Coming soon
(early 2030’s)

AWAKE: a plasma wakefield accelerator for particle physics

M. Turner and the AWAKE Collaboration

Outline

- Introduction / motivation
- Status of AWAKE
- Plans to move towards first particle physics experiments
- AWAKE and ESPP
- Summary & conclusions

Wakefield excitation schemes

Forced wakefields regime

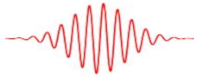
Drivers:

+ dense ($n_b \sim n_{pe}$) or intense ($a_0 \geq 1$)
+ lengths on the order of λ_{pe}

+ single driver excites a high amplitude wave (linear, quasilinear, blow-out regime)

Beams (e+,e-)
~10 GeV, < 40 J

- limited energy per particle, limited energy per pulse/bunch



Laser pulses (ph)
<1.5 kJ

- low phase velocity and energy per particle (photons)

→ reaching particle physics energy scales requires staging

Wakefield excitation schemes

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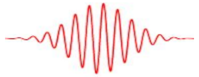

Laser pulses (ph)
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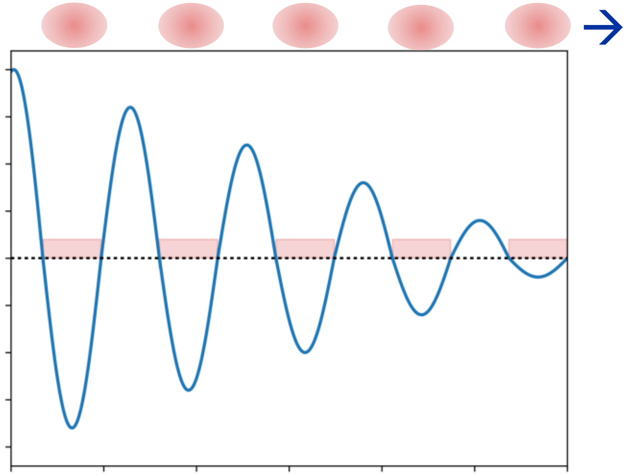
Resonant excitation with multiple bunches

Drivers: **particle physics energies in a single stage**

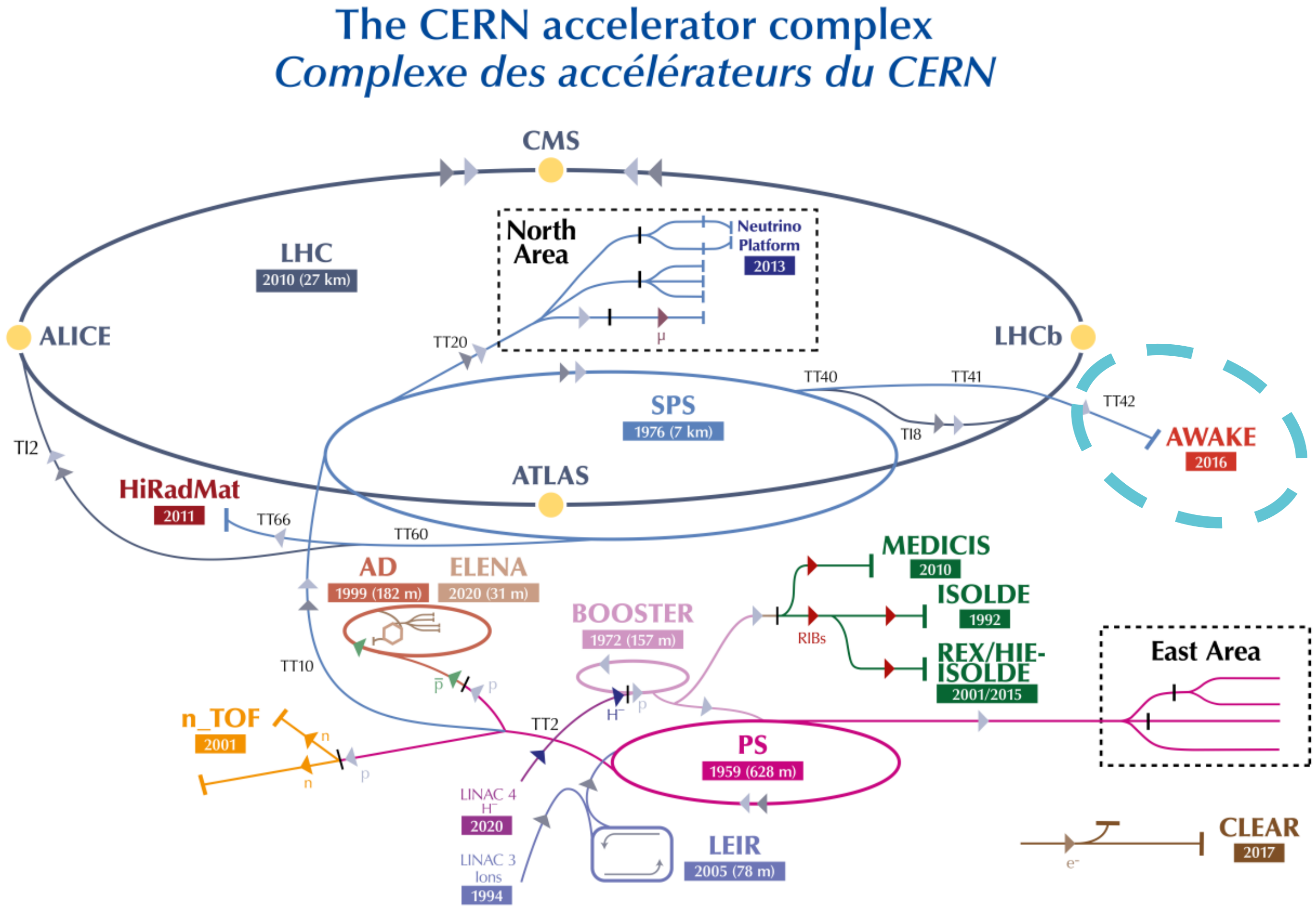
+ high energy per particle, high energy/bunch and high phase velocity
- $n_b < n_{pe}$
- $\sigma_z >> \lambda_{pe}$



- multiple, short drivers resonantly excite high amplitude wave

Proton bunches @ CERN

High energy per particle and per bunch



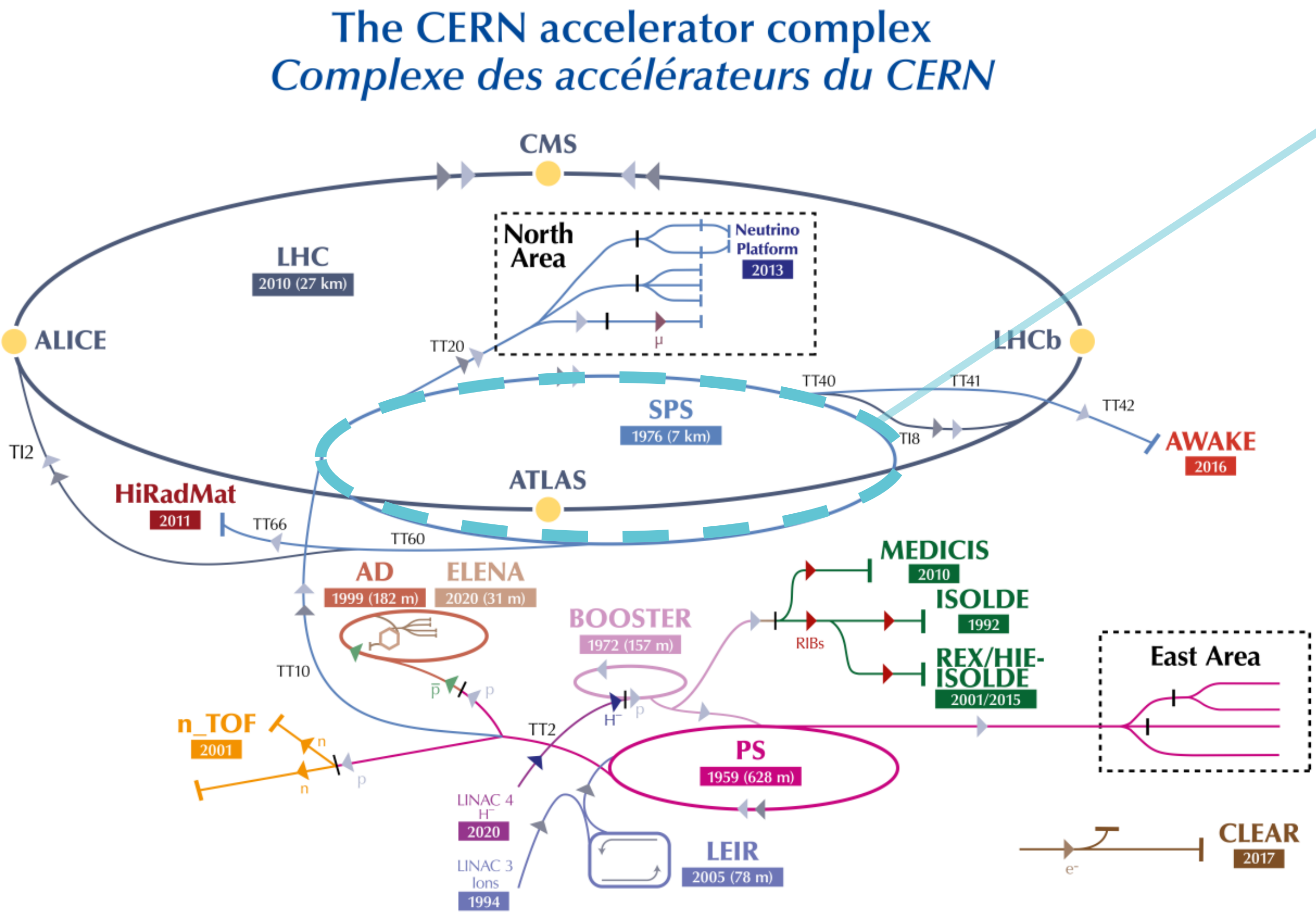
Plasma wakefield experiment at CERN:

AWAKE

Goal: develop concept proton-driven plasma wakefield acceleration, to enable high electron energies in a single plasma.

Proton bunches @ CERN

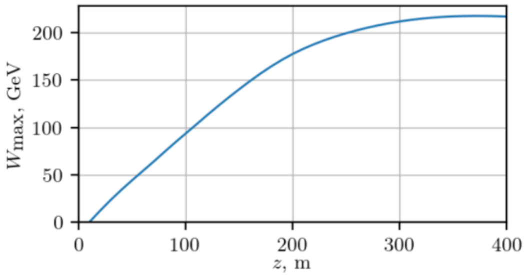
High energy per particle and per bunch



SPS Driver (400 GeV, 19 kJ):

~ 200 GeV in ~200 m

~ 10^9 e$^-$



Lotov and Tuev, PPCF (2021)

