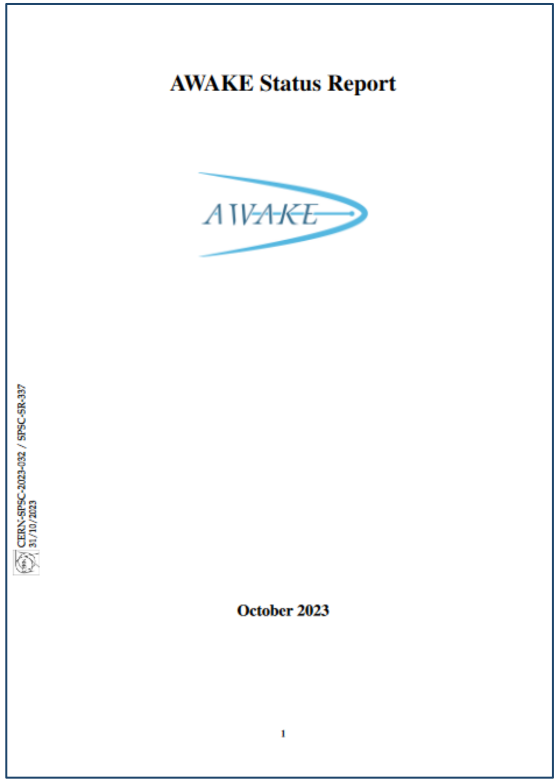
Status and Plans for the AWAKE Experiment

M. Turner for the AWAKE collaboration


AWAKE Status Report

CERN-SPSC-2023-032 / SPSC-SR-337
31/10/2023

October 2023

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AWAKE Collaboration: 23 Institutes World-Wide

- University of Oslo, Oslo, Norway
- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Oxford University, UK
- Max Planck Institute for Physics, Munich, Germany
- Max Planck Institute for Plasma Physics, Greifswald, Germany
- UCL, London, UK
- UNIST, Ulsan, Republic of Korea
- Philipps-Universität Marburg, Marburg, Germany
- Heinrich-Heine-Universität of Düsseldorf, Düsseldorf, Germany
- University of Liverpool, Liverpool, UK
- ISCTE – Instituto Universitéario de Lisboa, Lisbon, Portugal
- 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 is a Plasma Wakefield Acceleration Experiment

- Use high amplitude fields sustained in a plasma wave (plasma wakefields) to accelerate electrons (e^-)

- Accelerate to higher energies in shorter distances than with RF cavities

$$eE = m_e \omega_{pe} c \sim 100 \frac{eV}{m} \sqrt{n_{pe}[cm^{-3}]}$$

(Cold plasma wavebreaking field)

i.e.:
~1 GeV/m for a plasma electron density n_{pe} of $10^{14}cm^{-3}$ (AWAKE)

Plasma Wakefield Acceleration

Plasma
Quasi-neutral plasma in which **electrostatic interactions dominate** and charged particles are dense enough to support **collective behaviour**

Drive bunch or pulse
Relativistic **charged particle** bunch/es
or
laser pulse/s

Plasma Wakefield Acceleration

Plasma

Quasi-neutral plasma in which **electrostatic interactions dominate** and charged particles are dense enough to support **collective behaviour**

Drive bunch or pulse

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+ Plasma ion
− Plasma electron

Plasma Wakefield Acceleration

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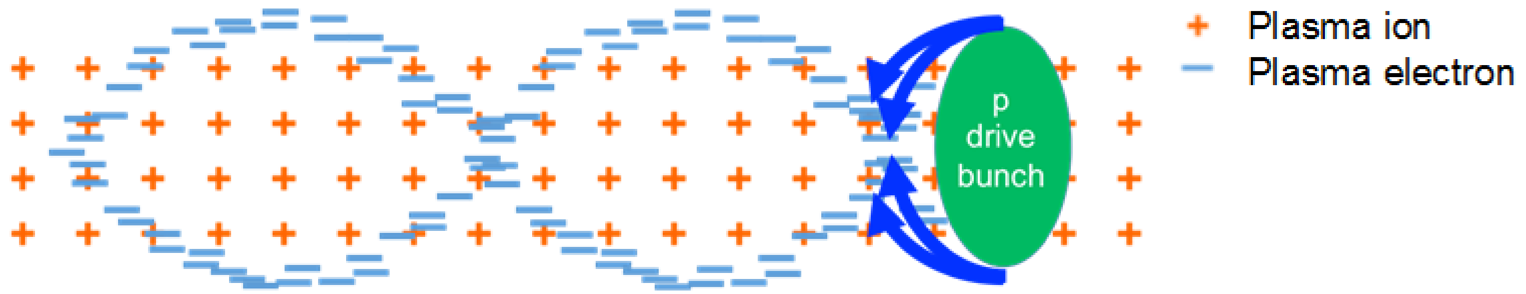

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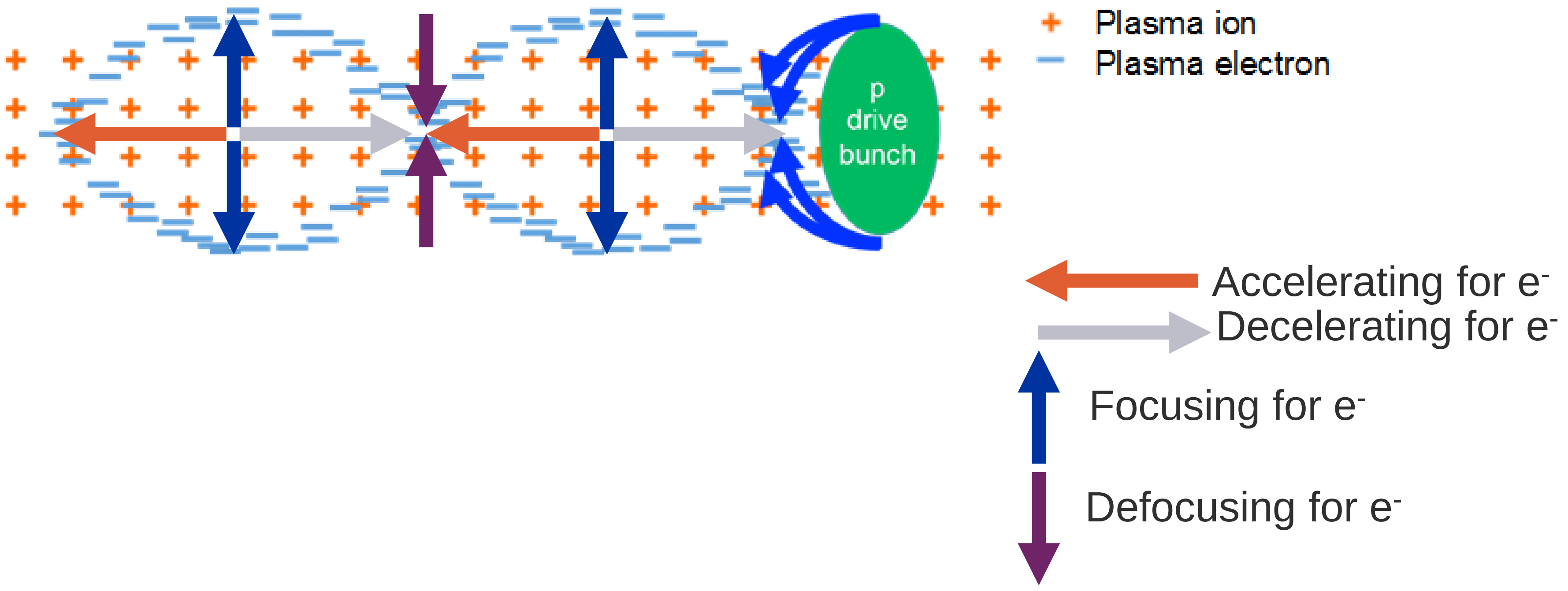

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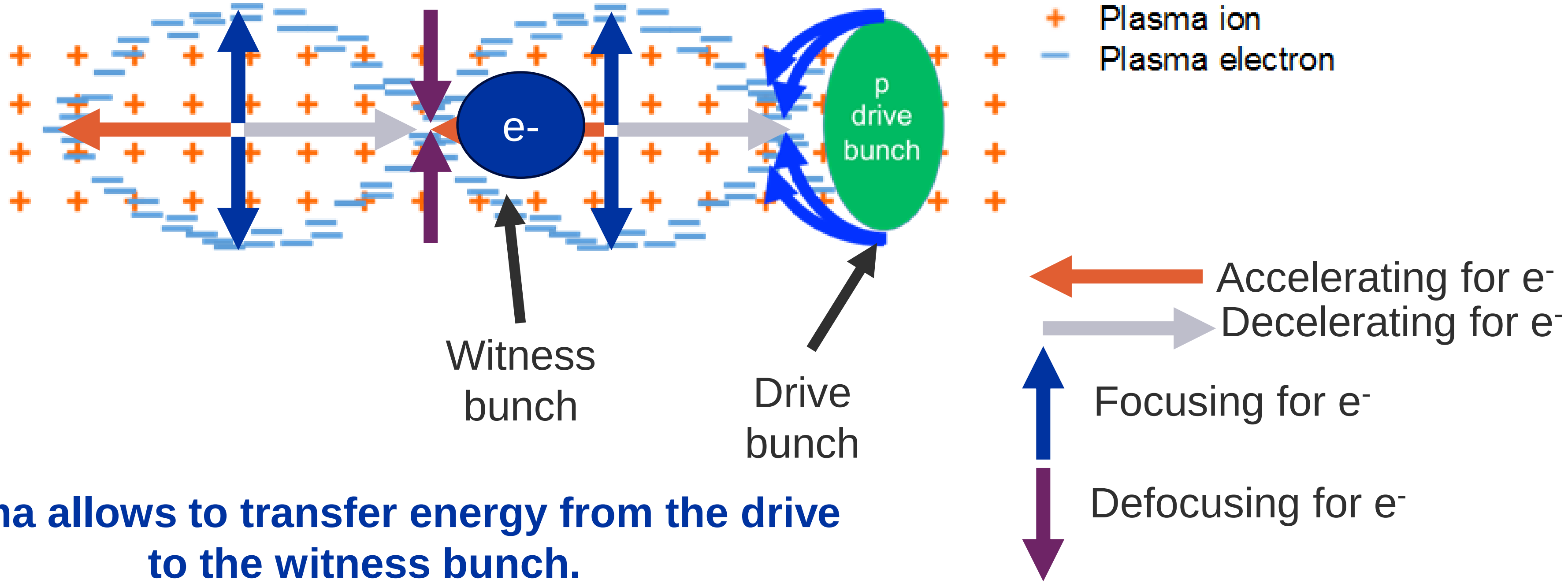
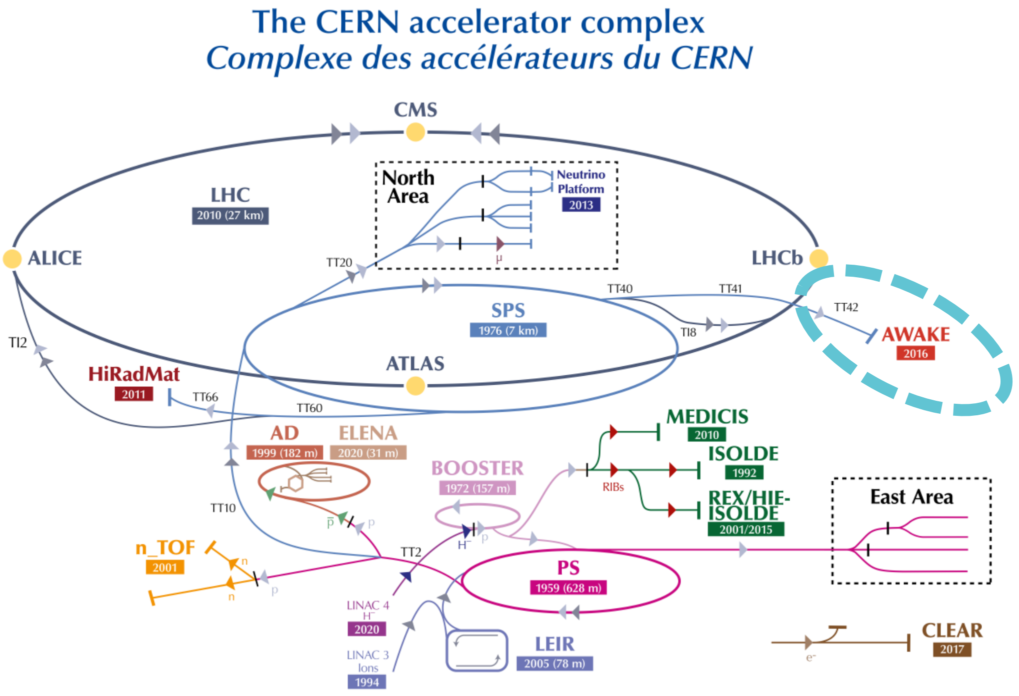


Plasma allows to transfer energy from the drive to the witness bunch.

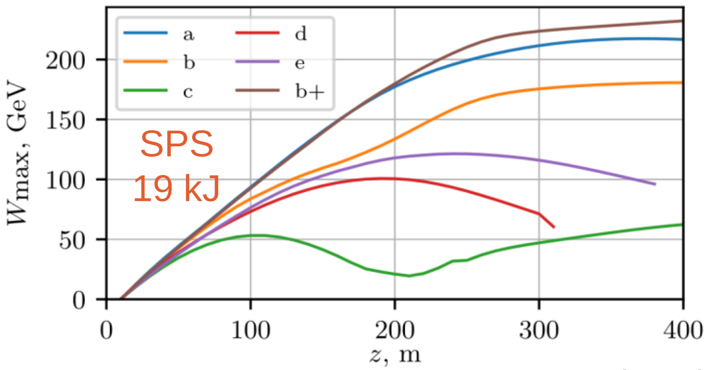
AWAKE is Unique in Using Proton Drivers

- Driving wakefields in plasma with a **proton bunch** (p^+)
  - Highly-relativistic, highly-energetic (hundreds of kJ) bunches are available at CERN
- Accelerating externally-injected electrons (e^-) to GeV (SPS) or TeV (LHC) energy scale



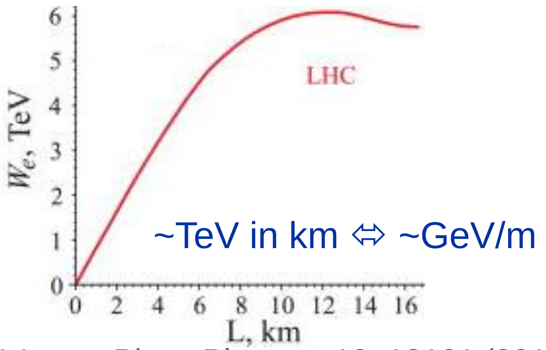
SPS Driver (19 kJ):
~ 200 GeV in ~200 m
~ 10^9 e^-

2D numerical simulation results



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

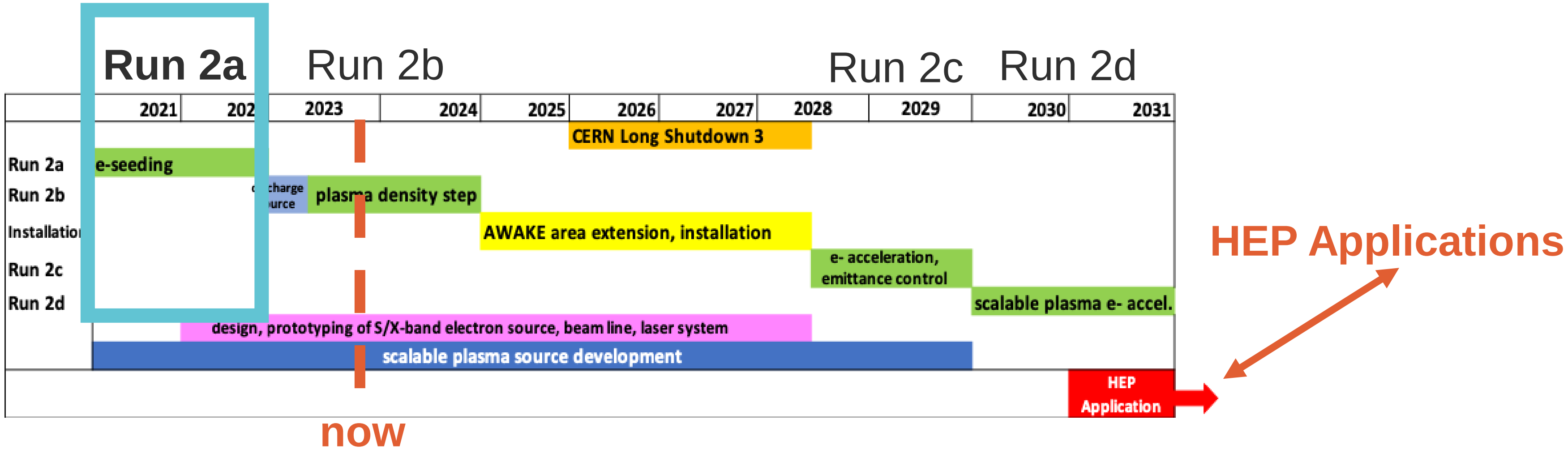
LHC Driver (112 kJ):
~ 5 TeV in ~7 km
~ 10^9 e^-



