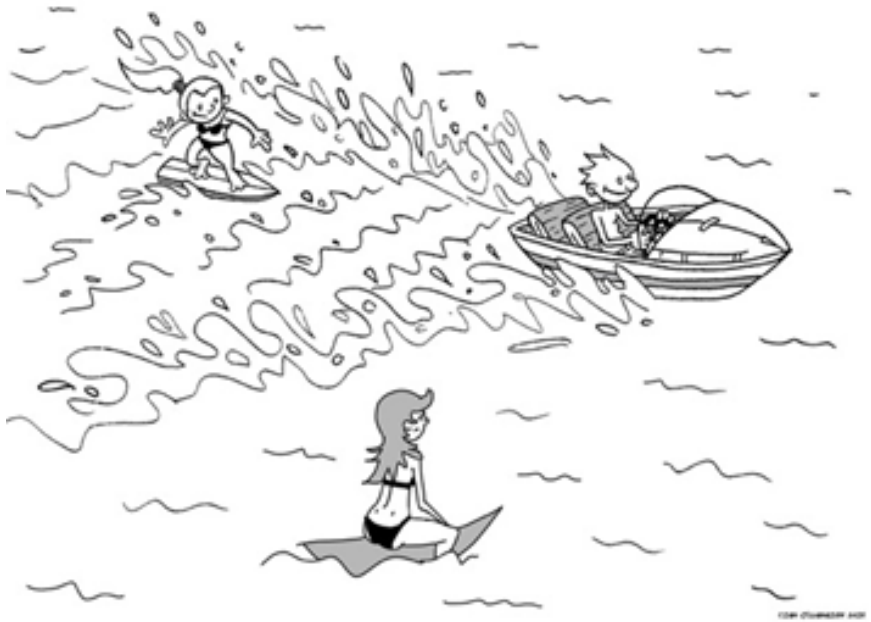
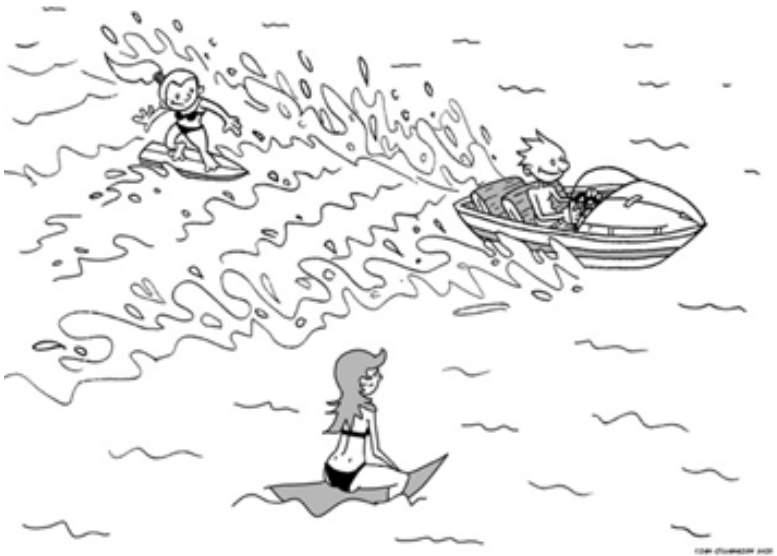
Status and Prospects for the AWAKE Experiment

Marlene Turner, CERN
for the AWAKE Collaboration

Outline of this Talk

- **Introduction**
  - Concept of plasma wakefield acceleration
  - AWAKE experiment
  - Seeded self-modulation
- **Status** of the AWAKE experiment
  - Seeded self-modulation measurements results
  - 2018: electron acceleration
- **Prospects**
  - AWAKE run 2
- **Summary**





Concept of plasma wakefield acceleration

Why plasma wakefield acceleration ?

The general **goal** of the work done in our field is to:

- use plasma wakefields for **charged particle acceleration;**
- accelerate to **higher energies** in **shorter distances** than with RF cavities.

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Particle acceleration in **radiofrequency** cavities limited to fields ~100 MV/m due to electrical **breakdown** in the structure.

Accelerate charged particles with **plasma wakefields**, because plasma can sustain higher electric fields.
Estimate of the achievable accelerating gradient is the cold plasma wave-breaking field (E):

$$eE = m_e \omega_{pe} c \sim 100 \frac{eV}{m} \sqrt{n_{pe}[cm^{-3}]}$$

i.e. **~1 GeV/m** for a plasma electron density n_{pe} of $10^{14} cm^{-3}$
~100 GeV/m for 10^{18} electrons/cm^3

How to Create a Plasma Wakefield?

Plasma:

Quasi-neutral plasma in which **electrostatic interactions dominate** and charged particles are close enough to support **collective behaviour.**

Drive bunch or pulse:

Typically a relativistic **charged particle** bunch

or

laser pulse/s.

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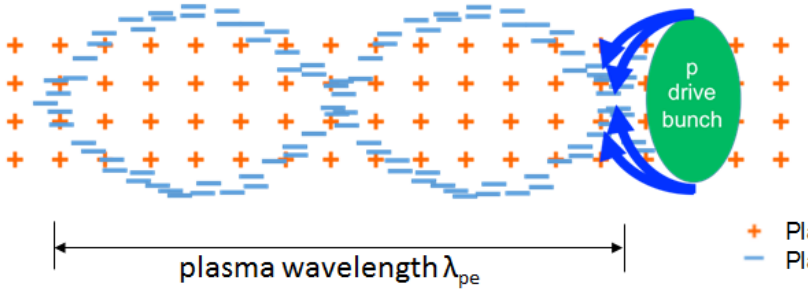

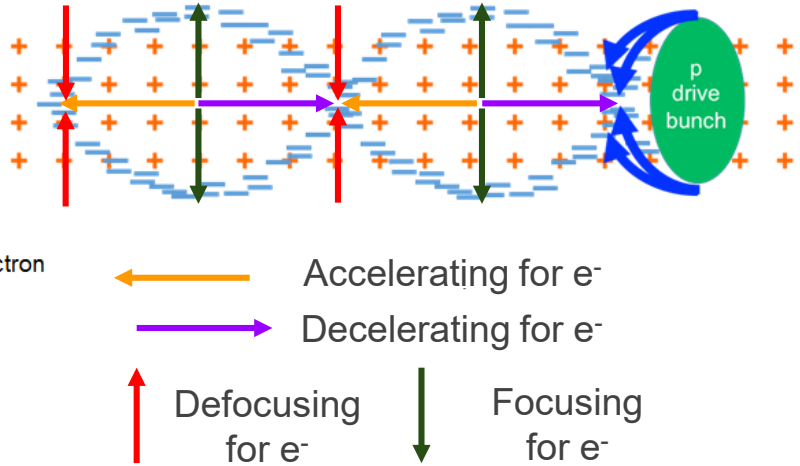

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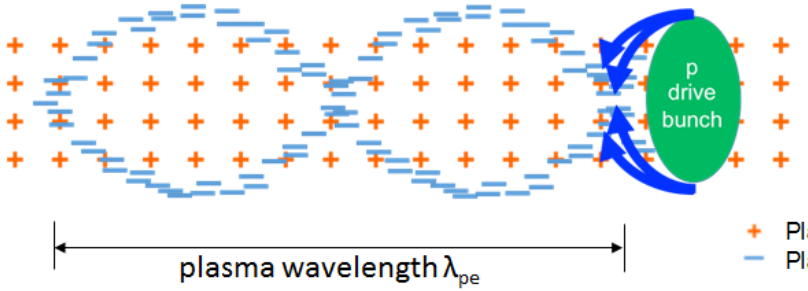
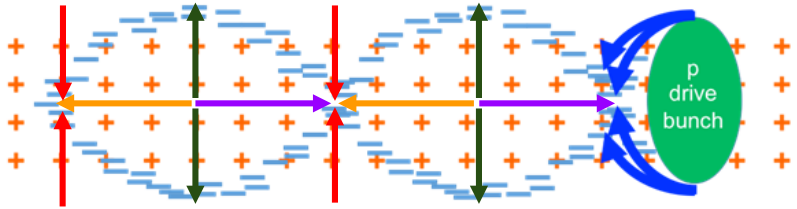




