Status and plans of AWAKE

155th Meeting of the SPSC

26/11/2024

Michele Bergamaschi for the AWAKE collaboration

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- Introduction to AWAKE
- Results from 2024 experiments (Year 2 of Run 2b)
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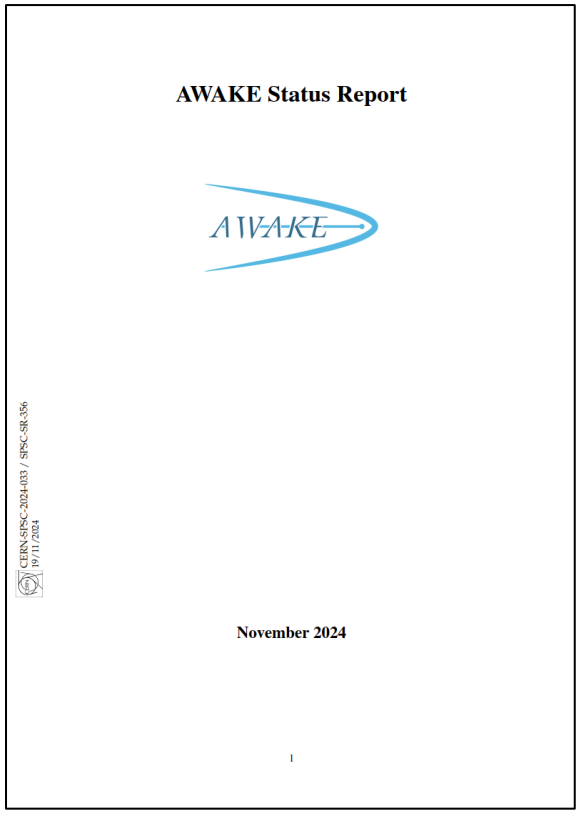
- Summary



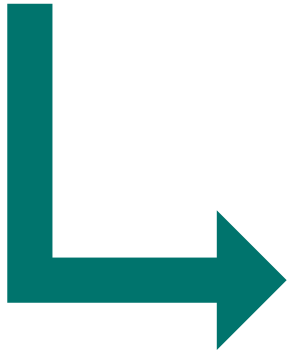
https://cds.cern.ch/record/2917426/files/SPSC-SR-356.pdf

AWAKE Collaboration: 21 Institutes World-Wide

- University of Oslo, Oslo, Norway
- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Oxford University, 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-Universität of Düsseldorf, Düsseldorf, Germany
- University of Liverpool, Liverpool, UK
- ISCTE – Instituto Universitéario de Lisboa, Lisbon, Portugal
- GoLP/Institutode Plasmas e Fusao Nuclear, Instituto Superior Téchnico, Universidade de Lisboa, Lisbon, Portugal
- Ludwig-Maximilians-Universität, Munich, Germany
- University of Wisconsin, Madison, US
- Uppsala University, Uppsala, Sweden
- Wigner Institute, Budapest, Hungary
- Swiss Plasma Center group of EPFL, Lausanne Switzerland

Plasma wakefield acceleration

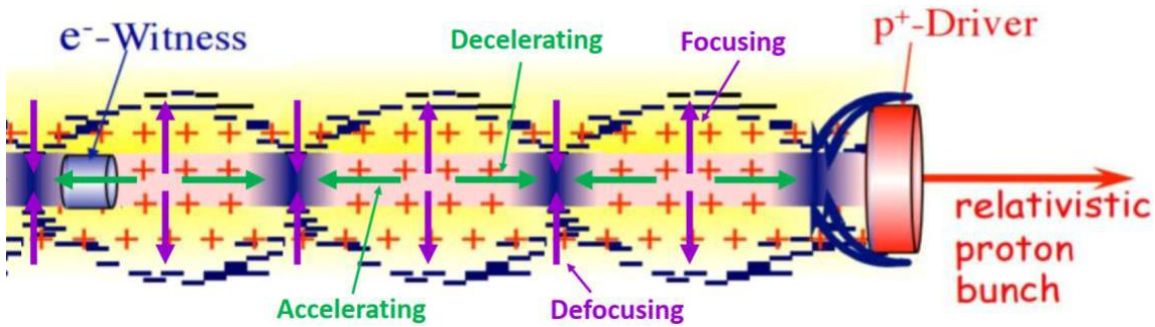
RF accelerators have limited acceleration gradient because of RF cavities maximum field. The limit of the order of 100 MeV/m due to electrical breakdown in resonant cavities



Use of plasma, already ionized i.e. conductor and gradients above 100 GeV/m have been demonstrated

Plasma wakefield acceleration

A laser pulse or a charged particle bunch that travel in the plasma can induce a modulation of the plasma electron density that sustains longitudinal and transverse field which are called **wakefield**



Wakefield can be used to accelerate particles

AWAKE:

- SPS proton bunch as driver of wakefields
- Accelerate externally injected electron witness bunch

AWAKE is a plasma wakefield acceleration experiment using a proton driver

Why a proton plasma wakefield accelerator?

PW laser ≈ 40J/Pulse

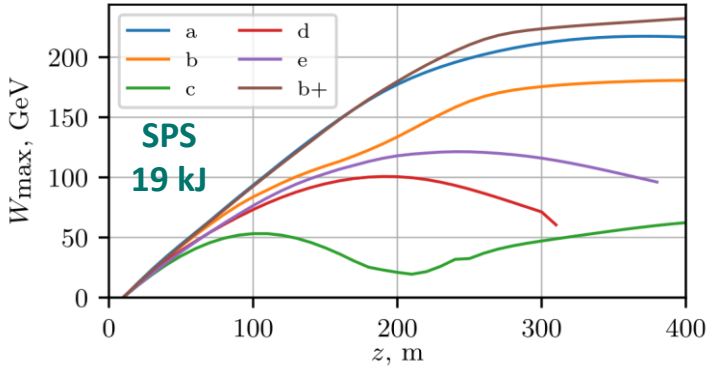
FACET (electron PWFA) ≈ 30J/Pulse

SPS 19 kJ/bunch

LHC 112kJ/bunch

} **High energy gain in a single plasma**

2D numerical simulation results

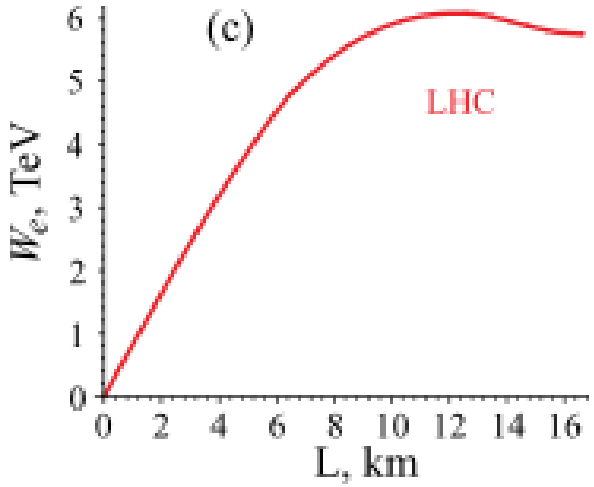


K. V. Lotov & P. V. Tuev, Plasma wakefield acceleration beyond the dephasing limit with 400 GeV proton driver, *Plasma Phys. and Control. Fusion, 63*, 125027 (2021)

TeV in km ≈ GeV/m

100 µm long p^+ bunch driver

Energy gain LHC bunch



A. Caldwell & K. V. Lotov. Plasma wakefield acceleration with a modulated proton bunch, *Physics of Plasmas*, *18*(10), 103101, (2011)