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

Clear Time Line Towards an Accelerator

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



- **Milestones for AWAKE Run 2: → transition from proof-of-principle to applications**
  - ✔ **Run 2a – Seeding:** Demonstrate the seeding of the self-modulation of the entire proton bunch with an electron bunch

Clear Time Line Towards an Accelerator

(2016-2018)
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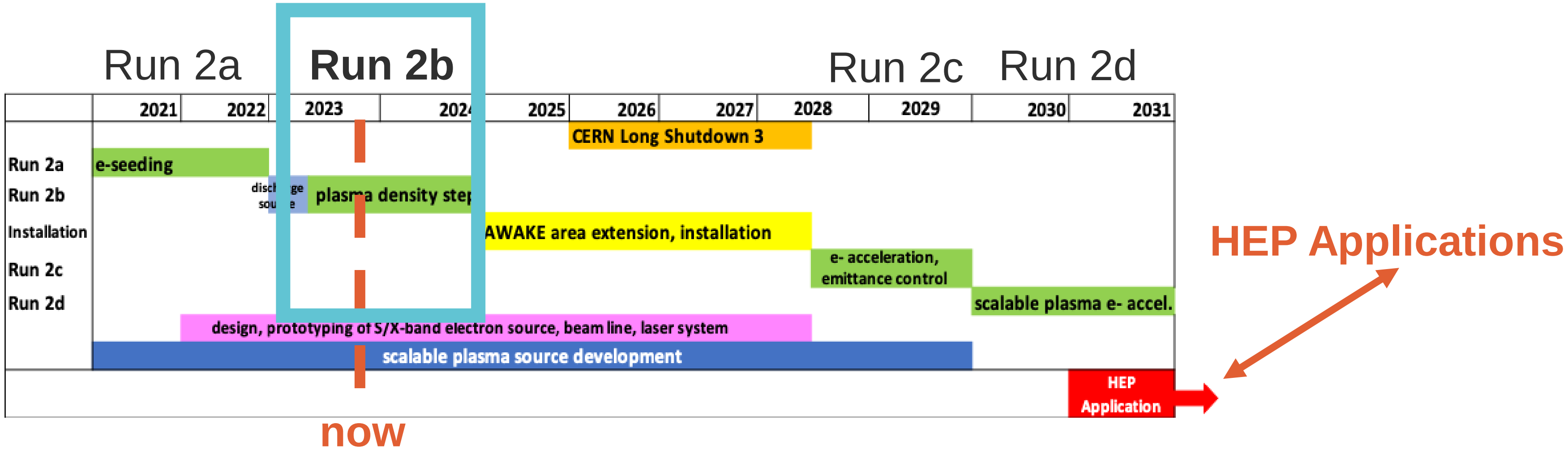
Proof-of-principle

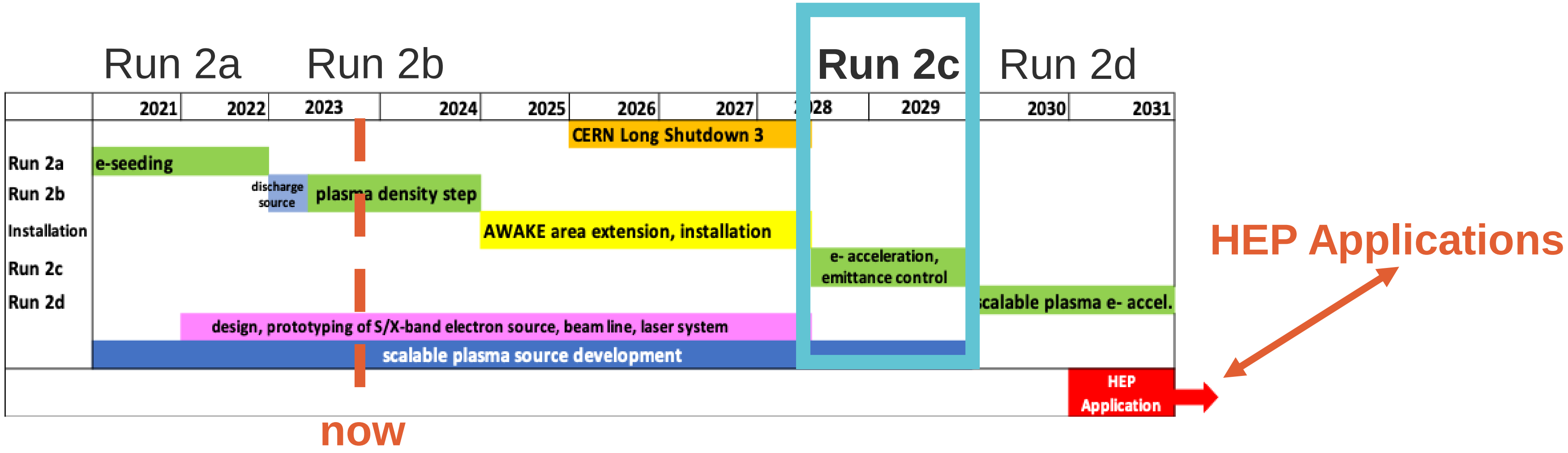


- **Milestones for AWAKE Run 2: → transition from proof-of-principle to applications**

- **Run 2a:** Demonstrate the seeding of the self-modulation of the entire proton bunch with an electron bunch
- now **Run 2b - Stabilization:** Maintain large wakefield amplitudes over long plasma distances by introducing a step in the plasma density

Clear Time Line Towards an Accelerator

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

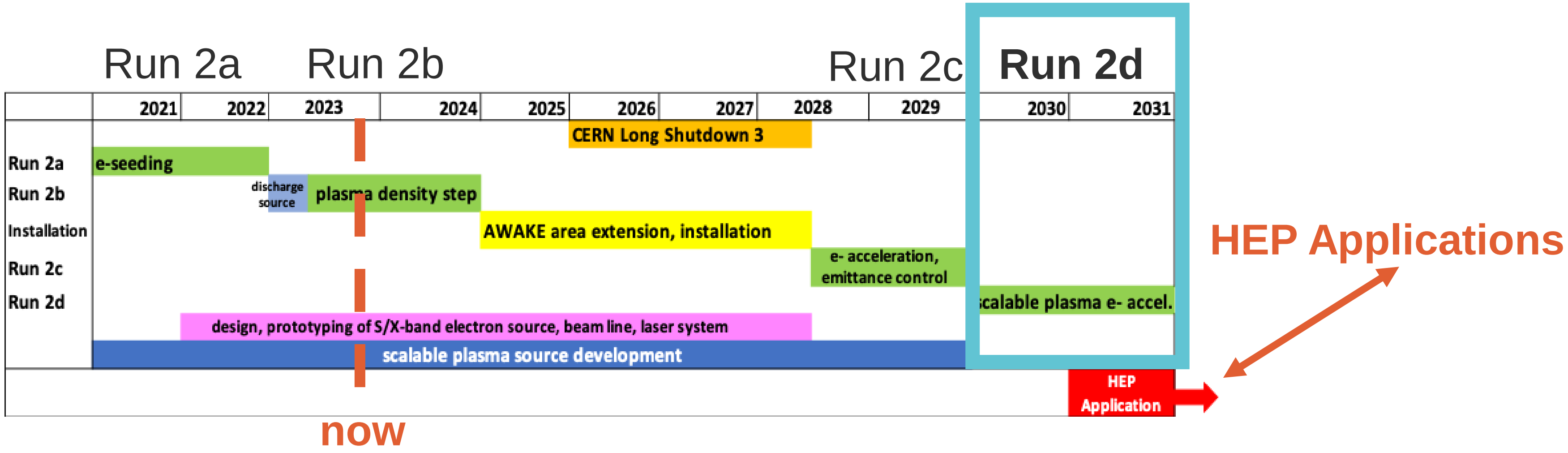


➢ **Milestones for AWAKE Run 2: → transition from proof-of-principle to applications**

- ➢ **Run 2a:** Demonstrate the seeding of the self-modulation of the entire proton bunch with an electron bunch
- ➢ **Run 2b:** Maintain large wakefield amplitudes over long plasma distances by introducing a step in the plasma density
- 2028 ➢ **Run 2c- Quality:** Demonstrate electron acceleration and emittance control of externally injected electrons.

Clear Time Line Towards an Accelerator

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



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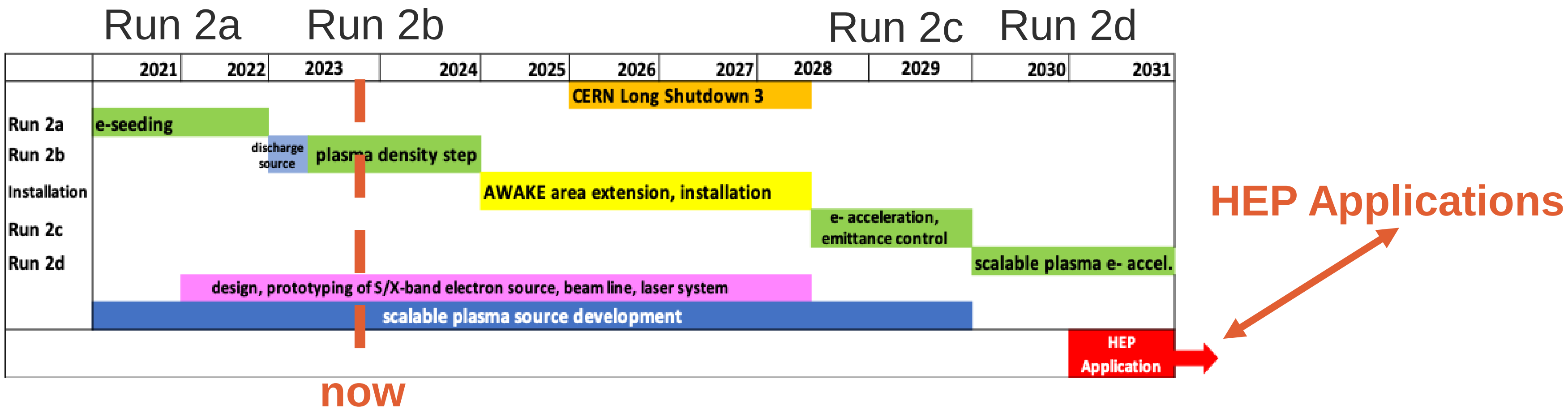
  - **Run 2a:** Demonstrate the seeding of the self-modulation of the entire proton bunch with an electron bunch
  - **Run 2b:** Maintain large wakefield amplitudes over long plasma distances by introducing a step in the plasma density
  - **Run 2c:** Demonstrate electron acceleration and emittance control of externally injected electrons.
  - 2030 **Run 2d - Scalability:** Development of scalable plasma sources to 100s meters length with sub-% level plasma density uniformity.

Clear Time Line Towards an Accelerator

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



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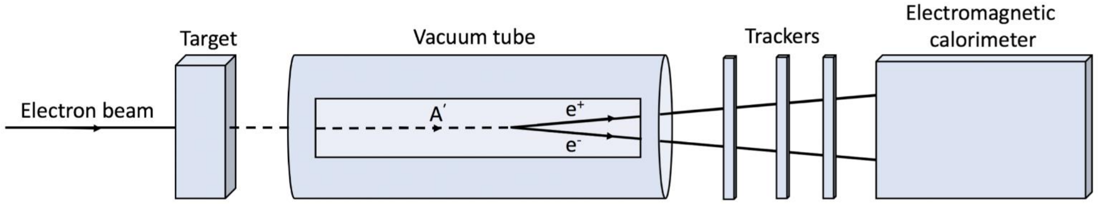
  - ✅ **Run 2a:** demonstrate the seeding of the self-modulation of the entire proton bunch with an electron bunch
  - now **Run 2b:** maintain large wakefield amplitudes over long plasma distances by introducing a step in the plasma density
  - **Run 2c:** demonstrate electron acceleration and emittance control of externally injected electrons.
  - **Run 2d:** development of scalable plasma sources to 100s meters length with sub-% level plasma density uniformity.
  - **Propose first applications for particle physics experiments with 50-200 GeV electron bunches**

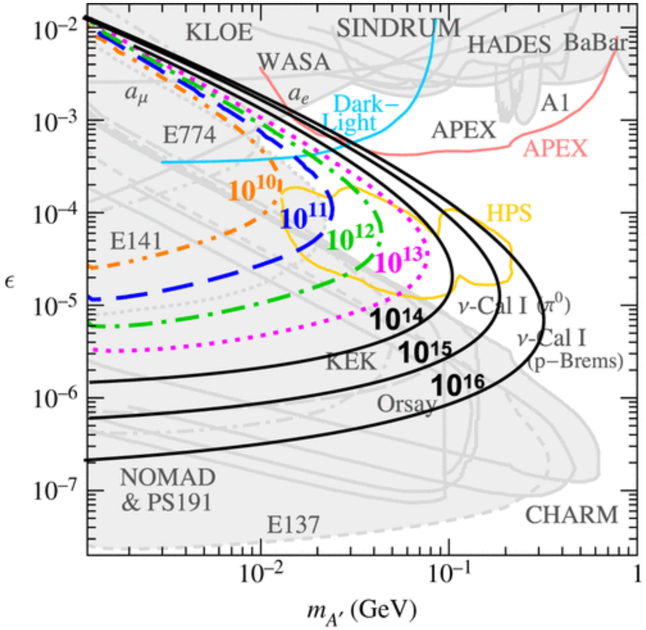
Possible Applications to Particle Physics

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

- 20-200 GeV e-, using SPS p^+ bunch as driver:
  - Fixed target, beam-dump experiments: search for dark photons
  - Nonlinear QED: e^-/photon collisions
  - ep or eA collisions, QCD, structure of matter
  - …

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





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

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

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

ESPP Roadmap

Advanced Accelerator Community

R. Pattathil,
presented at EAAC 2023

AWAKE

	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 is 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)**

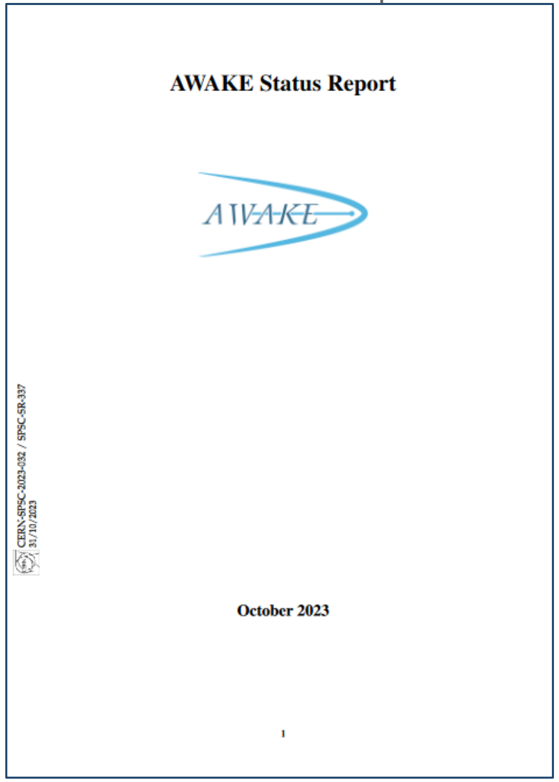
	Timeline (approximate/aspirational)				
	0-5 years	**5 - 10 years**	**10-15 years**	**15-25 years**	**25+ years**
Multi-stage accelerators (Electron-driven or laser-driven)	**Pre-CDR (HALHF)** Simulation study to determine self-consistent parameters (demonstration goals)	**Demonstration of:** scalabe 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)

Outline

- Introduction to AWAKE
- Results from the 2023 experiments (Year 1 of Run 2b)
  - Discharge plasma source
  - New Rb vapor source with plasma density step
- Run plan for 2024 (Year 2 of Run 2b)
  - Beam time request
- Ongoing preparation for Run 2c
- Summary

https://cds.cern.ch/record/2878573/files/SPSC-SR-337.pdf


AWAKE Status Report

AWAKE

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AWAKE Requires Microbunching of p^+ Bunch