Plasma ion

Plasma electron

Accelerating for e⁻

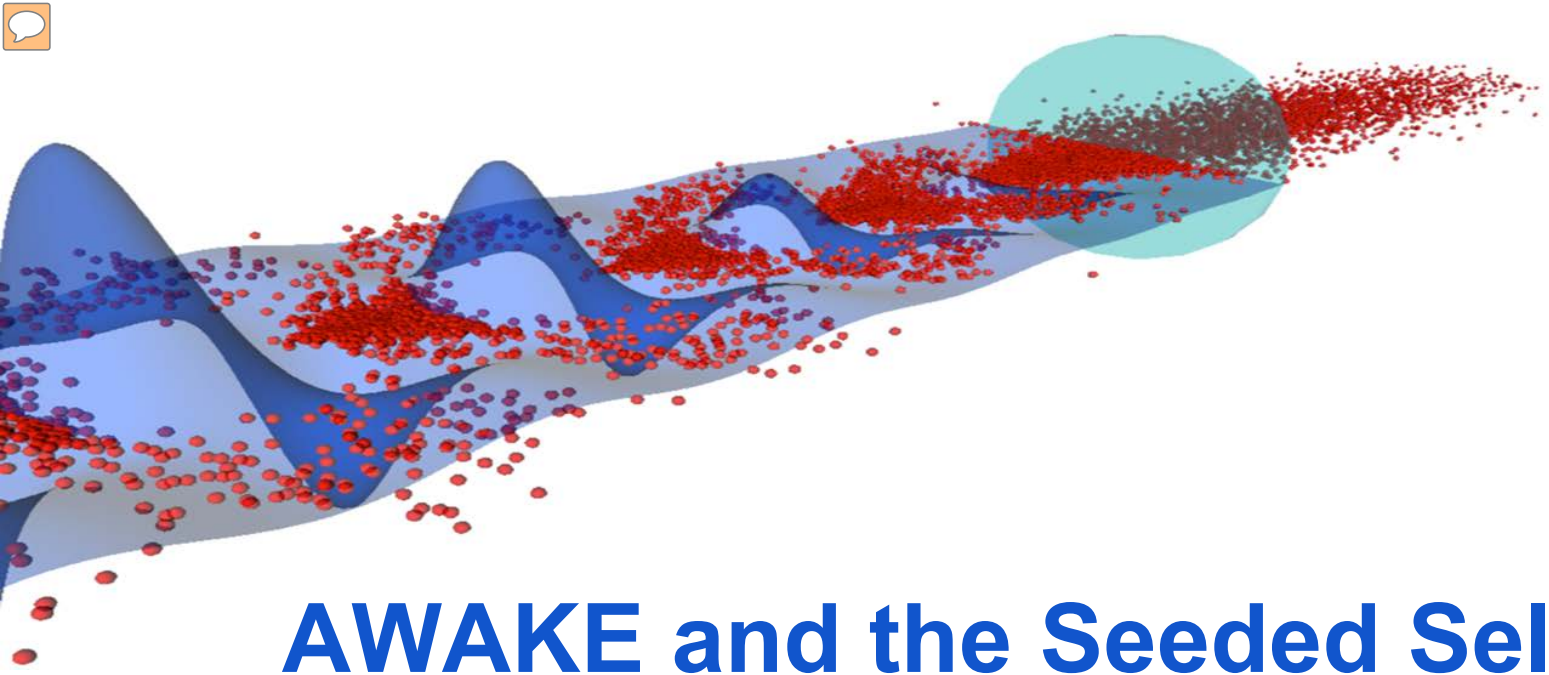
Decelerating for e⁻

Defocusing for e⁻

Focusing for e⁻

Larger plasma e⁻ density implies **smaller** plasma e⁻ wavelength⇒ smaller structures

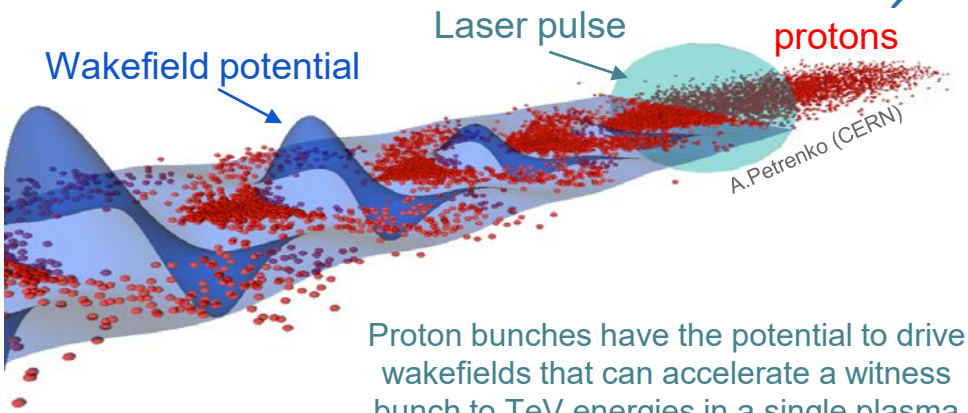
$$\lambda_{pe} = \frac{2\pi c}{\omega_{pe}} \propto \frac{1}{\sqrt{n_{pe}}}$$



AWAKE and the Seeded Self-Modulation (SSM)

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.



Proton bunches have the potential to drive wakefields that can accelerate a witness bunch to TeV energies in a single plasma

Caldwell A et al., *Nature Physics* **volume 5**, pages 363–367 (2009)

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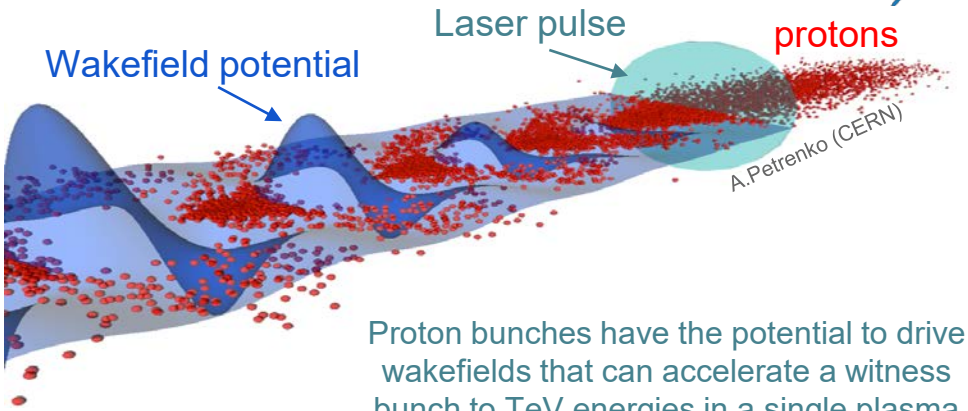

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10m Rb vapor cell

Developed by MPP

The seeded self-modulation

Why protons?

The length over which wakefields can be sustained depends on the drive bunch energy

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

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To effectively excite wakefields (from linear plasma wakefield theory)**:**

$$k_{pe}\sigma_z \approx \sqrt{2} \qquad k_{pe}\sigma_r \approx 1$$

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

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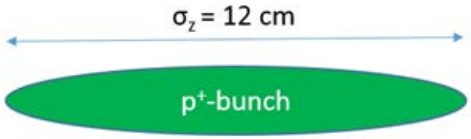
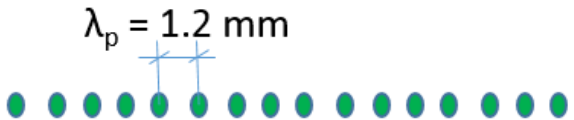
CERN SPS proton bunch: very long!

Longitudinal beam size (**σ_z= 6-15 cm**) is much longer than plasma wavelength (**λ_{pe}= 1 mm, n_{pe} = 7 x 10^{14} e^-/cm^3**)

⇒ Seeded Self-Modulation (SSM)

Before self modulation:

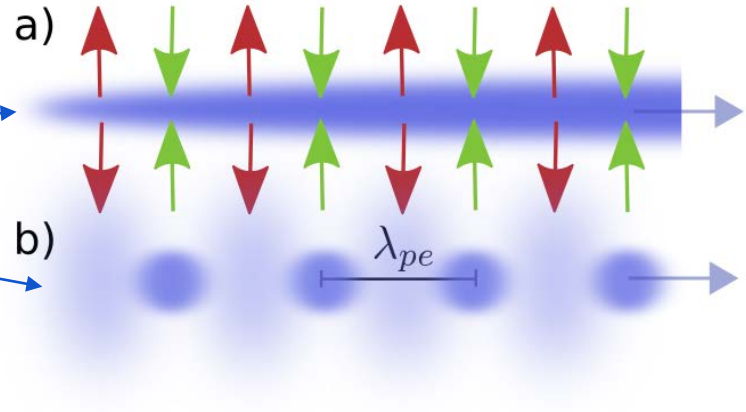




The seeded self-modulation

1) When entering the plasma, the bunch drives **wakefields** at the **initial seed value**.
2) The initial wakefields **act back** on the proton bunch itself. The on-axis density is modulated. The contribution to the wakefields is $\propto n_b$.
3) **Density modulation** on axis (Micro-bunches).

Micro- bunches separated by λ_{pe}.Drive wakefields resonantly.



