AWAKE: An Experiment at CERN with an International Collaboration and a Well-Defined Program of Work

Edda Gschwendtner, CERN

AWAKE Collaboration Meeting, 11– 13 March 2024

Slides presented at the AWAKE External Review, 5/2/2024, CERN

AWAKE at CERN is Unique

Advanced WAKEfield Experiment

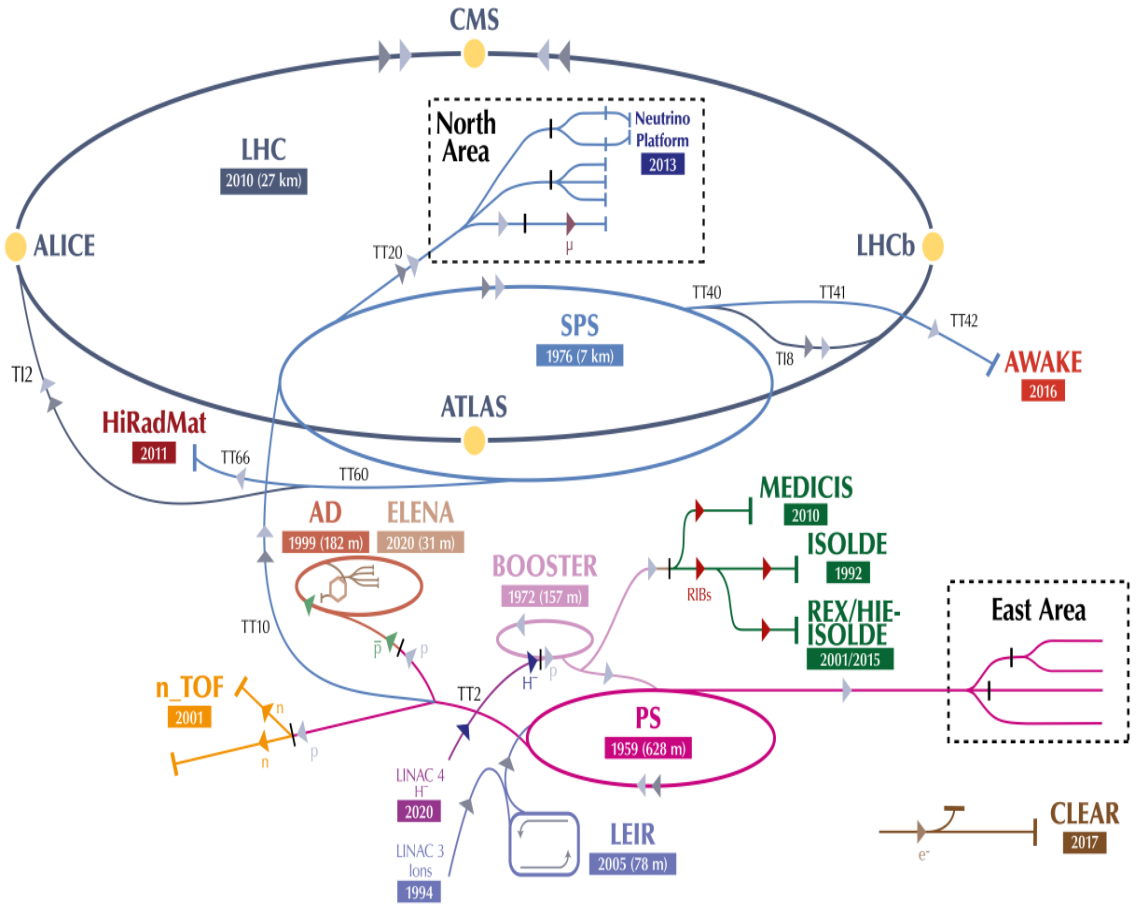
➔Accelerator R&D experiment at CERN.

➔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 profits from rich expertise at CERN



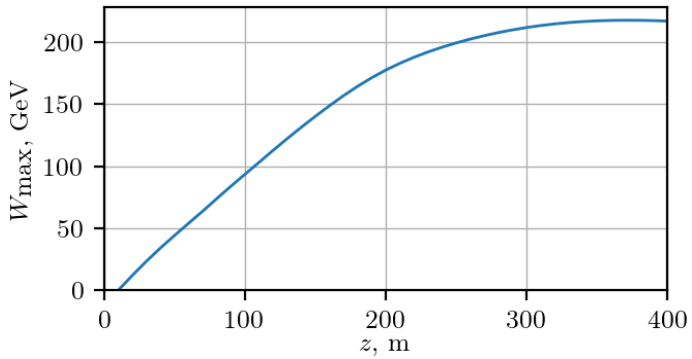
AWAKE at CERN is Unique

➔ 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

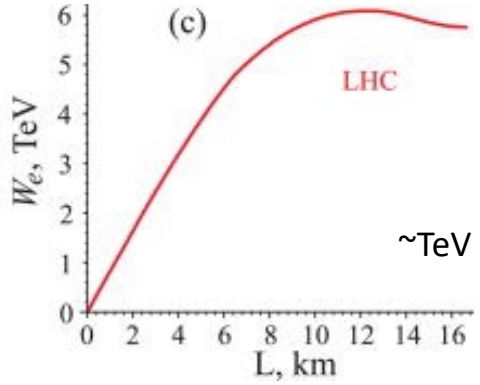
SPS Driver (19 kJ): ~ 150 GeV in ~200 m, 10^9 e^-

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

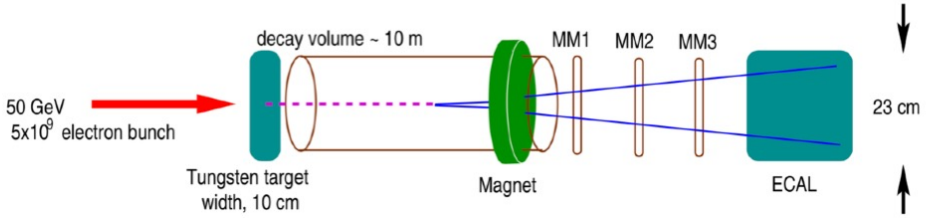
Contributing to CERN's Diversity

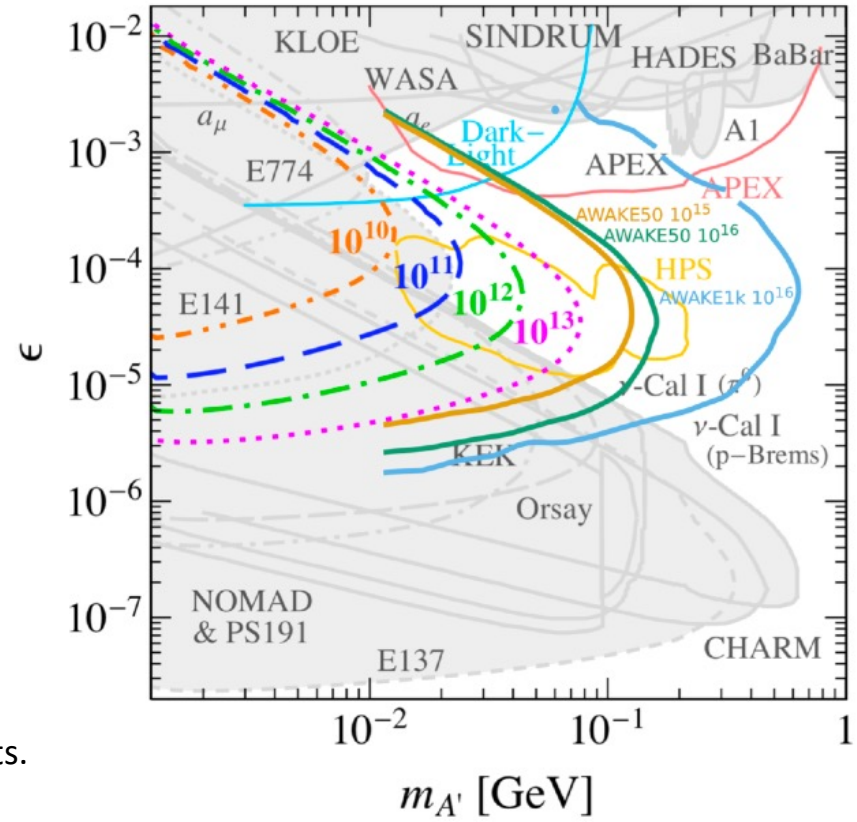
➔ Within the context of the **Physics Beyond Colliders Project (PBC),** AWAKE performed preliminary studies on possible first particle physics applications in the nearer future.

Dark sectors with light, weakly-coupling particles are a compelling possibility for new physics.
Search for dark photons using an AWAKE like electron beam:

➔ Beam dump experiments

- Decay of dark photons into visible particles (e.g. e+/e-)
- Energy and flux is important, but relaxed parameters for emittance

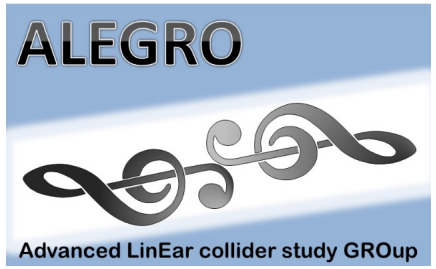




10^{16} electrons on target with AWAKE-like beam (Factor 1000 more than NA64)

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

AWAKE in the International Context



Gather the community and concentrate on addressing the recent progress and necessary steps towards realising a linear collider for particle physics based on novel-accelerator technology.

Co-chairs: Brigitte Cros, Patric Muggli
Program committee: ICFA ANA Panel

AWAKE in the International Context

ALEGRO
Advanced LinEar collider study GROup

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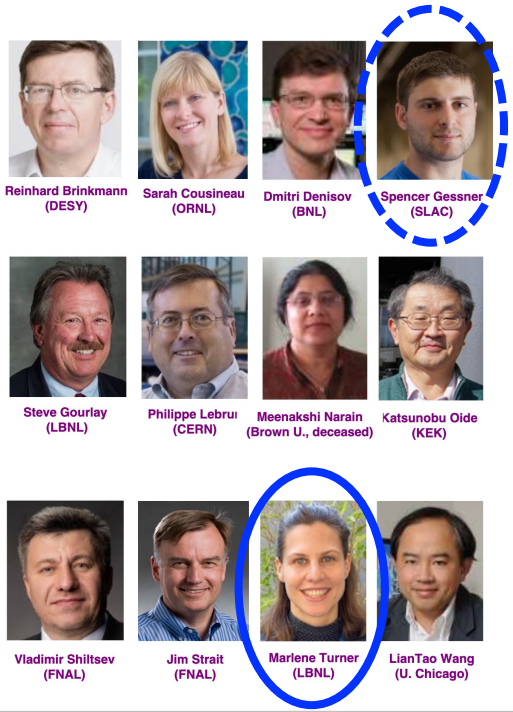
Snowmass 2021 Accelerator Frontier Collider Implementation Task Force

- The Collider Implementation Task Force (ITF) was charged with the evaluation and **fair and impartial comparison** of future collider proposals, including R&D needs, schedule, cost (using the same accounting rules), and **environmental impact and sustainability**.
- The full report is published in Journal of Instrumentation (TR et al, 2023 JINST **18** P05018).



