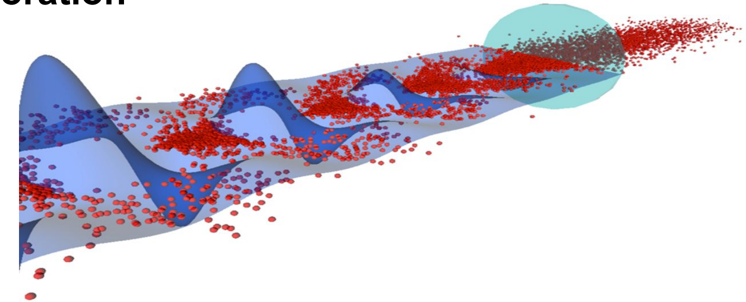
Electron Acceleration in a Proton Driven Plasma Wave

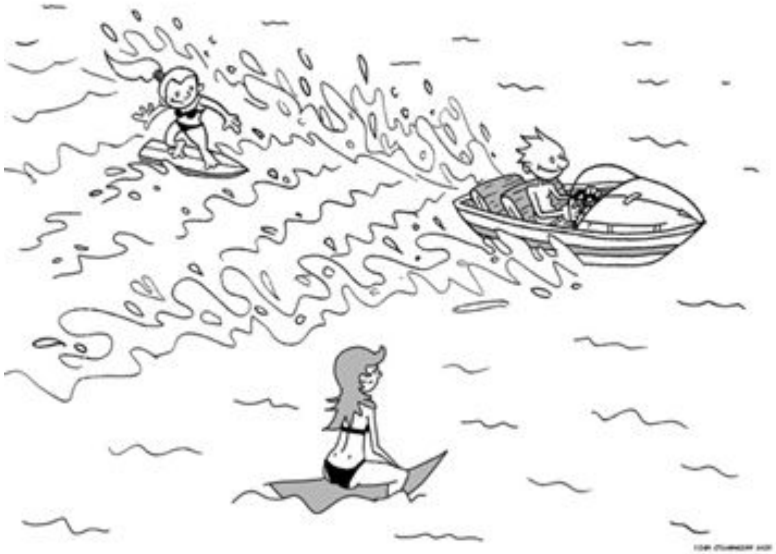
Recent Results from the Advanced Wakefield Experiment (AWAKE) at CERN

M. Turner for the AWAKE collaboration



Outline of this Seminar

- ❏ **Introduction** to Plasma Wakefield Acceleration
- ❏ **Layout, Concept and Ideas** of the **AWAKE** Experiment
  - ❏ The Seeded Proton Bunch **Self-Modulation**
  - ❏ **Electron Acceleration** in Proton Driven Plasma Waves
- ❏ Experimental **Results**
- ❏ **Future** of AWAKE and Possible **Applications**
- ❏ Conclusions & Summary



Introduction to 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, non-relativistic 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

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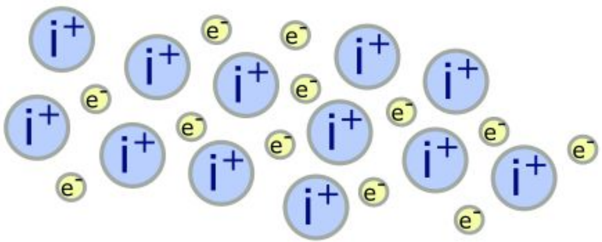
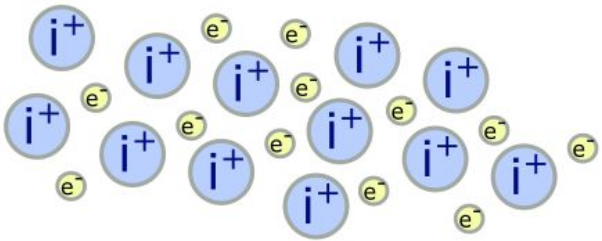
Introduction: Plasma Wakefield



quasi-neutral plasma in which electrostatic interactions dominate;
⇒ collective effects

Introduction: Plasma Wakefield



quasi-neutral plasma in which electrostatic interactions dominate;
⇒ collective effects

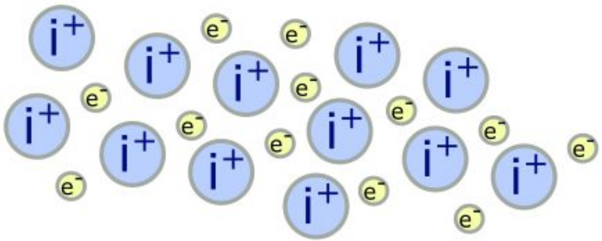
the ion mass is much larger than the electrons mass
⇒ treat the ions as imobile

$m_i \gg m_e$

$$\omega_{pi} = \sqrt{\frac{n_i Z_c^2 e^2}{\epsilon_0 m_i}} = \sqrt{\frac{n_e e^2}{\epsilon_0 m_i}} = \omega_{pe}\sqrt{\frac{m_e}{m_i}} \ll \omega_{pe}.$$

e.g. m_e = ~10^{-30}kg
m_i = 10^{-25} kg (Rubidium)

Introduction: Plasma Wakefield



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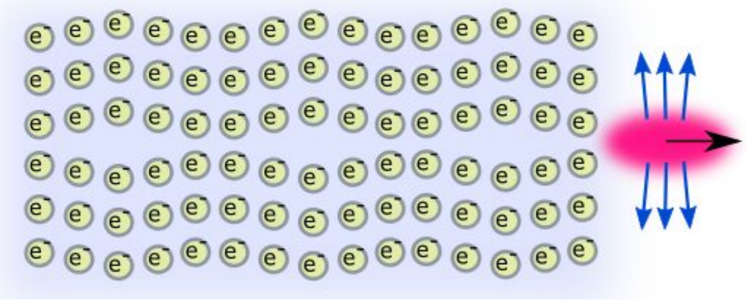

we use a particle bunch / laser pulse to excite an electrostatic (Langmuir) wave
mostly transverse electron motion
travelling electron plasma wave

⇒ electron density modulation ⇒ resulting electric field

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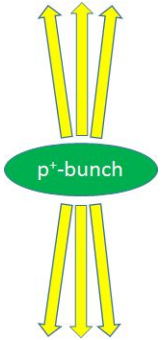
Introduction: Plasma Wakefield

to excite the plasma wave:

drive bunch or pulse:
typically a relativistic **charged particle** bunch
or
laser pulse/s.



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- to **accelerate** charged particles we need a longitudinal electric field;
- use plasma to **convert** the transverse electric field of the proton bunch into a longitudinal electric field.

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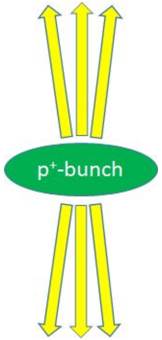

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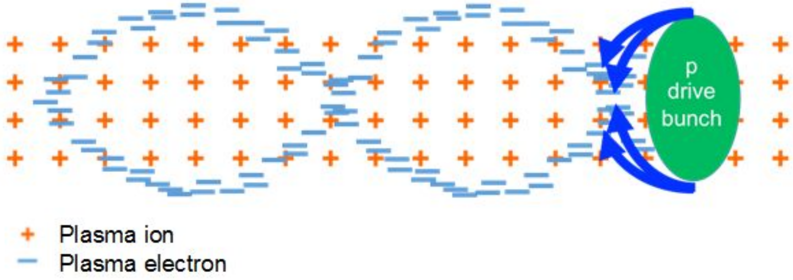

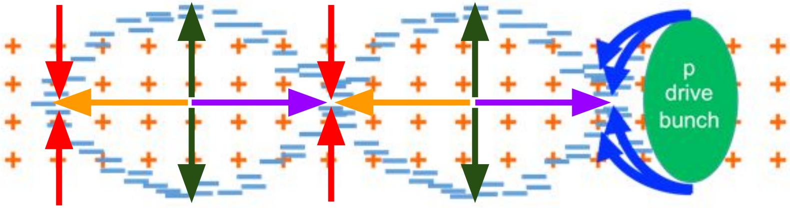

← accelerating for e$^-$

→ decelerating for e$^-$

↑ defocusing for e$^-$

↓ focusing for e$^-$

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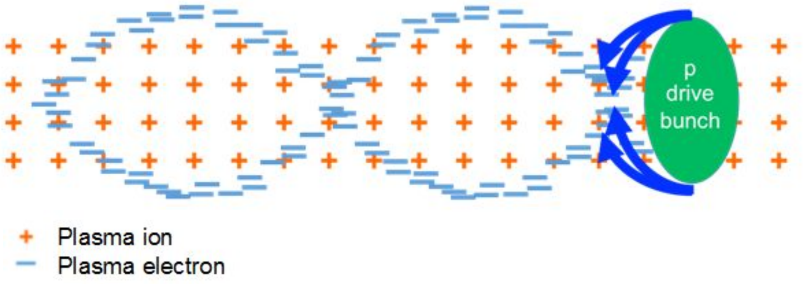
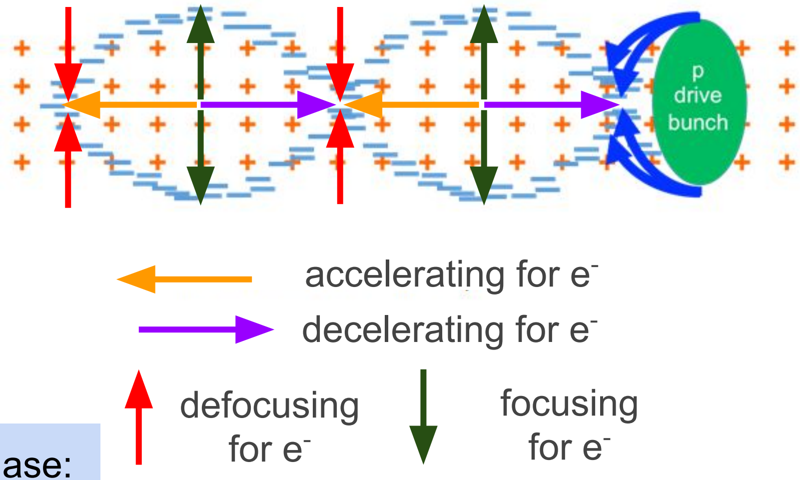
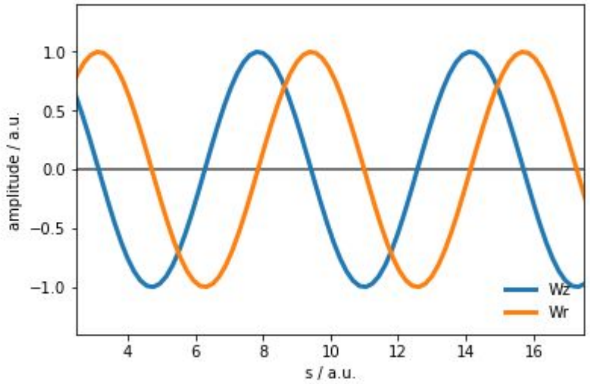
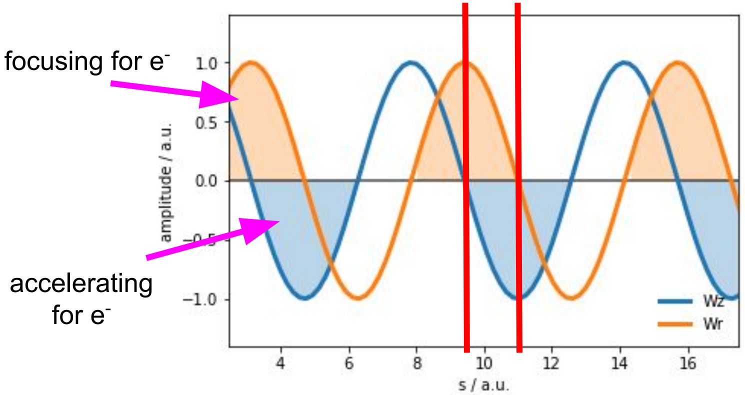
Introduction: Plasma Wakefield





Longitudinal and transverse wakefields are pi/2 out of phase:





only ¼ of the electron oscillation length is focusing and accelerating for charged particles

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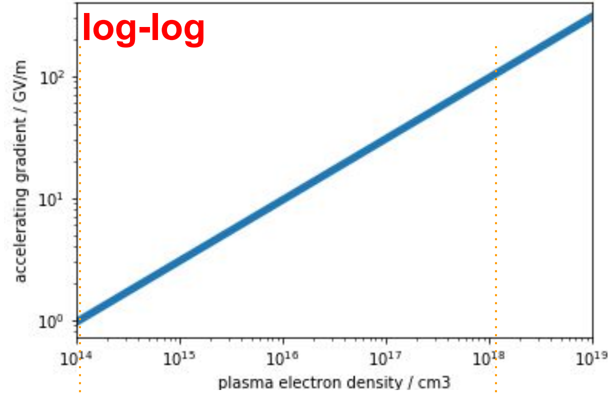
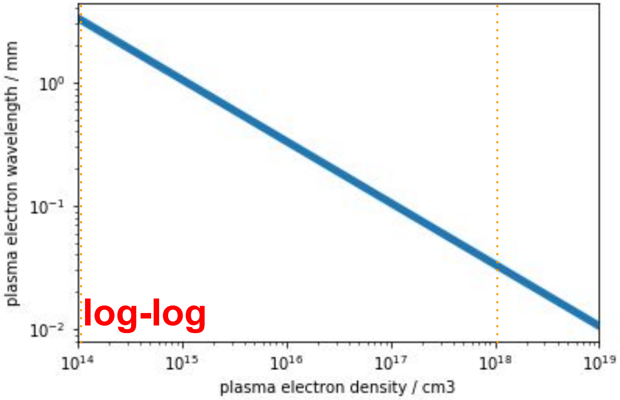
Scalings

the maximum **accelerating gradient** (E) increases with increasing plasma electron density.



$$eE \propto \sqrt{n_{pe}}$$

the **plasma electron wavelength** (λ_{pe}) decreases with increasing plasma electron density.



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

for $n_{pe} = 1e14/cm^3 \Rightarrow$ gradient: ~1 GV/m λ_{pe}: ~3.3 mm

for $n_{pe} = 1e18/cm^3 \Rightarrow$ gradient: ~100 GV/m λ_{pe}: ~33 um

Challenge: alignment!

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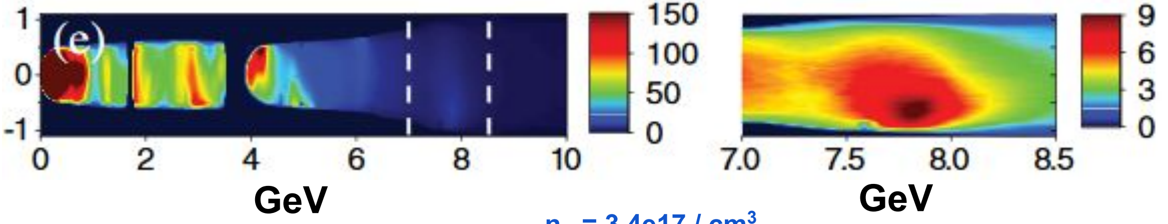
Some Previous Experimental Results...

E.g.:

- **7.8 GeV in 20 cm**
  10.1103/PhysRevLett.122.084801



n_{pe}= 3.4e17 / cm^3
acc. gradient = 39 GV/m

Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide

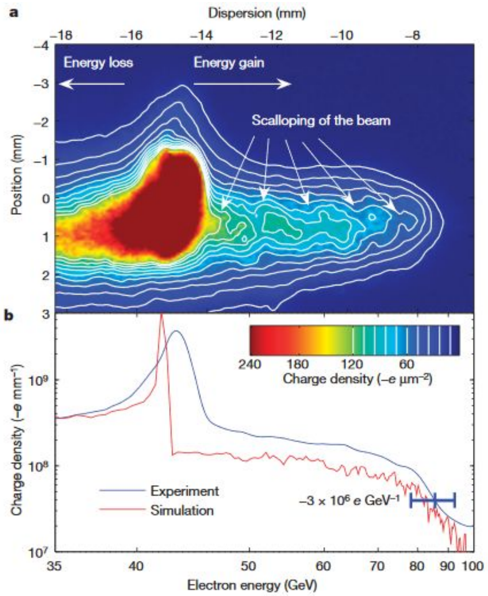
A. J. Gonsalves, K. Nakamura, J. Daniels, C. Benedetti, C. Pieronek, T. C. H. de Raadt, S. Steinke, J. H. Bin, S. S. Bulanov, J. van Tilborg, C. G. R. Geddes, C. B. Schroeder, Cs. Tóth, E. Esarey, K. Swanson, L. Fan-Chiang, G. Bagdasarov, N. Bobrova, V. Gasilov, G. Korn, P. Sasorov, and W. P. Leemans

- **42 GeV in 85 cm**
  10.1038/nature05538

LETTERS

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

Ian Blumenfeld[1], Christopher E. Clayton[2], Franz-Josef Decker[1], Mark J. Hogan[1], Chengkun Huang[2], Rasmus Ischebeck[1], Richard Iverson[1], Chandrashekhar Joshi[2], Thomas Katsouleas[3], Neil Kirby[1], Wei Lu[2], Kenneth A. Marsh[2], Warren B. Mori[2], Patric Muggli[3], Erdem Oz[3], Robert H. Siemann[1], Dieter Walz[1] & Miaomiao Zhou[2]



n_{pe} = 2.7e17 / cm3

acc. gradient = 52 GV/m

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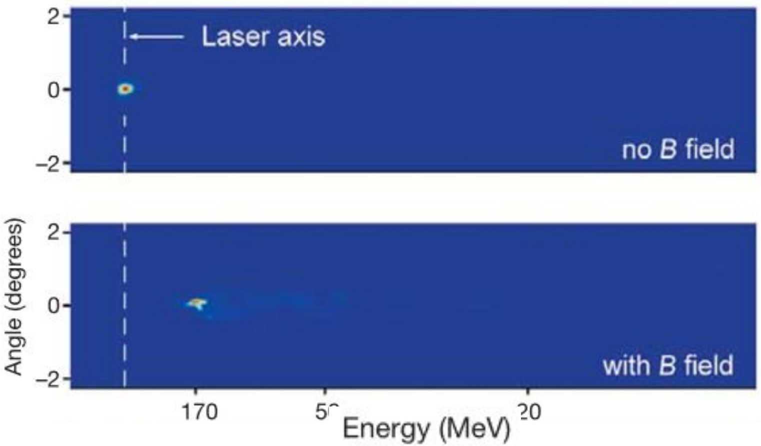
Some Previous Experimental Results...

