AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN

Edda Gschwendtner
on behalf of the AWAKE Collaboration

Outline

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

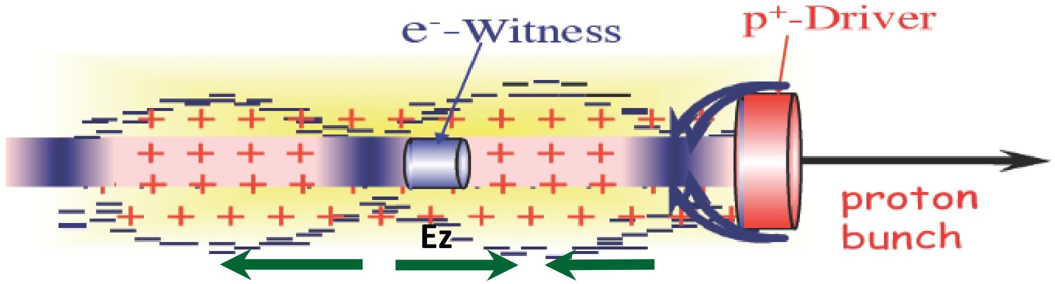
Why protons?

- 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 $n_p = 10^{15}$cm^{-3})

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

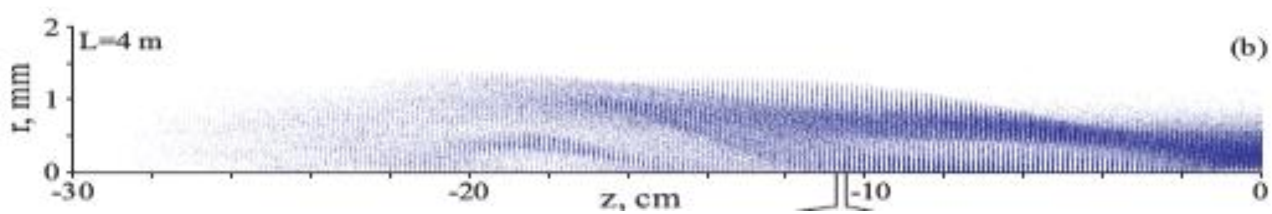
SPS beam: σ_z~12cm

→ 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

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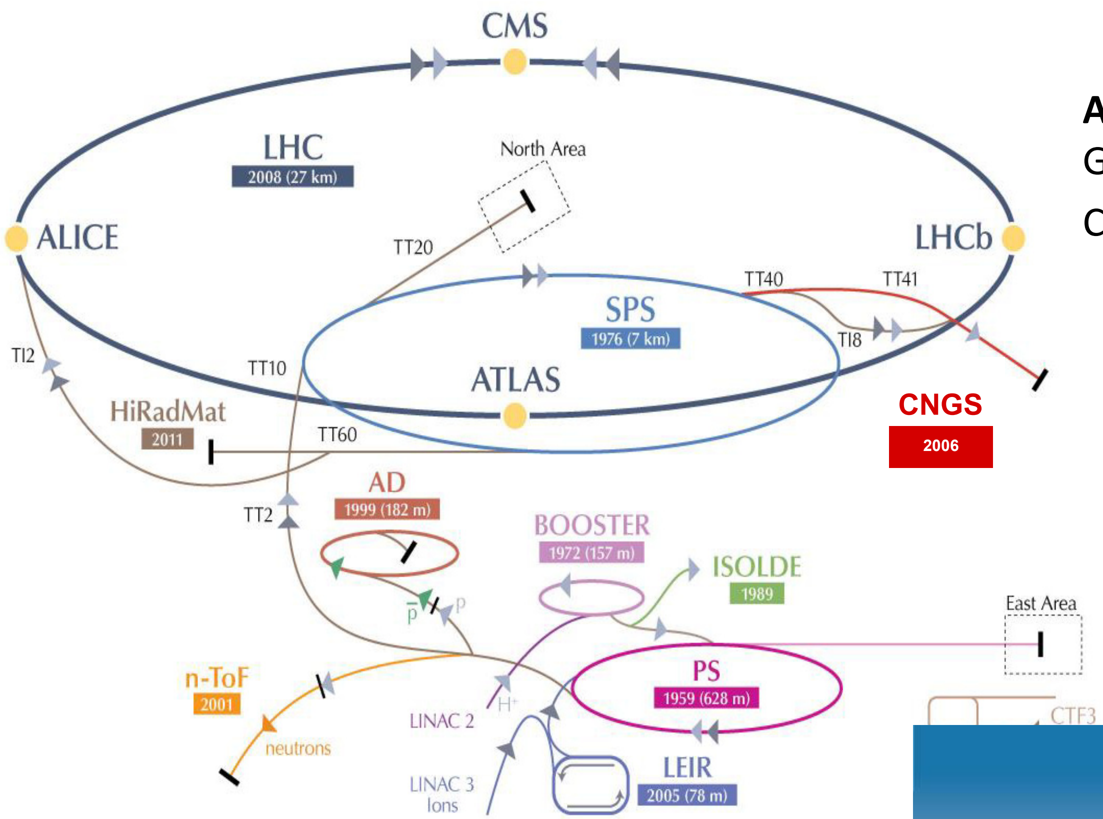
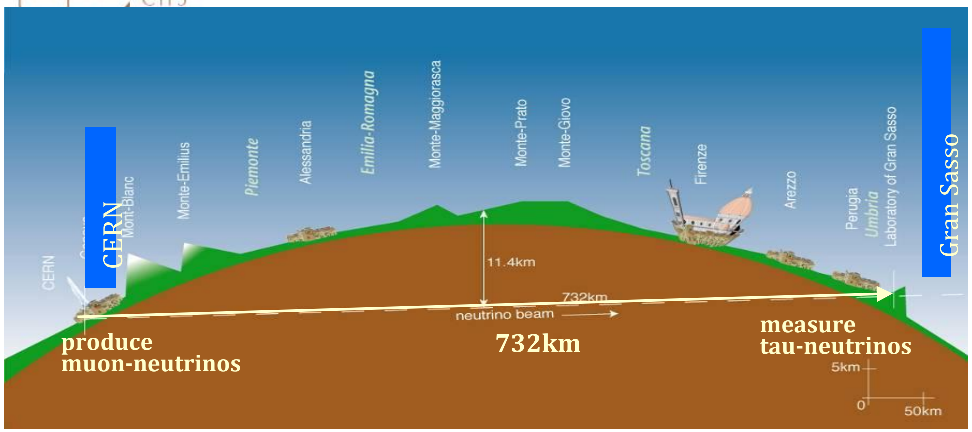


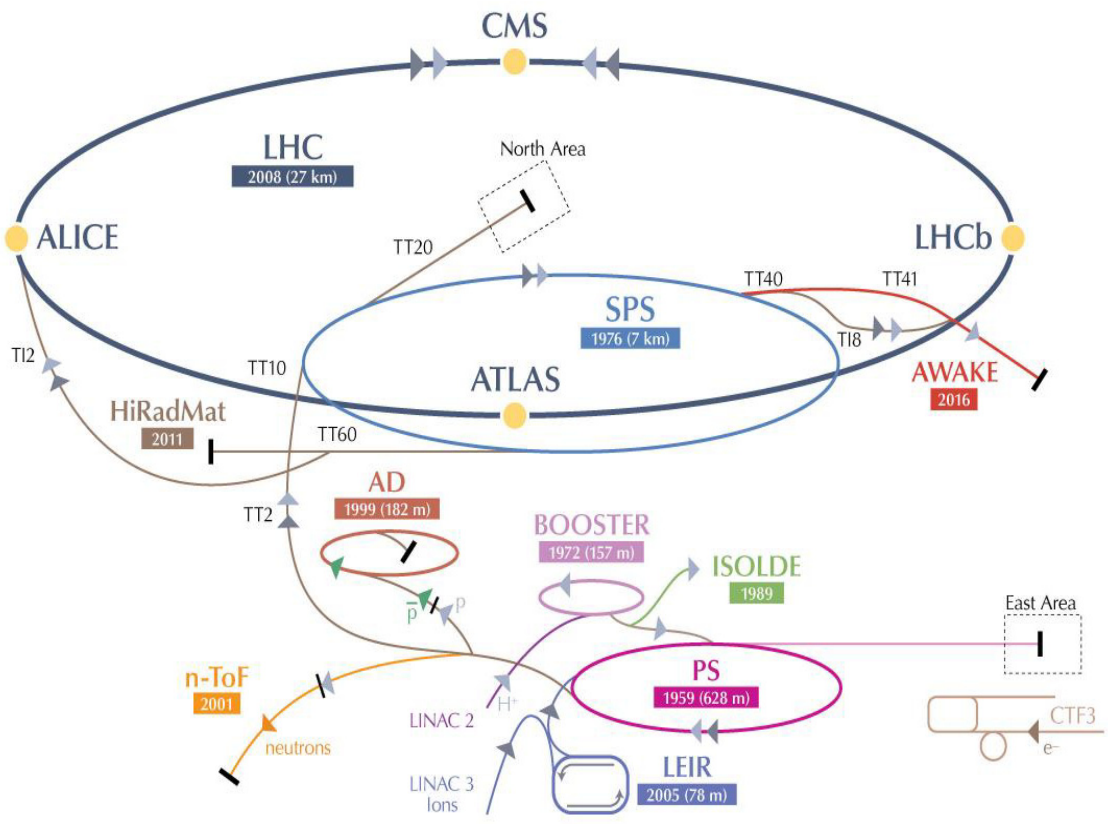
AWAKE in CNGS Facility (CERN Neutrinos to Gran Sasso)

