Status and Plans of the AWAKE Experiment

Edda Gschwendtner
for the AWAKE Collaboration

SPSC 18 October 2016

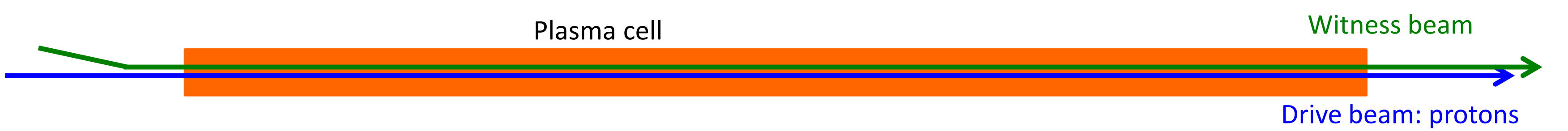
Outline

- Introduction
- AWAKE Facility and Equipment
- AWAKE Beam Commissioning
- Electron Acceleration Status
- AWAKE Run 2 after LS2
- Long-Term Perspectives for Proton-Driven Plasma Wakefield Accelerators
- Summary

Proton Drivers for Plasma Wakefield Acceleration

- Proton drivers: large energy content in proton bunches → interesting for plasma wakefield accelerators
- Drive beams:
  - Lasers: ~40 J/pulse
  - Electron drive beam: 30 J/bunch
  - Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

- Protons drives wakefields over much longer plasma lengths → to reach high energies of a witness beam possible in few stages.
- But: need short bunches → self-modulation instability



Modulated Proton Bunch

- 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)**

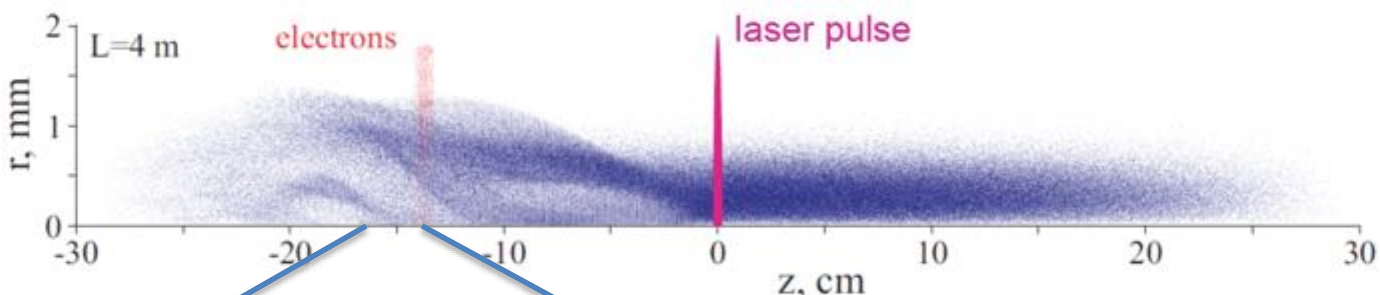
➔ AWAKE Experiment is based on **self-modulation instability**

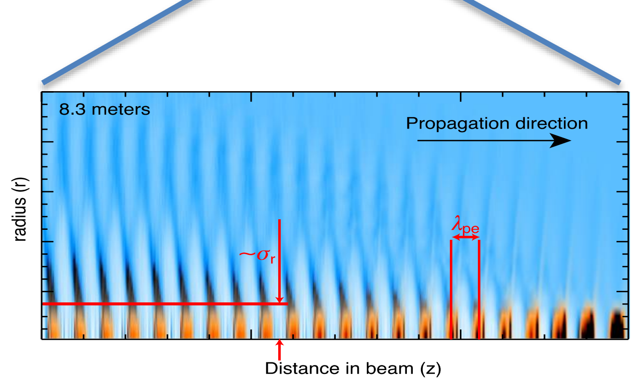
– Modulate long bunch to produce a series of 'micro-bunches' in a plasma with a spacing of plasma wavelength λ_p.

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

→ Resonantly drives the wakefield

→ Modulation should be seeded (with laser in AWAKE)





➔ Immediate use of CERN SPS beam

AWAKE

AWAKE Collaboration: 16+3 Institutes world-wide:

Collaboration members:

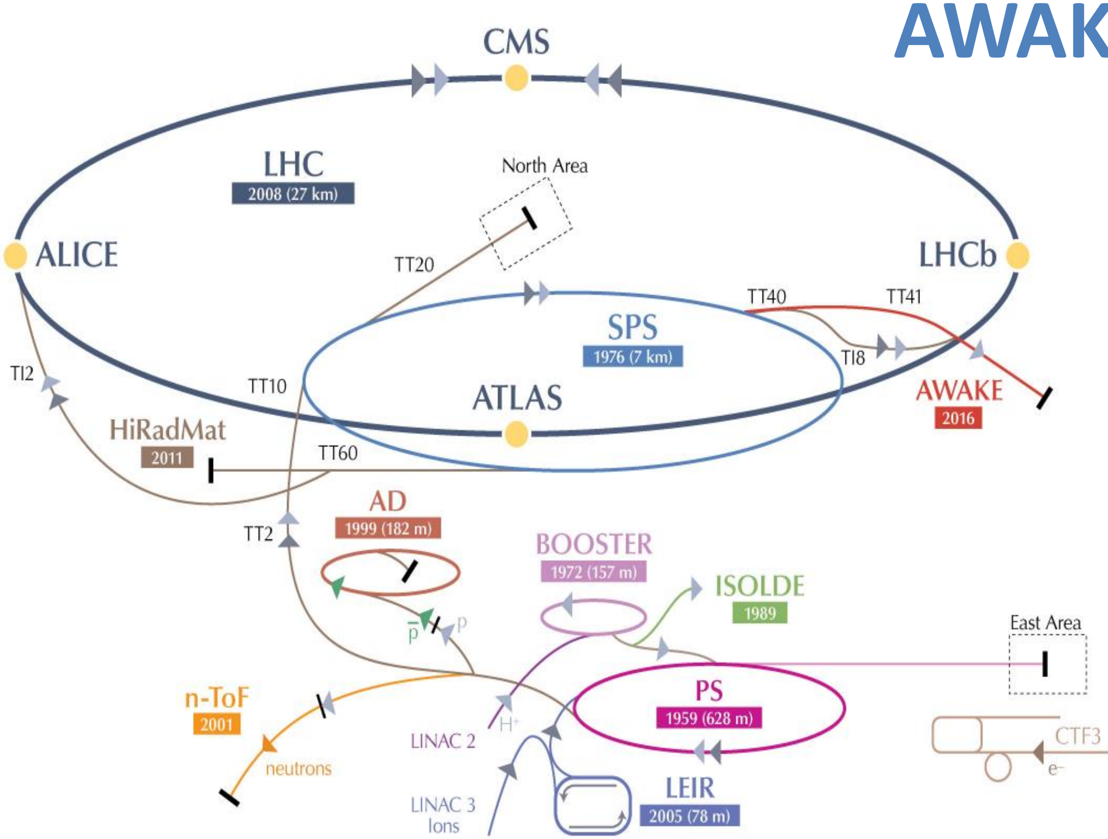
- John Adams Institute for Accelerator Science
- Budker Institute of Nuclear Physics & Novosibirsk State University
- CERN
- Cockcroft Institute
- DESY
- Heinrich Heine University, Düsseldorf
- Instituto Superior Tecnico
- Imperial College
- Ludwig Maximilian University
- Max Planck Institute for Physics
- Max Planck Institute for Plasma Physics
- Rutherford Appleton Laboratory
- TRIUMF
- University College London
- University of Oslo
- University of Strathclyde

Associated members:

- Ulsan National Institute of Science and Technology (UNIST), Korea
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL

Further groups have also expressed their interest to join AWAKE.

AWAKE at CERN



- **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
- Approved in August 2013
- First beam end 2016

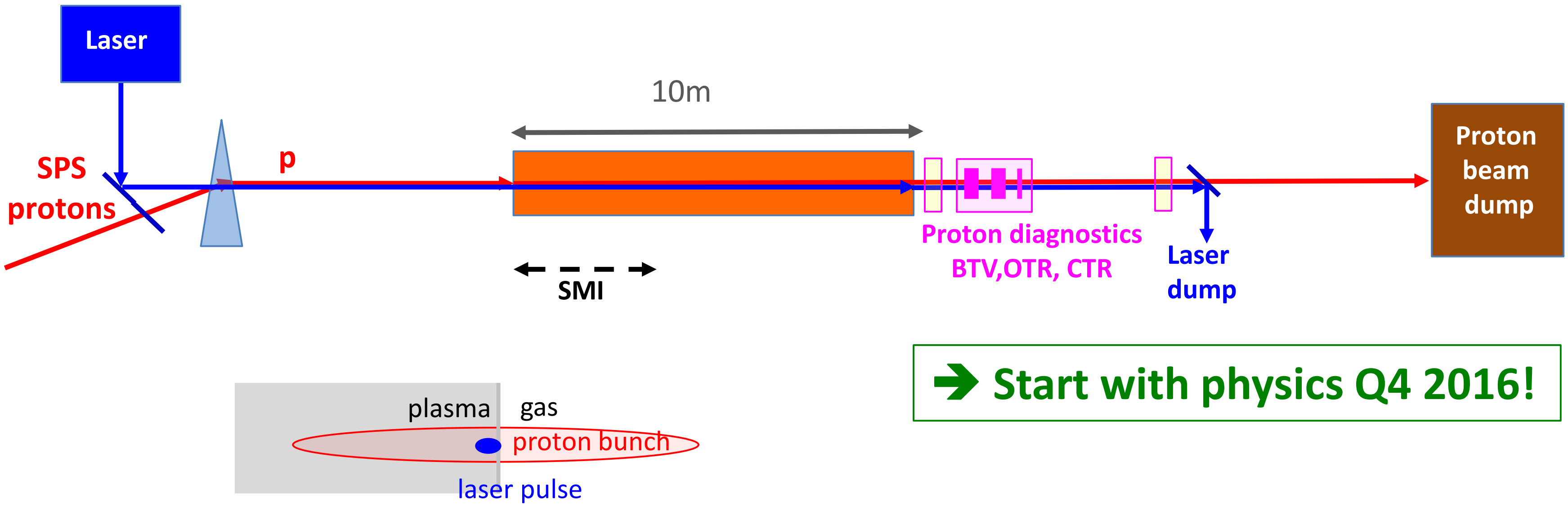
AWAKE Timeline

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022…
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**	
Experim-ental area	Study, Design, Procurement, Component preparation; Modification, Civil Engineering and installation									
e⁻ source and beam-line	Studies, design		Fabrication	Installation; Commissioning	**Phase 2**					

cont’d

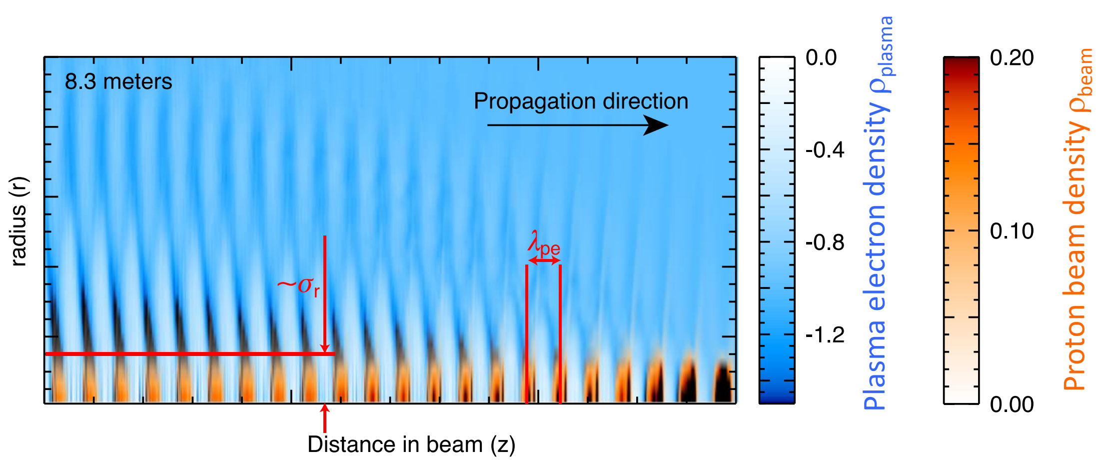
AWAKE: Experimental Program

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



➔ Start with physics Q4 2016!

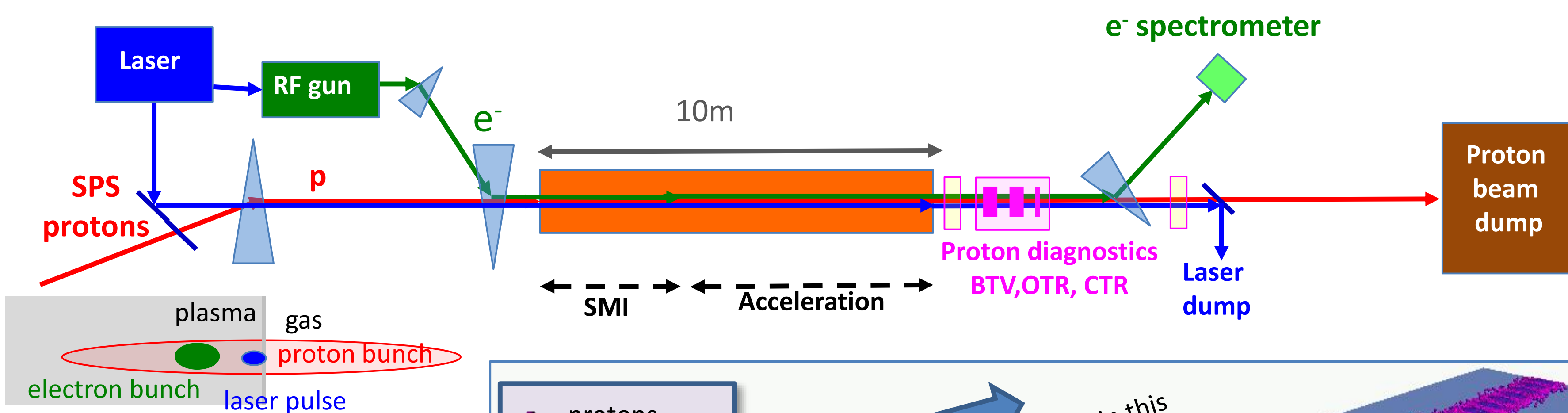
Self-modulated proton bunch resonantly driving plasma wakefields.

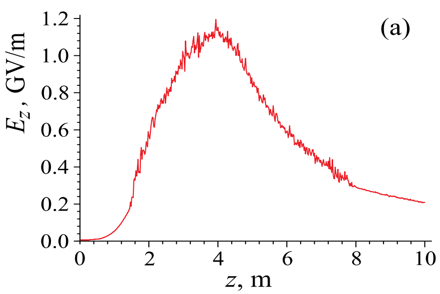


J. Vieira et al PoP 19063105 (2012)

AWAKE Experimental Program

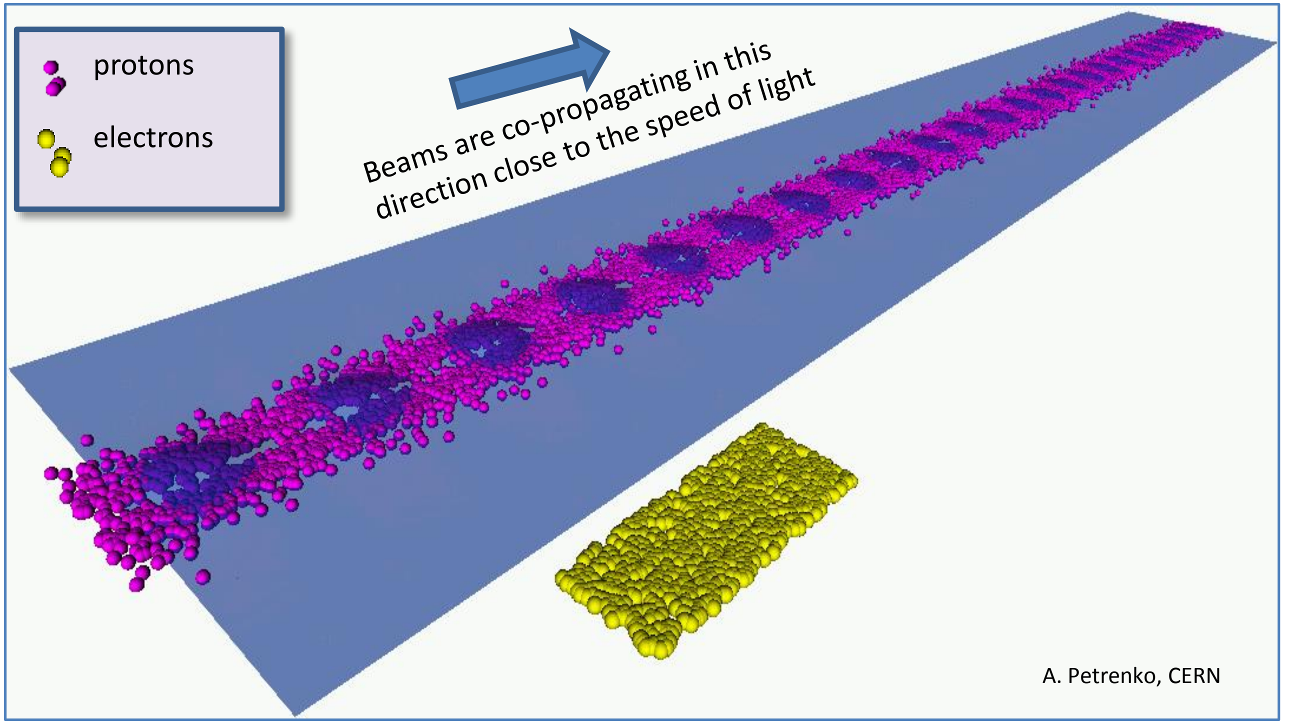
- Phase 1: Understand **the physics of self-modulation instability** processes in plasma.
- Phase 2: **Probe the accelerating wakefields** with externally injected electrons.





