2023 AWAKE Run Results

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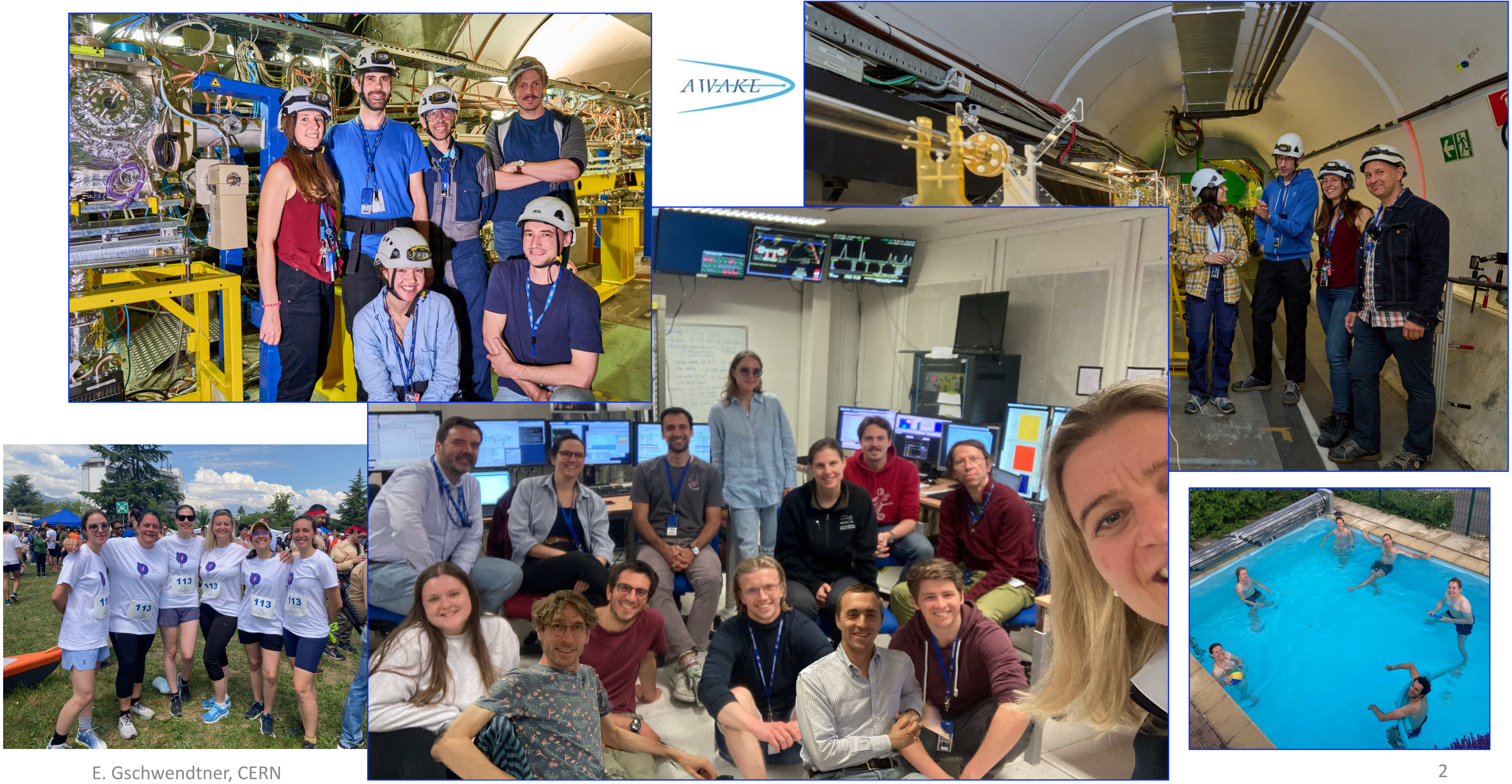
For the AWAKE Collaboration

6th European Advanced Accelerator Concepts Workshop,
La Biodola, Elba, Italy, September 17 – 23, 2022

Many thanks to valuable input from C. Amoedo, M. Bergamaschi, A. Clairembaud, J. Farmer, J. Mezger, P. Muggli, A. Sublet, N. Torrado, M. Turner, G. Zevi Della Porta

Many Thanks to the Fantastic AWAKE Team!

AWAKE

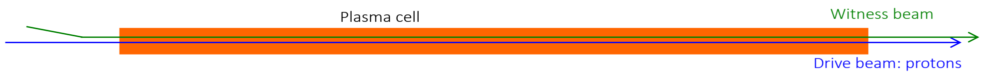


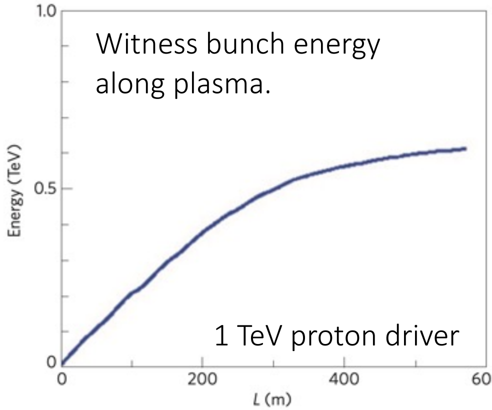
Outline

- Introduction
- The AWAKE Experiment
- AWAKE Run 2 Program
- Unique Opportunity of a Proton Run with the Discharge Plasma Source
- First Proton Runs with the New Vapor Plasma Source
- Summary

Introduction: Plasma Wakefield Accelerators – Proton Driven

Proton drivers: large energy content in proton bunches
SPS protons: 19kJ/pulse, LHC protons: 300kJ/pulse
(lasers/electron drivers: 10s J/pulse)
➔single stage acceleration to accelerate electrons to TeV level





A. Caldwell et al., Nature Phys. **5**, 363–367 (2009)

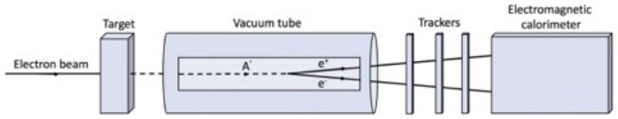
With existing proton beams the energy frontier with electrons can be reached!

- SPS p^+ (450 GeV): accelerate to 200 GeV electrons.
- LHC p^+ can yield to 3 TeV electrons

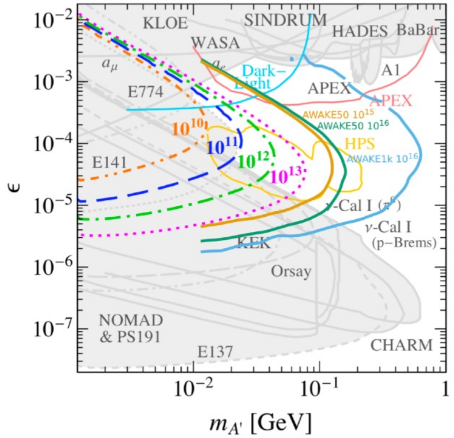
Many opportunities for first particle physics applications in the nearer future:

→ Beam quality sufficient for **fixed target experiments**

➔ **Beam Dump Experiment:** Search for dark photons.



→ Decay of dark photon into visible particles (e.g. e+/e-)



→ Extension of mixing strength of the kinematic coverage for 50 GeV electrons and even more for 1 TeV electrons

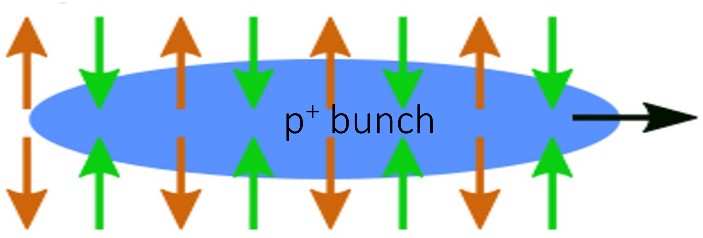
Introduction: Self-Modulation of the Proton Beam

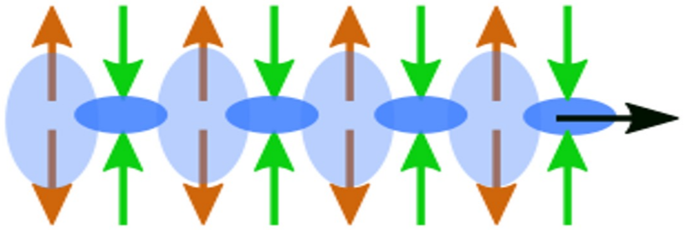
In order to create plasma wakefields efficiently, the drive bunch length has to be in the order of the plasma wavelength.

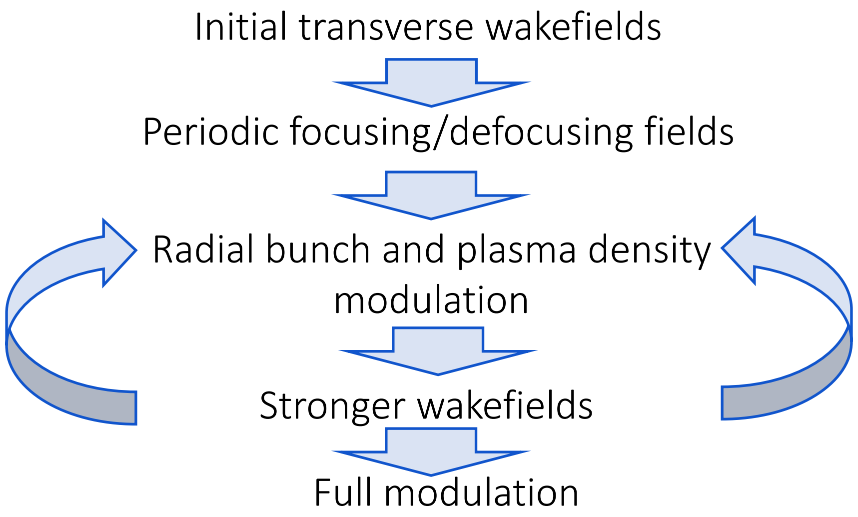
CERN SPS proton bunch: very long! (σ_z = 7 cm) → much longer than plasma wavelength (**λ = 1mm, in AWAKE**)

N. Kumar, A. Pukhov, K. Lotov,
PRL 104, 255003 (2010)

Self-Modulation Instability:







Initial transverse wakefields

Periodic focusing/defocusing fields

Radial bunch and plasma density modulation

Stronger wakefields

Full modulation

Density modulation on-axis → **micro-bunches**.

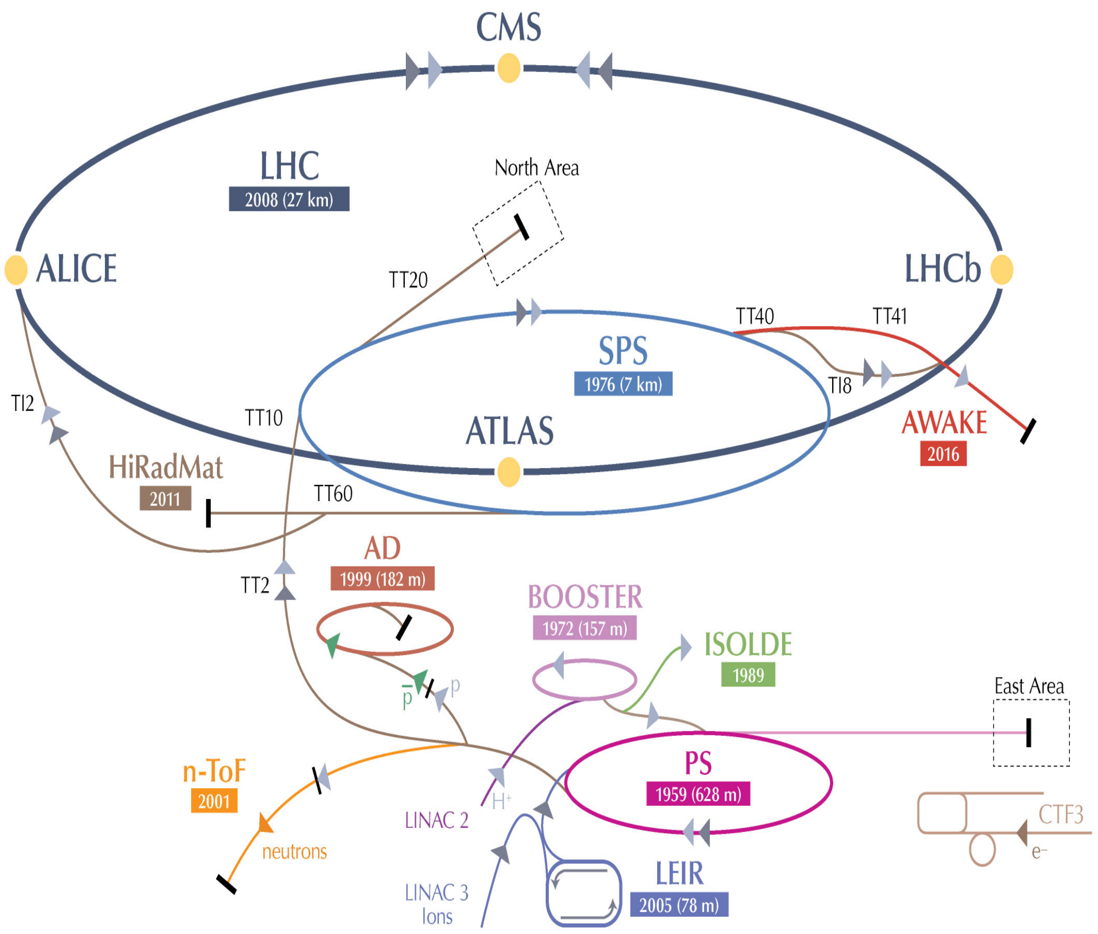
- Micro-bunches separated by λ_{pe}.
- Resonant wakefield excitation
- Large wakefield amplitudes

→ Immediate use of SPS proton bunch for driving strong wakefields!