E.g.:

- **production of monoenergetic beams**
  Nature **volume 431**, pages 541–544 (2004)

A laser–plasma accelerator producing monoenergetic electron beams

J. Faure[1], Y. Glinec[1], A. Pukhov[2], S. Kiselev[2], S. Gordienko[2], E. Lefebvre[3], J.-P. Rousseau[1], F. Burgy[1] & V. Malka[1]

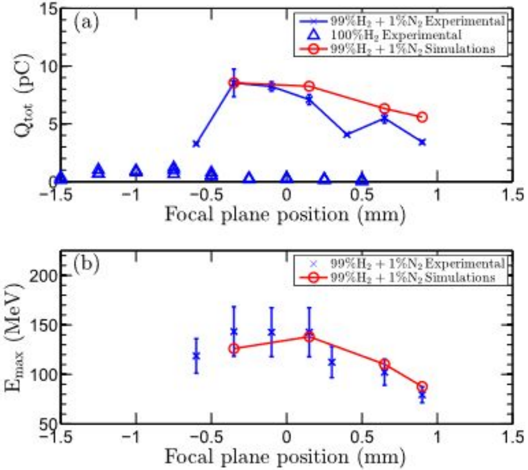


- **Beam quality / energy / charge optimization**
  For example: 10.1063/1.4942033

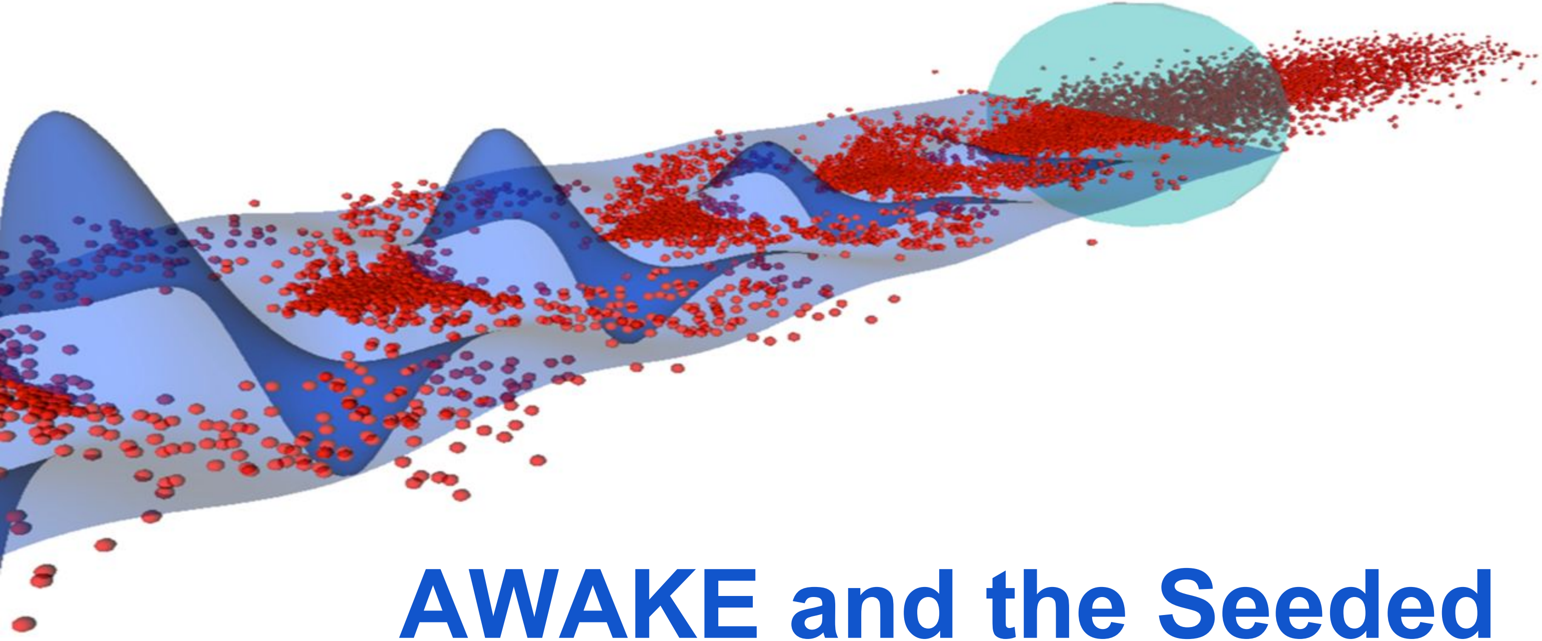
Investigation of ionization-induced electron injection in a wakefield driven by laser inside a gas cell

T. L. Audet,[1,a)] M. Hansson,[2] P. Lee,[1] F. G. Desforges,[1] G. Maynard,[1] S. Dobosz Dufrénoy,[3] R. Lehe,[4] J.-L. Vay,[4] B. Aurand,[2] A. Persson,[2] I. Gallardo González,[2] A. Maitrallain,[3] P. Monot,[3] C.-G. Wahlström,[2] O. Lundh,[2] and B. Cros[1,b)]

[1] *Laboratoire de Physique des Gaz et des Plasmas, CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France*
[2] *Department of Physics, Lund University, P.O. Box 118, S-22100 Lund, Sweden*
[3] *Laboratoire Interactions, Dynamique et Lasers, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France*
[4] *Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*



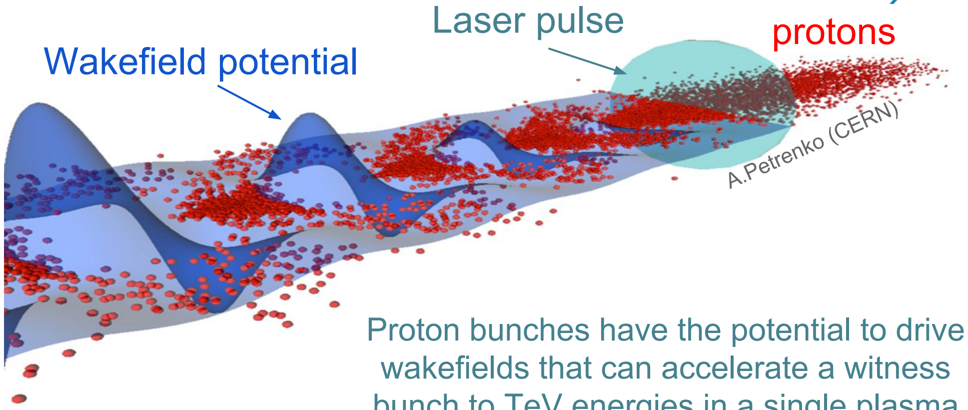
et al.



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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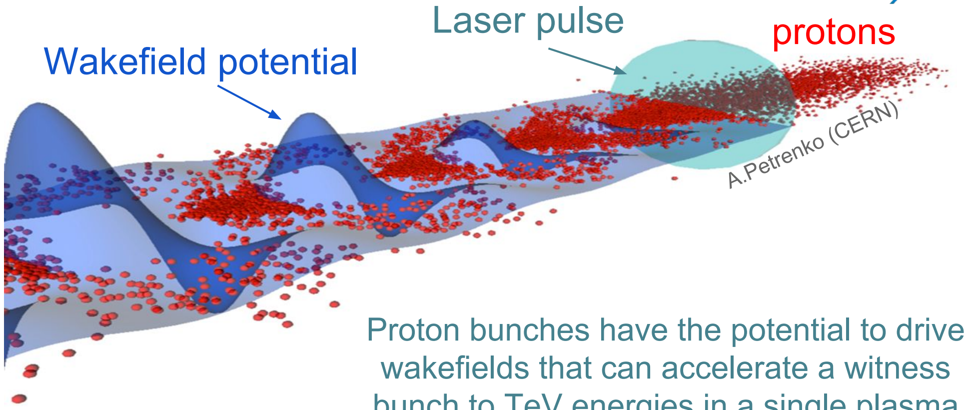

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Caldwell A *Nature Physics* **volume 5**, pages 363–367 (2009)

10m Rb vapor cell

Developed by MPP

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AWAKE Collaboration

AWAKE Collaboration: 19+2 Institutes world-wide:

Collaboration members:
University of Oslo, Oslo, Norway
CERN, Geneva, Switzerland
University of Manchester, Manchester, UK
Cockcroft Institute, Daresbury, UK
Lancaster University, Lancaster, UK
Max Planck Institute for Physics, Munich, Germany
Max Planck Institute for Plasma Physics, Greifswald, Germany
UCL, London, UK
UNIST, Ulsan, Republic of Korea
Philipps-Universität Marburg, Marburg, Germany
Heinrich-Heine-University of Düsseldorf, Düsseldorf, Germany
University of Liverpool, Liverpool, UK
ISCTE - Instituto Universitéario de Lisboa, Portugal
Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
Novosibirsk State University, Novosibirsk, Russia
GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
TRIUMF, Vancouver, Canada
Ludwig-Maximilians-Universität, Munich, Germany
Wigner Institute, Budapest
University of Wisconsin, Madison, US
Swiss Plasma Center group of EPFL

Associated members:
University of Texas
Helmholtz Institut Jena

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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)**:**

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

⇒ 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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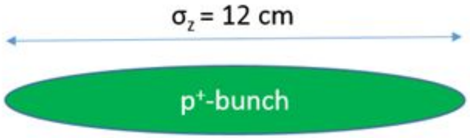
CERN SPS proton bunch: very long!

Longitudinal beam size ($\boldsymbol{\sigma_z = 6\text{-}12\ \mathrm{cm}}$) is much longer than plasma wavelength **($\boldsymbol{\lambda_{pe} = 1\ \mathrm{mm},\ n_{pe} = 7 \times 10^{14}\ e^-/\mathrm{cm}^3}$)**

⇒ Seeded Self-Modulation (SSM)

Before self modulation:



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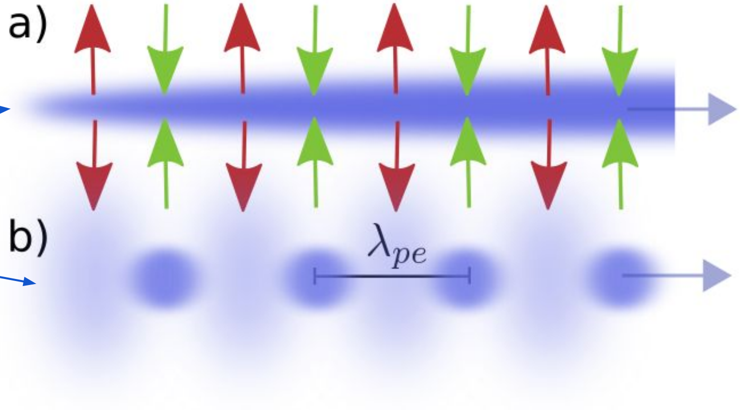
The seeded self-modulation

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 ∝ n_b.
3) **Density modulation** on axis (Micro-bunches).

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



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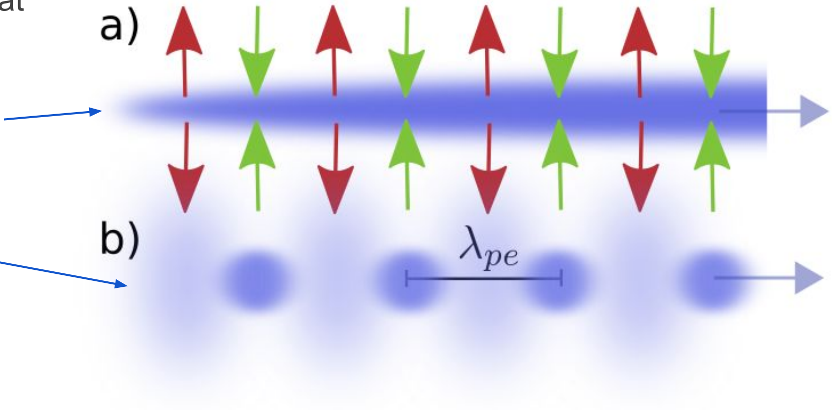

We **seed** the instability by:

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

⇒ **Seeded self-modulation (SSM)**

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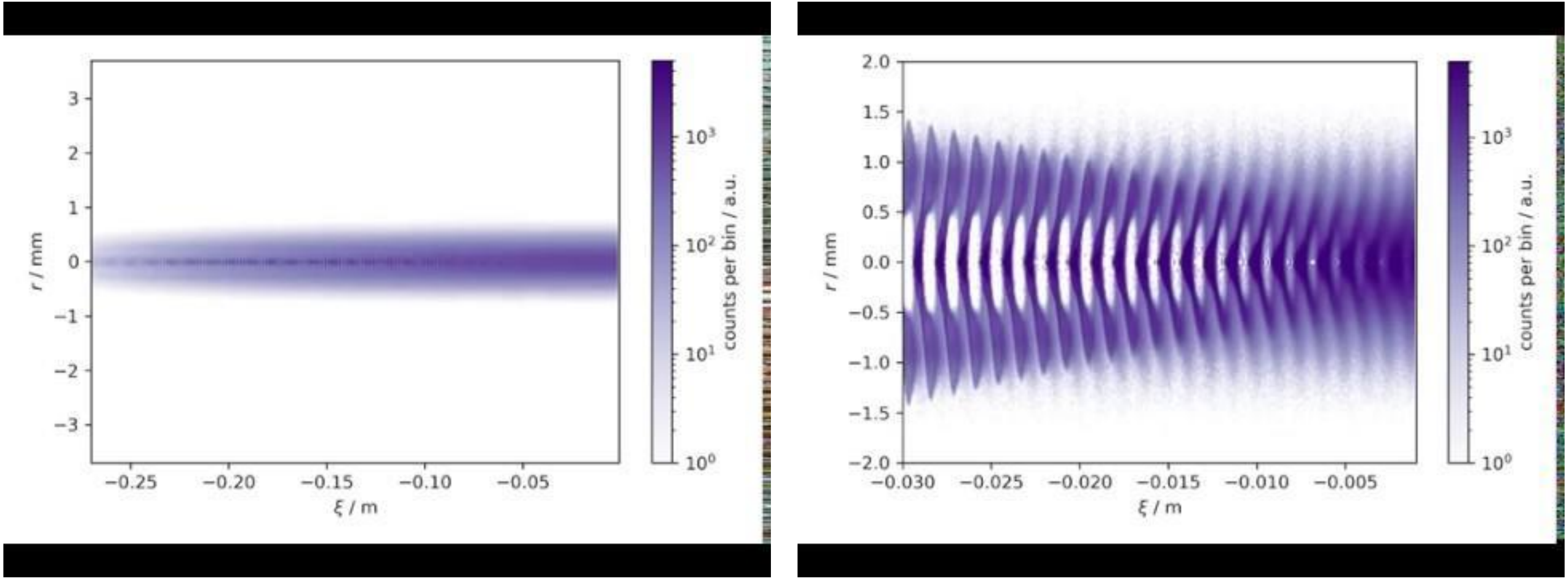
The seeded self-modulation

simulation of the AWAKE proton bunch propagating over 10 m of plasma with a plasma electron density of npe = 7e14/cm^3; rms bunch length ~100 λ_{pe}

LCODE (2D cylindrical quasi-static) simulation result

simulation box

zoom (seed position ξ = 0)



Logarithmic color scale!!

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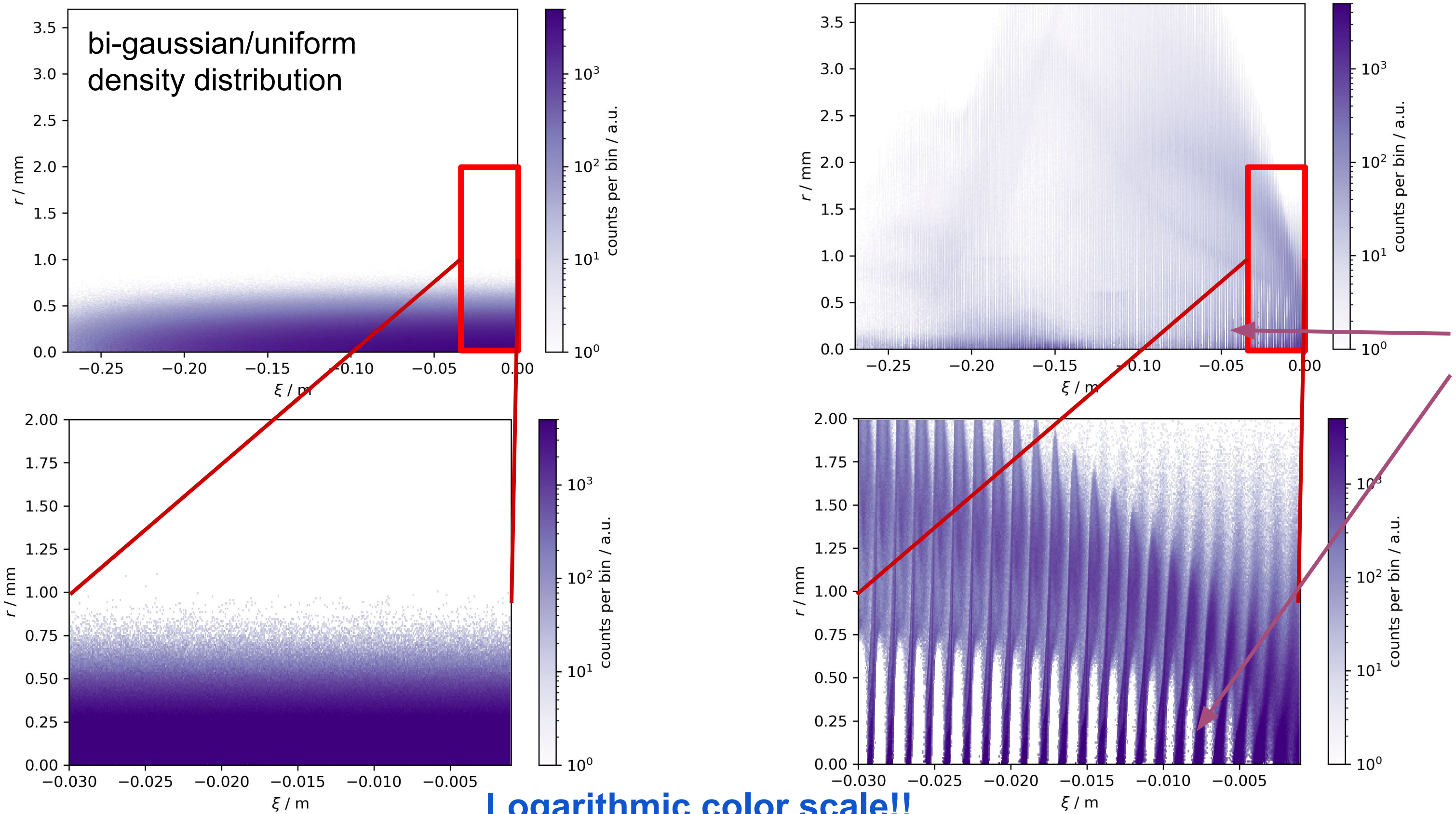
The seeded self-modulation


at z = 0 m (beginning of the plasma)

at z = 10 m (end of the plasma)

bi-gaussian/uniform density distribution

transverse proton motion

longitudinal micro-bunch structure of the beam density

Logarithmic color scale!!

