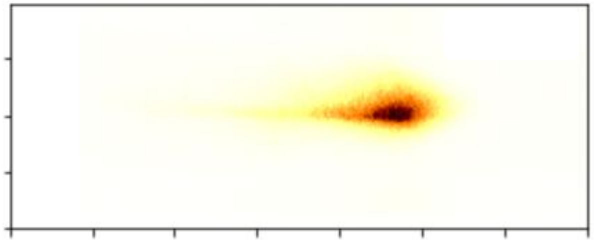
Acceleration of Electrons in the Plasma Wakefield of a Self-Modulated Proton Bunch

M. Turner for the AWAKE Collaboration



Overview

- Introduction to **AWAKE:**
  - Concept, Goals, Wakefields.
- **Electron Injection** in AWAKE:
  - Components, Challenges, Injection Geometry.
- Experimental **Results.**
- **Future**
  - AWAKE Run 2, possible first applications.
- Summary & Conclusion.

Introduction to AWAKE

Advanced Wakefield Experiment

AWAKE

- Plasma wakefield **acceleration** experiment:
  - Driver: highly-relativistic proton bunch.
  - Plasma: 10 m long ($n_{pe} = 10^{14}$-10^{15} cm^{-3}).
  - External electron injection.
- Proof-of-principle **R&D** experiment at CERN.
- Goal of **AWAKE Run 1** (2013-2018):
  - Self-modulate the proton bunch.
  - Accelerate electrons in proton driven plasma waves to GeV energies.
- Final **goal**:
  - Design a high quality and high energy electron accelerator for high energy physics applications.

Why Use a Proton Bunch Driver?

Available, **ultra-relativistic** proton bunches carry large amounts of energy; their velocity is very close to the **speed of light**.

e.g. CERN **SPS** bunch: 3e11 protons/bunch at 400 GeV/c ⇒ **19.2 kJ**, γ = 427

or

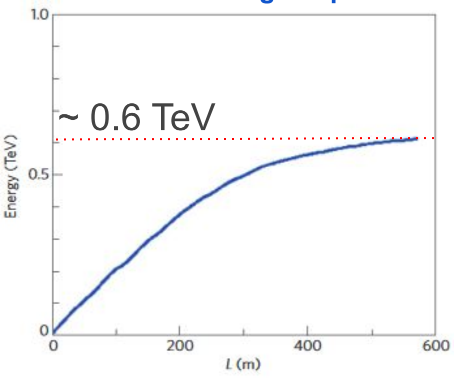
CERN **LHC** bunch: 1e11 protons/bunch at 7 TeV/c ⇒ **112 kJ**, γ = 7478

Used a σ_z = 100 um; 1 TeV/c, 1e11 p^+ driver

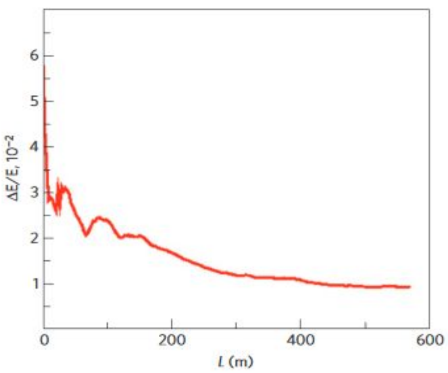
A. Caldwell et al., *Nature Physics* **volume 5**, pages 363–367 (2009)

single plasma stage

witness E along the plasma



ΔE/E along the plasma



But: CERN p+ bunches are 6-12 cm long.

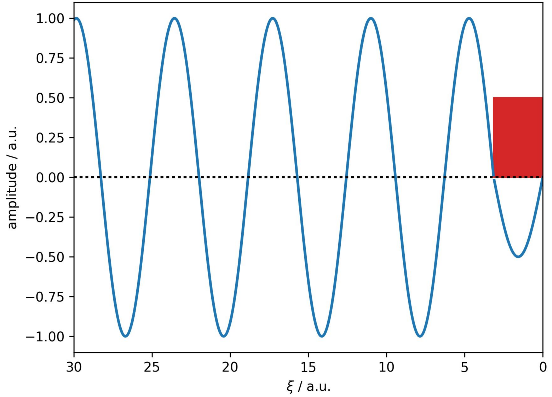
to reach GV/m field amplitudes ⇒ **Self-Modulation**

Why Self-Modulation ?

concept

Typically,

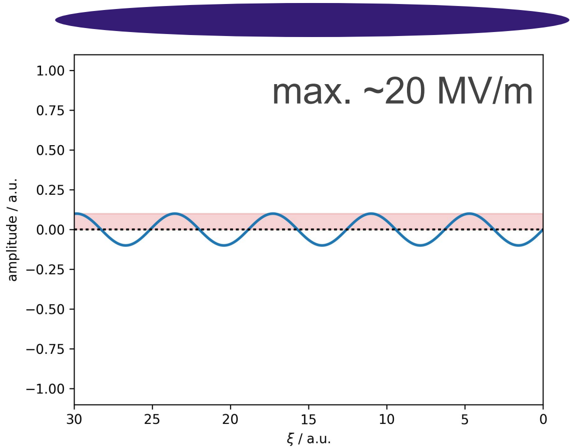
- $n_b \sim n_{pe}$
- $k_{pe}\sigma_r \simeq 1$
- $k_{pe}\sigma_z \simeq \sqrt{2}$



Proton bunches at CERN,

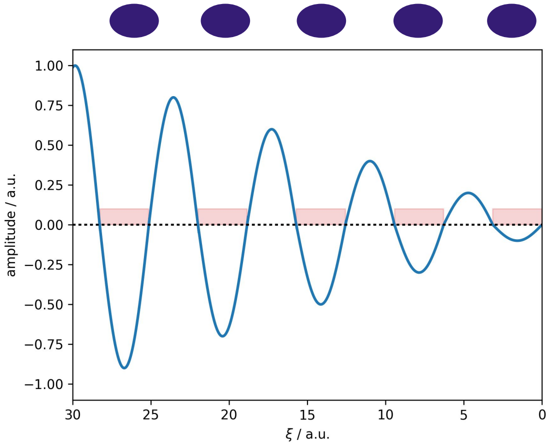
$\sigma_z \gg \lambda_{pe}$ (σ_z~10 cm)

and n_b (~10^{13} e^-/cm^3) < n_{pe}.



After Self-Modulation,

resonant wakefield excitation.

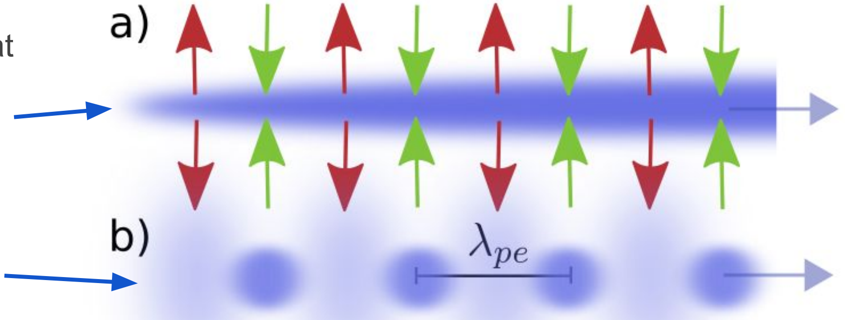


J. Krall and G. Joyce, Transverse equilibrium and stability of the primary beam in the plasma wakefield accelerator. Phys. Plasmas 2, 1326 (1995).
D.H. Whittum, Transverse two-stream instability of a beam with a Bennett profile. Phys. Plasmas 4, 1154 (1997).
N. Kumar, et al., Self-modulation instability of a long proton bunch in plasmas, PRL 104 (25), 255003 (2010).
A. Pukhov, et al., Phase velocity and particle injection in a self-modulated proton-driven plasma wakefield accelerator, PRL 107 (14), 145003 (2011).