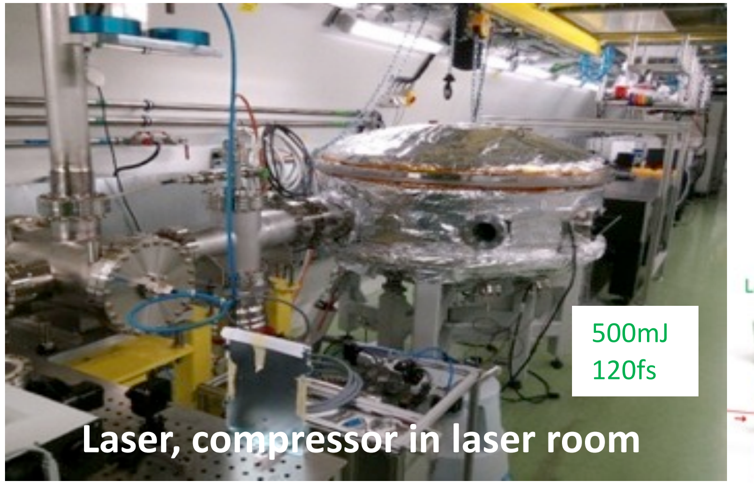
AWAKE at CERN

Advanced WAKEfield Experiment

- Accelerator R&D experiment at CERN to study proton driven plasma wakefield acceleration.
- Collaboration of 23 institutes world-wide

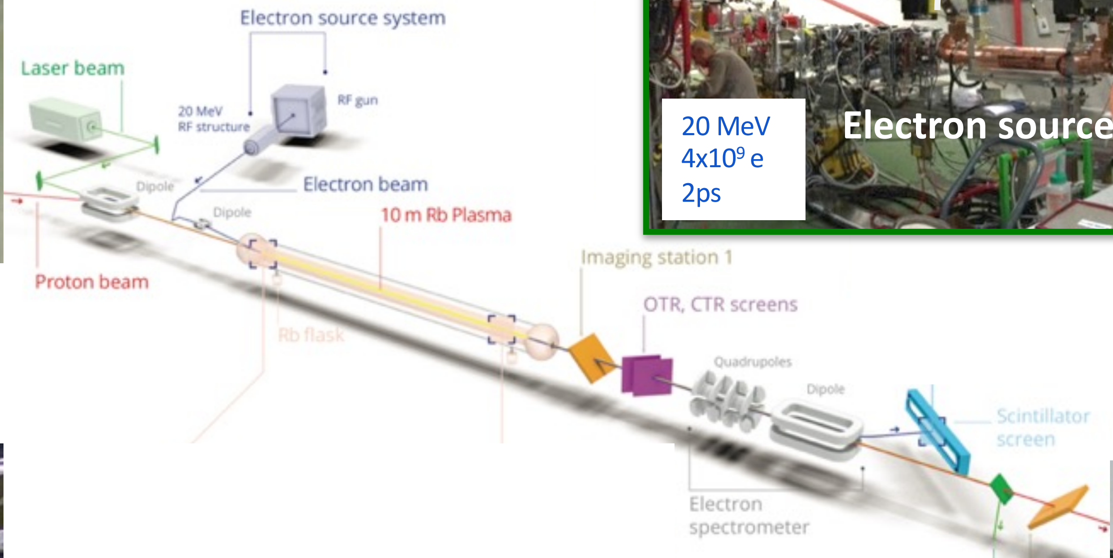


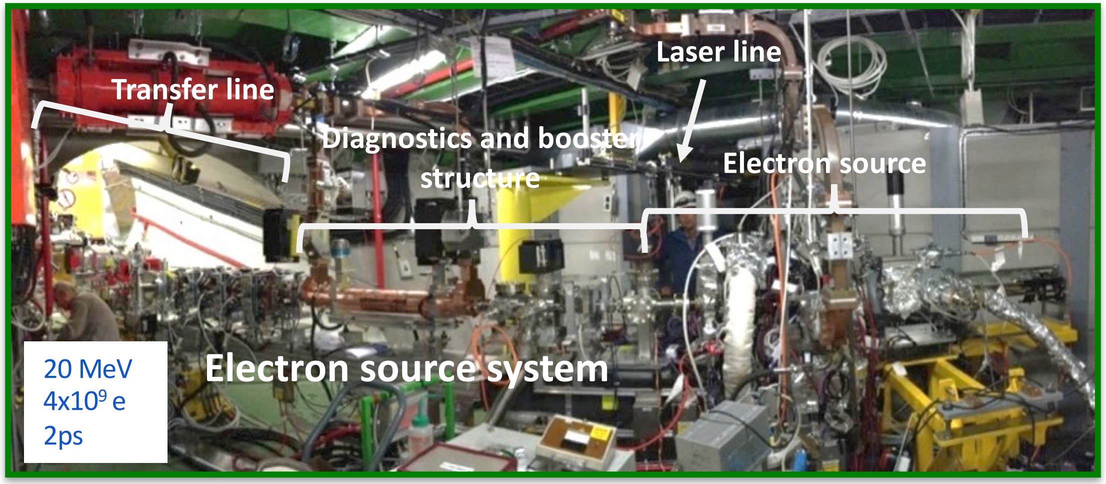
Key Ingredients of AWAKE



500mJ
120fs

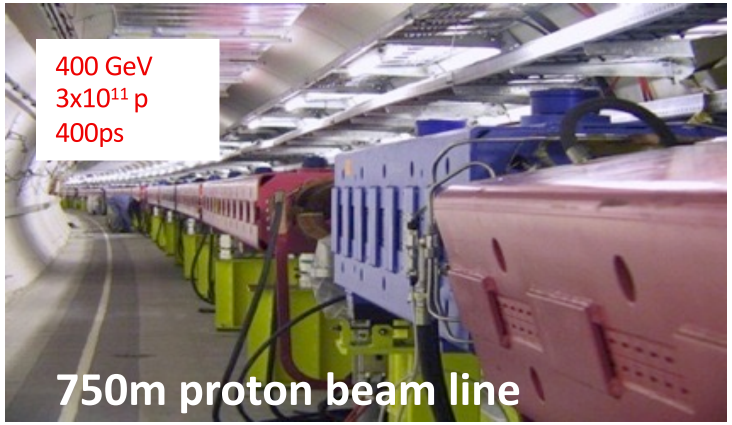
Laser, compressor in laser room





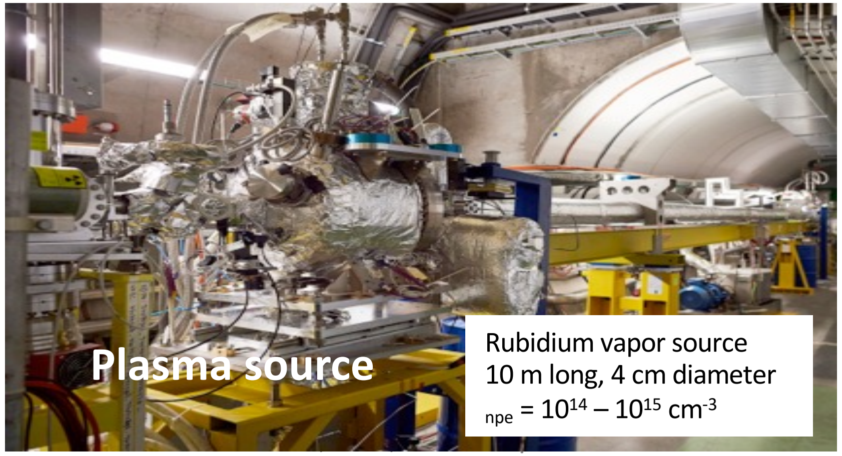
20 MeV
$4x10^9$ e
2ps

Electron source system



400 GeV
$3x10^{11}$ p
400ps

750m proton beam line



Plasma source

Rubidium vapor source
10 m long, 4 cm diameter
$_{npe} = 10^{14} – 10^{15}$ cm^{-3}

Diagnostics

AWAKE Timeline

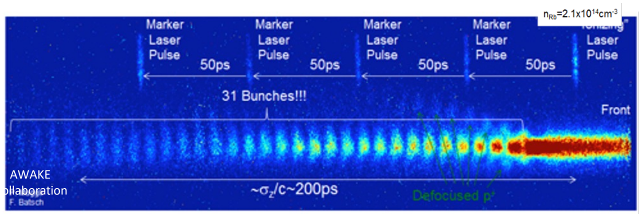
After Run 2: kick-off particle physics driven applications

2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031

AWAKE Run 1: 'Proof-of Concept'

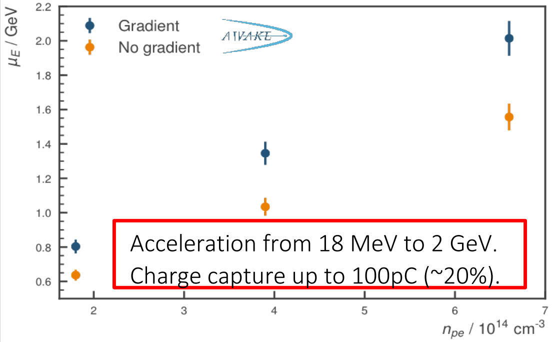
2021 – ~2029: AWAKE Run 2: 'Accelerator':

2016/17:
Seeded Self-Modulation of
proton beam in plasma



AWAKE Collaboration, Phys. Rev. Lett. 122, 054802 (2019).
M. Turner et al. (AWAKE Coll.), Phys. Rev. Lett. 122, 054801 (2019).
M. Turner, P. Muggli et al. (AWAKE Coll.), Phys. Rev. Accel. Beams 23, 081302 (2020)
F. Braunmueller, T. Nechaeva et al. (AWAKE Coll.), Phys. Rev. Lett. July 30 (2020).
A.A. Gorn, M. Turner et al. (AWAKE Coll.), Plasma Phys. Contr. Fus., Vol. 62, Nr 12 (2020).
F. Batsch, P. Muggli et al. (AWAKE Coll.), Phys. Rev. Lett. 126, 164802 (2021).

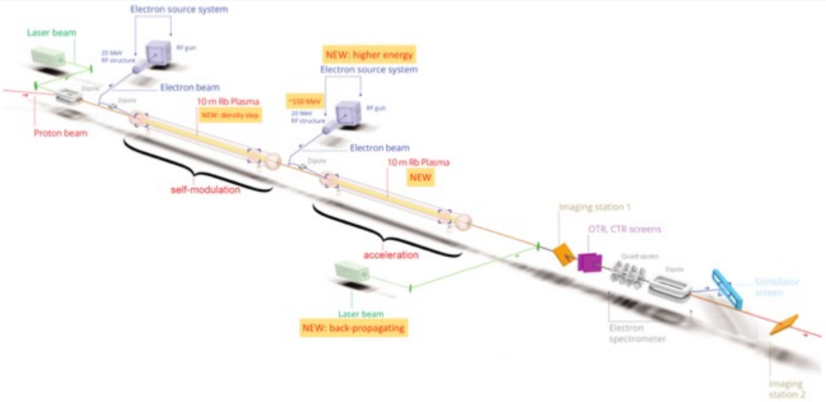
2018:
Electron acceleration
in plasma



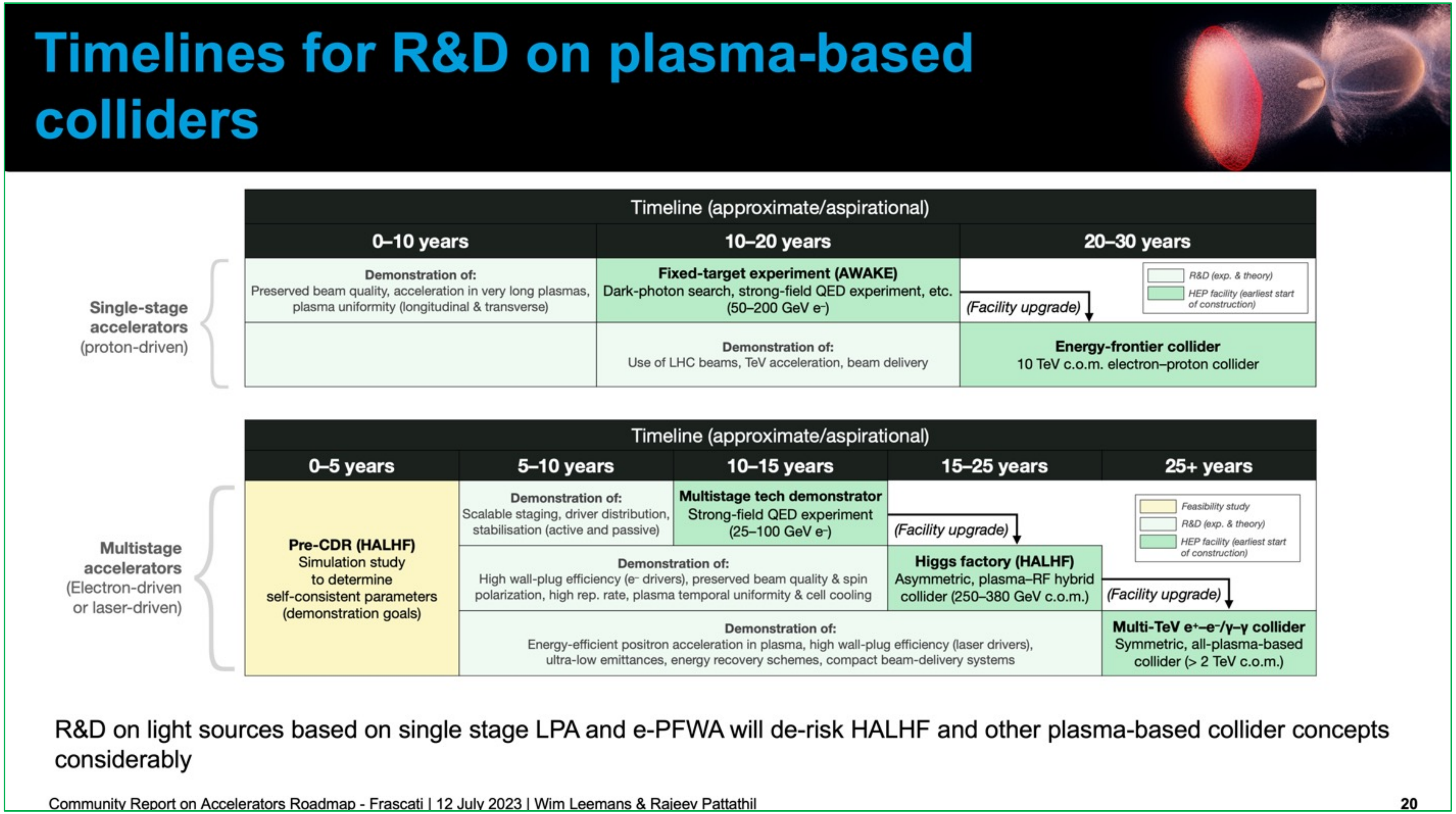
Acceleration from 18 MeV to 2 GeV.
Charge capture up to 100pC (~20%).

