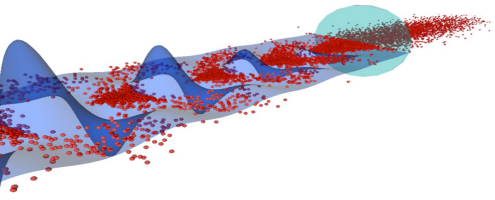
Observation of the Seeded Proton Bunch Self-Modulation in Plasma

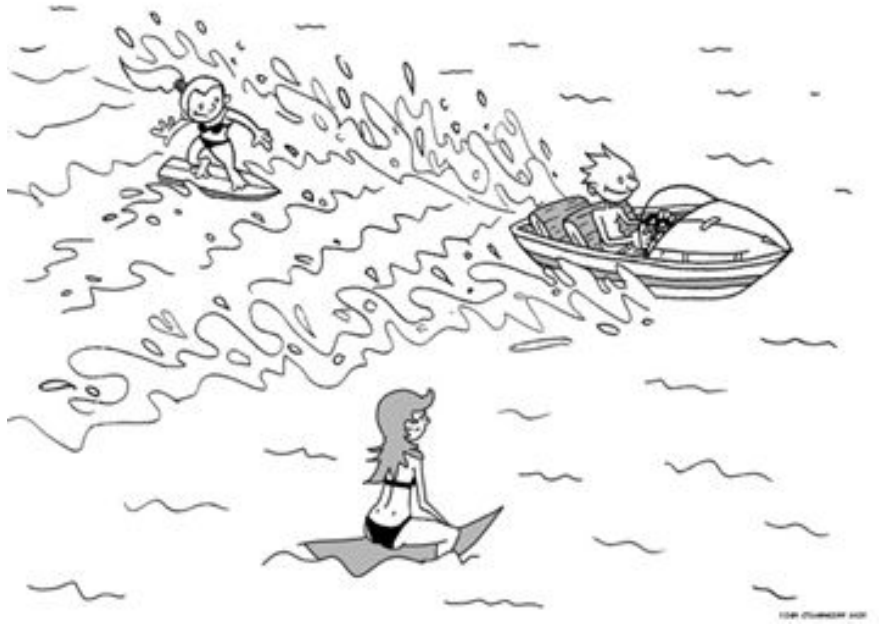
Marlene Turner, CERN
for the AWAKE Collaboration

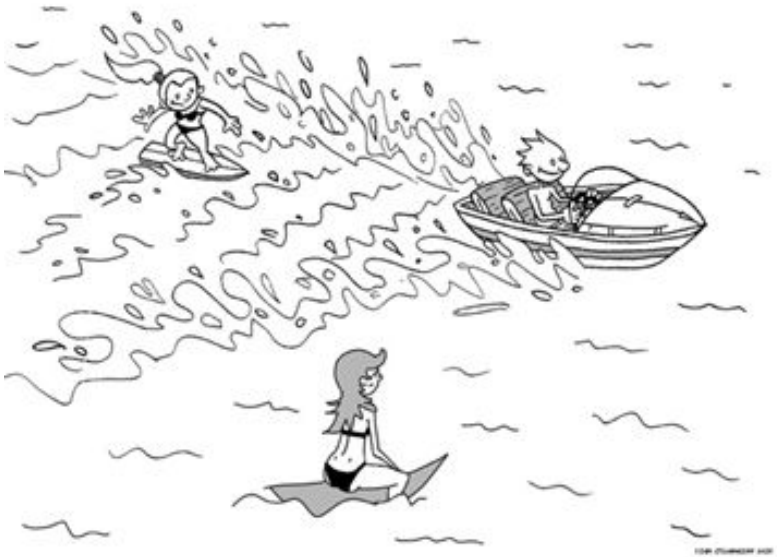
Supervisor CERN: Edda Gschwendtner
Supervisor TU Graz: Helmut Vincke



Outline of this Talk

- **Introduction**
  - Concept of plasma wakefield acceleration
- The **AWAKE** Experiment
  - Seeded Self-Modulation
  - Setup & Diagnostics
  - Measurement Concept
- Experimental **Results**
- **Summary** & Conclusions





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.

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.

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.

How to Create a Plasma Wakefield?

Plasma:

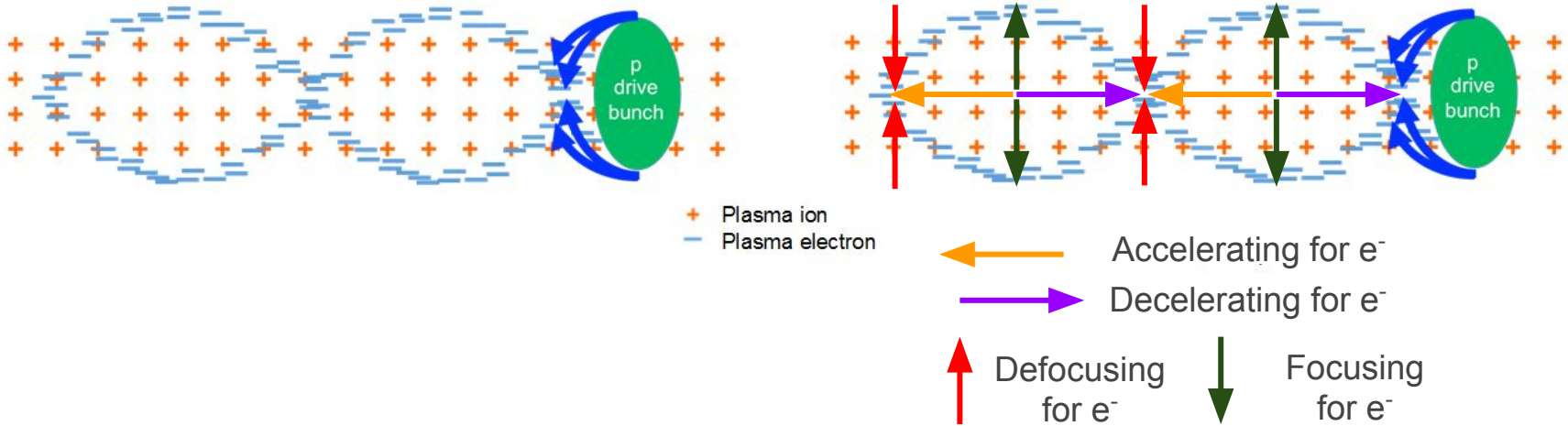
Quasi-neutral plasma in which **electrostatic interactions dominate** and charged particles are close enough to support **collective behaviour.**

Drive bunch or pulse:

Typically a relativistic **charged particle** bunch

or

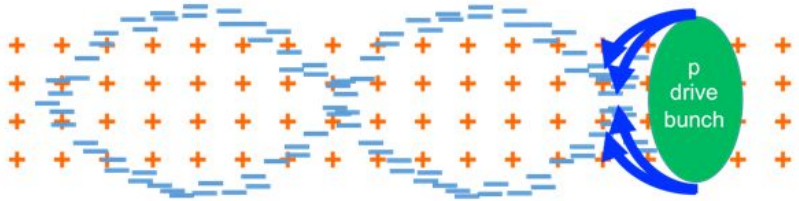
laser pulse/s.

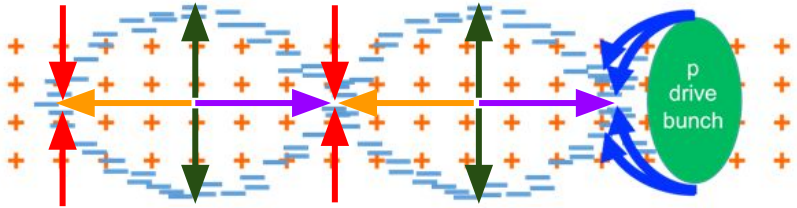


How to Create a Plasma Wakefield?

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.



