The AWAKE Experiment at CERN

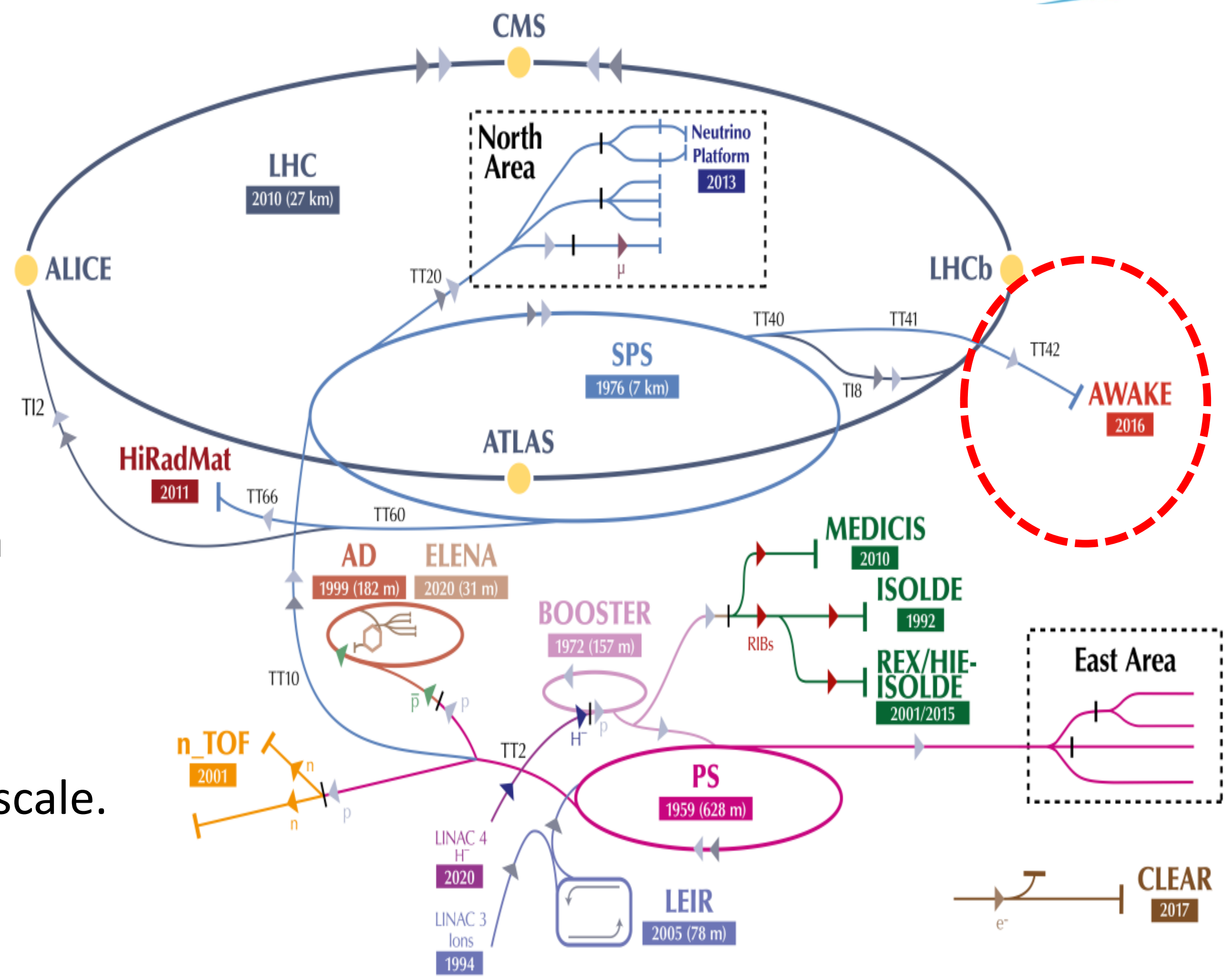
Edda Gschwendtner, CERN

EuPRAXIA-DN School on Plasma Accelerators
April 22 – 26, 2024
Orto Botanico di Roma, Italy

AWAKE at CERN

Advanced WAKEfield Experiment

- ➔Accelerator R&D experiment at CERN.
- ➔Unique facility driving wakefields in plasma with a proton bunch.
  - ➔At CERN highly relativistic protons with high energy (> kJ) available
- ➔Accelerating externally injected electrons to GeV scale.



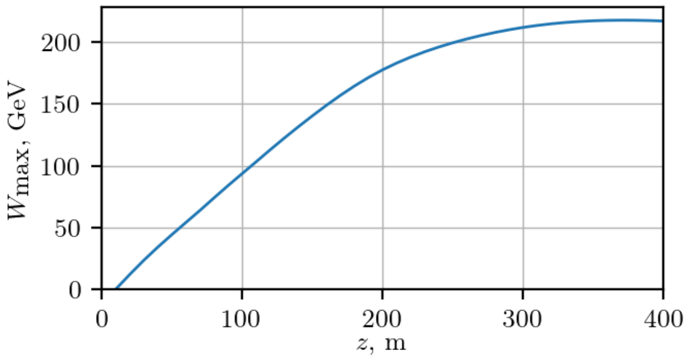
AWAKE at CERN is Unique

➔ **AWAKE addresses technology development for particle physics application, i.e. core business of CERN**

Proton drivers: large energy content in proton bunches
➔single stage acceleration to accelerate electrons to TeV level

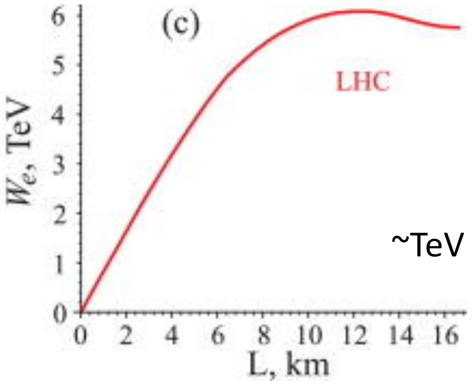
SPS Driver (19 kJ): ~ 150 GeV in ~200 m, 10^9 e^-

2D numerical simulation results



P. Tuev, K. V. Lotov, PPFC 63, 125027 (2021)

LHC Driver (112 kJ): ~ 5 TeV in ~7 km, ~ 10^9 e^-

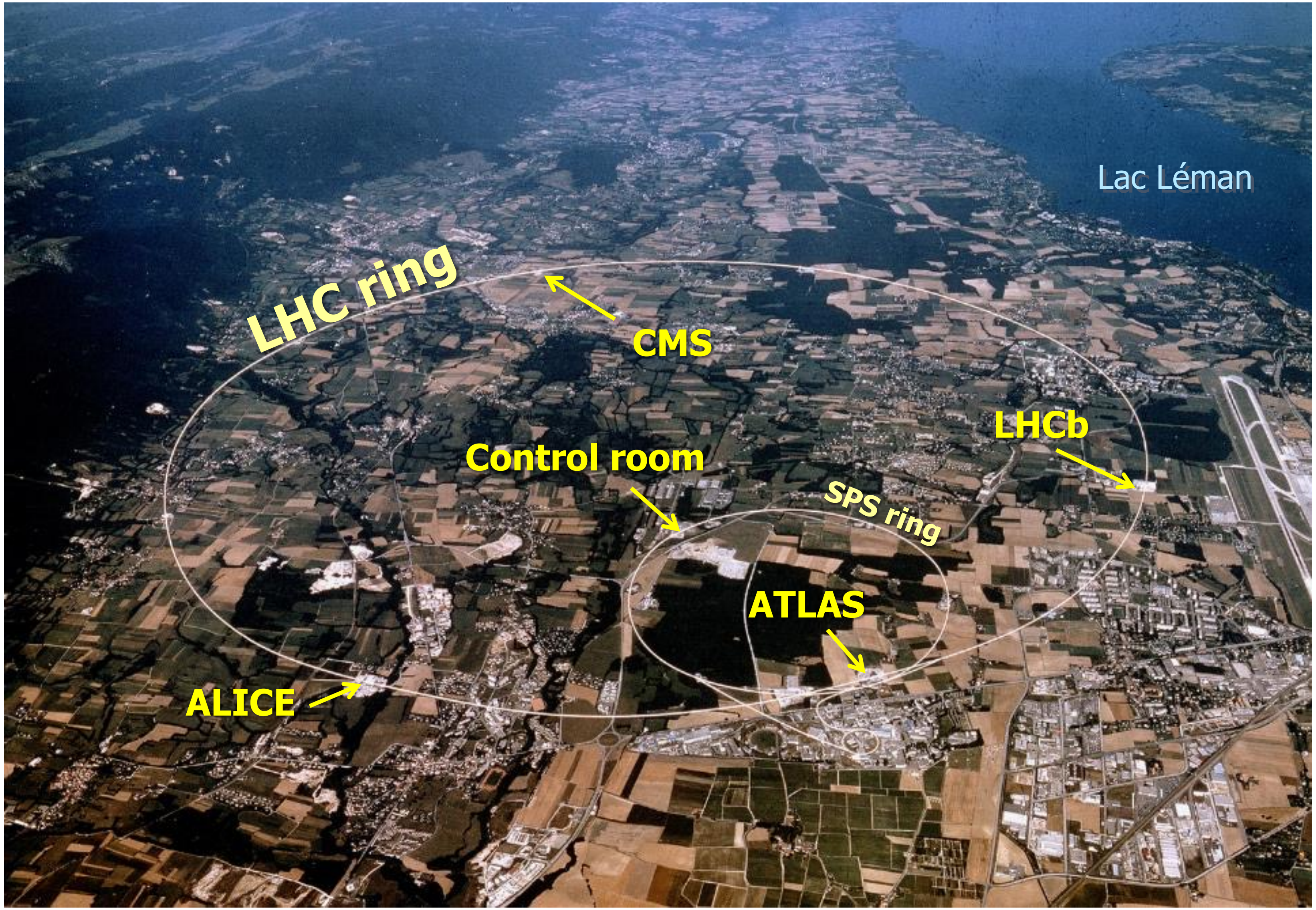


~TeV in km ⇔ ~GeV/m

A. Caldwell, K. V. Lotov, Phys. Plasmas 18, 13101 (2011)

Many opportunities for first particle physics applications in the nearer future: search for dark photons with beam dump experiments

Flagship Today: The Large Hadron Collider



- 27 km circumference
- Collision of protons (or lead) at 13.6 TeV c.o.m.
- High Luminosity upgrade in 2026-2028 to increase the integrated luminosity by a factor of 10
- Operating until 2042

Higgs Boson Discovery at the LHC in 2012
→ Nobel Prize in 2013

Open Questions

Despite of impressive progress and discoveries in the past decades several fundamental question remain open.

*Is there only a single type of **Higgs** boson and does it behave exactly as predicted?*

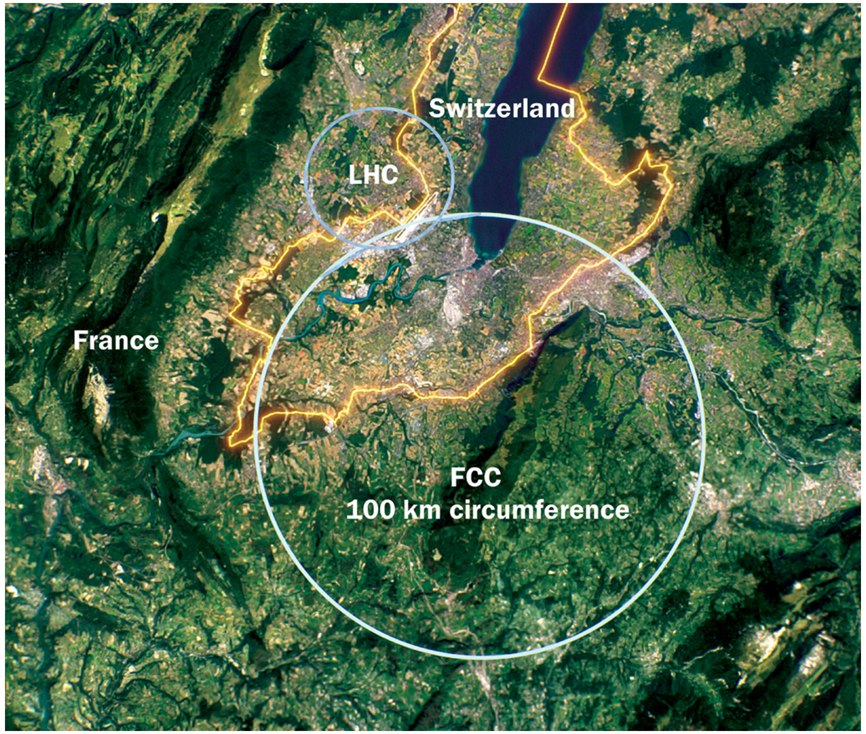
*Why is the universe composed only of matter? Where has the **anti-matter** gone that was produced simultaneously in the big bang?*

*Most of the **mass of the universe** is unknown.*
What is the universe made of?

*Why is the **gravitation** so much smaller than the other forces?*
How to reconcile gravitation with quantum mechanics?

➔ To Discover New Physics: Accelerate Particles to even Higher Energies

Circular Accelerators



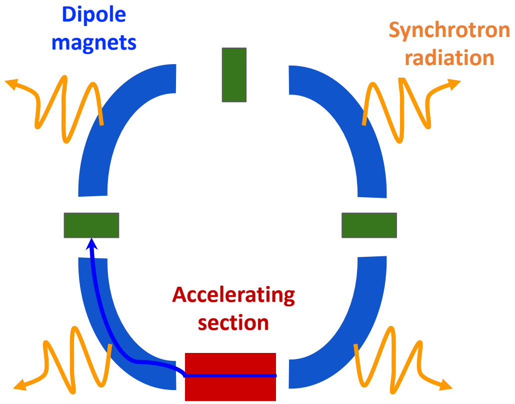
Conventional RF cavities ok for circular colliders:

👍 beam passes accelerating section several times.

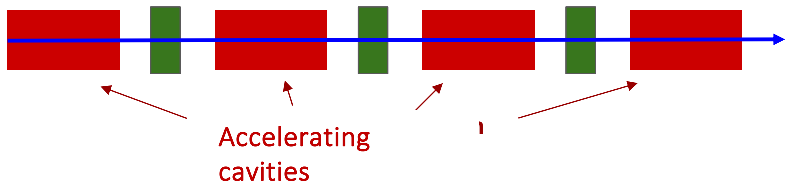
👎 **Limitations of electron-positron circular colliders:**

- Circular machines are limited by **synchrotron radiation** in the case of electron-positron colliders.
- These machines are unfeasible for collision energies beyond **~350 GeV** in case of FCCee.

$$P_{synchr} = \frac{e^2}{6\pi\varepsilon_0 c^7} \frac{E^4}{R^2 m^4}$$



Linear Colliders



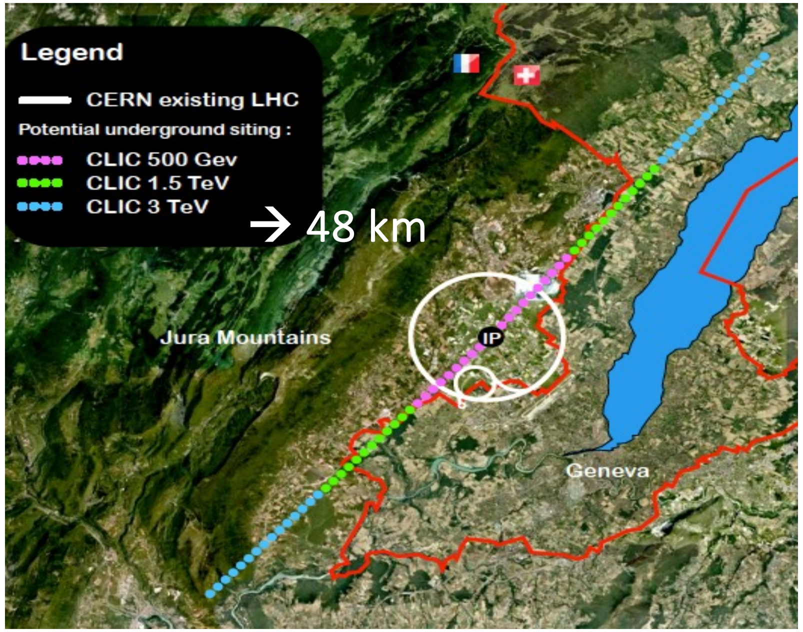
👍 Favorable for acceleration of low mass particles to high energies.

👎 **Limitations** to linear colliders:

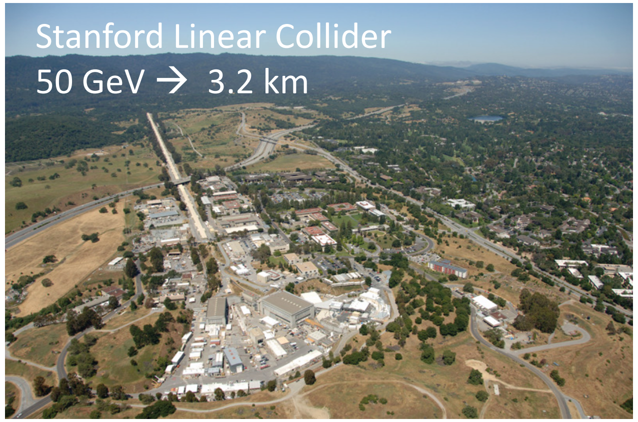
Linear machines accelerate particles in a **single pass.** The amount of acceleration achieved in a given distance is the ***accelerating gradient***. This number is **limited to 100 MV/m** for conventional copper cavities.

Particle energy = accelerating gradient*distance

e.g. accelerate electrons to 1 TeV (10^{12} eV):
100 MeV/m x 10000 m
or
100 GeV/m x 10 m



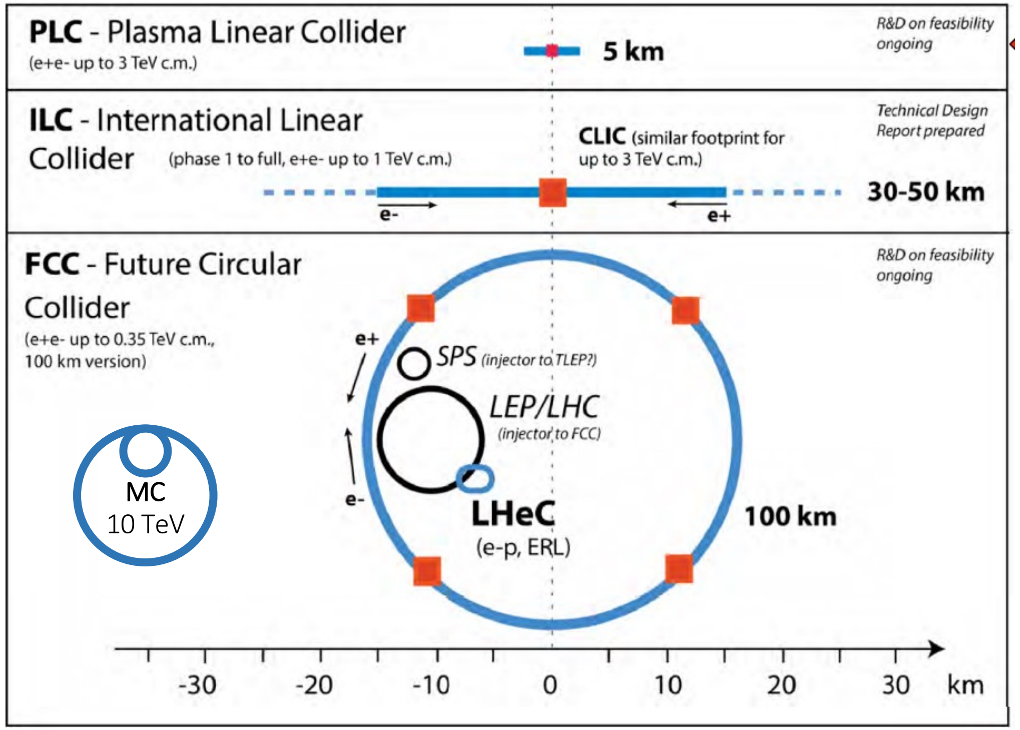
CLIC, electron-positron collider with 3 TeV energy



Plasma Wakefield Acceleration

The **high gradient of plasma wakefield acceleration** makes this technology very interesting for reducing the size (and cost) for future linear colliders.

100 MV/m ➔ 100 GV/m



Plasma Wakefield Accelerators – Electron/Laser Drivers

Witness beams (Surfers):

Electrons: 10^{10} particles @ 1 TeV ~few kJ

Drive beams (Boat):

Lasers: ~40 J/pulse

Electron drive beam: 30 J/bunch

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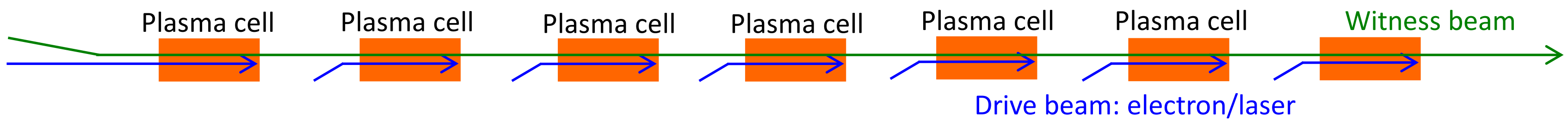
To reach TeV scale:

- **Electron/laser driven PWA**: need several stages, and challenging wrt to relative timing, tolerances, matching, etc…
  - effective gradient reduced because of long sections between accelerating elements….



Plasma Wakefield Accelerators – Proton Drivers

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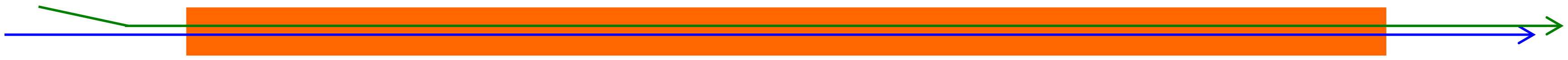
To reach TeV scale:

- **Proton drivers**: large energy content in proton bunches → allows to consider single stage acceleration:
  - A single SPS/LHC bunch could produce an ILC bunch in a single PDWA stage.