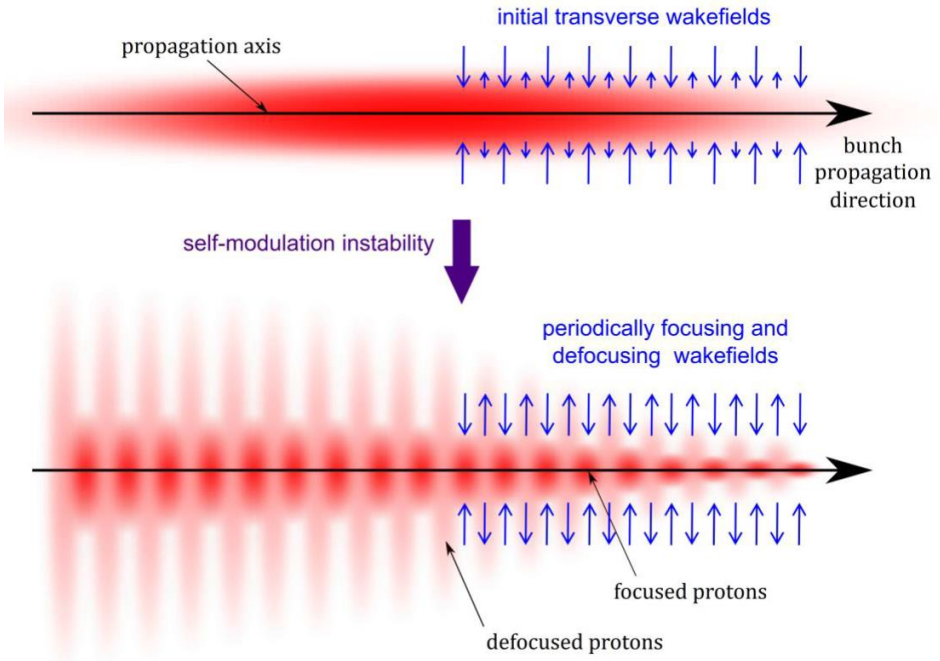
Self-modulation to reach ≈ 1 GeV/m

The SPS proton bunch length too long to drive efficiently

The process of Self-Modulation (SM) proposed in * to drive E_{wb}= 1 GV/m. Needed to **drive efficiently wakefield**, **proton microbunches** are formed and the self-modulated proton bunch **resonantly excite wakefield**

Simulations shows that formation of **Self-Modulation saturate within the plasma length of awake**

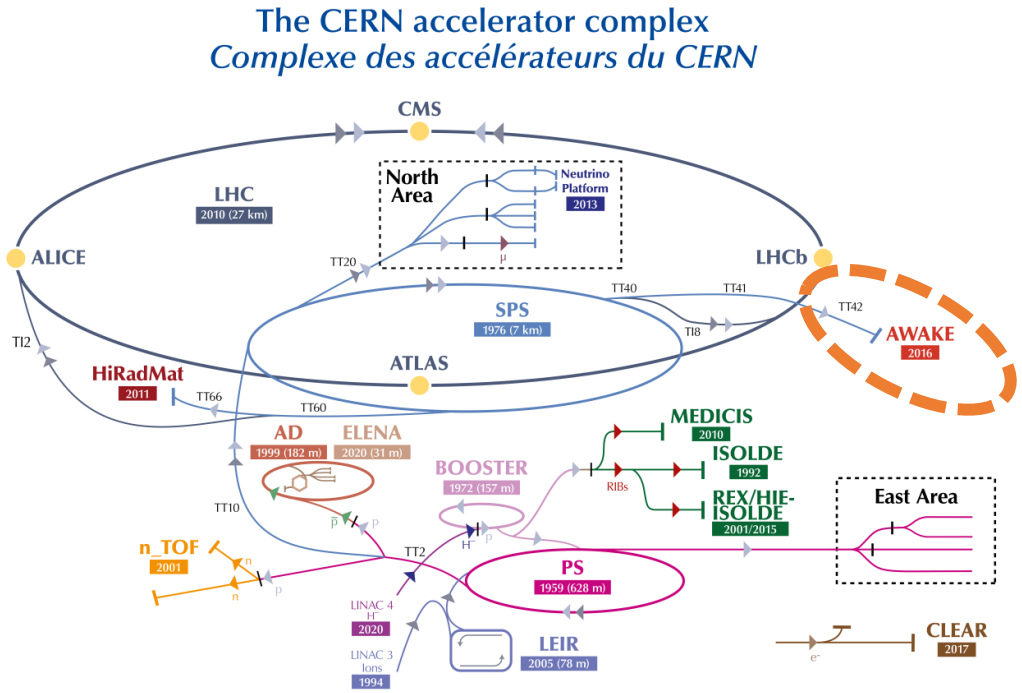
Self-Modulation Instability (SMI)



* N. Kumar, A. Pukhov, and K. Lotov, *Phys. Rev. Lett.* 104, 255003 (2010)

Image from F. Batch *PhD thesis*

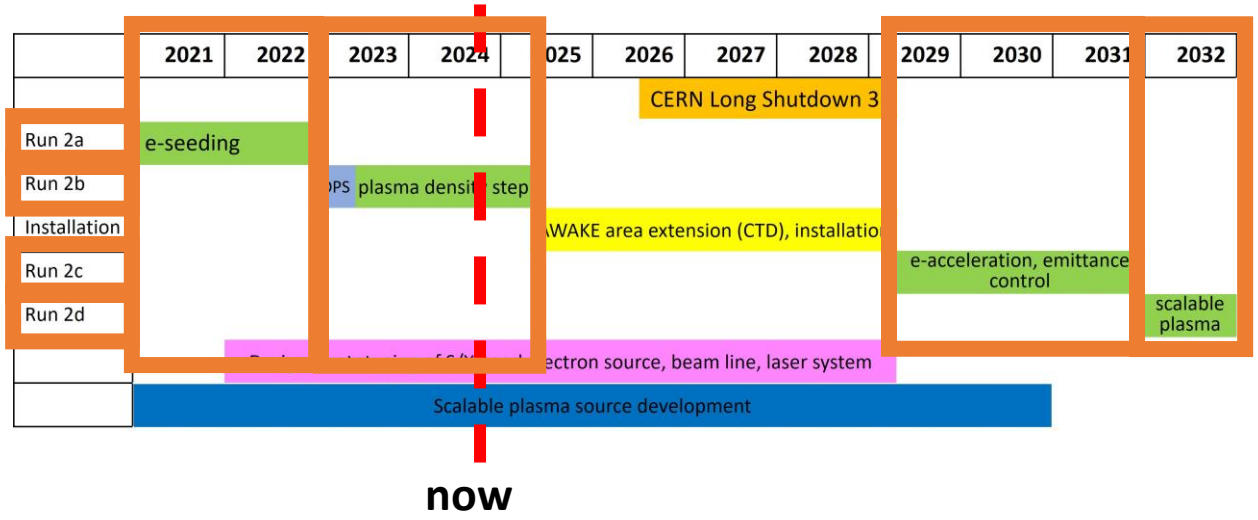
AWAKE is a plasma wakefield acceleration experiment using a proton driver



SPS Driver (19 kJ):
~ 200 GeV in ~200 m
~ 10^9 e^-

Clear Timeline Towards an Accelerator

(2016-2018)
Run 1
Proof-of-principle



→ Possible particle physics applications

➢ **AWAKE Run 2: → transition from proof-of-principle to applications (including LS3 shift)**

- **Run 2a:** Demonstrate the **seeding** of the self-modulation of the entire proton bunch with an **electron bunch**

now

- **Run 2b: Maintain large wakefield amplitudes** over long plasma distances by introducing a **step** in the plasma density