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

➔ Start with physics Q4 2017!



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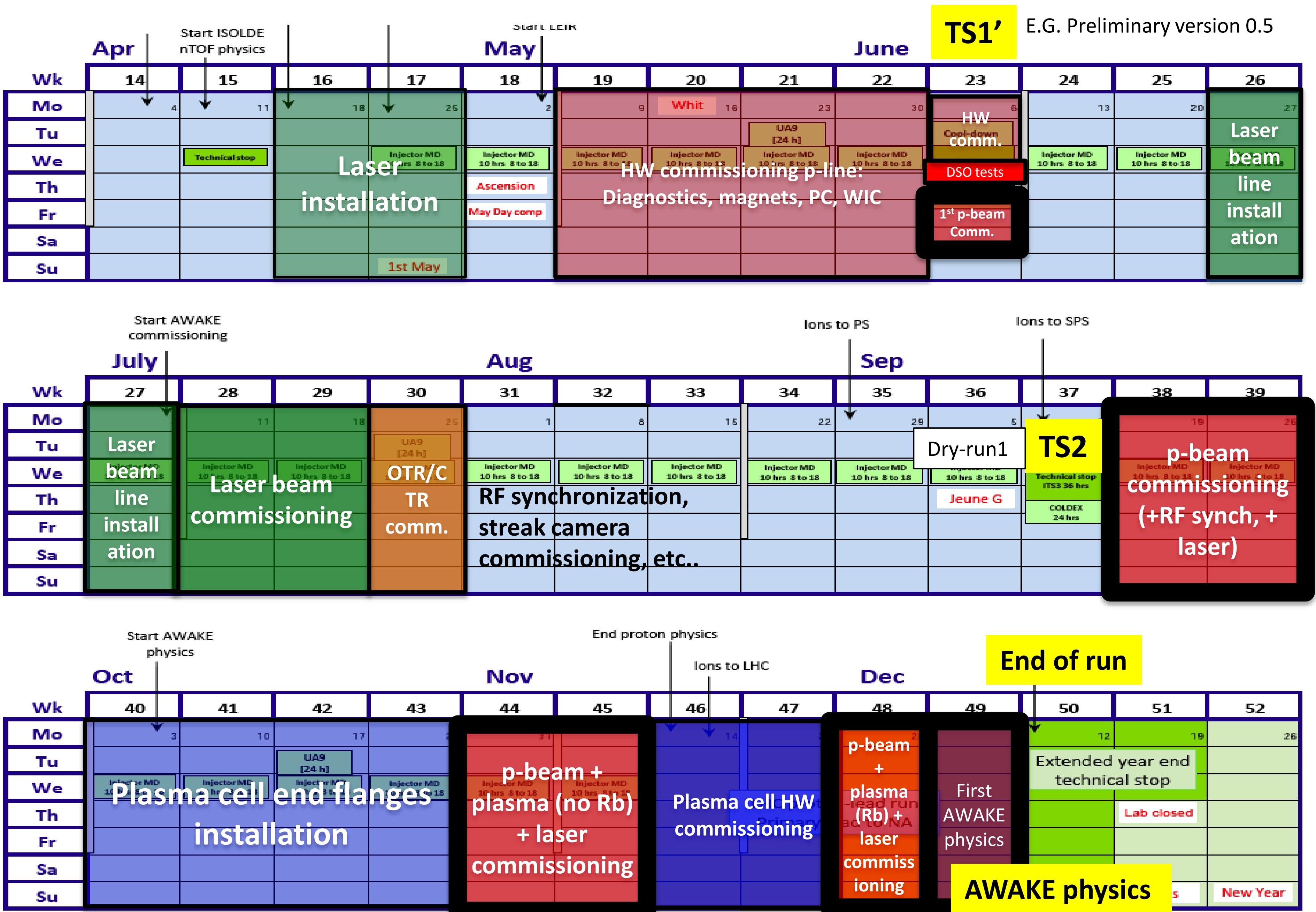
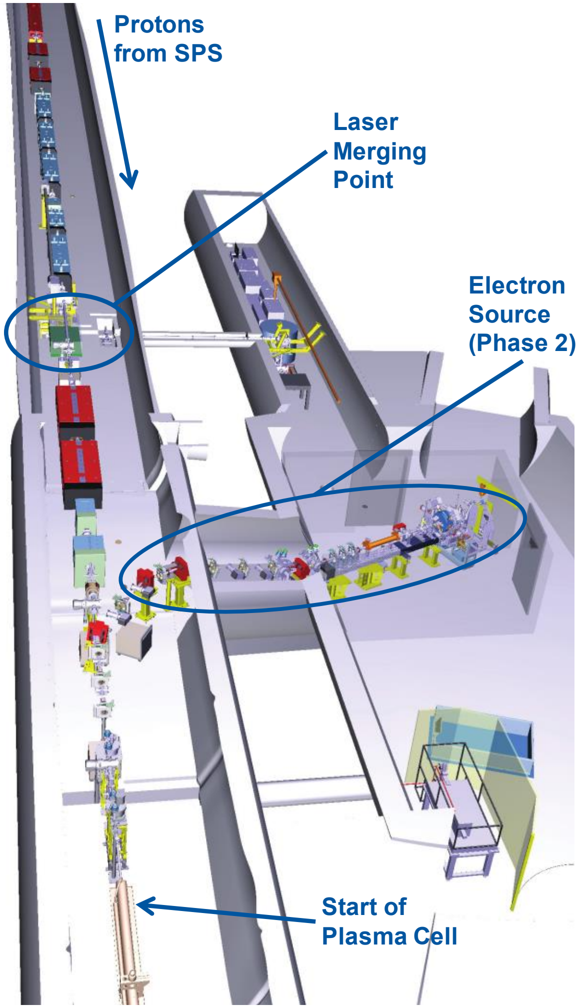
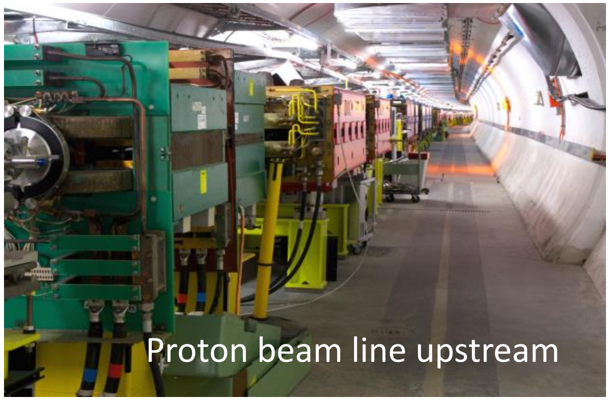
AWAKE Planning 2016



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

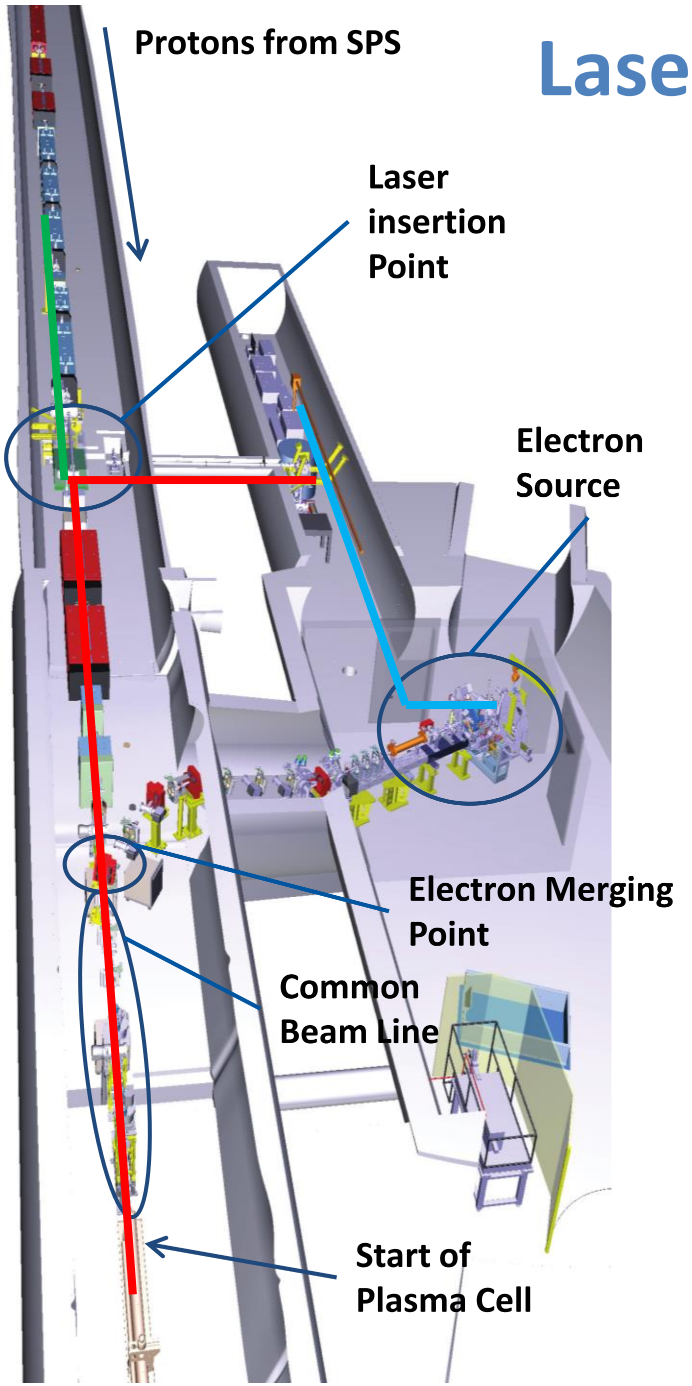



Proton beam line upstream


Proton beam line downstream

➔ **Proton beam line fully installed** (Magnets, Instrumentation, Vacuum)
Hardware commissioning finished

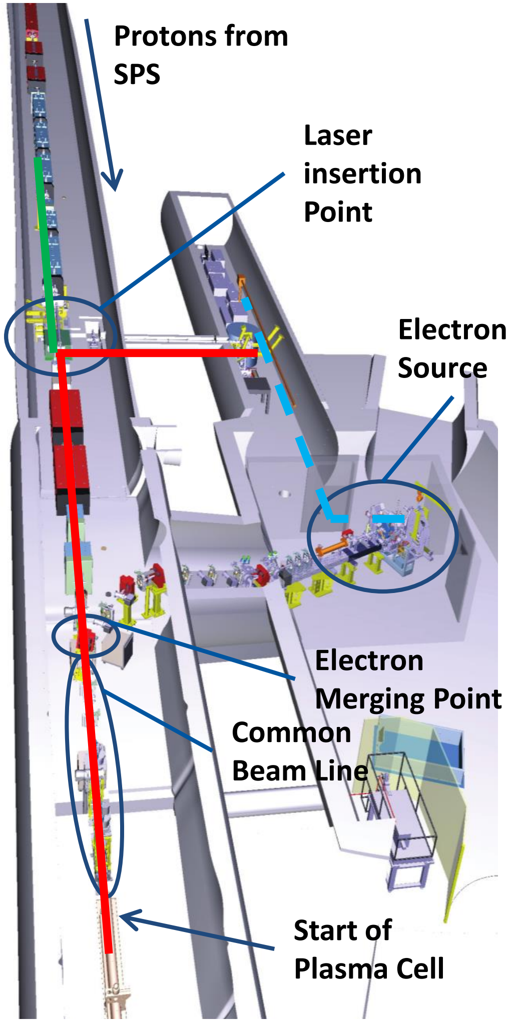
Laser and Laser Line

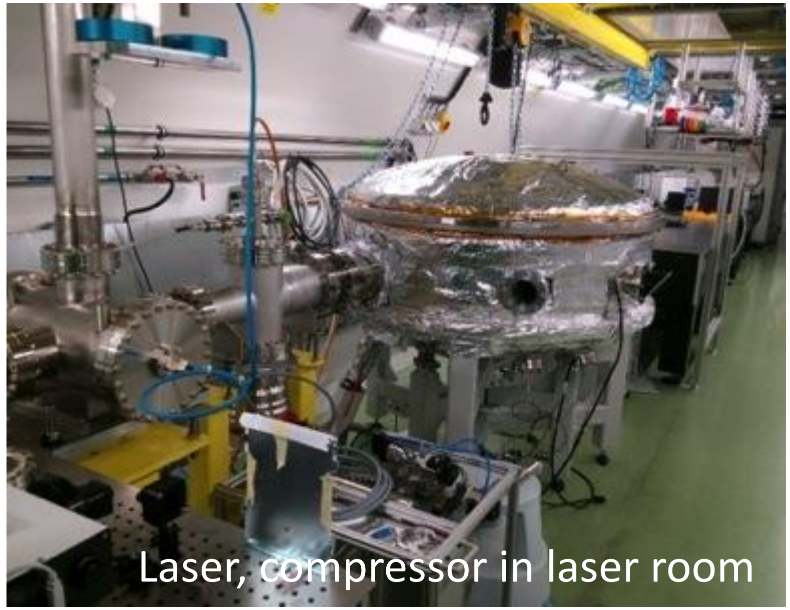


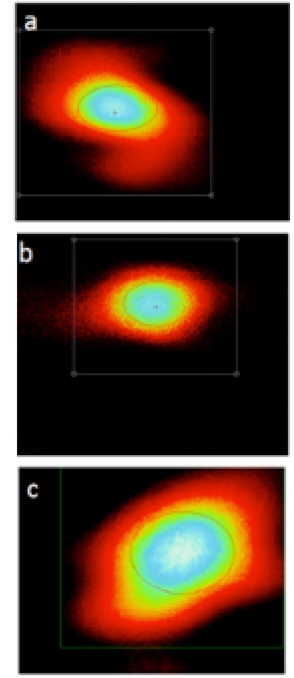
- **Laser beam line to plasma cell**
  - λ = 780 nm
  - t pulse = 100-120 fs
  - E = 450 mJ
- **Diagnostic beam line ("virtual plasma")**
  - λ = 780 nm
  - t pulse = 100-120 fs,
  - E ≈ 5 mJ
- ***Laser beam line to electron gun (to be installed in 2017)***
  - *λ = 260 nm*
  - *t pulse = 0.3-10 ps*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

➔ **Laser system installed** and **commissioned**:
- Laser, compressor, safety shutters, beam dumps, mirrors
- **Control system** → integrated in CERN control system
- Lots of **efforts** in commissioning of laser itself

Laser and Laser Line

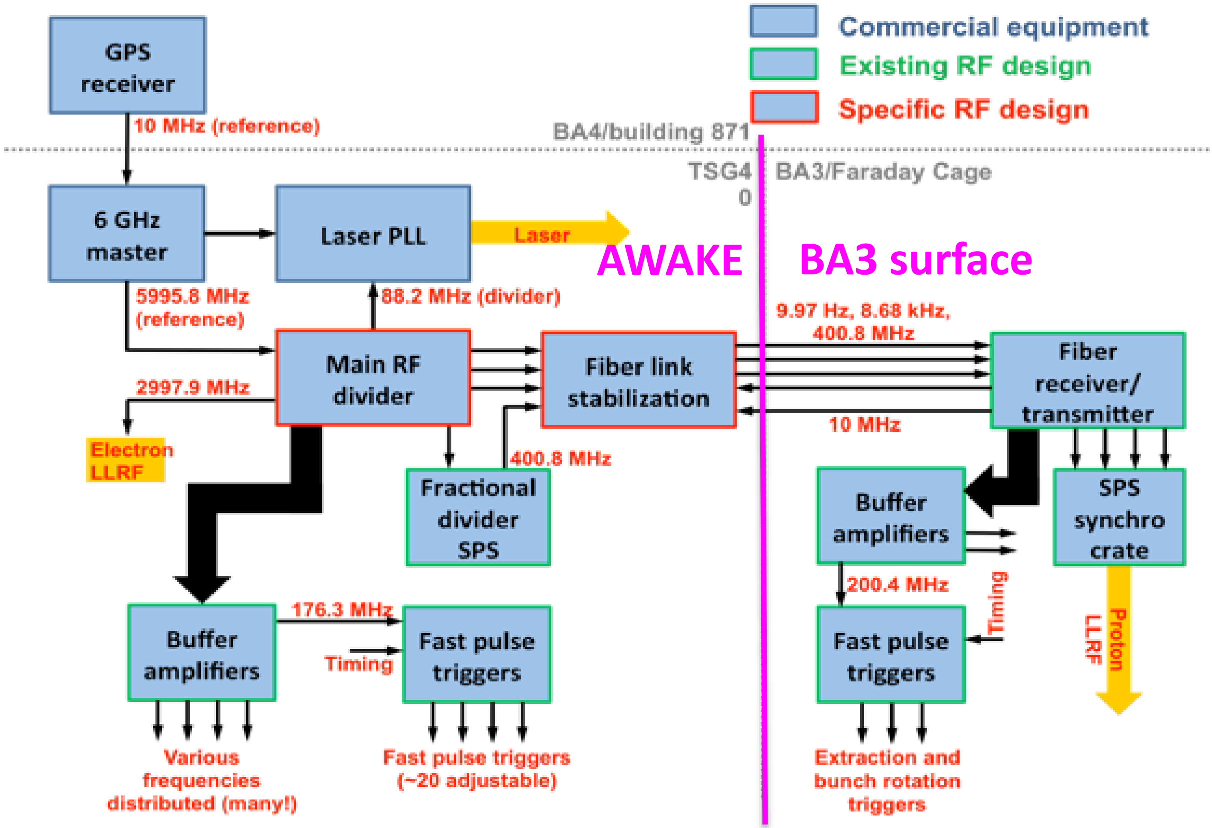


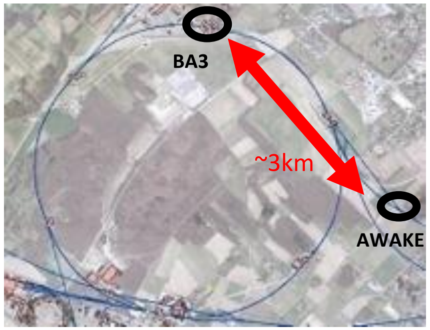




Laser profile on virtual transport line

AWAKE RF Synchronization





- **Deliver wide range of RF signals** for laser, proton and electron beams
- **Precision trigger pulses** for beam instrumentation
- **Active link stabilization** to the ps-level for 3km transmission from AWAKE to BA3