CNGS physics program finished in 2012

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



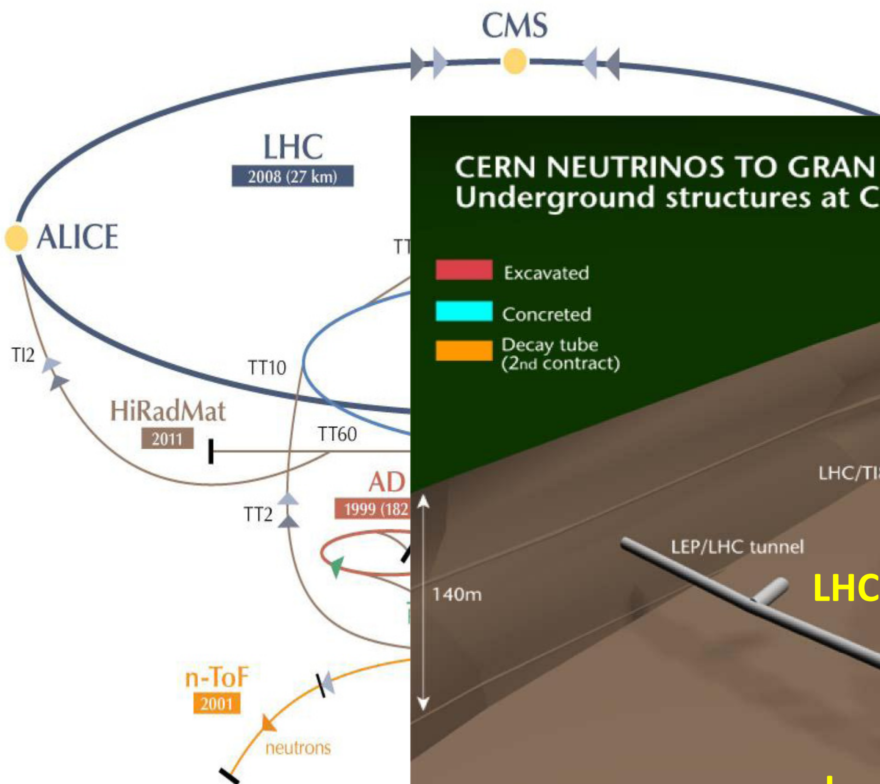
AWAKE at CERN

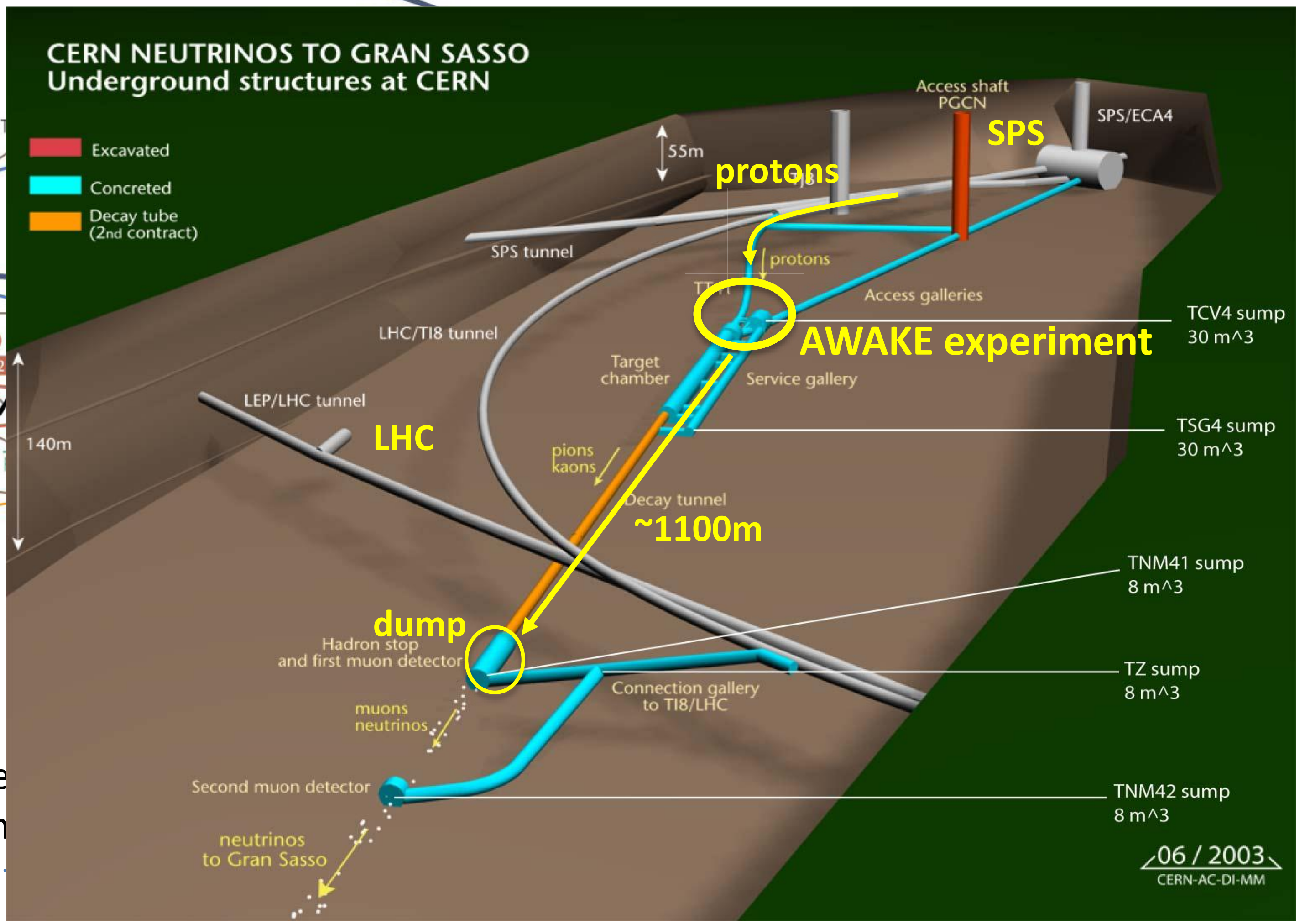


- Running underground facility
- Desired beam parameters

➔ adequate site for AWAKE

AWAKE at CERN





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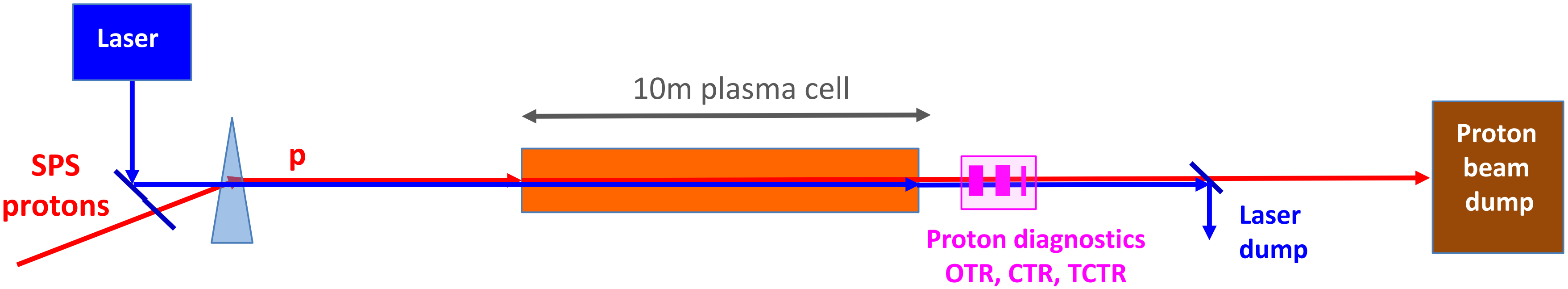
AWAKE Experimental Layout: 1st Phase

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



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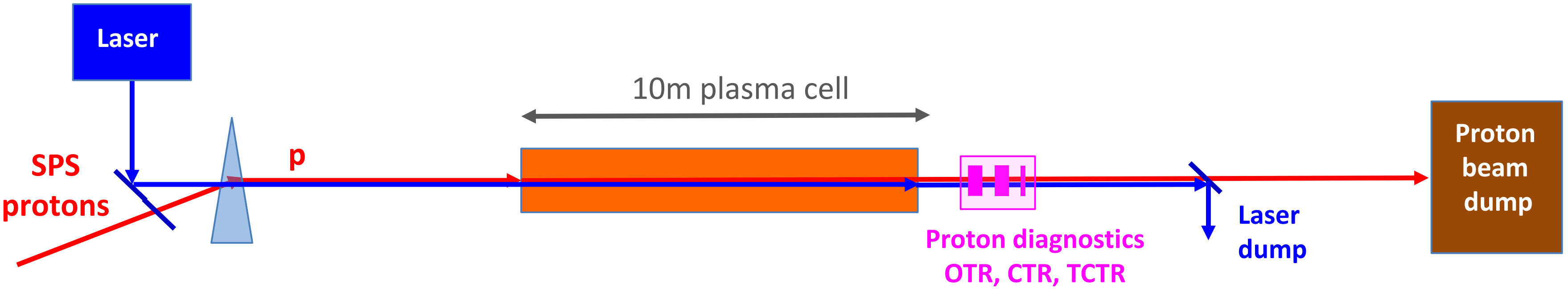
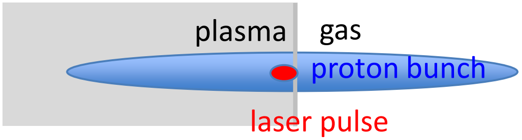


→ SPS proton bunch experiences **Self-Modulation Instability** (SMI) in the plasma.

→ **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 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

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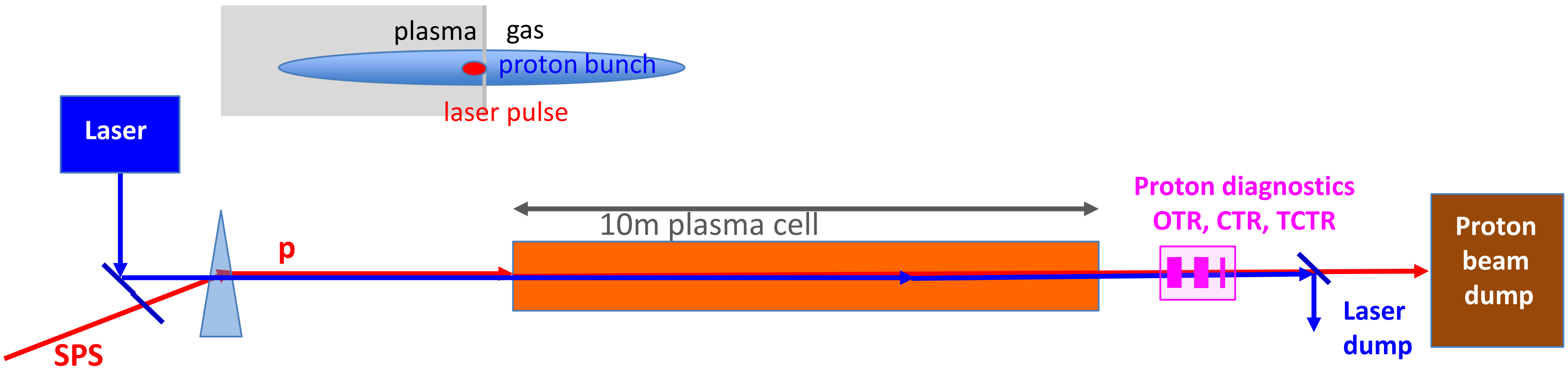
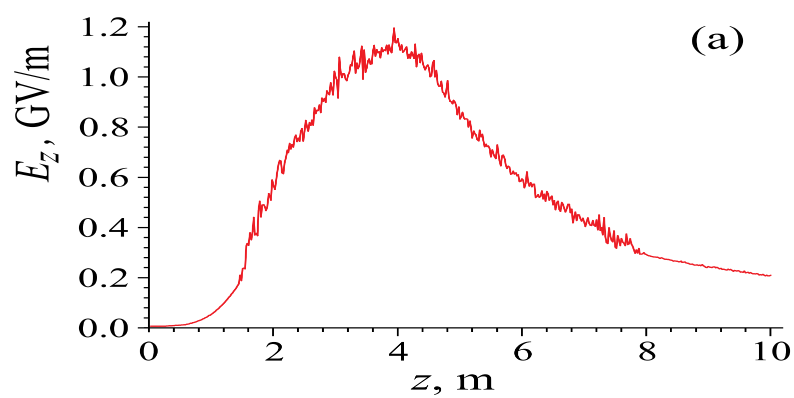


- Laser and proton beam synchronized at the **100 ps level**.
- Laser and proton beam **co-axial** over the full length of the plasma cell:
  - 100µm and 15 rad pointing accuracy
  - High resolution diagnostics to perform and monitor relative alignment
- Plasma density uniformity better than **0.2%**