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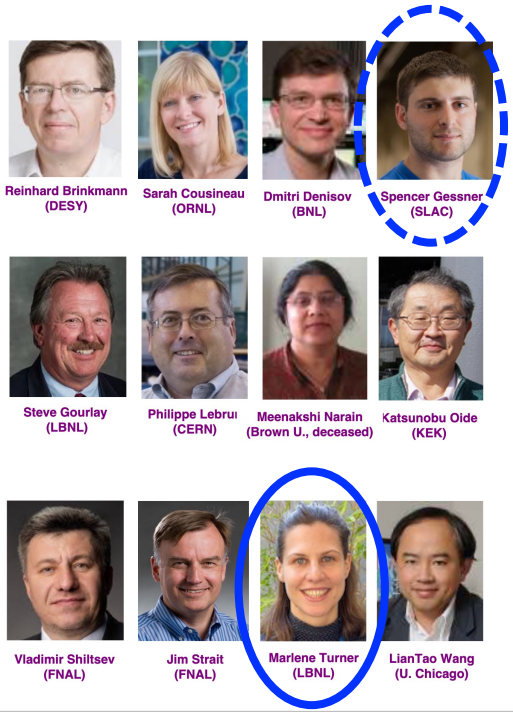


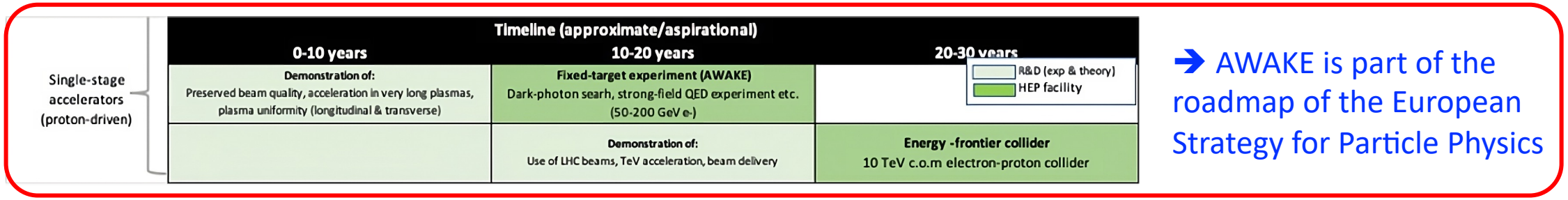
ESPP Expert Panel "High Gradient: Plasma and Laser Accelerators"

Follow-up Panel to European Strategy for Particle Physics
Panel proposes a plasma and laser accelerator R&D roadmap for the next ESPP Update

Panel members:
Chair: Ralph Assmann (DESY/INFN)
Deputy Chair: Edda Gschwendtner (CERN)
Kevin Cassou (IN2P3/IJCLab), Sebastien Corde (IP Paris), Laura Corner (Liverpool), Brigitte Cros (CNRS UPSay), Massimo Ferarrio (INFN), Simon Hooker (Oxford), Rasmus Ischebeck (PSI), Andrea Latina (CERN), Olle Lundh (Lund), Patric Muggli (MPI Munich), Phi Nghiem (CEA/IRFU), Jens Osterhoff (DESY), Tor Raubenheimer (SLAC), Arnd Specka (IN2PR/LLR), Jorge Vieira (IST), Matthew Wing (UCL).

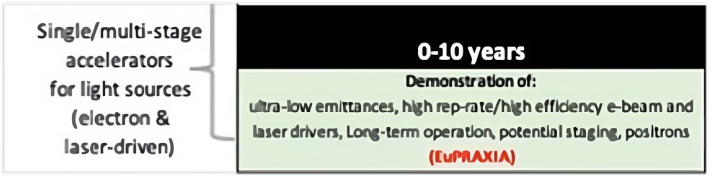
Panel associated members:
Cameron Geddes (LBNL), Mark Hogan (SLAC), Wei Lu (Tsinghua U.) , Pietro Musumeci (UCLA)

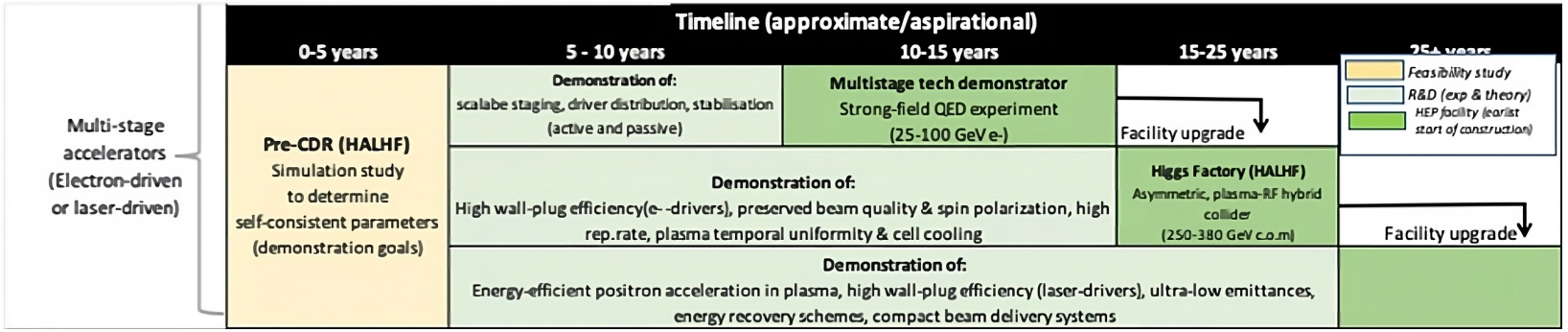
AWAKE as Part of the European Strategy Roadmap



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

e-p collider





R. Pattathil, presented at EAAC 2023

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

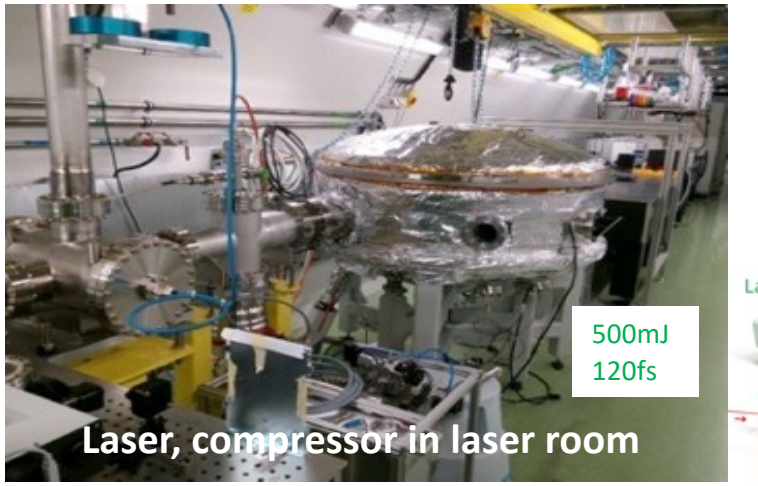
AWAKE is an International Collaboration

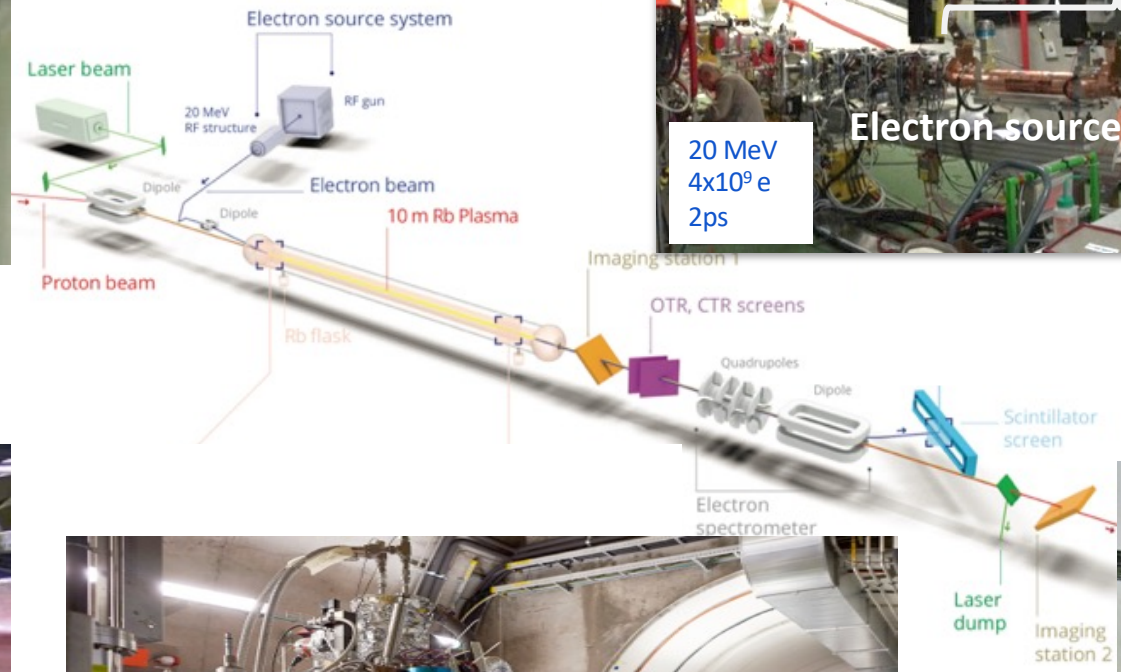
➔AWAKE is an international Collaboration, consisting of 22 institutes.

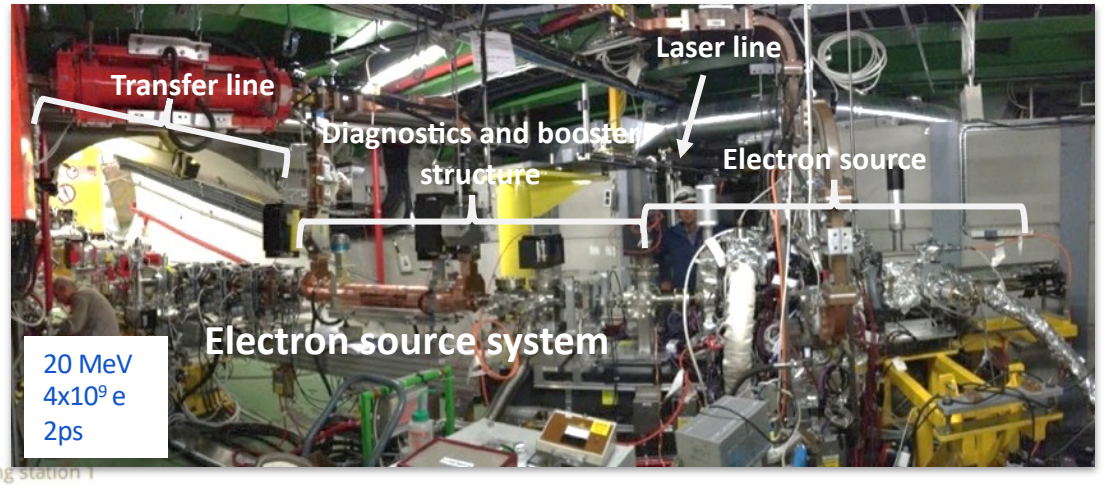
In AWAKE many general issues are studied, which are relevant for concepts that are based on plasma wakefield acceleration.