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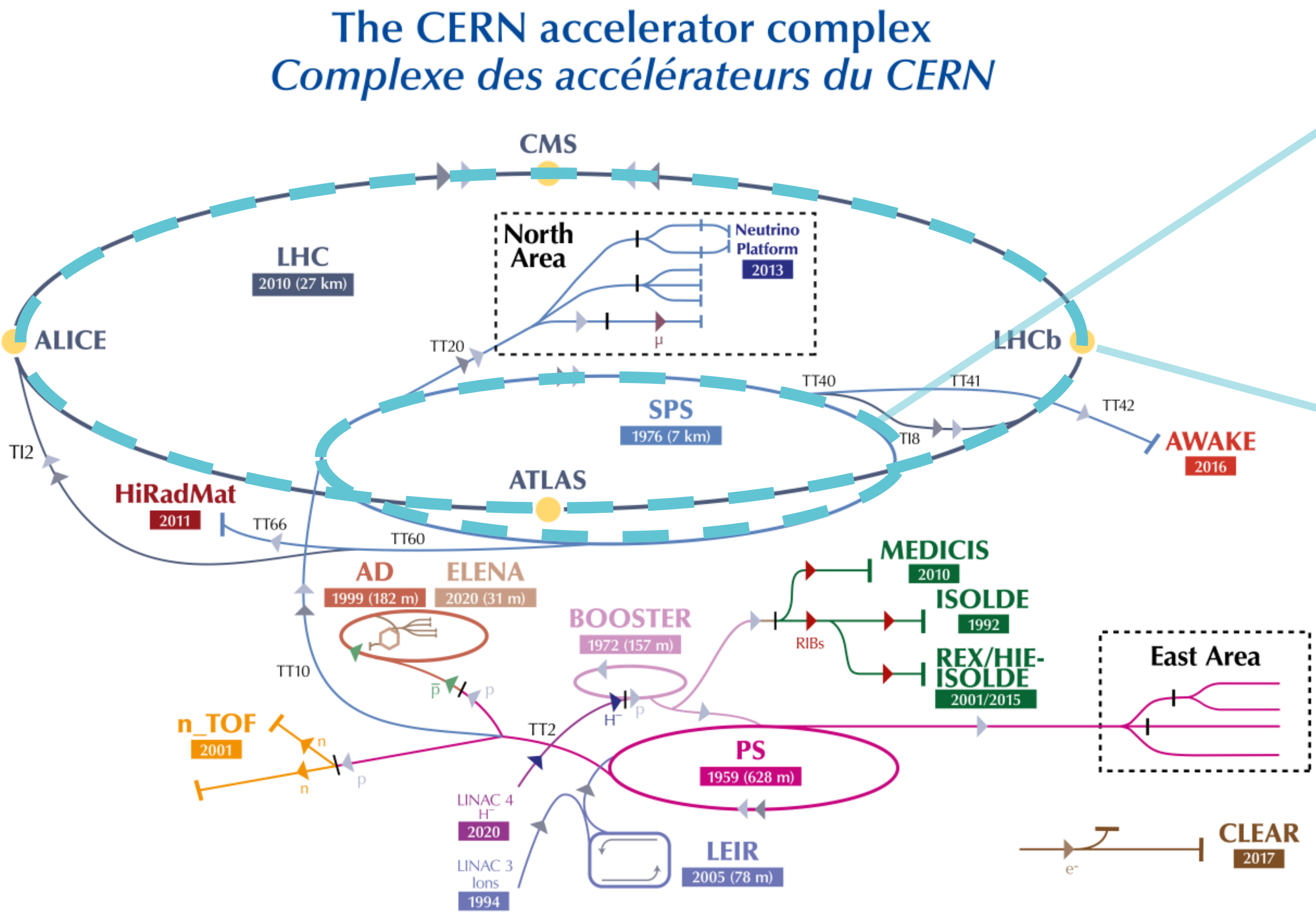
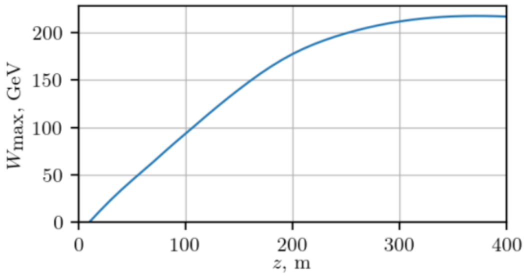


SPS Driver (400 GeV, 19 kJ,γ~400):

~ 200 GeV in ~200 m

~ 10^9 e^-

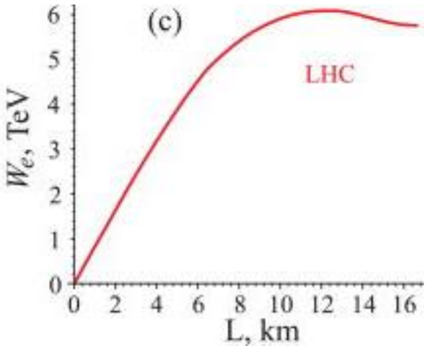


Lotov and Tuev, PPCF (2021)

LHC Driver (7 TeV, 112 kJ, γ~7400):

~ 5 TeV in ~7 km

~ 10^9 e^-



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

~TeV in km ⇔ ~GeV/m

AWAKE collaboration: 22 institutes world-wide

- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Oxford University, UK
- Max Planck Institute for Physics, Munich, Germany
- Max Planck Institute for Plasma Physics, Greifswald, Germany
- UCL, London, UK
- UNIST, Ulsan, Republic of Korea
- Philipps-Universität Marburg, Marburg, Germany
- Heinrich-Heine-Universität of Düsseldorf, Düsseldorf, Germany
- University of Liverpool, Liverpool, UK
- ISCTE – Instituto Universitéario de Lisboa, Lisbon, Portugal
- Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
- Novosibirsk State University, Novosibirsk Russia
- GoLP/Institutode Plasmas e Fusao Nuclear, Instituto Superior Téchnico, Universidade de Lisboa, Lisbon, Portugal
- TRIUMF, Vancouver, Canada
- Ludwig-Maximilians-Universität, Munich, Germany
- University of Wisconsin, Madison, US
- Uppsala University, Uppsala, Sweden
- Wigner Institute, Budapest, Hungary
- Swiss Plasma Center group of EPFL, Lausanne Switzerland

AWAKE has a clear timeline towards an accelerator

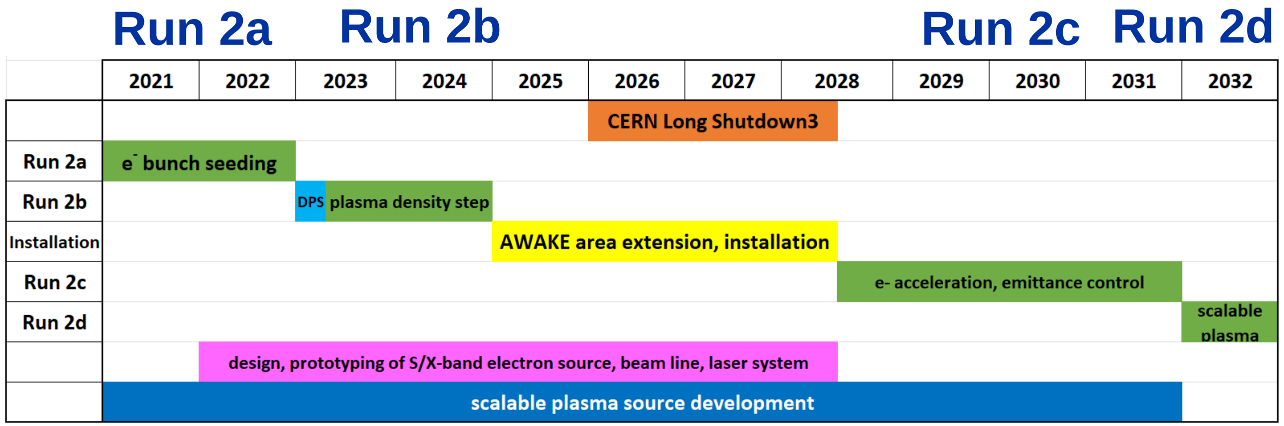
2016 – 2018:
Run 1
Proof-of-principle

‘Experiment’

2021 – 2032:
Run 2
Transition from proof-of-principle
to parameters for first application

2033 +:
Particle Physics Applications

‘Accelerator’



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
						CERN Long Shutdown3						
Run 2a	e$^-$ bunch seeding											
Run 2b			DPS plasma density step									
Installation					AWAKE area extension, installation							
Run 2c									e- acceleration, emittance control			
Run 2d												scalable plasma
		design, prototyping of S/X-band electron source, beam line, laser system										
	scalable plasma source development											

→ address physics questions relevant to resonant excitation scheme

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2021 – 2032:
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to parameters for first application

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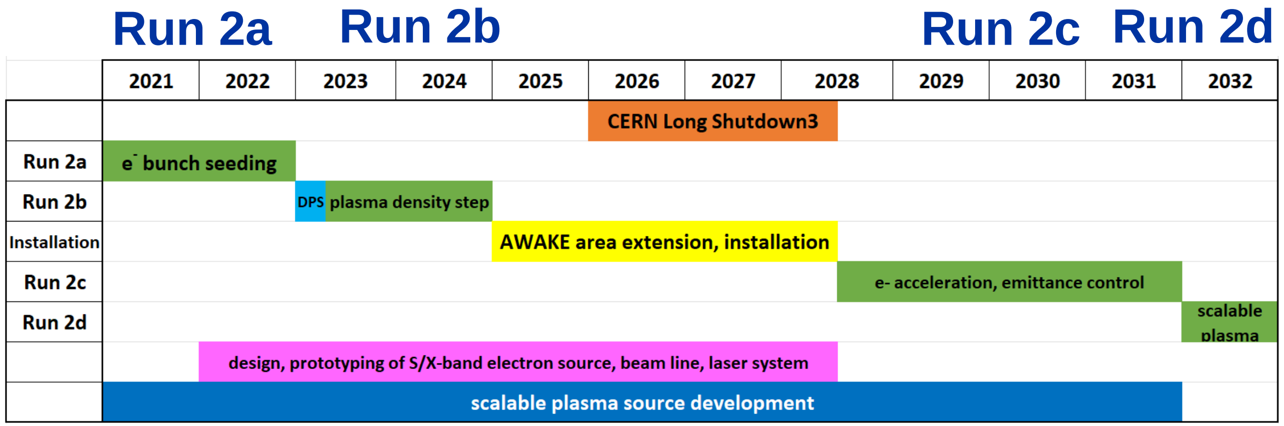
Particle Physics Applications

- \+ $k_{pe}\sigma_r \sim 1$
- \- $n_b \sim 10^{-3}\, n_{pe}$
- \- $k_{pe}\sigma_z \sim 300\ \lambda_{pe}$

$@\sim 1\mathrm{x}10^{15}\mathrm{cm}^{-3}$

For formation of bunch train:
→ self-modulation instability



Run 2a **Run 2b** **Run 2c** **Run 2d**

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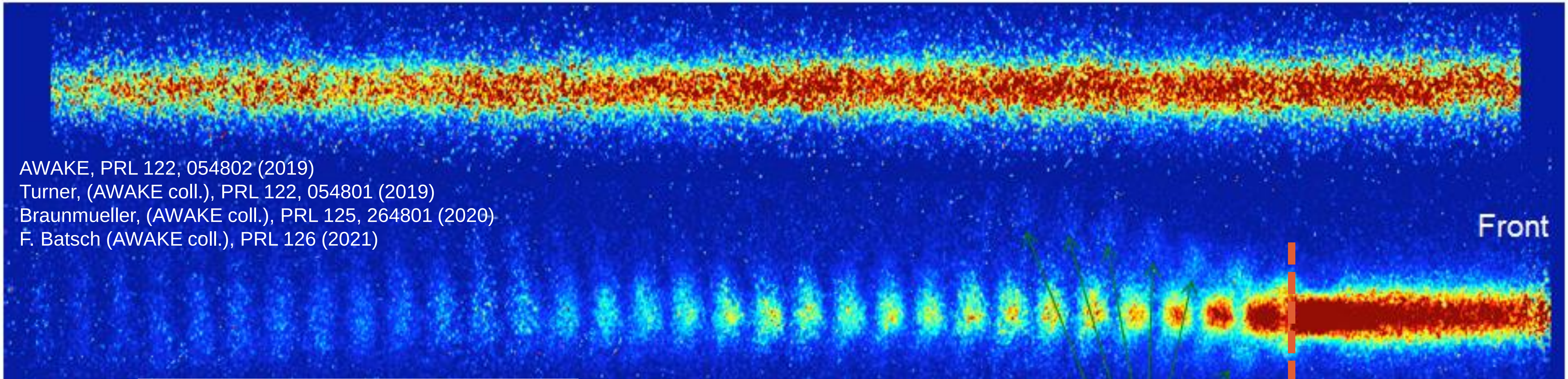
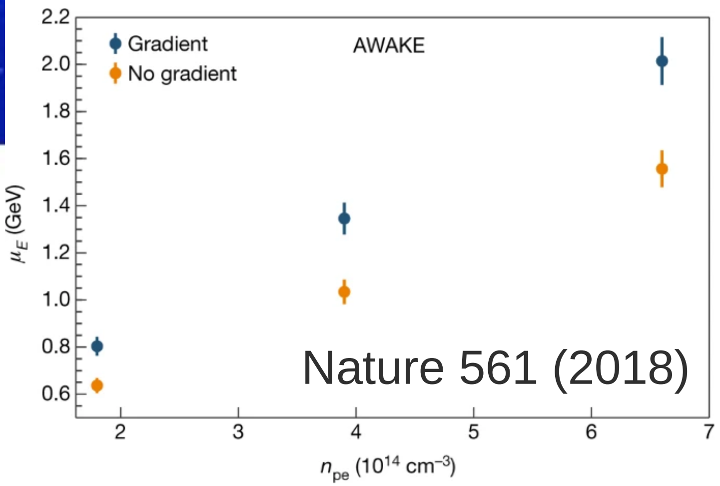
AWAKE Run 1: proof-of-principle concept demonstrated



AWAKE, PRL 122, 054802 (2019)
Turner, (AWAKE coll.), PRL 122, 054801 (2019)
Braunmueller, (AWAKE coll.), PRL 125, 264801 (2020)
F. Batsch (AWAKE coll.), PRL 126 (2021)