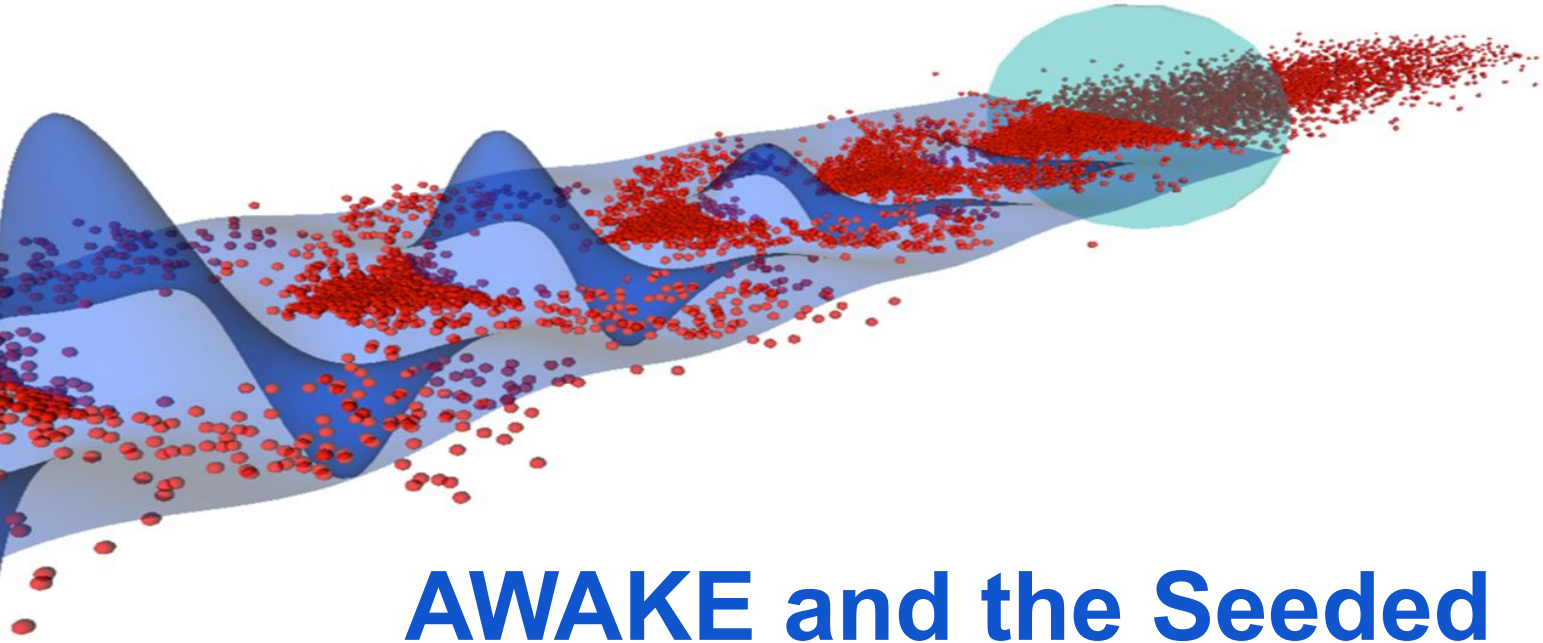


Plasma ion
Plasma electron

Accelerating for e⁻
Decelerating for e⁻
Defocusing for e⁻
Focusing for e⁻

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

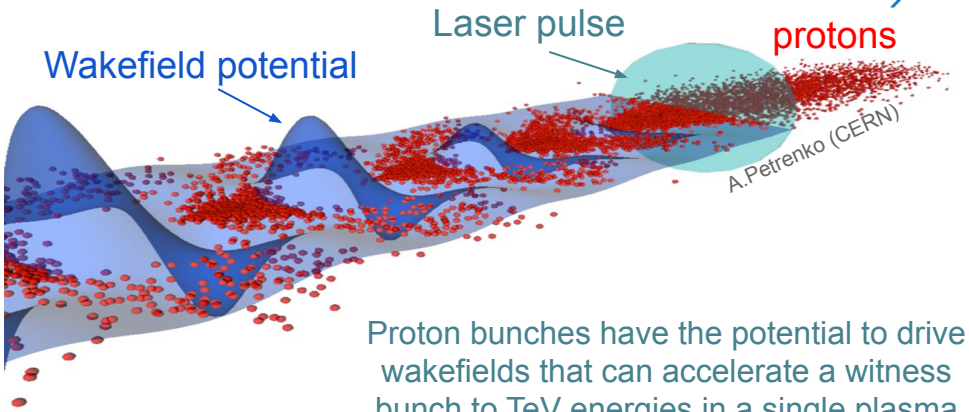
$$\lambda_{pe} = \frac{2\pi c}{\omega_{pe}} \propto \frac{1}{\sqrt{n_{pe}}}$$



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.

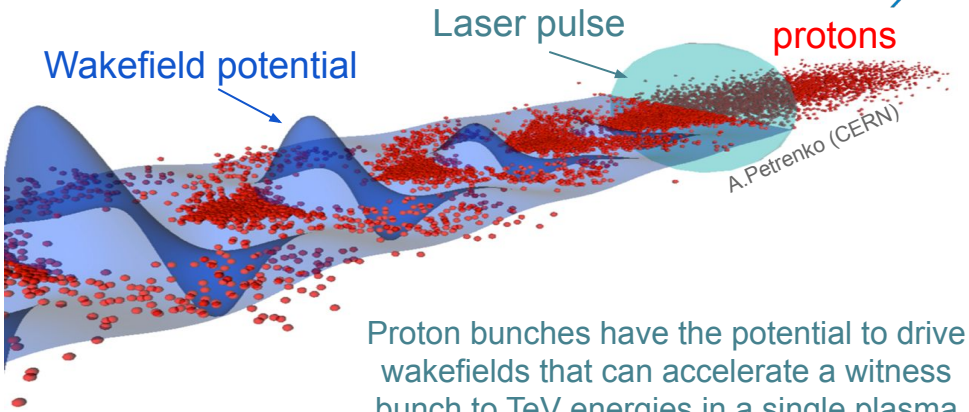


Proton bunches have the potential to drive wakefields that can accelerate a witness bunch to TeV energies in a single plasma

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

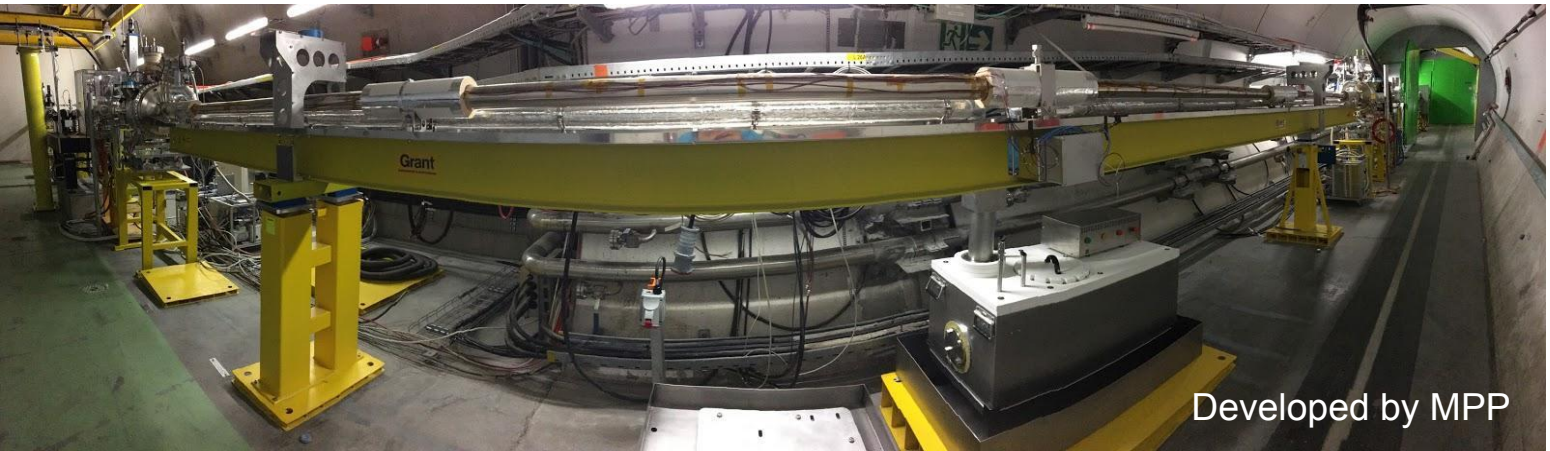
What is AWAKE?