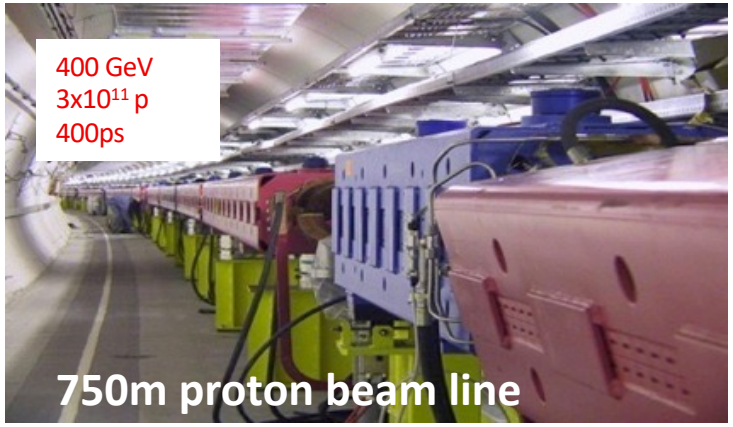
➔ Benefit from expertise from collaborating institutes.

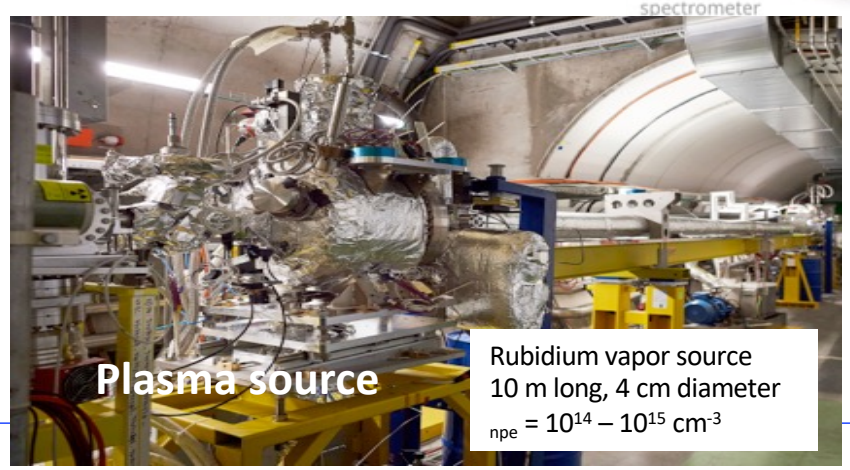
Key Ingredients of AWAKE (Run 1 and Run 2a/b)



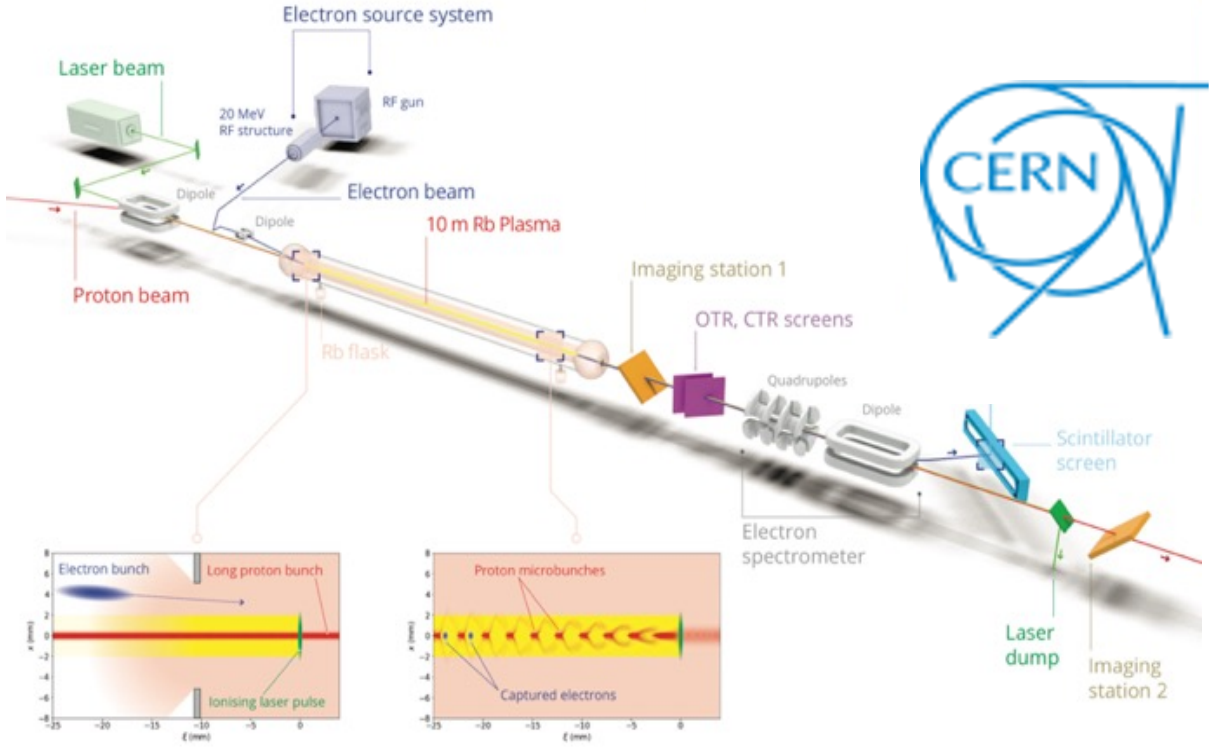




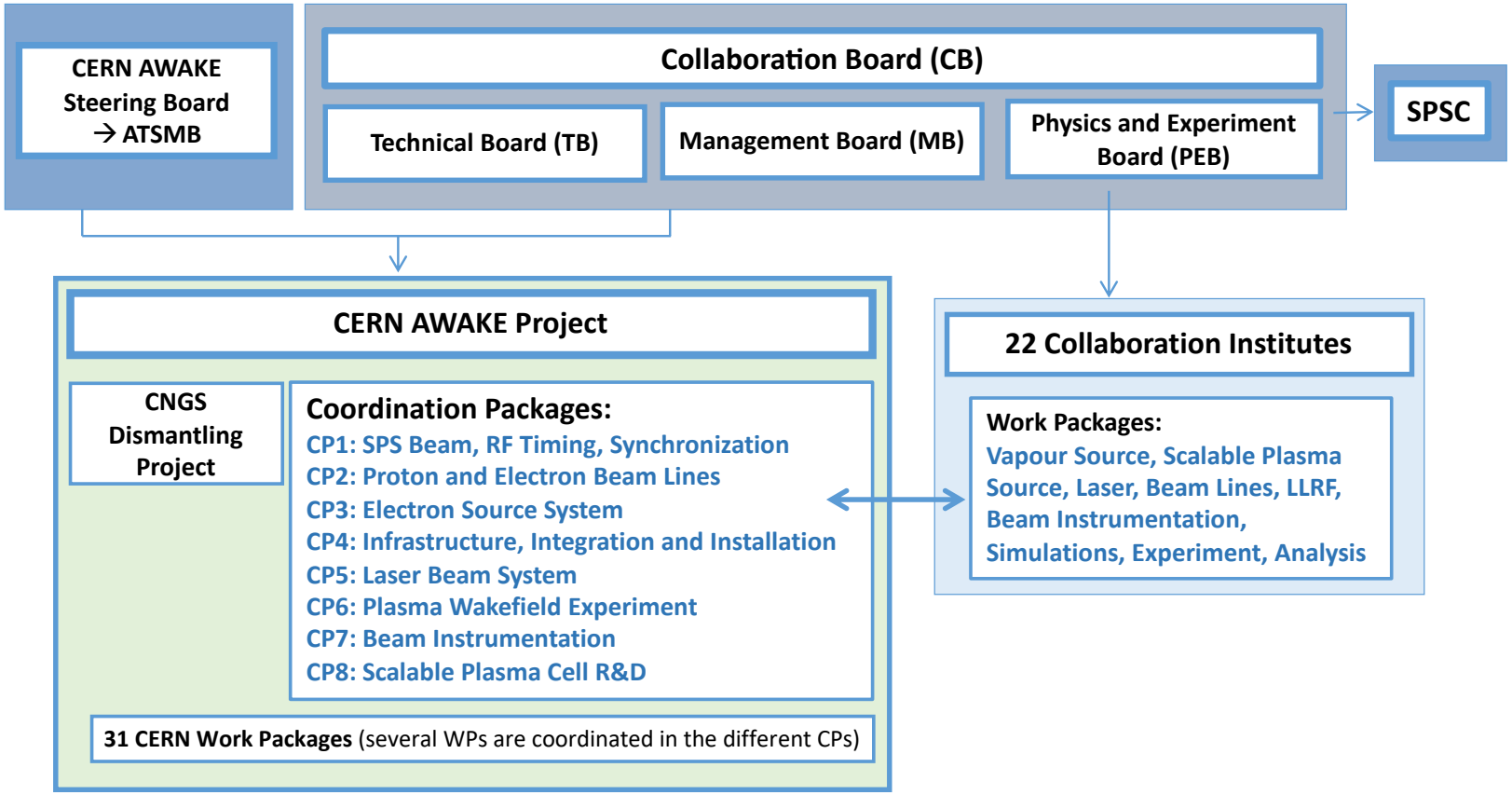




Strong Commitment from Institutes in AWAKE



AWAKE Organizational Structure



Spokesperson: Patric Muggli
Deputy: Matthew Wing
Collaboration Board Chair: Allen Caldwell
Technical Coordinator: Edda Gschwendtner
CERN AWAKE Project Leader: Edda Gschwendtner
Physics and Experiment Coordinator: Patric Muggli
Simulation Coordinator: Alexander Pukhov
CNGS Dismantling Project Leader: Ans Pardons
Run Coordinator: Giovanni Zevi Della Porta

AWAKE MoU: between CERN and Institutes → in-kind contributions
Addendum to MoU for any new institute, PJAS, new work program

Publication and Speakers Committee
> 100 papers

AWAKE has a Well-Defined Program

AWAKE Run 1 (2016- 2018): Proof-of-Concept:

✓ Demonstrated seeded self-modulation of the proton bunch and drive strong wakefields

✓ Accelerate externally injected electrons to 2 GeV

AWAKE Run 2 (2021 – 2033): Towards an Accelerator:

➔Accelerate an ***electron beam to high energies (gradient of 0.5-1GV/m)***

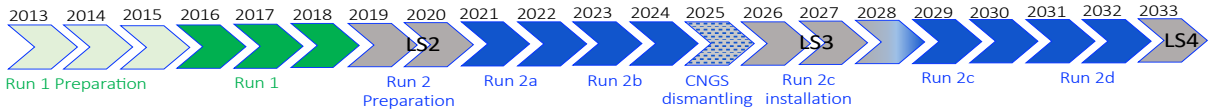
➔while controlling the ***electron beam quality (~10 mm-mrad emittance, 10% energy spread)***

➔demonstrate ***scalable plasma source technology.***

Once AWAKE Run 2 is demonstrated: First application of the AWAKE-like technology.

