

# **AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN**



Marlene Turner for the  
AWAKE Collaboration

# Outline



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

# AWAKE

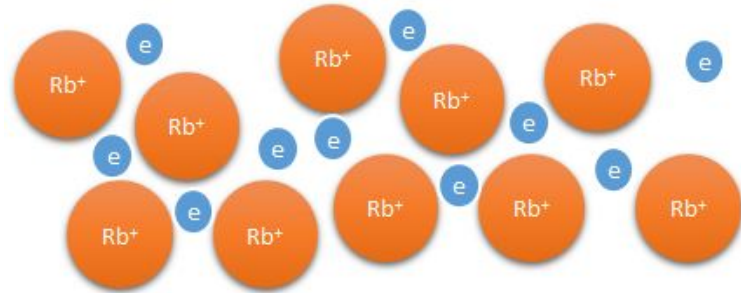
## Advanced Proton Driven Plasma Wakefield Acceleration Experiment



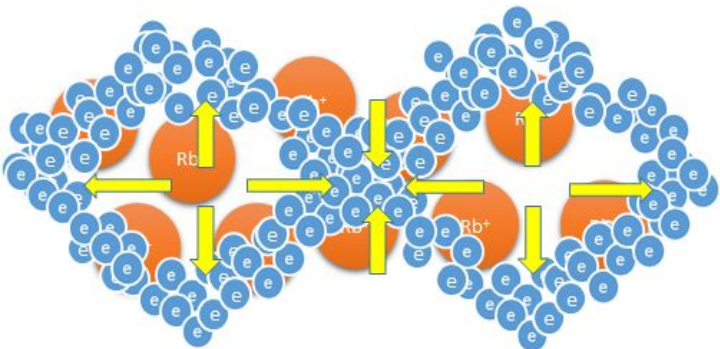
- ☐ Plasma ?
- ☐ Proton driven ?
- ☐ Wakefield acceleration ?

# Let's discuss the basics:

## What is a plasma?



## What are plasma wakefields?



- **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.
- **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.

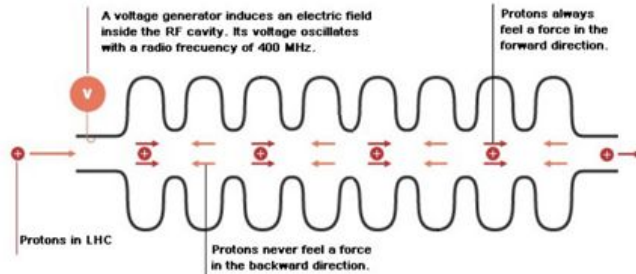


# Why are plasmas interesting for charged particle acceleration?

# Why plasma wakefield acceleration?

## Conventional Acceleration

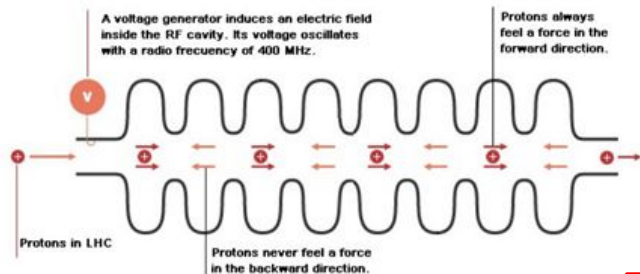
Limited to approx. 100 MV/m due to electric breakdowns (ionization).



# Why plasma wakefield acceleration?

## Conventional Acceleration

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

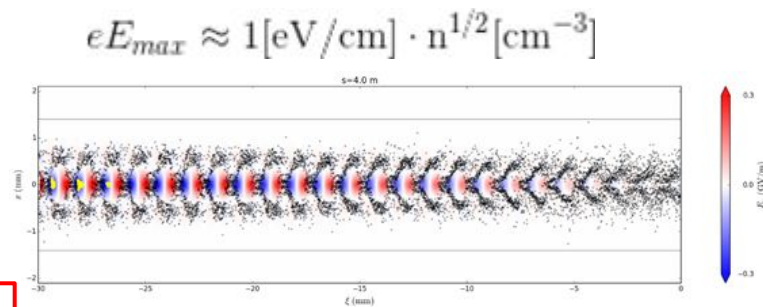


It's all about  
the  
accelerating  
gradient

$$E = U/d$$

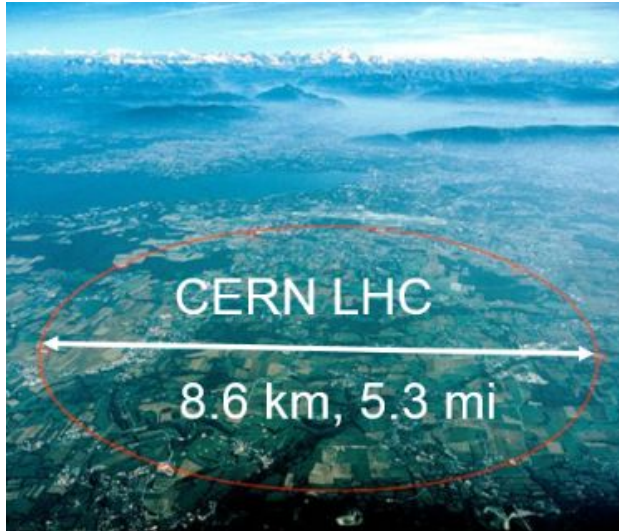
## Plasma Wakefield Acceleration

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



# Circular vs linear collider

## Circular collider



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

**Energy gain per turn = Energy loss per turn**

$$r_{Larmor} = \frac{\gamma mc}{qB_0} = r_{accelerator}$$

$$P_{synchr} = \frac{e^2}{6\pi\epsilon_0 c^7} \frac{E^4}{R^2 m^4}$$

# Circular vs linear collider

## Linear collider



- Charged particle only passes once through the accelerating section
  - $\Rightarrow$  almost no synchrotron radiation losses

