AWAKE, Summary of 2016 and Plans for 2017

Edda Gschwendtner for the AWAKE Collaboration

MSWG, 2 June 2017

Outline

- Introduction
- The AWAKE Experiment
- Commissioning of AWAKE 2016
- First Beam Results 2016
- Run Program 2017
- Electron Acceleration Status
- What’s Next
- Summary

Proton Drivers for Plasma Wakefield Acceleration

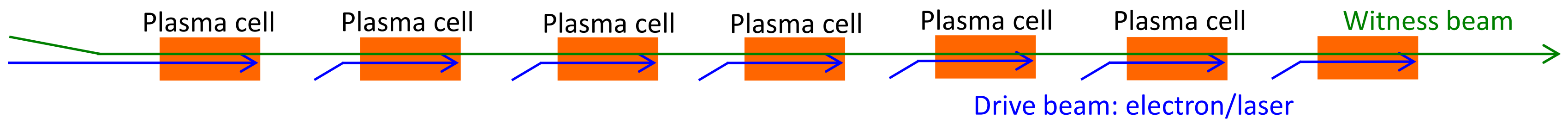
Proton bunches as drivers of plasma wakefields are interesting because of the very large energy content of the proton bunches.

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

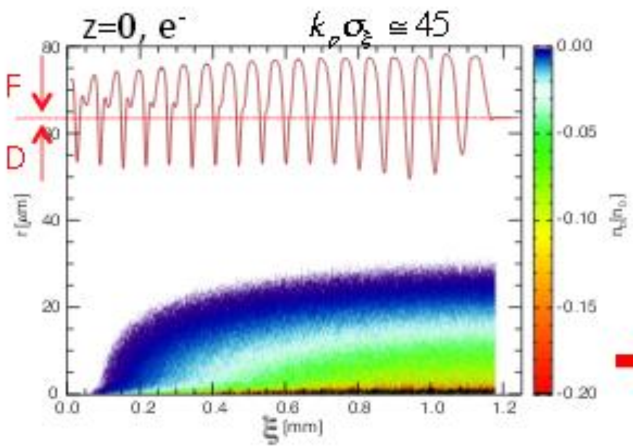
Self-Modulation Instability

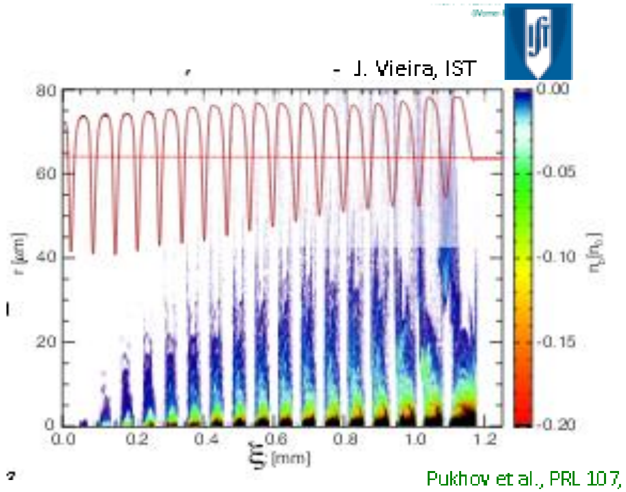
- In order to create plasma wakefields efficiently, the drive bunch length has to be in the order of the plasma wavelength.
- **CERN SPS proton bunch: very long!**
- Longitudinal beam size (**σ_z = 12 cm**) is much longer than plasma wavelength **(λ = 1mm)**

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

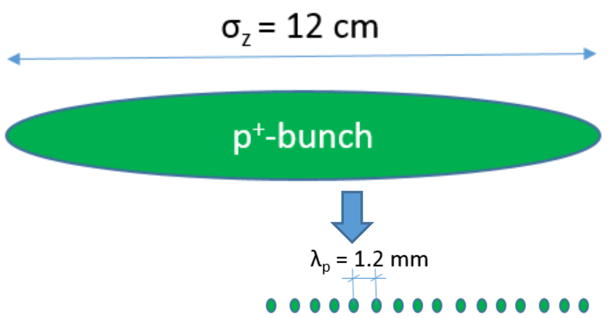
Self-Modulation Instability

- 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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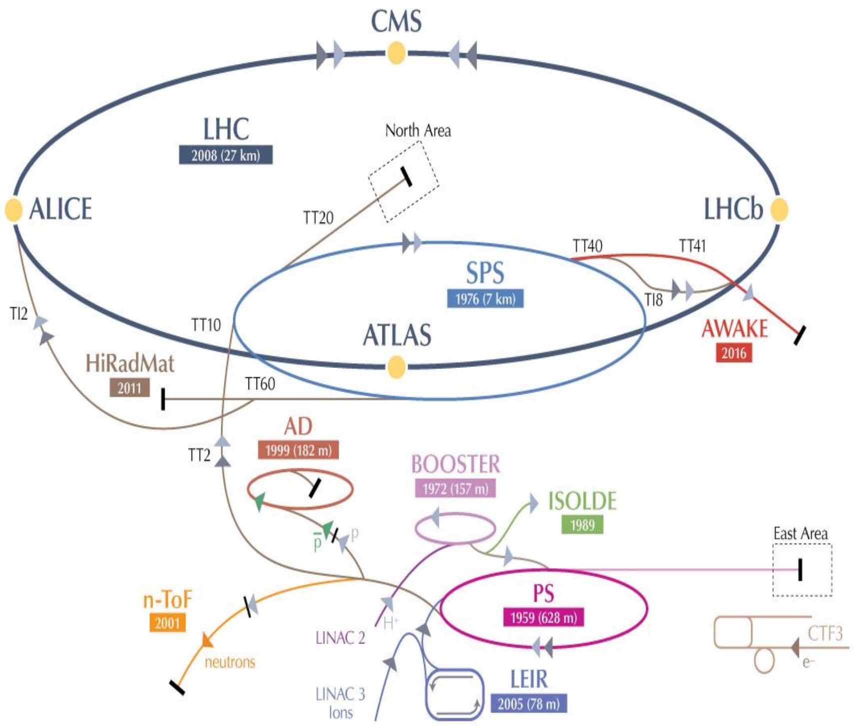
AWAKE at CERN



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		Long Shutdown 2 24 months		Data taking RUN 2	
Experimental area	Study, Design, Procurement, Component preparation	Modification, Civil Engineering and installation			Phase 1					
e^- source and beam-line	Studies, design		Fabrication	Installation	Commissioning	Phase 2				

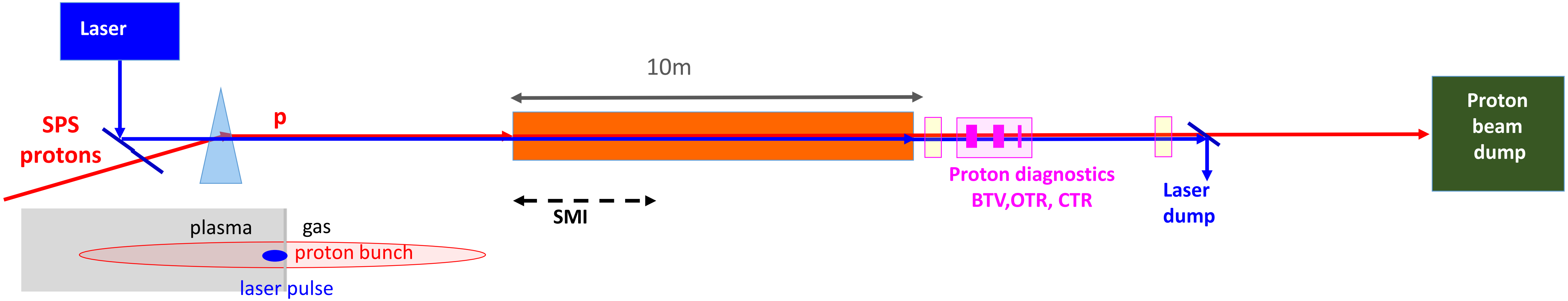
Run 1 – until LS2 of the LHC.

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

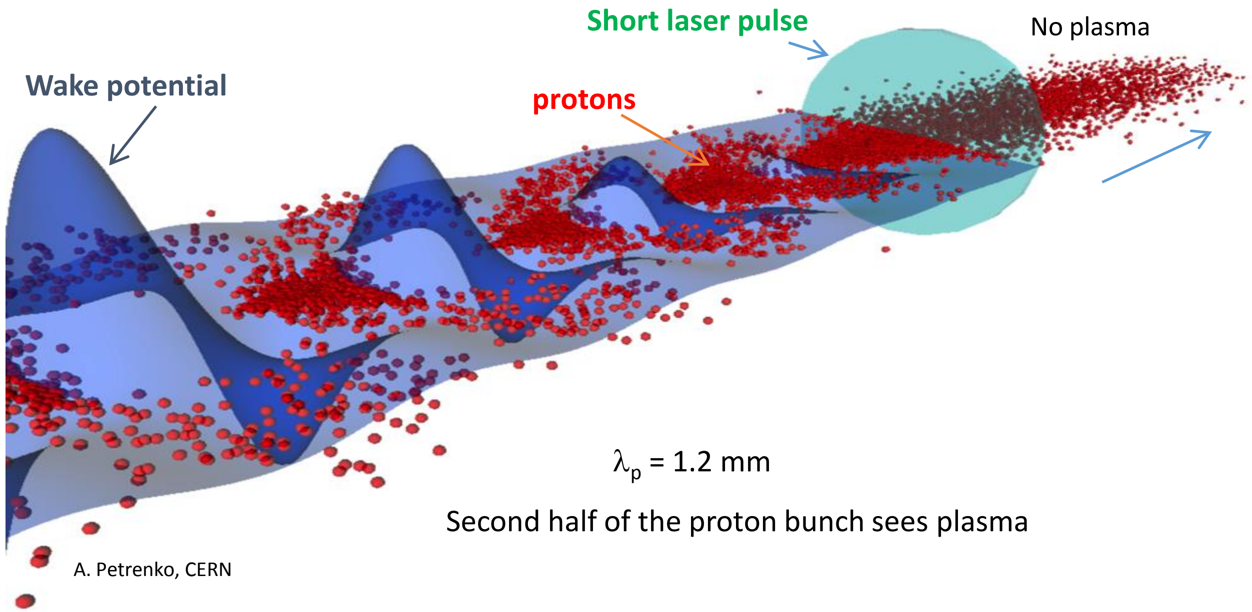
After Run 2 – kick off particle physics driven applications

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.

