AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN

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for the AWAKE Collaboration

European Physical Society Conference on High Energy Particle Physics 2015

22-29 July 2015, Vienna, Austria

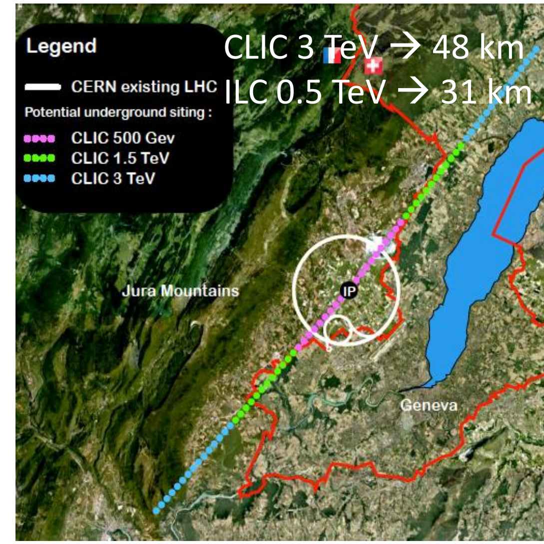
Outline

- Motivation
- Plasma Wakefield Acceleration
- AWAKE at CERN
- AWAKE Experimental Program
- Components of the AWAKE Experiment
- Installation of the AWAKE Facility
- Summary

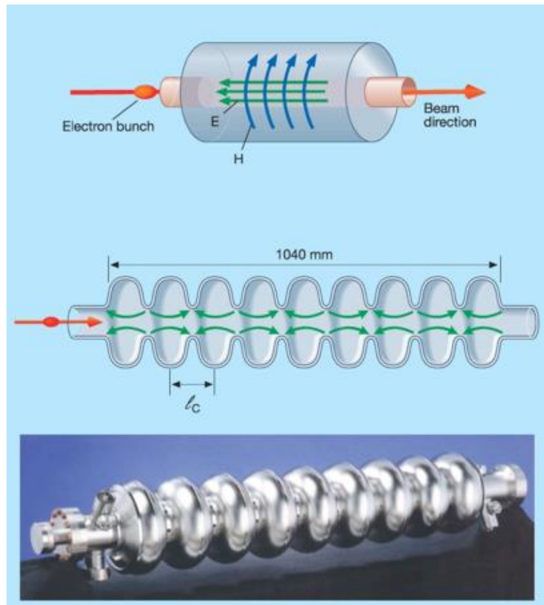
Motivation – Cavities vs. Plasma

Today's RF cavities or microwave technology: accelerating fields is limited to <100 MV/m

→ several **tens of kilometers for future linear colliders**



- Typical gradients:
  - LHC: 5 MV/m
  - ILC: 35 MV/m
  - CLIC: 100 MV/m



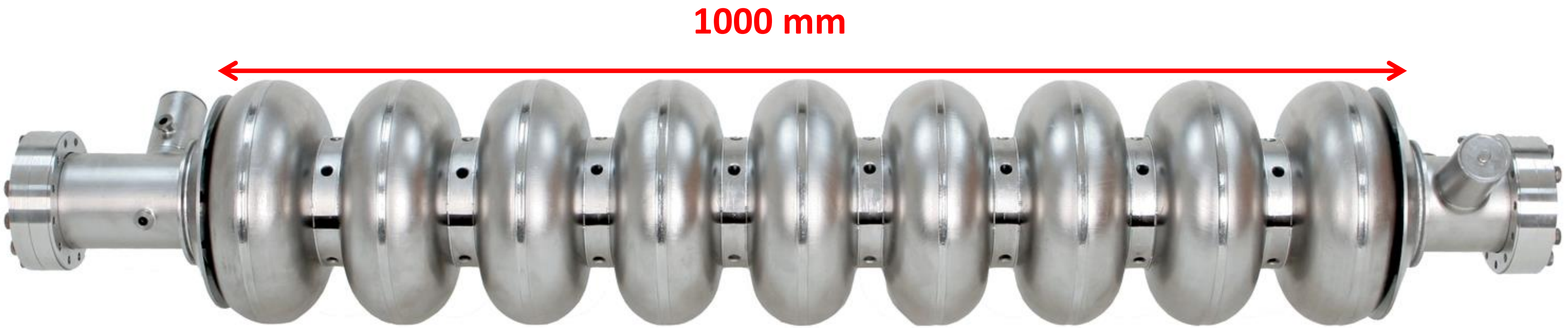
Use plasma as 'cavity'!

- Plasma can sustain up to **three orders of magnitude higher gradients**
  - SLAC experiment: **50 GV/m**

→ **much shorter linear colliders!**

Motivation – Cavities vs. Plasma

- ILC Cavity: 35 MV/m

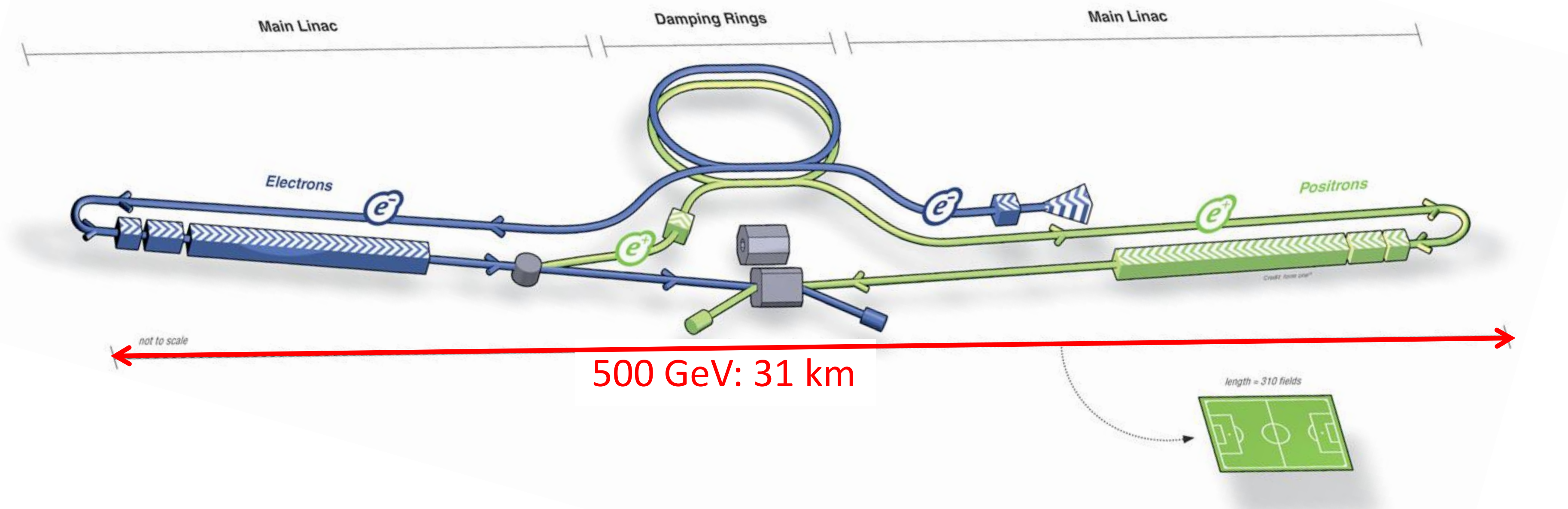


- Plasma cell: 35 GV/m ➔ **35 MV/mm!!**

(Not to scale!)

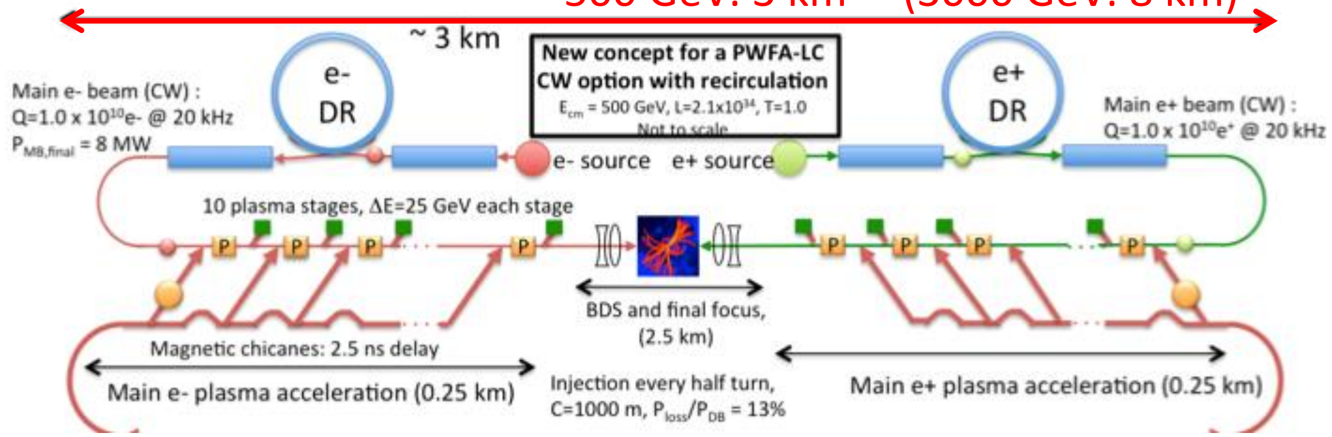
Motivation – Linear Colliders

ILC



Plasma based Linear Collider

500 GeV: 3 km (3000 GeV: 8 km)



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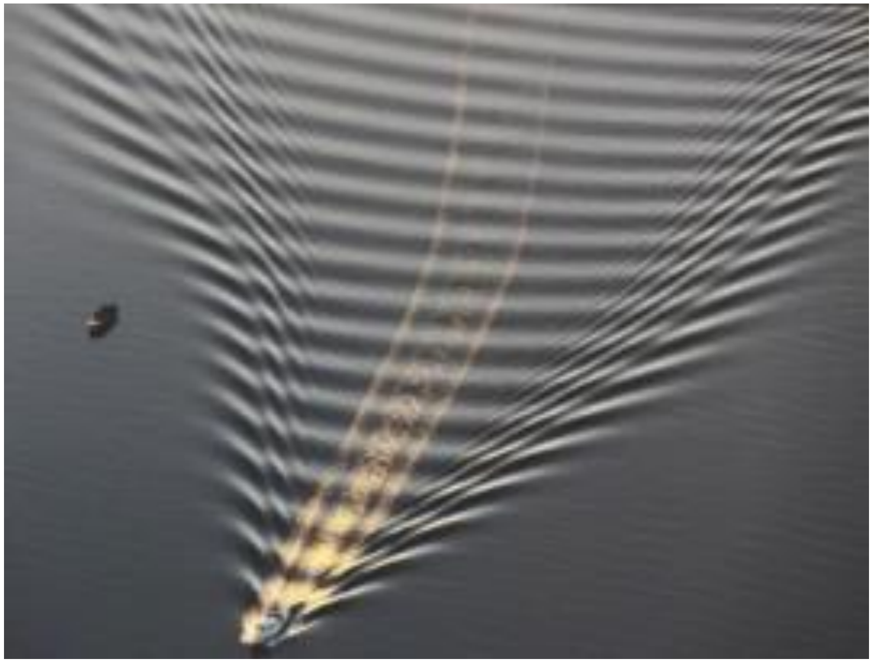
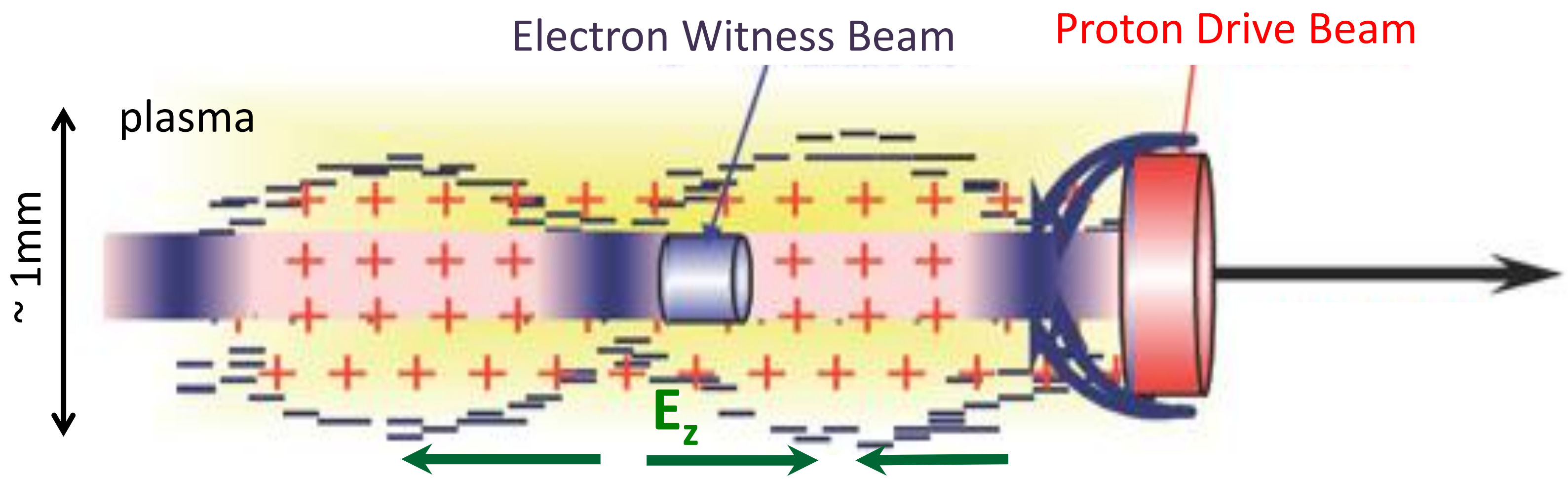
Plasma Wakefield Acceleration