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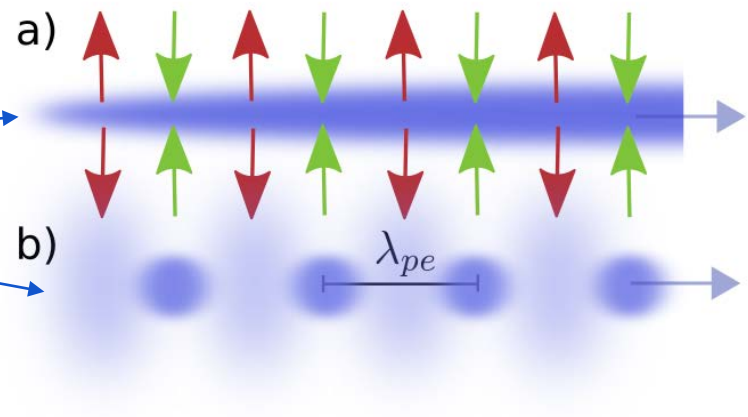
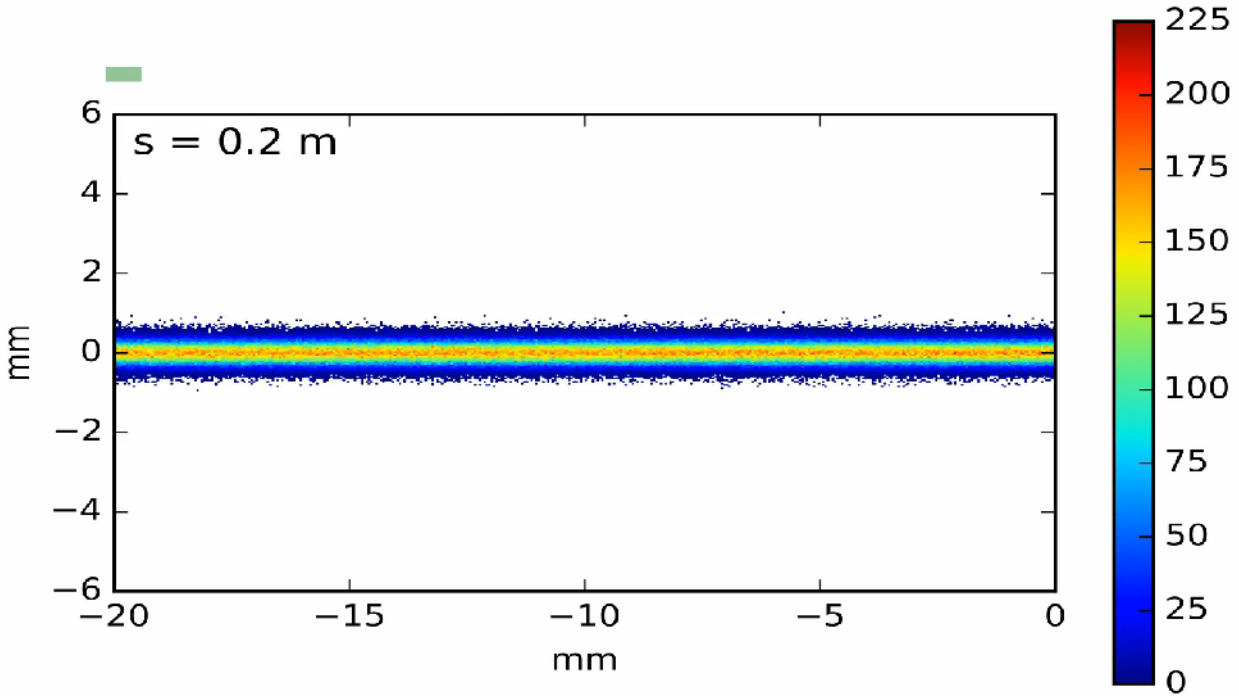


We **seed** the instability by:

- Placing the laser close to the **center** of the proton bunch
- **Sudden onset** of the proton density

⇒ **Seeded self-modulation (SSM)**


s = 0.2 m
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4
2
0
−2
−4
−6
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−20
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75
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25
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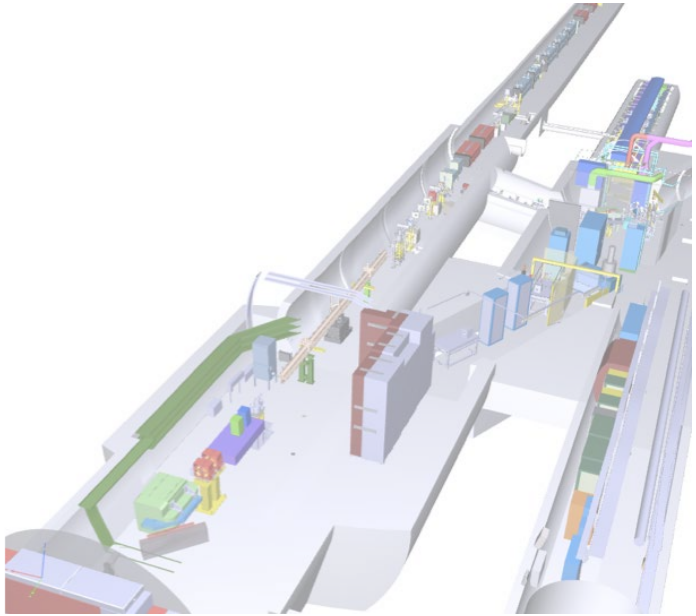

The AWAKE experimental setup

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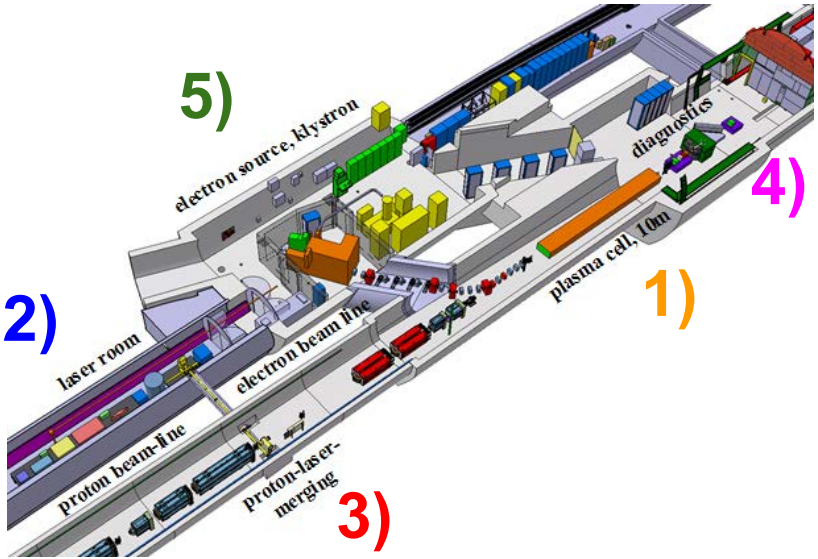


1. 10 m long **rubidium vapour source** with a vapour density adjustable from 10^{14}-10^{15} atoms/cm^3 and a density uniformity of 0.2%.

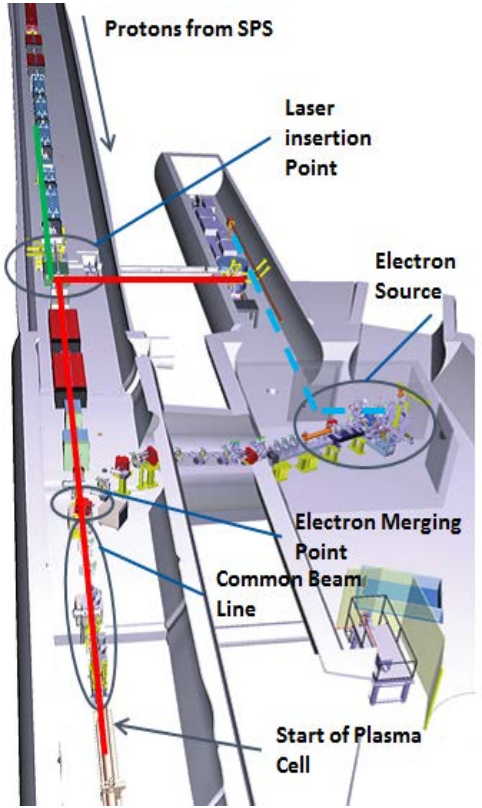
2. **Laser** system that produces a 120 fs, 450mJ laser pulse.

3. **Proton** beam line that transfers a 400 GeV/c proton bunch with a RMS length of 6-15 cm, a radial RMS size of 0.2 mm and 3x10^{11} protons/bunch from the CERN SPS to AWAKE.

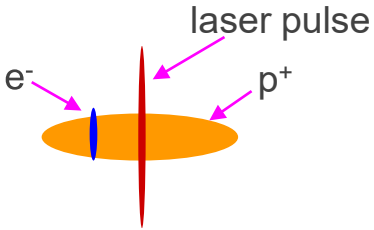
4. Experiment **diagnostics**.

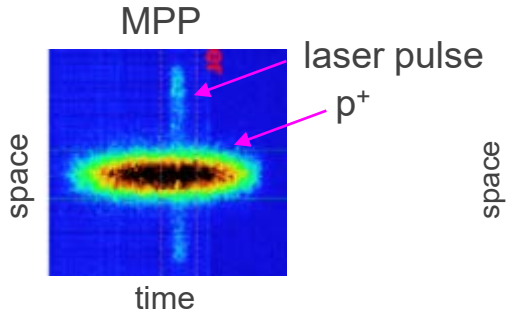
5. **Electron** photoinjector and transfer line that produces a 10-20 MeV electron bunch with a RMS length of 1 mm a RMS size of ~0.2 mm and ~10^9 electrons/bunch.