RF Hardware Development and Installation

AWAKE TSG40 | BA3/Faraday Cage **BA3 surface**

Link compensation

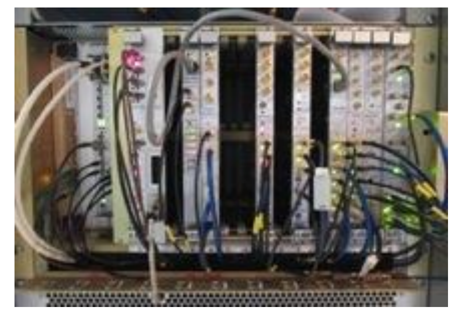
Fast triggers

Synchro crate

Main divider, RF trains

Distribution, frac. divider

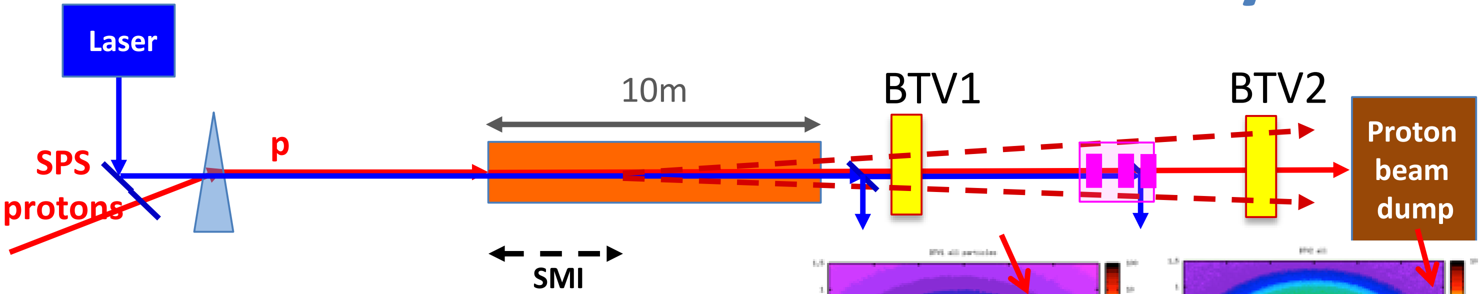
AWAKE crate

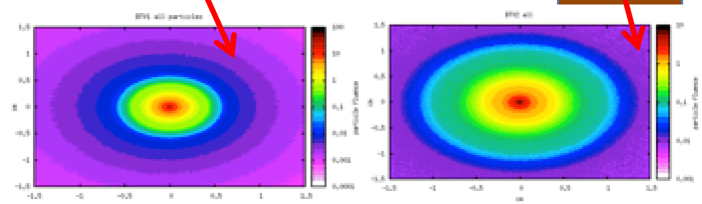


➔ **Tests and validation steps done to synchronize protons with laser:**

1. Use signals from AWAKE
   - ✓ All frequencies in **correct range**
2. Coarse alignment of SPS proton bunch and laser pulse
   - ✓ **Proton bucket selection** mechanism in AWAKE LLRF **validated**
3. Fine phase of protons at SPS extraction (within one ‘half bucket’)
   - ✓ **Temporary set-up** works **as expected**

Self-Modulation Instability Detectors

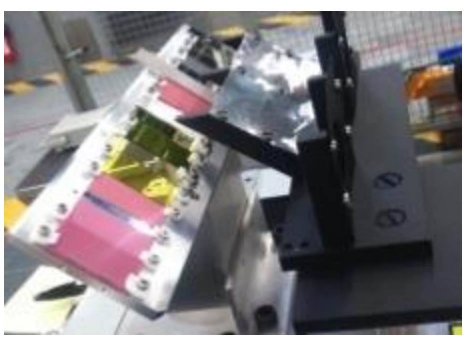




Indirect SMI Measurement:
Measure the **angle of the maximum defocused protons** to indirectly prove the SMI development of the proton beam and **reconstruct the saturation** point of the SMI.

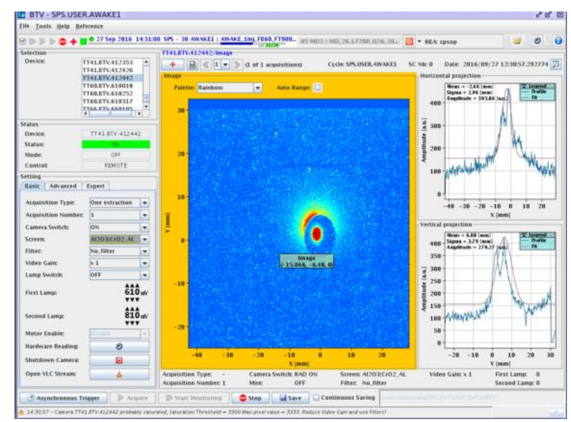
Measurements in the HiRadMat Facility
→ **Defined the choice** for the BTV screens (1mm Chromox Al_2O_3:CrO_2)

➔ Installed and commissioned



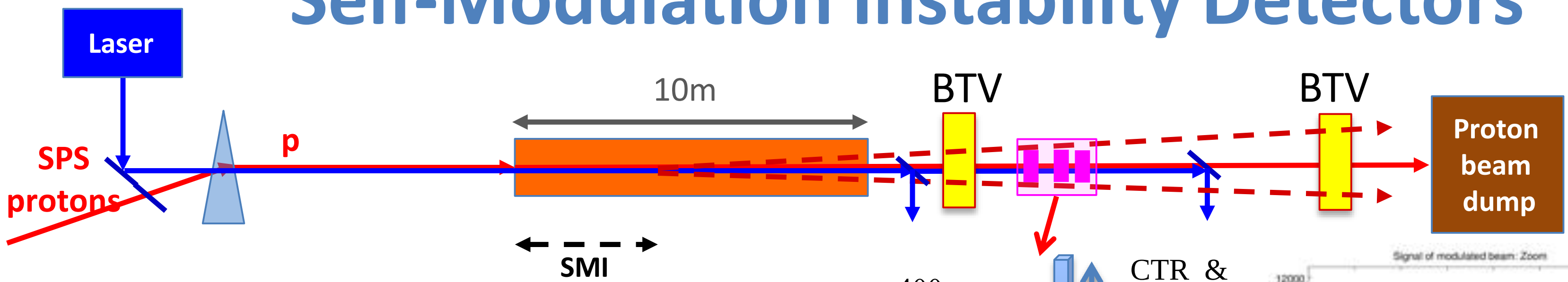
HiRadMat setup

Chromox screen



Measured proton beam on BTV2

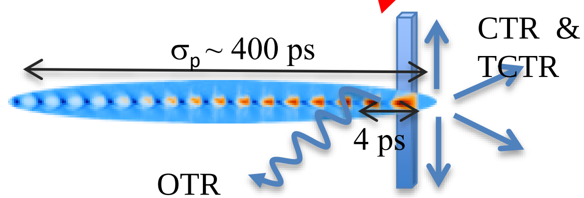
Self-Modulation Instability Detectors

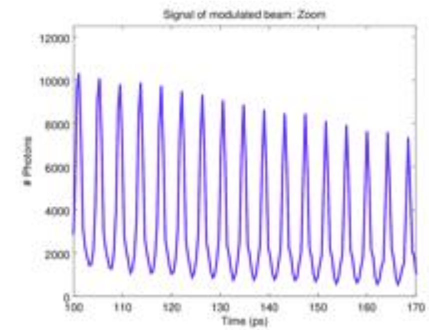


Direct SMI Measurement:

Radiation emitted by bunch when traversing dielectric material

→ Streak camera





➔ Installed and commissioned

OTR/CTR table with installation

Light transport to streak camera

Streak camera

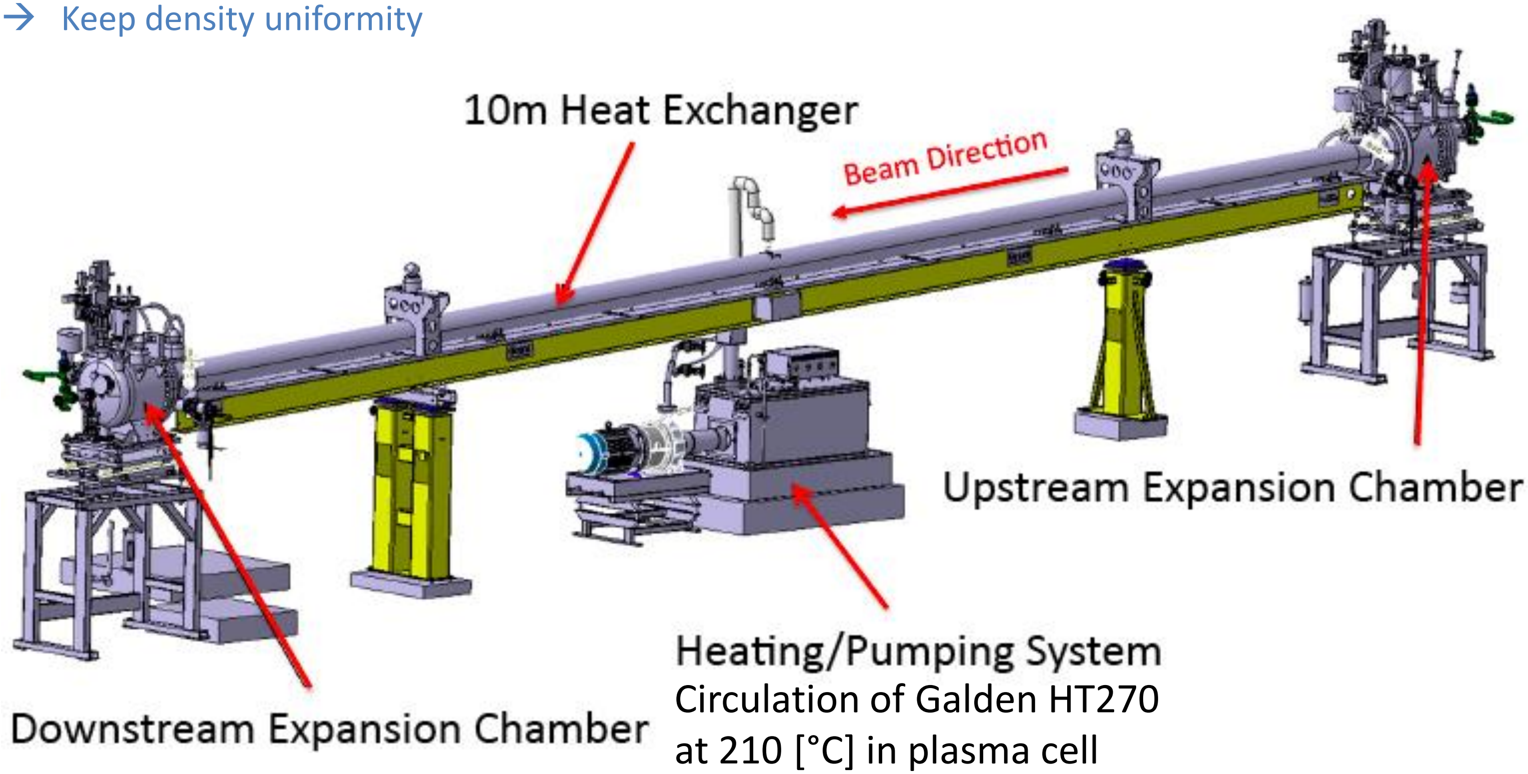
Plasma Cell

Rubidium Vapour Source

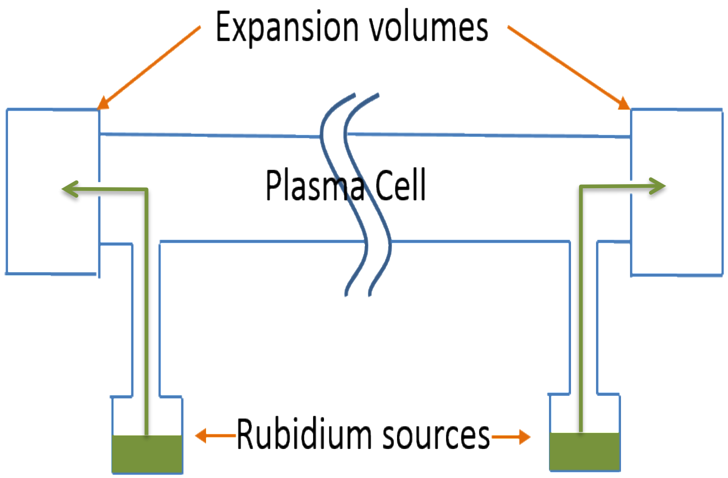
- Density adjustable from **$10^{14} - 10^{15}$ cm^{-3}**, 10 m long, 4 cm diameter

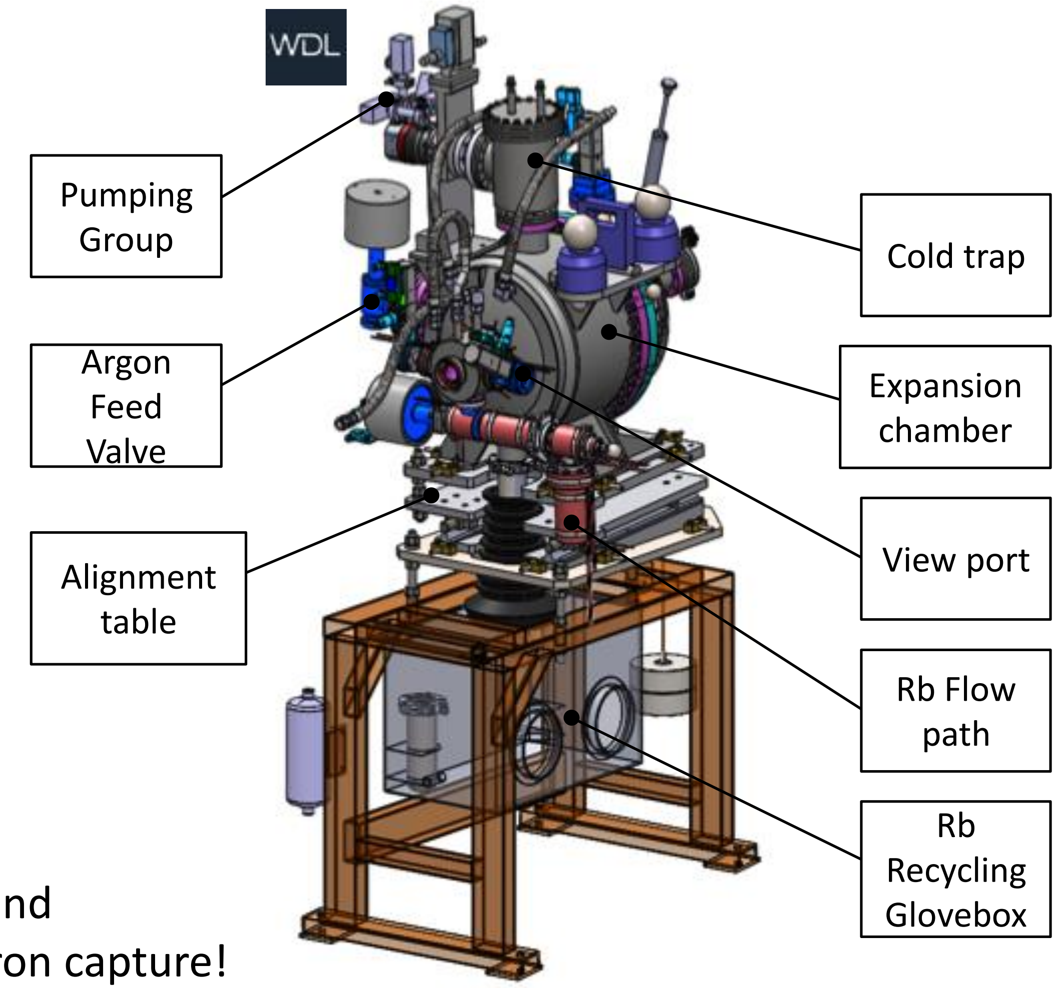
- Plasma formed by field ionization of Rb
  - Ionization potential Φ_{Rb} = 4.177eV
  - above intensity threshold (I_{ioniz} = 1.7 x 10^{12}W/cm^2) 100% is ionized.

- System is oil-heated ~ 210˚ C
  - → keep temperature uniformity at T_{op} ± 0.1 [°C] over the 10 [m] cell length
  - → Keep density uniformity



Why this Complex Plasma End Flange?





Revised solution for source ends
Valves resulted in long Rb density ramp and slow refill time. → strong effect on electron capture!