Wakefield excitation



Particle acceleration

Principle of Plasma Wakefield Acceleration



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

➔ **Produce 'mini cavities' (~1mm) inside the plasma cell**

→ **Proton beam produces (*drives)* accelerating wakefield in the plasma**

→ **Injected electron beam surfs (*witnesses)* on that wakefield and gets accelerated.**

→ Size of the accelerating structure is set by the plasma density: plasma wavelength λ_p **=1mm**, (for typical plasma density of $n_p = 10^{15}cm^{-3}$)

→ **Gradients at several GV/m**

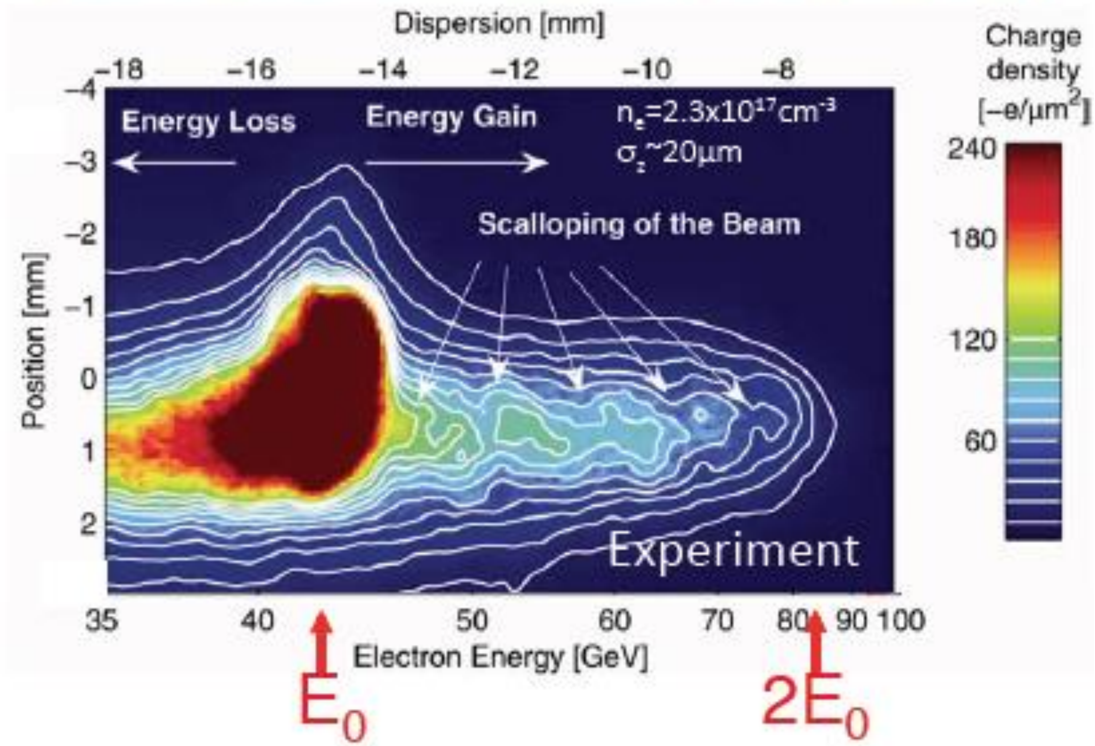
$$\lambda_p = \frac{2\pi}{k_p} = 1mm\sqrt{\frac{1\cdot 10^{15}\ \mathrm{cm}^{-3}}{n_p}}$$

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

First Results: Electron Beam Driven PWA

➔ Experimental results show success of PWFA and its research ➔ **SLAC beam:**

Blumenfeld, Nature 445, 741 (2007)



42 → 84 GeV in 85 cm! ➔ 50 GV/m

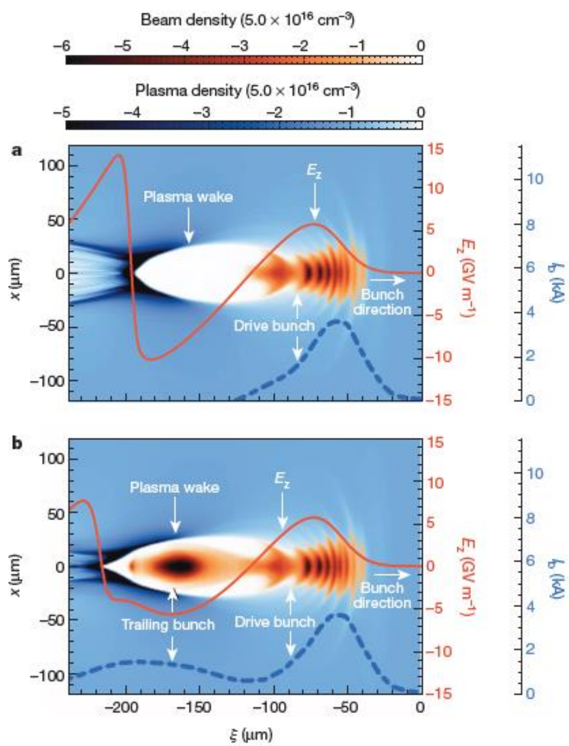
SLAC – FACET: Latest Results

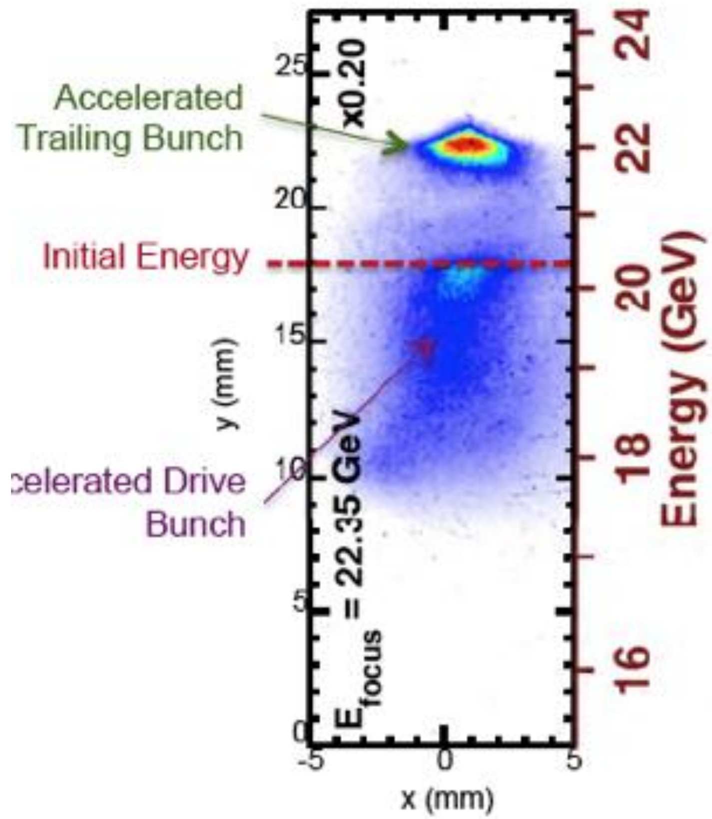
High-Efficiency acceleration of an electron beam in a plasmas wakefield accelerator

M. Litos et al., doi, Nature, 6 Nov 2014, 10.1038/nature 13992

Result

- **Total efficiency is <29.1%> with a maximum of 50%.**
- **Final energy spread of 0.7 % (2% average)**





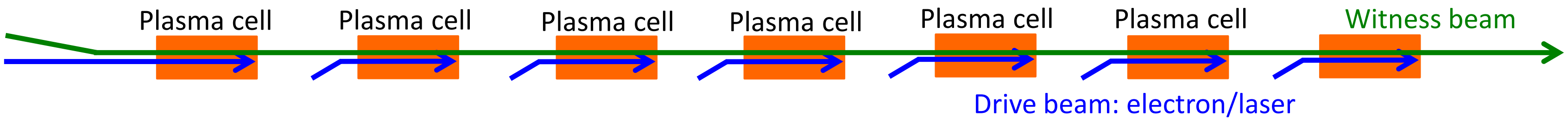
Laser or Electron Beam Driven PWA

- There is a limit to the energy gain of a witness bunch in the plasma:

  ➔ Today's electron beams usually < 100 J level.

  ➔ limitation of the energy carried by the drive beam (< 100J) and the propagation length of the driver in the plasma (<1m).

- To reach TeV scale with electron driven PWA: also need several stages, but need to have
  - relative timing in 10's of fs range
  - many stages
  - effective gradient reduced because of long sections between accelerating elements....



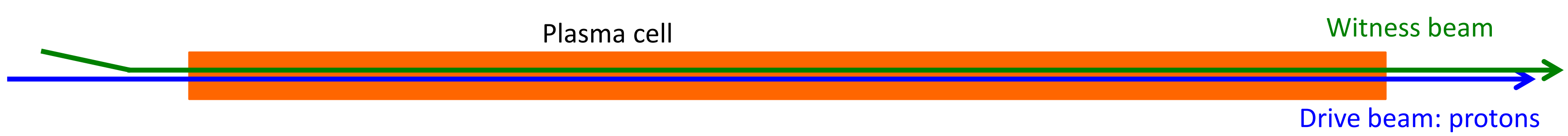
Proton Beam Driven PWA

Proton beams 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**.

A. Caldwell, K. Lotov, Physics of Plasma, 18,103101 (2011)



Beam-Driven Wakefield Acceleration: Landscape

Facility	Where	Drive (D) beam	Witness (W) beam	Start	End	Goal
AWAKE	CERN, Geneva, Switzerland	400 GeV **protons**	Externally injected electron beam (PHIN 15 MeV)	2016	2020+	**Use for future high energy e-/e+ collider.** - Study Self-Modulation Instability (SMI). - Accelerate externally injected electrons. - Demonstrate scalability of acceleration scheme.
SLAC-FACET	SLAC, Stanford, USA	20 GeV **electrons** and **positrons**	Two-bunch formed with mask (e^-/e^+ and e^--e^+ bunches)	2012	Sept 2016	- Acceleration of witness bunch with high **quality and efficiency** - Acceleration of positrons - FACET II proposal for 2018 operation
DESY-Zeuthen	PITZ, DESY, Zeuthen, Germany	20 MeV **electron** beam	No witness (W) beam, only D beam from RF-gun.	2015	~2017	- Study Self-Modulation Instability **(SMI)**
DESY-FLASH Forward	DESY, Hamburg, Germany	X-ray FEL type **electron** beam 1 GeV	D + W in FEL bunch. Or independent W-bunch (LWFA).	2016	2020+	- **Application (mostly) for x-ray FEL** - Energy-doubling of Flash-beam energy - Upgrade-stage: use 2 GeV FEL D beam
Brookhaven ATF	BNL, Brookhaven, USA	60 MeV **electrons**	Several bunches, D+W formed with mask.	On going		- **Study quasi-nonlinear PWFA regime.** - Study PWFA driven by multiple bunches - Visualisation with optical techniques

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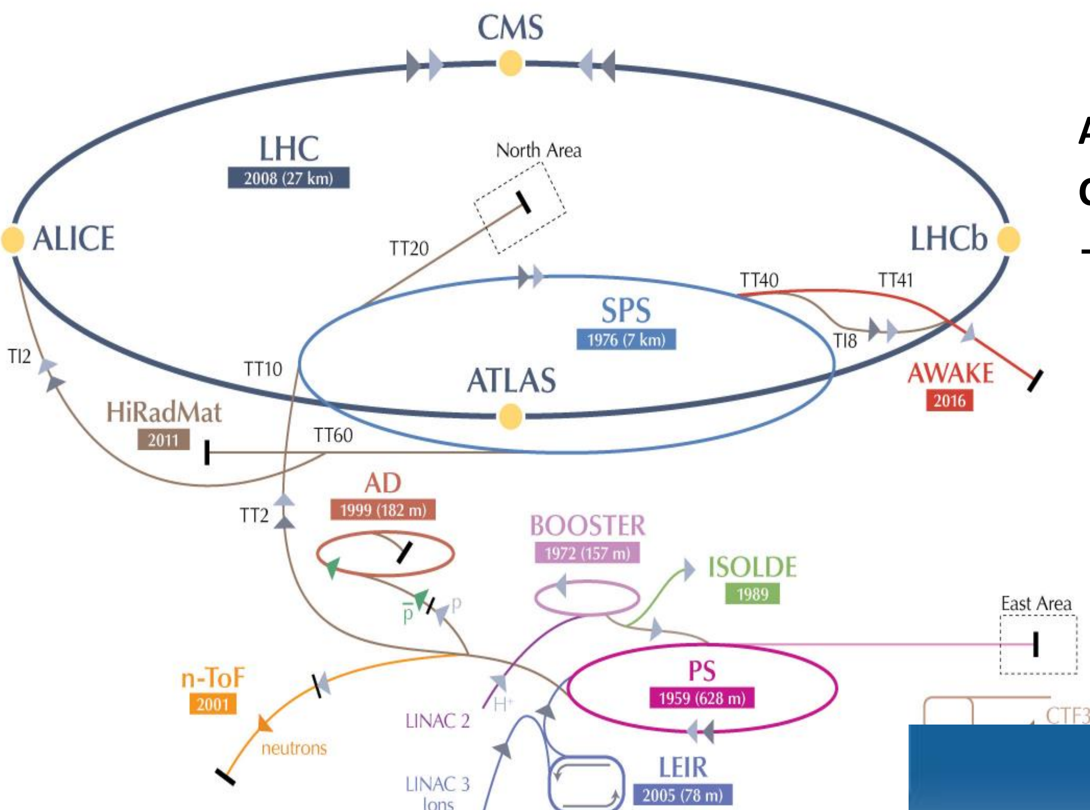
AWAKE

- **Advanced Proton Driven Plasma Wakefield Acceleration Experiment**
  - Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.