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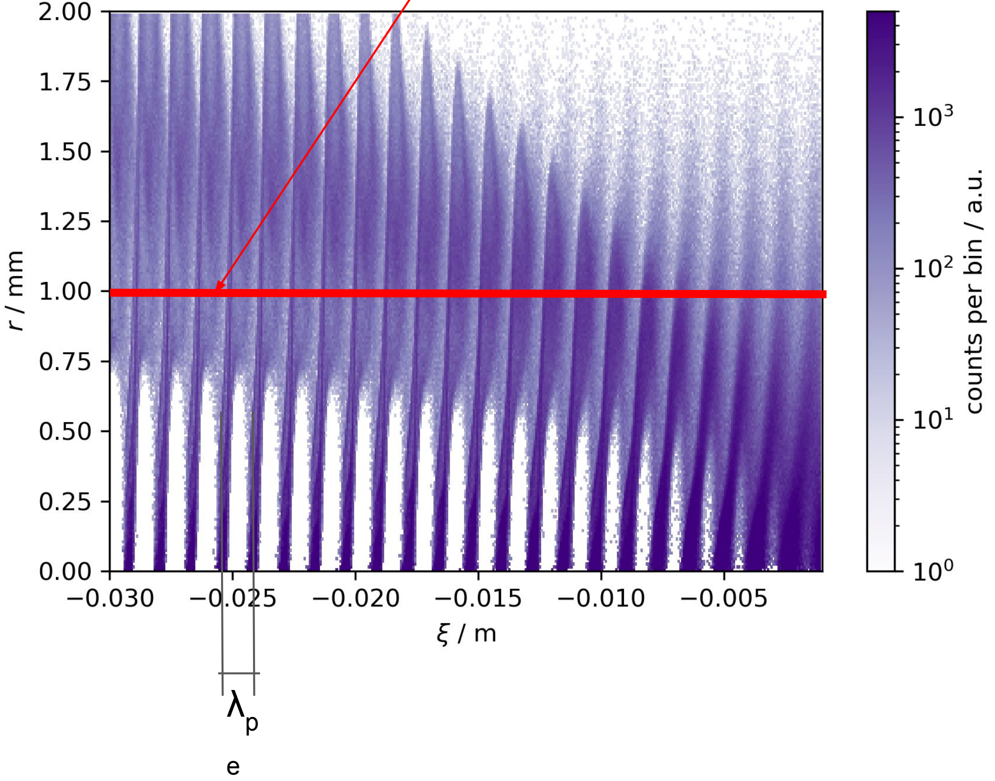
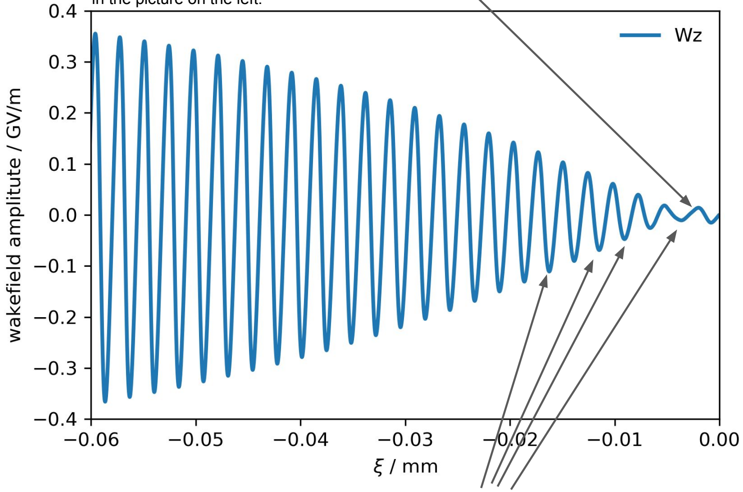
The seeded self-modulation



Transverse extent of the plasma

Each micro-bunch drives its own 'low-amplitude' wakefield



Disclaimer: simulation parameters different than in the picture on the left.

Since microbunches are spaced at λ_{pe}, wakefield amplitudes add along the bunch.

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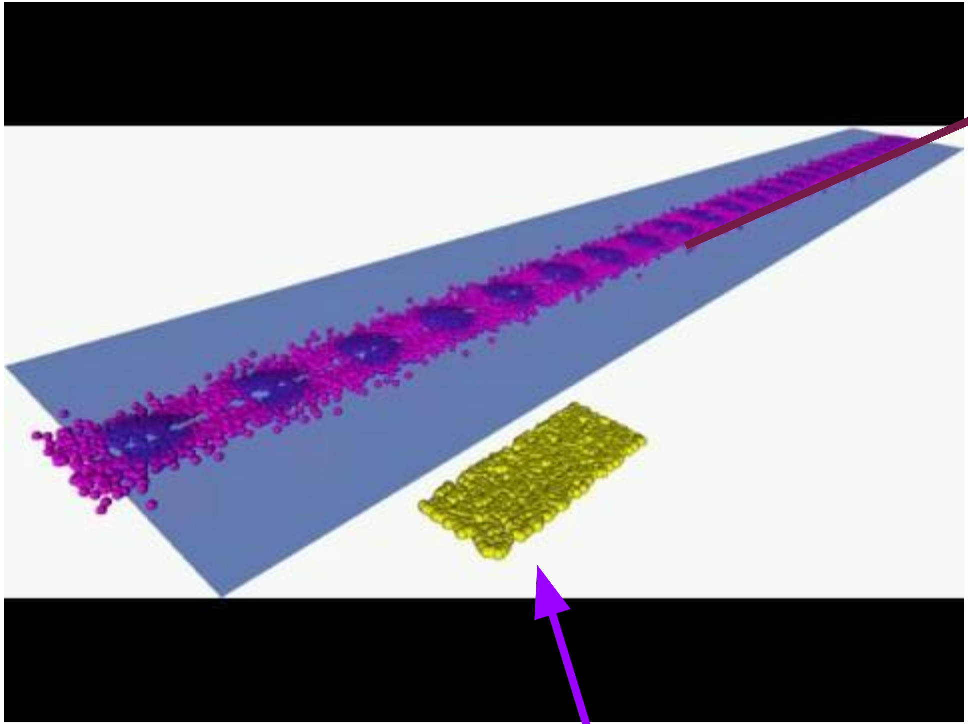
Electron acceleration



front of the bunch

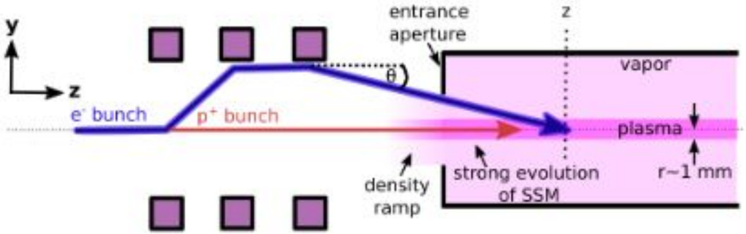
🟦 plasma and wakefield potential

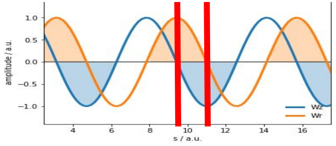
🟪 protons (drive bunch)

🟨 electrons (witness bunch)

Proof-of-principle experiment:
Inject a bunch much longer than $\lambda_{pe}/4$

Inject electrons from the side:
wakefield phase not stable during self-modulation.





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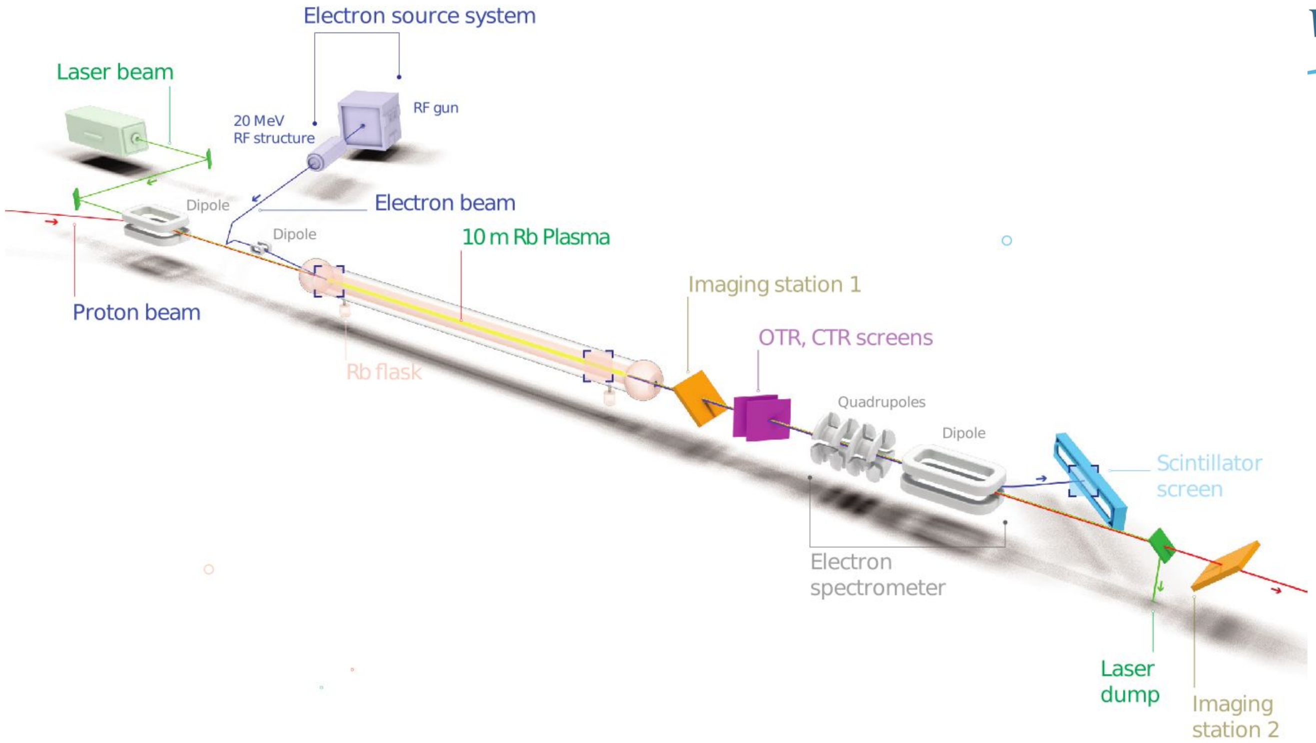
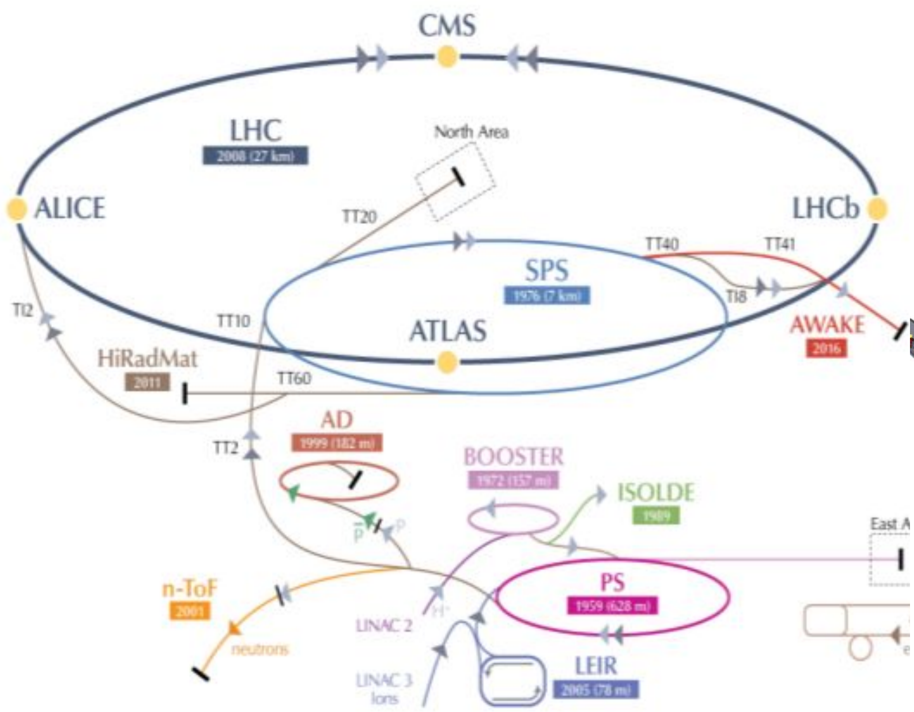


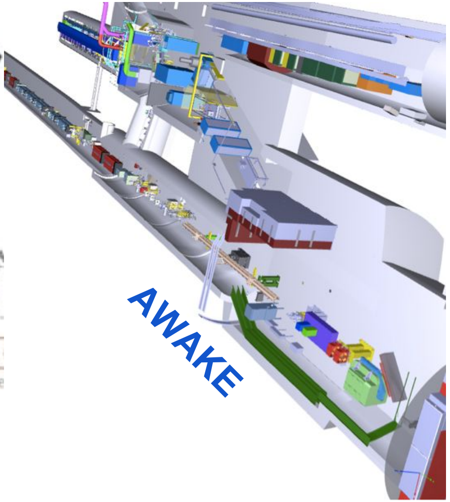
The AWAKE experimental setup

The AWAKE Experiment at CERN



CERN accelerator complex

- SPS proton bunch **momentum**: 400 GeV/c
- $3x10^{11}$ 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

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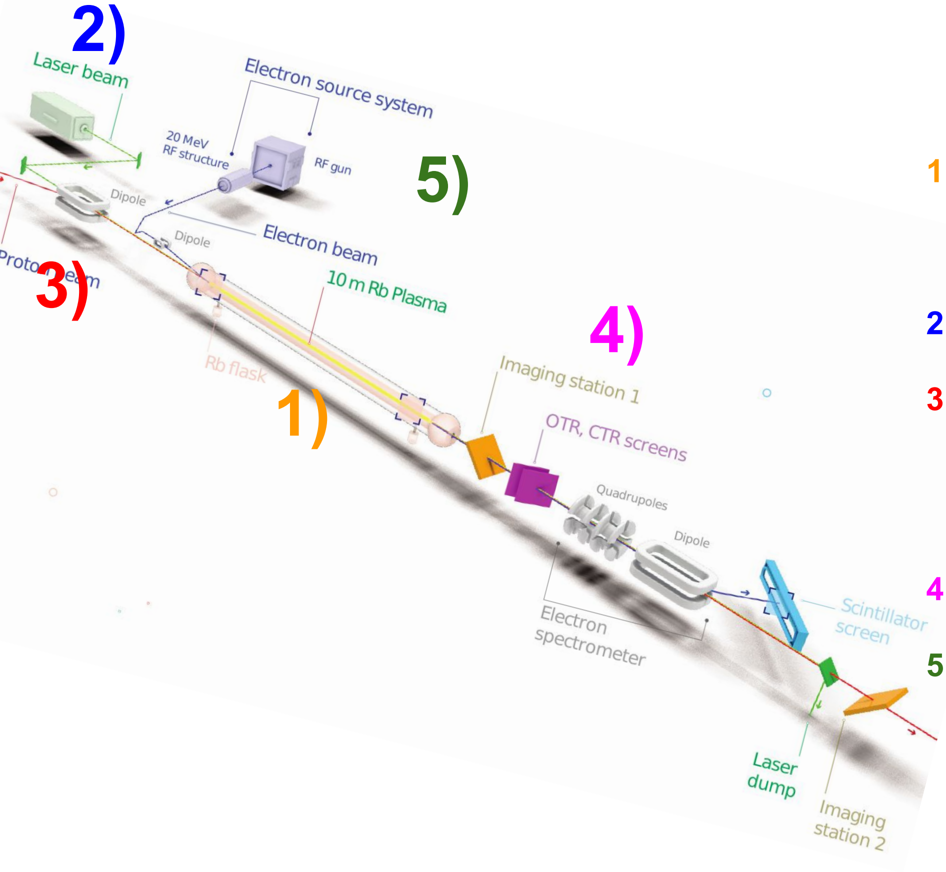
The AWAKE experimental setup



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 3×10^{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.

