Starting Up the AWAKE Experiment at CERN

Edda Gschwendtner, CERN
For the AWAKE Collaboration

IPAC17, Copenhagen, Denmark, 14-19 May 2017

TUOBB2

Outline

- Introduction
- The AWAKE Experiment
- Commissioning of AWAKE
- First Beam Results
- Electron Acceleration Status
- What's Next
- Summary

Proton Drivers for Plasma Wakefield Acceleration

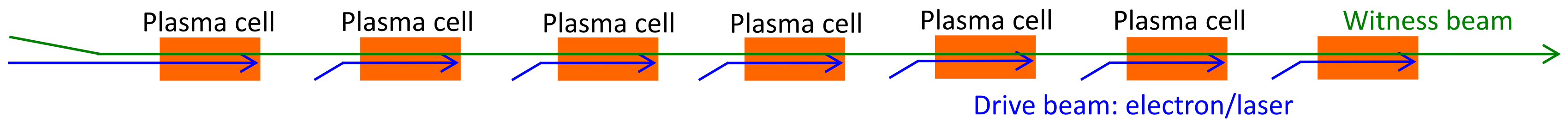
Proton bunches as drivers of plasma wakefields are interesting because of the very large energy content of the proton bunches.

Drive beams:
Lasers: ~40 J/pulse
Electron drive beam: 30 J/bunch
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

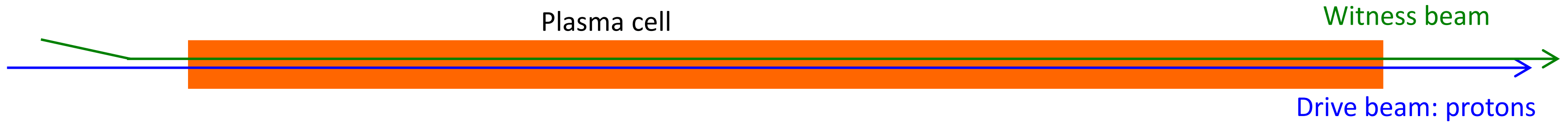
Witness beams:
Electrons: 10^{10} particles @ 1 TeV ~few kJ

To reach TeV scale:

- Electron/laser driven PWA: need several stages, and challenging wrt to relative timing, tolerances, matching, etc…
  - effective gradient reduced because of long sections between accelerating elements….



- **Proton drivers**: large energy content in proton bunches → allows to consider single stage acceleration



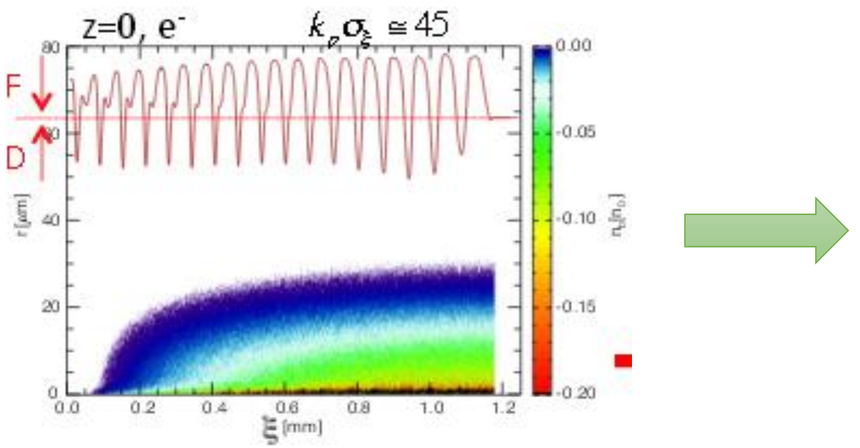
Self-Modulation Instability

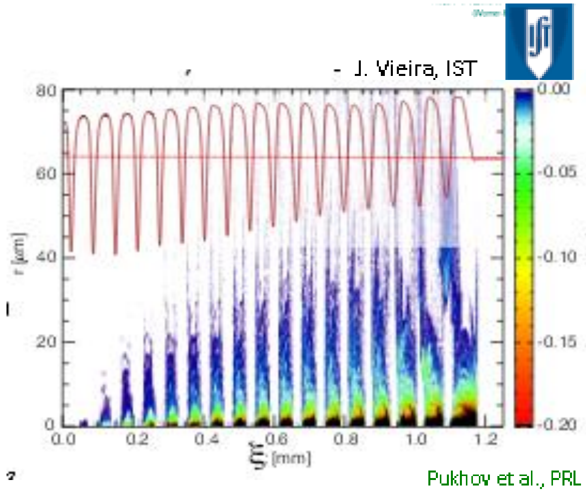
– In order to create plasma wakefields efficiently, the drive bunch length has to be in the order of the plasma wavelength.
– **CERN SPS proton bunch: very long!**
– Longitudinal beam size (**σ_z = 12 cm**) is much longer than plasma wavelength **(λ = 1mm**)

N. Kumar, A. Pukhov, K. Lotov, PRL 104, 255003 (2010)

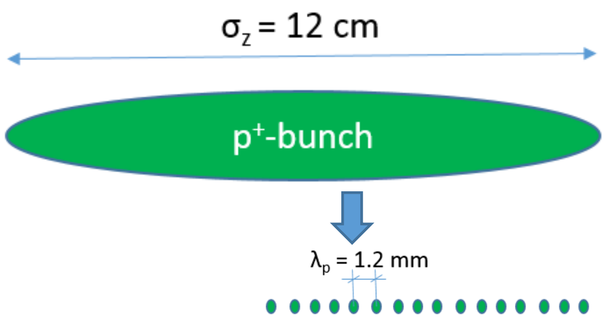
Self-Modulation Instability

– 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
  → **Resonantly drives the longitudinal wakefield**





Pukhov et al., PRL 107, 145003 (2011)
Schroeder et al., PRL 107, 145002 (2011)



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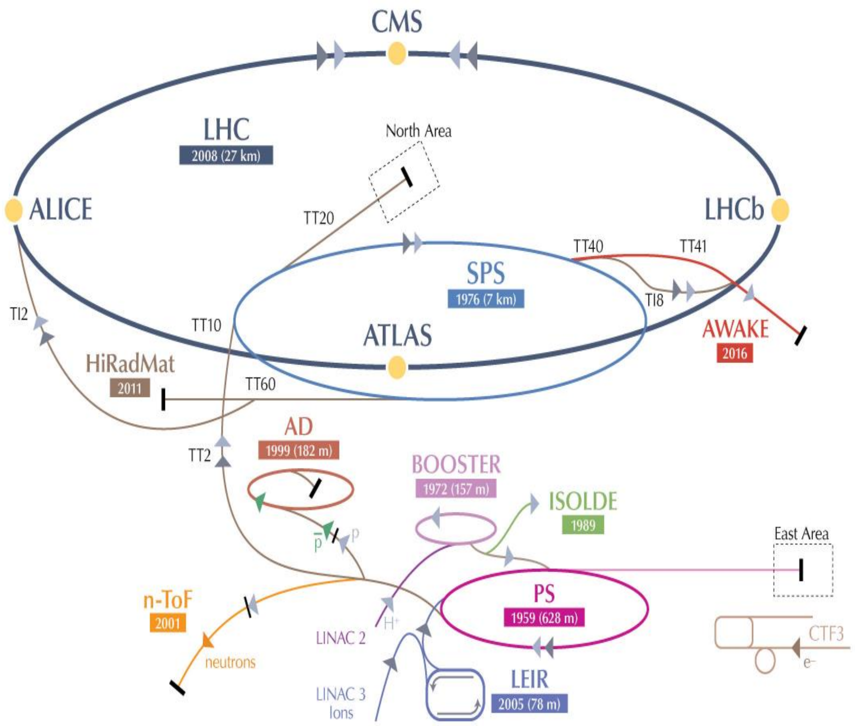
AWAKE at CERN



Advanced Proton Driven Plasma Wakefield Acceleration Experiment

- Proof-of-Principle Accelerator R&D experiment at CERN
- Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.
- AWAKE Collaboration: 16 institutes + 3 associate

- Approved in August 2013
- First beam end 2016

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022/23/24
Proton and laser beam-line	Study, Design, Procurement, Component preparation		Installation	Commissioning	Data taking RUN 1 Phase 1		Long Shutdown 2 24 months		Data taking RUN 2	
Experimental area	Study, Design, Procurement, Component preparation	Modification, Civil Engineering and installation		Commissioning						
e^- source and beam-line	Studies, design		Fabrication	Installation	Commissioning	Phase 2				

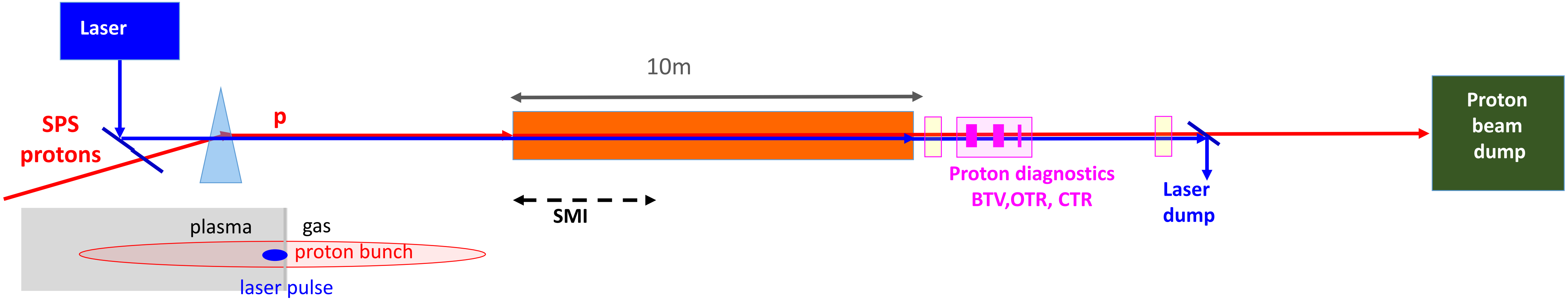
Run 1 – until LS2 of the LHC.