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 5 TeV electrons

The AWAKE Experiment

AWAKE is an International Collaboration

AWAKE CERN

Wigner
clear
UPPSALA UNIVERSITET
The Cockcroft Institute of Accelerator Science and Technology
Lancaster University
UNIVERSITY OF OXFORD
TRIUMF

MAX-PLANCK-INSTITUT FÜR PHYSIK
Philipps Universität Marburg
MAX PLANCK INSTITUTE FOR PLASMA PHYSICS
EPFL
WISCONSIN UNIVERSITY OF WISCONSIN-MADISON

22 Institutes

CERN
UKRI Science and Technology Facilities Council
MANCHESTER 1824 The University of Manchester
UNIVERSITY OF LIVERPOOL
Imperial College London
UCL

hhu Heinrich Heine Universität Düsseldorf
TÉCNICO LISBOA
UNIST ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY 2007
Novosibirsk State University *THE REAL SCIENCE
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AWAKE's Strong Scientific and Educational Output

22 AWAKE Collaboration papers in high-level journals

Authors	Title	Journal	Year
L. Verra, et al. (AWAKE Collaboration)	Filamentation of a Relativistic Proton Bunch in Plasma		2023
T. Nechaeva, et al. (AWAKE Collaboration)	Hosing of a long relativistic particle bunch in plasma		2023
L. Verra, et al. (AWAKE Collaboration)	Development of the Self-Modulation Instability of a Relativistic Proton Bunch in Plasma	PoP	2023
E. Gschwendtner, et al. (AWAKE Collaboration)	The AWAKE Run 2 programme and beyond	Symmetry	2022
L. Verra, et al. (AWAKE Collaboration)	Controlled Growth of the Self-Modulation of a Relativistic Proton Bunch in Plasma	PRL	2022
S. Gessner, et al. (AWAKE Collaboration)	Evolution of a plasma column measured through modulation of a high-energy proton beam		2020
V. Hafych, et al. (AWAKE Collaboration)	Analysis of Proton Bunch Parameters in the AWAKE Experiment	JINST	2021
P.I. Morales Guzman, et al. (AWAKE Collaboration)	Simulation and experimental study of proton bunch self-modulation in plasma with linear density gradients	PRAB	2021
F. Batsch, et al. (AWAKE Collaboration)	Transition between Instability and Seeded Self-Modulation of a Relativistic Particle Bunch in Plasma	PRL	2021
J. Chappell, et al. (AWAKE Collaboration)	Experimental study of extended timescale dynamics of a plasma wakefield driven by a self-modulated proton bunch	PRAB	2021
F. Braunmüller, et al. (AWAKE Collaboration)	Proton Bunch Self-Modulation in Plasma with Density Gradient	PRL	2020
A. A. Gorn, et al. (AWAKE Collaboration)	Proton beam defocusing in AWAKE: comparison of simulations and measurements	PPCF	2020
M. Turner, et al. (AWAKE Collaboration)	Experimental study of wakefields driven by a self-modulating proton bunch in plasma	PRAB	2020
E. Gschwendtner, et al. (AWAKE Collaboration)	Proton-driven plasma wakefield acceleration in AWAKE	PTRSA	2019
M. Turner, et al. (AWAKE Collaboration)	Experimental Observation of Plasma Wakefield Growth Driven by the Seeded Self-Modulation of a Proton Bunch	PRL	2019
AWAKE Collaboration	Experimental Observation of Proton Bunch Modulation in a Plasma at Varying Plasma Densities	PRL	2019
AWAKE Collaboration	Acceleration of electrons in the plasma wakefield of a proton bunch	Nature	2018
P. Muggli, et al. (AWAKE Collaboration)	AWAKE readiness for the study of the seeded self-modulation of a 400 GeV proton bunch	PPCF	2018
E. Gschwendtner, et al. (AWAKE Collaboration)	AWAKE, The Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN	NIMA	2016
A. Caldwell, et al. (AWAKE Collaboration)	Path to AWAKE: Evolution of the concept	NIMA	2016
C. Bracco, et al. (AWAKE Collaboration)	AWAKE: A Proton-Driven Plasma Wakefield Acceleration Experiment at CERN	NPPP	2016
AWAKE Collaboration	Proton-driven plasma wakefield acceleration: a path to the future of high-energy particle physics	PPCF	2014

> 70 papers related to AWAKE

> 90 Conference proceedings and papers

AWAKE courses and seminars

EPFL

JAI John Adams Institute for Accelerator Science

CERN Teacher Program

USPAS, JUAS, CAS

➔ 4 doctoral thesis prizes, 2 early career awards!

> 28 PhD students

> 11 Master students

> 20 Post-docs

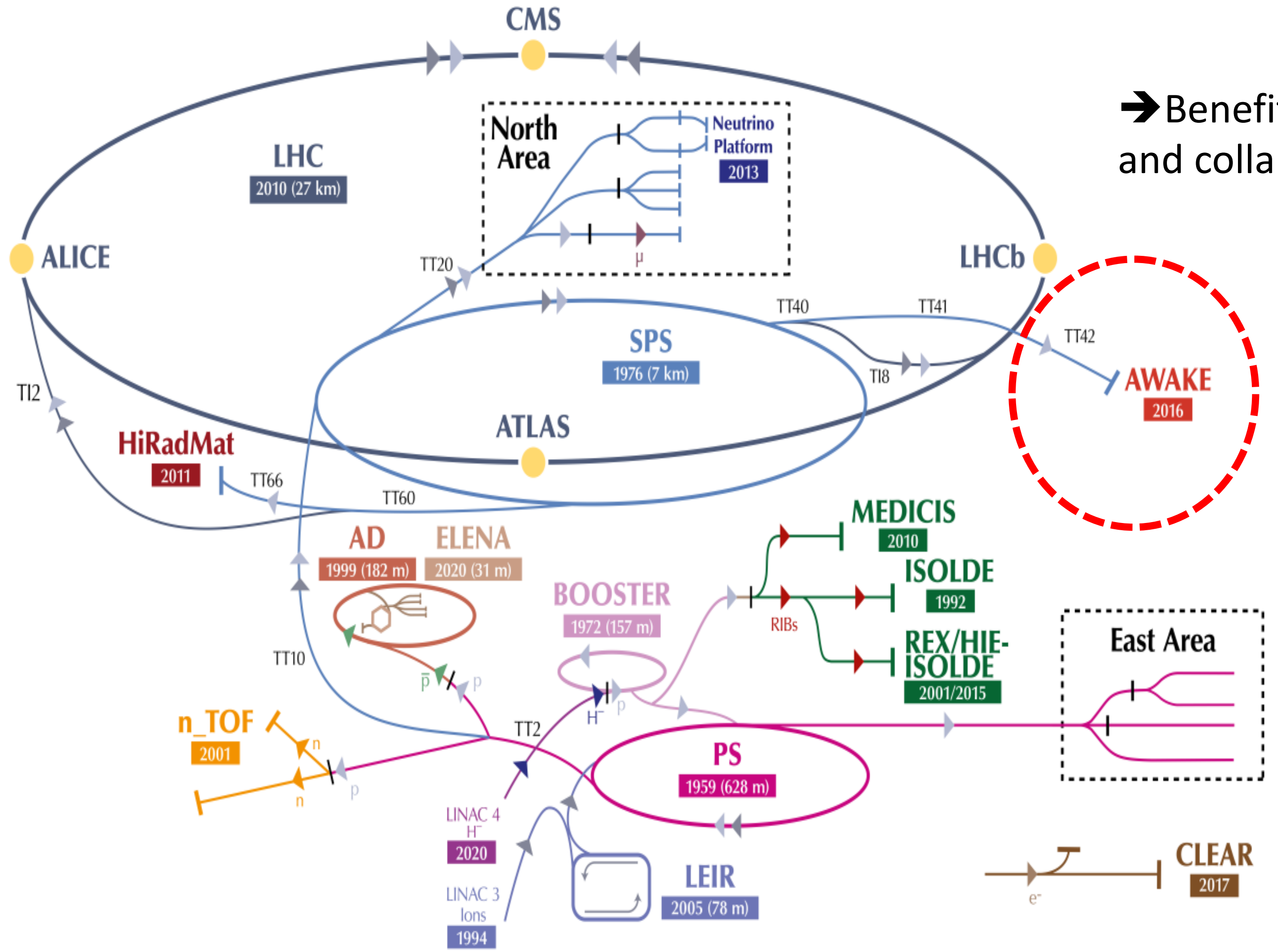
Outreach: Newspapers, TEDX, …

TEDxCERN
x = independently organized TED event

ask symmetry

A new wave of particle physics

AWAKE at CERN

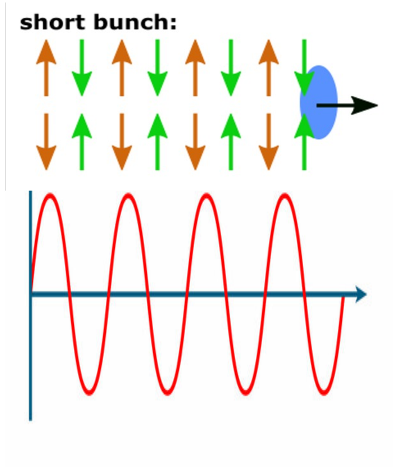


➔Benefit from expertise from CERN and collaborating institutes

➔Proton bunch from SPS is extracted to AWAKE

Proton Bunch as a Drive Beam

In order to create high wakefield amplitudes, the drive bunch length must be in the order of the plasma wavelength.



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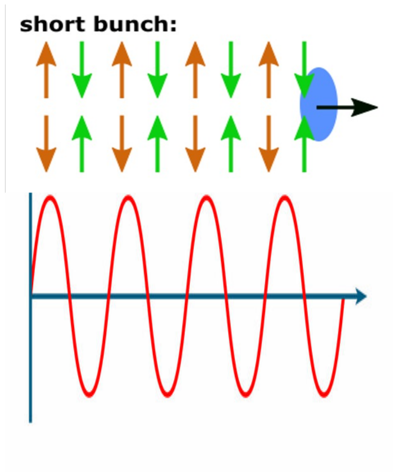
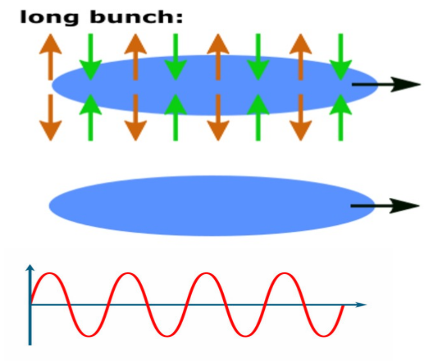
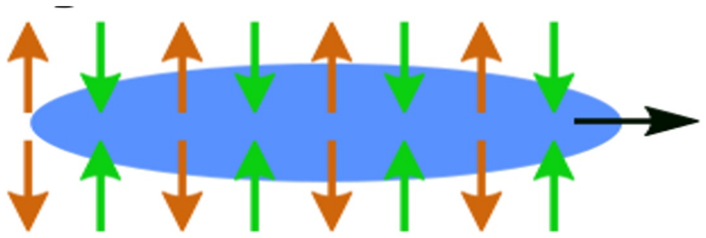


CERN SPS proton bunch: very long! (σ_z = **6 - 10 cm**) → much longer than plasma wavelength (λ = **1mm**)
→ Would create only small wakefield amplitudes



Self-Modulation of the Proton Bunch

Self-Modulation Instability:



p^+ bunch

Initial transverse wakefields

Periodic focusing/defocusing fields

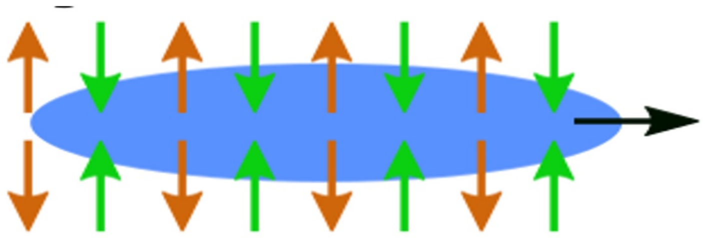
Radial bunch and plasma density modulation

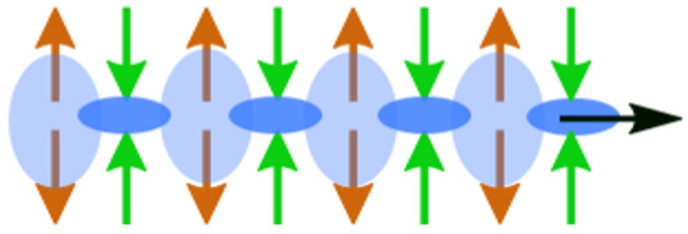
Stronger wakefields

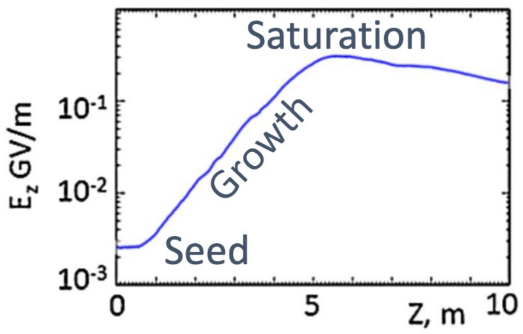
Full modulation

Self-Modulation of the Proton Bunch

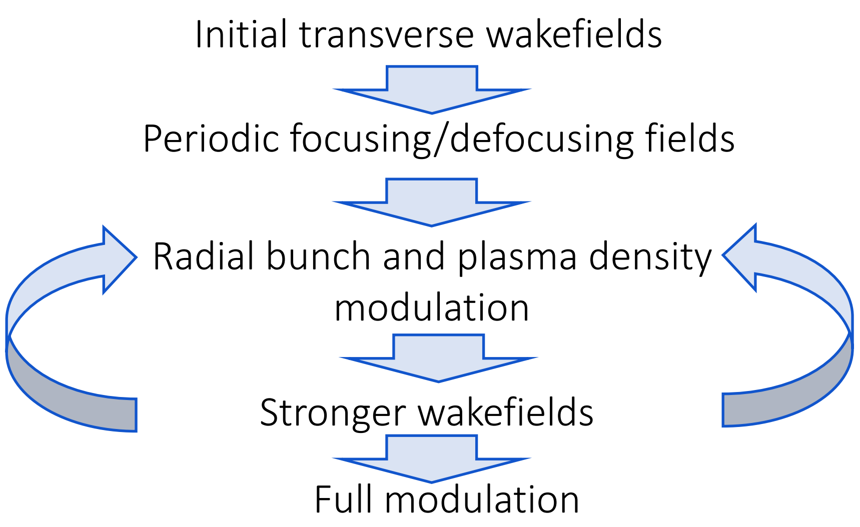
Self-Modulation Instability:





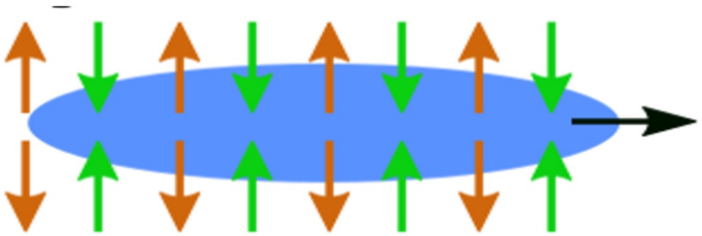


Pukhov, PRL107 145003 (2011)

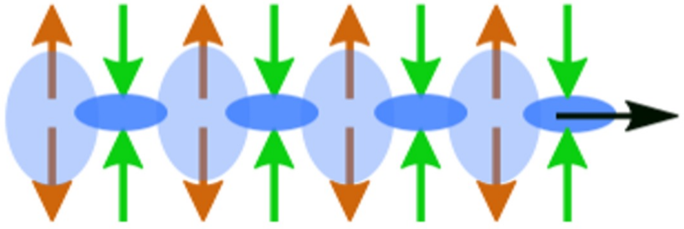


Self-Modulation of the Proton Bunch

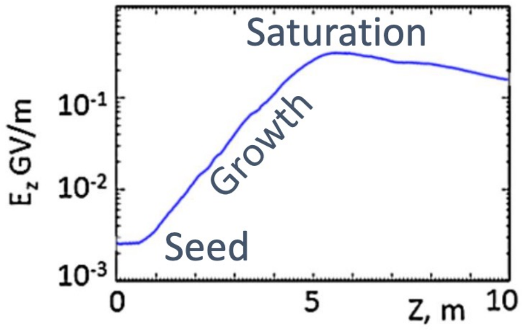
Self-Modulation Instability:



p^+ bunch



Density modulation on-axis → **micro-bunc**



Pukhov, PRL107 145003 (2011)

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

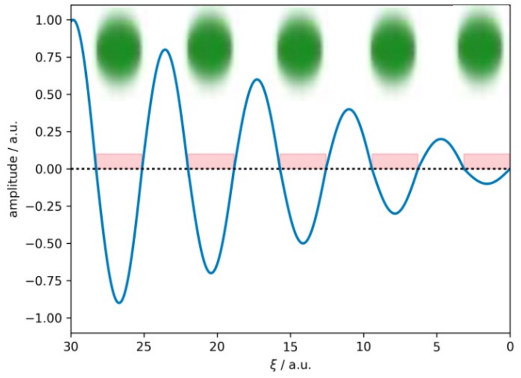
Initial transverse wakefields

Periodic focusing/defocusing fields

Radial bunch and plasma density modulation

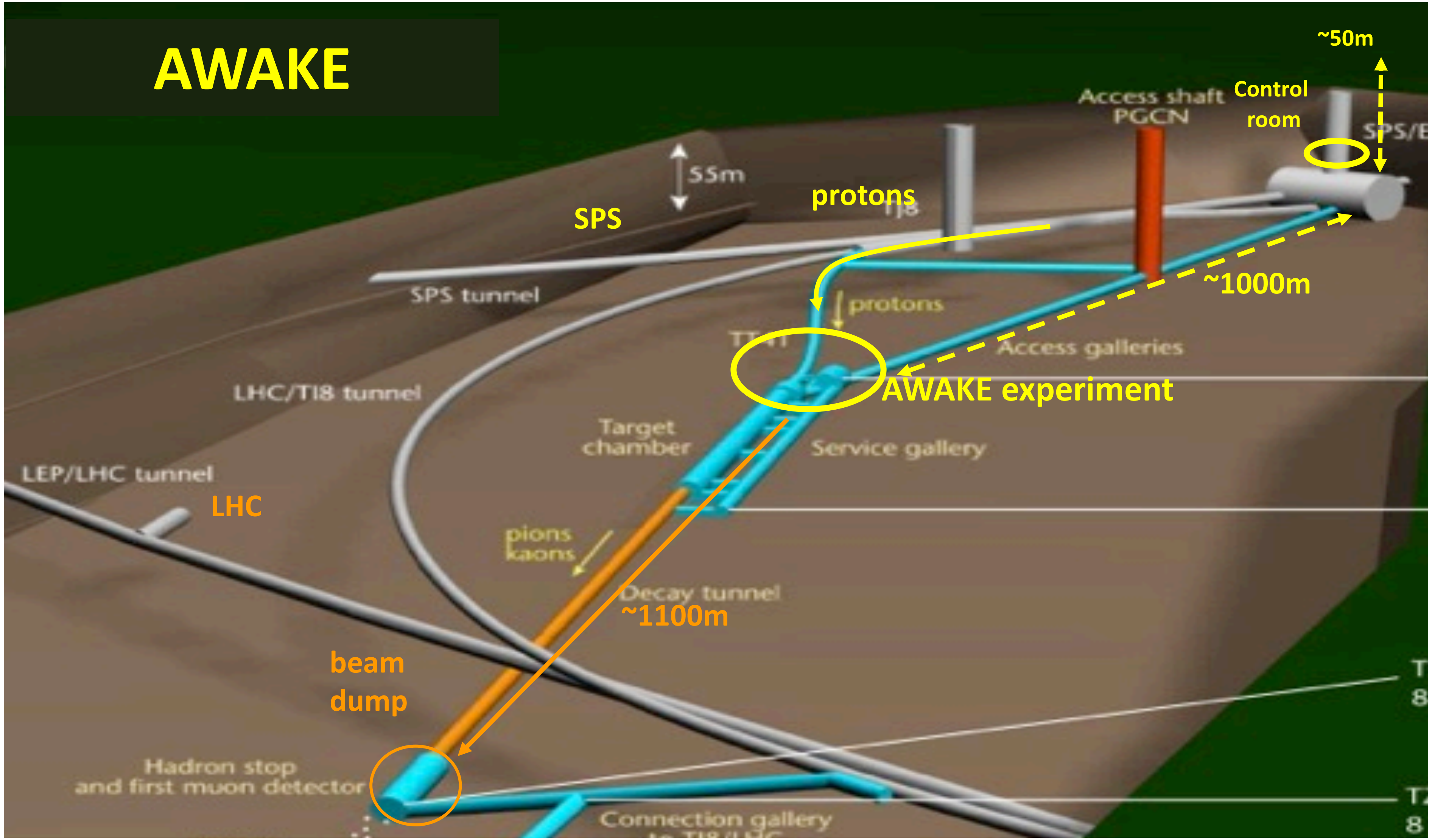
Stronger wakefields

Full modulation



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

AWAKE at CERN



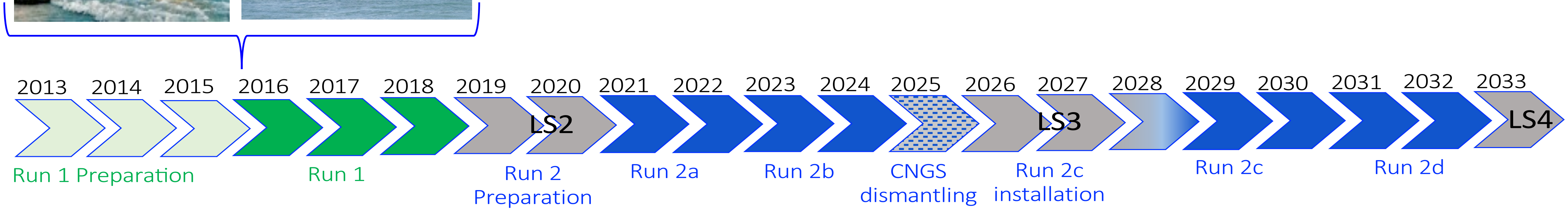
AWAKE installed in CERN underground area

AWAKE has a Well-Defined Program

RUN 1 (2016-2018)

p+ self-modulation

2 GeV e- acceleration



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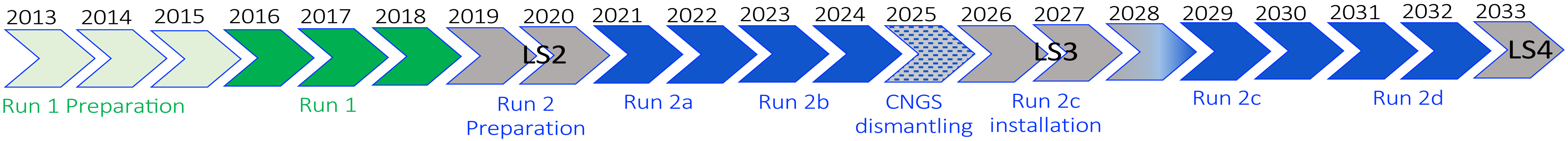
p+ self-modulation

2 GeV e- acceleration

RUN 2 (2021-2032)

e- acceleration to several GeV,
beam quality control, scalability



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2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033

LS2 LS3 LS4

Run 1 Preparation | Run 1 | Run 2 Preparation | Run 2a | Run 2b | CNGS dismantling | Run 2c installation | Run 2c | Run 2d

→ **First applications >2033**

AWAKE is Part of the European Strategy Roadmap

Single-stage accelerators (proton-driven)	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-)	
		Demonstration of: Use of LHC beams, TeV acceleration, beam delivery	**Energy -frontier collider** 10 TeV c.o.m electron-proton collider

Timeline (approximate/aspirational). Legend: R&D (exp & theory); HEP facility

→ AWAKE is part of the roadmap of the European Strategy for Particle Physics

e-p 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)

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

Timeline (approximate/aspirational). Legend: Feasibility study; R&D (exp & theory); HEP facility (earliest start of construction)

R. Pattathil, presented at EAAC 2023

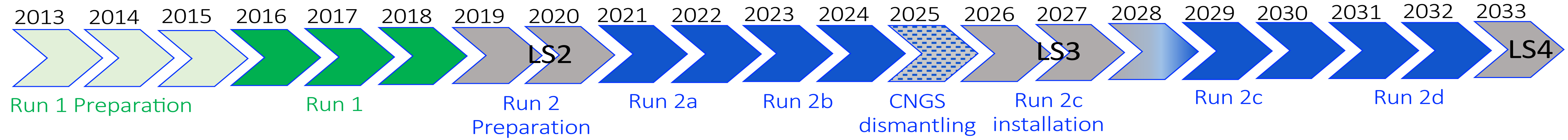
→ AWAKE allows to bridge the gap between the PWFA development in general and a e+/e- collider.