2029

- **Run 2c *:** Demonstrate electron acceleration and **emittance control** of externally injected electrons

2032

- **Run 2d *:** Development of **scalable plasma** sources to 100s meters length with sub-% level plasma density uniformity.
- **Possible first applications for particle physics experiments with 50-200 GeV electron bunches**

*** AWAKE Run 2c and 2d has been approved in this year's MTP**

ESPP Roadmap

Advanced Accelerator Community

R. Pattathil,
presented at EAAC 2023

Single-stage accelerators (proton-driven)

Timeline (approximate/aspirational)		
0-10 years	**10-20 years**	**20-30 years**
Demonstration of: Preserved beam quality, acceleration in very long plasmas, plasma uniformity (longitudinal & transverse)	**Fixed-target experiment (AWAKE)** Dark-photon searh, strong-field QED experiment etc. (50-200 GeV e-)	R&D (exp & theory); HEP facility
	Demonstration of: Use of LHC beams, TeV acceleration, beam delivery	**Energy -frontier collider** 10 TeV c.o.m electron-proton collider

Single/multi-stage accelerators for light sources (electron & laser-driven)

0-10 years
Demonstration of: ultra-low emittances, high rep-rate/high efficiency e-beam and laser drivers, Long-term operation, potential staging, positrons **(EuPRAXIA)**

AWAKE is part of the ESPP process

Multi-stage accelerators (Electron-driven or laser-driven)

Timeline (approximate/aspirational)				
0-5 years	**5 - 10 years**	**10-15 years**	**15-25 years**	**25+ years**
Pre-CDR (HALHF) Simulation study to determine self-consistent parameters (demonstration goals)	**Demonstration of:** scalabe staging, driver distribution, stabilisation (active and passive)	**Multistage tech demonstrator** Strong-field QED experiment (25-100 GeV e-)	Facility upgrade	Feasibility study; R&D (exp & theory); HEP facility (earlist start of construction)
	Demonstration of: High wall-plug efficiency(e- -drivers), preserved beam quality & spin polarization, high rep.rate, plasma temporal uniformity & cell cooling		**Higgs Factory (HALHF)** Asymmetric, plasma-RF hybrid collider (250-380 GeV c.o.m)	Facility upgrade
	Demonstration of: Energy-efficient positron acceleration in plasma, high wall-plug efficiency (laser-drivers), ultra-low emittances, energy recovery schemes, compact beam delivery systems			

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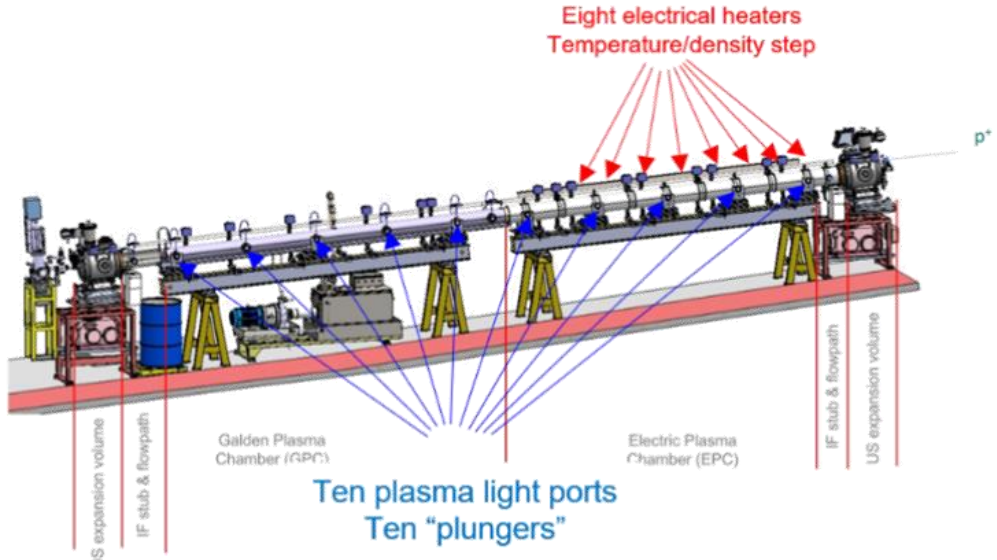
Results from 2024 experiments

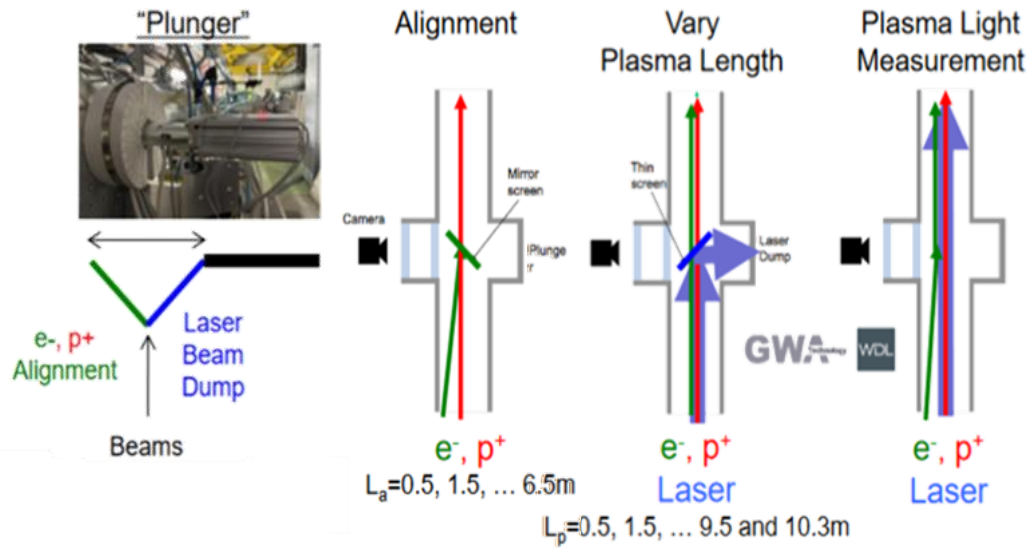
(Year 2 of Run 2b)

Plasma source upgrade, plungers' installation

Plungers installed and **commissioned on schedule** in June 2024:

- **Align e^- and p^+ beams** inside plasma source for :
  - Acceleration, side injection
  - e^- Seeding of Self-Modulation (e^- SSM)
  - e^- Seeding of hosing
- **Vary plasma length** to perform:
  - **Acceleration gradient** measurements
  - Growth of the wakefields
  - Growth of hosing