**Linear colliders favorable for acceleration of low mass particles.**

**$\Rightarrow$  Accelerating gradient and desired energy gives the length of the accelerator**

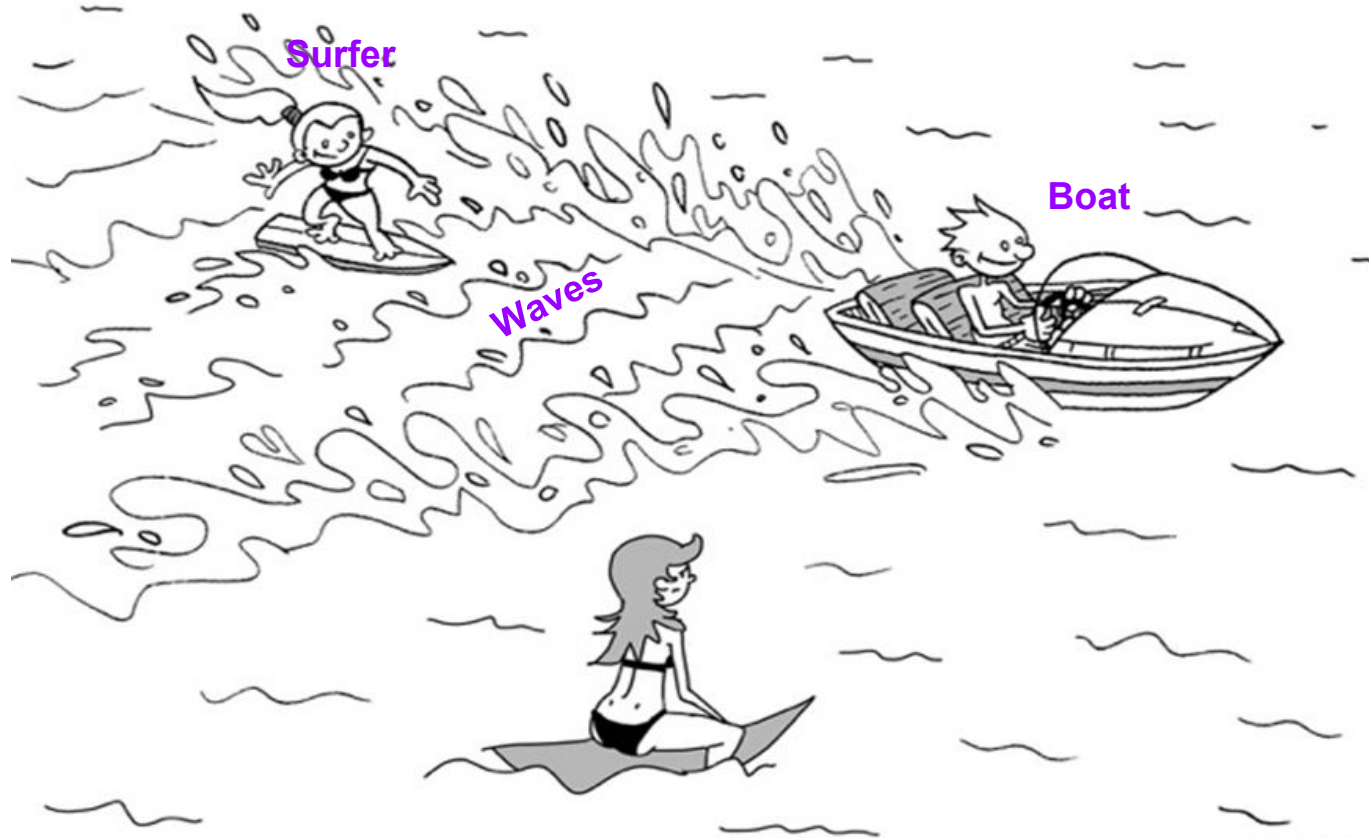
With plasma wakefields we can achieve higher gradients than with conventional accelerators

# Let's repeat..

- ❑ What are **plasma wakefields**?
- ❑ Why do we want to use plasmas for **acceleration** of charged particles?
- ❑ Why / when do we want to use **linear colliders**?

# How to create a plasma wakefield?

# Let me give you an analogy...

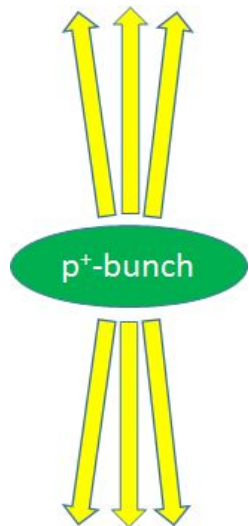


# Let me give you an analogy...



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

Available at CERN:



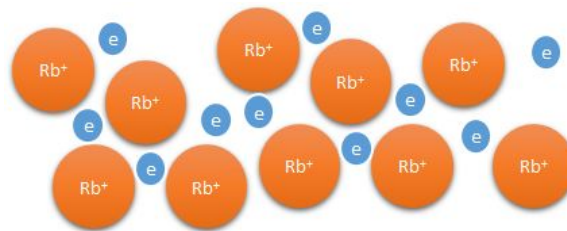
Proton bunches at CERN  
carry energies  
of kJ to MJ!

Charged particle bunches carry almost purely **transverse electric** fields:

**What we need:**

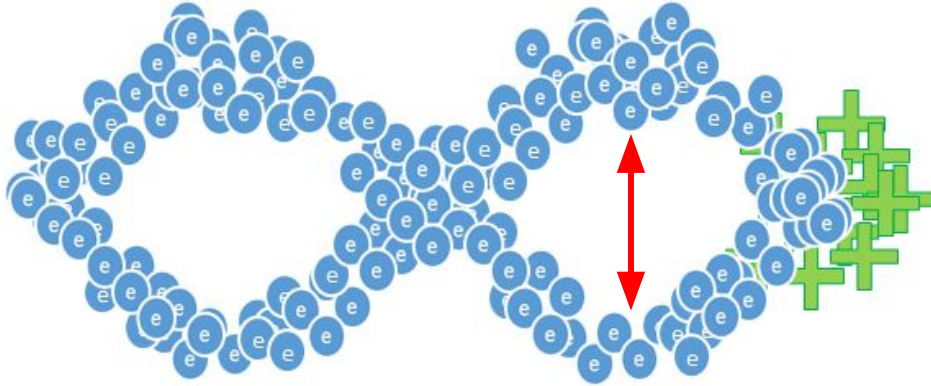
Longitudinal electric field to accelerate charged particles.

**Our Tool:**



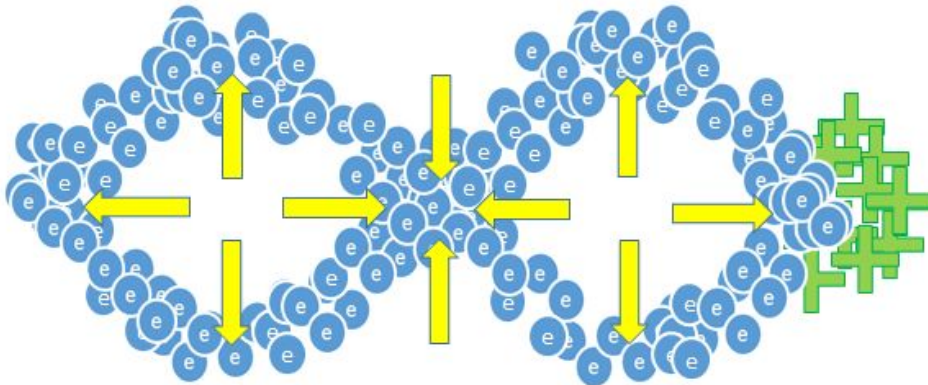
- Use plasma to convert the transverse electric field of the proton bunch into a longitudinal electric field in the plasma.
- The more energy is available, the longer (distance-wise) these plasma wakefields can be sustained.

# How to create a plasma wakefield?

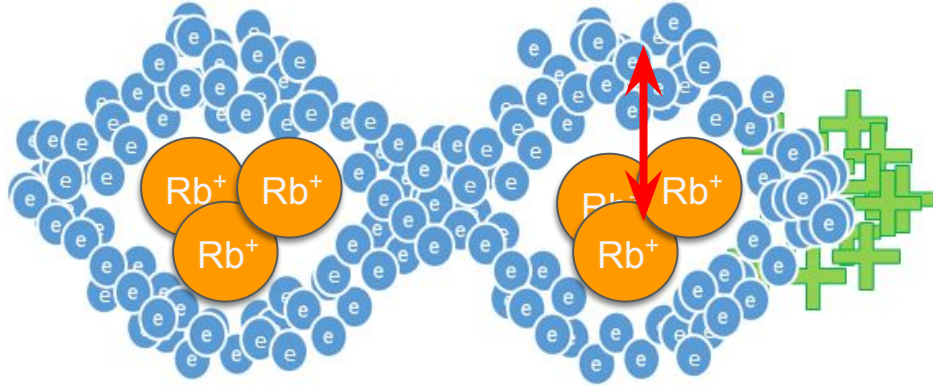


## Important to understand:

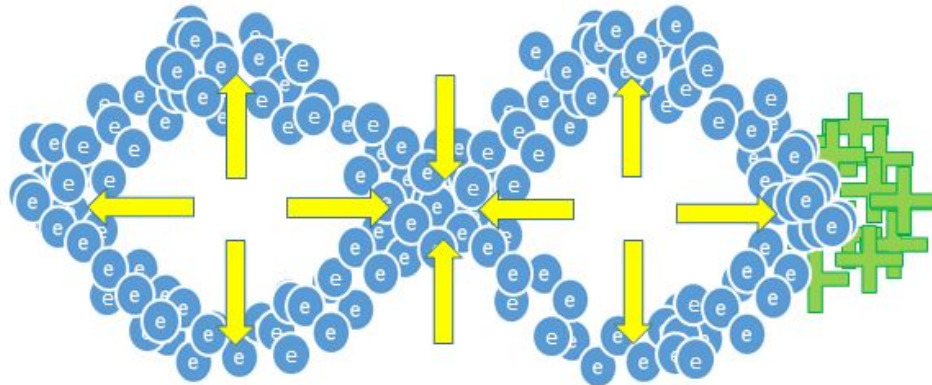
- Plasma electron motion is mostly **transverse**
- Electrons do not move significantly longitudinally
- Rb ions (not shown) heavy and do not move