After LS2 – proposing Run 2 of AWAKE (during Run 3 of LHC)

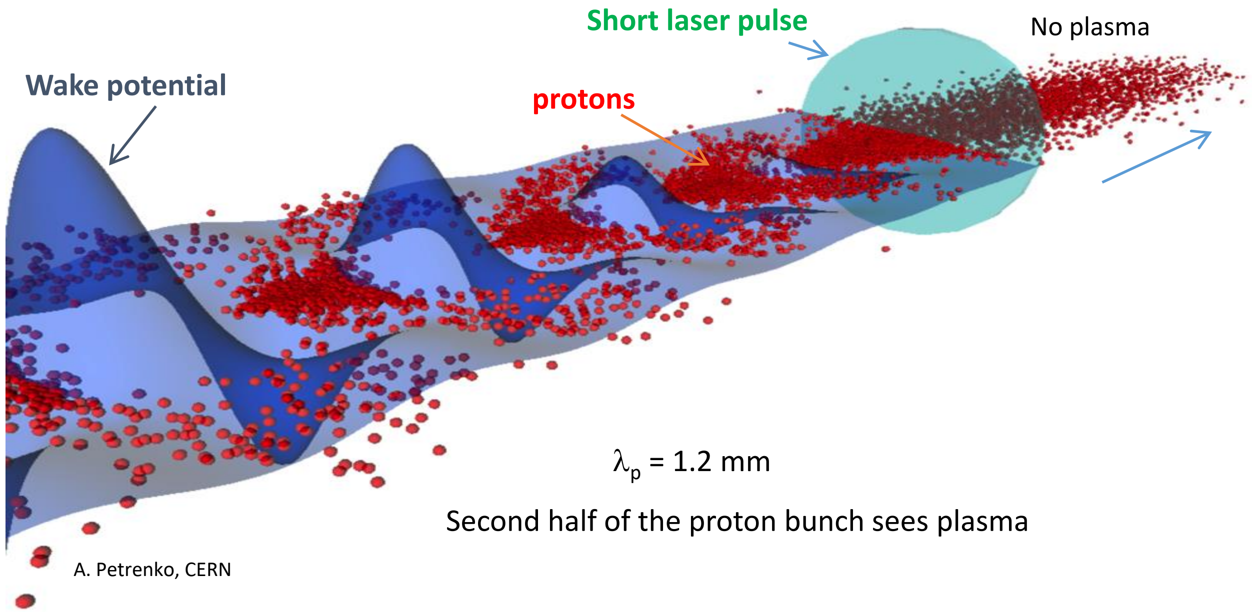
After Run 2 – kick off particle physics driven applications

AWAKE Experimental Program Run 1, 2016/17

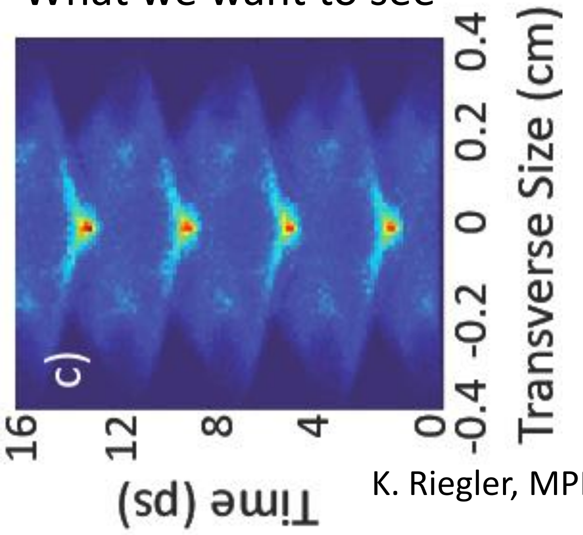
Phase 1: Understand **the physics of self-modulation instability** processes in plasma.



Self-modulated proton bunch resonantly driving plasma wakefields.



What we want to see

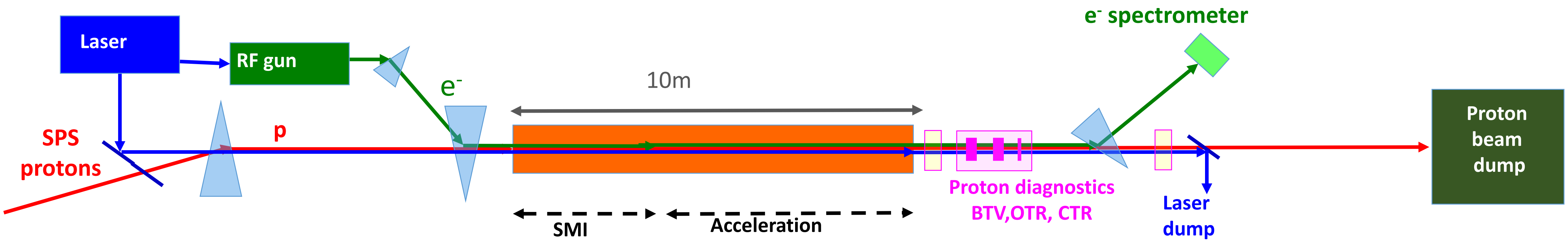


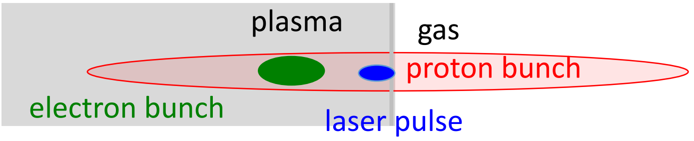
K. Riegler, MPP

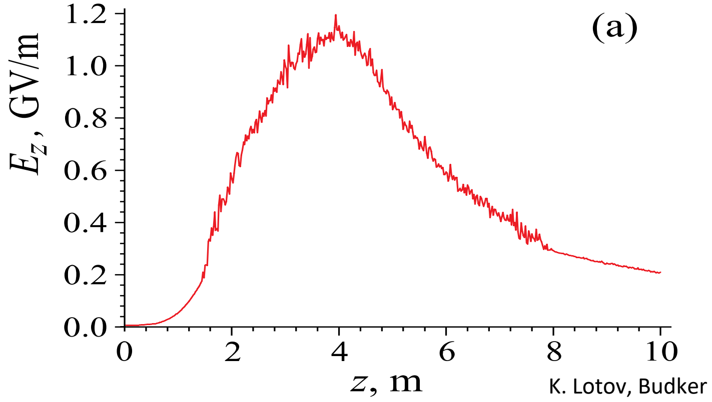
AWAKE Experimental Program Run 1, 2017/18

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

Phase 2: **Probe the accelerating wakefields** with externally injected electrons.



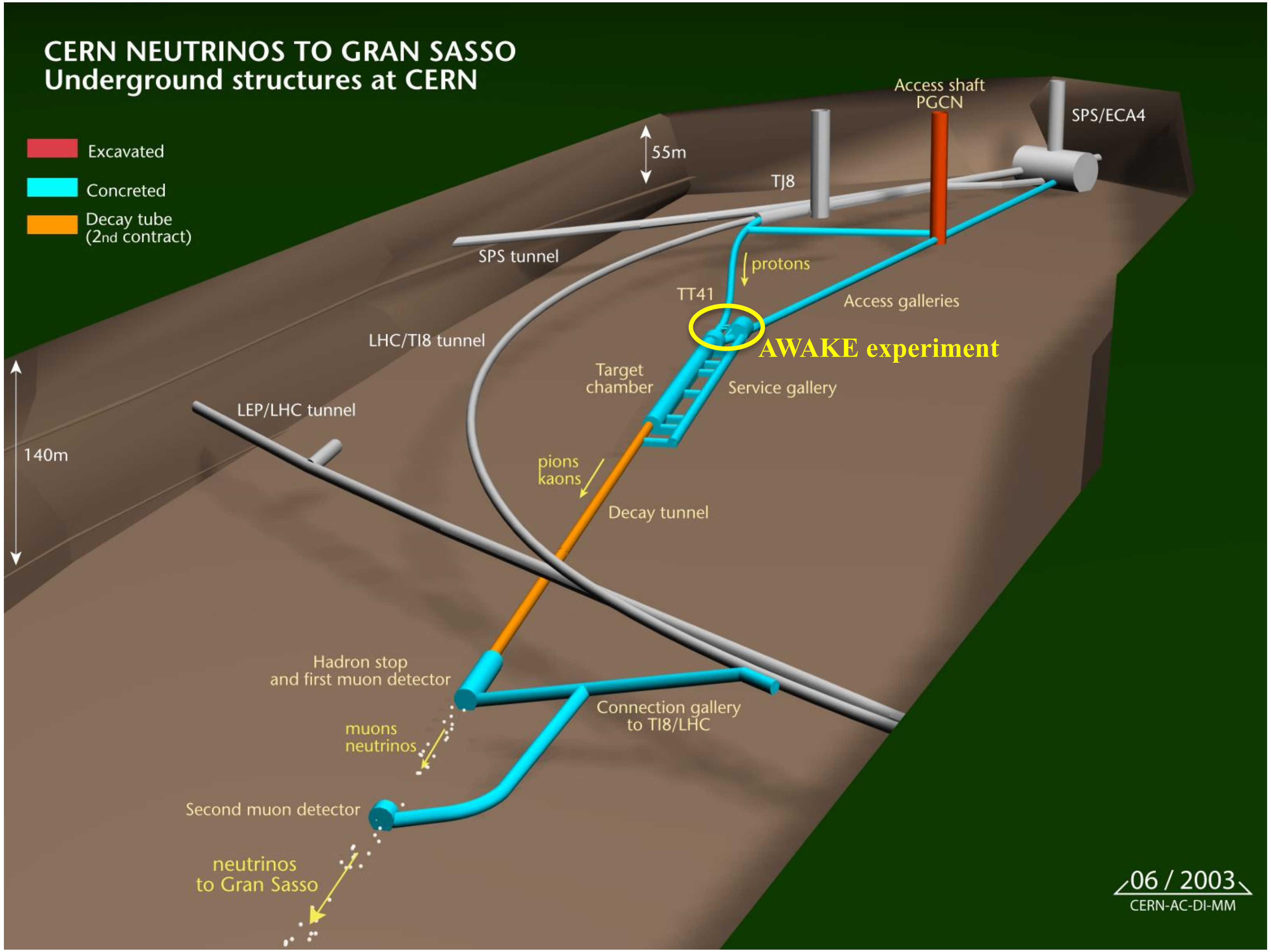




$\mathbf{E_{z,max}}$ along the plasma.
Saturation of SMI at ~4m.