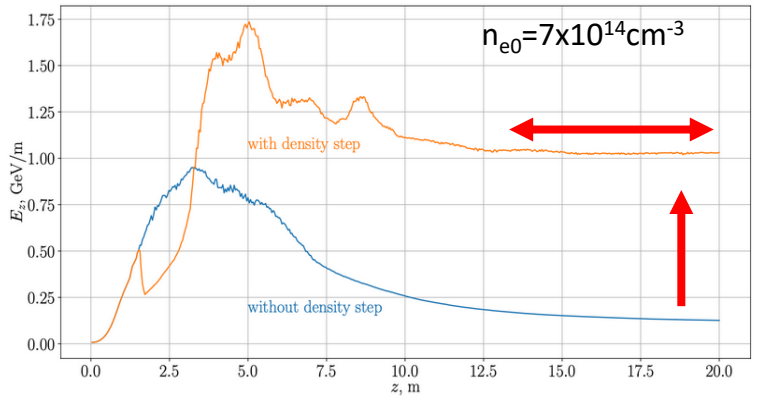




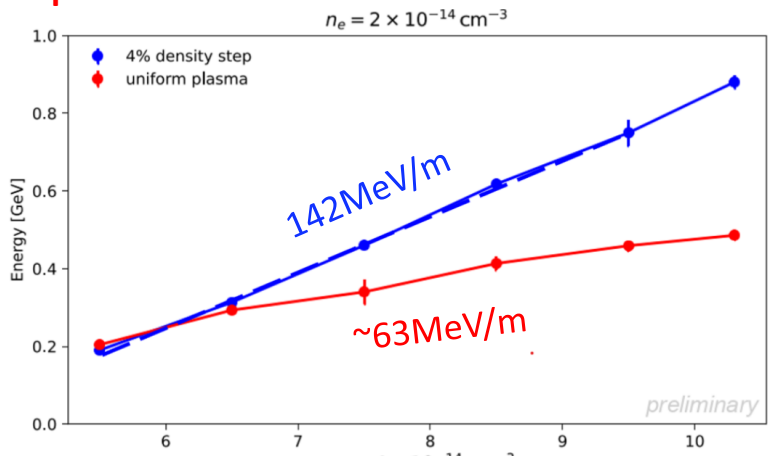
Physics studies in 2024

Plasma density step increases energy gain, constant acceleration gradient

Plasma density (up) step to **make E_z** and **acceleration constant past the SM saturation point**



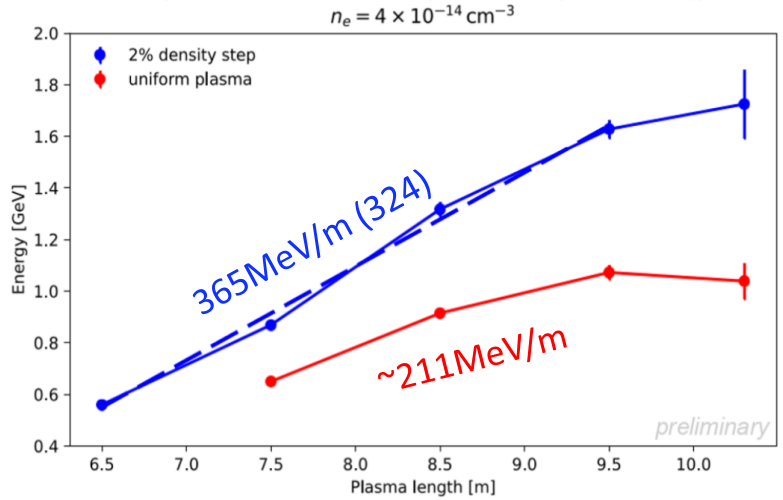
AWAKE status report 2024, https://cds.cern.ch/record/2917426/files/SPSC-SR-356.pdf



880MeV

Step-up

486MeV



1.73GeV

Step-up

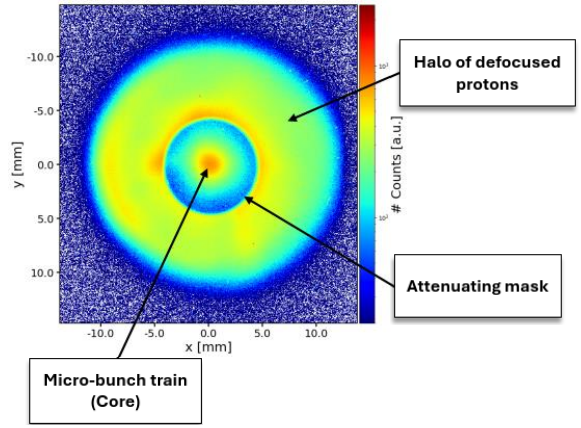
1.04GeV

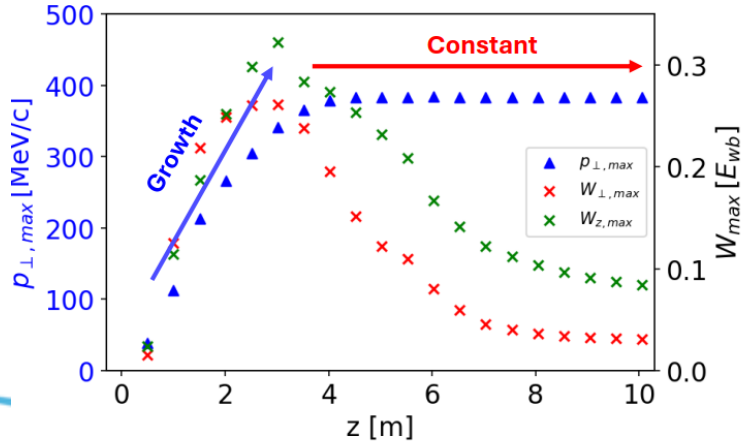
- **Clear increase in final energy** (L_p=10.3m): 1.04 → 1.73GeV
- **Clear increase in accelerating gradient:** ~211 → 365MeV/m

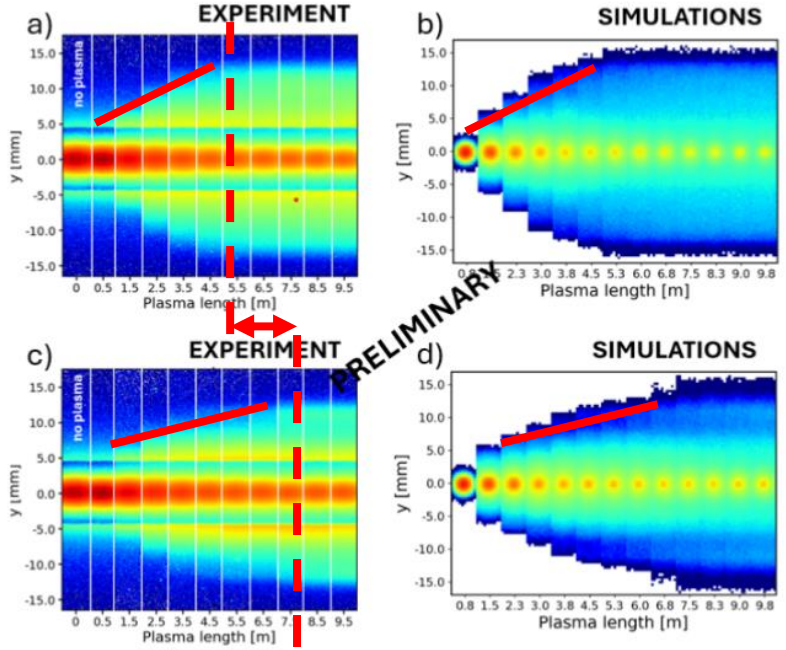
Physics studies in 2024

Growth of the wakefields: SM saturates in less than 10m => Self-modulator for Run 2c