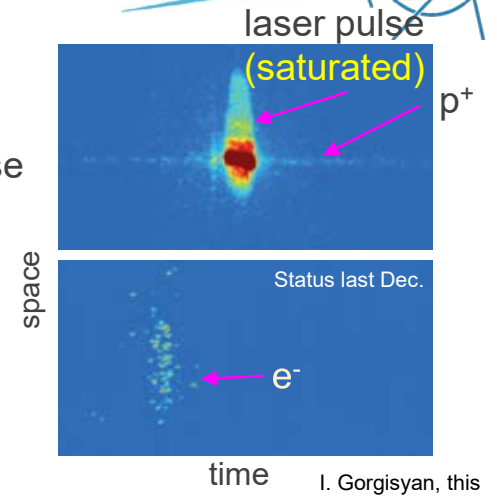
Alignment of p^+, e^- and laser pulse



Temporal alignment:







I. Gorgisyan, this proceeding

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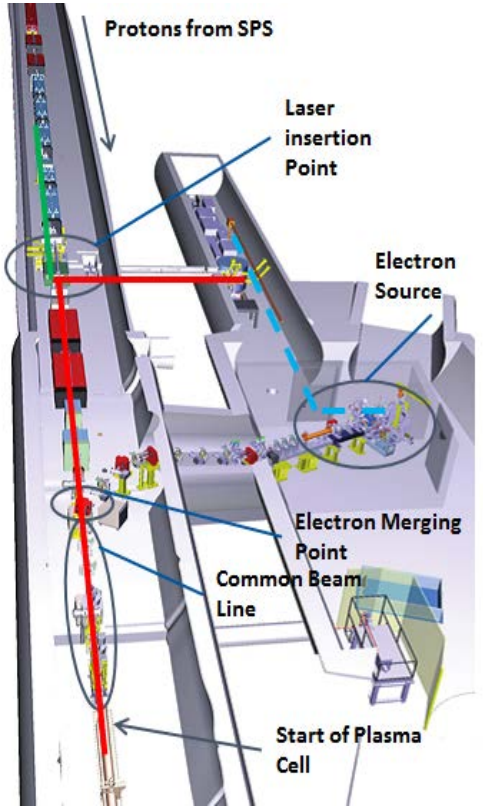

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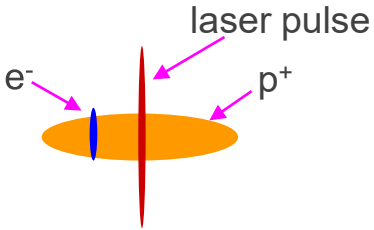

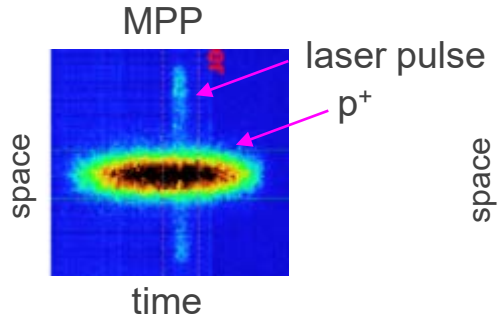

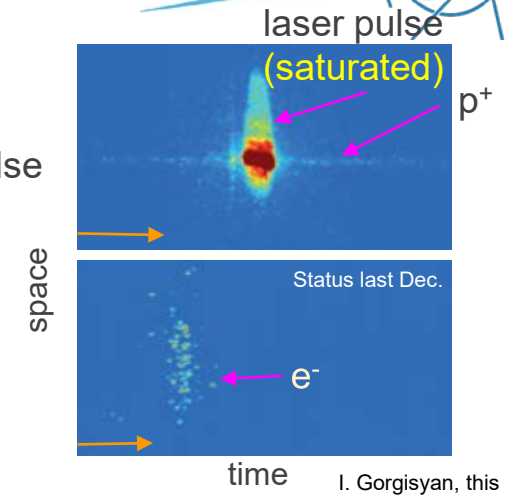

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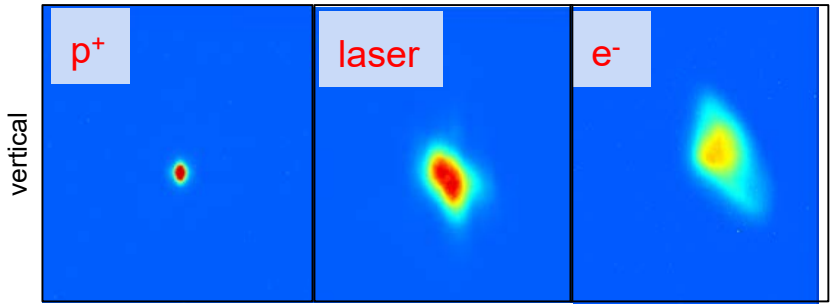
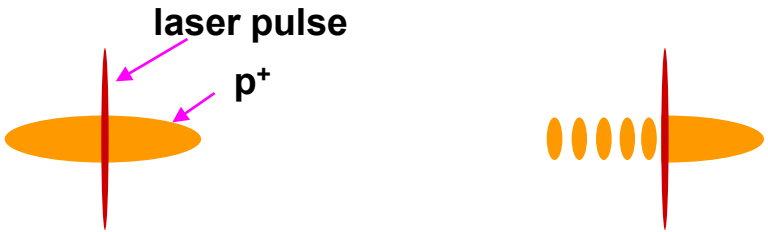
Spatial alignment:



~2m upstream the plasma

The AWAKE experiment (Run 1)

1. **Self-modulate** a long (compared λ_{pe}) 400 GeV/c proton bunch in plasma.



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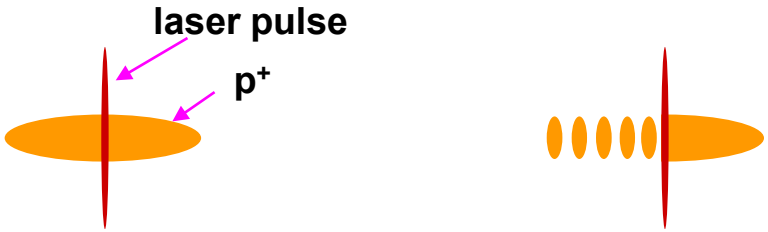
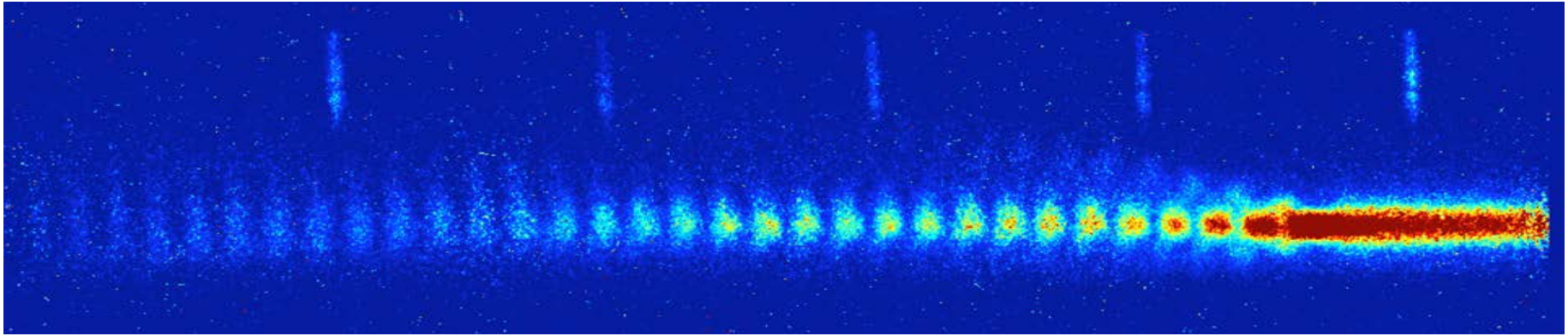
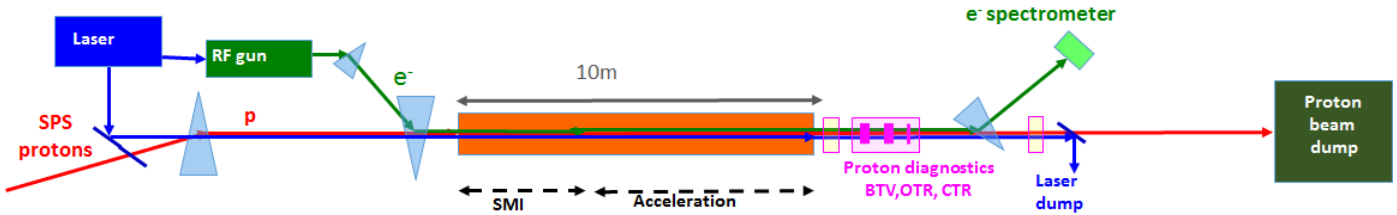


1. **Accelerate** externally injected 10- 20 MeV electrons to GeV energies (2018).



