Introduction to the AWAKE project and its technical challenges

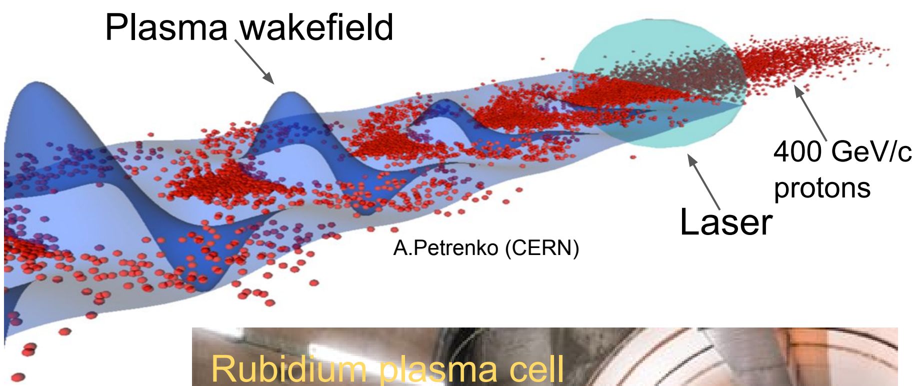
M. Turner, E. Gschwendtner representing the AWAKE Collaboration

Outline

1. What is AWAKE?
2. Physics behind AWAKE
3. Realization of the project
4. Technical Challenges
5. Latest Results
6. Outlook & Summary

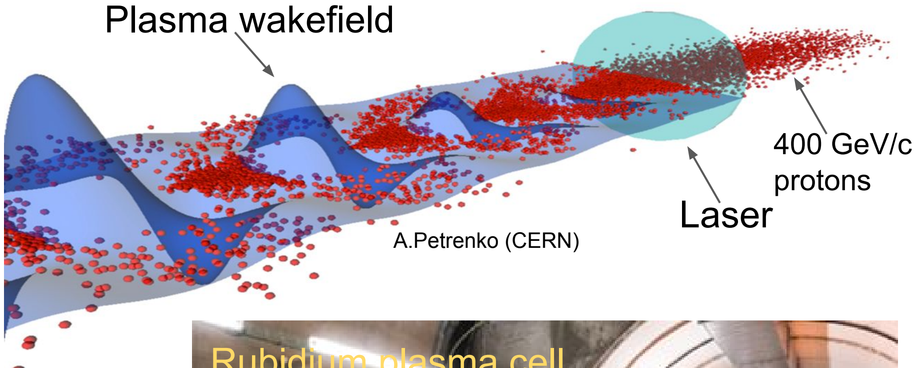
What is AWAKE?

- AWAKE stands for: **A**dvanced Proton Driven Plasma **Wak**efield **E**xperiment.
- AWAKE is a R&D project to study proton driven plasma wakefields at CERN.
- **Final Goal:** Design high quality & high energy electron accelerator based on acquired knowledge.



What is AWAKE?

- AWAKE stands for: **A**dvanced Proton Driven Plasma **Wak**efield **E**xperiment.
- AWAKE is a R&D project to study proton driven plasma wakefields at CERN.
- **Final Goal:** Design high quality & high energy electron accelerator based on acquired knowledge.



Why is plasma wakefield acceleration interesting?

$$eE_{max} \approx 1[\mathrm{eV/cm}] \cdot n^{1/2}[\mathrm{cm}^{-3}]$$

$$\lambda_{pe} \approx 1\,\mathrm{mm}\sqrt{\frac{10^{15}\,\mathrm{cm}^{-3}}{n_{pe}}}$$

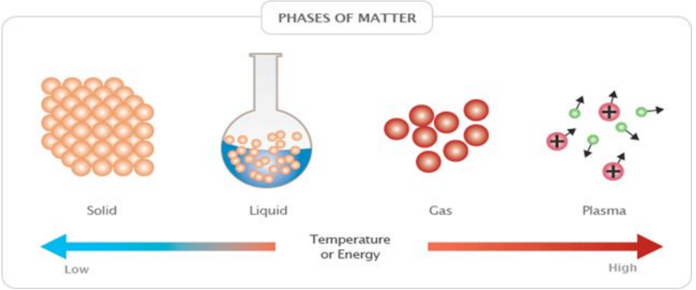
i.e. 1 GeV/m for a plasma density (n) of 10^{14} electrons/cm^3.

For LWFA: n~10^{18} electrons/cm^3
⇒ 100 GeV/m

Larger plasma e^- density implies smaller plasma e^- wavelength
⇒ smaller structures

Physics behind AWAKE

What is a plasma?



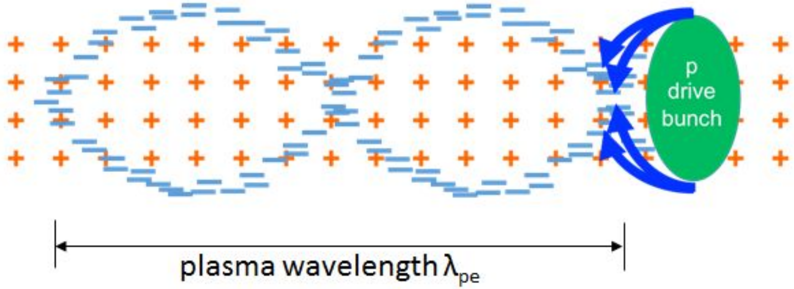
Quasi-neutrality: the overall charge of a plasma is about zero.

Collective effects: Charged particles must be close enough together that each particle influences many nearby charged particles.

Electrostatic interactions dominate over collisions or ordinary gas kinetics.

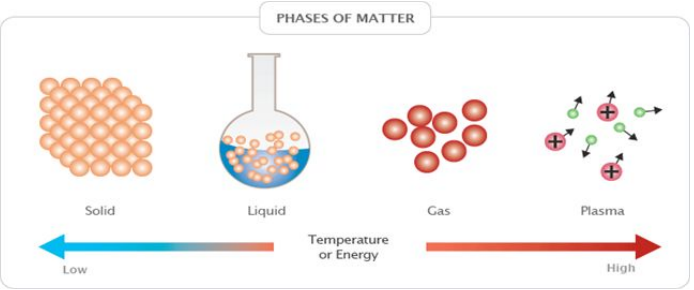
What are plasma wakefields?

Fields created by a plasma wave.



Physics behind AWAKE

What is a plasma?



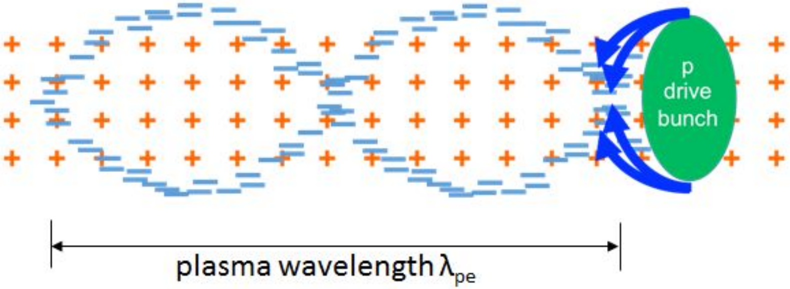
Quasi-neutrality: the overall charge of a plasma is about zero.