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

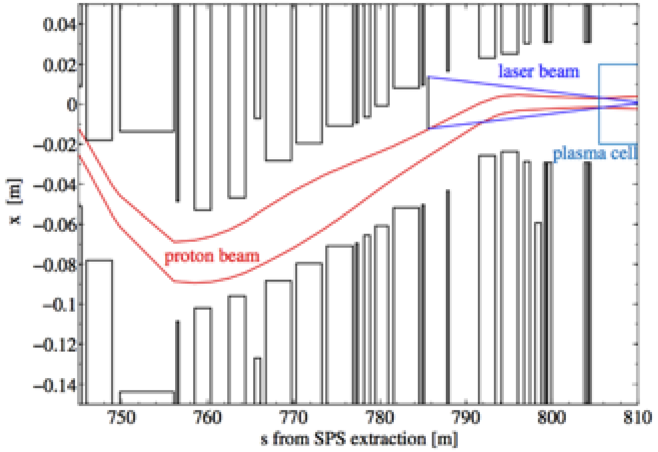
The AWAKE Facility

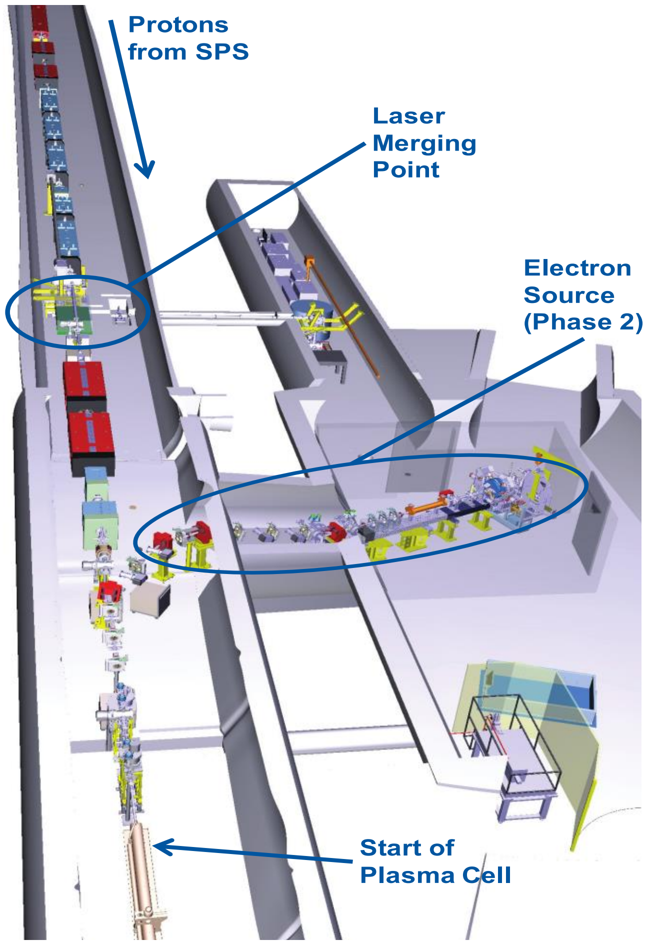


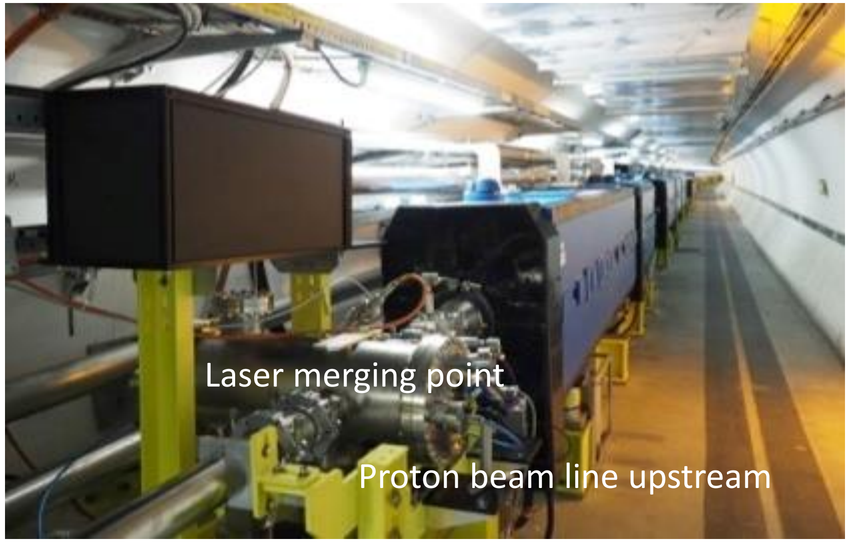
AWAKE Proton Beam Line

Parameter	Protons
Momentum [MeV/c]	400 000
Momentum spread [%]	±0.035
Particles per bunch	$3 \cdot 10^{11}$
Charge per bunch [nC]	48
Bunch length [mm]	120 (0.4 ns)
Norm. emittance [mm·mrad]	3.5
Repetition rate [Hz]	0.033
1σ spot size at focal point [μm]	200 ±20
β-function at focal point [m]	5
Dispersion at focal point [m]	0

Change of the proton beam line in the **downstream part (~80m)**
→ e.g. create a chicane for the laser merging integration







Laser and Laser Line

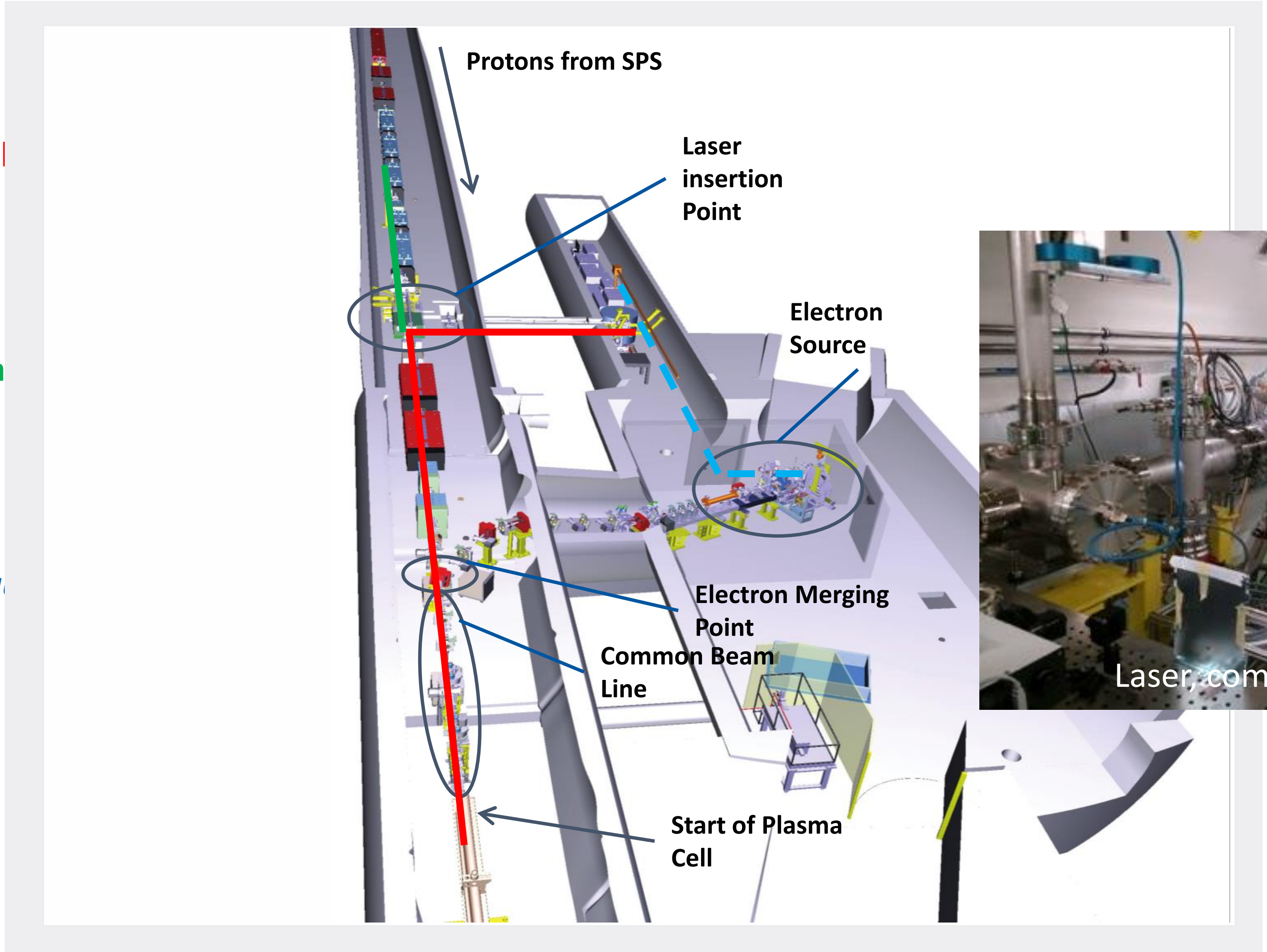
- Laser beam line to plasma cel
  - λ = 780 nm
  - t pulse = 100-120 fs
  - E = 450 mJ
- Diagnostic beam line (“virtua
  - λ = 780 nm
  - t pulse = 100-120 fs,
  - E ≈ 5 mJ
- *Laser beam line to electron g*
  2017)
  - *λ = 260 nm*
  - *t pulse = 0.3-10 ps*
  - *E = 0.5 mJ*