Seeded Self-Modulation

development

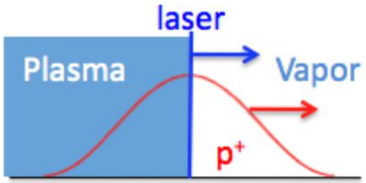
1) When entering the plasma, the bunch drives **wakefields** at the **initial seed value**.
2) The initial wakefields **act back** on the proton bunch itself. The on-axis density is modulated. The contribution to the wakefields is $\propto n_b$.
3) **Density modulation** on axis (micro-bunches).



For highly relativistic bunches: SM process is transverse; longitudinal modulation (ɣ = 427) insignificant.

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

Seed the self-modulation process:



Laser pulse creating relativistic ionization front. Seed wakefields proportional to height of proton density step at seed point $n_b(\xi)$.

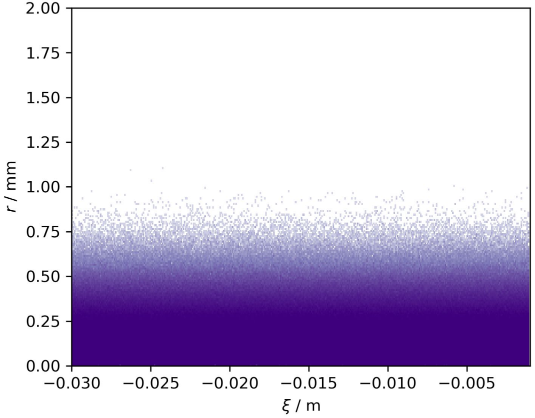
P. Muggli and the AWAKE Collaboration, AWAKE readiness for the study of the seeded self-modulation of a 400 GeV proton bunch. Plasma Phys. Control. Fusion 60, 1, (2017).

Seeded Self-Modulation

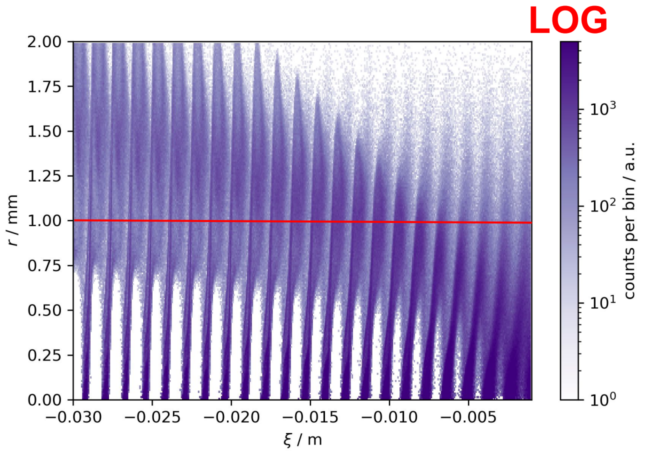
simulation results

all simulations performed with LCODE (2D cylindrical, quasistatic)

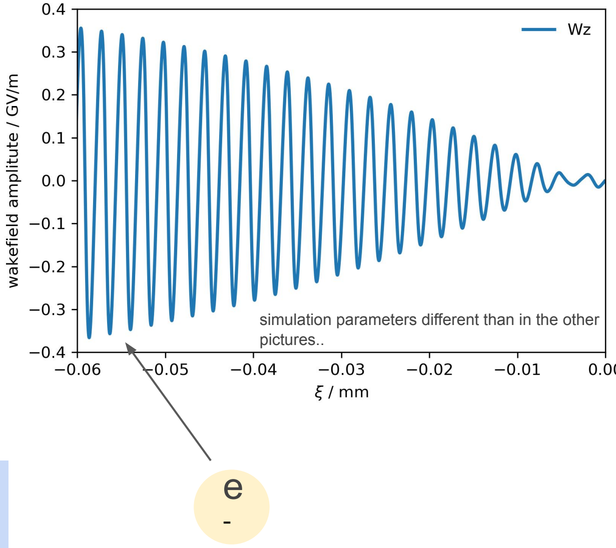
proton bunch density in the beginning of the plasma



proton bunch density after 10 m of plasma



resonant wakefield excitation



Wakefield amplitudes growing along the bunch and along the plasma due to the SSM.

M. Turner
for the AWAKE collaboration

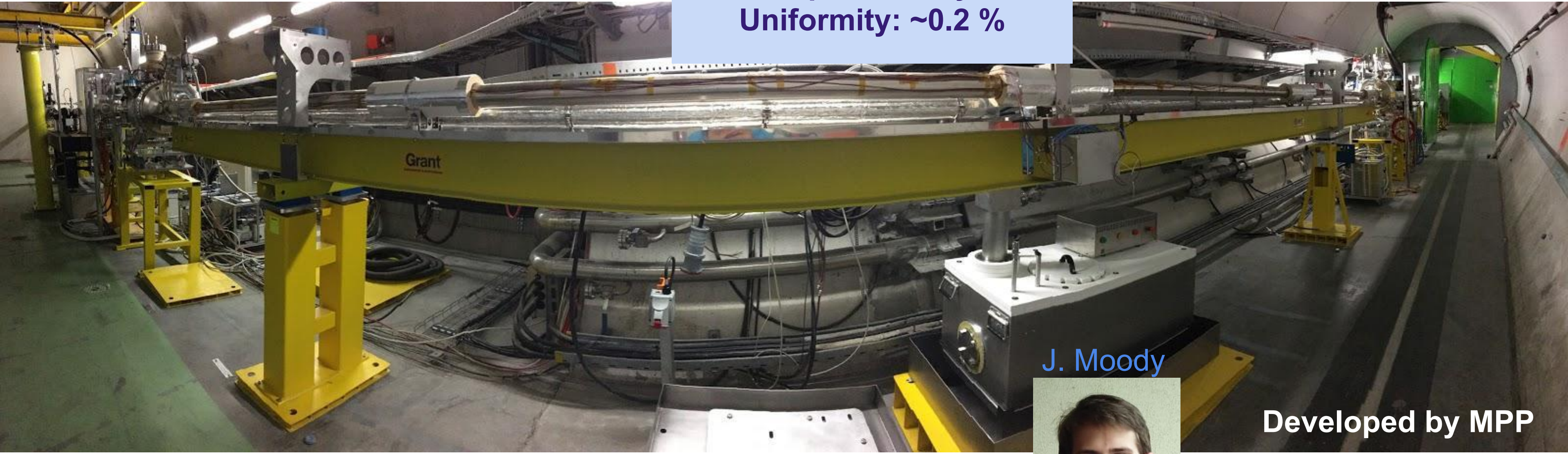
Electron Injection in AWAKE

The AWAKE plasma

10 m long rubidium vapor source

To allow for resonant excitation.
Vapor density Uniformity: ~0.2 %

E. Oz et al., A novel Rb vapor plasma source for plasma wakefield accelerators. Nucl. Instrum. Methods Phys. Res. A 740, 197-202, 2014.