# How to create a plasma wakefield?



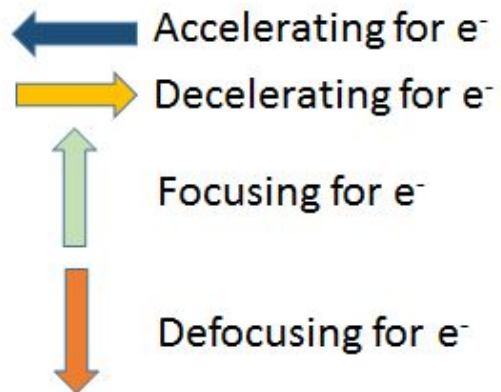
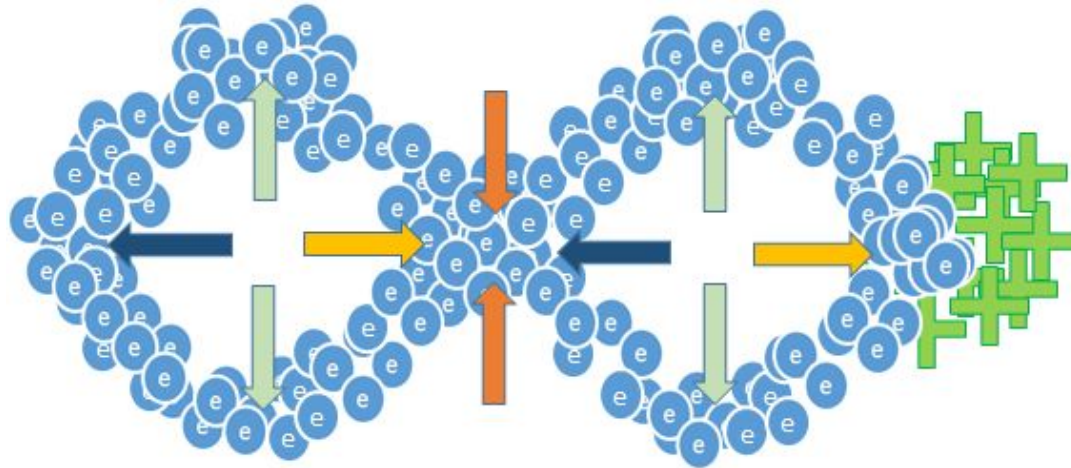
Charge separation  $\rightarrow$  Electric field



Where should we put the electrons to be accelerated?



# Plasma wakefields



# Let's repeat..

- ❑ What do we need to **create** plasma wakefields?
- ❑ Why do plasma wakefields **accelerate** charged particles?

# Physics in AWAKE: The seeded proton bunch self-modulation

# The seeded proton bunch self-modulation

## Requirement:

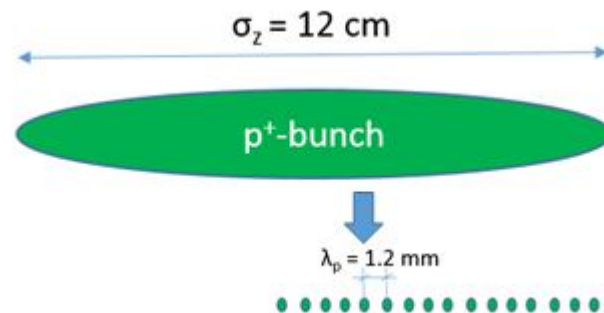
In order to create plasma wakefields efficiently, the drive bunch length has to be in the order of the **plasma wavelength**.

## Problem:

The SPS proton bunches are 12 cm long, and  
The AWAKE plasma wavelength is 1.2 mm.

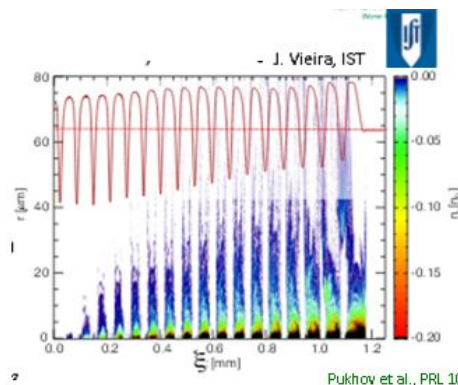
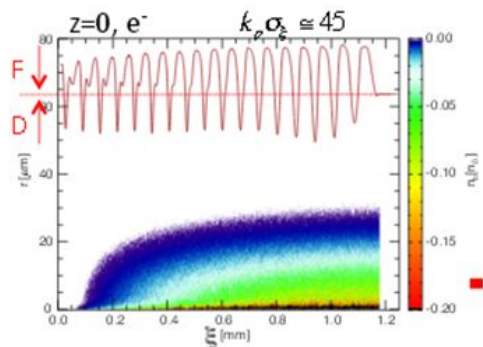
## Solution:

The experiment relies on the self-modulation instability  
To micro-bunch the long proton beam into micro-bunches.

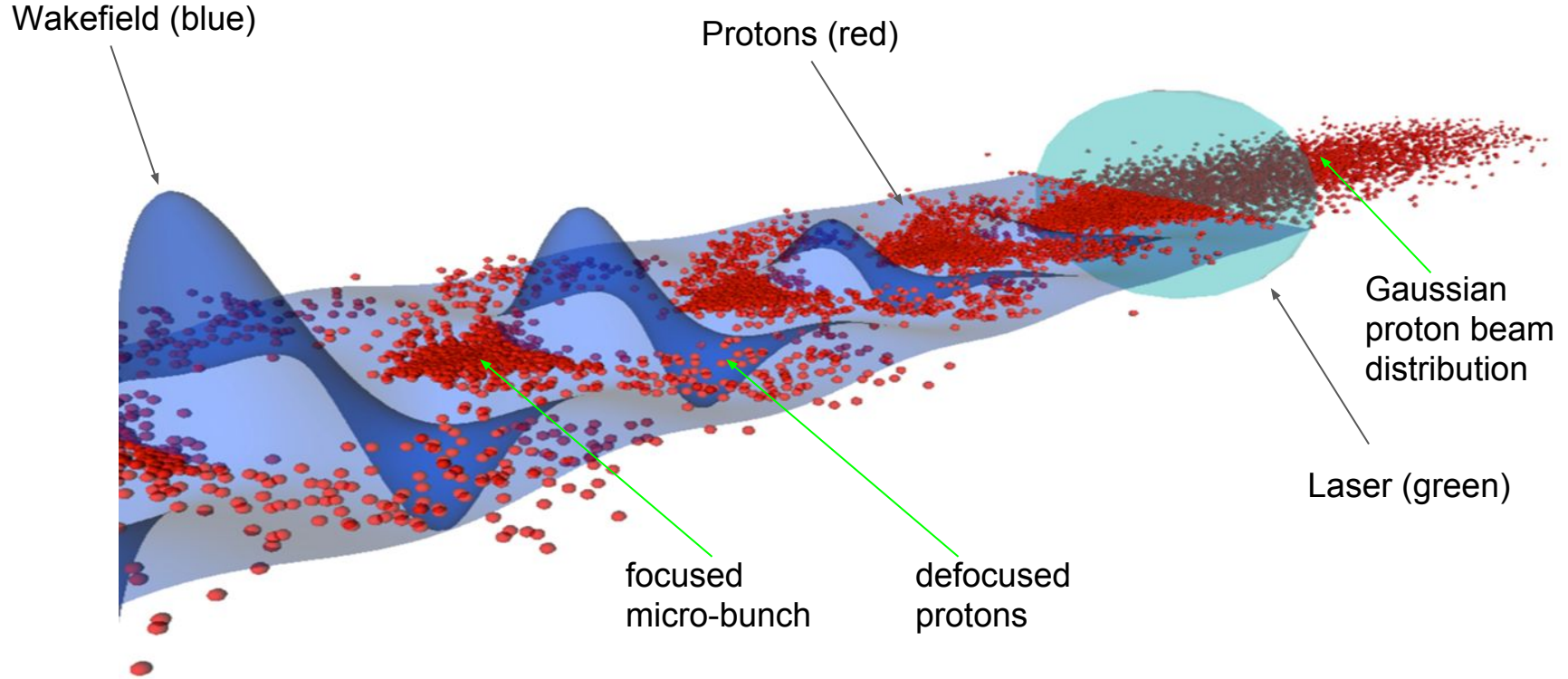


?