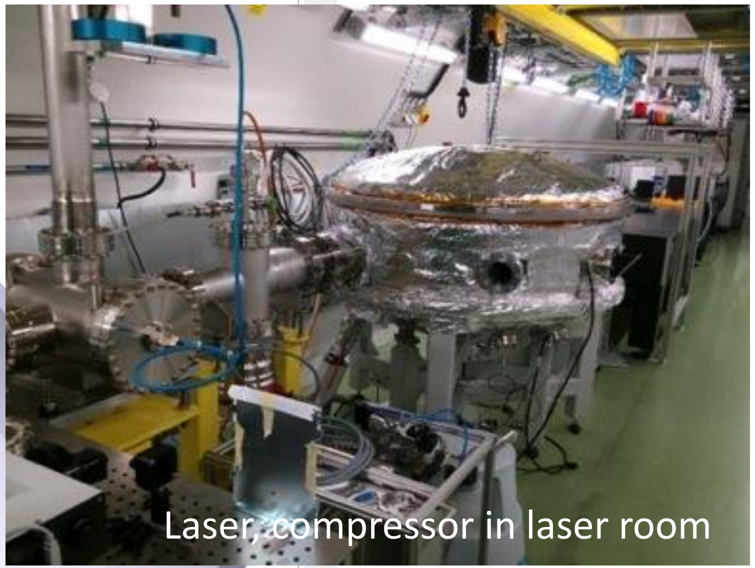
Requirements

This installation requires Adobe Acrobat Reader 7.0 or Adobe Acrobat 7.0

You must install one of these products before installation of the plug-in. Adobe products are able on Adobe web site: www.adobe.com

infos@seemage.com



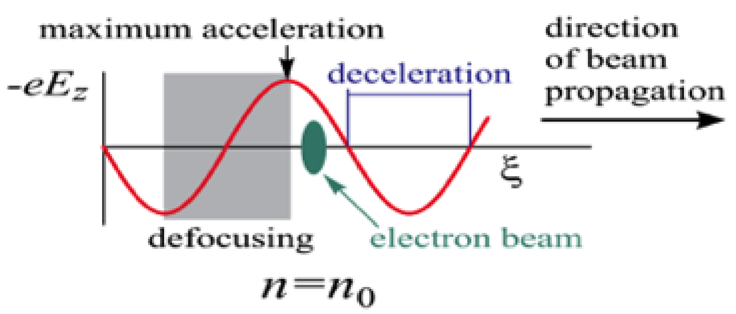


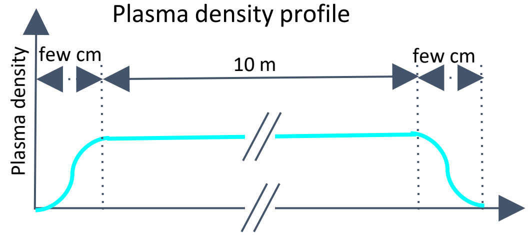
Laser, compressor in laser room

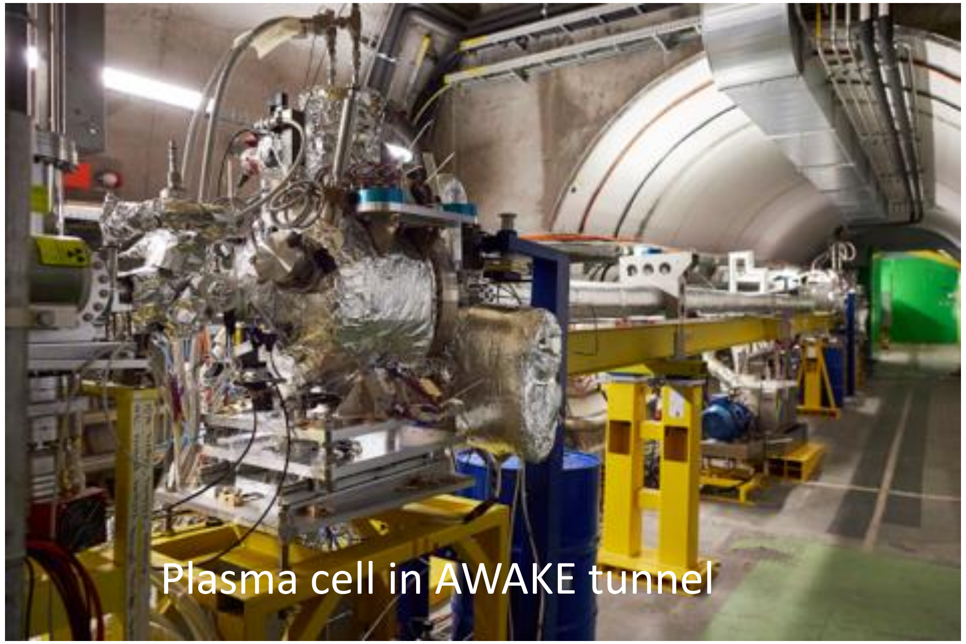
The AWAKE Plasma Cell

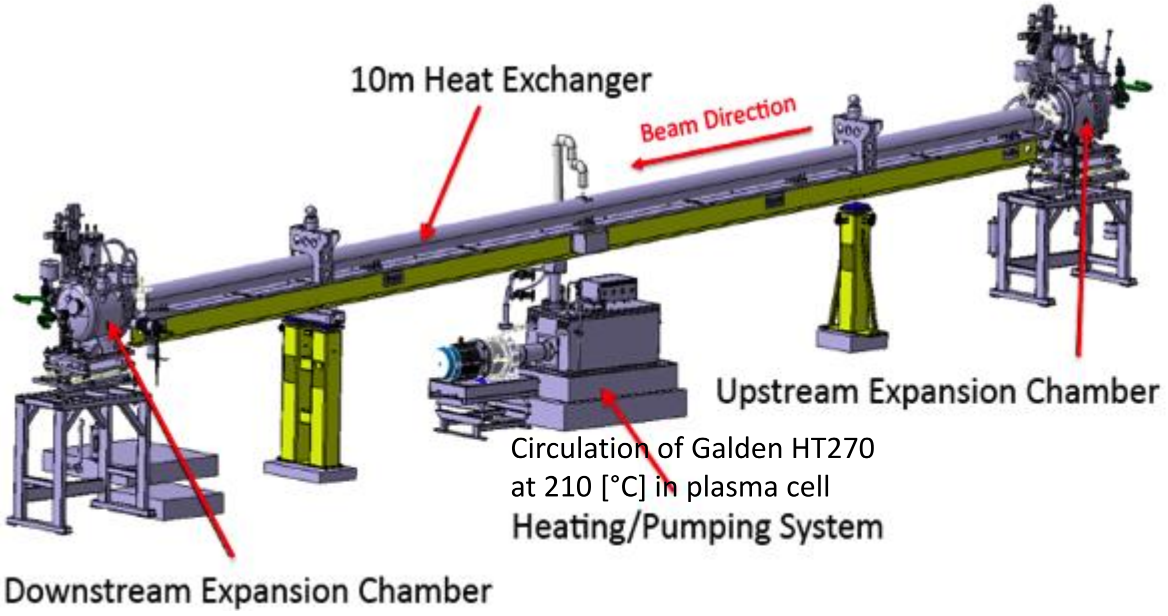
E. Oez, P. Muggli, MPP, Munich

- **10 m long**, 4 cm diameter
- Rubidium vapor, field ionization threshold ~10^{12} W/cm^2
- Density adjustable from 10^{14} – 10^{15} cm^{-3} ➔ **7x 10^{14} cm^{-3}**
- Requirements:
  - **density uniformity better than 0.2%**
    - Fluid-heated system (~220 deg)
    - Complex control system: 79 Temperature probes, valves
  - Transition between plasma and vacuum as sharp as possible

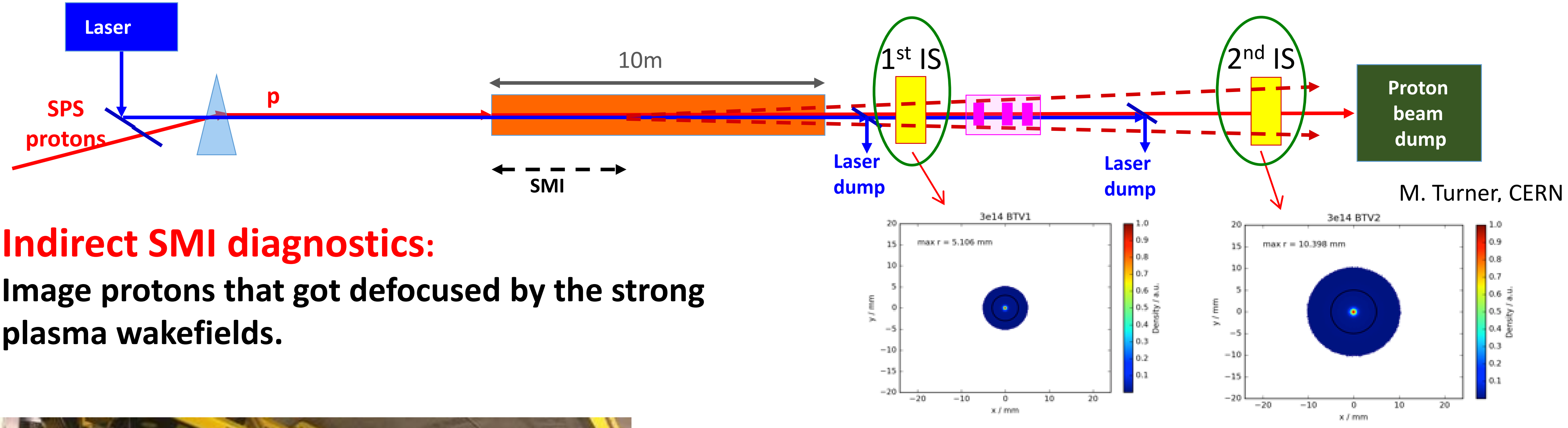






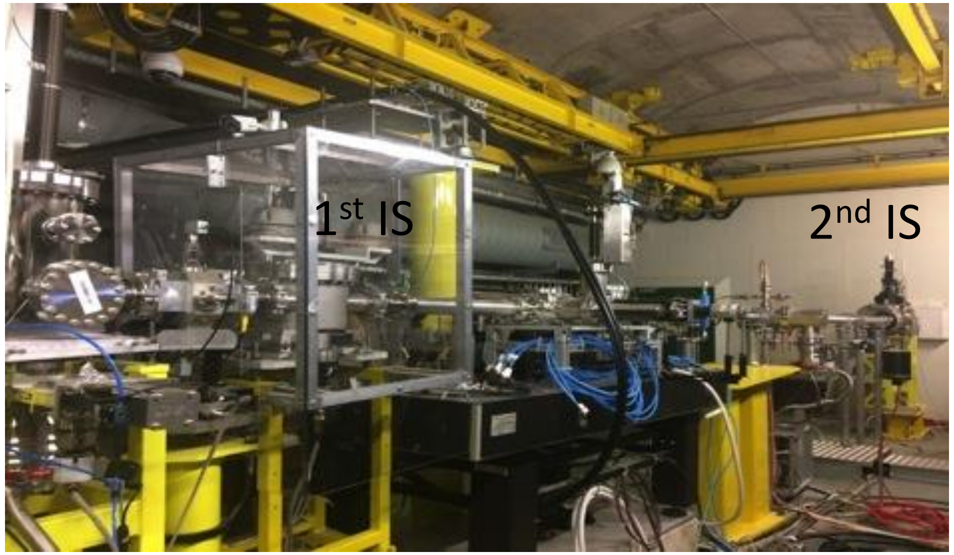


Self-Modulation Instability Diagnostics I



Indirect SMI diagnostics:

Image protons that got defocused by the strong plasma wakefields.