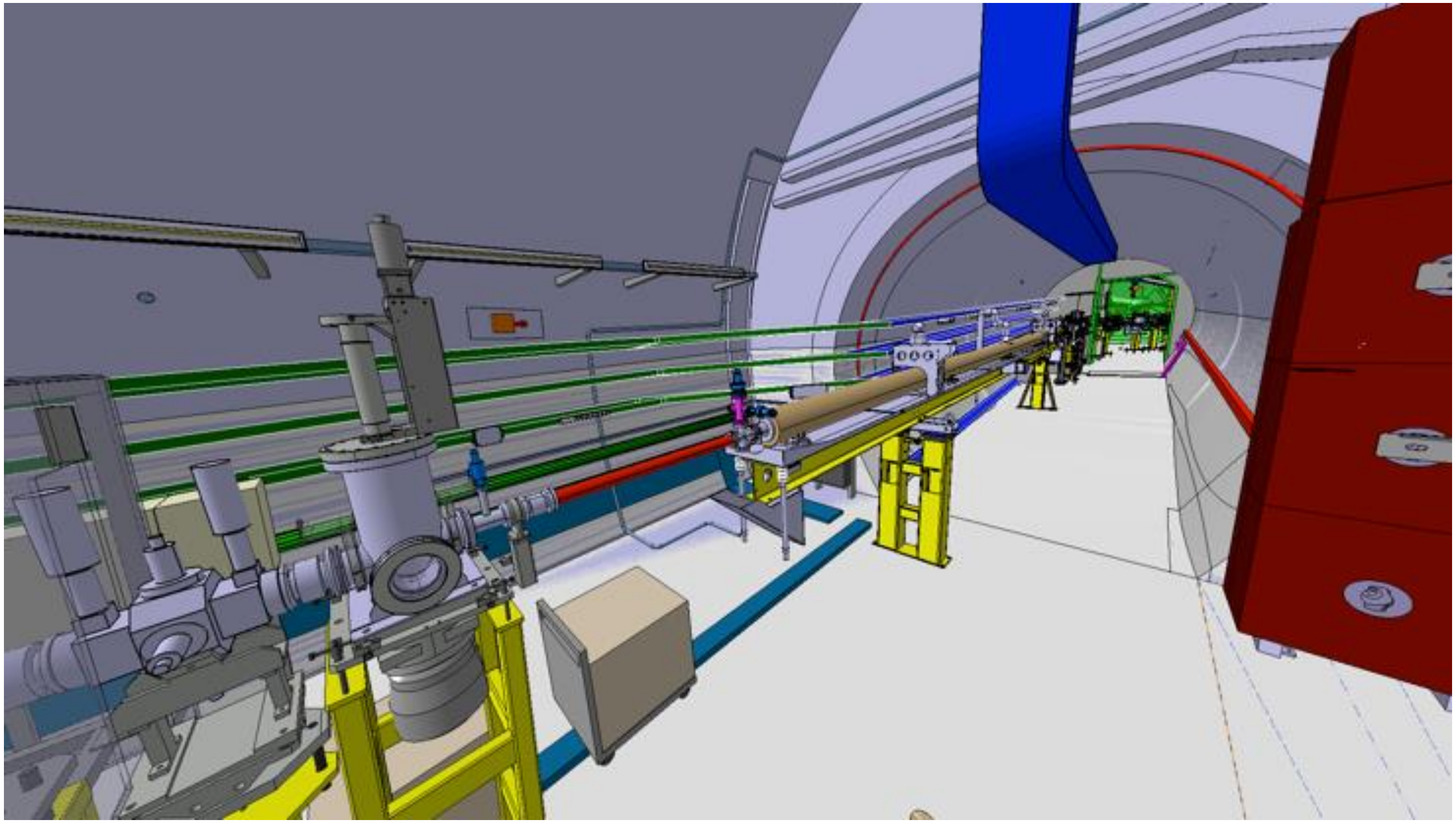
→ New solution: continuous flow through small aperture

→ 2016: final design and manufacturing

Plasma Cell: Current Status

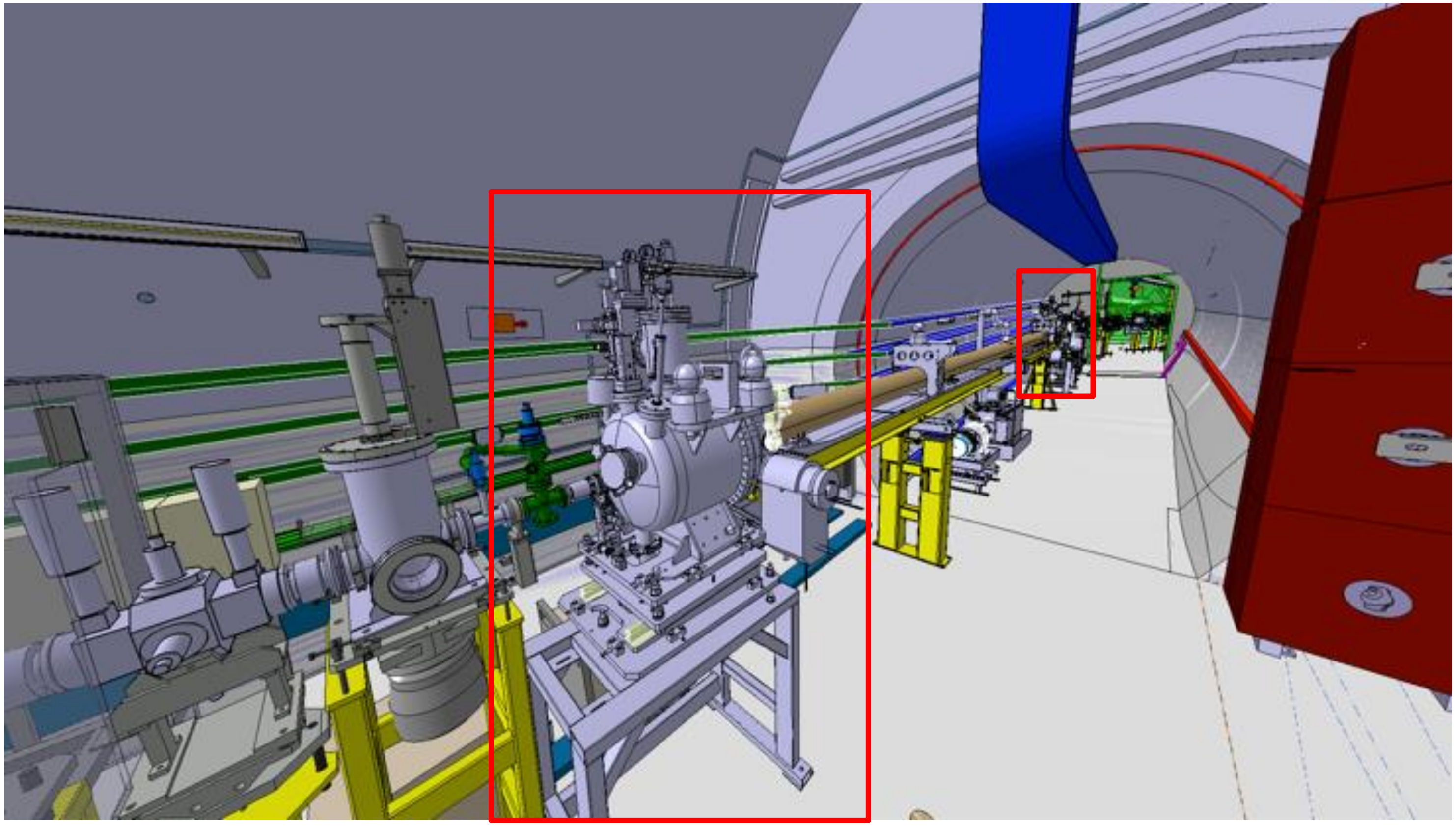
10m long plasma cell installed in Feb 2016

For beam commissioning: Connected to vacuum system with spare vacuum tube



Plasma Cell End Flange Integration

Plasma cell end flange installation

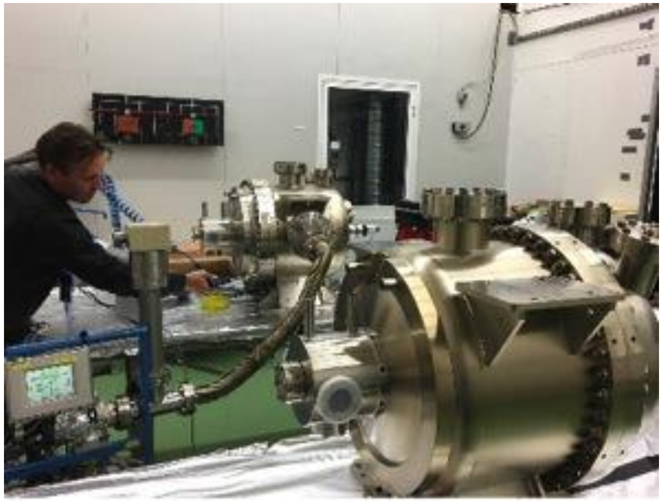


AWAKE Plasma End Flanges

Delivered to CERN in September 2016

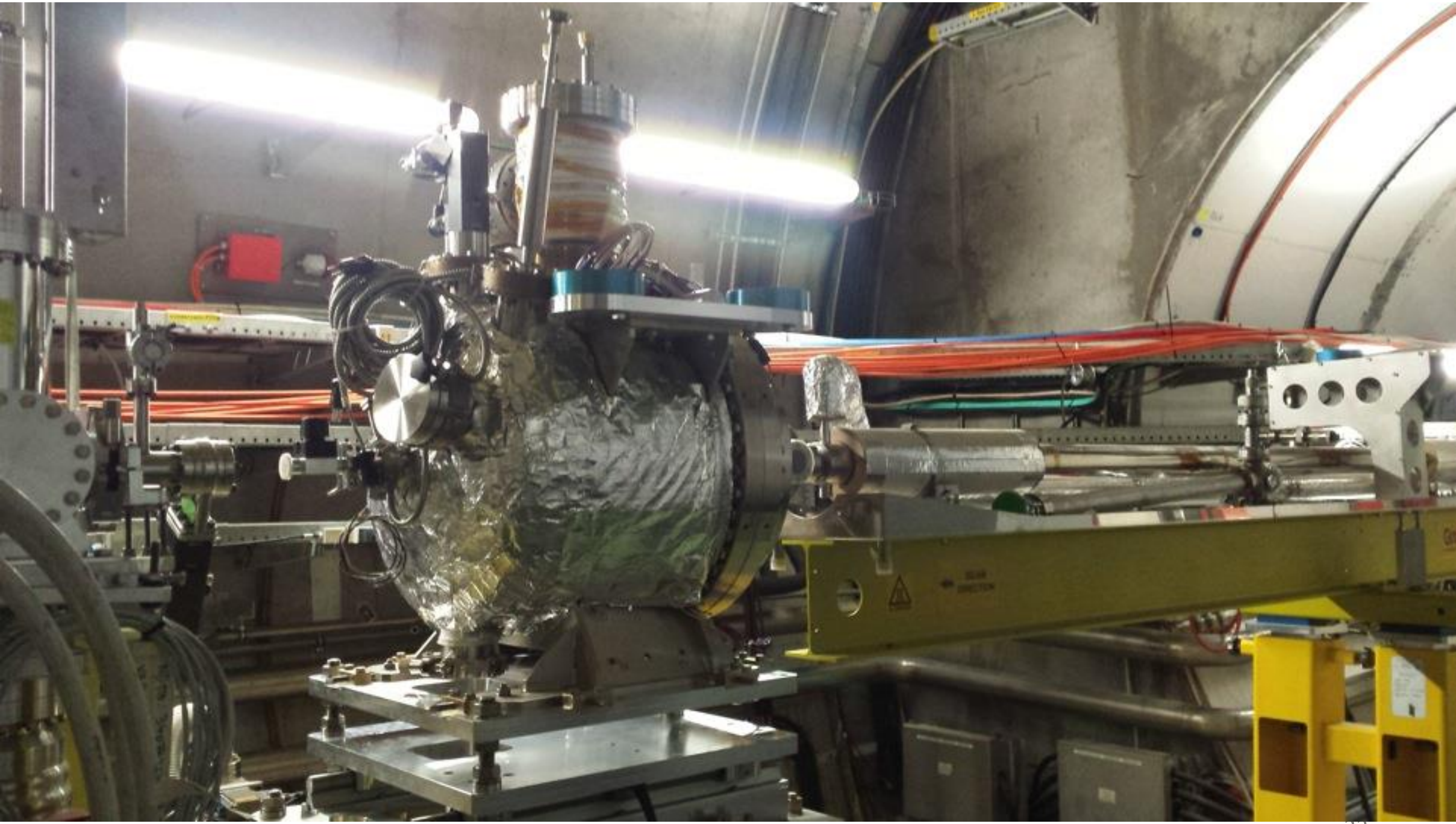
Clean Room Activities:

- UHV vacuum reception tests
- Alignment



Plasma End Flanges in AWAKE Tunnel

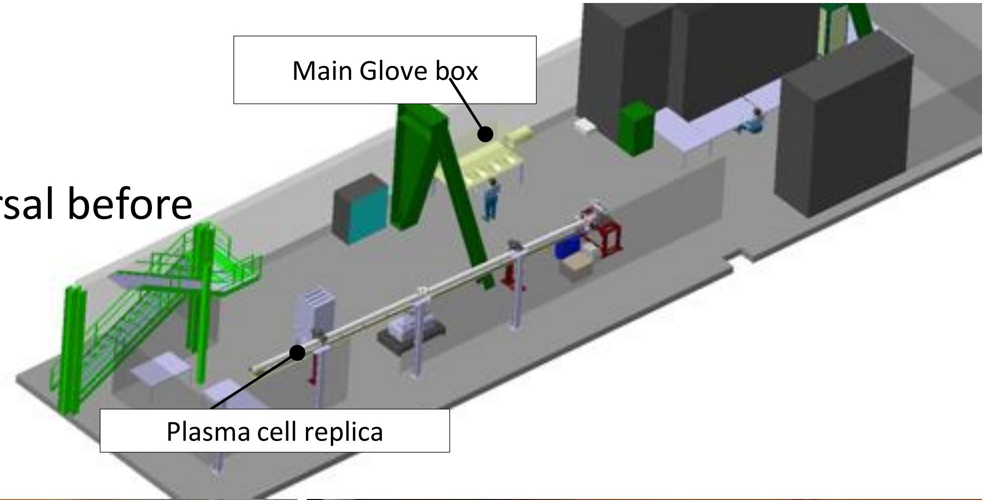
➔ **Installed and aligned 17 October 2016**



EHN1 Surface Plasma Cell Test Area

Main activities

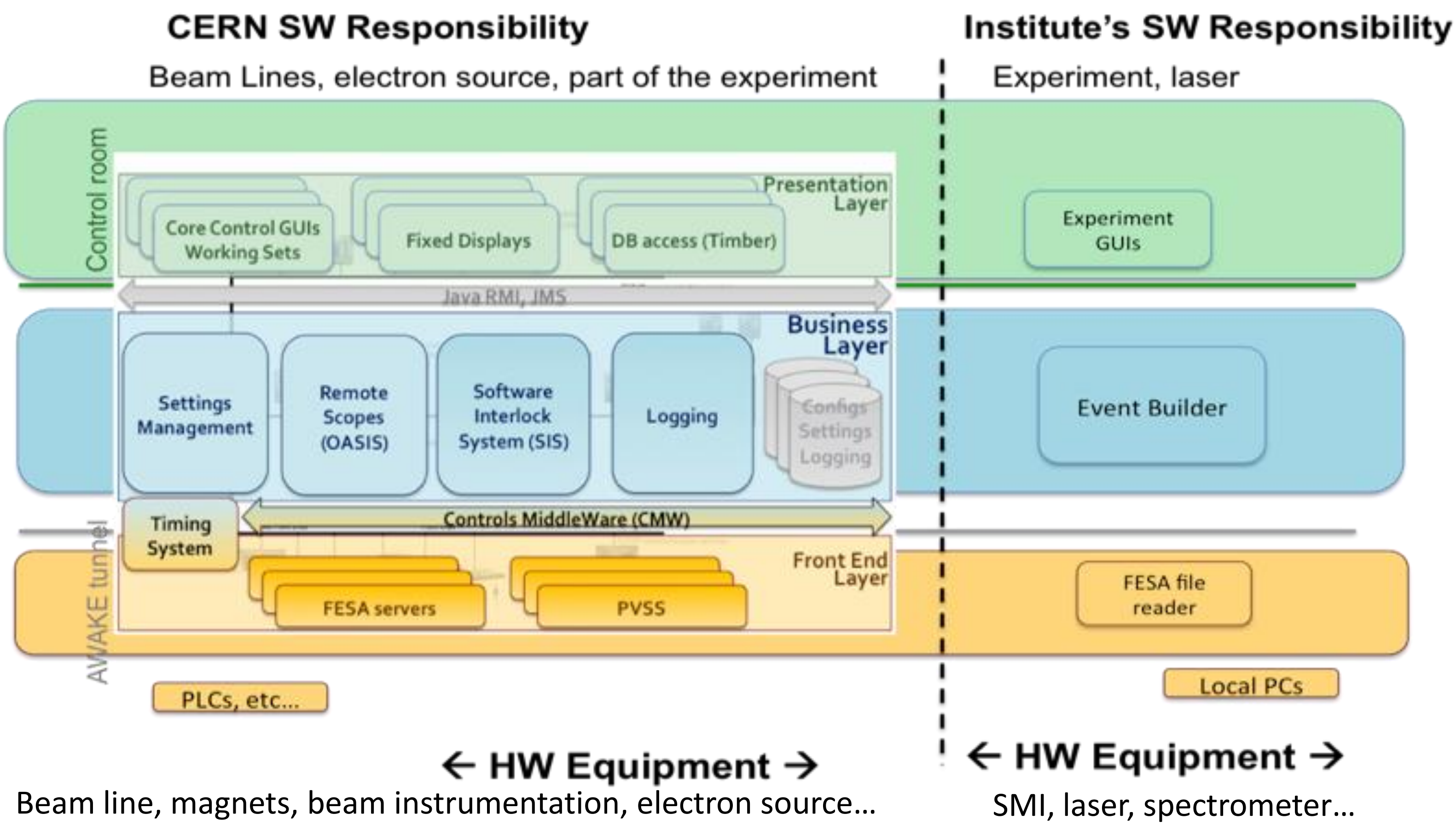
- **Control system**: integration and test
- Probes calibration
- **Rb handling processes**: testing and rehearsal before Rb will be installed in the tunnel



AWAKE Control System

Built on architecture provided by the CERN accelerator controls group.
Strong collaboration between **CERN controls groups, CERN equipment groups and institutes** to develop technical solutions for integration of AWAKE specific equipment.

