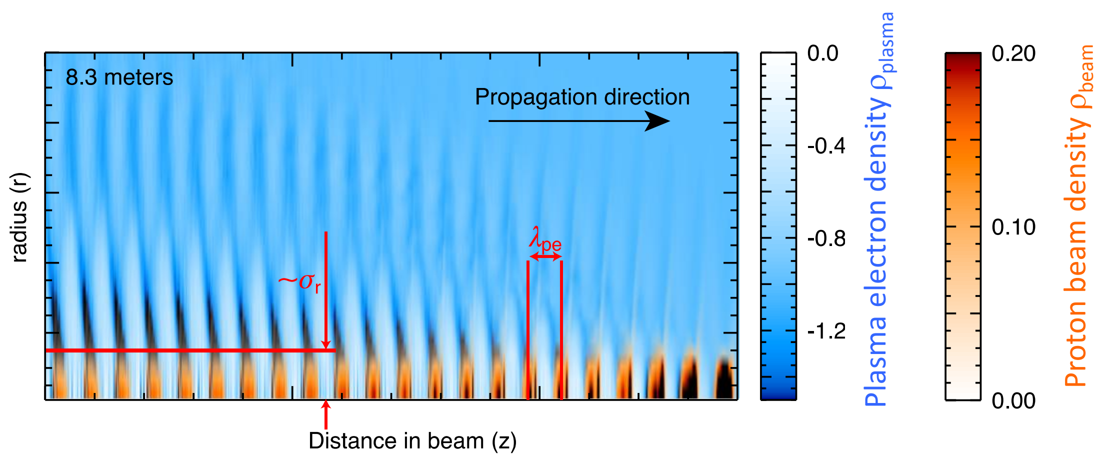


AWAKE Experimental Layout: 1st Phase



- Laser and proton beam synchronized at the **100 ps level**.
- Laser and proton beam **co-axial** over the full length of the plasma cell:
  - 100 μm and 15 μrad pointing accuracy
  - High resolution diagnostics to perform and monitor relative alignment
- Plasma density uniformity better than **0.2%**

Self-modulated proton bunch resonantly driving plasma wakefields.

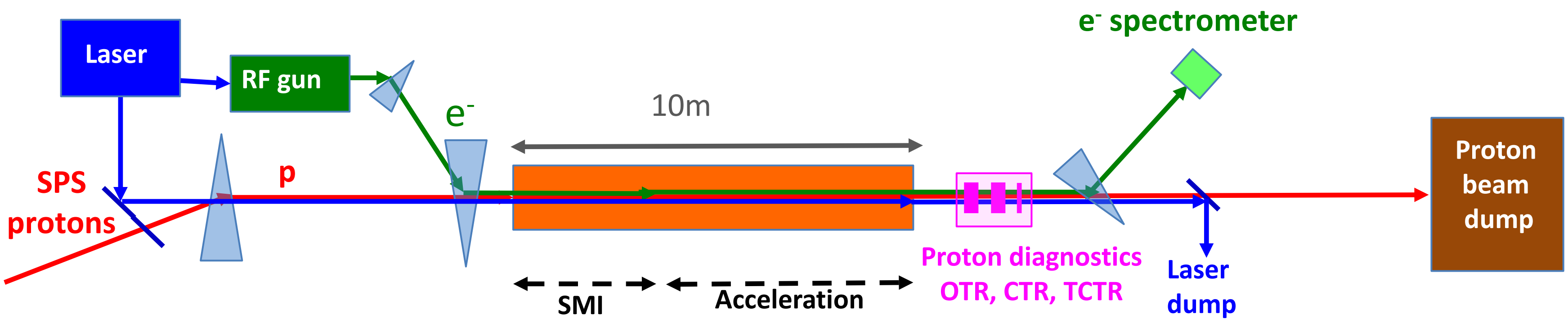


Outline

- Motivation
- AWAKE at CERN
- AWAKE Experimental Layout: 1st Phase
- AWAKE Experimental Layout: 2nd Phase
- AWAKE Experimental Facility at CERN
- Electron Source
- Summary