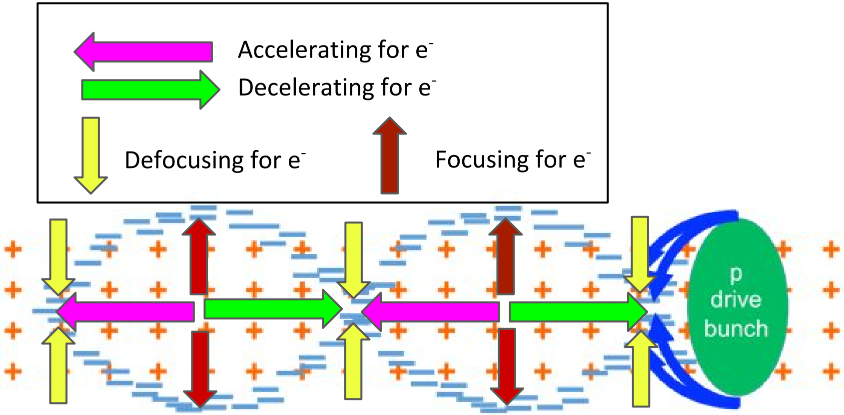
Collective effects: Charged particles must be close enough together that each particle influences many nearby charged particles.

Electrostatic interactions dominate over collisions or ordinary gas kinetics.

What are plasma wakefields?

Fields created by a plasma wave.





$$\lambda_{pe} \approx 1\ \text{mm} \sqrt{\frac{10^{15}\ \text{cm}^{-3}}{n_{pe}}}$$

⇒ defines the optimal drive bunch length

M. Turner for the AWAKE collaboration

The self-modulation instability

Why protons?:

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

⇒ In order to create plasma wakefields efficiently, the **drive bunch length** has to be in the order of the **plasma wavelength**. --> mm scale proton bunches do not exist.

CERN SPS proton bunch: very long!

Longitudinal beam size ($\boldsymbol{\sigma_z}$**= 12 cm**) is much longer than plasma wavelength **(λ_{pe}= 1mm, n_{pe} = 7 x 10^{14} e^-/cm^3**)

⇒ Self Modulation Instability (SMI)

Micro-bunches can then resonantly drive the plasma wave.

The self-modulation instability

Why protons?:

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

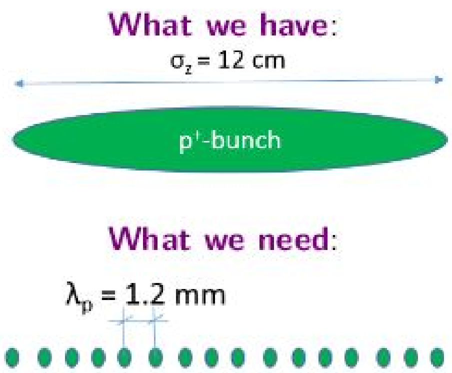
⇒ In order to create plasma wakefields efficiently, the **drive bunch length** has to be in the order of the **plasma wavelength**. --> mm scale proton bunches do not exist.

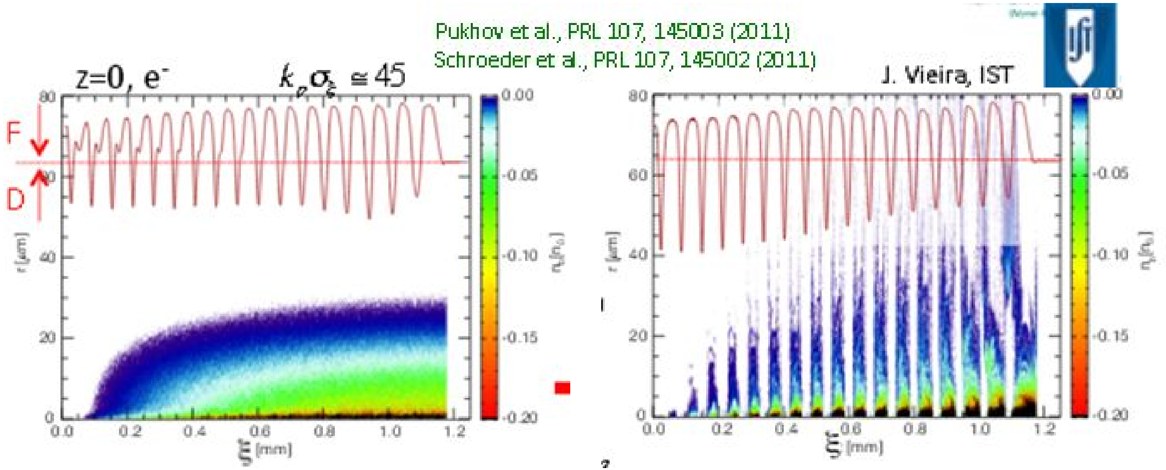
CERN SPS proton bunch: very long!

Longitudinal beam size ($\boldsymbol{\sigma_z}$ **= 12 cm**) is much longer than plasma wavelength **($\boldsymbol{\lambda_{pe}}$= 1mm, $\boldsymbol{n_{pe}}$ = 7 x $\boldsymbol{10^{14}}$ $\boldsymbol{e^-/cm^3}$)**

⇒ Self Modulation Instability (SMI)

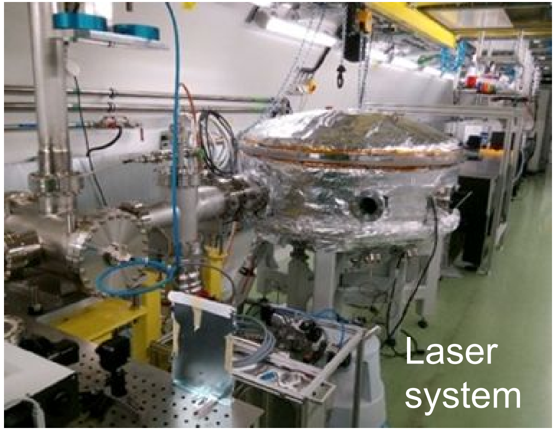
Micro-bunches can then resonantly drive the plasma wave.