Halo radius shows Self-Modulation saturation length







Constant density plasma

$N_b = 3 \times 10^{11}$

$n_{pe} = 2 \times 10^{14}$/cc

RIF +100ps

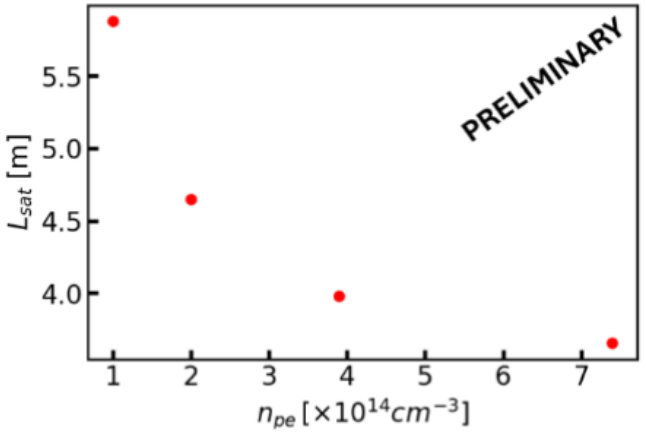
Plasma with density step

$N_b = 3 \times 10^{11}$

$n_{pe} = 2 \times 10^{14}$/cc

RIF +100ps

4% step

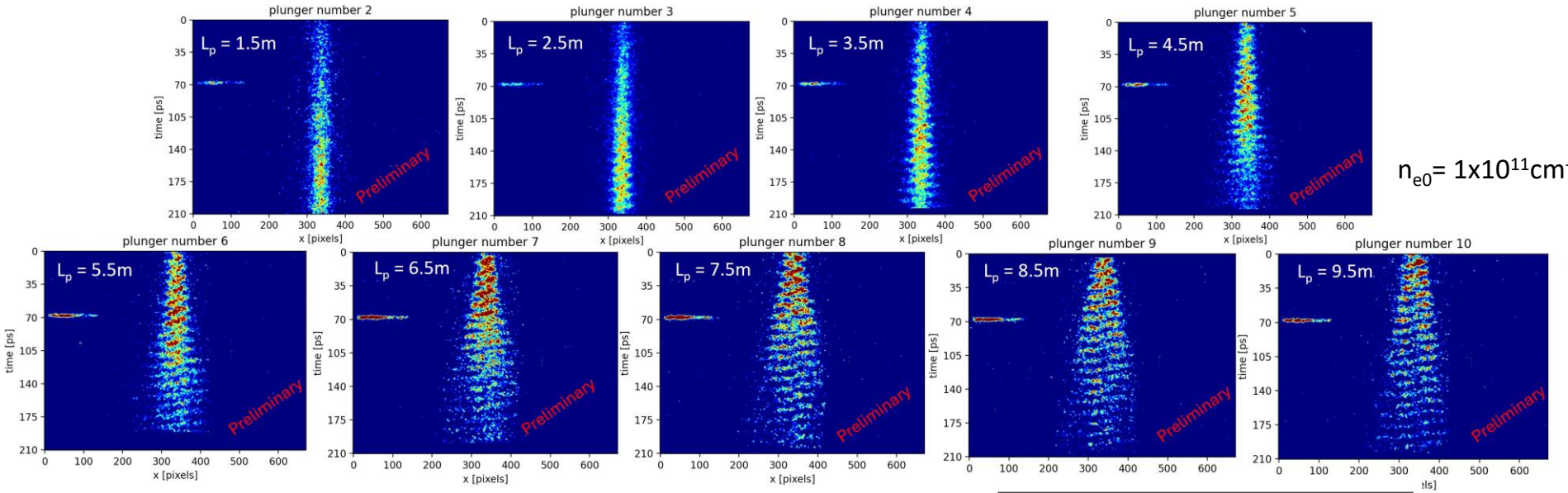


Dependency of saturation length on plasma density

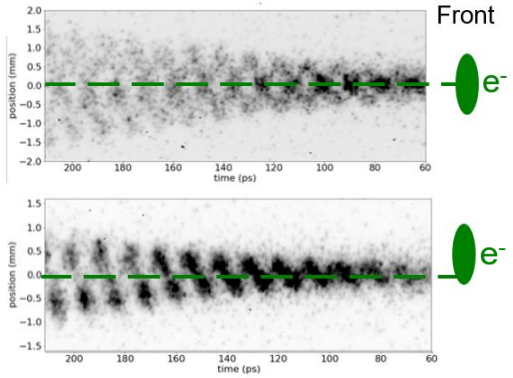
Physics studies in 2024

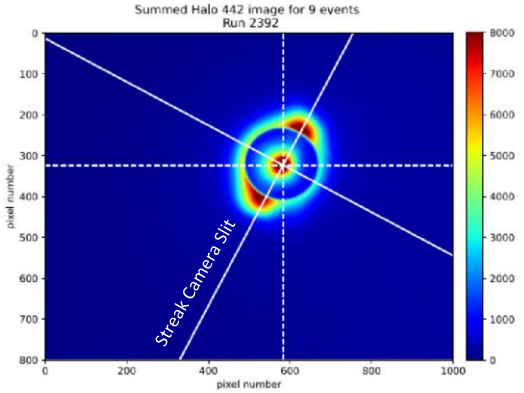
Growth of hosing: understand and control as it must be suppressed

Hosing grows along the plasma, seeded by misaligned e-bunch



n_{e0}= 1x10^{11}cm^{-3}

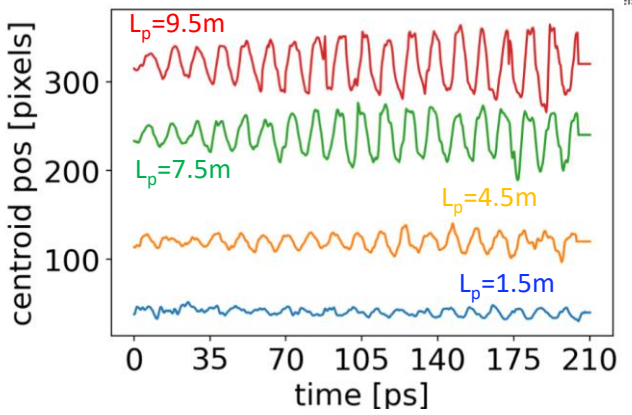




Clear growth: time-resolved images

Hosing in the plane of misalignment: time-integrated images

- Plane of the streak camera slit

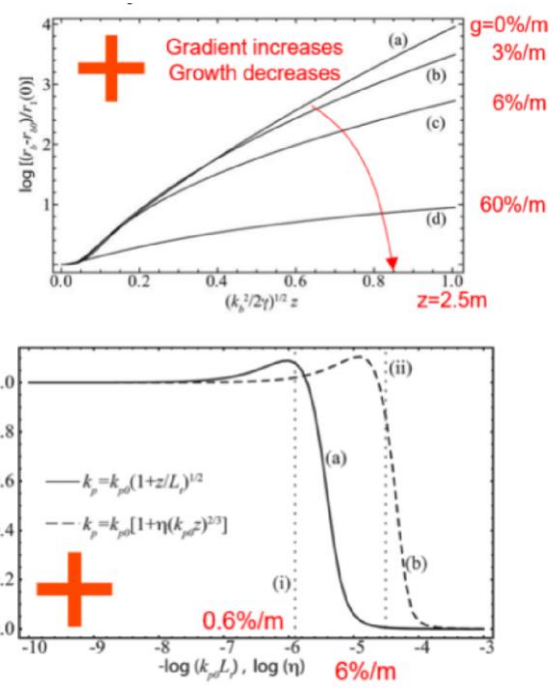


Physics studies in 2024

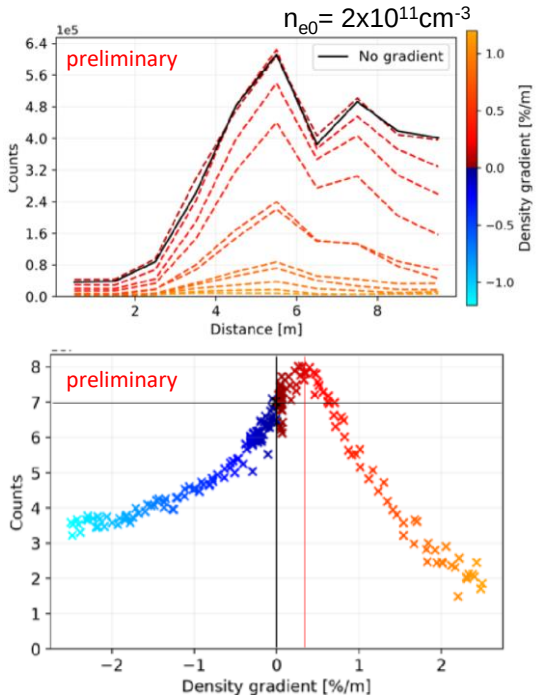
Effect of density gradient on Seeded Self-Modulation