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



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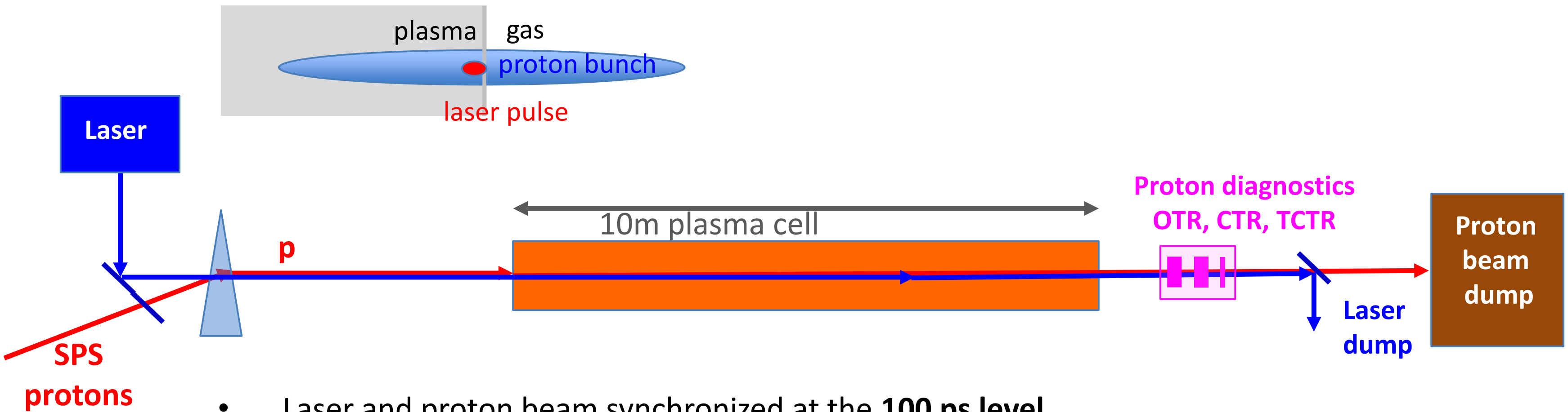

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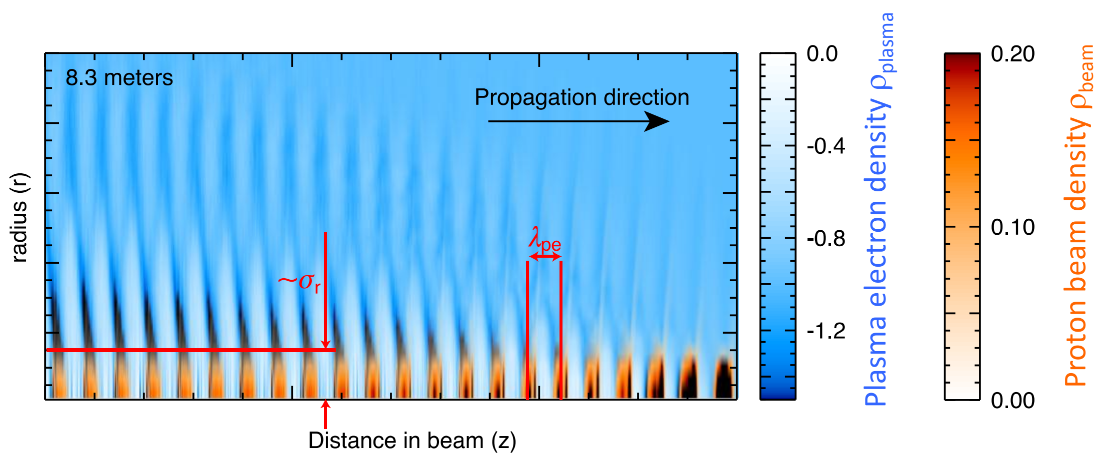
Self-modulated proton bunch resonantly driving plasma wakefields.



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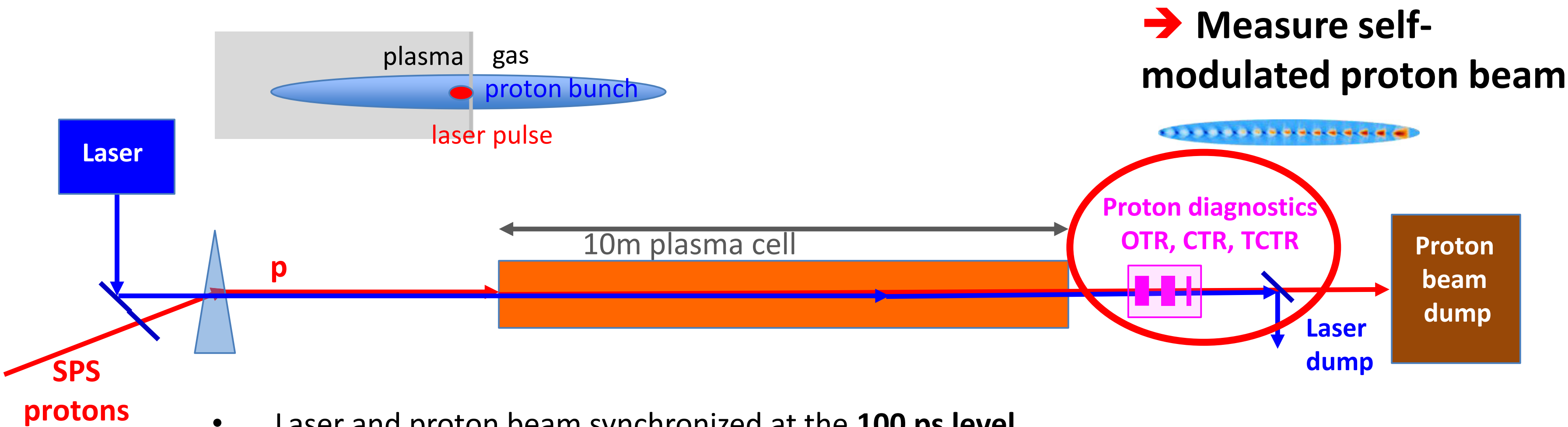

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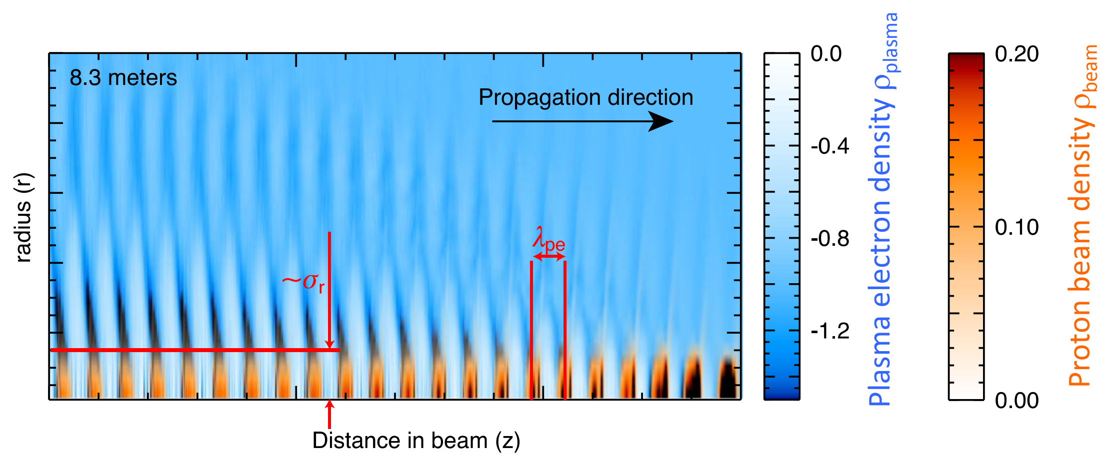

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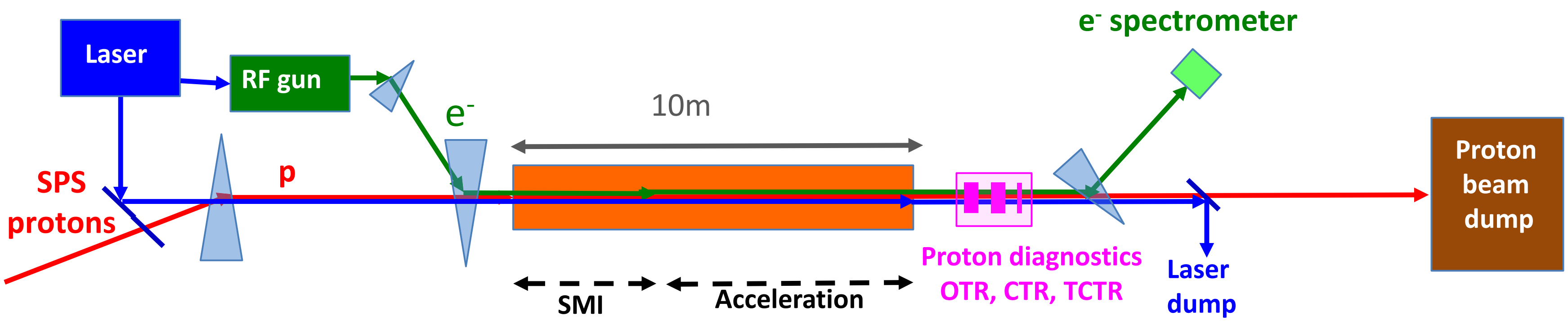
AWAKE Experimental Layout: 2nd Phase

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



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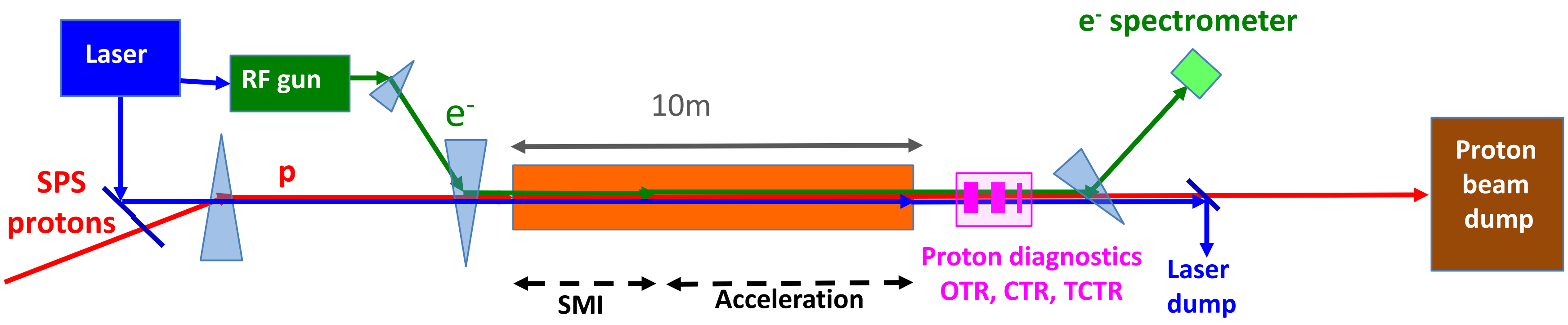

Electron beam	
Momentum	**16 MeV/c**
Electrons/bunch (bunch charge)	**1.2 E9 (0.2 nC)**
Bunch length	**σ_z =4ps (1.2mm)**
Bunch size at focus	**$\sigma^*_{x,y}$ = 250 µm**
Normalized emittance (r.m.s.)	2 mm mrad
Relative energy spread	$\Delta p/p = 0.5\%$
Beta function	$\beta^*_x = \beta^*_y = 0.4$ m
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	±2.5% r.m.s.