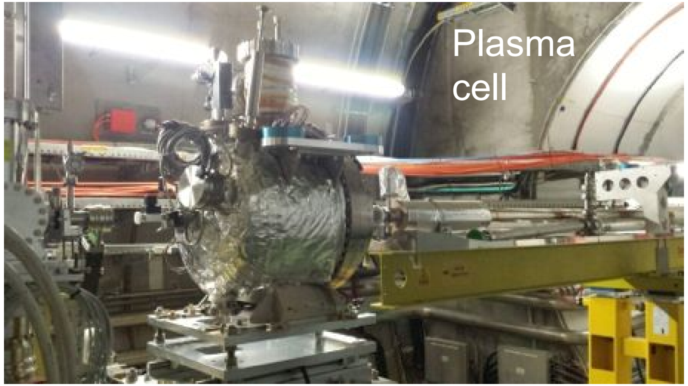




he
oration

Components of a R&D proton driven plasma wakefield accelerator



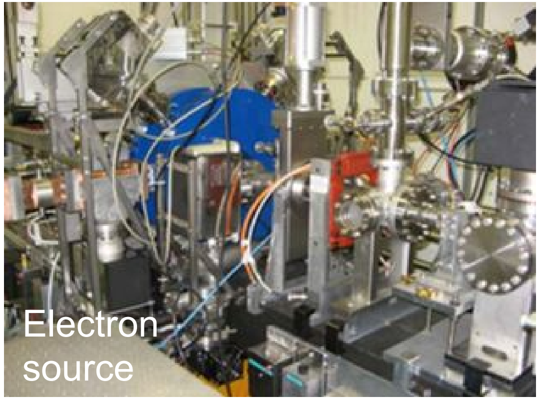


- ❑ Rubidium vapor
- ❑ Laser

} **10 m of Plasma**

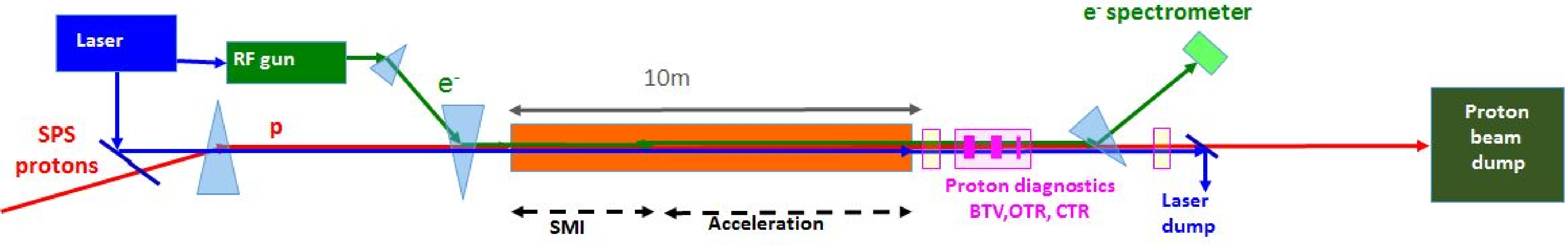
- ❑ Proton beam (400 GeV/c)
  - ⇒ **Driver**
- ❑ Electron beam (10-20 MeV)
  - ⇒ **Witness**
- ❑ **Diagnostics!**
  - ❑ Proton
  - ❑ Laser
  - ❑ Electron

Challenge Nr 1!!!: Integration into the CNGS tunnel.

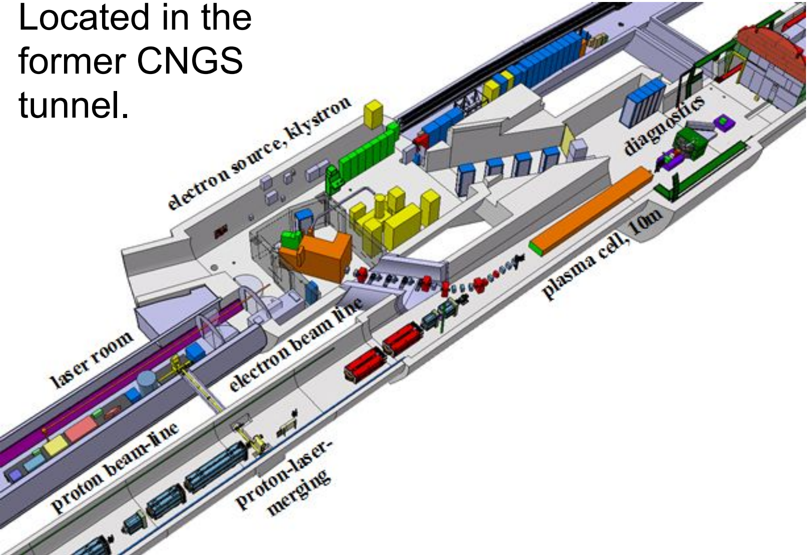


AWAKE collaboration

The AWAKE facility



Located in the former CNGS tunnel.



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

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

M. Turner for the AWAKE collaboration

Technical Challenge Nr 2:

The AWAKE plasma

Physics requirement:

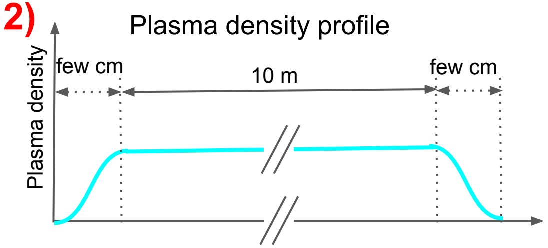
1. The plasma density uniformity needs to be better than 0.2% over the 10 meters of plasma.
2. The transition between the plasma and the vacuum must be as sharp as possible.
3. Ion motion in the plasma must be negligible.
4. Sharp plasma edge inside the proton bunch (Sudden turn on of the plasma).

Technical Challenge Nr 2:
The AWAKE plasma

Physics requirement:

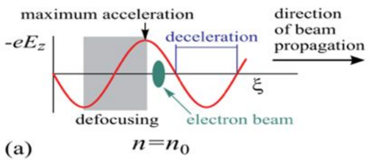
1. **The plasma density uniformity needs to be better than 0.2% over the 10 meters of plasma.**
2. **The transition between the plasma and the vacuum must be as sharp as possible.**
3. **Ion motion in the plasma must be negligible.**
4. **Sharp plasma edge inside the proton bunch (Sudden turn on of the plasma).**

1+ 2)



If the plasma density n_{pe} changes, the plasma wavelength λ_{pe} changes.

$$\lambda_{pe} \approx \quad 1\,\text{mm} \sqrt{\frac{10^{15}\,\text{cm}^{-3}}{n_{pe}}}$$

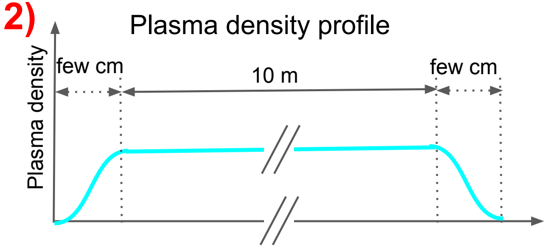


Technical Challenge Nr 2:
The AWAKE plasma

Physics requirement:

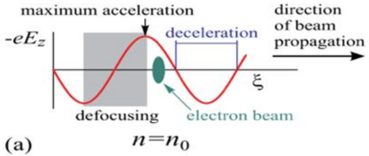
1. **The** plasma density uniformity **needs to be better than 0.2% over the 10 meters of plasma.**
2. **The transition between the plasma and the vacuum must be as** sharp as possible**.**
3. **Ion motion in the plasma must be** negligible**.**
4. Sharp plasma edge **inside the proton bunch (Sudden turn on of the plasma).**

1+ 2)



If the plasma density n_{pe} changes, the plasma wavelength λ_{pe} changes.

$$\lambda_{pe} \approx 1\,\mathrm{mm}\sqrt{\frac{10^{15}\,\mathrm{cm}^{-3}}{n_{pe}}}$$



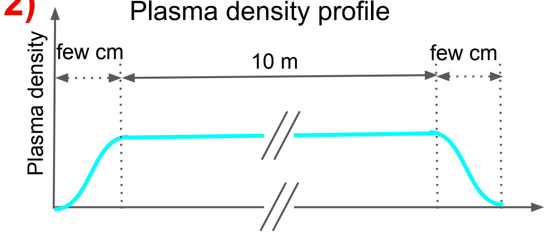
3) If ions move, the structure of the wakefield would be modified.
Choice Rubidium: 1) Heavy alkali metal (easy to ionize outermost electron)
2) high vapour pressure so we need a lower temperature to reach a certain density than f.e. with sodium.