AWAKE Collaboration, Nature 561, 363 (2018)

High-charge bunches of electrons accelerated to **high energy (0.5-1 GeV/m),** maintain **beam quality** through the plasma and show **scalability of the process**.



AWAKE – Program



Timelines for R&D on plasma-based colliders

	Timeline (approximate/aspirational)		
	0–10 years	**10–20 years**	**20–30 years**
Single-stage accelerators (proton-driven)	**Demonstration of:** Preserved beam quality, acceleration in very long plasmas, plasma uniformity (longitudinal & transverse)	**Fixed-target experiment (AWAKE)** Dark-photon search, strong-field QED experiment, etc. (50–200 GeV e^-)	*(Facility upgrade)*
		Demonstration of: Use of LHC beams, TeV acceleration, beam delivery	**Energy-frontier collider** 10 TeV c.o.m. electron–proton collider

⬜ *R&D (exp. & theory)*
🟩 *HEP facility (earliest start of construction)*

	Timeline (approximate/aspirational)				
	0–5 years	**5–10 years**	**10–15 years**	**15–25 years**	**25+ years**
Multistage accelerators (Electron-driven or laser-driven)	**Pre-CDR (HALHF)** Simulation study to determine self-consistent parameters (demonstration goals)	**Demonstration of:** Scalable staging, driver distribution, stabilisation (active and passive)	**Multistage tech demonstrator** Strong-field QED experiment (25–100 GeV e^-)	*(Facility upgrade)*	
		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			**Multi-TeV e^+–e^-/γ–γ collider** Symmetric, all-plasma-based collider (> 2 TeV c.o.m.)

🟨 *Feasibility study*
⬜ *R&D (exp. & theory)*
🟩 *HEP facility (earliest start of construction)*

R&D on light sources based on single stage LPA and e-PFWA will de-risk HALHF and other plasma-based collider concepts considerably

Community Report on Accelerators Roadmap - Frascati | 12 July 2023 | Wim Leemans & Rajeev Pattathil 20

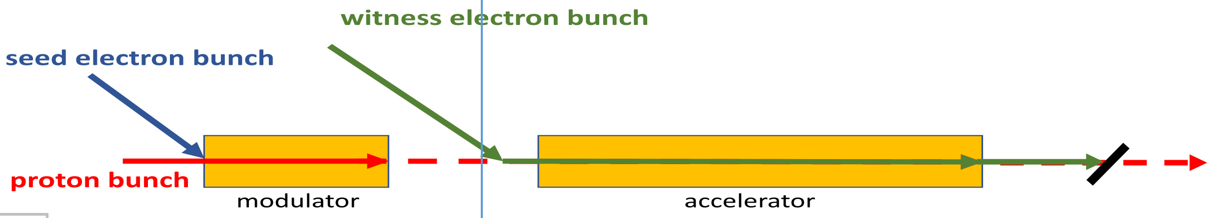
➔ AWAKE is part of the global ESPP

Outline

AWAKE Run 2 – Program Phases

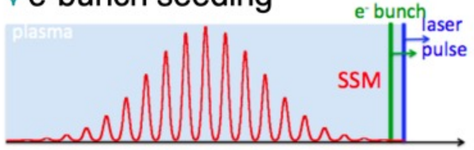
Optimize self-modulation of the proton bunch

Optimize acceleration of electrons in p-driven plasma wakefield



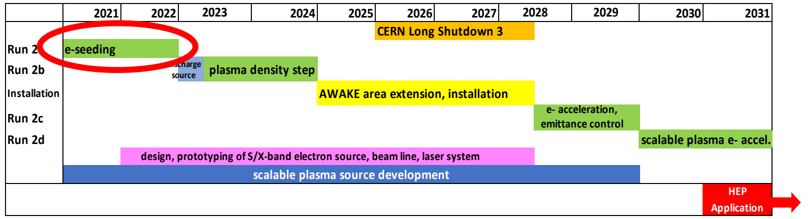
AWAKE Run 2a: self-modulation of entire p-bunch seeded with an e-bunch

✧e-bunch seeding



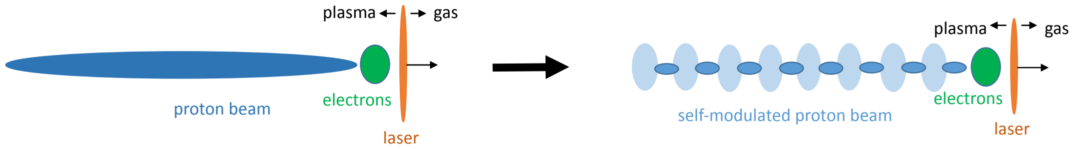
2021-22

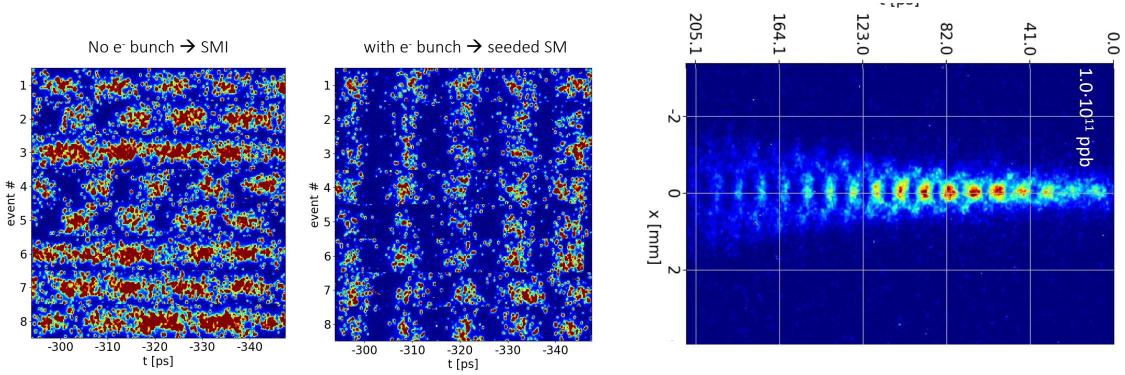
Results AWAKE Run 2a (2021-22)



➔ Electron seeding

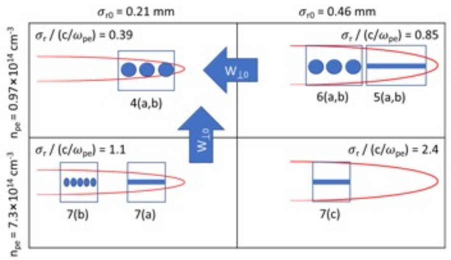
AWAKE Run 2: the entire proton bunch to be modulated before the 2nd cell



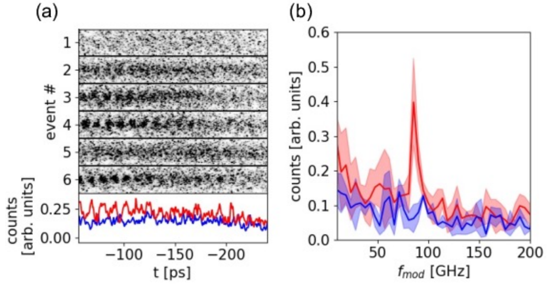


L. Verra et al. (AWAKE Collaboration), Phys. Rev. Lett. 129, 024802 (2022)

➔ SMI development

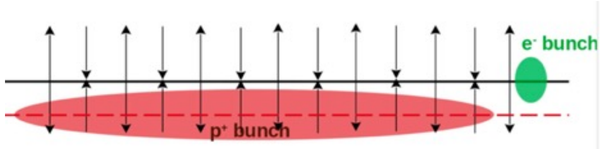


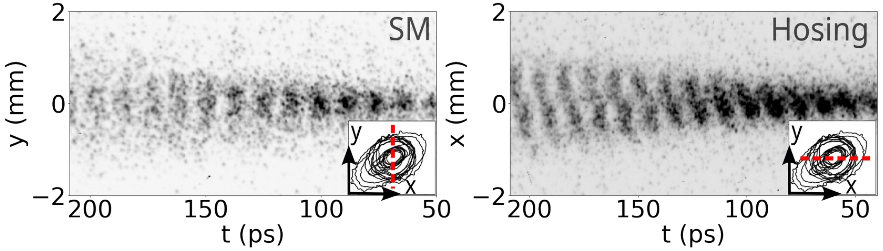
Wide p bunch, later time range.



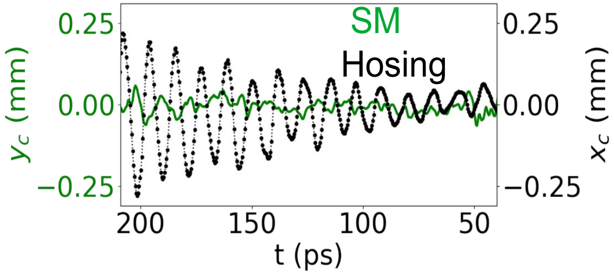
L. Verra, S. Wyler et al. (AWAKE Collaboration), Physics of Plasma 30, 083104 (2023)

➔ Hosing instability





oscillation of the proton bunch centroid position

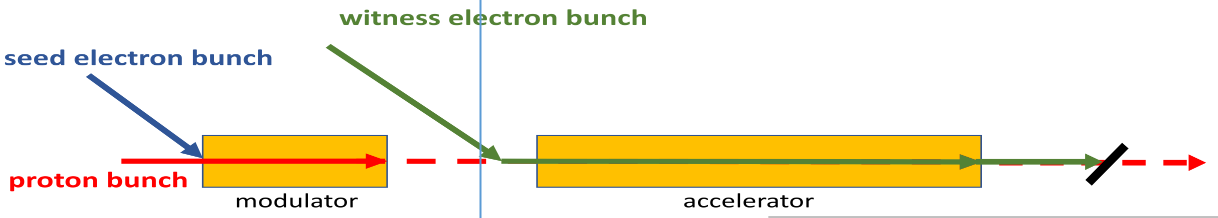


T. Nechaeva, MPP et al. (AWAKE Collaboration), https://arxiv.org/abs/2309.03785

AWAKE Run 2 – Program Phases

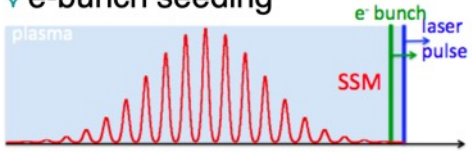
Optimize self-modulation of the proton bunch

Optimize acceleration of electrons in p-driven plasma wakefield



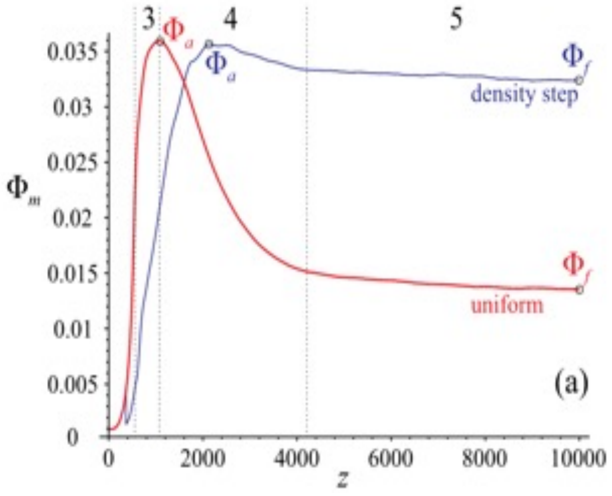
AWAKE Run 2a: self-modulation of entire p-bunch seeded with an e-bunch

✧e-bunch seeding



2021-22

AWAKE Run 2b: stabilization of the micro-bunches with a density step in the plasma cell and maintain high gradient



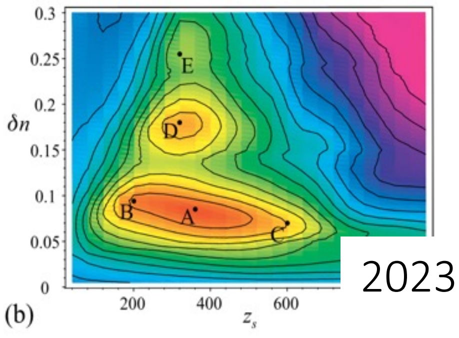


FIG. 4. The map of step efficiencies $\Phi_f(\delta n, z)$ in two projections.