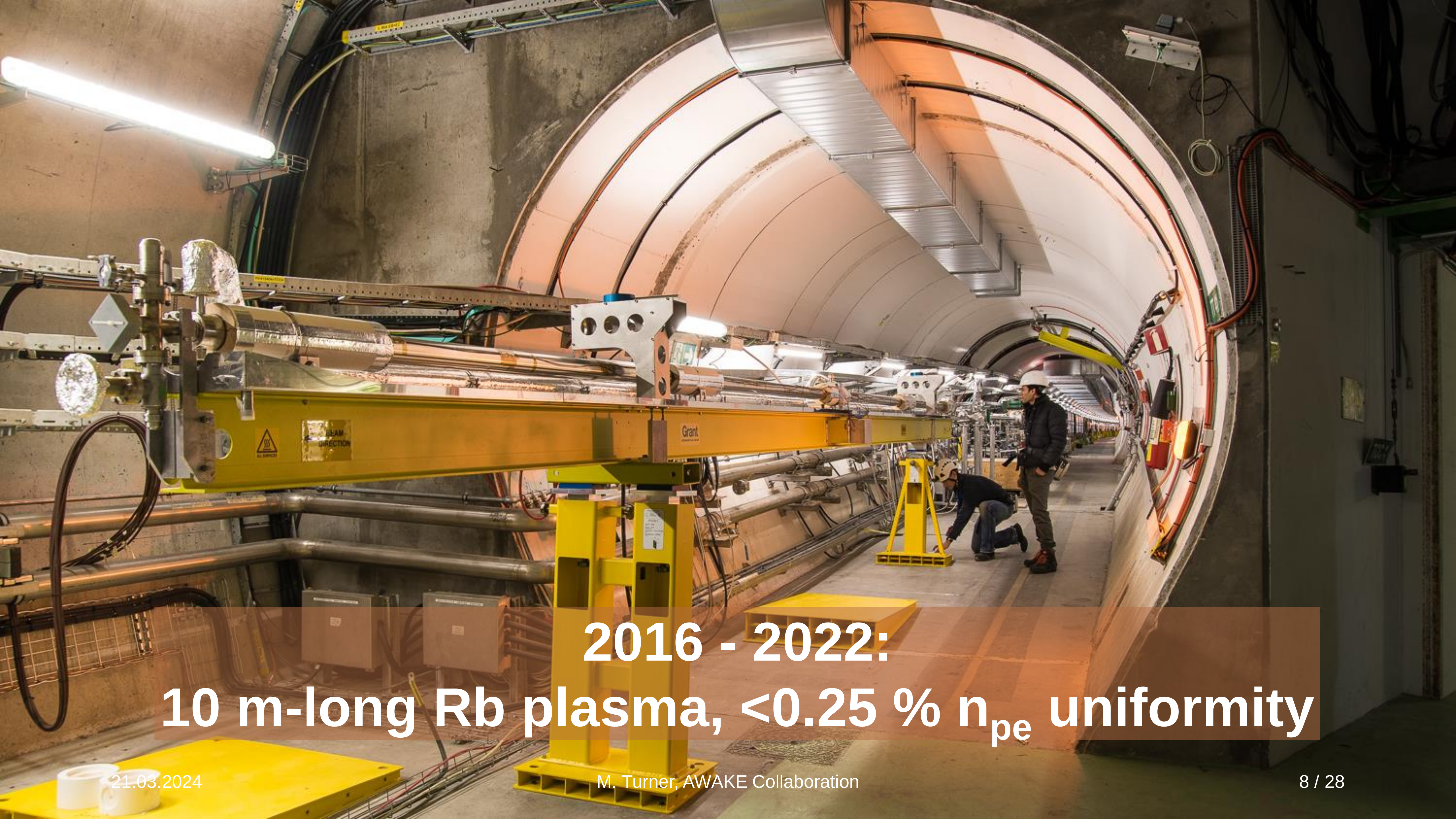
AWAKE, PRL 122, 054802 (2019)



Nature 561 (2018)

- Self-modulation observed
  - Seeded with relativistic ionization front

- Acceleration of externally-injected test e$^-$



2016 - 2022:
10 m-long Rb plasma, <0.25 % n_{pe} uniformity

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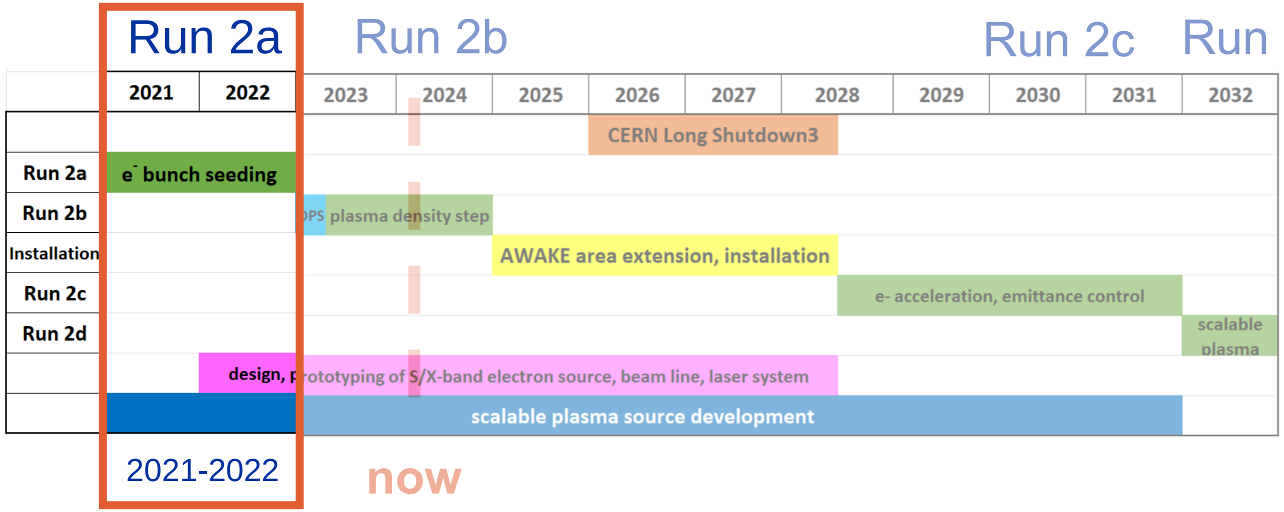
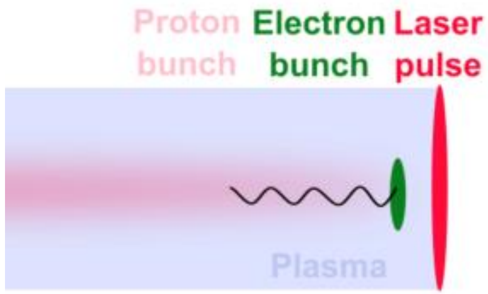


2033 +:
Particle Physics Applications

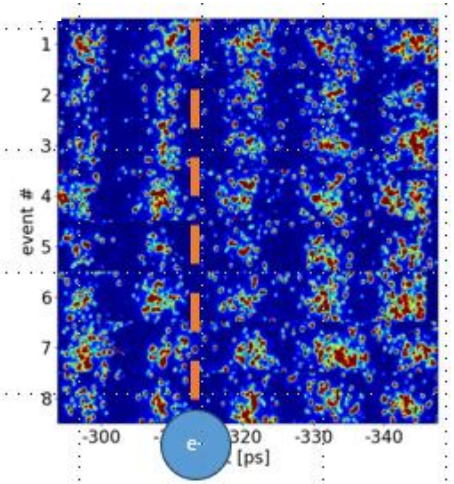
✓ **Run 2a - Seeding:** demonstrate the seeding of the self-modulation of the entire proton bunch with an electron bunch

→ Any accelerator requires a reproducible and controllable phase



Electron bunch drives Seed wakefields

L. Verra (AWAKE Collaboration), PRL **129, 024802** (2022)



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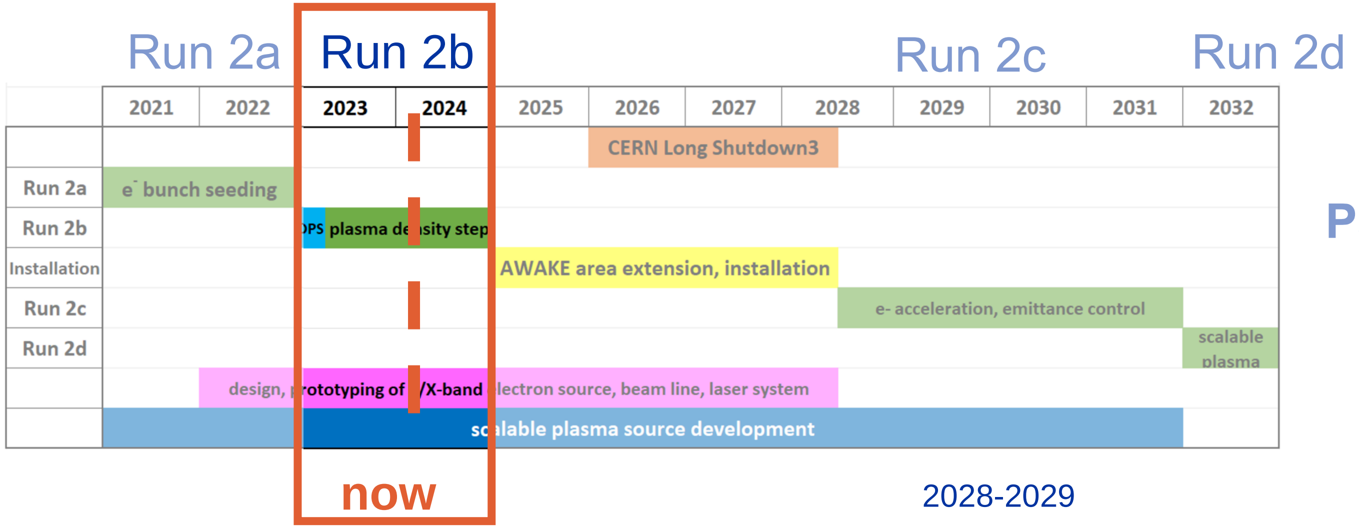


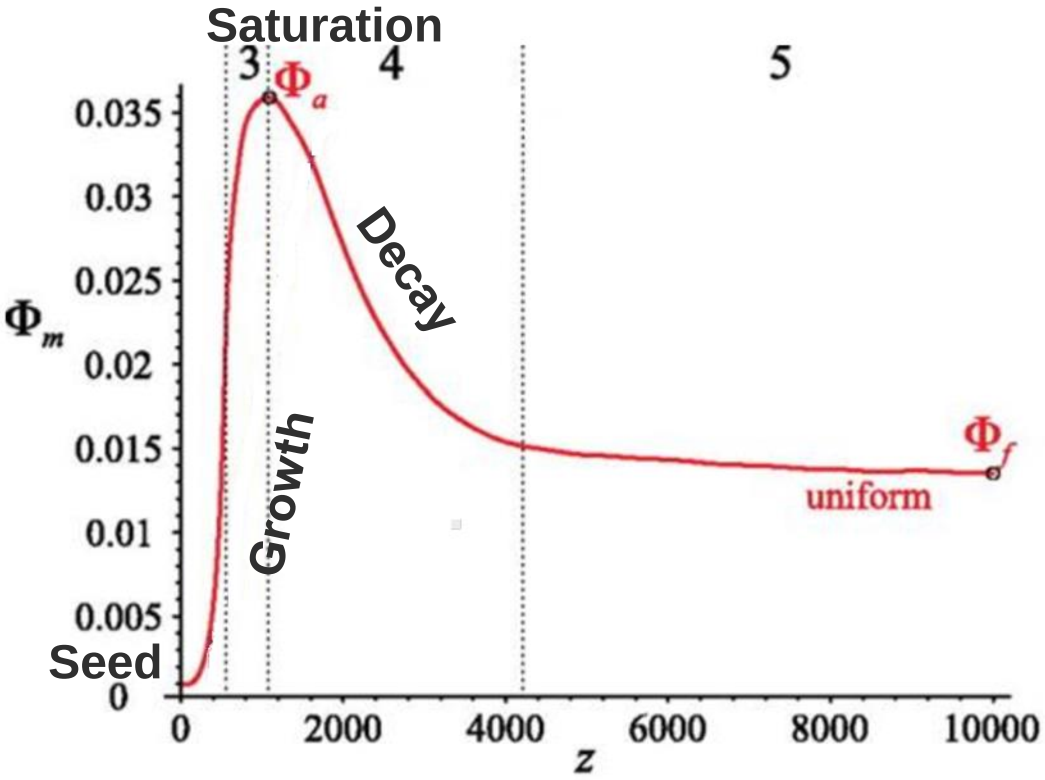
2033 +:
Particle Physics Applications

Run 2 Milestones:

- ✓ **Run 2a - Seeding:** demonstrate the seeding of the self-modulation of the entire proton bunch with an electron bunch
- now **Run 2b – Stabilization:** maintain large wakefield amplitude over long plasma distances by introducing a step in the plasma density