Technical Challenge Nr 2:
The AWAKE plasma

Physics requirement:

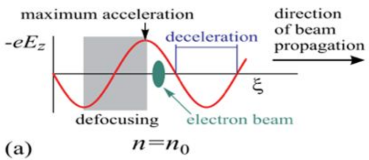
1. **The plasma density uniformity needs to be better than 0.2% over the 10 meters of plasma.**
2. **The transition between the plasma and the vacuum must be as sharp as possible.**
3. **Ion motion in the plasma must be negligible.**
4. **Sharp plasma edge inside the proton bunch (Sudden turn on of the plasma).**

1+ 2)



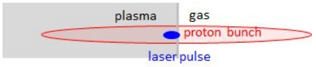
If the plasma density n_{pe} changes, the plasma wavelength λ_{pe} changes.

$$\lambda_{pe} \approx 1\text{ mm}\sqrt{\frac{10^{15}\text{ cm}^{-3}}{n_{pe}}}$$



3) If ions move, the structure of the wakefield would be modified.
Choice Rubidium: 1) Heavy alkali metal (easy to ionize outermost electron)
2) high vapour pressure so we need a lower temperature to reach a certain density than f.e. with sodium.

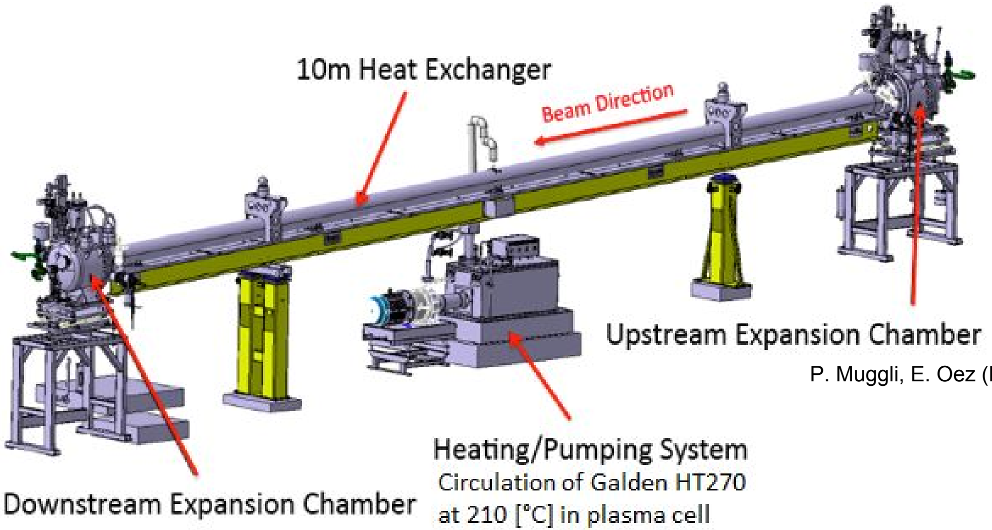
4) to seed the self-modulation instability, because:



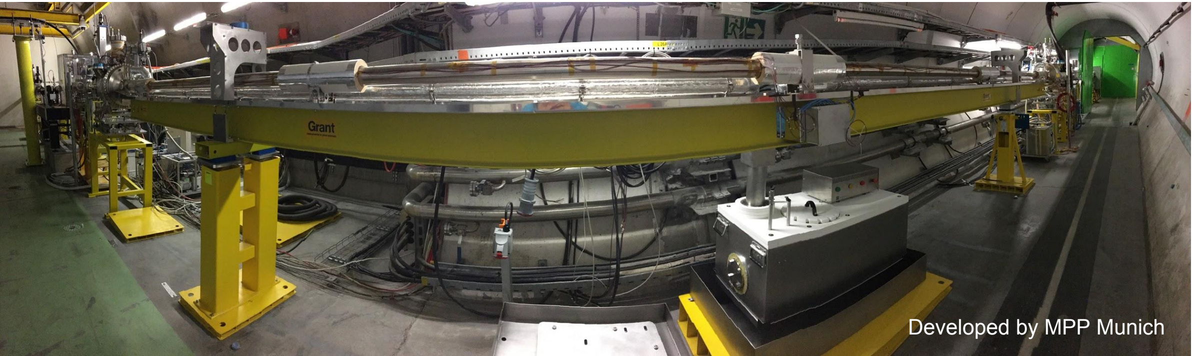
1) Self- Modulation Instability does not grow from noise.
2) Fix the phase of the wakefield.
3) Avoid competing instabilities.

M. Turner for the AWAKE collaboration

Technical Challenge Nr 2:
Plasma density uniformity



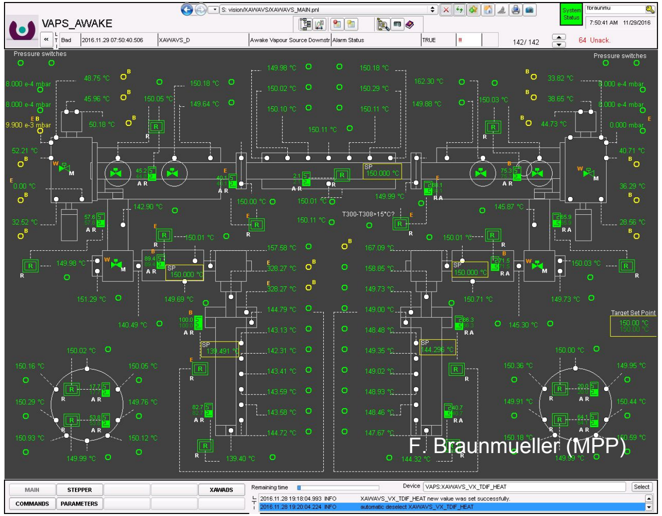
P. Muggli, E. Oez (MPP)



Fluid heated system:

- ❑ Control the vapour density by precisely controlling the temperature to <0.1 K.
- ❑ 79 temperature probes.

Control system for the vapour cell



M. Turner for the AWAKE collaboration

Technical Challenge Nr 2:
Plasma density ramp

Requirement: 2) The transition between the plasma and the vacuum must be as sharp as possible.
⇒ Fast valves **do not** work (density ramp of 50 cm not acceptable).