➔ **Validated during dry-run and commissioning run**



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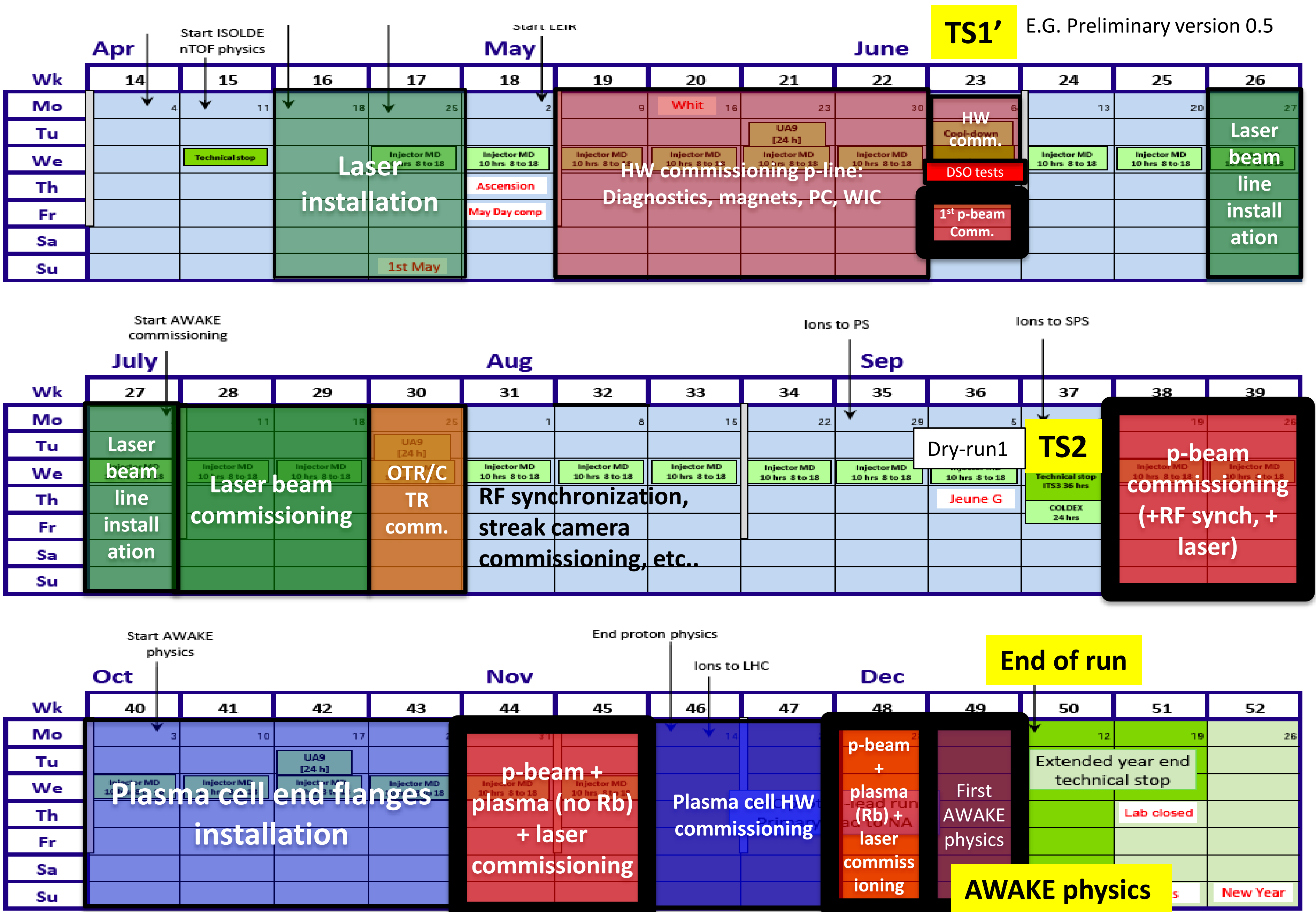
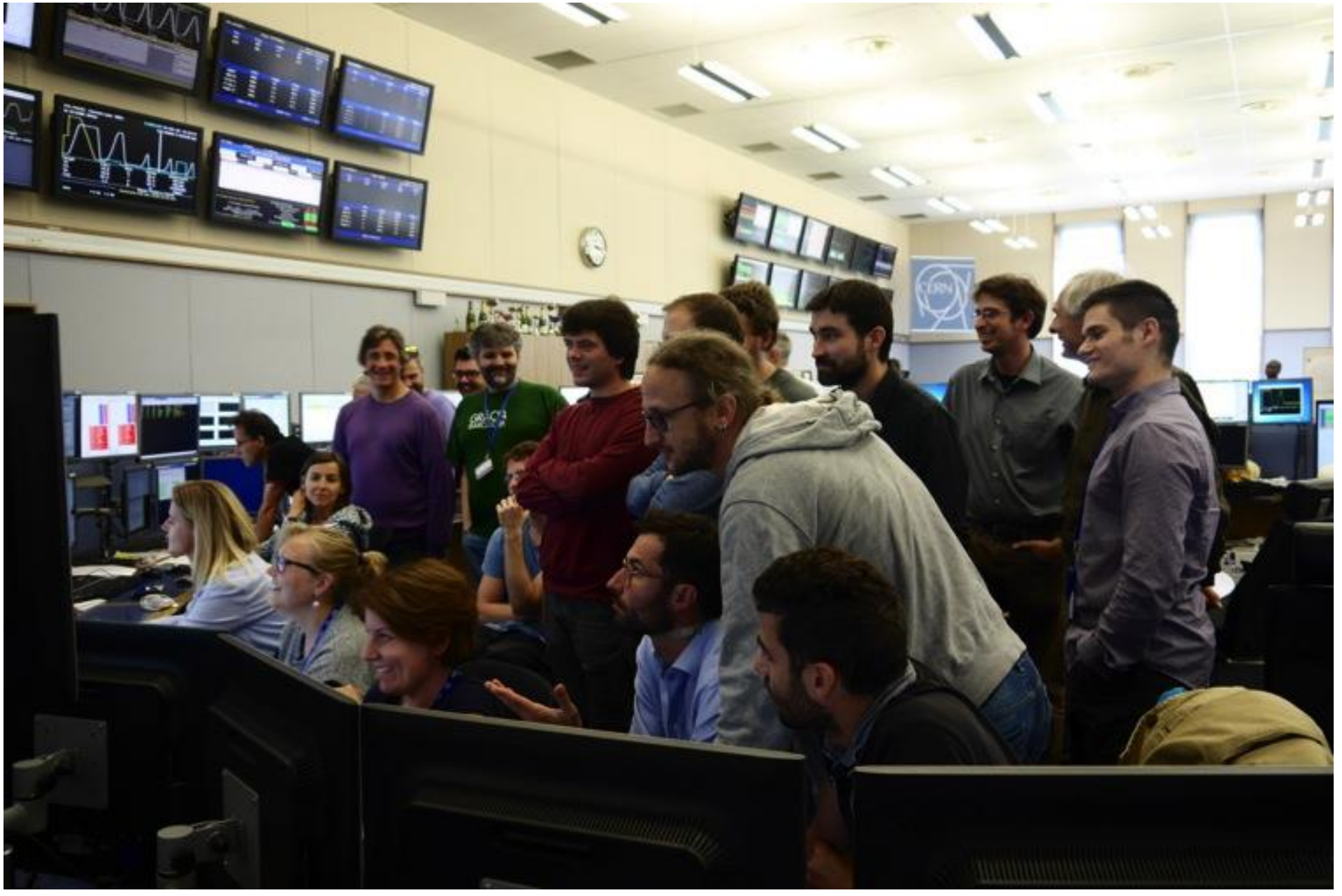
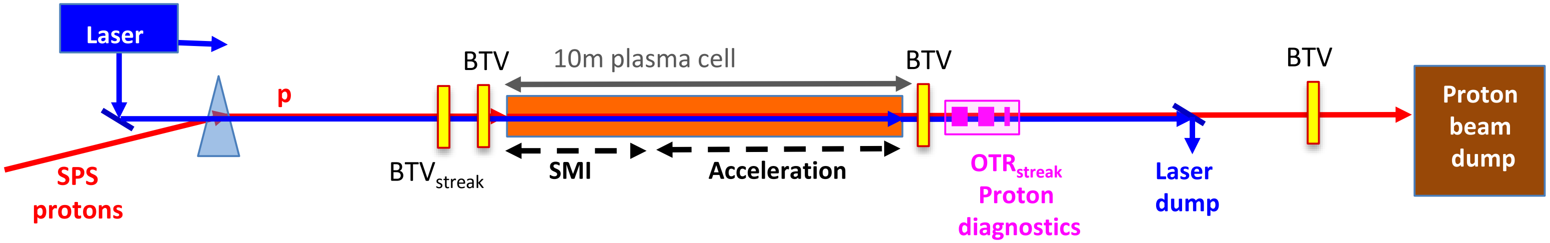


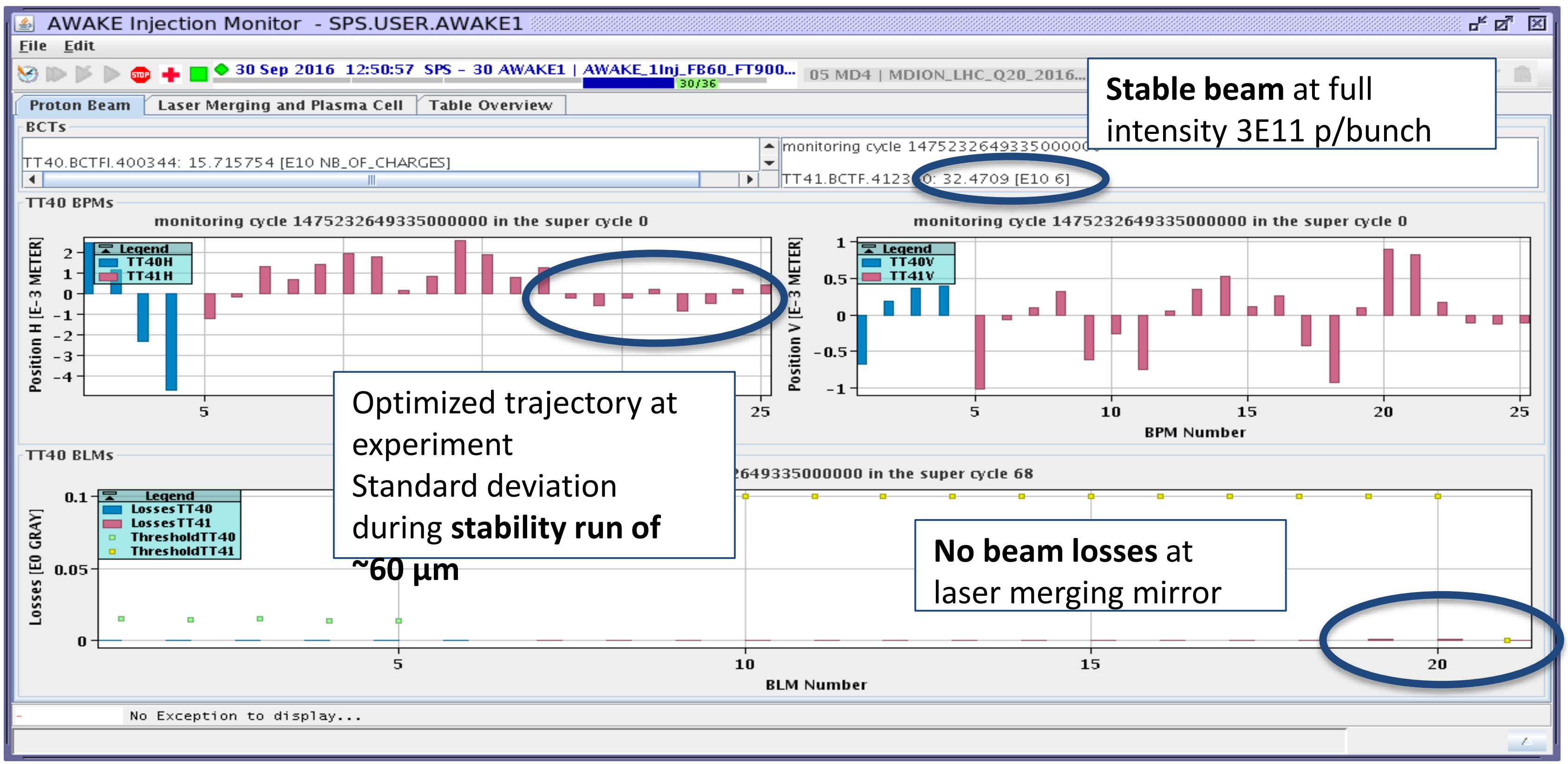
Proton and Laser Beam Commissioning 2016



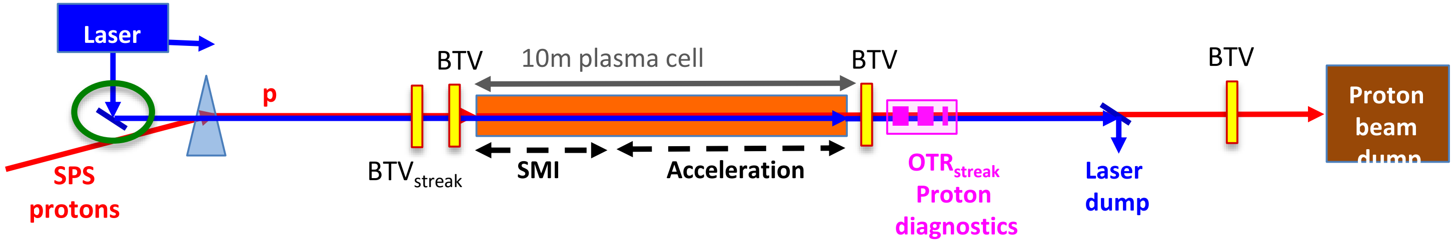
Results Proton Beam Commissioning

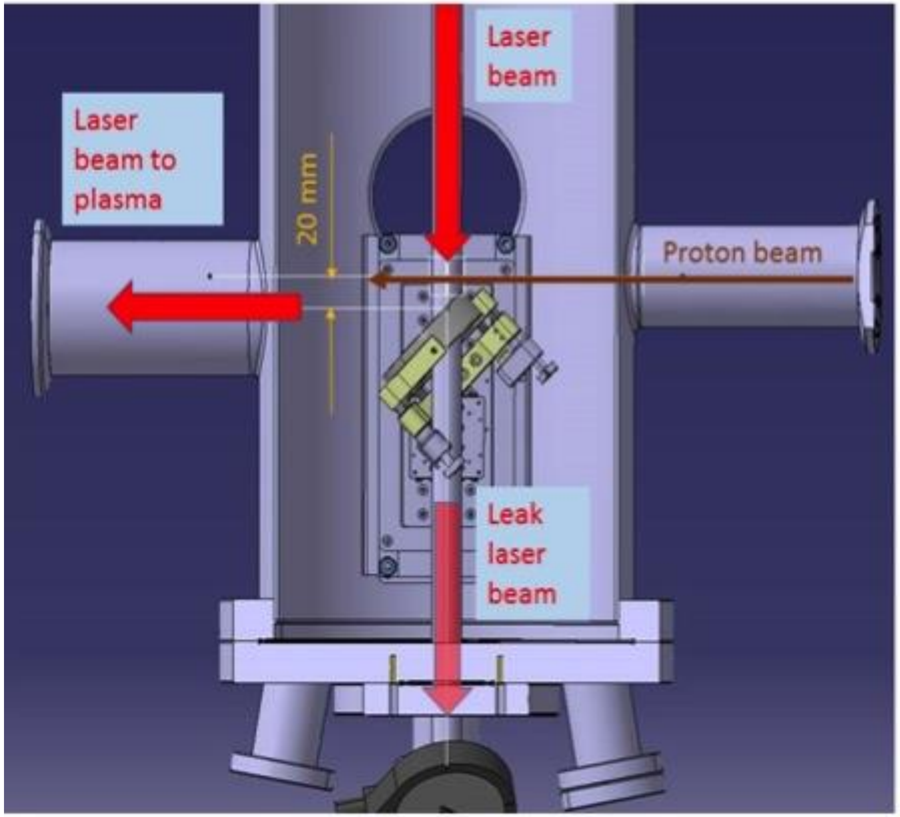


➔ Proton beam line **commissioned and running stable** with full intensity and matching the specifications