Run 2b measurement goal

Demonstrate that a density step stabilizes wakefield amplitude



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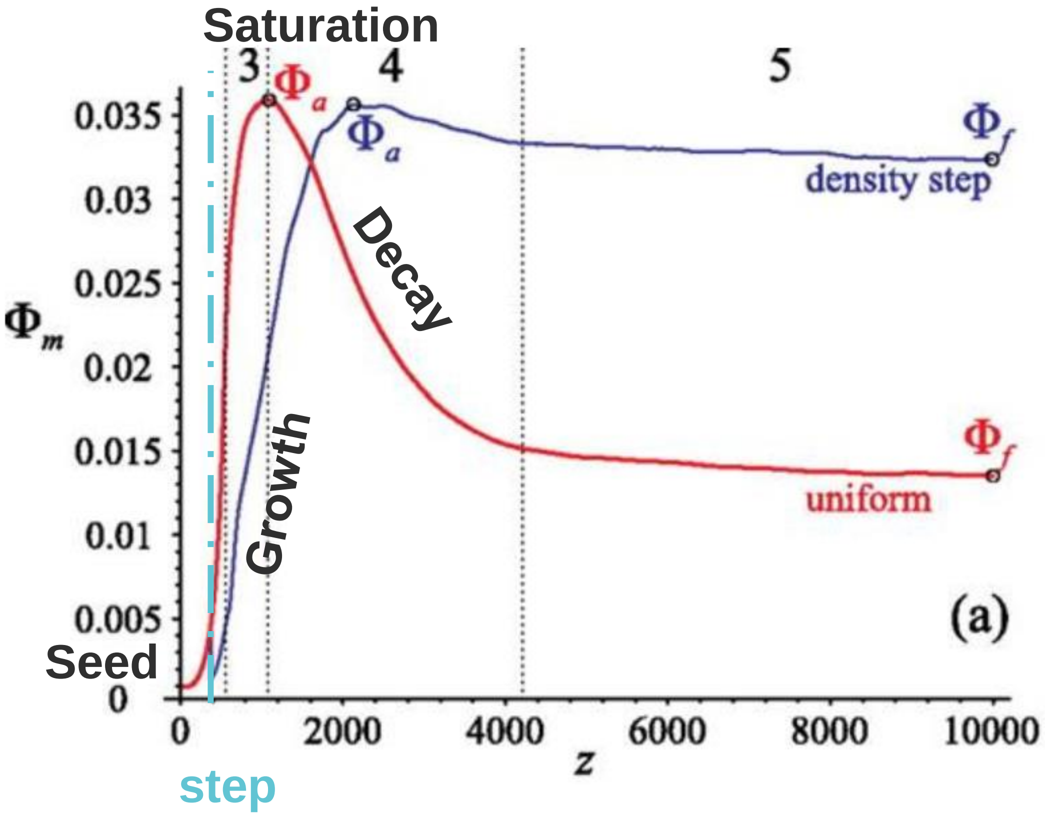
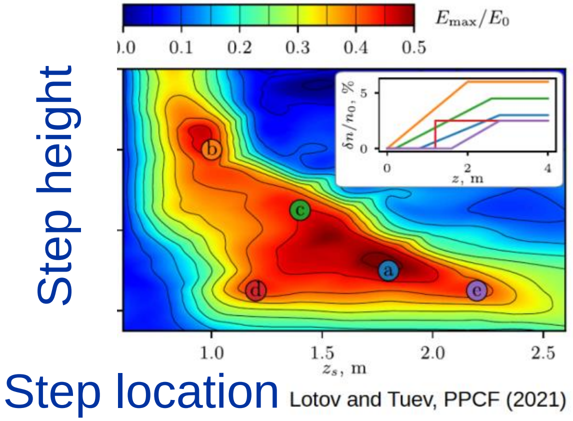


K. V. Lotov, Physics of Plasmas 22, 103110 (2015)

Predicted by numerical simulation results:

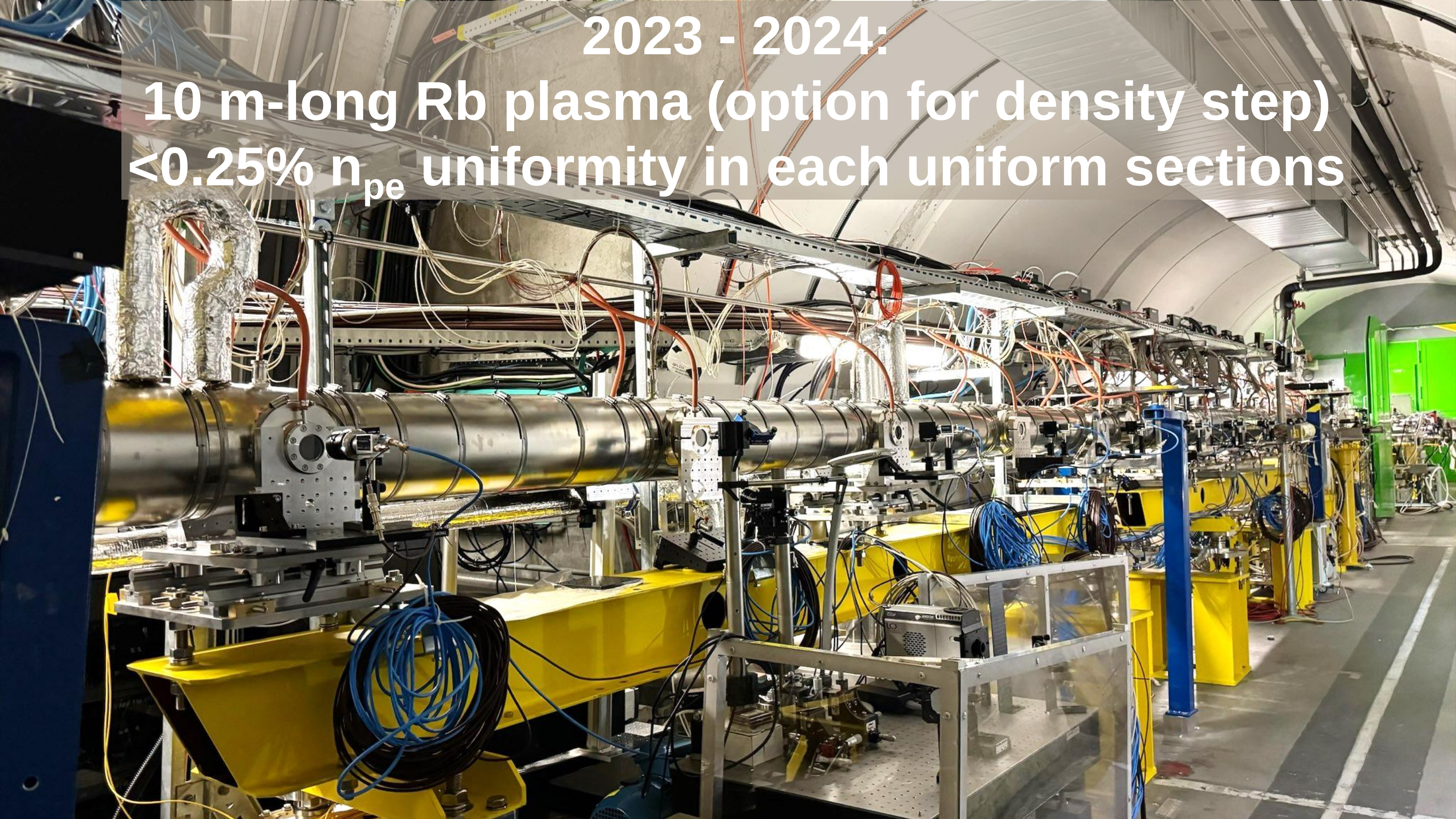
- Verification of the prediction
- Optimization of density step
- Confirm by the measurement of energy gain of 20 MeV side-injected (after the step).

→ Measurements restarting April 2024



Lotov and Tuev, PPCF (2021)

2023 - 2024:
10 m-long Rb plasma (option for density step)
<0.25% n_{pe} uniformity in each uniform sections



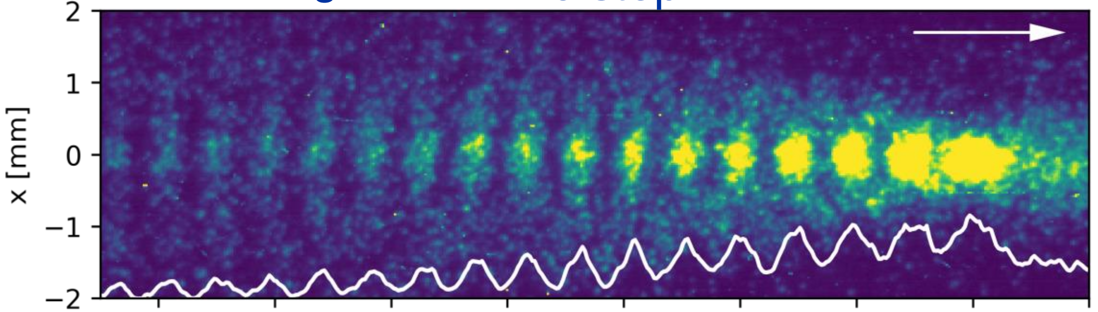
Run 2b: first results from 2023

Effect of the Density Step

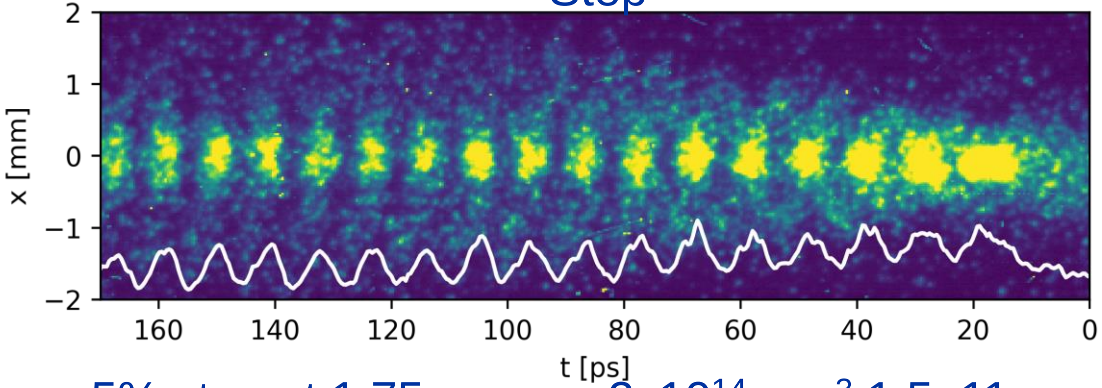
Clear effect!

- Longer bunch trains on the streak camera images

No step



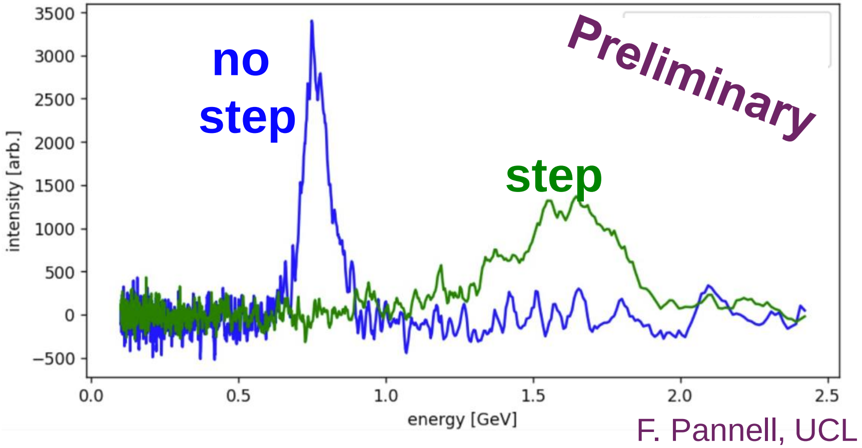
Step



5% step at 1.75m, n_{pe} ~ 2×10^{14} cm^{-3},1.5e11 p+/bunch

Preliminary

- Energy of accelerated e^- greatly increased for certain density steps

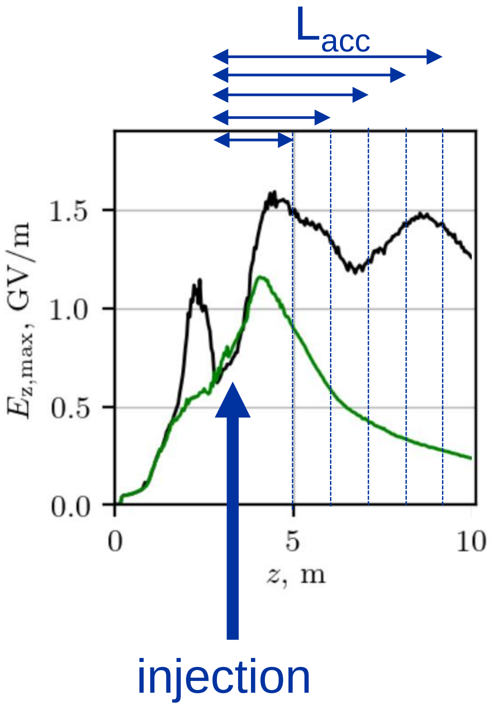


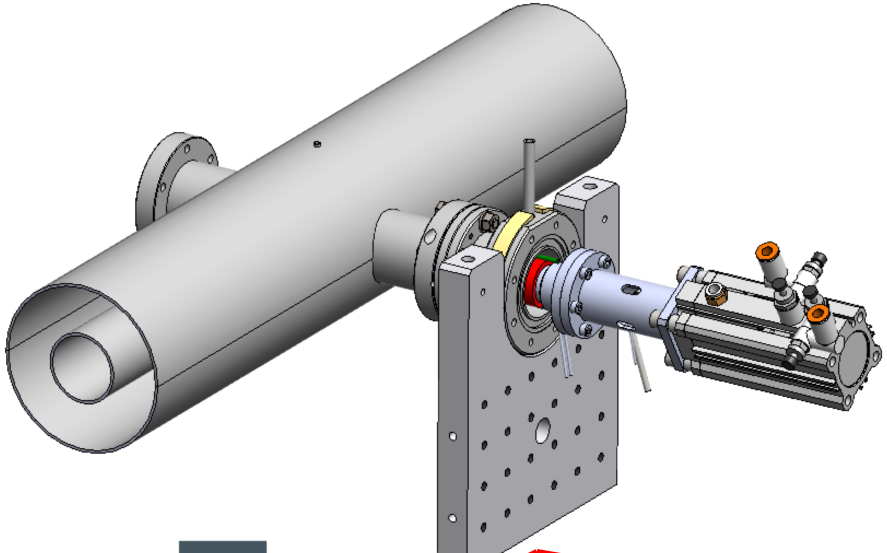
F. Pannell, UCL

n_{pe} ~ 6.2×10^{14} cm^{-3}, 2.3% step at 1.75 m, seed = -0.1 ns, 3×10^{11} p^+/bunch