Solution: Cold expansion chambers with an open flow - the rubidium condenses on a cold surface.
⇒ not good, but acceptable

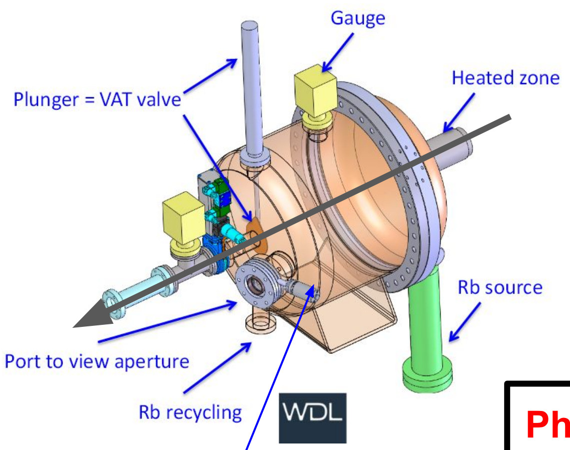
Physics principle: Gas expanding through an aperture(∅= 1 cm) to infinite volume ⇒ length of the ramp in the order of the opening of the aperture.

Technical Challenge Nr 2:
Plasma density ramp

Requirement: 2) The transition between the plasma and the vacuum must be as sharp as possible.
⇒ Fast valves **do not** work (density ramp of 50 cm not acceptable).

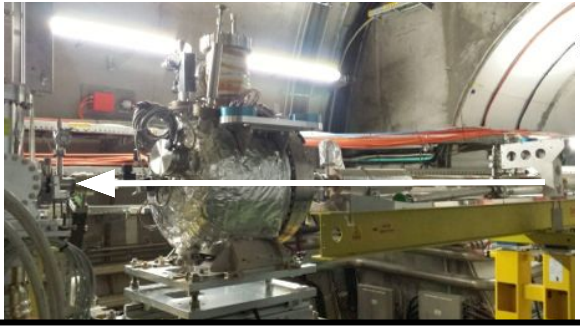
Solution: Cold expansion chambers with an open flow - the rubidium condenses on a cold surface.
⇒ not good, but acceptable

Rubidium expansion chambers:

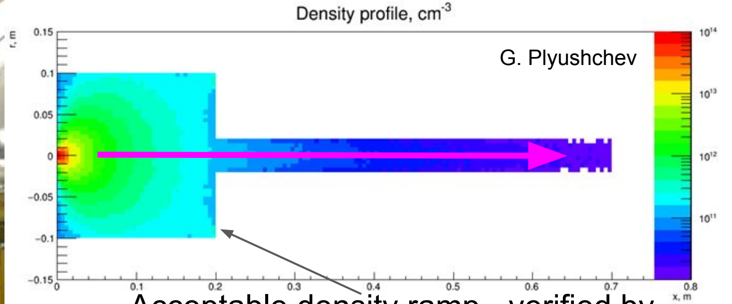


Temperature of the walls kept below 28°C condensation temperature of rubidium.

Expansion chambers installed in AWAKE

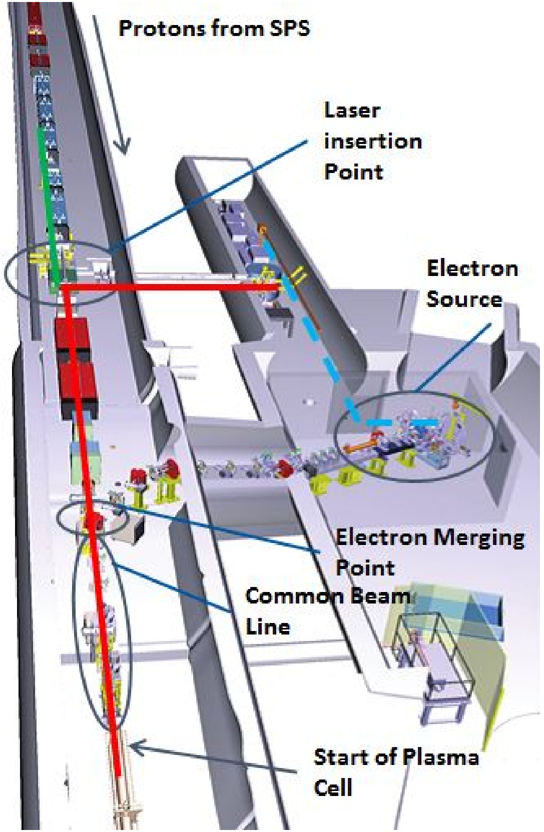


Physics principle: Gas expanding through an aperture(∅= 1 cm) to infinite volume ⇒ length of the ramp in the order of the opening of the aperture.

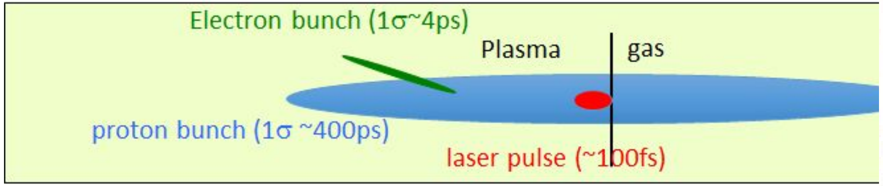


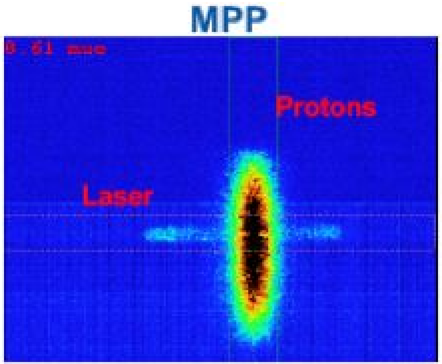
Acceptable density ramp - verified by plasma simulations

Technical Challenge Nr 3:
Alignment of a proton, laser and electron beam



Temporal alignment

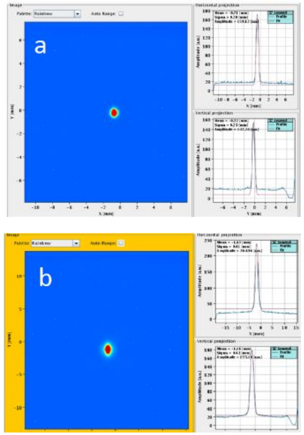




Streak camera measurement of the timing between the proton and laser pulse.