2023-24

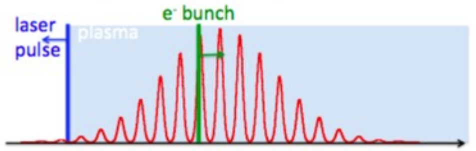
K. V. Lotov, Physics of Plasmas 22, 103110 (2015)
K. V. Lotov and P. V. Tuev 2021 PPFC ***63*** *125027*

AWAKE Run 2c: electron acceleration and emittance control

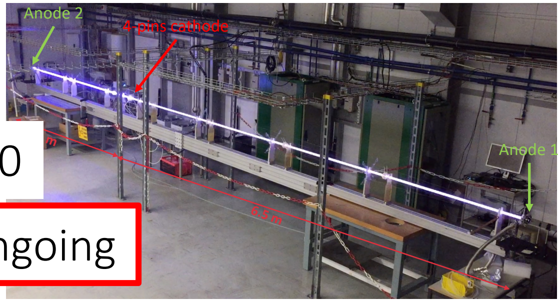
2nd electron source, 150MeV, 200fs

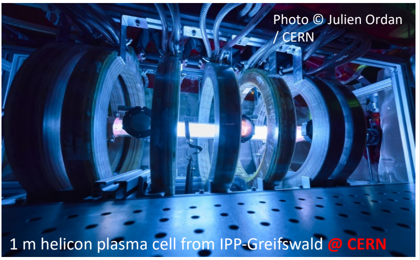
2028-29

✧2nd, pre-formed plasma



AWAKE Run 2d: scalable plasma sources





1 m helicon plasma cell from IPP-Greifswald @ CERN

2029-30

R&D ongoing

➔ See E.G., Talk, Thu WG10

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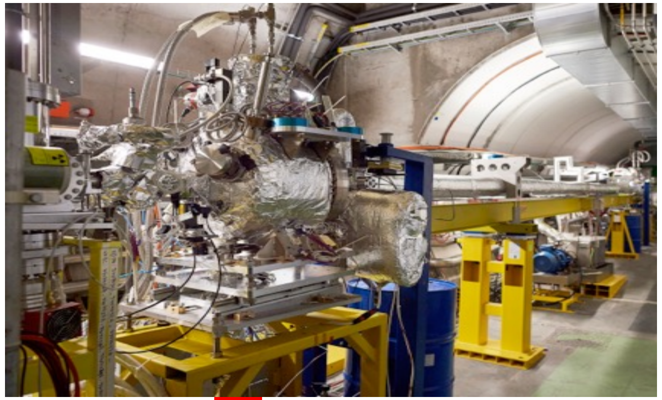
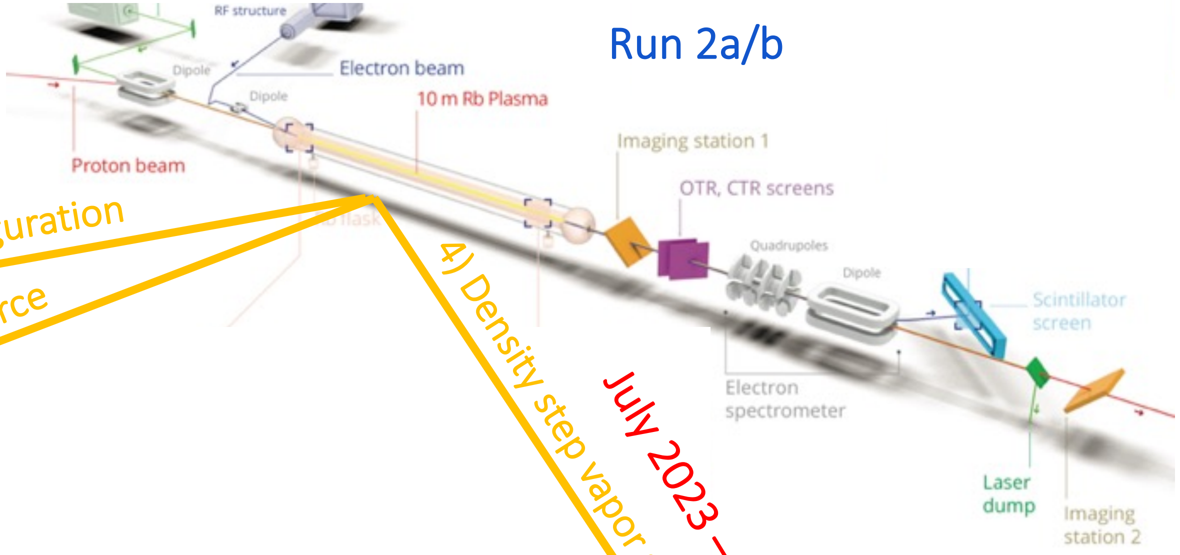
AWAKE Run 2b – 2023/24 Program

Run 2a



Run 2a/b



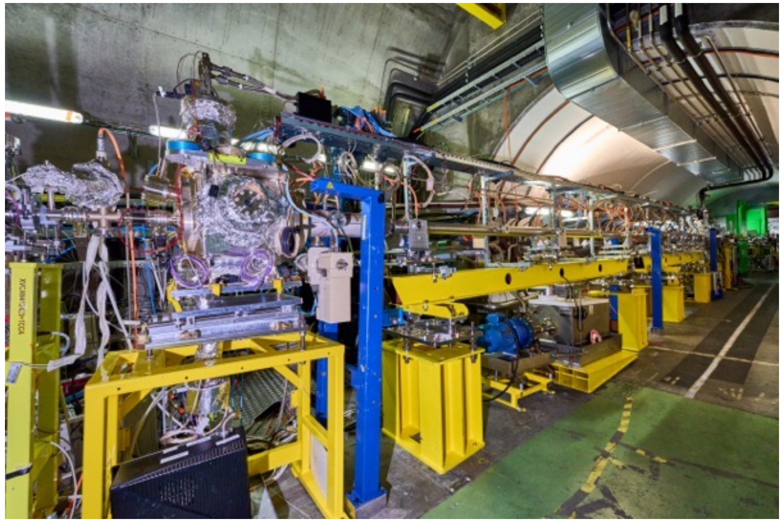
1) 2021/2022 configuration

2) Decommission Run 2a vapor source

4) Density step vapor source

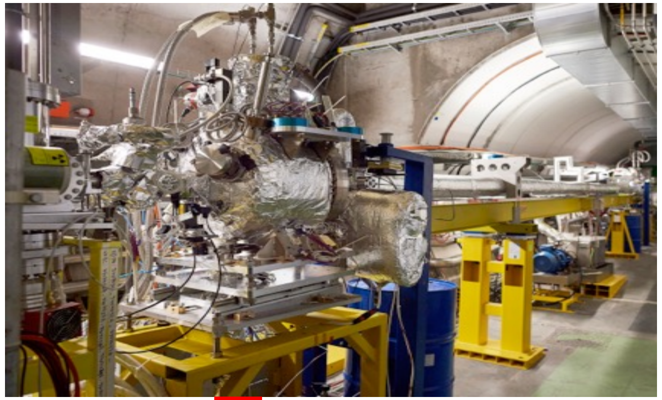
July 2023 – 2024

Run 2b

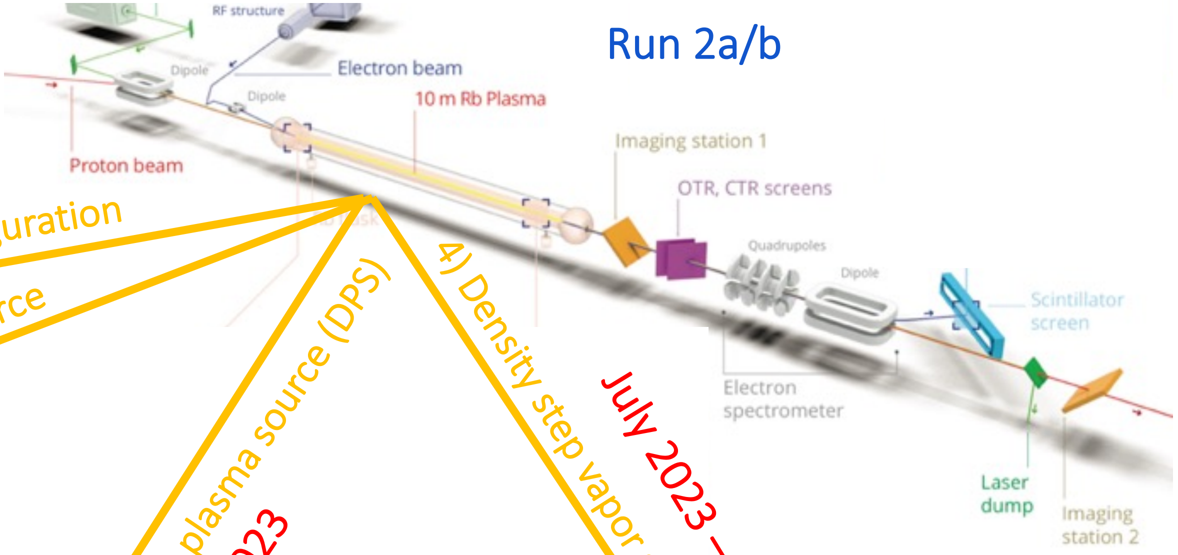


AWAKE Run 2b – 2023/24 Program

Run 2a



Run 2a/b



1) 2021/2022 configuration

2) Decommission Run 2a vapor source

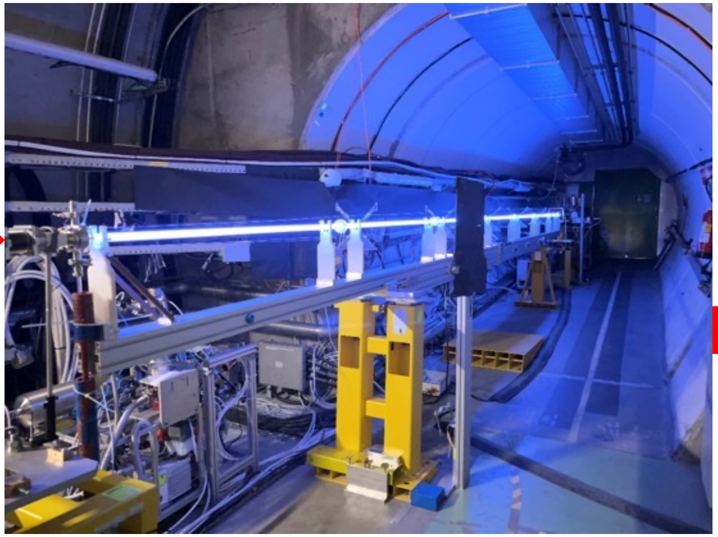
3) Discharge plasma source (DPS)

May 2023

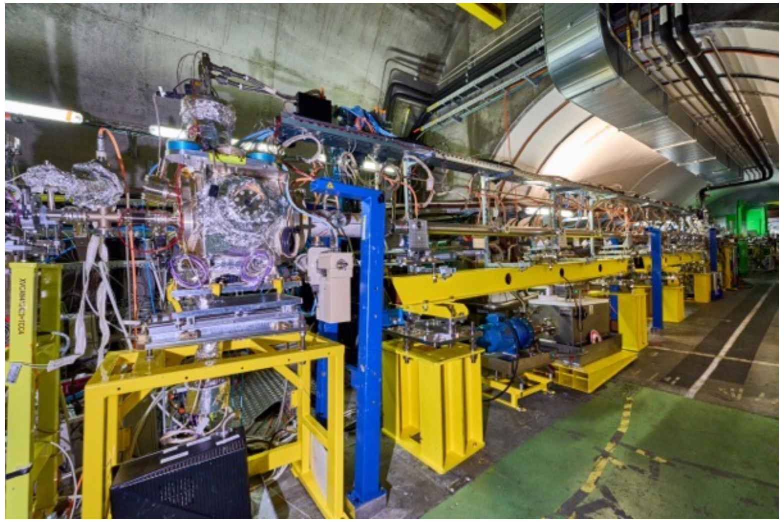
4) Density step vapor source

July 2023 – 2024

Discharge Plasma source test



Run 2b



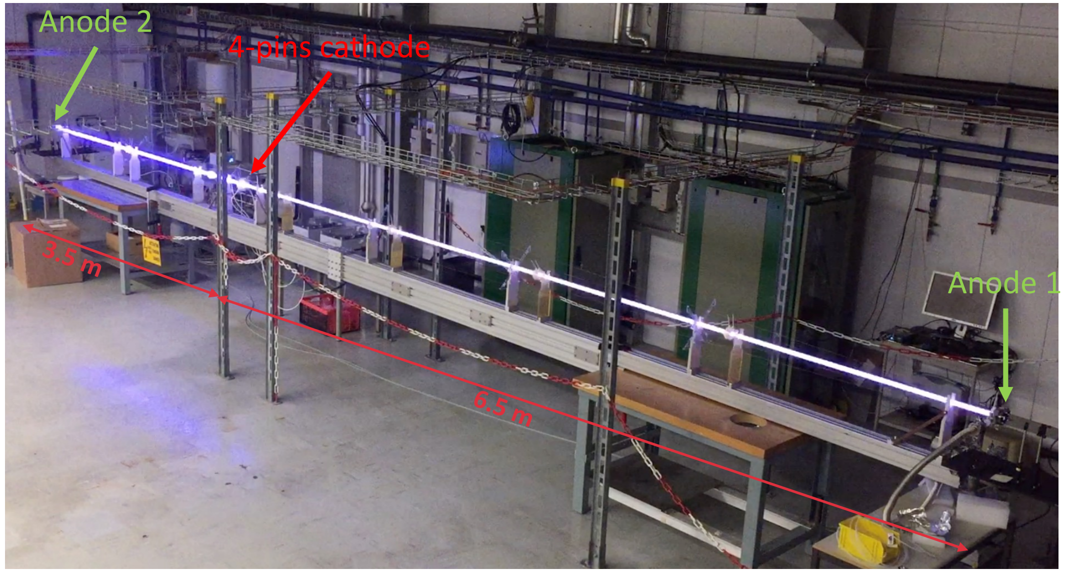
Discharge Plasma Source

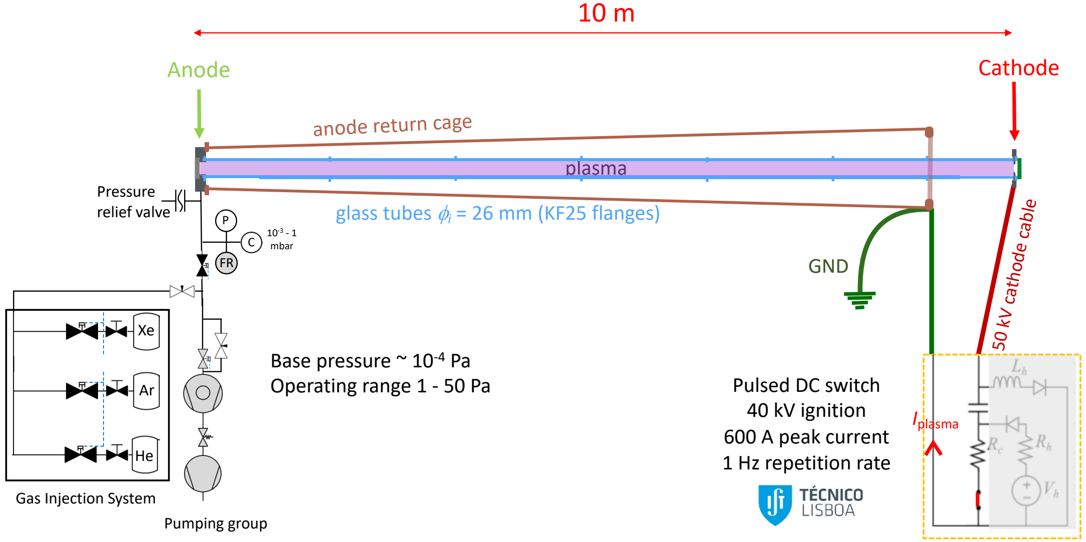
R&D ongoing on **scalable, several-meter long plasma sources**: discharge plasma and Helicon plasma sources.