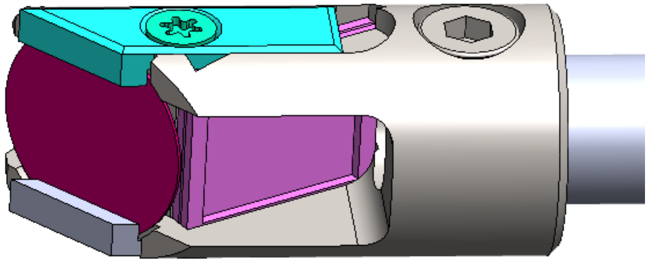
Changing plasma length to measure gradients

Vary plasma length by stopping the ionizing laser





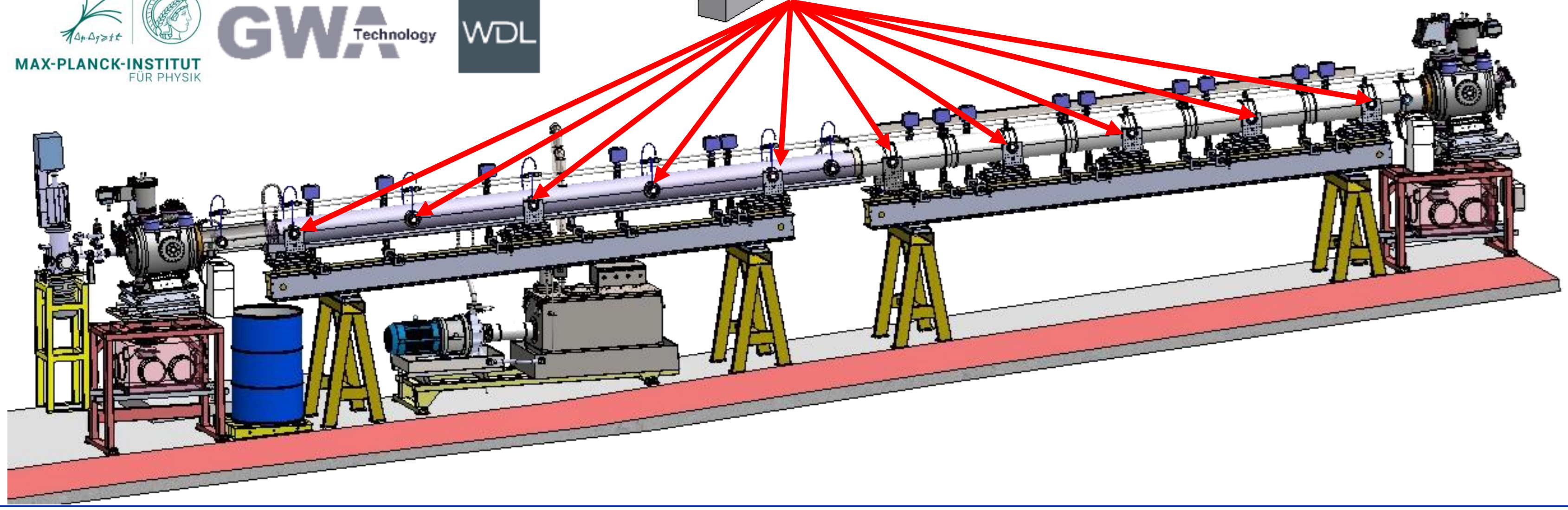
Thin beam dumps for changing plasma length



MAX-PLANCK-INSTITUT FÜR PHYSIK

GWA Technology

WDL



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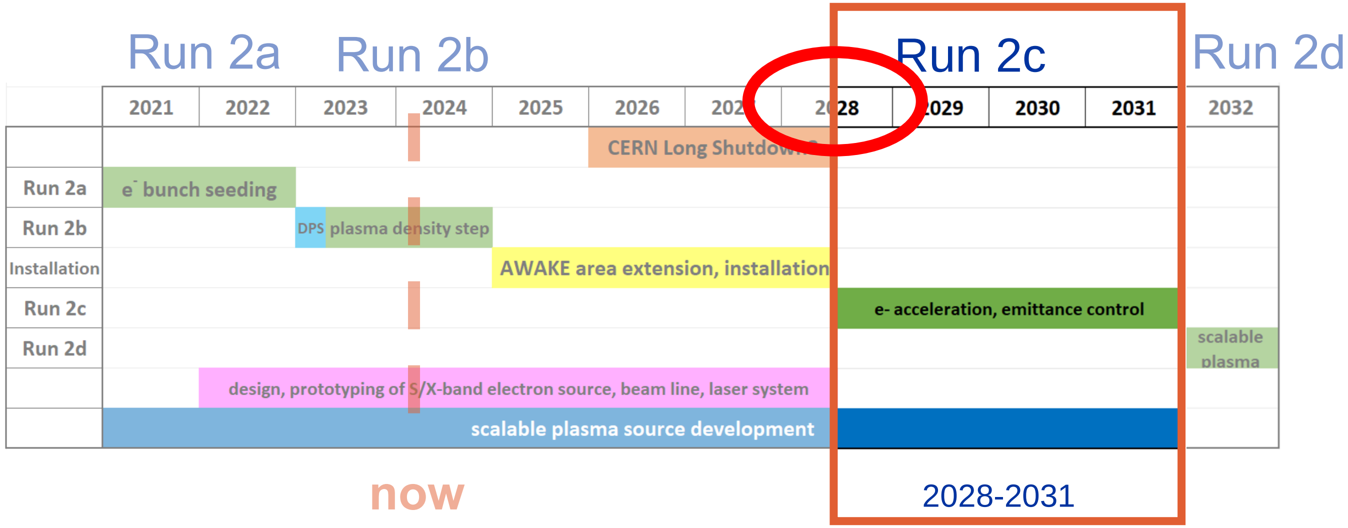

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2033 +:
Particle Physics
Applications

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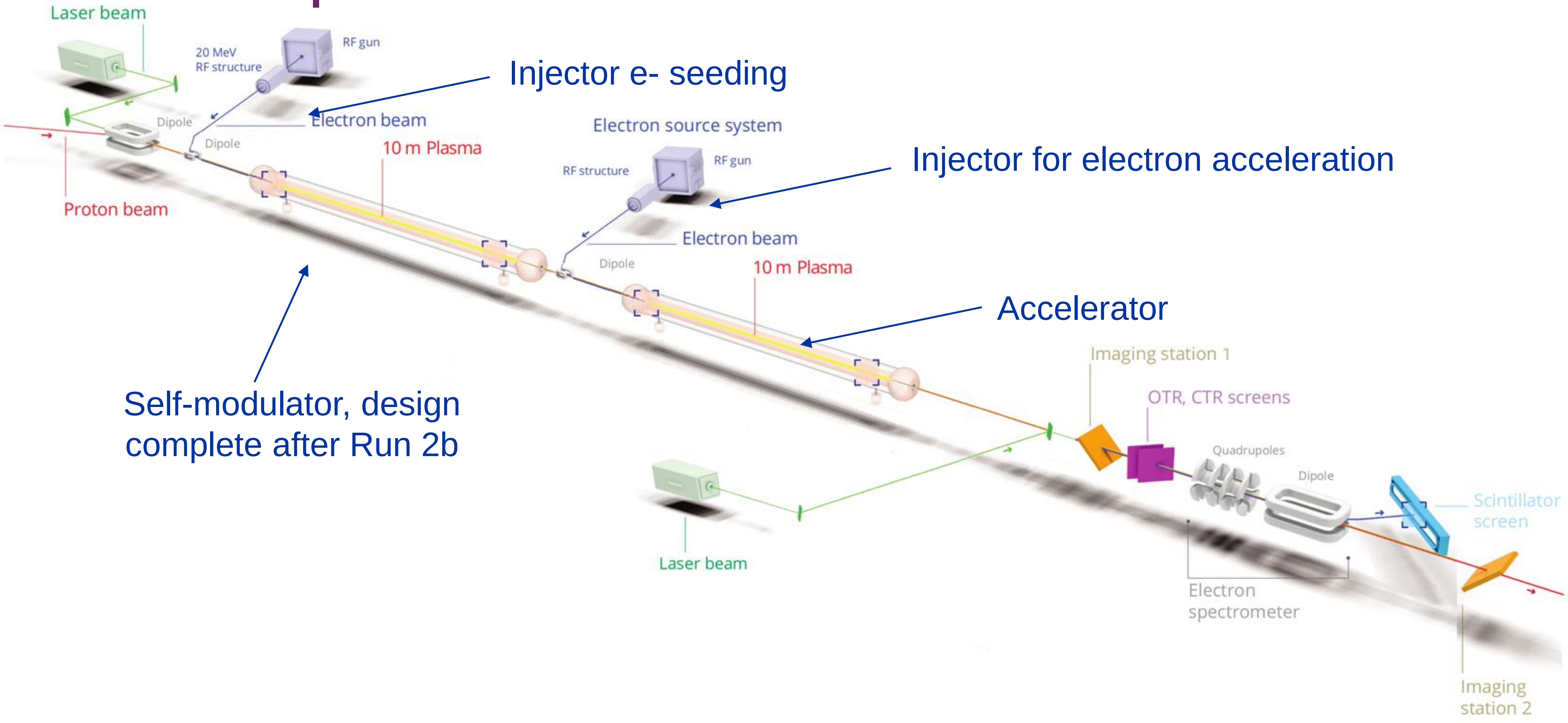
- now **Run 2b – Stabilization:** maintain large wakefield amplitude over long plasma distances by introducing a step in the plasma density
- **Run 2c - Quality Acceleration:** demonstrate acceleration and emittance control of externally injected electron bunch.