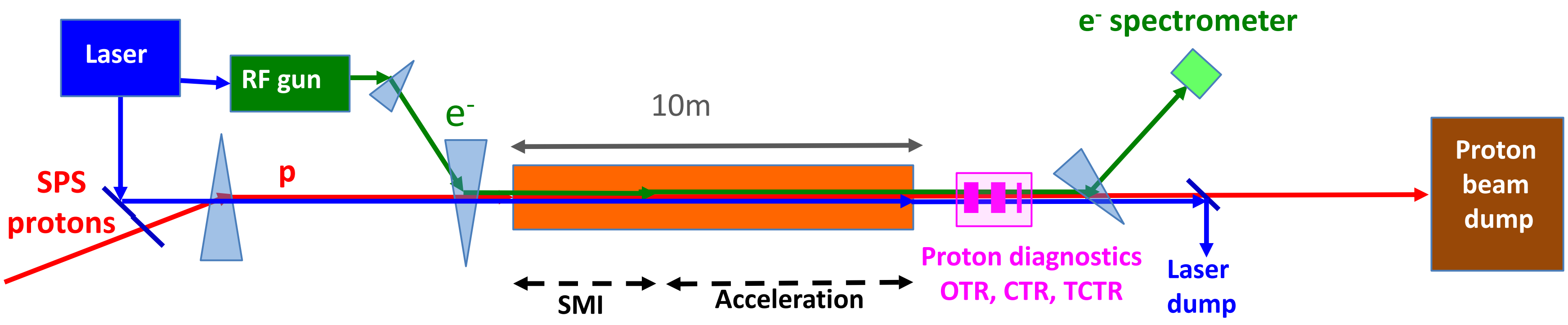
AWAKE Experimental Layout: 2nd Phase

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



AWAKE Experimental Layout: 2nd Phase

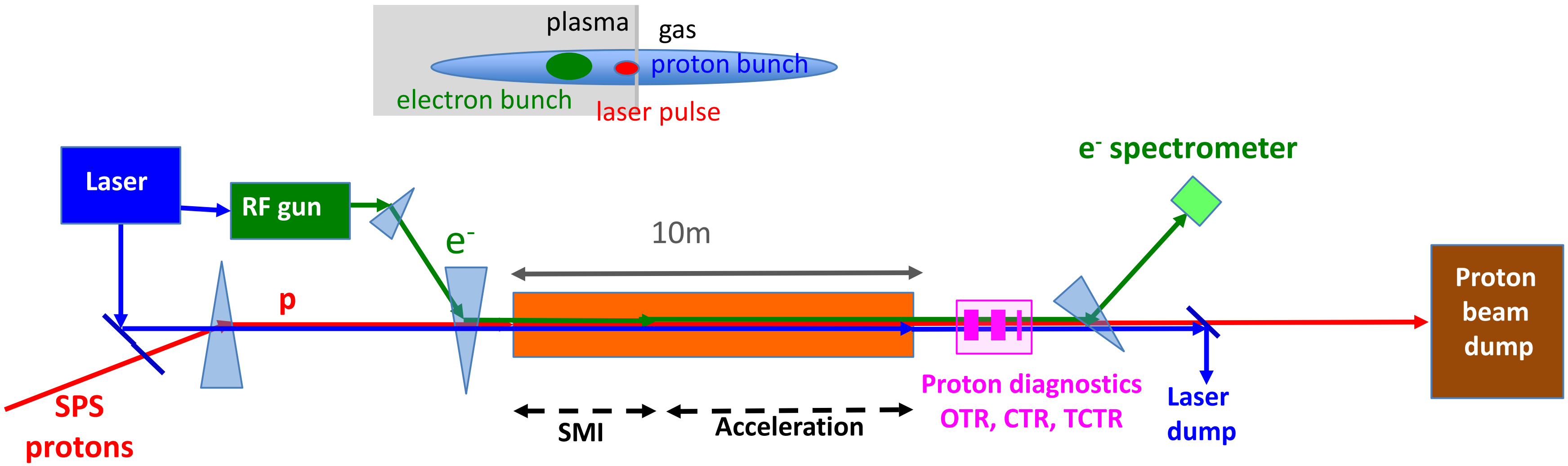
- **Probe the accelerating wakefields with externally injected electrons**, including energy spectrum measurements for different injection and plasma parameters.



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.)	500 μJ
Electron source cathode	Copper
Quantum efficiency	3.00 E-5
Energy stability	$\pm$2.5% r.m.s.

AWAKE Experimental Layout: 2nd Phase



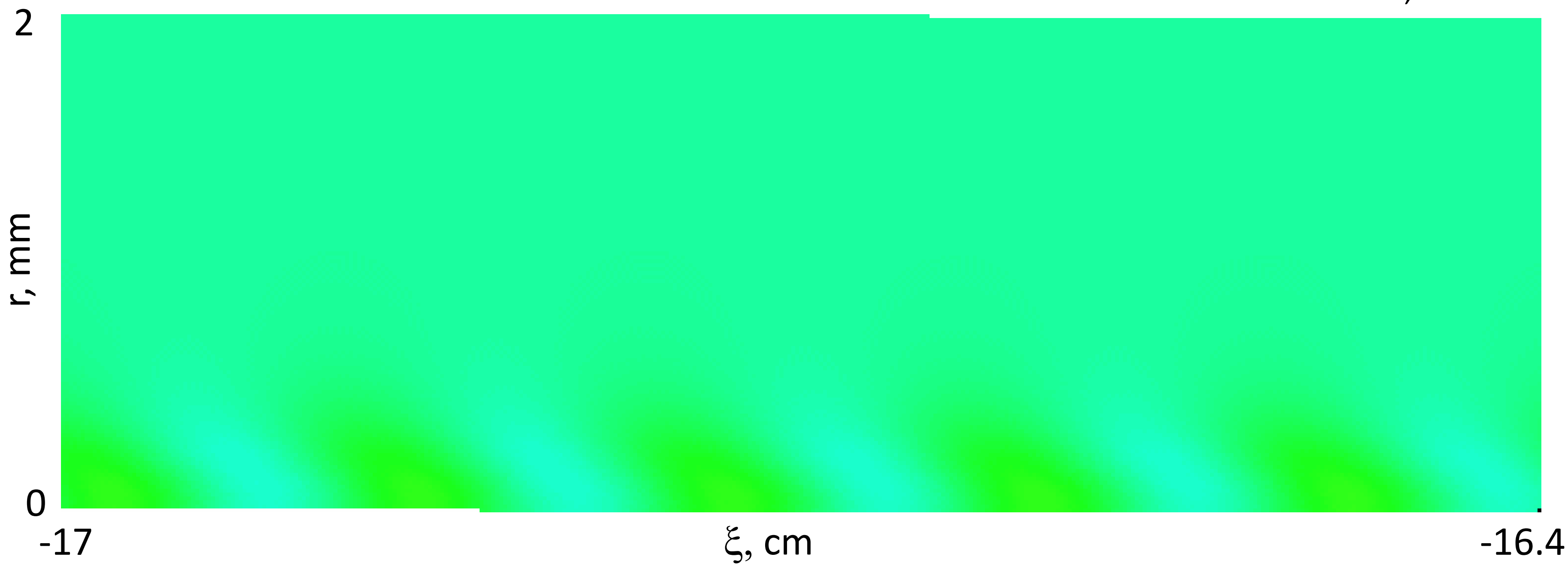
- Laser and electron beam synchronized at the **< 1 ps level**.
- **Electron bunch is externally injected** into the plasma cell, on-axis and collinearly with the proton and laser beam.
- **On-axis injection** point is upstream the plasma cell.