- 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.



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

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



10m Rb vapor source

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.

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.

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.

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.

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

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

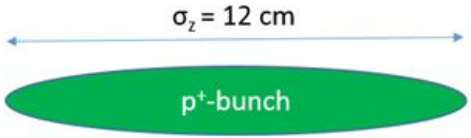
⇒ In order to create plasma wakefields effectively, the **drive bunch length** has to be in the order of the **plasma wavelength** ⇒ mm scale proton bunches do not exist.

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)

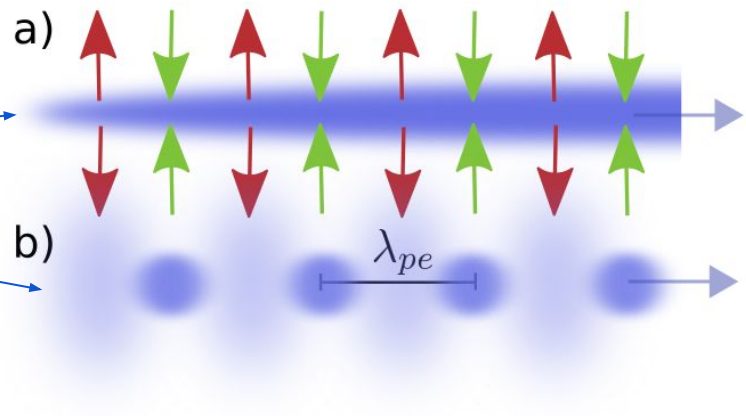
Before self modulation:



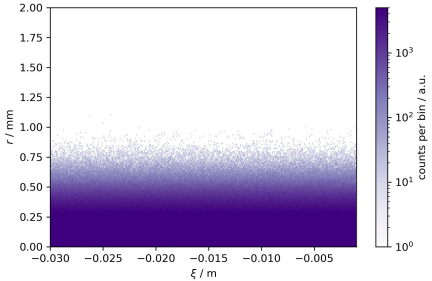
The Seeded Self-Modulation

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).

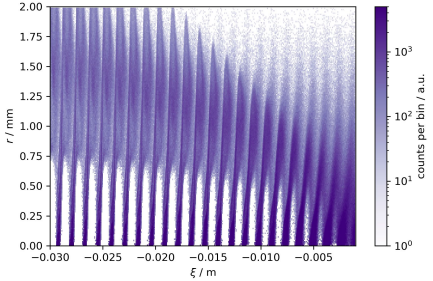
Micro- bunches separated by λ_{pe}.Drive wakefields resonantly.



Before SM



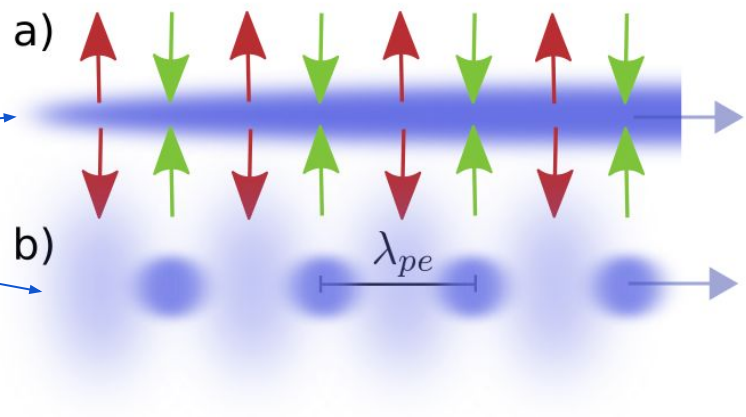
After SM



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).

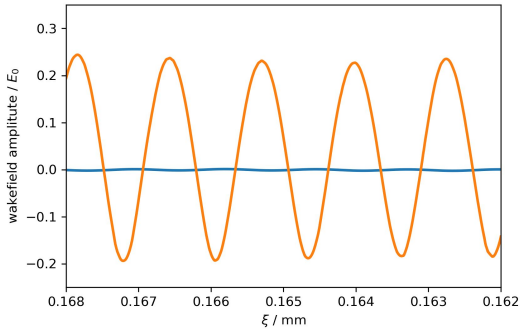
Micro-bunches separated by λ_{pe}.
Drive wakefields resonantly.

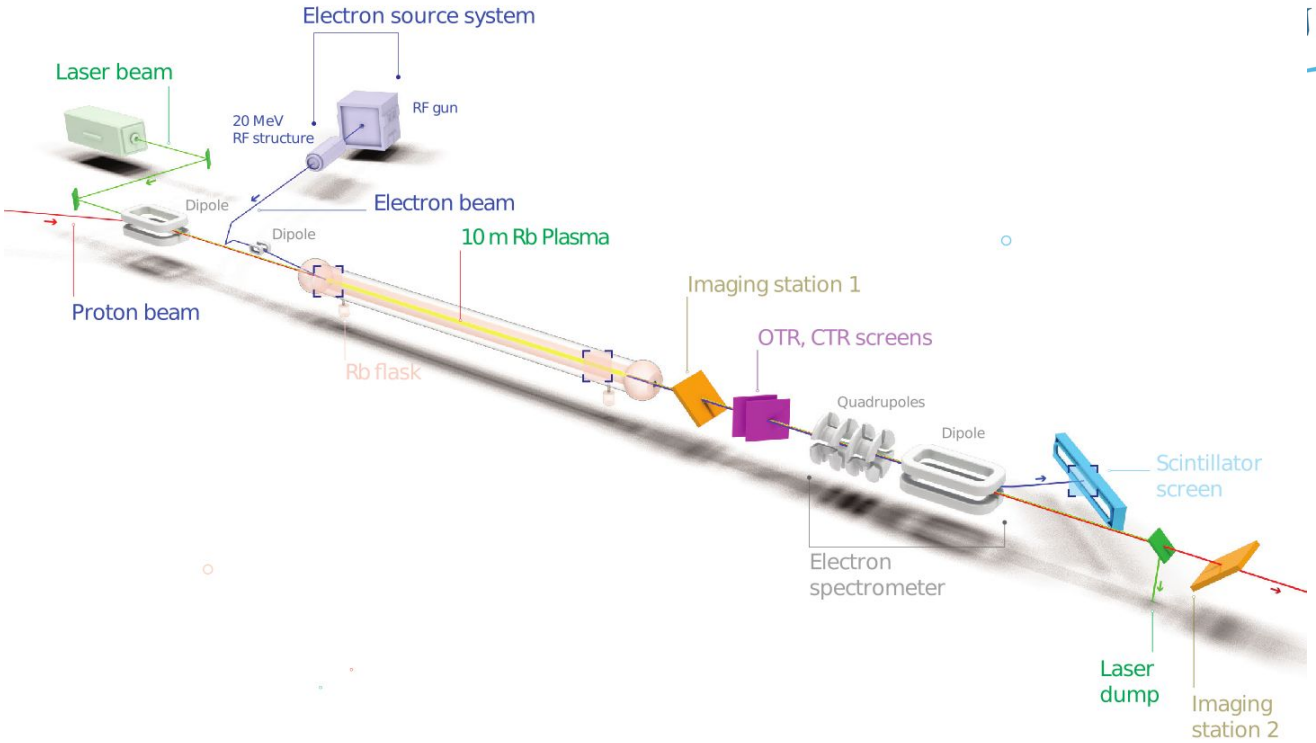


We **seed** the instability by:

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

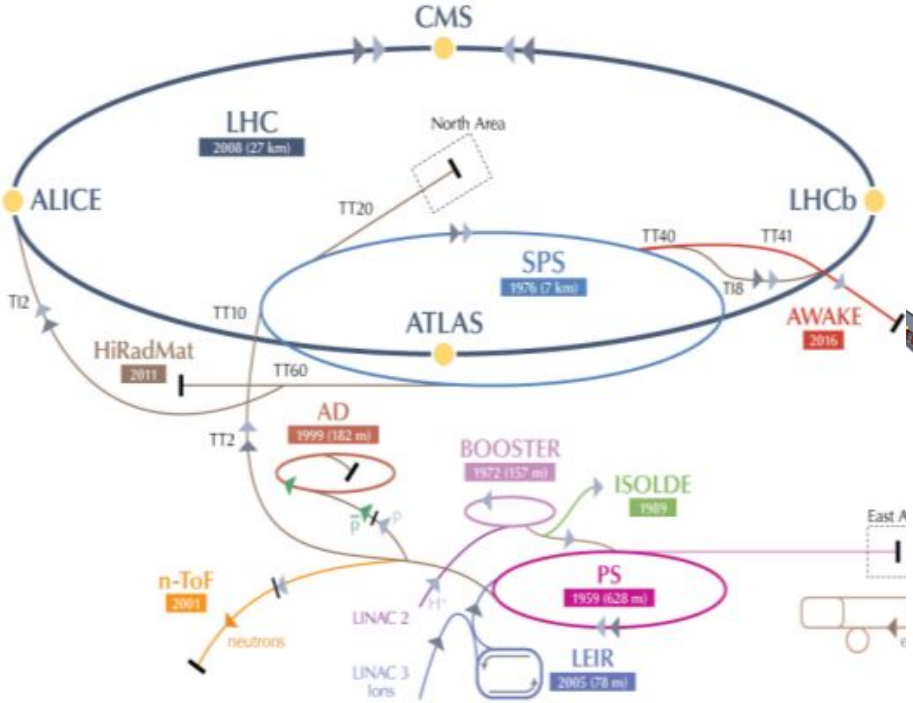
⇒ Seeded self-modulation (SSM)





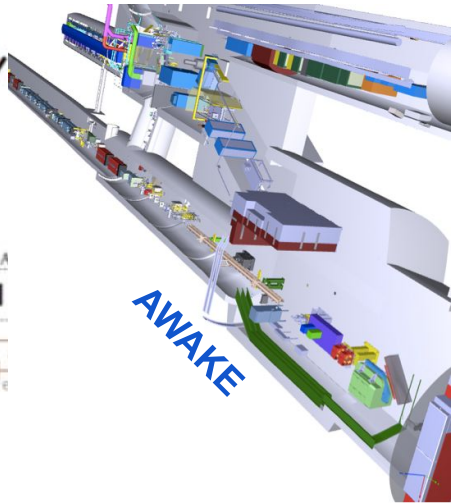
The AWAKE Experimental Setup

The AWAKE Experiment at CERN



CERN accelerator complex

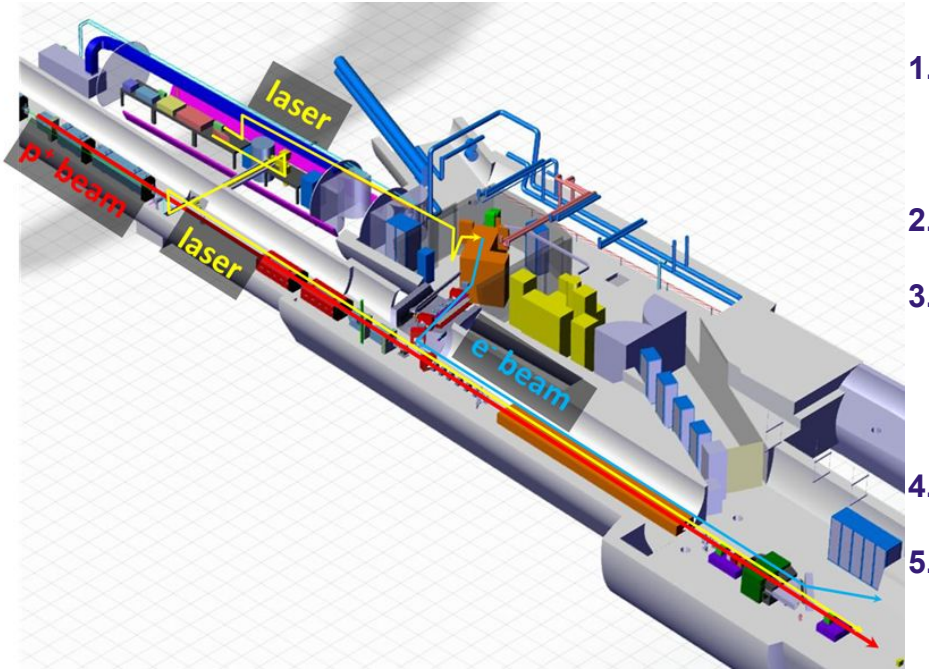
- SPS proton bunch **momentum**: 400 GeV/c
- 3×10^{11} protons/bunch at ~0.03 Hz
- **rms bunch length:** σ_z = 6-12 cm



radial bunch size at plasma entrance:

- σ_r = ~0.2 mm

The AWAKE Experimental Setup



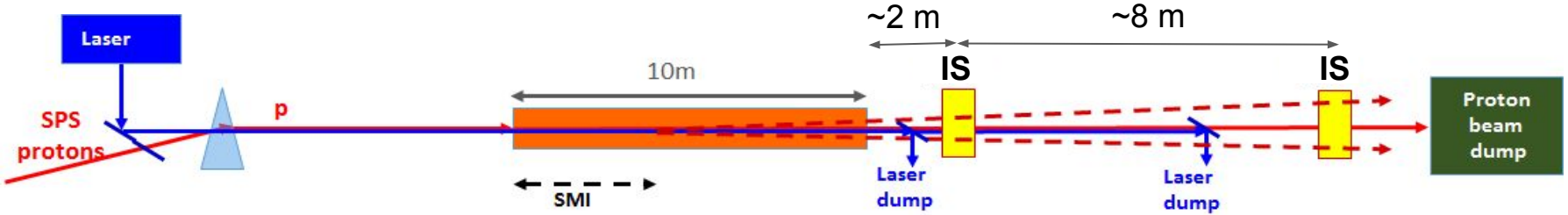
1. 10 m long **rubidium vapour source** with a vapour density adjustable from 10^{14}-10^{15} atoms/cm^3 and a density uniformity of 0.2%.
2. **Laser** system that produces a 120 fs, 450mJ laser pulse.
3. **Proton** beam line that transfers a 400 GeV/c proton bunch with a RMS length of 6-15 cm, a radial 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.

Plenary talk by Edda Gschwendtner,

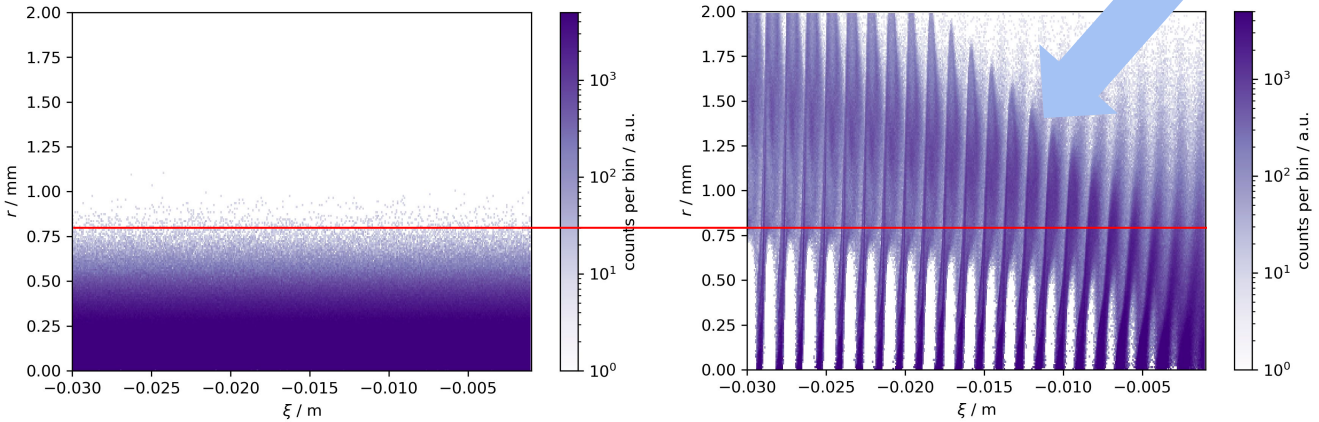
Thursday 10:50 G 30.