Developed by MPP

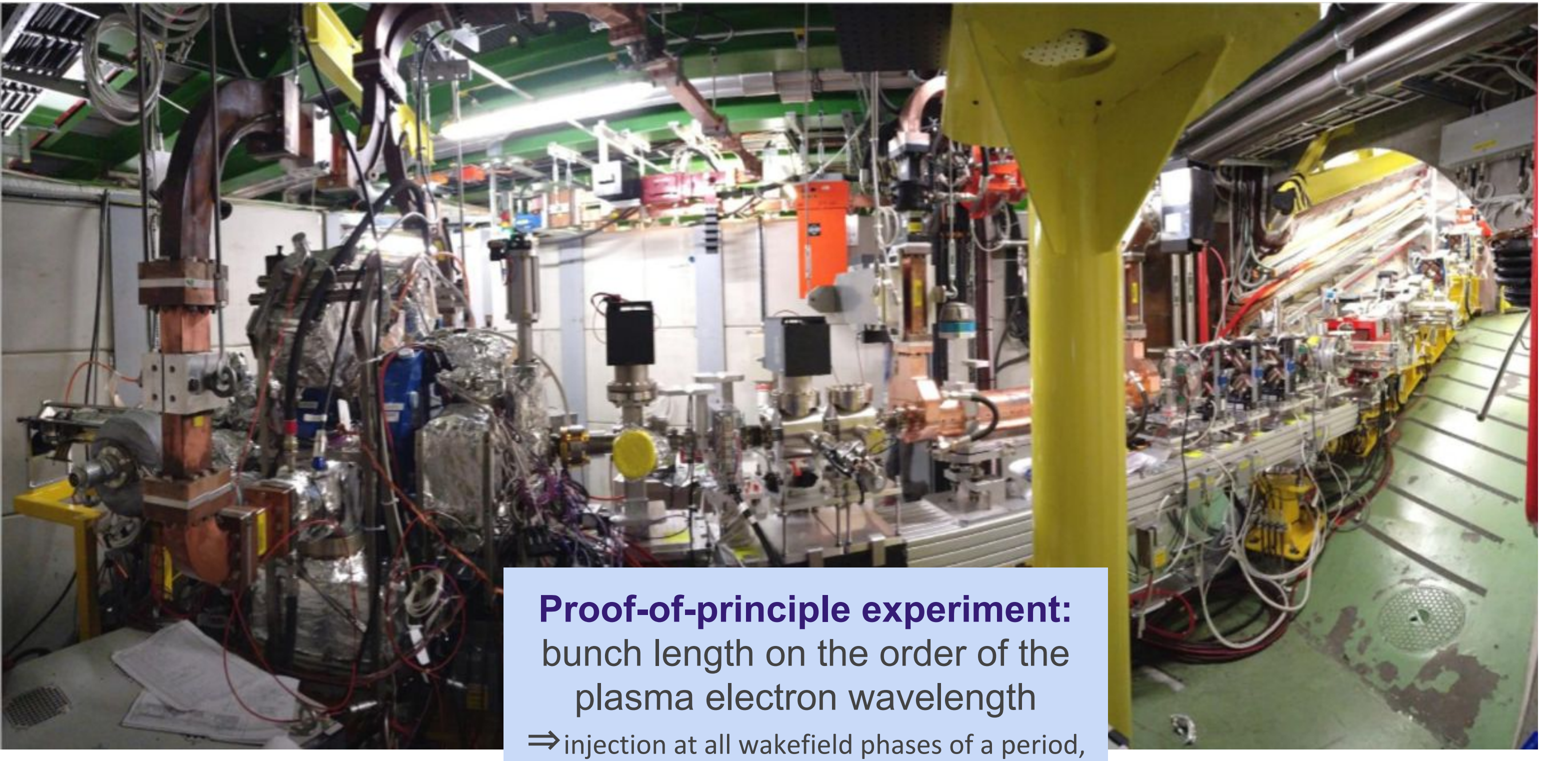
J. Moody

Ionizing Laser Propagation at AWAKE.
POSTER MON 19h

To create the plasma:
Ti:Sapphire laser system
120 fs, <450mJ laser pulse; w_0 = 1 mm; Rayleigh length: 5m
⇒ **Plasma:** 10 m long plasma with r > 1mm.

The AWAKE Experimental Setup

witness bunch



Proof-of-principle experiment:
bunch length on the order of the plasma electron wavelength
⇒injection at all wakefield phases of a period, so no precise timing necessary.

2-½ cell photoinjector with an RF linac;

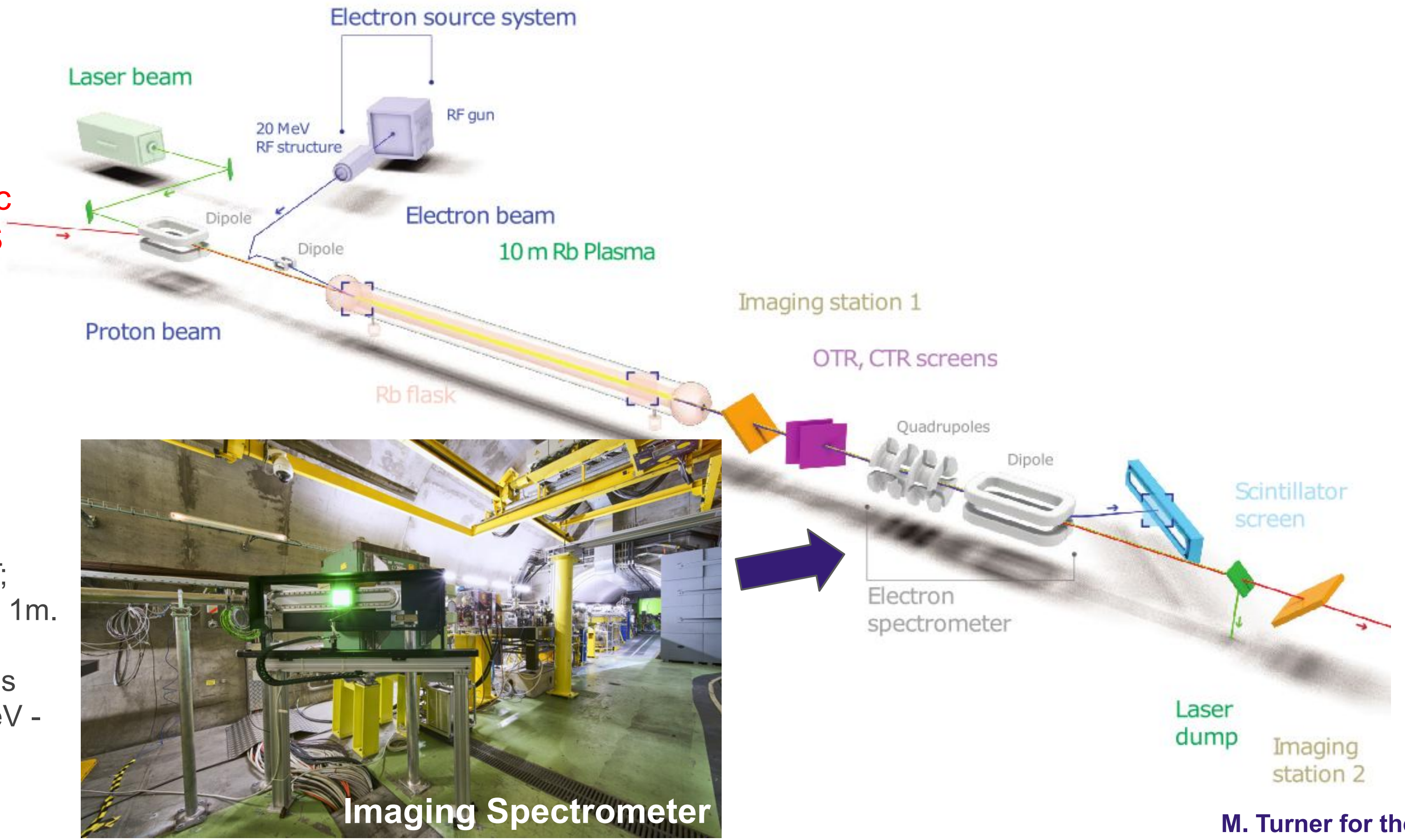
E ~ 20 MeV;

bunch charge: 0.1-0.6nC

σ_z ~ 4ps;

Experimental Setup: Electron Injection

400 GeV/c
from SPS



F. Keeble et al., The AWAKE electron Spectrometer, IPAC 2018
J. Bauche et al., Nucl. Instrum. Meth. A 940 (2019) 103.

B = 0.1 - 1.5 T;
magnetic length = 1m.

detect electrons
energies : 30 MeV -
8.5 GeV

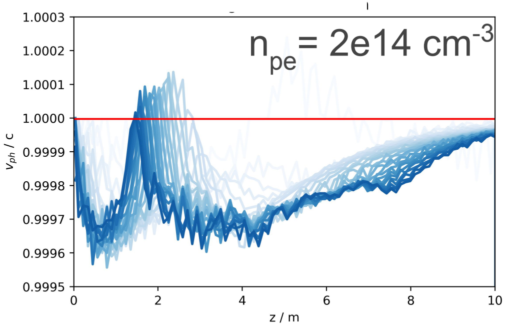
Wakefields along the plasma

external electron injection: challenges

1) wakefields phase velocity during SSM.

