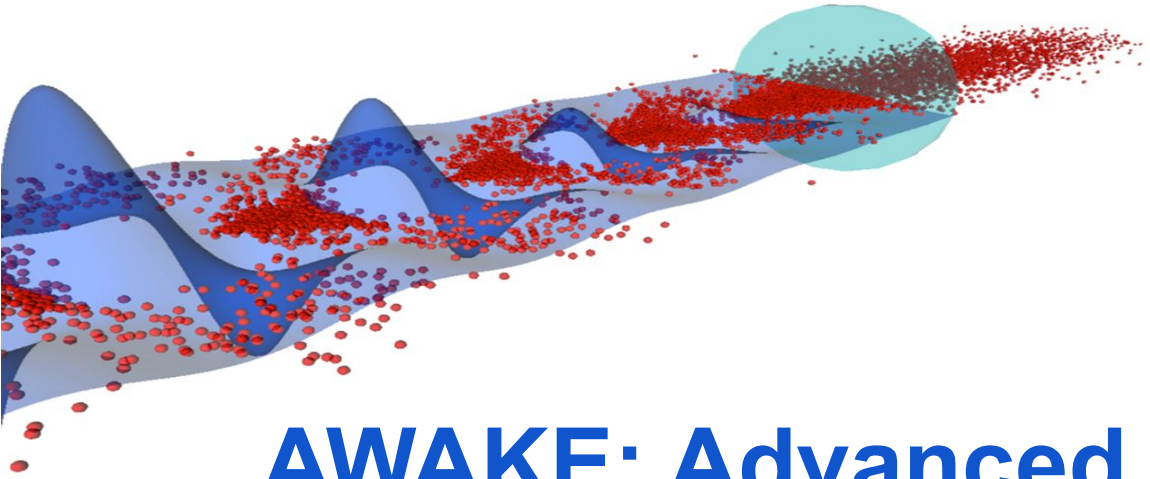

AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN

Marlene Turner for the
AWAKE Collaboration

To make the lecture a bit more interactive:

We are currently at ?

Fermilab.

SLAC.

DESY.

CERN.

Do not be afraid of giving a wrong answer…

It just tells me to repeat / explain more carefully.

I can comfortably explain the unique properties of a plasma.

Yes

No

I have heard about plasma wakefield acceleration.

Yes

No

I have heard about the AWAKE experiment.

Yes

No

Outline

- What is the **AWAKE** experiment, and why is it important?
- The **physics** behind plasma wakefields
- The AWAKE **experimental setup**
- Latest AWAKE **results**

AWAKE:

Advanced Proton Driven Plasma Wakefield Acceleration Experiment

- Plasma ?
- Proton driven ?
- Wakefield acceleration ?

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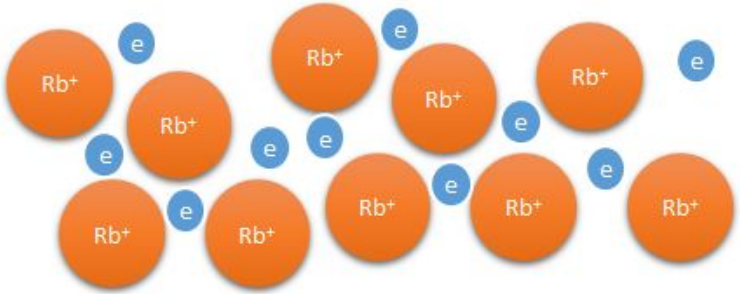
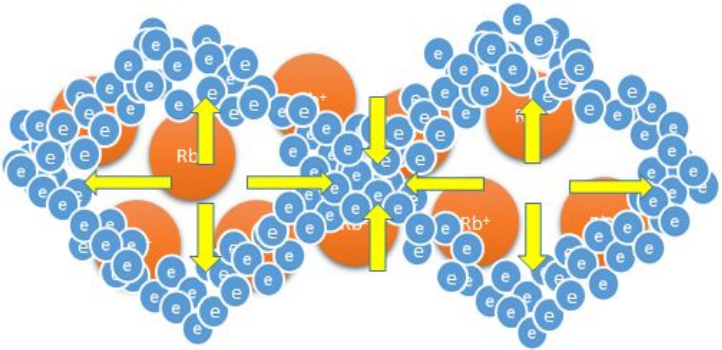
Let's discuss the basics:

What is a plasma?



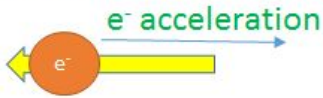
- **Ionised gas**
  - **Quasi-neutrality:** the overall charge of a plasma is about zero.
  - **Collective effects:** Charged particles must be close enough together that each particle influences many nearby charged particles.
  - **Electrostatic interactions dominate** over collisions or ordinary gas kinetics.

What are plasma wakefields?



- **Fields** created by collective motion of plasma particles are called plasma wakefields.
- In our case : Excited by a **proton drive bunch**

Note:
To accelerate charged particles we need longitudinal electric fields.



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Why are plasmas interesting for charged particle acceleration?

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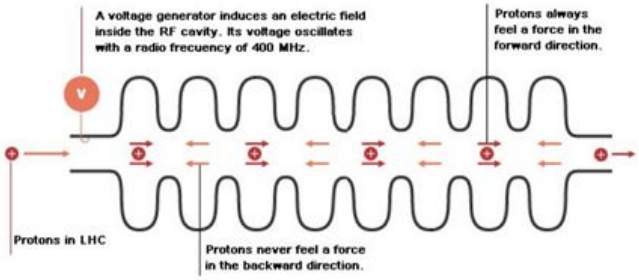
Why plasma wakefield acceleration?

Conventional Acceleration

Limited to approx. 100 MV/m due to electric breakdowns (ionization).



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Why plasma wakefield acceleration?

Conventional Acceleration

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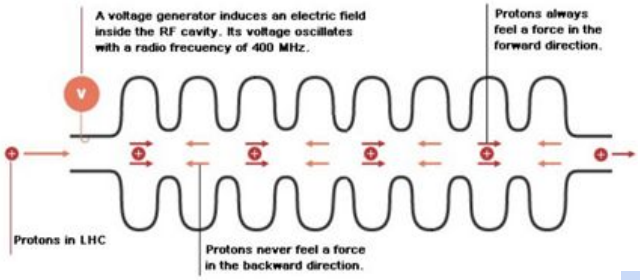


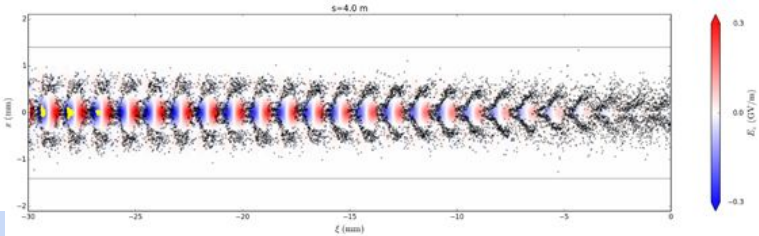
It's all about the accelerating gradient

E = U/d

Plasma Wakefield Acceleration

Plasma is already ionized or "broken-down" and can sustain electric fields in the order of 100 GV/m.

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



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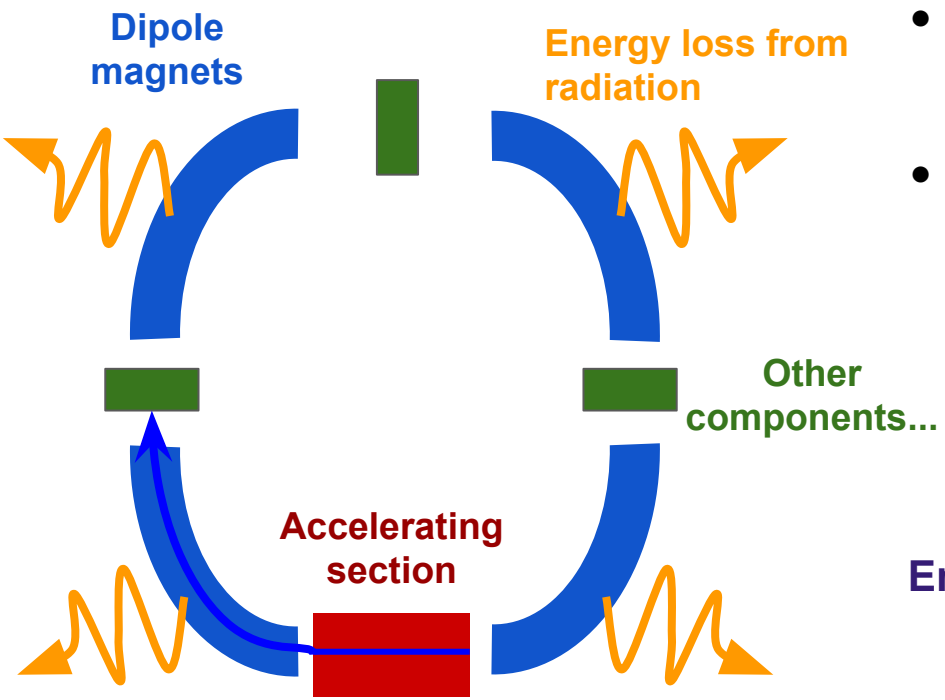
Circular vs linear collider



- **Big advantage:** charged particle passes through the accelerating section many times
- Beam held on a circular trajectory by **bending magnets:**
  - ⇒ Synchrotron radiation $\propto E^4/r^2m^4$

m_e = 511 keV

m_p = 936 MeV

Energy gain per turn = Energy loss per turn

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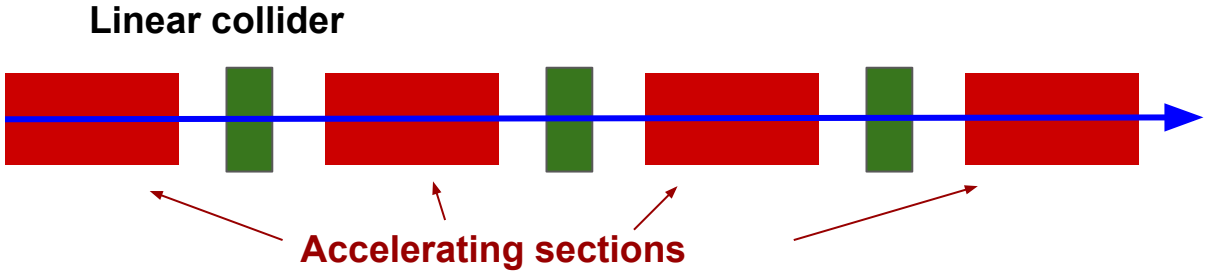
Circular vs linear collider



- Charged particle only passes once through the accelerating section
  - ⇒ almost no synchrotron radiation losses

Linear colliders favorable for acceleration of low mass particles.

⇒ Accelerating gradient and desired energy gives the length of the accelerator

With plasma wakefields we can achieve higher gradients than with conventional accelerators

zB. To accelerate electrons to 1 TeV (10^{12} eV):
100 MeV/m x 10000 m or
100 GeV/m x 10 m

Let’s repeat..

Physicists want a new linear collider. For what?

To accelerate protons.

To accelerate neutrons.

To accelerate electrons.

All of the answers are correct.

What is NOT a property of plasma?