AWAKE Run 1

RUN 1 (2016-2018)

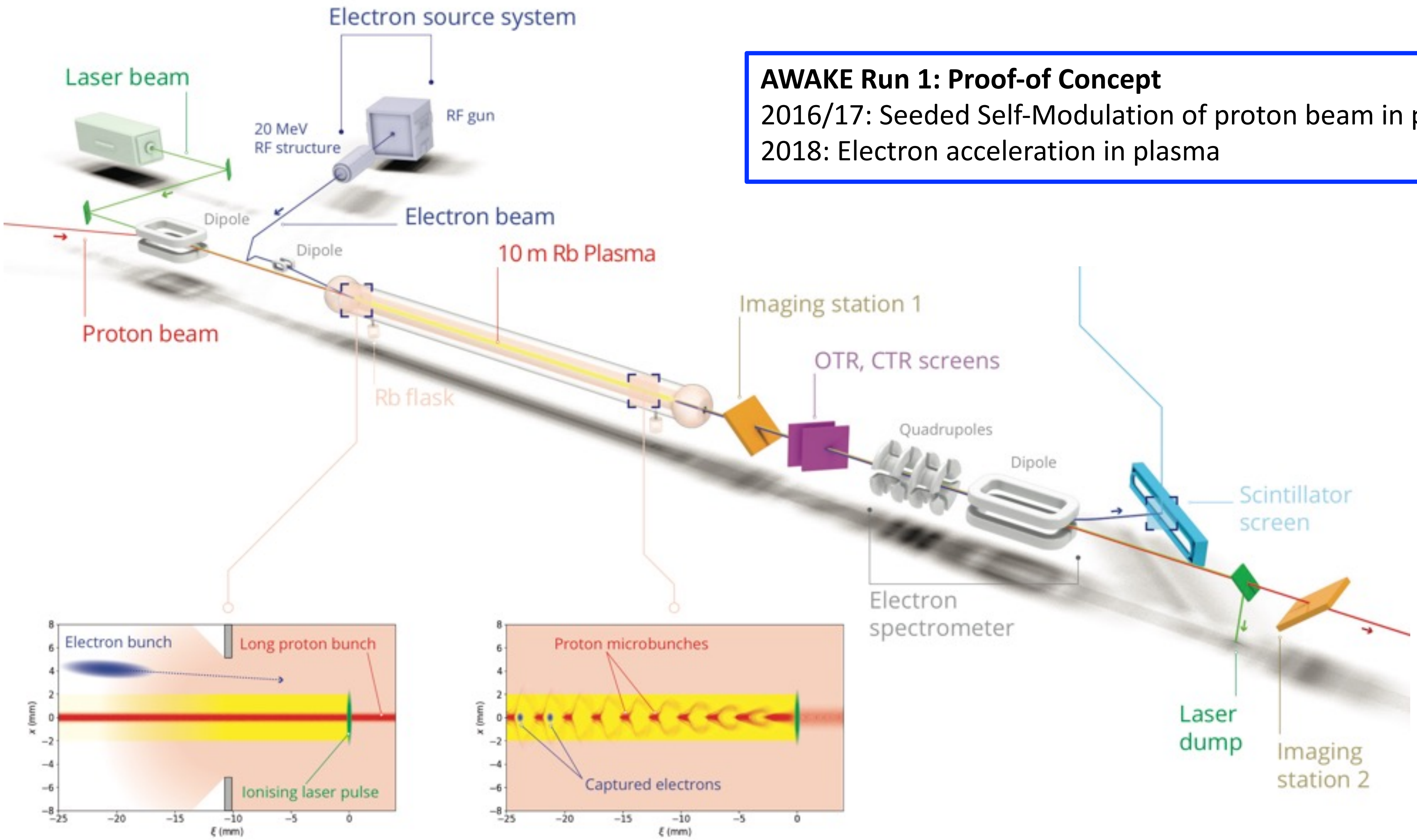
p+ self-modulation

2 GeV e- acceleration



AWAKE Experiment

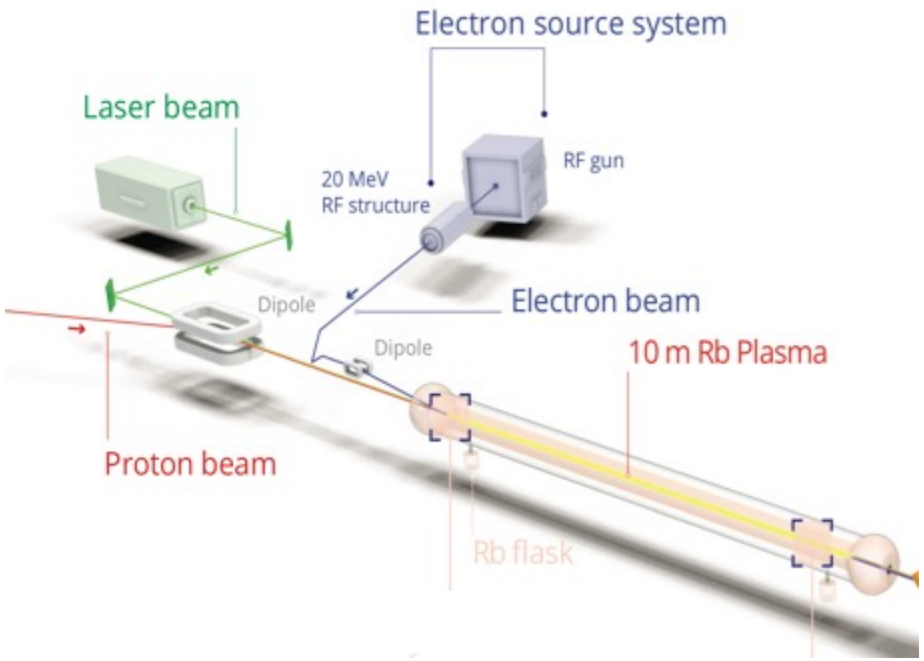
AWAKE Run 1: Proof-of Concept
2016/17: Seeded Self-Modulation of proton beam in plasma
2018: Electron acceleration in plasma

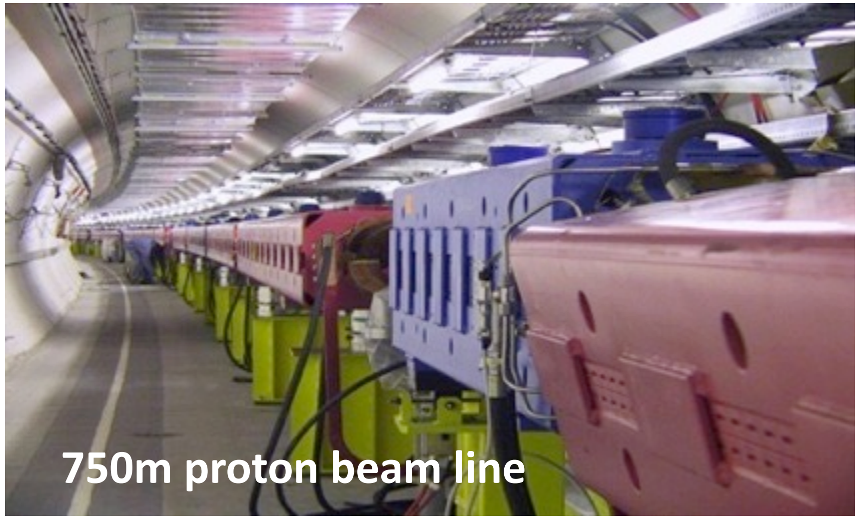


AWAKE Proton Beam Line

Parameter	Protons
Momentum [MeV/c]	400 000
Momentum spread [%]	±0.035
Particles per bunch	$3 \cdot 10^{11}$
Charge per bunch [nC]	48
Bunch length [mm]	120 (0.4 ns)
Norm. emittance [mm·mrad]	3.5
Repetition rate [Hz]	0.033
1σ spot size at focal point [μm]	200 ±20
β-function at focal point [m]	5
Dispersion at focal point [m]	0

Plasma linear theory: $k_{pe}\, \sigma_r \leq 1$
With **σ_r = 200 µm**
$k_{pe} = \omega_{pe}/c = 5\ \mathrm{mm}^{-1}$
➔ **$n_{pe} = 7\times10^{14}\ \mathrm{cm}^{-3}$**

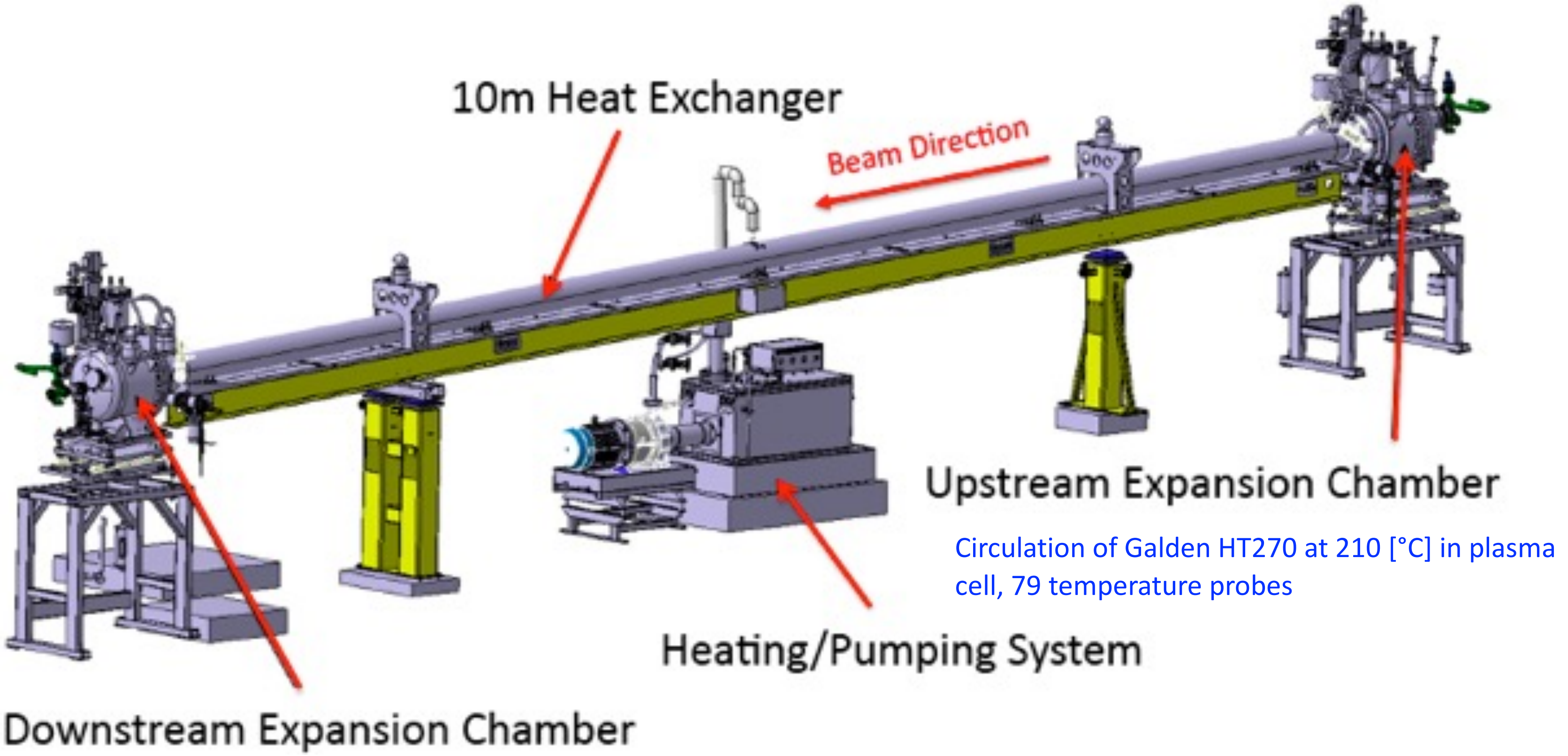



750m proton beam line

The AWAKE beamline is designed to deliver **a high-quality beam** to the experiment. The proton beam must be steered around a mirror which **couples a terawatt class laser** into the beamline.
Further downstream, the **witness electron beam** will be injected into the same beamline.

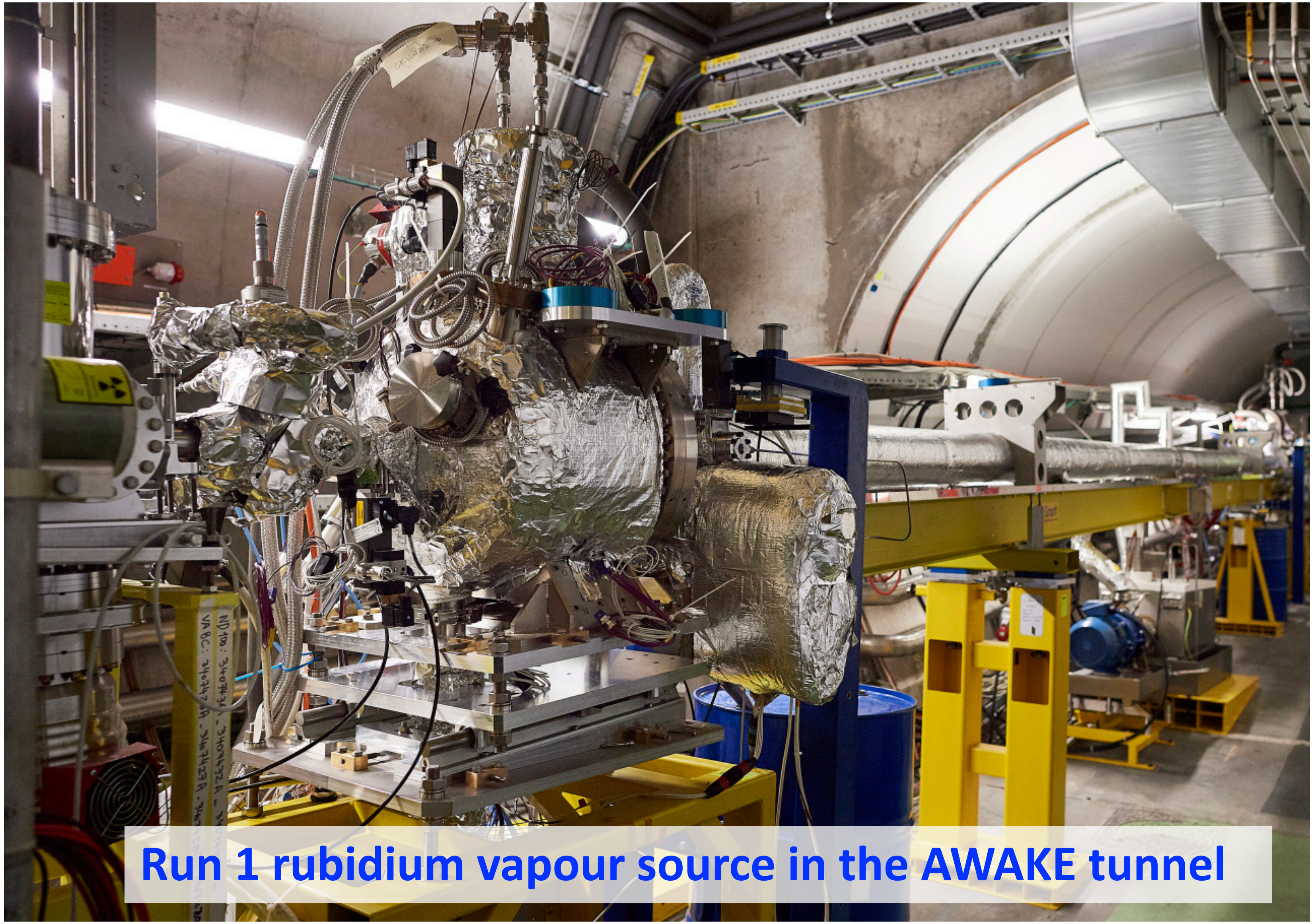
AWAKE Plasma Cell

- **10 m long**, 4 cm diameter **Rubidium** vapour source
- **Laser** ionizes Rb vapour to become Rb plasma.
- Density adjustable from 10^{14} – 10^{15} cm^{-3} ➔ desired: 7x 10^{14} cm^{-3}
- Density uniformity: < 0.2%



Circulation of Galden HT270 at 210 [°C] in plasma cell, 79 temperature probes

AWAKE Plasma Source



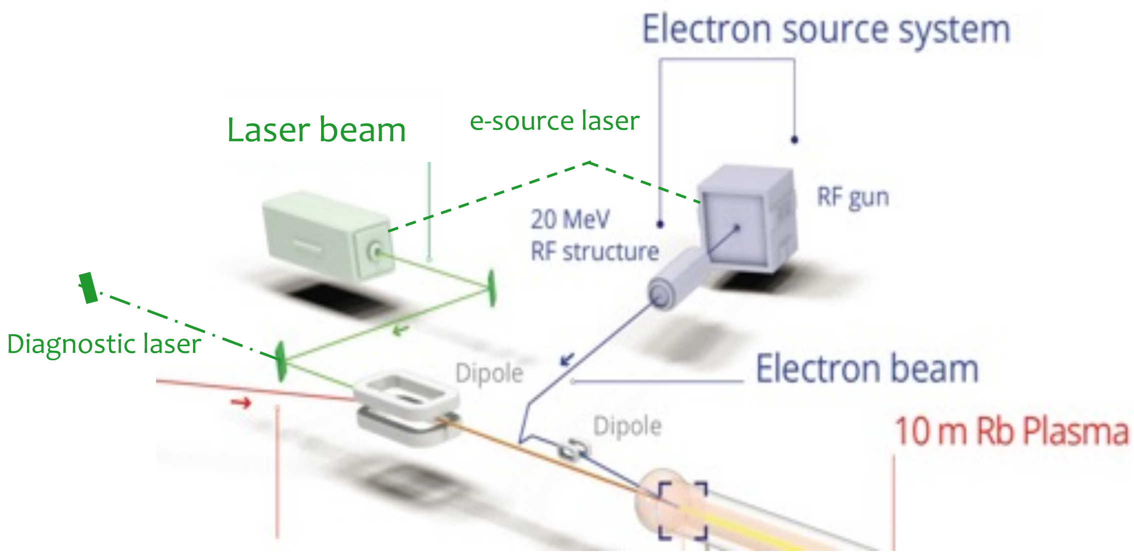
GWA Technology

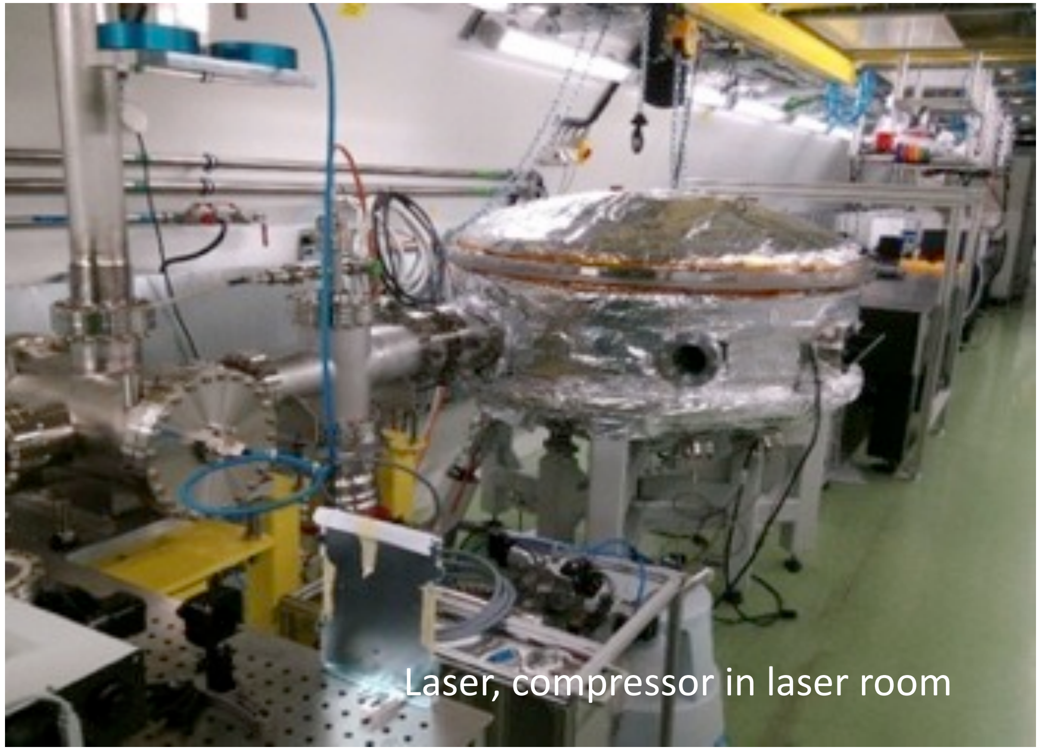
WDL

MAX-PLANCK-INSTITUT FÜR PHYSIK

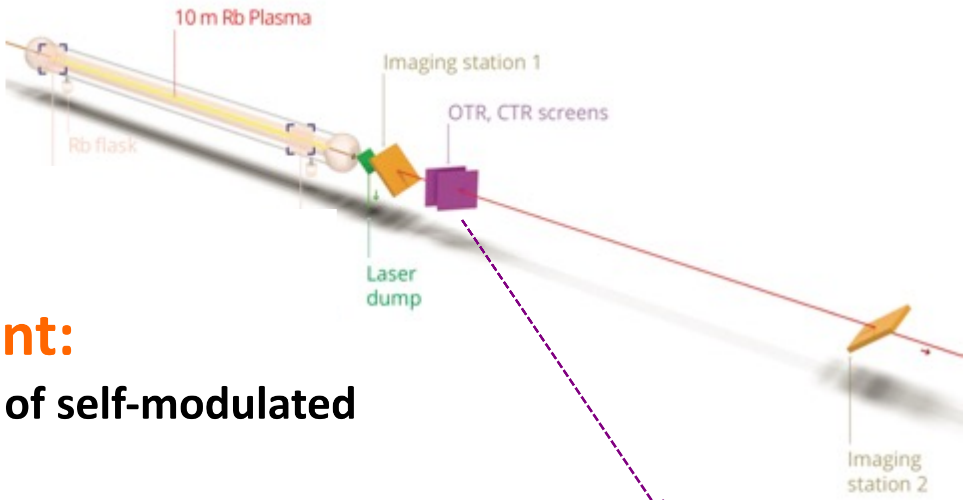
Laser and Laser Line

AWAKE uses a short-**pulse Titanium:Sapphire laser** to ionize the rubidium source.
→ Seeding of the self-modulation with the relativistic ionization front.
The laser can deliver up **to 500 mJ in a 120 fs pulse envelope**.