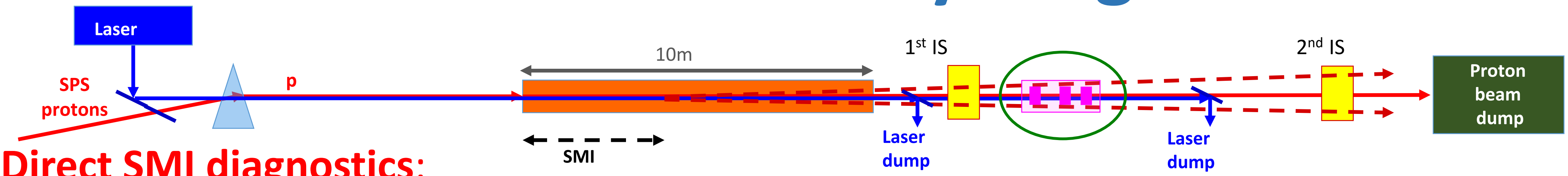


Two imaging stations (IS) to measure the radial proton beam distribution 2 and 10 m downstream the end of the plasma.

→ Compare transverse size of beam with and without plasma.
→ Growth of tails governed by the transverse fields in the plasma.

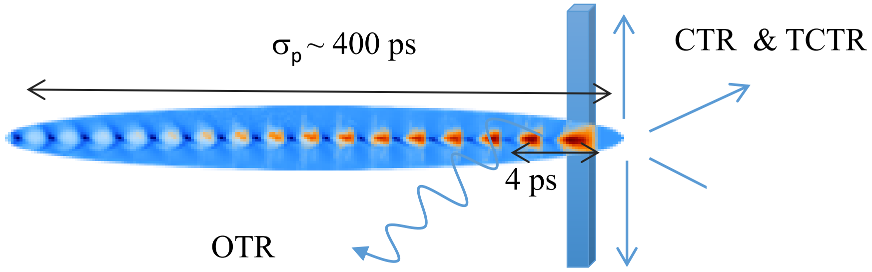
M. Turner, TUPIK001

Self-Modulation Instability Diagnostics II



Direct SMI diagnostics:

Measure frequency of modulation.



OTR: Optical Transition Radiation: Temporal intensity of the OTR carries information on bunch longitudinal structure.

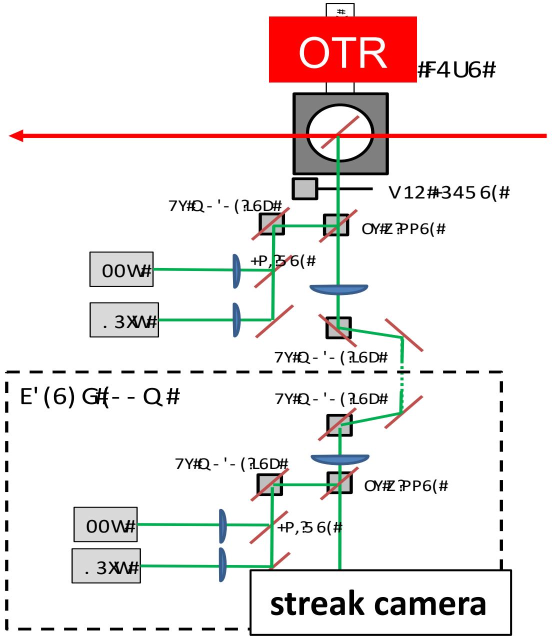
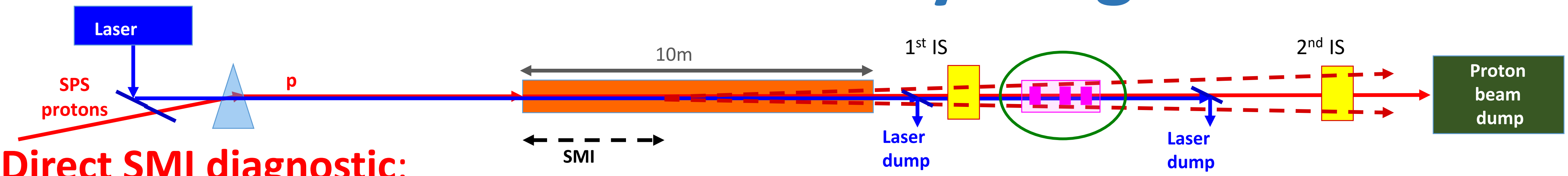


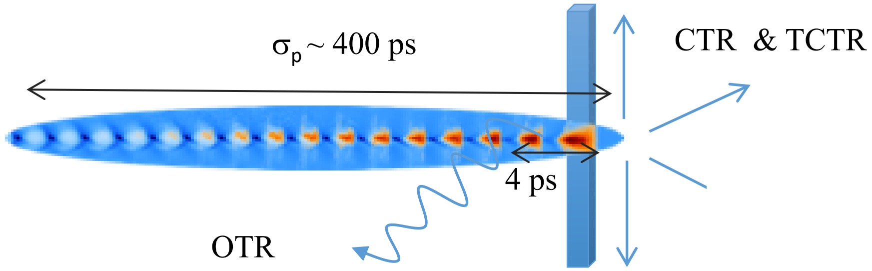
Fig. 18: Schematic of the OTR and CTR setup installed on the proton beam line.

Self-Modulation Instability Diagnostics II



Direct SMI diagnostic:

Measure frequency of modulation.



OTR: Optical Transition Radiation: Temporal intensity of the OTR carries information on bunch longitudinal structure.

CTR: Coherent Transition Radiation: Radiation is coherent for

o-bunches (90-300GHz).

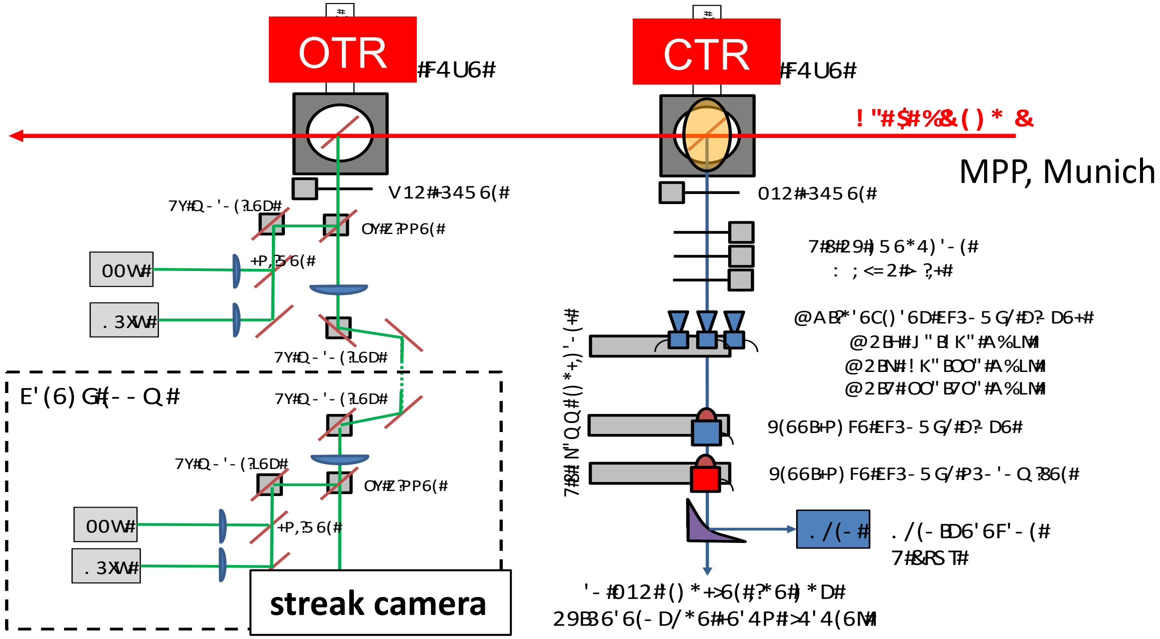


Fig. 18: Schematic of the OTR and CTR setup installed on the proton beam line.