Discharge Plasma Source (DPS) could be a possible candidate for 2nd plasma source in Run 2c/d

- Much simpler
- Reach very long plasma lengths by stacking them
- wide plasma → no alignment

➔ See A. Sublet, Talk, Wed WG 8

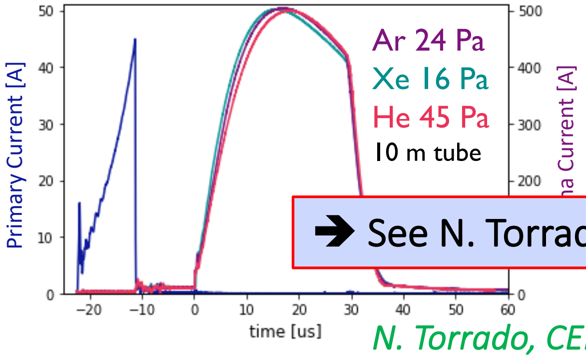




Base pressure ~ 10^{-4} Pa
Operating range 1 - 50 Pa

Pulsed DC switch
40 kV ignition
600 A peak current
1 Hz repetition rate

➔ current pulse 10 ns maximum jitter, peak current stability < 1%



➔ See N. Torrado, Mon Poster

N. Torrado, CERN, IST

Unique run during May 2023 with the discharge plasma source.
➔ proof-of-principle of the DPS

Discharge Plasma Source Tests in May 2023

→ SMI only experiment: no laser and no electron beam, reduced constraint on axial uniformity

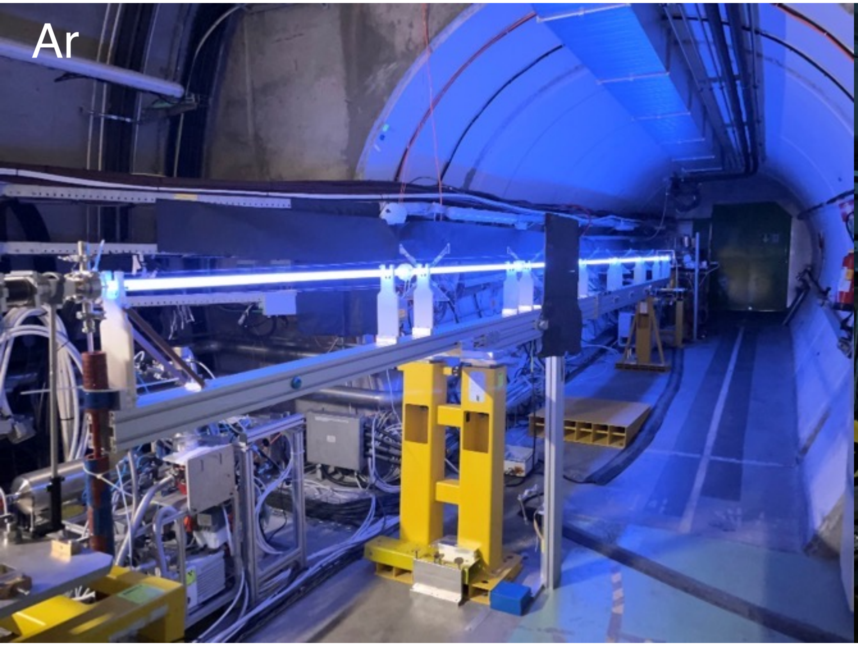
Operation:

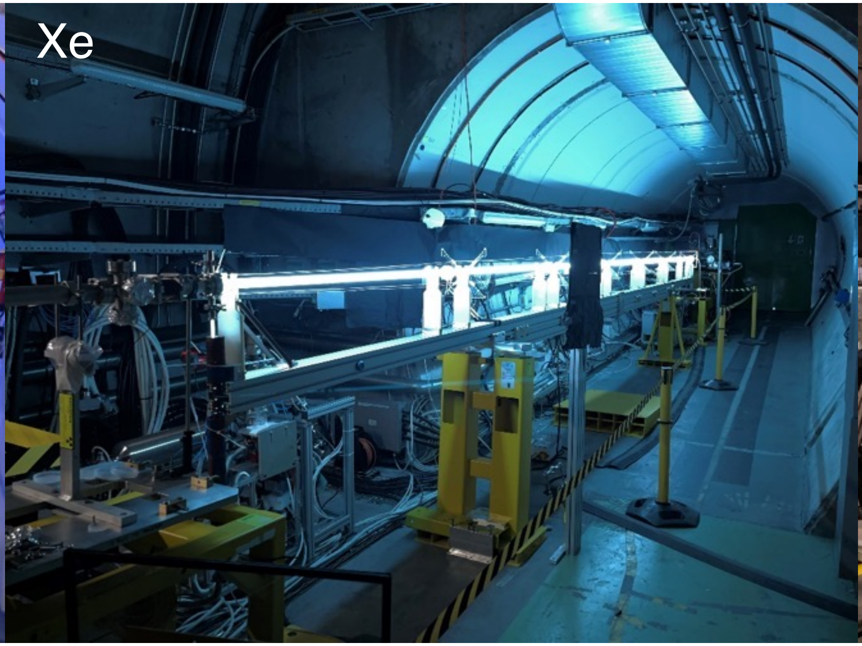
- Ar/Xe/He at 5 pressures 8/16/24/30/45 Pa
- 3 plasma lengths: 3.5/6.5/10 m
- Density density range: 2x10^{13} to 2x10^{15} cm^{-3}

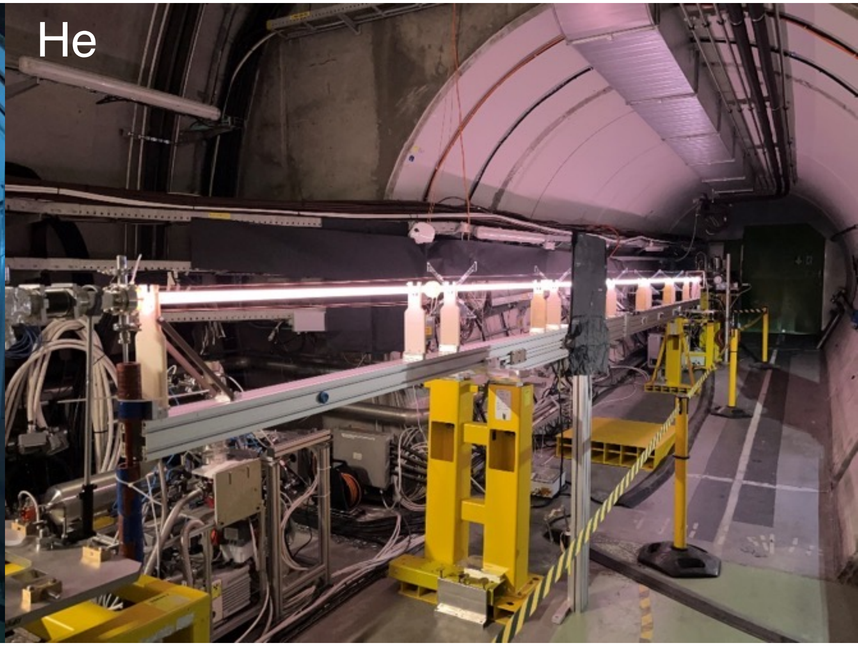
→ 22000 discharges over 3 weeks

Study unique physics:

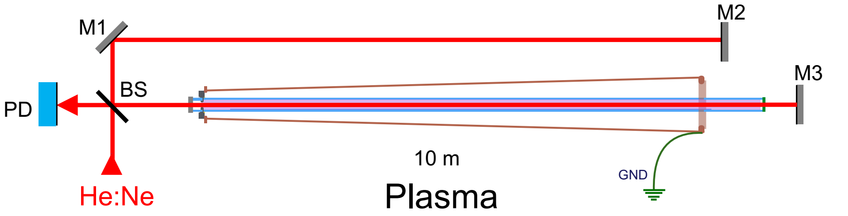
→ Self-modulation, impact ionisation, plasma ion motion, Current Filamentation Instability, plasma light, …







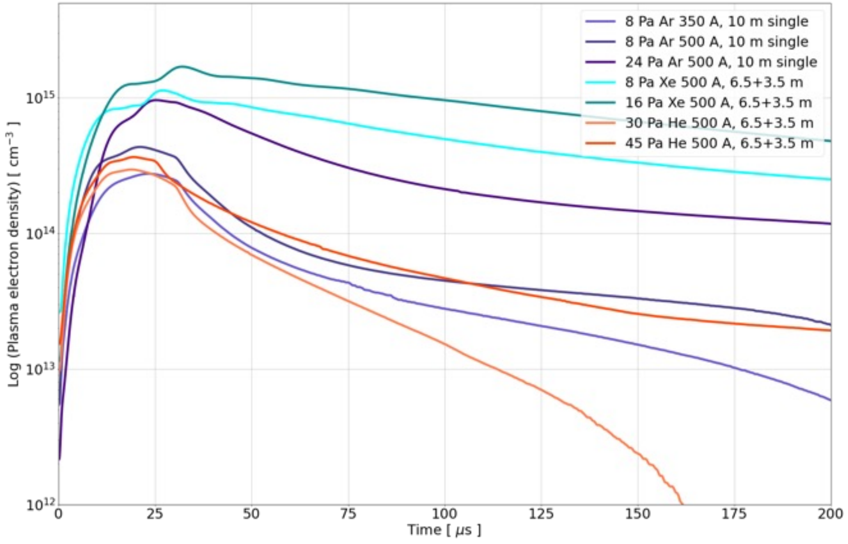
Benchmark DPS Interferometry with Plasma Density from SMI Frequency



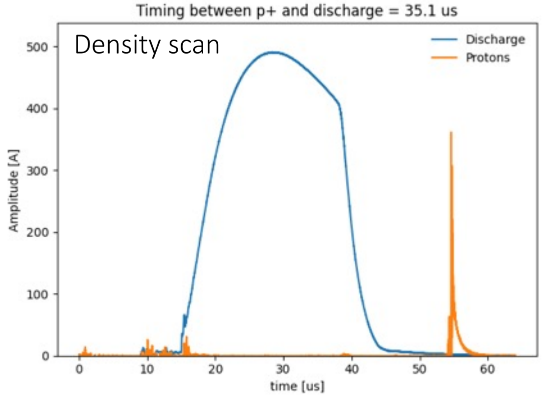
Laser light propagating along 10 m plasma sees refractive index (n) change due to plasma

→ **proportional to plasma density ($\boldsymbol{n_e}$)**

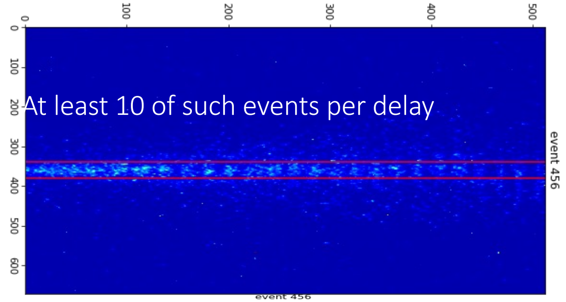
$$n = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}$$