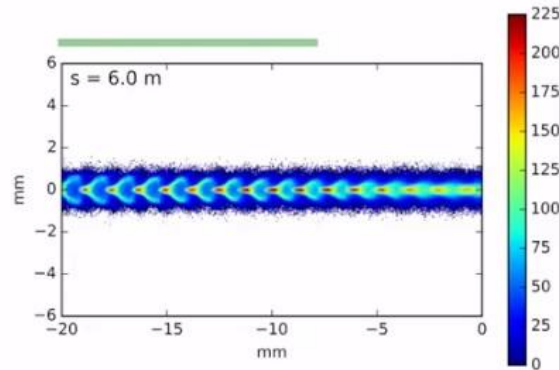
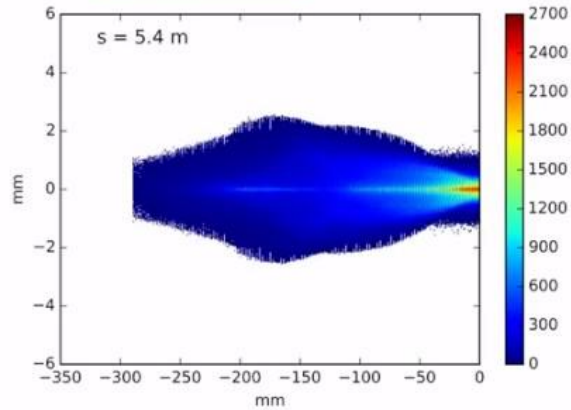
M. Turner et al. 20



# Simulation Result

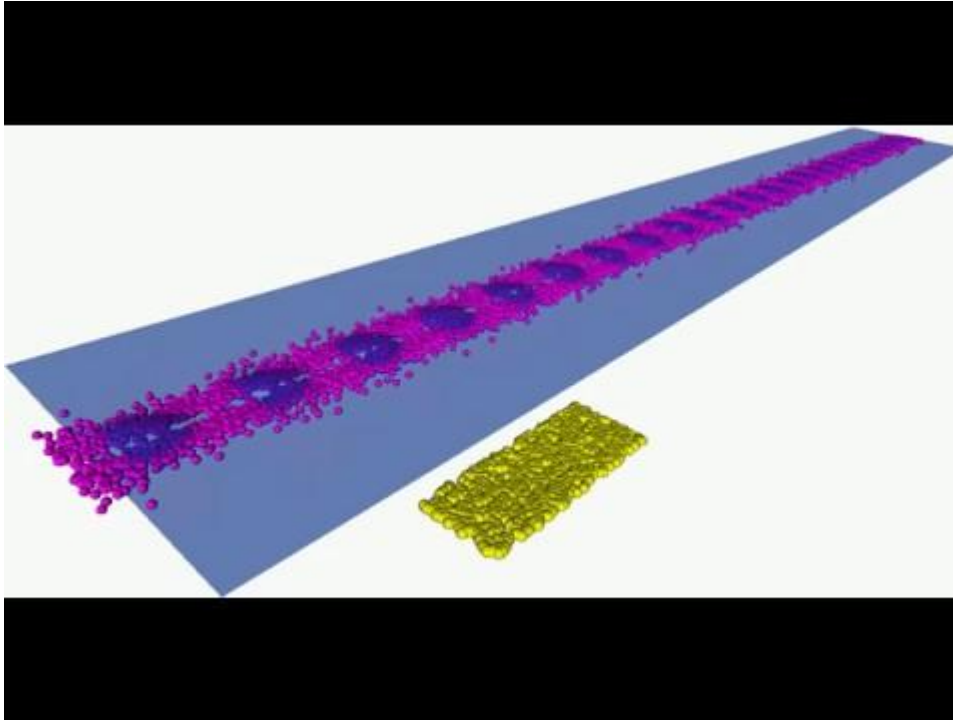


# Development of the Instability



Co-moving frame.  
The frame moves  
at the speed of  
light.

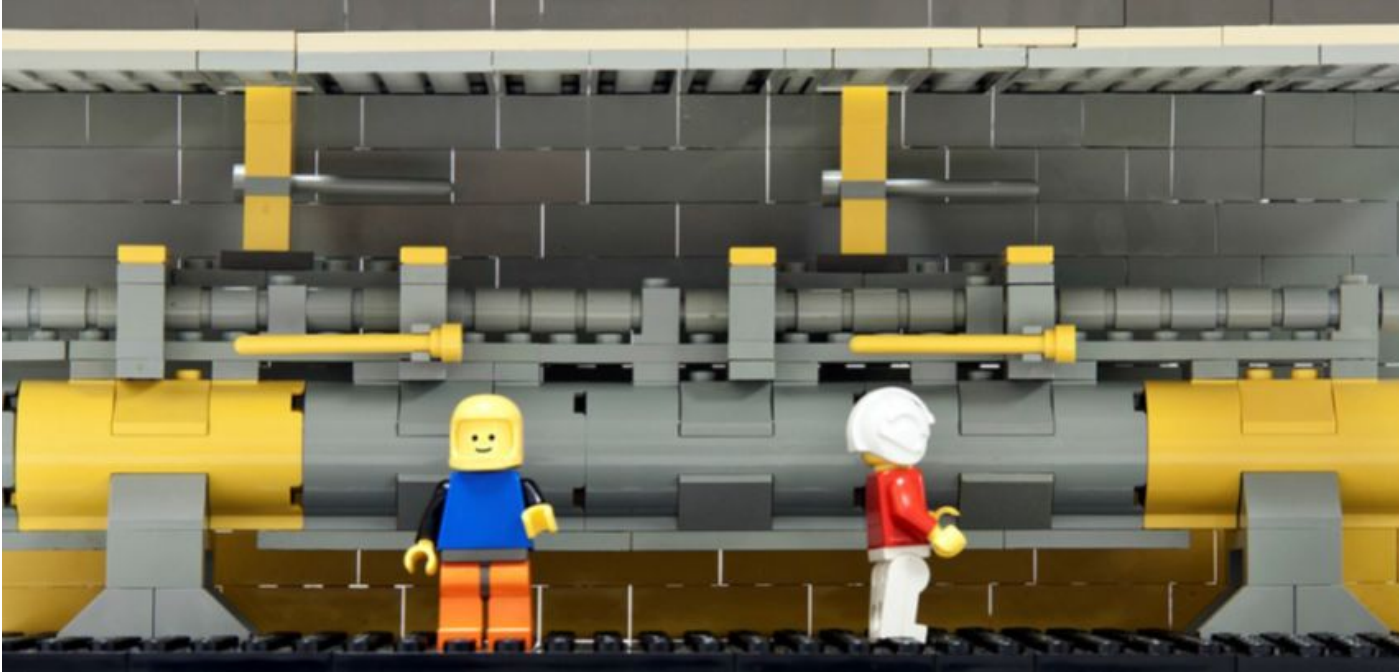
# Electron acceleration



# Let's repeat...

- ❑ Why do we need the **seeded self-modulation**?
- ❑ How does the bunch **self-modulate**?