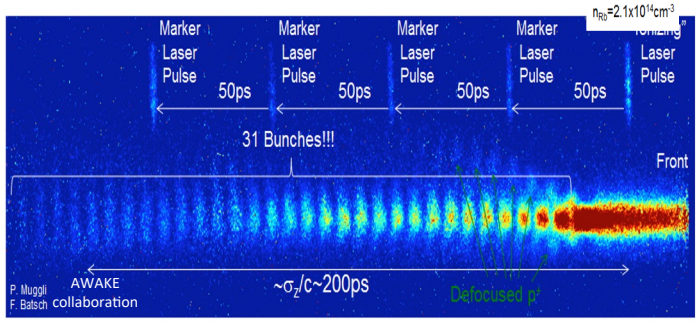
➔ *develop physics case for particle physics experiments*

AWAKE Highlights



➔ **To date AWAKE has achieved all milestones!**

Run 1a: Demonstrated phase stable and reproducible self-modulation of the p+ bunches (2016-2017)



AWAKE Collaboration, Phys. Rev. Lett. 122, 054802 (2019).
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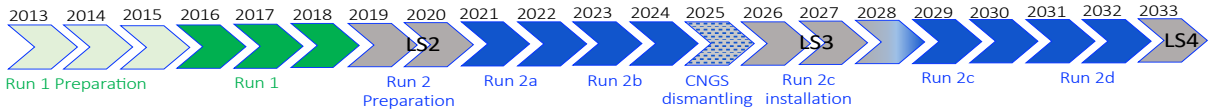

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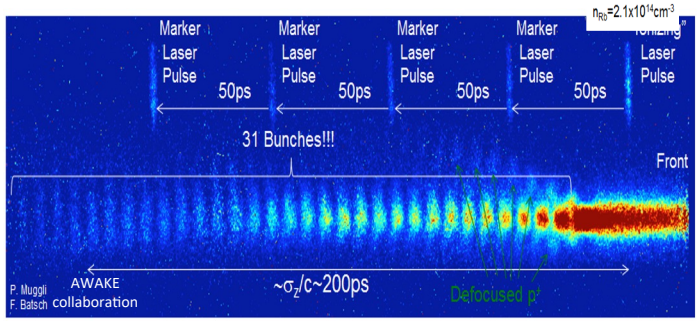

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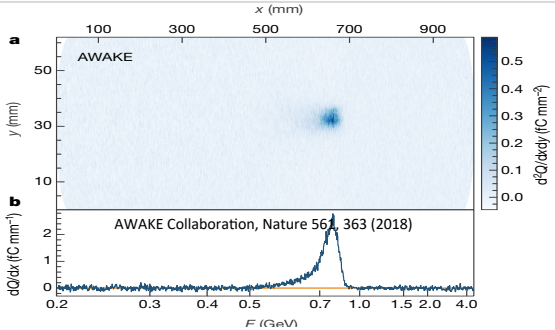
Run 1b: Demonstrated acceleration from 18 MeV to 2 GeV with up to 20% charge capture (2017-2018)



nature Accelerated Article Preview

LETTER
doi:10.1038/s41586-018-0485-4
Acceleration of electrons in the plasma wakefield of a proton bunch

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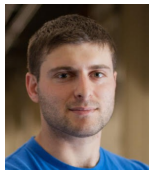

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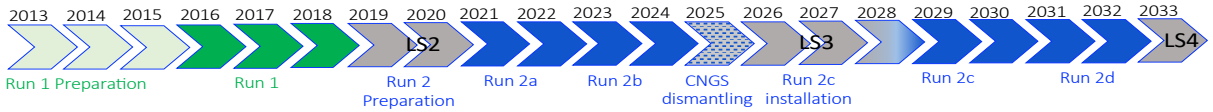

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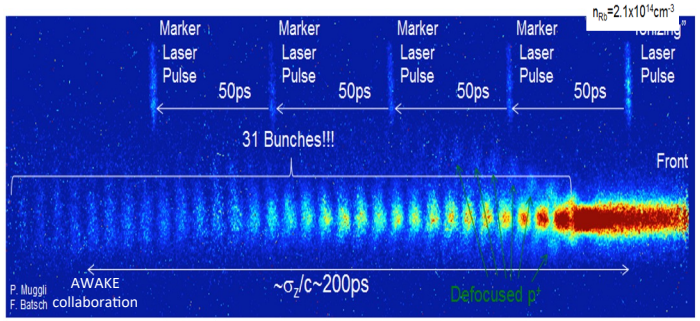

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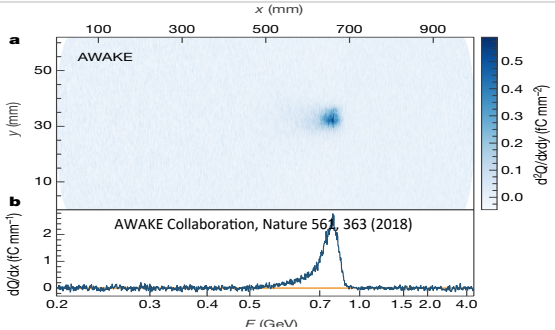
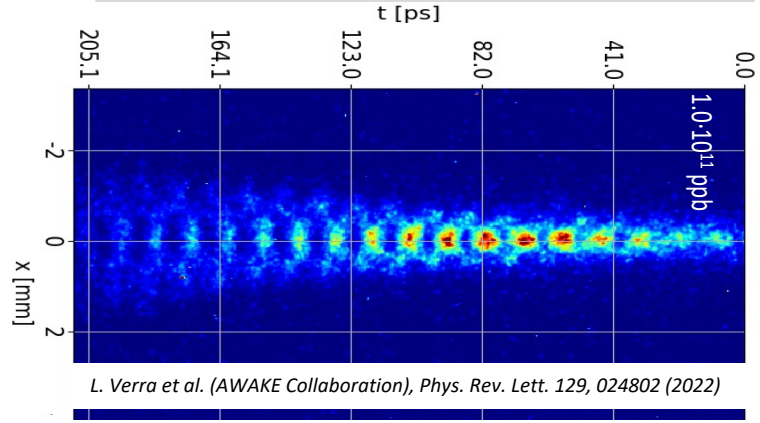


nature Accelerated Article Preview

LETTER
doi:10.1038/s41586-018-0485-4
Acceleration of electrons in the plasma wakefield of a proton bunch

Run 2a: Demonstrated electron seeding of proton bunch self-modulation (2021-2022)



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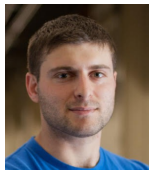

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→ Livio Verra received the EPS Plasma Physics Division PhD Award 2023.

AWAKE's Strong Scientific and Educational Output

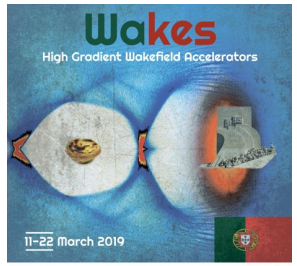
22 AWAKE Collaboration papers in high-level journals

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

> 28 PhD students

> 11 Master students

> 20 Post-docs

Outreach: Newspapers, TEDX, …

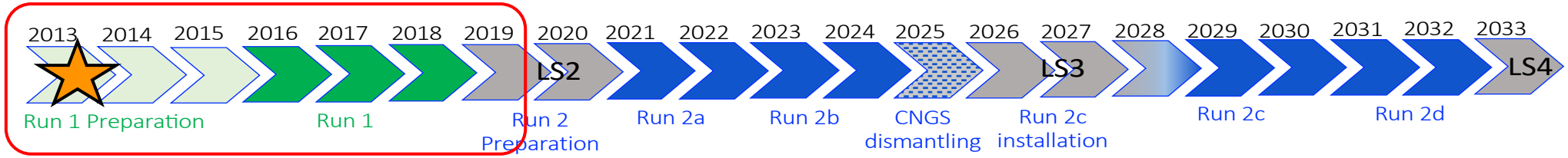
TEDx CERN
x = independently organized TED event

ask symmetry

A new wave of particle physics

AWAKE Reviews and Recommendations I

Since 2013, every year in autumn, the AWAKE physics program is reviewed by the **SPS Committee, SPSC.** Every year very positive feedback and recommendations: *"… The SPSC congratulates the AWAKE Collaboration for their scientific achievements and rich harvest of publications… The SPS is pleased to see that the preparations towards the beam tests have progressed as planned… The SPSC considers the Run programme interesting and recommends the requested beam time…"*



March 2013: submitted Design Report
August 2013: Approval of AWAKE → **Record approval time!**

AWAKE Reviews and Recommendations I

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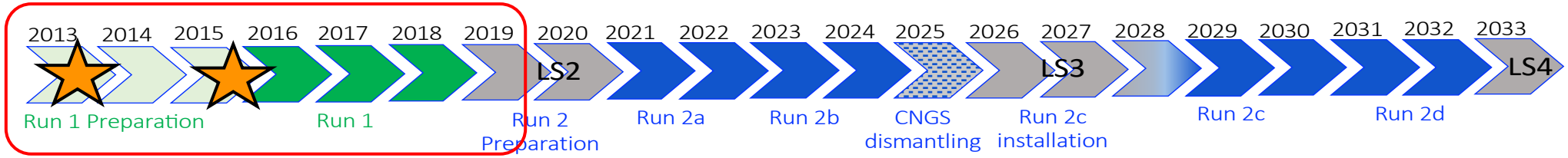

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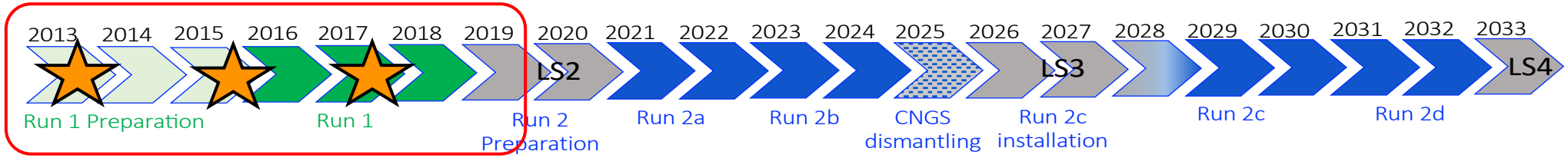

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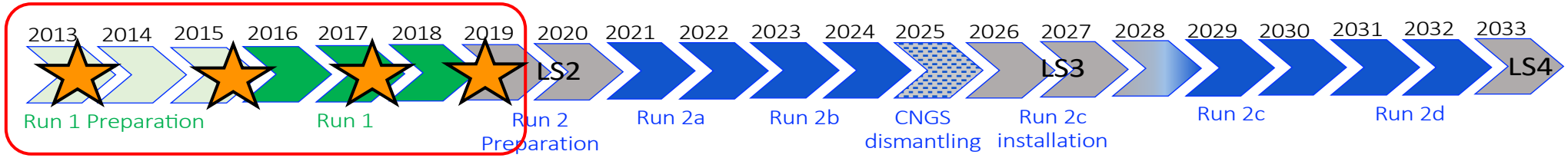

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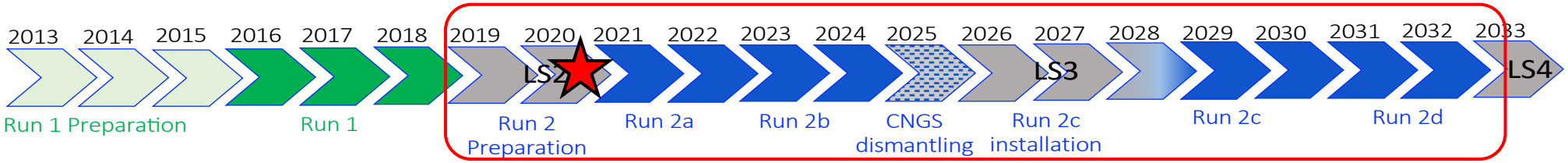
AWAKE Run 1 met all milestones and was on schedule and budget.
2019: 'White Paper for Run 2' to CERN management **(no Cost and Schedule Review!):**
→ AWAKE Run 2 and part of the Run 2 budget was included in the MTP until 2030.