To effectively excite wakefields**:**

- The drive bunch length has to be on the order of the plasma wavelength

$$k_{pe}\sigma_z \approx \sqrt{2}$$

For AWAKE → mm-scale bunch length

CERN SPS proton bunch length is ~6 cm

Plasma e^- angular frequency:

$$\omega_{pe} = \left(\frac{n_{e0}e^2}{\epsilon_0 m_e}\right)^{1/2}$$

$$k_{pe} = \omega_{pe}/c$$

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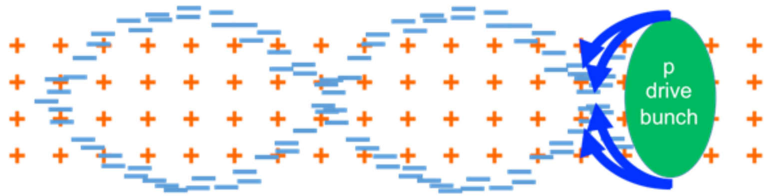
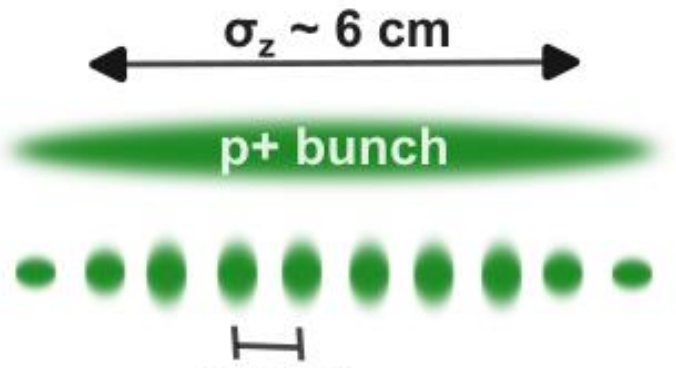


Plasma e^- angular frequency:

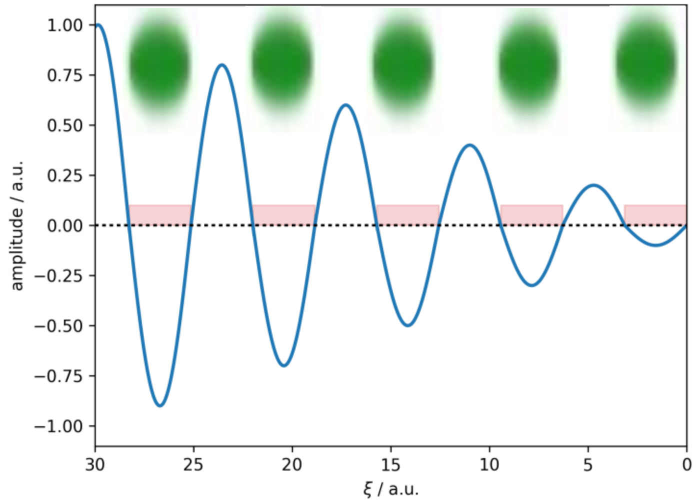
$$\omega_{pe} = \left(\frac{n_{e0}e^2}{\epsilon_0 m_e}\right)^{1/2}$$

$k_{pe} = \omega_{pe}/c$

⇒ Plasma process: Self-Modulation Instability (SMI), can be seeded (SSM)



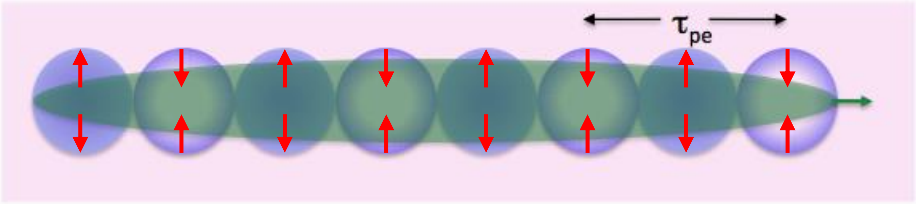
Resonant excitation



- Wakefields driven resonantly to large amplitude
- Self-modulation necessary to drive ~GV/m accelerating fields in 10^{14} cm^{-3} density plasma

Self-Modulation Process

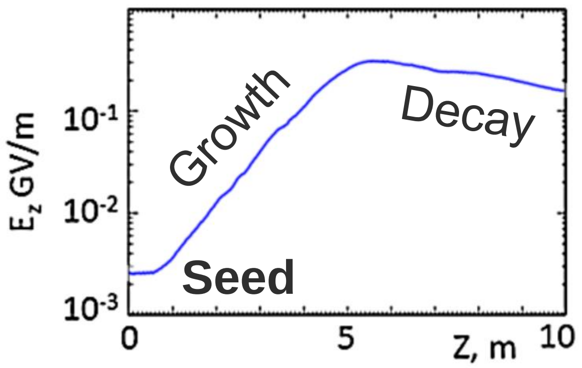
Long driver (p^+), dense plasma,
$\sigma_t >> 1/\omega_{pe}$, $\sigma_r \sim c/\omega_{pe}$



Growth mechanism:

Initial (transverse) wakefields

Saturation



Pukhov, PRL107 145003 (2011)

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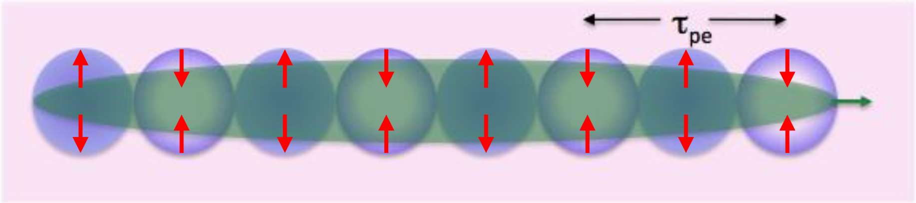
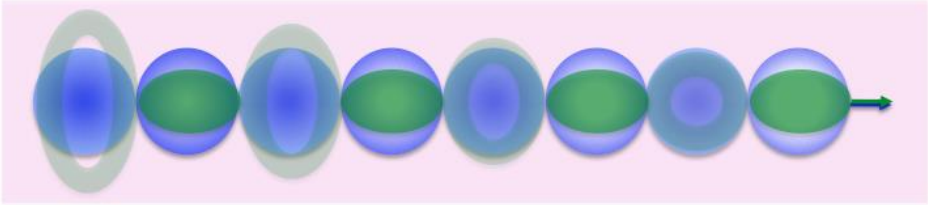


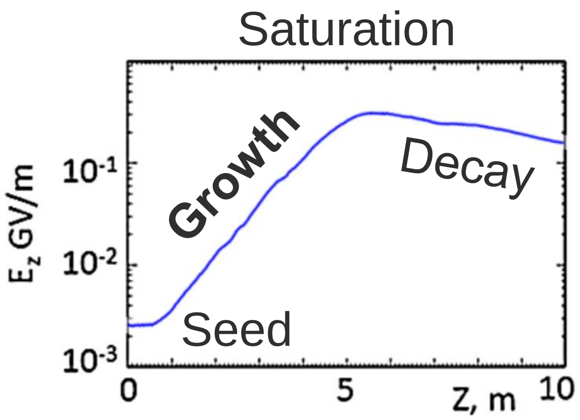
Self-modulation



Growth mechanism:

Initial (transverse) wakefields

Periodic focusing/defocusing



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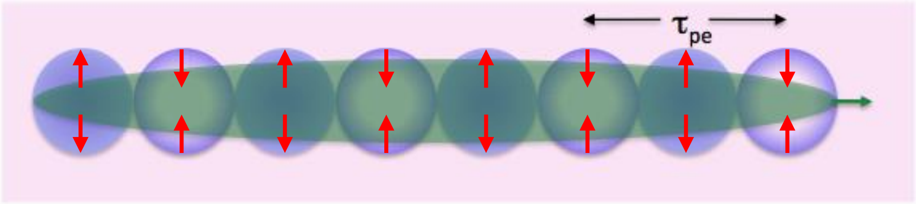
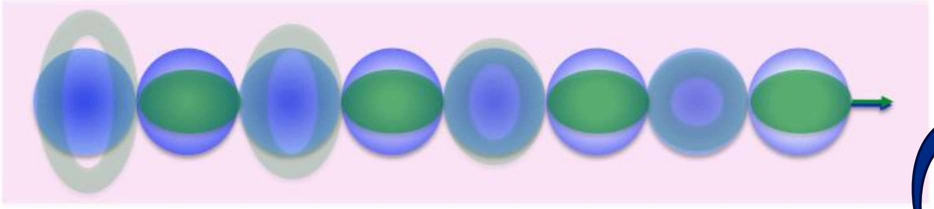
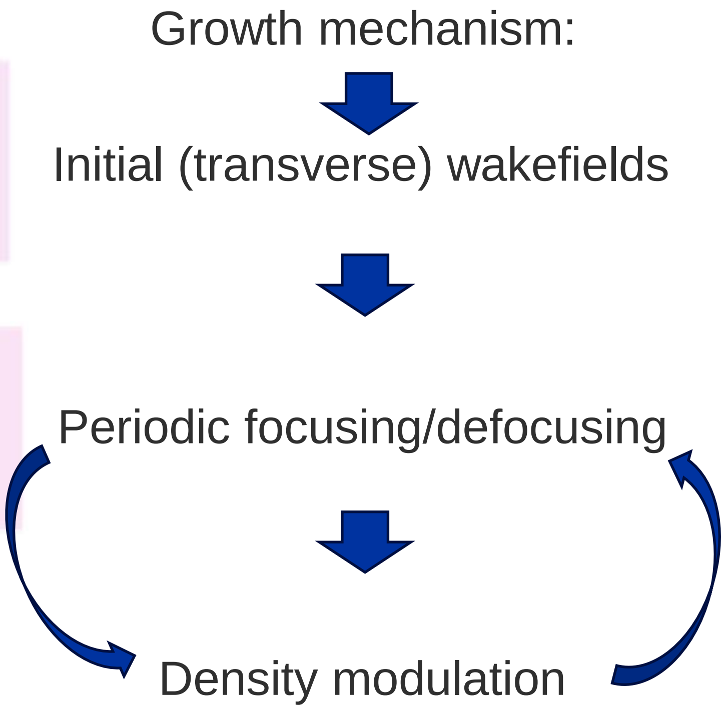
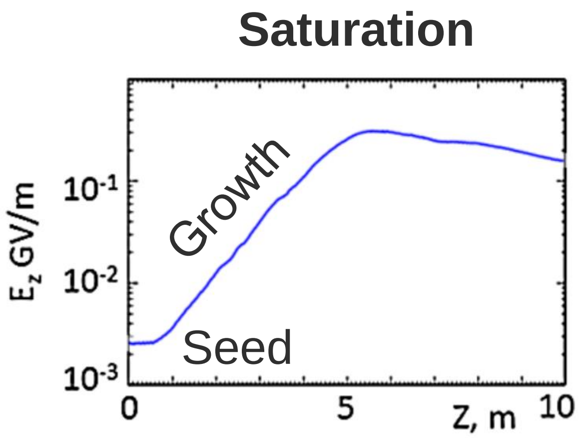


Self-modulation



Self-modulated bunch





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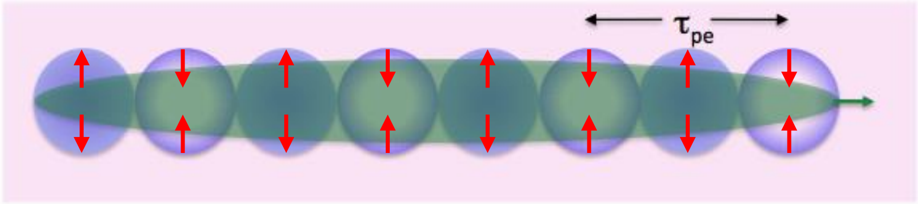
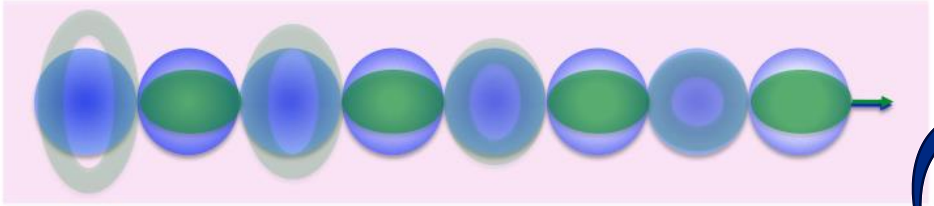
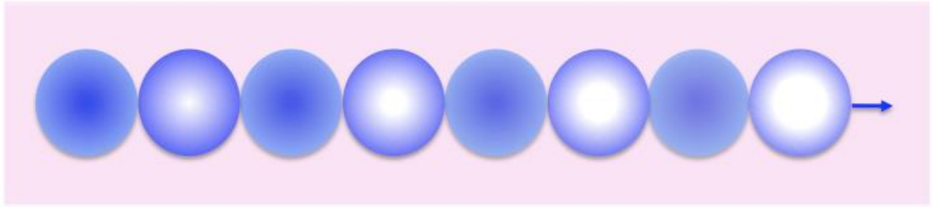


Self-modulation



Self-modulated bunch

Plasma wakefields



Growth mechanism:

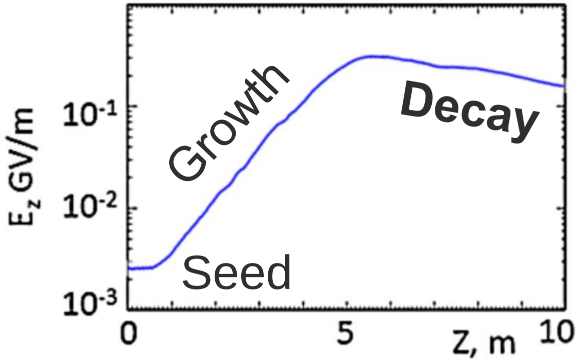
Initial (transverse) wakefields

Periodic focusing/defocusing

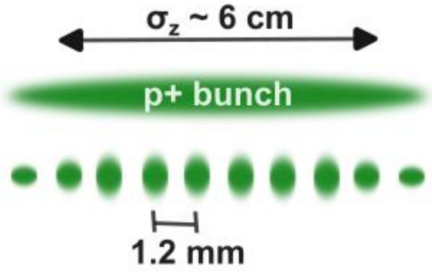
Density modulation

Full modulation – bunch train

Saturation



Pukhov, PRL107 145003 (2011)



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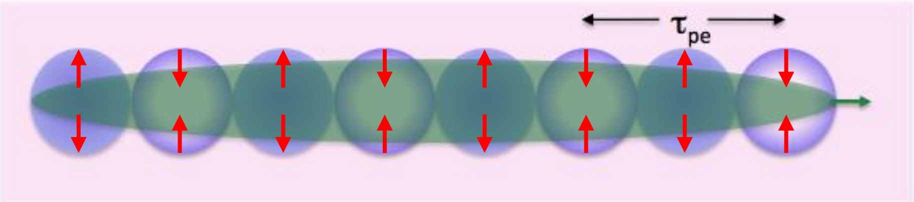
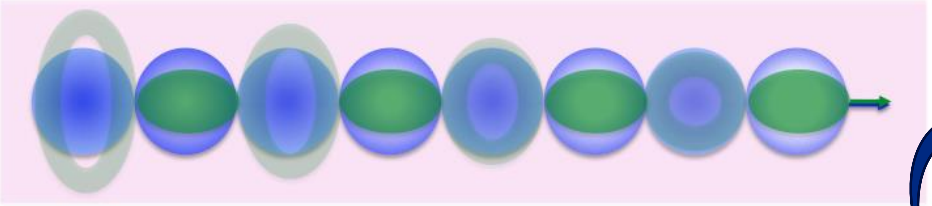
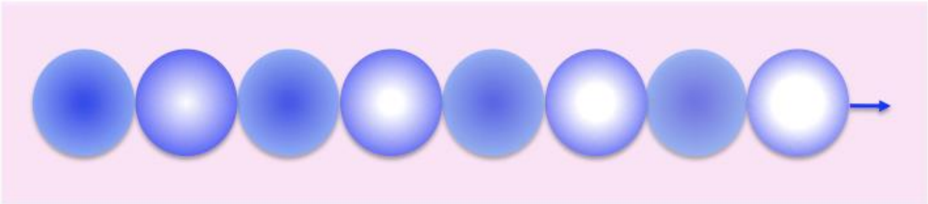