Diagnostics for Proton Bunch Self-Modulation

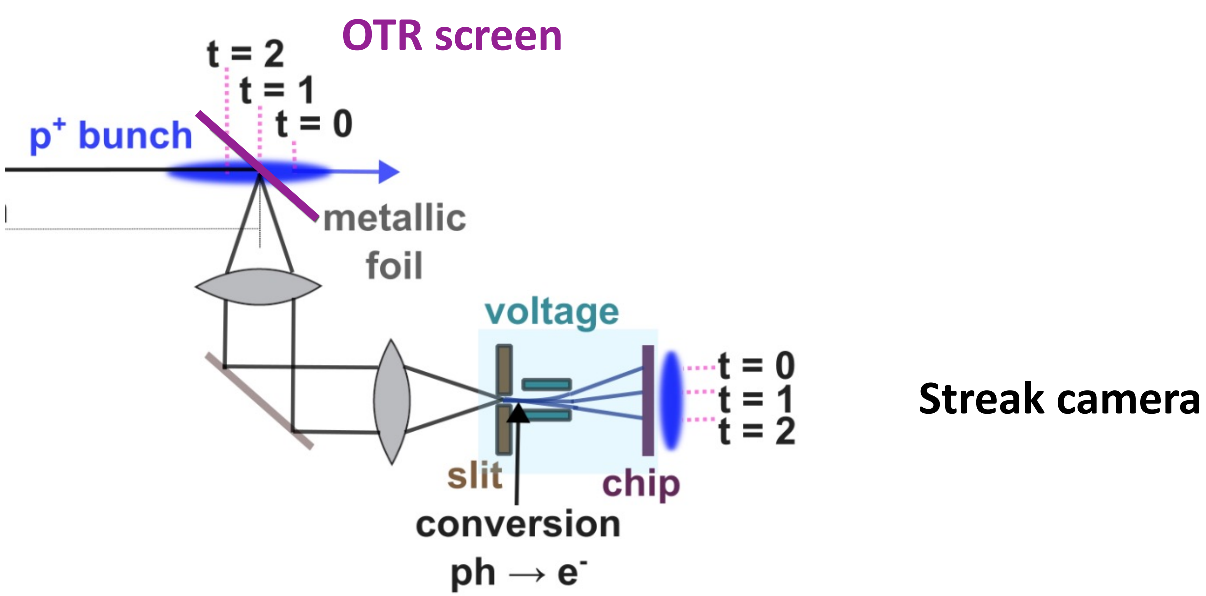


Direct SSM Measurement:

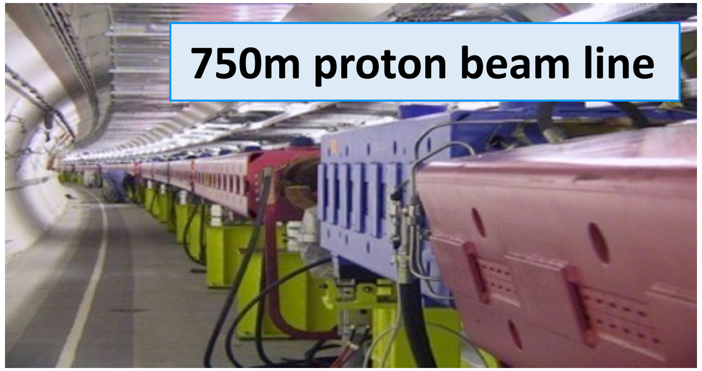
Measure longitudinal structure of self-modulated proton bunch.

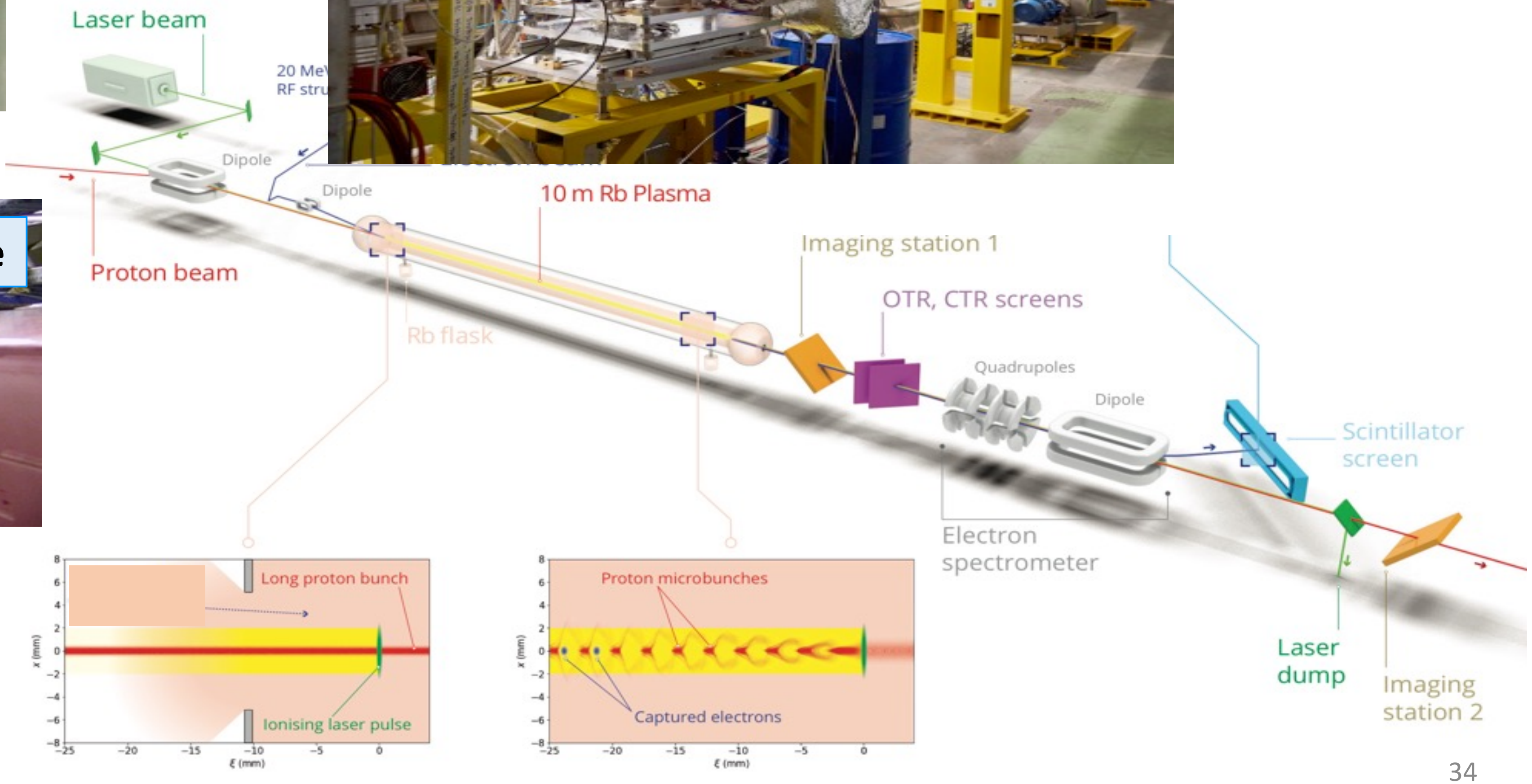
→ Image OTR light onto the slit of a streak camera.

→ Time resolved measurement.

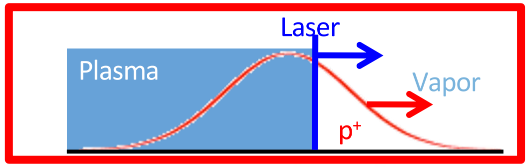


AWAKE Experiment and Run 1 Results

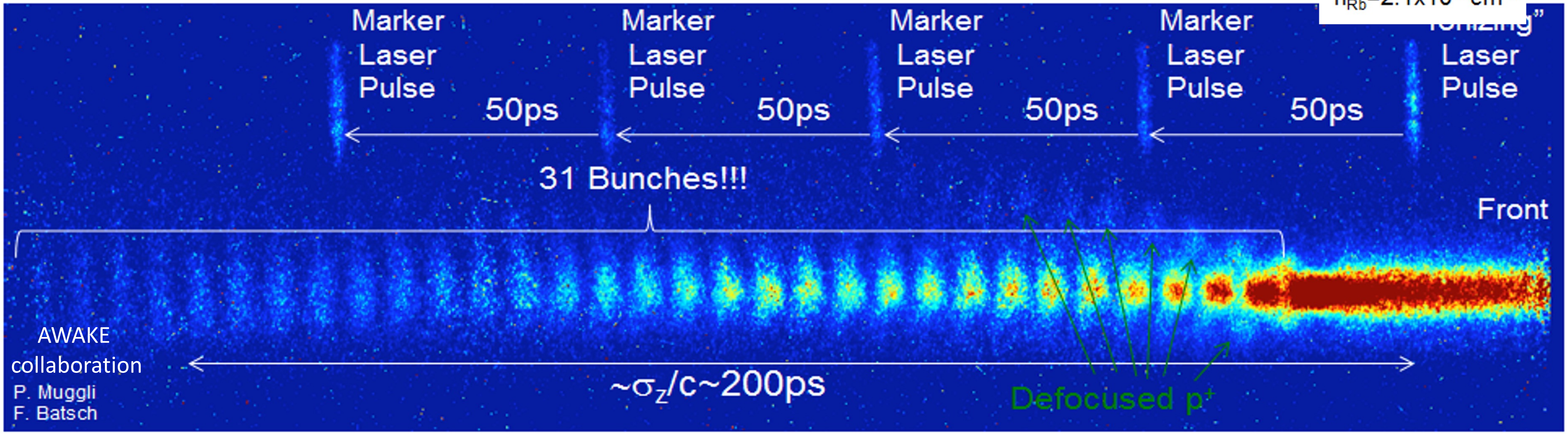




Results Run 1: Direct Seeded Self-Modulation Measurement



$n_{Rb}=2.1\times10^{14}cm^{-3}$

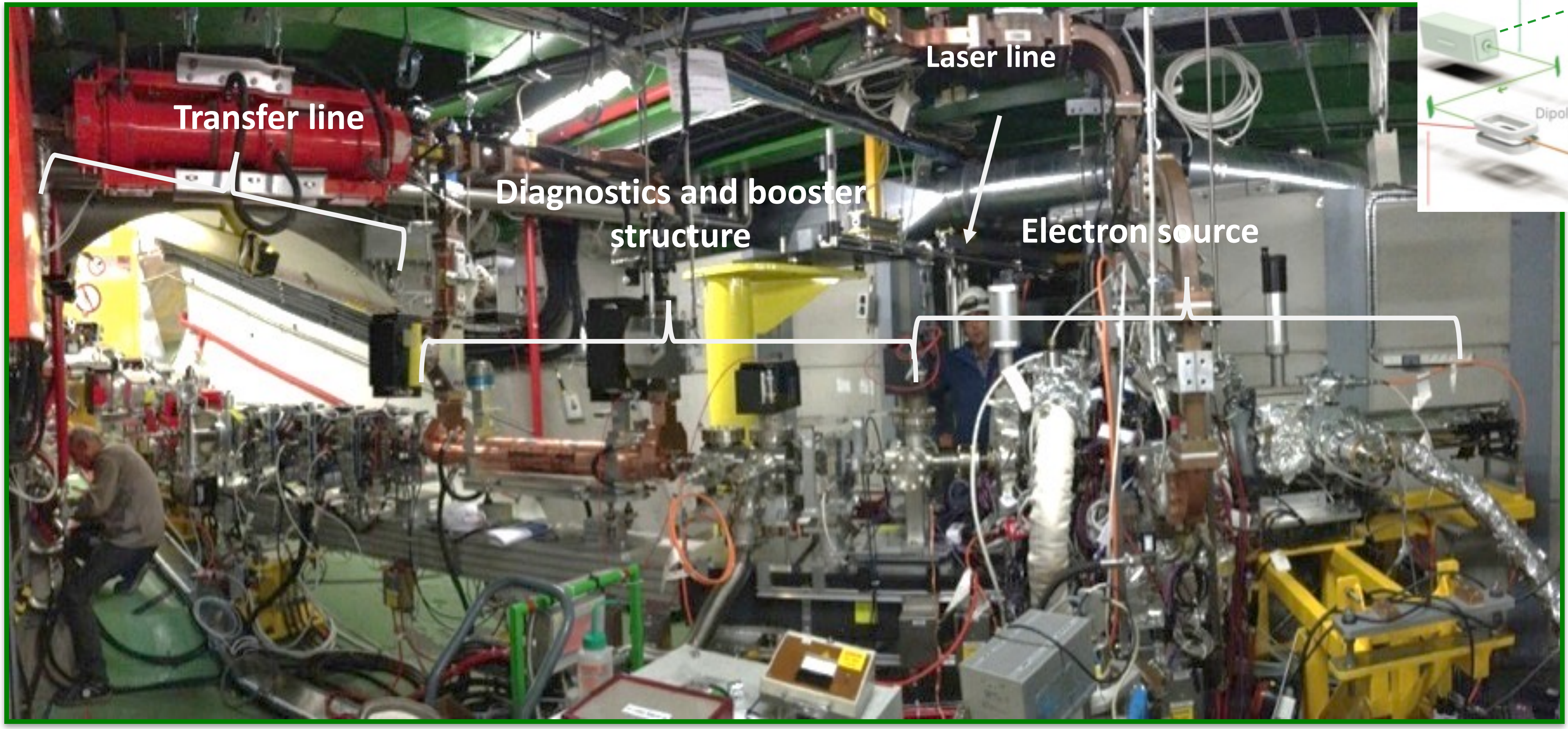


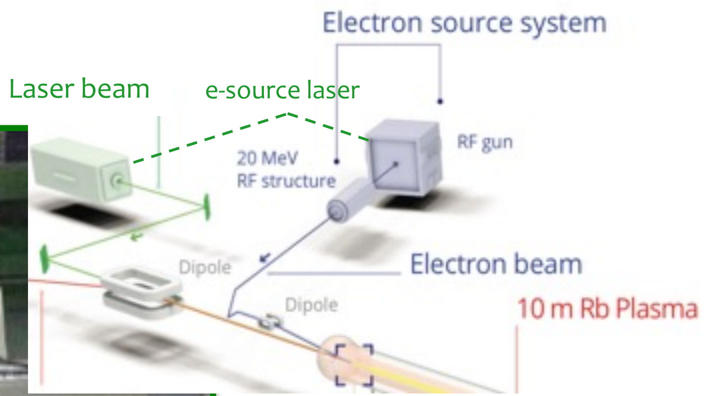
- Effect starts at laser timing → **SM seeding**
- **Density modulation** at the ps-scale visible
- Micro-bunches **present over long time scale** from seed point
- **Reproducibility** of the µ-bunch process against bunch parameters variation
- **Phase stability** essential for e^- external injection.

→ 1st AWAKE Milestone reached

AWAKE Collaboration, Phys. Rev. Lett. 122, 054802 (2019).
M. Turner et al. (AWAKE Collaboration), 'Phys. Rev. Lett. 122, 054801 (2019).
M. Turner, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Accel. Beams 23, 081302 (2020)
F. Braunmueller, T. Nechaeva et al. (AWAKE Collaboration), Phys. Rev. Lett. July 30 (2020).
A.A. Gorn, M. Turner et al. (AWAKE Collaboration), Plasma Phys. Control Fusion, Vol. 62, Nr 12 (2020).
F. Batsch, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Lett. 126, 164802 (2021).

Electron Beam System

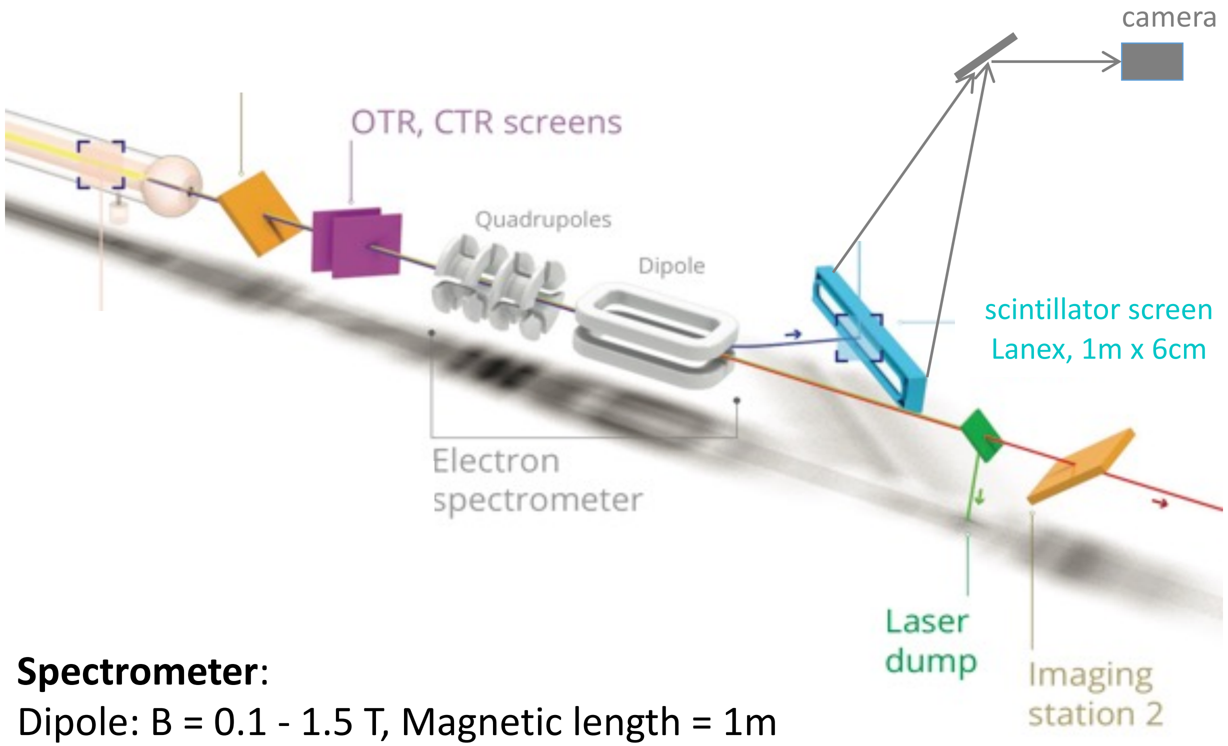




A Photo-injector originally built for a CLIC test facility is now used as electron source for AWAKE producing **short electron bunches at an energy of ~20 MeV/c.**
A **completely new 12 m long electron beam line** was designed and built to connect the electrons from the e-source with the plasma cell.

Challenge: cross the electron beam with the proton beam inside the plasma at a precision of ~100 µm.