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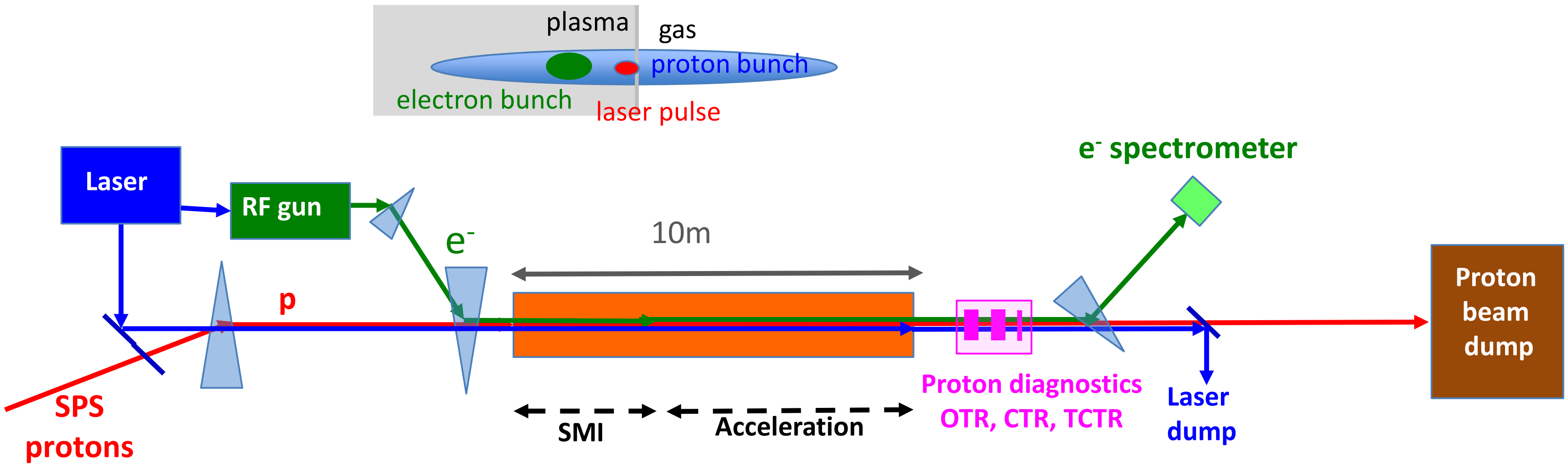
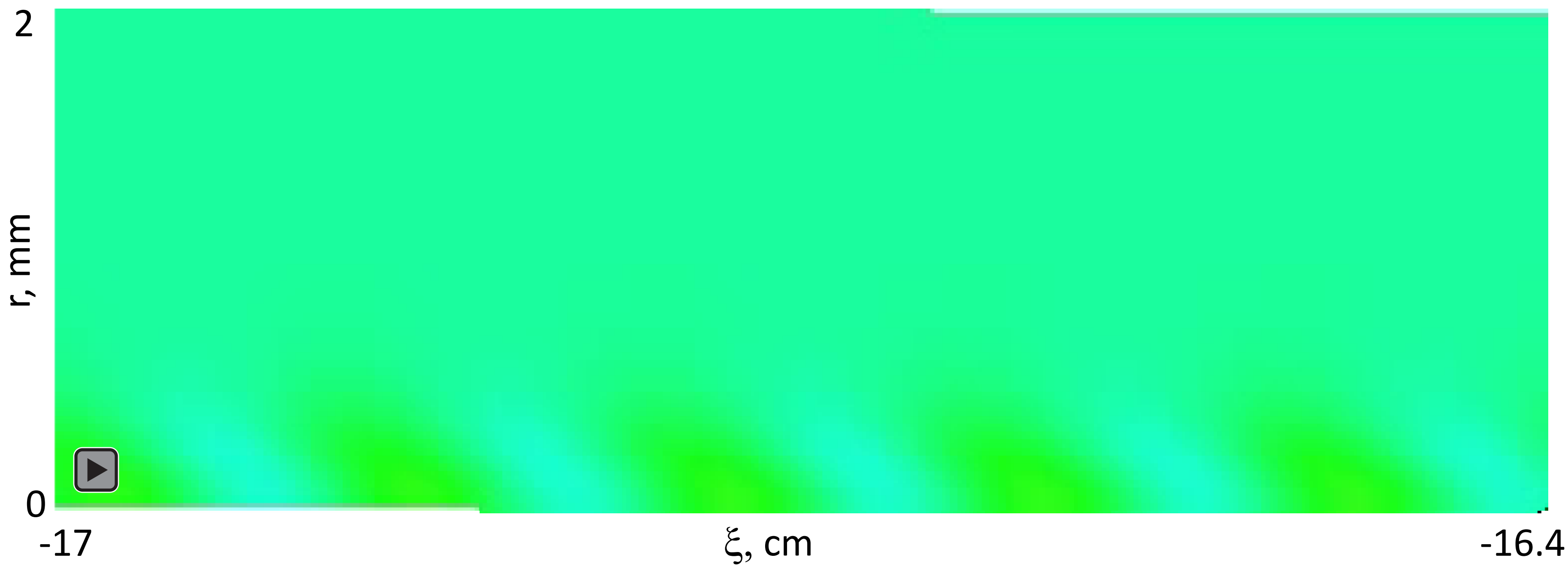


- Laser and electron beam synchronized at the **< 1 ps level**.
- **Electron bunch is externally injected** into the plasma cell, on-axis and collinearly with the proton and laser beam.
- **On-axis injection** point is upstream the plasma cell.

AWAKE Experimental Layout: 2nd Phase

On-axis injection: animation of trapping and acceleration

black points – injected electrons, false colors – wakefield potential



- 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

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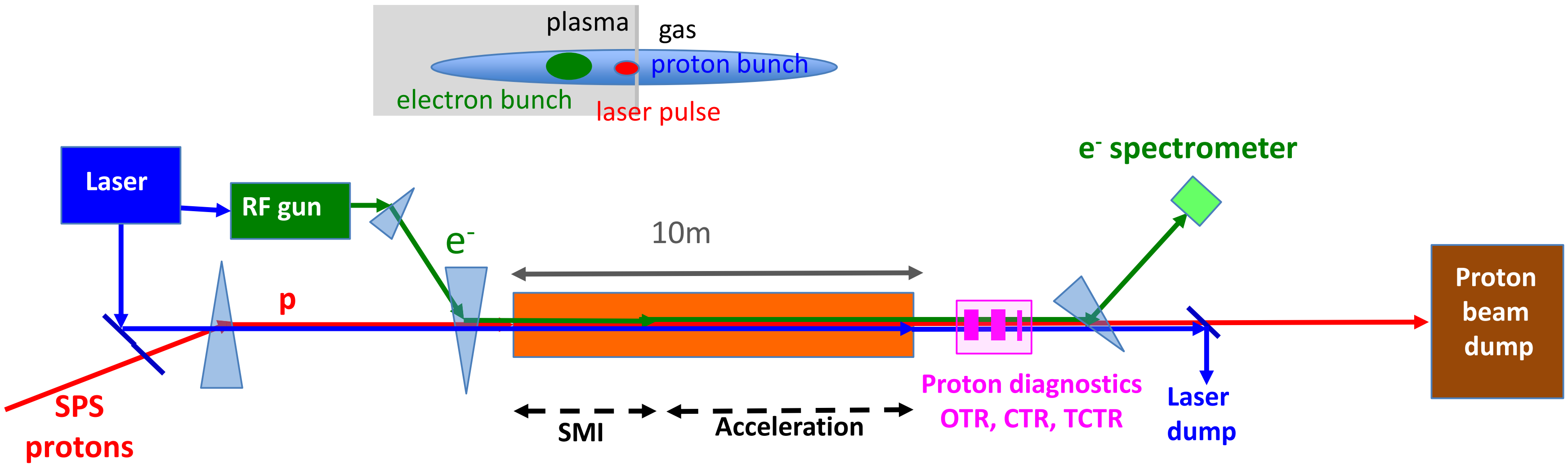

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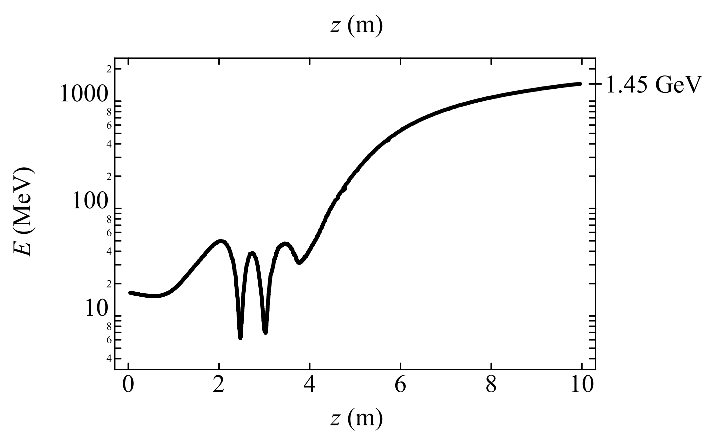

Energy of the electrons gained along the 10 m long plasma cell.

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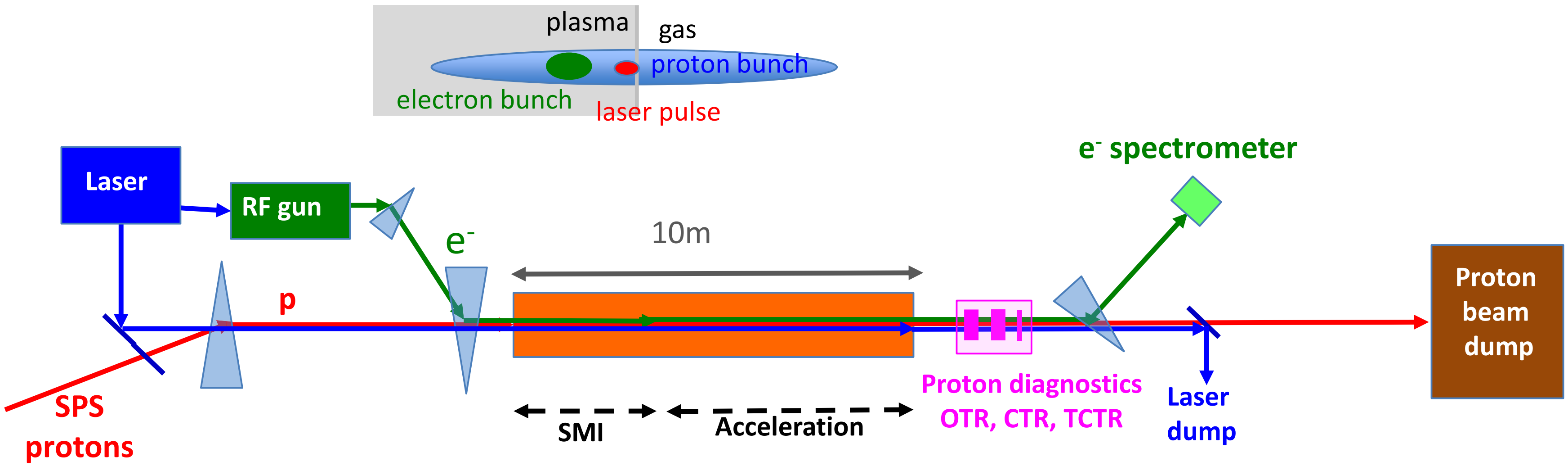

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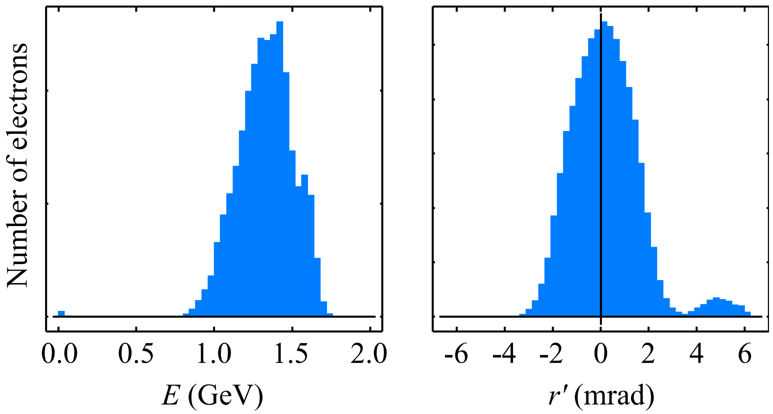
- Trapping efficiency: **10 – 15 %**
- Average energy gain: **1.3 GeV**
- Energy spread: ± 0.4 GeV
- Angular spread up to ± 4 mrad