AWAKE Reviews and Recommendations II

SPSC in October 2020 and January 2021: Presented the **entire AWAKE Run 2 Physics Program:**

*"**The Committee recognises the high importance of the accelerator R&D** to prove the scalability of the AWAKE technique as detailed in the addendum (SPSC-SR-285) to the Design Report, submitted by the AWAKE Collaboration. The SPSC considers the demonstration of stabilisation of high gradients over long distances to be of high scientific merit and **recommends approval of the AWAKE Run-2** programme towards this important step. The Committee considers one of the cost drivers of the proposed R&D programme, **the clearing of the former CNGS area to be fundamental to reach the scientific goal of demonstrating the scalability of the technique**."*



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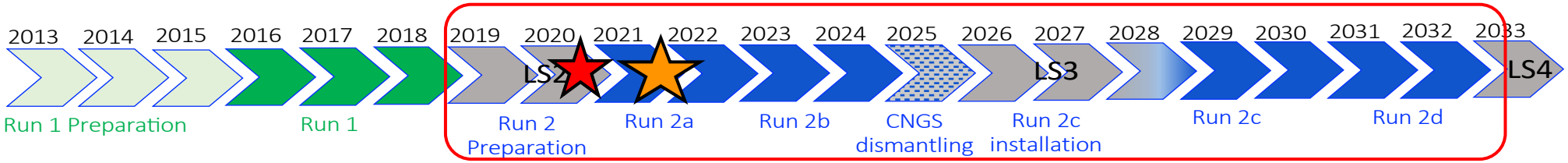

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- **Additional budget (15 MCHF + 12MCHF) requested to complete Run 2 is properly estimated and detailed**.
- **Strong commitment from the collaborating institutes.**
- **A detailed breakdown of the CERN staff resources necessary for Run 2 is available,** with some missing staff identified.
  - ➔ **Some of this already addressed: e.g. hiring of a plasma physicist.**
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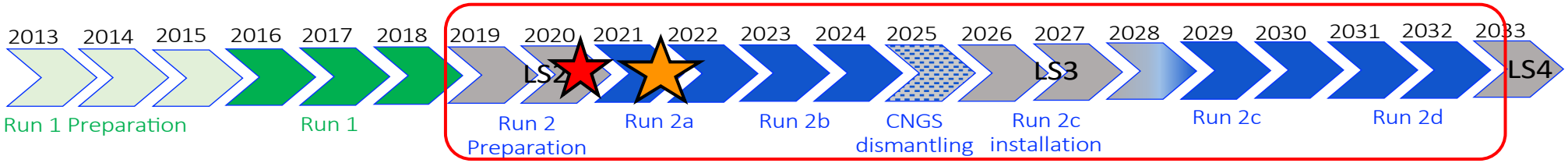

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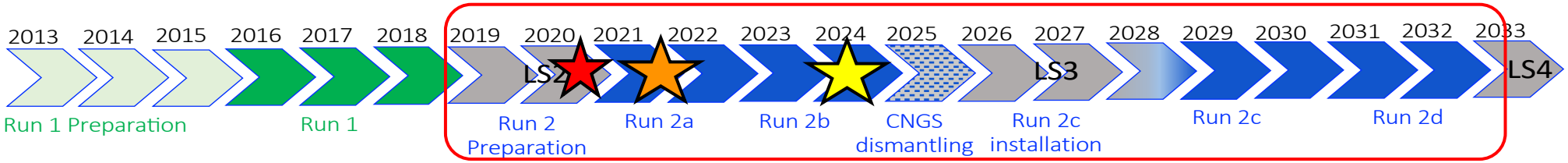

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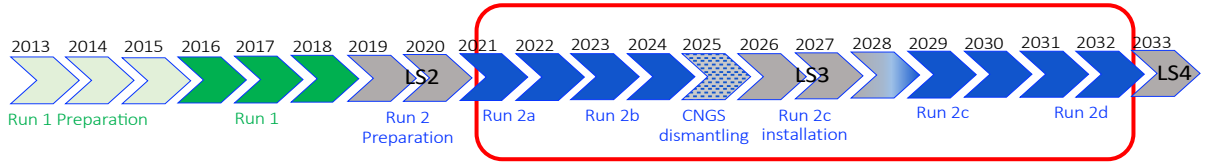
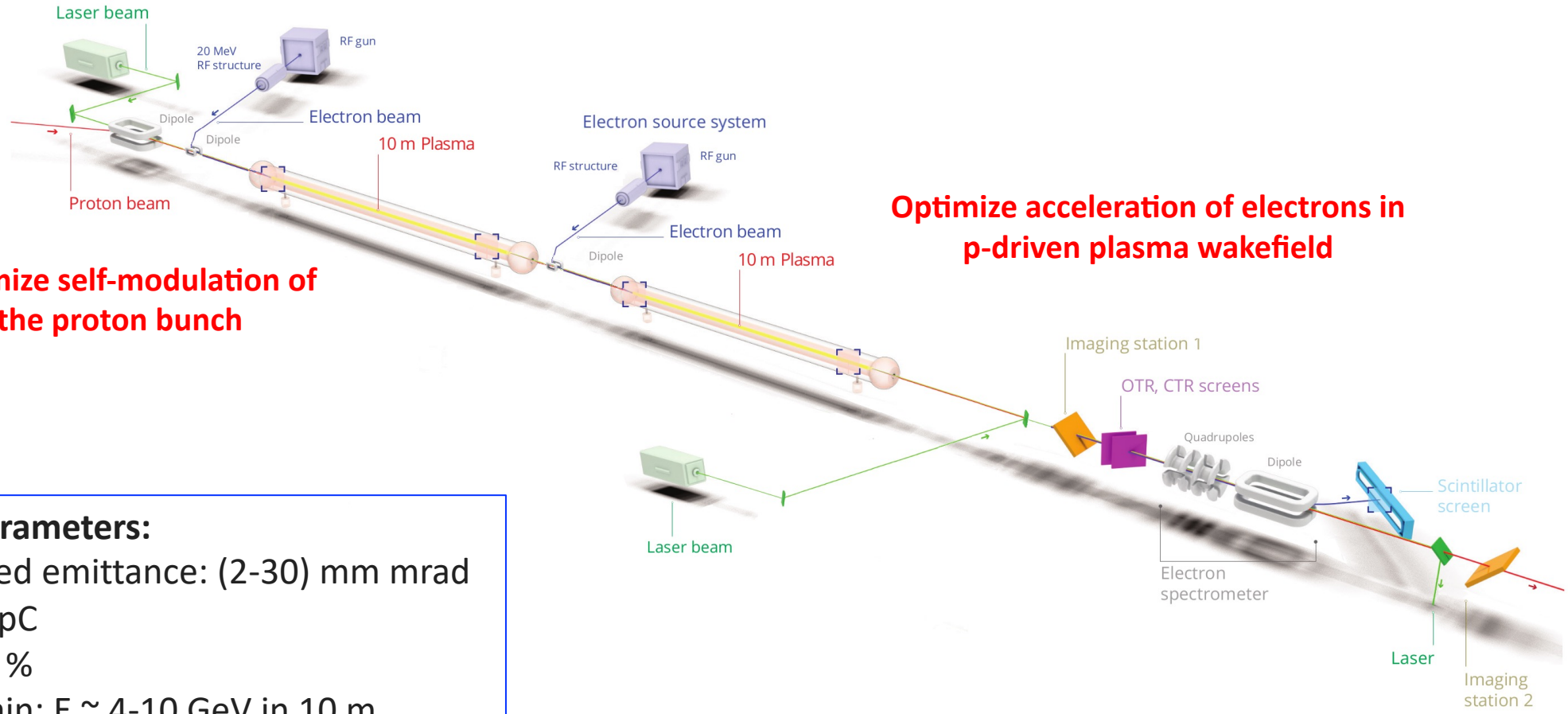
2024: Today: External Review:
The evaluation made by this review of the technical and scientific case will feed into the CERN budget decision.

AWAKE Run 2

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





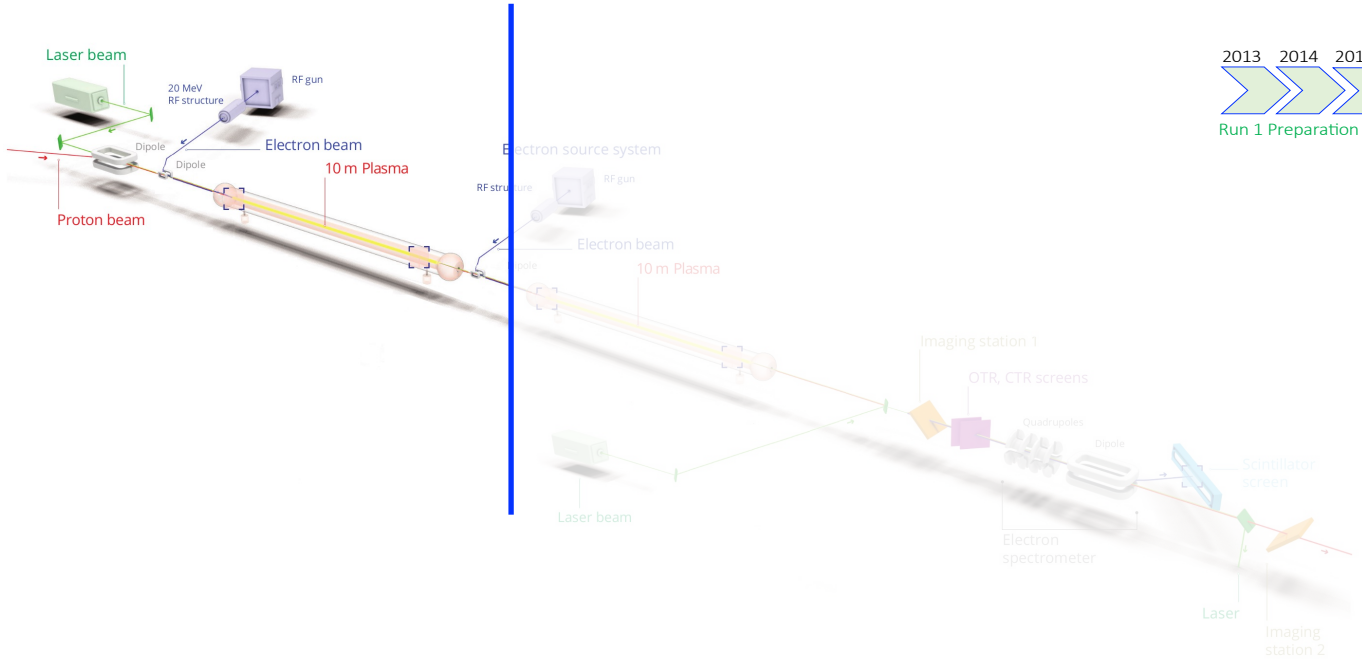
Optimize self-modulation of the proton bunch