C. Amoedo, CERN

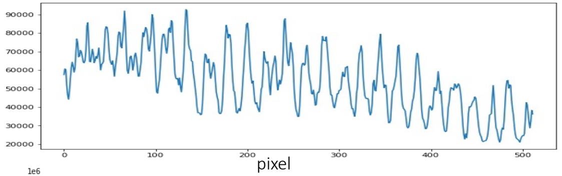


Streak camera image

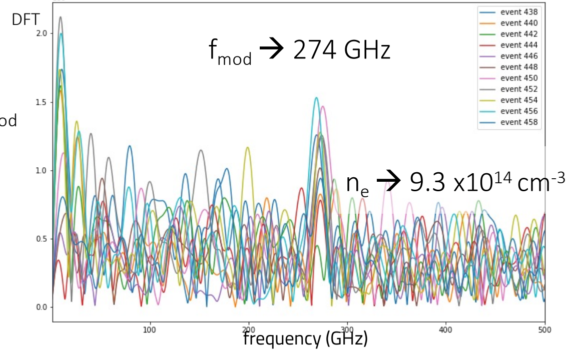


At least 10 of such events per delay

raw profile micro-bunches



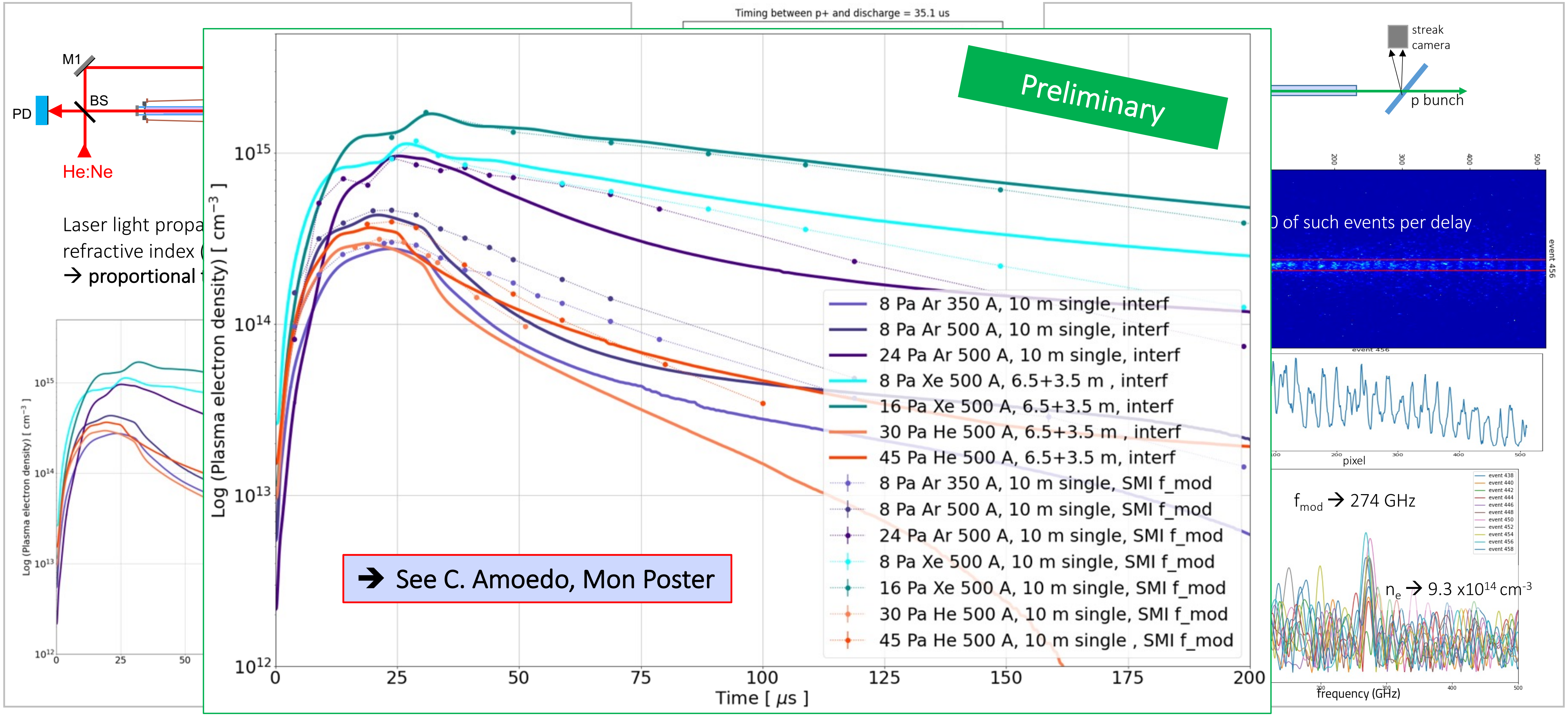
DFT → f_{mod}



f_{mod} → 274 GHz

n_e → 9.3 x10^{14} cm^{-3}

Benchmark DPS Interferometry with Plasma Density from SMI Frequency



Laser light propa
refractive index (
→ proportional

Preliminary

➔ See C. Amoedo, Mon Poster

0 of such events per delay

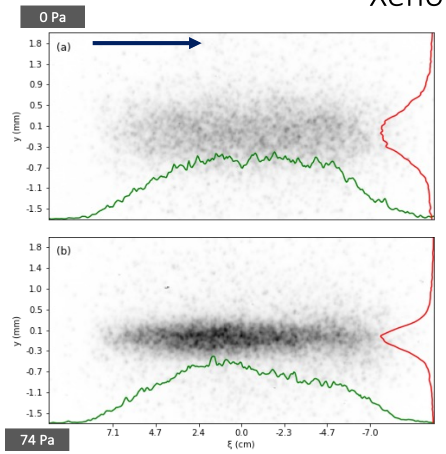
f_{mod} → 274 GHz

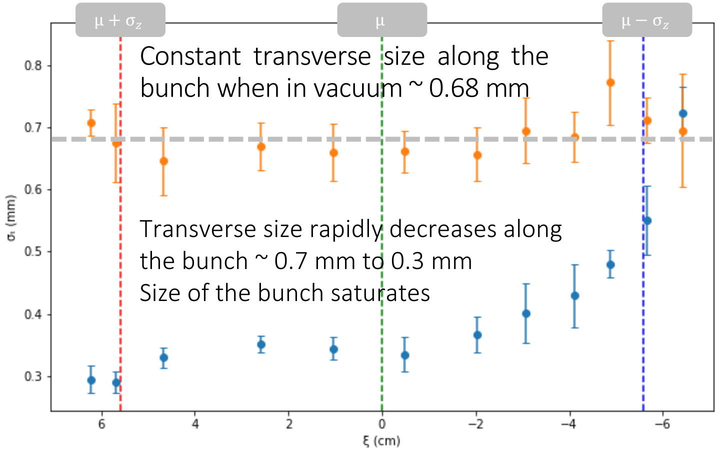
n_e → 9.3 x10^{14} cm^{-3}

DPS Impact Ionisation Studies

Impact Ionization effect in gas

Xenon



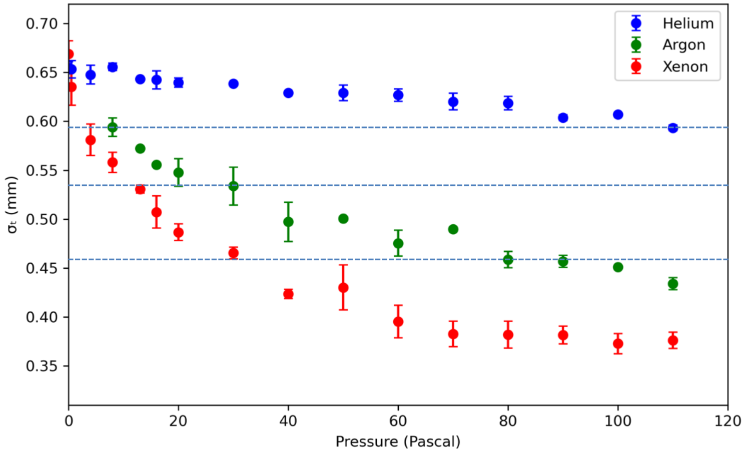


Constant transverse size along the bunch when in vacuum ~ 0.68 mm

Transverse size rapidly decreases along the bunch ~ 0.7 mm to 0.3 mm
Size of the bunch saturates

A. Clairembaud, CERN, CEA

Mean transverse size of the bunch



Pressure scan with three different gases

Preliminary

- When the bunch propagates in gas, it focuses transversely
- This focusing effect:
  - increases along the bunch
  - increases with pressure
  - is larger for Xenon than for Argon, and for Argon than Helium

- At operating pressures the gas density is 2 orders of magnitude smaller than the plasma density ($n_{pe,\ discharge}$ = 7x10^{14} cm^{-3}).

➔ Impact ionization is negligible when propagating in the AWAKE plasma (Helium, Argon, Xenon or Rubidium) → does not cause detuning of SMI

DPS Ion Motion Studies

DPS Current Filamentation Studies

Preliminary

Ions move due to the ponderomotive force of the radial wakefields

- ➔ Change in plasma wavelength and therefore resonance condition
- ➔ Appearance of beam tail when ion motion becomes significant and wakefield stopped growing

n_p = 3 x 10^{11} protons/bunch

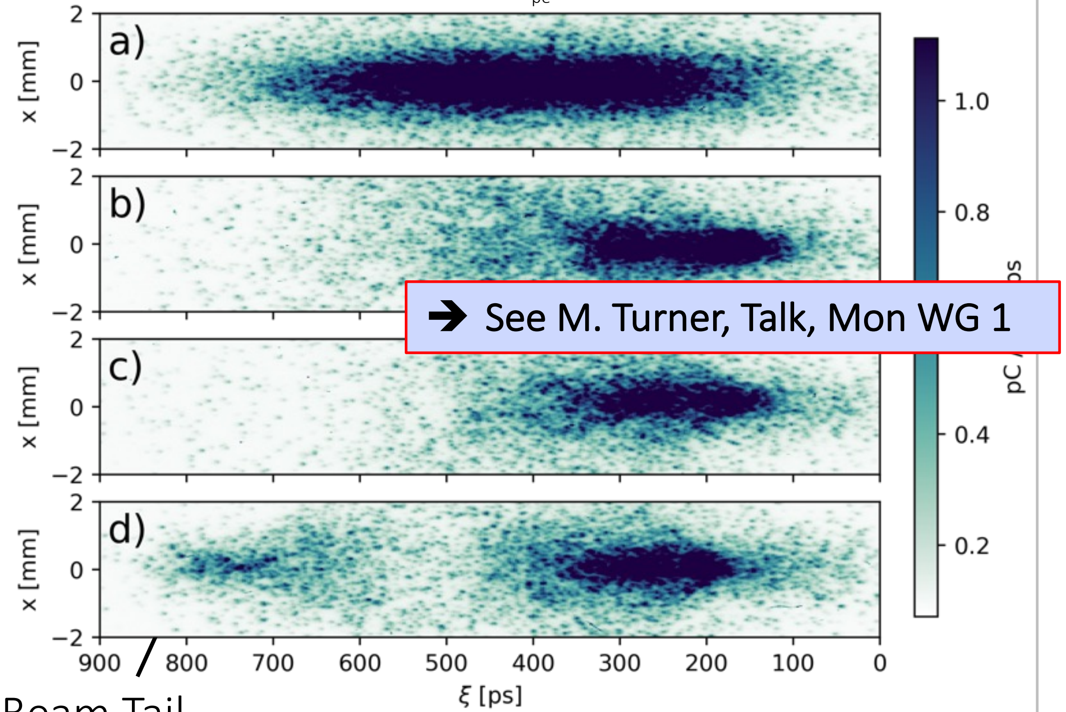
n_{pe} = 4.8 x 10^{14} cm^{-3} ⟶

No plasma

Xenon (A=131)

Argon (A=40)

Helium (A=4)



➔ See M. Turner, Talk, Mon WG 1

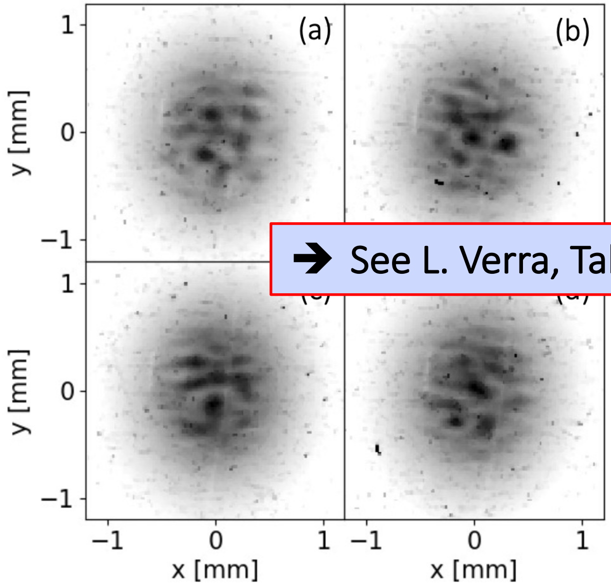
Beam Tail

M. Turner, CERN

If proton bunch is wider than plasma skin depth ➔ CFI.

High plasma density of $n_{pe,\ discharge} = 9\text{x}10^{14}$ cm^{-3}.