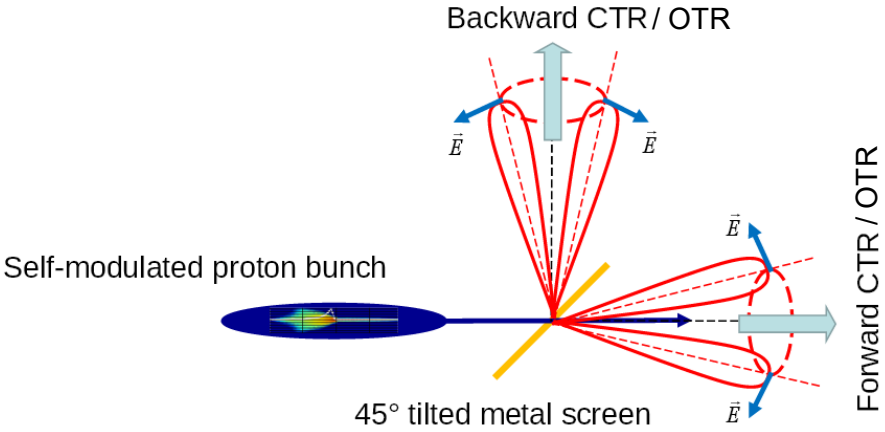
First results of the AWAKE experiment

Did the bunch self-modulate?

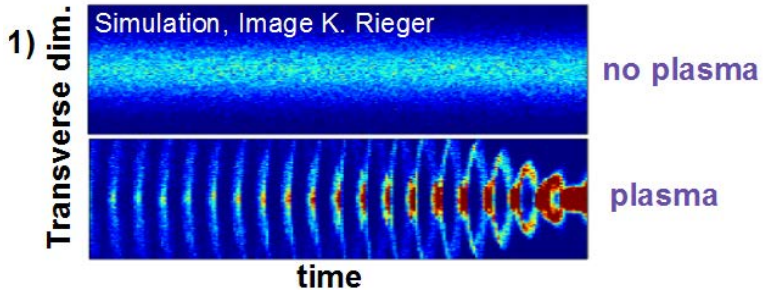


Generally we measure what is going **into the plasma** and what is **coming out of the plasma** ⇒ what has happened inside the plasma.

OTR Streak camera measurement



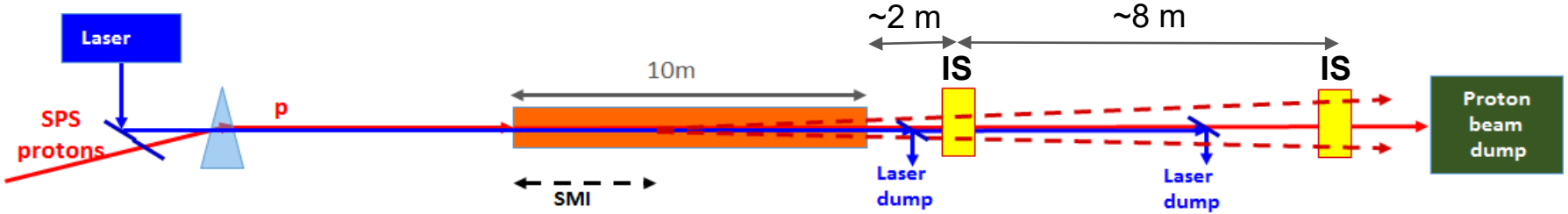
Streak camera imaging OTR light ⇒ time resolved image of the proton bunch.

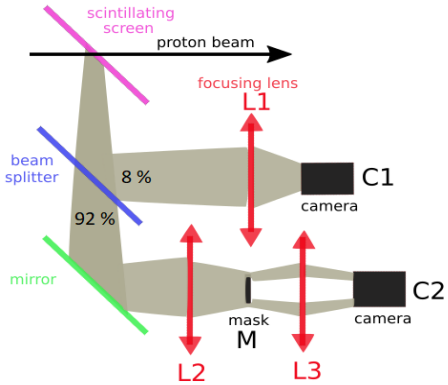


The imaging stations

2 Imaging stations ⇒ Transverse time integrated bunch profile.

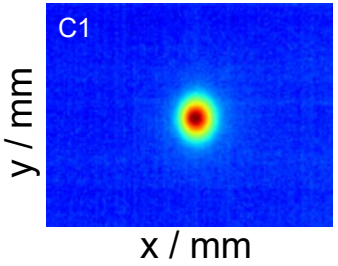
Goal: Detect protons that got defocused by the strong plasma wakefields.

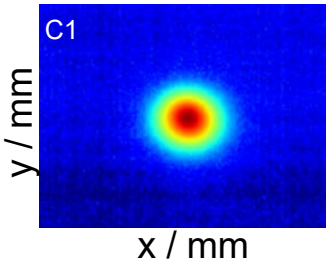




No plasma:

No ionizing laser pulse; bunch propagates through rb vapor





Log scale!

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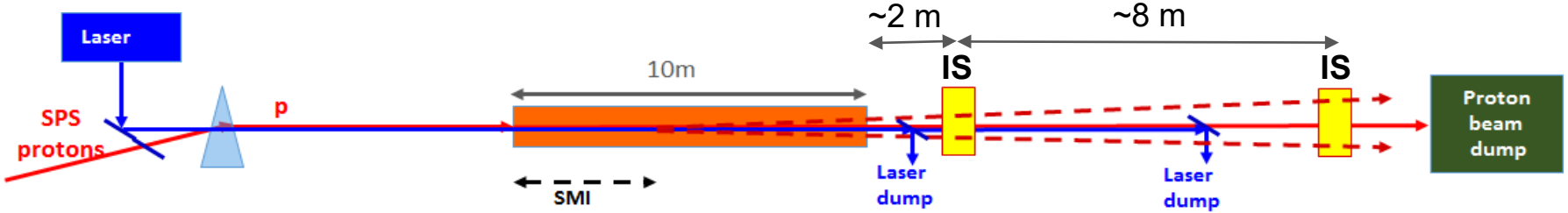
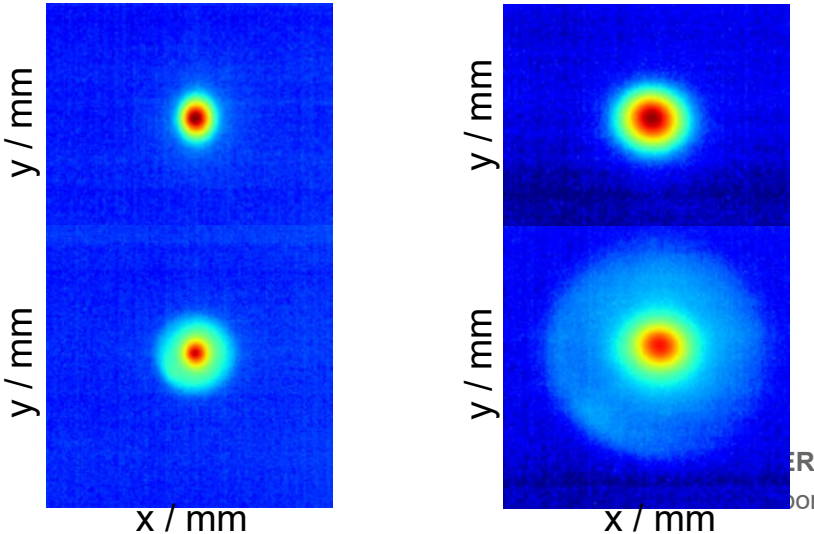


From the **radial distribution** of the defocused protons, we try to learn about the **transverse effects** of SSM

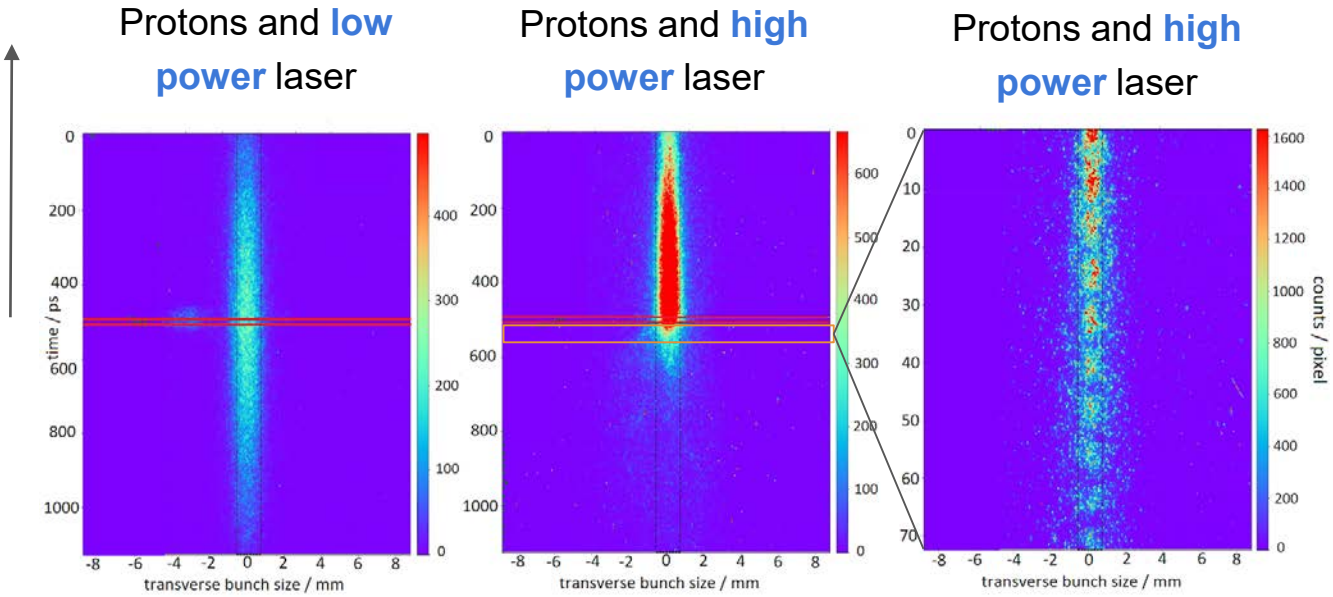
No plasma:

Plasma:



Log scale!