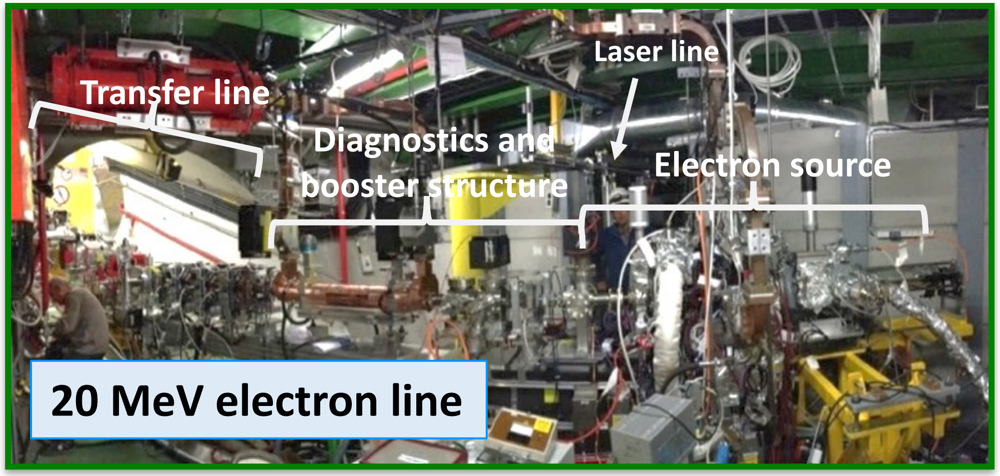
Electron Acceleration Diagnostics

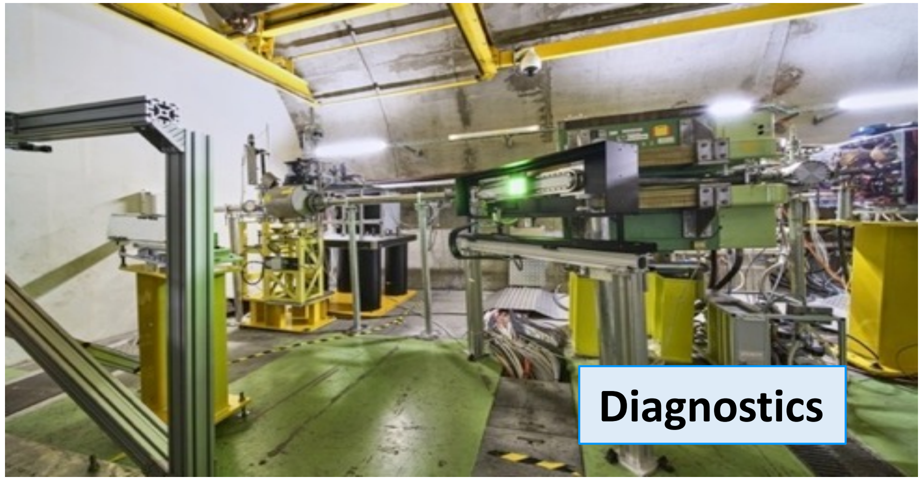


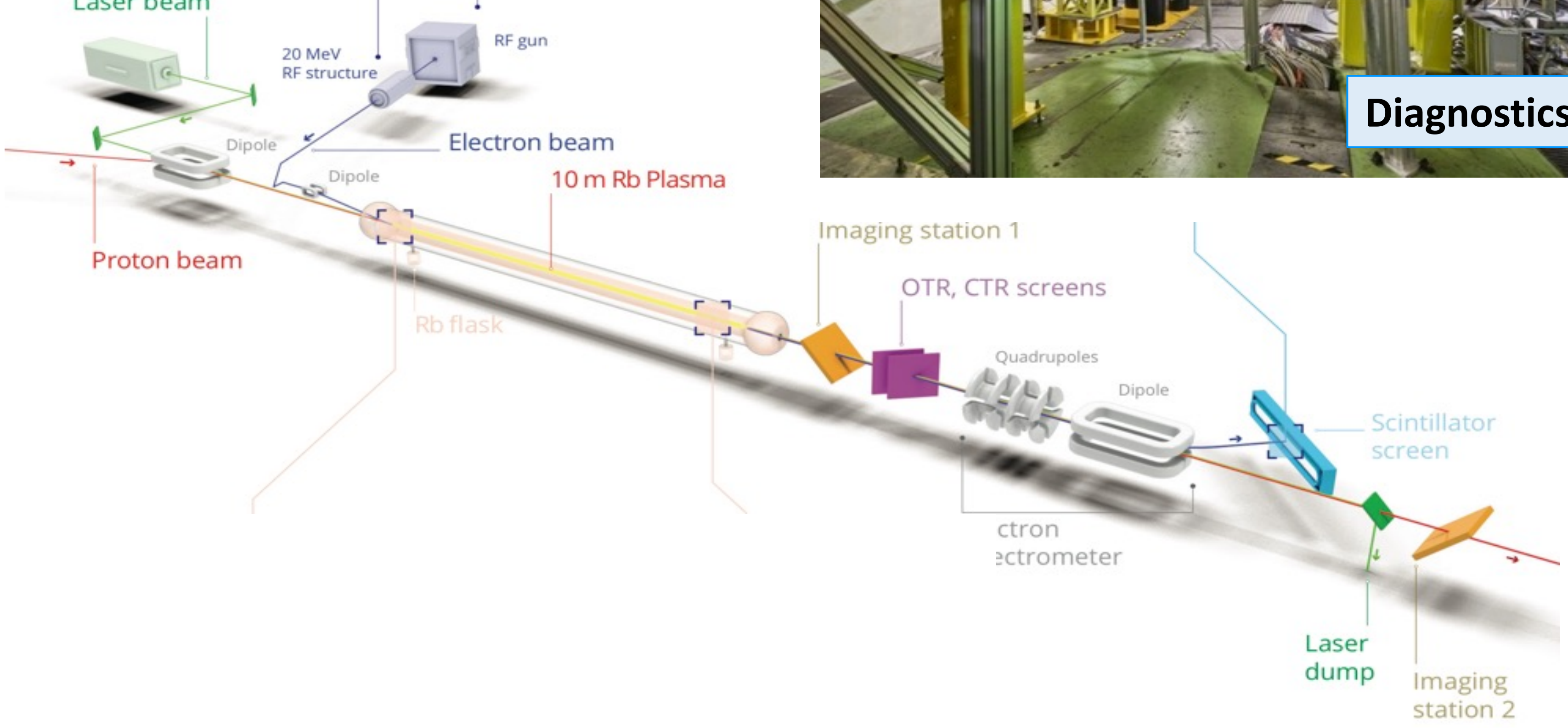
Spectrometer:
Dipole: B = 0.1 - 1.5 T, Magnetic length = 1m
→ detect electrons with energies ranging from 30MeV - 8.5 GeV

Electrons will be accelerated in the plasma. To measure the energy the electrons pass through a **dipole spectrometer and the dispersed electron impact on the scintillator screen.**
The resulting light is collected with an intensified CCD camera.

AWAKE Experiment and Run 1 Results

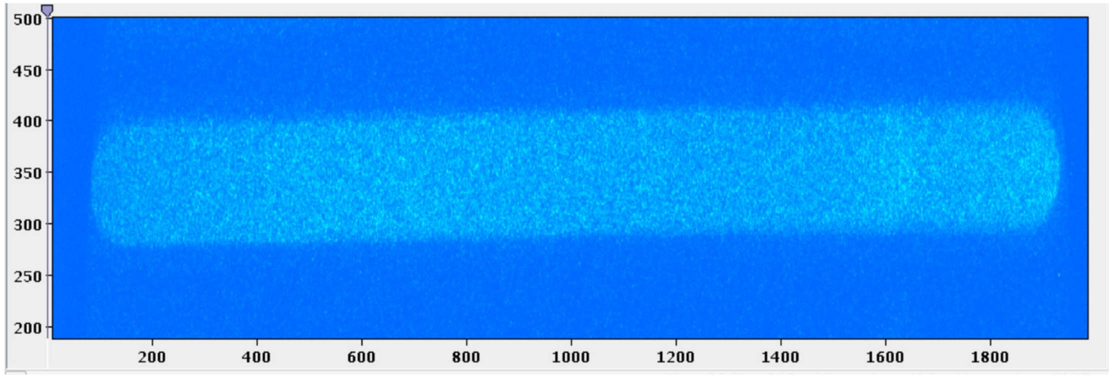




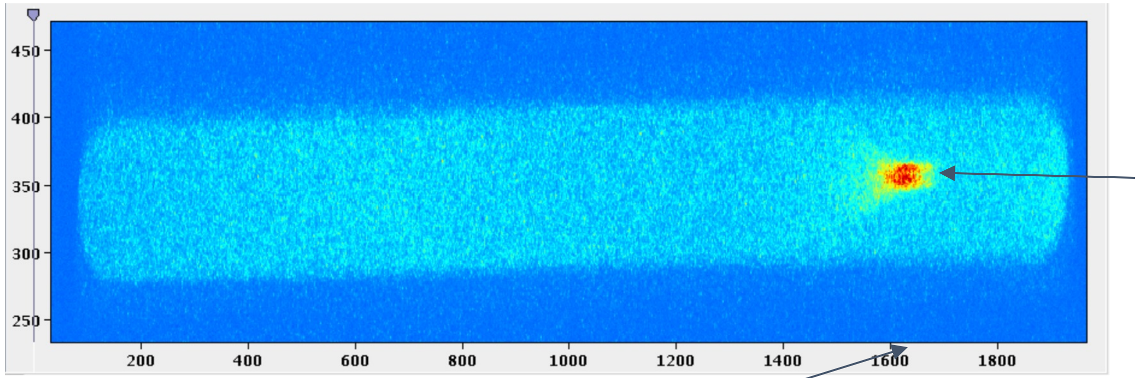


Run 1 Results: Electron Acceleration

#2: Demonstration of Electron Acceleration in Plasma Wakefield



No accelerated electrons



Accelerated electrons

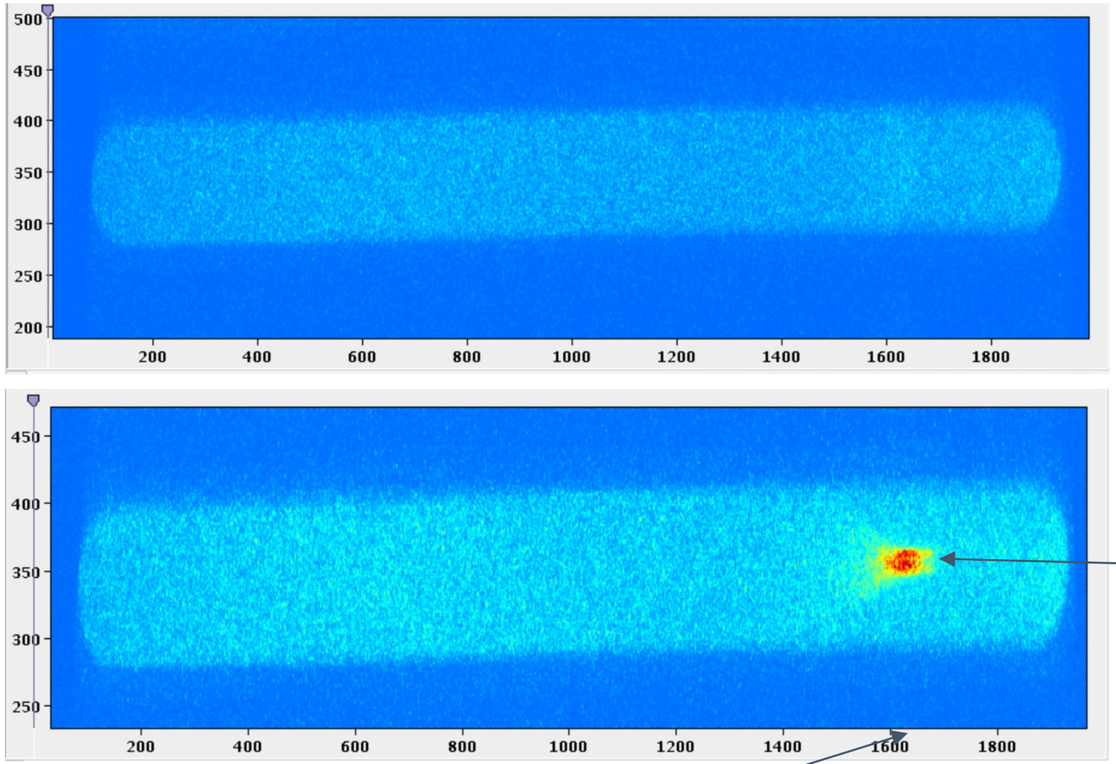
Convert pixel-size and dipole setting to energy

E. Gschwendtner, CERN

Run 1 Results: Electron Acceleration

#2: Demonstration of Electron Acceleration in Plasma Wakefield

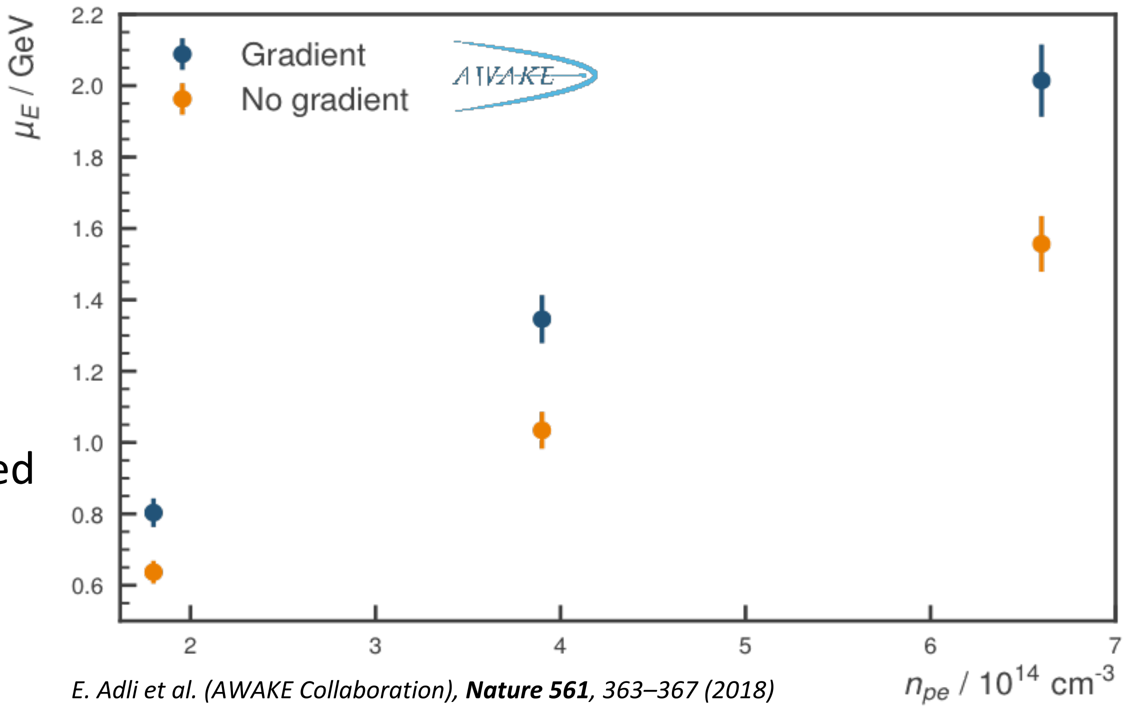
- **Acceleration up to 2 GeV** has been achieved.
- Charge capture up to 20%.



No accelerated electrons

Accelerated electrons

Convert pixel-size and dipole setting to energy



E. Adli et al. (AWAKE Collaboration), ***Nature 561****, 363–367 (2018)*

AWAKE Run 2

➔AWAKE has developed a clear scientific roadmap towards first particle physics applications within the next decade !

➔In AWAKE many general issues are studied, which are relevant for concepts that are based on plasma wakefield acceleration.

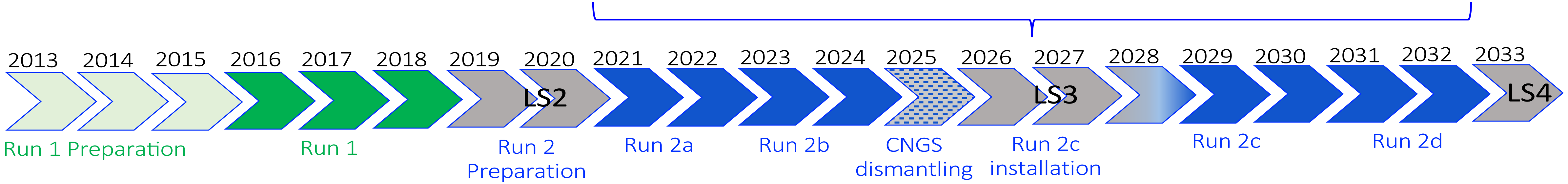
Paradigm change:

➔ Move from 'acceleration R&D' to an 'accelerator'

AWAKE Program

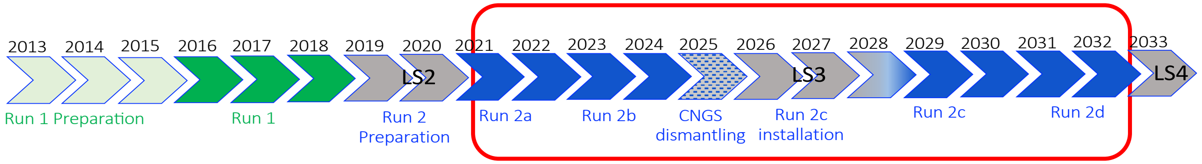
RUN 2 (2021-2032)

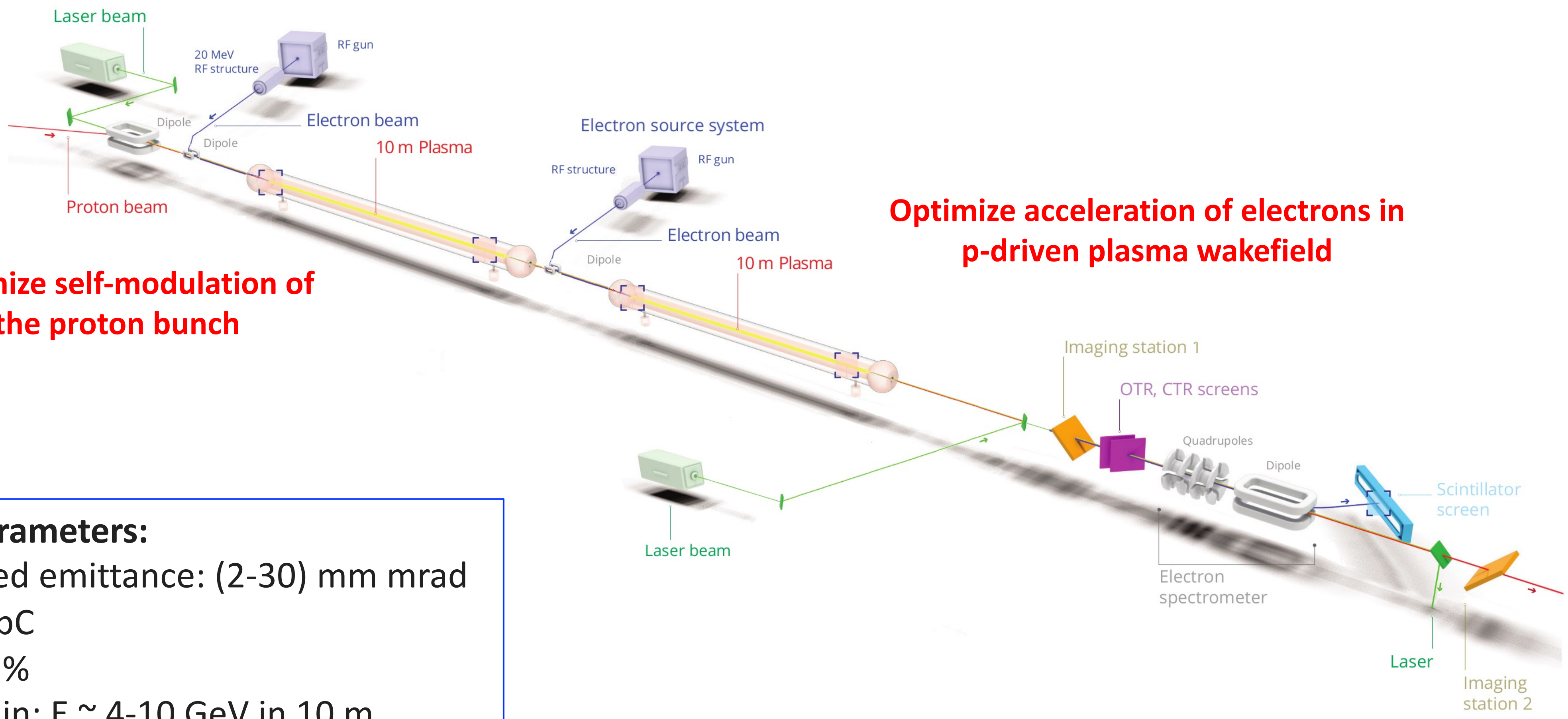
e- acceleration to several GeV, beam quality control, scalability



AWAKE Run 2

Accelerate an electron beam to **high energies**, while controlling the electron **beam quality** and demonstrate **scalable plasma source** technology.