# Experimental realization at CERN -AWAKE-



**From a concept and an idea to reality !**

# Components of a R&D proton driven plasma wakefield accelerator



Laser

## Plasma:

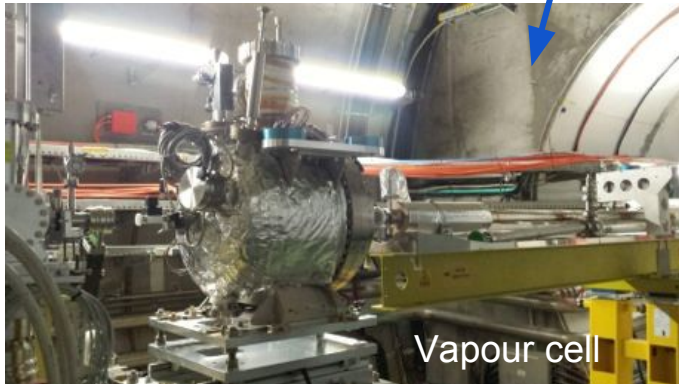
- ☐ Laser
- ☐ Rubidium vapor

## Drive Bunch:

- ☐ Proton beam (400 GeV/c)

## Witness Bunch:

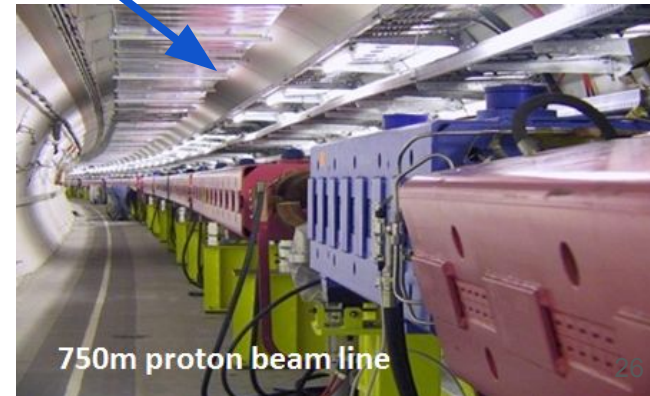
- ☐ Electron beam (10-20 MeV)



Vapour cell

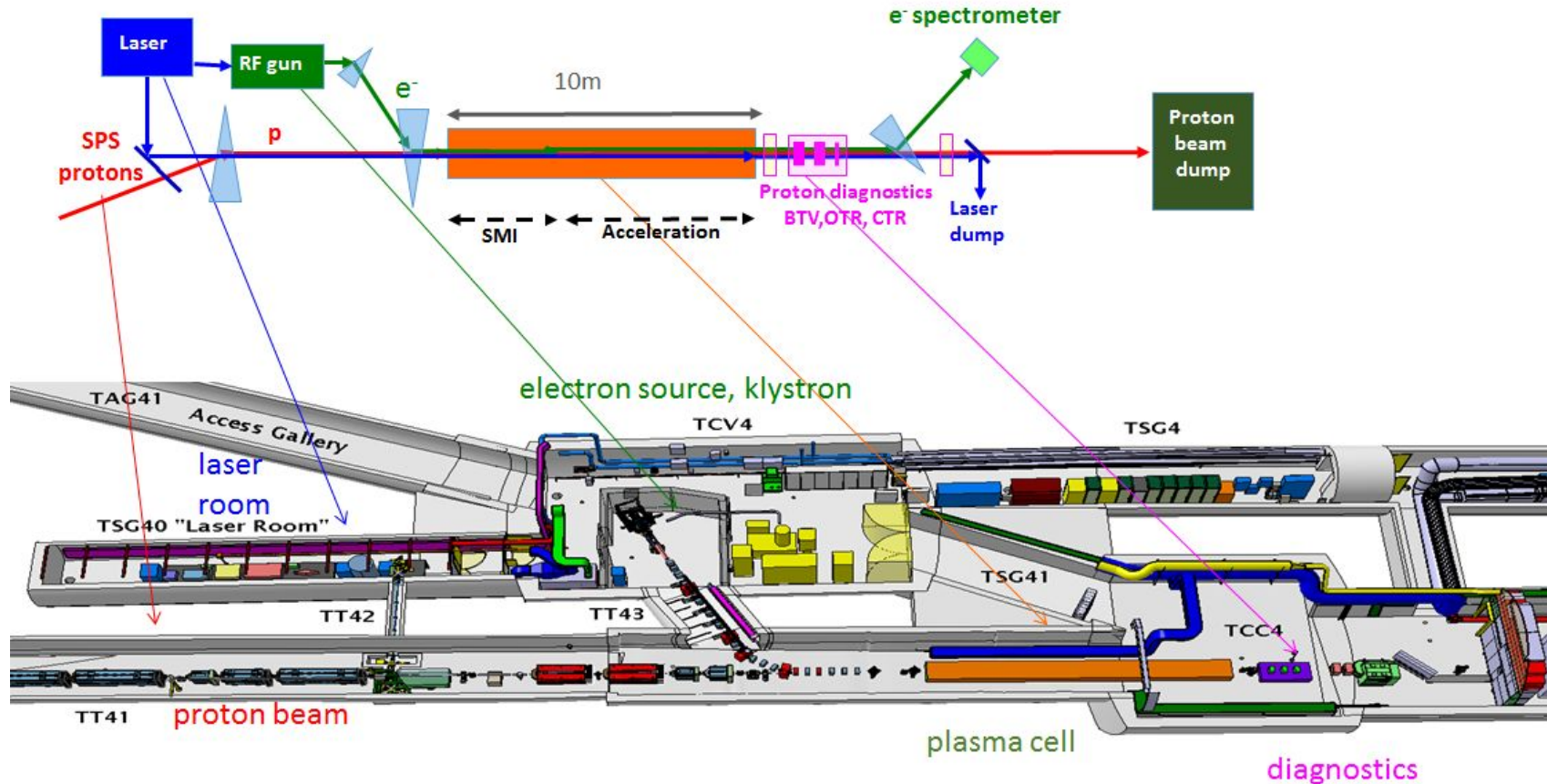
## Diagnostics:

- ☐ Proton
- ☐ Laser
- ☐ Electron

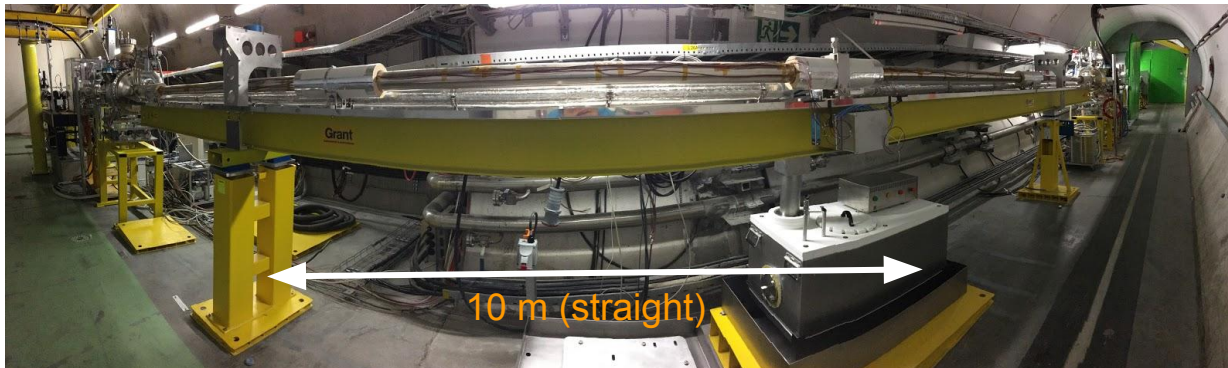
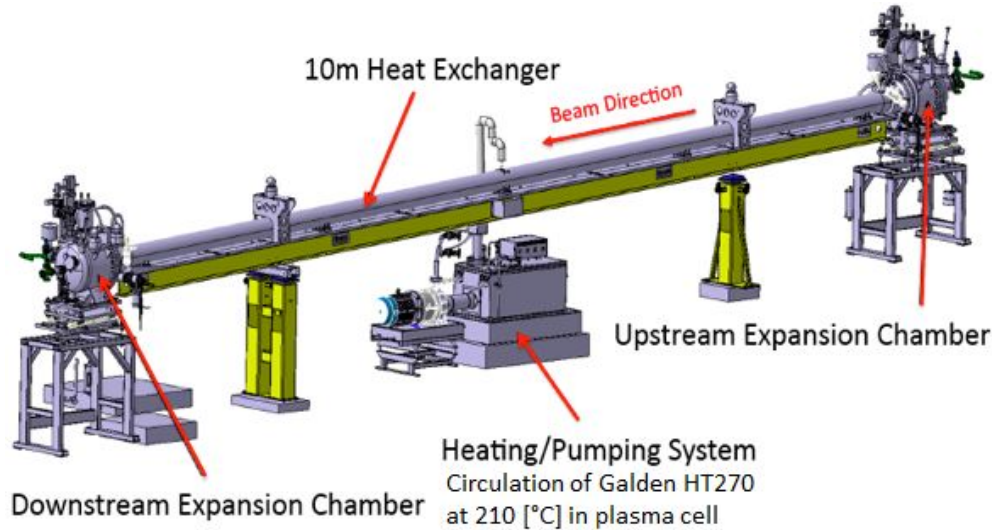


750m proton beam line

# Layout of the experiment

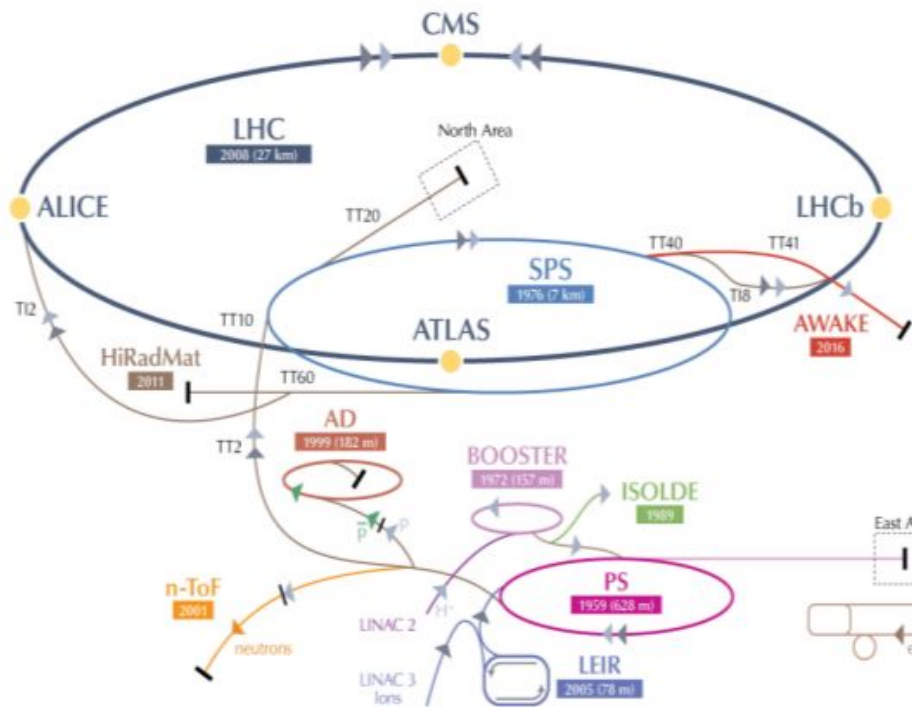


# The AWAKE plasma

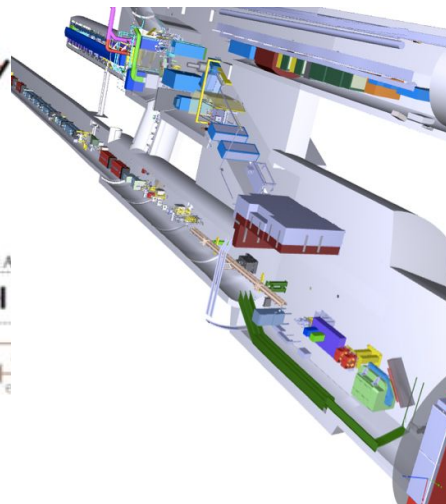


- ❑ Rubidium vapour cell.
- ❑ The laser **ionizes** the outermost electron of each rubidium atom.
- ❑ Desired **plasma density**:  
 $\sim 1\text{-}10 \times 10^{14}$  electrons/cm<sup>3</sup>.

# The AWAKE Experiment at CERN



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

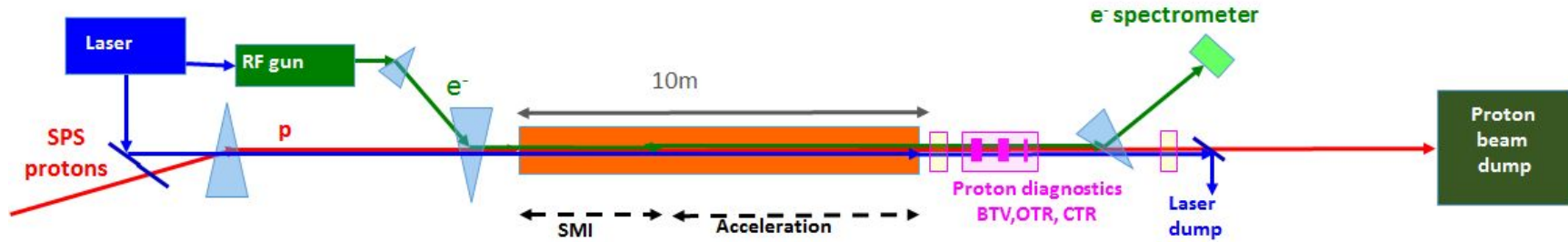


Radial bunch size at plasma entrance:

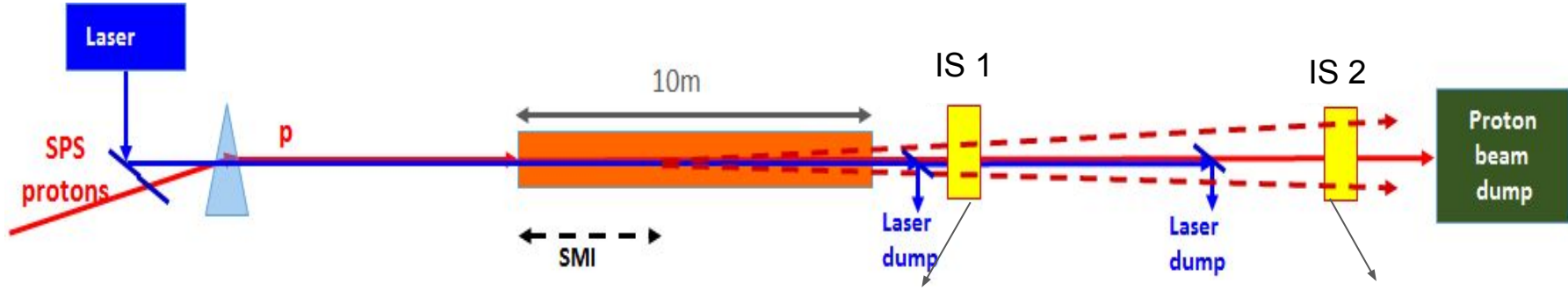
- ❑  $\sigma_r = 0.2$  mm

## 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?



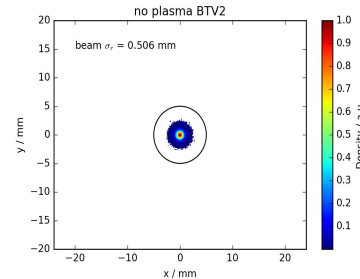
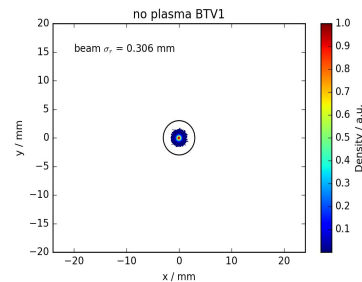
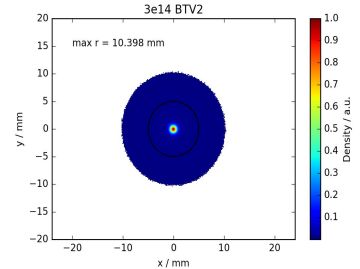
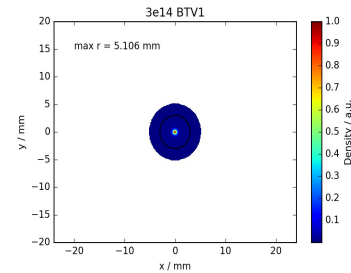
# Does the proton bunch self-modulate?



## Two-screen measurement

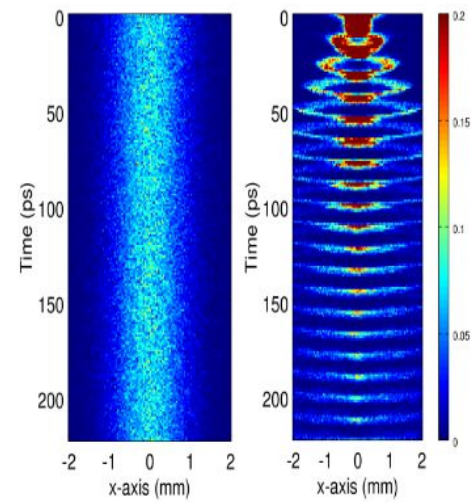
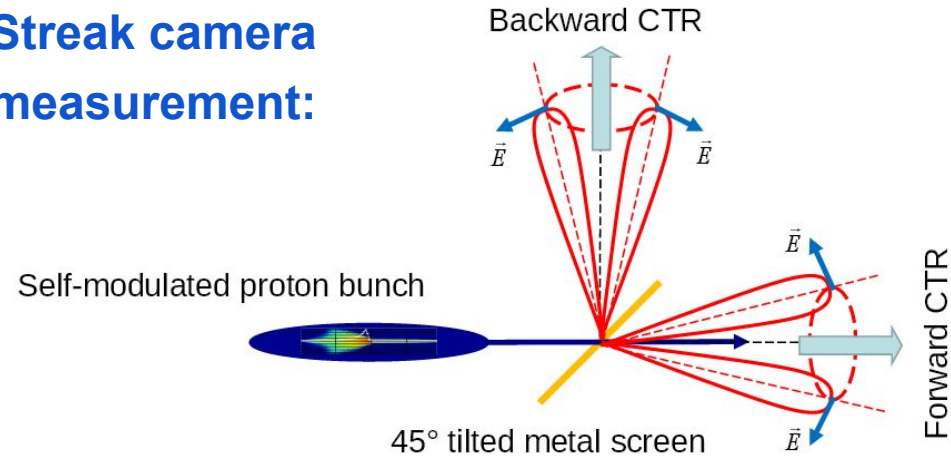
**Goal:** Image protons that got defocused by the strong plasma wakefields

To prove that plasma wakefields were present in plasma.



# Does the proton bunch self-modulate?

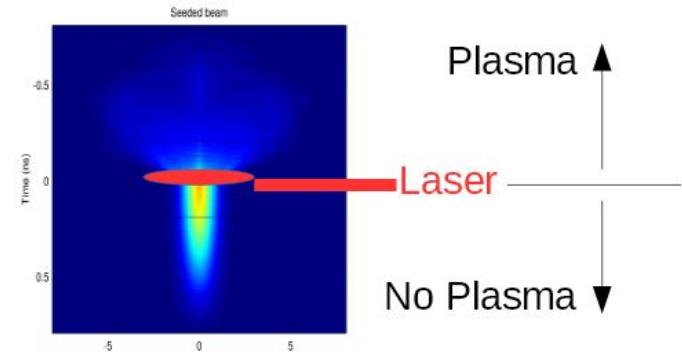
## Streak camera measurement:



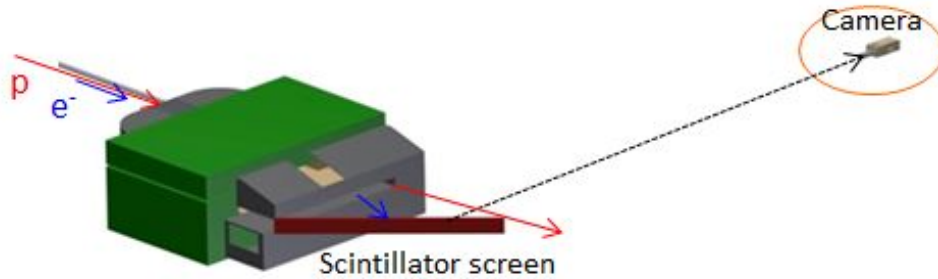
Foil emits waves up to the plasma wavelength of the foil:

- 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.

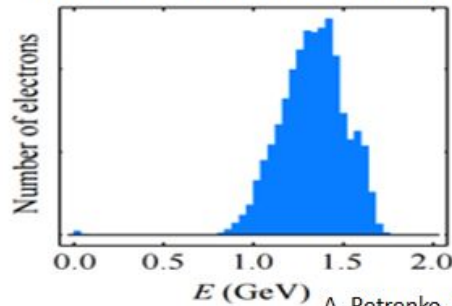


# What is the energy of accelerate electrons?



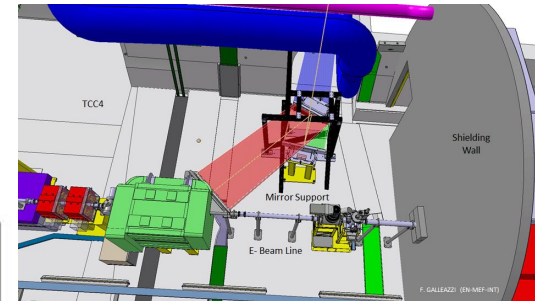
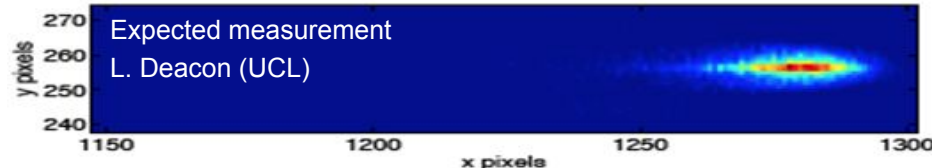
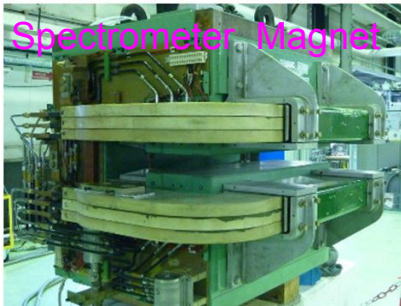
- ❑ Electrons will be injected with an energy around 10-20 MeV.
- ❑ Accelerated electrons are sent through a **spectrometer magnet** and deposit energy on a scintillating screen which is imaged by a camera.