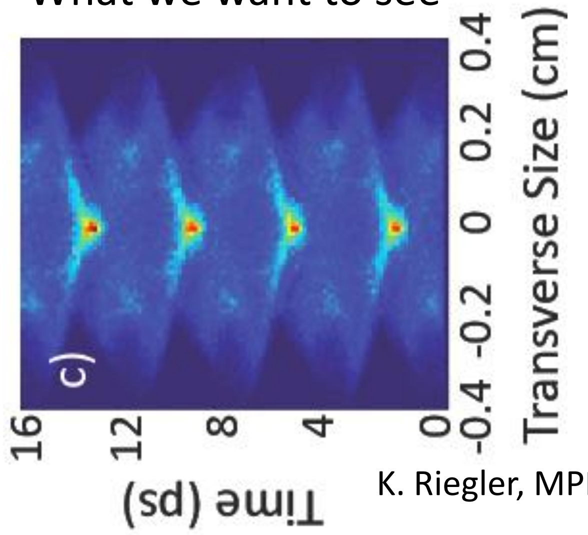


λ_p = 1.2 mm

Second half of the proton bunch sees plasma

A. Petrenko, CERN

What we want to see

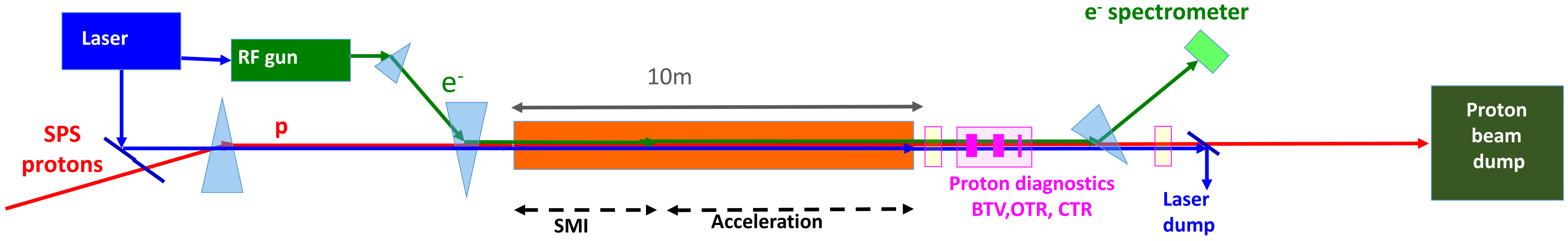


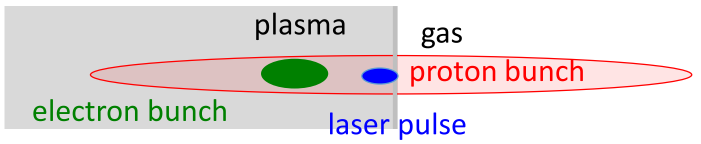
K. Riegler, MPP

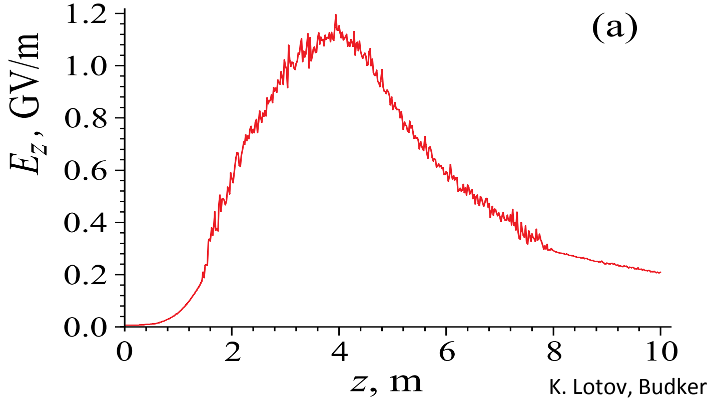
AWAKE Experimental Program Run 1, 2017/18

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

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



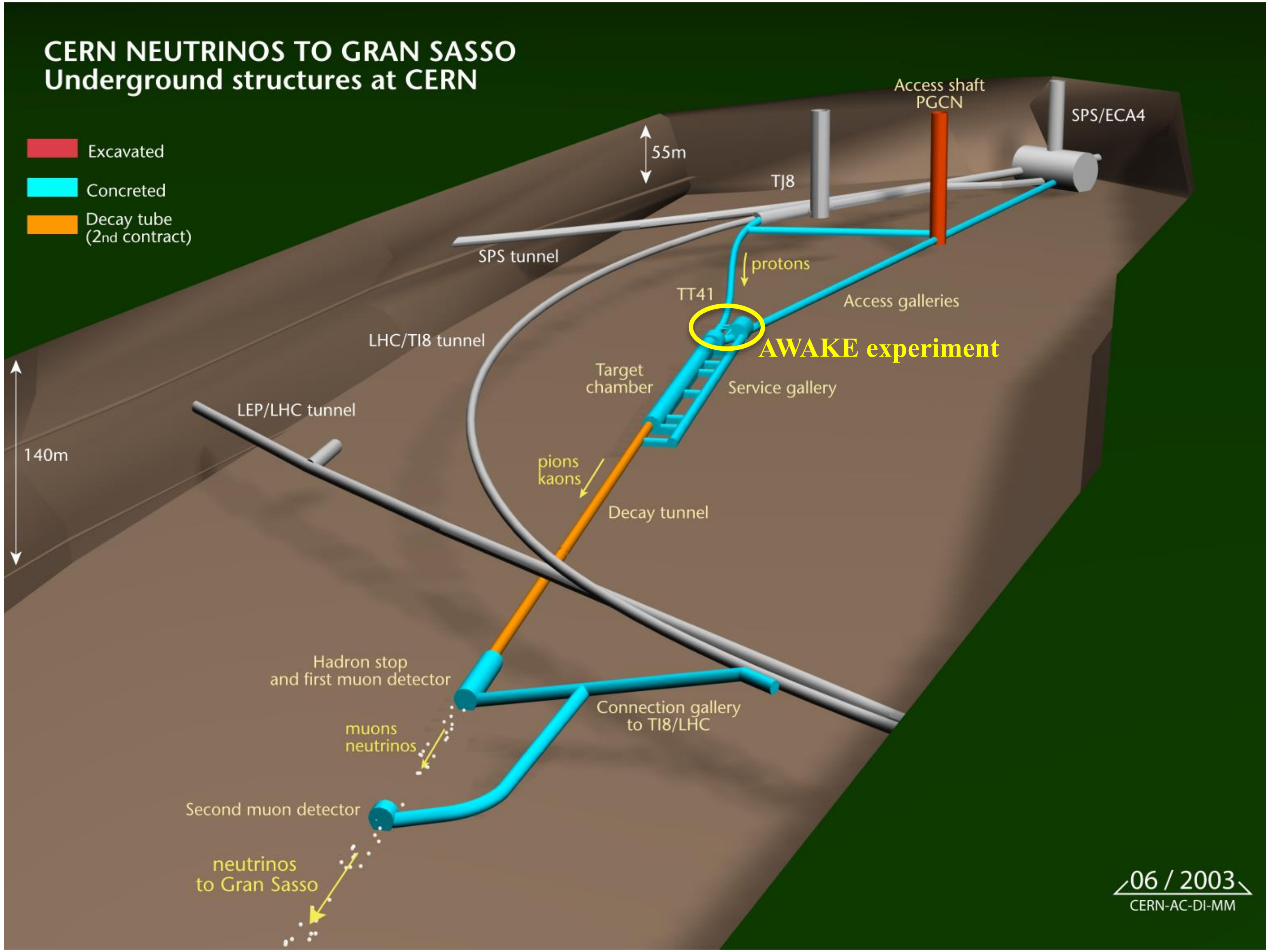




$E_{z,max}$ along the plasma.
Saturation of SMI at ~4m.