Diagnostics: The Two-Screen Setup

2 Imaging stations ⇒ transverse time integrated bunch profile.



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

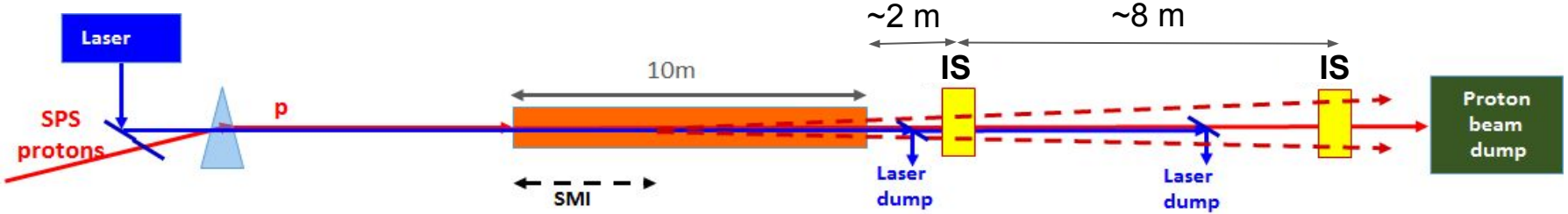


Learn about transverse wakefields amplitude by looking at the maximum radius of the distribution

The Two-Screen Setup

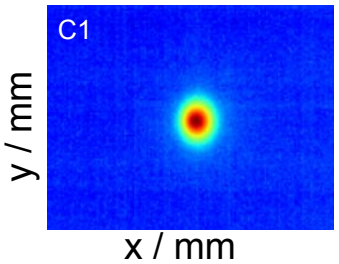
2 Imaging stations ⇒ Transverse time integrated bunch profile.

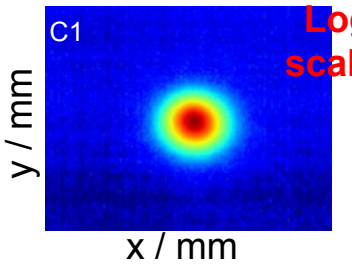
Goal: Detect protons that got defocused by the strong plasma wakefields.



No plasma:

No ionizing laser pulse; bunch propagates through rb vapor

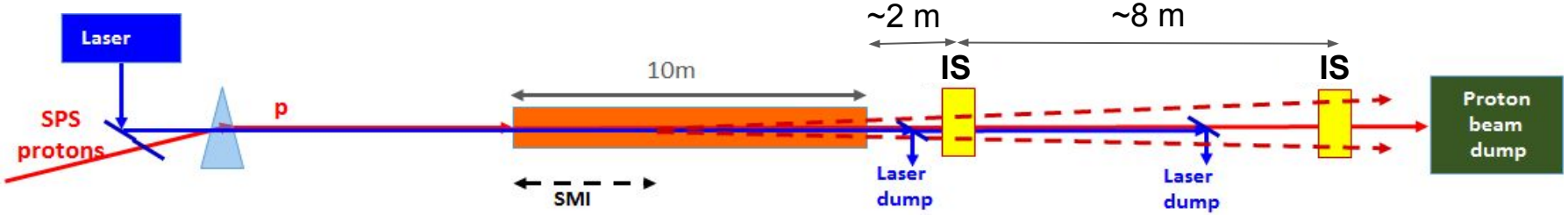




The Two-Screen Setup

2 Imaging stations ⇒ Transverse time integrated bunch profile.

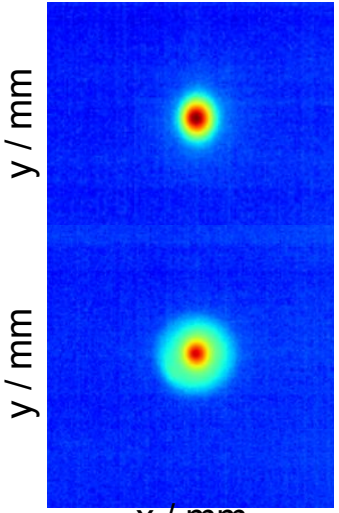
Goal: Detect protons that got defocused by the strong plasma wakefields.

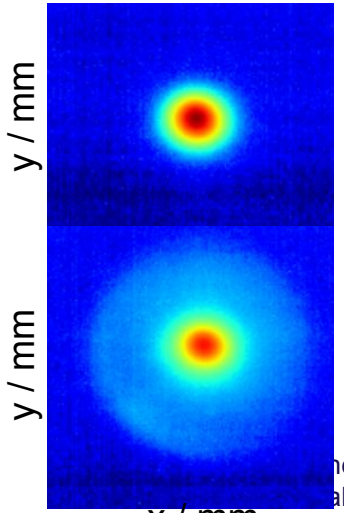


From the **radial distribution** of the defocused protons, we try to learn about the **transverse effects** of SSM

No plasma:

Plasma:

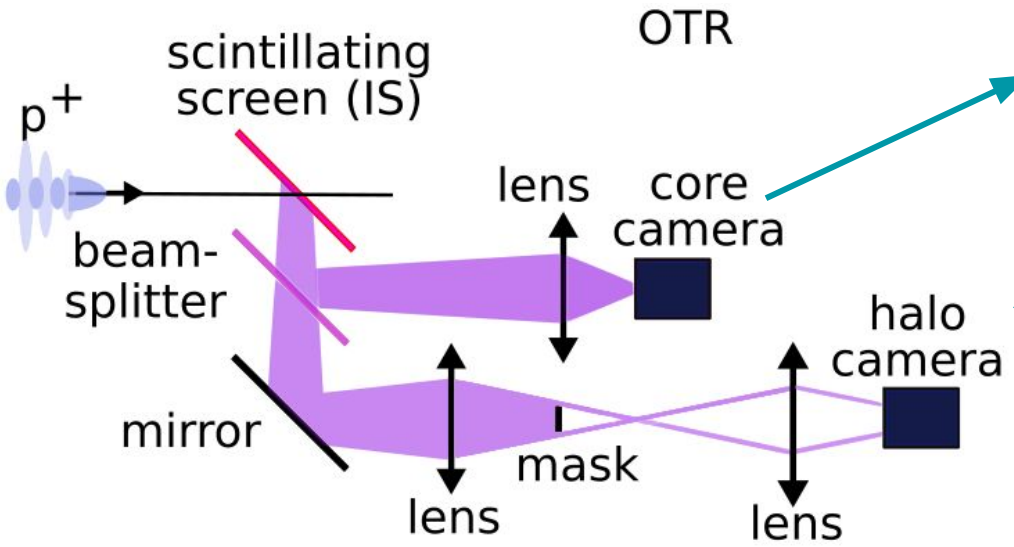


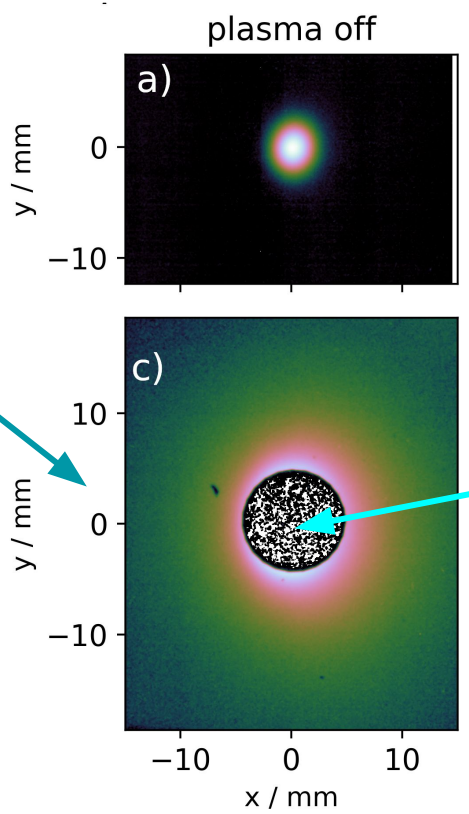


Log scale!