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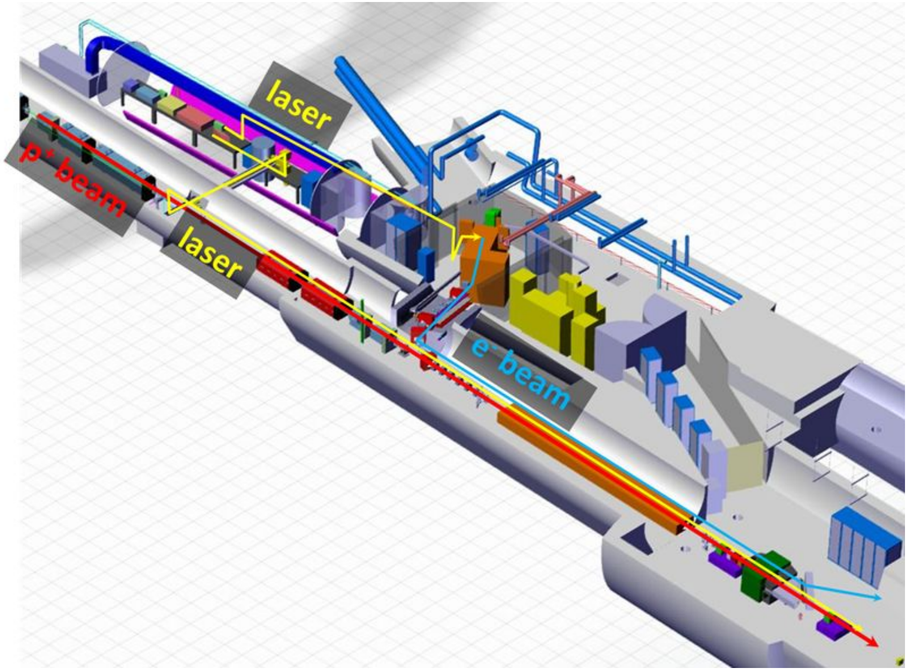
The AWAKE experimental setup



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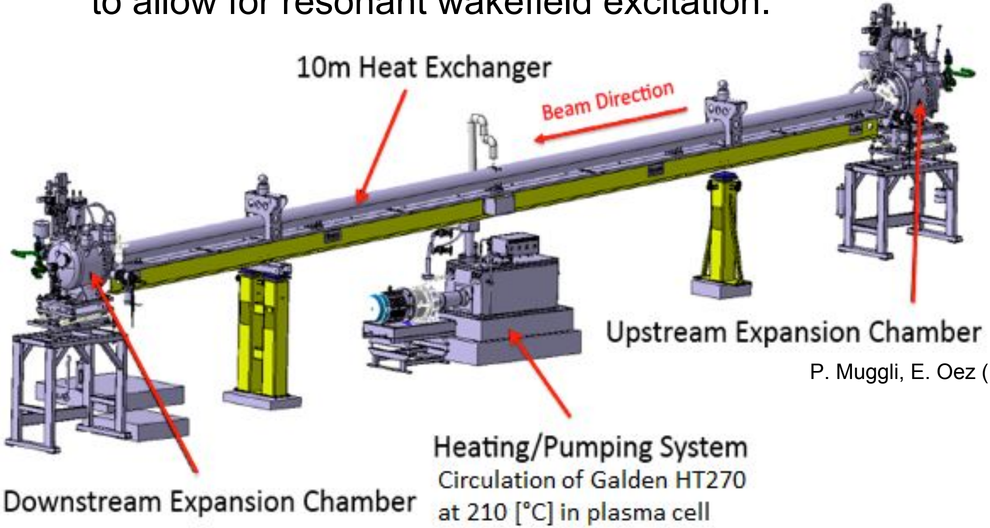
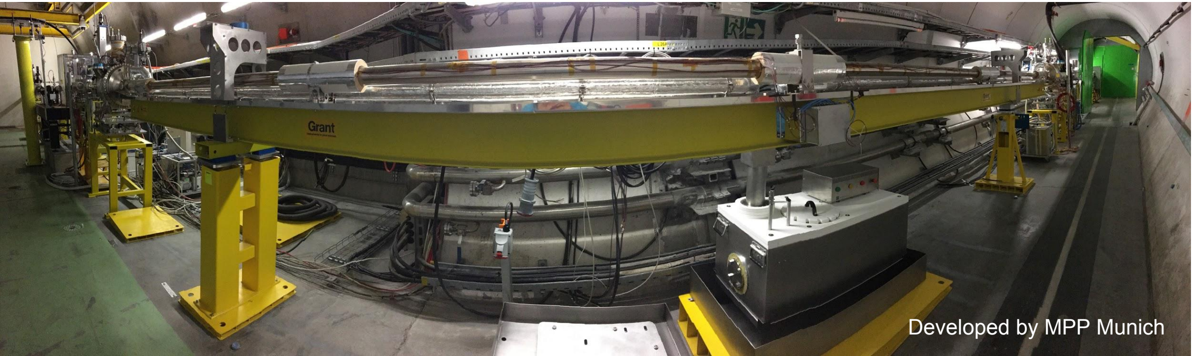
The AWAKE plasma

challenge: plasma density uniformity better than 0.2% over 10m to allow for resonant wakefield excitation.



P. Muggli, E. Oez (MPP)

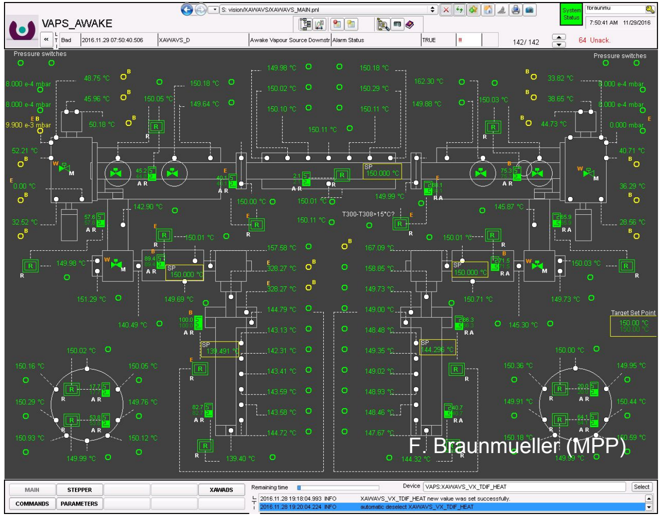


Developed by MPP Munich

Fluid heated vapor source:

- laser pulse ionized rubidium vapor
- Control the vapour density by precisely controlling the temperature to <0.1 K.
- 79 temperature probes.

Control system for the vapour cell



```
2016.11.28 19:18:04.993 INFO    XAWAVS_VX_TDIF_HEAT new value was set successfully.
2016.11.28 19:20:04.224 INFO    automatic deselect XAWAVS_VX_TDIF_HEAT
```

F. Braunmueller (MPP)

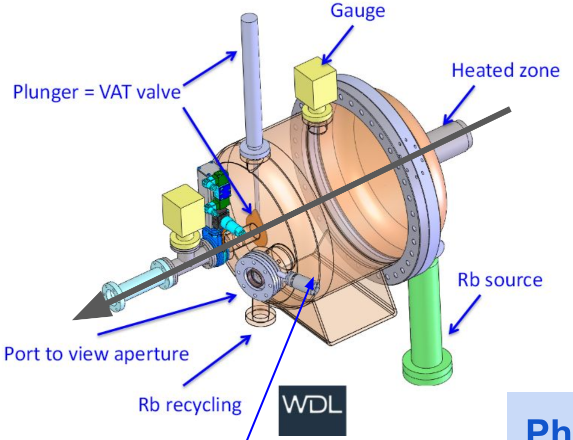
M. Turner et al.

Plasma entrance and exit

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).

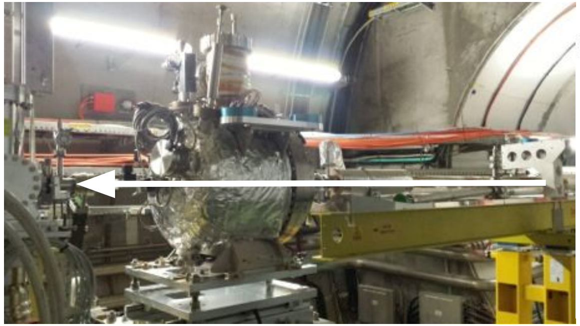
Solution: Cold expansion chambers with an open flow - the rubidium condenses on a cold surface.
⇒ not good, but acceptable (verified by simulations)

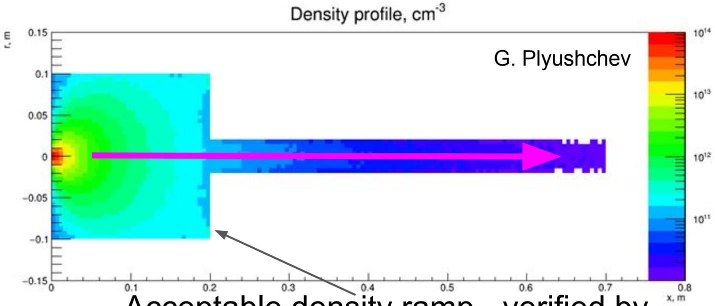
Rubidium expansion chambers:



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

Expansion chambers installed in AWAKE





Acceptable density ramp - verified by plasma simulations

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.

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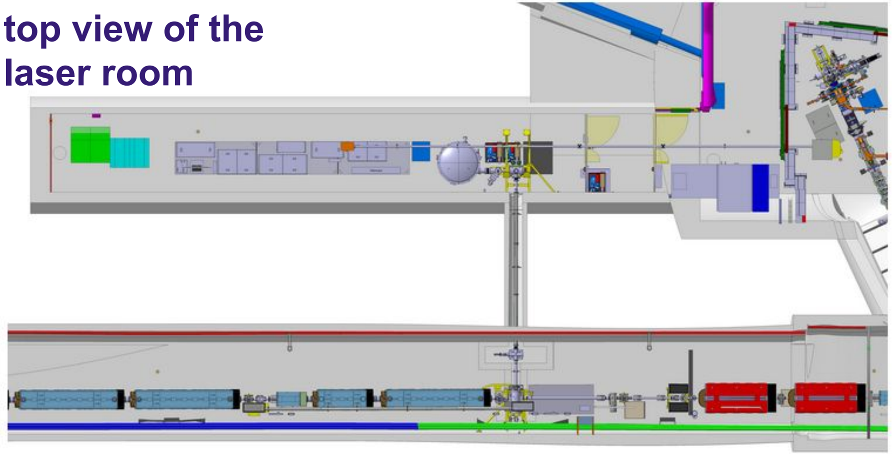
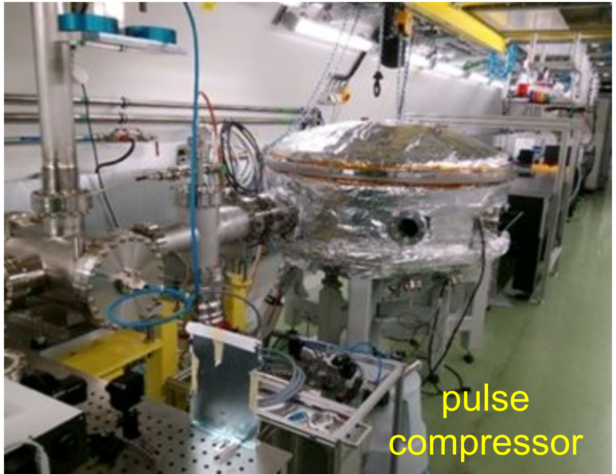
The AWAKE LASER

top view of the laser room



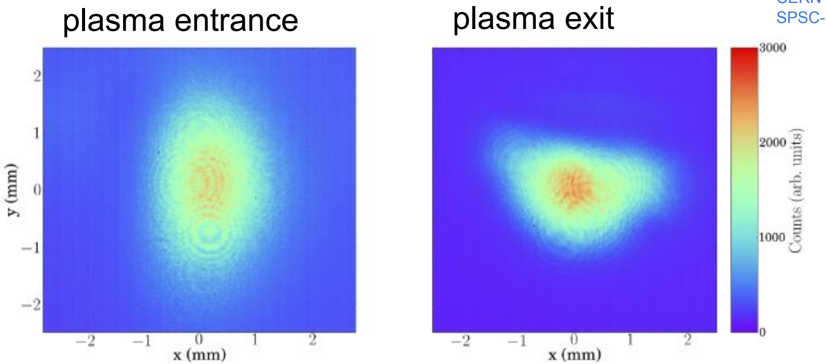


Ti:Sapphire laser focused to a peak intensity of ~1.2×10^{14} W/cm^2 with a spot with radius 1 mm and propagate with a Rayleigh length of ~5 m. This laser:

1) ionizes the Rb vapor
2) supplies the UV pulse for the photocathode
3) Supplies the marker laser for self-modulation studies

Fiber/Ti:Sapphire Laser				
Central Wavelength	λ_0	780	-	nm
Bandwidth	$\Delta\lambda_0$	±5	-	nm
Pulse Length	τ_0	120	-	fs
Max. Compressed Energy	$E_{\max}$	450	-	mJ
Focused Size	r_l	1	-	mm
Rayleigh Length	Z_r	5	-	m

images and table from: CERN-SPSC-2017-039 / SPSC-SR-222

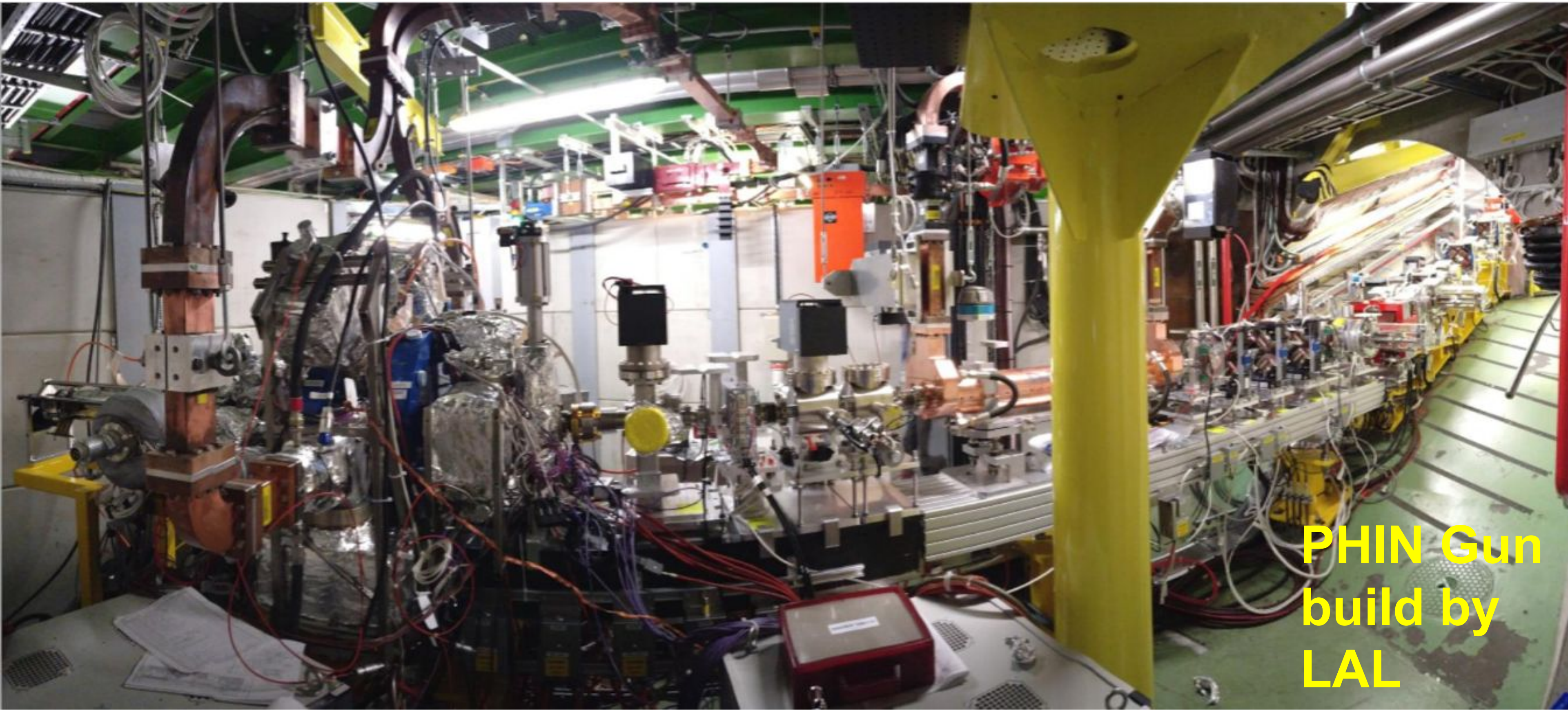

plasma entrance

plasma exit

t al.

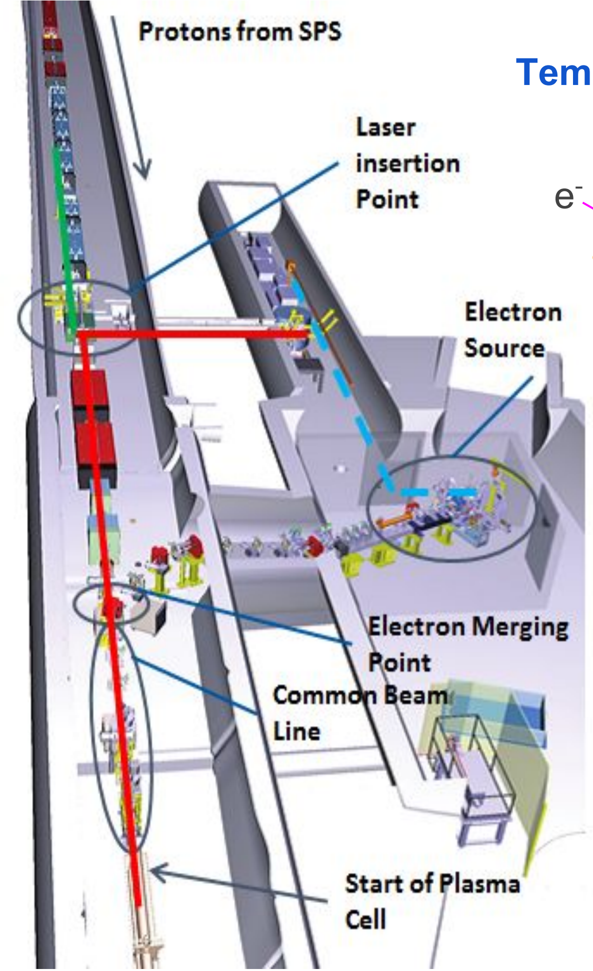
The AWAKE Electron Bunch

2-½ cell photoinjector with an RF linac; E~10-20 MeV;σ_z ~4ps; bunch charge: 0.1-0.6nC