Large acceptance spectrometer (aperture and magnetic field)



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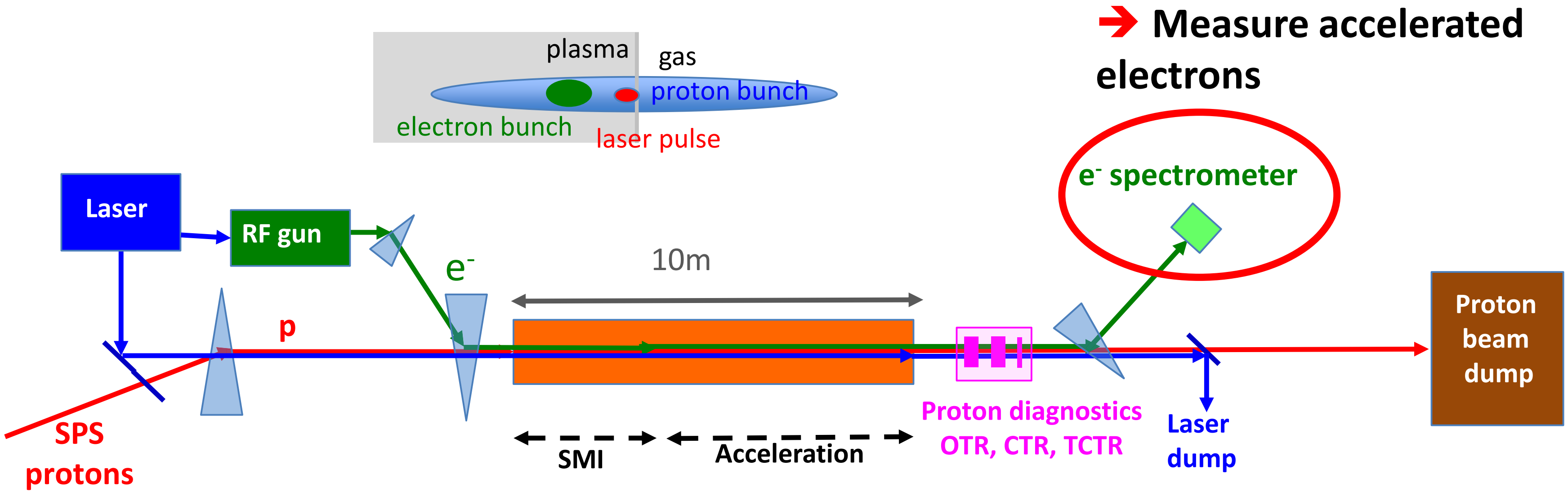

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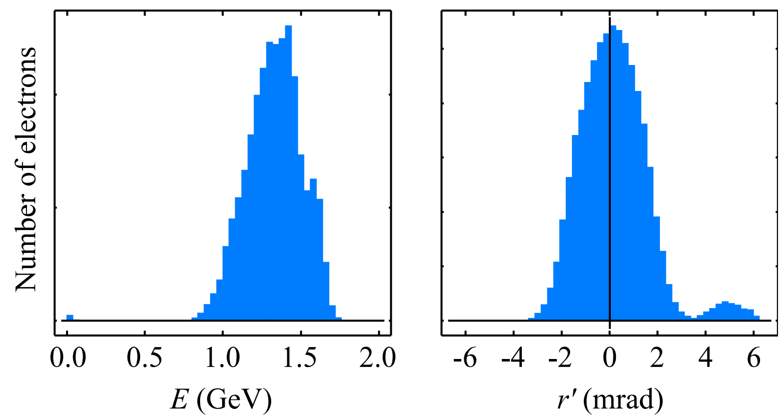

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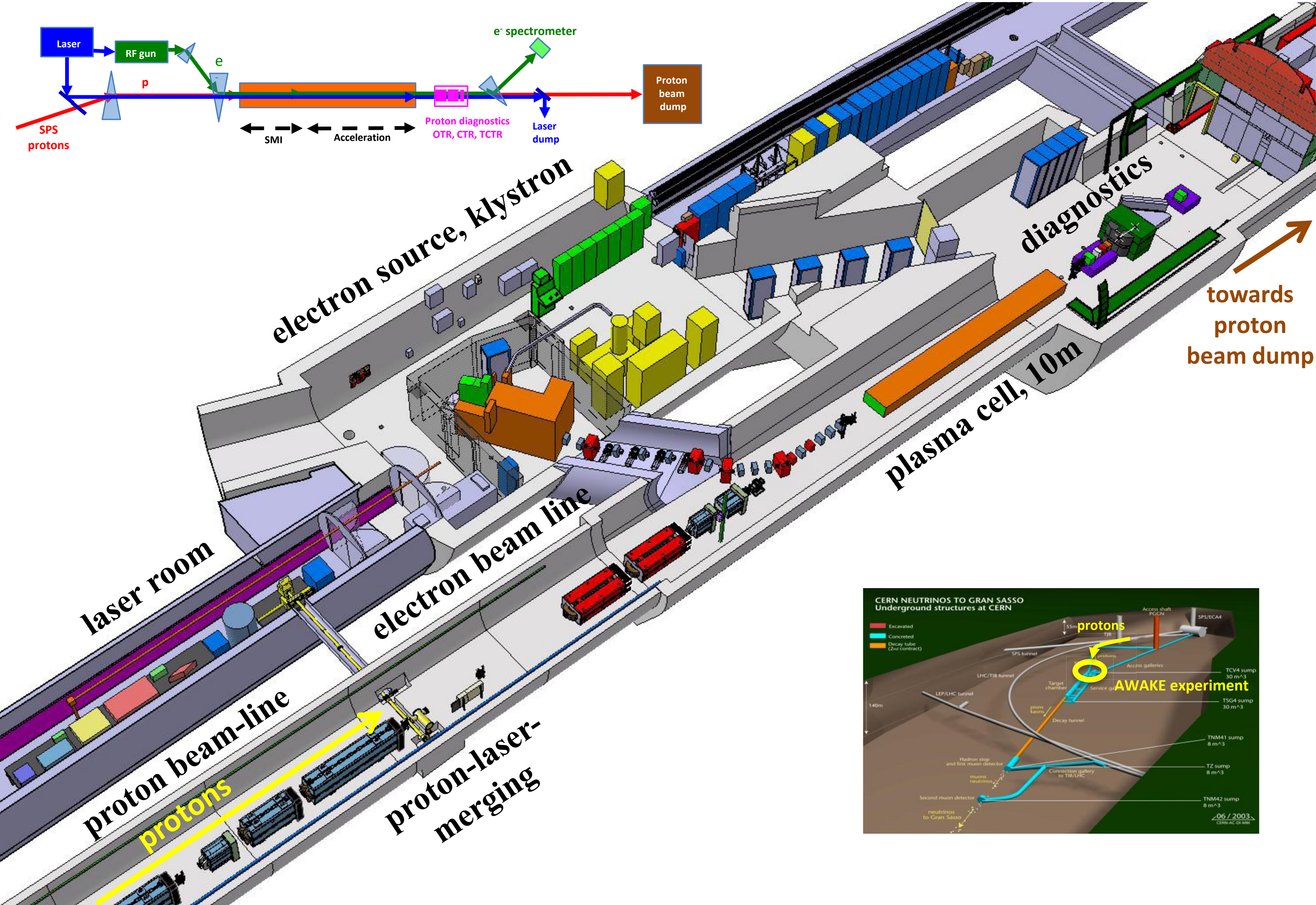
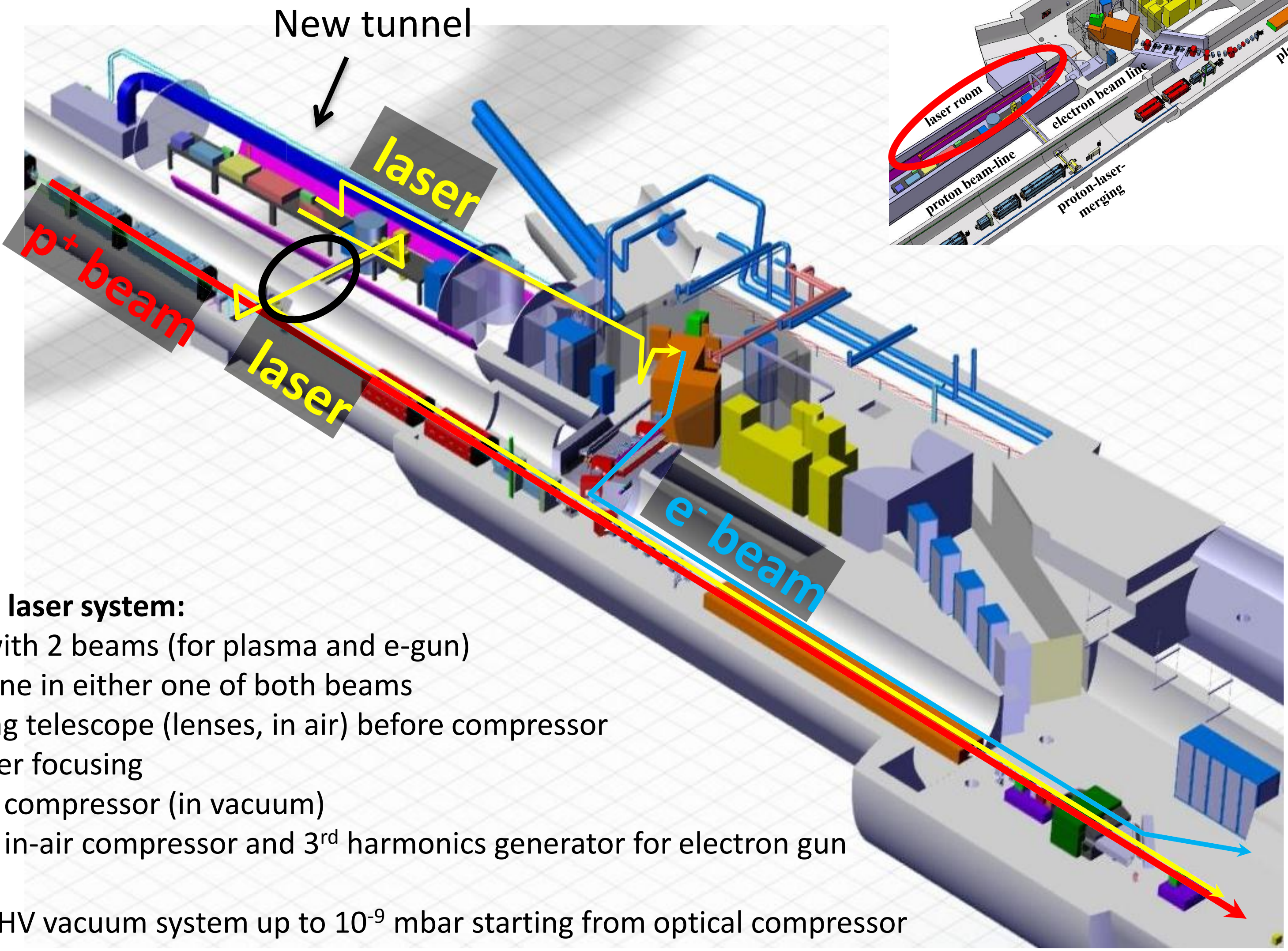
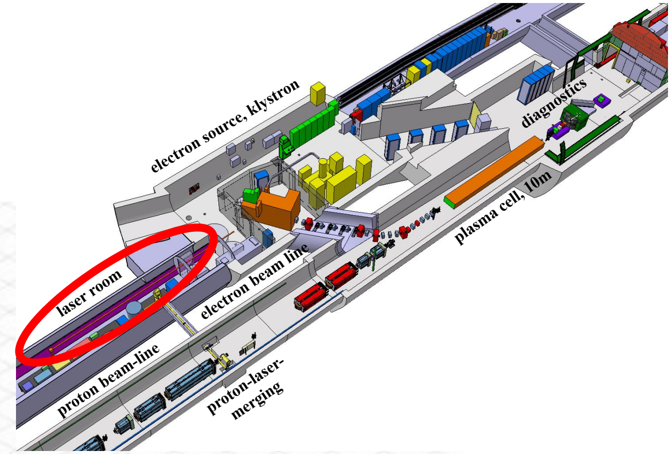