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

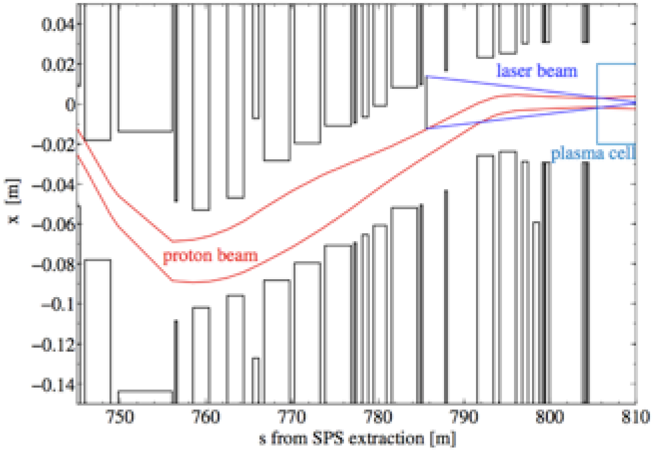
The AWAKE Facility

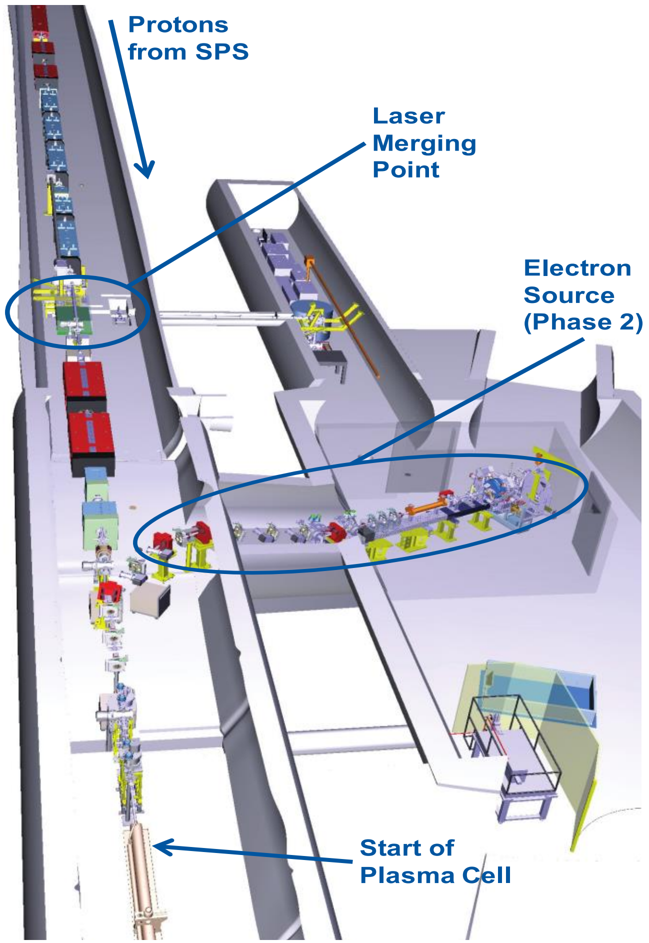


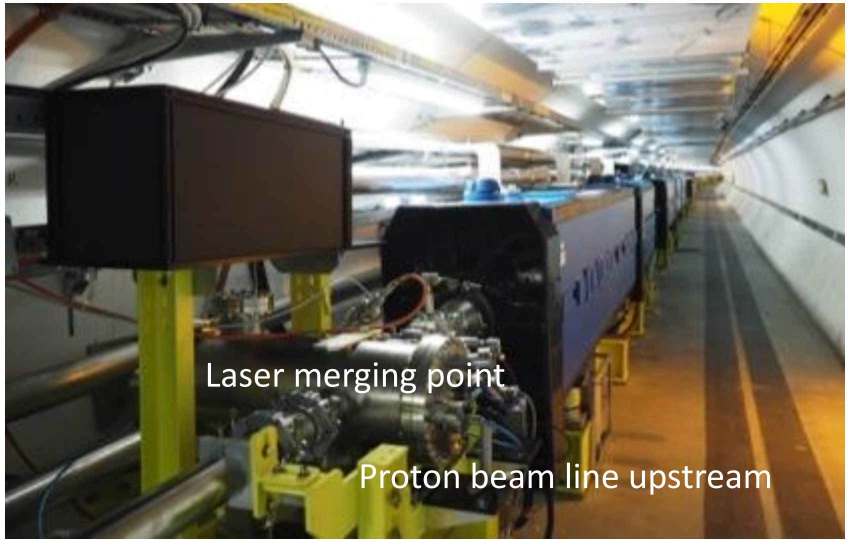
AWAKE Proton Beam Line

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

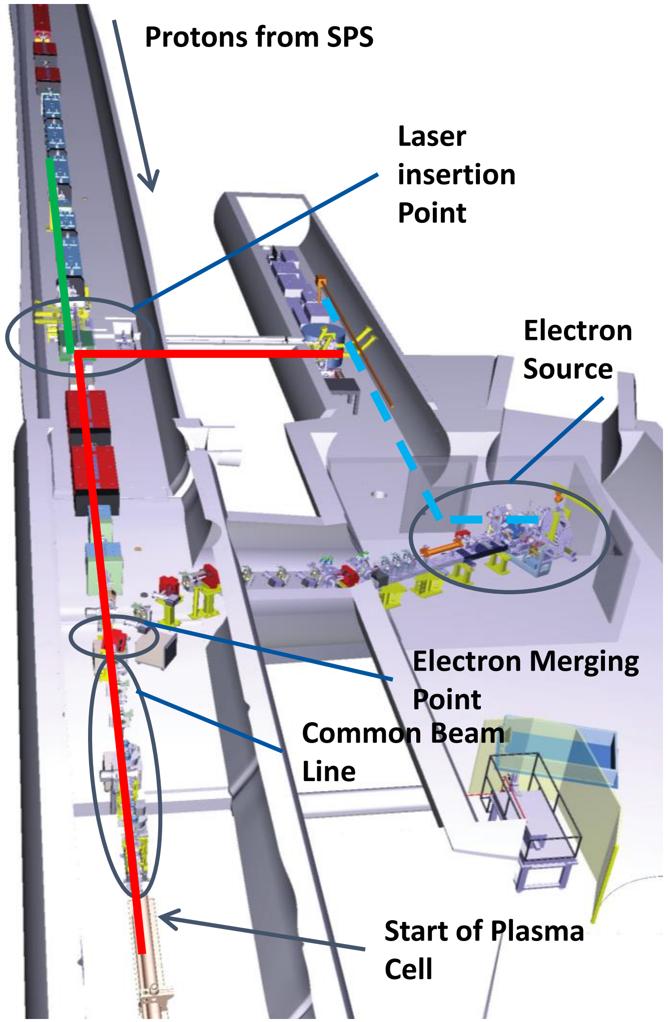


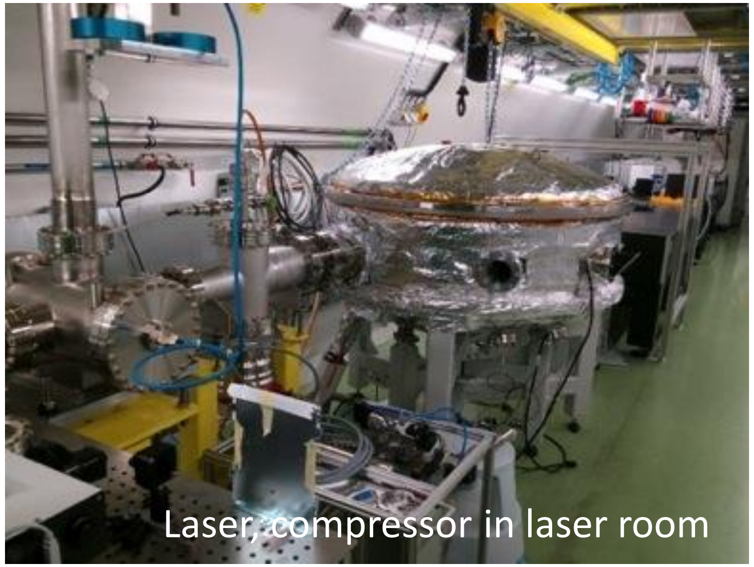




Laser and Laser Line

- **Laser beam line to plasma cell**
  - λ = 780 nm
  - t pulse = 100-120 fs
  - E = 450 mJ
- **Diagnostic beam line ("virtual plasma")**
  - λ = 780 nm
  - t pulse = 100-120 fs,
  - E ≈ 5 mJ
- ***Laser beam line to electron gun (installed in 2017)***
  - *λ = 260 nm*
  - *t pulse = 0.3-10 ps*
  - *E = 0.5 mJ*

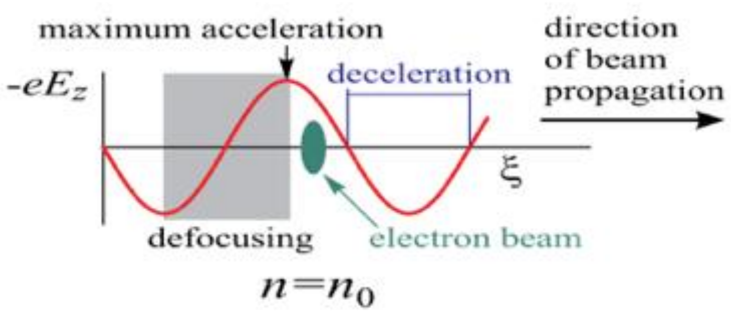


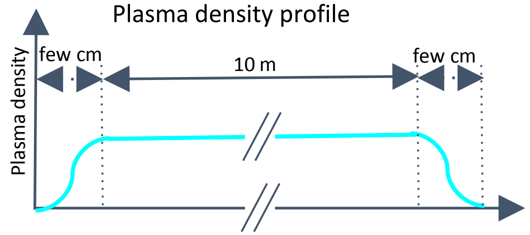


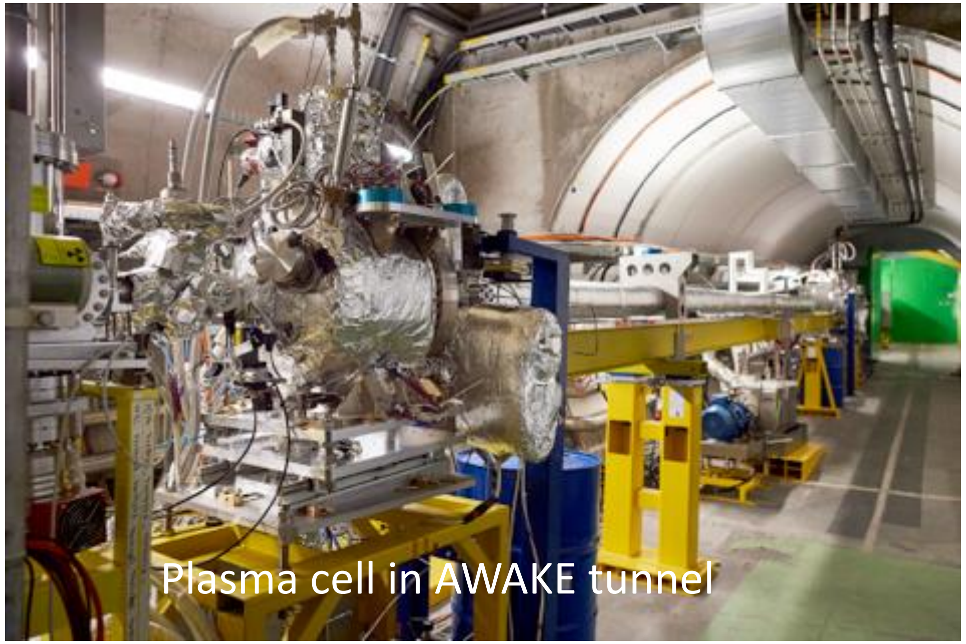
The AWAKE Plasma Cell

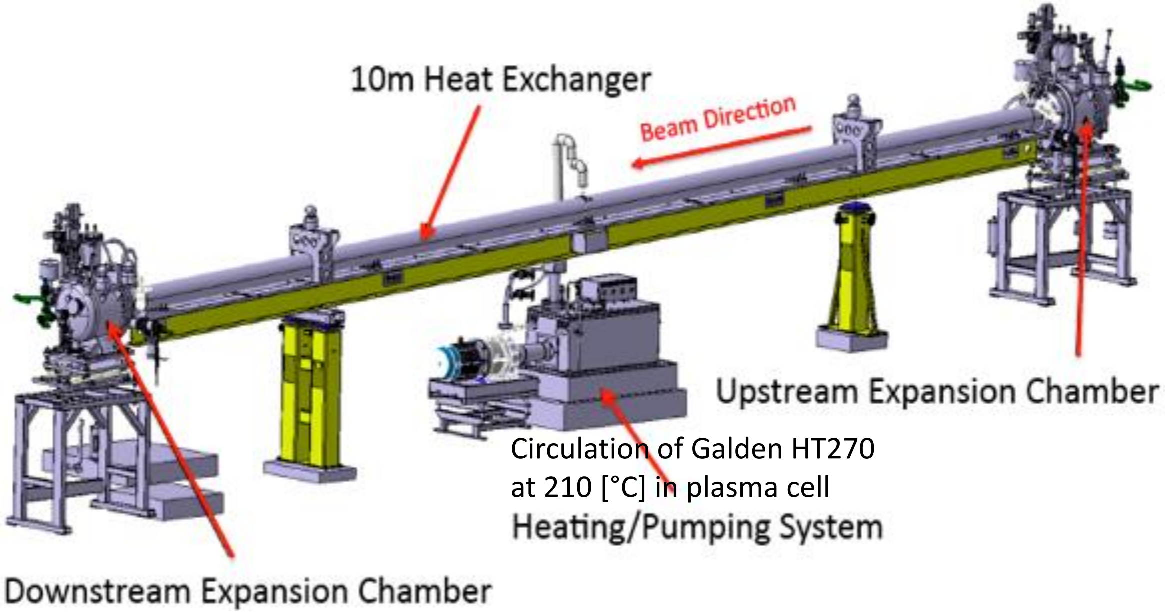
E. Oez, P. Muggli, MPP, Munich

- **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

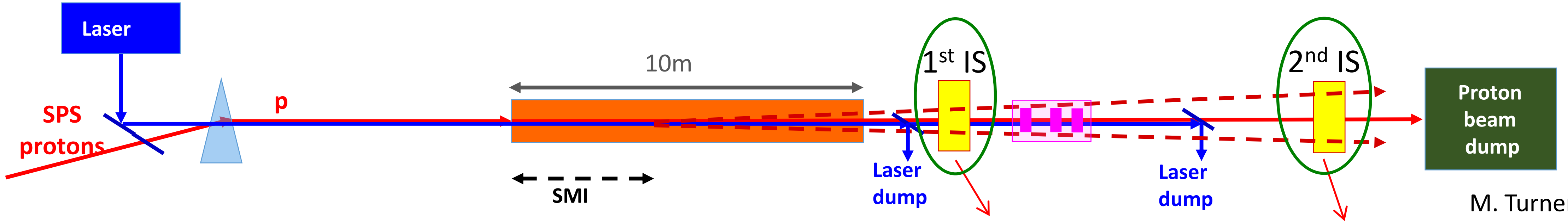




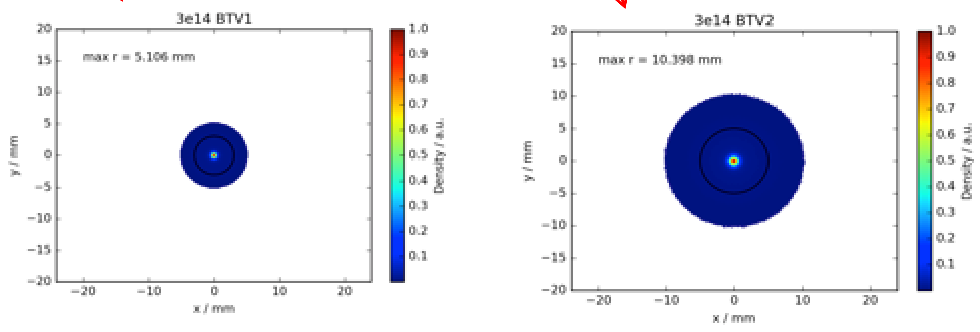




Self-Modulation Instability Diagnostics I

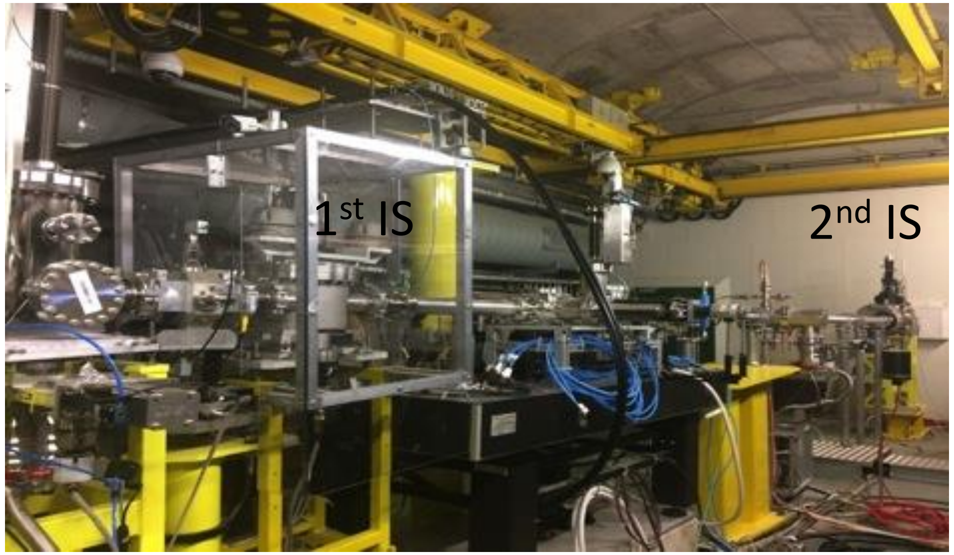


M. Turner, CERN



Indirect SMI diagnostics:

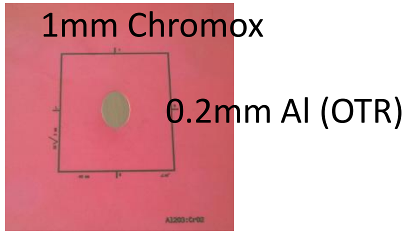
Image protons that got defocused by the strong plasma wakefields.



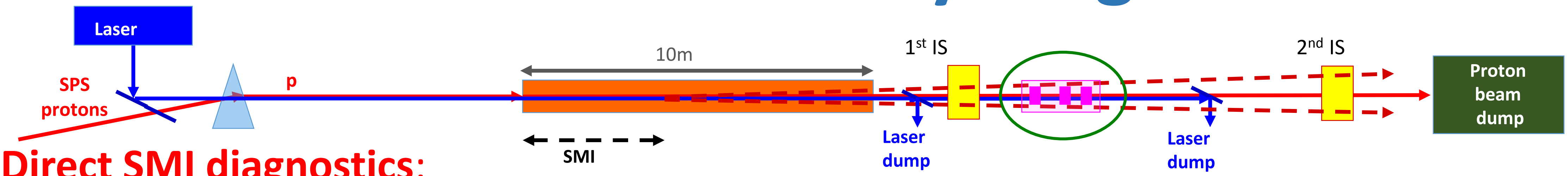
Two imaging stations (IS) to measure the radial proton beam distribution 2 and 10 m downstream the end of the plasma.

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

Handling the dynamic range of tails and intense beam core: Combined screen

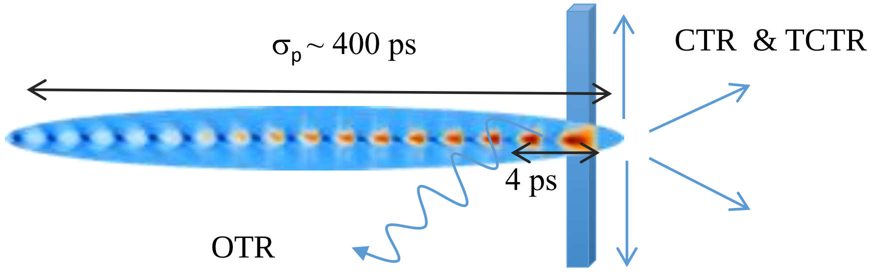


Self-Modulation Instability Diagnostics II

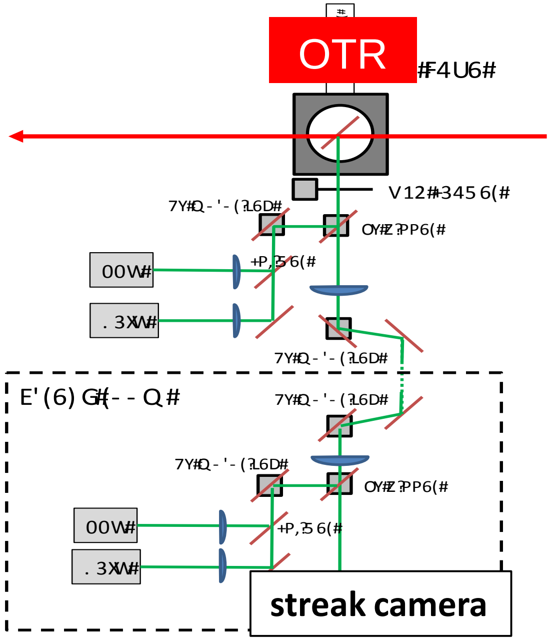


Direct SMI diagnostics:

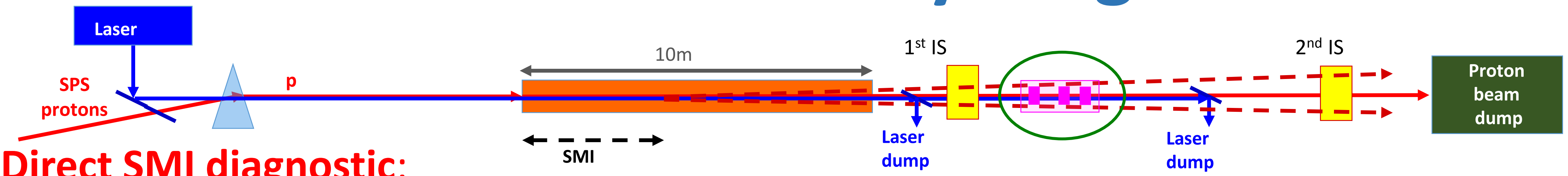
Measure frequency of modulation.



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

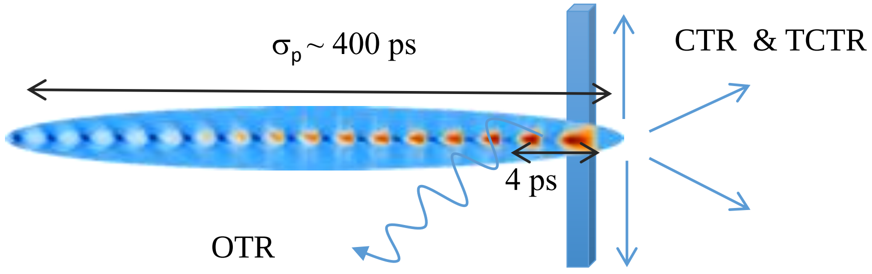


Self-Modulation Instability Diagnostics II



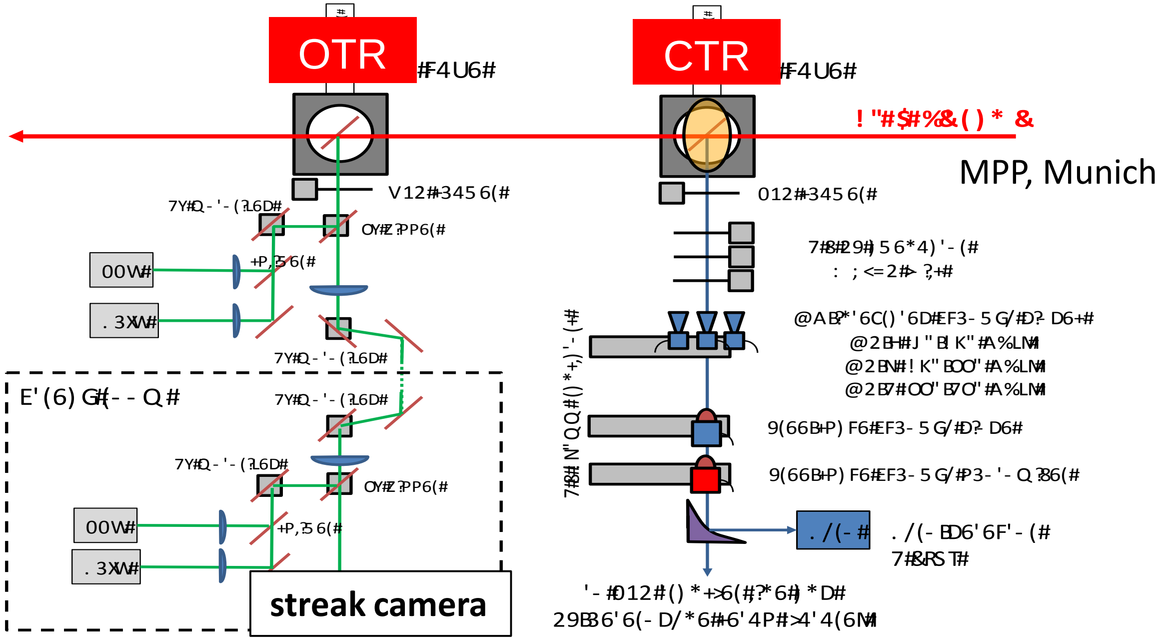
Direct SMI diagnostic:

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 wavelengths bigger than the structure of the micro-bunches (90-300GHz).



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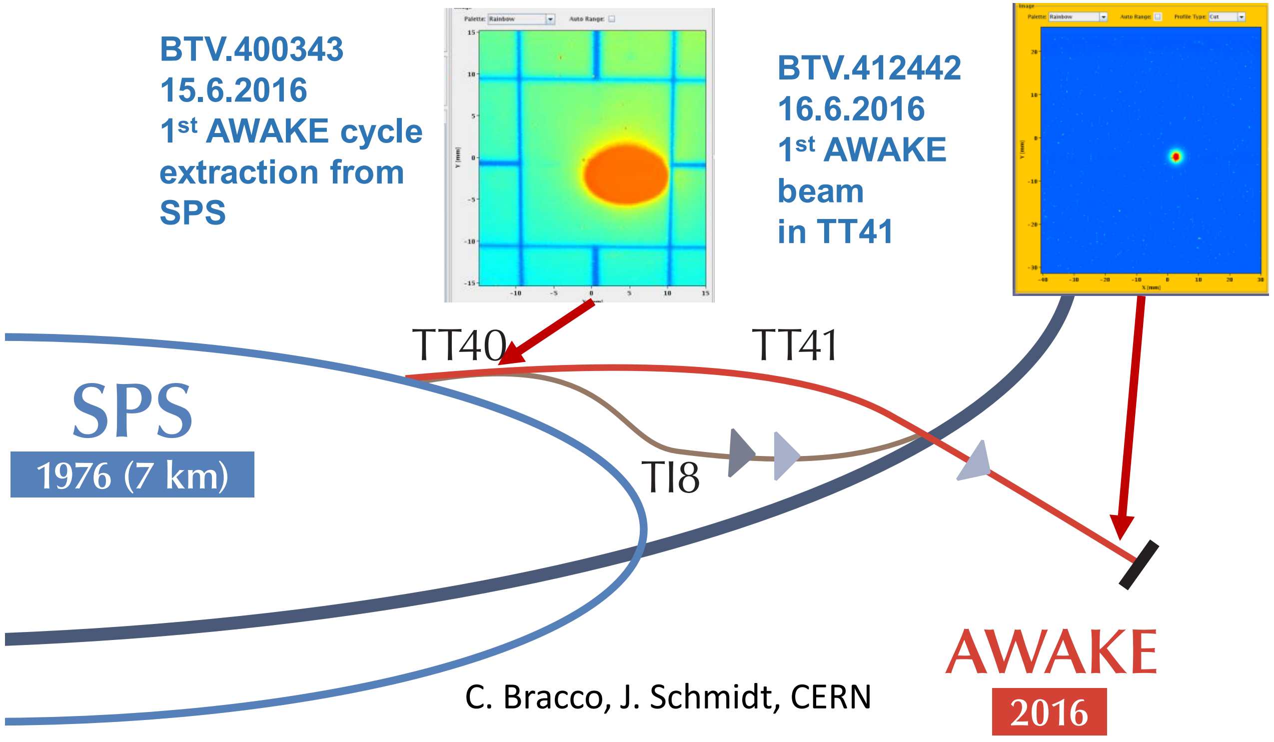
AWAKE Beam Commissioning 2016