Quasi-Neutrality.

Collective behavior.

Electrostatic effects dominate.

Particle collisions dominate.

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What is the advantage of plasma wakefield acceleration?

Low acceleration gradient.

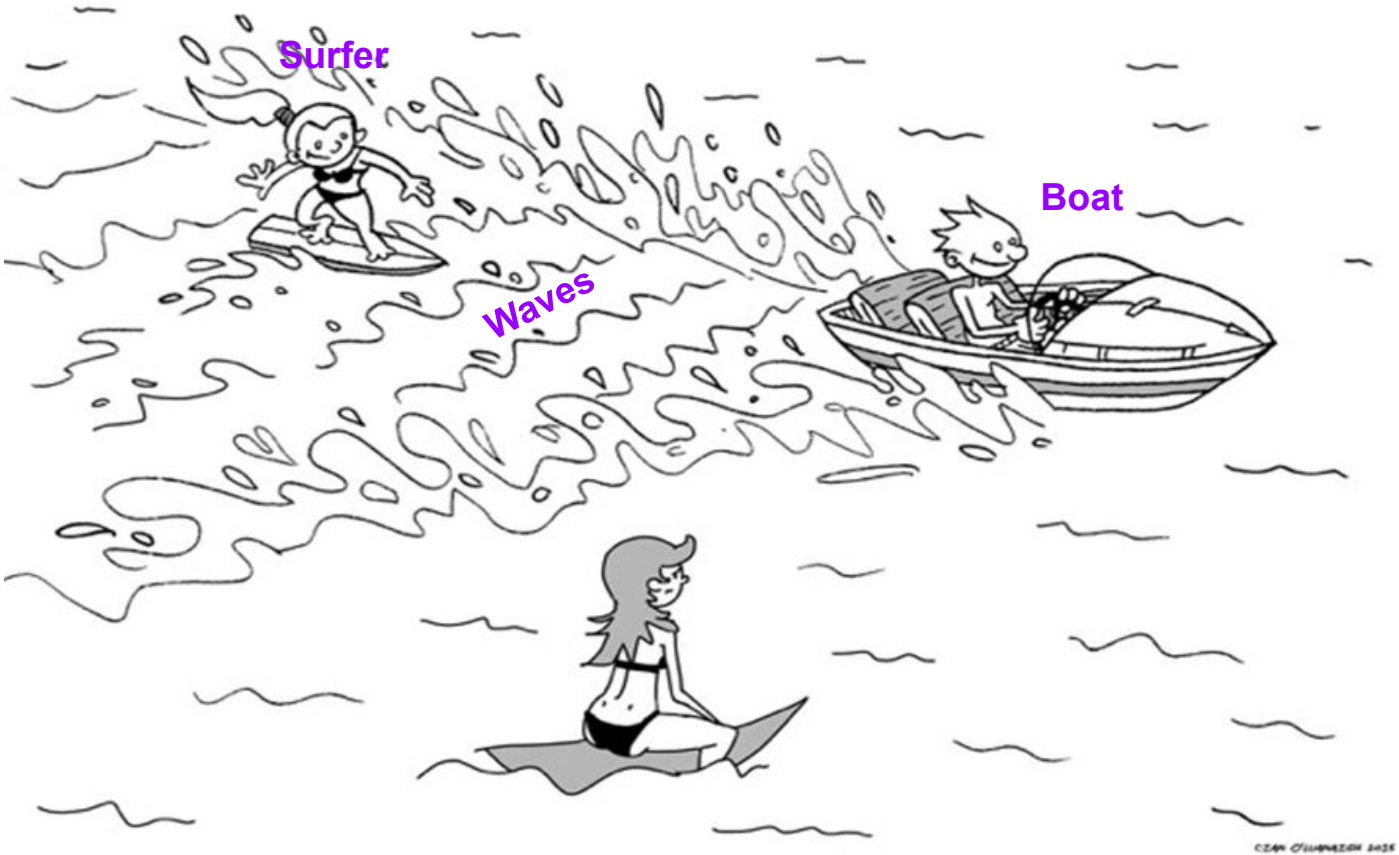
Acceleration of heavier particles.

High acceleration gradient.

Longer acceleration distance.

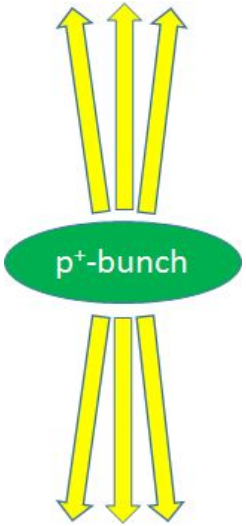
How to create a plasma wakefield?

Let me give you an analogy...



Let's talk about our boat.. or as we call it: the drive bunch

Available at CERN:



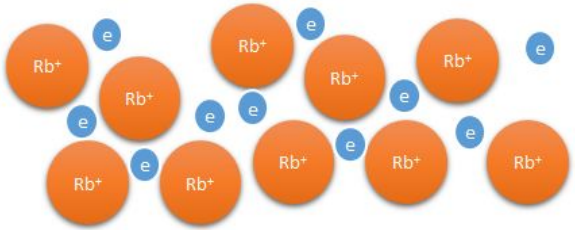
Proton bunches at CERN carry energies of kJ to MJ!

Relativistic charged particle bunches carry almost purely **transverse electric** fields:

What we need:

Longitudinal electric field to accelerate charged particles.

Our Tool:



- Use plasma to convert the transverse electric field of the proton bunch into a longitudinal electric field in the plasma.
- The more energy is available, the longer (distance-wise) these plasma wakefields can be sustained.

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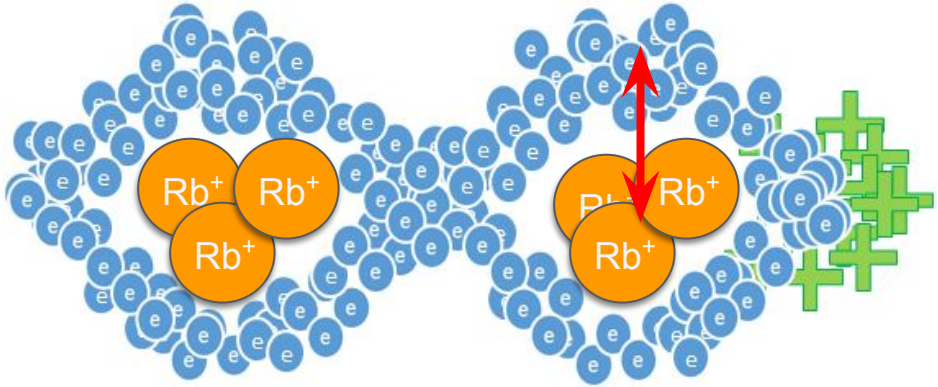
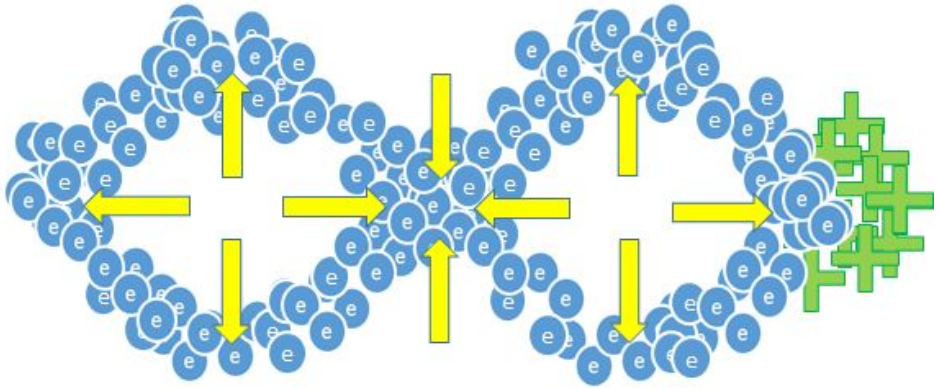
How to create a plasma wakefield?





Important to understand:

- Plasma electron motion is mostly **transverse**
- Electrons do not move significantly longitudinally
- Rb ions (not shown) heavy and do not move

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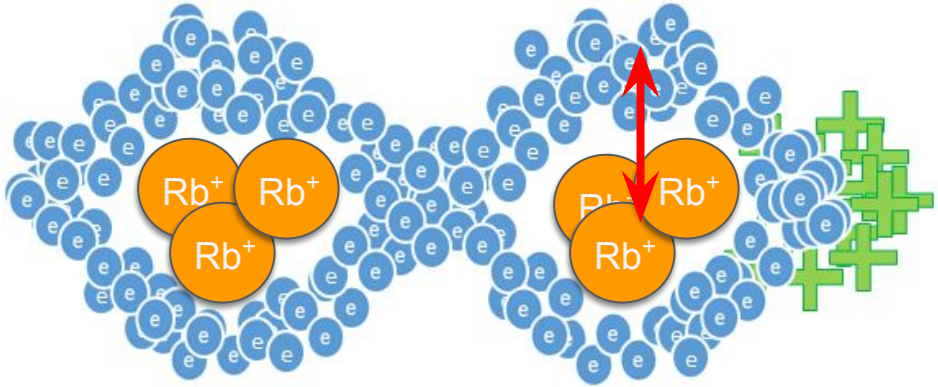
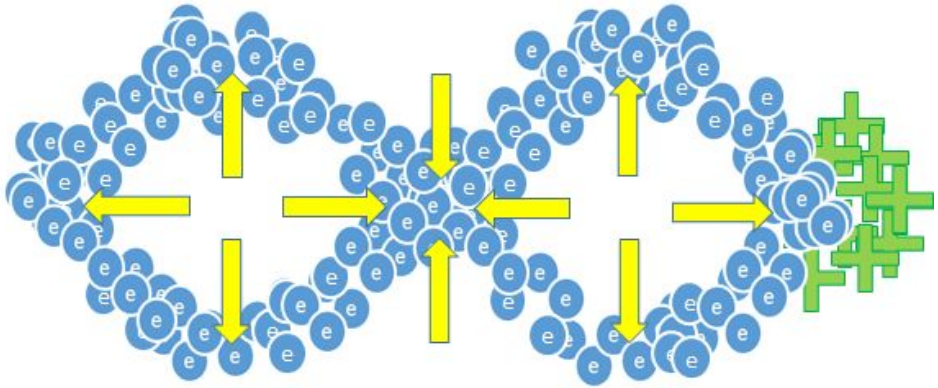
How to create a plasma wakefield?



Charge separation -> Electric field



Where should we put the electrons to be accelerated?