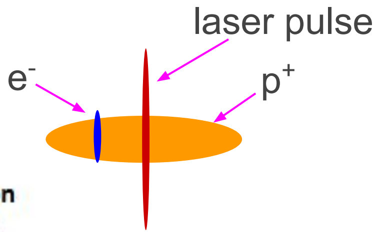


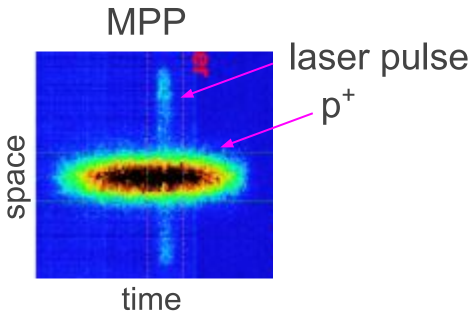
PHIN Gun build by LAL

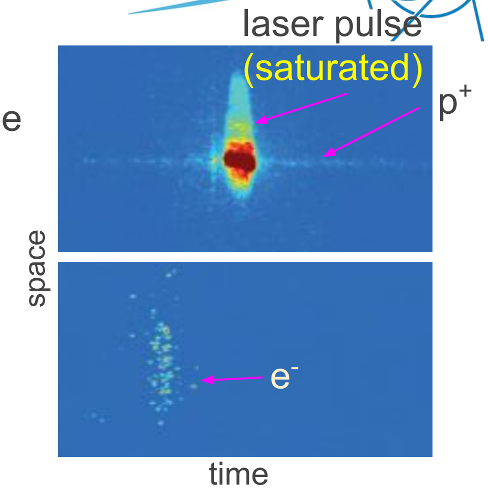
Alignment of p^+, e^- and laser pulse



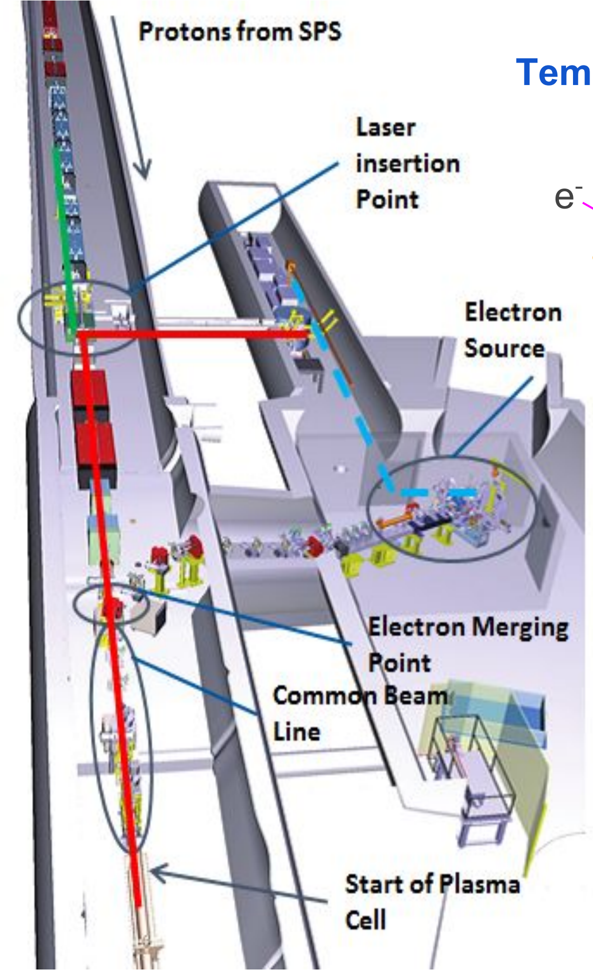
Temporal alignment:



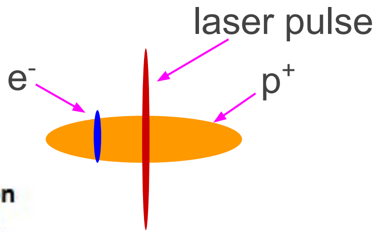


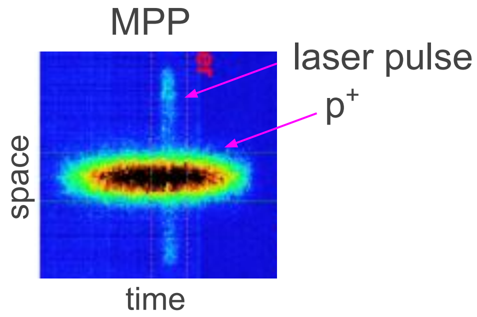


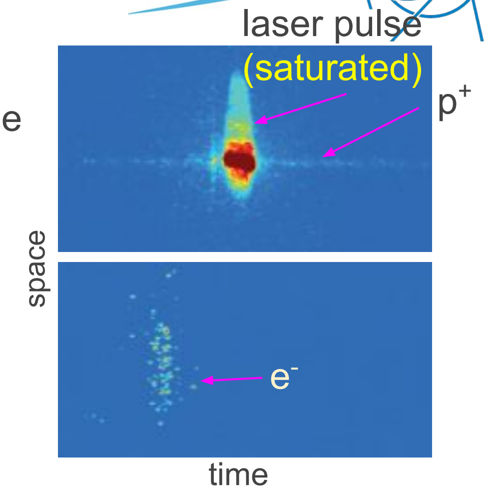
Alignment of p^+, e^- and laser pulse



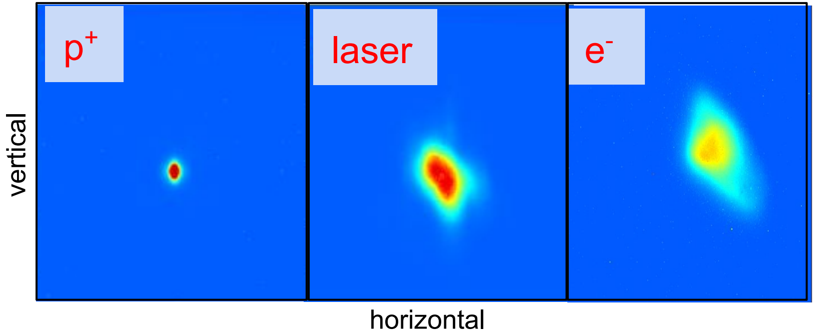
Temporal alignment:







Spatial alignment:



~2m upstream
the plasma
entrance

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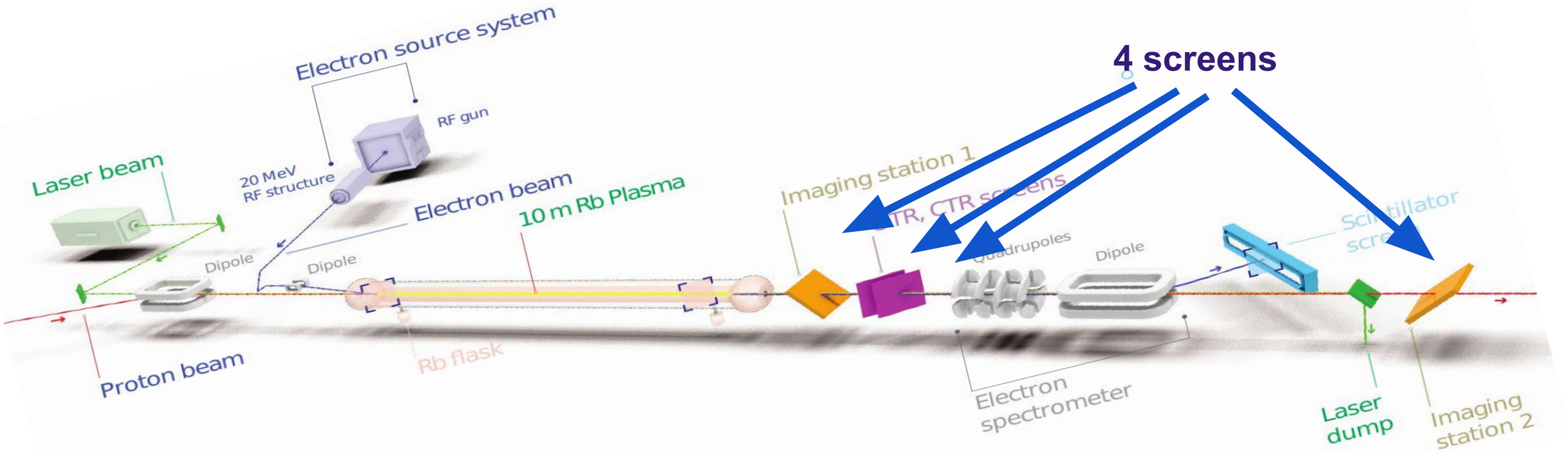
Diagnostics

To **characterize** the proton bunch downstream the plasma we insert screens into the proton bunch path:



time-structure of the proton bunch:

1 metallic foil ⇒ image Optical Transition Radiation (OTR) onto the slit of a streak camera

transverse (time-integrated) bunch profile:

2 scintillating (Chromox) screens ⇒ image the light onto 4 cameras

micro-bunch frequency:

1 metallic foil ⇒ measure the Coherent Transition Radiation (CTR) using diodes and heterodyne mixing system

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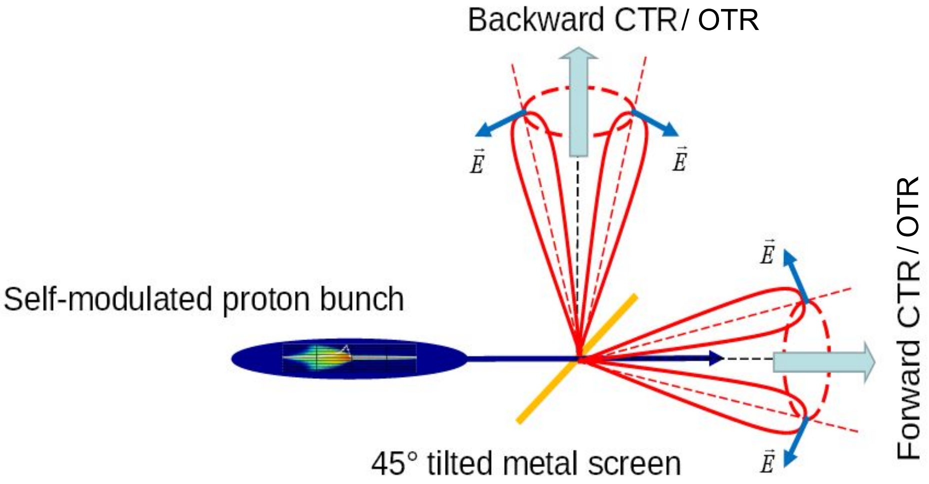
Diagnostics: Streak camera

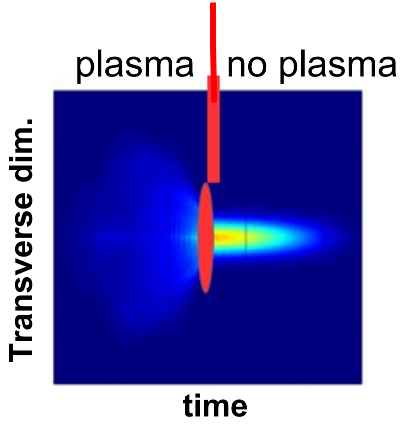
To study the Seeded Self-Modulation

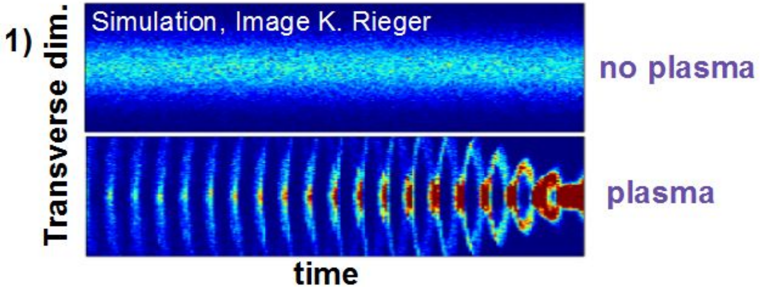


emission of waves up to the plasma wavelength of the foil:

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

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

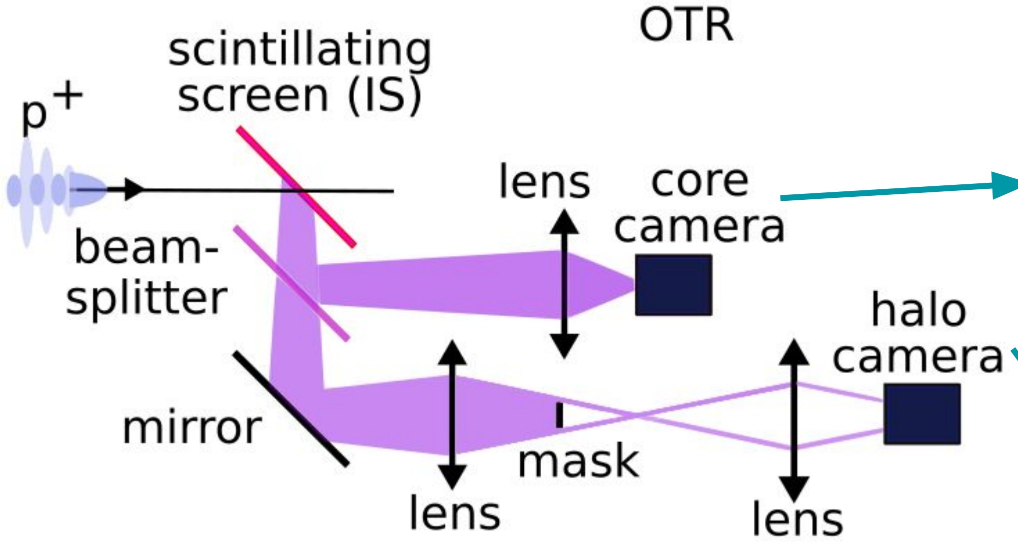




K. Rieger, PhD Thesis (in progress)

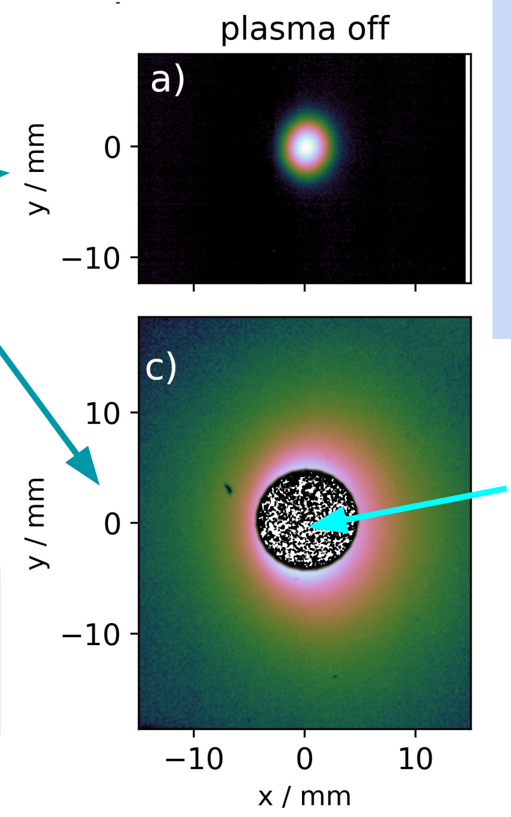
Diagnostics: Imaging Stations

2m and 10m downstream the end of the plasma



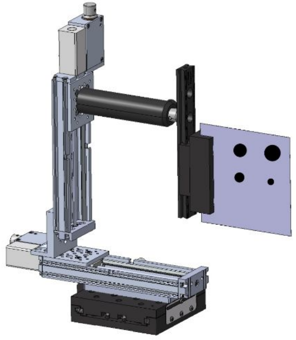
goal: detect protons that got defocused by the plasma wakefields.

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



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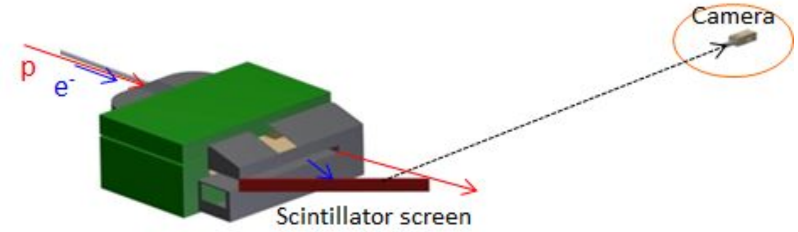
M. Turner, PhD Thesis (2018)

The electron spectrometer

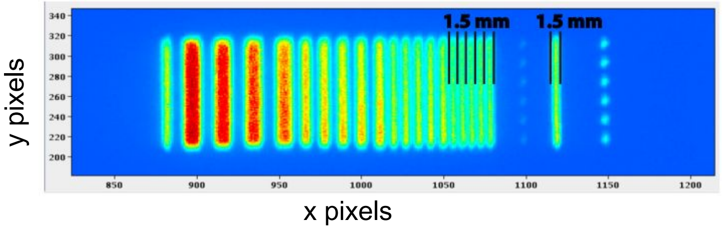
accelerated electrons are sent through an imaging **spectrometer** and deposit energy on a **scintillating screen** which is imaged by a camera.



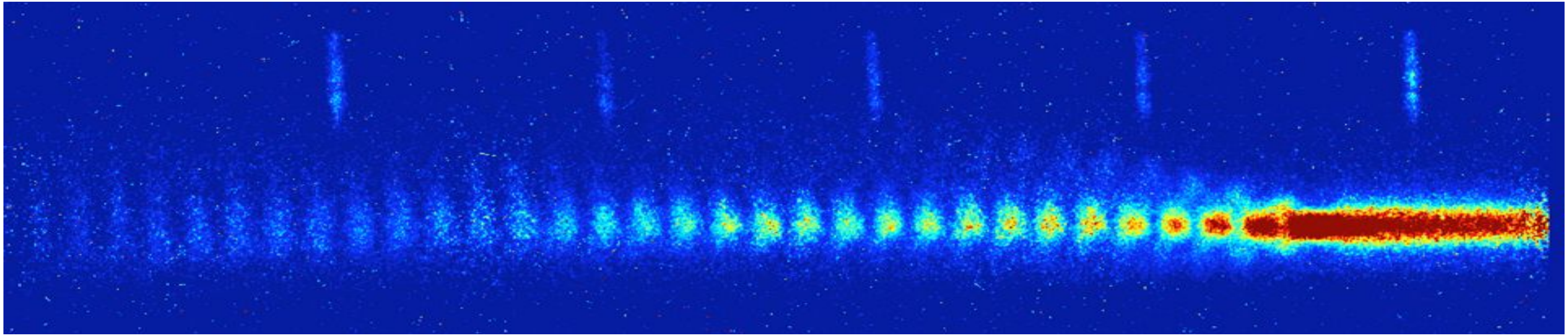
B = 0.1 - 1.5 T
magnetic length = 1m

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

Calibration image of the spectrometer



See Keeble F et al., The AWAKE electron Spectrometer, IPAC 2018

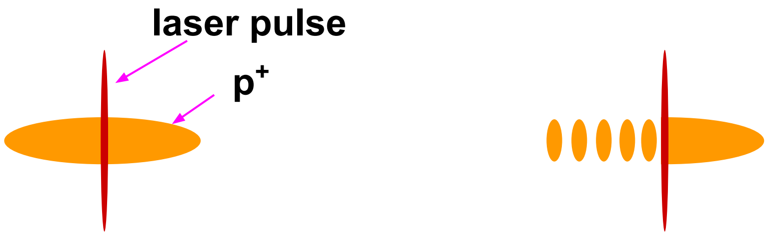


Latest AWAKE Results

M. Turner et al.

The AWAKE experiment (Run 1)

1. **self-modulate** a long (compared λ_{pe}) 400 GeV/c proton bunch in plasma (2016-2017).