Optimize self-modulation of the proton bunch

Optimize acceleration of electrons in p-driven plasma wakefield

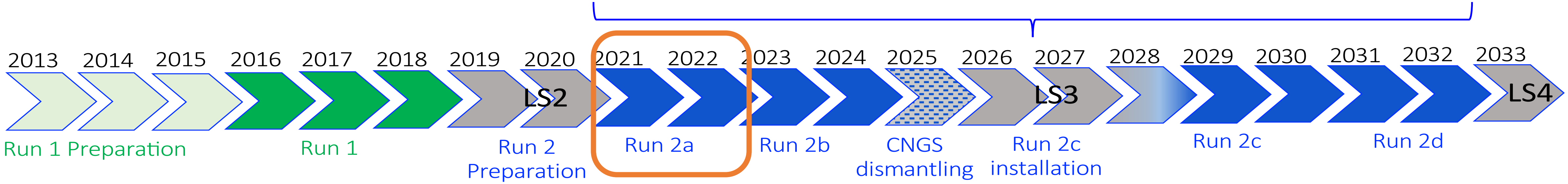
Expected parameters:

- Normalized emittance: (2-30) mm mrad
- Q_e = 100 pC
- dE/E: 5-8 %
- Energy gain: E ~ 4-10 GeV in 10 m

AWAKE Program

RUN 2 (2021-2032)

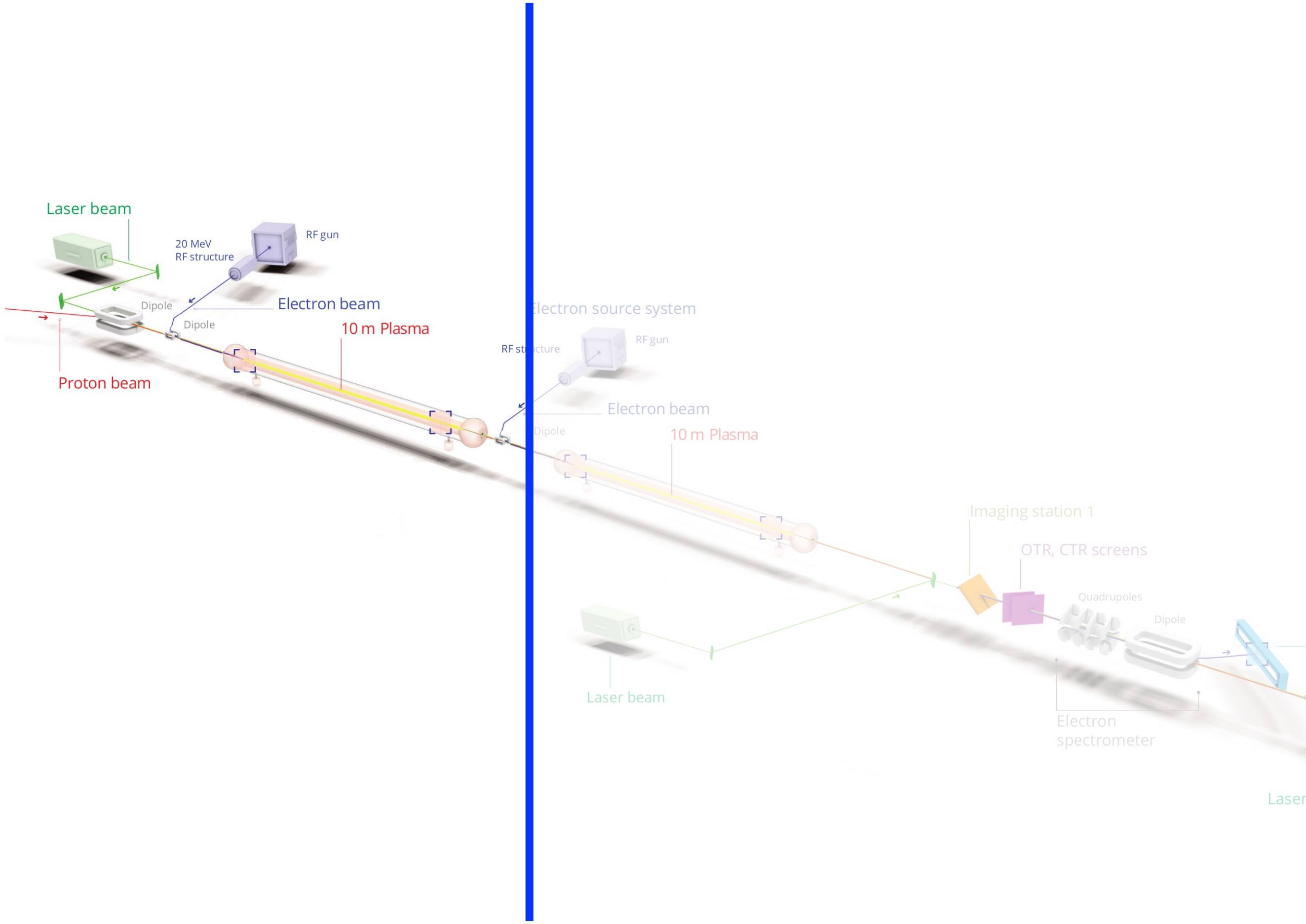
e- acceleration to several GeV,
beam quality control, scalability



✓ **Run 2a (2021-2022): CONTROL: demonstrate the *seeding of the self-modulation of the entire proton bunch with an electron bunch***

Run 2a Results – Seeding the Self-Modulation

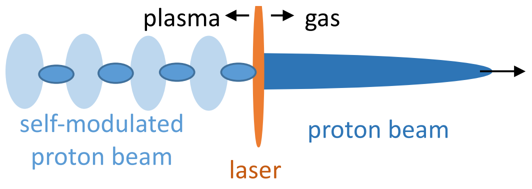
➔ Proton-bunch self-modulation process must be **reproducible, reliable and stable.**



Run 2a Results – Seeding the Self-Modulation

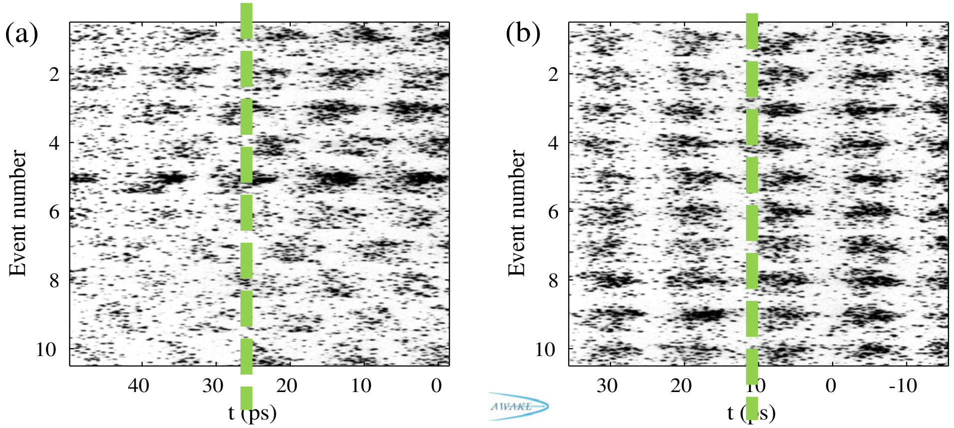
➔ Proton-bunch self-modulation process must be **reproducible, reliable and stable.**

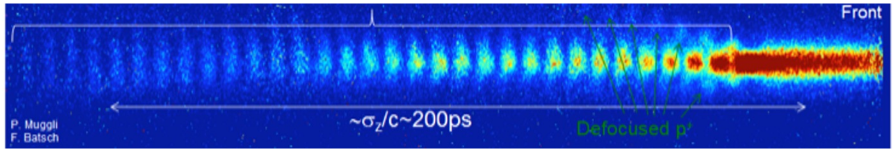
Seeding with the relativistic ionization front



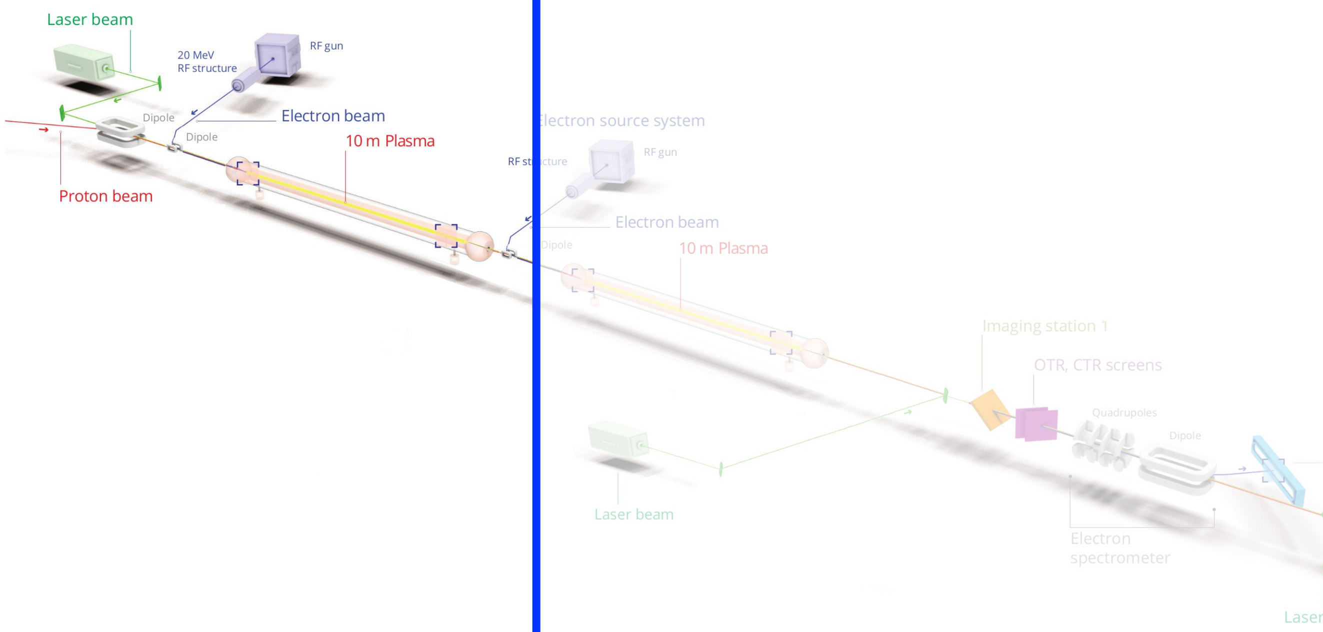
Unseeded: phase not reproducible

Seeded with laser ionization front





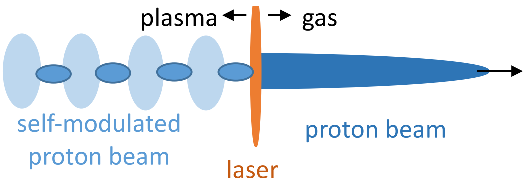
F. Batsch, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Lett. 126, 164802 (2021).

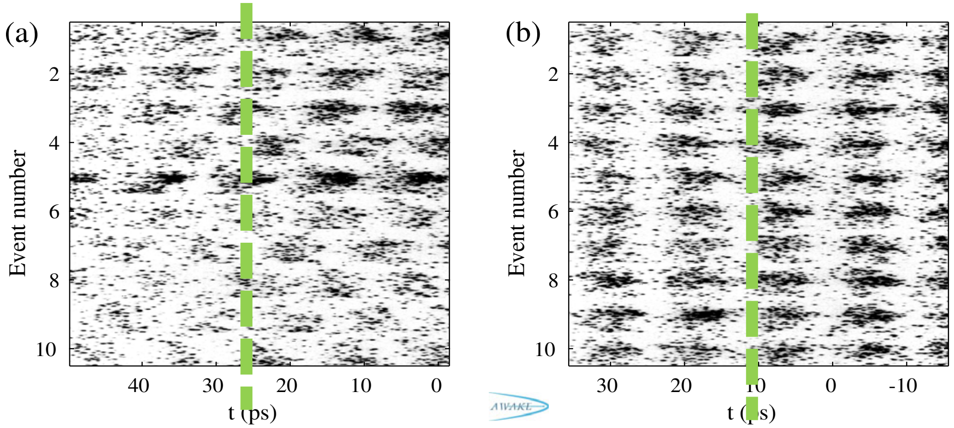


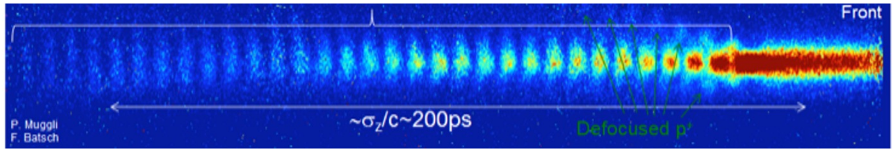
Run 2a Results – Seeding the Self-Modulation

➔ Proton-bunch self-modulation process must be **reproducible, reliable and stable.**

Seeding with the relativistic ionization front

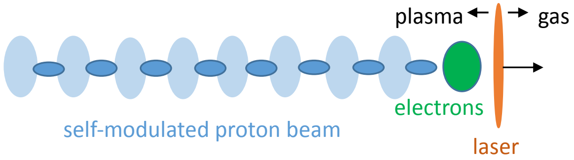


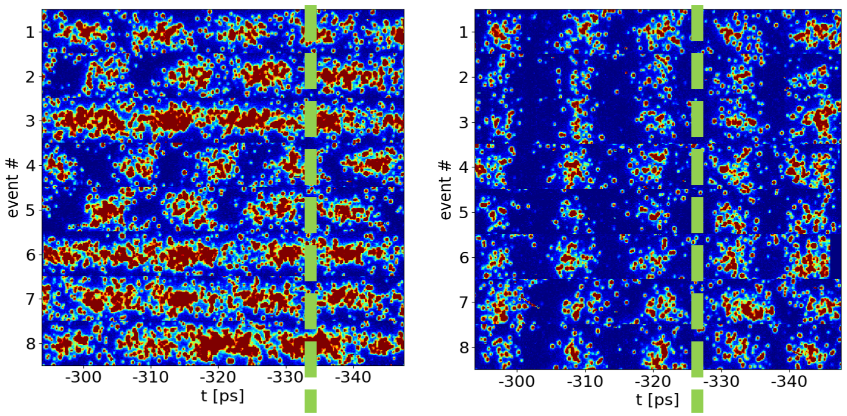


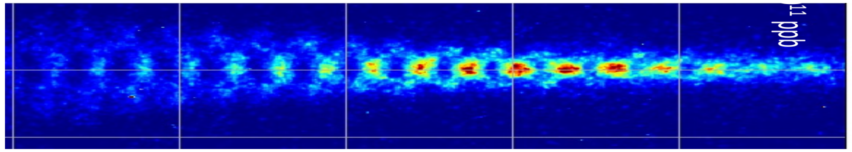


F. Batsch, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Lett. 126, 164802 (2021).

Seeding with the electron bunch





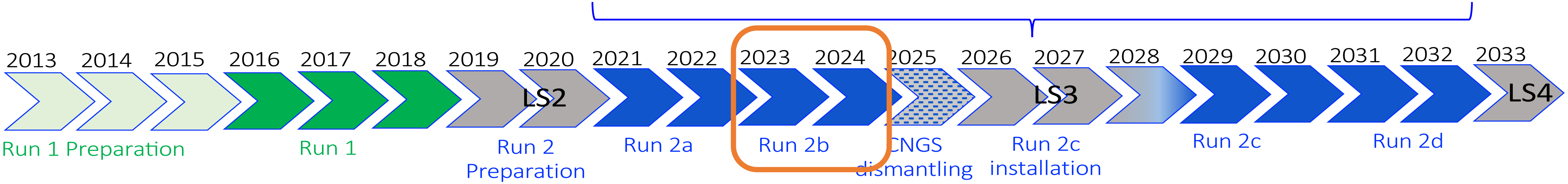


L. Verra et al. (AWAKE Collaboration), Phys. Rev. Lett. 129, 024802 (2022)

AWAKE Program

RUN 2 (2021-2032)

e- acceleration to several GeV,
beam quality control, scalability

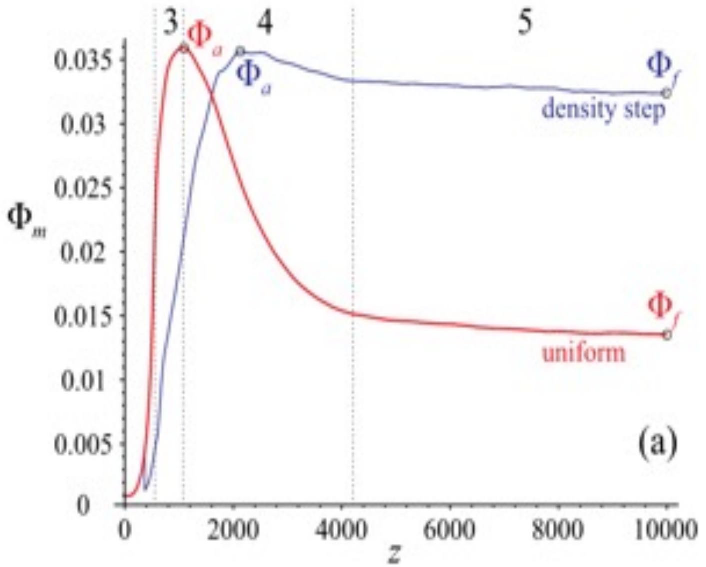


✓ **Run 2a (2021-2022): CONTROL: demonstrate the *seeding of the self-modulation of the entire proton bunch with an electron bunch***

➔ **Run 2b (2023-2024): STABILIZATION: *maintain large wakefield amplitudes*** over long plasma distances by introducing a step in the plasma density

Run 2b Results – Stabilizing Large Wakefield Amplitudes

Introducing a density step in the plasma cell
➔ stabilization of the micro-bunches
➔ Increased wakefield amplitudes after SSM saturation



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

Run 2b Results – Stabilizing Large Wakefield Amplitudes

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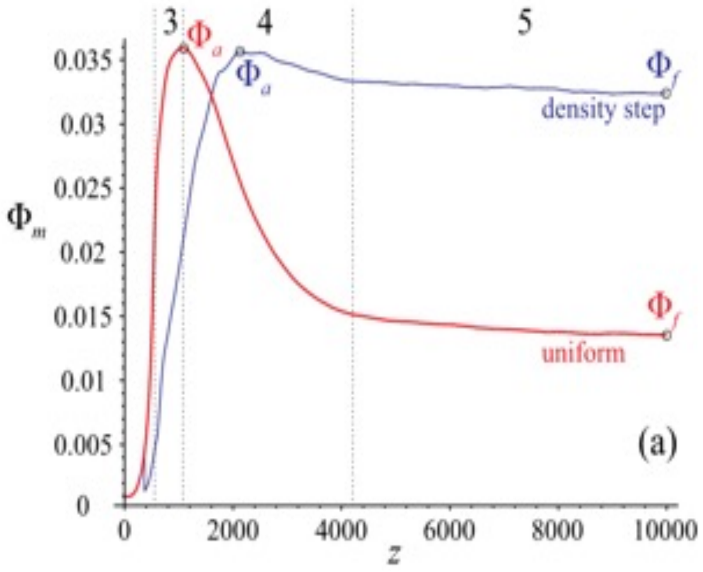
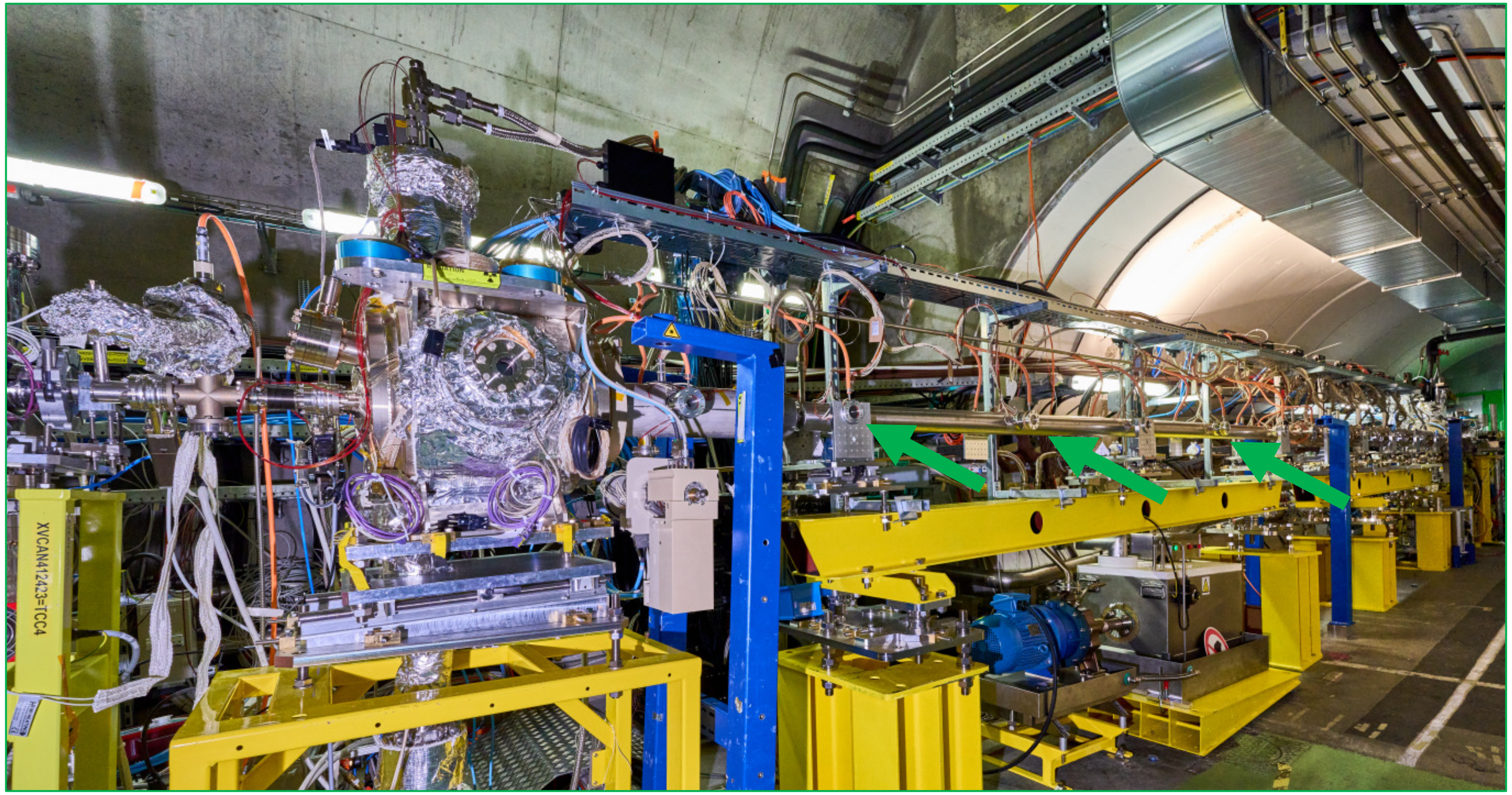