- Proof-of-Principle Accelerator R&D experiment at CERN
  - **First proton driven wakefield experiment worldwide**
  - Demonstration of high-gradient acceleration of electrons
  - Approved in 2013
  - First beam expected in **2016**

- AWAKE Collaboration: 16 Institutes world-wide

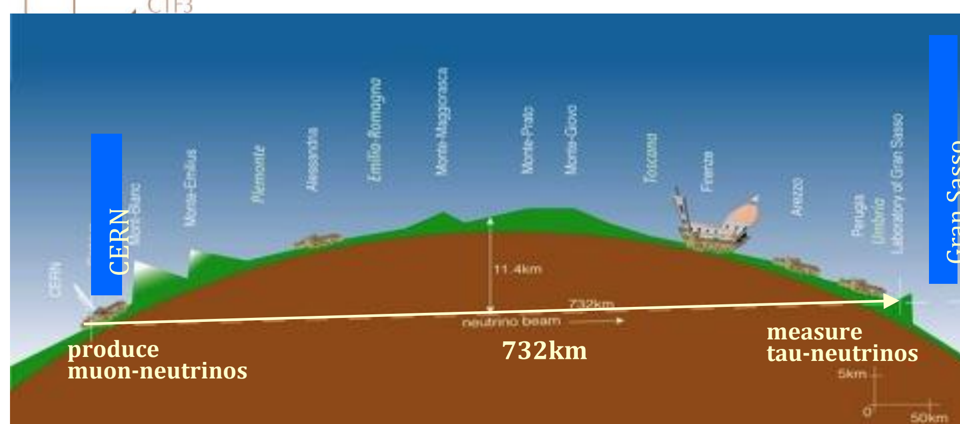
AWAKE at CERN



AWAKE installed in

CNGS Facility (CERN Neutrinos to Gran Sasso)

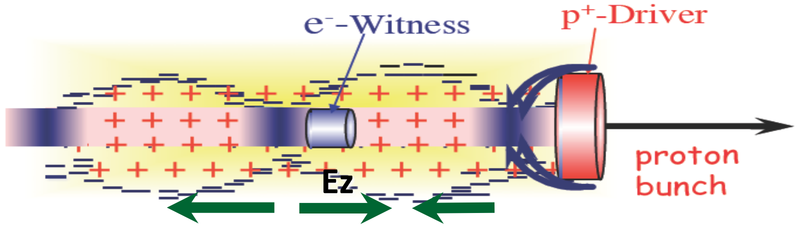
→ CNGS physics program finished in 2012



- Running underground facility
- Desired beam parameters

➔ adequate site for AWAKE

CERN SPS Proton Beam – SMI Instability



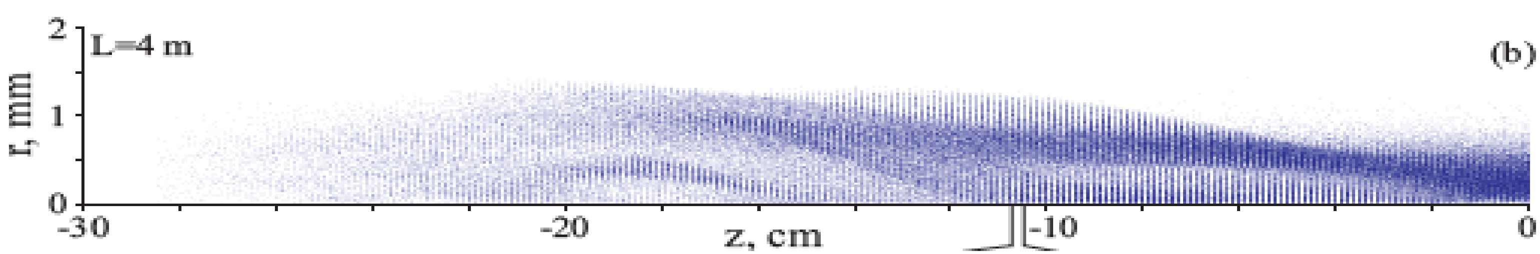
- Drive beam for AWAKE: 400 GeV/c SPS proton beam
- SPS longitudinal beam size (**σ_z = 12 cm**) is much longer than plasma wavelength **(λ = 1mm**)

➔ AWAKE Experiment is based on **self-modulation instability**

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

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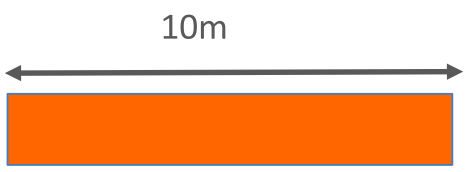

Plasma cell

→ Rb vapour source

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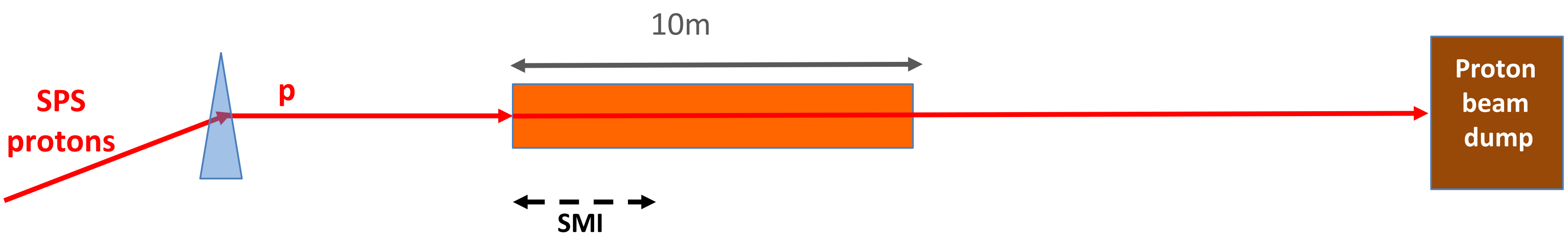

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Proton beam

→ 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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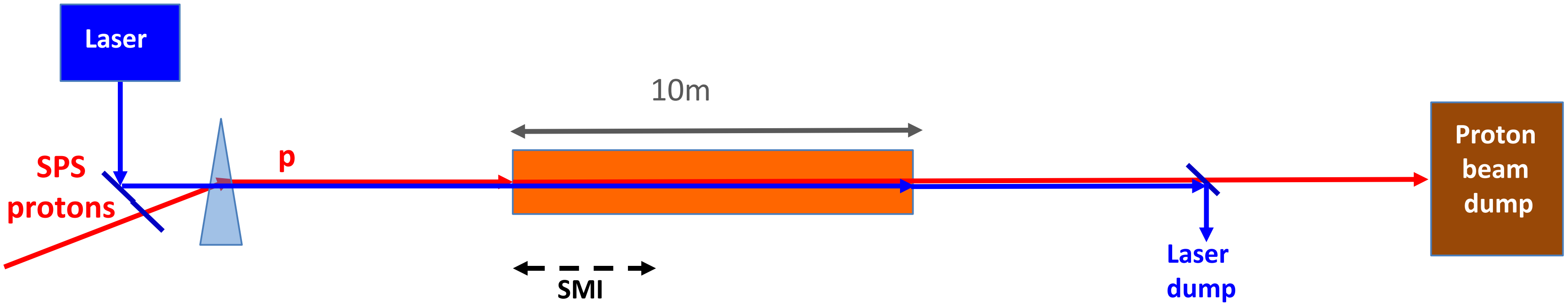

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Laser beam:

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

→ 4.5 TW laser, 100 fs

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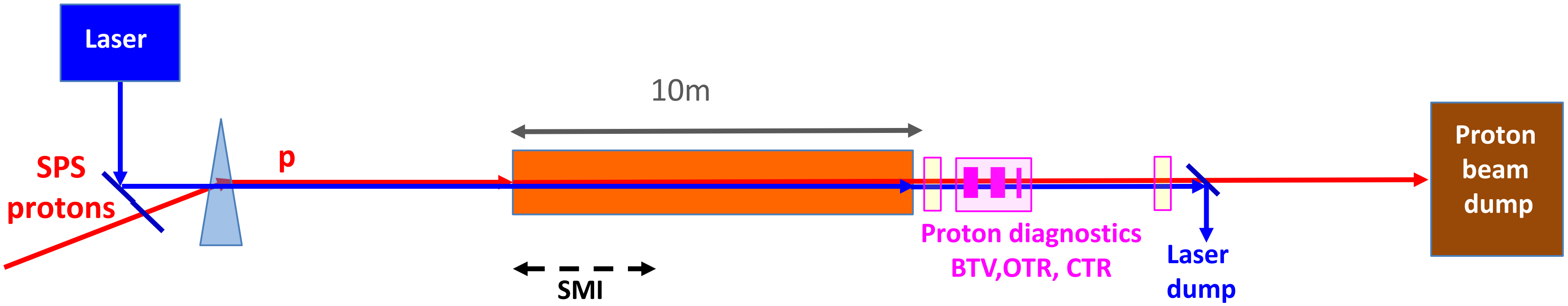

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Diagnostics

→ BTVs, OTR, CTR

AWAKE: Experimental Program

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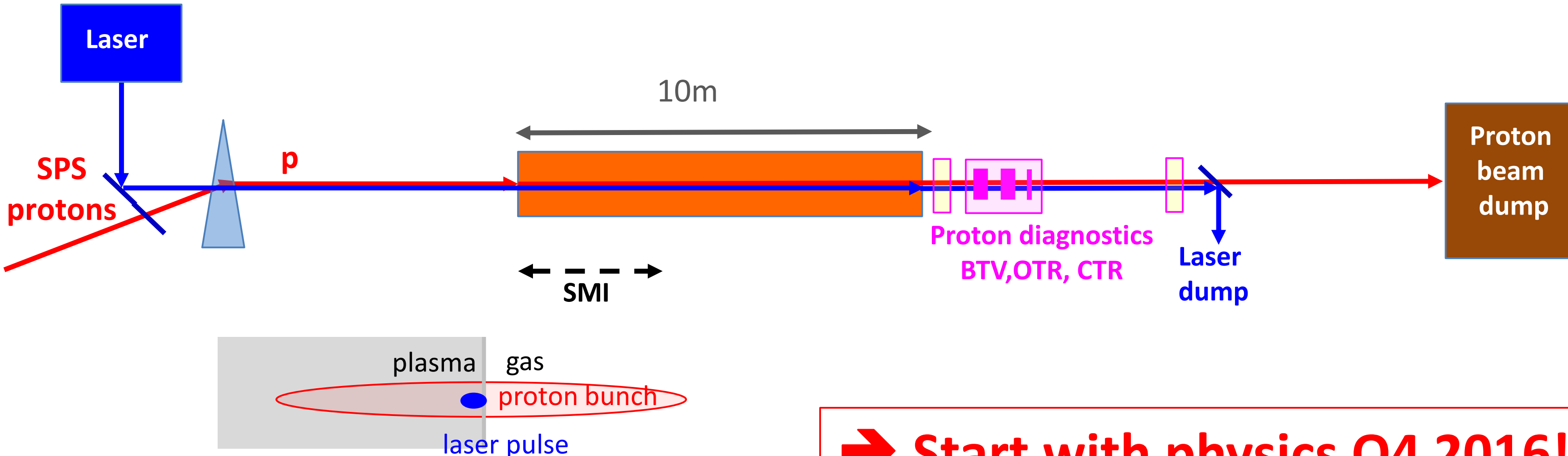
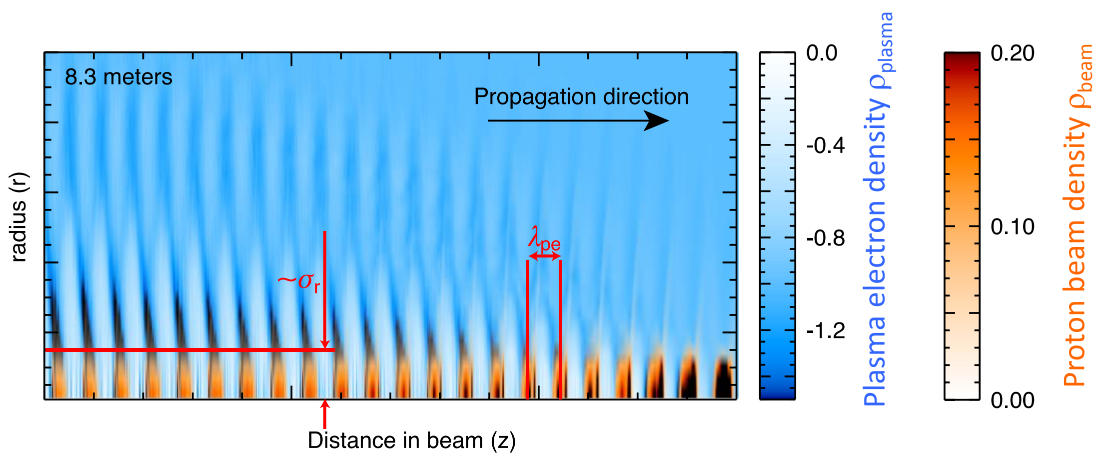