M. Turner et al.

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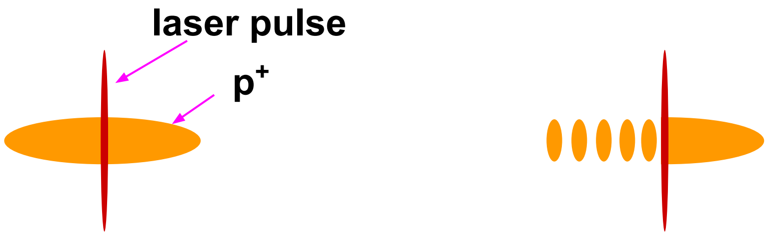

2. **accelerate** externally injected 10- 20 MeV electrons to GeV energies (2018).

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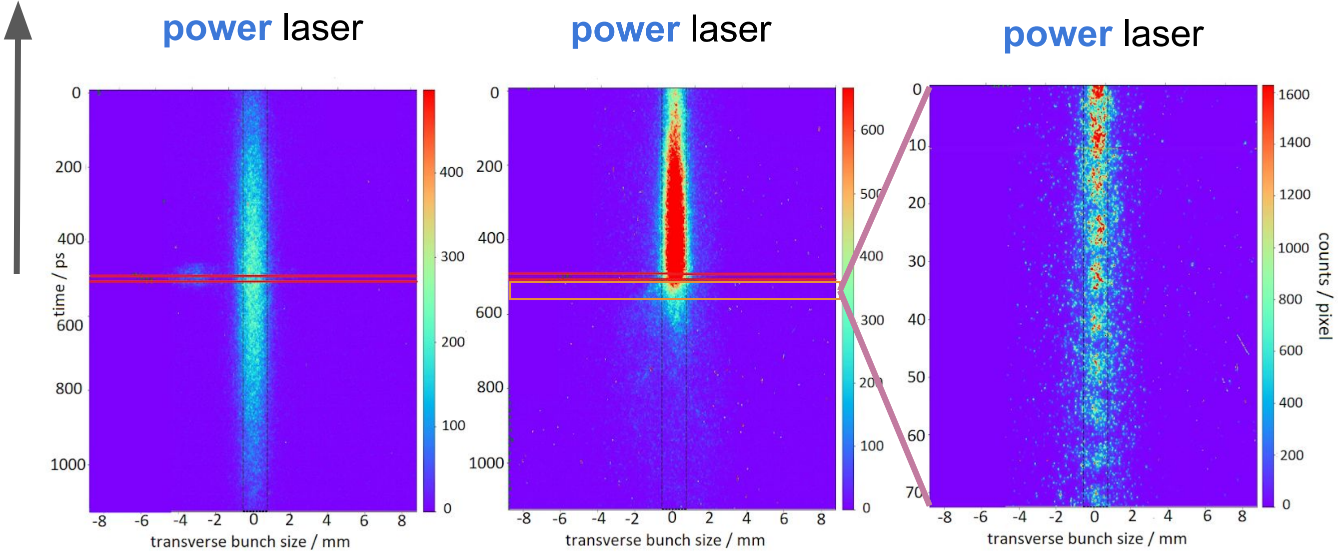
Seeded Self-Modulation


Protons and **low power** laser

Protons and **high power** laser

Protons and **high power** laser

$n_{pe} = 2.1e14/cm^3$

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

AWAKE Collaboration Phys. Rev. Lett. 122, 054802

M. Turner et al.

The AWAKE experimental team

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

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Seeded Self-Modulation

marker laser

- ☐ **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.

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Seeded Self-Modulation

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

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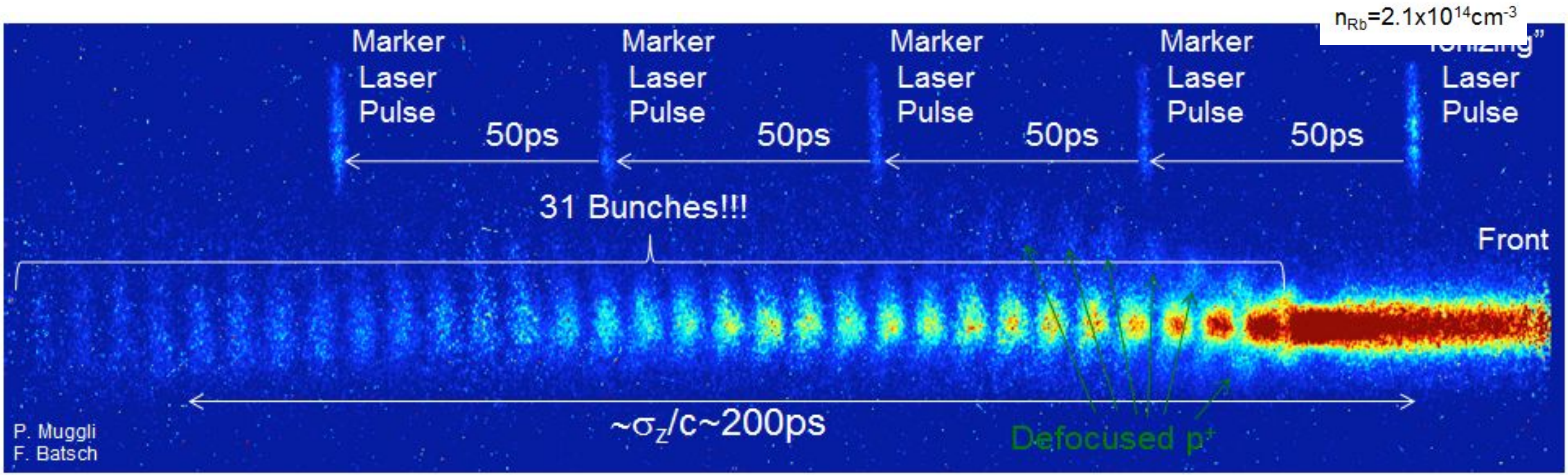
Seeded Self-Modulation



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

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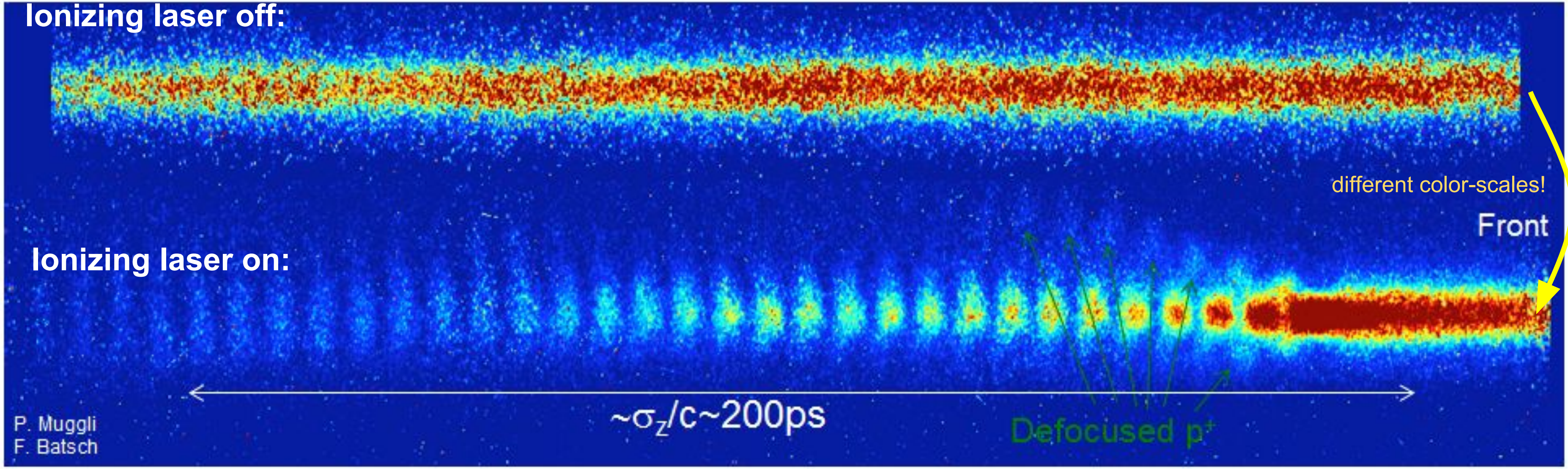
Seeded Self-Modulation

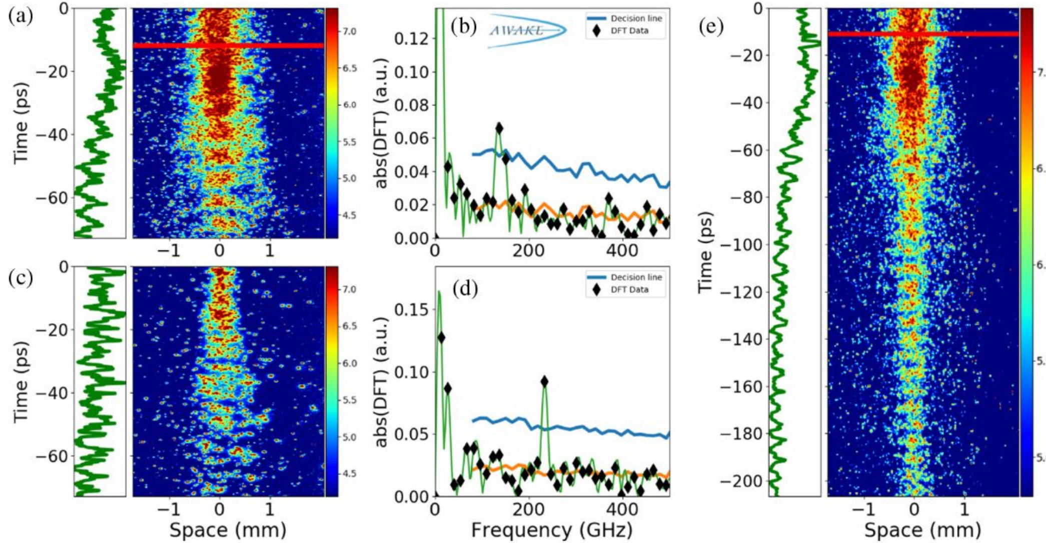


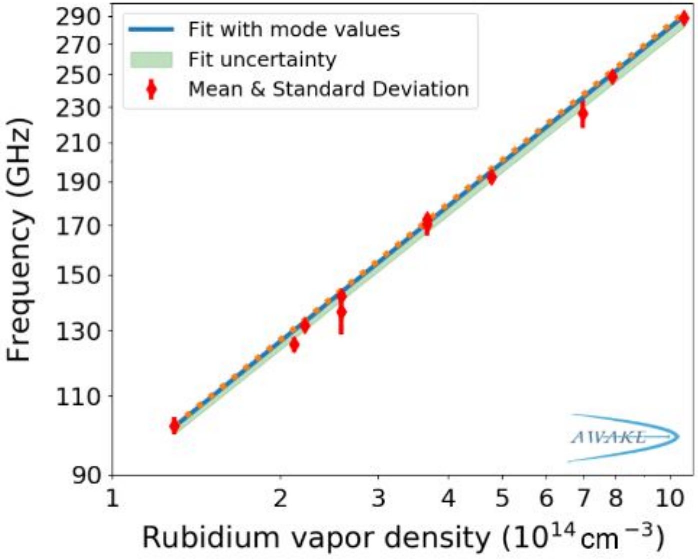
P. Muggli
F. Batsch

- **Micro-bunches** present over long time scale from seed point
- “Stitching” demonstrates **reproducibility** of the micro-bunch process against bunch parameters variations ($N=2.5\times10^{11}\pm10\%$, $s_{zt}=220\pm10$ps, s_r)
- **Phase stability** essential for e^- external injection!

M. Turner et al.

The Physics Properties of the Seeded Self-Modulation





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

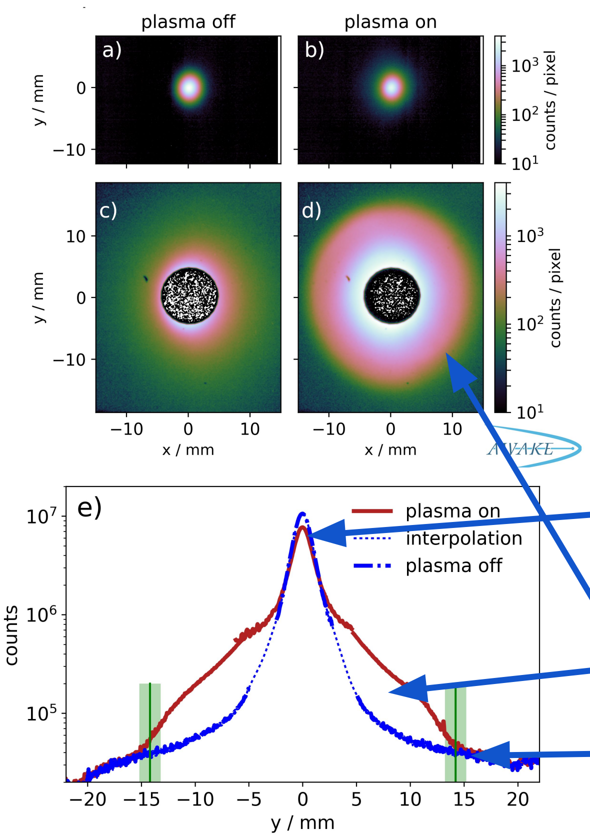
Demonstrate that:

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

M. Turner et al.

AWAKE Collaboration Phys. Rev. Lett. 122, 054802

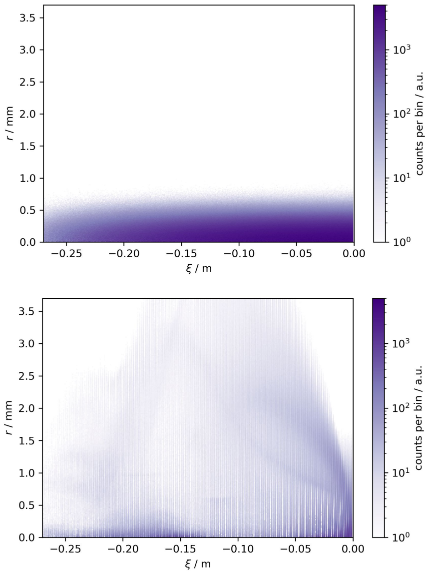
The Physics Properties of the Seeded Self-Modulation



charge in the core decreases

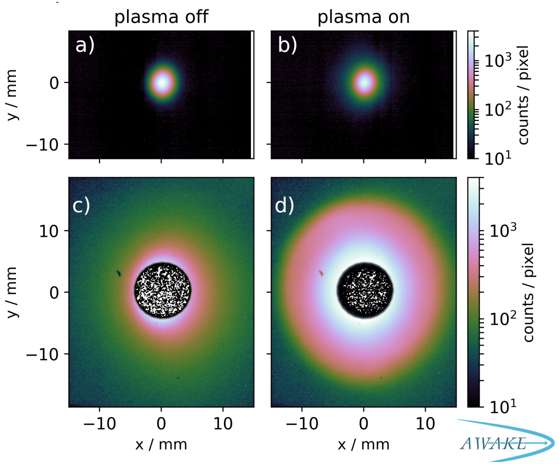
charge in the halo increases

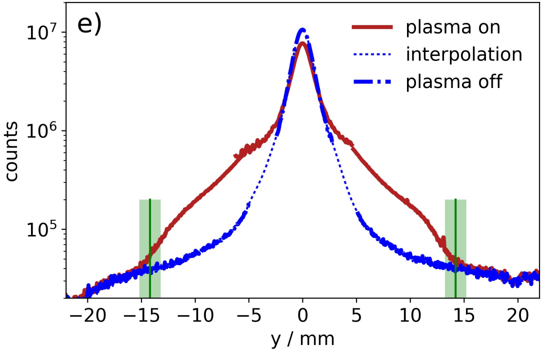
identify a maximum radius of defocused protons



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

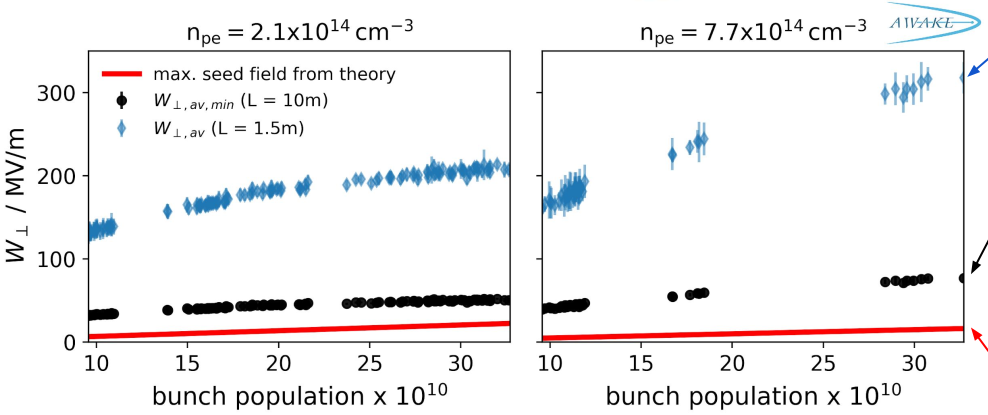
The Physics Properties of the Seeded Self-Modulation





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

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



Assuming the protons interact with the plasma over 1.5 m and exit after 4m (most realistic)

Assuming the protons interact with the plasma over 10 m (worst case)

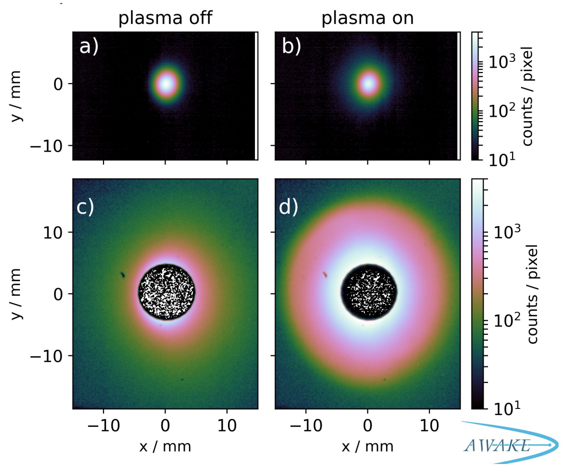
Max. seed field amplitude (from theory)