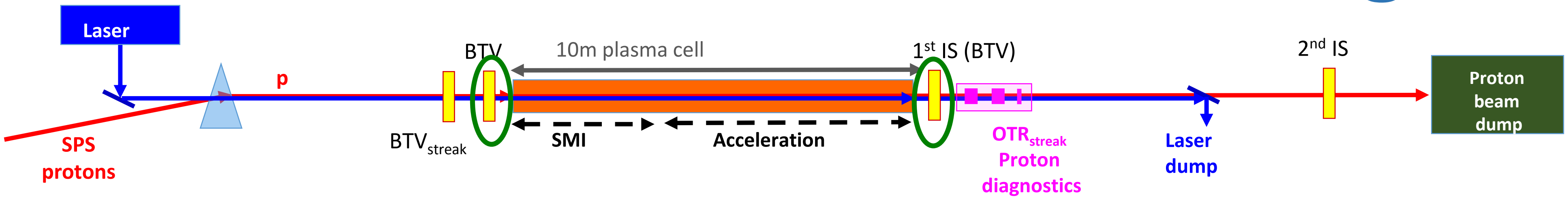
3 periods of commissioning:
June, September, November 2016



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

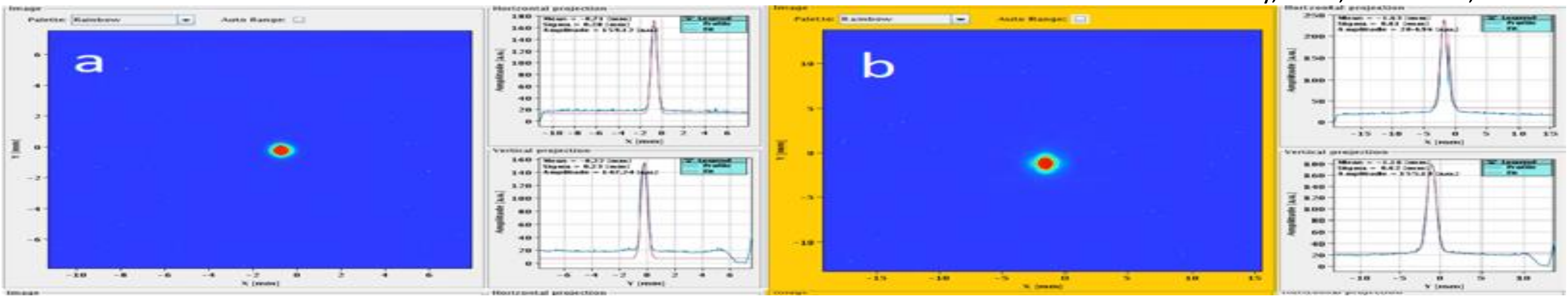
Results Laser Beam Commissioning



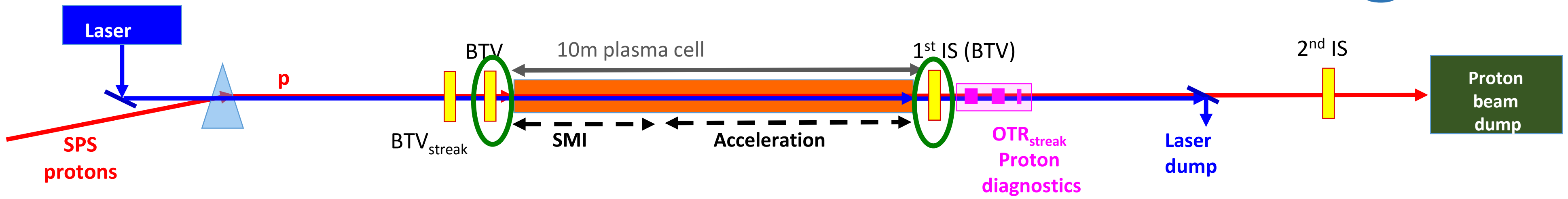
➔ **Transversal alignment** of proton and laser beam (spatial overlap)

J. Moody, MPP; J. Schmidt, CERN

p-beam



Results Laser Beam Commissioning

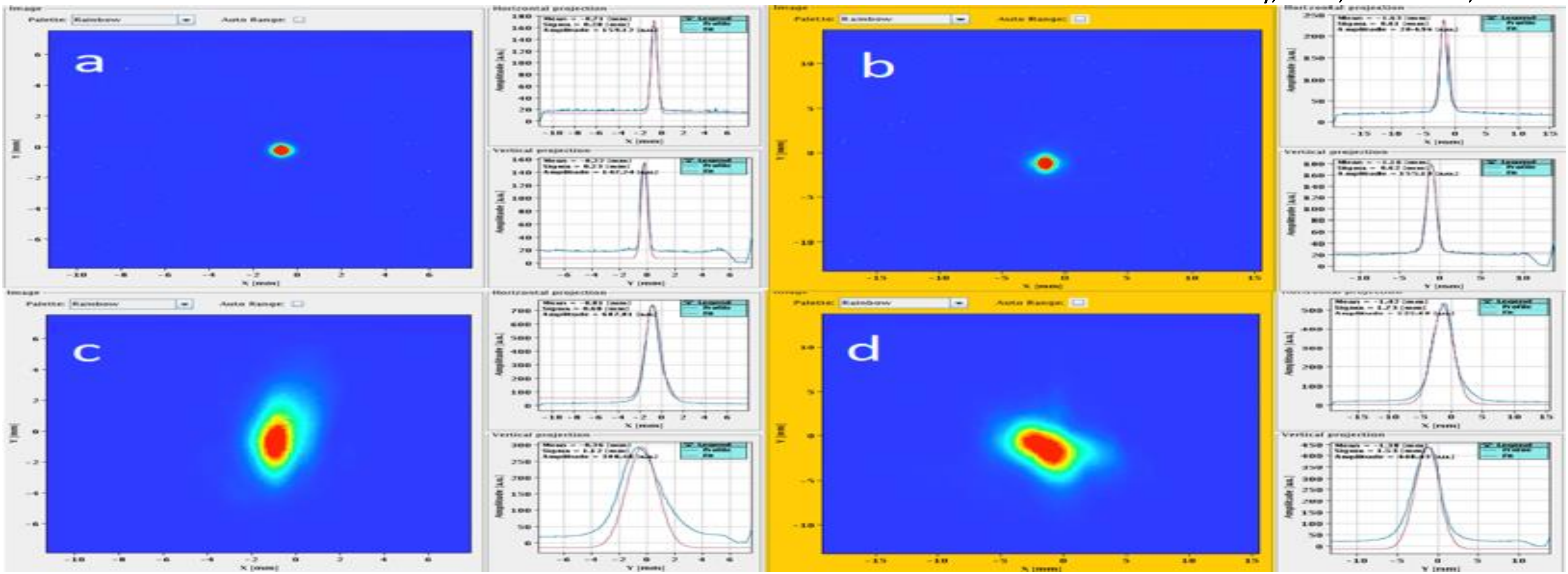


➔ **Transversal alignment** of proton and laser beam (spatial overlap)

J. Moody, MPP; J. Schmidt, CERN

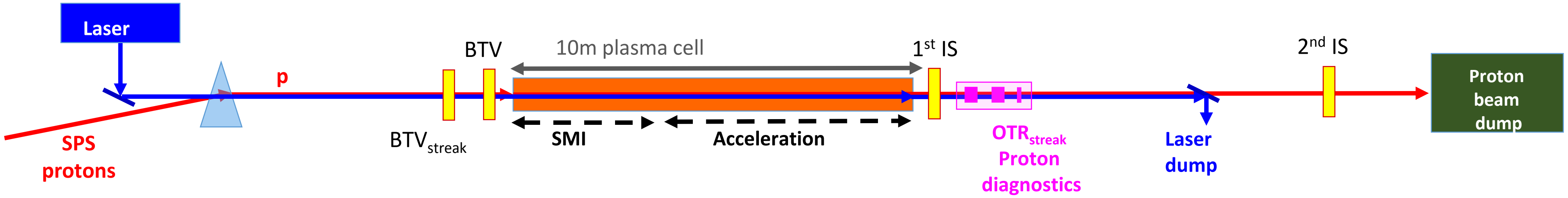
p-beam

laser

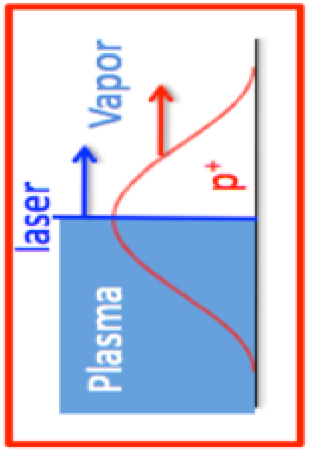


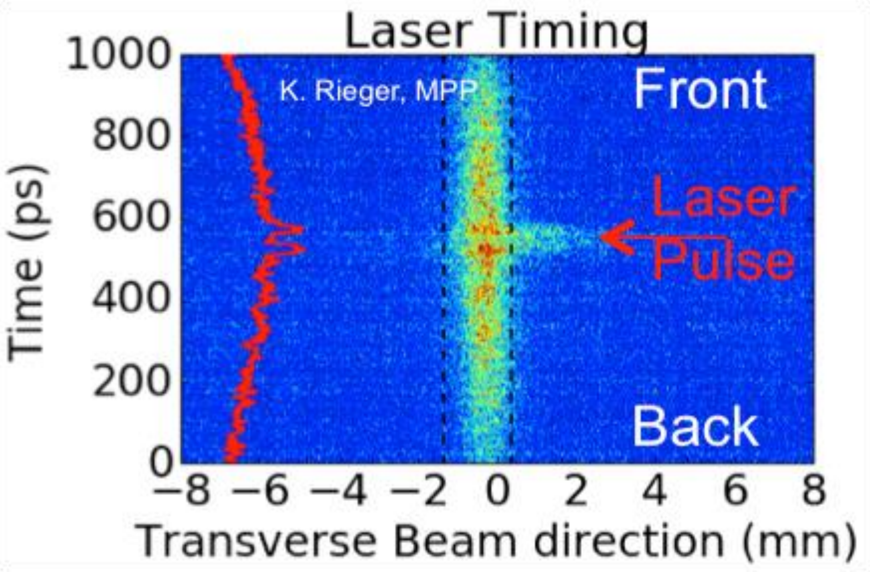
Laser positioned on proton beam references to within 300 microns (corresponds to 6 µrad pointing jitter)