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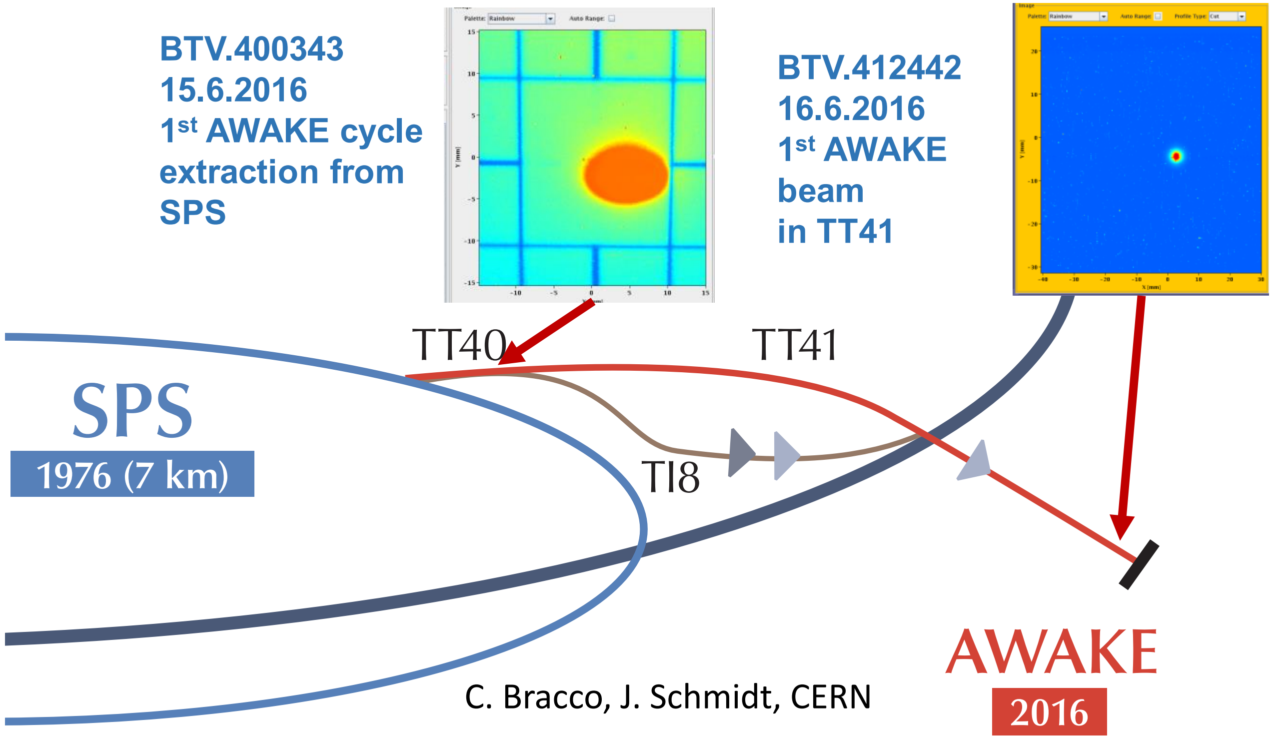
AWAKE Beam Commissioning 2016

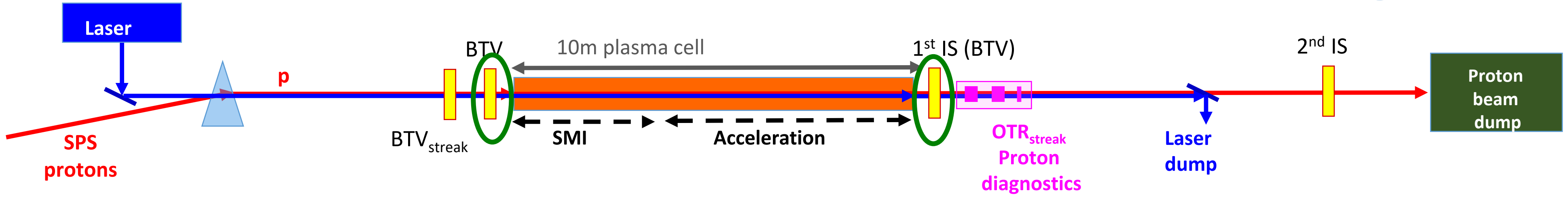
3 periods of commissioning:
June, September, November 2016



Proton beam line **commissioned and running stable** with full intensity and matching specifications

→ Optimized trajectory at experiment: Standard deviation during **stability run of ~60 µm**
→ **Stable beam** at full intensity 3E11 p/bunch
→ **No beam losses** at laser merging mirror

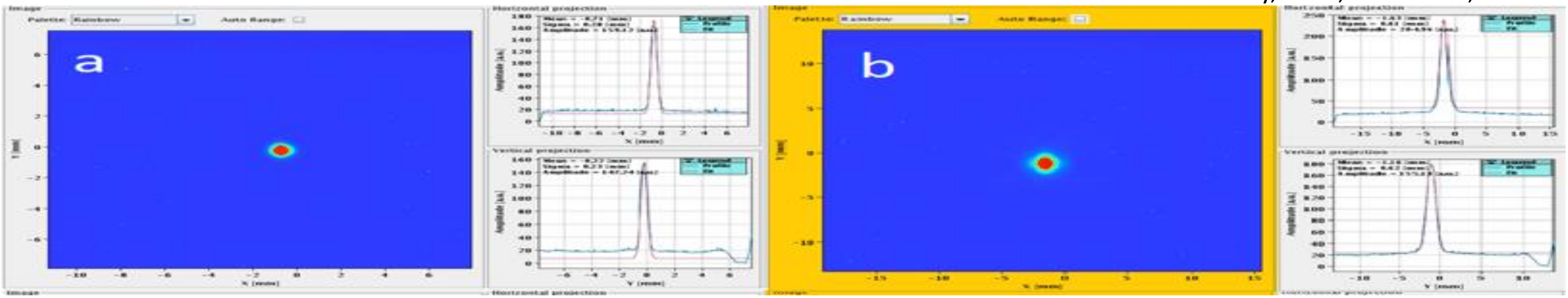
Results Laser Beam Commissioning



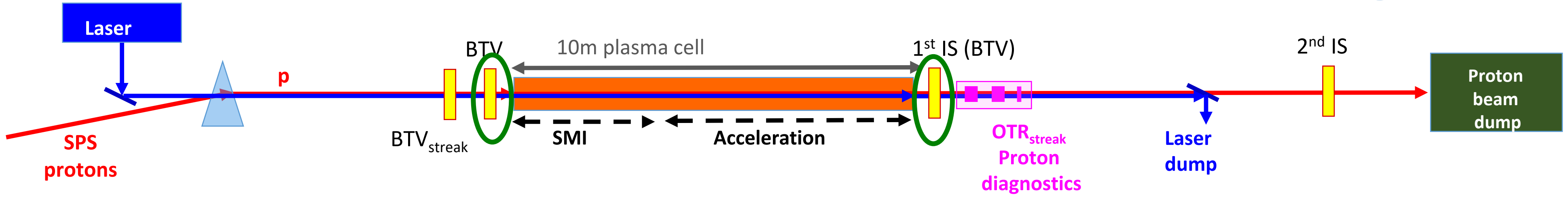
➔ **Transversal alignment** of proton and laser beam (spatial overlap)

J. Moody, MPP; J. Schmidt, CERN

p-beam



Results Laser Beam Commissioning

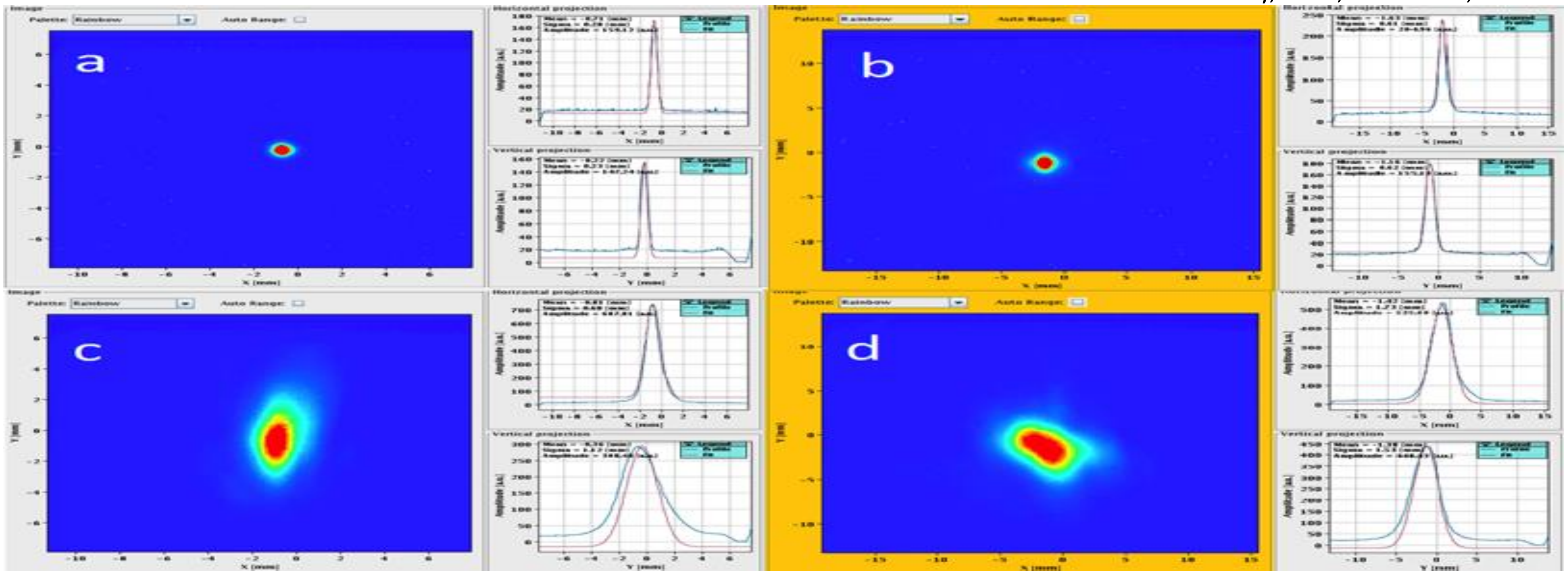


➔ **Transversal alignment** of proton and laser beam (spatial overlap)