A. Pukhov, et al., Phys. Rev. Lett. 107, 145003

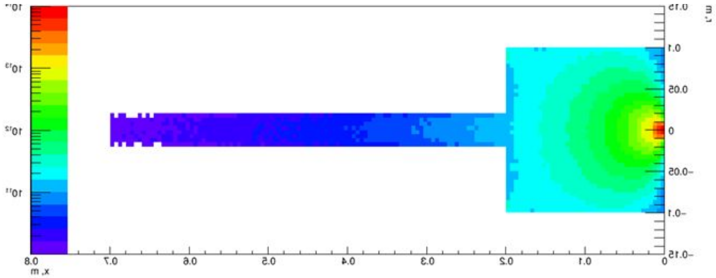
C. B. Schroeder, et al. Phys. Rev. Lett. 107, 145002



- wakefield phase evolves over the first few meters of plasma; mostly defocusing for electrons before SM develops.

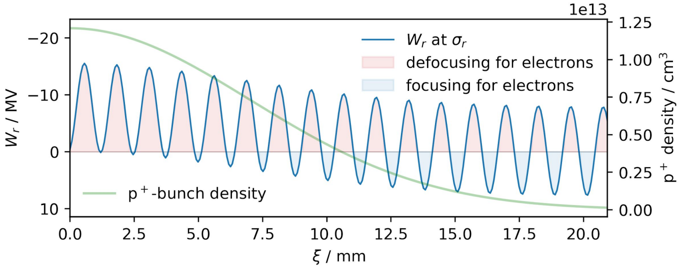
3) density ramps.

LOG



- externally injected electrons may be defocused before significant acceleration.

2) transverse field mostly defocusing.



⇒ oblique external electron injection.

M. Turner
for the AWAKE collaboration

Wakefields along the plasma

challenges

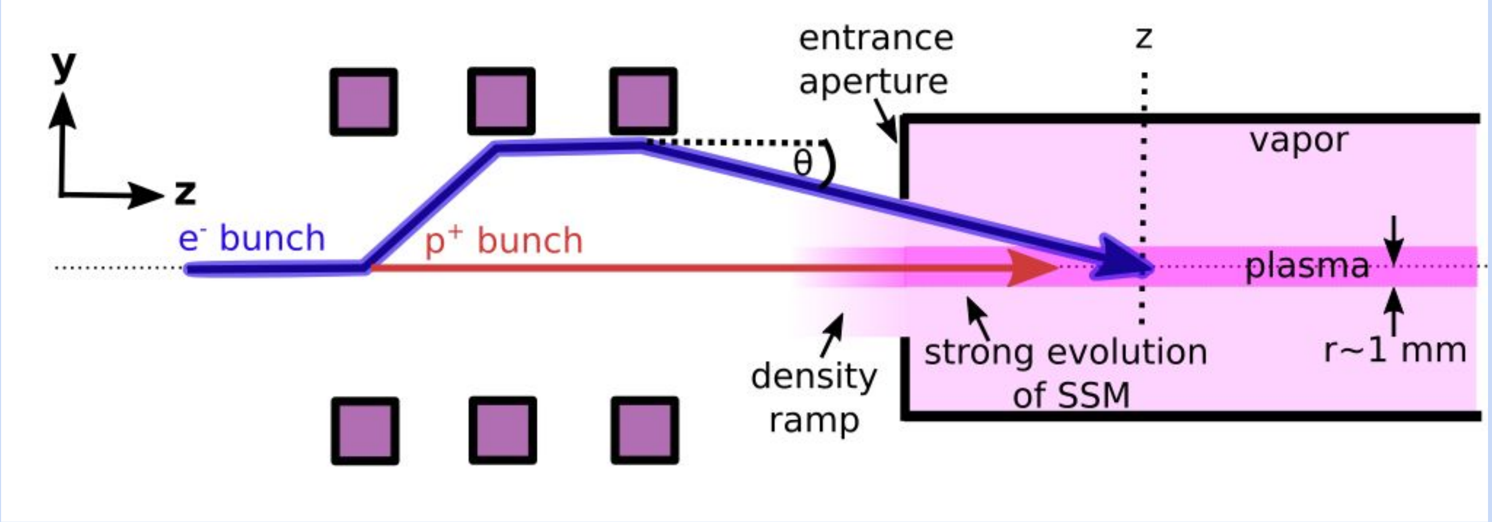
F. Asmus

POSTER MON 19h

Predicting the Trajectories of Relativistic Electron Beams for External Injection in Plasma Wakefield Acceleration.

1) phase velocity during SSM.

2) density r

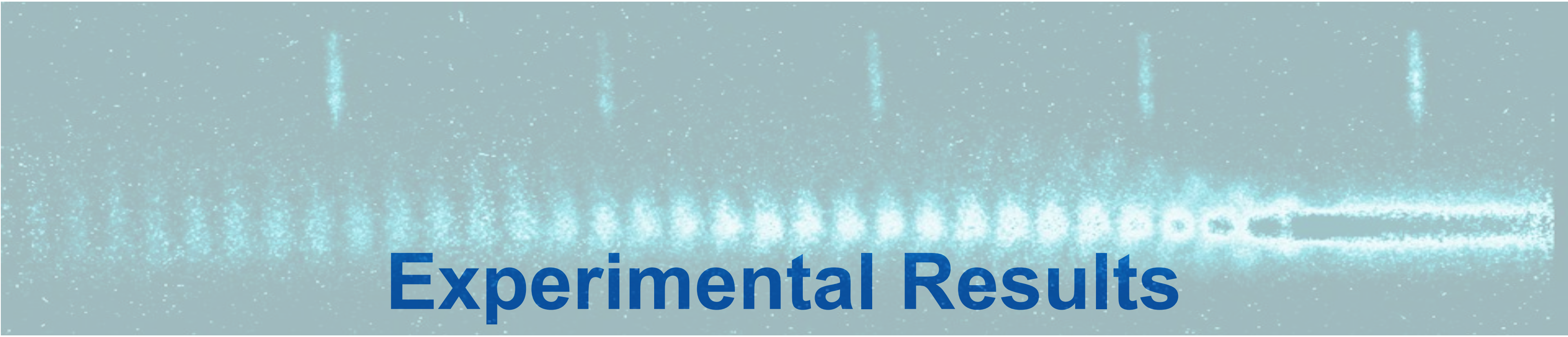


xternal Electron
he AWAKE
eedings of AAC
3.

Inject electrons obliquely: offset + angle.

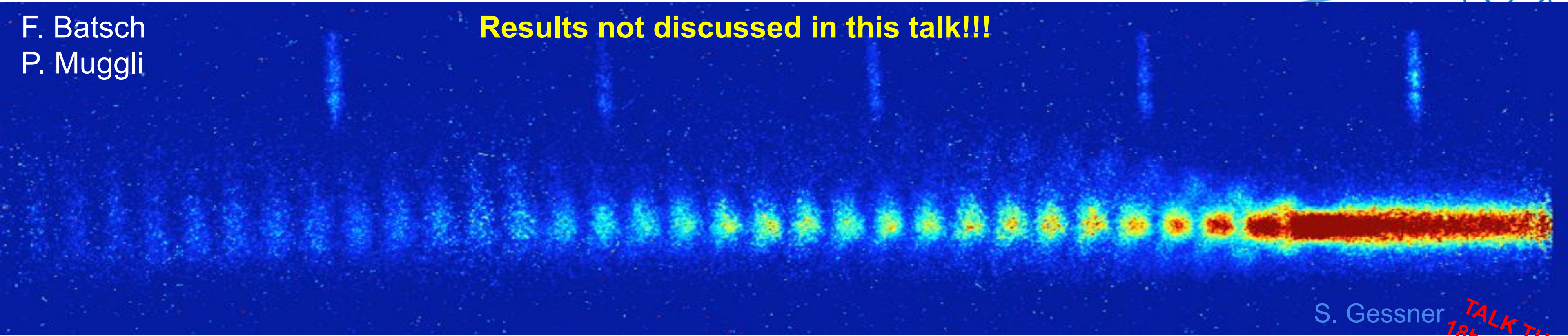
⇒ e^- skip 1) entrance density ramps and 2) defocusing seed wakefields.