Result Proton and Laser Beam Synchronization



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





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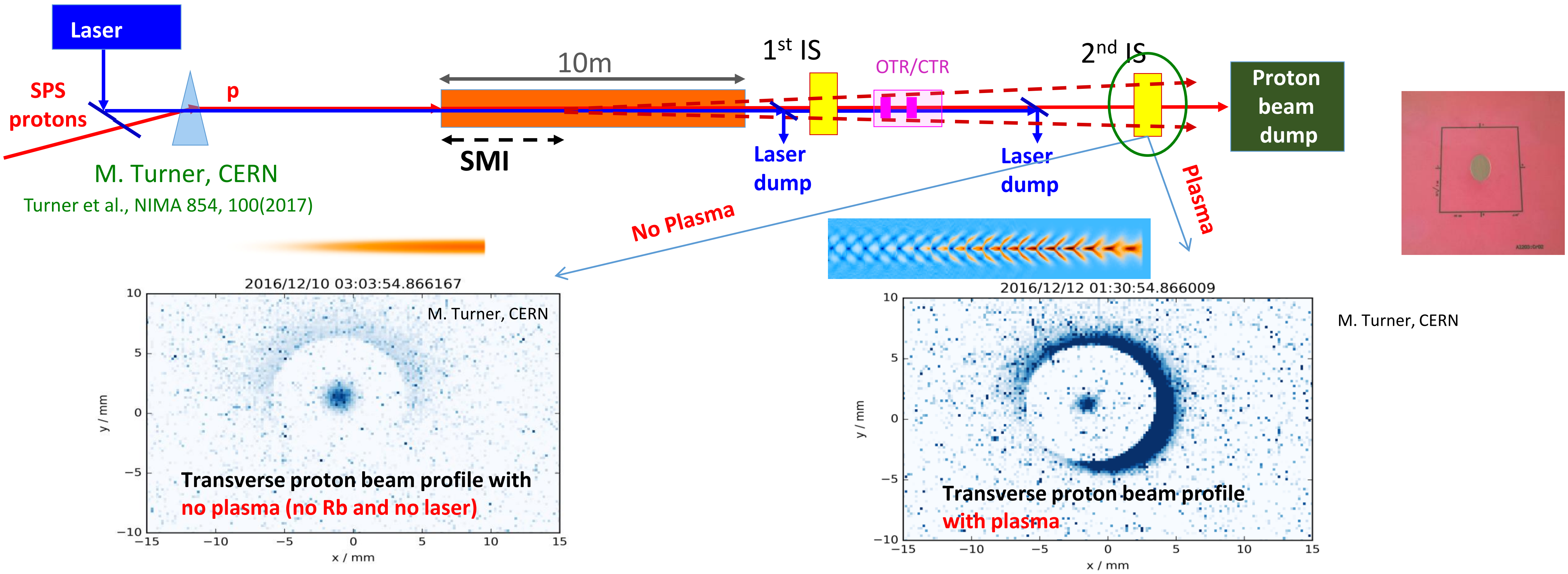
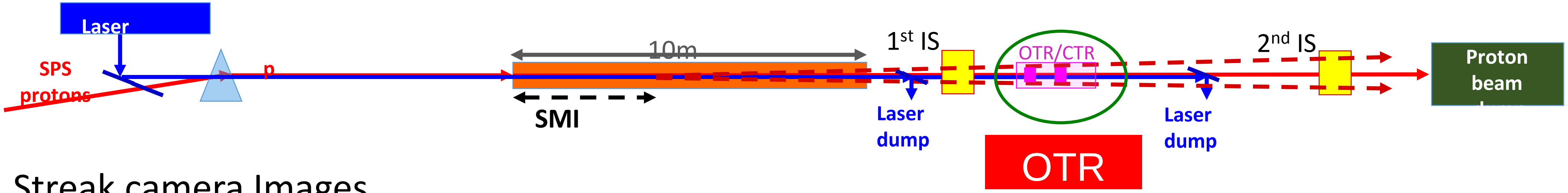
Indirect SMI Measurement Results



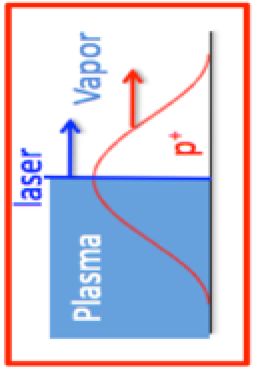
- → p^+ defocused by the transverse wakefield (SMI) form a halo
- → p^+ focused form a tighter core
- → Estimate of the transverse wakefields amplitude ($\int W_{per} dr$)

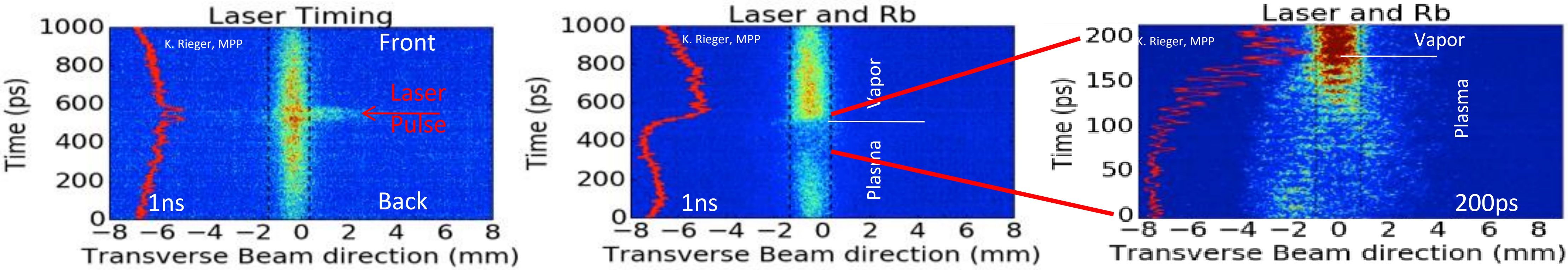
Direct SMI Measurements, OTR



Streak camera Images

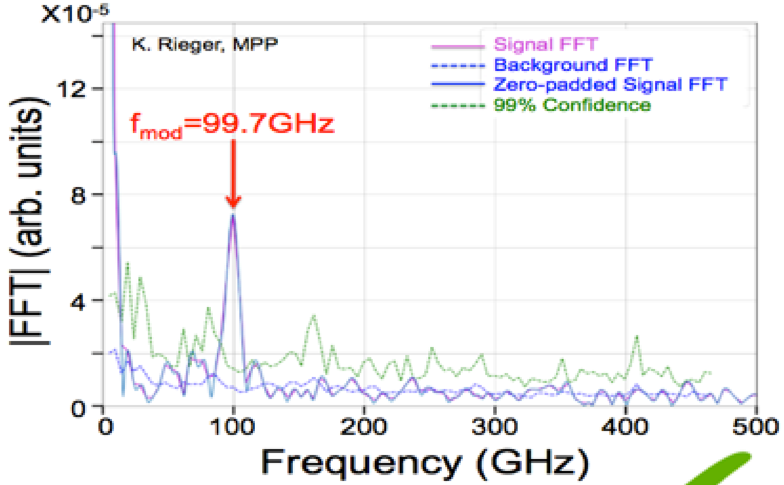
K. Rieger, MPP





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

- → n_{Rb}=1.34x10^{14}cm^{-3} → f_{pe}=103.7GHz
- → FFT peak at f_{mod}=99.7GHz~f_{pe}
- → Δf_{FFT}=4.5GHz



→ Successful first SMI physics run: 48h

→ Operation at low plasma density: ~1.5x10^{14}cm^{-3} → 103.7 GHz

→ SMI signal detected on all three diagnostics (IS, OTR, CTR)

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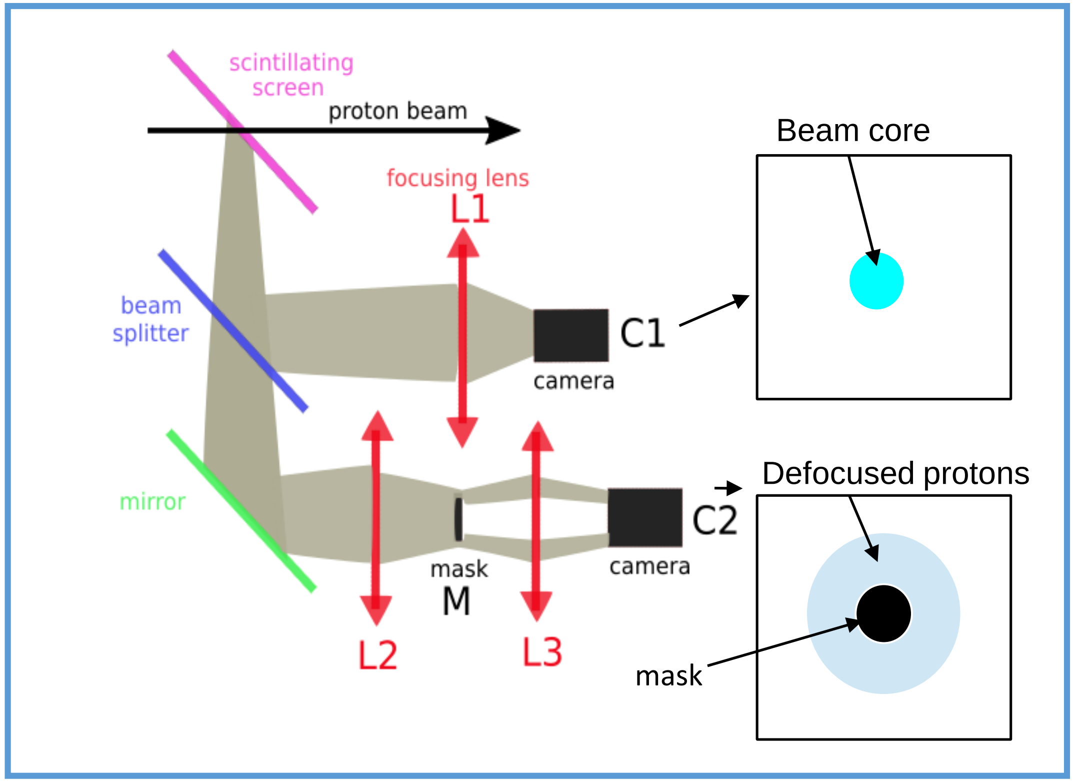
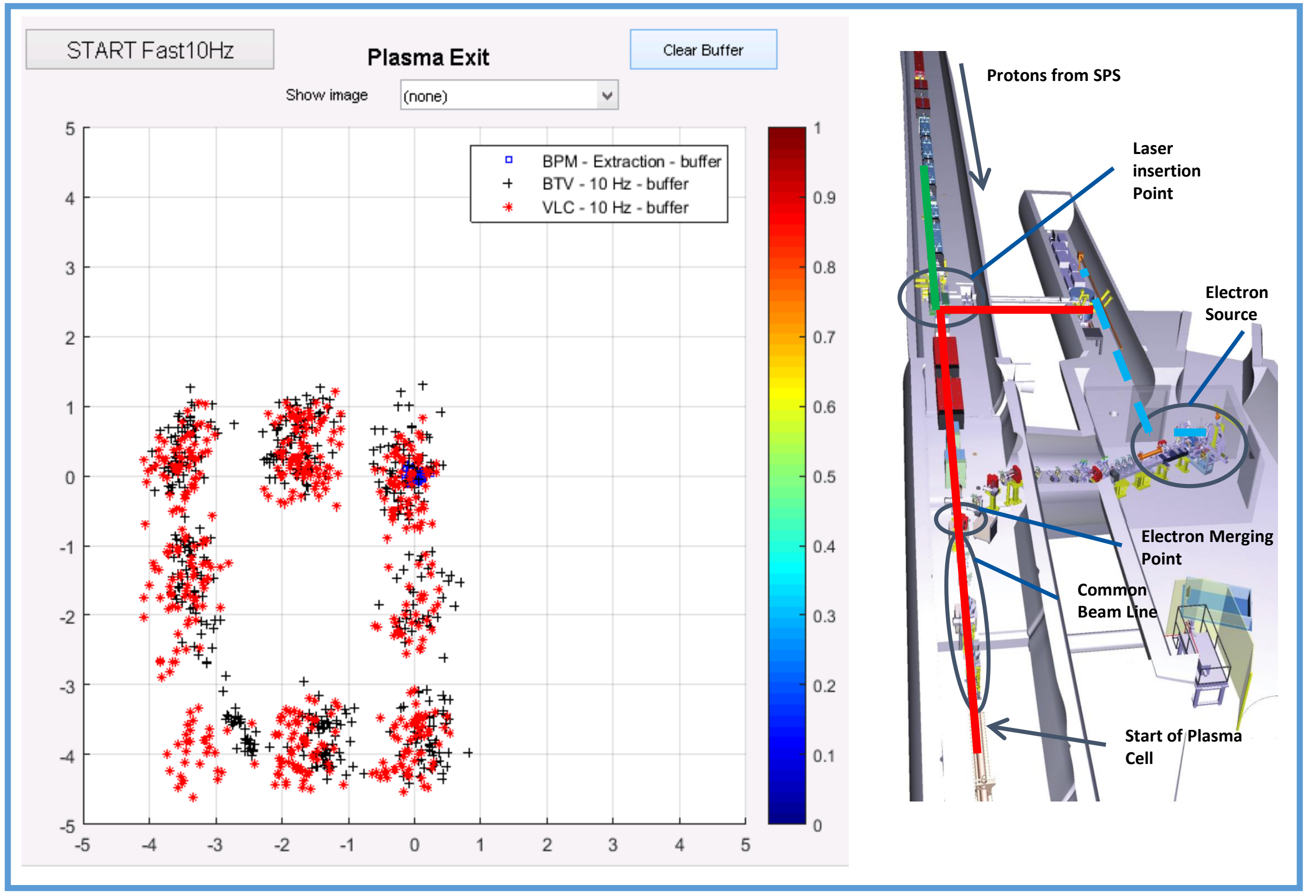
May/June Run 2017