J. Moody, MPP; J. Schmidt, CERN

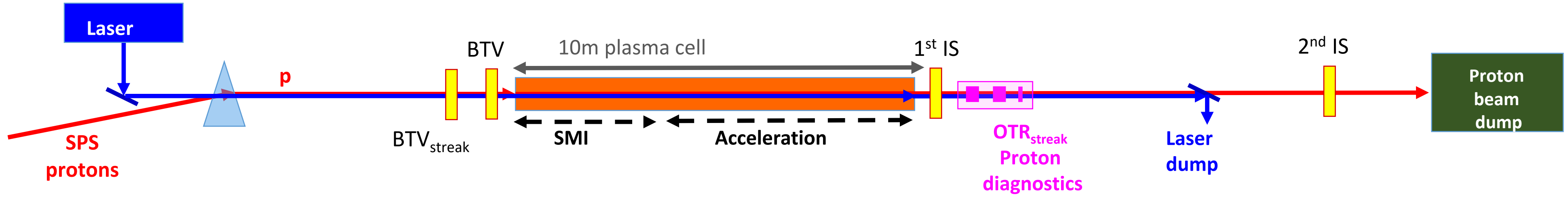
p-beam

laser

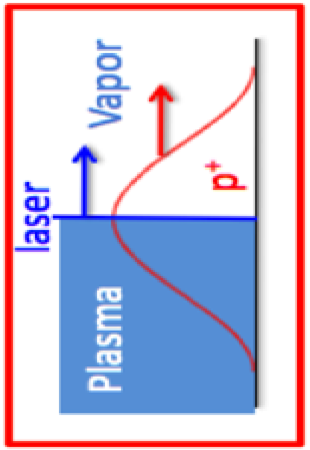


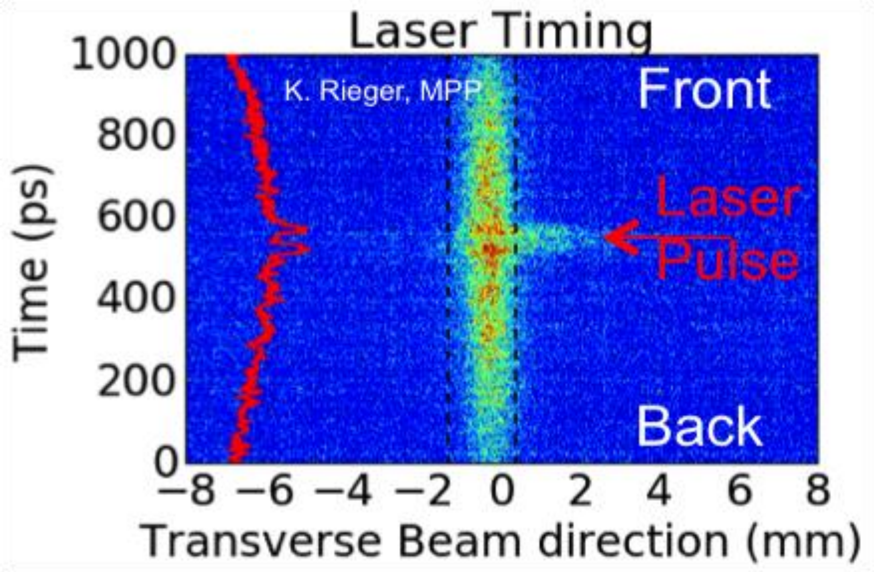
Laser positioned on proton beam references to within 300 microns (corresponds to 6 µrad pointing jitter)

Result Proton and Laser Beam Synchronization



➔ **SPS proton beam synchronized with AWAKE laser within ~20ps accuracy**





S. Mazzoni MOPAB119

J. Schmidt, TUPIK032

V. Olsen, TUPIK061

J. Schmidt, THPAB050

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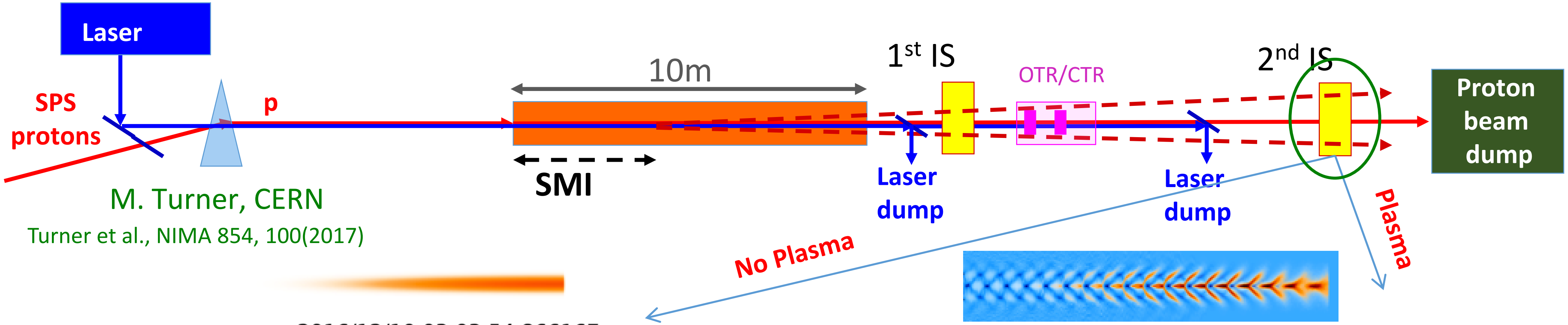
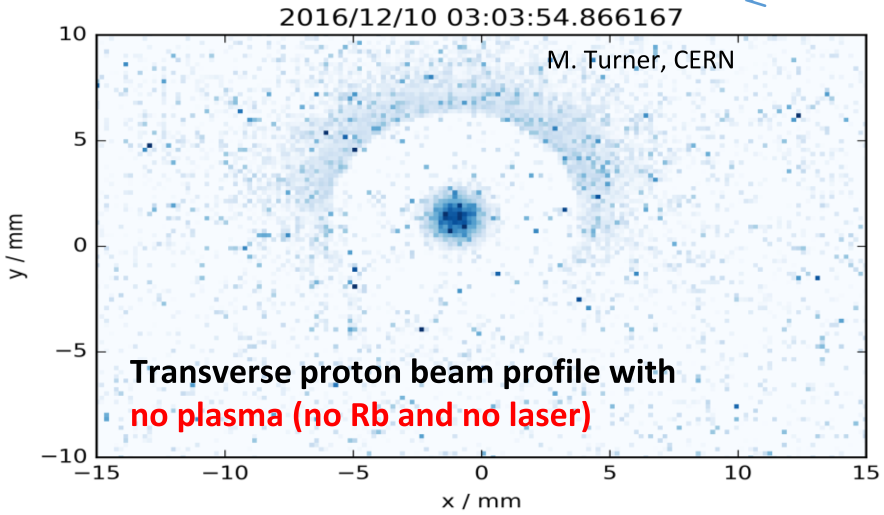
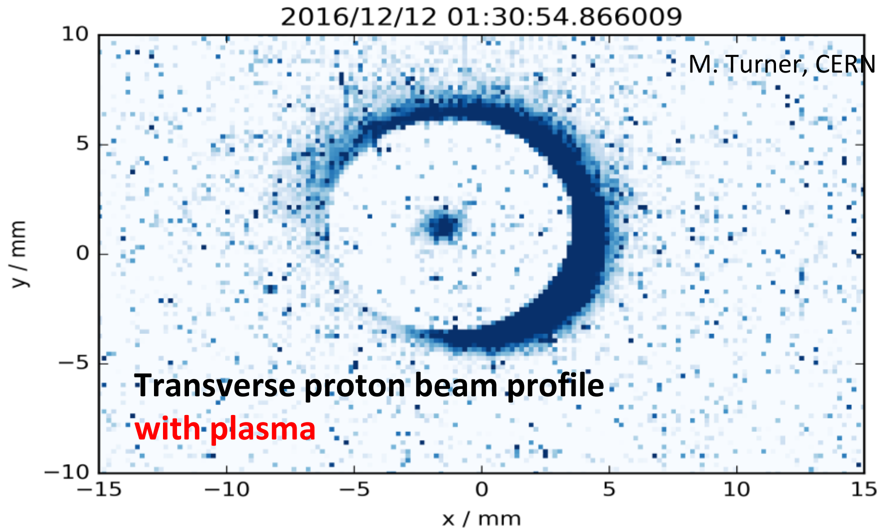
Indirect SMI Measurement Results

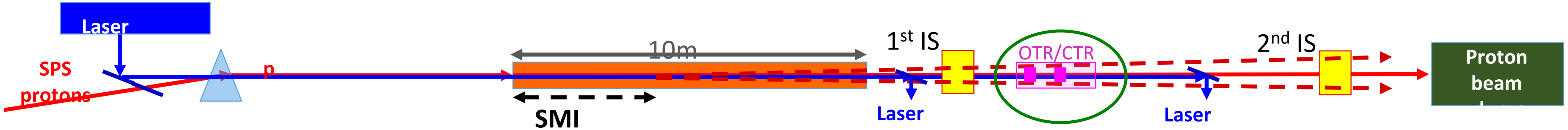






- → p^+ defocused by the transverse wakefield (SMI) form a halo
- → p^+ focused form a tighter core
- → Estimate of the transverse wakefields amplitude ($\int W_{per} dr$)

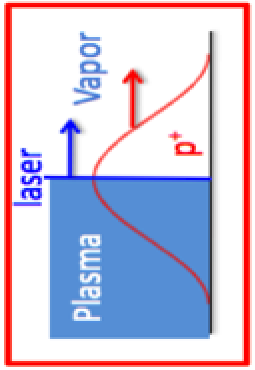
Direct SMI Measurements, OTR

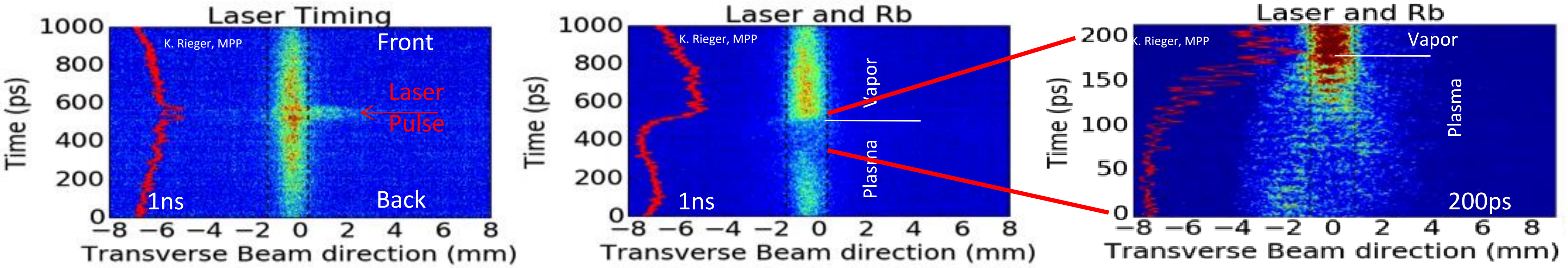


OTR

Streak camera Images

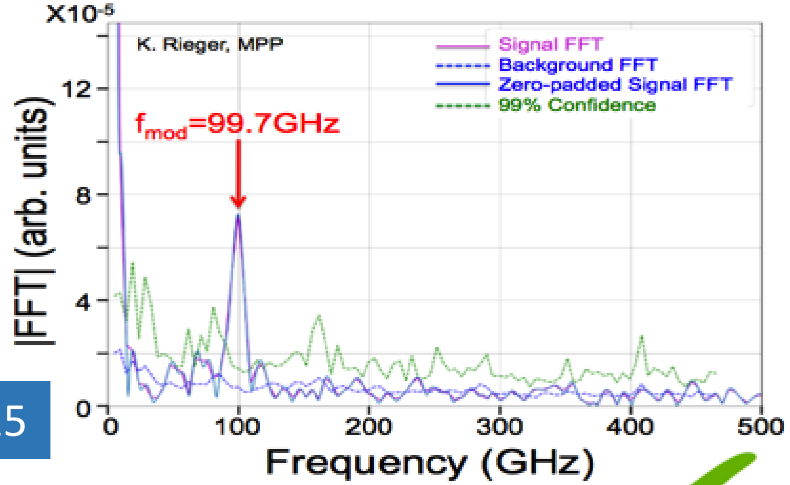
K. Rieger, MPP





- → Timing at the ps scale
- → Effect starts at laser timing
- → Density modulation at the 10ps-scale visible