Wakefield phase evolves over the first few meters of plasma.



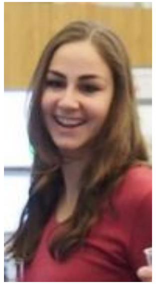
Experimental Results

Proton Bunch Seeded Self-Modulation



TALK TUE 18h40 WG 5

A. Bachmann



Suggested Talk
TALK WED 16h WG1

Seeded Self-Modulation of a Relativistic Proton Drive Bunch in Plasma.

K. Lotov

POSTER MON 19h

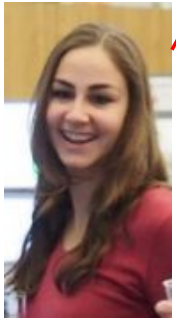
Comparison of OSIRIS/LCODE/QV3D simulations with the measurements of the proton beam in AWAKE experiment.

P. Muggli for F. Batsch

POSTER MON 19h

Self-Modulation and Micro-Bunching Phase Stability Studies in AWAKE

A. Bachmann



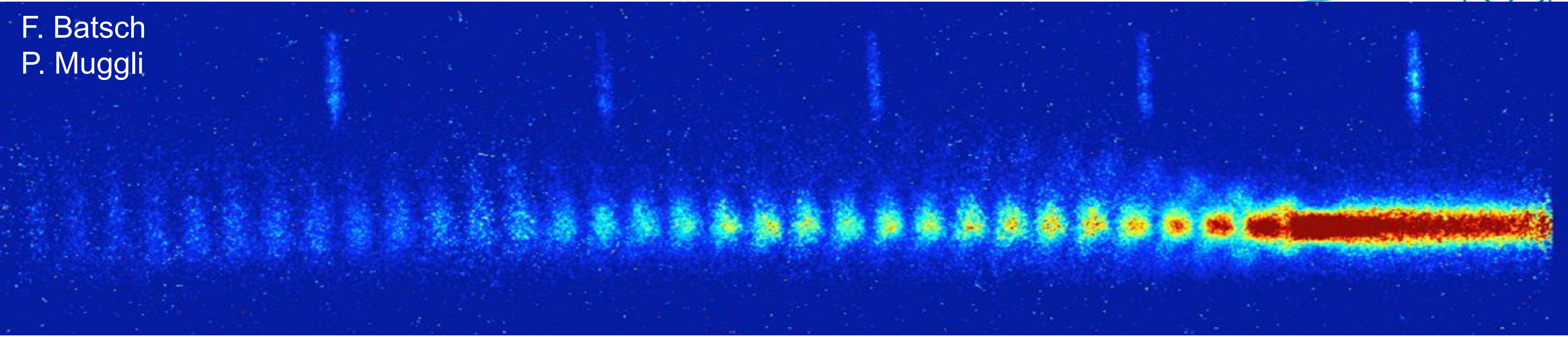
POSTER MON 19h

Study of the Seeded Self-Modulation Growth in the AWAKE Experiment.

Evolution of an ionized plasma column measured by proton beam self-modulation.

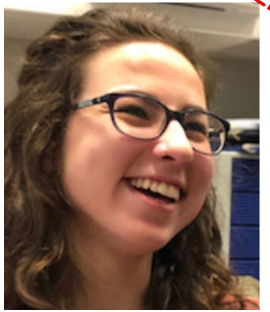
M. Turner for the AWAKE Collaboration

Proton Bunch Seeded Self-Modulation



M. Moreira

POSTER WED 19h



The dynamics and interplay of beam hosing and self-modulation in experimental conditions.

M. Hüther

TALK WED 16h20

Observation of the Hosing Instability in AWAKE.

P. Muggli

POSTER WED 19h

Seeding with an electron bunch the self-modulation of a long, relativistic particle bunch in a plasma

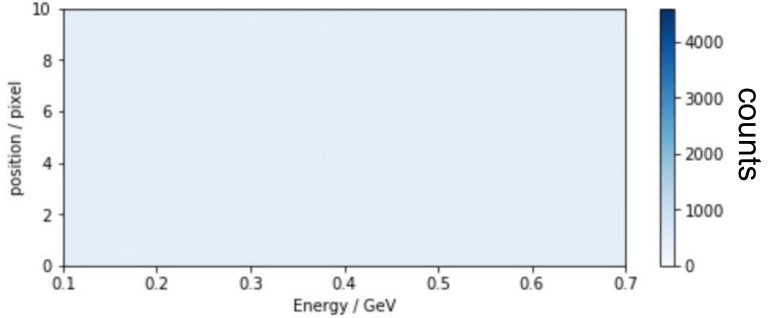
P. Muggli for A. Perera

POSTER MON 19h

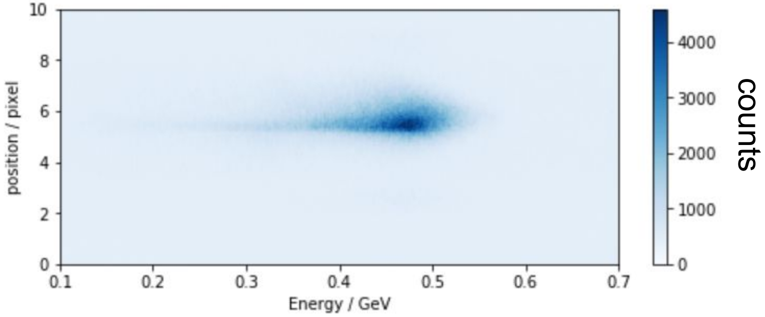
Seeded Self Modulation of Transversely Asymmetric Long Proton bunches in Plasma.

Observation of Electron Acceleration

Electrons off (protons & high power laser on)



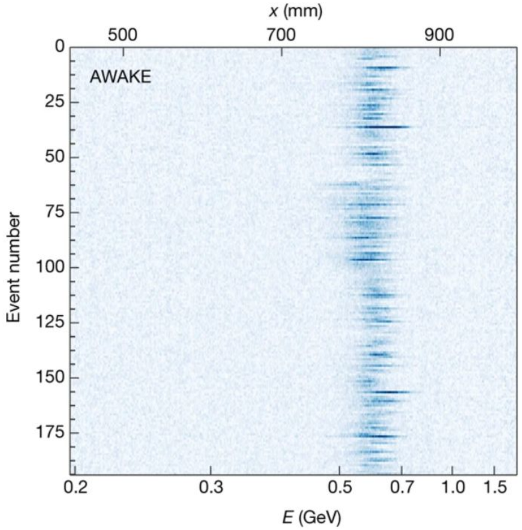
Electrons on (protons & high power laser on)



- electron acceleration in wakefields driven by a self-modulating proton bunch:
- finite electron energy spread.

Proof of longitudinal wakefields

- relative energy spread as low as 8%.
- accelerated amount of charge up to 95pC (~20% charge capture).
- reproducible.

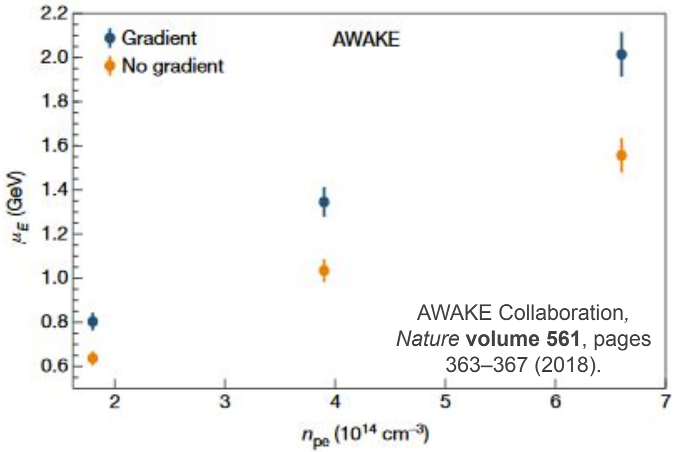


Nature **volume 561**, pages 363–367 2018.