AWAKE Experimental Layout: 2nd Phase

On-axis injection: animation of trapping and acceleration

black points – injected electrons, false colors – wakefield potential

K. Lotov, LCODE

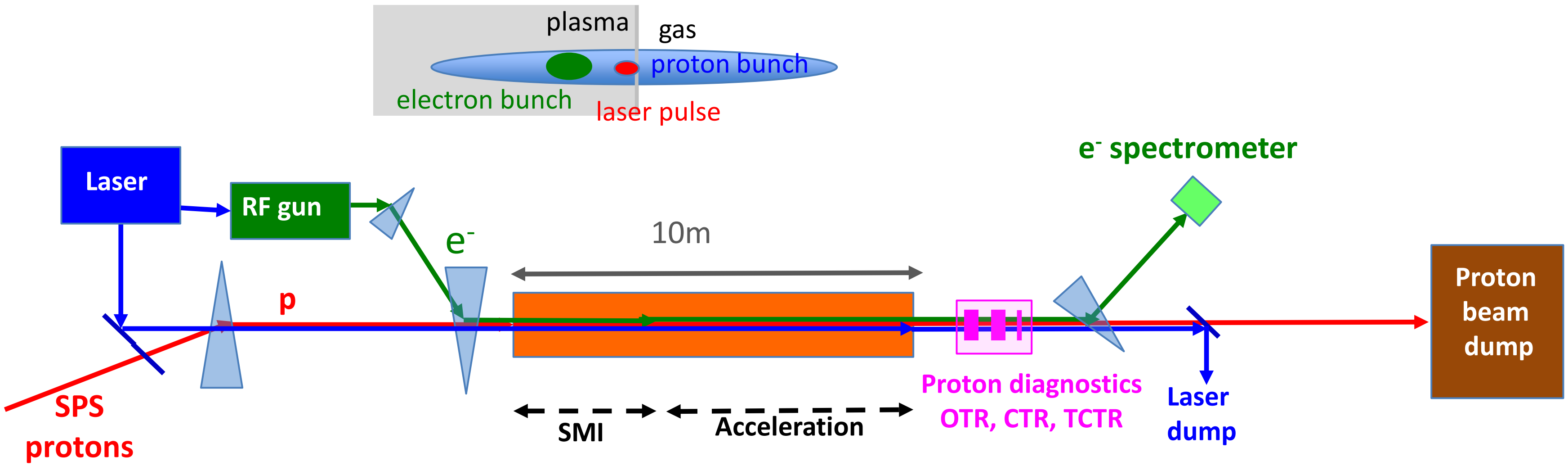


•Electrons are trapped from the very beginning by the wakefield of seed perturbation

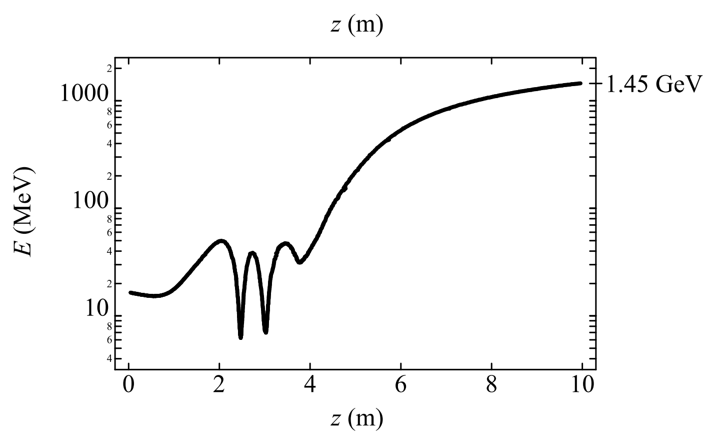
•Trapped electrons make several synchrotron oscillations in their potential wells