Run 2c: acceleration of a witness bunch with quality

Separation between self-modulator and accelerator



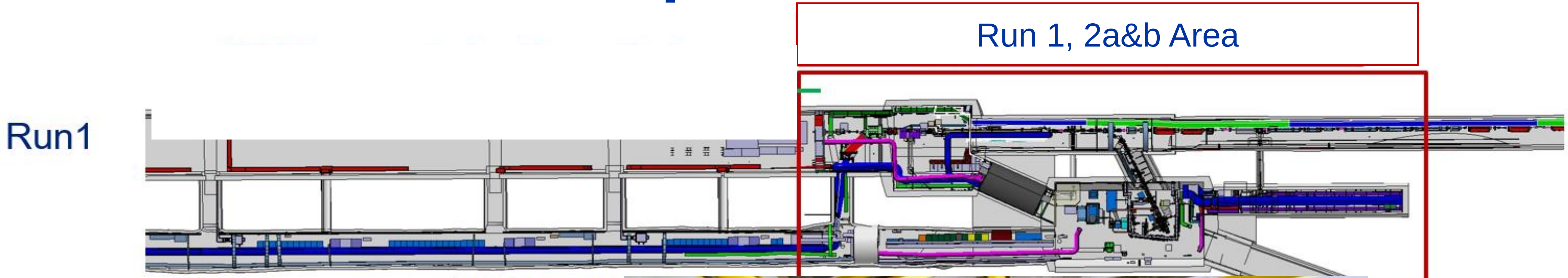
Injector e- seeding

Injector for electron acceleration

Accelerator

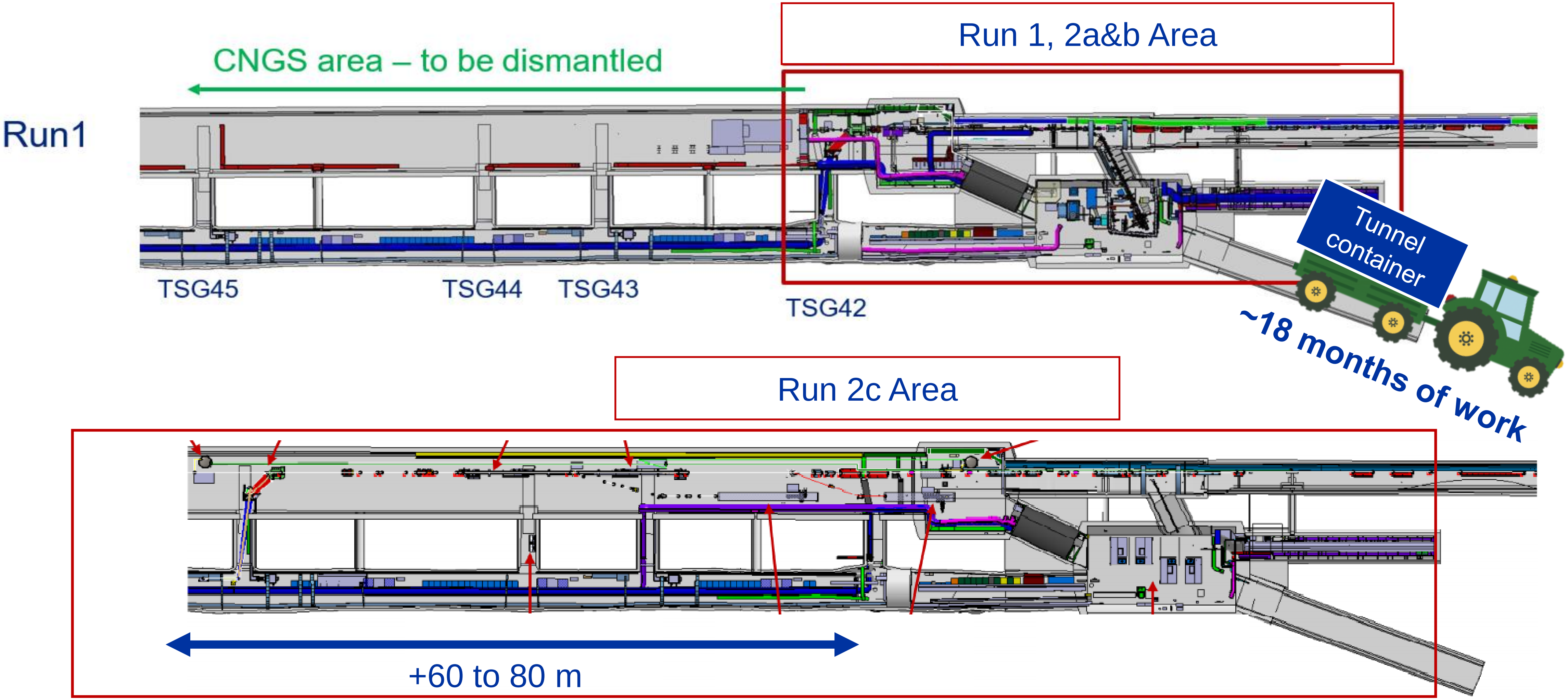
Self-modulator, design complete after Run 2b

More space for AWAKE



Shielding Wall

More space for AWAKE



Run 1, 2a&b Area

CNGS area – to be dismantled

Run1

Tunnel container

~18 months of work

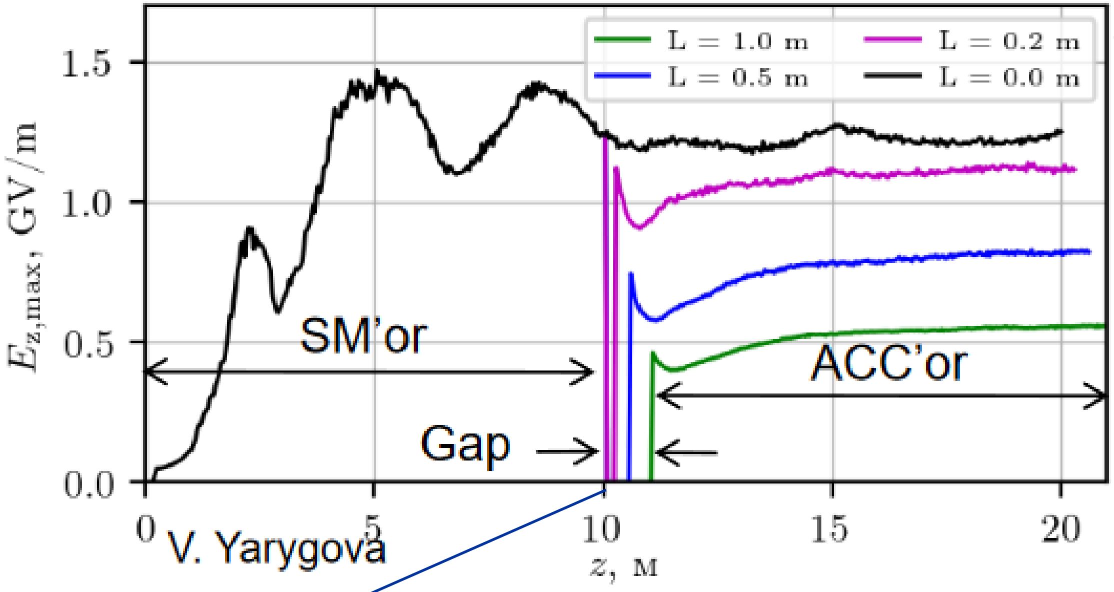
Run 2c Area

+60 to 80 m

AWAKE Run 2c physics goal

Goal: acceleration of a bunch with 'quality'

see Poster by J. Farmer tonight



V. Yarygova

Expected parameter reach:

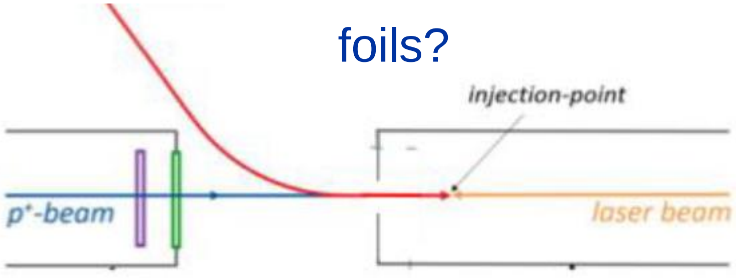
- ε_N=(2-30) mm-mrad
- Q = 100pC, N_{e-}~6x10^8e-
- ΔE/E = 5-8%
- Run 2c: E ~ 4-10GeV, 10m

'good enough' quality for first (fixed-target) particle physics applications

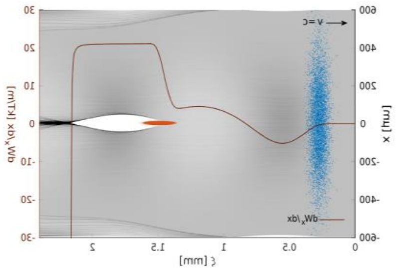
achieved by:

challenge: design of the injection region

foils?

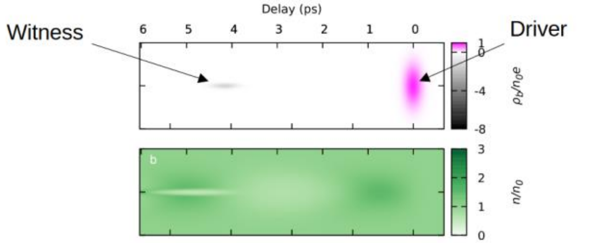


low emittance witness drives its own blowout



V. Olsen et al., PRAB (2018)

"quasi-matching" to nonlinear wakefield



J. Farmer et al., in preparation

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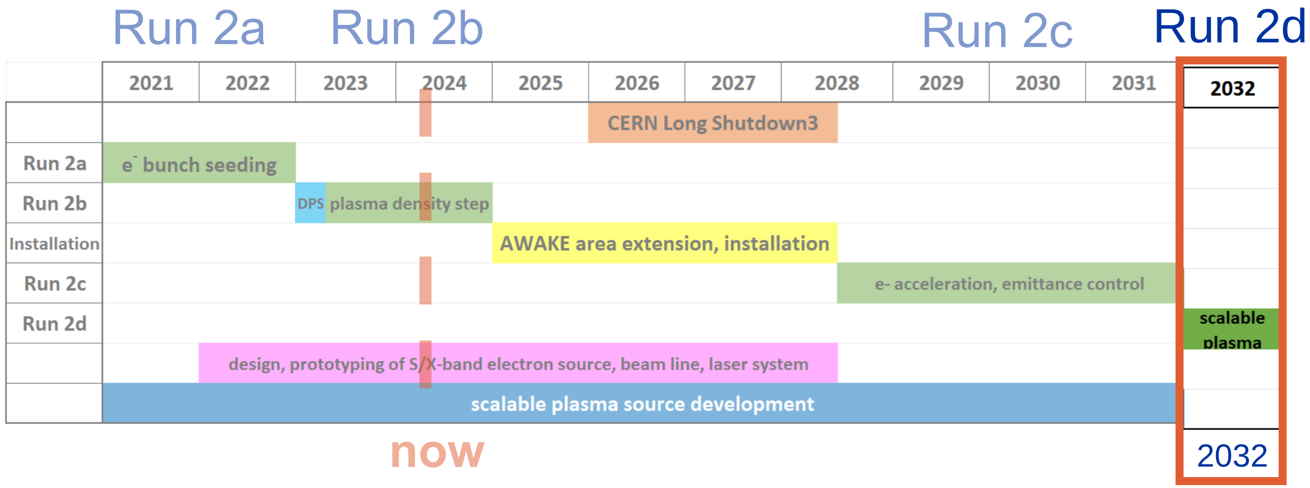

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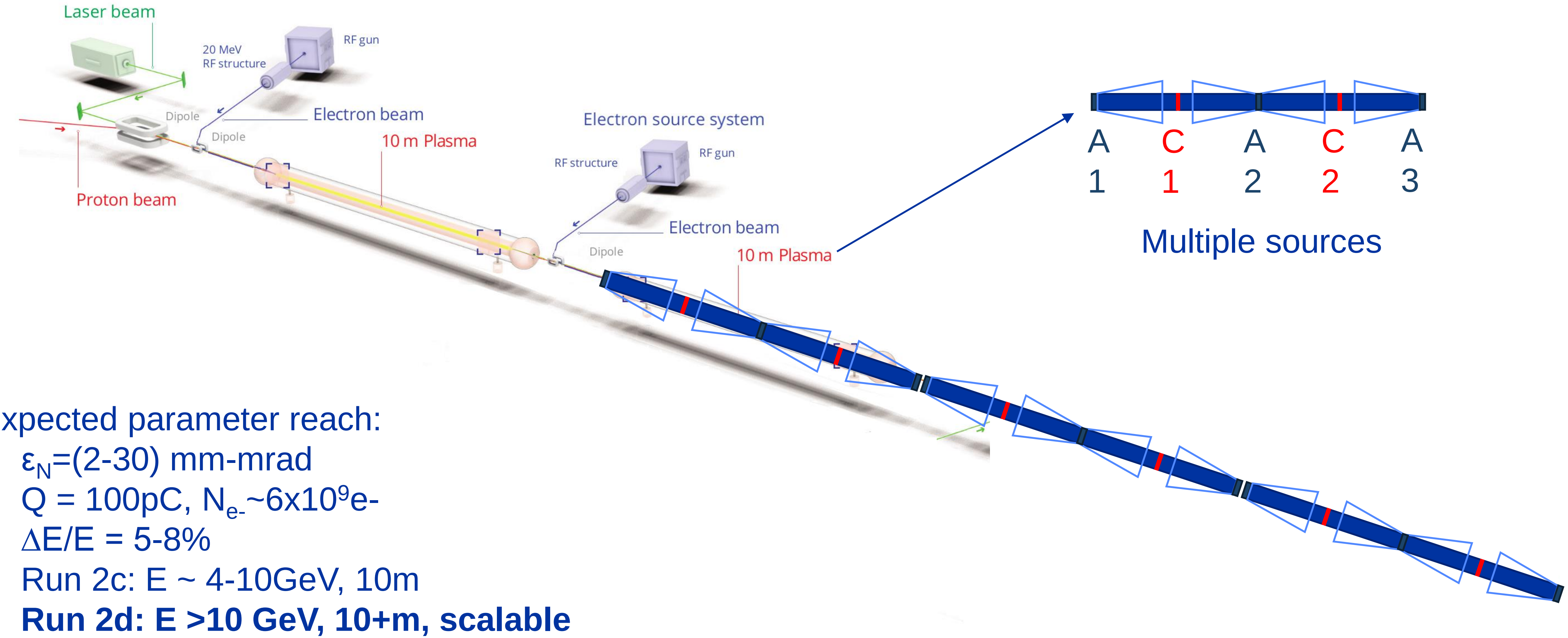
- **Run 2c - Quality Acceleration:** demonstrate acceleration and emittance control of externally injected electron bunch.
- **Run 2d – Scalability:** development of scalable plasma sources to 10s-100s meters length with sub-% level plasma density uniformity.