Self-modulation



Self-modulated bunch

Plasma wakefields



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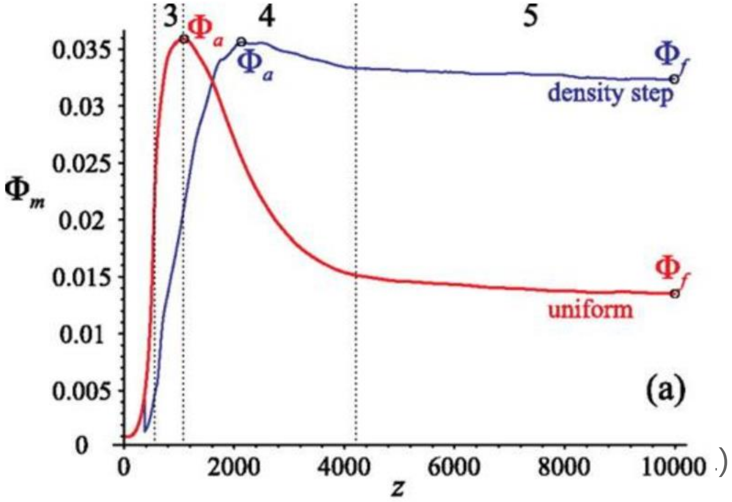

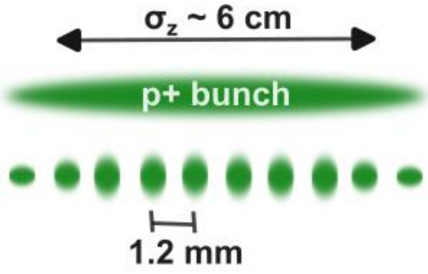

Self-Modulation Process

Long driver (p^+), dense plasma,
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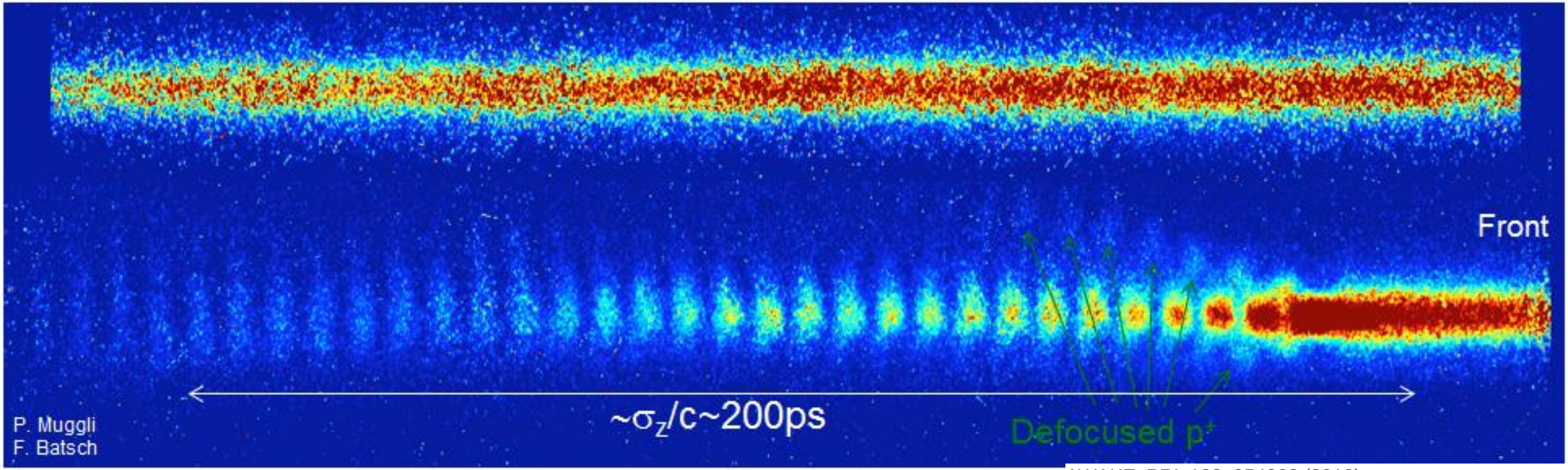
Growth mechanism:

AWAKE Run 1 Result



Full modulation – bunch train

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)

Self-Modulation Process

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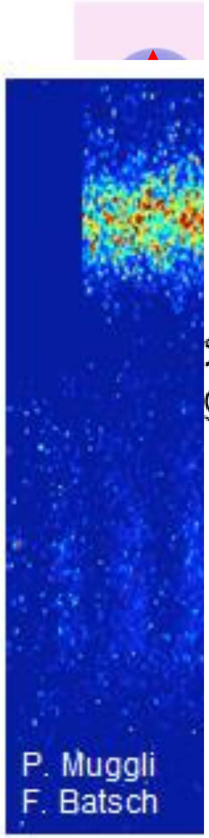
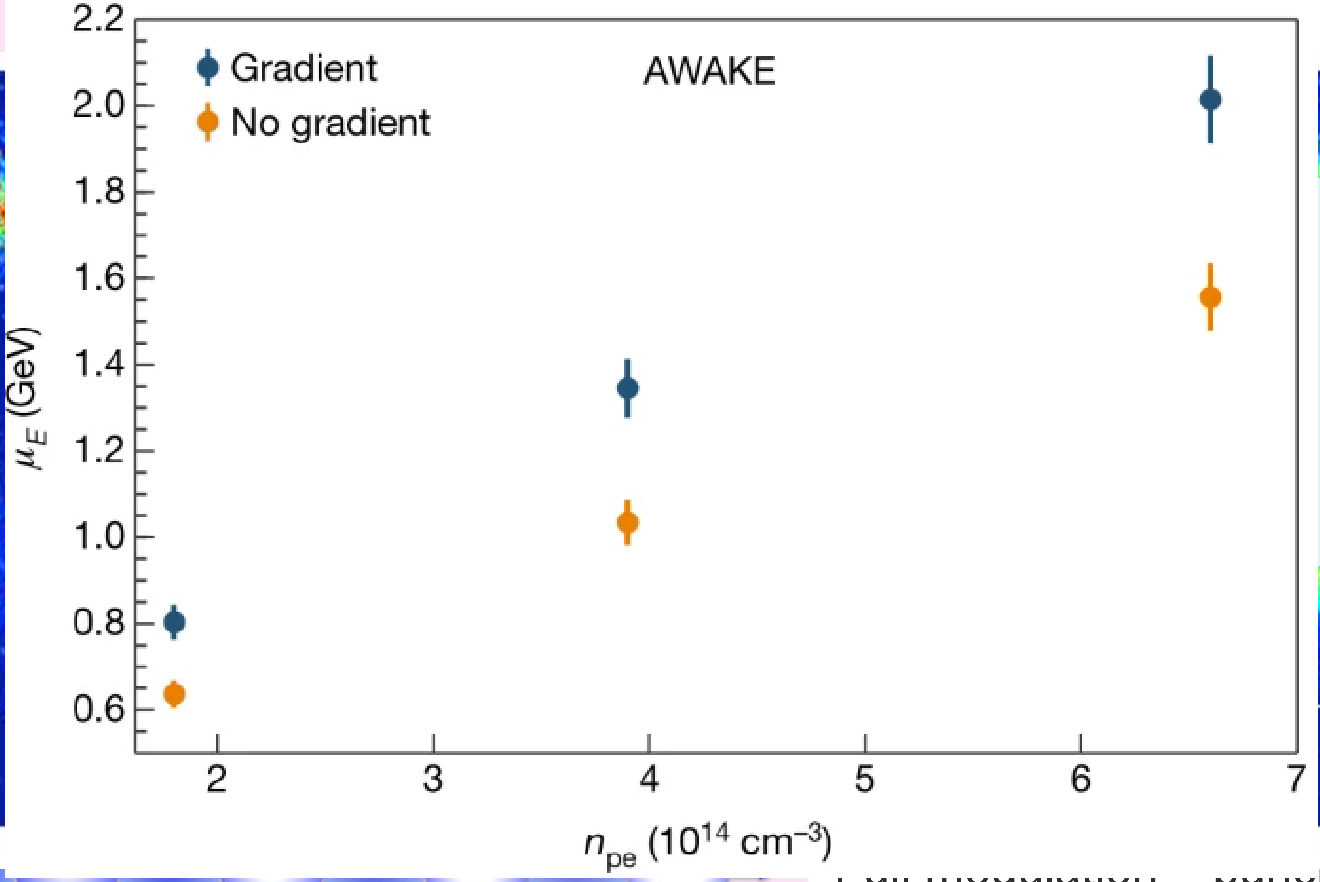
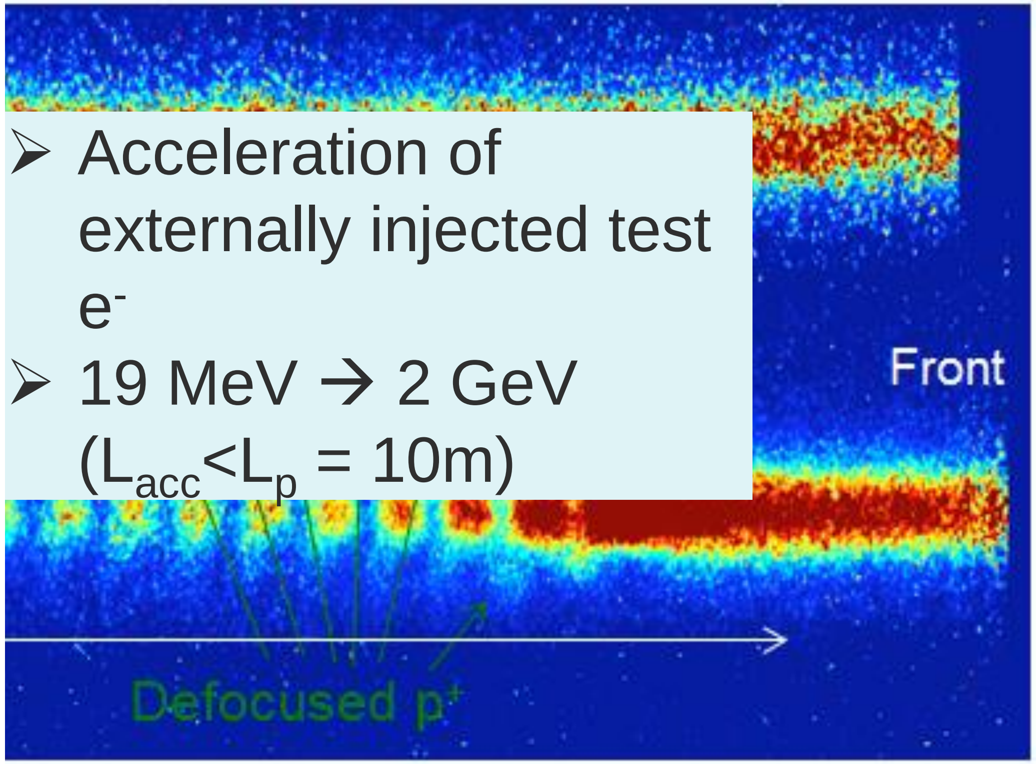
Growth mechanism:

AWAKE Run 1 Result





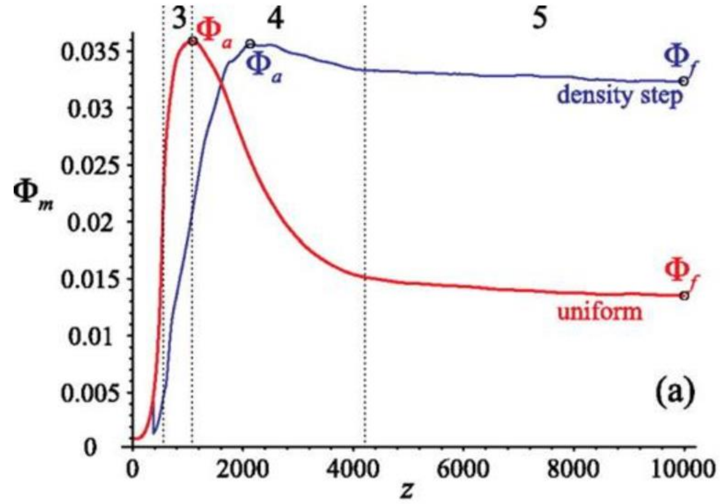


- Acceleration of externally injected test e^-
- 19 MeV → 2 GeV ($L_{acc}<L_p$ = 10m)

Run 1:
One, Uniform, 10m long Rb Plasma

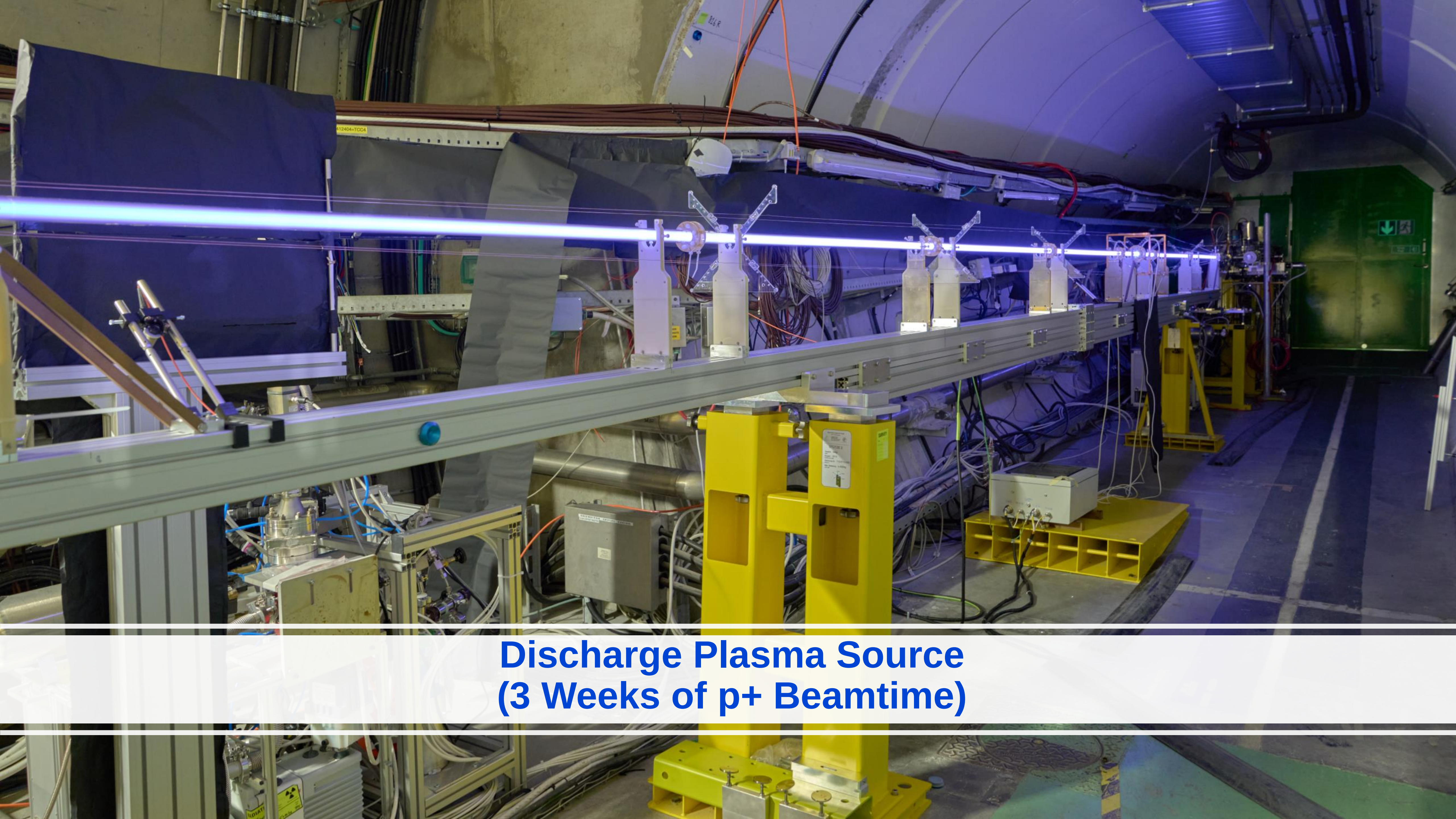
- **Next: Two plasmas for bunch quality (Run 2c)**
  - Separate Self-Modulator and Accelerator, inject on axis with dense beam that is matched

- **Next: Density step for high average amplitude (Run 2b)**
  - Plasma source that allows for density step



Results from the 2023 Experiments

(Year 1 of Run 2b)