The Two-Screen Setup

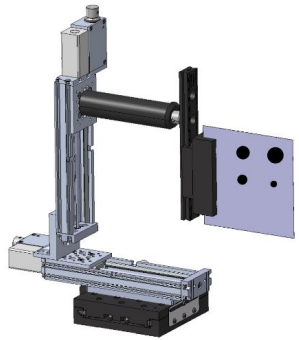
Goal: detect protons that got defocused by the plasma wakefields.
to study the transverse properties of the self-modulation process.





The beam density of the proton bunch core is 2-3 orders of magnitude more intense than the defocused protons

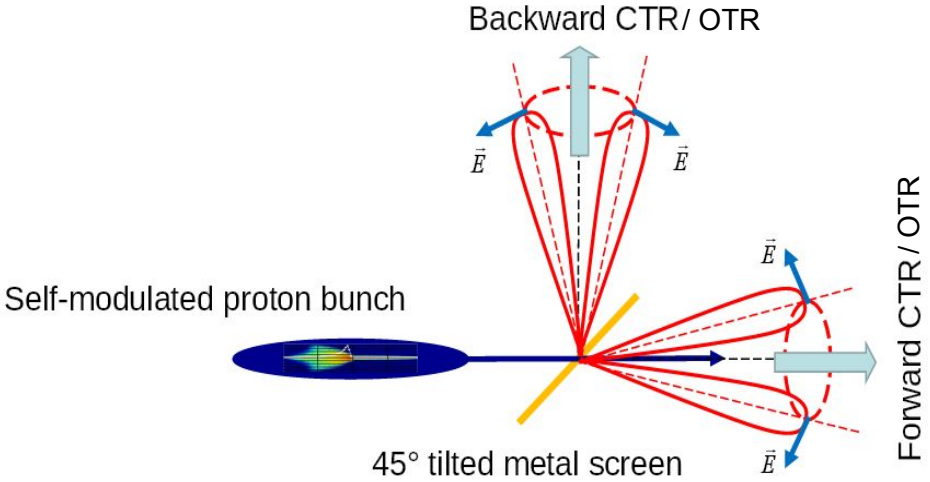
⇒ block the light with a mask



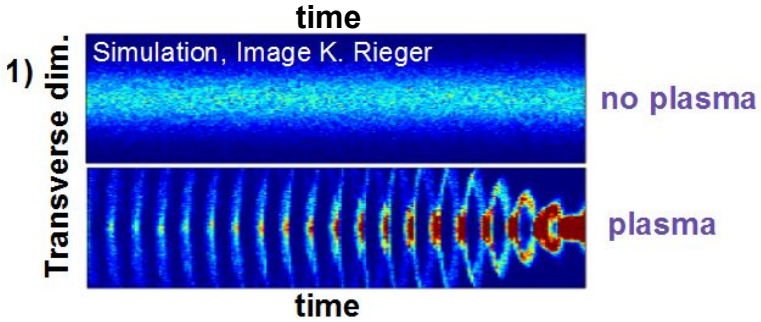
M. Turner, PhD Thesis (2018)

Diagnostics: Streak camera

To study the Seeded Self-Modulation



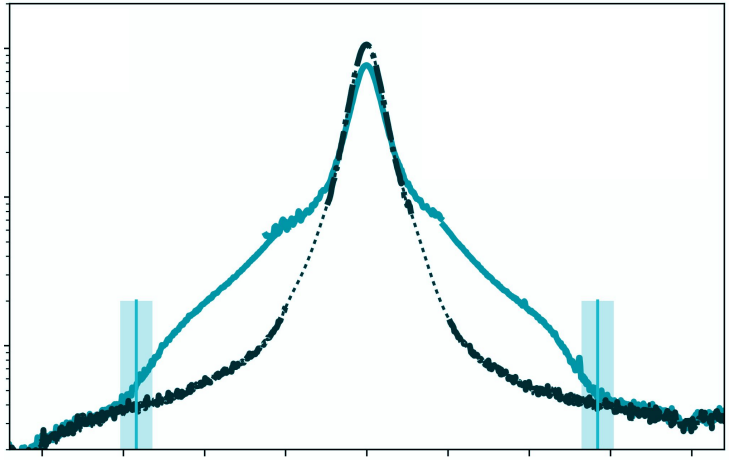
Streak camera imaging OTR light ⇒ time resolved image of the proton bunch.



emission of waves up to the plasma wavelength of the foil:

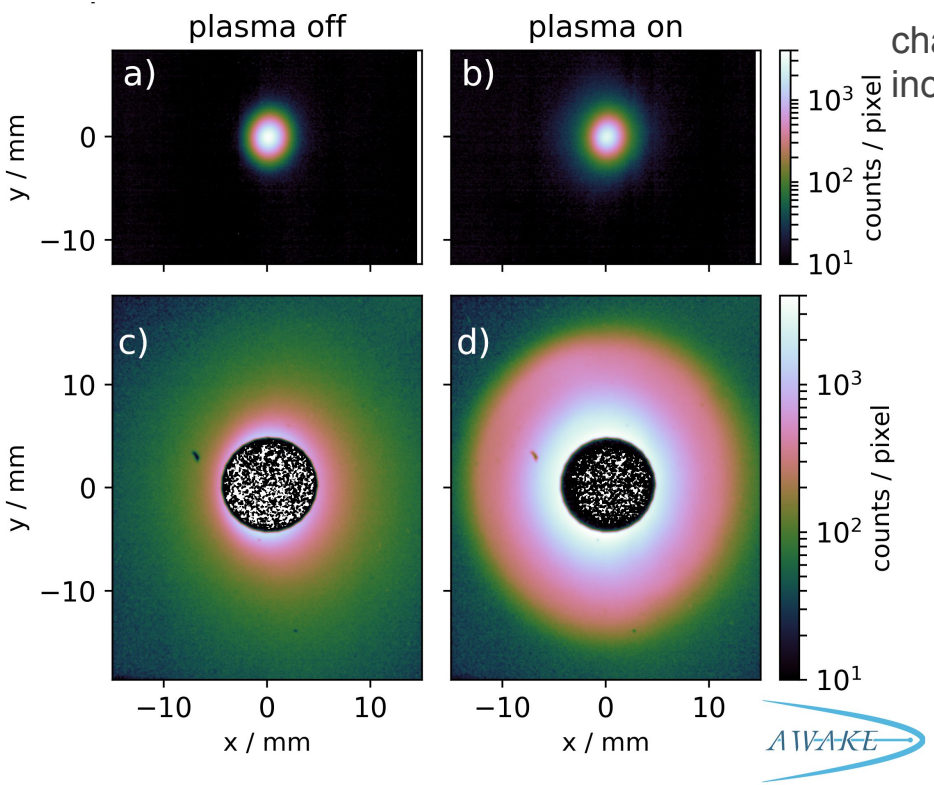
- ❏ including radiation in the optical range (OTR).
- ❏ radiation is coherent (CTR) for wavelengths bigger than the structure of the micro-bunches.