Laser System



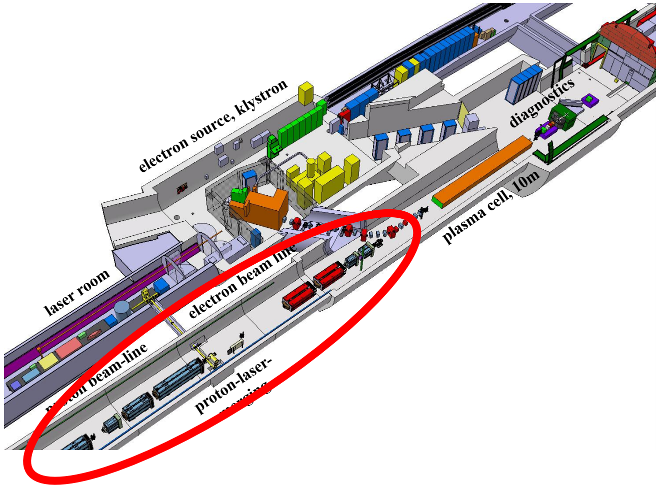


Ti: Sapphire laser system:

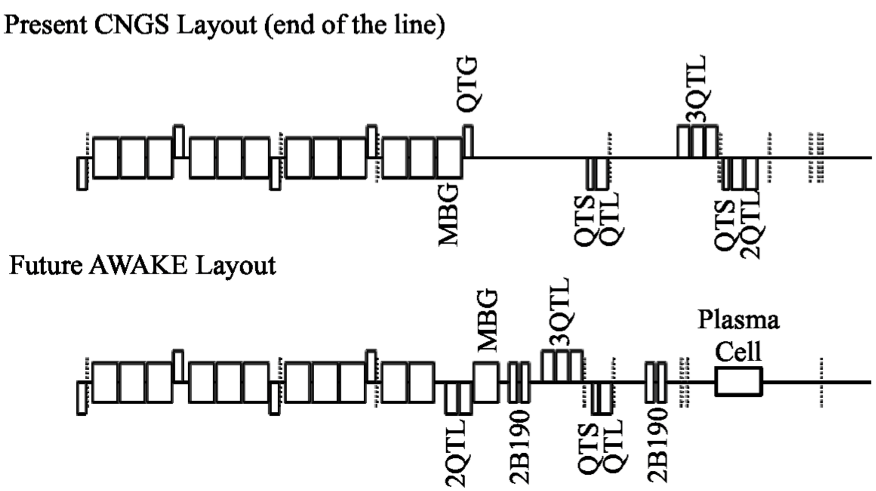
- Laser with 2 beams (for plasma and e-gun)
- Delay line in either one of both beams
- Focusing telescope (lenses, in air) before compressor
- 35 meter focusing
- Optical compressor (in vacuum)
- Optical in-air compressor and 3rd harmonics generator for electron gun

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

Proton Beam Line

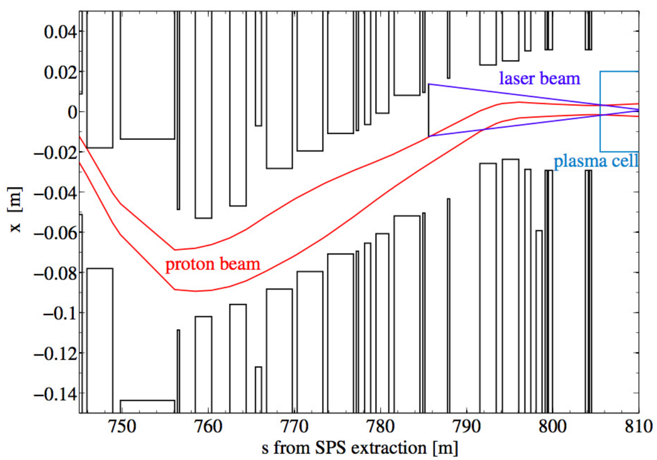


Change of the proton beam line only in the **downstream part (~80m)**



→ **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.

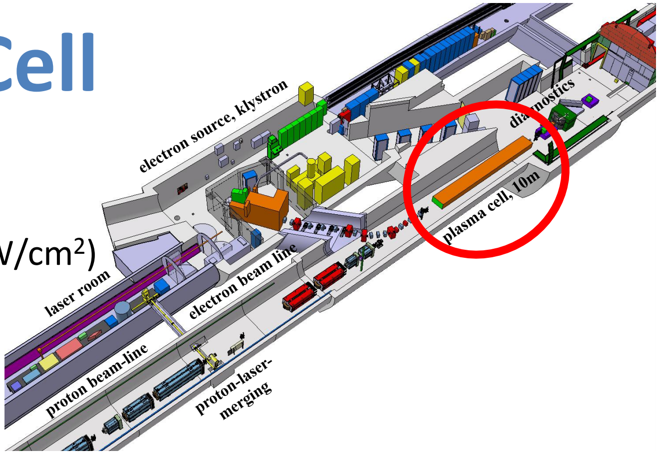


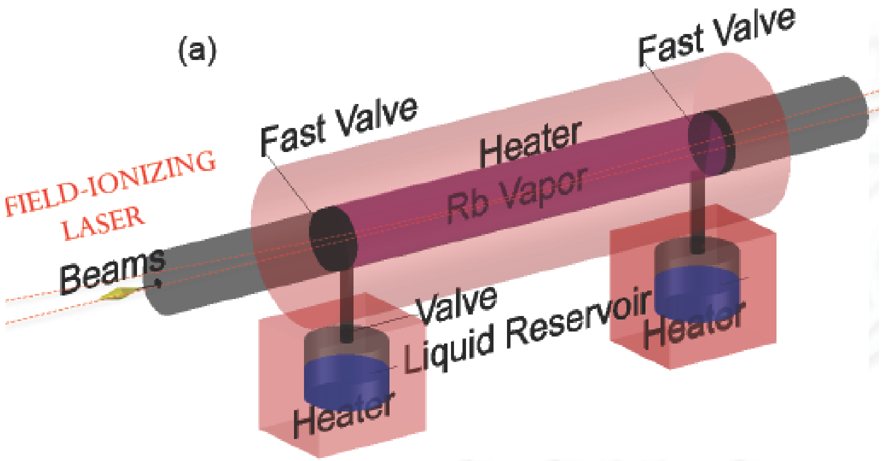
Laser-proton merging 20m upstream the plasma cell

Rubidium Vapour Plasma Cell

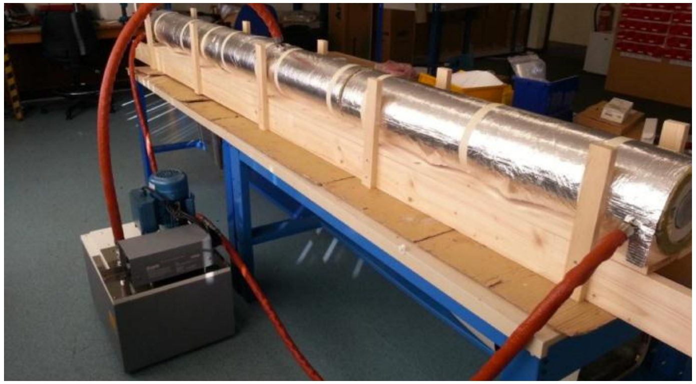
- Density adjustable from **10^{14} – 10^{15} cm^{-3}**
- 10 m long, 4 cm diameter
- Plasma formed by **field ionization of Rb vapour** using laser pulse (~1.7 10^{12} W/cm^2)
- System is oil-heated → keep temperature uniformity ➔ density uniformity

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

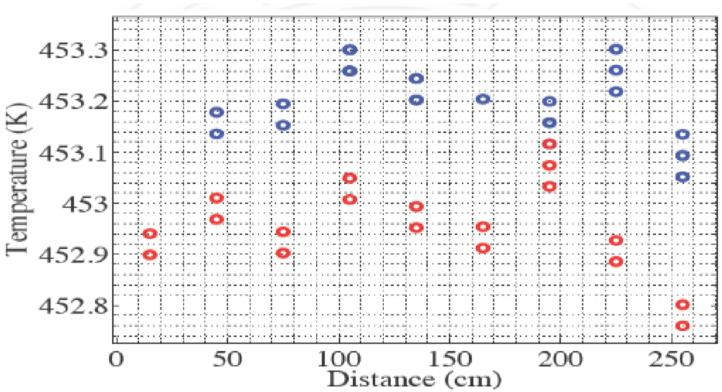




3m prototype

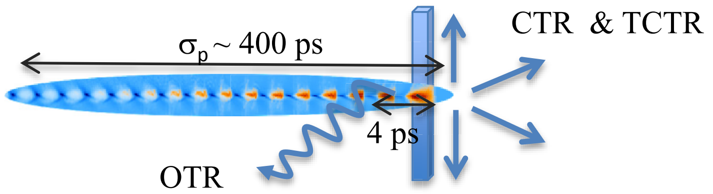


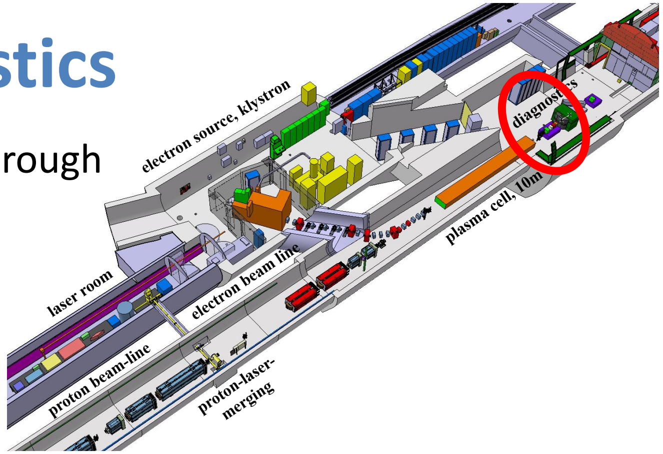
Temperature profiles along the heat exchanger
Measurements **remain < ± 0.1 K**