Run 2d: demonstration of scalability

Use scalable plasma source technology for acceleration



Expected parameter reach:

- ε_N=(2-30) mm-mrad
- Q = 100pC, N_{e-}~$6x10^9$e-
- $\Delta E/E$ = 5-8%
- Run 2c: E ~ 4-10GeV, 10m
- **Run 2d: E >10 GeV, 10+m, scalable**

AWAKE is developing plasma source technologies

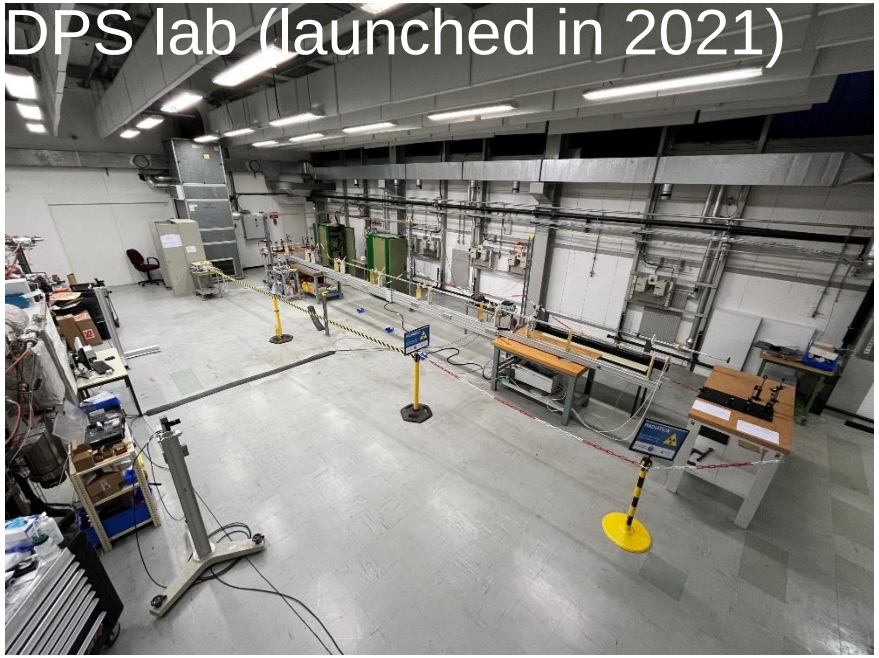
A. Sublet (CERN)

- AWAKE dedicated plasma sources R&D program launched in 2018
- Well defined plan with 5 institutes + CERN as host, 6 PhD works
- **Two dedicated labs at CERN**, capable to house up to 20 m long source and diagnostics

HPS lab (launched in 2019)

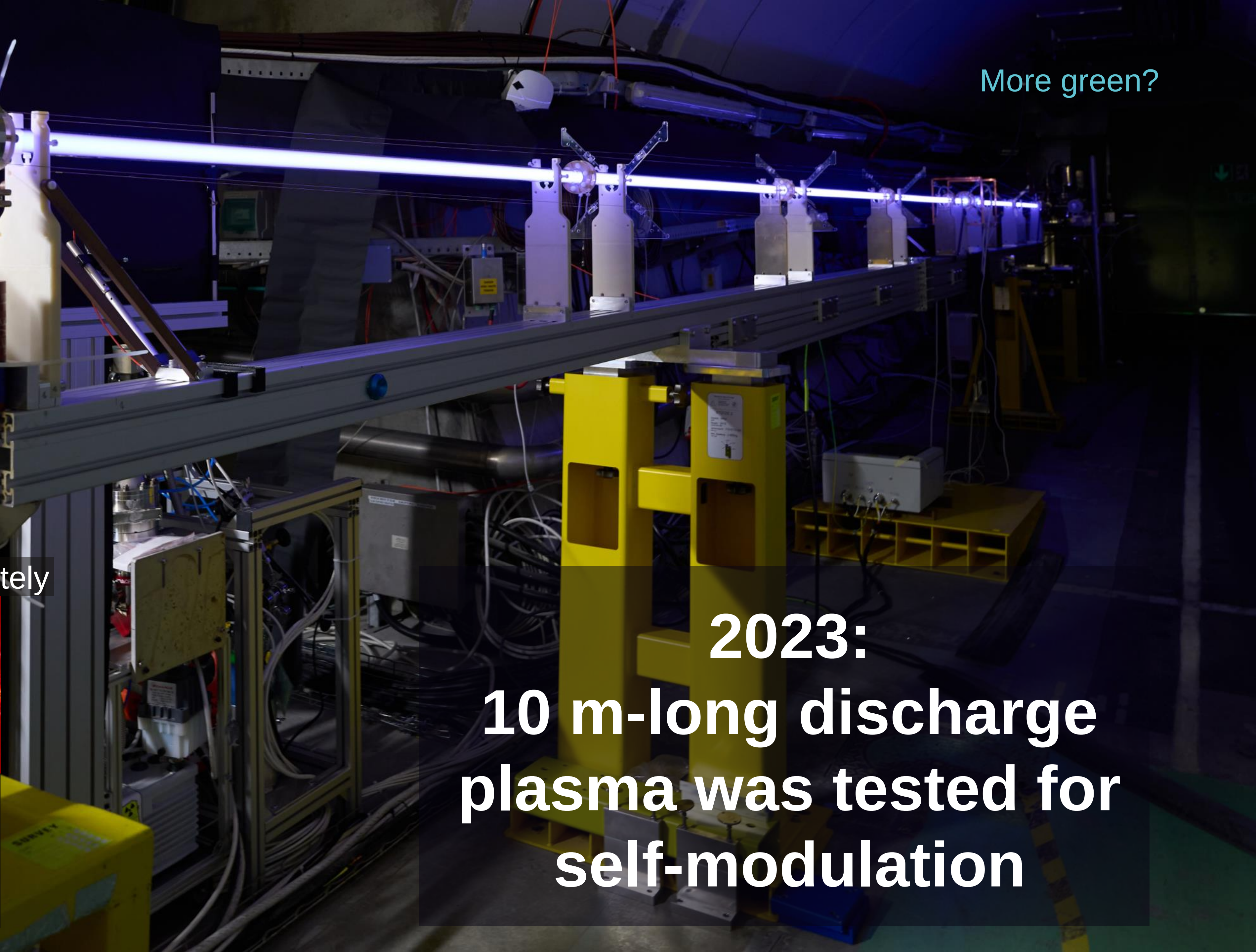
1 m HPS in 169 lab, Ar 8 Pa, 3x10 kW RF/400 A DC

DPS lab (launched in 2021)



Already demonstrated:
→ Density ~10^{15} cm^{-3}

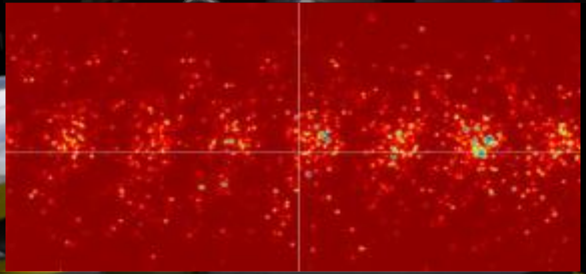
To be demonstrated:
→ uniformity (+measurement)
→ tunability



More green?

2023: 10 m-long discharge plasma was tested for self-modulation

SM was observed immediately

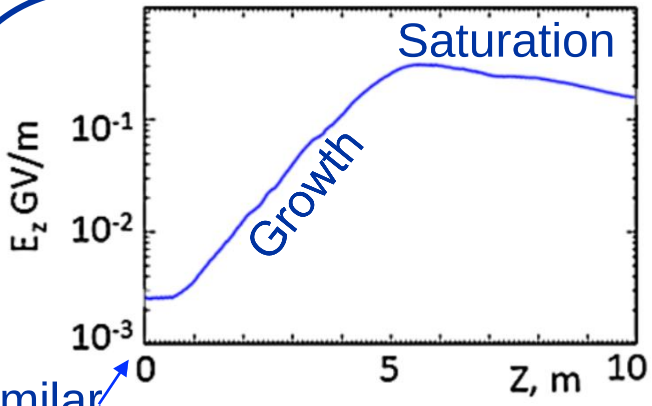


Studies of source performance by C. Amoedo, N. Torrado, N. Lopes, A. Sublet

Physics Studies enabled by the DPS

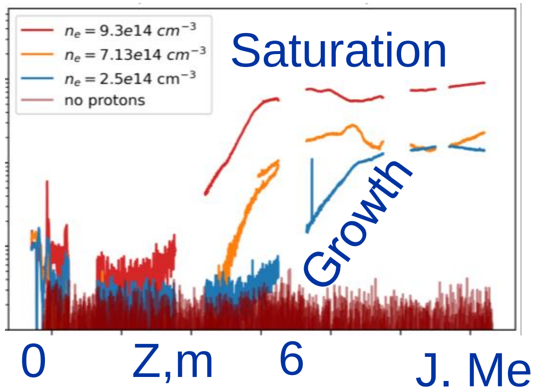
Preliminary

Plasma Light



similar features

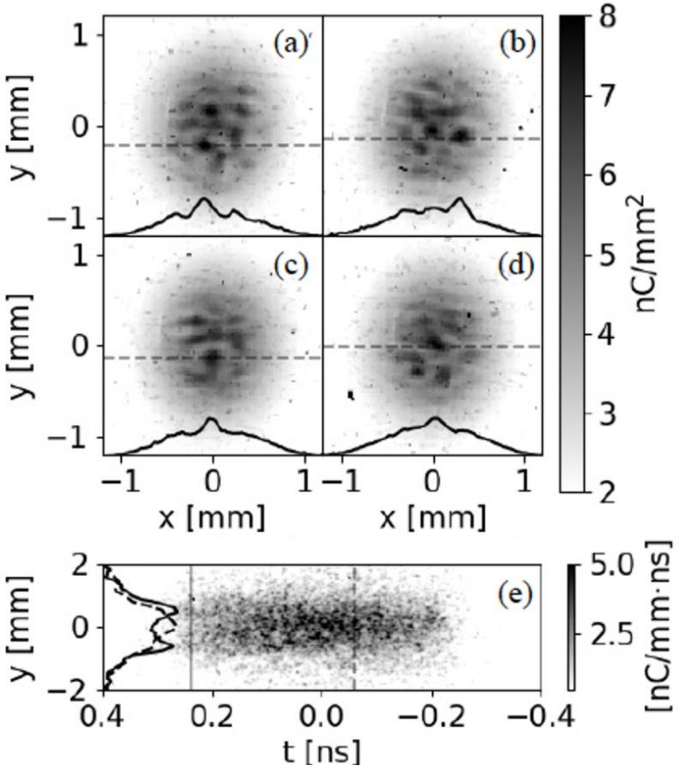
Pukhov, PRL 107 145003 (2011)