K. V. Lotov, Physics of Plasmas 22, 103110 (2015)
K. V. Lotov and P. V. Tuev 2021 PPFC ***63 125027***

New Rubidium vapour source with density step installed in 2023

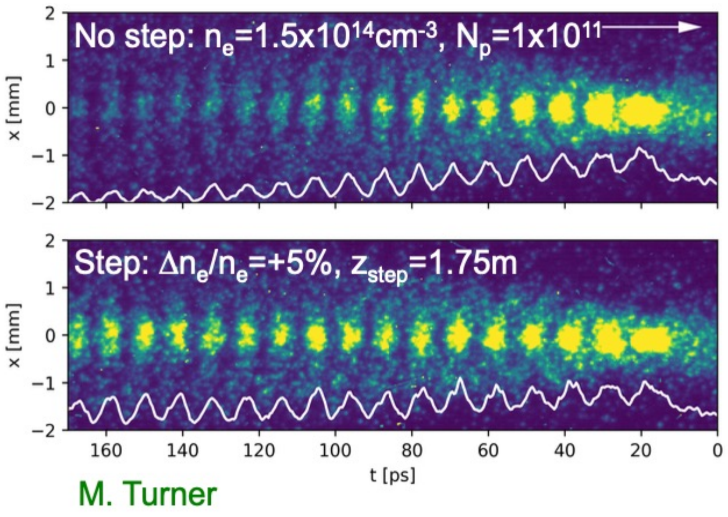


- Length: ~ 10 m, independent electrical heater of 50 cm from 0.25 to 4.75 m, Step height up to ±10%
- 10 diagnostic viewport ➔ to measure light emitted by wakefields dissipating after the passage of the proton bunch

Run 2b Results – Stabilizing Large Wakefield Amplitudes

Physics program: study the effect of the plasma density and test whether wakefields maintain a larger amplitude

Proton Bunch Time-Resolved Images



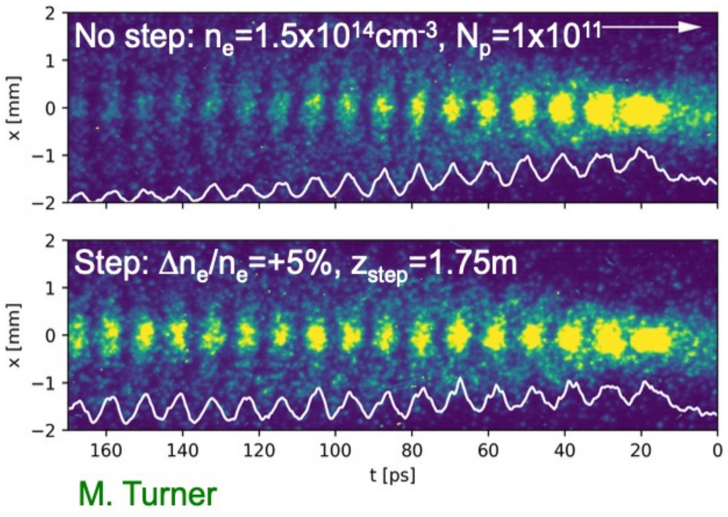
➔ plasma density step clearly influences seeded self-modulation: Longer bunch train with more charge

Preliminary

Run 2b Results – Stabilizing Large Wakefield Amplitudes

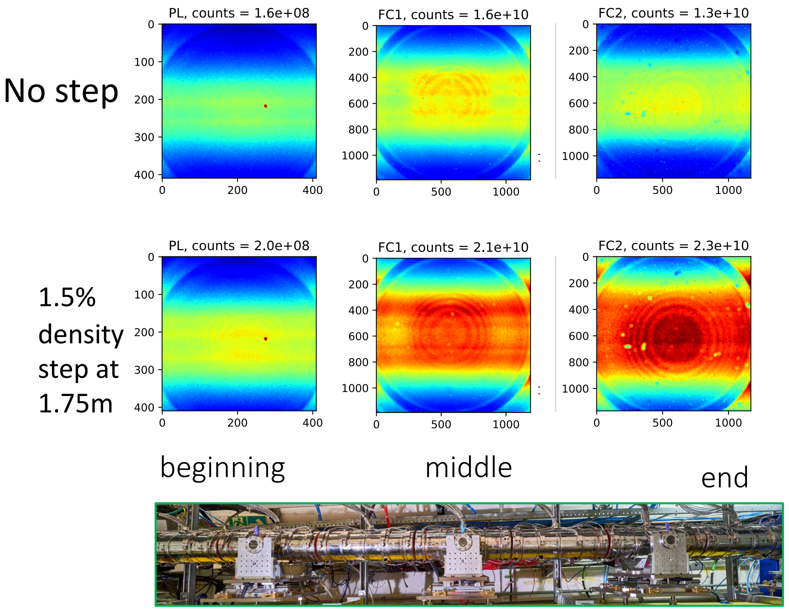
Physics program: study the effect of the plasma density and test whether wakefields maintain a larger amplitude

Proton Bunch Time-Resolved Images



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

Plasma Light



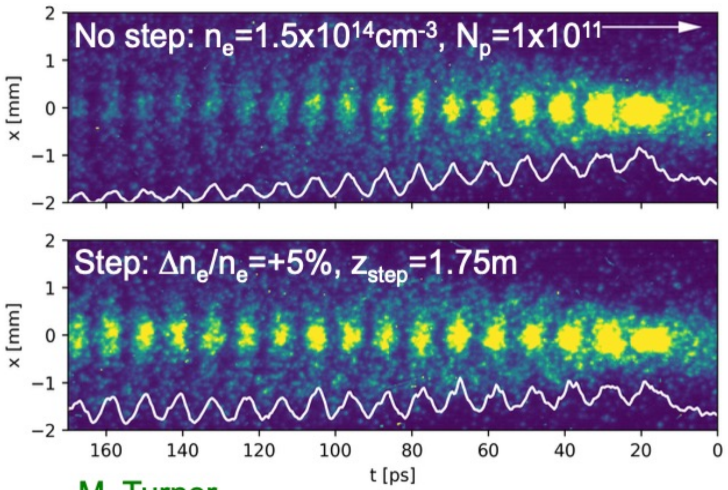
➔ plasma density step clearly influences plasma light from dissipating wakefields

Preliminary

Run 2b Results – Stabilizing Large Wakefield Amplitudes

Physics program: study the effect of the plasma density and test whether wakefields maintain a larger amplitude

Proton Bunch Time-Resolved Images



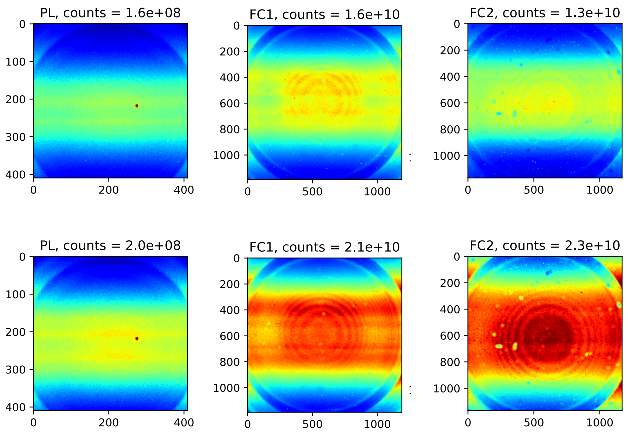
M. Turner

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

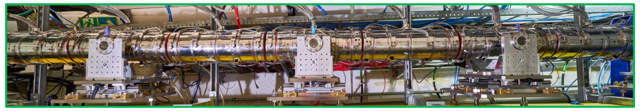
Plasma Light

No step

1.5% density step at 1.75m



beginning middle end

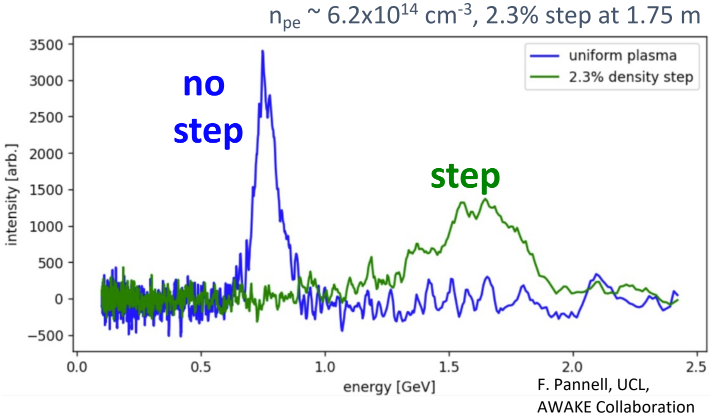


➔ plasma density step clearly influences plasma light from dissipating wakefields

Electron Acceleration

External injection downstream of the density step

n_{pe} ~ 6.2x10^{14} cm^{-3}, 2.3% step at 1.75 m



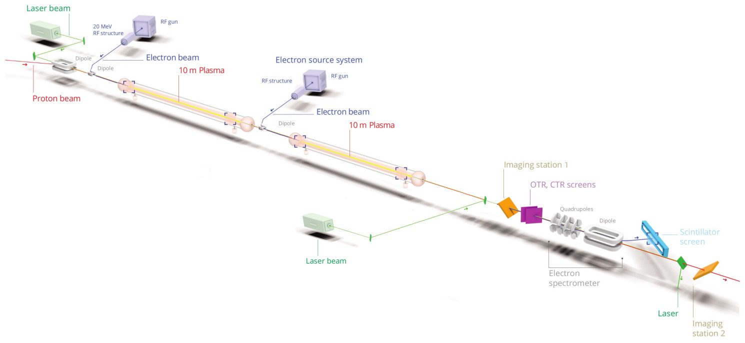
F. Pannell, UCL, AWAKE Collaboration

➔ Plasma density step clearly influences energy of the accelerated electrons: electron energy much higher

Preliminary

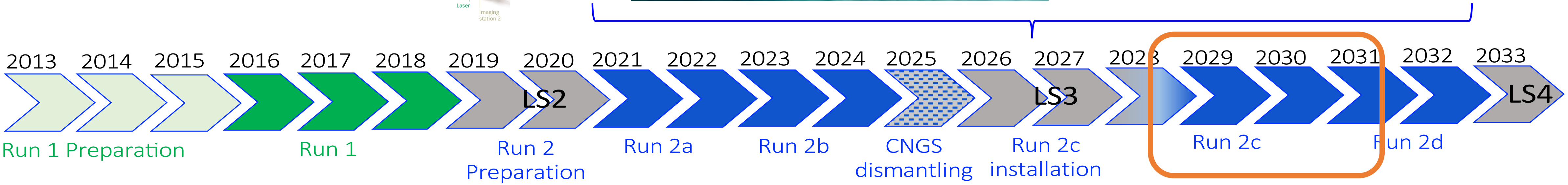
➔ **Complete the measurements during 2024 run!**

AWAKE Program



RUN 2 (2021-2032)

e- acceleration to several GeV,
beam quality control, scalability



✓ **Run 2a (2021-2022): CONTROL: demonstrate the *seeding of the self-modulation of the entire proton bunch with an electron bunch***

➔ **Run 2b (2023-2024): STABILIZATION: *maintain large wakefield amplitudes*** over long plasma distances by introducing a step in the plasma density

➔ *(2025-2027): CNGS dismantling, CERN Long Shutdown LS3, installation of Run 2c*

➔ **Run 2c (2028-2031): QUALITY**: demonstrate ***electron acceleration and emittance control of externally injected electrons***.

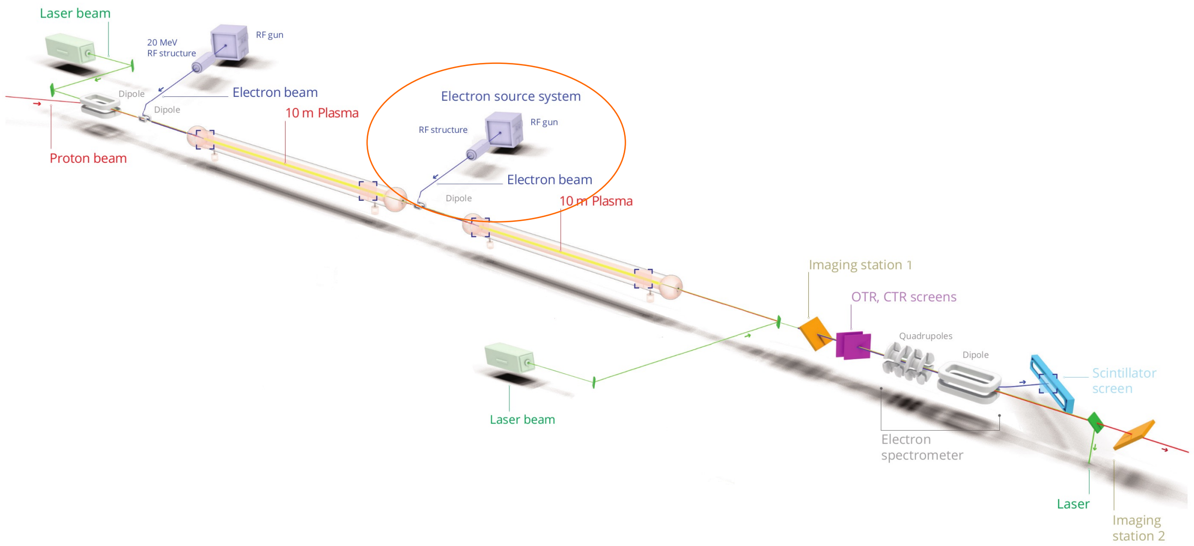
AWAKE Run 2c – Demonstrate Electron Acceleration and Emittance Control

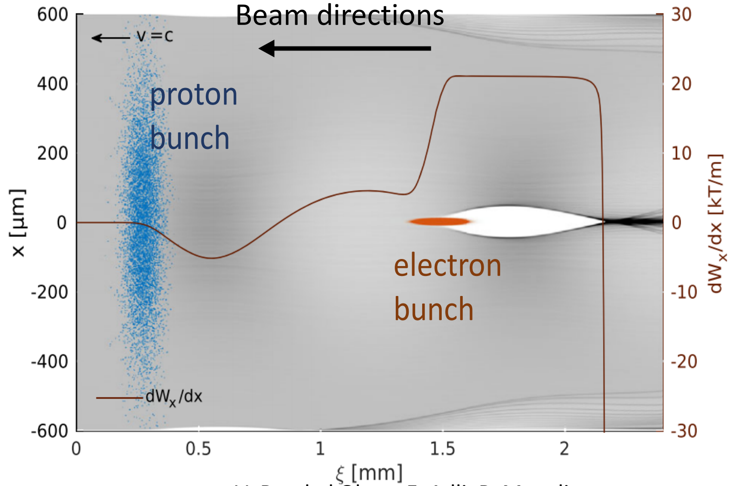
New electron beam: 150 MeV, 200 fs, 100 pC, σ = 5.75 µm

Blow-out regime

Beam loading: reach small ∂E/E

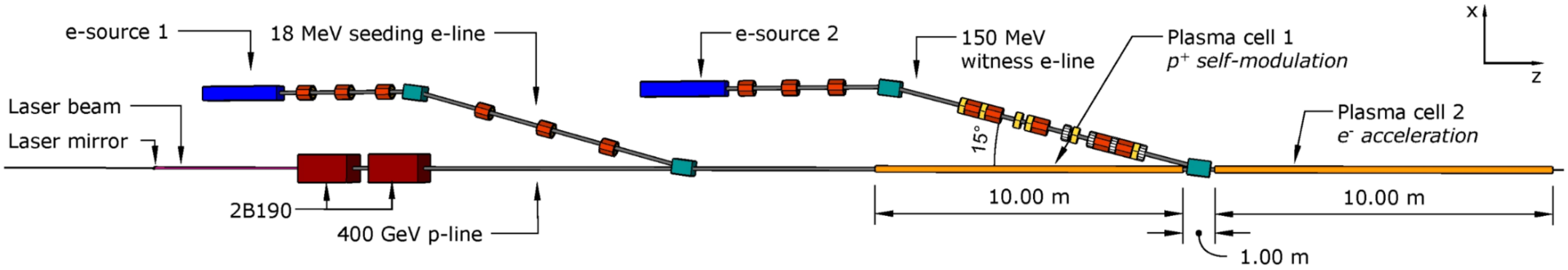
Match electron beam transverse properties to the plasma



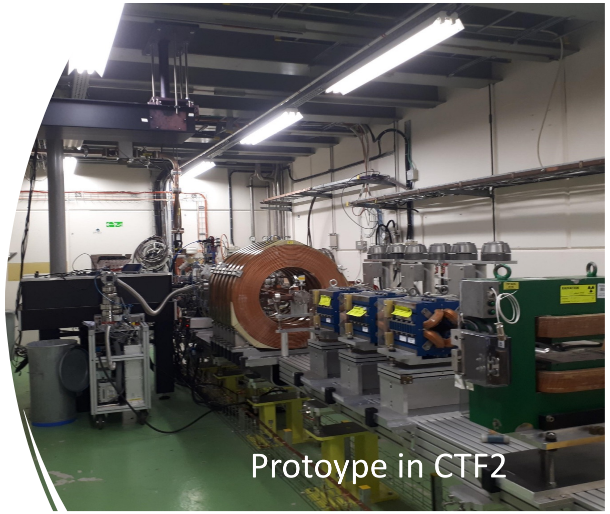


V. Berglyd Olsen, E. Adli, P. Muggli,
Phys. Rev. Accel. Beams, 21 (2018) 011301

AWAKE Run 2c – Ongoing Studies

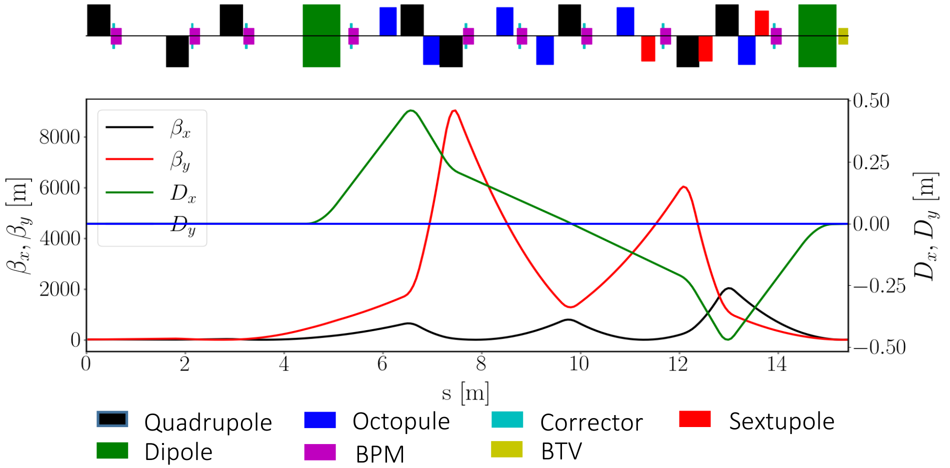


Run 2c electron source prototype

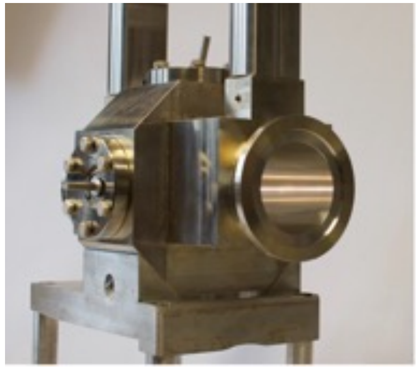


S-band e-gun (INFN) with
X-band accelerator (CLIC/CLEAR)

150 MeV beamline



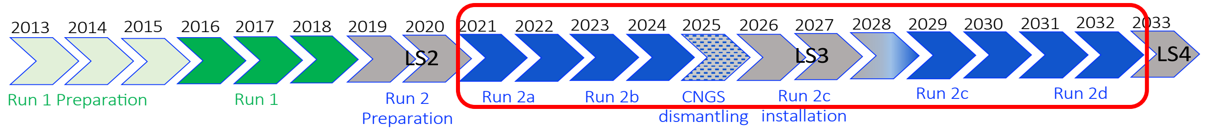
Beam instrumentation



BPMs 10 μm resolution

Run 2 – Broader Impact

Examples of technological advancements



Machine Learning

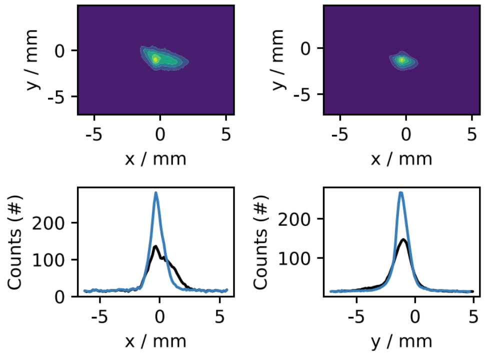
→ Running test-bed for operation efficiency studies and Machine Learning

Synergy with CERN and external institutes:

- Low energy e-beam line perfect for testing ML techniques
- Setup available in between runs used by users

Outcome:

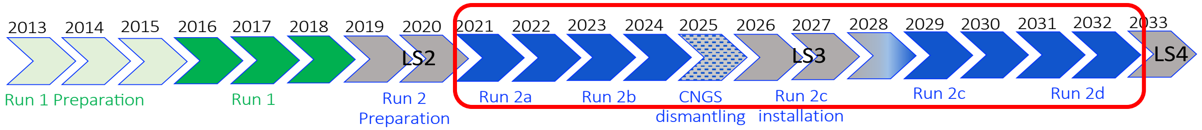
- Development of beyond state-of-the art ML tools for accelerators
- 8 publications + proceedings



Velotti, F. M., et al. *Machine Learning: Science and Technology* 4.2 (2023): 025016.

Run 2 – Broader Impact

Examples of technological advancements



Machine Learning

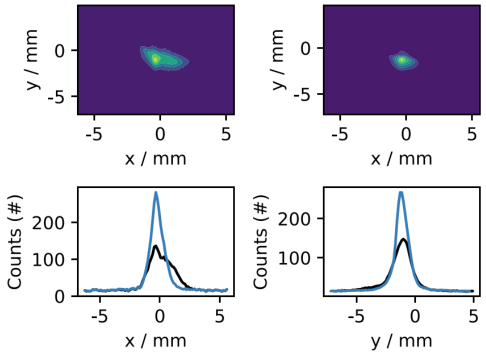
→ Running test-bed for operation efficiency studies and Machine Learning

Synergy with CERN and external institutes:

- Low energy e-beam line perfect for testing ML techniques
- Setup available in between runs used by users

Outcome:

- Development of beyond state-of-the art ML tools for accelerators
- 8 publications + proceedings



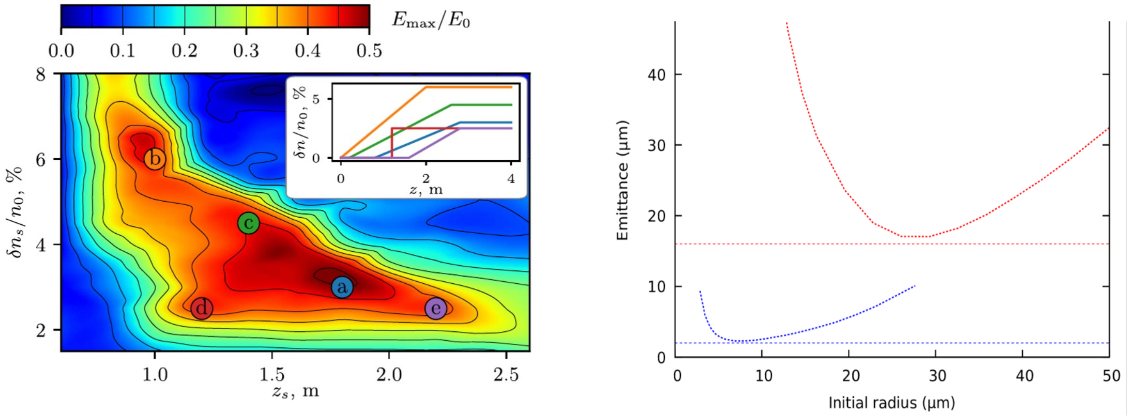
Velotti, F. M., et al. *Machine Learning: Science and Technology* 4.2 (2023): 025016.