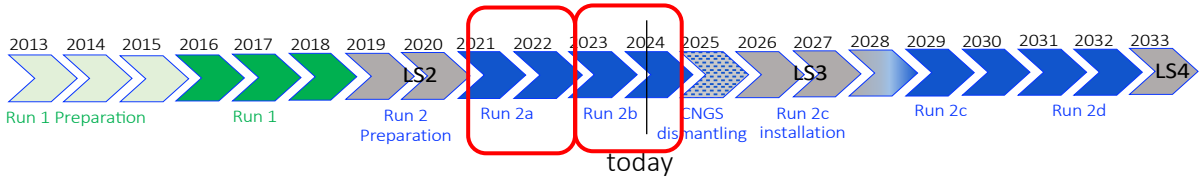
Optimize acceleration of electrons in p-driven plasma wakefield

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 Run 2 Well-Defined Scientific Roadmap – Milestones





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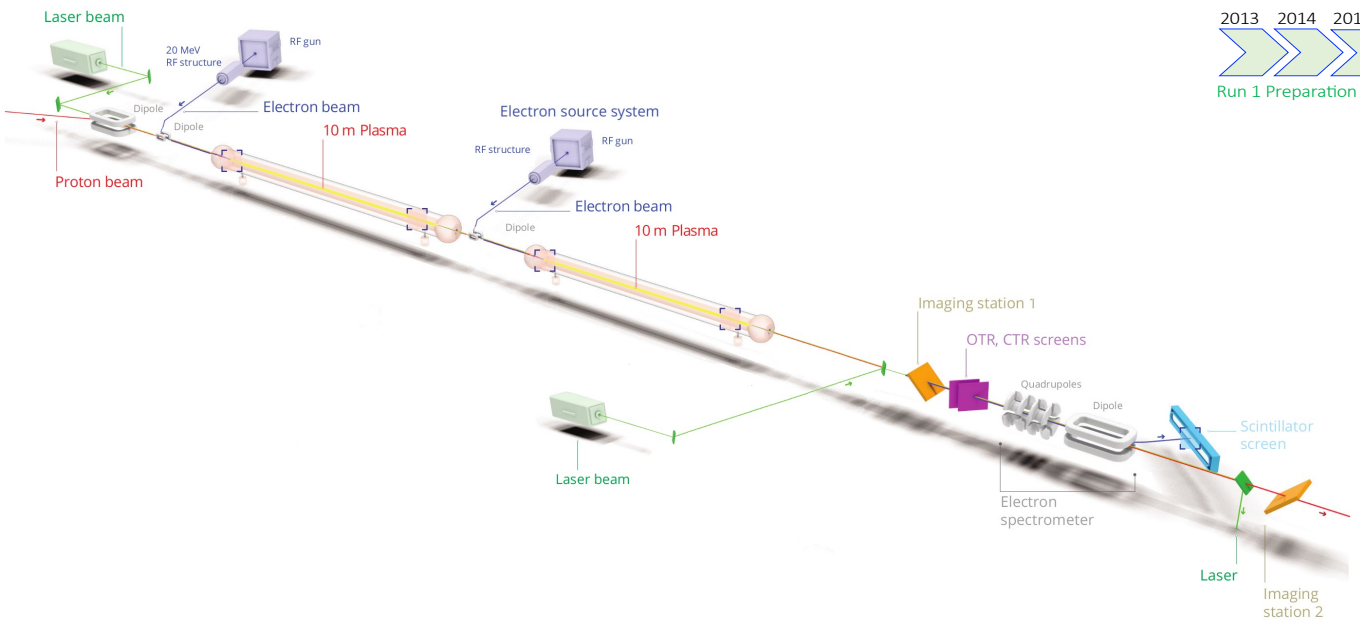

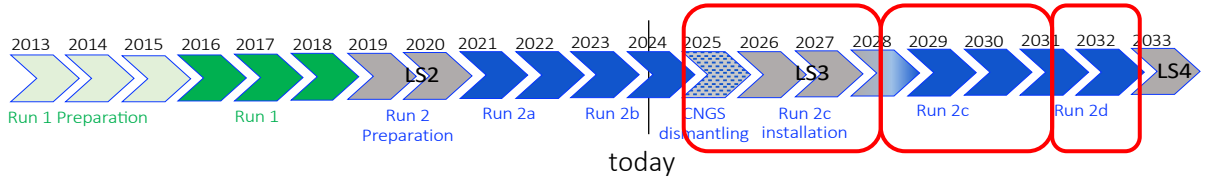

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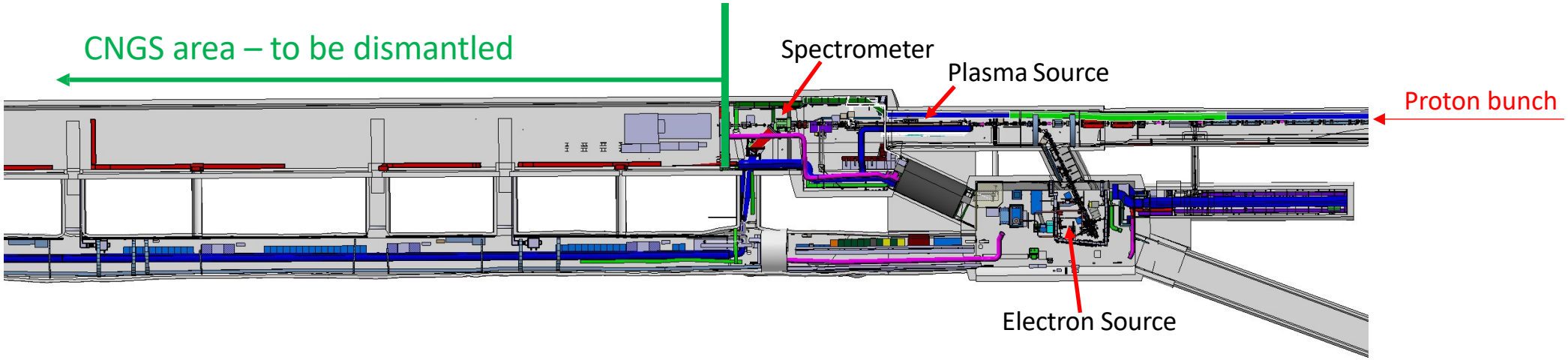
➔ *(2025-2027): CNGS dismantling, CERN Long Shutdown LS3, installation of Run 2c*

➔ **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 2 – Integration

Run1,
Run 2a/b



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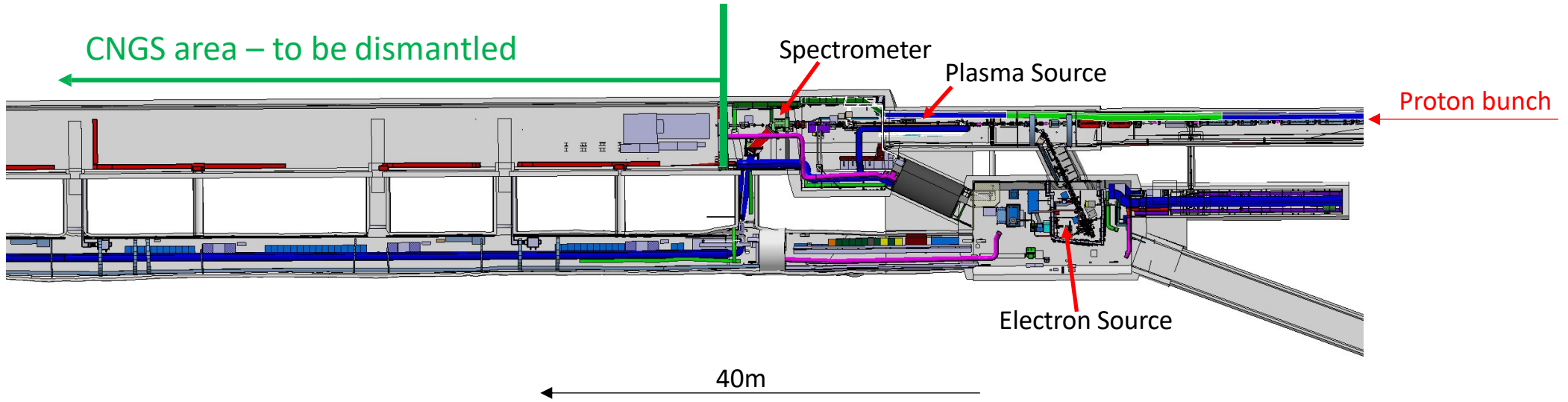
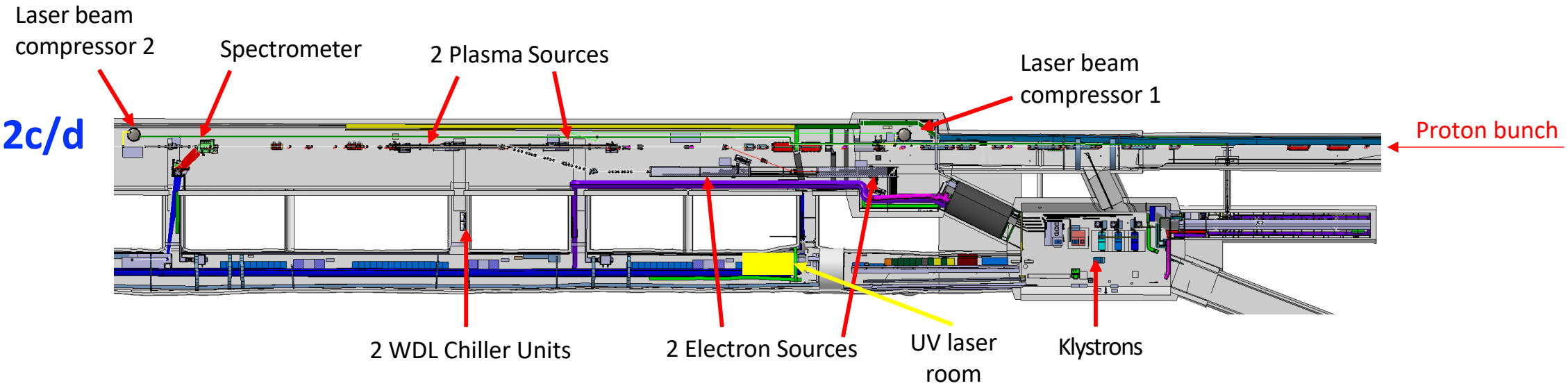
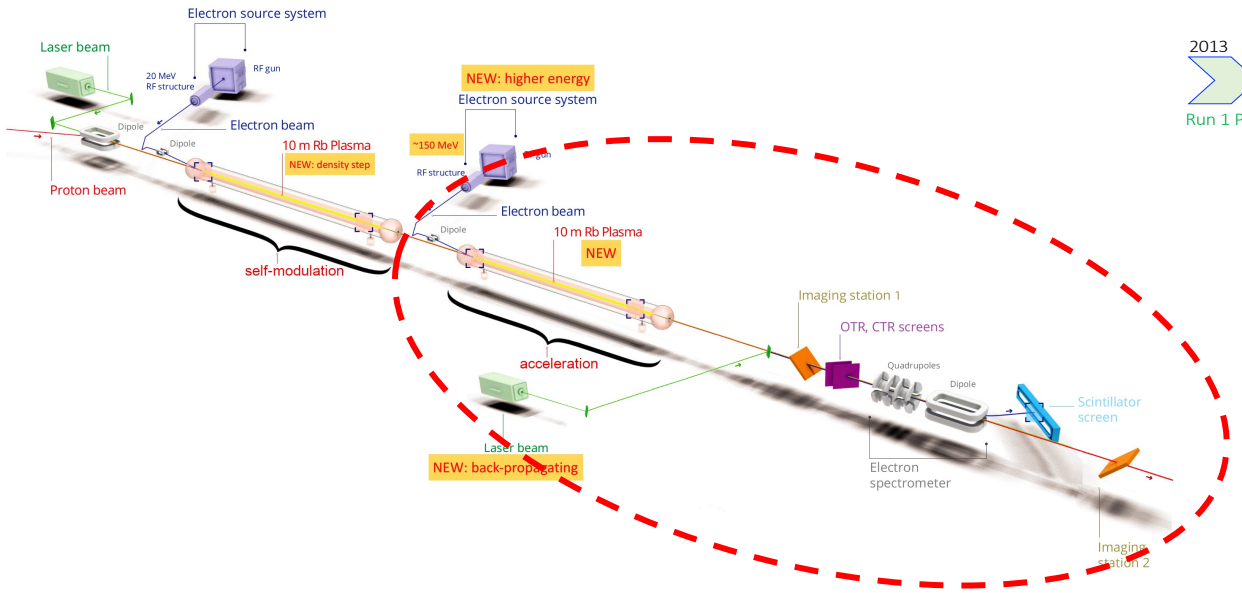
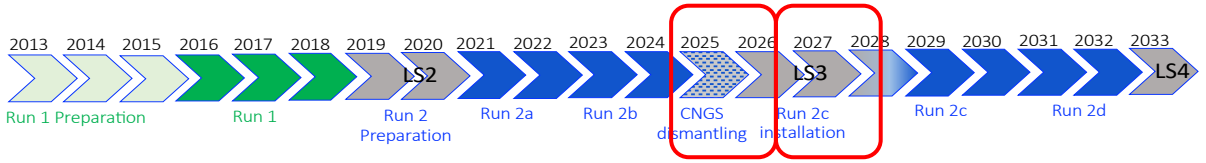