•After z=4 m the wakefield moves forward in the light velocity frame

AWAKE Experimental Layout: 2nd Phase

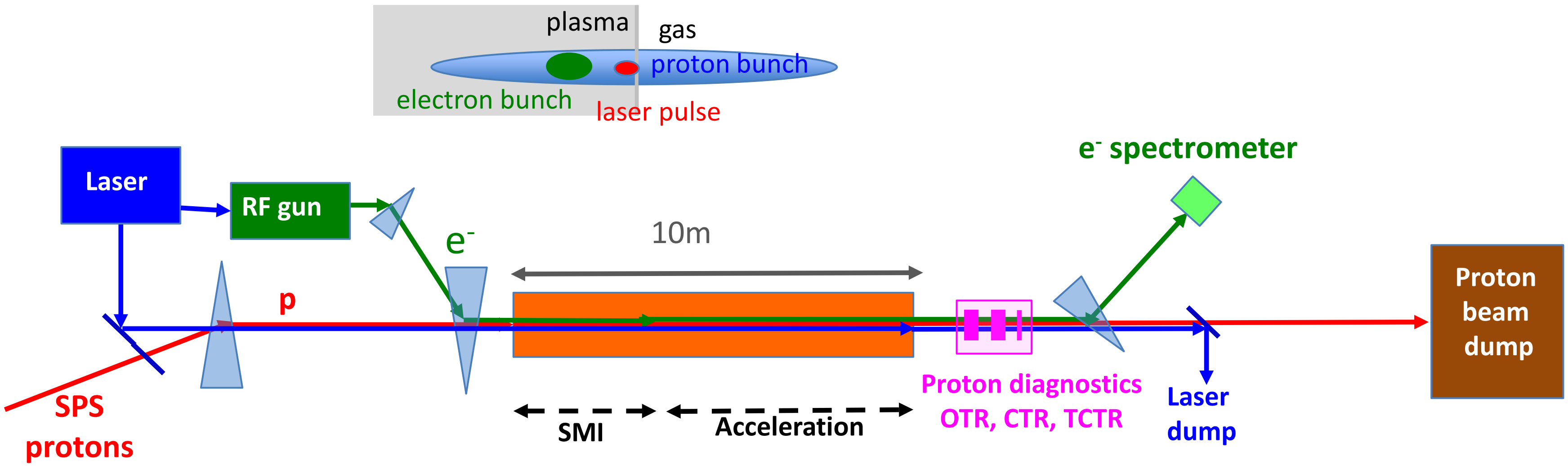


- Laser and electron beam synchronized at the **< 1 ps level**.
- **Electron bunch is externally injected** into the plasma cell, on-axis and collinearly with the proton and laser beam.
- **On-axis injection** point is upstream the plasma cell.



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

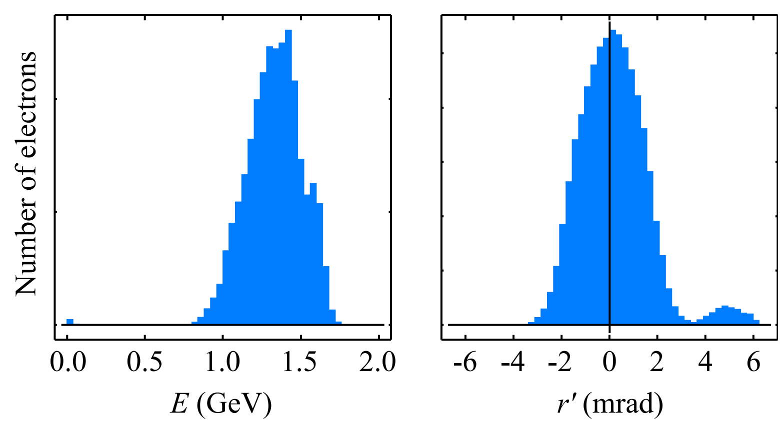
AWAKE Experimental Layout: 2nd Phase



- 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.

- Trapping efficiency: **10 – 15 %**
- Average energy gain: **1.3 GeV**
- Energy spread: $\pm$ 0.4 GeV
- Angular spread up to $\pm$ 4 mrad

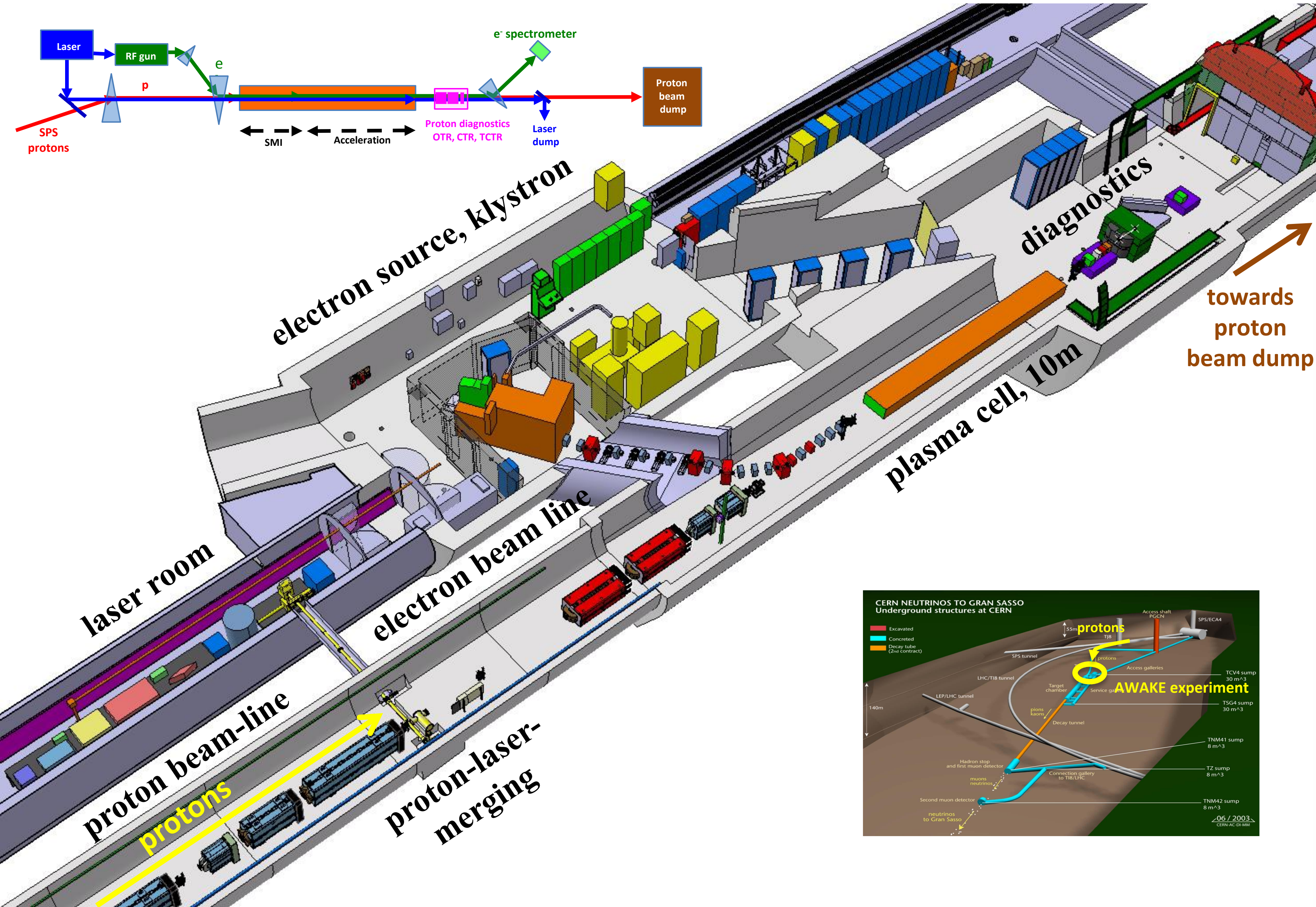
} Large acceptance spectrometer (aperture and magnetic field)