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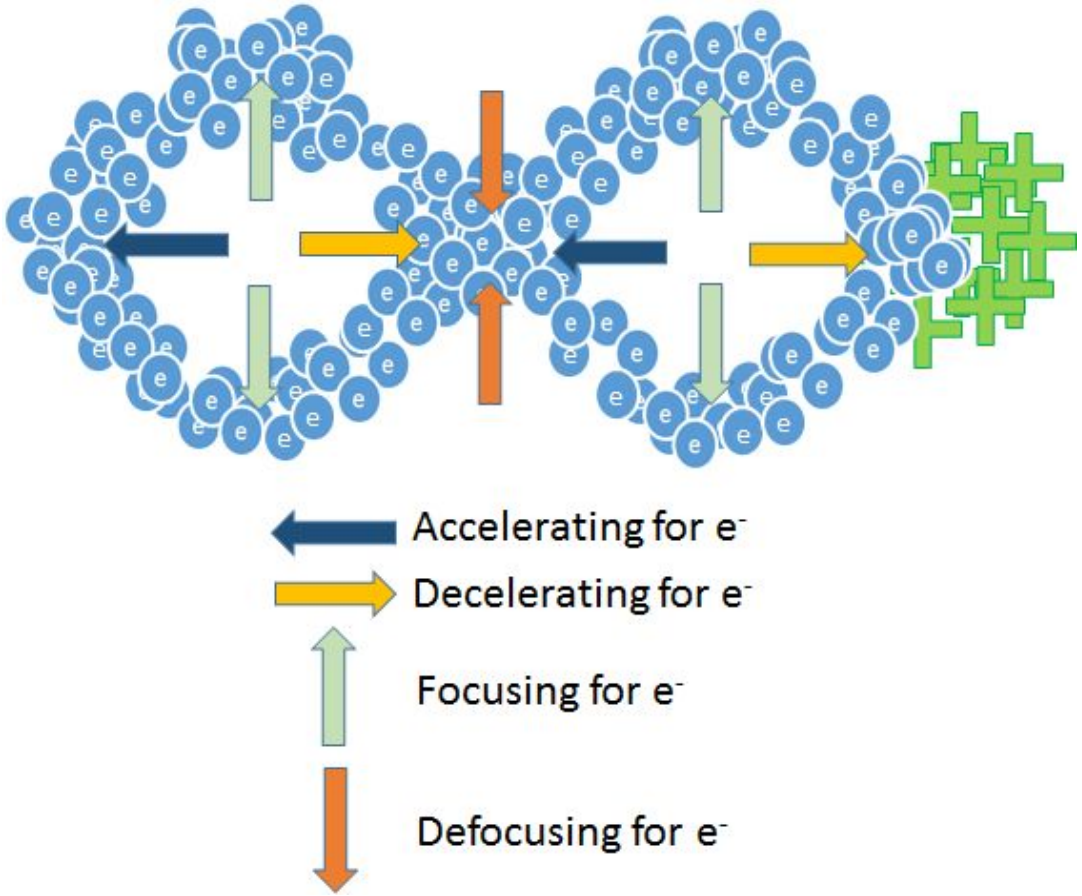
Plasma wakefields



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Let’s repeat..

To create a plasma wakefield, we DON'T need?

A plasma.

An electron witness bunch.

A proton drive bunch.

We need all of the others.

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The accelerating fields of a plasma wake are a result of what?

Magnetic fields.

Plasma ion motion.

Electron-ion charge separation.

Electron-electron charge separation.

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Why do plasma wakefields accelerate charged particles?

Longitudinal magnetic field.

Transverse electric field.

Longitudinal electric field.

Transverse magnetic field.

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Physics in AWAKE: The seeded proton bunch self-modulation

The seeded proton bunch self-modulation

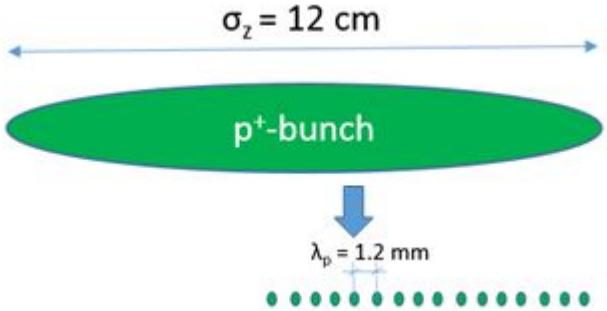
Requirement:

In order to create plasma wakefields efficiently, the drive bunch length has to be in the order of the **plasma wavelength**.

Problem:

The SPS proton bunches are 12 cm long, and

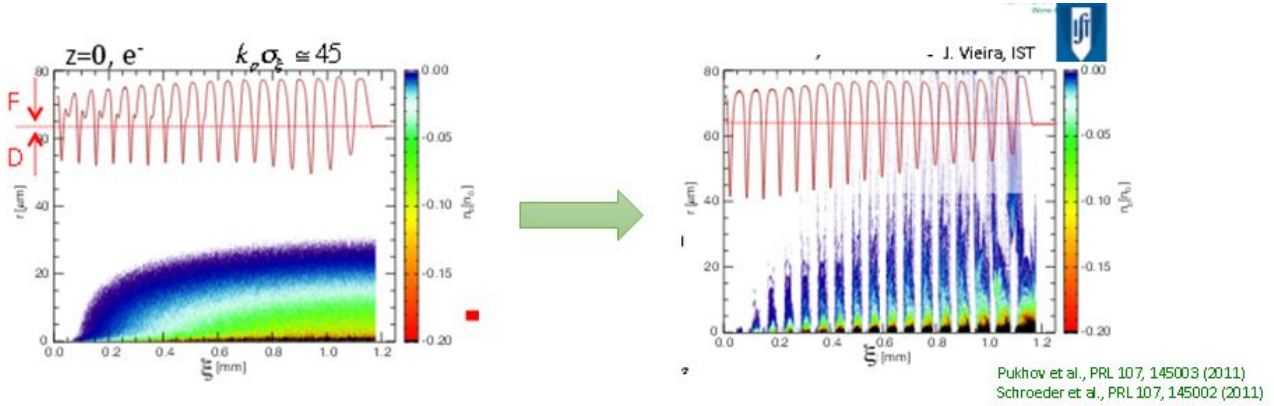
The AWAKE plasma wavelength is 1.2 mm.



Solution:

The experiment relies on the self-modulation instability

To micro-bunch the long proton beam into micro-bunches.



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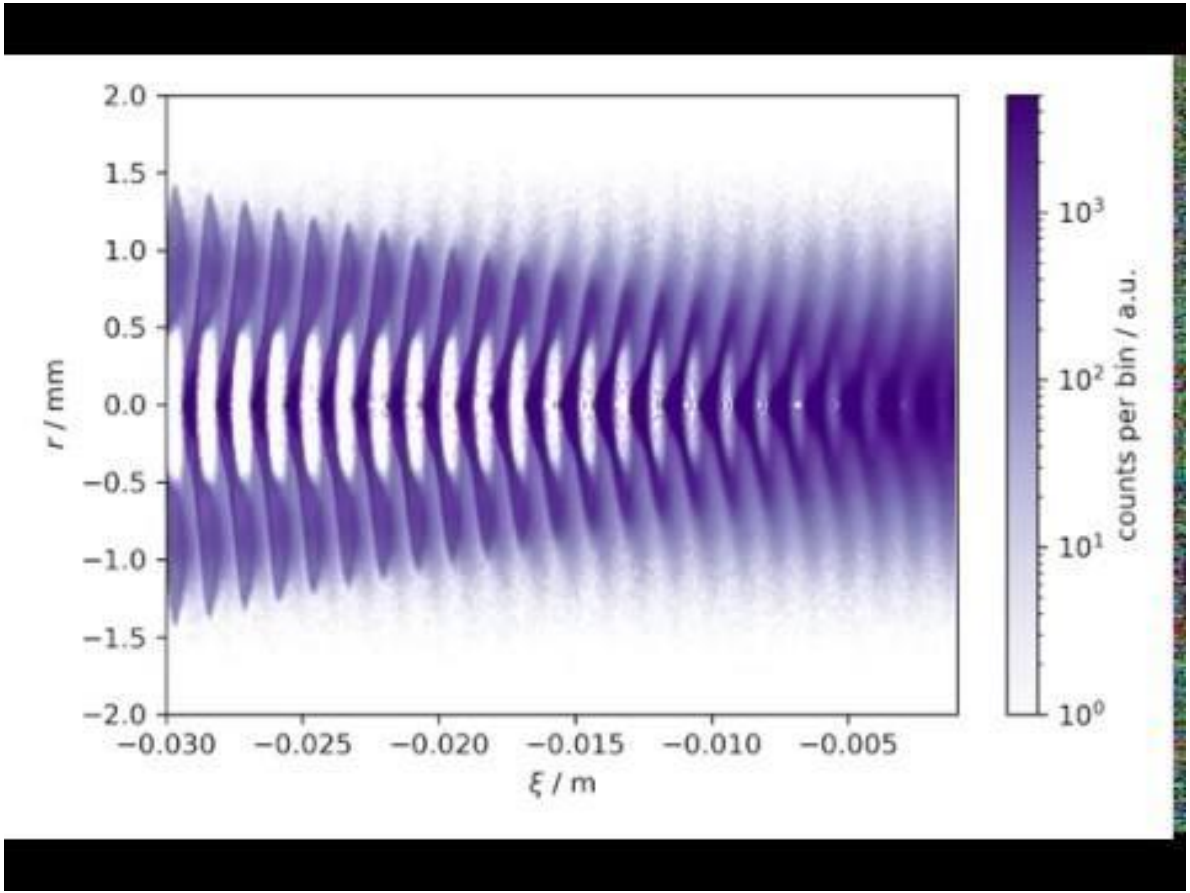
The seeded self-modulation



Logarithmic color scale!!

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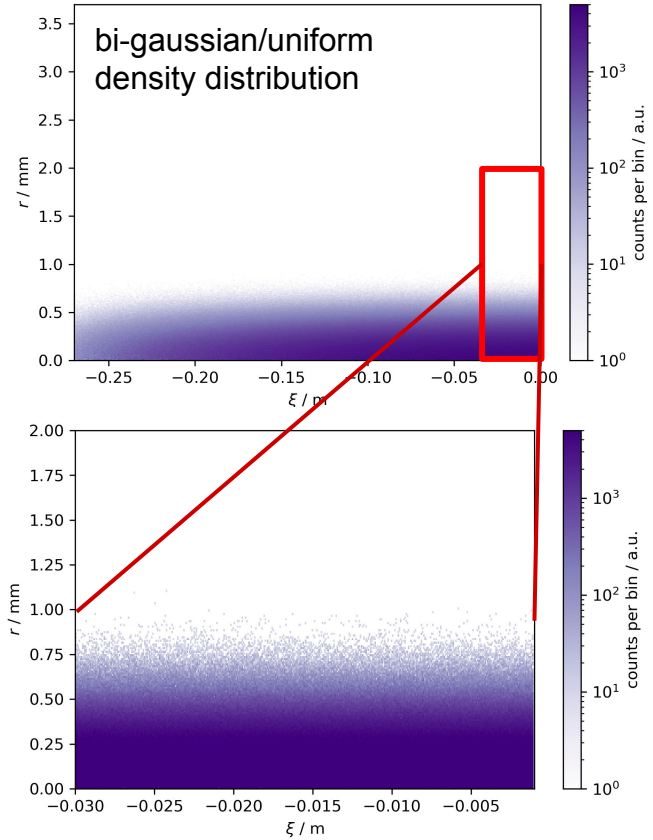
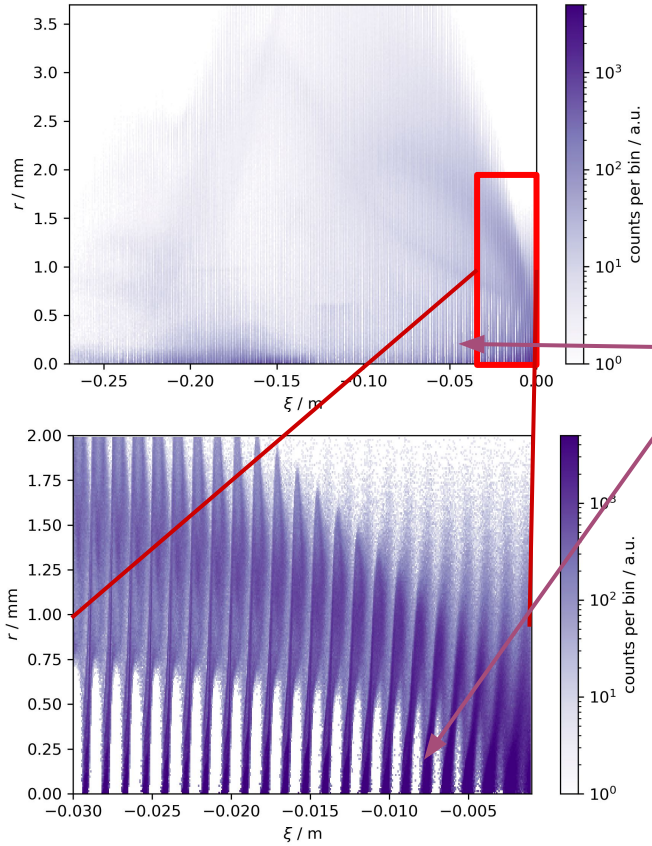
The seeded self-modulation