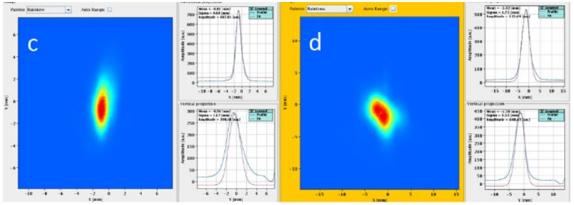
Spatial alignment

Proton bunch: measured on the proton beamline BTVs



Overlap the laser with the proton beam (reference)

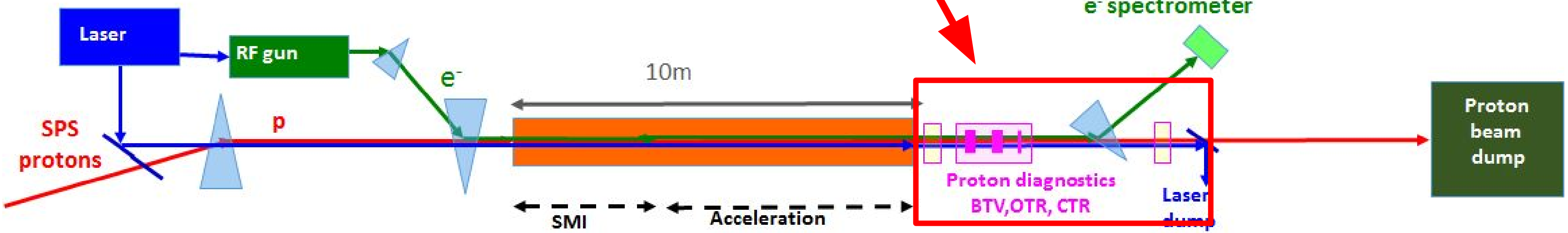
Laser: measured on the proton beamline BTVs



Technical Challenge Nr 4:
Diagnostics

Interesting information:

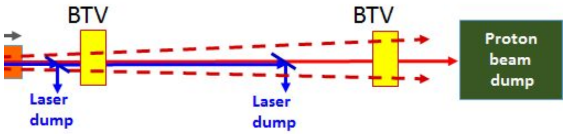
- ❑ What is the plasma density?
- ❑ Did the proton beam self-modulated over the 10 m of plasma?
- ❑ What is the energy of the accelerated electrons?



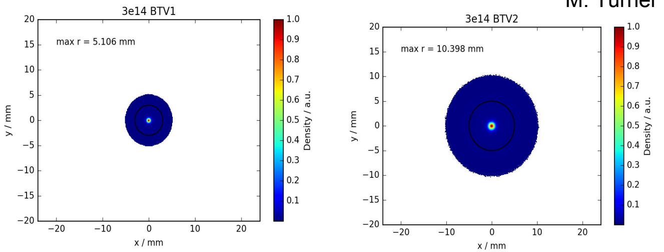
4 different diagnostics based on:

- ❑ Scintillation (Indirect SMI two screen measurement)
- ❑ Streak camera and Optical Transition radiation (OTR)
- ❑ 2x Coherent transition Radiation (CTR)

Indirect SMI two-screen measurement (Scintillation):



M. Turner

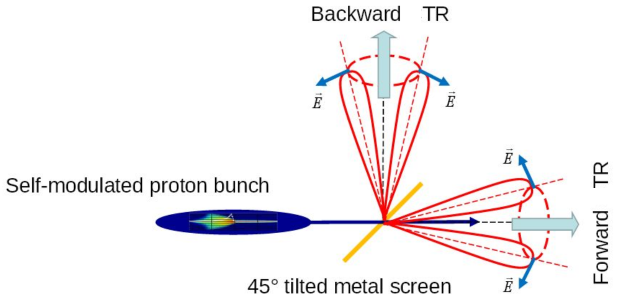


Goal: Image protons that got defocused by the strong plasma wakefields
To prove that plasma wakefields were present in plasma.

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

M. Turner for the AWAKE collaboration

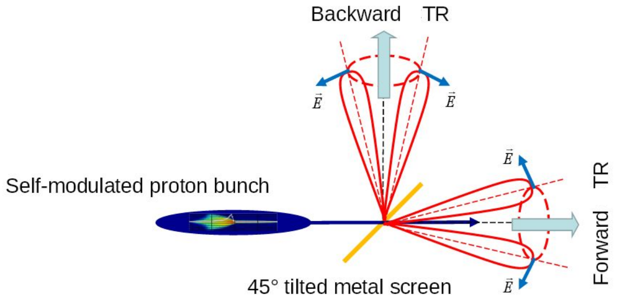
Technical Challenge Nr 4:
Diagnostics



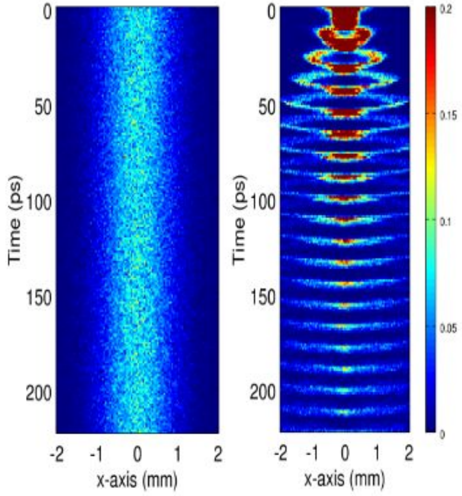
Foil emits waves up to the plasma wavelength of the foil:

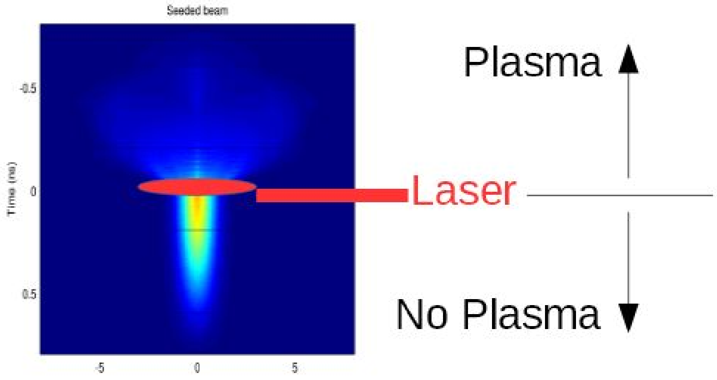
- including radiation in the optical range (OTR).
- Radiation is coherent (CTR) for wavelengths bigger than the structure of the micro-bunches.

Technical Challenge Nr 4:
Diagnostics



Streak camera and OTR:





Foil emits waves up to the plasma wavelength of the foil:

- including radiation in the optical range (OTR).
- Radiation is coherent (CTR) for wavelengths bigger than the structure of the micro-bunches.

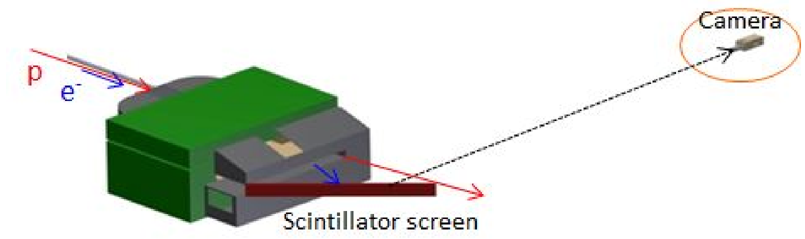
2 more diagnostics not covered in this talk.

The streak camera time-resolves the micro-bunches visually.