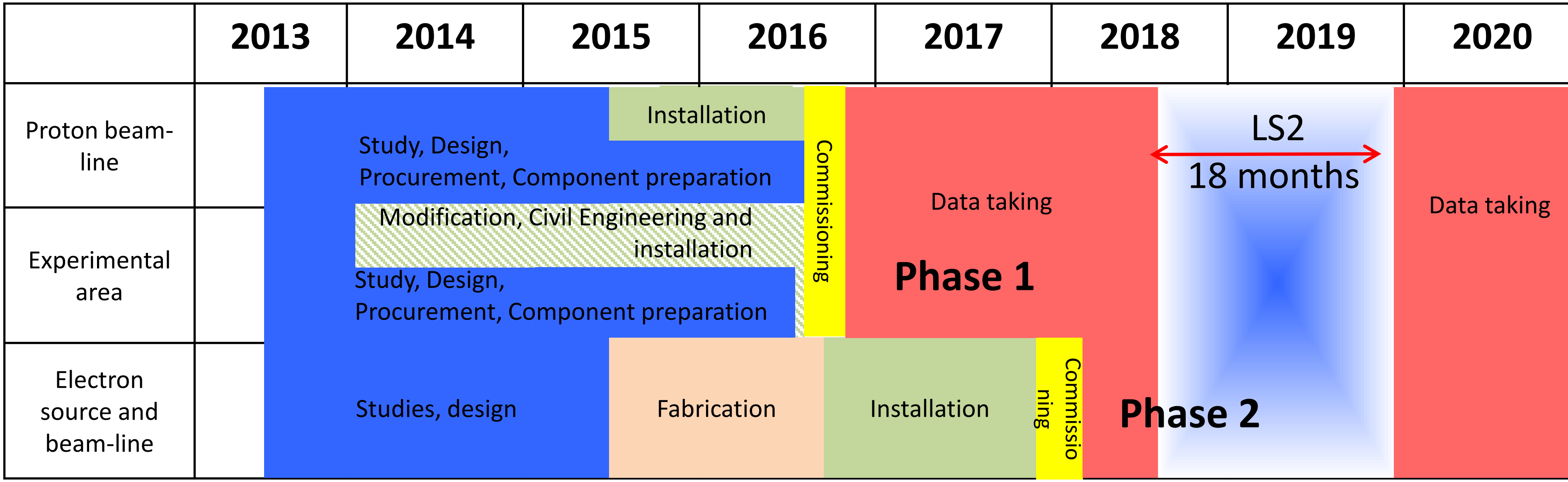
Outline

- Motivation
- AWAKE at CERN
- AWAKE Experimental Layout: 1st Phase
- AWAKE Experimental Layout: 2nd Phase
- AWAKE Experimental Facility at CERN
- Electron Source
- Summary

AWAKE Experimental Facility at CERN



Planning



- 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

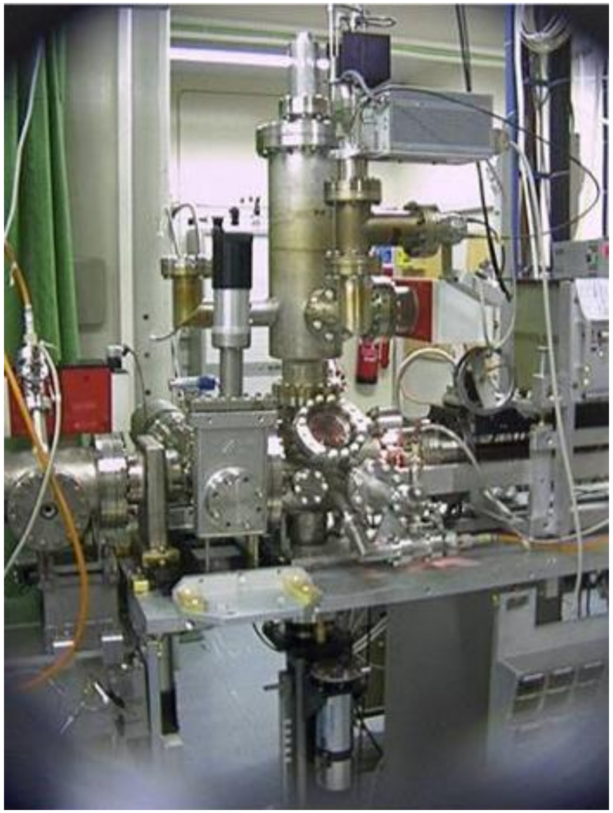
Run-scenario	Nominal
Number of run-periods/year	**4**
Length of run-period	**2 weeks**
Total number of beam shots/year (100% efficiency)	**162000**
Total number of protons/year	**4.86×10^{16} p**
Initial experimental program	**3 – 4 years**