➔ Start with physics Q4 2016!

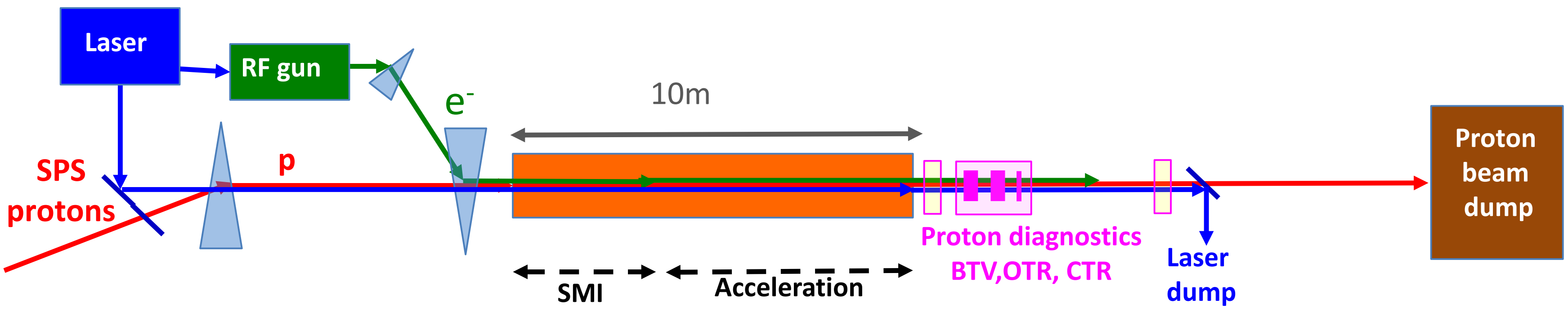
Self-modulated proton bunch resonantly driving plasma wakefields.



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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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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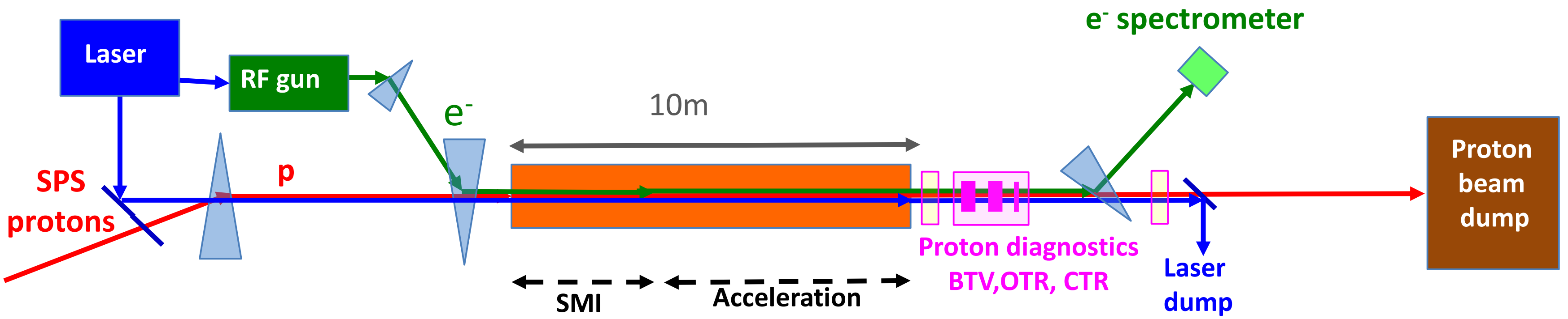

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Electron spectrometer system

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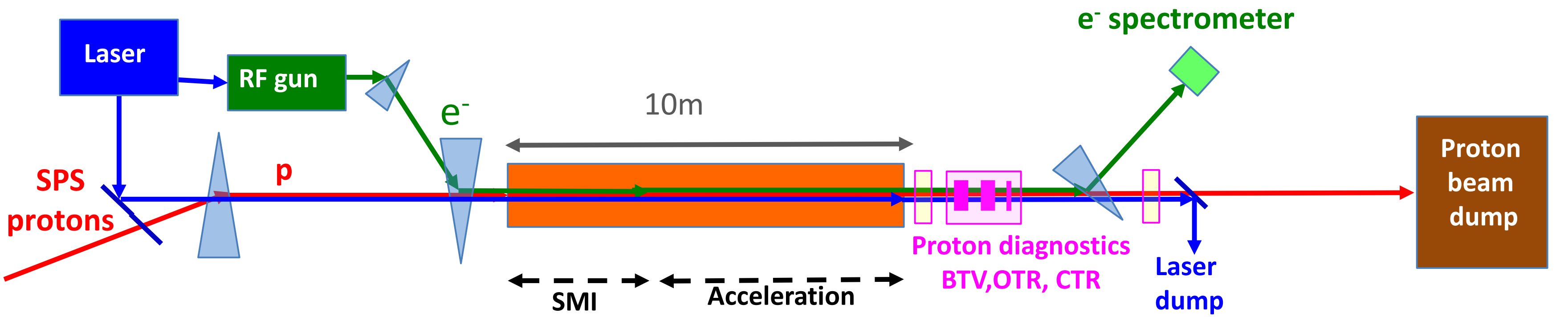

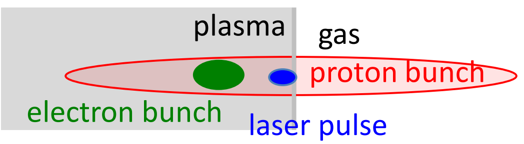

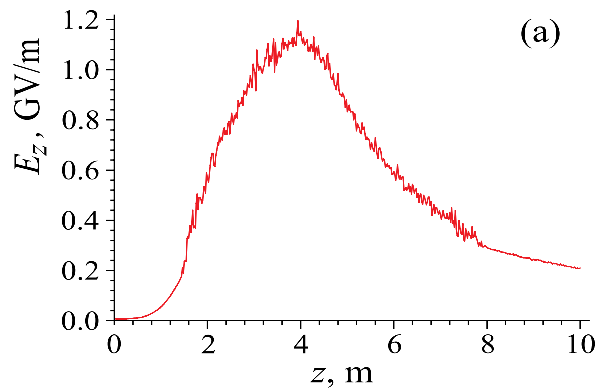

Maximum amplitude of the **accelerating field E_z** as a function of position along the plasma. Saturation of the SMI at ~4m.

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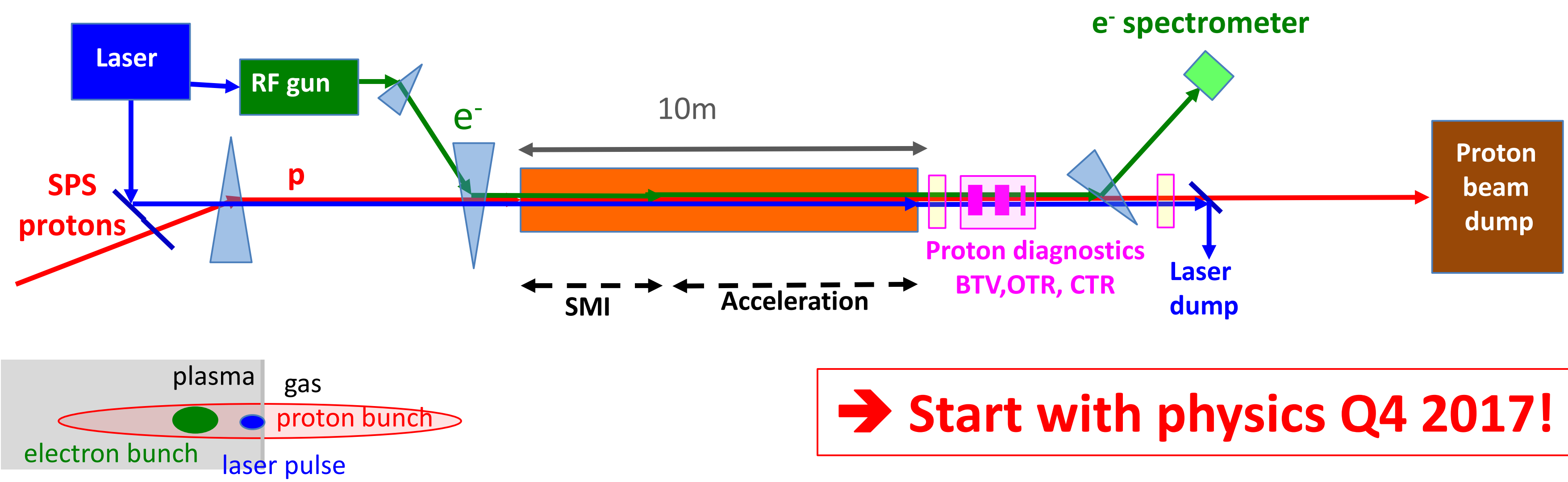
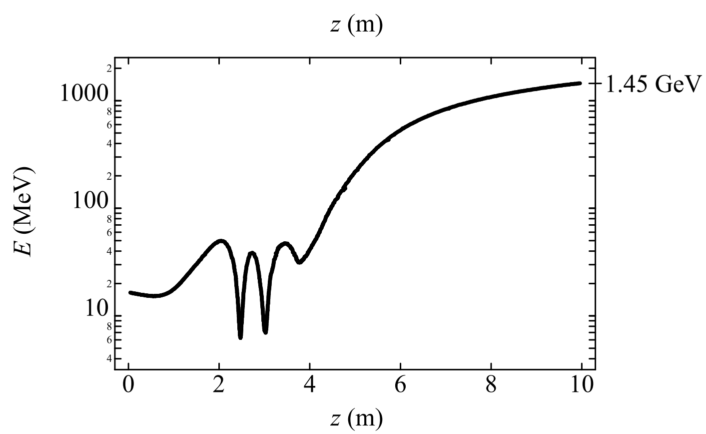


➔ Start with physics Q4 2017!



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

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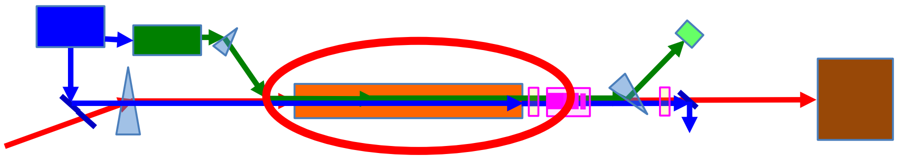
Plasma Source: Rubidium Vapor Source



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

- Plasma formed by field ionization of Rb
  - Ionization potential Φ_{Rb} = 4.177eV
  - above intensity threshold (I_{ioniz} = 1.7 x 10^{12}W/cm^2) 100% is ionized.