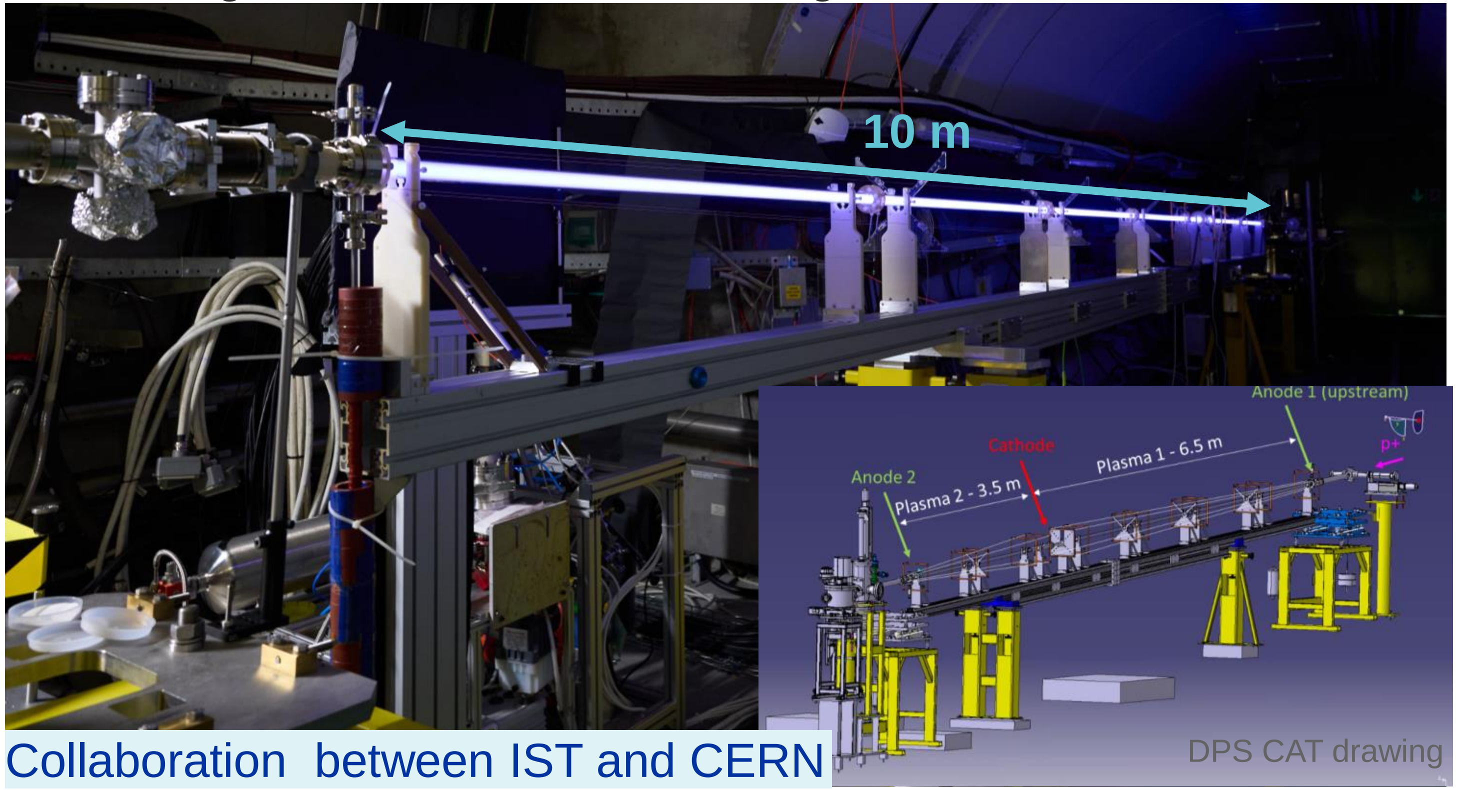
Discharge Plasma Source
(3 Weeks of p+ Beamtime)

Discharge Plasma Source (DPS)

Candidate for Run 2c,d and particle physics applications → 50-200 m plasma

- **May 2023:** Opportunity to test discharge plasma source (DPS) with protons (unseeded, no electrons)
  - Scalable technology
    → **Long plasma length**
- **Commissioning Goal:**
  - Successful operation
- **Physics Program:**
  - Profit from:
    - Flexibility: variable plasma length, density, gas filling pressure and ion species
    - No beam alignment → wide plasma
    - Glass tube allowed for plasma light imaging with cameras

Gas-filled glass tube + electric discharge

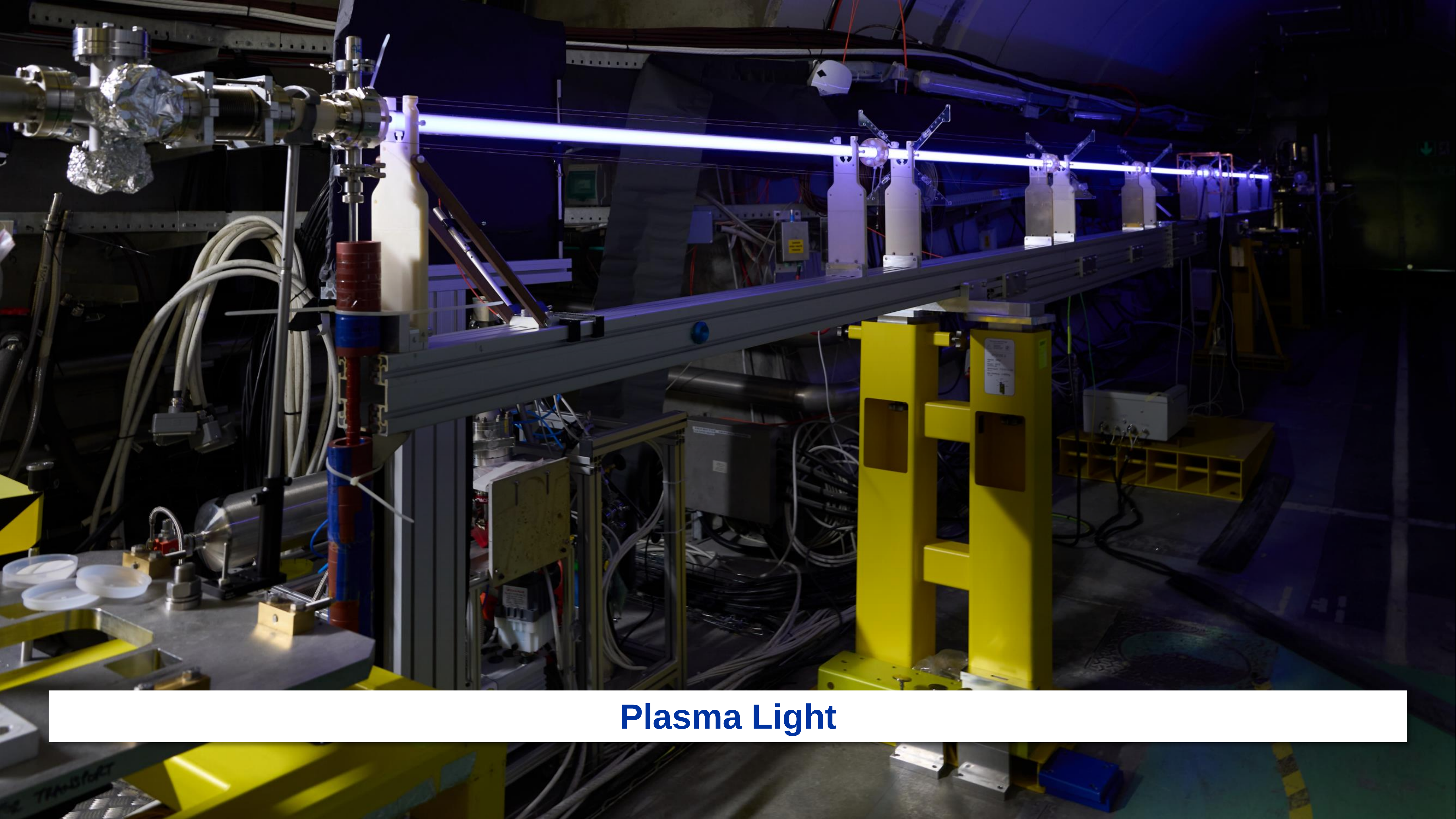


DPS CAT drawing

Collaboration between IST and CERN

Photograph of DPS installed in the AWAKE tunnel

→ Observed successful proton bunch self-modulation

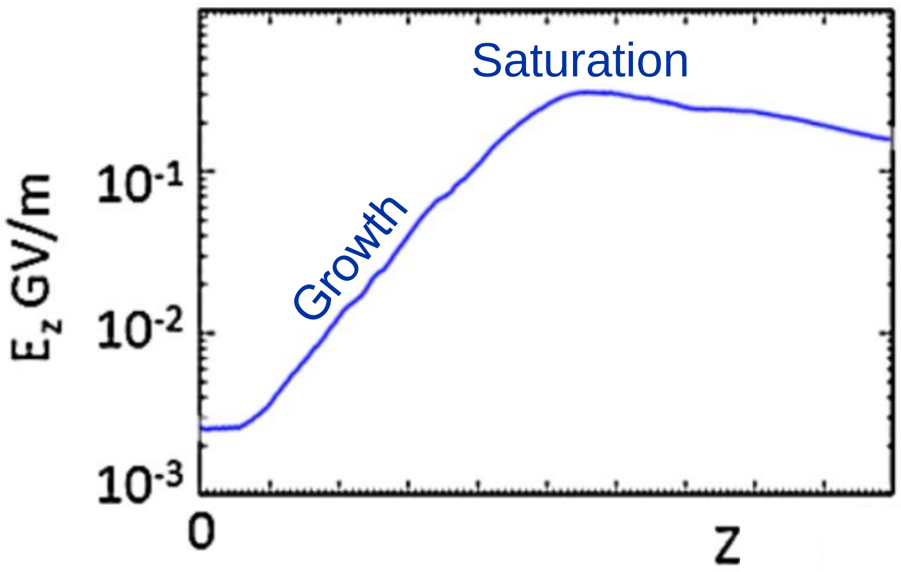


Plasma Light

DPS Physics Studies
Plasma Light

Expectation

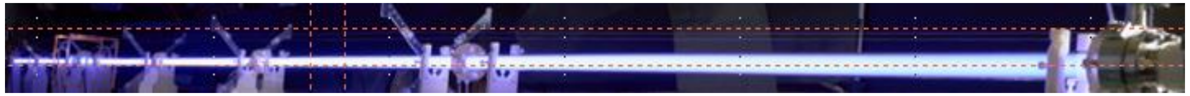
Wakefield amplitude growth along the plasma as self-modulation develops



Pukhov, PRL107 145003 (2011)

DPS Physics Studies

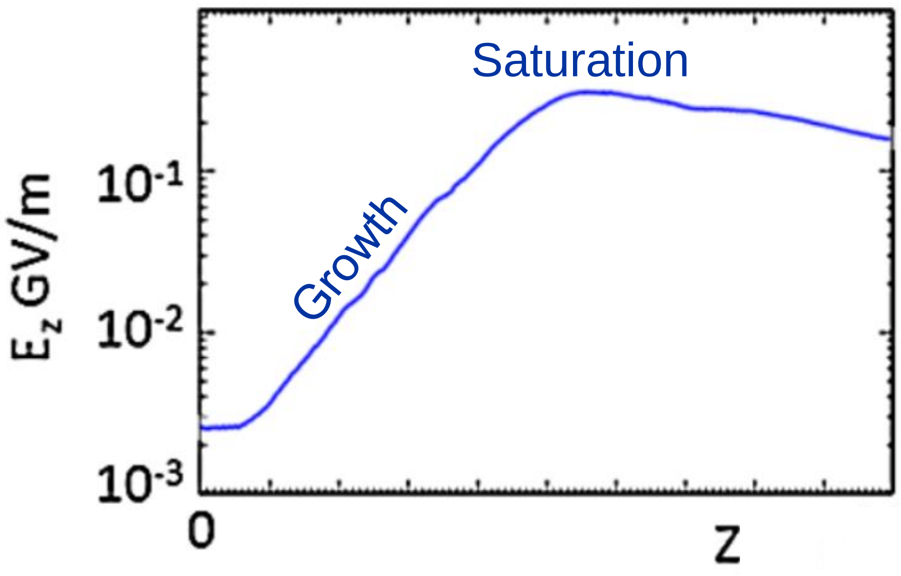
Plasma Light



- Plasma light from discharge + additional light from energy deposited by protons driving wakefields
- **Idea:** Additional light is proportional to wakefield amplitude

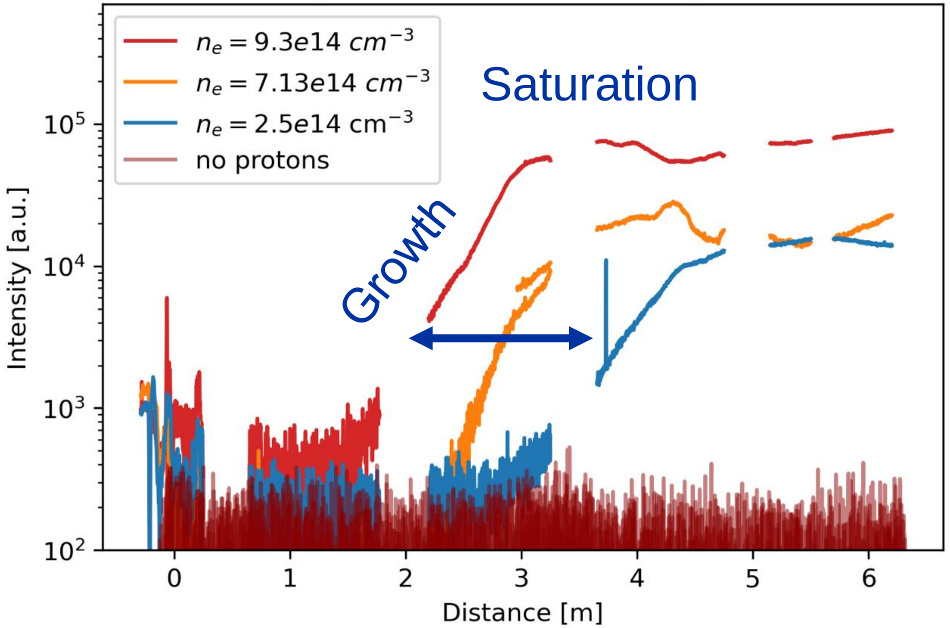
Expectation

Wakefield amplitude growth along the plasma as self-modulation develops



Pukhov, PRL107 145003 (2011)