at z = 0 m (beginning of the plasma)



at z = 10 m (end of the plasma)



transverse proton motion

longitudinal micro-bunch structure of the beam density

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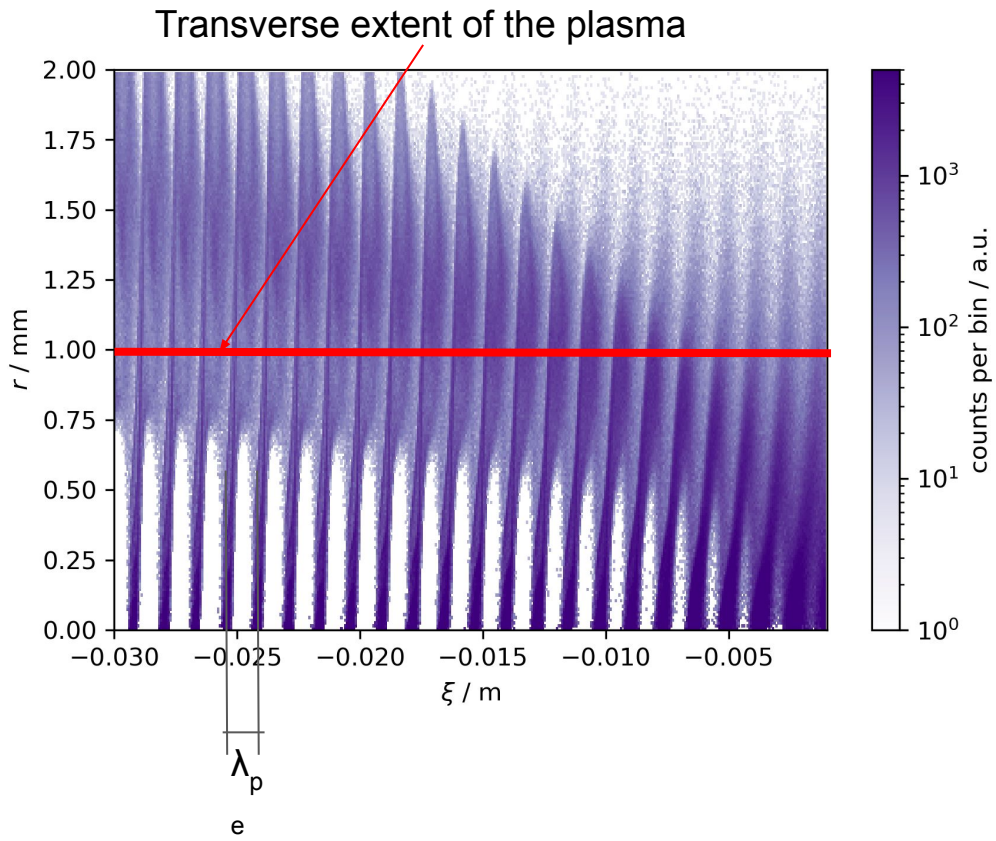
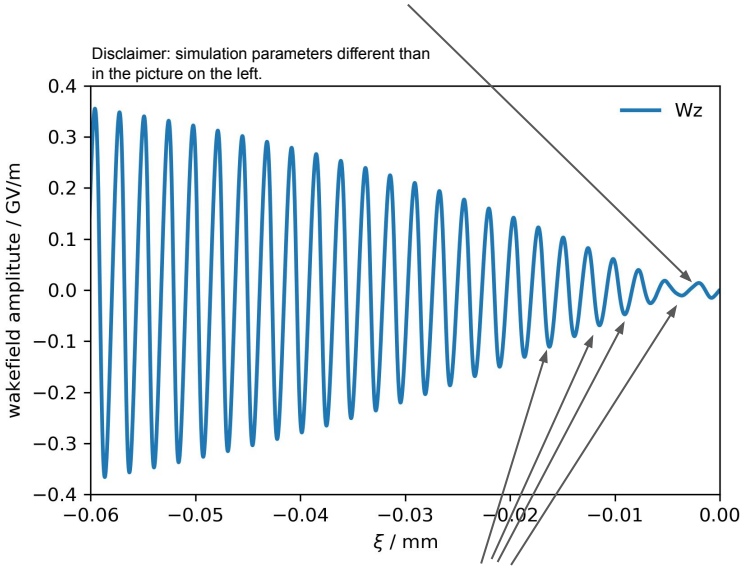
The seeded self-modulation



Each micro-bunch drives its own ‘low-amplitude’ wakefield



Resonant wakefield excitation.

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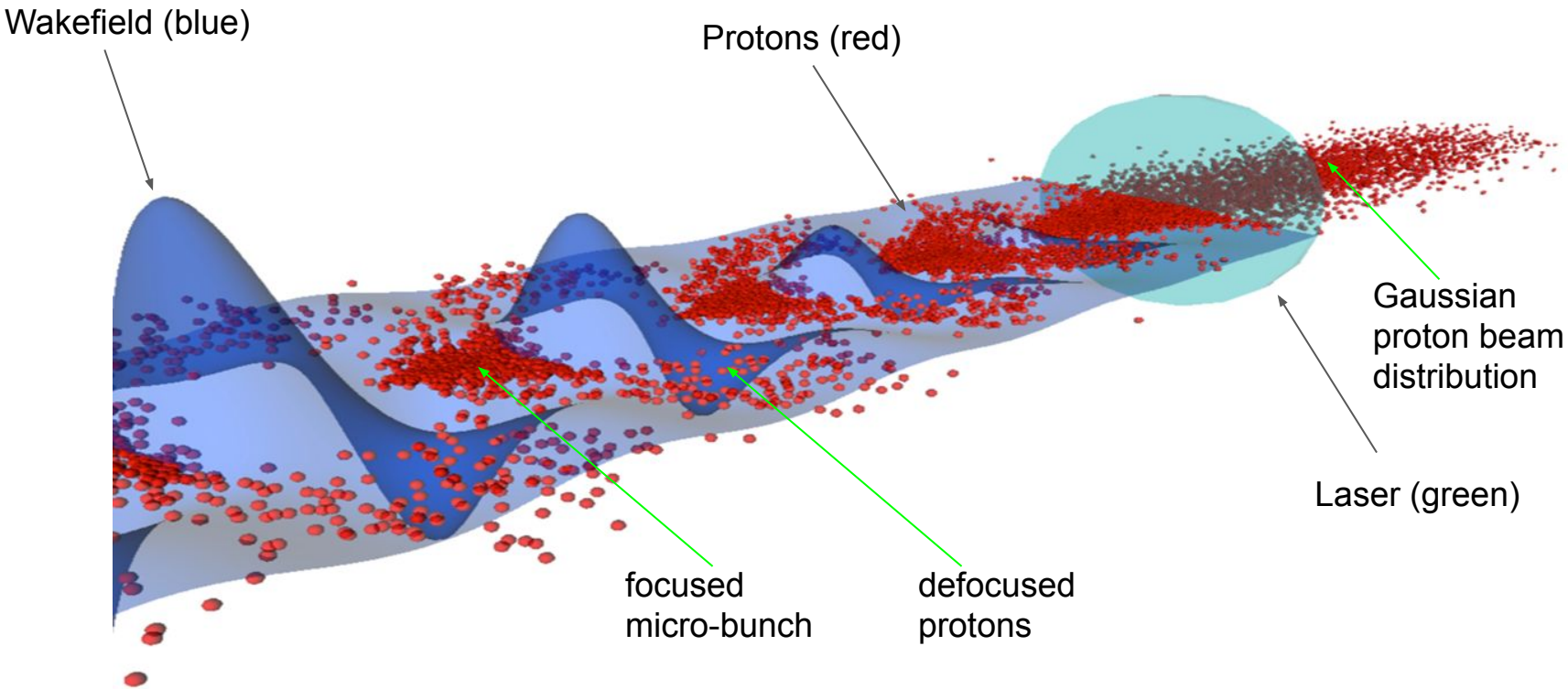
Simulation Result



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Let’s repeat...

Why do we need the seeded proton bunch self-modulation?

To modulate the plasma.

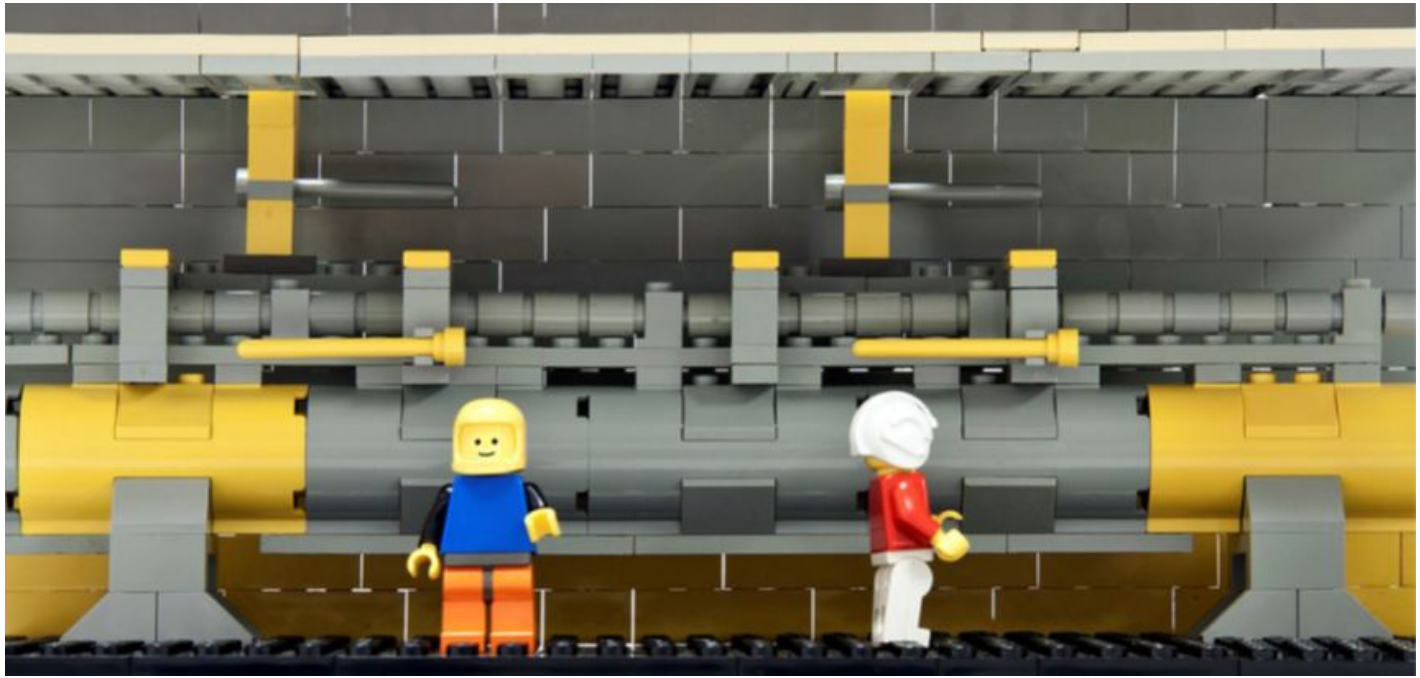
To modulate the proton bunch density.