Outline

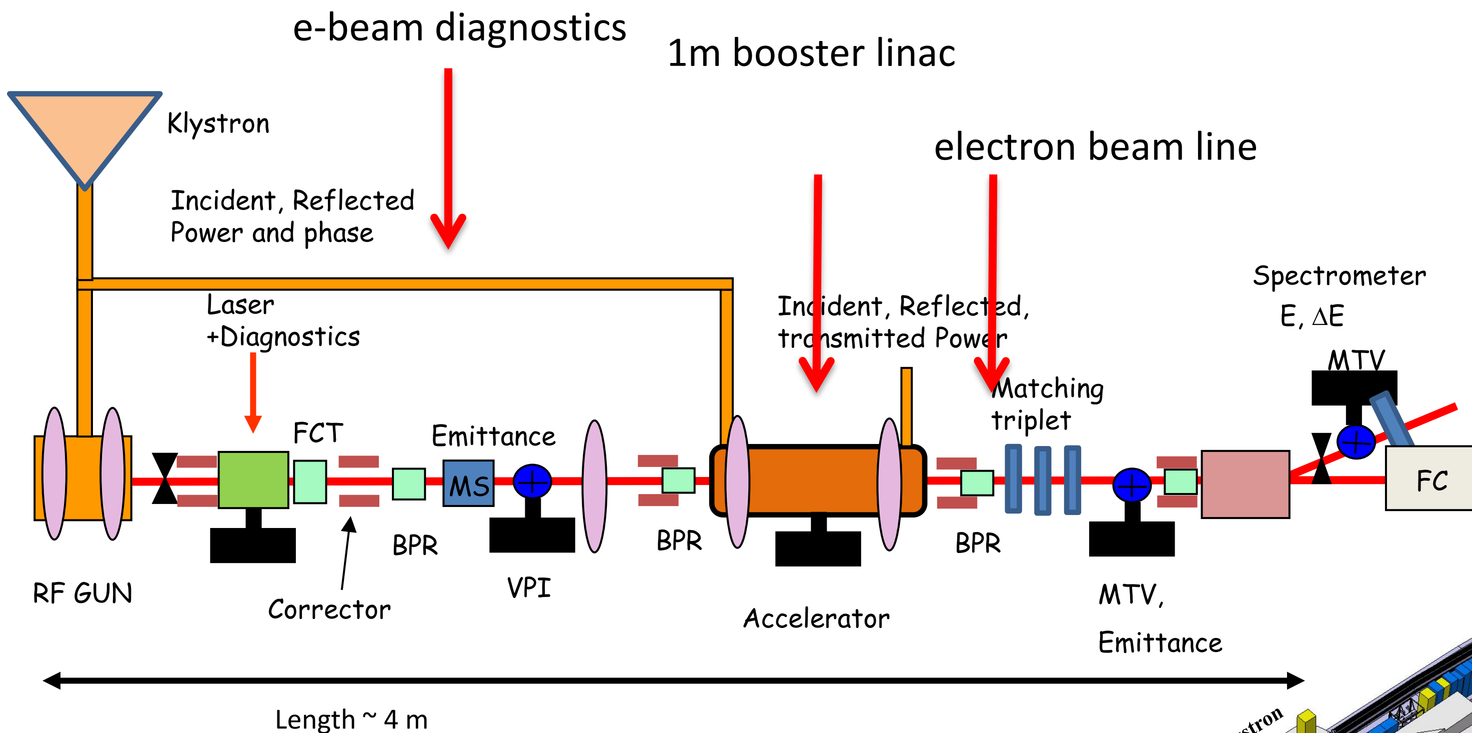
- Motivation
- AWAKE at CERN
- AWAKE Experimental Layout: 1st Phase
- AWAKE Experimental Layout: 2nd Phase
- AWAKE Experimental Facility at CERN
- Electron Source
- Summary

Electron Source

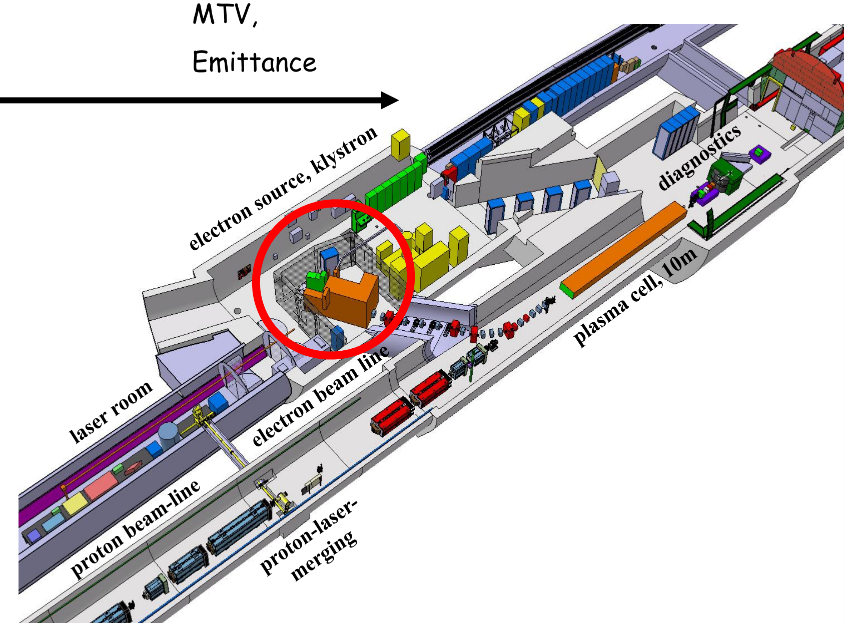
- Agreement between AWAKE and CLIC Collaboration in spring 2014:
  - Photo injector (**PHIN**) from CTF2 at CERN (5 MeV electrons) to use as electron source for AWAKE.
  - Klystron and modulator from CTF3
  - Booster from Cockcroft/Lancaster 5 MeV→ 20 MeV