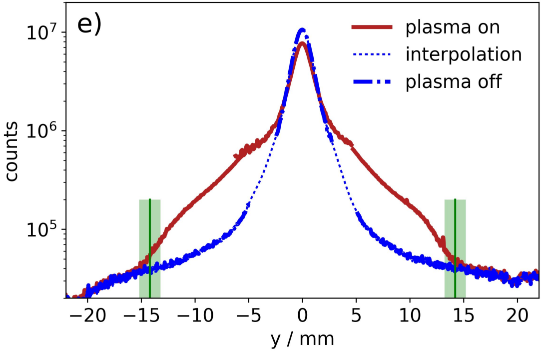
average field amplitudes much higher than the initial seed field amplitudes ⇒ proof of wakefield growth due to self-modulation along the plasma

M. Turner et al.

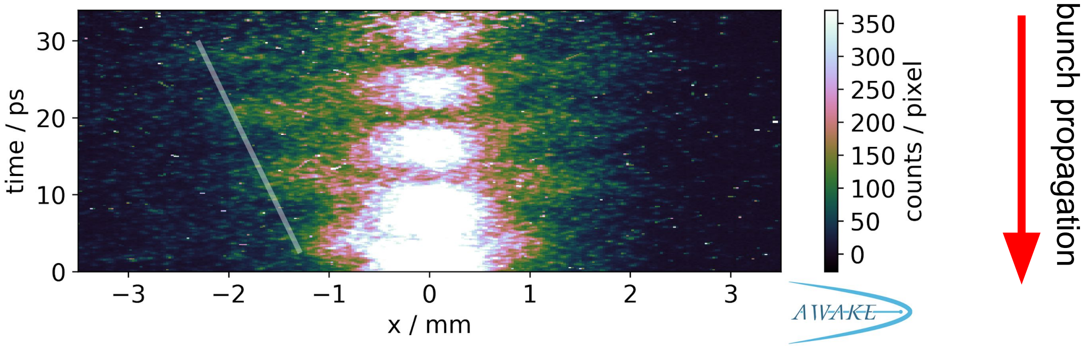
M. Turner *et al.* (AWAKE Collaboration); Phys. Rev. Lett. 122, 054801

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

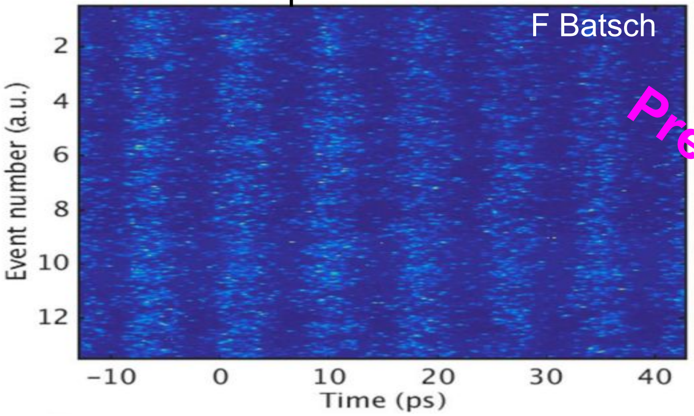
M. Turner et al.

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

Other Studies

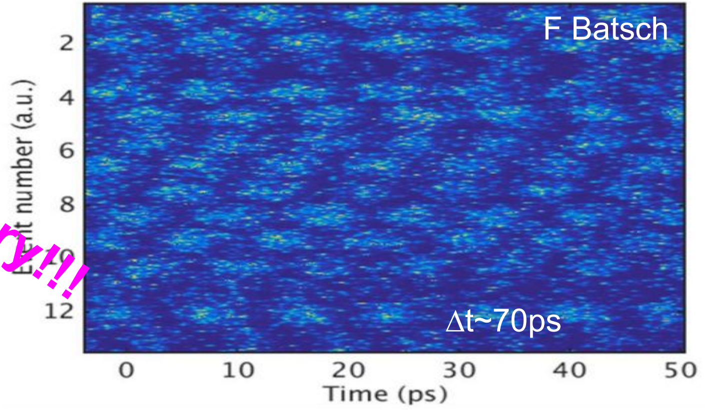
Phase Stability / Instability

Laser Pulse: +125ps



F Batsch

Laser Pulse: +650ps



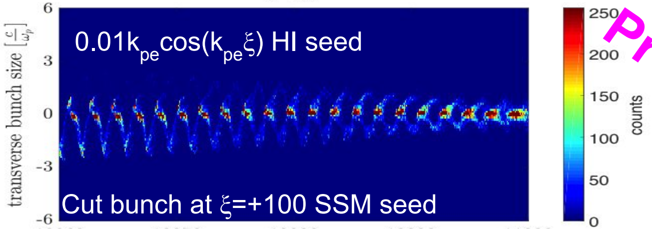
F Batsch

Preliminary!!!

where is the transition?

Hosing Instability

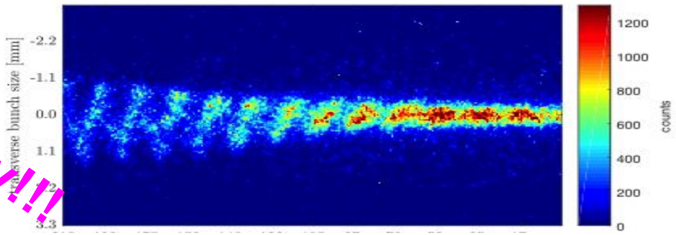
Simulations: Osiris (**M. Moreira**)



$0.01k_{pe}\cos(k_{pe}\xi)$ HI seed

Cut bunch at ξ=+100 SSM seed

Experiment (**M. Huether**)



Preliminary!!!

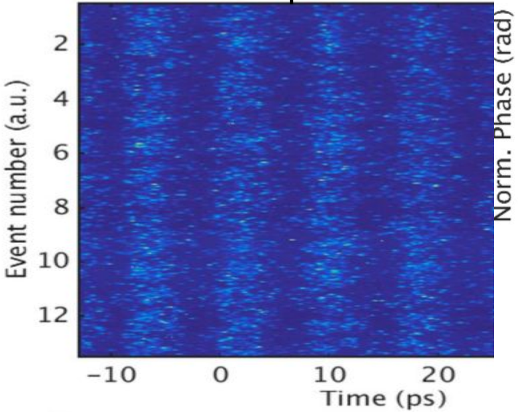
- Similarities in simulations and experiments
- Challenge: quantify HI…

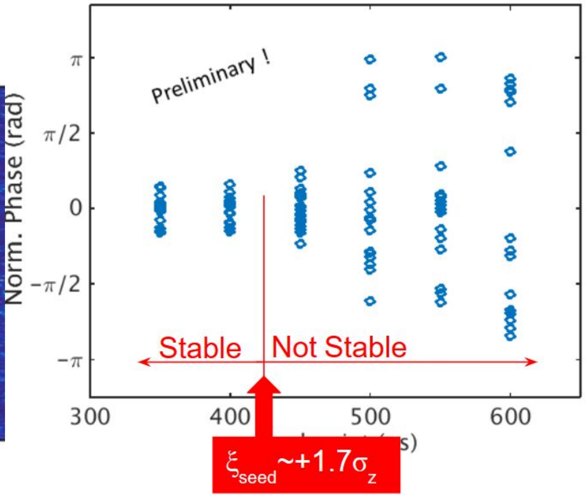
M. Turner et al.

Other Studies

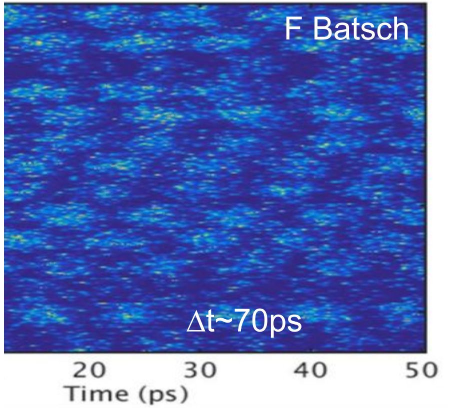
Phase Stability / Instability

Laser Pulse: +125ps





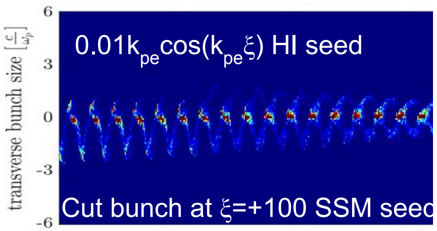
0ps

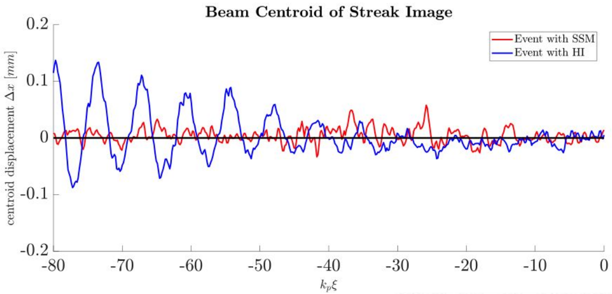


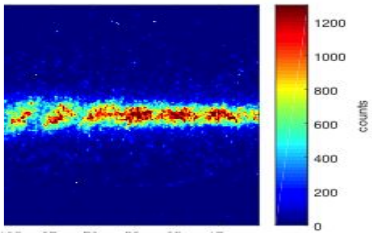
where is the transition?

Hosing Instability

Simulations: Osiris (**M. M** **Huether**)







- Similarities in simulations and experiments
- Challenge: quantify HI…

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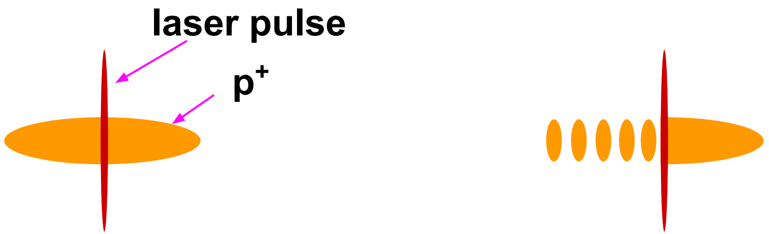
The AWAKE experiment (Run 1)

1. **self-modulate** a long (compared λ_{pe}) 400 GeV/c proton bunch in plasma (2016-2017).



2. **accelerate** externally injected 10- 20 MeV electrons to GeV energies (2018).

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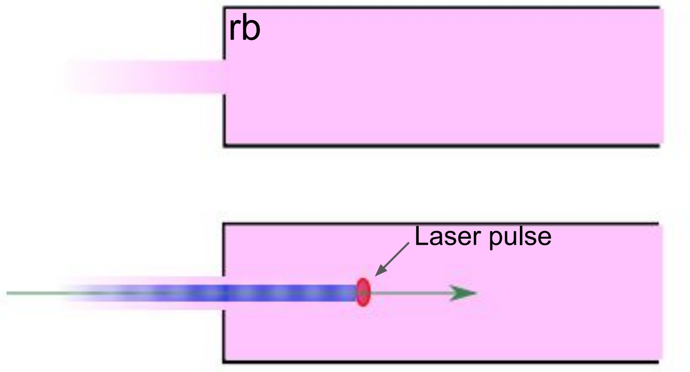
Electron injection

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



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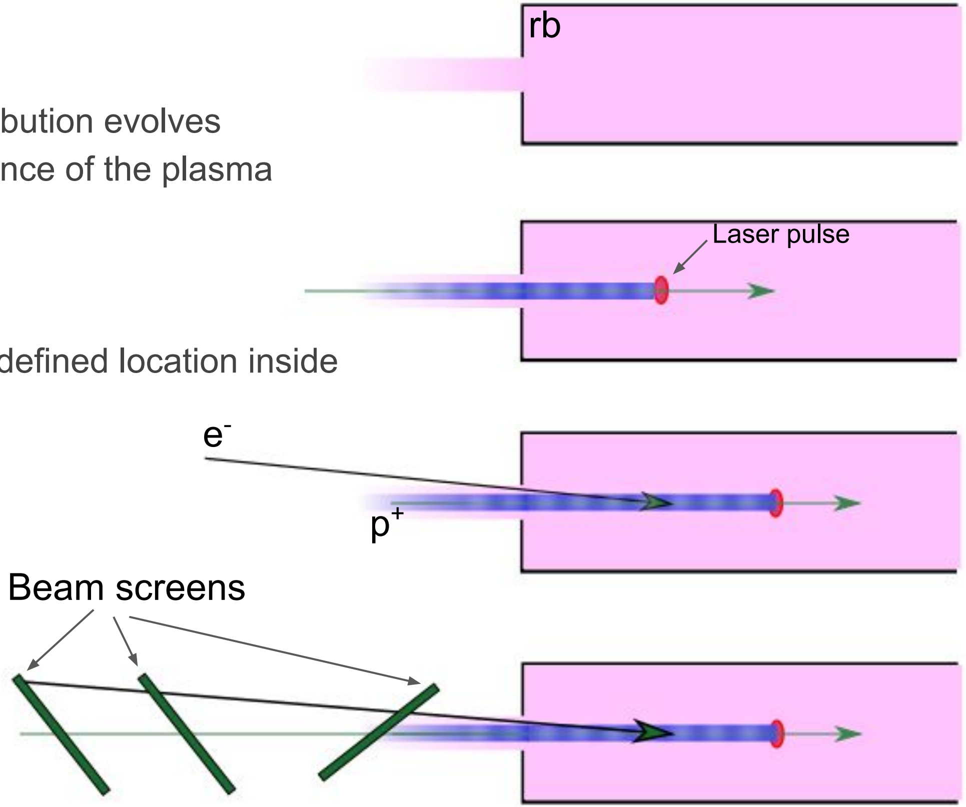
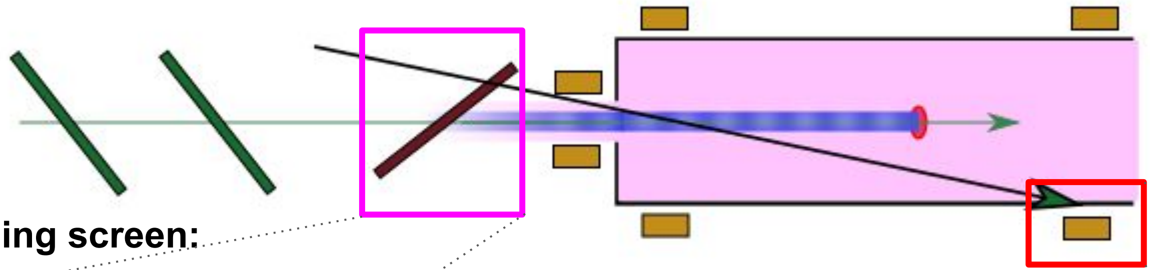
Electron injection

AWAKE is getting ready for electron acceleration:

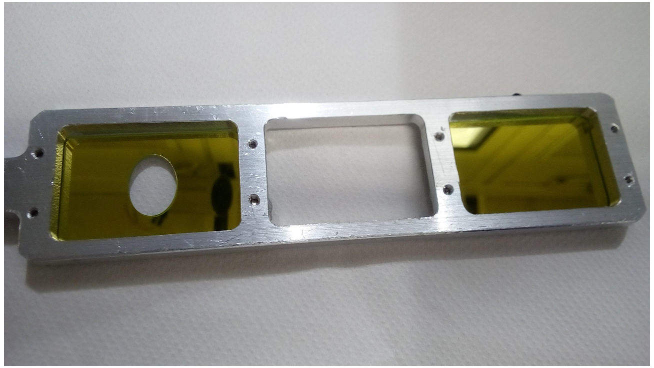
- **Challenge:**
  - During the **SSM** the proton bunch distribution evolves
  - Short plasma density ramp at the entrance of the plasma ⇒ change of wakefield phase
- Instead of injecting bunches co-linear ⇒ **Cross** the electron and proton bunch at a defined location inside the plasma.
- Radial bunch size:
  - proton : ~150 um
  - electron : ~200 um



Electron injection diagnostics

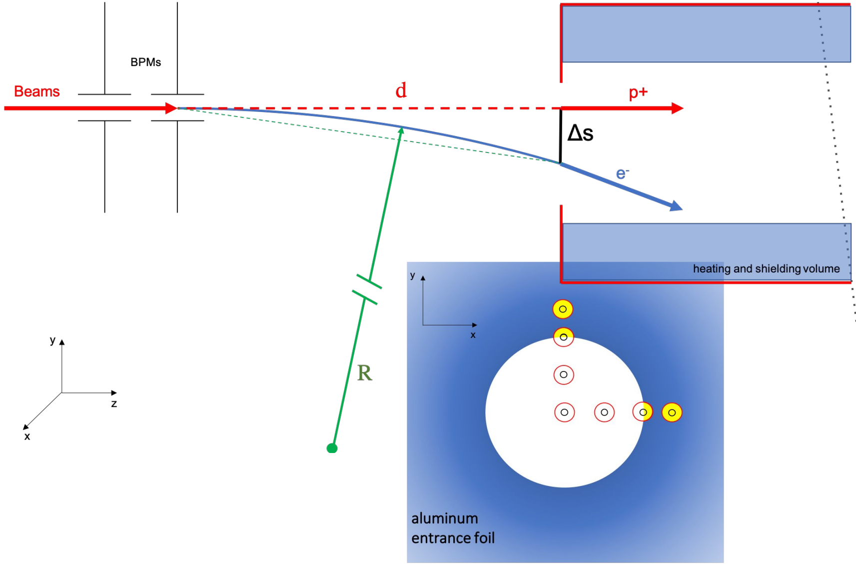


Advanced imaging screen:



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

Electron beam loss monitors:



L.Verra

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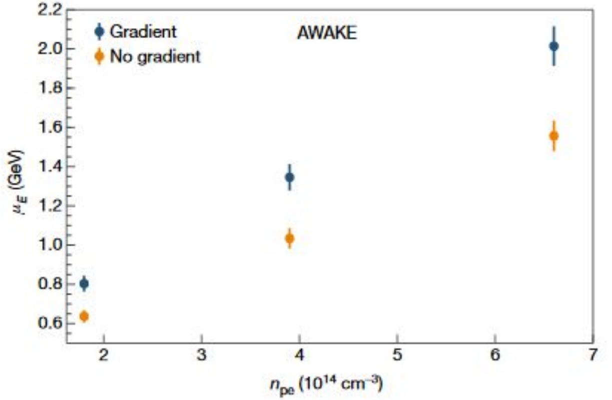
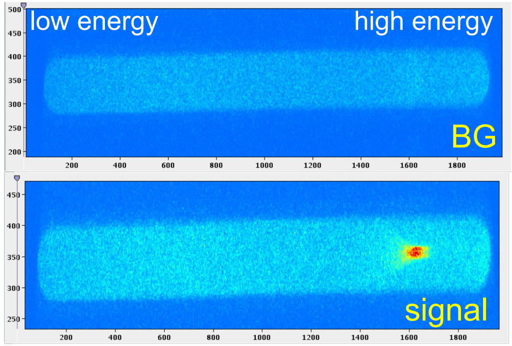
Electron Acceleration Results