SM can be detuned and suppressed by (linear) density gradients

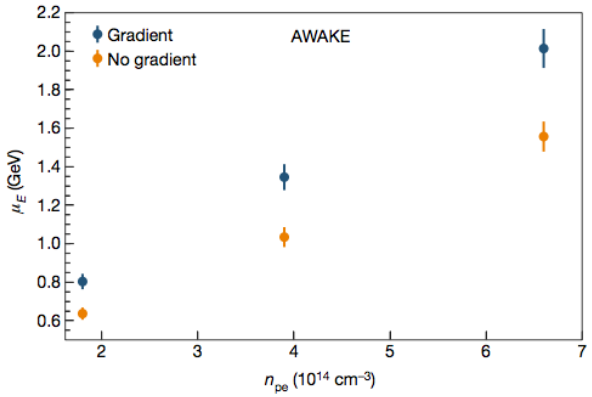
Theory predictions



Plasma Light Measurements



Acceleration results (Run 1)



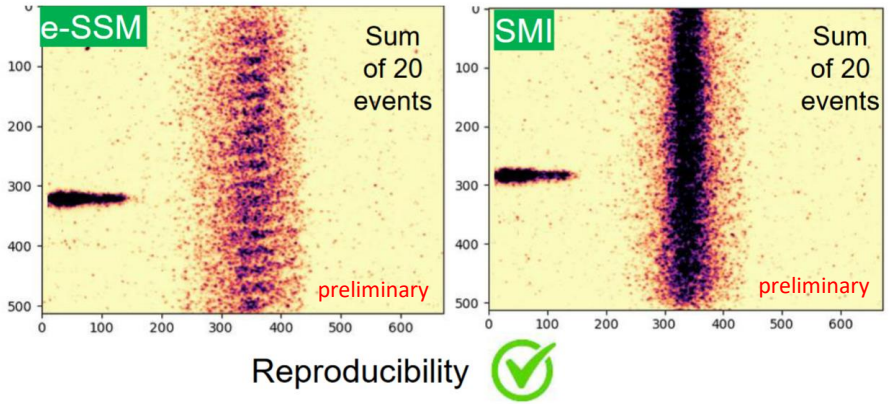
C. B. Shroeder et al., *Phys. Plasmas* 19, 010703 (2012)

- **Clear observation of SM suppression**: light, halo and time-resolved (not shown) diagnostics
- **Asymmetry** positive/negative gradients
- **Higher fields** with small positive gradient **consistent with higher energy gain observation**

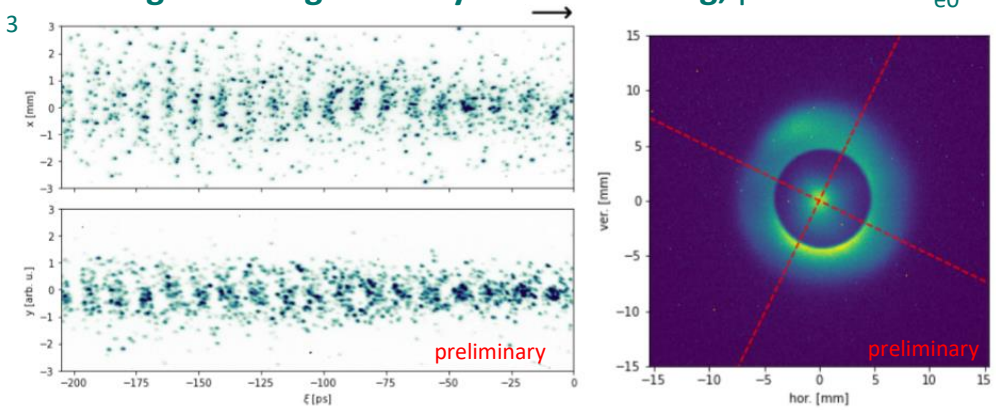
Physics studies in 2024

Several other measurements where possible

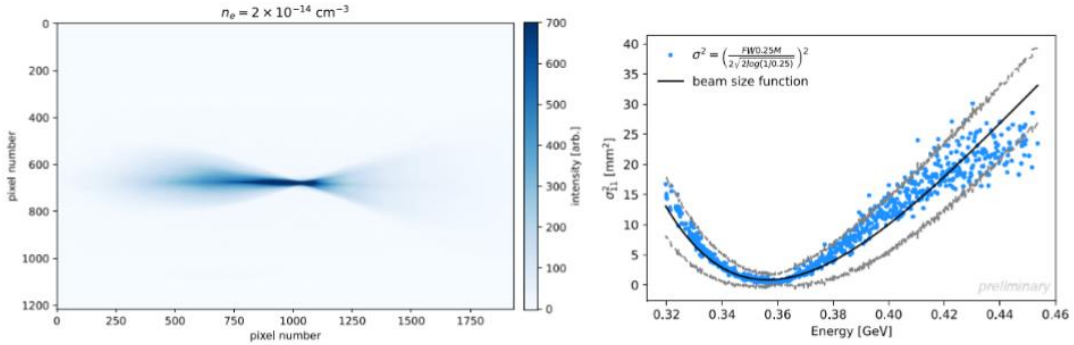
e⁻ Seeding SM with n_{e0}=7x10^{14} and N_{p+}=1x10^{11}



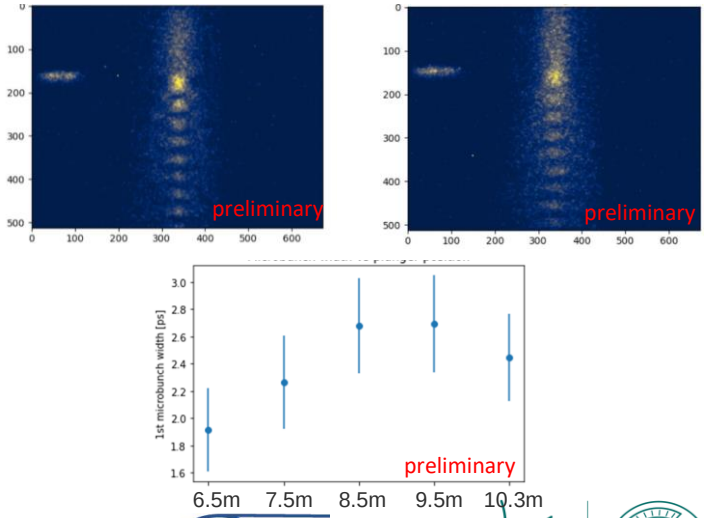
e⁻ Seeding SM at high density without hosing, possible at n_{e0}=1x10^{14}cm^{-3}



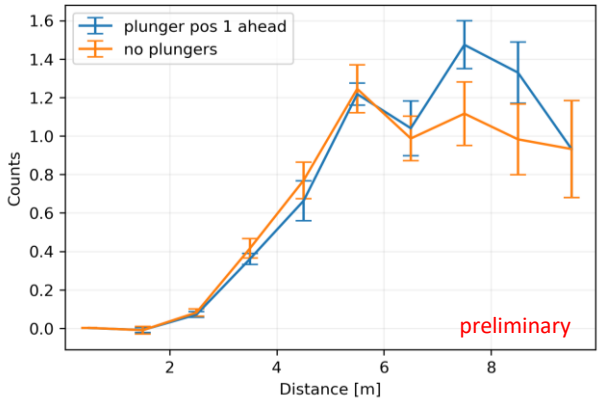
Proof-of-principle of single-shot emittance measurement