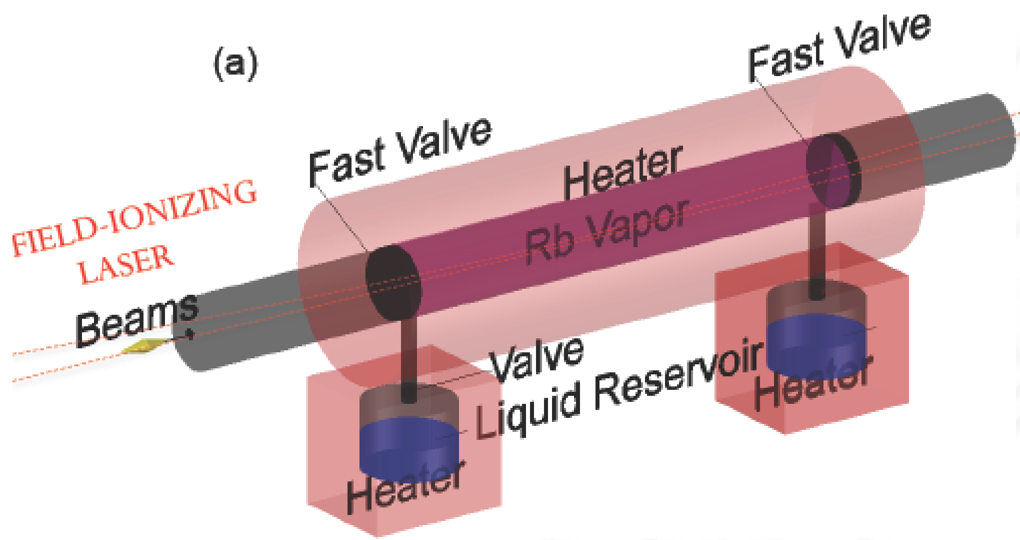
- Plasma density = vapor density

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

Required:

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

(a)



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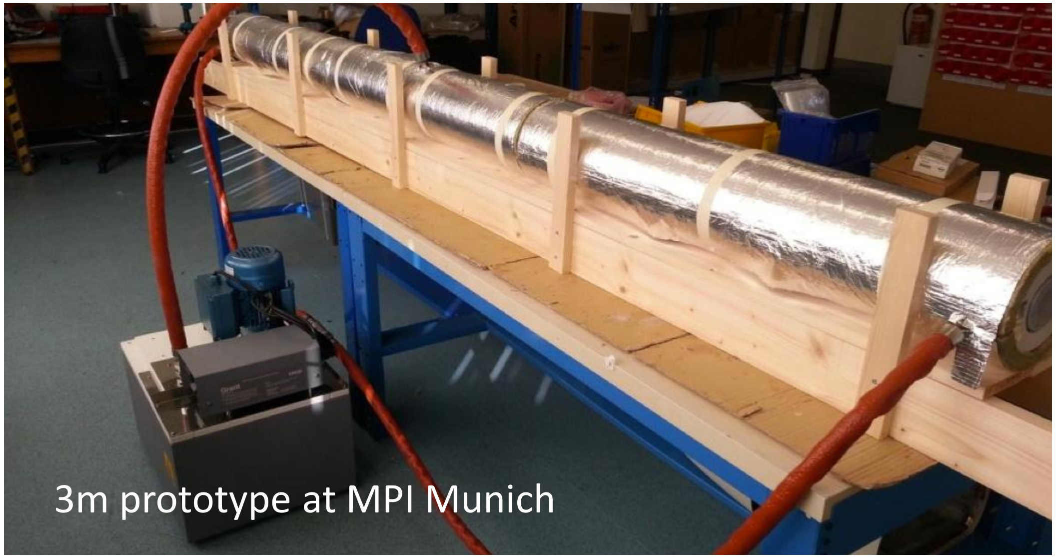
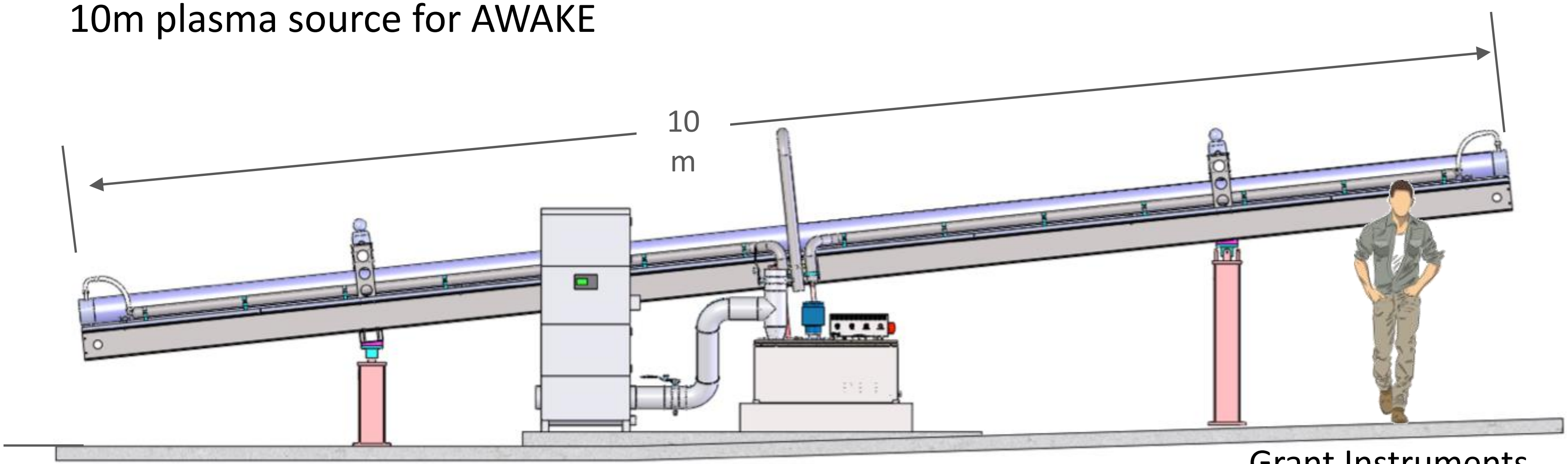


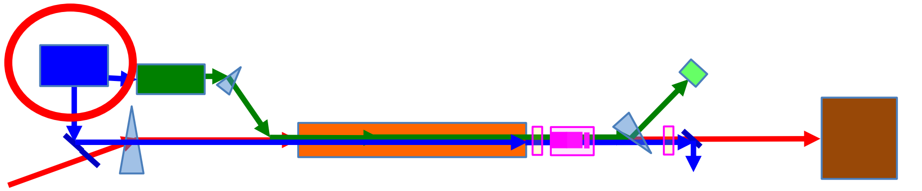
10m plasma source for AWAKE

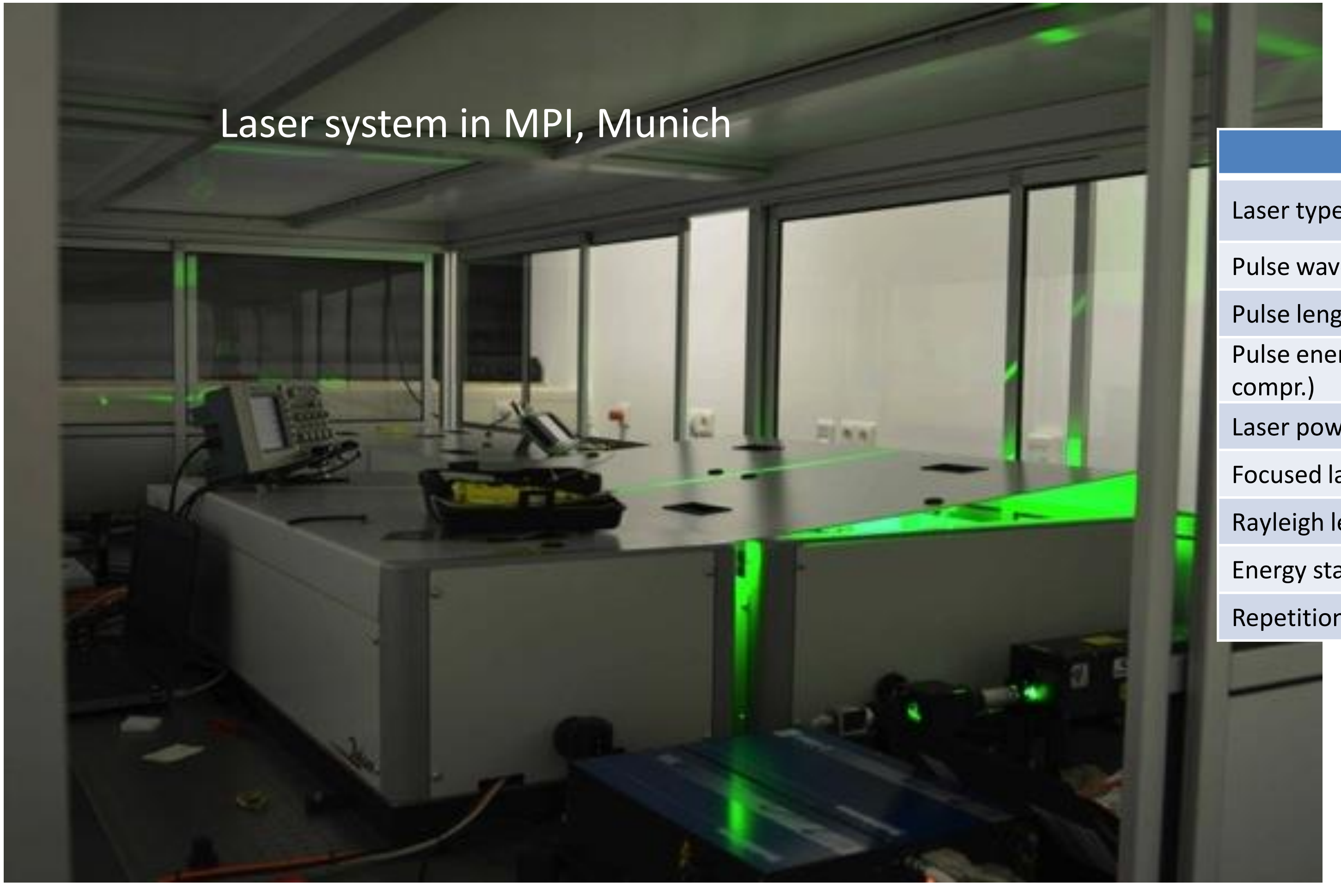


Grant Instruments

Laser

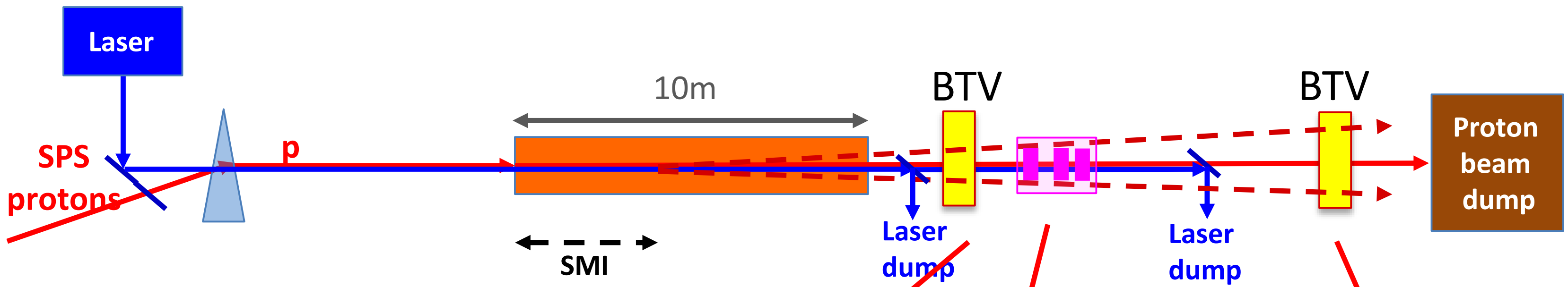
- Laser intensity must exceed ionization intensity at the plasma end (L=10m) over a plasma radius of r > 3σ = 600 μm.