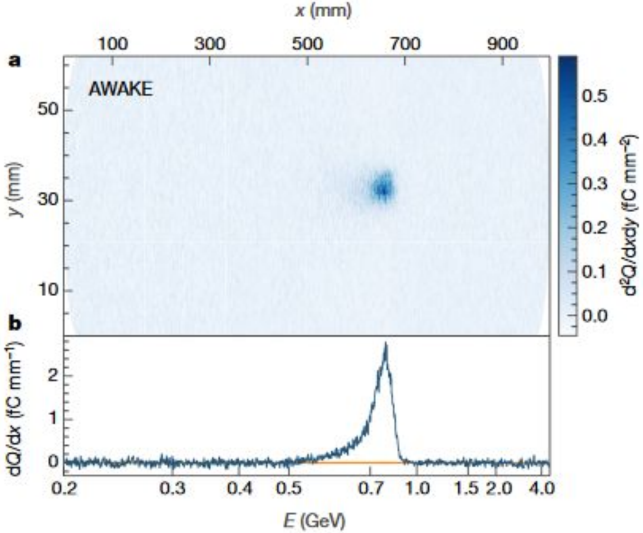
AWAKE Collaboration, *Nature* **volume 561**, pages 363–367 (2018)

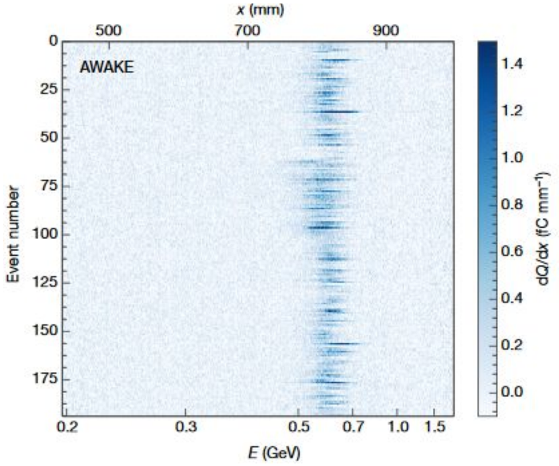
- electron energies up to **2 GeV** (from ~18.6 MeV)
- **finite** electron energy spread (typically ~10%)
- accelerated charge up to **~95 pC** (from ~450 pC)



obtained images







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The AWAKE experimental team

Shortly after we have observed electron acceleration for the first time!

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Electron Acceleration Results

many more studies…

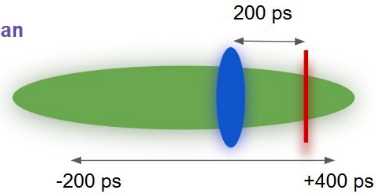
we also varied:

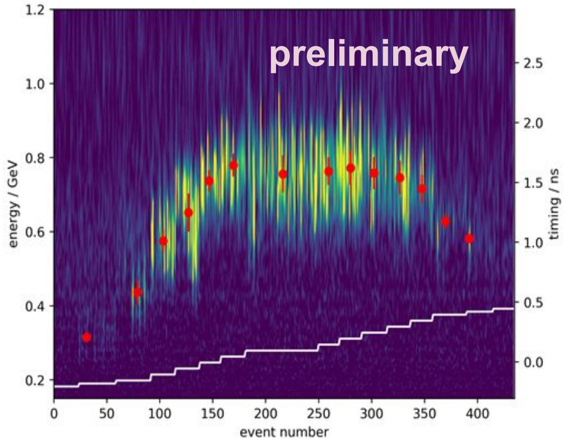
- laser pulse **energy**
- timing of the **electron delay** wrt. seeding position
- timing of the **seeding position** (electron delay fixed)
- proton bunch **population** (N_p)
- horizontal injection **alignment**
- **injection** scheme (on-axis / off-axis)
- current of the **quadrupoles** in the imaging spectrometer

Goal: study the amplitude of the wakefields along the bunch and along the plasma under different conditions ⇒ understand the underlying physics

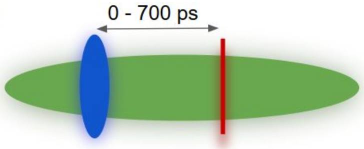
analysis ongoing

Seed Delay Scan





Electron Delay Scan



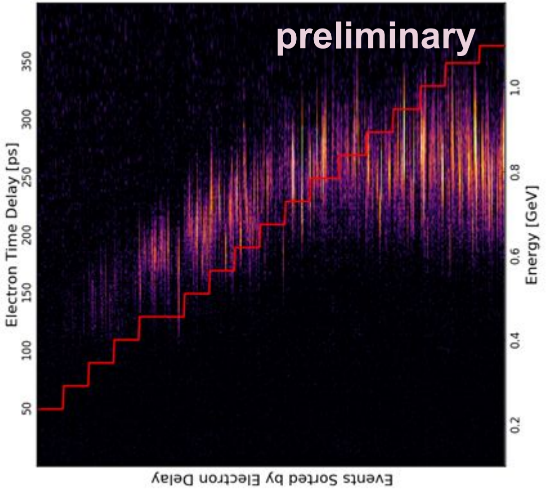
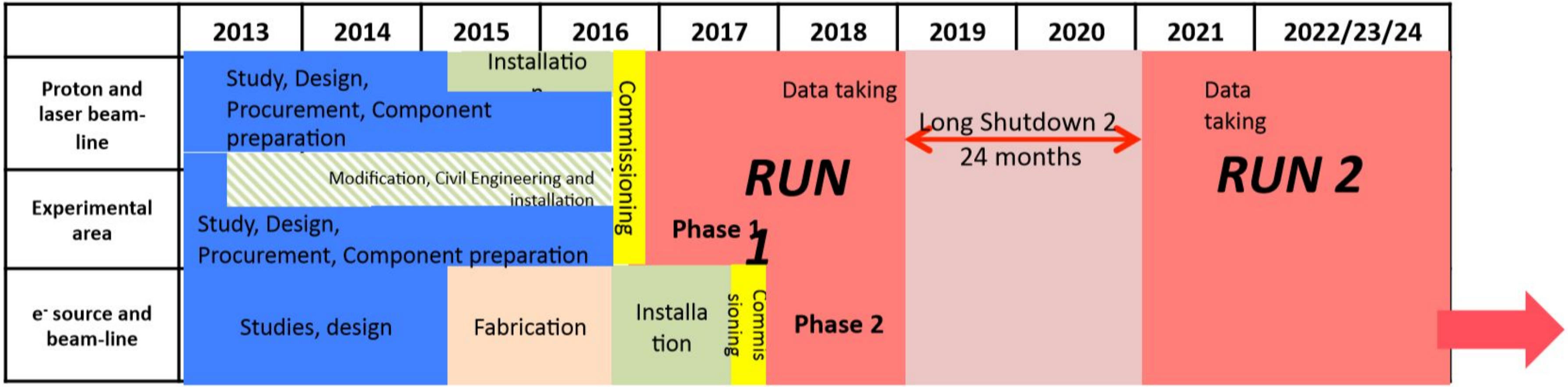


figure from E. Gschwendtner



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

Future of AWAKE and Possible Applications

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 accelerated bunch **charge** O(100pC)

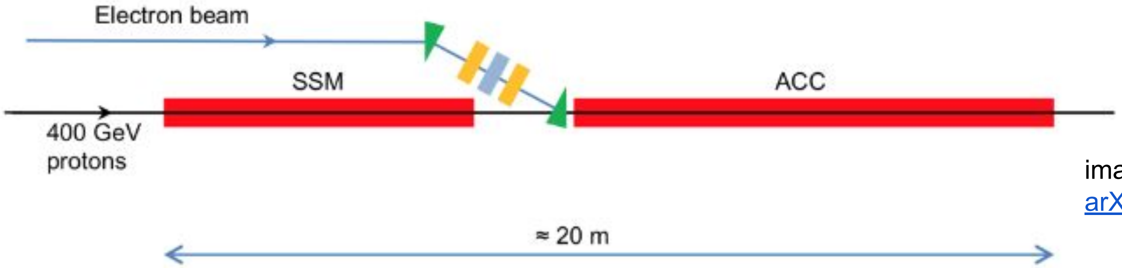


image: arXiv:1812.08550

After Run 2: get ready for first HEP applications:

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

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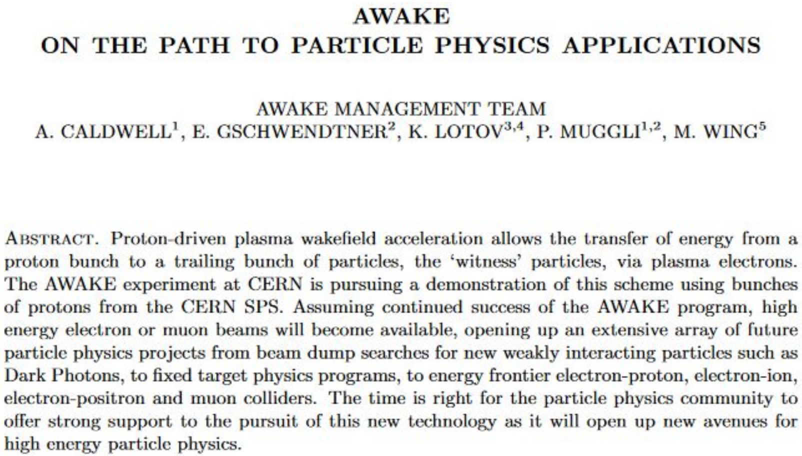
Particle physics applications of the AWAKE acceleration scheme

2 Documents submitted as input for the **European Particle Physics Strategy Update**

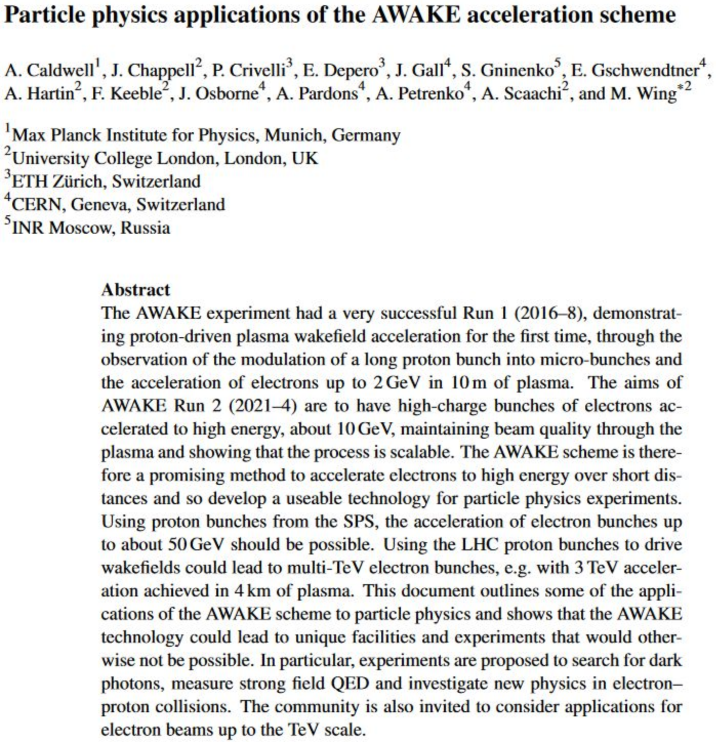


AWAKE
ON THE PATH TO PARTICLE PHYSICS APPLICATIONS

AWAKE MANAGEMENT TEAM
A. CALDWELL[1], E. GSCHWENDTNER[2], K. LOTOV[3,4], P. MUGGLI[1,2], M. WING[5]

ABSTRACT. Proton-driven plasma wakefield acceleration allows the transfer of energy from a proton bunch to a trailing bunch of particles, the 'witness' particles, via plasma electrons. The AWAKE experiment at CERN is pursuing a demonstration of this scheme using bunches of protons from the CERN SPS. Assuming continued success of the AWAKE program, high energy electron or muon beams will become available, opening up an extensive array of future particle physics projects from beam dump searches for new weakly interacting particles such as Dark Photons, to fixed target physics programs, to energy frontier electron-proton, electron-ion, electron-positron and muon colliders. The time is right for the particle physics community to offer strong support to the pursuit of this new technology as it will open up new avenues for high energy particle physics.

arXiv:1812.08550



Particle physics applications of the AWAKE acceleration scheme

A. Caldwell[1], J. Chappell[2], P. Crivelli[3], E. Depero[3], J. Gall[4], S. Gninenko[5], E. Gschwendtner[4], A. Hartin[2], F. Keeble[2], J. Osborne[4], A. Pardons[4], A. Petrenko[4], A. Scaachi[2], and M. Wing[*2]

[1]Max Planck Institute for Physics, Munich, Germany
[2]University College London, London, UK
[3]ETH Zürich, Switzerland
[4]CERN, Geneva, Switzerland
[5]INR Moscow, Russia

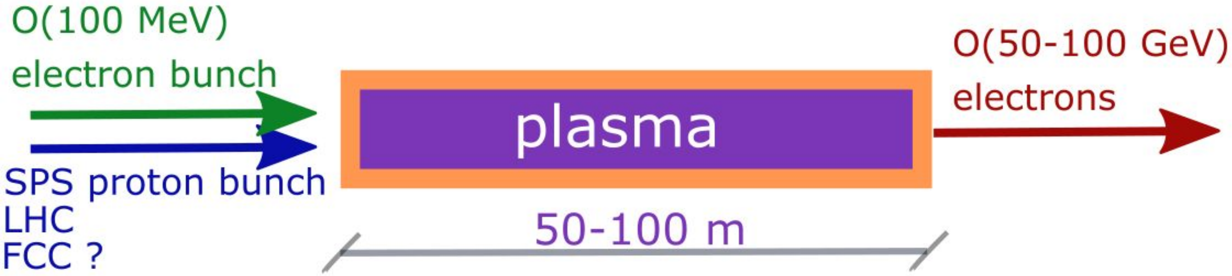
Abstract

The AWAKE experiment had a very successful Run 1 (2016–8), demonstrating proton-driven plasma wakefield acceleration for the first time, through the observation of the modulation of a long proton bunch into micro-bunches and the acceleration of electrons up to 2 GeV in 10 m of plasma. The aims of AWAKE Run 2 (2021–4) are to have high-charge bunches of electrons accelerated to high energy, about 10 GeV, maintaining beam quality through the plasma and showing that the process is scalable. The AWAKE scheme is therefore a promising method to accelerate electrons to high energy over short distances and so develop a useable technology for particle physics experiments. Using proton bunches from the SPS, the acceleration of electron bunches up to about 50 GeV should be possible. Using the LHC proton bunches to drive wakefields could lead to multi-TeV electron bunches, e.g. with 3 TeV acceleration achieved in 4 km of plasma. This document outlines some of the applications of the AWAKE scheme to particle physics and shows that the AWAKE technology could lead to unique facilities and experiments that would otherwise not be possible. In particular, experiments are proposed to search for dark photons, measure strong field QED and investigate new physics in electron–proton collisions. The community is also invited to consider applications for electron beams up to the TeV scale.

arXiv:1812.11164

AWAKE ++

first applications of the AWAKE concept


O(100 MeV)
electron bunch
SPS proton bunch
LHC
FCC ?
plasma
50-100 m
O(50-100 GeV)
electrons

1) **beam dump experiments:**
search for weakly interacting particles (e.g. dark photons)


filter bulk of
known particles
absorber
'beam dump'

From: arXiv:1812.11164

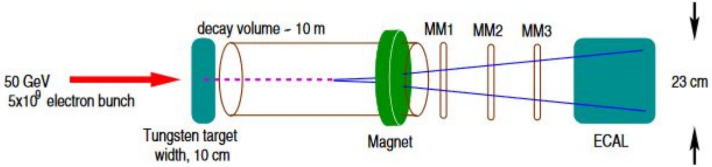


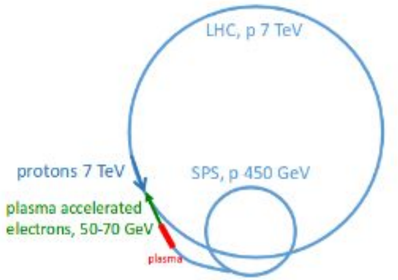
Fig. 2: A sketch of the experimental setup for a bunch of 5×10^9 electrons each of 50 GeV produced via the AWAKE scheme impinging on a tungsten target of depth 10 cm. The target is followed by a decay volume and a dipole magnet to separate the electrons and positrons which are then tracked through three tracker planes (MM1, MM2 and MM3), followed by an electromagnetic calorimeter (ECAL).

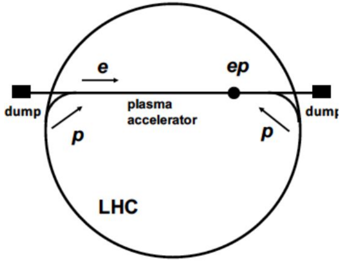
2) **fixed target experiments:**
typically lepton beams produced from high energy protons on target

AWAKE ++

3) electron-proton / electron-ion collider:

- PEPIC (Plasma Electron Proton/Ion Collider), use SPS as driver for 50 GeV e^-; collide with LHC p^+.
- VHEep (Very High Energy electron-Proton collider): One LHC proton beam used for electron acceleration to then collide with other proton beam.





4) others:

- use the plasma to accelerate muons.

⇒ use LHC (or FCC) to create multi-TeV electron bunches
TeV-energies electron positron collider

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The AWAKE Collaboration!

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Summary and Conclusions

- **Plasma wakefield acceleration** offers the possibility to accelerate particles with gradients > 1 GV/m.
- AWAKE uses highly relativistic **self-modulating proton bunches** to drive wakefields over 10m.
- AWAKE recently demonstrated **experimentally** that:
    - proton bunches do **self-modulate** in plasma and wakefield growth due to the evolution
    - externally injected electrons can be **accelerated** in this wake
- **Future**: AWAKE Run 2, then AWAKE ++
    - many possible **applications**: beam dump experiments, electron-proton colliders, linear electron-positron collider….

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Thank you for your attention!