First micro-bunch evolution along the plasma



Plasma light emission along the plasma



Run plan and measurement program 2025

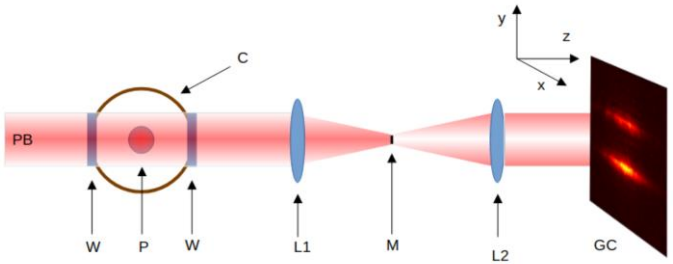
CERN LS3 has been postponed:

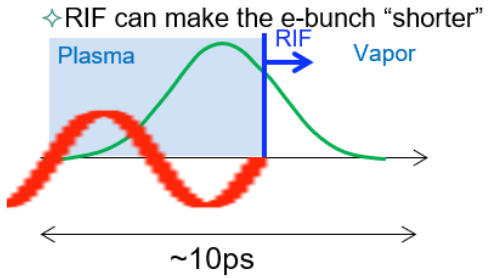
- Take advantage of YETS: experiment with e^- beam and laser pulse
- Experiment in 2025 with p^+ beam

Measurements during YETS

- **Laser propagation and ionization experiments for plasma column characterization (Wigner/MPP):**
  - Transverse measurement of the plasma column : Schlieren imaging to study evolution of plasma radius
  - Longitudinal measurements: back-propagating blue light (2024/2025) -> determine fractional ionization
  - Simultaneous measurement of plasma light, of the laser envelop with different plasma density steps

- **Electron beam :**
  - Further e-beam characterization studies, e^- beam alignment preparation for seeding/hosing studies
  - Experiment with e^- beam in **plasma**, including Relativistic Ionization Front (RIF) in e^- beam. Monitor plasma light (for e-beam seed level) function of laser/ e^- beam delay + e^- beam deceleration





Run2b: 2025 Measurement Program

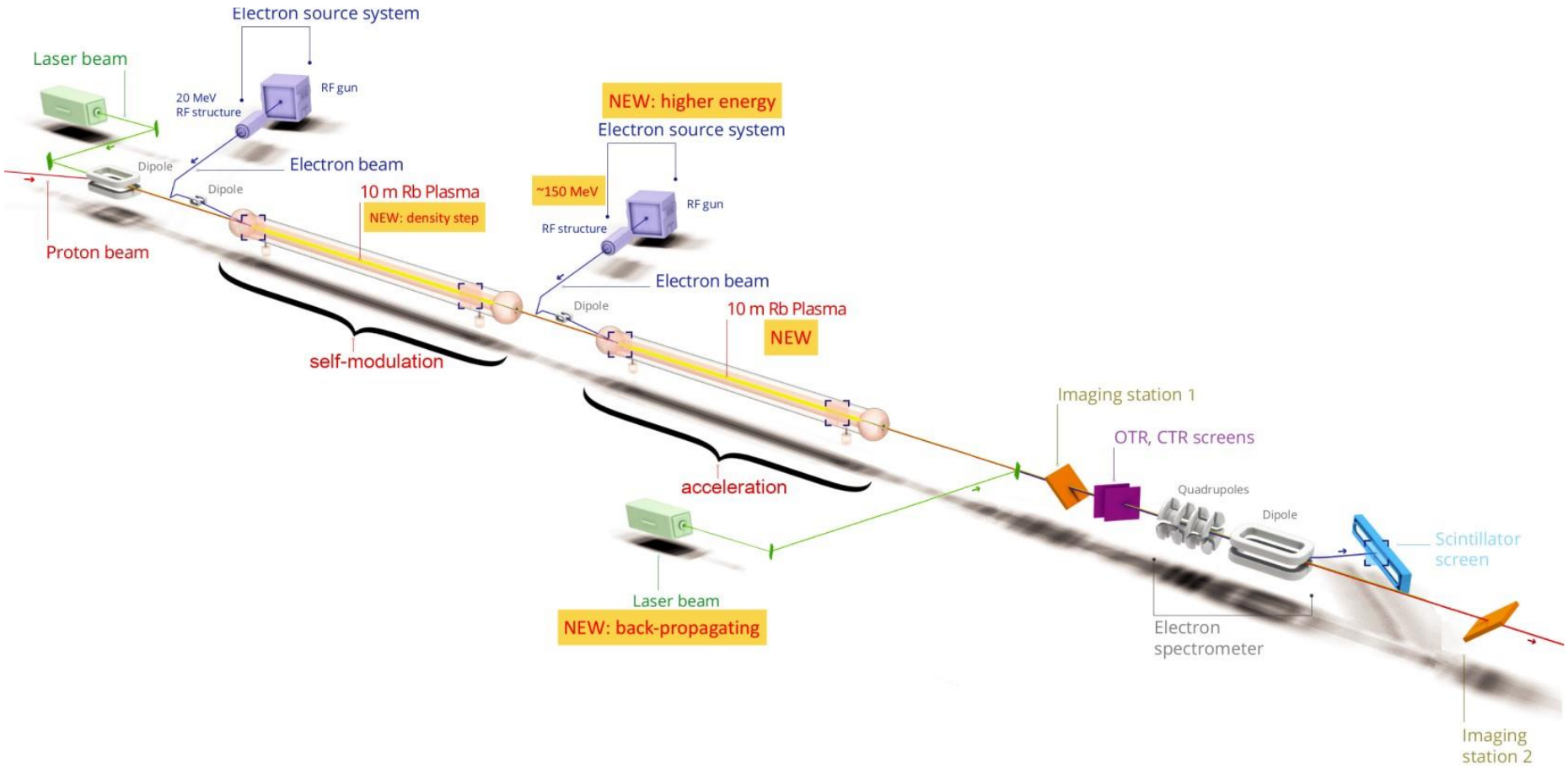
- Programmatic points to address for Run2c :
  - **e^- beam seeding** at **high density without hosing** and high p^+ bunch population
  - **Sensitivity** to misalignment of **hosing**
  - Emittance measurements, effect of **plasma density ramp** at plasma end

- Physics studies for plasma acceleration:
  - **Asymmetry** in **Self-Modulation suppression** with plasma density gradient
  - **Plasma e^- filament** formation in density ramp
  - **Growth** of **Self-Modulation** versus plasma length
  - **Growth** of **hosing** versus plasma length

2025 Beam time request

- AWAKE requests **5 weeks** of proton time:
  - **No beam in 2026** for CNGS Target area Dismantling (CTD), because of shift of LS3
  - Experiment need to **stop running by 2 June** for the AWAKE decommissioning as AWAKE de-cabling campaign must happen before YETS 2025 to allow for CTD to start
  - Starting in 2025 as soon as SPS can deliver beam to AWAKE
  - 2 blocks of proton run; 2 weeks + 3 weeks separated by 1 week of no beam
- **Last opportunity for experiments, before a long stop** (proton beam back in 2029):
  - To **explore more in details parameters for Run 2c** (e^- beam seeding)
  - Also **interesting for all plasma acceleration community** (seeding, hosing, injections..)
- For the physics program we need stable conditions, i.e. continuous AWAKE cycle in the super-cycle, with no interruptions
  - Important: reproducible, high-quality beam
- Operation for a maximum of 14 hours a day (typically around ~10 hours)
  - Ask to be removed from super cycle when not using beam for >1hr.