Seeded Self-Modulation



N_{pe} = 2.1e14/ccm

- **Effect** starts at the laser position.
- **Micro-bunches** are visible on a fast time-scale.

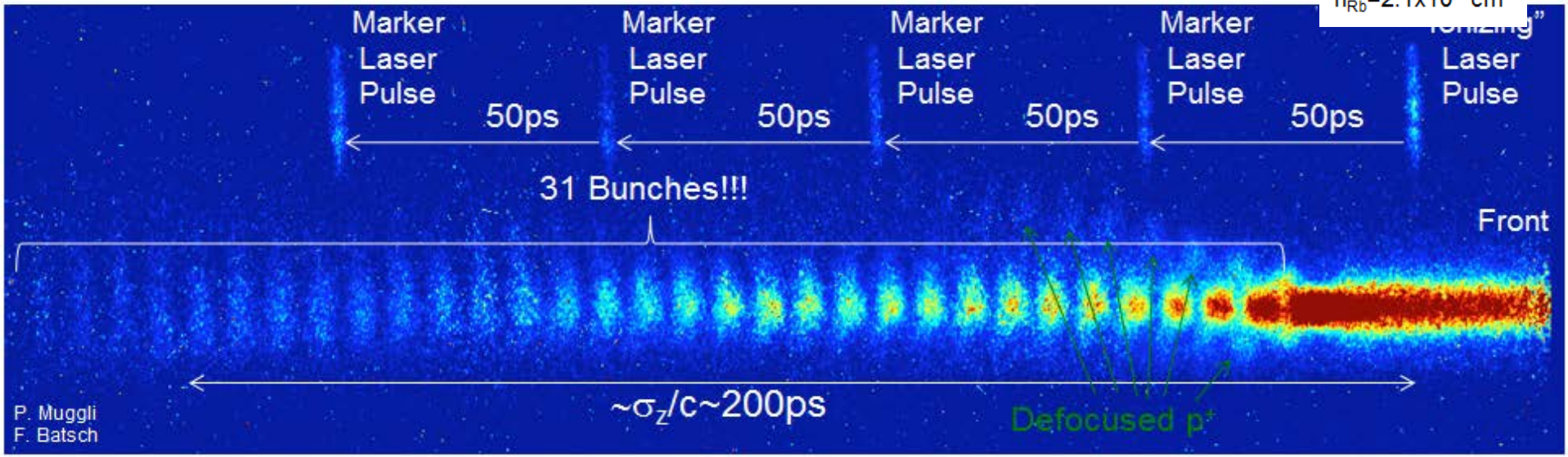
Seeded Self-Modulation

- **Single** streak camera measurement
- Time scale ~73 ps
- Streak camera trigger jitter (~20ps rms): **Marker laser** pulsed synchronized with ionization laser pulse at the 10 ps time scale.

Seeded Self-Modulation

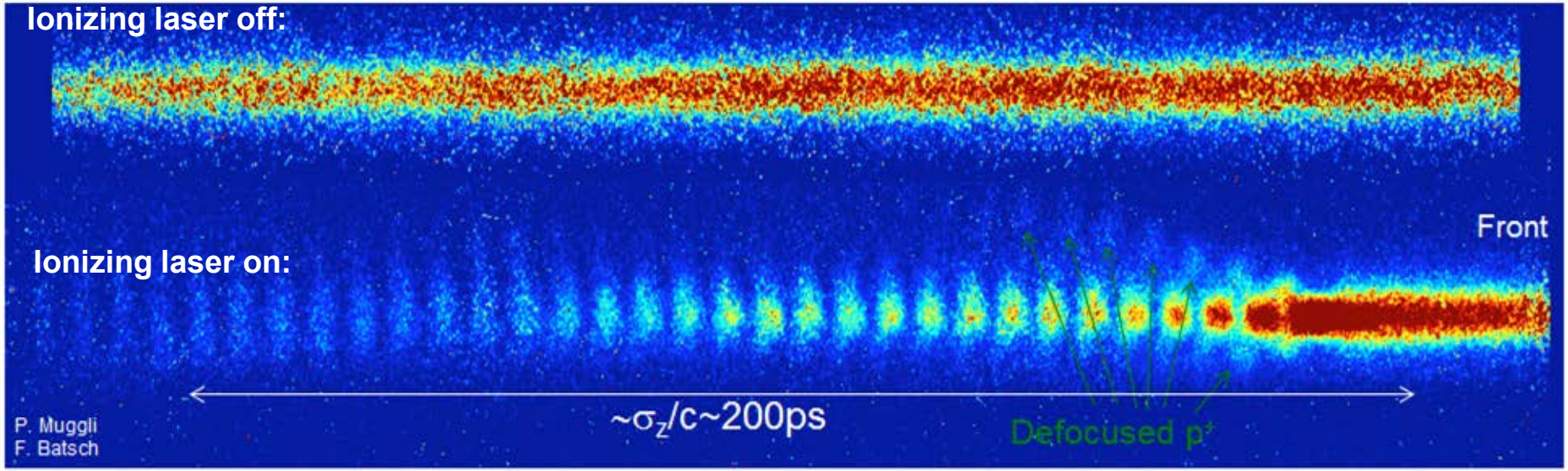
- **10 consecutive events** aligned to marker laser pulse
- Bunches add:
  - Modulation fixed wrt **ionizing laser pulse**
  - Modulation fixed wrt to **seed**

Seeded Self-Modulation



- 5 sets of 10 events each
- Possible because: **marker laser** pulsed synchronized with ionization laser pulse at the ps time scale

Seeded Self-Modulation

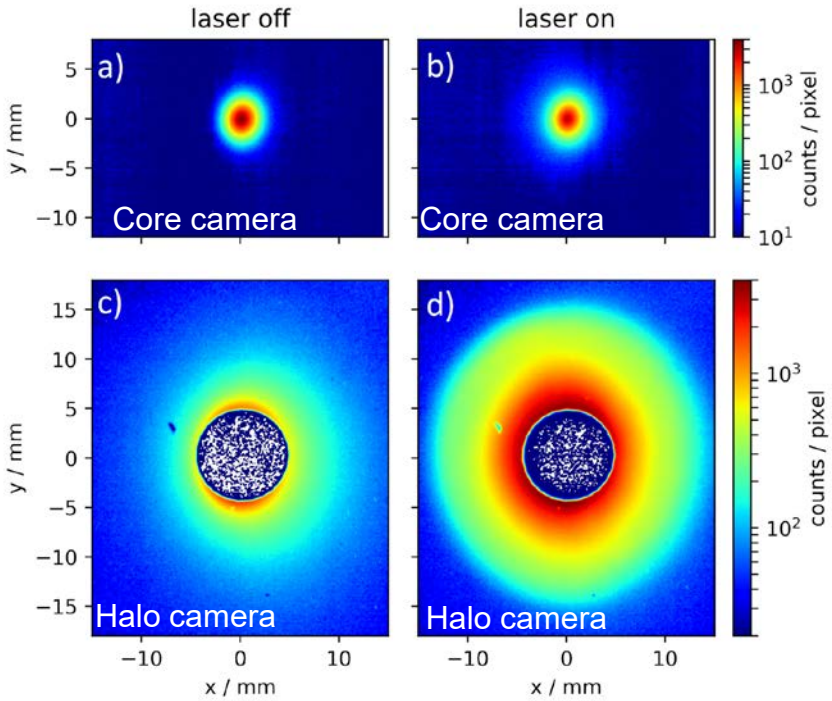


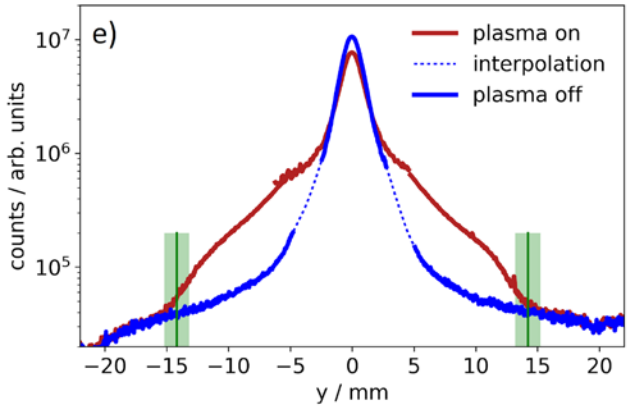
- **Micro-bunches** present over long time scale from seed point
- "Stitching" demonstrates **reproducibility** of the micro-bunch process against bunch parameters variations (N=2.5x10^{11}±10%, s_{zt}=220±10ps, s_r)
- **Phase stability** essential for e^- external injection!