It is the transverse wakefields that modulate the proton bunch?

Yes

No

Experimental realization at CERN -AWAKE-



From a concept and an idea to reality !

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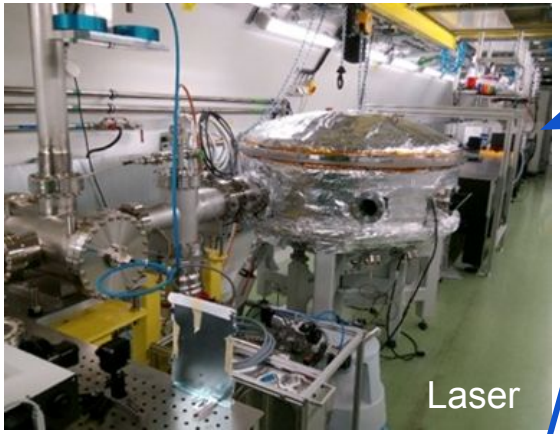
Components of a R&D proton driven plasma wakefield accelerator



Plasma:

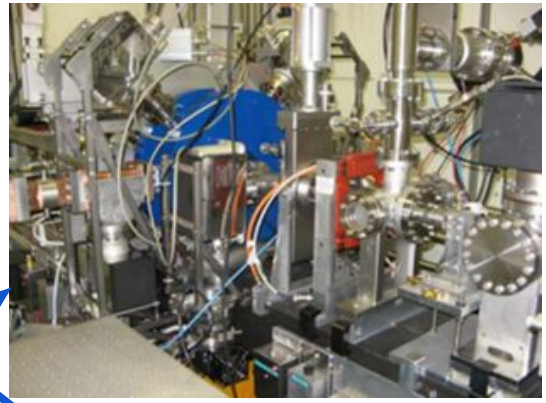
- ❑ Laser
- ❑ Rubidium vapor

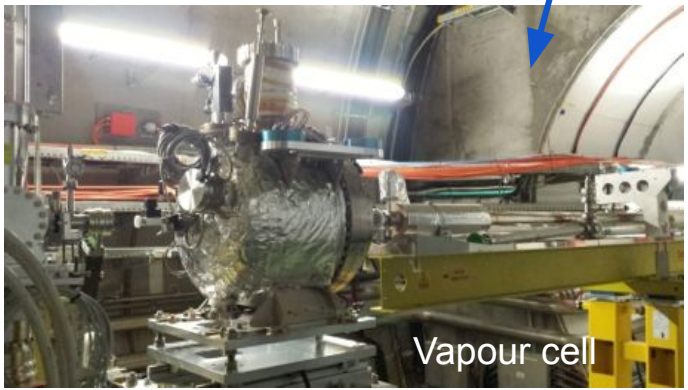
Drive Bunch:

- ❑ Proton beam (400 GeV/c)

Witness Bunch:

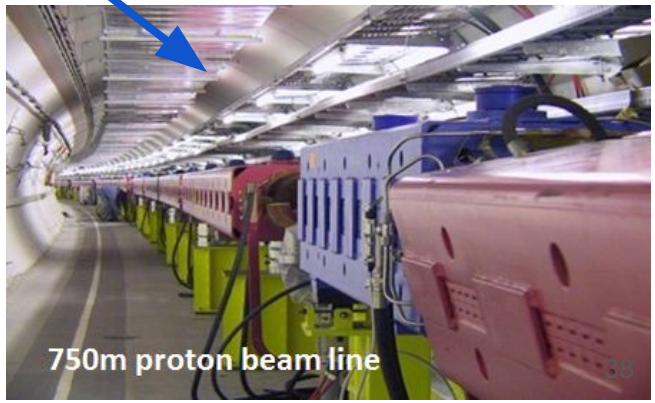
- ❑ Electron beam (10-20 MeV)



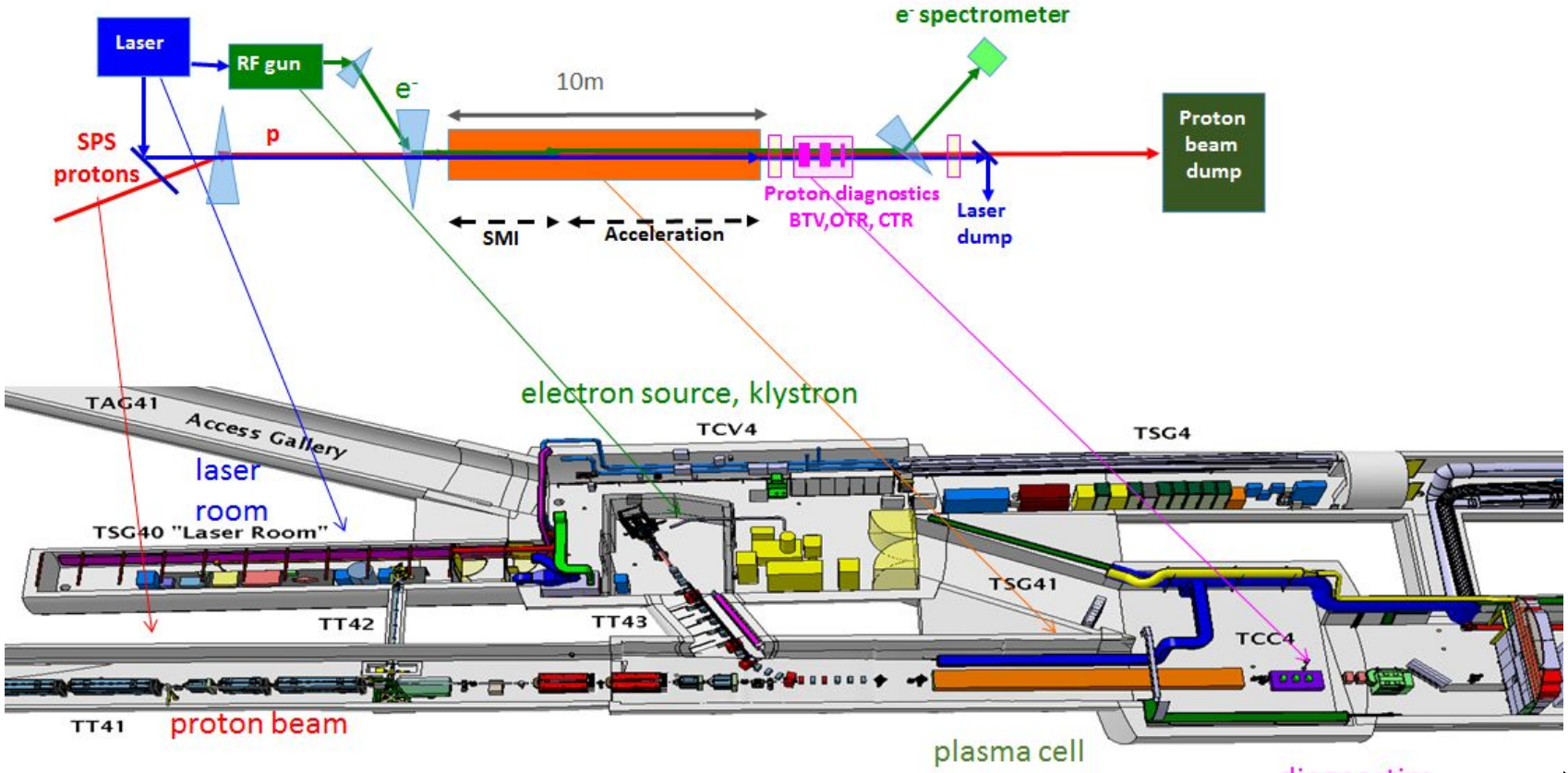


Diagnostics:

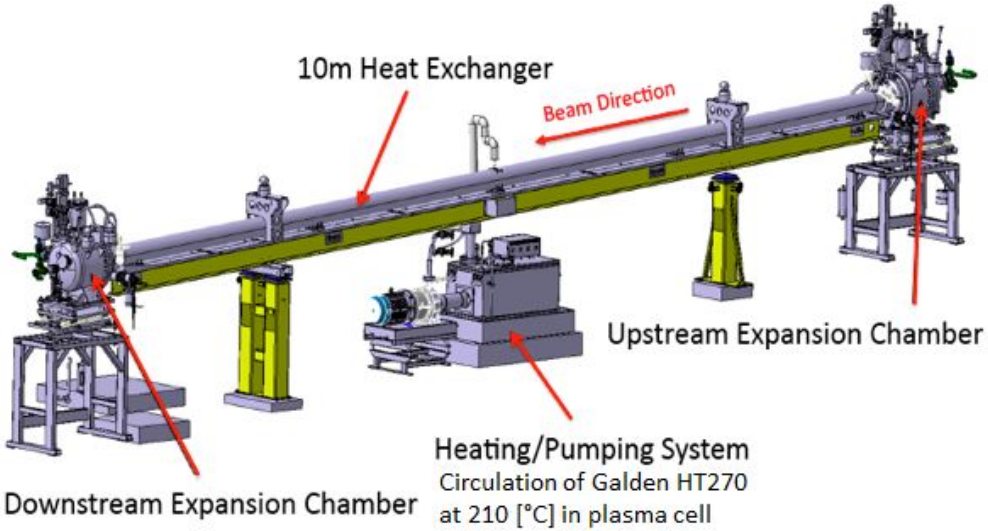
- ❑ Proton
- ❑ Laser
- ❑ Electron



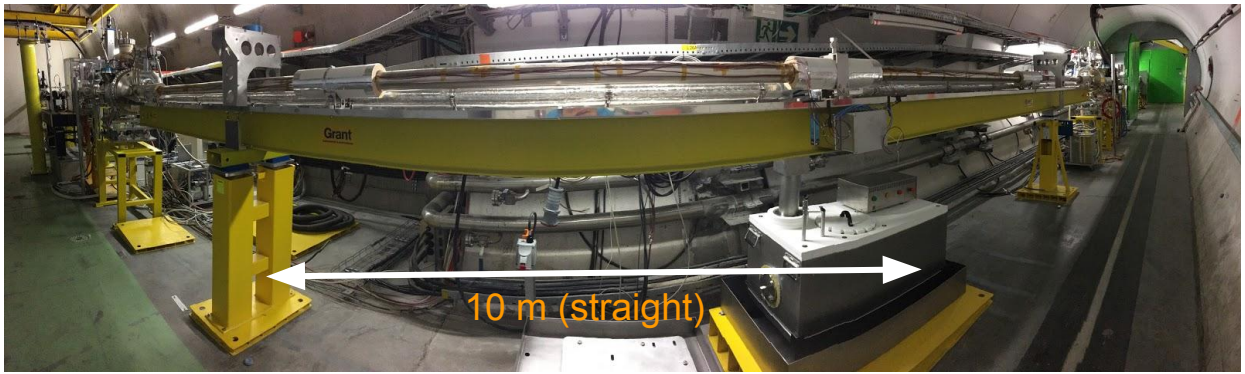
Layout of the experiment



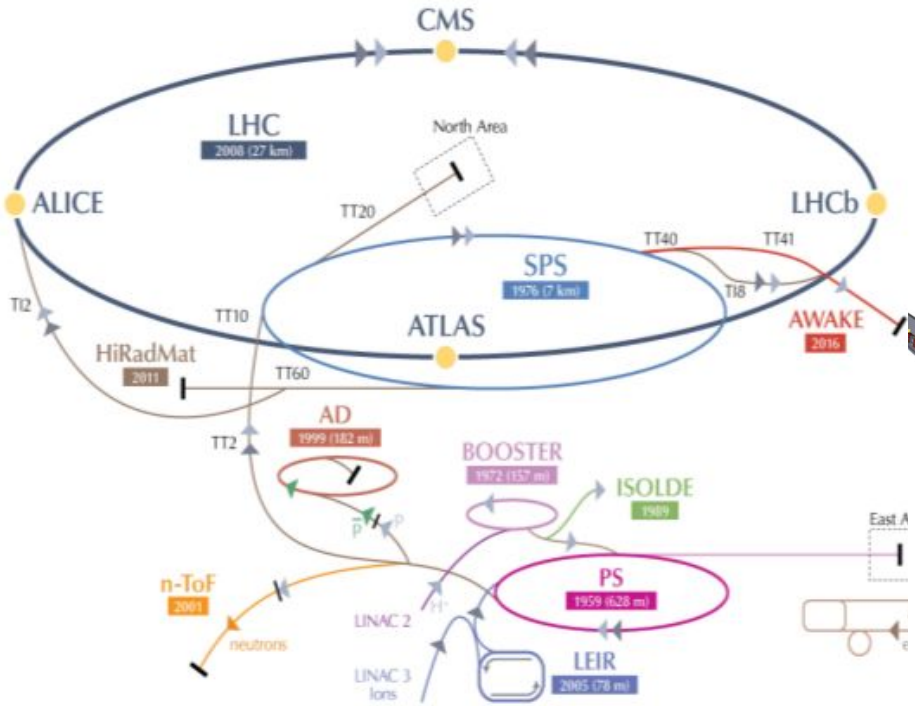
The AWAKE plasma



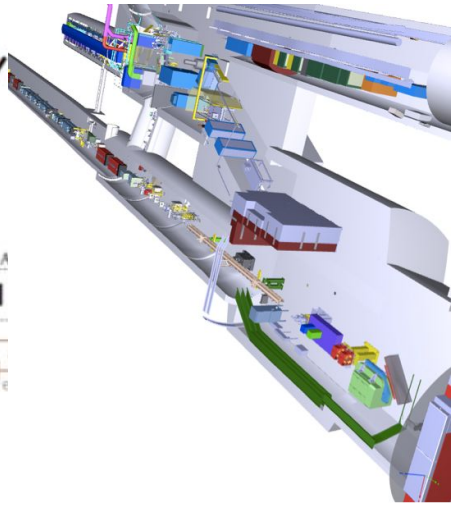
- **Rubidium vapour** cell.
- The laser **ionizes** the outermost electron of each rubidium atom.
- Desired **plasma density**: ~1-10x10^{14} electrons/cm^3.



The AWAKE Experiment at CERN



- Proton bunch **momentum**: 400 GeV/c
- $3*10^{11}$ protons/bunch
- **Bunch length:** σ_z = 12 cm



Radial bunch size at plasma entrance:

- σ_r = 0.2 mm

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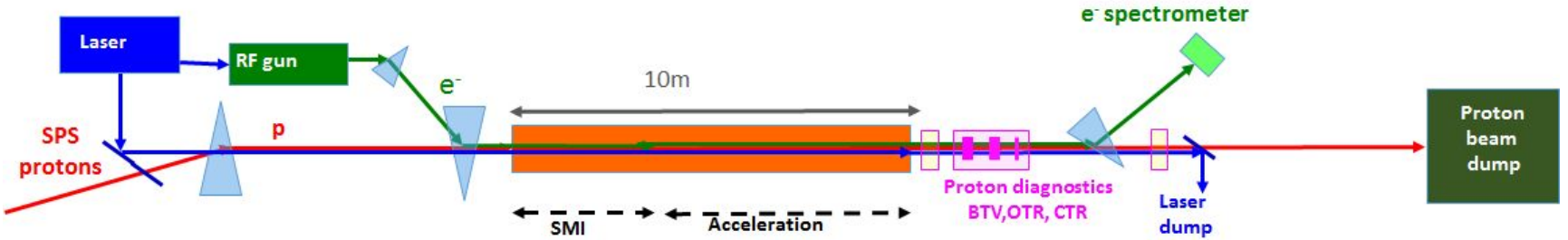
Diagnostics

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?



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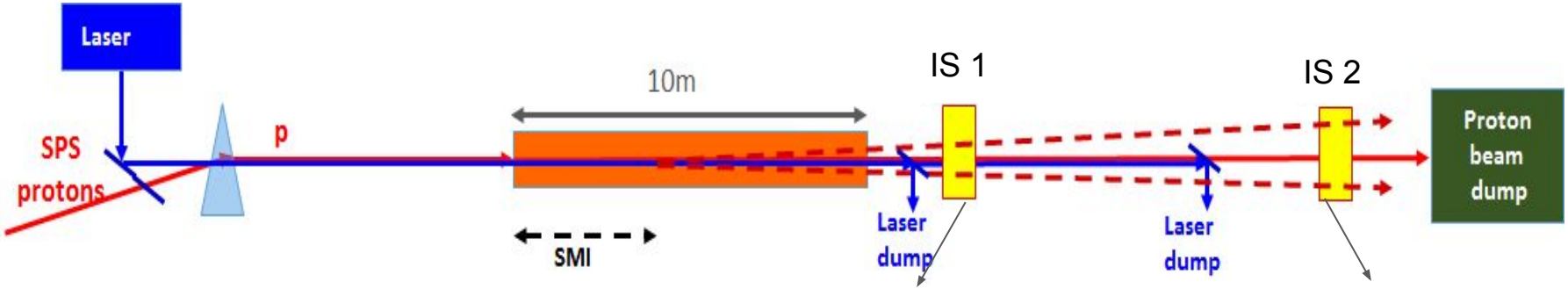
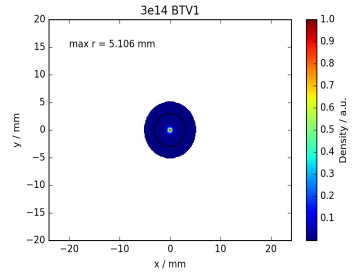
Does the proton bunch self-modulate?

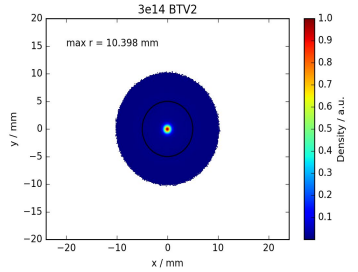


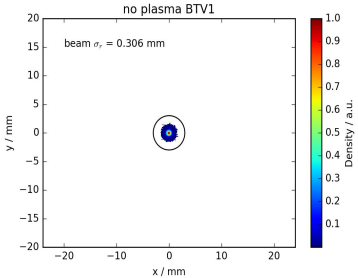
Two-screen measurement

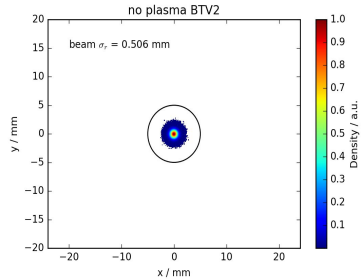
Goal: Image protons that got defocused by the strong plasma wakefields

To prove that plasma wakefields were present in plasma.



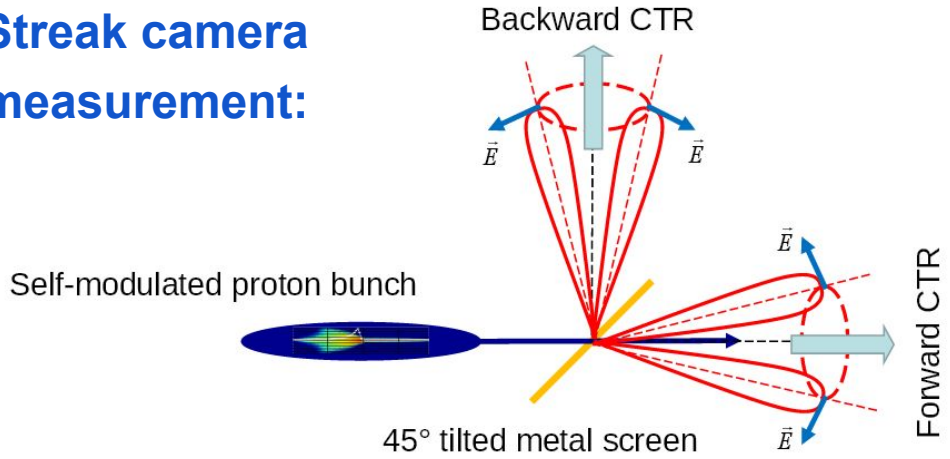


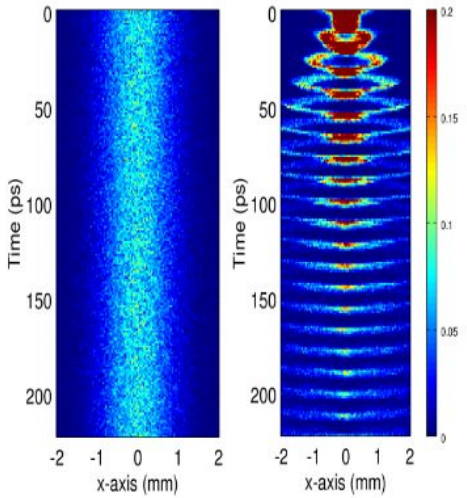




Does the proton bunch self-modulate?