Electron Source

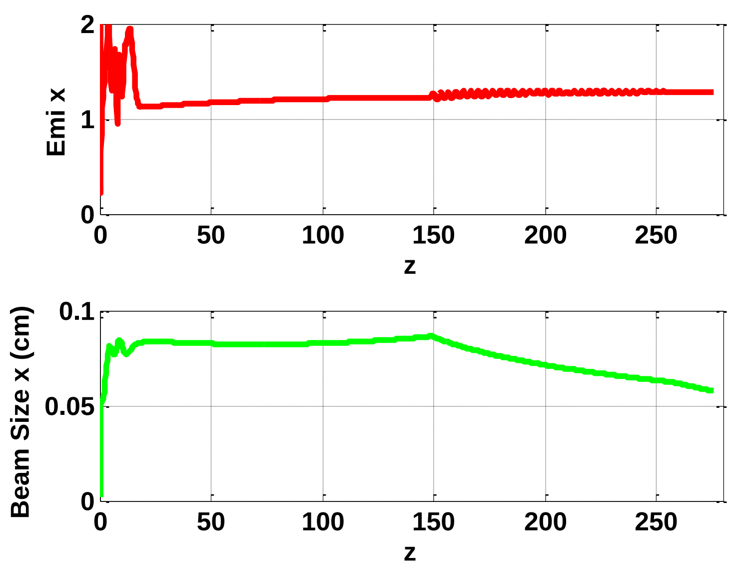


Instrumentation	How many	Resolution
BPMs	3	~ 50 mm
Screen	3	20 mm
Multi slit	1	< mm mrad
FCT	1	10 pC
Faraday Cup	1	10 pC
Spectrometer	1	10 keV
Streak Camera	1	< ps



Awake Electron Beam Requirements

Parameter	Baseline Phase 2	Range to check
Beam Energy	16 MeV	10- 20 MeV
Energy spread (σ)	0.5 %	< 0.5 % ?
Bunch Length (σ)	4 ps	0.3-10 ps
Beam Focus Size (σ)	250 μm	0.25 – 1mm
Normalized Emittance (rms)	2 mm mmrad	0.5 - 5 mm mrad
Bunch Charge	0.2 nC	0.1 - 1 nC



Parmela simulation with r= 0.5mm, E=100 MV/m, Q=0.2 nC

→ ε = 1.3 mm mrad

Tests in CTF3 for AWAKE

- → use PHIN as test area in 2015 and 2016
- → Optimization and performance tests

- Planning:

  2015:
  - Prototype tests in PHIN
    - Diagnostics: e.g. BPMs from TRIUMF

  2016
  - Booster structure tests
  - High power tests
  - → integrated test of AWAKE electron source

  2017:
  - install the electron source in the AWAKE facility

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

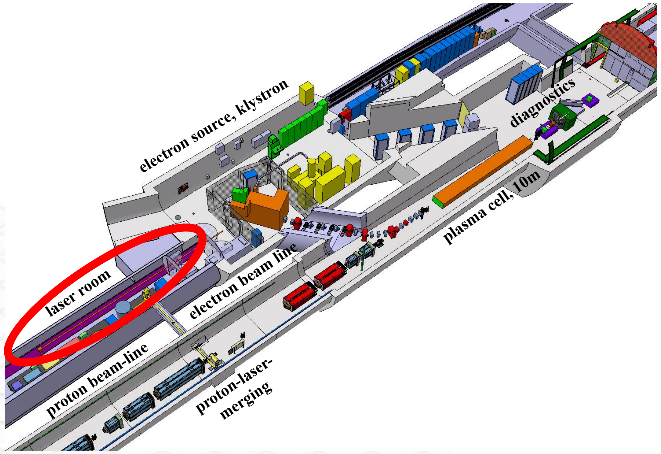
- AWAKE program
  - Study the physics of self-modulation instability as a function of plasma and proton beam parameters (1st Phase, 2016)

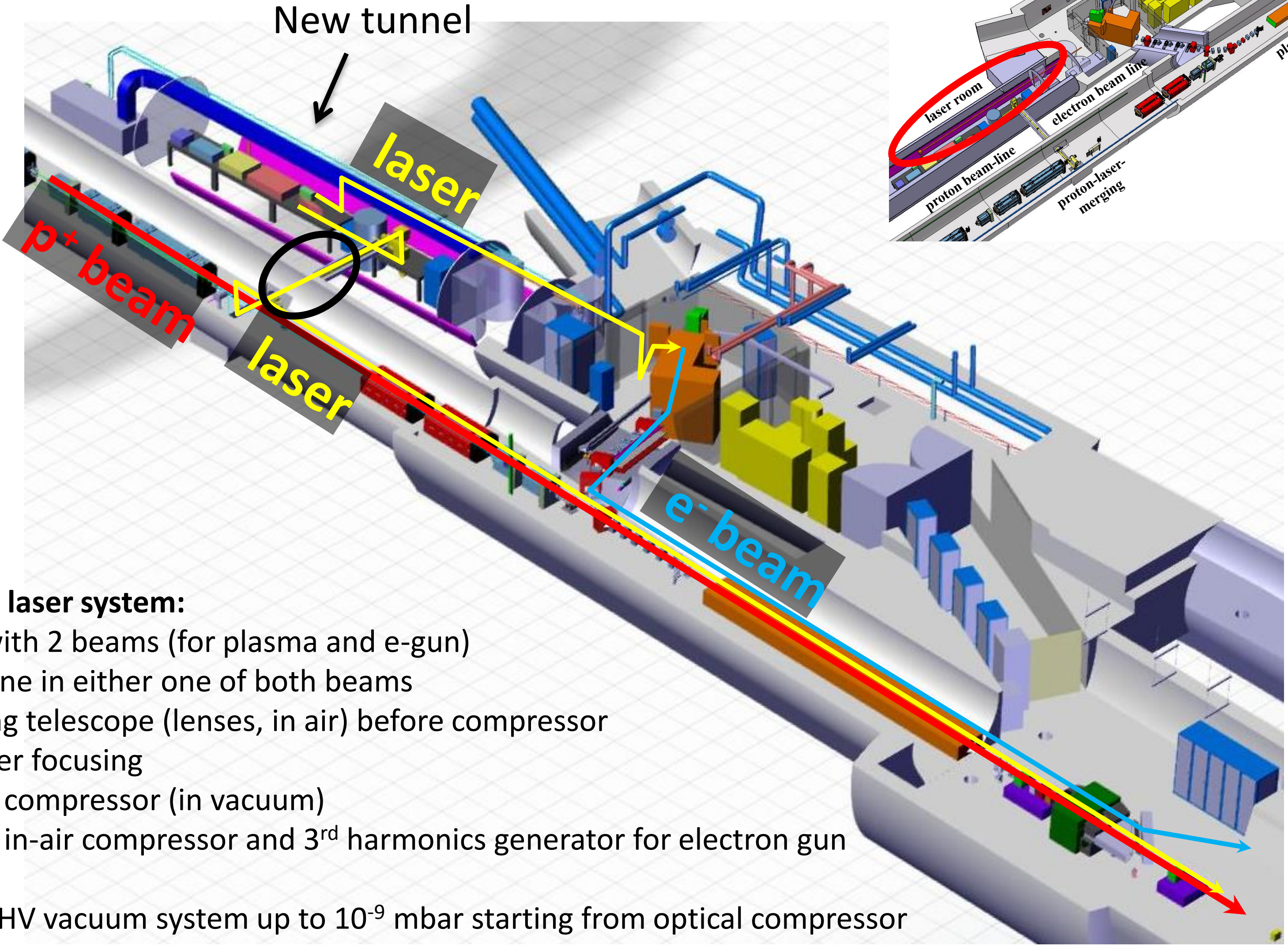
  - Probe the longitudinal accelerating wakefields with externally injected electrons (2nd Phase, 2017-)