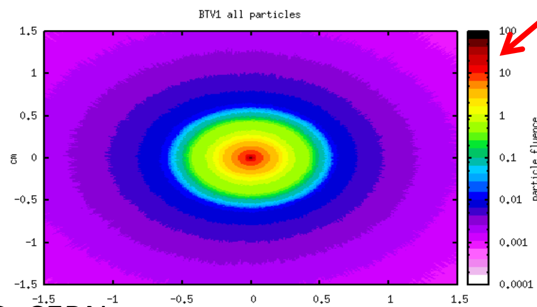


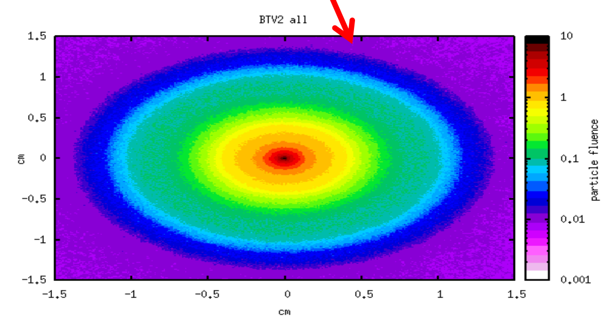
Laser Beam	
Laser type	Fiber Ti:Sapphire
Pulse wavelength	λ_0 = 780 nm
Pulse length	100-120 fs
Pulse energy (after compr.)	**450 mJ**
Laser power	**4.5 TW**
Focused laser size	**$\sigma_{x,y}$ = 1 mm**
Rayleigh length Z_R	5 m
Energy stability	±1.5% r.m.s.
Repetition rate	10 Hz

Phase 1: Proton Drive Beam Diagnostics



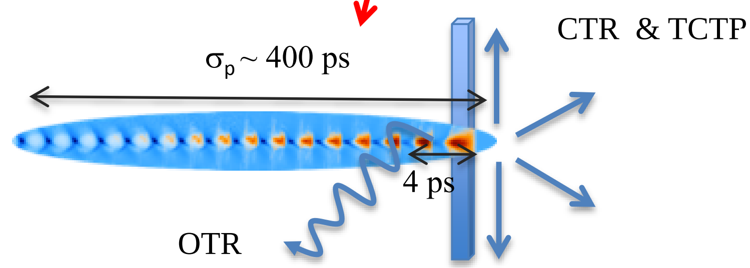
Indirect SMI Measurement:
Defocusing of the proton beam

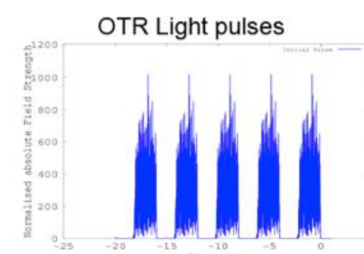




M. Turner, A. Petrenko, E.G, CERN

Direct SMI Measurement:
Radiation emitted by bunch when traversing dielectric material
→ Streak camera



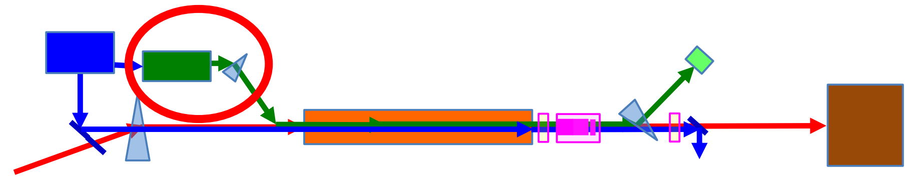


K. Rieger, P. Muggli, MPI

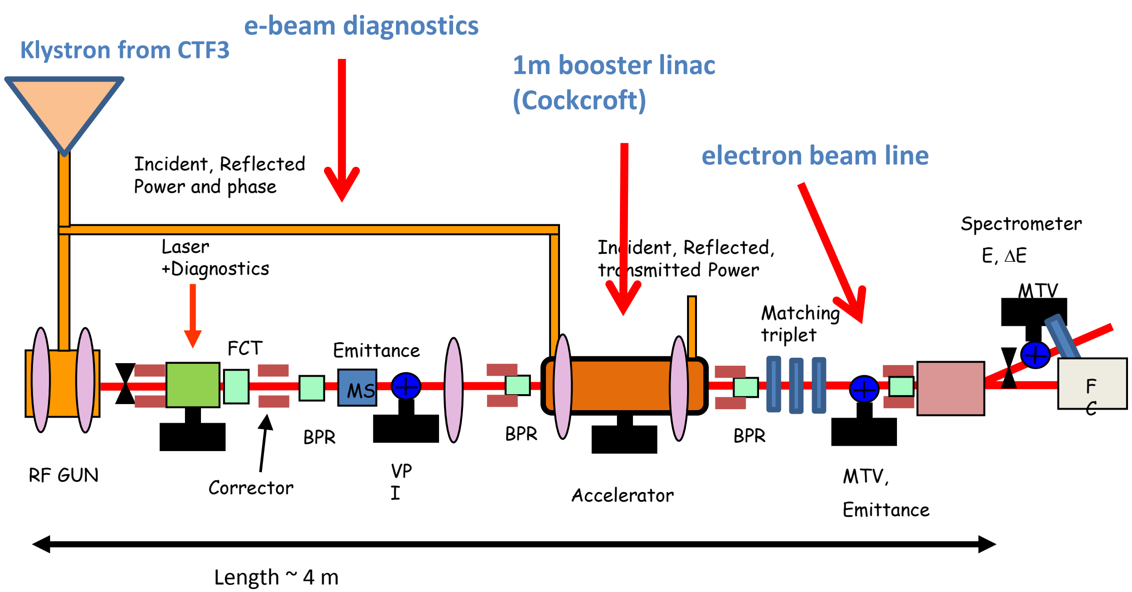
Phase 2: Electron Witness Beam – Electron Source

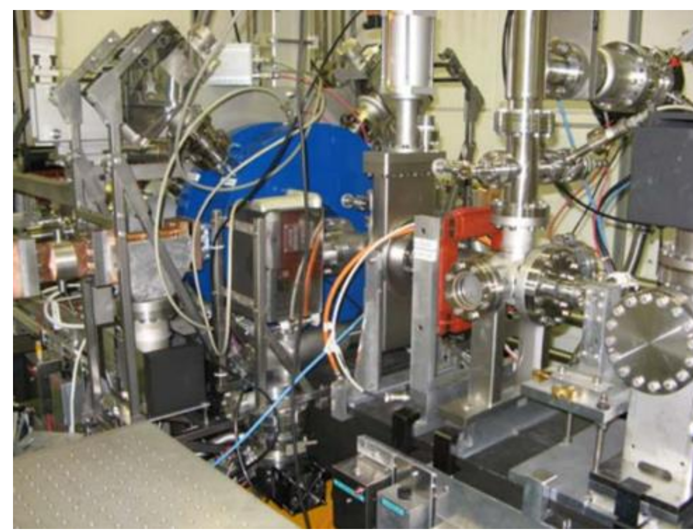
PHIN Photo-injector for CTF3/CLIC:

→ **Program will stop end 2015**

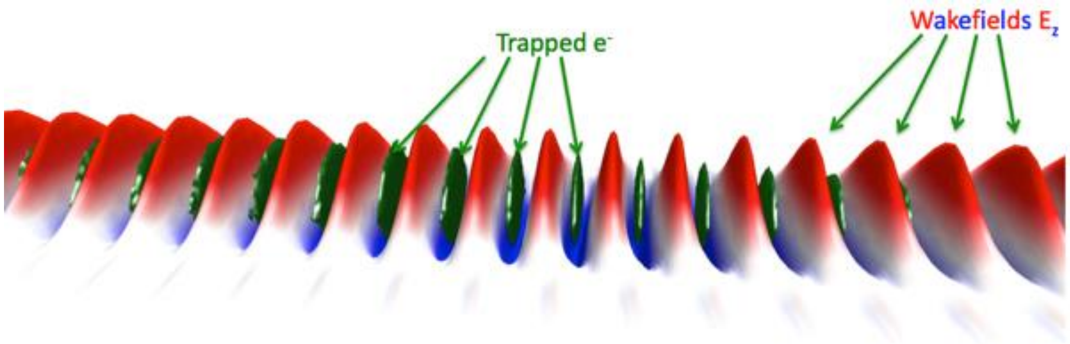


→ Fits to requirements ➔ used as electron beam source for AWAKE



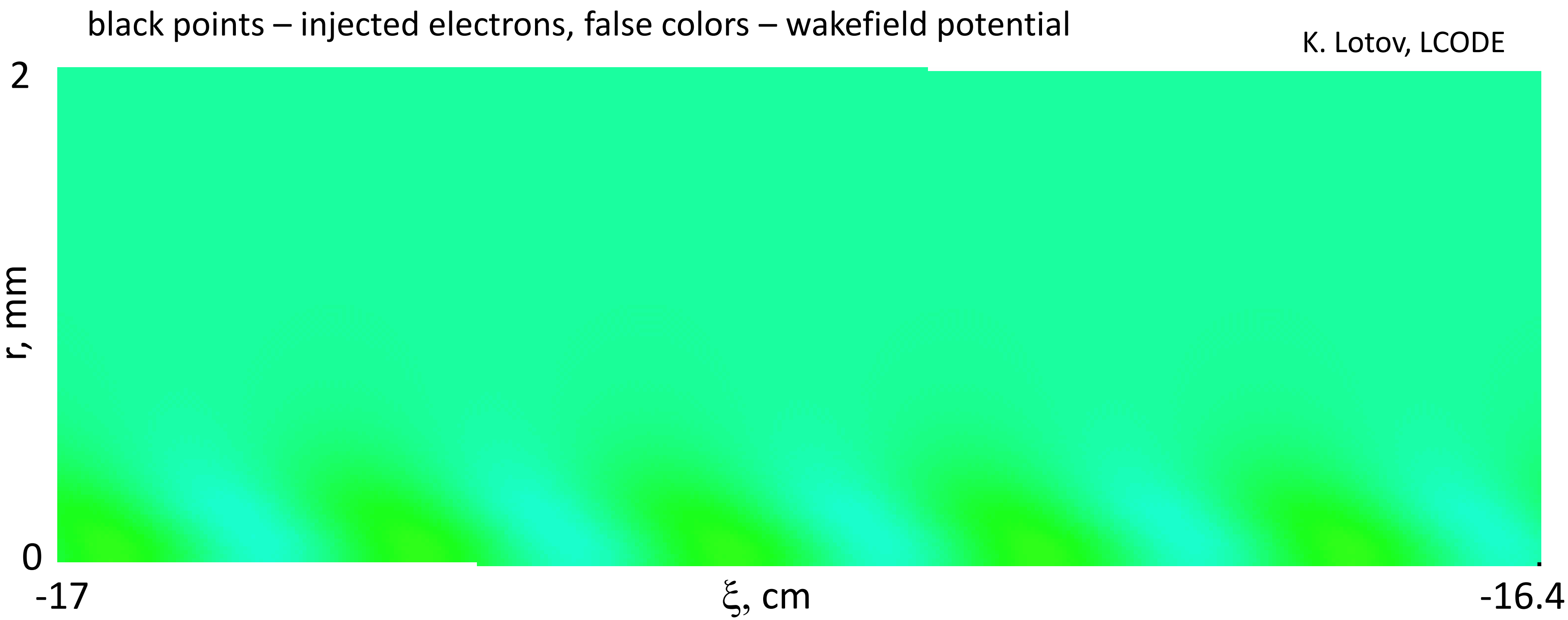


Phase 2: Electron Witness Beam



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	$\Delta p/p$ = 0.5%	<0.5%

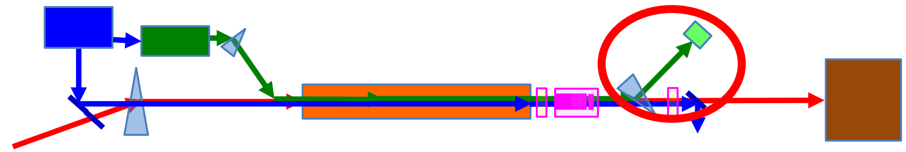
Electron Beam Trapping and Acceleration in the Plasma Wakefield



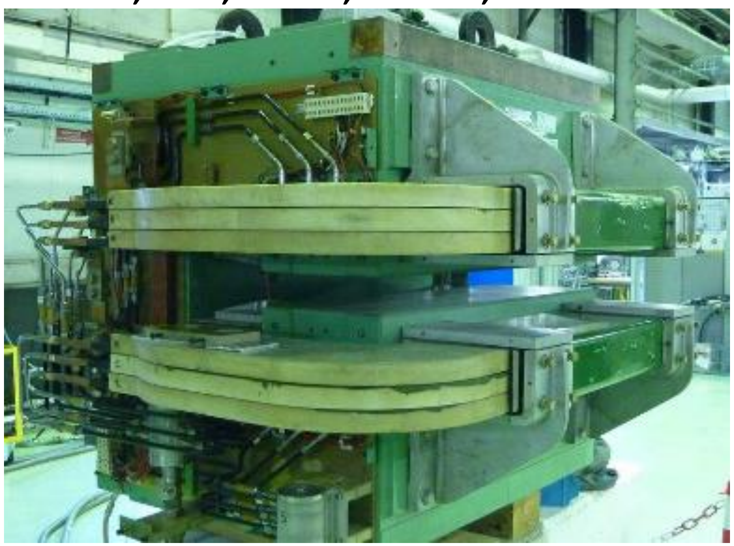
- Electrons are trapped from the very beginning by the wakefield
- Trapped electrons make several synchrotron oscillations in their potential wells
- After z=4 m the wakefield moves forward in the light velocity frame