Run 2c/d



Preparing for AWAKE Run 2c/d during LS3





CNGS area content (~600m³):

- **~500 large shielding blocks** (0,05-0,6 mSv/h)
- A few **high dose-rate elements** (50mSv/h)
- 70-meter-long aluminum **He-tank**
- **Various** supports, ducts…

AWAKE program: start Run 2c in 2028 right after LS3

→ **CNGS dismantling: end 2024 – mid 2026**

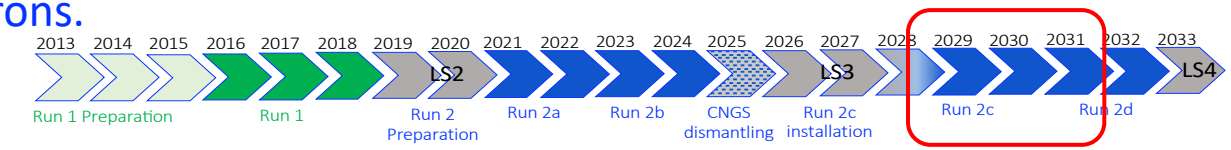
→ **Run 2c installation: mid 2026– mid 2028**

→ Leverage CERN resources outside LS3 for CNGS dismantling

→ Ensure resources during LS3 for installation

AWAKE Run 2c – Ongoing Studies

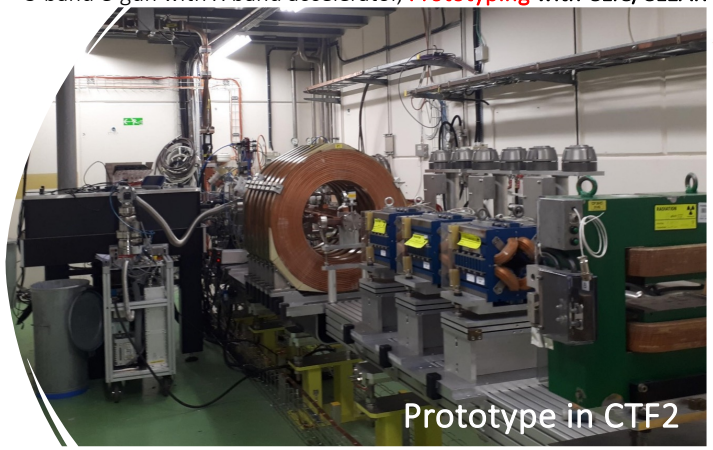
Acceleration and **emittance control** of **externally injected** electrons.

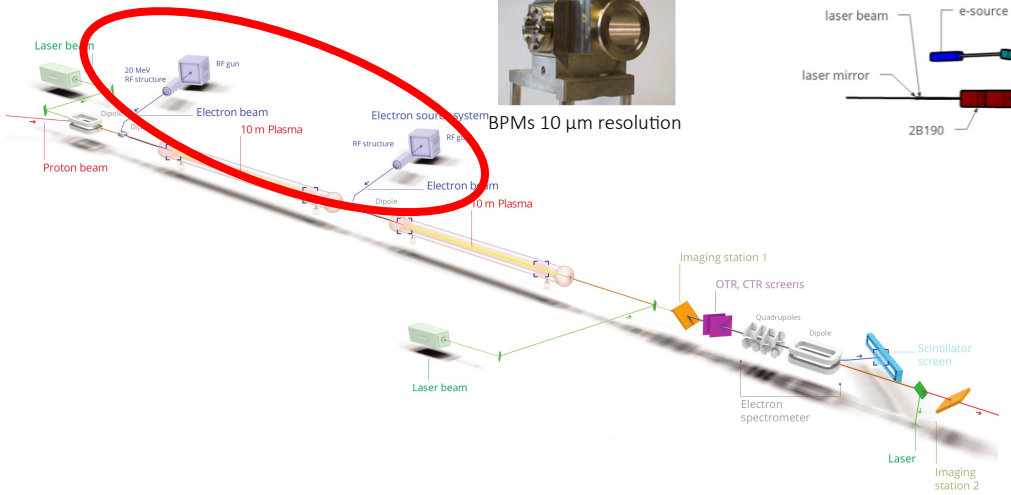


Studies, design and prototyping already advancing well for several experimental elements of Run 2c/d.

New electron-source:

→ S-band e-gun with X-band accelerator, Prototyping with CLIC/CLEAR

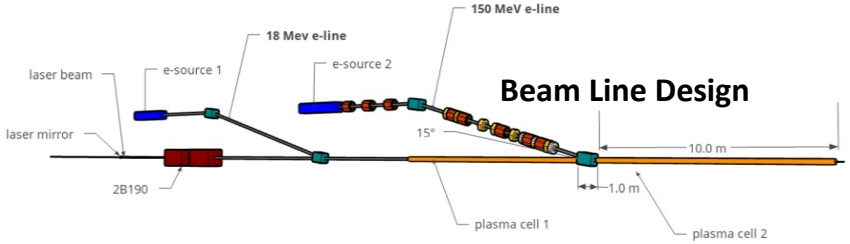




Beam Instrumentation

BPMs 10 µm resolution

Beam Line Design



→ Strong synergy with CERN and the institutes.
→ CERN acquires additional expertise needed for other future electron facilities/colliders.

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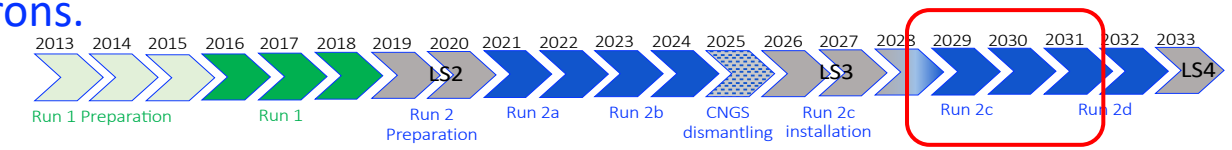

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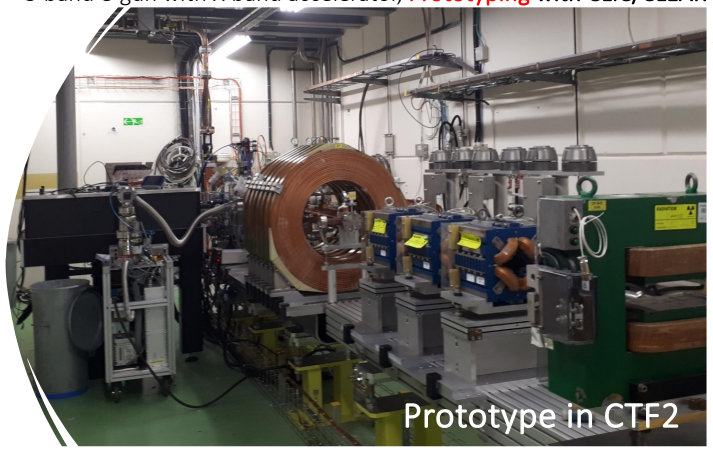

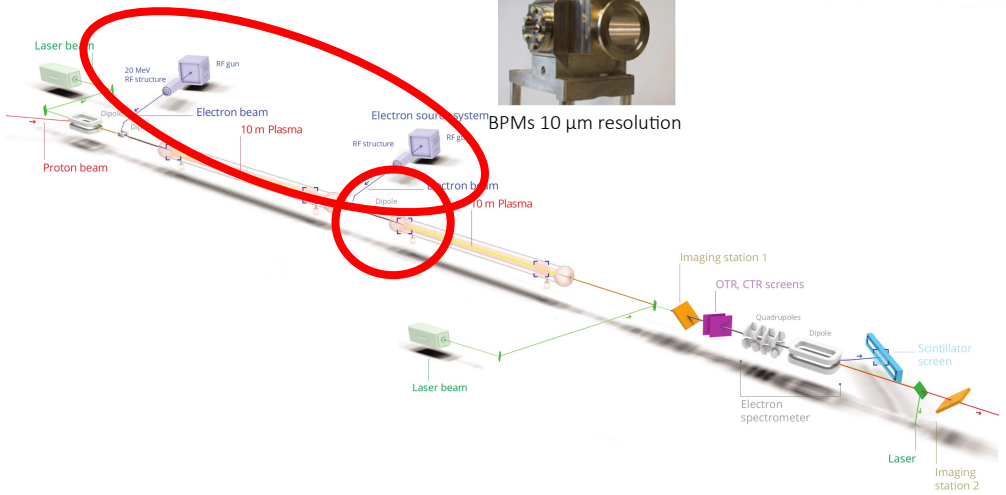

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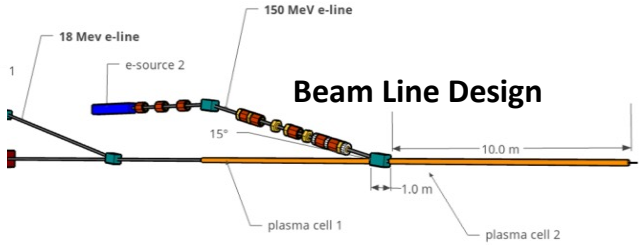

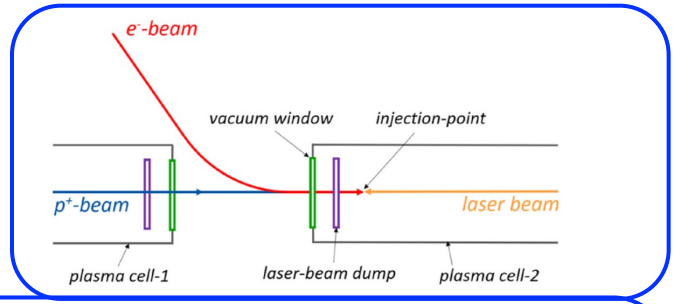

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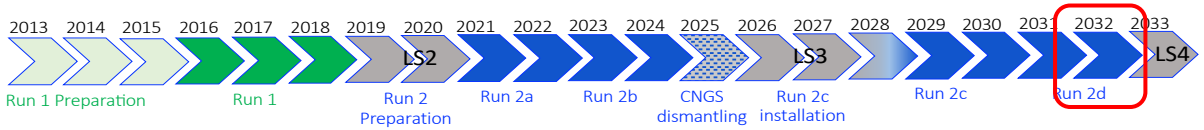
Injection area at conceptual design level.
Move from physics level to engineering level.