Detection of defocused protons

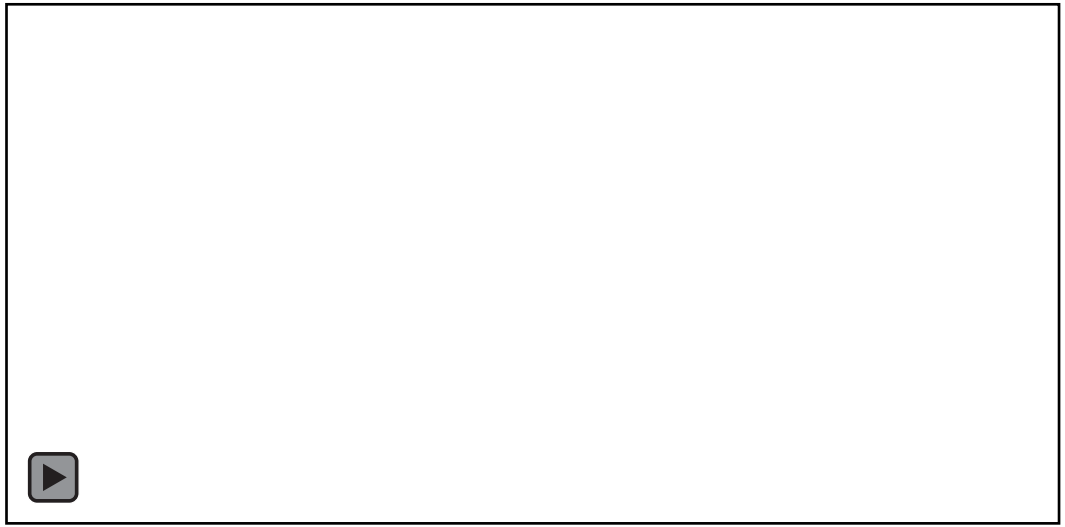
Two consecutive measurements:

- Close to **AWAKE** baseline parameters.





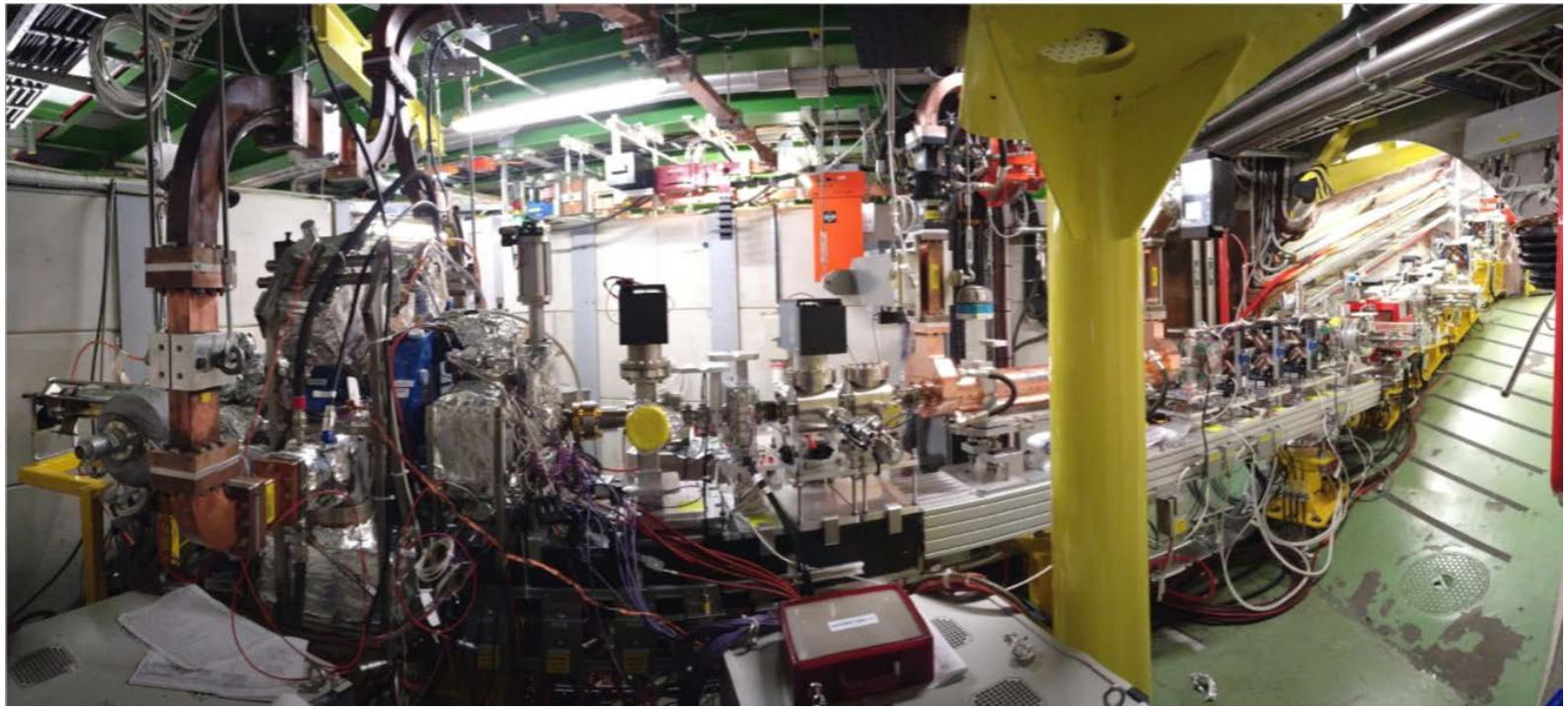
- Proton density in core **decreases**, proton density at large radii **increases** (appearance of halo).
- Protons get defocused up to a **maximum radius** of 14.5 mm for a plasma density of 7.7e14/cm^3.
- Halo symmetric ⇒ **no hose instability.**



Electron acceleration

The AWAKE electron bunch

- The **electron gun** and **transport line** has been installed in 2017.

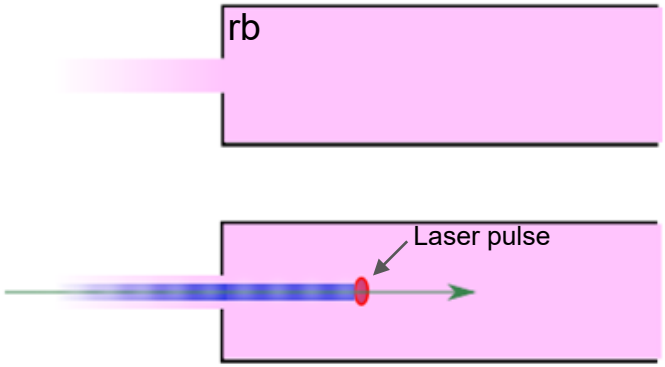


- The electron system is now under **commissioning**.

Electron injection

AWAKE is getting ready for electron acceleration:

- **Challenge:**
  - During the **SSM** the proton bunch distribution evolves
  - Short plasma density ramp at the entrance of the plasma
    ⇒ change of wakefield phase



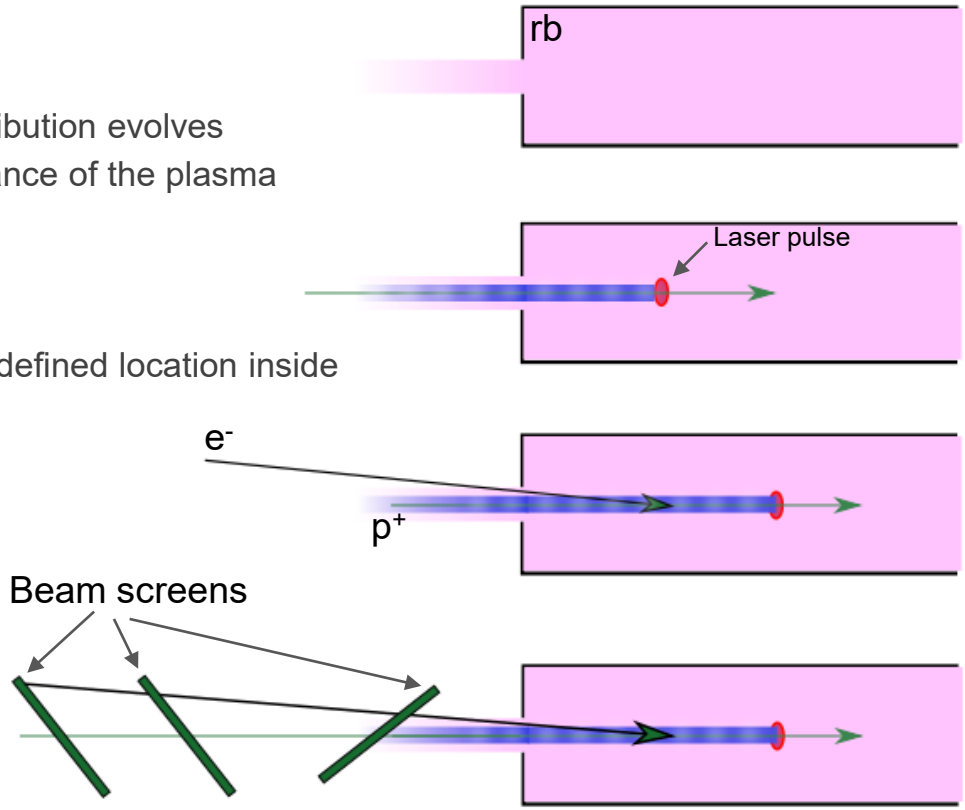
Electron injection

AWAKE is getting ready for electron acceleration:

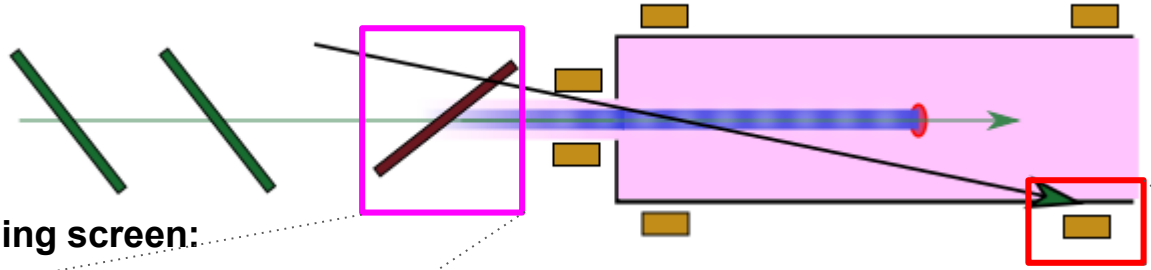
- **Challenge:**
  - During the **SSM** the proton bunch distribution evolves
  - Short plasma density ramp at the entrance of the plasma
    ⇒ change of wakefield phase

- Instead of injecting bunches co-linear
  ⇒ **Cross** the electron and proton bunch at a defined location inside the plasma.

- Radial bunch size:
  - proton : ~150 um
  - electron : ~200 um



Electron injection diagnostics



Advanced imaging screen:

Goal: see the electron bunch in presence of the protons and the ionizing laser pulse

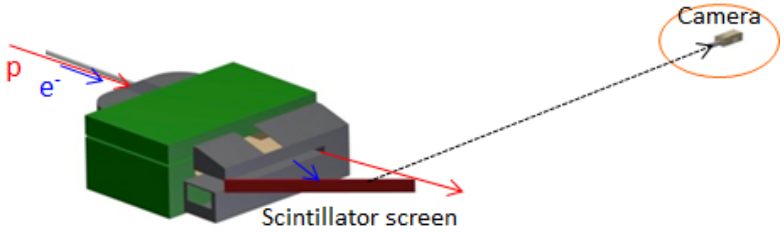
Electron beam loss monitors:

L.Verra

What is the energy of accelerated electrons?

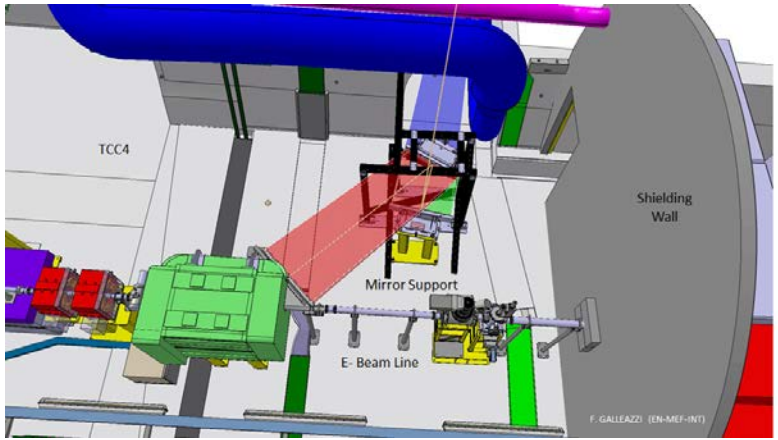
Accelerated electrons are sent through an imaging **spectrometer** and deposit energy on a **scintillating screen** which is imaged by a camera.

See Keeble F et al., The AWAKE electron Spectrometer, this proceedings

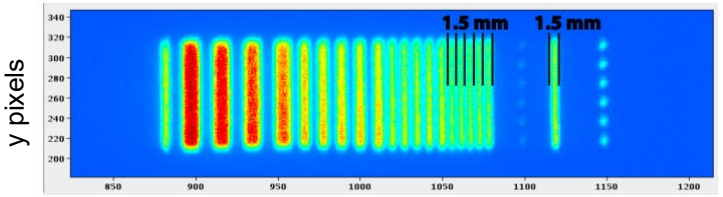


B = 0.1 - 1.5 T
Magnetic length = 1m

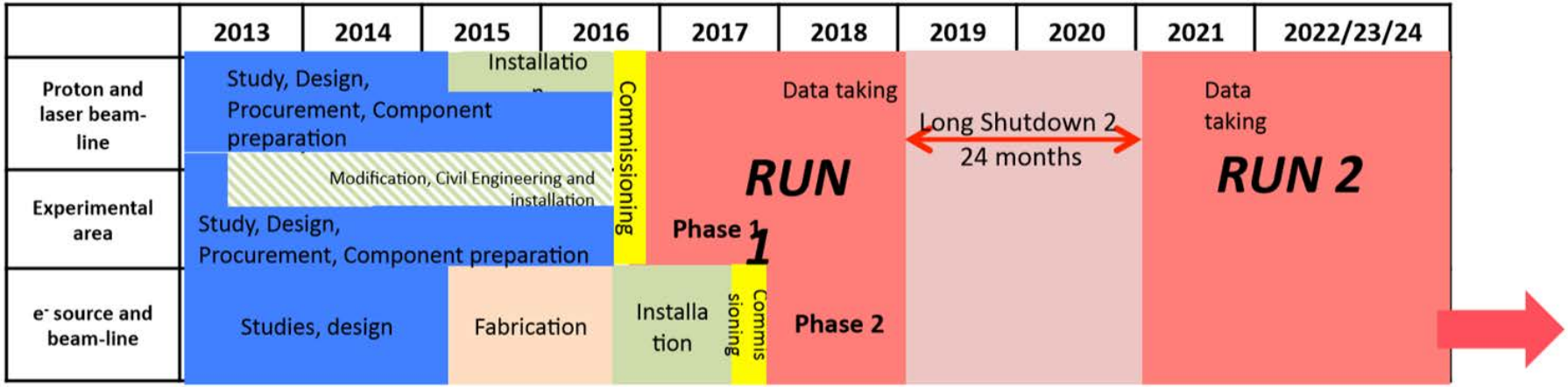
We can detect electrons with energies ranging from: 30 MeV - 8.5 GeV



Calibration image of the spectrometer



Spectrometer fully commissioned

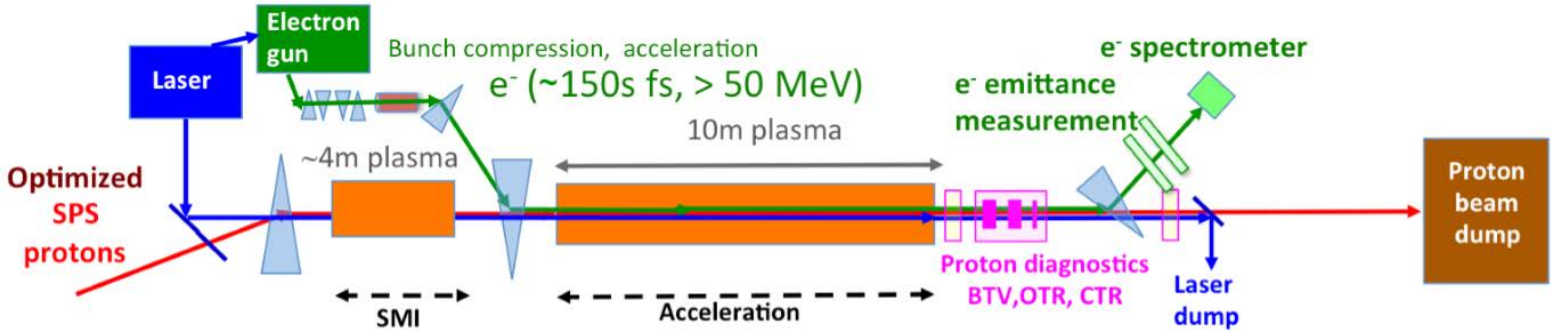

2013
2014
2015
2016
2017
2018
2019
2020
2021
2022/23/24
Proton and laser beam-line
Experimental area
e- source and beam-line
Study, Design, Procurement, Component preparation
Installatio
Modification, Civil Engineering and installation
Study, Design, Procurement, Component preparation
Commissioning
Data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

Prospects

AWAKE Run 2

Goal: The next big step for AWAKE is to demonstrate **scalability** of the AWAKE concept and that we can control the parameters of the accelerated electron bunch to the level where it can be used for first applications:

- ❑ a micron-level normalized **emittance**
- ❑ a percent level relative **energy spread**
- ❑ high **charge**



After Run 2: get ready for first HEP applications:

Use bunches from SPS with 3.5 E11 protons every ~5sec, electron beam of up to O (50GeV).

The AWAKE Collaboration!

Conclusions and Summary

- The goal of the **AWAKE** experiment is to: **accelerate electrons** with plasma wakefields driven by a **self-modulated proton** bunch.
- We demonstrated that the **SSM develops** over the 10m of plasma and that its physics properties scale as expected.
- The **electron beam system** has been installed and is under commissioning.
- **Electron acceleration** experiments are foreseen for 2018.