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



A. Petrenko, CERN

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

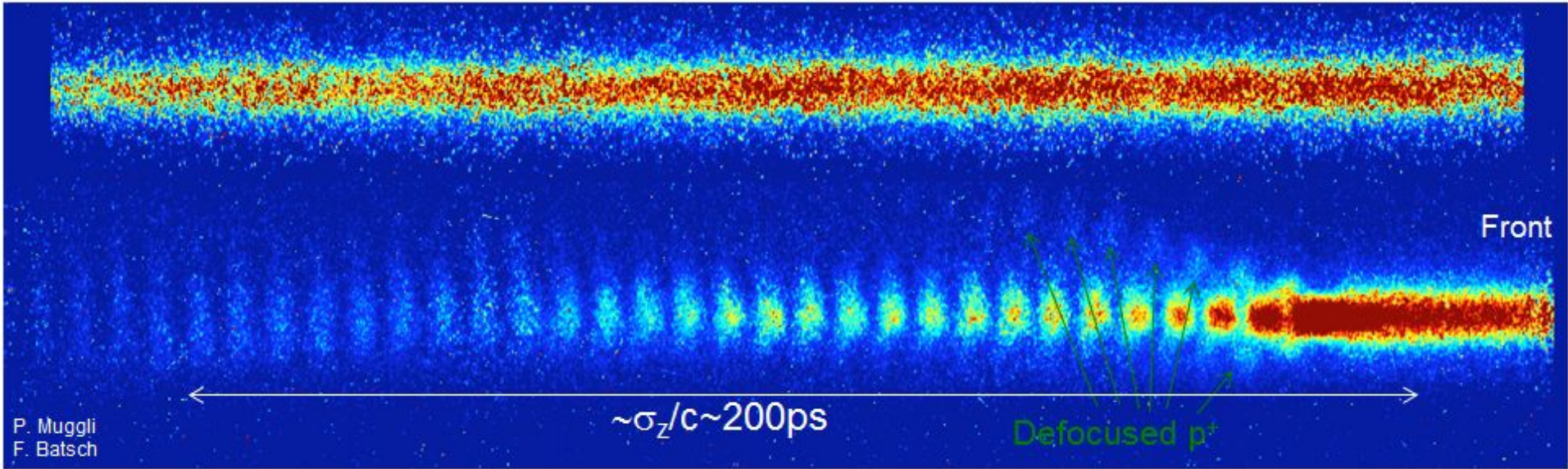


# Let's repeat...

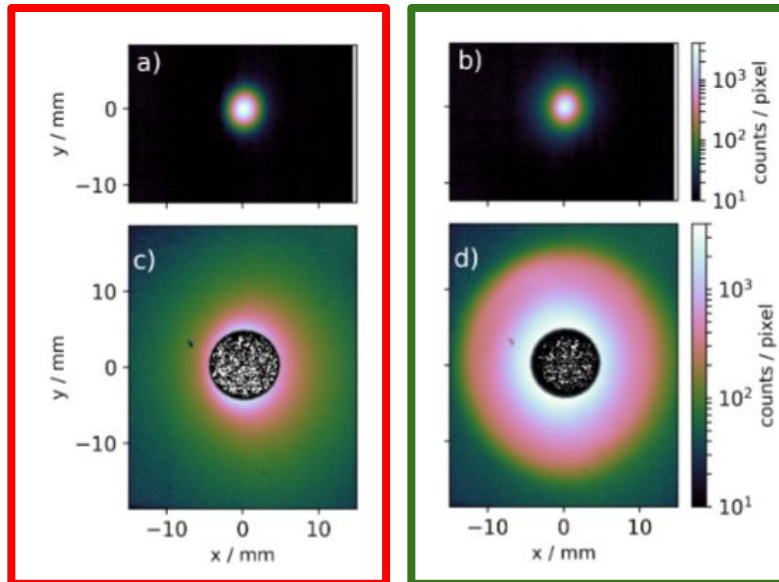
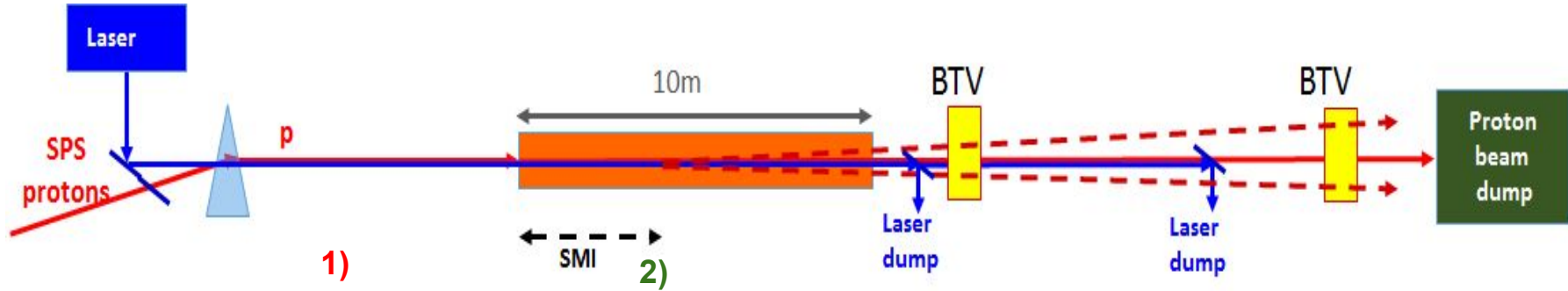
- ❑ What do we need to create the plasma **experimentally**?
- ❑ How do we measure that what **we expect to happen** actually happens?

# Latest AWAKE results

# Streak camera results



# The two-screen measurement



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

# 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.

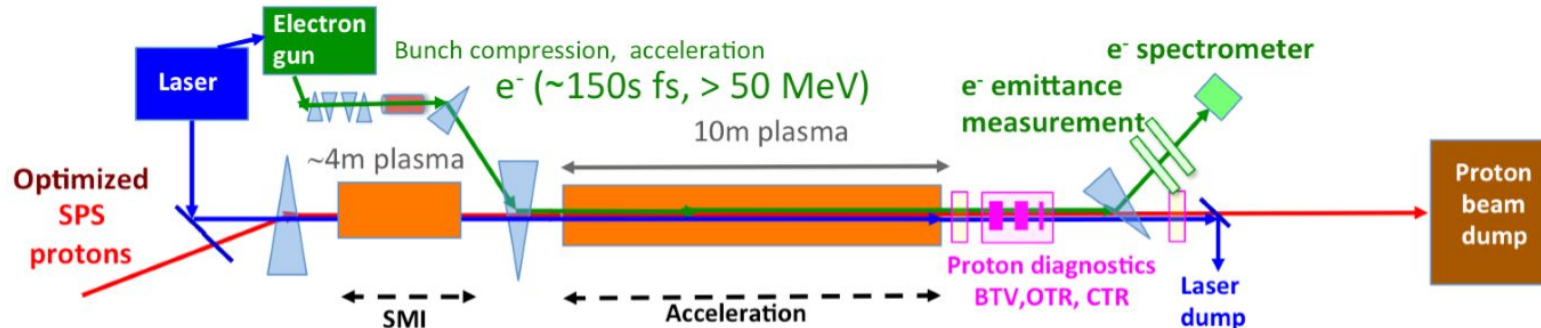
## Short term:

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

## Long term:

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**.



# The AWAKE experimental team

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



- ❑ **AWAKE** is a **proof-of-principle accelerator R&D experiment** currently in operation at CERN
  - ❑ **First proton-driven** wakefield acceleration experiment worldwide.
  - ❑ The experiment opens a pathway towards **plasma-based TeV lepton 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

# Principle of Plasma Wakefield Acceleration



Surfing wakefields to create smaller accelerators



CERN is famous for its big machines, for studying the tiniest constituents of matter to answer the biggest questions about the universe. Edda Gschwendtner is looking at radical yet simple ways of making our enormous machines smaller and more affordable.

TEDxCERN 9 October 2015

<http://tedxcern.web.cern.ch/>

Video:

<https://youtu.be/5Ryp6UTCeUo>