M. Turner for the AWAKE Collaboration

Higher Energies with Density Gradients

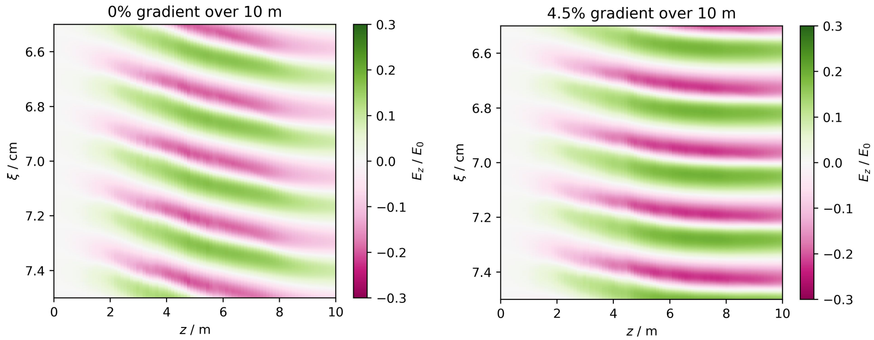
Observation:
Higher electron energy gain with higher n_{pe} and when small positive n_{pe} gradients are applied.



Nature **volume 561**, pages 363–367 2018.

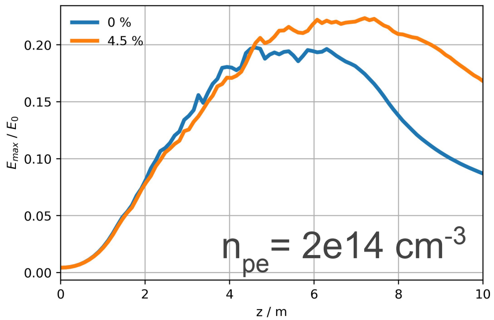
1) wakefields phase velocity

LCODE simulations for $2\text{x}10^{14}$ / cm^3



With small positive density gradients **higher v_{ph}**

2) wakefield amplitude



With small positive density gradients **higher W_z**

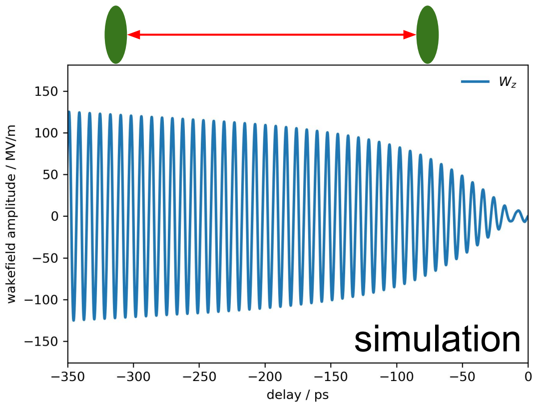
Also discussed in:
K.V. Lotov, Physics of Plasmas 22, 103110 (2015); A. Petrenko, K. Lotov and A. Sosedkin, NIM A 826 (2016) 63-66; A. Petrenko et al. Proceedings of IPAC 2014.

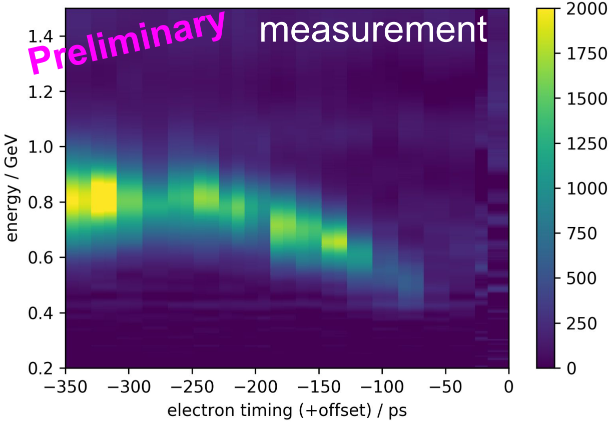
M. Turner for the AWAKE Collaboration

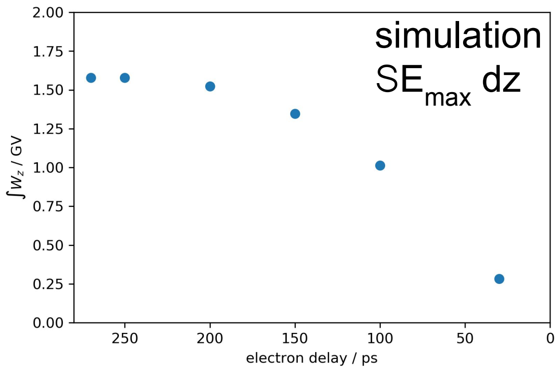
Electron Delay Scan

wakefield growth along the bunch

change the delay (0-350 ps) between the electron bunch and the laser pulse:







Observation: wakefields are growing along the bunch consistent with resonant wakefield excitation.

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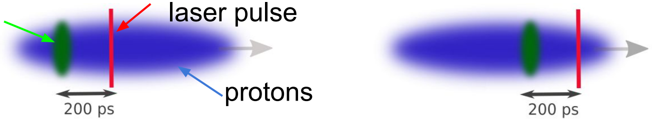
Seed Position Scan

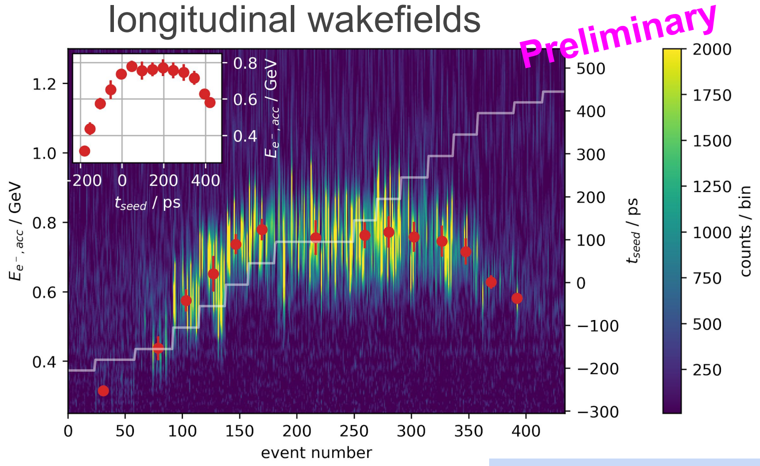
wakefield growth along the plasma

vary the delay (-200ps - 400ps) between the laser pulse and the proton bunch; keel electron bunch at constant delay

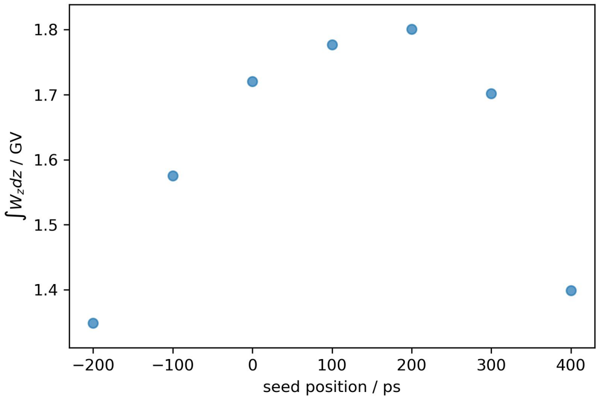


⇒ change **seed** wakefield amplitude and **number of protons** in plasma.

longitudinal wakefields



Simulation: $\int E_{max}\, dz$



Observation: wakefields are growing along the plasma consistent with expectations of the SSM growth.