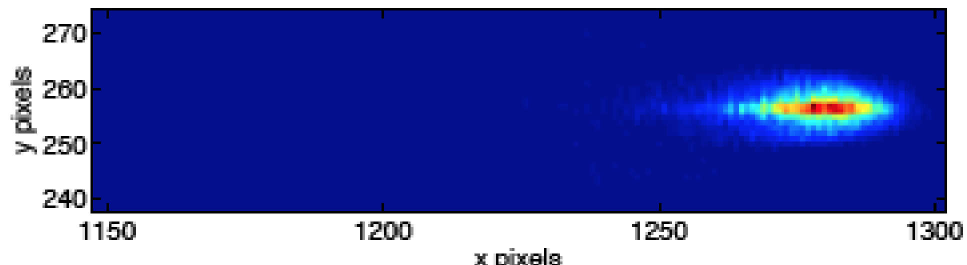
Phase 2: Electron Witness Beam Acceleration Diagnostics

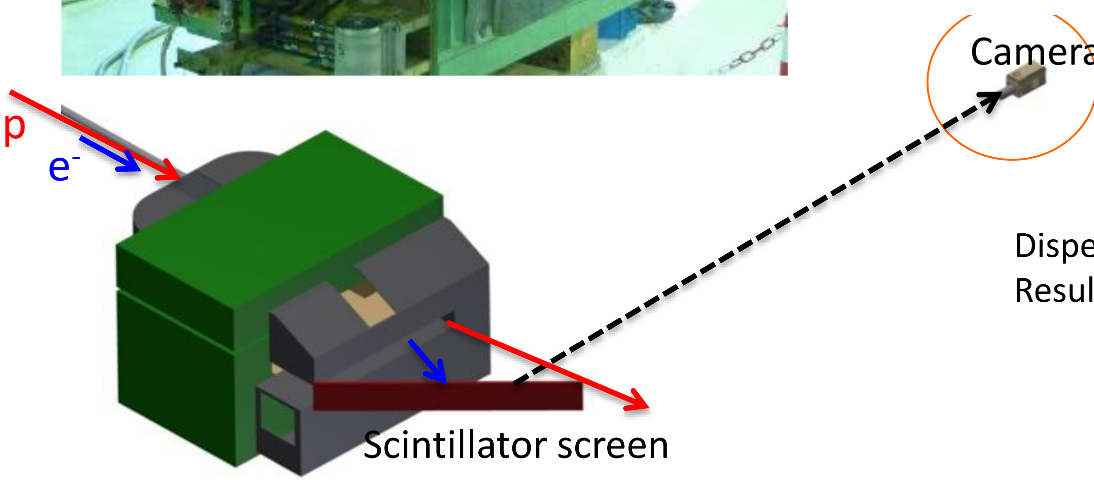
Probe the accelerating wakefields with externally injected electrons → Electron spectrometer



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.

Outline

- Motivation
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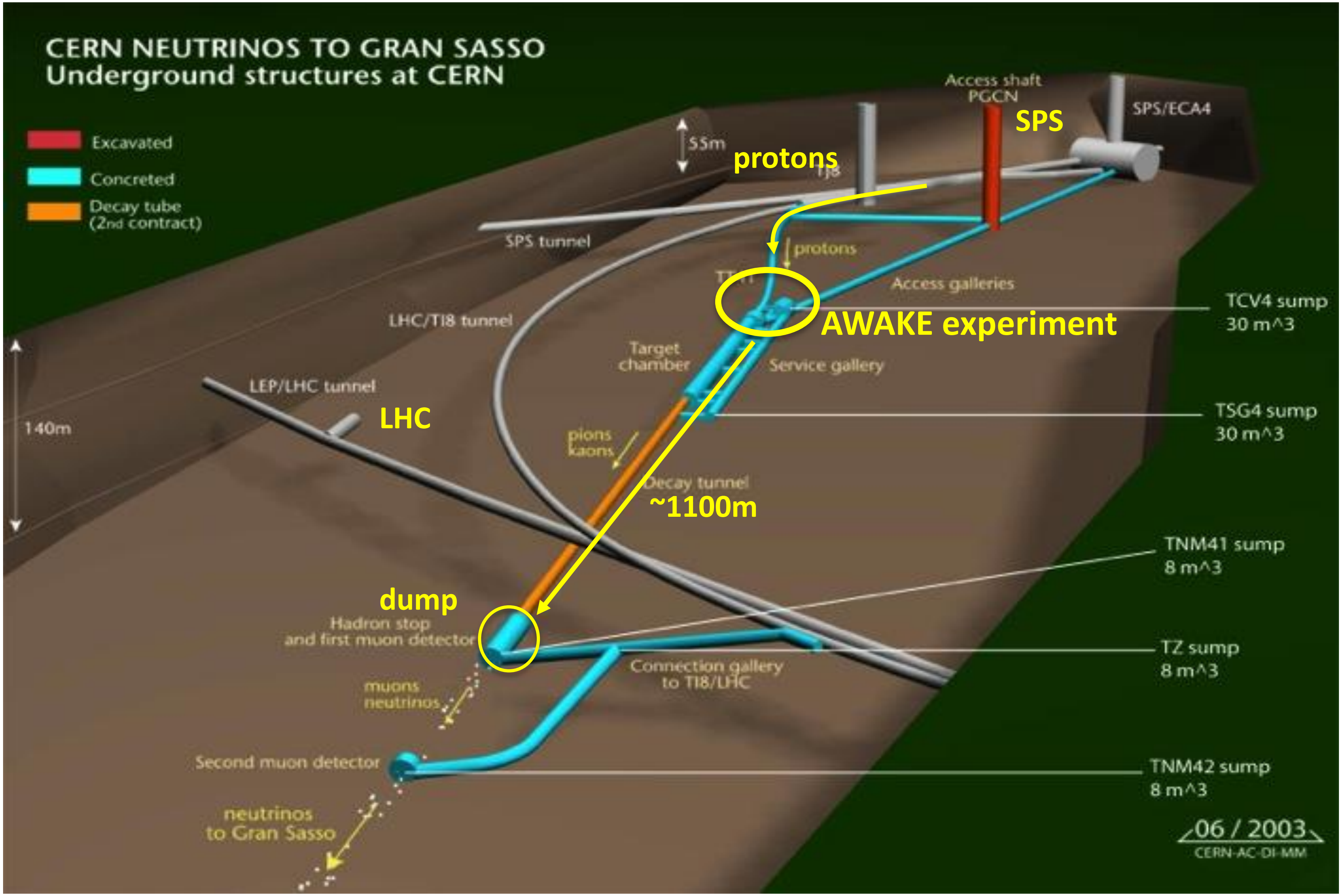
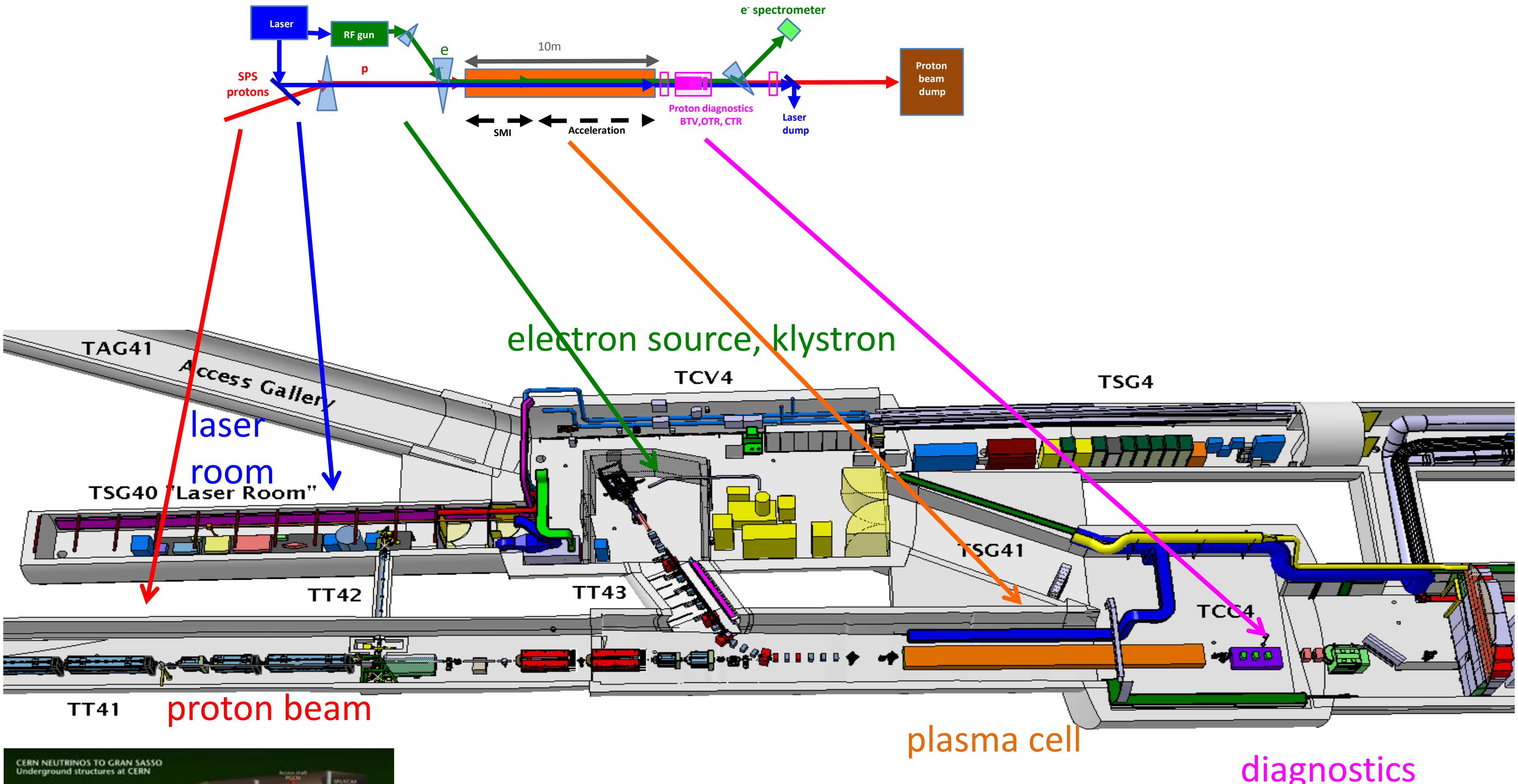
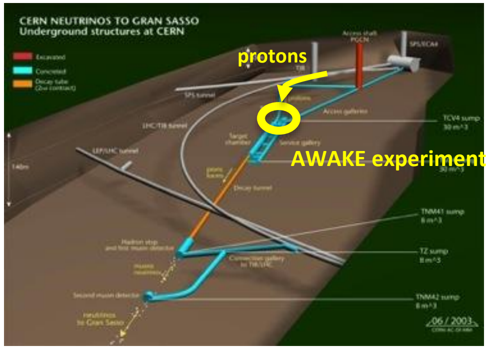
- Components of the AWAKE Experiment
- Installation of the AWAKE Facility
- Summary