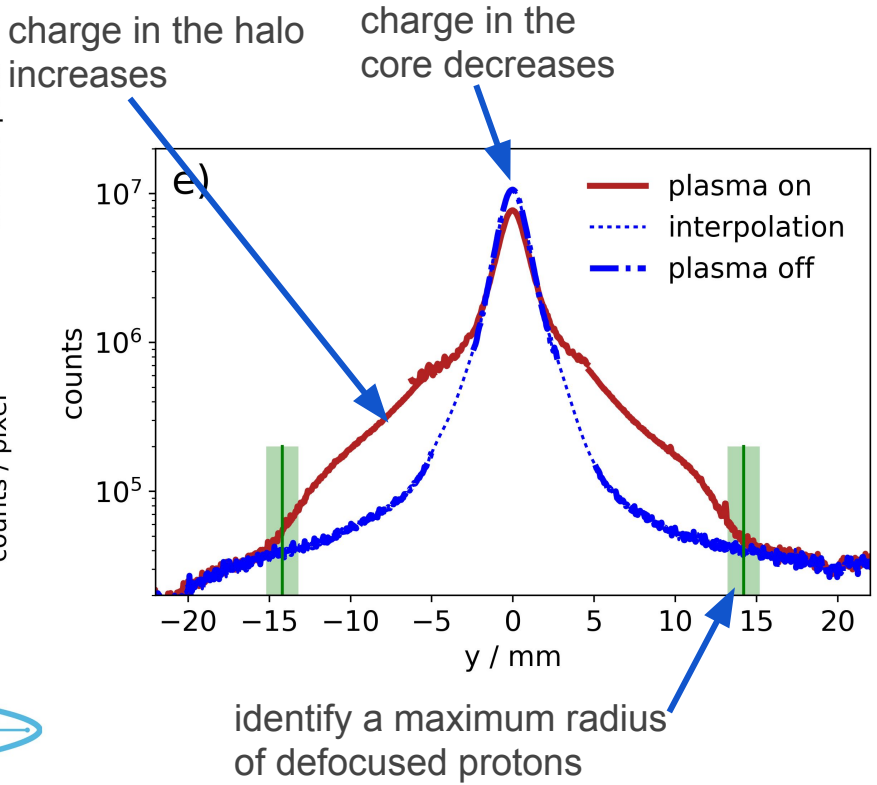
K. Rieger et al., Review of Scientific Instruments **88**, 025110 (2017)



Experimental Results

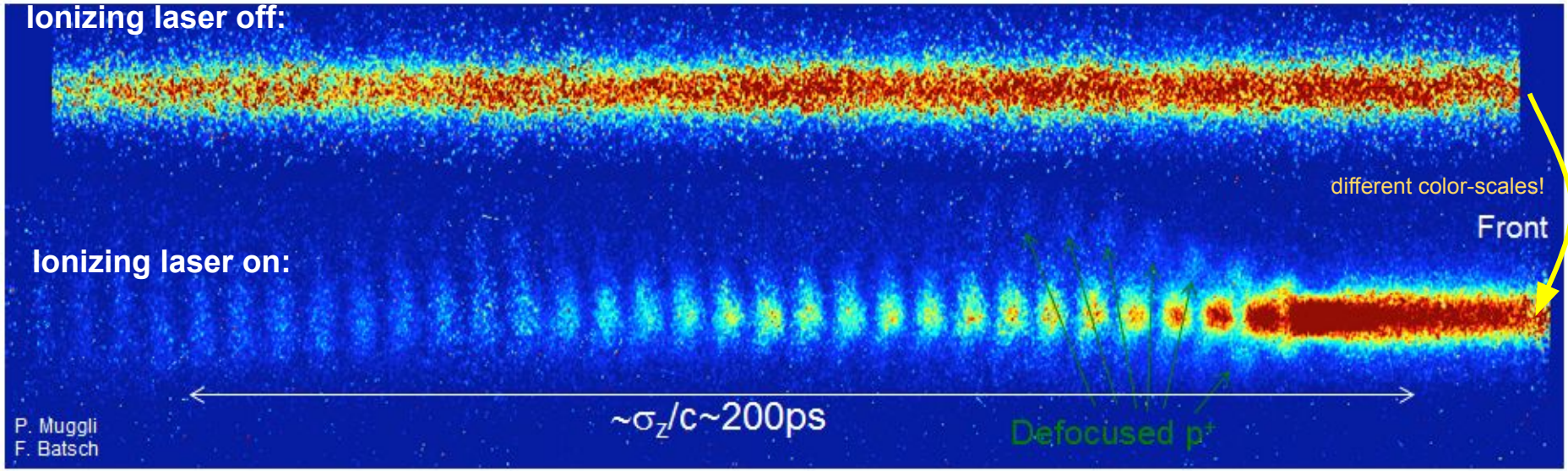
Observation of Proton Defocusing





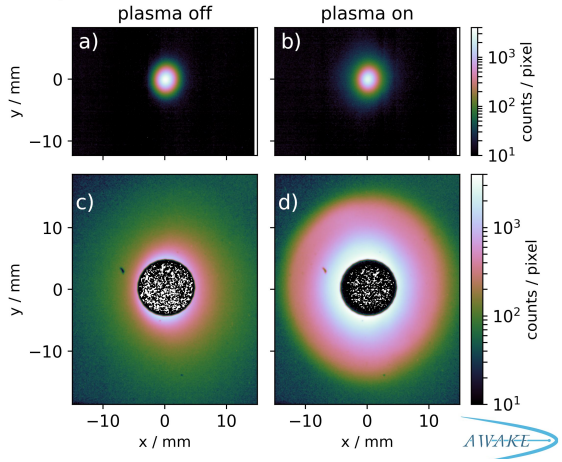
M. Turner *et al.* (AWAKE Collaboration), Phys. Rev. Lett. 122, 054801

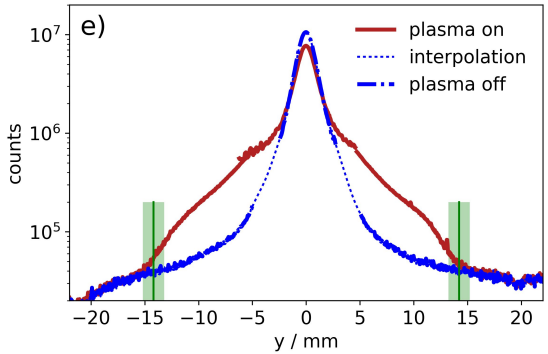
Longitudinal Bunch Density



Clear proof of proton bunch SM in plasma

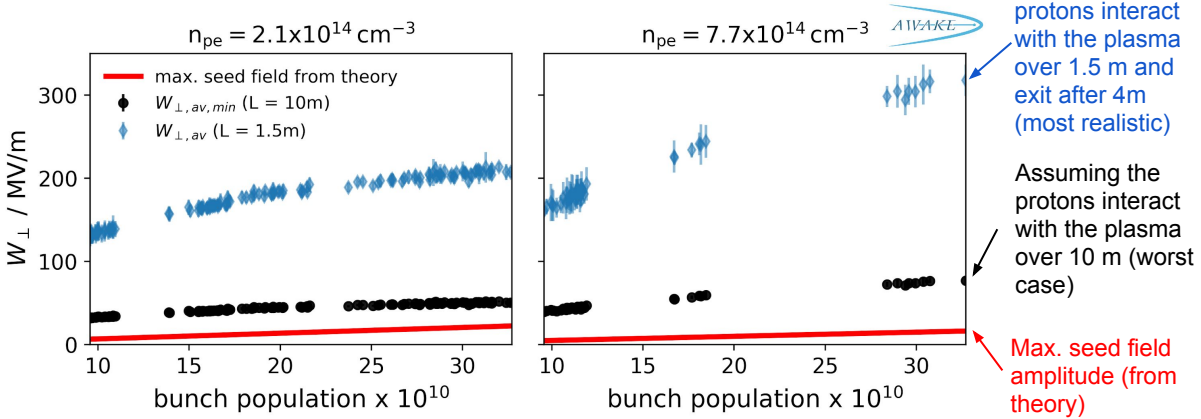
The Physics Properties of the Seeded Self-Modulation





from the maximum radius of the defocused protons ⇒ estimate their transverse momentum