Streak camera measurement:

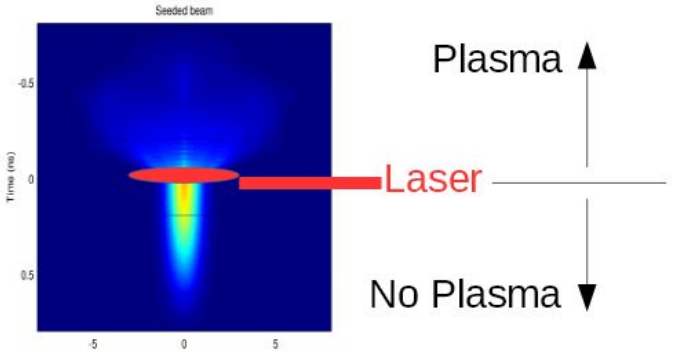




Foil emits waves up to the plasma wavelength of the foil:

- 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.



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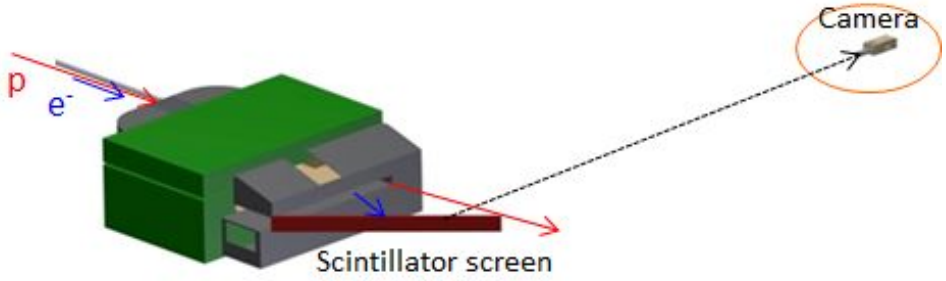
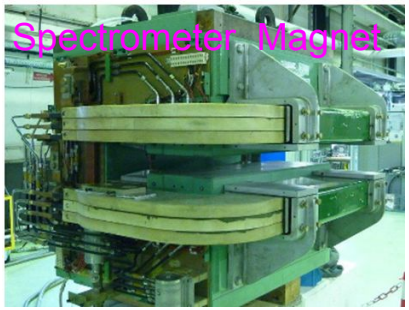
What is the energy of accelerate electrons?

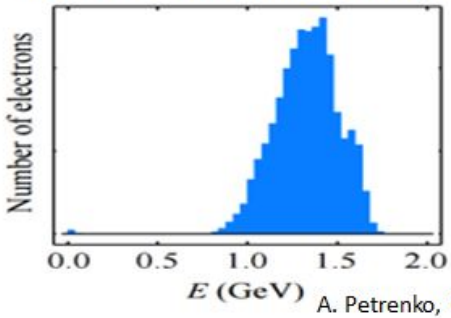


- Electrons will be injected with an energy around 10-20 MeV.
- Accelerated electrons are sent through a **spectrometer magnet** and deposit energy on a scintillating screen which is imaged by a camera.

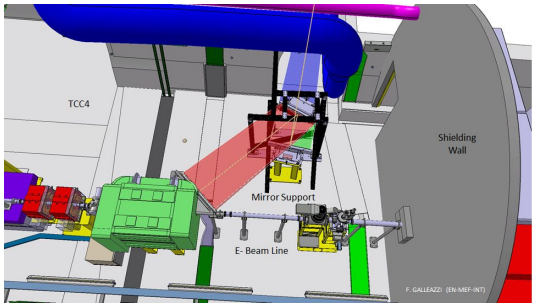
8.5 ton, 1.2 T, 1.3 Tm, L=1.6 m, W=1.3 m



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



A. Petrenko, CERN



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Let’s repeat...

To create our plasma, we do NOT need?

Rubidium vapor.

Electron bunch.

Short ionizing laser pulse.

Transverse magnetic fields.

What is NOT a diagnostics installed in AWAKE?

Two-screen measurement.

Streak camera.

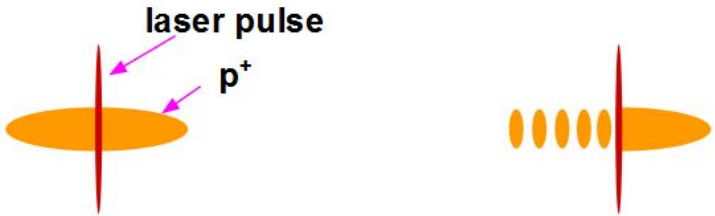
Electron energy spectrometer.

Wire scanners.

Latest AWAKE results

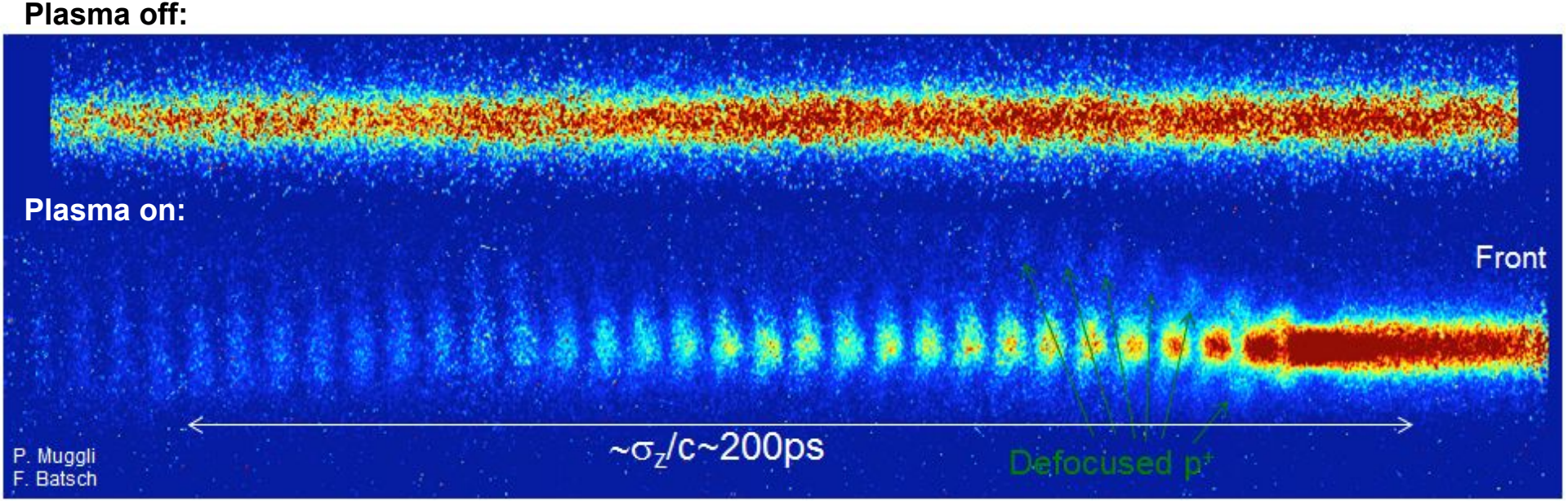
The AWAKE experiment (Run 1)

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

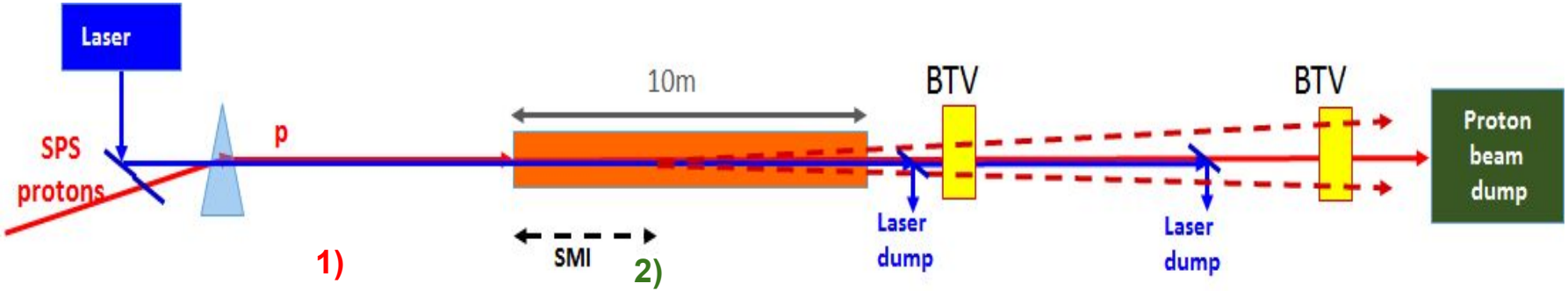


1. **Accelerate** externally injected 10- 20 MeV electrons to GeV energies (2018).

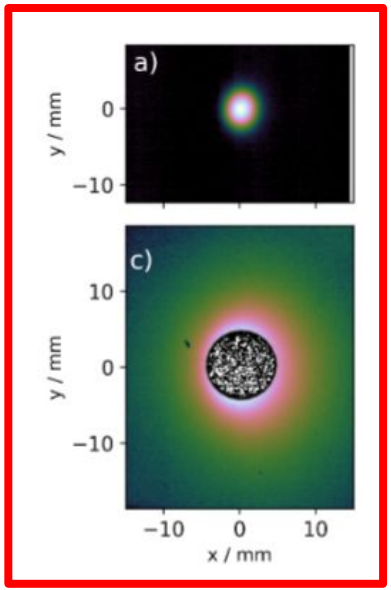
Streak camera results



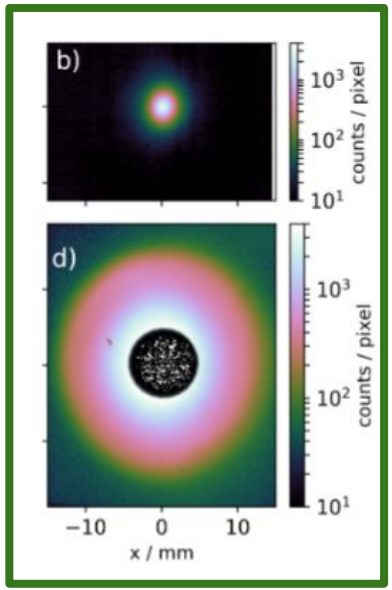
The two-screen measurement



1)



2)



In which of the 2 measurements did the bunch self-modulate?

The AWAKE experimental team

Shortly after we have observed the Seeded-Self Modulation for the first time!