- Strong interest to use PHIN in 2015 and 2016 as test area for AWAKE

- Extra slides

Laser System



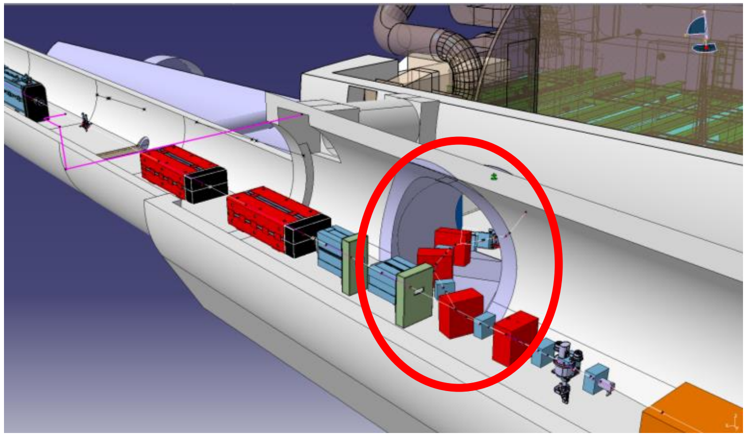


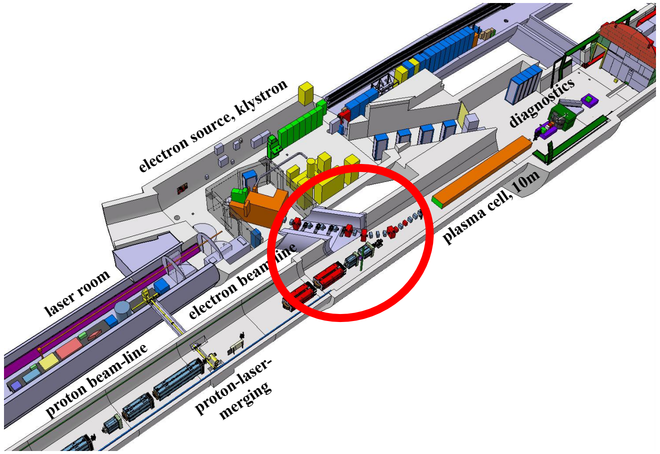
Ti: Sapphire laser system:

- 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

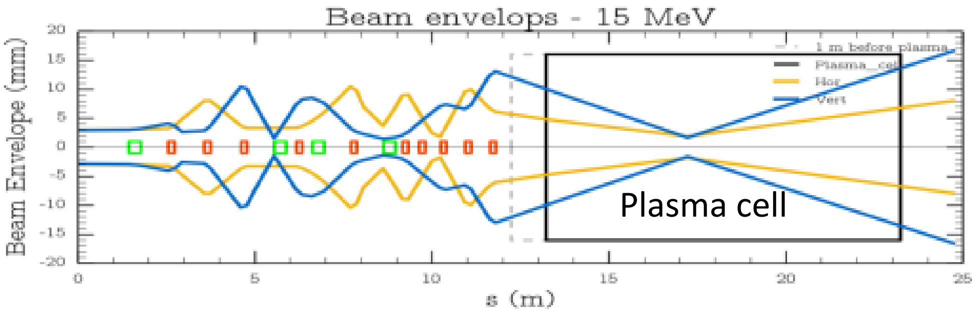
Complete UHV vacuum system up to 10^{-9} mbar starting from optical compressor

Electron Beam Line





- Completely **new beam line and tunnel**:
  - Horizontal angle of 60 deg,
  - 20% slope of the electron tunnel → 1m level difference
  - 7.2% slope of the plasma cell
  - ~5 m common beam line between electron and proton
- **Common diagnostics** for proton (high intensity, 3E11 p) and electron beam (low intensity, 1.2E9 e)
- **Flexible electron beam optics**: focal point can be varied by up to 6 m inside the plasma cell



Electron beam envelope (H, V)