M. Turner for the AWAKE collaboration

Technical Challenge Nr 4:
Diagnostics

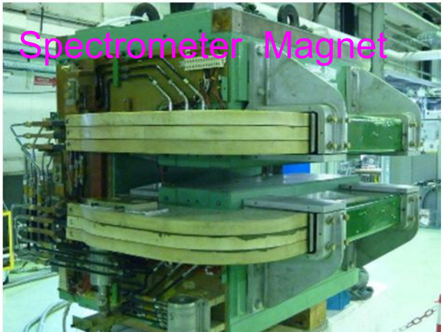
- What is the energy of the accelerated electrons?



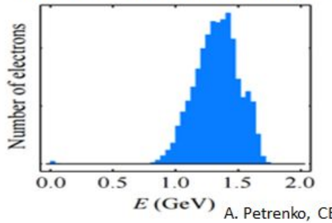
- Accelerated electrons are sent through a spectrometer magnet and deposit energy on a scintillating screen which is imaged by a camera.

- Electron acceleration is planned for 2018. (Installation and commissioning of the electron beam line: 2017)
- Electrons will be injected with an energy around 10-20 MeV.

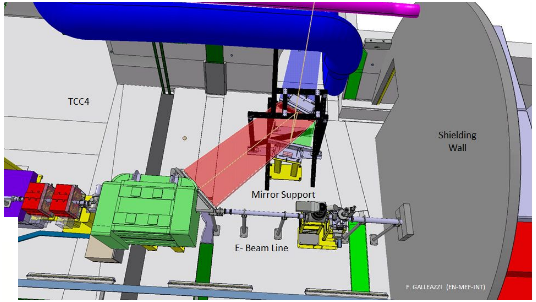
8.5 ton, 1.2 T, 1.3 Tm, L=1.6 m, W=1.3 m



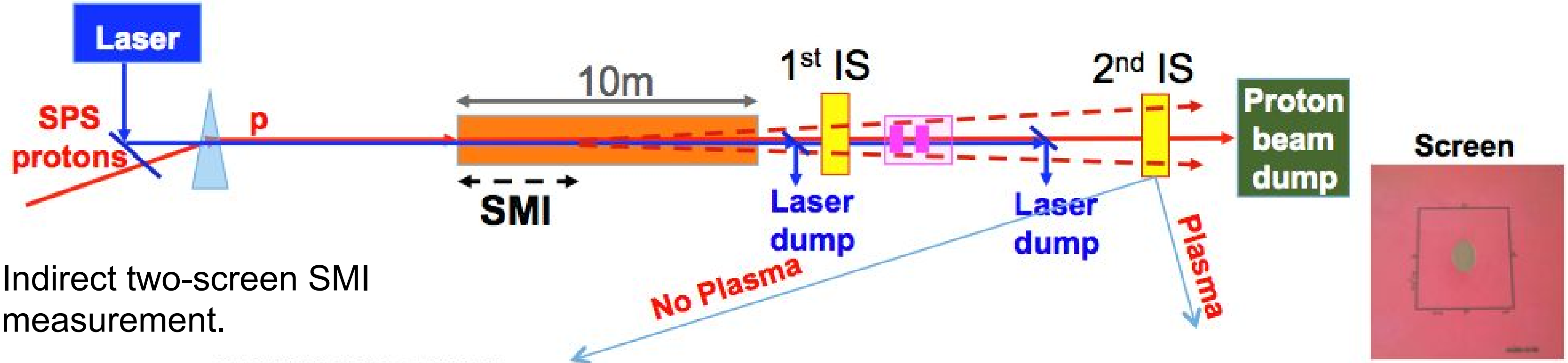
Typical final energy distribution of the accelerated electron beam after 10 m plasma:



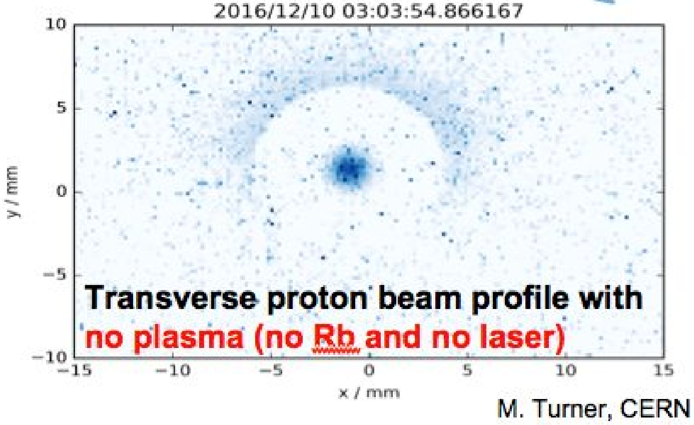
A. Petrenko, CERN

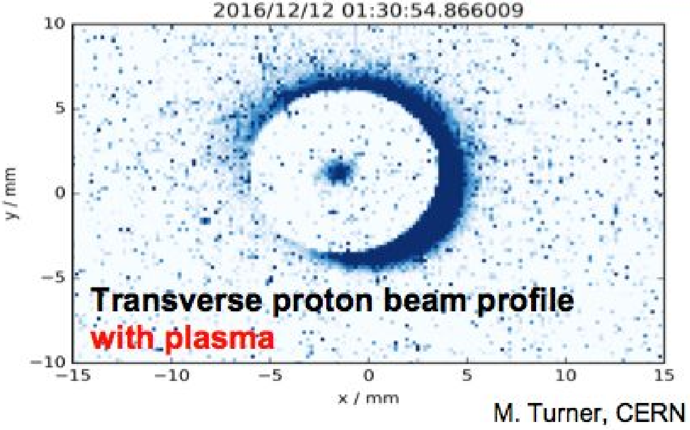


First Results



Indirect two-screen SMI measurement.