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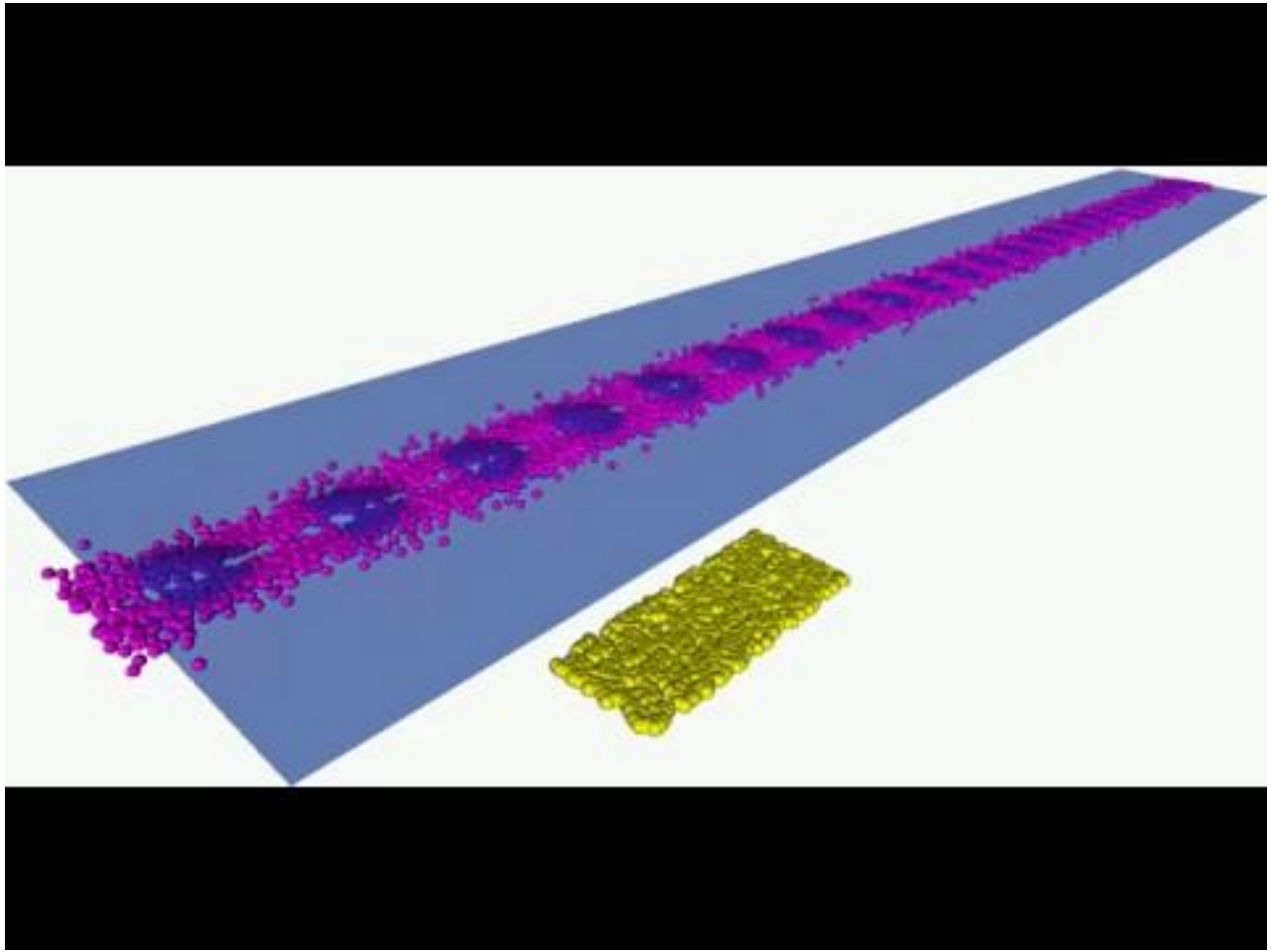
Electron acceleration



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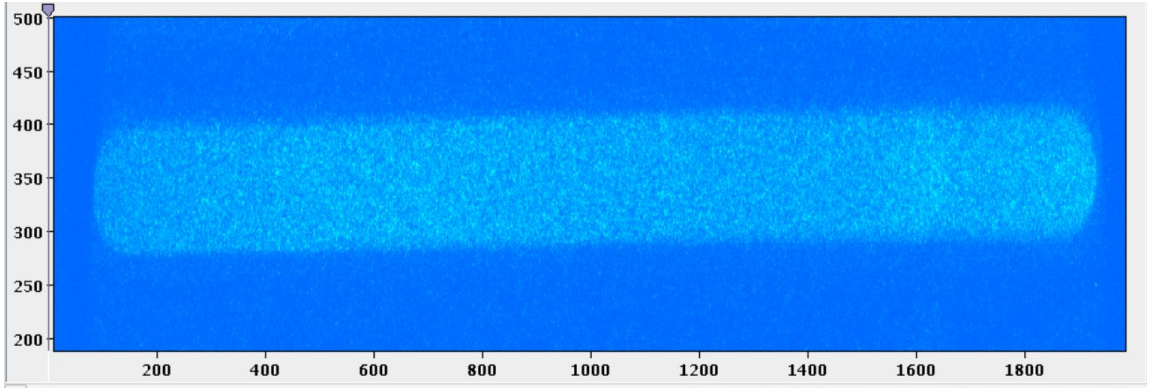
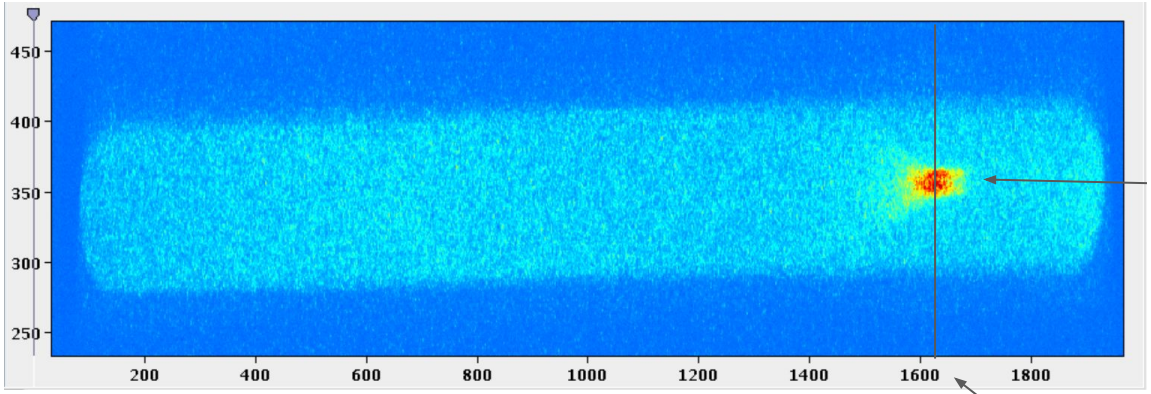
Electron acceleration



No electrons accelerated.



Accelerated electrons.

Convert position to energy

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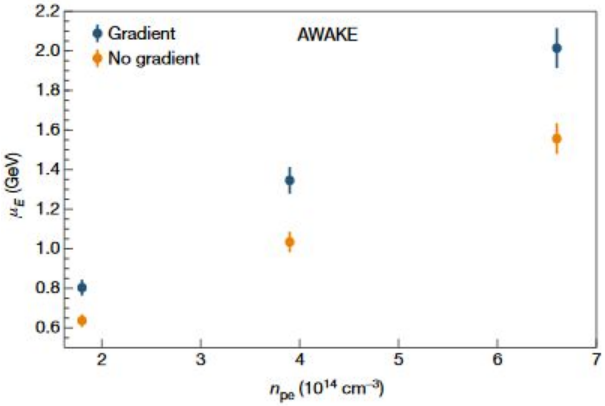
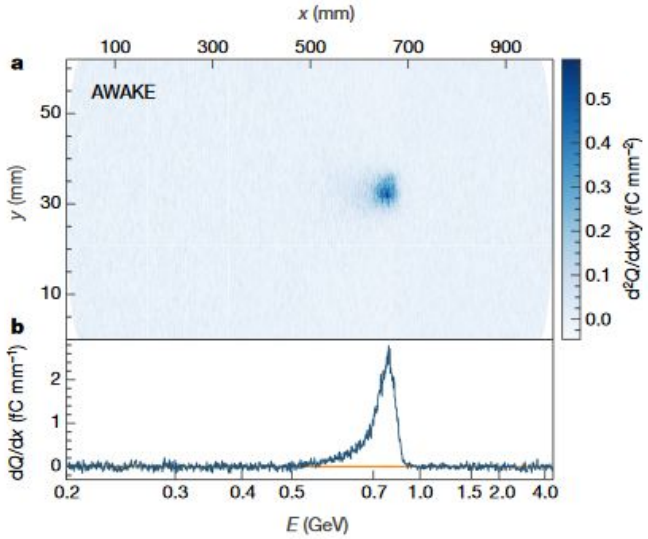
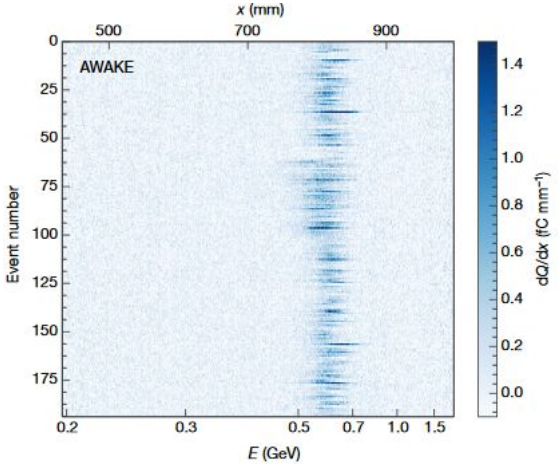
Electron Acceleration Results

AWAKE Collaboration, *Nature* **volume 561**, pages 363–367 (2018)







The AWAKE experimental team

Last May run!

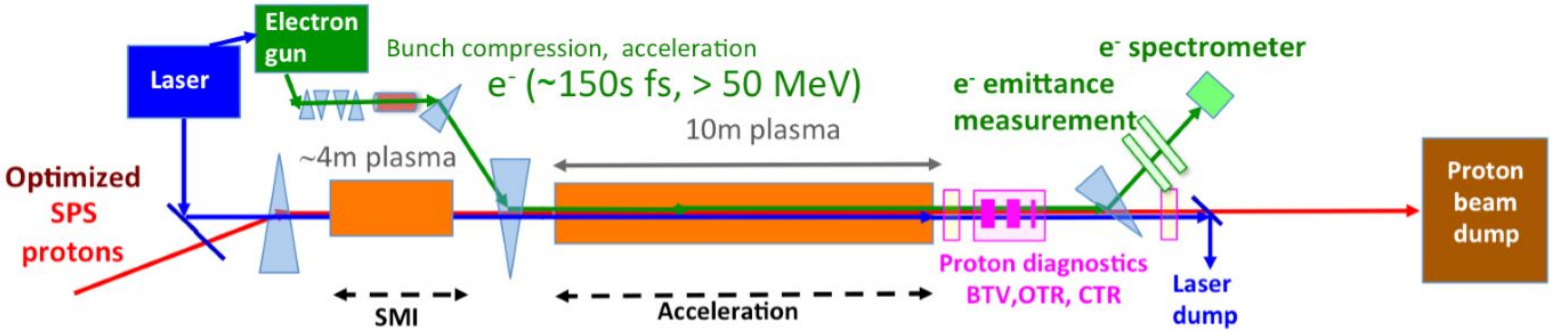
The Future of AWAKE

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

Long term:

AWAKE run 2: 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.**



Summary

- **AWAKE** is a **proof-of-principle accelerator R&D experiment** at CERN:
  - **First proton-driven** wakefield acceleration experiment worldwide.
  - The experiment opens a pathway towards a **plasma-based TeV electron collider**.

- **Final Goal:** Design high quality & high energy electron accelerator based on acquired knowledge.

- AWAKE uses a:
  - **400 GeV** SPS proton beam as drive beam
  - **10-20 MeV** electrons as witness beam
  - **4.5 TW** laser beam for plasma ionization
  - **10 m** long rubidium vapor source