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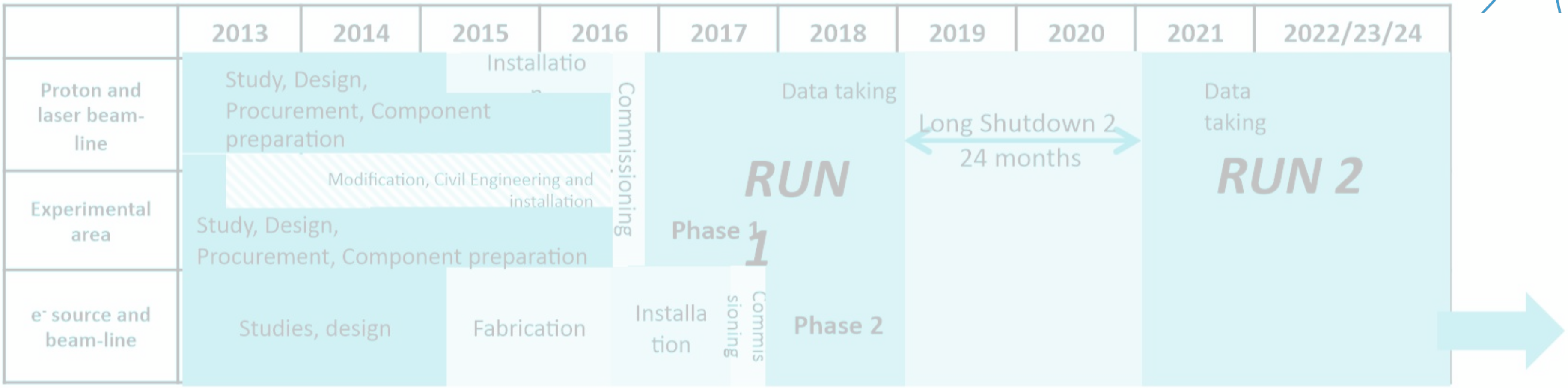

2013
2014
2015
2016
2017
2018
2019
2020
2021
2022/23/24
Proton and laser beam-line
Experimental area
e- source and beam-line
Study, Design, Procurement, Component preparation
Installatio n
Modification, Civil Engineering and installation
Study, Design, Procurement, Component preparation
Commissioning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

Future

AWAKE Run 2 (2021+)

Goal: The next big step for AWAKE is to demonstrate 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)

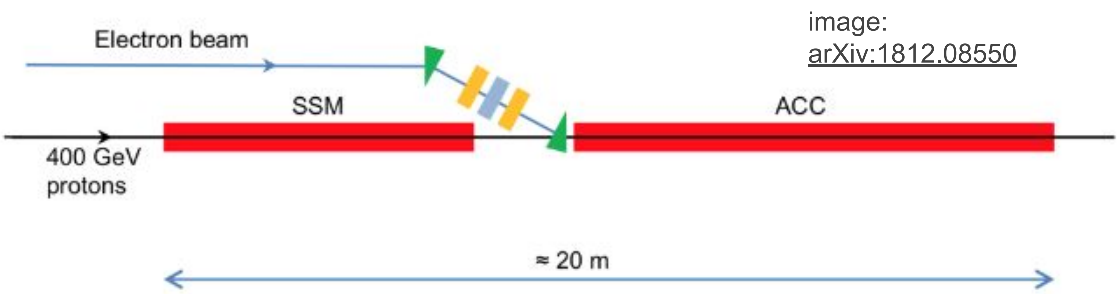


image: arXiv:1812.08550

E. Gschwendtner
The AWAKE Run 2 Facility.
POSTER WED 19h

P. Muggli
Physics Plans for AWAKE Run 2.
TALK THU 18h40 WG1

B. Williamson
POSTER MON 19h

Betatron radiation diagnostic for AWAKE Run 2

S. Doebert
POSTER MON 19h

Design studies of the electron injector and beam transport for external injection at AWAKE Run 2.

A. Pardons
POSTER MON 19h

Installation and infrastructure for big PWA facilities: what we learnt from AWAKE Run 1 and challenges for AWAKE Run 2.

L. Verra
Study of External Electron Beam Injection into Proton Driven Plasma Wakefields for AWAKE Run 2.
POSTER MON 19h

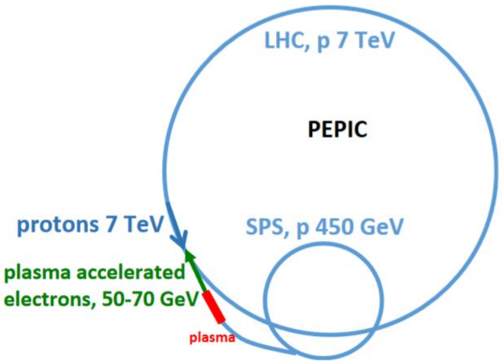
M. Turner for the AWAKE Collaboration

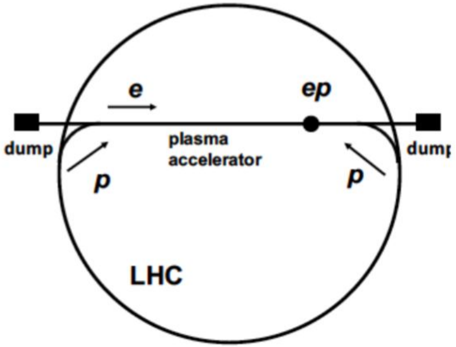
AWAKE ++

first applications

- **Fixed target test facility:** use bunches from SPS with 3.5×10^{11} protons every ~5 sec, electron beam of up to O (50 GeV).
  - deep inelastic scattering, non-linear QED, search for dark photons.

- **Electron/Proton or Electron/Ion Collider:** accelerate electrons by using the SPS or the LHC beam as a driver, 50-70 GeV or ~TeV electron bunches possible.





VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

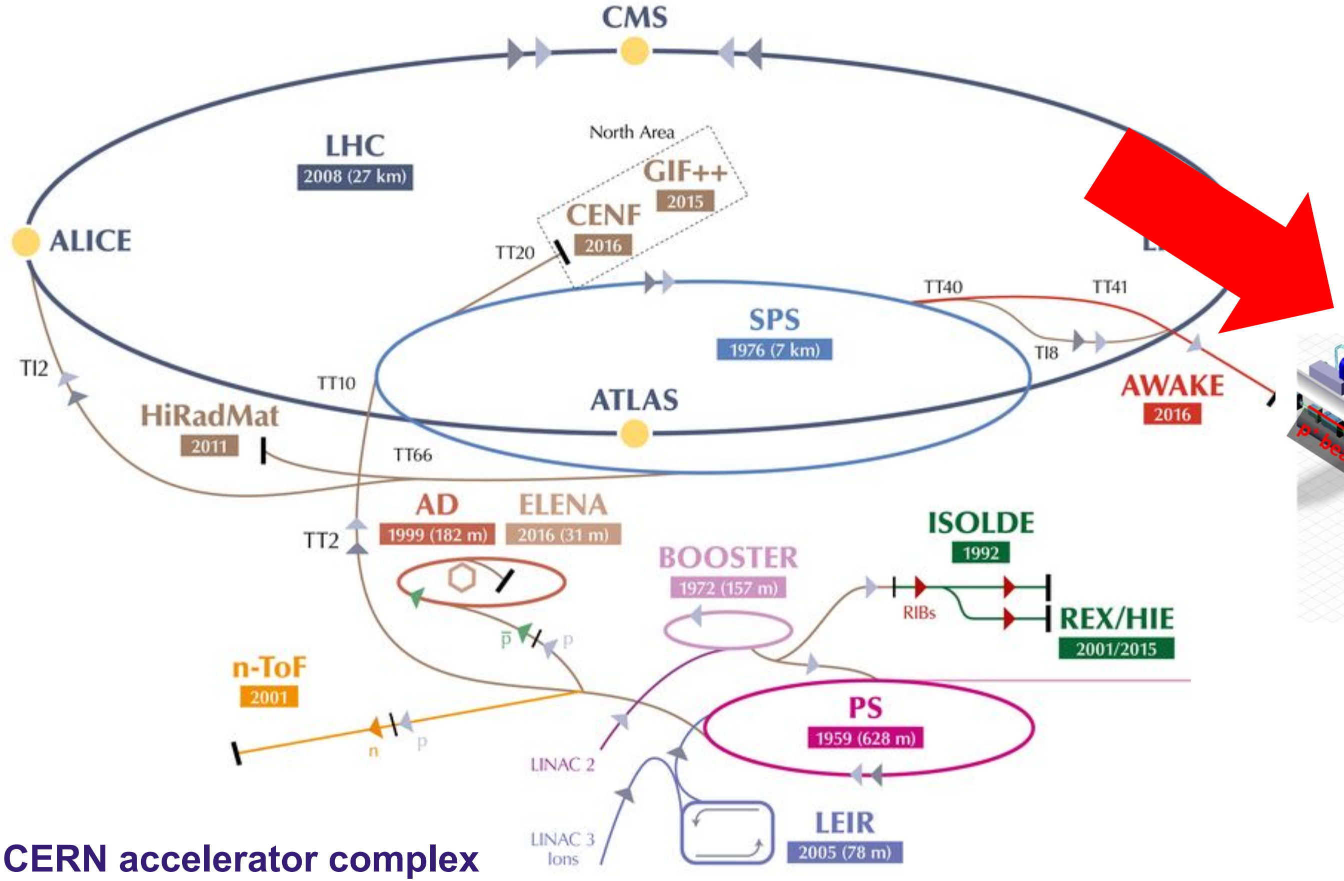
Summary & Conclusions

Summary & Conclusion

- AWAKE is a **proton driven** plasma wakefield experiment.
- Wakefields excited by a **self-modulating** proton bunch.
- Electrons (~20 MeV) injected **obliquely** into the wakefields.
- Accelerated electron energies up to **2 GeV**.
- Next step ⇒ AWAKE **Run 2**;
  - separation of the self-modulator and accelerator to demonstrate good beam quality.

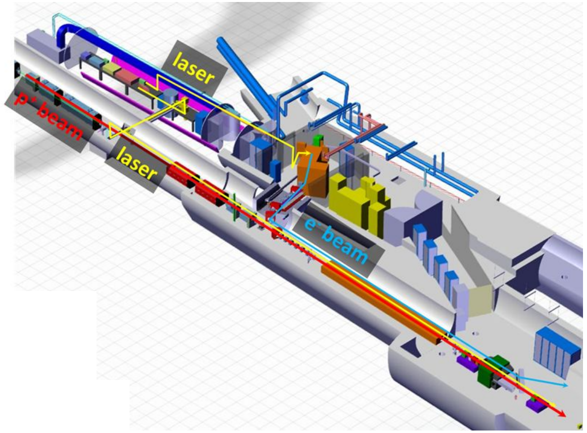
AWAKE @ CERN

2) drive bunch

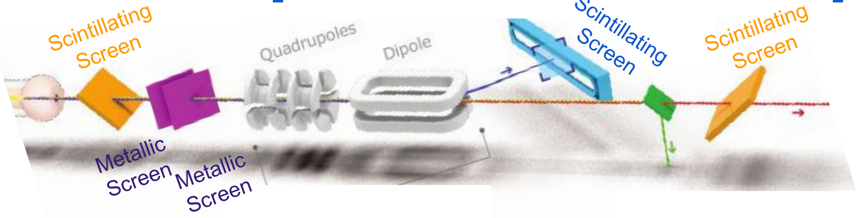


CERN accelerator complex

p$^+$ bunch:
400 GeV/c
3e11 p$^+$/bunch
σ_z~ 6-12 cm



The AWAKE Experimental Setup



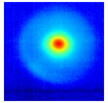
4) diagnostics downstream the plasma

Proton Bunch Self-Modulation

Metallic / Scintillating Screens

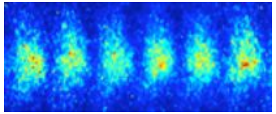
1) Image emitted scintillation light on CCD cameras.

transverse, time-integrated bunch structure



2) Image to optical part of the transition radiation onto the slit of the streak camera.

time-resolved structure



3) Measure the coherent part of the transition radiation with...

frequency

Electron Energy Gain

B = 0.1 - 1.5 T; magnetic length = 1m
detect electrons energies : 30 MeV - 8.5 GeV

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

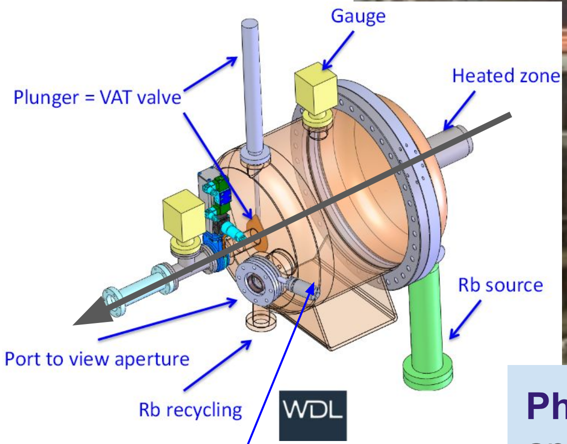
Plasma Entrance and Exit

Density ramps need to be short to allow for external electron injection, to avoid proton/electron/plasma interactions upstream.

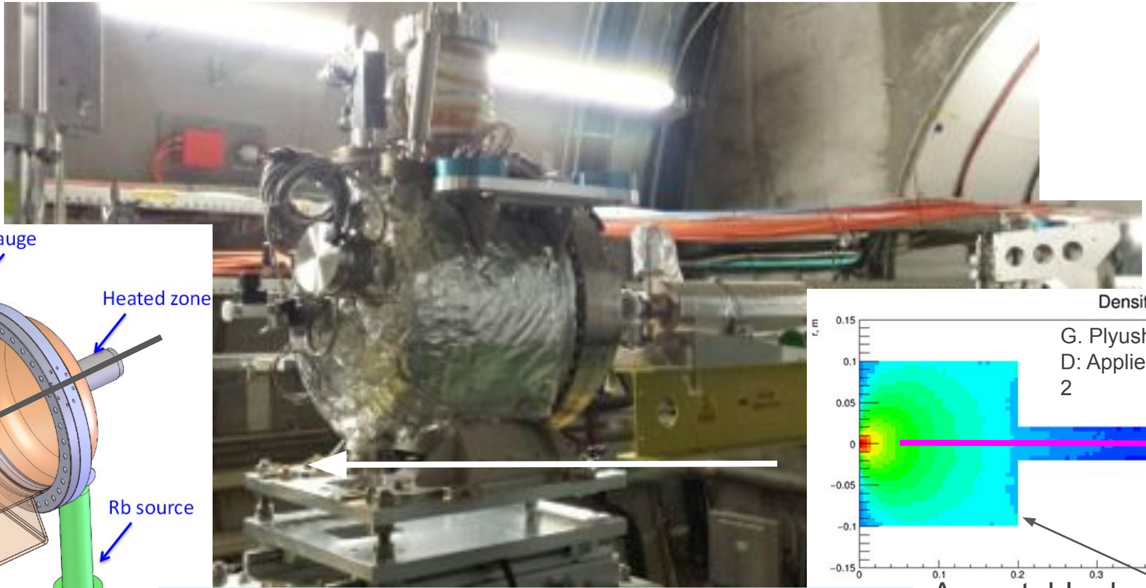
Cold **expansion chambers** with an open flow - the rubidium condenses on a cold surface.

-

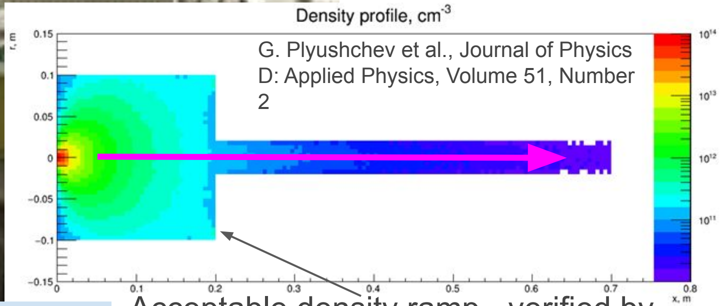
Rubidium expansion chambers:



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



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.



Acceptable density ramp - verified by plasma simulations

M. Turner for the AWAKE Collaboration