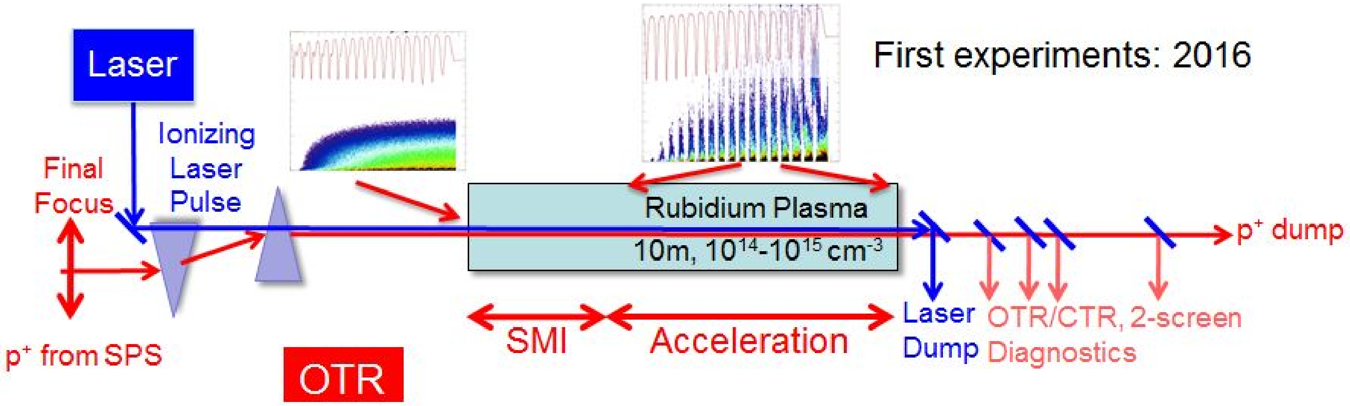




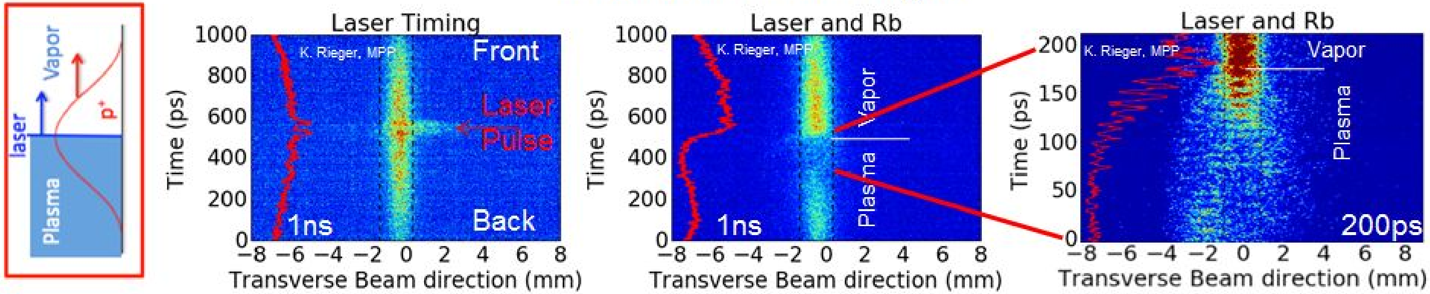
- Particles with large radii detected in the presence of plasma!

First Results

First experiments: 2016



Streak camera Images



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

K. Rieger, MPP

M. Turner for the
AWAKE collaboration

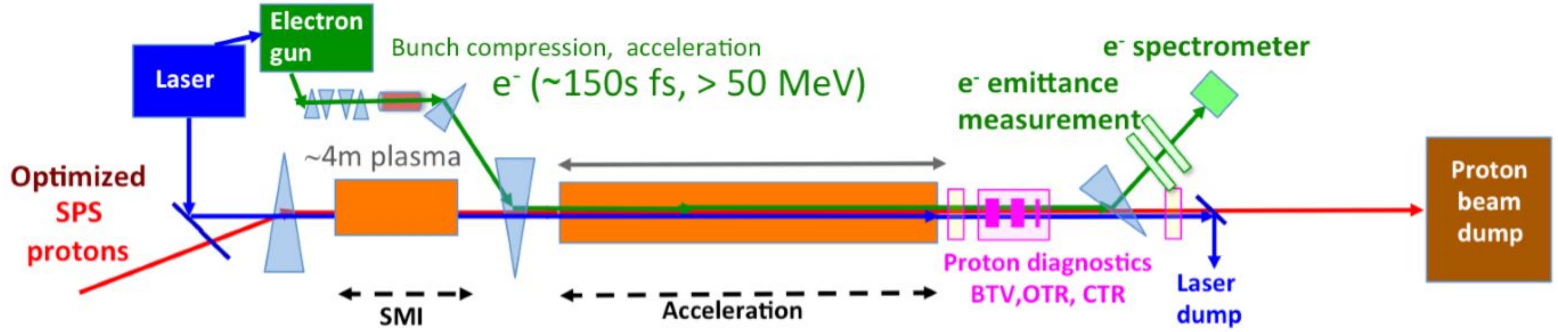
The future of AWAKE

AWAKE is an **R&D experiment** to develop a plasma based acceleration technique driven by a proton bunch.

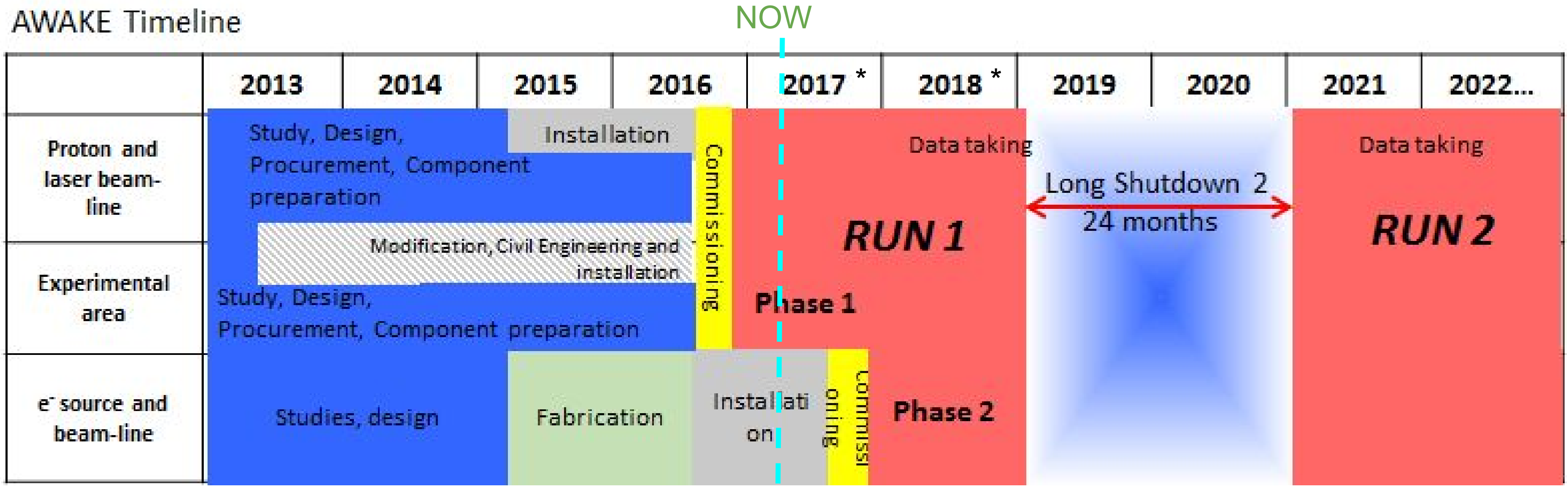
Short term: Further study of the self modulation instability (2017) and electron acceleration (2018).

AWAKE run 2: (after LS2) use for high-energy physics:

- ❑ demonstrate **scalability** of the AWAKE concept.
- ❑ demonstrate to preserve the electron beam **quality**.
- ❑ proton driven electron beam with **50-100 GeV/c**.



AWAKE Planning



*8 weeks of data taking per year.

Summary

- AWAKE is a **R&D project** to study proton driven plasma wakefields at CERN. AWAKE uses the first time ever protons to drive the plasmas wakefield.

- The goal is to **accelerate electrons** using GV/m plasma wakefields.

- The **plasma** is created by ionizing 10 m of rubidium vapour with a laser pulse and the wakefields are created by a self-modulated 400 GeV/c proton bunch.

- AWAKE was able to obtain **first results** on the self-modulation instability during a 48h beam-time last December.

- **Electron acceleration** is planned for 2018.