- 26 May to 30 May 2017: commissioning of proton beam line, laser line, diagnostics, timing, logging, etc…
  - Alignment of laser wrt beam, laser to plasma wrt laser in virtual beam line!

Upgrade of the two-screen imaging diagnostics:
Split the signal from BTV screen, 1) image beam core to camera C1. 2) block core with several possible masks and measure maximum defocused beam with C2.



Correlation measurements of laser virtual line and laser to plasma



May/June 2017 Program

Similar program for August 2017

- Heating up the Rb plasma cell during TS now; Start physics 1 June 2017
  - Repeat SMI measurements of Dec 2017, i.e. with low plasma density of **$1.5x10^{14}cm^{-3}$ (f_p~104 GHz)**
  - Go to nominal plasma density of **$7x10^{14}cm^{-3}$ (f_p ~250 GHz)**, measure SMI with IS, OTR, CTR

Physics Measurements	Purpose/Goal
Recover December Results	Reproduce Dec-results: 1.3e14 & low laser power, ramp laser intensity, shift laser timing
Seeding of SMI	Changing Laser/p+ timing
Density Scan - 200/500/800	Systematic measurement of the plasma frequency 200/500/800ps behind laser
Two Screen SMI measurement	Measure the defocusing angle and saturation point for different seeding positions
Two Screen SMI measurement	Measure the defocusing angle and saturation point for different plasma densities (i.e. 2e13, 5e13, 1.3e14, 3e14, 7e14, 1e15)
CTR measurement	Systematic f_plasma-measurement of CTR with heterodyne system: Scan in reference freq. on 4 plasma freq.s
Beam focusing on LBDP2	Send high power laser onto laser dump to see what effect it has on the beam
Density Gradient Measurements	Study seeding and bunching depth sensitivity to changing the plasma gradient
Density Step Measurement	Study effect of a rapid increase in plasma density on seeding and phase stability
Scan laser position with respect to beam	Systematic study of the "tilted wake" effect observed in the 2016 data. Understand alignment tolerances.
CTR correlations	Try correlating CTR-amplitude with Laser x-y-position

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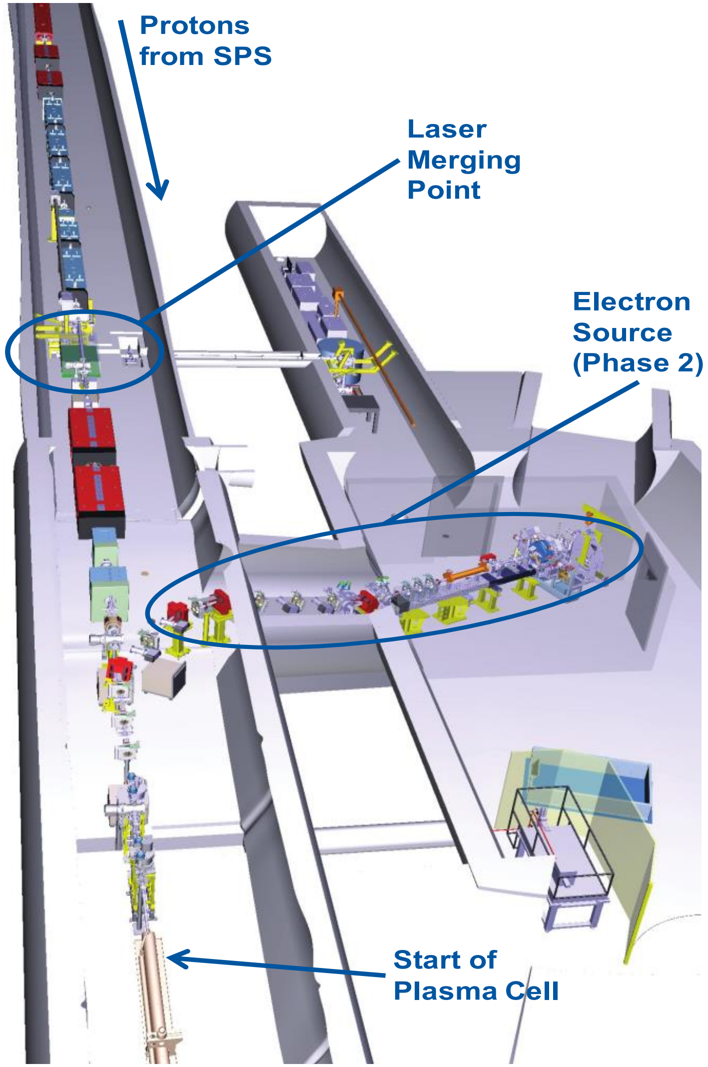
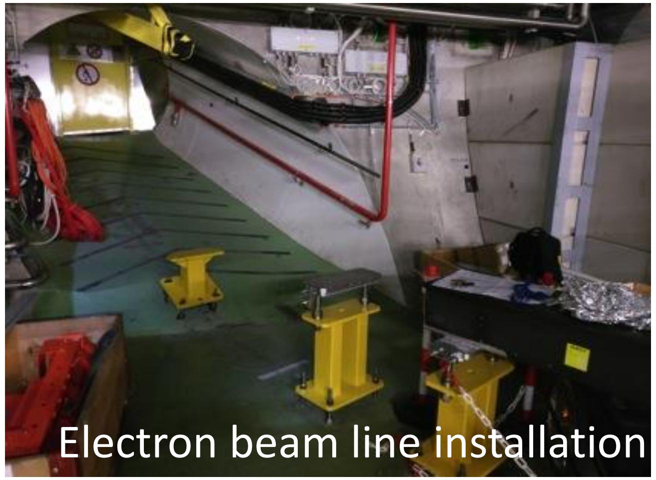
Electron Source



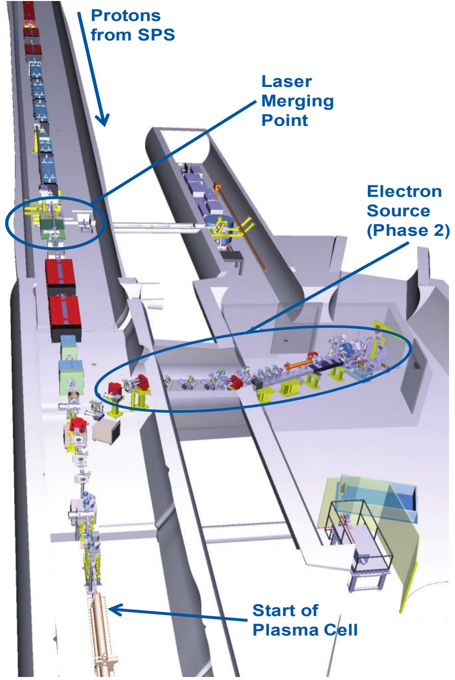
Electron beam	Baseline	Range for upgrade phase
Momentum	16 MeV/c	10-20 MeV
Electrons/bunch (bunch charge)	1.25 E9	0.6 – 6.25 E9
Bunch charge	0.2 nC	0.1 – 1 nC
Bunch length	σ_z =4ps (1.2mm)	0.3 – 10 ps
Bunch size at focus	$\sigma^*_{x,y}$ = 250 μm	0.25 – 1mm
Normalized emittance (r.m.s.)	2 mm mrad	0.5 – 5 mm mrad
Relative energy spread	$\Delta p/p$ = 0.5%	<0.5%

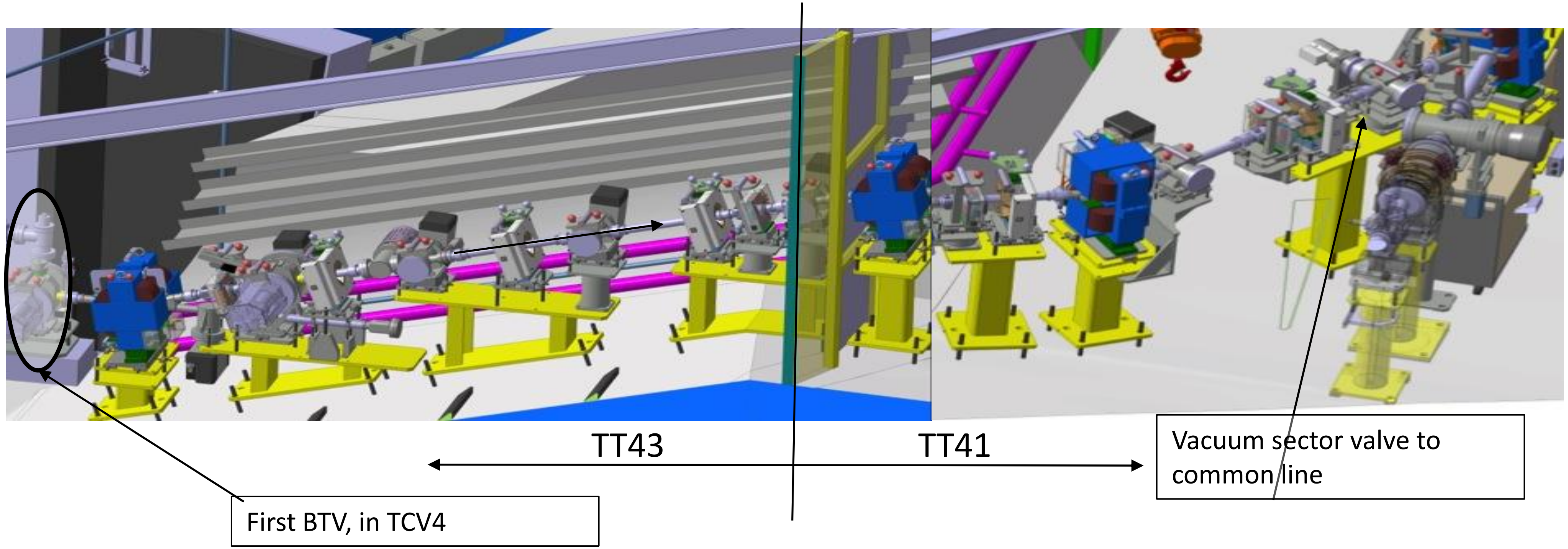
Electron Beam Line



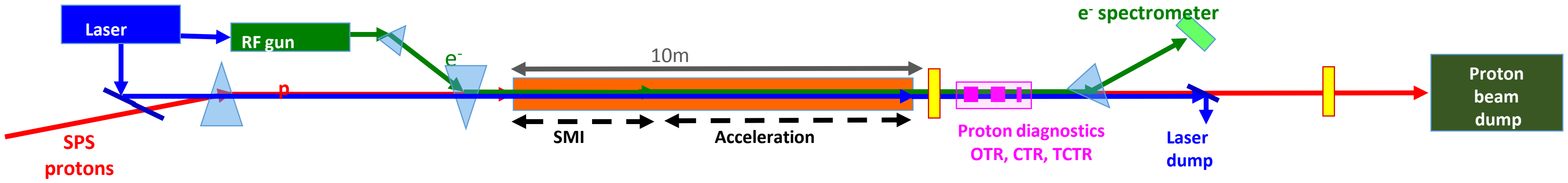
Completely **new beam line and tunnel**:

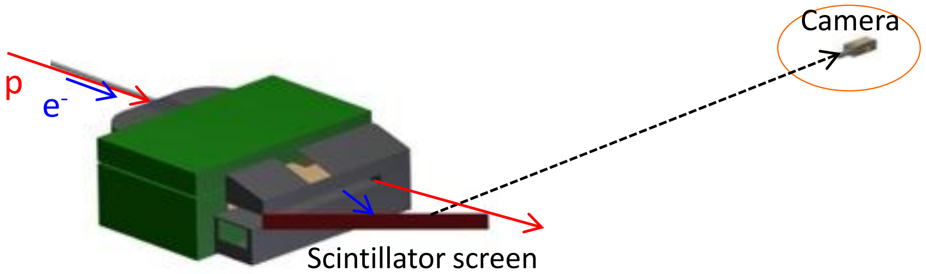
- Horizontal angle of 60 deg,
- 20% slope of the electron tunnel→Δ=1.16m
- 5.66% slope of the plasma cell
- ~5 m common beam line of e^- and p.



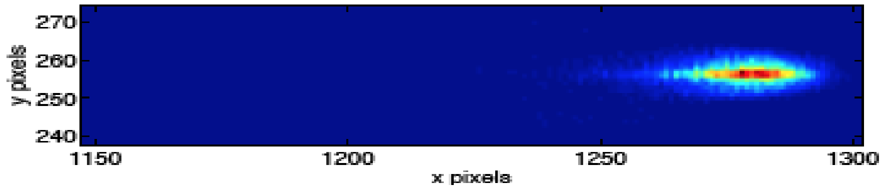


AWAKE Electron Acceleration Diagnostics

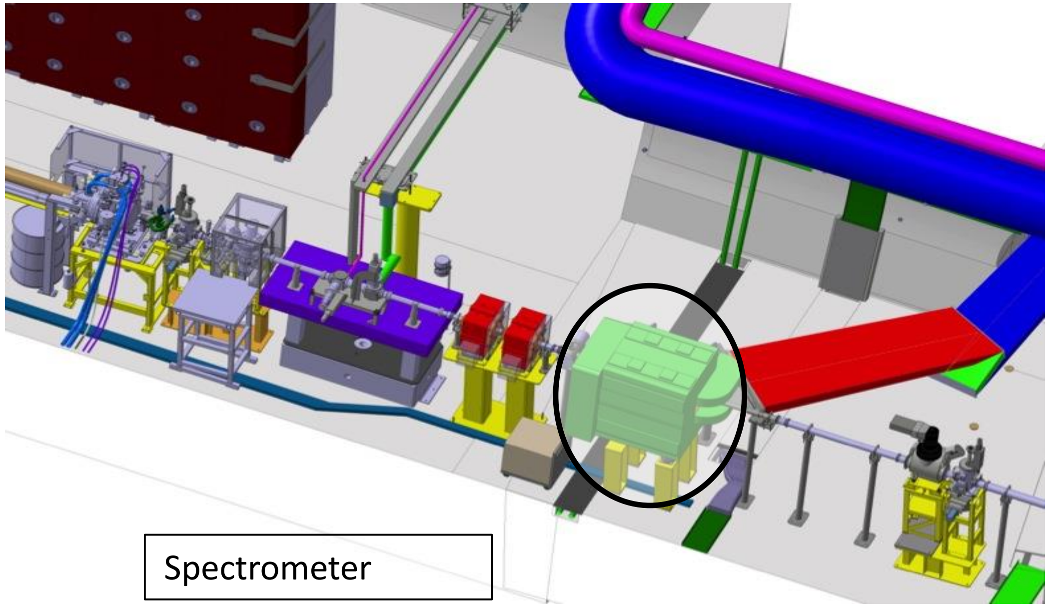




L. Deacon, UCL

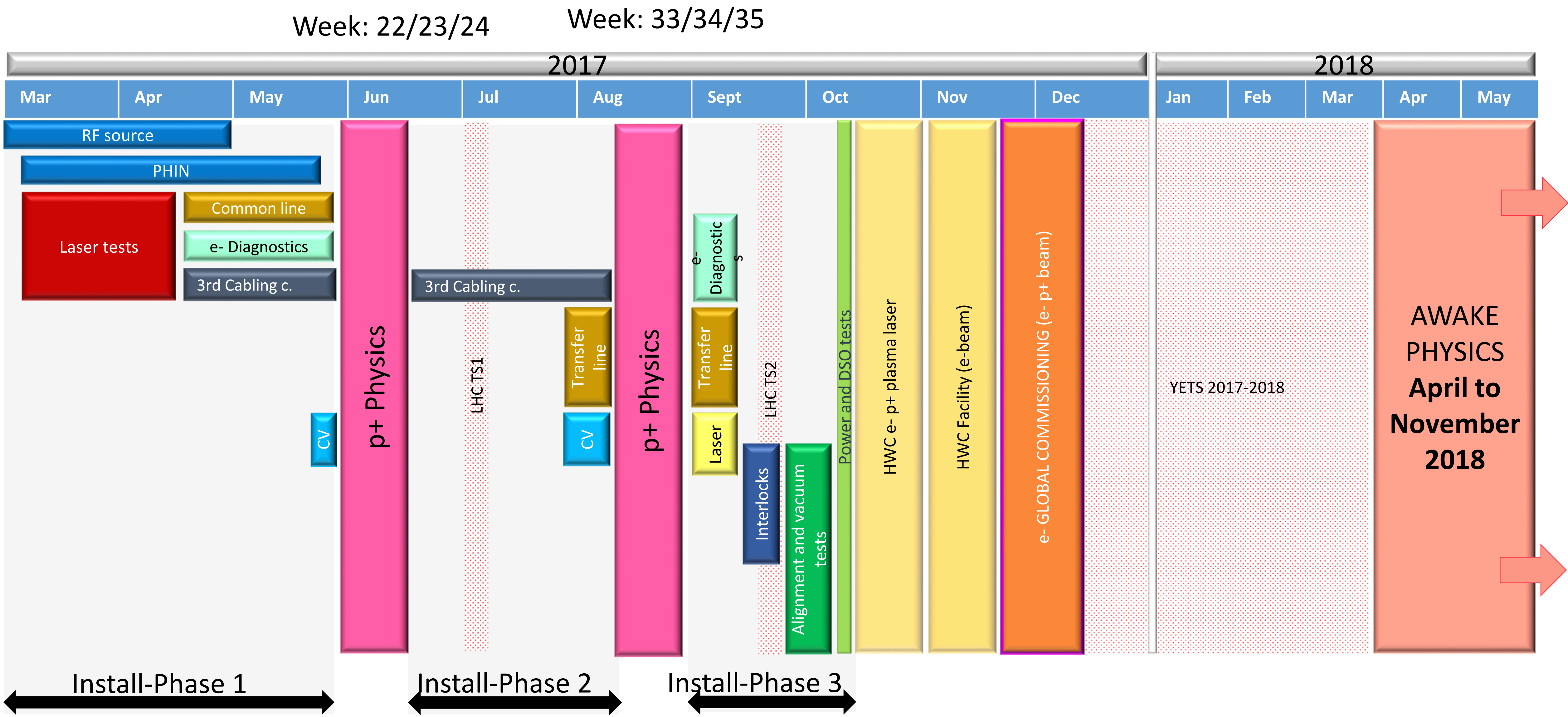


Dispersed electron impact on scintillator screen.
Resulting light collected with intensified CCD camera.
%-level energy resolution achieved with a S/N ratio larger than 1000:1



Electron spectrometer installation, looking downstream

Schedule Overview 2017/2018



Outline

- Introduction
- The AWAKE Experiment
- Commissioning of AWAKE 2016
- First Beam Results 2016
- Run Program 2017
- Electron Acceleration Status
- What's Next
- Summary

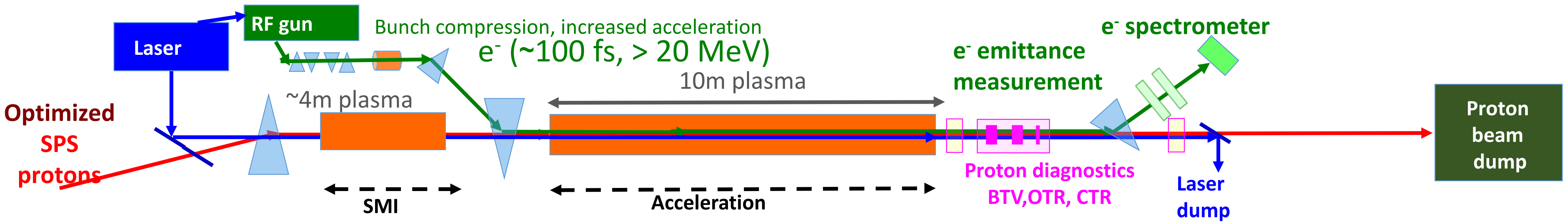
AWAKE Proposal Run 2

Goals:

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

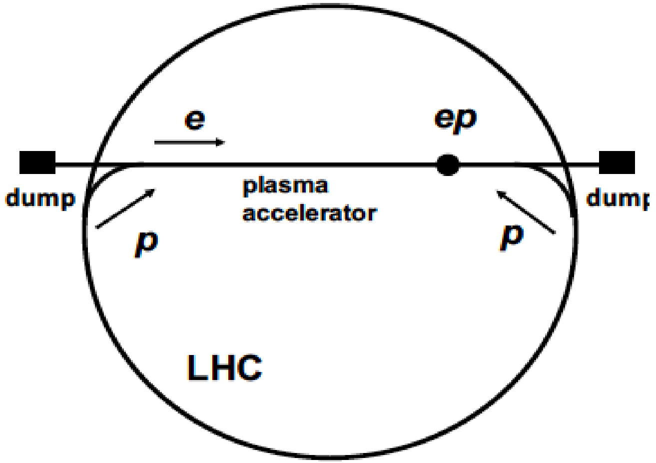
Preliminary Run 2 electron beam parameters

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 to accelerating electrons with ~1 GV/m gradient using **self-modulation instability** of a **long proton bunch in a plasma (σ_z>>λ_{pe})**
- The AWAKE facility was **successfully commissioned in 2016**
- **First signs of SMI** were seen on all three diagnostics during a 48hr run in **December 2016**
- Two **SMI runs in 2017**: weeks **22/23/24** and weeks **33/34/35**
- Electron acceleration experiment: commissioning starting in **October 2017, physics in 2018**
- **Run 2** is proposed for after 2020: preserve electron beam quality, scalability
- First studies on applications of p-driven PWFA