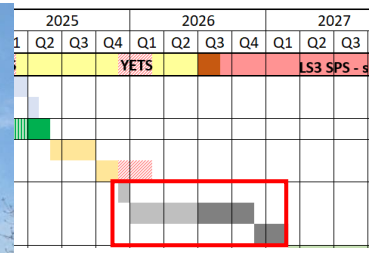
Ongoing preparation for Run 2c



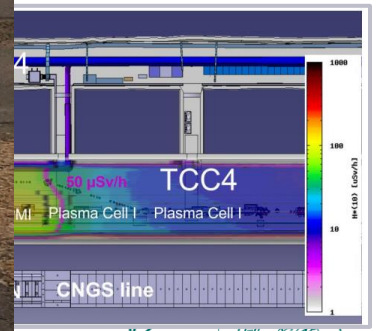
CNGS

Set-up of wo area

- Checking all requirement a met (evacuatio sirens, tempor wifi, etc.)
- SAS installatio
- Protection of TCC4 (floors, walls, etc.)
- Removing AWAKE-CNGS separation wal



Cleaning & decontamination



t dose rate after CFD

AWAKE

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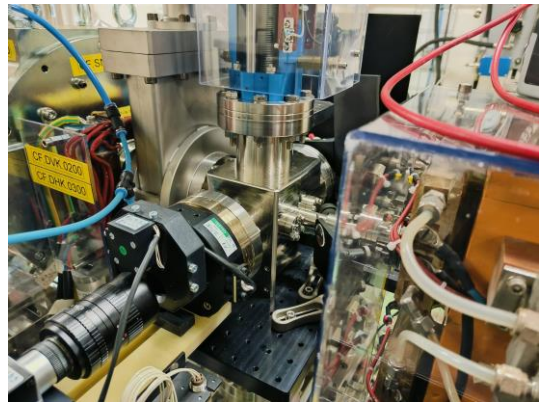
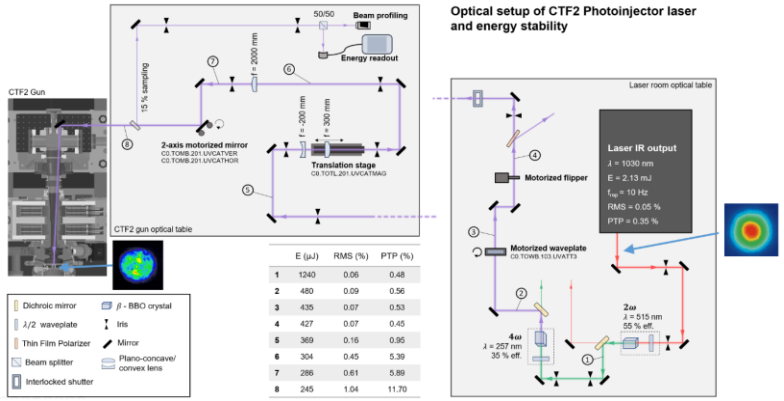
Additional Run 2c, 2d Preparations

- New electron source
  - Successful commissioning of the prototype RF-gun with beam for 150MeV e^- beamline



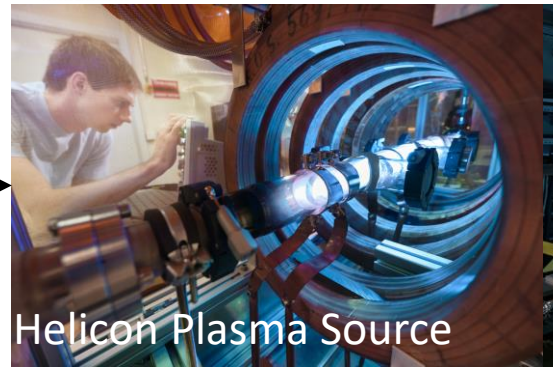
- Beam instrumentation upgrade
  - collaboration with institutes

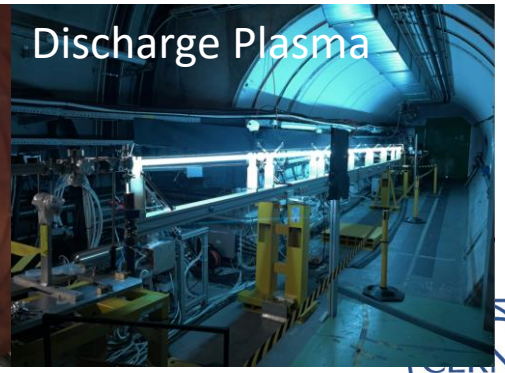


- Beam transport line upgrades
  - Electron, laser and proton

- Simulation studies

- Scalable plasma source R&D
  - collaboration with institutes





Summary

Latest publications

- D.A. Cooke et al. (AWAKE Collaboration), Measurement of the emittance of accelerated electron bunches at the AWAKE experiment, arXiv:2411.08681 (2024)
- M. Turner, et al. (AWAKE Collaboration), Experimental Observation of Motion of Ions in a Resonantly Driven Plasma Wakefield, arXiv:2406.16361 (2024)
- L. Verra, et al. (AWAKE Collaboration), Filamentation of a relativistic proton bunch in plasma, Phys. Rev. E 109, 055203 (2024)
- Nechaeva, et al. (AWAKE Collaboration), Hosing of a long relativistic particle bunch in plasma, Phys. Rev. Lett. 132, 075001 (2024)
- C. Stollberg, et al., First Thomson scattering results from AWAKE's helicon plasma source, *Plasma Phys. Control. Fusion* 66 115011 (2024)
- H. Saberi, et al., Elevating electron energy gain and betatron x-ray emission in proton-driven wakefield acceleration, *Phys. Plasmas* 31, 093104 (2024)
- E. Walter, et al., Wakefield-driven filamentation of warm beams in plasma, Phys. Rev. E 110, 035208 (2024)
- J. P. Farmer and G. Zevi Della Porta, Wakefield regeneration in a plasma accelerator, arXiv:2404.14175v1 (2024)
- J Farmer *et al* 2024, Preliminary investigation of a Higgs factory based on proton-driven plasma wakefield acceleration, *New J. Phys.* 26 113011 (2024)
- K. Oguzhan, et al. , A decomposition algorithm for streak camera data, *JINST* 19 P04005 (2024)
- M. Martinez-Calderon, et al., Fabrication and rejuvenation of high quantum efficiency caesium telluride photocathodes for high brightness and high average current photoinjectors, Phys. Rev. Accel. Beams 27, 023401 (2024)
- E. Senes, et al., Selective electron beam sensing through coherent Cherenkov diffraction radiation, Phys. Rev. Research 6, 023278 (2024)

An updated list of AWAKE publications is maintained at:
https://twiki.cern.ch/twiki/bin/view/AWAKE/AwakePublic

Summary

- **Highly successful** installation and commissioning with the **upgrade of Rb vapor source (plungers)**
  - Improved operations efficiency and precision for e^- beam/proton alignment
  - Acquired several important and interesting experiment results
  - **Many physics measurements performed**
  - Observed clear effect of density step, **stabilization of acc. gradient** at higher level and **energy gradient increased**
  - Possible to study directly the growth of self-modulation along plasma
  - Possible to study directly the growth of hosing along plasma
- LS3 postponed:
  - **Experiment** with laser/electron and plasma **during YETS**
  - **Beam request for 2025** to define parameters for Run 2c
- Continue **clear plan** towards applications to particle physics in 2030's
- **Clear scientific program**
  - Run 2b: plasma density step
  - Run 2c: external injection of e-bunch in second plasma, quality
  - Run 2d: operation with acceleration in scalable plasma source

Thank you for your attention