Wide proton bunch optics: $\frac{\sigma}{\delta}$ ~3



➔ See L. Verra, Talk, Wed WG 1

Clear evidence of filamentation

→ Important for PWFA design

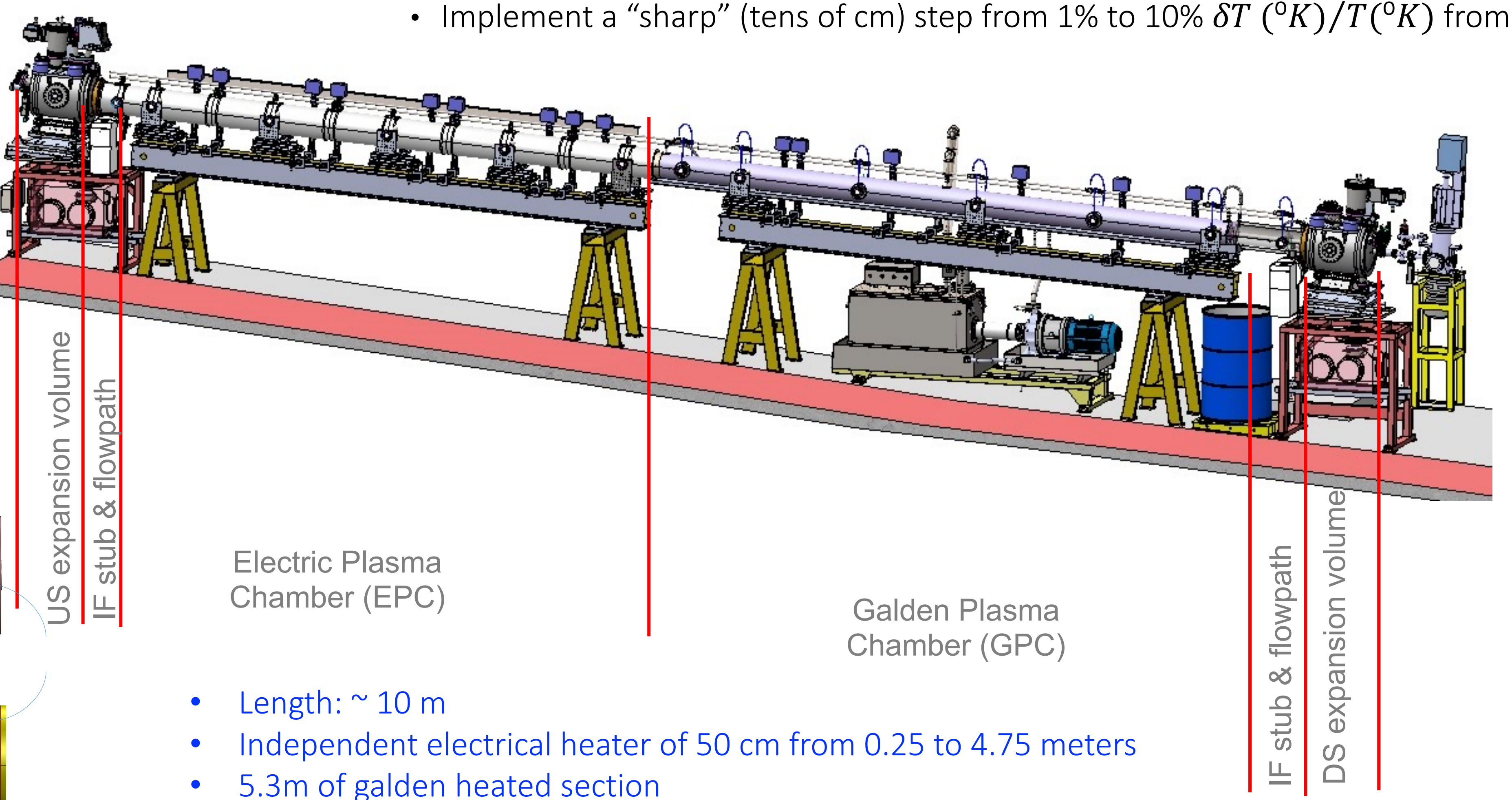
L. Verra, INFN

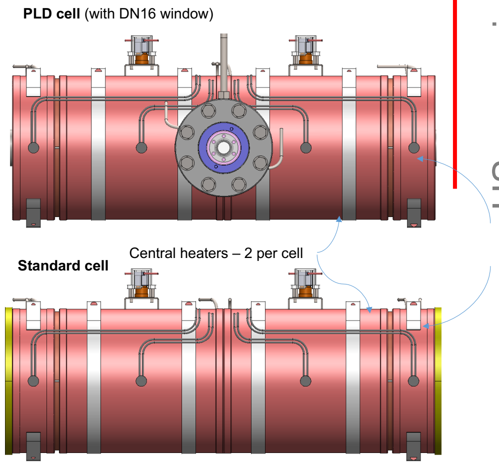
Outline

- Introduction
- The AWAKE Experiment
- AWAKE Run 2 Program
- Unique Opportunity of a Proton Run with the Discharge Plasma Source
- First Proton Runs with the New Vapor Plasma Source
- Summary

New Vapor Plasma Source with Density Step

- Same requirements as Run 1 for Rb density uniformity $\delta T\ (^{o}K)/T(^{o}K) \approx 0.2\%$
- Implement a "sharp" (tens of cm) step from 1% to 10% $\delta T\ (^{o}K)/T(^{o}K)$ from 5 to 50°C

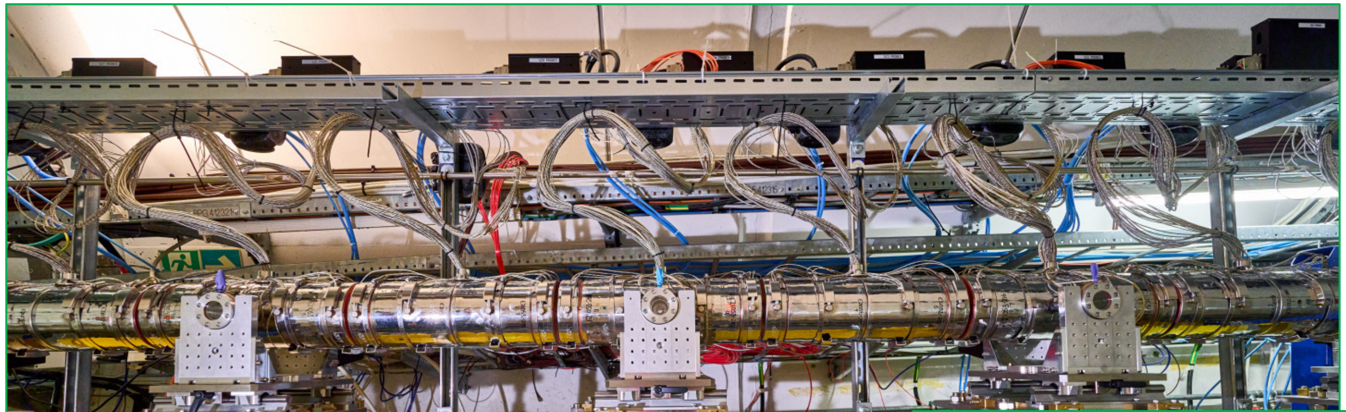




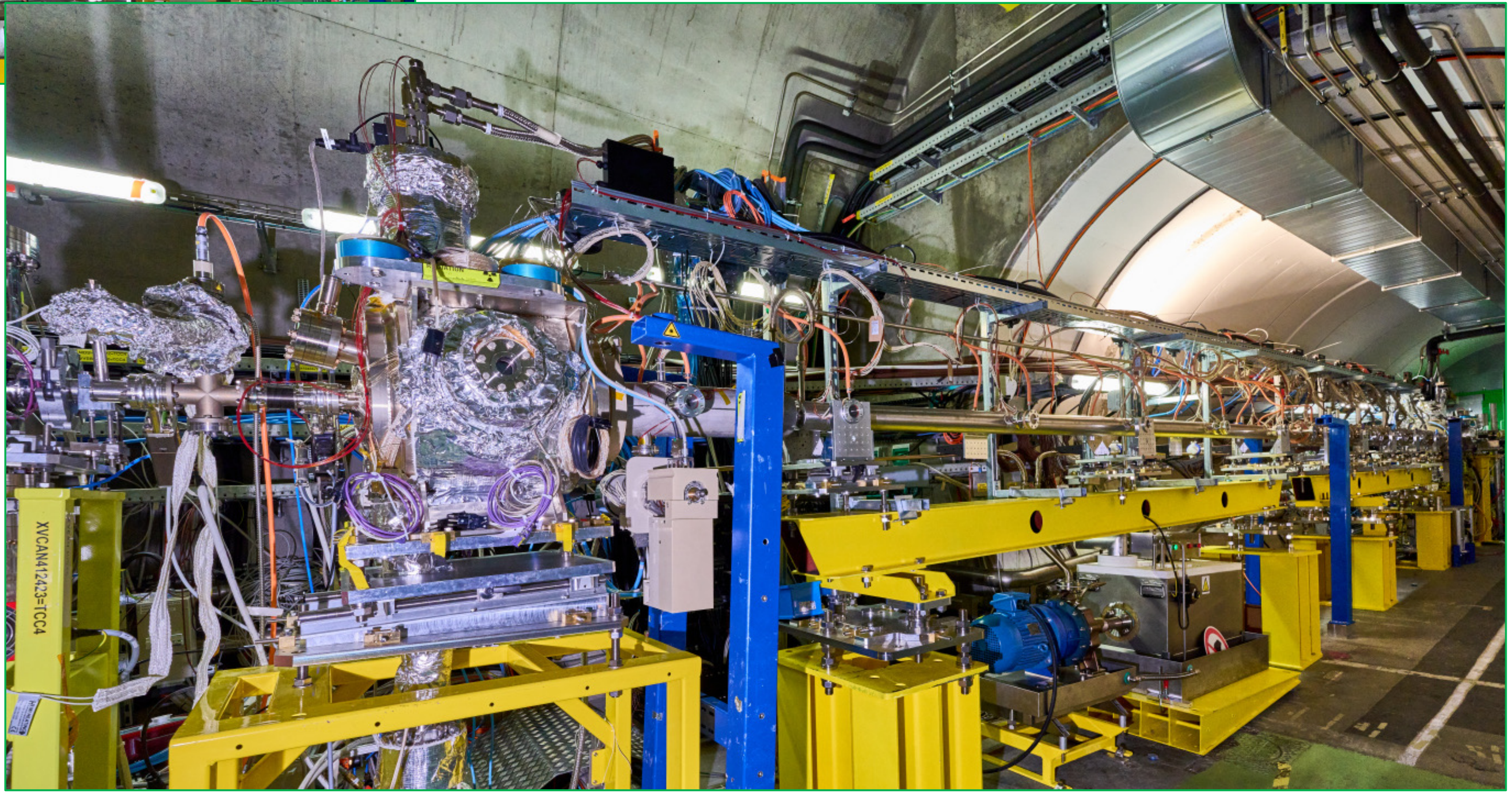
- Length: ~ 10 m
- Independent electrical heater of 50 cm from 0.25 to 4.75 meters
- 5.3m of galden heated section
- Step height up to ±10%
- 10 diagnostic viewport, for plasma light + 3 for density diagnostic

M. Bergamaschi, MPP

New Vapor Plasma Source with Density Step



Installed on schedule and running!



Run 2b measurement schedule:
- 2x 2 weeks in August/September 2023
- 2 more weeks in October 2023
- Continue in 2024

New Vapor Plasma Source – Proton Bunch Images

Measurement program during the Aug/Sept runs:

→ Commissioning of the new plasma source and diagnostics

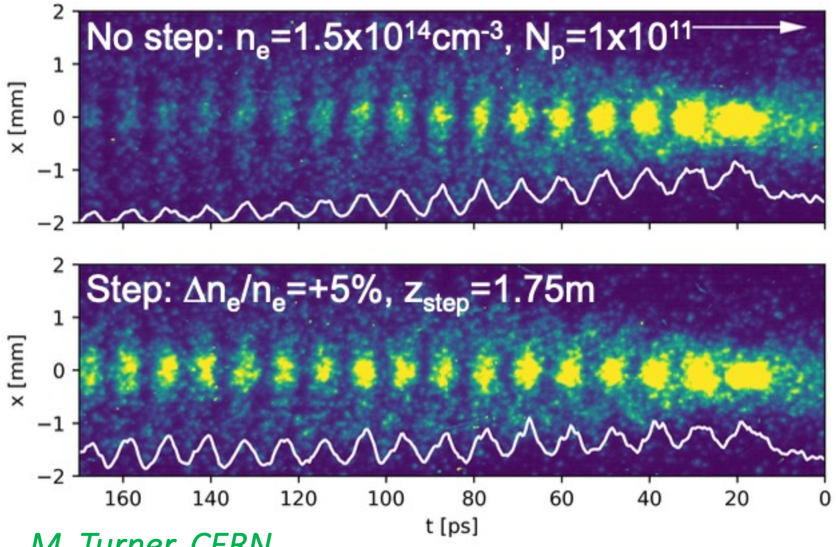
→ First studies of the effect of the plasma density step on

- Proton bunch time-resolved images
- Proton bunch time-integrated images
- Plasma light from dissipating wakefields

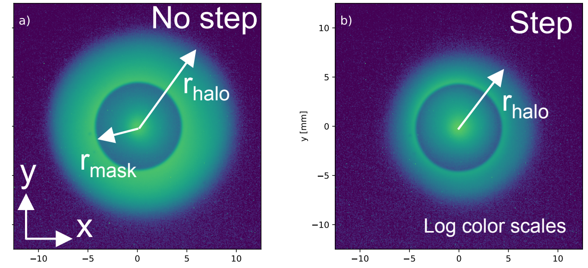
Variation of

- density steps (0%, 1.5%, 3%, 4.5%, 5%, 6%, 9%)
- density step locations (1.25m, 1.75m, 2.25m, 3,25m, 4.25m)
- plasma densities (1x10^{14} to 4x10^{14} cm^{-3})
- Proton bunch intensities (0.5x10^{11} to 3x10^{11} p/bunch)