➔ Challenges of external injection relevant for other PWFA

AWAKE Run 2d: Scalability – Towards First Particle Physics Experiments

Development and demonstration of scalable plasma sources



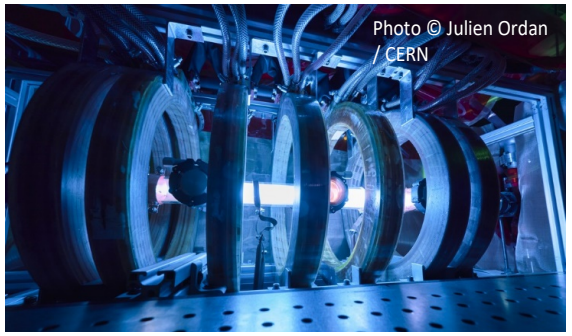
Scalable plasma source R&D program:

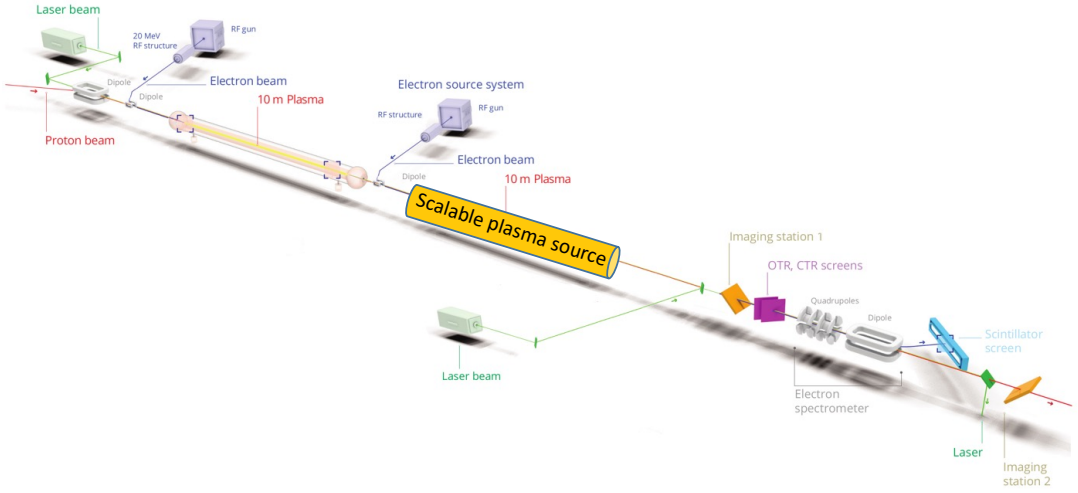
➔ Dedicated plasma source labs at CERN

➔ 5 collaborating institutes

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

1m Helicon Plasma Source



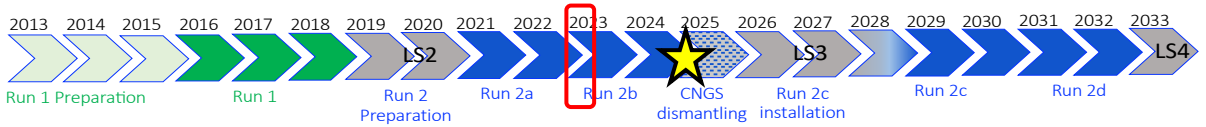


10m Discharge Plasma Source

➔ R&D of scalable long plasma sources added in ESPP as experimental demonstration R&D milestone

➔ Relevant for e+/e- collider designs based on PWFA

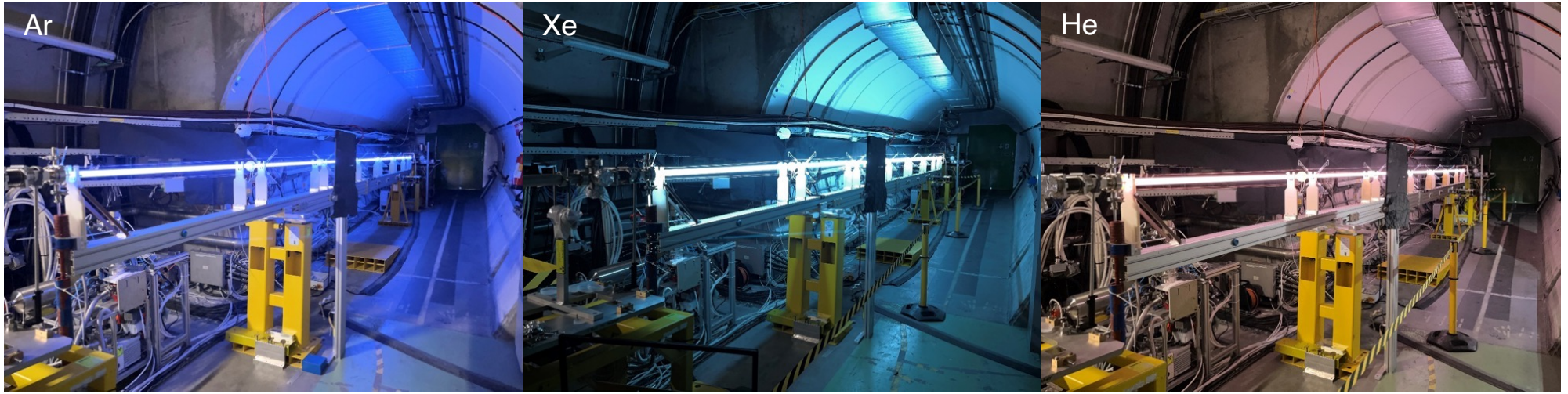
AWAKE Run 2d: Scalability – Towards First Particle Physics Experiments



Baseline for Run 2c is Rb vapour.

★ Internal review in 2025 whether scalable technology can already be used for Run 2c.

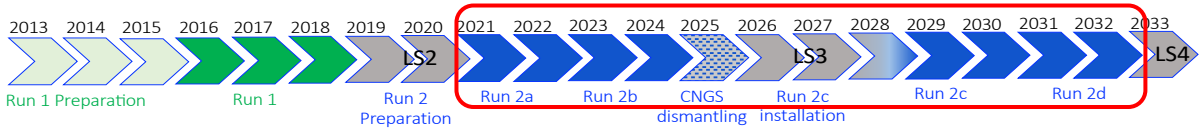
Unique opportunity in 2023:



Successfully installed, commissioned and operated a 10m long discharge prototype plasma source during the May 2023 Run ➔ profited from CERN's accelerator technology expertise!

Run 2 – Broader Impact

Examples of technological advancements



Machine Learning

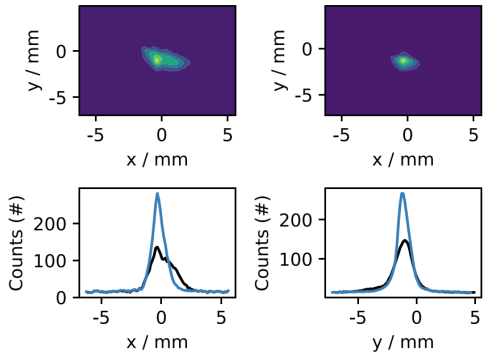
→ Running test-bed for operation efficiency studies and Machine Learning

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.

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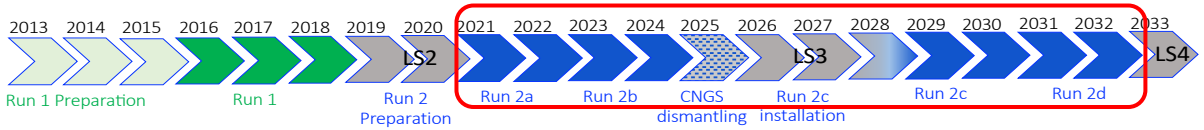

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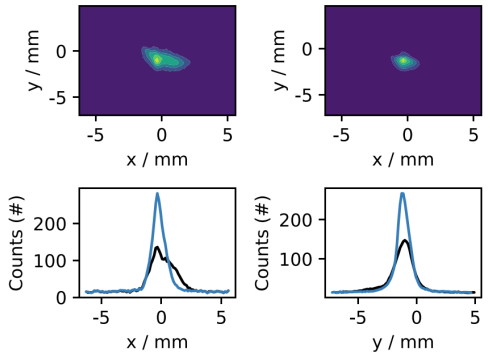

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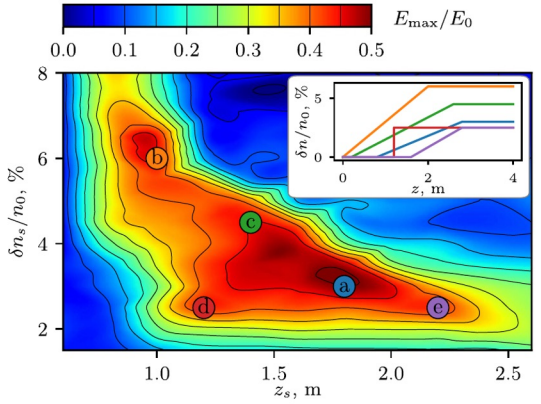
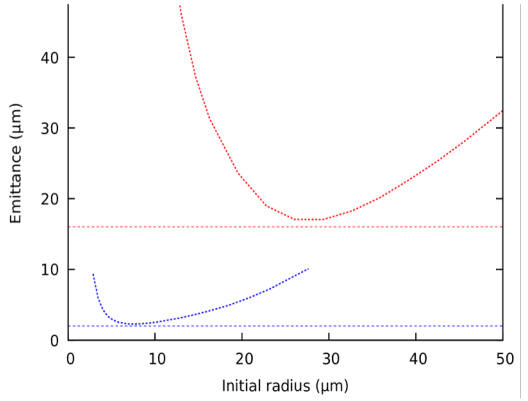
Simulations

→ 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.





Summary

- AWAKE is a unique proton-driven plasma wakefield acceleration experiment at CERN
  - Using 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 is part of the European Strategy Roadmap
  - AWAKE developed a well-defined plan towards first applications of particle physics experiments
  - High visibility in the international context
- AWAKE has substantial impact on plasma wakefield acceleration community and strategy
  - AWAKE Run 2 addresses key challenges of the community
  - AWAKE met all milesetones to date
  - High number of prizes, thesises and papers in high-impact journals
  - The results of AWAKE are relevant for concepts based on plasma wakefield acceleration