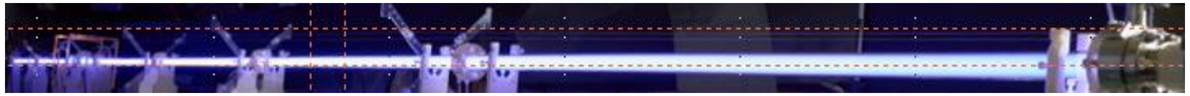
J. Mezger, MPP



→ Earlier onset of growth for higher plasma density

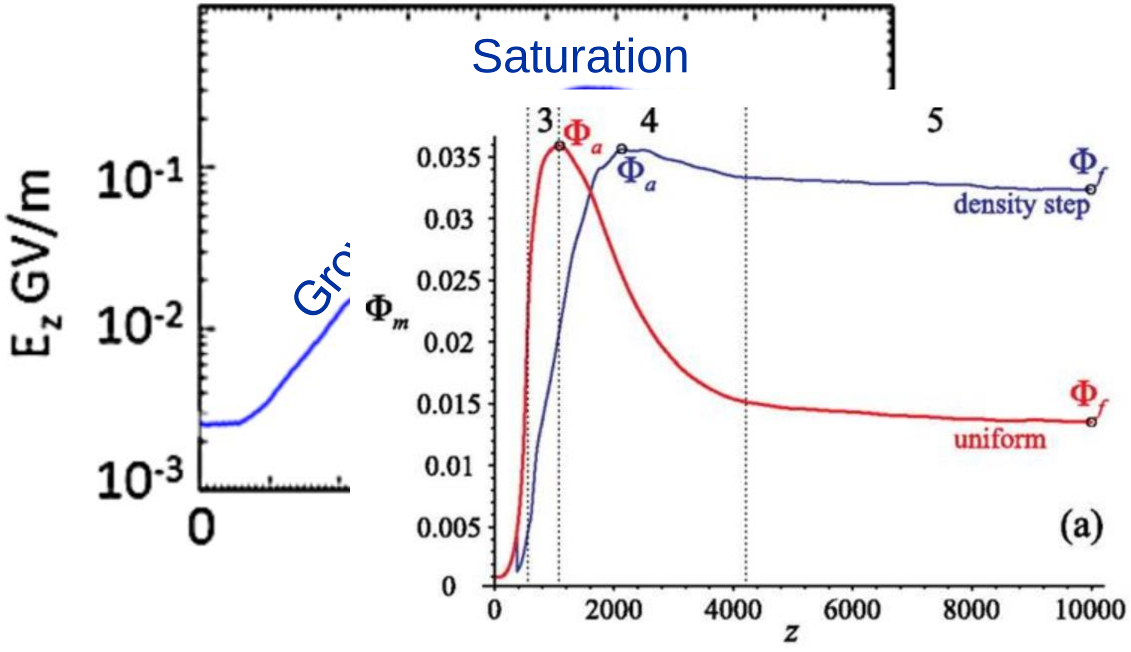
DPS Physics Studies

Plasma Light



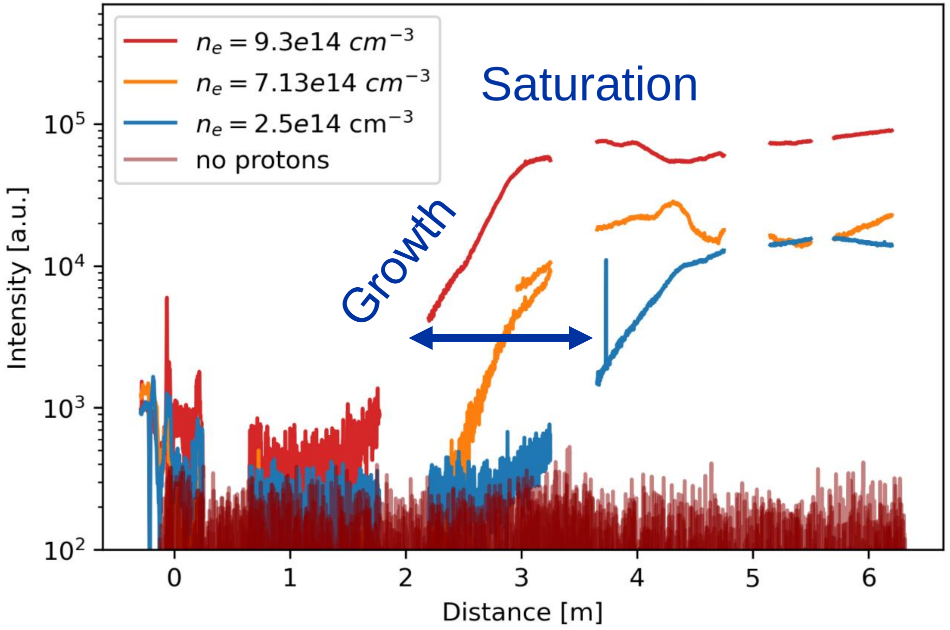
Expectation

Wakefield amplitude growth along the plasma as self-modulation develops

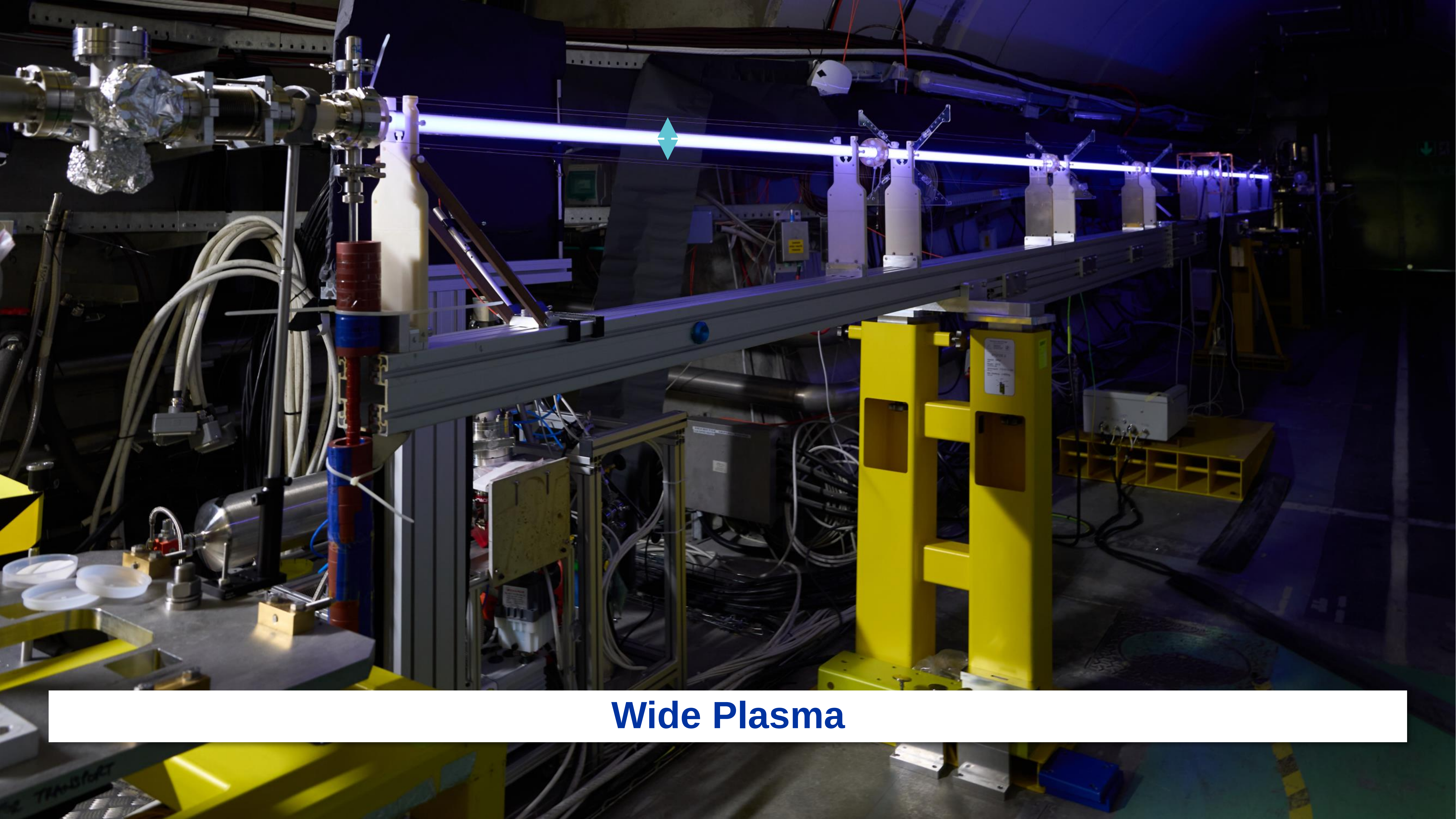


- Plasma light from discharge + additional light from energy deposited by protons driving wakefields
- **Idea:** Additional light is proportional to wakefield amplitude

J. Mezger, MPP



→ Earlier onset of growth for higher plasma density



Wide Plasma

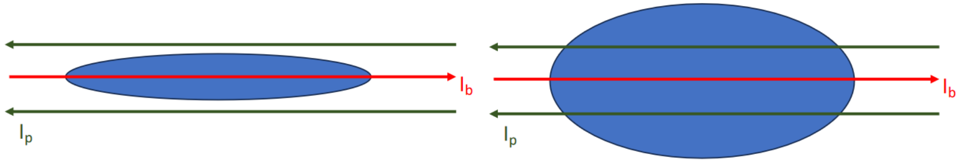
DPS Physics Studies

Filamentation Instability

Plasma responds on the scale length of the plasma skin depth (c/ω_{pe}) ~ 200 μm for AWAKE

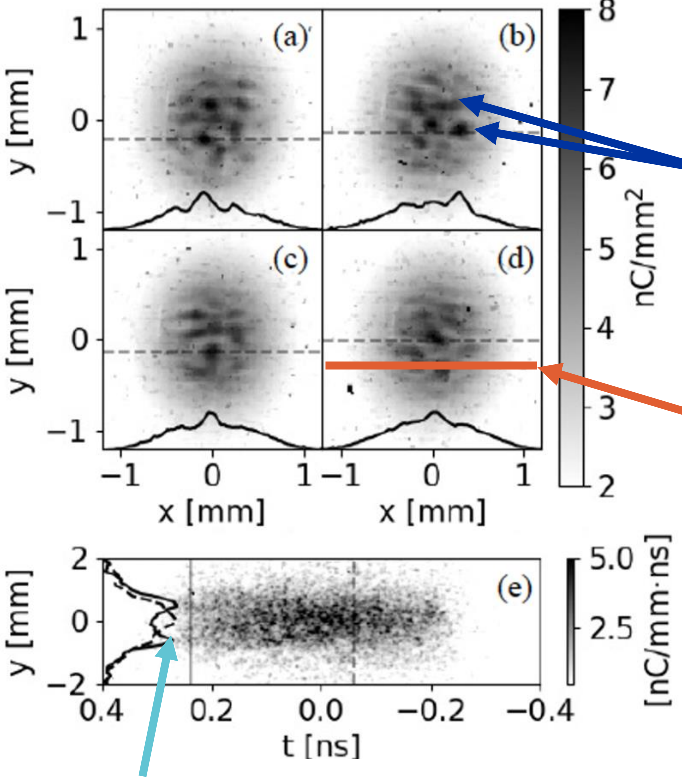
- Longitudinal response, when $\sigma_t >> c/\omega_{pe}$ → SM and microbunching, for AWAKE σ_t ~ 6cm
- Transverse response usually suppresses as $\sigma_r < c/\omega_{pe}$, for AWAKE σ_r ~ 160 μm

- **Prediction:** Transverse filamentation when $\sigma_r >> c/\omega_{pe}$ (typically avoided in wakefield experiments)
  - Increased $\sigma_r \sim 3\ c/\omega_{pe}$ in the experiment → observed filamentation



Plasma on:

L. Verra and the AWAKE Collaboration (in preparation)

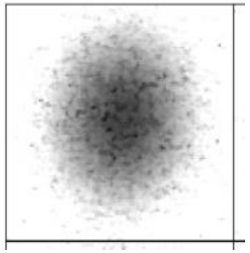


Clear observation of transverse structure on time integrated images

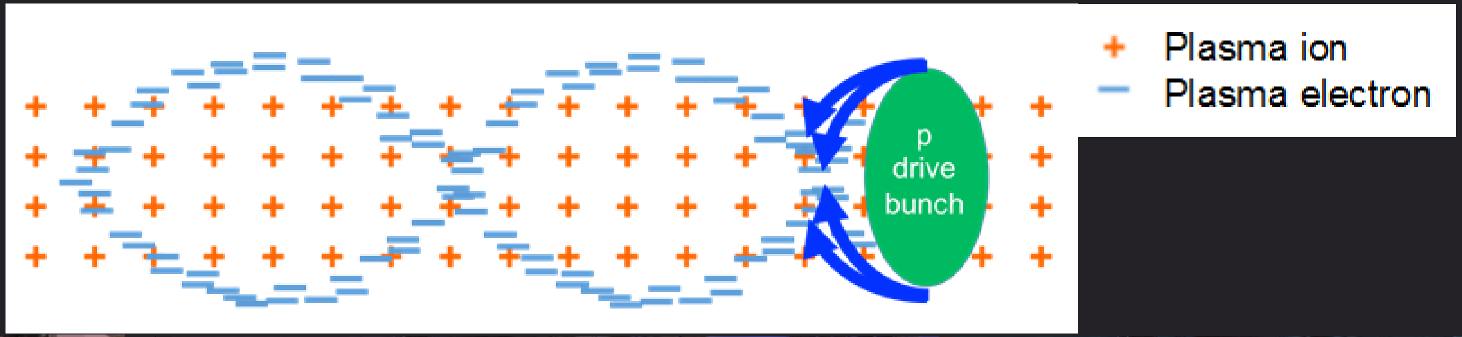
Separation on c/ω_{pe} scale length

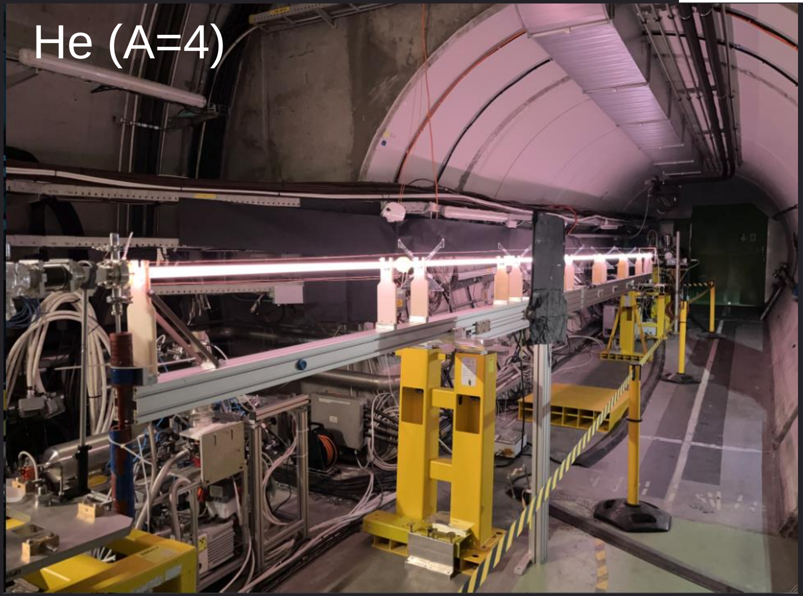
Time-resolved images suggest growth along the bunch

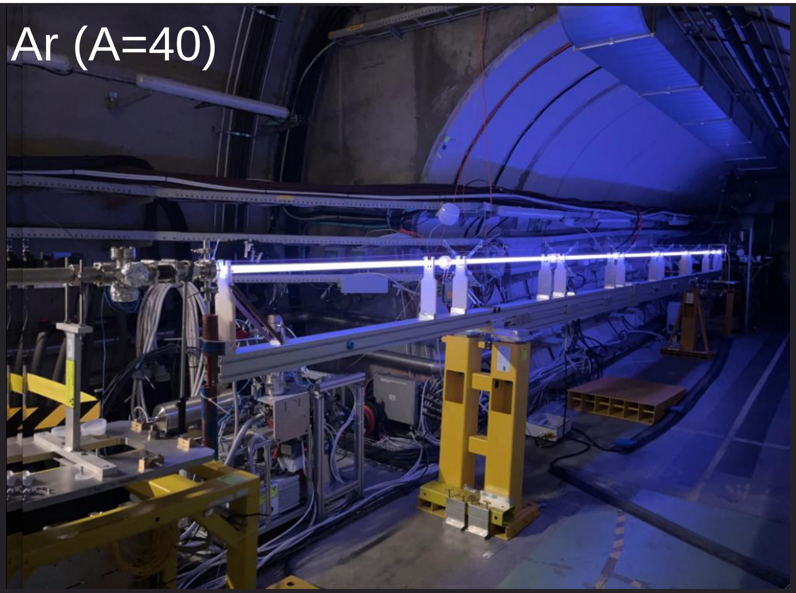
Plasma off:

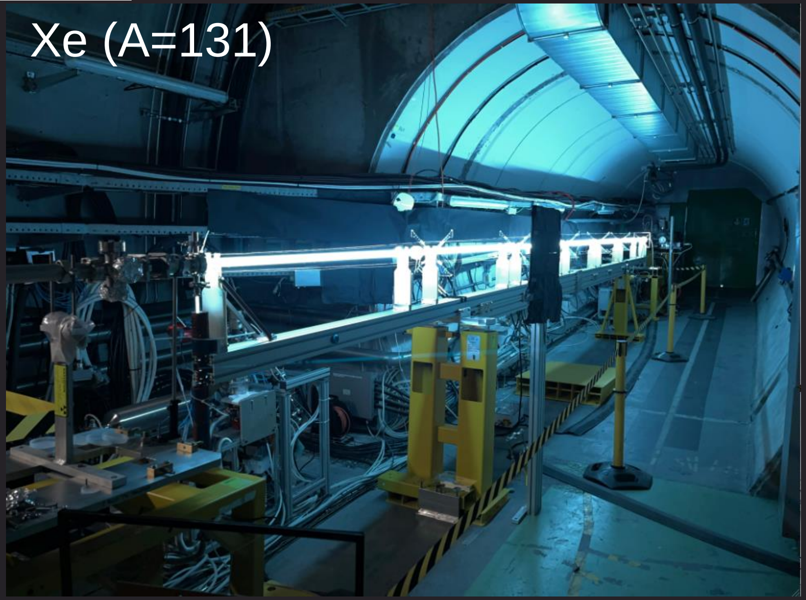


Ion Motion







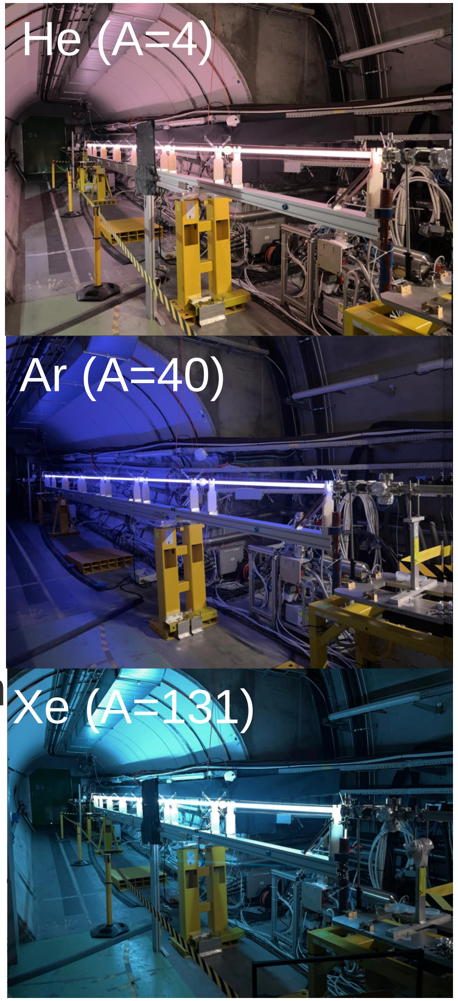


DPS Physics Studies
Ion Motion

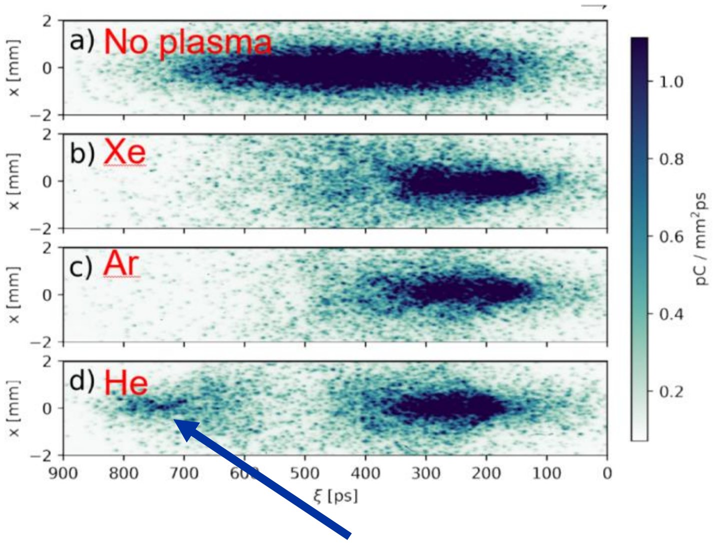
- **Motivation:** understand how ion motion affects resonantly driven wakefields accelerators.

- Plasma species: ions and electrons
  - Due to their heavy mass, ions usually assumed to be immobile, electron oscillation sustains fields
  - If ions start moving, they interfere with wakefields (local changes in the restoring force)
  - More ion motion for: lighter ions, higher wakefield amplitudes

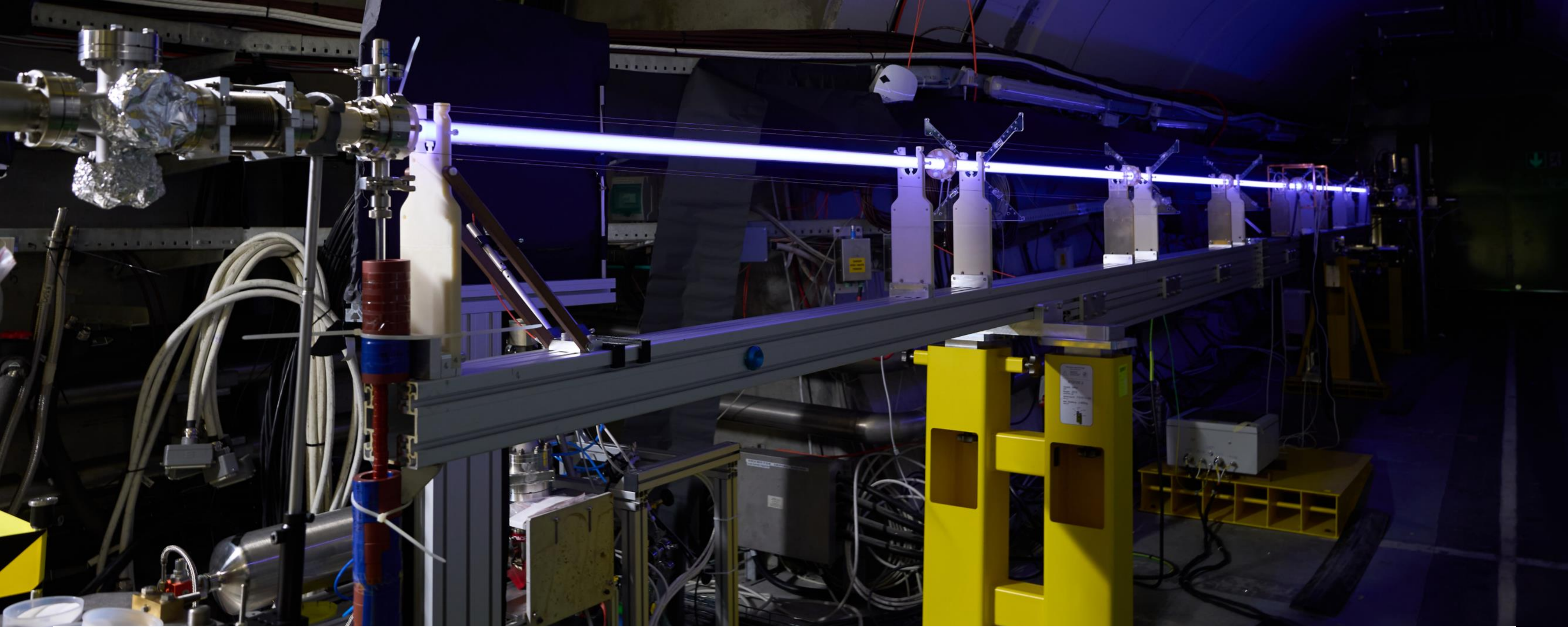
Conclusion: Effect of ion motion was clearly observed in Helium and in Argon at very high densities (field amplitudes).
→ **No effects of ion motion are expected when using Rubidium (A=85-87) with the AWAKE parameters**



M, Turner, in preparation



Observation of beam tail when ion motion becomes significant, due to a change of the resonance condition



- We showed that the DPS works in the accelerator and for self-modulation

- Tested physics relevant to SM, to plasma-based accelerators and to physics in general

Rb Vapor Source with Density Step

(~6 weeks of p+ beamtime)

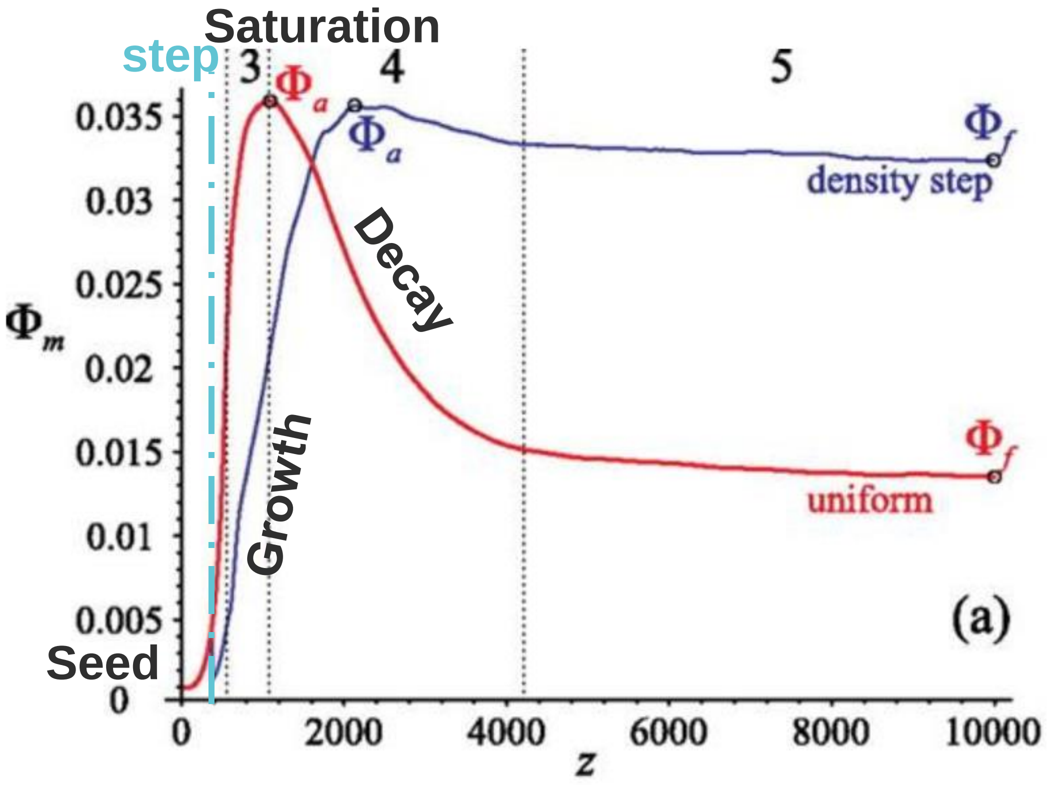
Experimental Plans of Run 2b With the New Rb Vapor Source

- **Commissioning:** of the new vapor source and associated diagnostics. ✅

- **Physics plan:** test the ability of a density step (placed withing the SSM growth region) to make wakefields maintain a large amplitude past their saturation location:

  - Predicted by numerical simulation results:
    - 1) Verification of the prediction
    - 2) Optimization of density step using plasma light signals
    - 3) Confirm by the measurement of energy gain of 20 MeV side-injected (after the step) test electrons.

Simulations predict that a density step leads to increased wakefield amplitudes after SSM saturation.



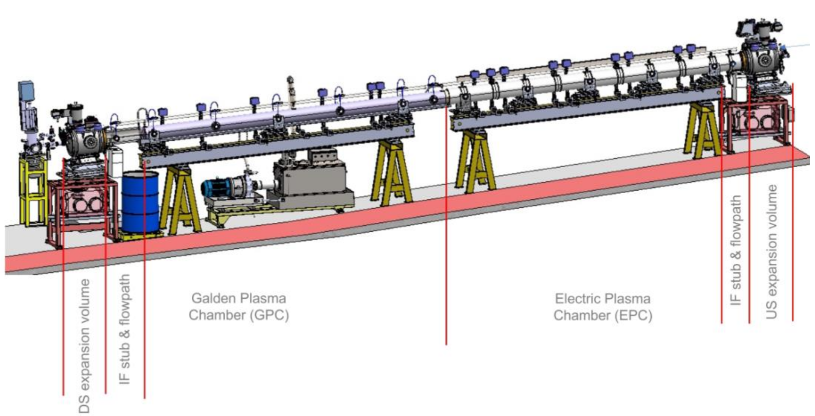
K. V. Lotov, Physics of Plasmas 22, 103110 (2015)

Installation and Commissioning of New Rubidium Vapor Source with Density Step

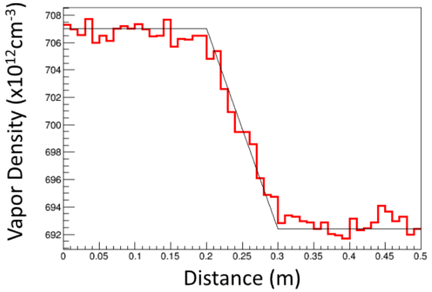
- Laser-ionized Rb vapor source
- Allows for a density step:
  - Position: 0.5 - 4.25 m, height: 0 - 10%
- Ten observation ports:
  - Allow to measure light emitted by wakefields dissipating after the passage of the proton bunch

- Installed on time ✓
- Commissioning complete ✓
- Successful operation ✓

MPP Munich, WDL



G. Plyuschev, J. Phys. D: 51(2), 025203 (2018)

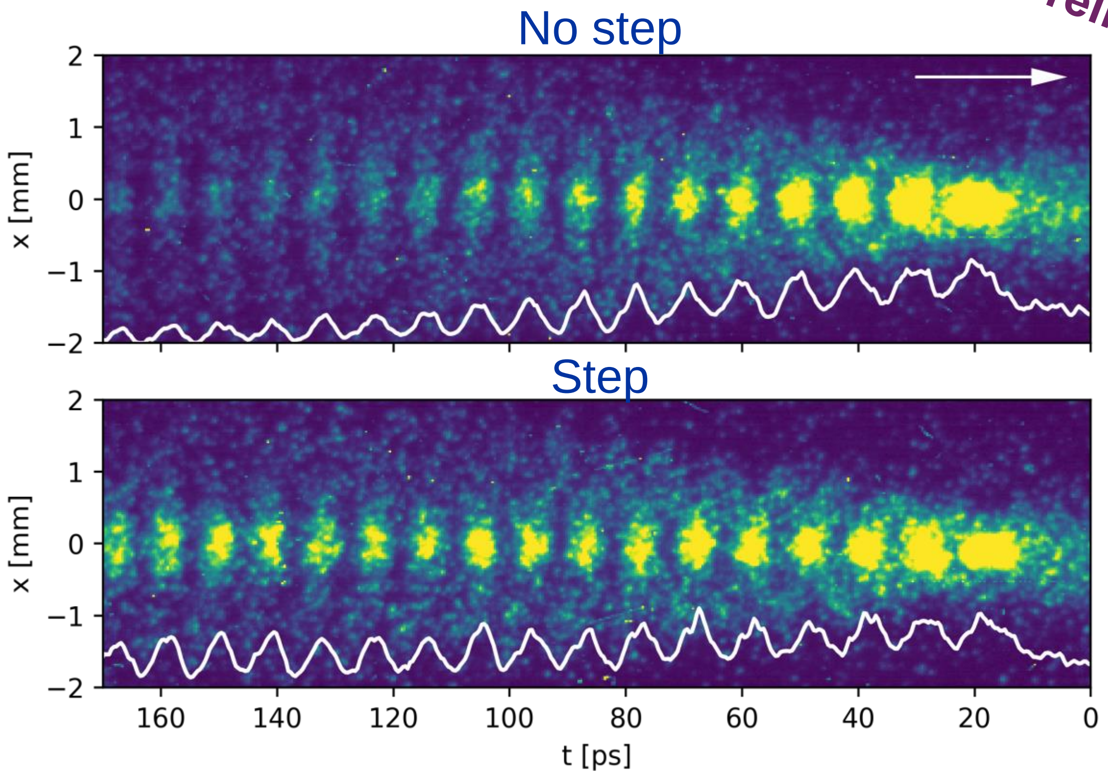


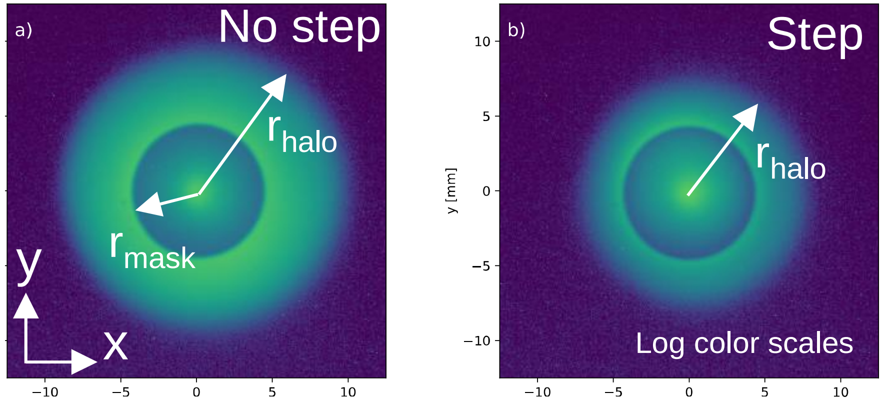
Run 2b: First Results from 2023

Effect of the Density Step

- Placing a density step shows a clear effect:
  - Longer bunch trains on the streak camera images

Preliminary





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

Clear effect!