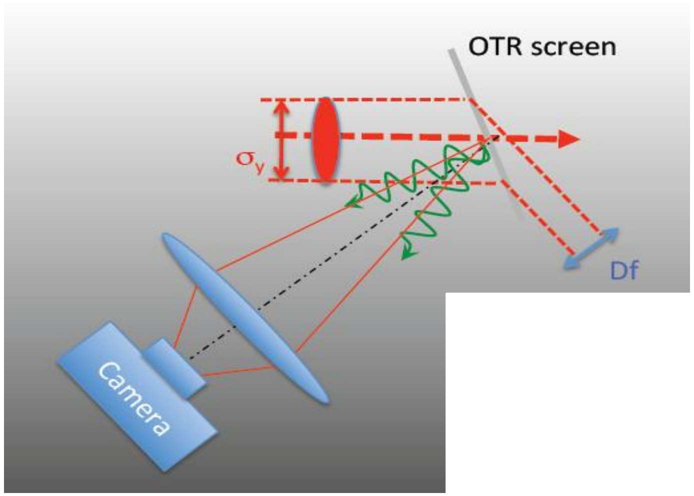
Self-Modulation-Instability Diagnostics

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

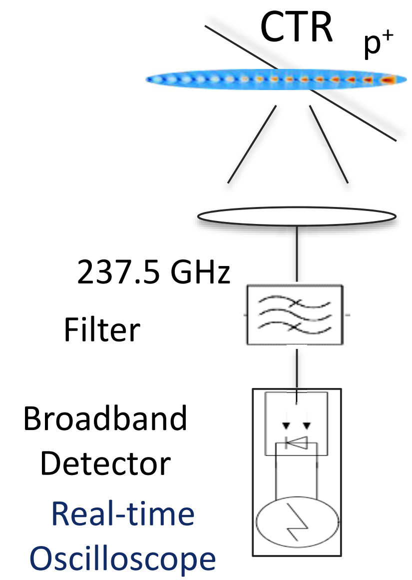




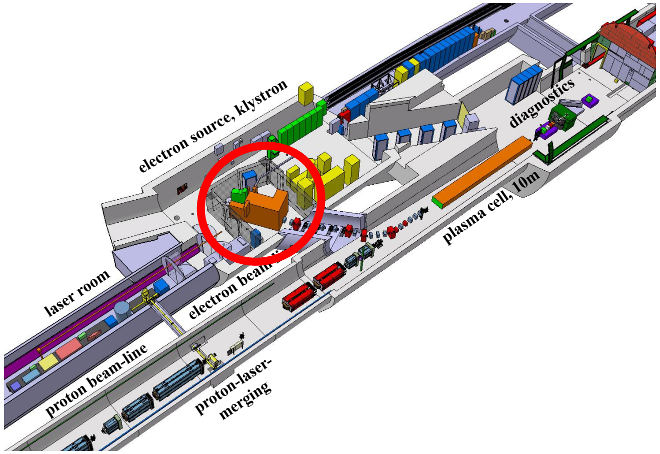
- Optical Transition Radiation (OTR):
  - Time-resolve bunch radius variation with streak-camera (~100fs resolution)
  - Measure relative phasing of laser pulse, proton bunch and electron bunch
- Coherent Transition Radiation (CTR) and Transverse Coherent Transition Radiation (TCTR)
  - High frequency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



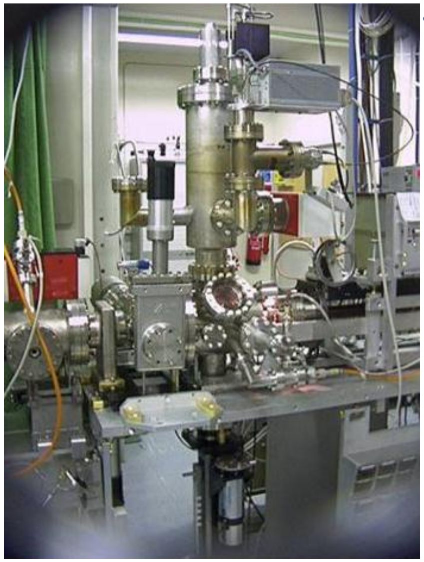
→ Look at cut-off frequency

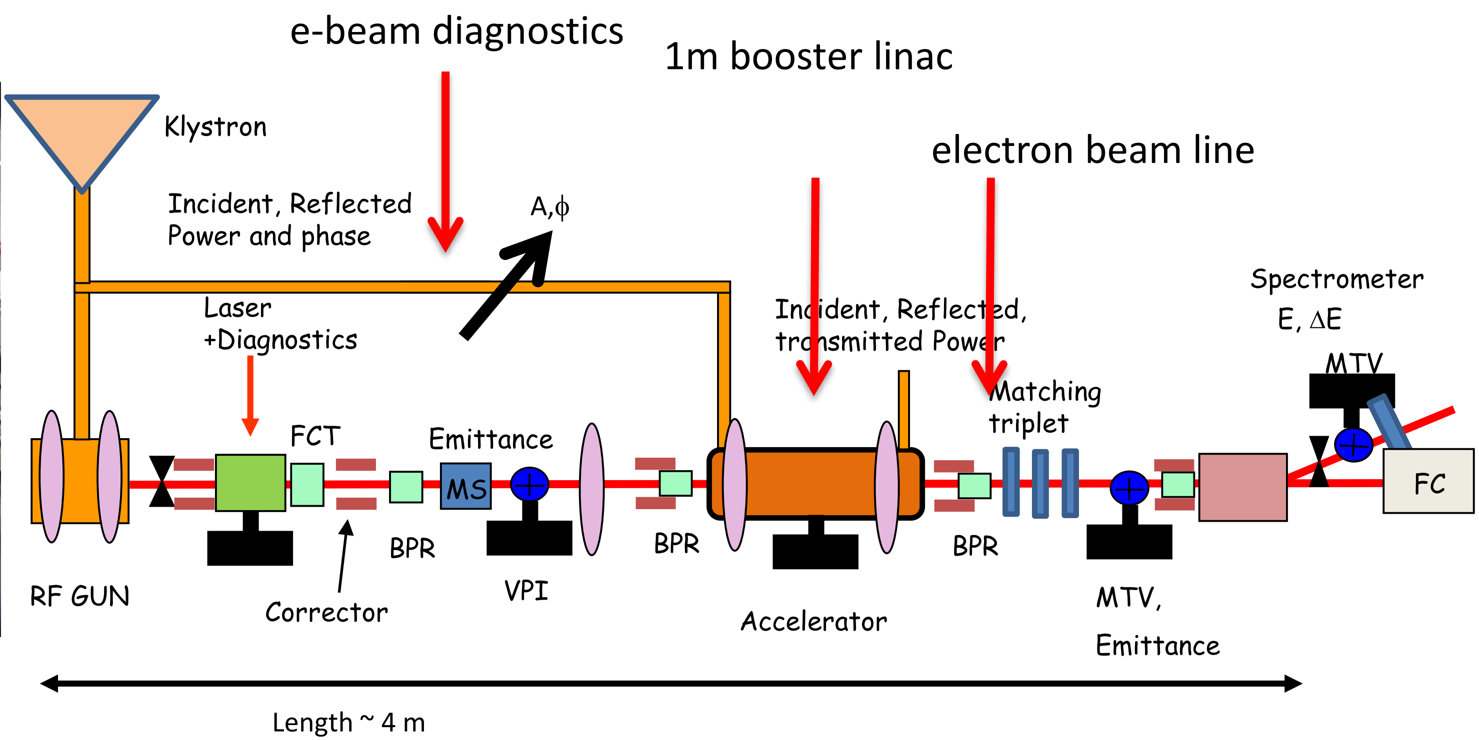


Electron – Source

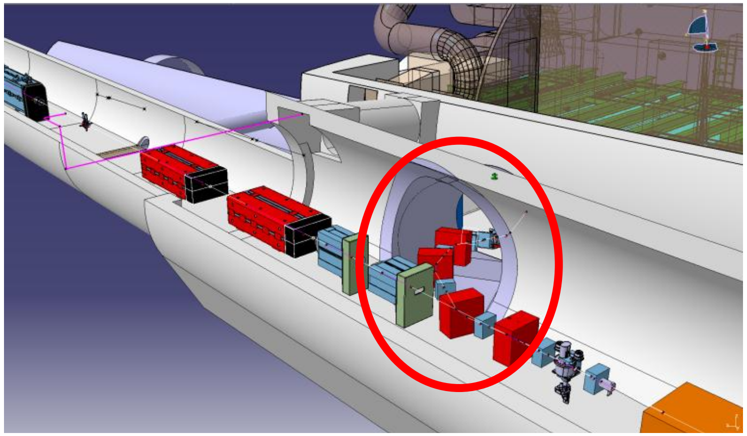


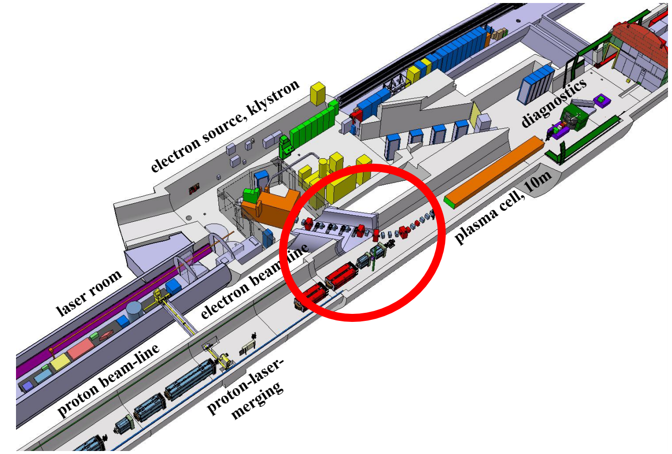
- Baseline:
  - Photo injector (**PHIN**) from CTF2 at CERN (5 MeV electrons)
  - Klystron and modulator from CTF3
  - Booster from Cockcroft/Lancaster 5 MeV→ 20 MeV
- Optimize and test performance of complex system.
  - use as test area after 2015.



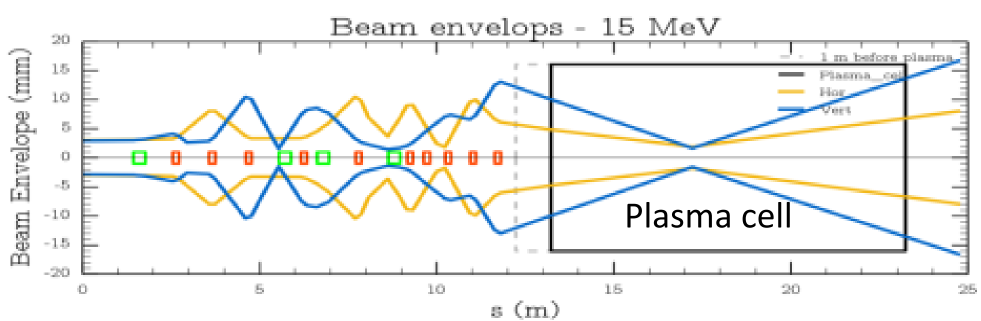


Electron Beam Line



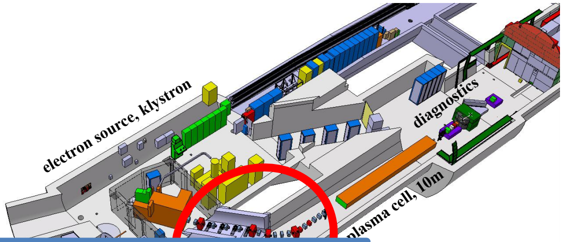


- Completely **new beam line and tunnel**:
  - Horizontal angle of 60 deg,
  - 20% slope of the electron tunnel → 1m level difference
  - 7.2% slope of the plasma cell
  - ~5 m common beam line between electron and proton
- **Common diagnostics** for proton (high intensity, 3E11 p) and electron beam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