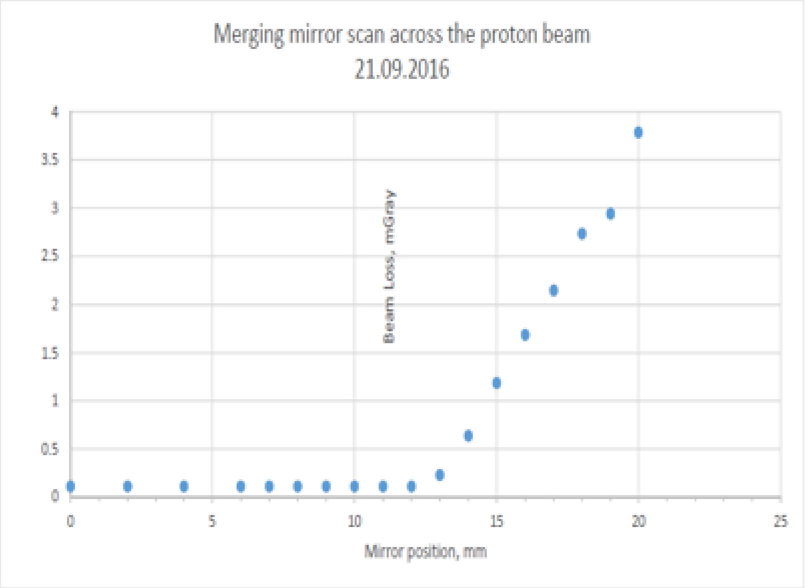


Results Laser Beam Commissioning



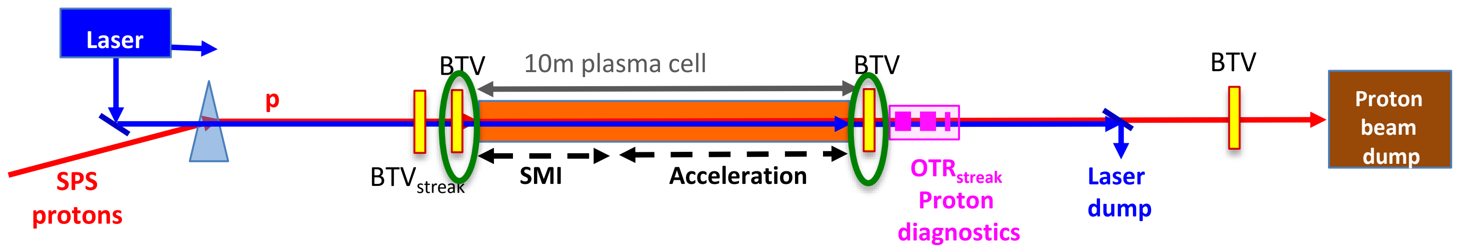


Merging mirror scan across the proton beam

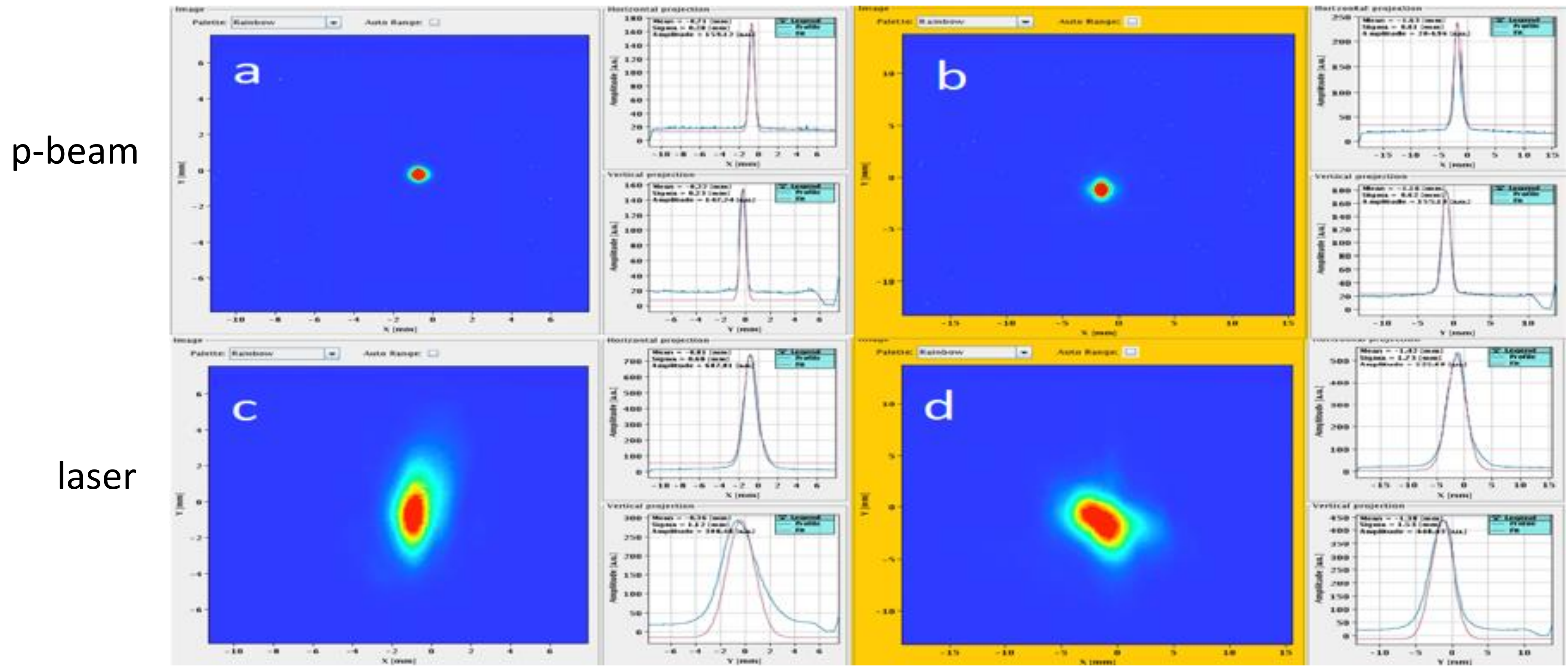


Operational Point: 11 mm
No losses on BLMs even with full intensity of 3E11 protons

Results Laser Beam Commissioning

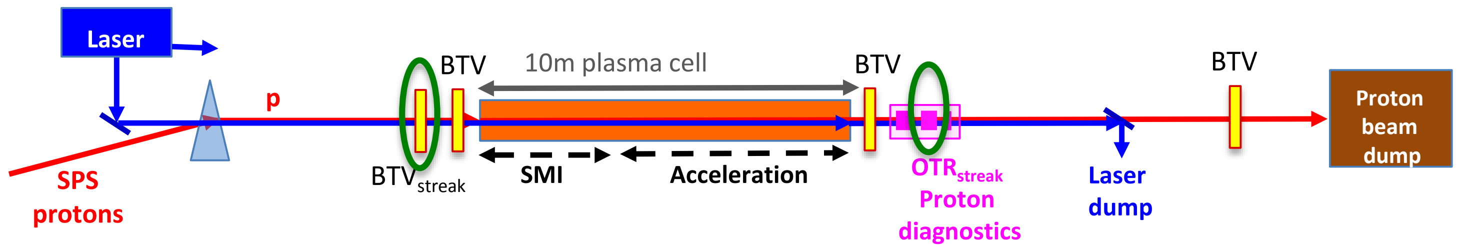


➔ **Transversal alignment** of proton and laser beam (spatial overlap)



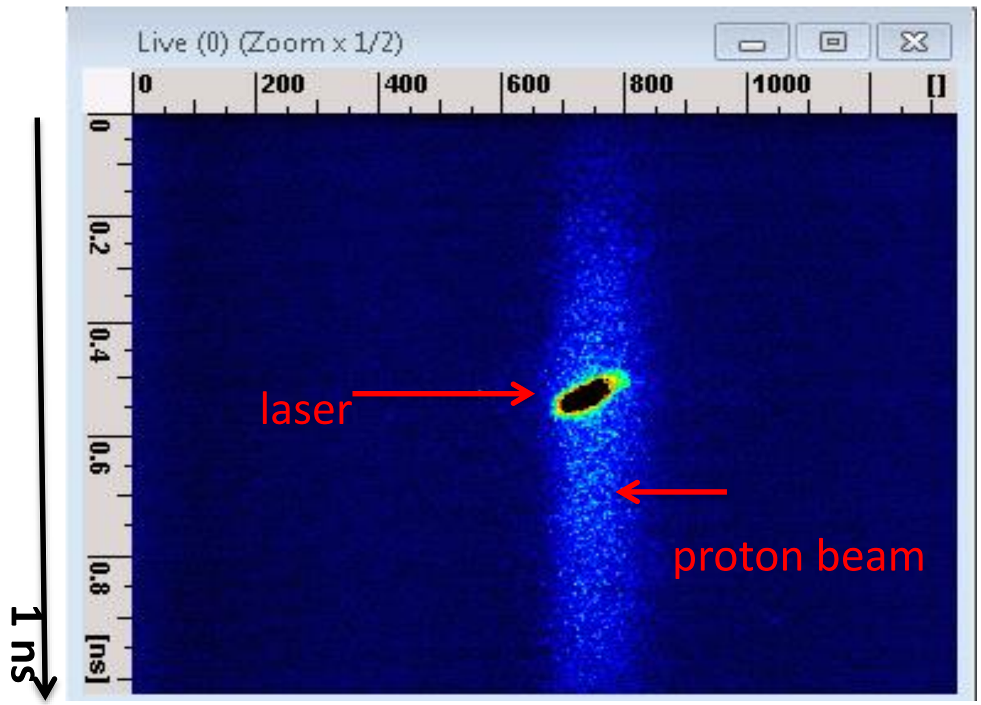
Laser positioned on proton beam references to within 300 microns

Result Proton and Laser Beam Synchronization

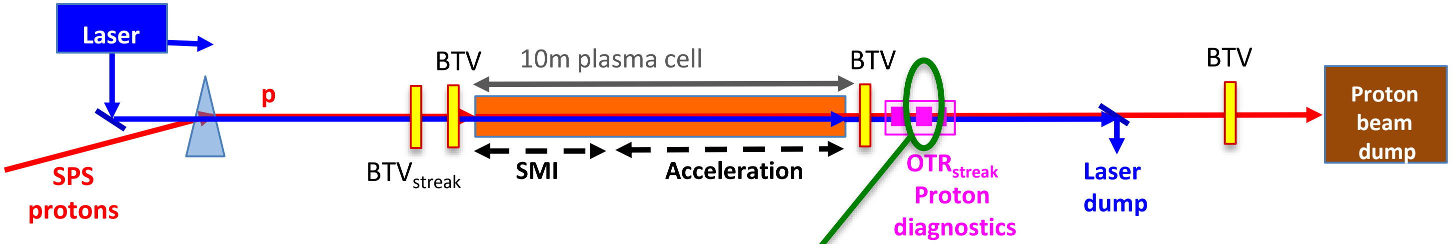


➔ **SPS proton beam synchronized with AWAKE laser within ~20ps accuracy**

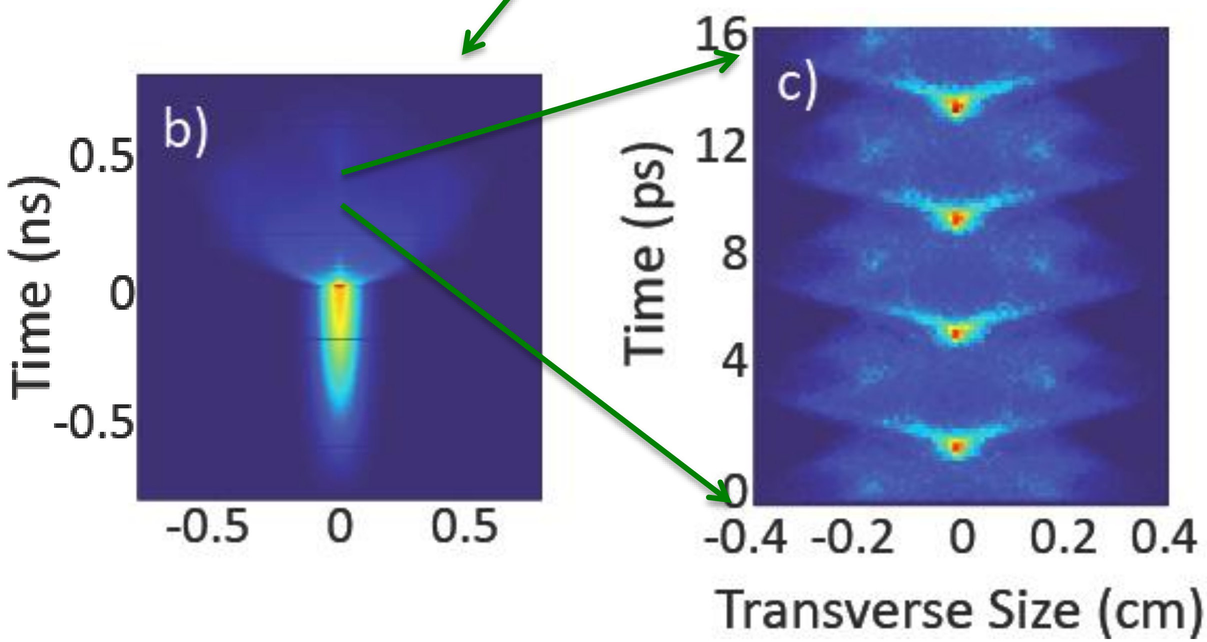
BTV upstream plasmas cell



What We Want to See During Physics Run Dec. 2016



Proton Beam Self-Modulation Instability



Proton beam undergoes Self-Modulation Instability when passing through plasma

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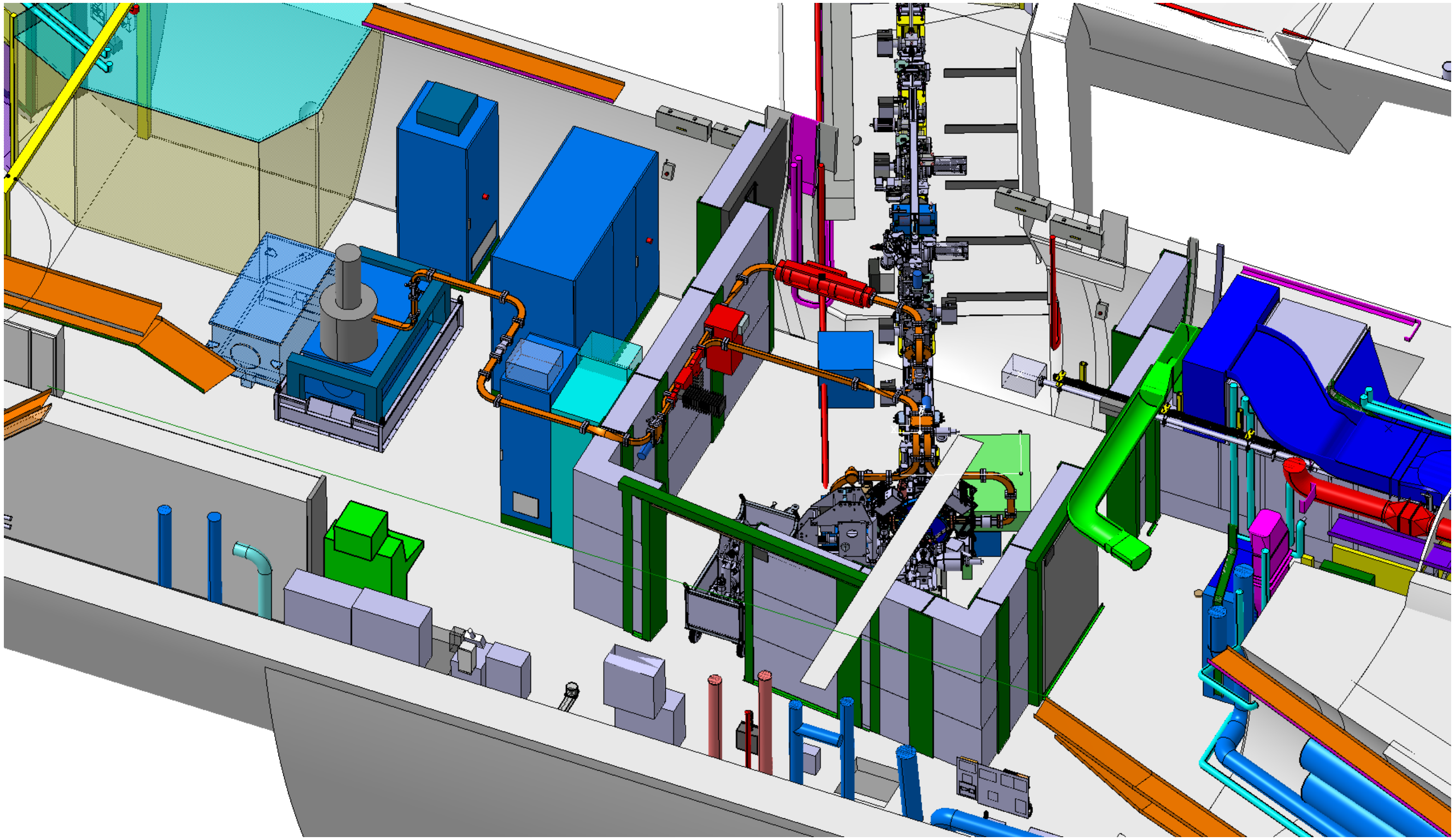
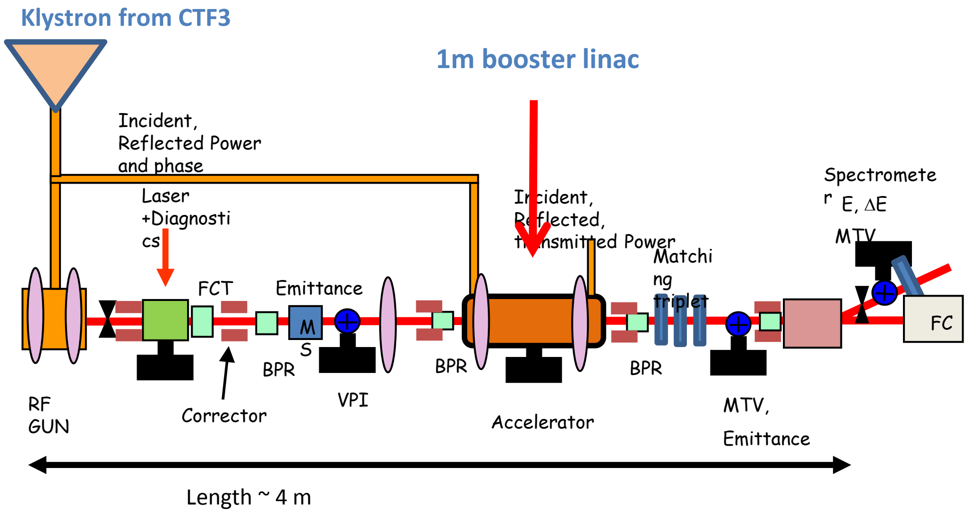
Electron Source in AWAKE