J. Mezger

→ Monitoring of plasma light allowed insight into wakefield growth due to SMI

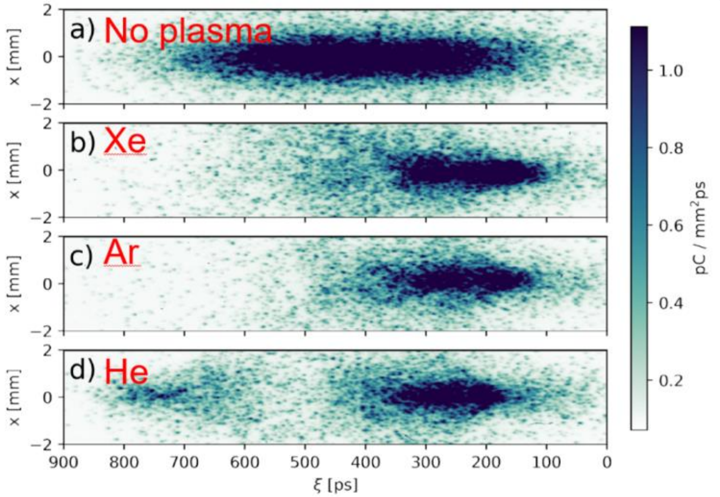
Filamentation Instability

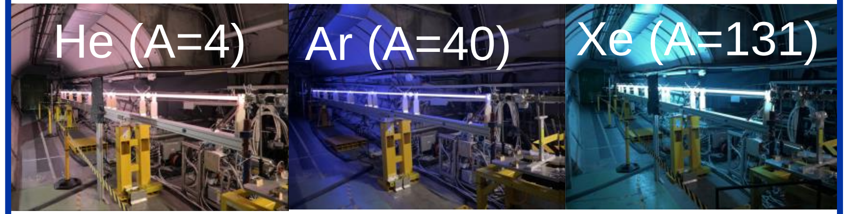


→ Wide plasma allowed to study the filamentation instability

L. Verra et al., Submitted to PRE

Ion Motion



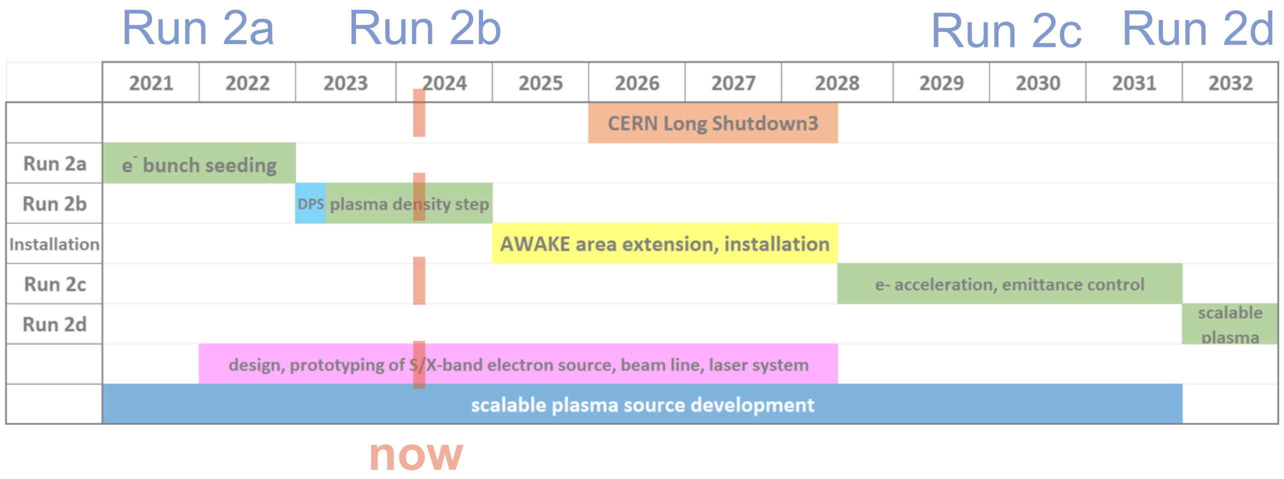


→ Flexibility in plasma ion species allowed to study the effect of ion motion on wakefields

M. Turner et al., in preparation for PRL

AWAKE has a clear timeline towards an accelerator

2016-2018:
Run 1
Proof-of-principle



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
						CERN Long Shutdown3						
Run 2a	e^- bunch seeding											
Run 2b			DPS plasma density step									
Installation					AWAKE area extension, installation							
Run 2c									e- acceleration, emittance control			
Run 2d												scalable plasma
		design, prototyping of S/X-band electron source, beam line, laser system										
	scalable plasma source development											

2033 +:
Particle Physics Applications

Run 2 Milestones:

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

now **Run 2b – Stabilization:** maintain large wakefield amplitude over long plasma distances by introducing a step in the plasma density

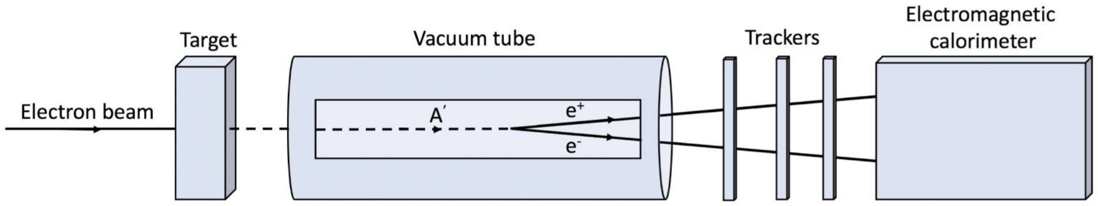
- **Run 2c - Quality Acceleration:** demonstrate acceleration and emittance control of externally injected electron bunch.
- **Run 2d – Scalability:** development of scalable plasma sources to 10s-100s meters length with sub-% level plasma density uniformity.

→ **Propose first applications for particle physics experiments with 50-200 GeV electron bunches**

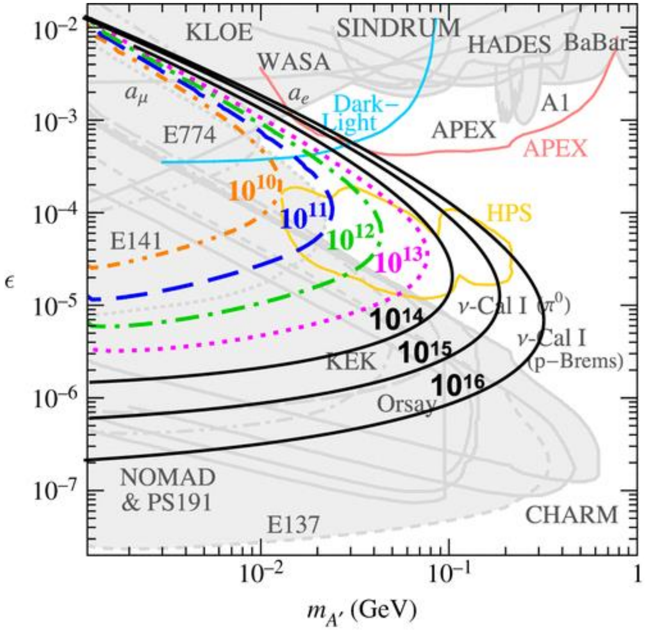
Possible applications to particle physics

Once Run 2 completed, AWAKE will be in a position to start with first particle physics applications

- 50-200 GeV e-, using SPS p^+ bunch as driver:
  - Fixed target, beam-dump experiments: search for dark photons
  - Nonlinear QED: e^-/photon collisions
  - …



M. Wing, Phil. Trans. Royal Soc 377,20180185 (2019)
AWAKE collaboration, Symmetry 2022, 14(8), 1680



A. Caldwell and M. Wing, The European Physical Journal C76, (2016)

- TeV e-, using LHC p^+ bunch as driver:
  - High energy ep or eA collider
    - QCD, structure of matter

- Luminosity of collider applications limited by single use of low rep-rate p^+ bunch production.

AWAKE addresses questions relevant for all plasma-based concepts

Development/study of the external injection scheme important for the entire community

- Required for any plasma wakefield accelerator with tailored witness bunches
- Required for staging

Study of handling/overlapping/timing/coupling of multiple beams and bunches with plasma

- Important for any wakefield accelerator

Develop plasma sources with tunable and repeatable parameters

- Important for quality acceleration to high energies

General physics studies

- Hosing, Ion Motion, Filamentation Instability,…

AWAKE external review results

CERN management requested an external review on the scientific and technical challenges of AWAKE run 2

The work is very synergistic with CERN's plans to ramp-up efforts on FCCee, as experts on electron acceleration trained on AWAKE, can definitely contribute to the success of any future CERN project involving electron accelerators.

Charge Question: 'Assess the feasibility and coherence of the full AWAKE Run 2 roadmap'
→ Response: …the Run 2 program has identified all the key challenges that the AWAKE program will need to meet to enable future particle physics experiments...

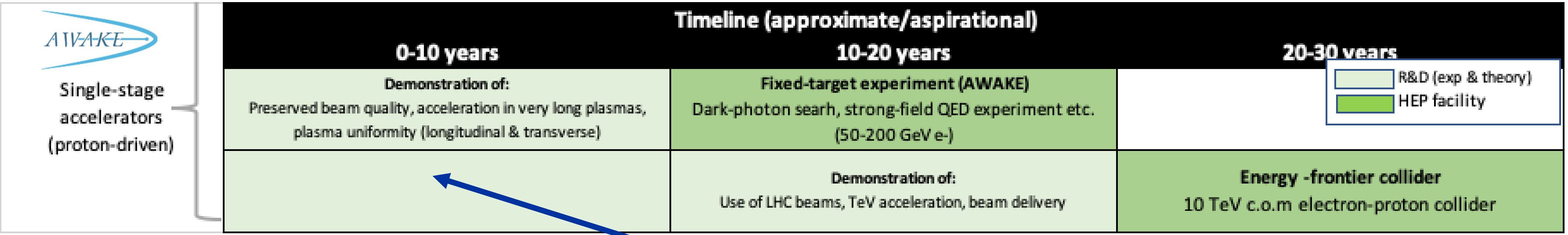
Charge Question: "Evaluate the scientific merits of the accelerator physics and technological advancements expected from the AWAKE Run 2c and 2d programmes, their complementarity with other ongoing initiatives, and their impact on the overall PWFA field"
→…results obtained will benefit the AWAKE program as well as being of significant interest. to the entire field…
→ …Other plasma accelerator concepts for particle physics, such as HALHF and multi-TeV collider concepts, will benefit from outputs of the AWAKE program, such as the development of multi-meter plasma stages…

→ The committee strongly endorses AWAKE's plan

ESPP roadmap

Advanced accelerator community

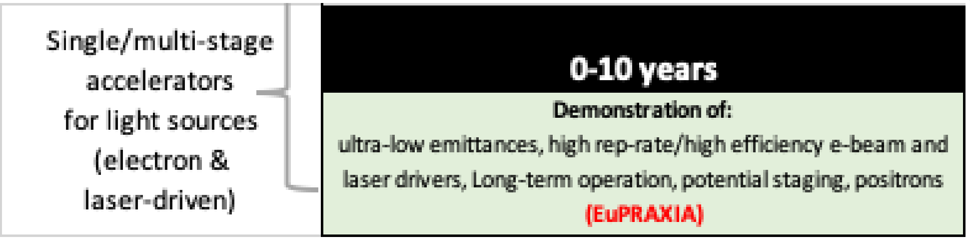
R. Pattathil,
presented at EAAC 2023



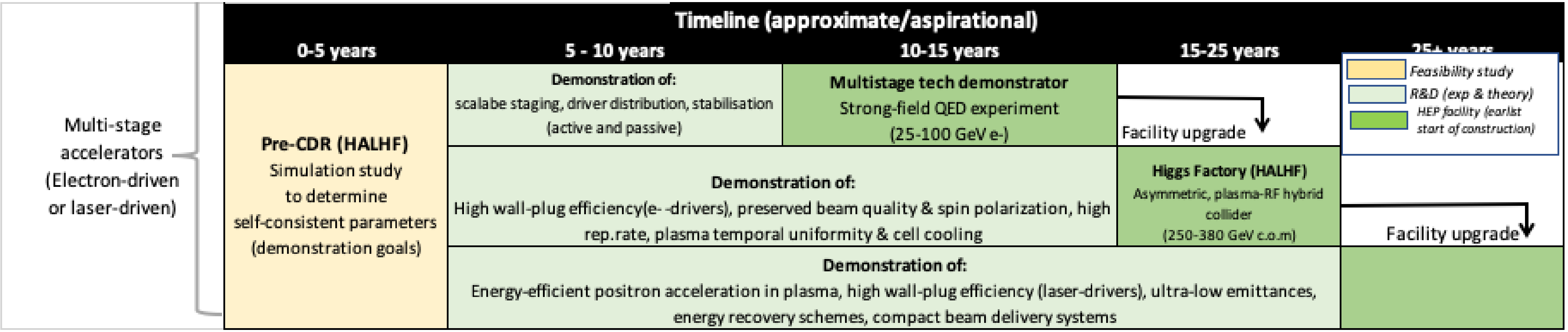
	Timeline (approximate/aspirational) 0-10 years	10-20 years	20-30 years
Single-stage accelerators (proton-driven)	**Demonstration of:** Preserved beam quality, acceleration in very long plasmas, plasma uniformity (longitudinal & transverse)	**Fixed-target experiment (AWAKE)** Dark-photon searh, strong-field 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

🟩 R&D (exp & theory)
🟩 HEP facility

AWAKE aims for particle physics applications and is therefore part of the ESPP process



	0-10 years
Single/multi-stage accelerators for light sources (electron & laser-driven)	**Demonstration of:** ultra-low emittances, high rep-rate/high efficiency e-beam and laser drivers, Long-term operation, potential staging, positrons **(EuPRAXIA)**



	Timeline (approximate/aspirational) 0-5 years	5 - 10 years	10-15 years	15-25 years	25+ years
Multi-stage accelerators (Electron-driven or laser-driven)	**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			

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

Summary & conclusions

- AWAKE demonstrates physics concepts required for **resonant excitation** (self-modulation, etc..) and of **general interest** to the wakefield community (external injection, physics studies,…)

- AWAKE has a **clear timeline** towards an accelerator:
  - Self-modulator expected to be demonstrated end of 2024
  - Acceleration of a beam with quality ~ 2030
  - Demonstration of scalability of the concept for acceleration before 2032
    - R&D on plasma sources development ongoing since 2019
  - R&D program finished in the early 2030's → concept ready for **first particle physics applications**

- AWAKE aims to serve particle physics applications and is therefore **well-integrated** in the ESPP process
  - Recent 'External Review' on the Scientific and Technical Challenges of AWAKE Run 2 underlines importance of AWAKE efforts for the community