Proton Bunch Time-Resolved/Integrated Images



M. Turner, CERN

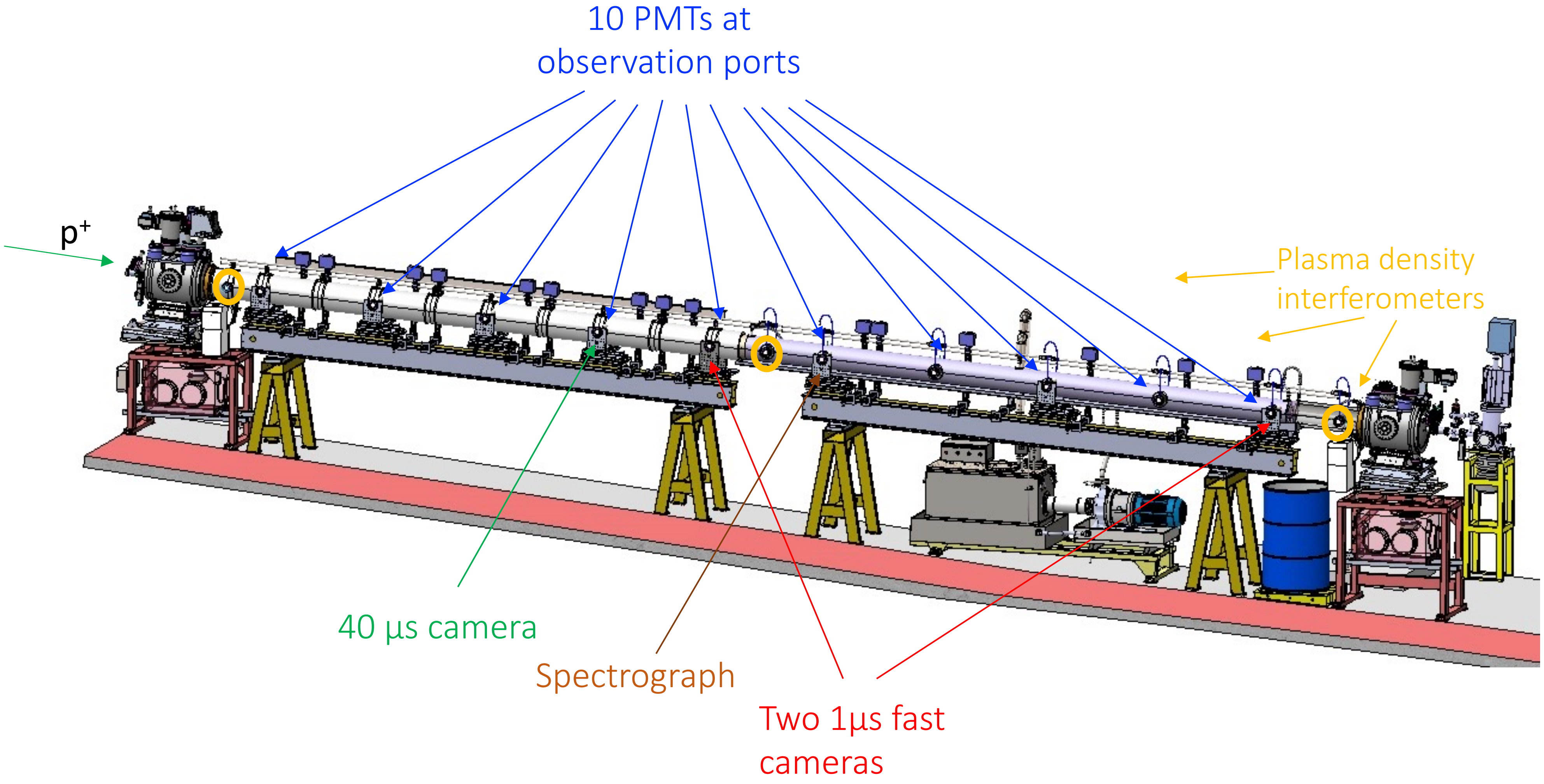


A. Clairembaud, CERN, CEA
P. Muggli, MPP

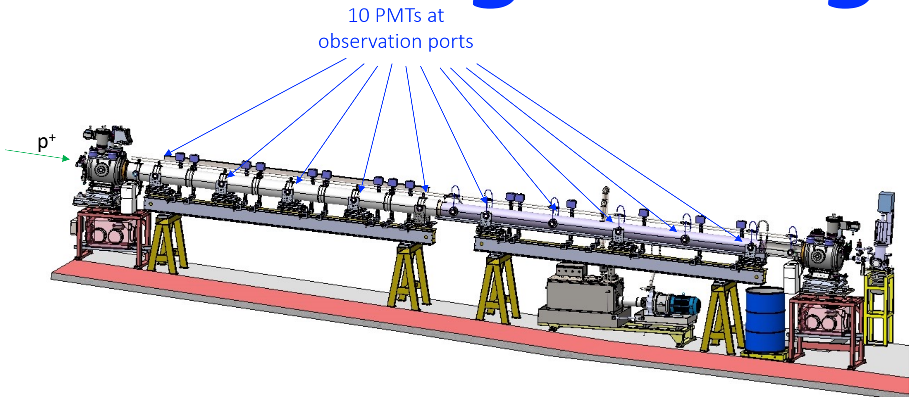
Preliminary

➔ plasma density step clearly influences seeded self-modulation
  ➔ Longer bunch train with more charge
  ➔ Smaller halo

New Vapor Plasma Source – Plasma Light Diagnostics



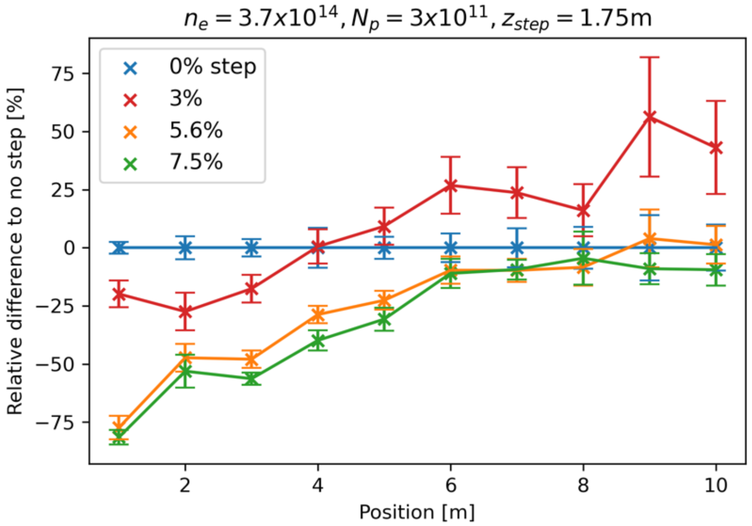
Plasma Light Diagnostics – PMTs



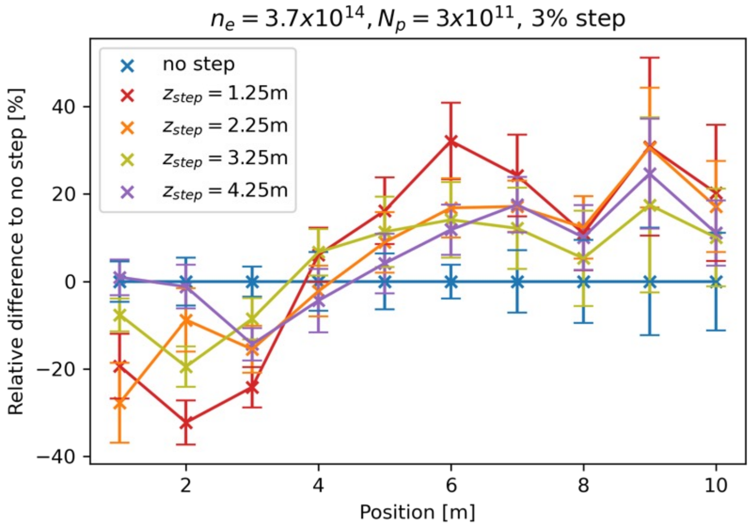
➔ plasma density step clearly influences plasma light from dissipating wakefields

Preliminary

Plot relative change wrt no step and for each PMT, arbitrary signal



Relatively more plasma light with 3% density height at z=1.75m (z>5m)

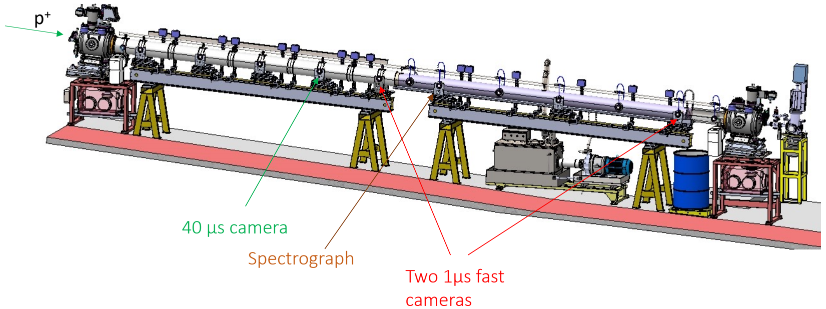


Little difference of step position for 3% density height

J. Mezger, M. Bergamaschi, MPP

Plasma Light Diagnostics – Fast Cameras

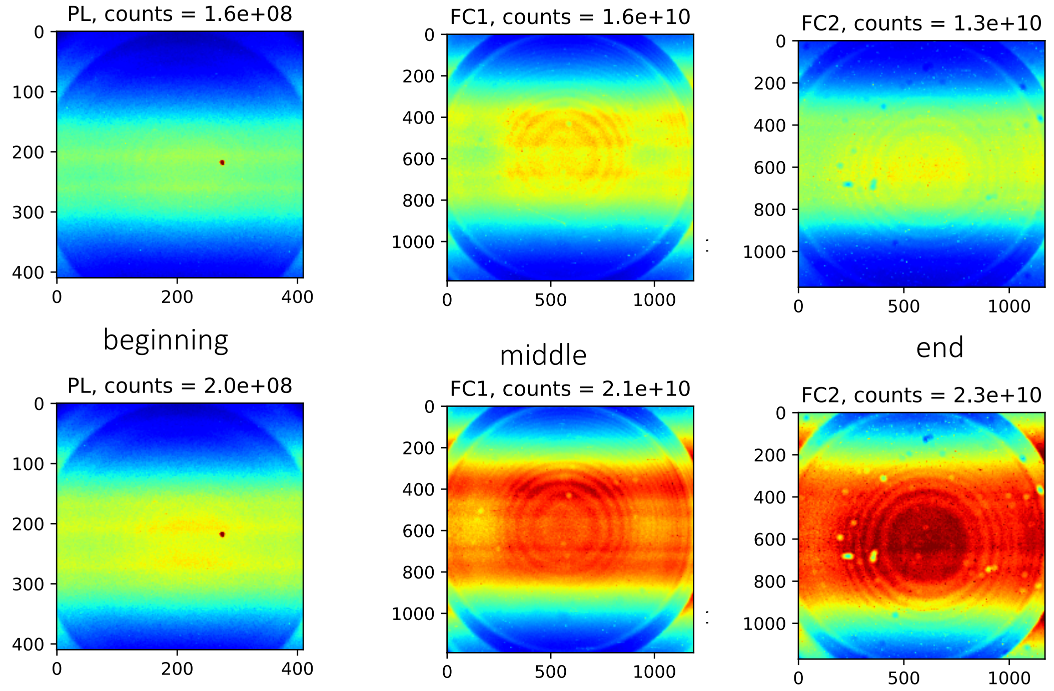
➔ Complementary studies to PMTs



Study plasma light radius/time delay,…

No step

1.5% density step at 1.75m



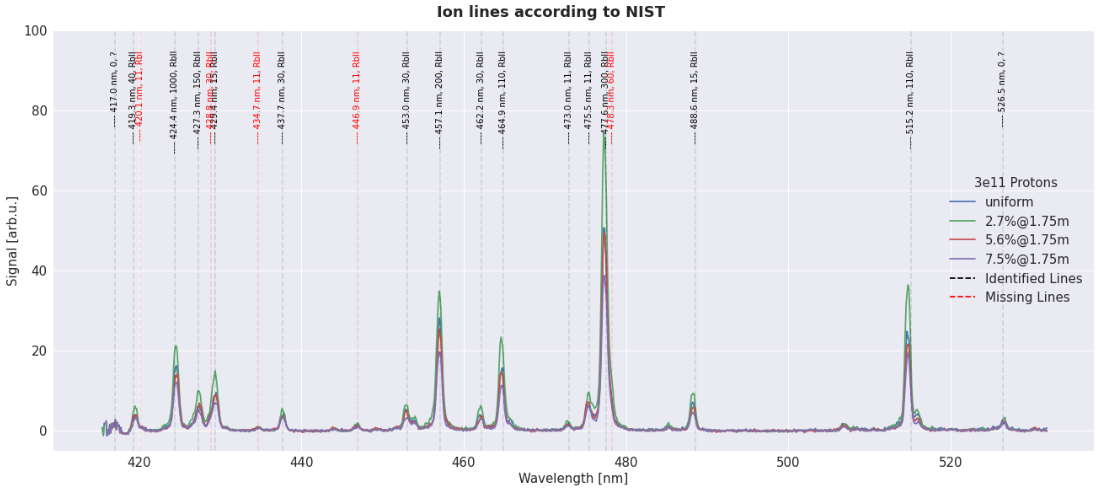
beginning

middle

end

A. Clairembaud, CERN, CEA

Study plasma light spectrum, spectral intensity shift,…



P. Blum, CERN

Preliminary

➔ plasma density step clearly influences plasma light from dissipating wakefields

Summary

- **AWAKE has had a very successful year 2023, with a wealth of excellent data and first results.**

- The **proof-of-concept of a 10m long Discharge Plasma Source has been demonstrated.**
- Preliminary results on SMI, current filamentation instability, ion motion, impact ionization were shown.

- **A new vapor plasma source with a density step** has been designed, installed, commissioned and is now running until end 2024.
- **First measurements show clear effects of the plasma density step** on the number and charge of microbunches, the halo formed by the defocused protons, the plasma light and spectrum emitted by the dissipating wakefields.
- In the coming runs we
    - **Further explore** the landscape of various parameters
    - Identify optimal parameters
    - Confirm larger wakefield amplitudes with a step through the energy gain of externally injected electrons.

- **AWAKE has developed a clear scientifc roadmap** towards first particle physics applications within the next decade.

AWAKE Talks and Posters in EAAC2023

Talks:

- M. Turner, Mon, 18/9, 17.45, WG1: Experimental Observation of Beam-Plasma Resonance Detuning due to Motion of Ions
- L. Verra, Wed, 20/9, 17:25, WG1: Laboratory Astrophysics and Plasma Wakefield Acceleration: Experimental Study of Magnetic Field Generation by Current Filamentation Instability of a Relativistic Proton Bunch in Plasma
- A. Sublet, Wed, 20/9, 17:45, WG8: First test of a 10 m discharge plasma source with a proton beam in the AWAKE experiment
- E.G., Thu, 21/9, 17:25, WG10: AWAKE and future colliders

Posters:

- C. Amoedo: Mon 18/9, Poster: Proton Beam Self-Modulation Instability in a DC Discharge Plasma Source at AWAKE
- J. Farmer, Mon 18/9, Poster: Wakefield regeneration in a plasma accelerator
- N. Torrado, Mon 18/9, Poster: Double pulse generator for AWAKE scalable discharge plasma source
- S. Marini, Mon 18/9, Poster: Integrated beam physics for the laser wakefield accelerator project EARLI
- G. Zevi Della Porta, Tue 19/9, Poster: A tale of three beams: towards stable and reproducible operation of the AWAKE facility
- N. Z. Van Gils, Tue 19/9, Poster: External Electron Injection for the AWAKE Run 2b Experiment