Simulations

→ External injection of witness electron relevant for any plasma-based collider concept

→ Validation of simulation tools

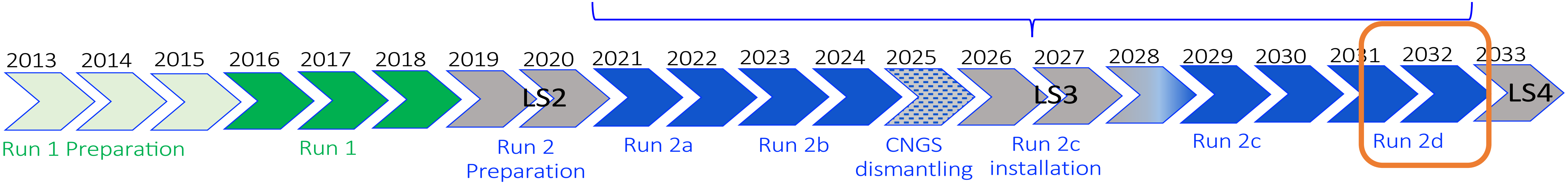
Simulations predict broad tolerances for SMI control via a density step and for emittance control in quasilinear wakefield.



AWAKE Program

RUN 2 (2021-2032)

e- acceleration to several GeV,
beam quality control, scalability



✓ **Run 2a (2021-2022): CONTROL: demonstrate the *seeding of the self-modulation of the entire proton bunch with an electron bunch***

➔ **Run 2b (2023-2024): STABILIZATION: *maintain large wakefield amplitudes*** over long plasma distances by introducing a step in the plasma density

➔ *(2025-2027): CNGS dismantling, CERN Long Shutdown LS3, installation of Run 2c*

➔ **Run 2c (2028-2031): QUALITY**: demonstrate ***electron acceleration and emittance control of externally injected electrons***.

➔ **Run 2d (2032- LS4): SCALABILITY**: ***development of scalable plasma sources with sub-% level plasma density uniformity.***

AWAKE Run 2d: Demonstrate Scalable Plasma Sources

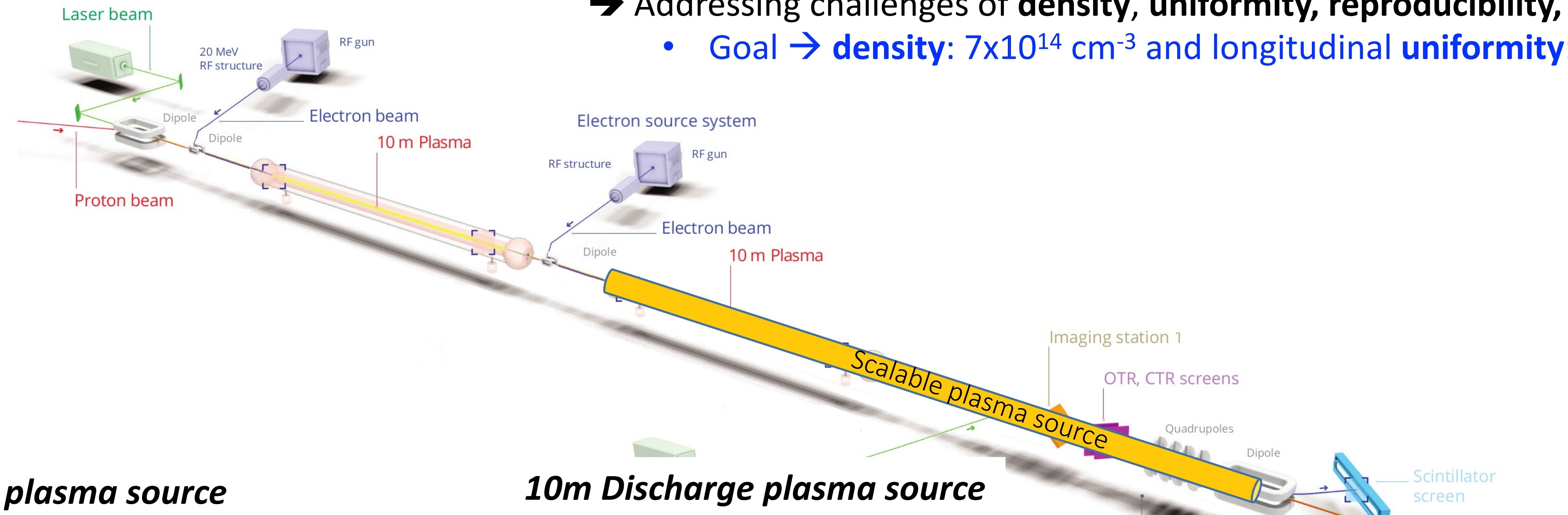
Scalable plasma source R&D program:

➔ Dedicated plasma source labs at CERN

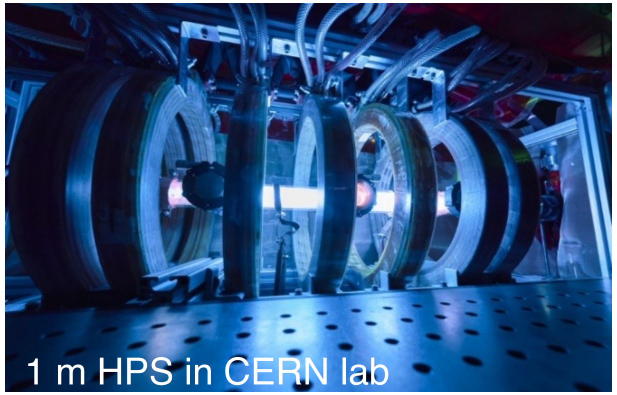
➔ 5 collaborating institutes

➔ Addressing challenges of **density**, **uniformity, reproducibility, scalability**

- Goal → **density**: $7\text{x}10^{14}$ cm^{-3} and longitudinal **uniformity**: 0.25%



1m Helicon plasma source



10m Discharge plasma source

10 m Discharge Plasma Source in AWAKE

➔ Possible candidate for plasma source in Run 2c/d and particle physics applications

Unique opportunity to test the discharge plasma source in May 2023 with protons in the AWAKE facility

Successfully installed, commissioned and operated the 10m long discharge prototype plasma source

➔ Demonstrated self-modulation of the proton bunch

➔ Flexible operation allowed to study various physics effects.

DPS Ion Motion Studies

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

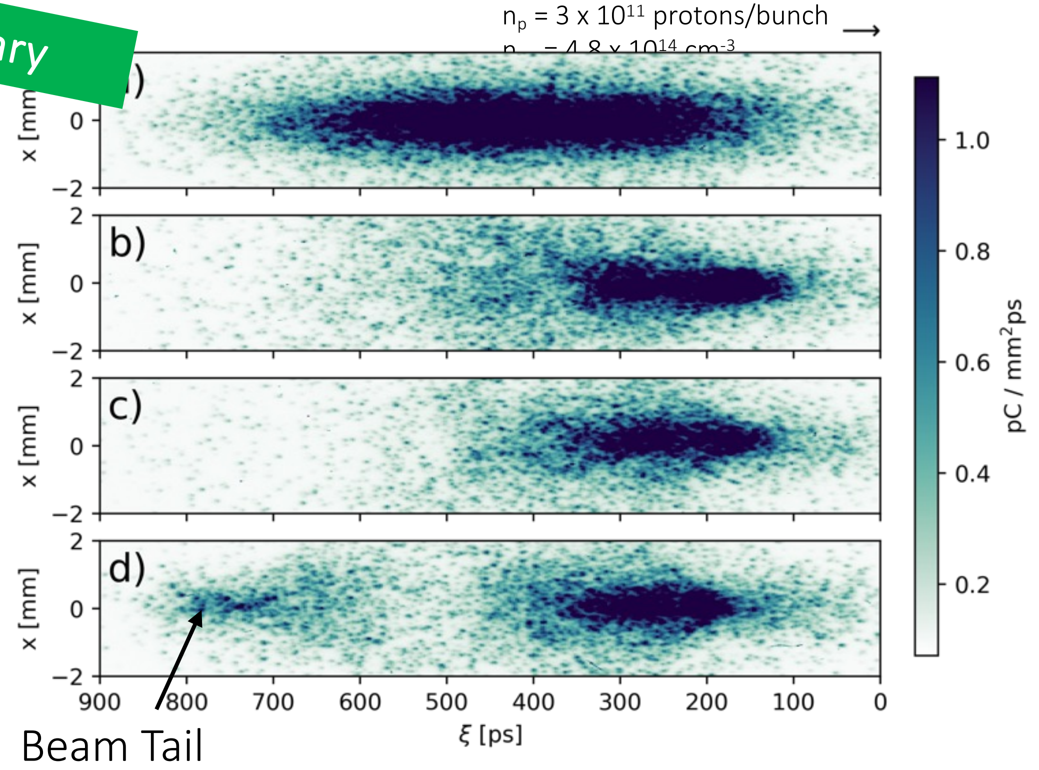
Preliminary

No plasma

Xenon (A=131)

Argon (A=40)

Helium (A=4)



M. Turner, CERN

DPS Ion Motion Studies

Ions move due to the ponderomotive force of the radial wakefields
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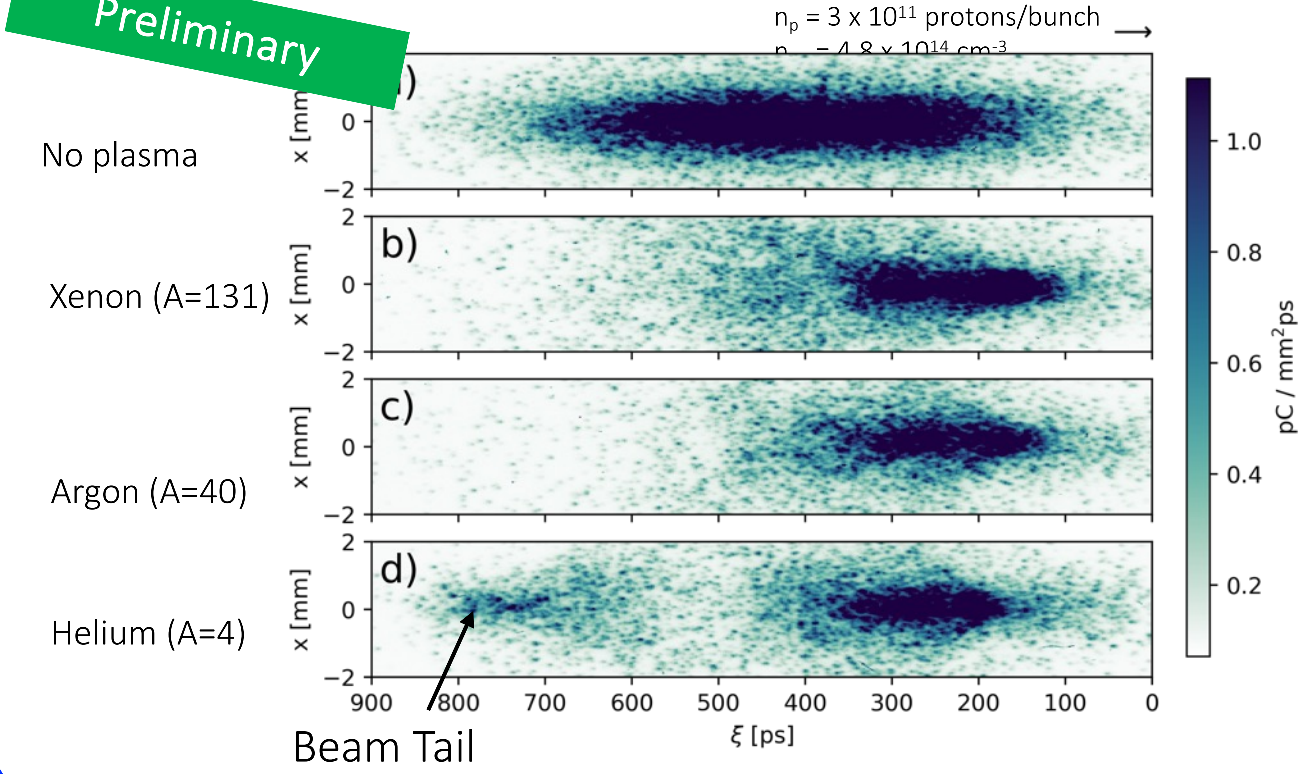
Preliminary



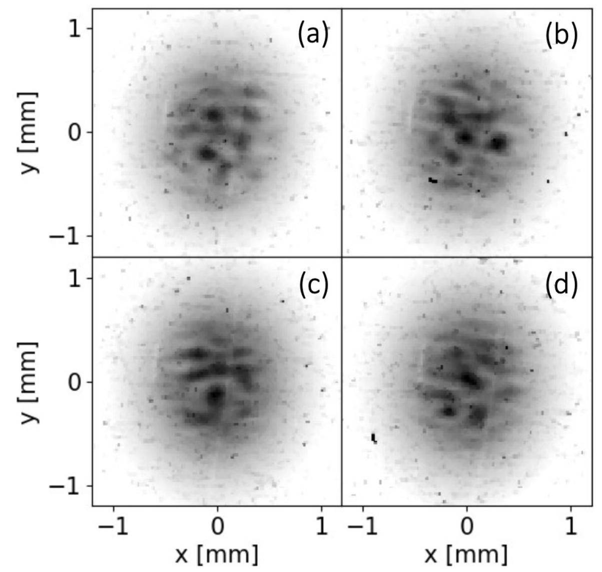
M. Turner, CERN

DPS Current Filamentation Studies

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

High plasma density of $n_{pe,\,discharge} = 9\times10^{14}\ cm^{-3}$.

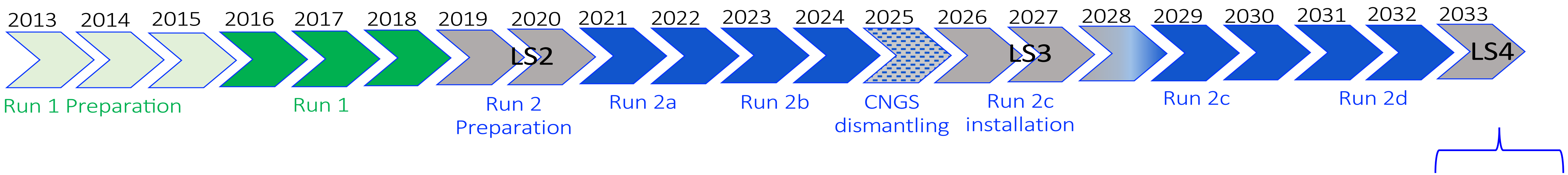
Wide proton bunch optics: $\frac{\sigma}{\delta}$ ~3



Clear evidence of filamentation→ Important for PWFA design

L. Verra et al. (AWAKE Collaboration), accepted in PRE, (2024)
https://arxiv.org/abs/2312.13883

AWAKE Program



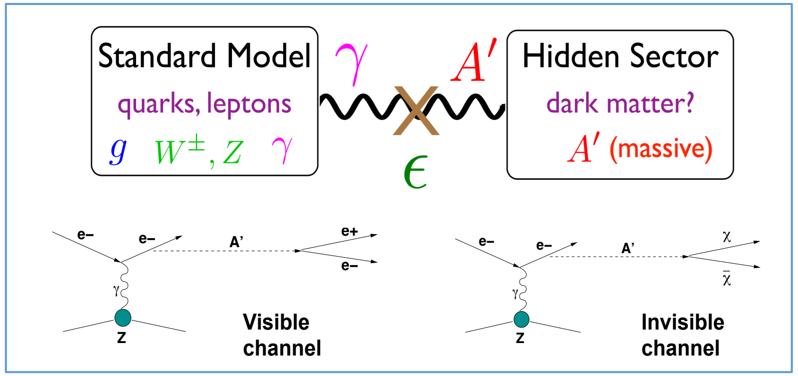
→ **First applications >2033**

Applications with AWAKE-Like Scheme

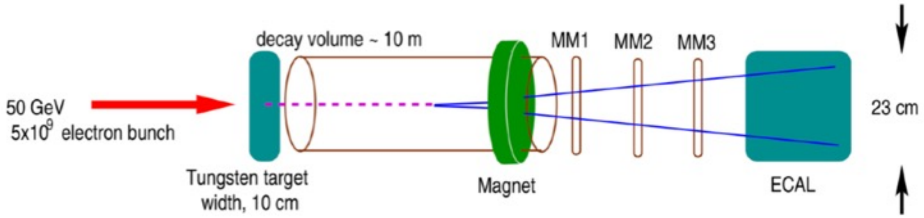
➔ **Requirements on emittance are moderate for fixed target experiments and e/p collider experiments, so first experiments in not-too far future!**

First Application: Fixed target test facility

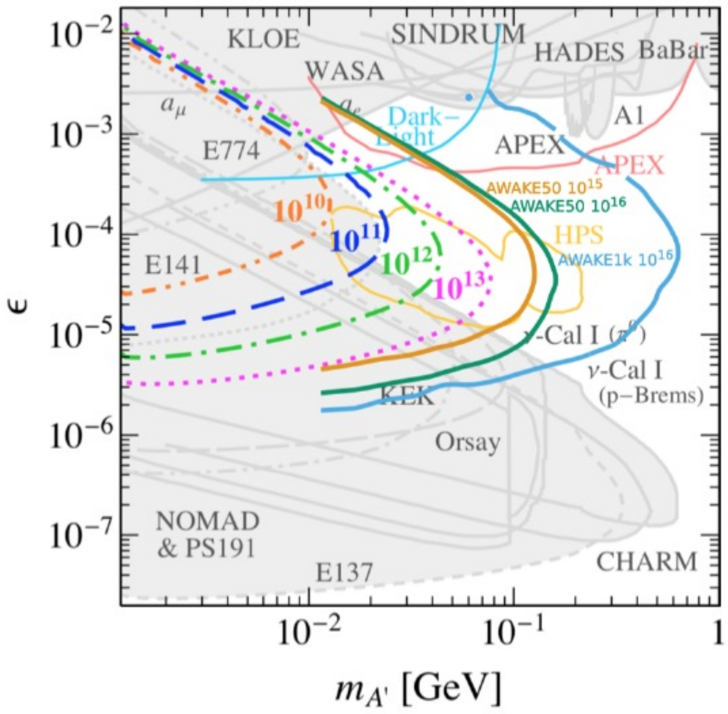
→ Deep inelastic scattering, non-linear QED, **search for dark photons**



→ Decay of dark photon into visible particles (e.g. e+/e-)
→ Energy and flux is important
→ Relaxed parameters for emittance



Experimental conditions modeled on NA64 experiment.



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

10^{16} electrons on target with AWAKE-like beam (**Factor 1000 more than NA64)**

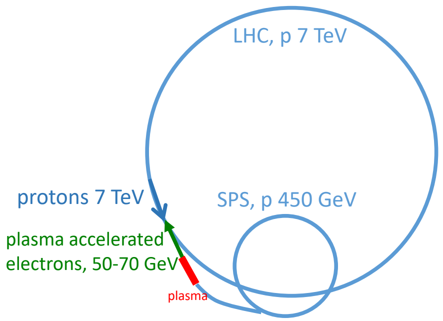
- **50 GeV e-beam**: Extend sensitivity further to *ε~ 10^{-3} – 10^{-5}* and to high masses*~0.1 GeV*.
- 1 TeV e-beam: : Similar *ε* values, approaching *1 GeV, b*eyond any other planned experiments.

Applications with AWAKE-Like Scheme

➔ Investigate non-linear QED in **electron- photon collisions**.

➔ Produce **TeV-range electrons with an LHC p_+ bunch:** use for lower luminosity measurements in electron-proton or electron-ion collisions.

- $\mathcal{L}$ Limited by proton accelerator repetition rate – look for high-cross-section processes to compensate.



- **PEPIC:** Low-luminosity version of LHeC (50 GeV electrons)
  - Use the SPS to drive electron bunches to 50 GeV and collide with protons from the LHC
  - Modest luminosity → only interesting should the LHeC not go ahead

- **EIC:**
  - use the RHIC-EIC proton beam to accelerate electron

- **3 TeV VHEeP**
  - use the LHC protons to accelerate electrons to 3 TeV and collide with protons from LHC with 7 TeV
  - Yields centre-of-mass energy of 9 TeV, Luminosity is relatively modest ~1028 – 10^{29} cm^{-2} s^{-1}, i.e. 1bp^{-1}/yr.
  - New energy regime means new physics sensitivity even at low luminosities.

- **Fixed target** variants with these electron beams

Summary

- AWAKE is a unique proton-driven plasma wakefield acceleration experiment at CERN
  - Proton-driven plasma wakefield acceleration interesting because of large energy content of driver.
  - Modulation process means existing proton machines can be used.
  - AWAKE uses protons from CERN's SPS.
  - Complex experiment, which capitalizes on CERN's accelerator technology expertise.
  - AWAKE is an international collaboration with strong contributions from collaborating institutes.

- AWAKE developed a well-defined plan towards first applications of particle physics experiments
  - AWAKE Run 2 is ongoing.
  - AWAKE met all milestones to date.
  - AWAKE is an integral part of the European Strategy Plasma Roadmap.
  - Once Run 2 is demonstrated, first particle physics application could be proposed.