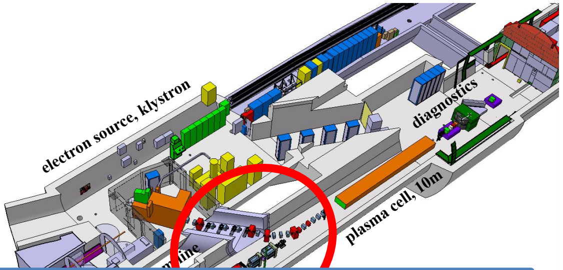
Electron beam envelope (H, V)

Electron Beam Line



Status 4 weeks ago

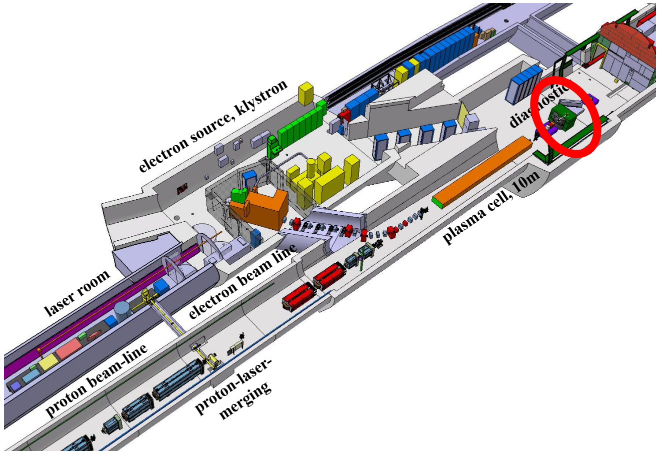
Electron Beam Line



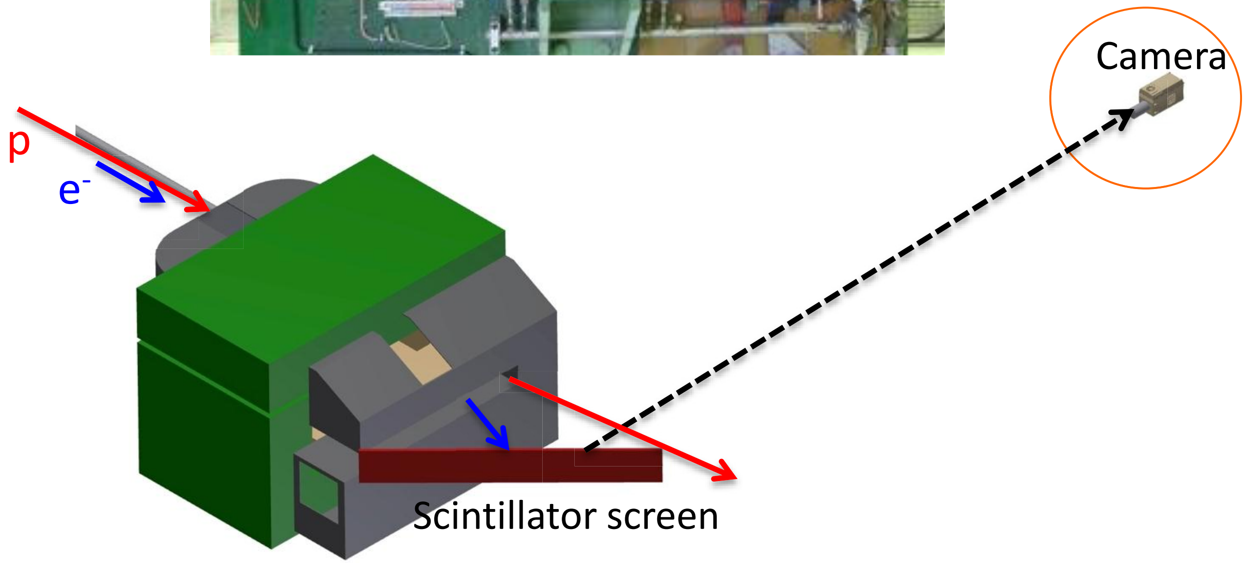
Status 1 week ago

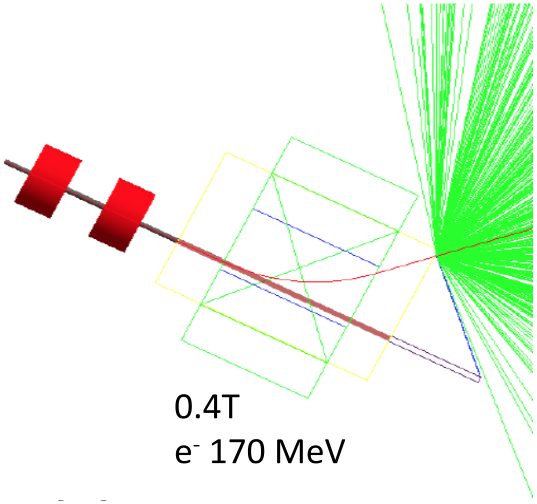
Electron Spectrometer

- 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.



MBPS magnet (CERN): 15 ton
1.84 T, 3.80 Tm
Vert. aperture: 110-200 mm
Horiz. Aperture: 300 mm
L=1670 mm, W=1740 mm

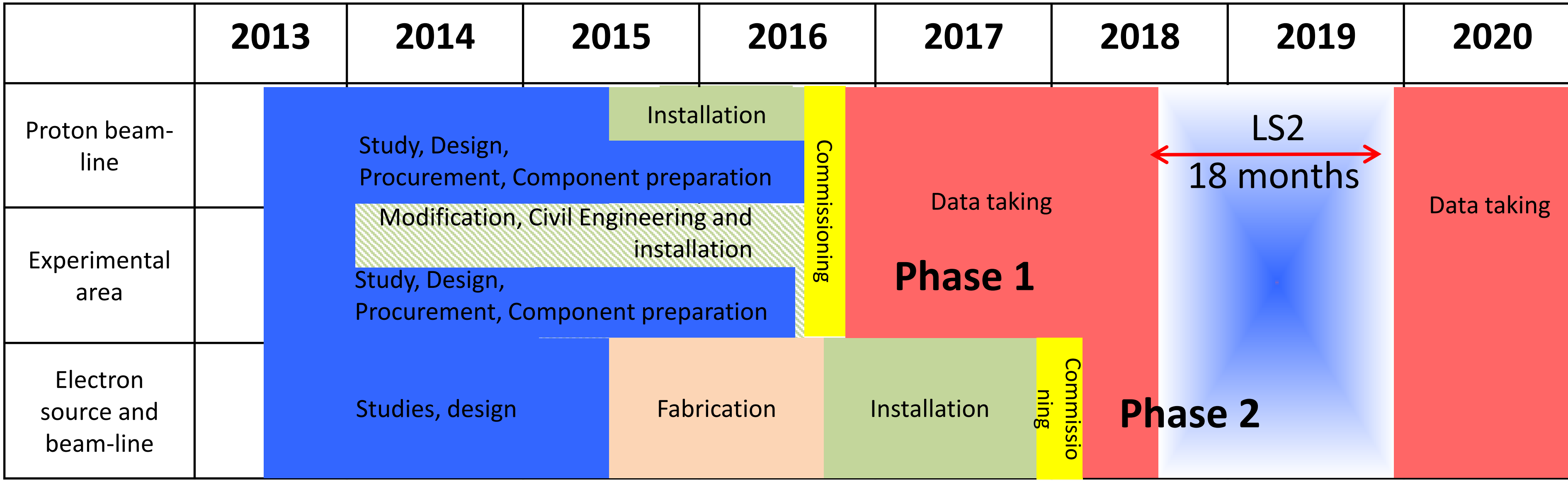




Outline

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

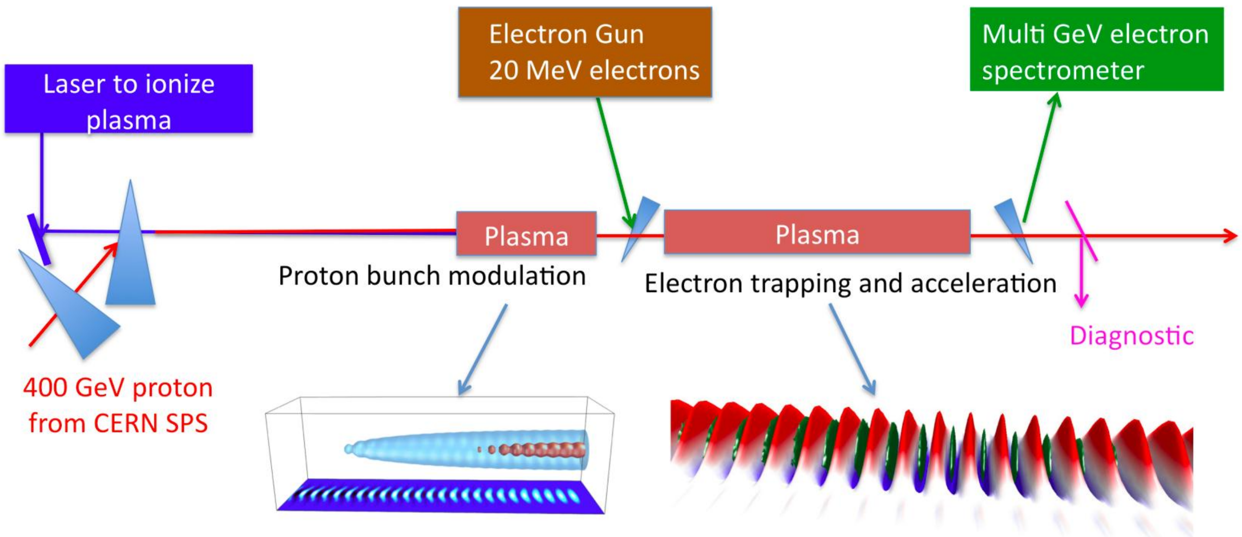
Planning



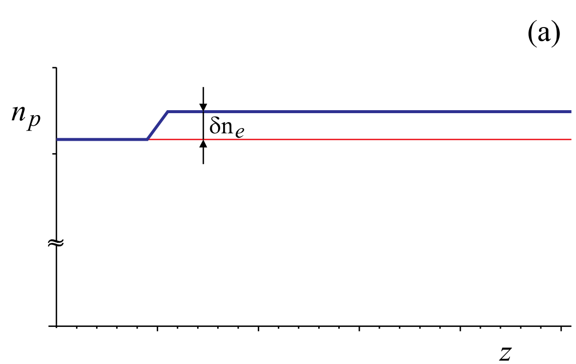
- AWAKE was approved in August 2013
- **1st Phase:** First proton and laser beam in 2016
- **2nd Phase:** first electron beam in 2017
- Physics program for 3 – 4 years

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**

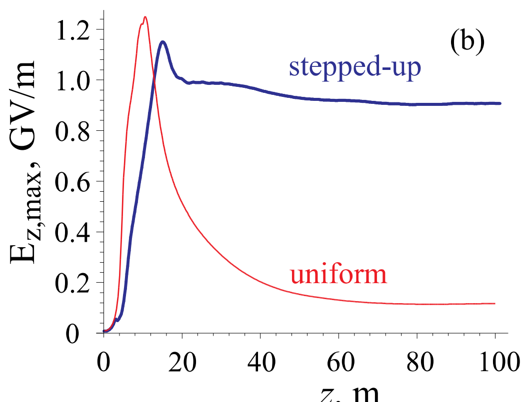
Next Steps



- **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

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, 2017-2018)
  - **Develop long scalable and uniform plasma** cells, production of **shorter electron and proton bunches** (2020)