AWAKE Installation

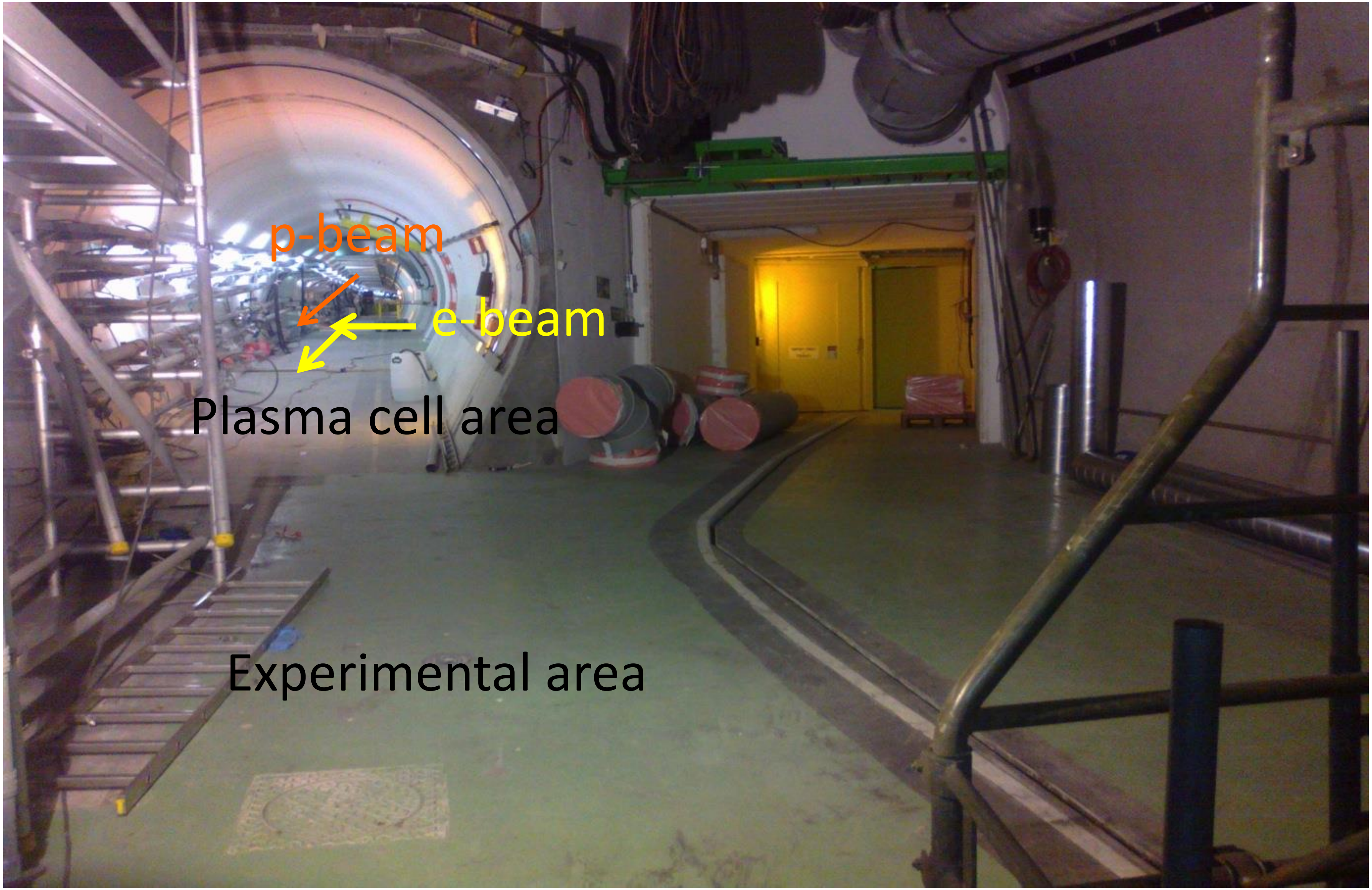


AWAKE Experimental Facility

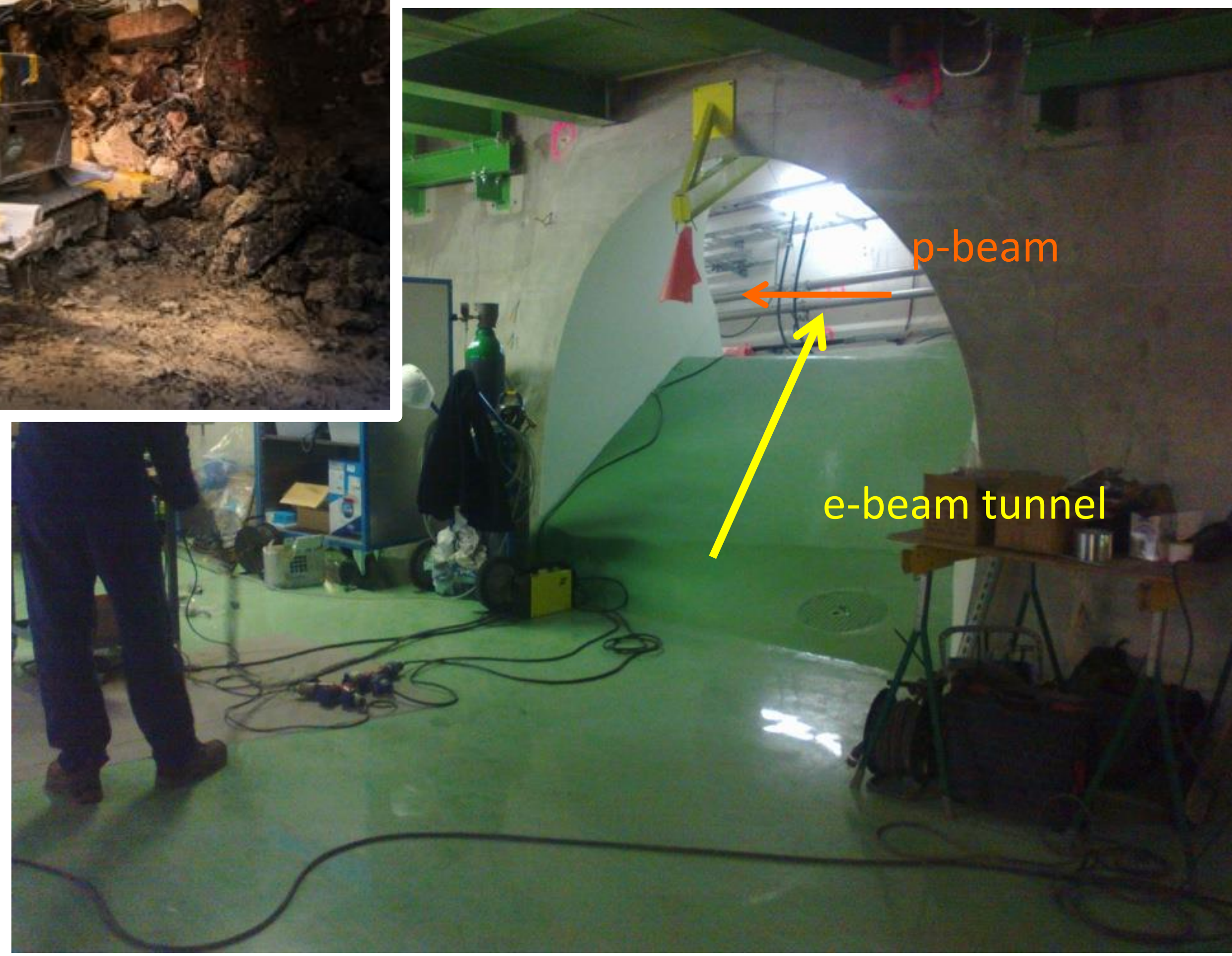




AWAKE Facility Preparation



AWAKE Facility Preparation



Proton Beam Line

Proton beam line from SPS extraction to ~80 m upstream the AWAKE facility.

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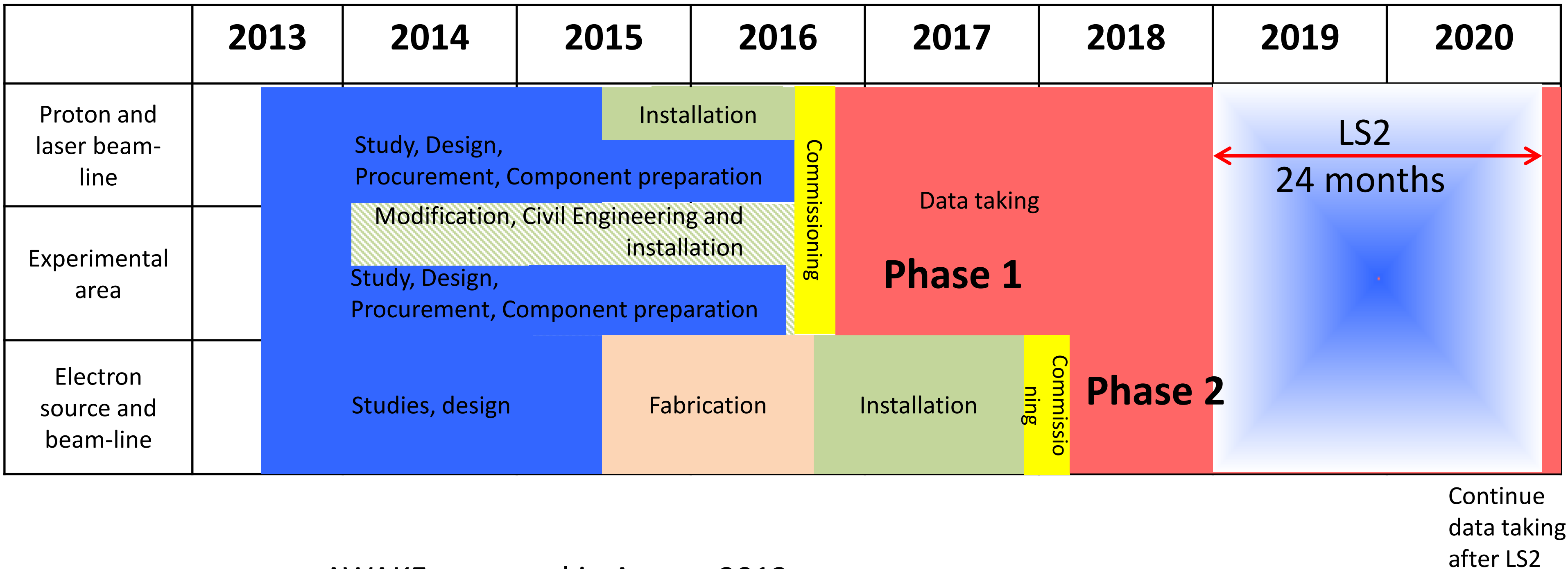
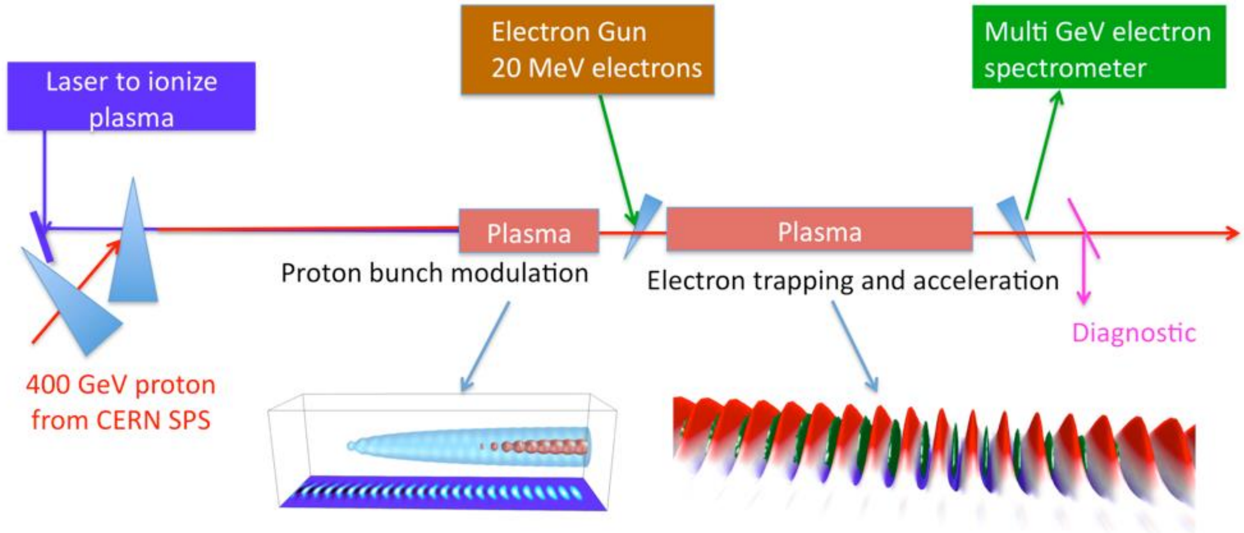
AWAKE Time Line

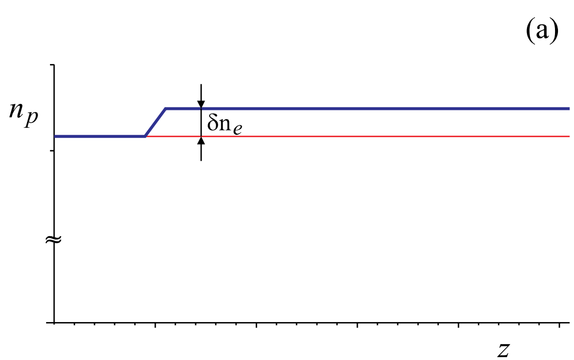


- AWAKE approved in August 2013
- **1st Phase:** First proton and laser beam in 2016
- **2nd Phase:** first electron beam in 2017+
- Physics program for 3 – 4 years

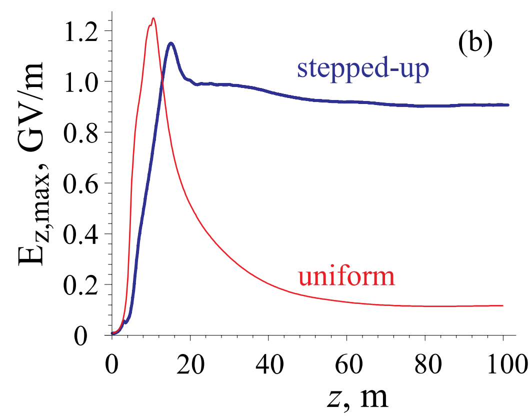
Next Steps (Phase 3)



- **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



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.
  - Strong motivation of the community: long-term prospects for proton-driven PWA exiting
    - Provide a design for a particle physics frontier machine by 2022
    - Needs extensive experimental program NOW, results with electrons, …

- 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)
  - **Reach higher gradients, develop long scalable and uniform plasma** cells, production of **shorter electron and proton bunches** (2020)