- → $n_{Rb}=1.34\times10^{14}\text{cm}^{-3}$ ➔ $f_{pe}=103.7\text{GHz}$
- → FFT peak at $f_{mod}=99.7\text{GHz}\sim f_{pe}$
- → $\Delta f_{FFT}=4.5\text{GHz}$



→ Successful first SMI physics run: 48h
→ Operation at low plasma density: $\sim1.5\times10^{14}\text{cm}^{-3}$
→ SMI signal detected on all three diagnostics (IS, OTR, CTR)

E. Oz, TUPIK015

➔ 2017: further investigation of SMI

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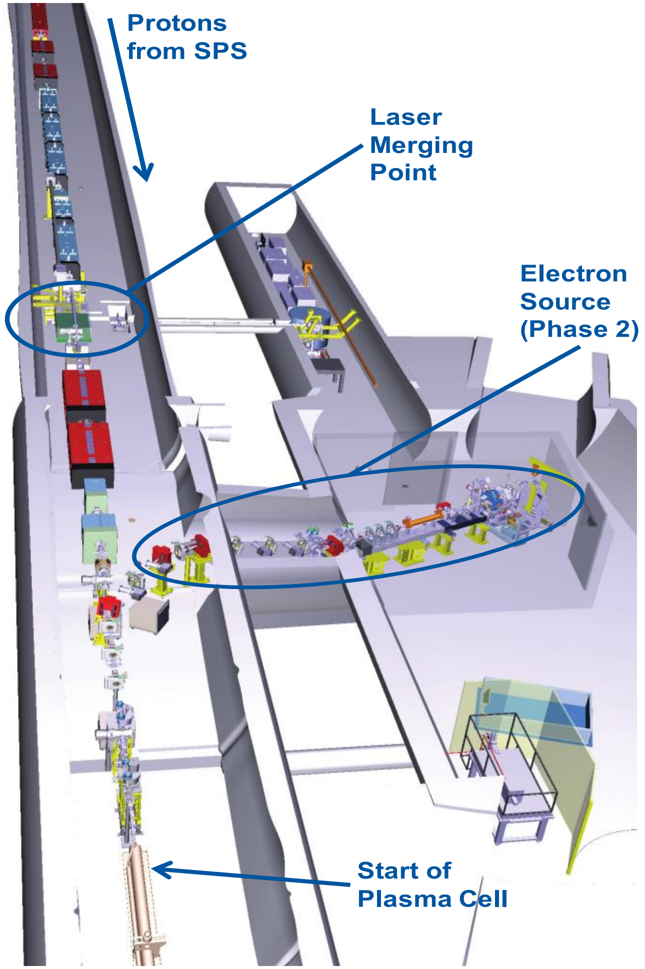
Electron Source and Beam Line

A. Martinez, WEPVA105



Electron beam	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%

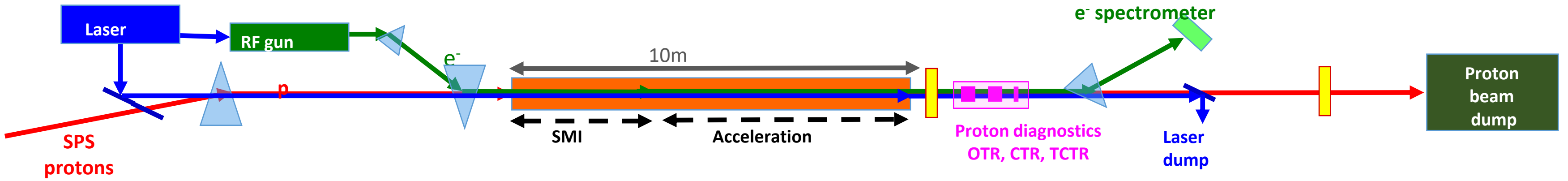
Electron gun installed

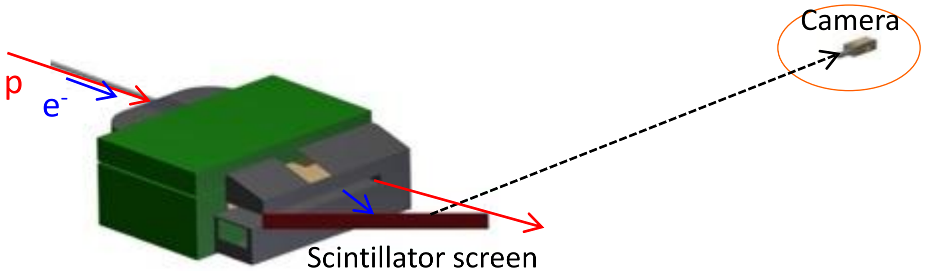
Electron beam line installation ongoing

Completely **new beam line and tunnel**:

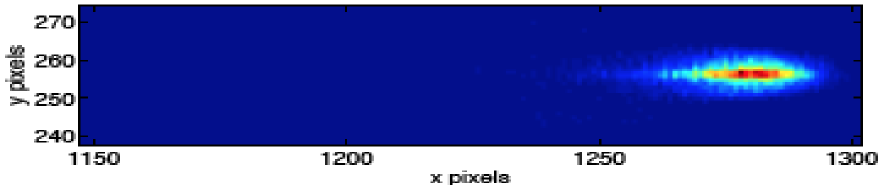
- Horizontal angle of 60 deg,
- 20% slope of the electron tunnel→Δ=1.16m
- 5.66% slope of the plasma cell
- ~5 m common beam line of e^- and p.

AWAKE Electron Acceleration Diagnostics





L. Deacon, UCL



Dispersed electron impact on scintillator screen.
Resulting light collected with intensified CCD camera.
%-level energy resolution achieved with a S/N ratio larger than 1000:1


Electron spectrometer installation, looking downstream

➔ Start commissioning end 2017
Physics in 2018

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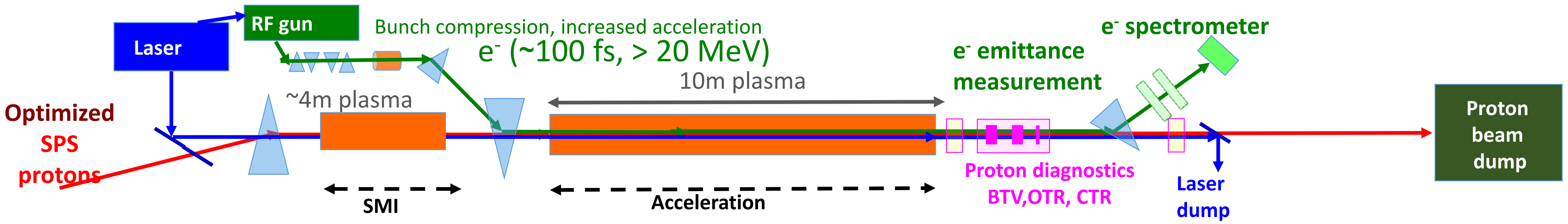
AWAKE Proposal Run 2

Goals:

- **Accelerate an electron beam to high energy**
- **Preserve electron beam quality** as well as possible
- **Demonstrate scalability** of the AWAKE concept

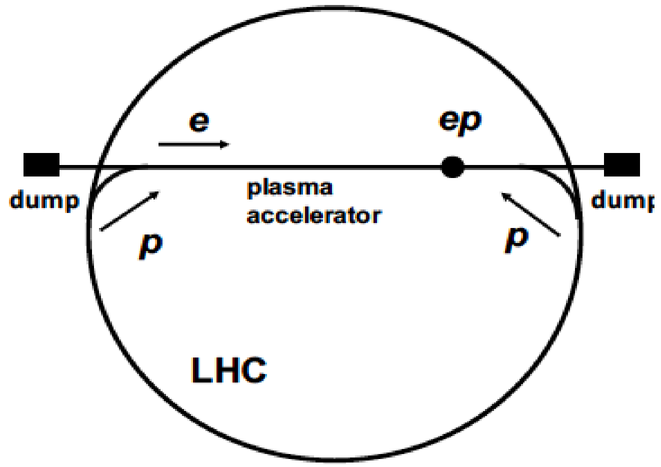
Preliminary Run 2 electron beam parameters

Parameter	Value
Acc. gradient	>0.5 GV/m
Energy gain	10 GeV
Injection energy	$\gtrsim$ 50 MeV
Bunch length, rms	40–60 μm (120–180 fs)
Peak current	200–400 A
Bunch charge	67–200 pC
Final energy spread, rms	few %
Final emittance	$\lesssim$ 10 μm



After Run 2: get ready for first applications:

- Use bunches from SPS with 3.5 E11 protons every ~5sec, electron beam of up to O (50GeV).
- Using the LHC beam as a driver, TeV electron beams are possible.



VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

Summary

- AWAKE is a **proton driven** plasma wakefield experiment at CERN
- AWAKE aims accelerating electrons with ~1 GV/m **gradient using self-modulation instability** of a long proton bunch in a plasma ($\sigma_z >> \lambda_{pe}$)
- The AWAKE facility was **successfully commissioned**
- **First signs of SMI** were seen on all three diagnostics during a 48hr run in December 2016
  → **further investigation in 2017**
- **Electron acceleration experiment**: commissioning end 2017, physics in 2018
- **Run 2** is proposed for after 2020: preserve electron beam quality, scalability
- First studies on **applications** of p-driven PWFA