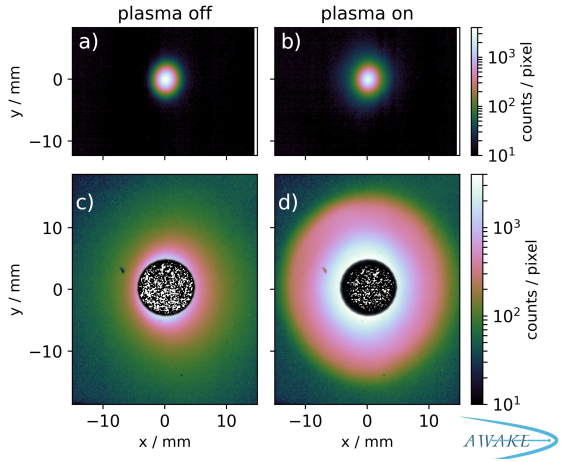
$$W_{\perp,av} = \frac{\theta \cdot p_{\parallel} c}{qL}$$

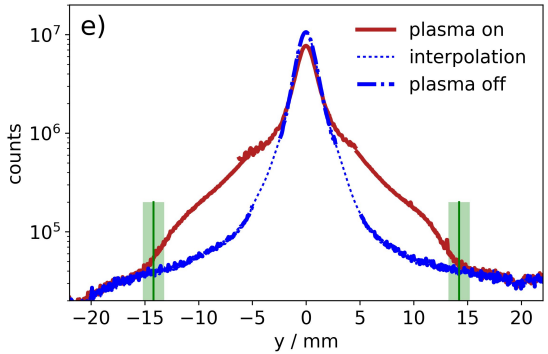


average field amplitudes much higher than the initial seed field amplitudes ⇒ proof of wakefield growth due to self-modulation along the plasma

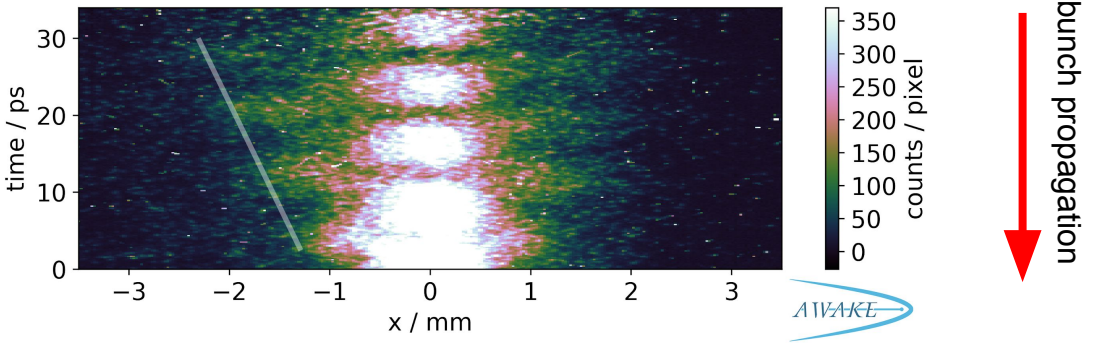
M. Turner *et al.* (AWAKE Collaboration), Phys. Rev. Lett. 122, 054801

The Physics Properties of the Seeded Self-Modulation





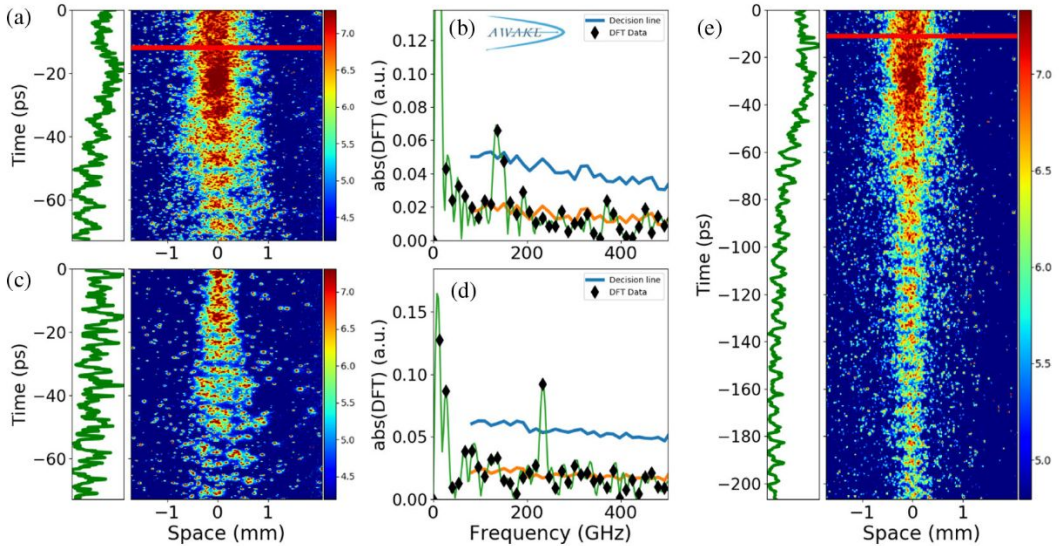
average field amplitudes much higher than the initial seed field amplitudes ⇒ proof of wakefield growth due to self-modulation along the plasma

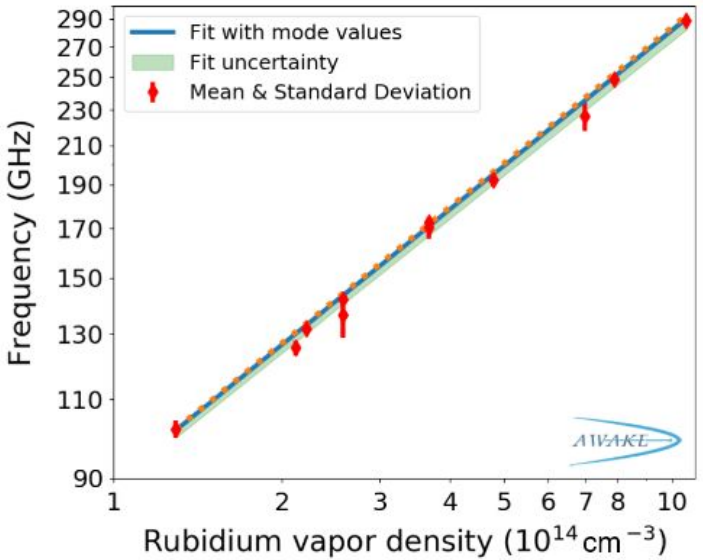


maximum radius of the defocused protons increases along the bunch ⇒ proof of wakefield growth due to self-modulation along the bunch

M. Turner *et al.* (AWAKE Collaboration), Phys. Rev. Lett. 122, 054801

Microbunch frequency





Analyse the streak camera images using the fast fourier transform ⇒ obtain the frequency of the micro-bunches

Demonstrated that:

$$f = \frac{\omega_{pe}}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\epsilon_0 m_e}}$$

AWAKE Collaboration, Phys. Rev. Lett. 122, 054802

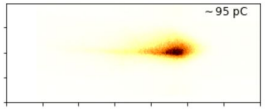
First proton bunch self-modulation !!!!!

Summary & Conclusions

- AWAKE is a **proton driven** plasma wakefield experiment.
- After the proton bunch **self-modulates** it can resonantly drive high-amplitude wakefields in plasma.
- Experimentally, AWAKE proved that the bunch was **self-modulating** and driving amplitudes above **seed level**.

- Electron acceleration experiments will be discussed in a **plenary talk** by:

  Edda Gschwendtner, Thursday 10:50 G 30.



M. Turner; the AWAKE collaboration