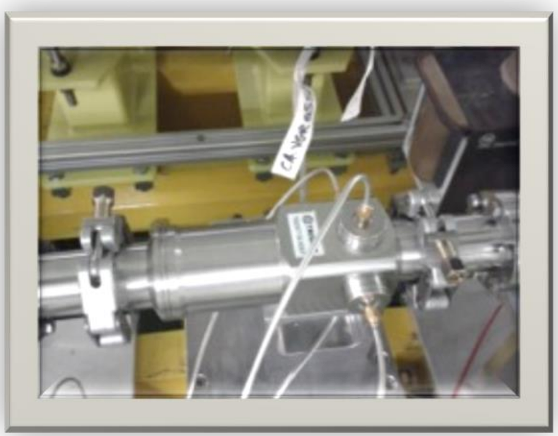


- **Electron source design finished**, construction of hardware ongoing
- Waveguide system: **launched production**
- **Shielding designed and decided** to have a separate access zone for the electron source
- **Dismantling of PHIN will start next month**

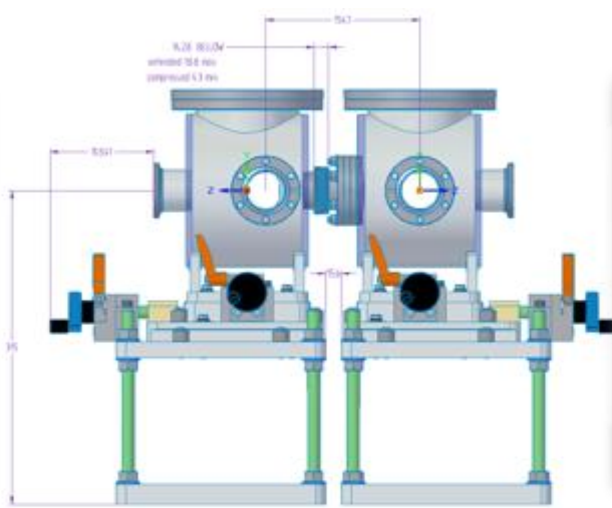
Collaborations for Electron Source

- Good progress in collaborations:
  - TRIUMF BPM's and Faraday Cup:
    - First successful test in CALIFES
  - Pepper pot from Manchester:
    - Designed, most of equipment ordered
  - Booster structure together with Lancaster and Cockcroft
    - fabrication, prototypes accepted





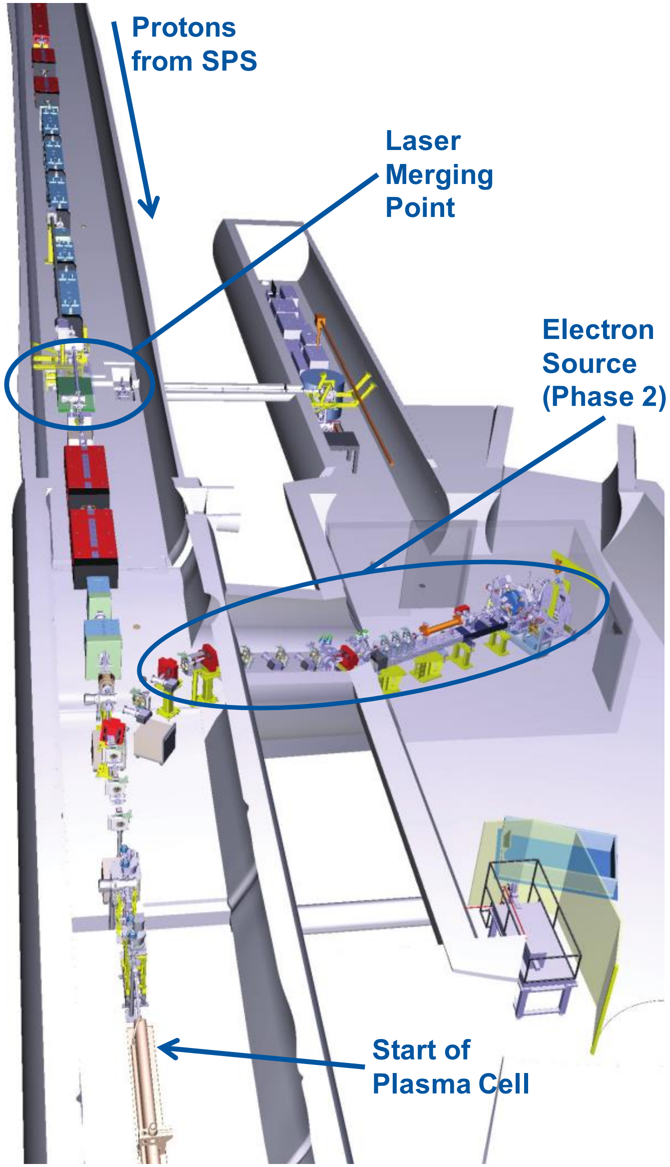
Triumf BPM



Pepper pot

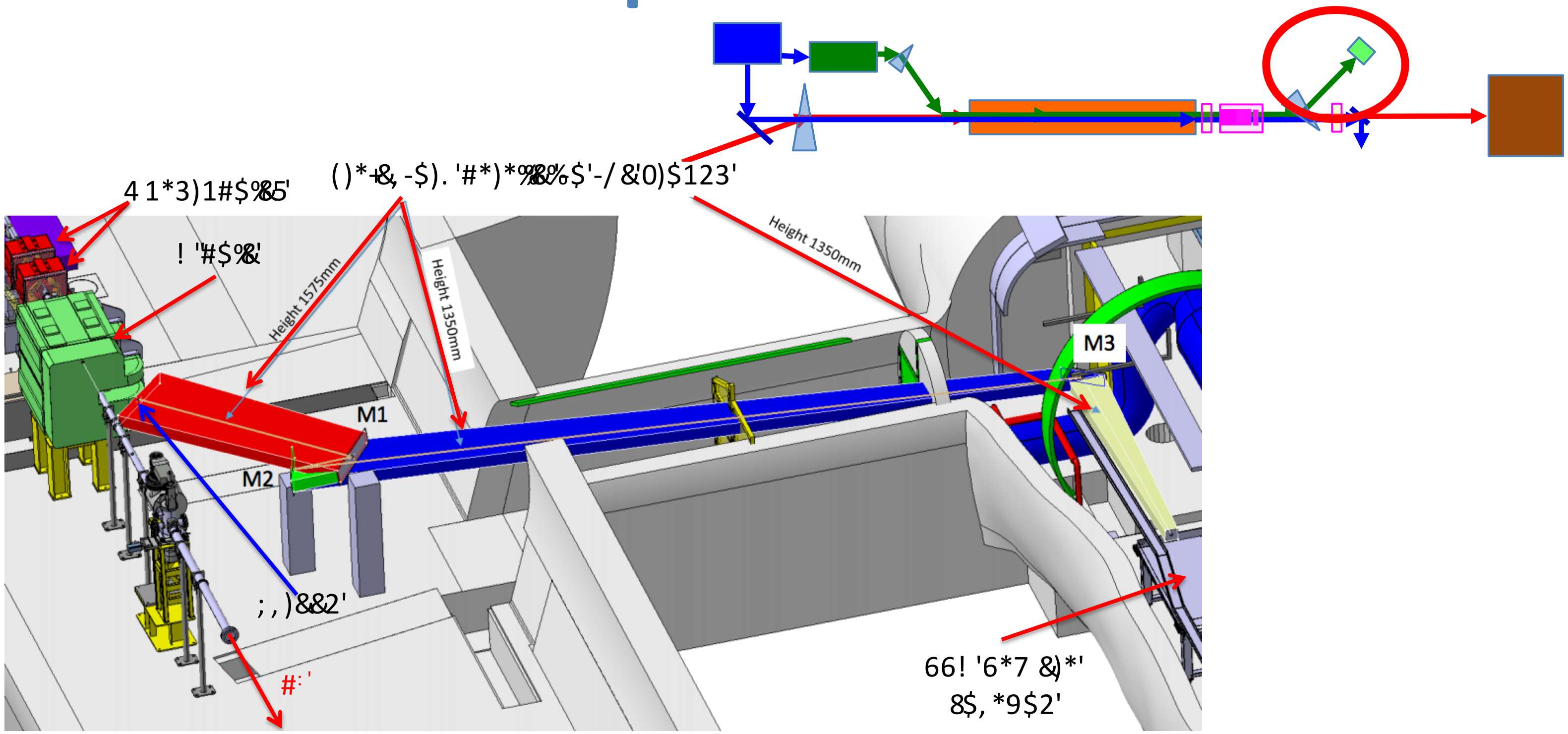
Booster structure

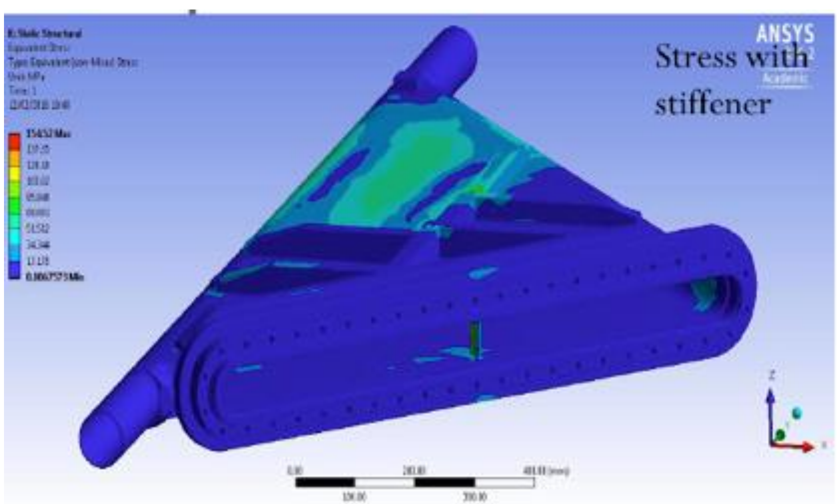
Status of the Electron Beam Line



- **Layout, specifications frozen**
- Magnets, power converters **ordered**
- **Cabling** for BTVs done

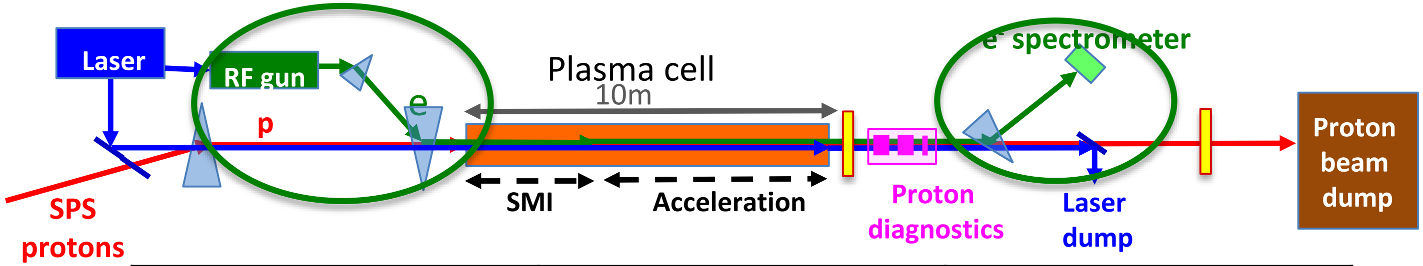
Electron Spectrometer



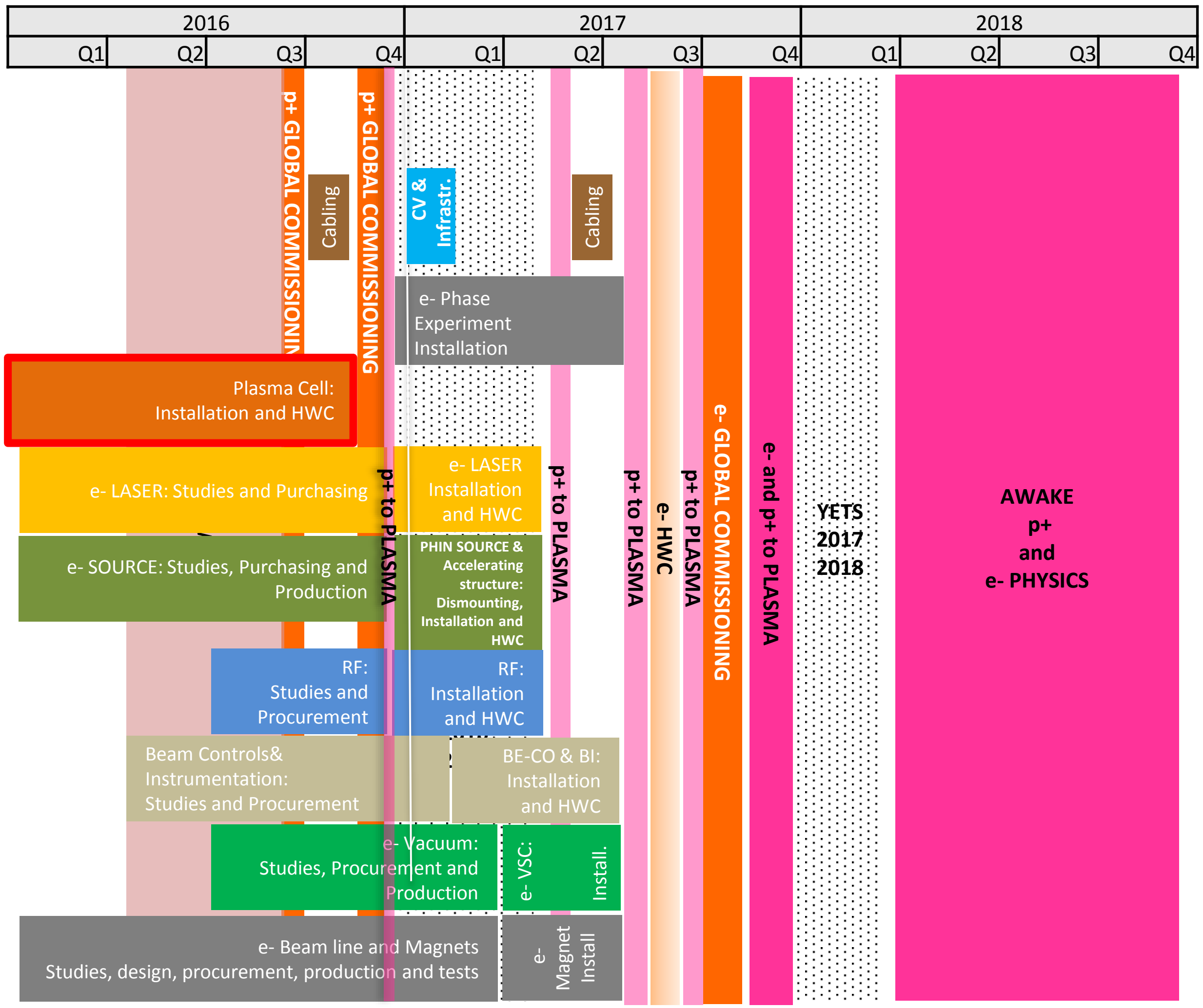


- **Design of the light transport line** from the spectrometer screen to the CCD camera done
- **Spectrometer vacuum window design**: **2mm Al**
  → no risk of buckling of the window
  → scattering of electrons negligible compared to camera resolution

Electron Phase Master Schedule



on track



Outline

- Introduction
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AWAKE Run 2 and Beyond

AWAKE Run 1 until LS2 : proof-of-concept experiment **– fully funded**

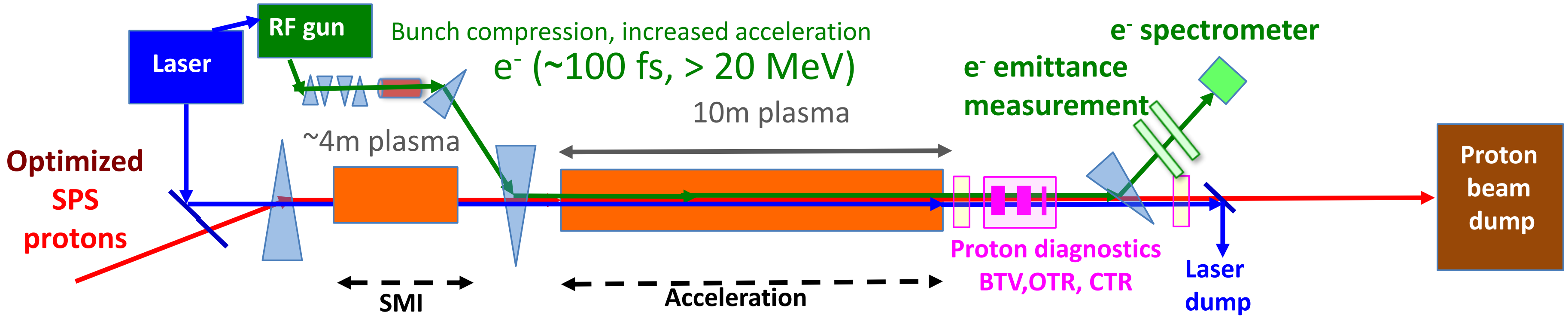
AWAKE Run 2:

Goals:

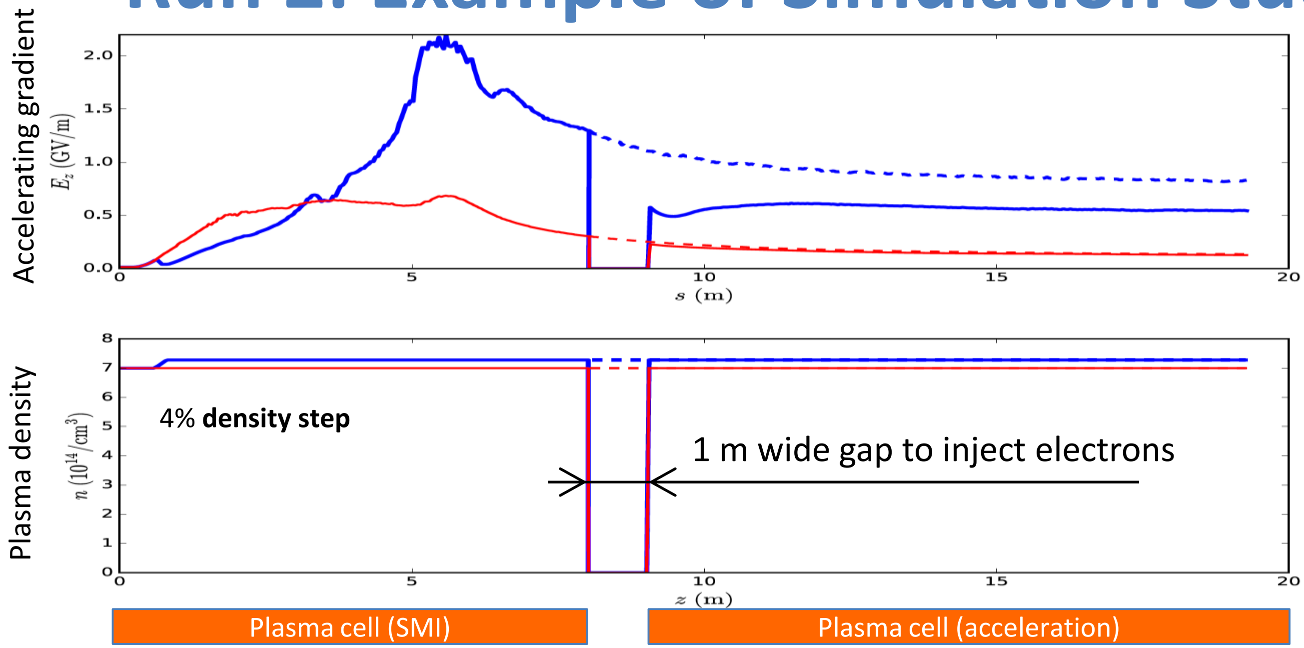
- Accelerate an electron beam, while **preserving beam quality** as well as possible
- **Demonstrate scalability** of the AWAKE concept

Requirement:

- Compressed proton beam in SPS
- Sustain gradient in SMI wake over long distance → density step for freezing modulation
- Short electron bunch with higher energy for loading wakefield
- Scalable length plasma sources

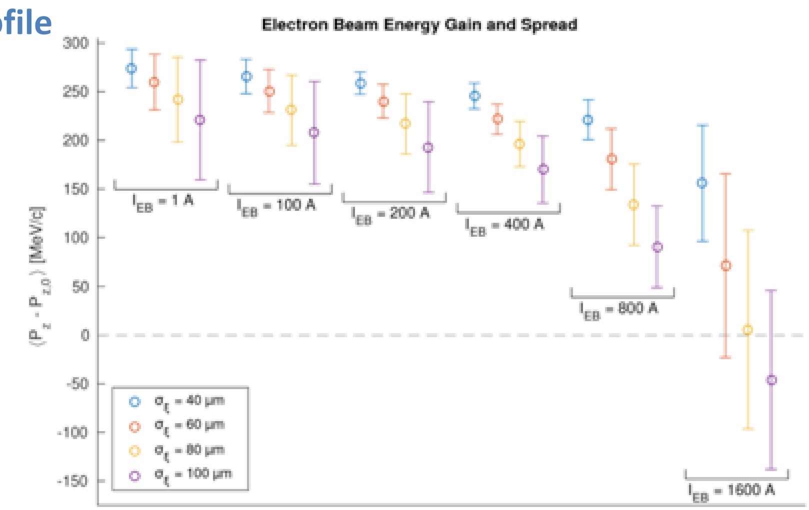


Run 2: Example of Simulation Studies



→ Freezing the modulation:

- Wakefield amplitude quickly drops after the beam gets modulated
- **Remedy:** control the wave phase by **the plasma density profile**

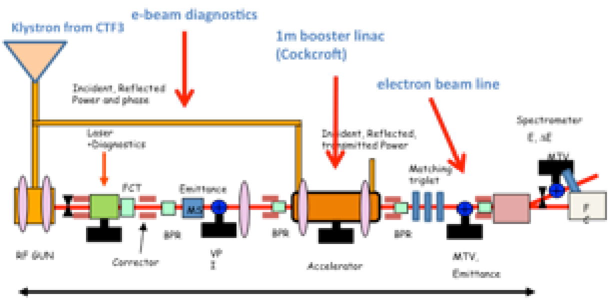


Other Simulation studies:

- Emittance preservation, tolerances, staging
- Reach **%-level of energy spread** of the electron beam with beam loading.
- **Typical electron beam parameters:**
  - **40 – 60 µm (100 fs)** bunch length
  - **Few 100 A** peak current
  - **> 50 MeV** Injection energy

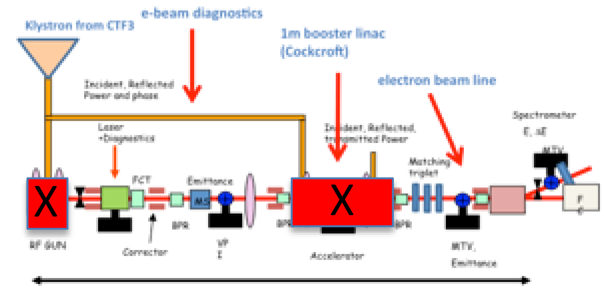
Run 2: Options for Electron Injector

Modify phase 2 injector (S-band)



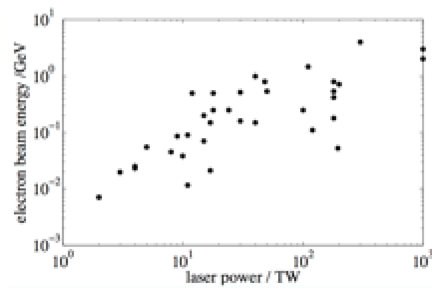
Can Run 1 AWAKE injector (PHIN S-band photo-injector) be modified to provide 50 MeV and 400 A, within space constraints ?

Modify phase 2 injector, upgrade with X-band



X-band structure? ~60 MV/m gives required boost
X-band gun? Based on best SLAC results could provide required energy and current in available space. Requires development work.

Laser wakefield acceleration injector



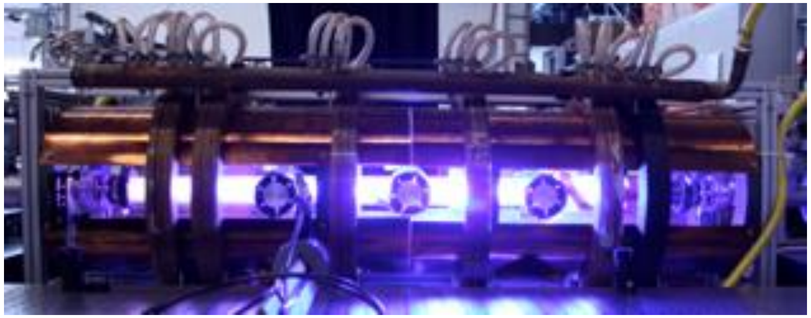
100+ MeV routinely reached with few MW Ti:Sa laser

- very short bunches possible (few um)
- compact
- AWAKE energy requirement (< 100 MeV) relaxed with respect to state-of-the-art (4 GeV)

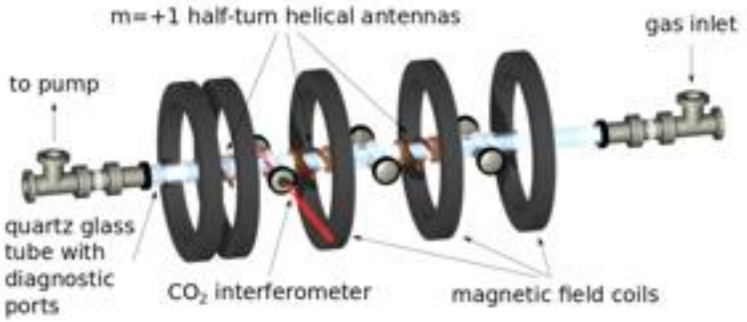
→ collaboration with LWFA-experts initiated

Run 2: Scalable Plasma Sources

Helicon development



Current 1m prototype in Greifswald

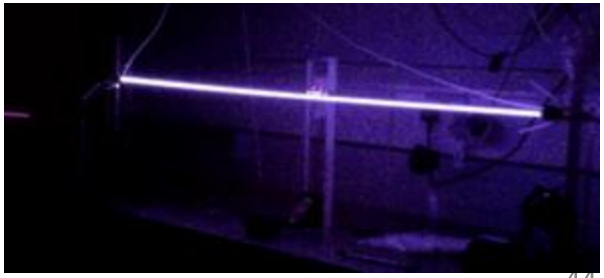


- Does not need laser ionization
- Fully modular (no gaps)
- Required density reached
- Uniformity (spatial, temporal) needs work
- Need to move from prototype to AWAKE-compatible technology

→ Collaboration between MPP Greifswald, EPFL SPC and CERN is being set up

Gas discharge development

3m prototype developed by Imperial College and IST (Lisbon)
Construction of prototype is pending funding



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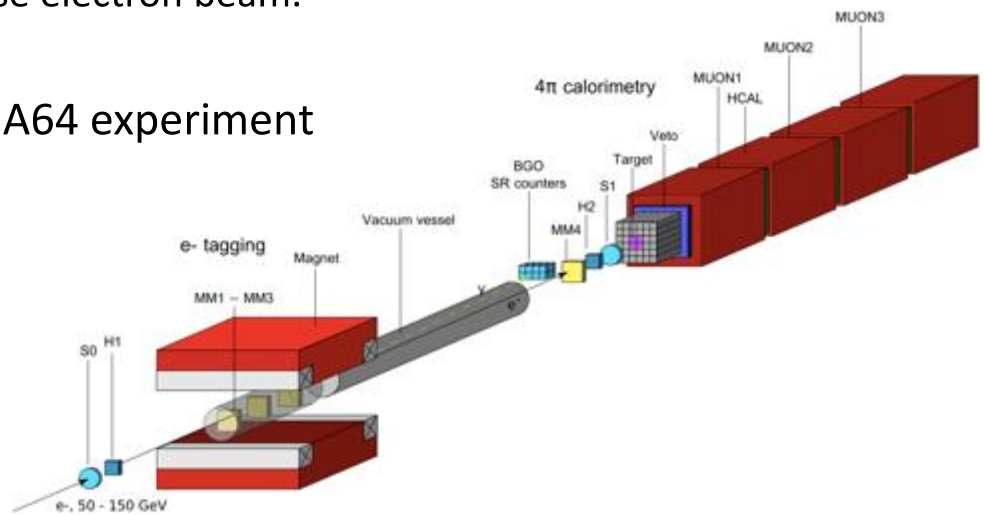
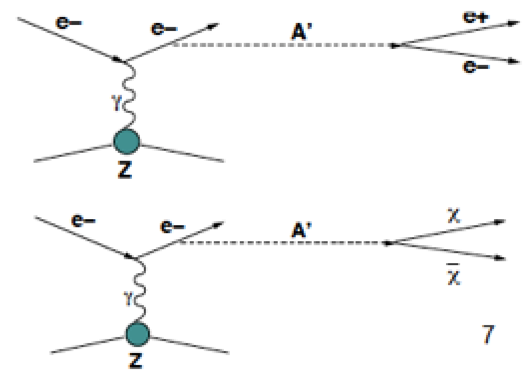
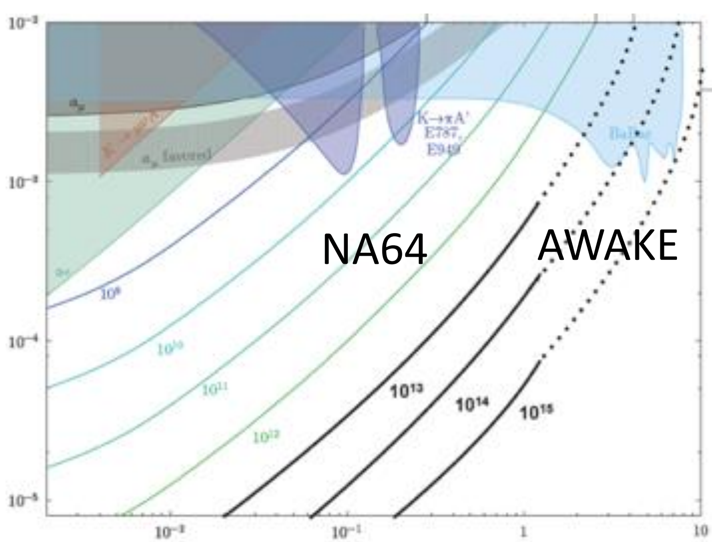
Fixed Target Experiments with High Energy Electron Beam

So far, no experimental hints on particle nature of dark matter.
Interest in low-mass particle solutions increasing; e.g., **dark photons**.
Light shining through walls experiments …
Here, use electron beam.

NA64 experiment







NA64: expect 10^6 electrons/spill; 10^{12} electrons for 3 months

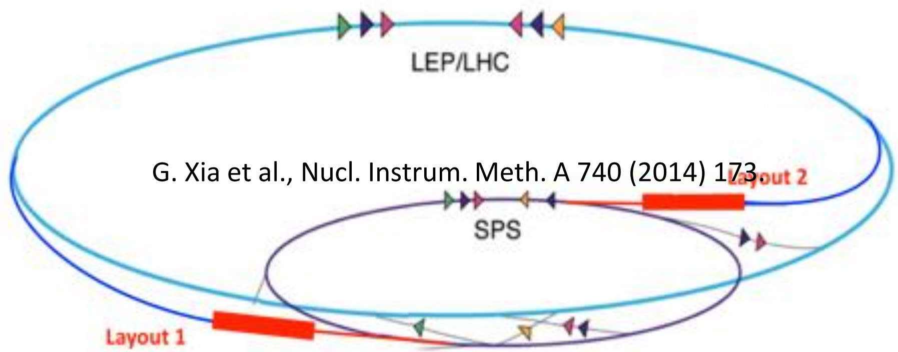
AWAKE-like electron beam driven by SPS proton bunch. Assuming 10^9 electrons/bunch, would give **3 orders of magnitude** increase.

M. Wing, Physics Beyond Colliders Kickoff Workshop, 7/Sep/2016, CERN

Physics with an Electron-Proton or Electron-Ion Collider

LHeC-Like:

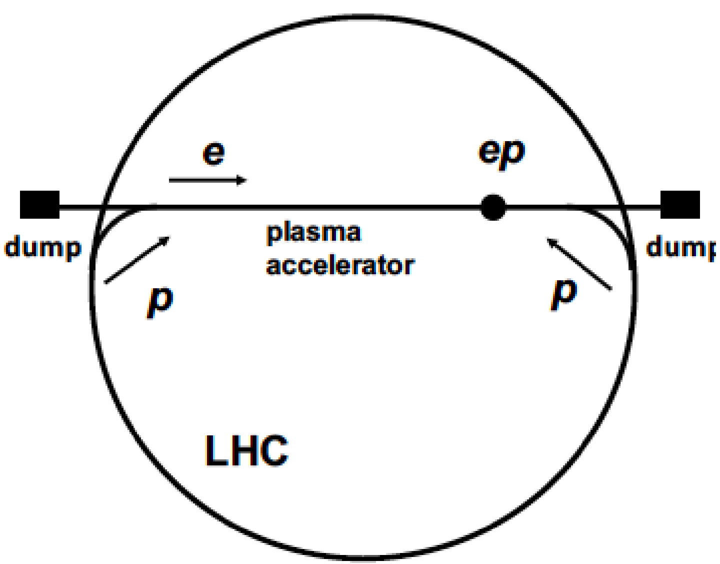
- **Focus on QCD:** Large cross sections → low luminosity enough (HERA level)
- Many open physics questions !
  → High energy ep collider: E_e up to O(50 GeV), colliding with LHC proton;
  → e.g. E_e = 10 GeV, Ep = 7 TeV, √s = 530 GeV already exceeds HERA cm energy.



G. Xia et al., Nucl. Instrum. Meth. A 740 (2014) 173.

Create ~50 GeV electron beam within 50–100 m of plasma driven by SPS protons,
But luminosity < 10^{30} cm^{-2} s^{-1}.

VHEeP:



- Choose **E_e = 3 TeV** as a baseline and **with E_p = 7 TeV** yields √s = 9 TeV. Can vary.
- Centre-of-mass energy ~30 higher than HERA.
- Reach in (high) Q^2 and (low) Bjorken x extended by ~1000 compared to HERA.
- Opens new physics perspectives
- Luminosity ~ 10^{28} – 10^{29} cm^{-2} s^{-1} gives ~ 1 pb−1 per year.

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

Strategy for Run 2 and Beyond

- Created a Run 2 Coordination Package
  - Define goals, technology and work-packages

- Gives opportunity to new institutes interested in joining.

- CERN AWAKE Project Leader Mandate Extended:
  - Leading the CERN AWAKE project towards and during Run 2
  - Coordinating and organizing the general proton driven plasma wakefield acceleration studies at CERN
  - Coordinating all resources associated with the AWAKE project and the proton driven plasma wakefield studies.

→ Have a first proposal of Run 2 program ready by end 2017

Summary

➔ Great progress in installation and commissioning of AWAKE Run 1

➔ On track for first AWAKE physics in 1st week in December 2016

➔ On track with installation for electron acceleration phase in 2017

- Run 2 and beyond:
  - Preparation of proposal for Run 2
  - Long-term prospects: Start to develop particle physics program that could be persued with an AWAKE-like beam.