5% step at 1.75m,
1.5e11 p+/bunch

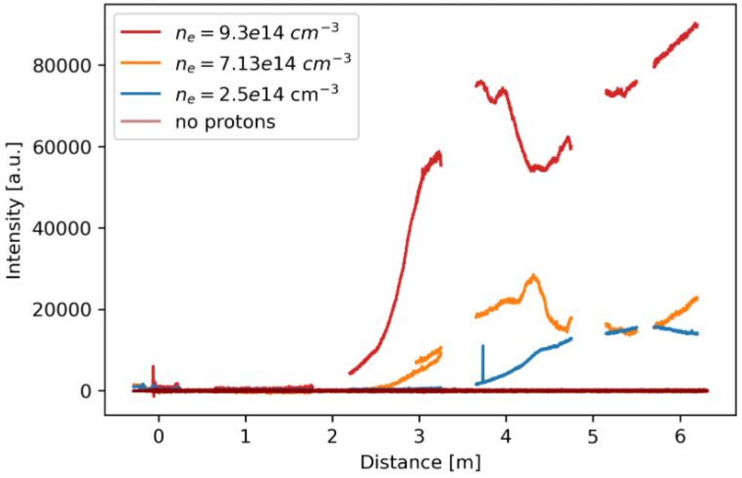
Run 2b: First Results from 2023

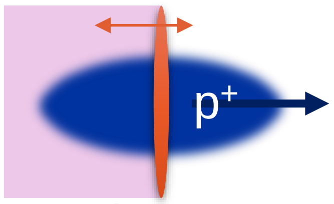
Plasma Light

Reminder: plasma light measurement from the DPS experiments:

Unseeded

J. Mezger, MPP

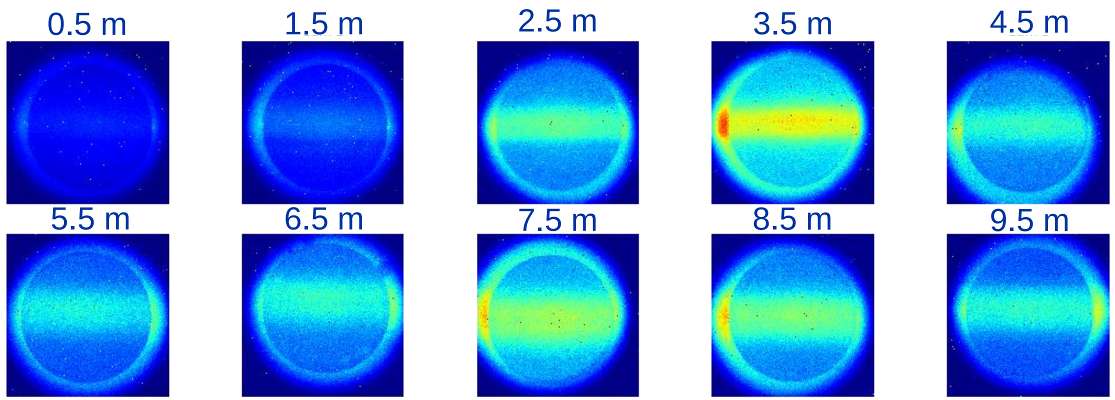




Laser pulse

$n_{pe} \sim 3.7x10^{14}\ cm^{-3}$,$1x10^{11}\ p^+$/bunch, uniform plasma

With new vapor source: ten viewports



M. Turner, CERN

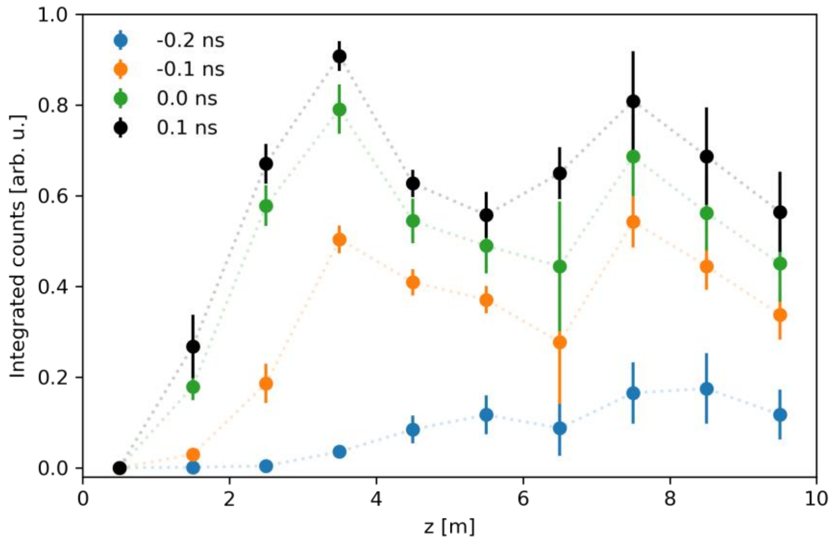
Preliminary

Growth:

Faster when more p^+ in plasma

Amplitude:

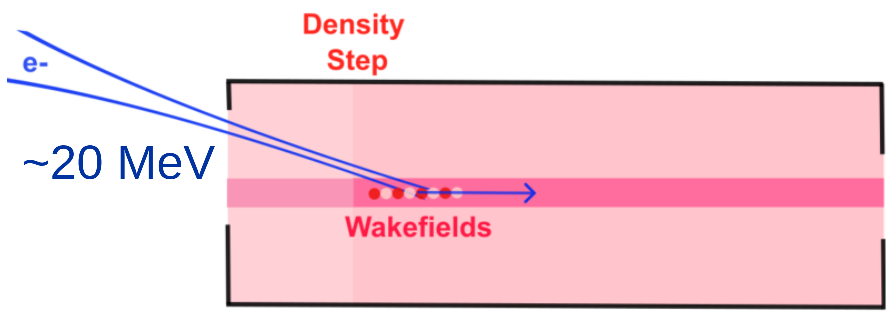
Higher when more p^+ in plasma

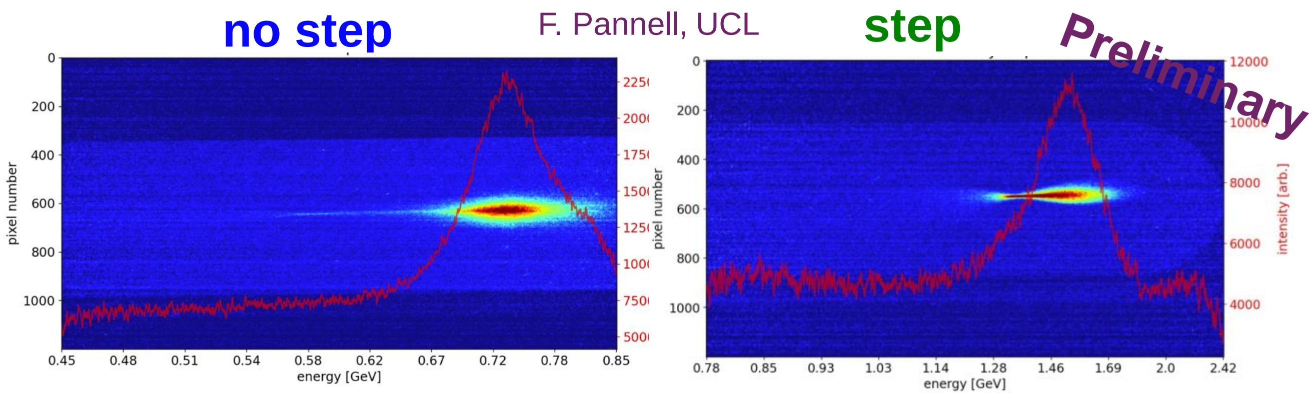


Run 2b: First Results from 2023

Acceleration of Test Electrons

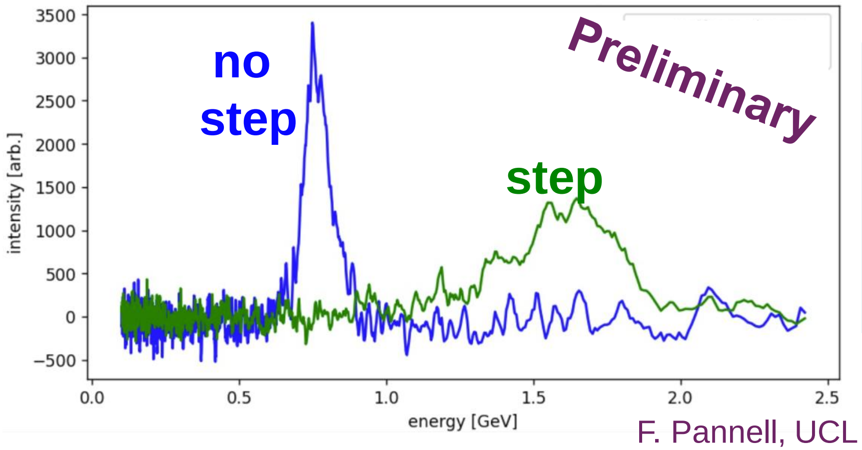
External injection downstream of density step:





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

Excess light on plasma light cameras allowed to verify e^- injection location.



Energy of accelerated e^- approximately **double** for this density step

Clear effect!

Results preliminary, verification and analysis ongoing!

2024 Run Plan

Possible Improvements to the Experimental Setup

Streak Cameras

Goal: Simultaneous measurement of proton bunch modulation and electron acceleration.
→ transporting light emitted by screen downstream of the spectrometer

Plasma Length

Goal: change plasma length by stopping the ionizing laser pulse.
This could be done in principle by inserting screens that would be thick enough to block the laser pulse, but thin enough to let through high-energy electrons through.

Schlieren Imaging

Goal: Determine plasma radius evolution during p^+ operation.

Larger Plasma Radius

Goal: larger plasma radius to increase alignment tolerances.
Laser pulse focusing system uses transmissive optics
→ limits the fluence on compressor gratings
Upgrade: use of reflective optics (off-axis parabolas) after the compressor allowing for larger plasma.

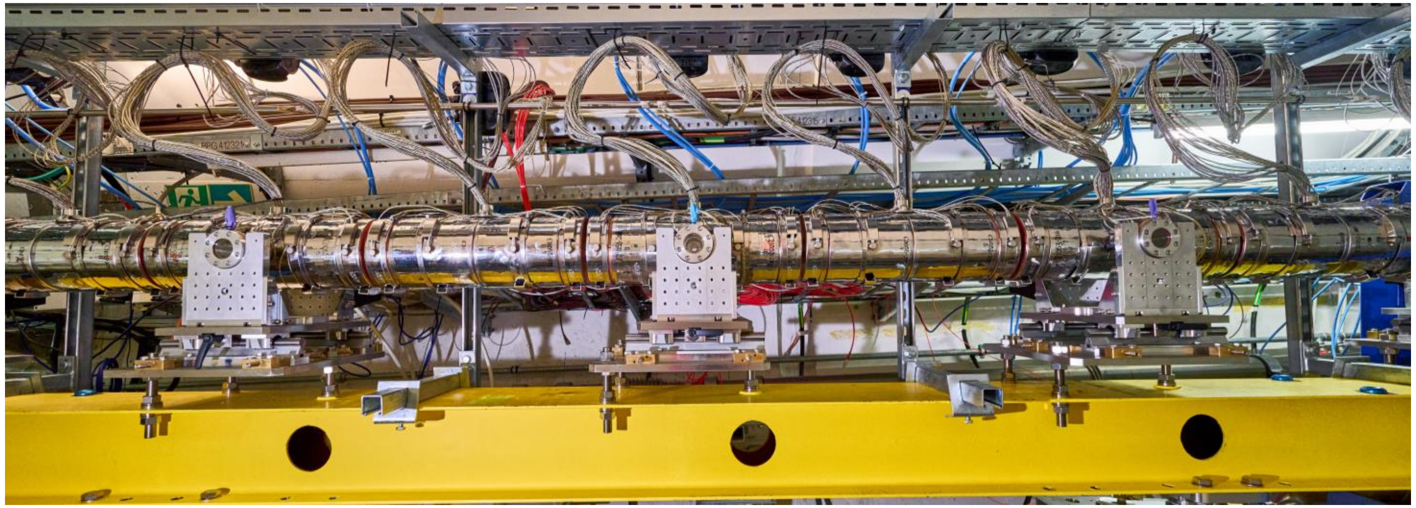
Upgrade during the YETS

Run 2b: 2024 Measurement Program

- Will focus on the optimization of the plasma density steps using the new Rb vapor source
  - Confirm that a density step stabilizes accelerating gradient, using information from:
    - Plasma light diagnostic
    - Proton beam diagnostic (streak camera, halos)
    - Injection of test electrons and acceleration over different plasma lengths

→ Slow process

Thermal system



- Benefit from important upgrades and studies on the electron and laser beamline, as well as diagnostics upgrades during the YETS.

2024 Beam Time Request

- Adapting to the reduced beam-time in 2024, AWAKE requests 10 weeks of proton run:
  - Original request of 12 weeks reduced by 2 weeks due to CERN wide energy savings
  - Starting as soon as possible
  - 2–3-week blocks of proton run, separated by at least 2 weeks
  - Stop by September 30th (CNGS dismantling)

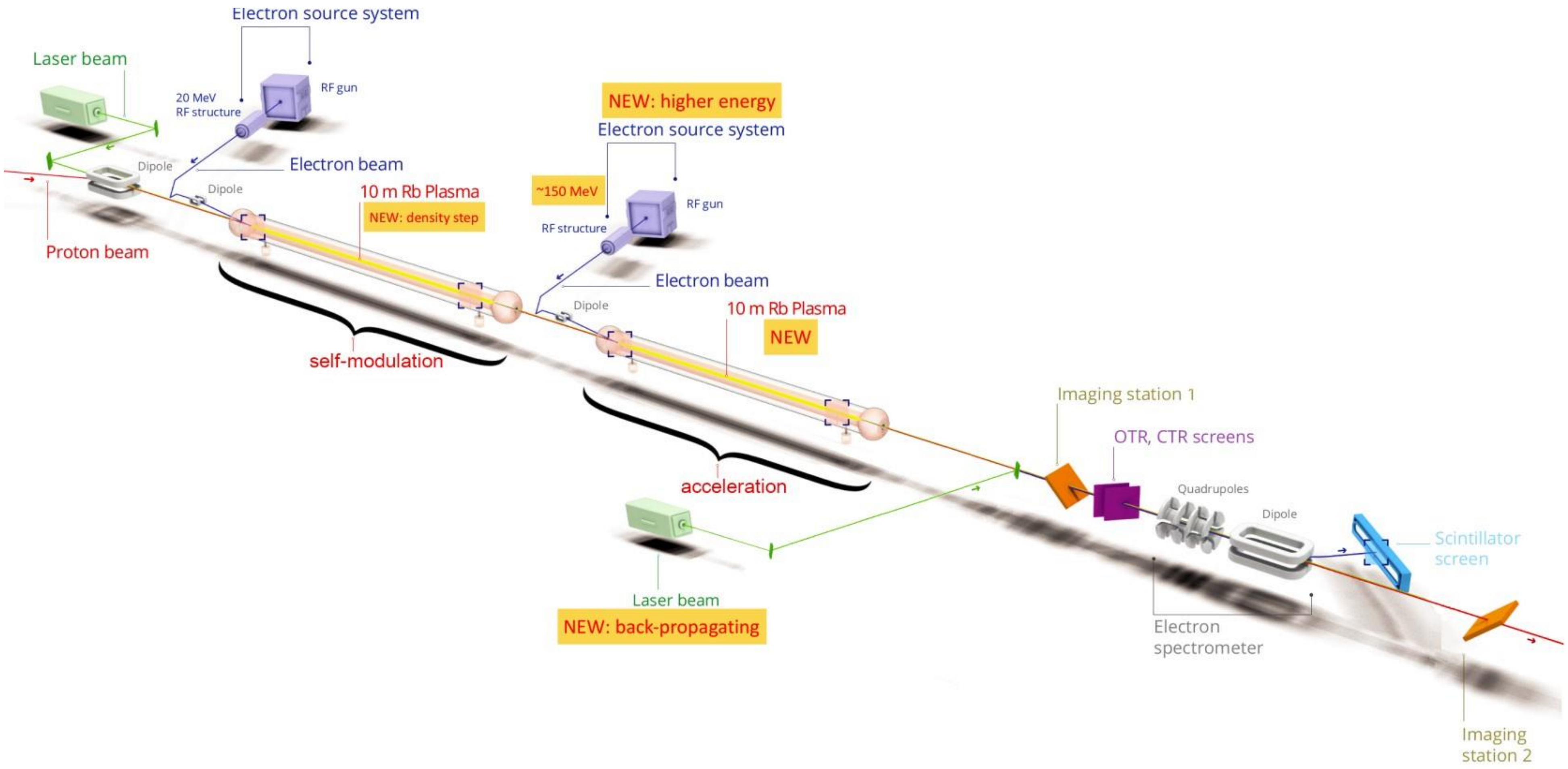
- For the physics program we need stable conditions, i.e. continuous AWAKE cycle in the super-cycle, with no interruptions
  - Important: reproducible, high-quality beam

- Operation for a maximum of two shifts per day 16 hrs (typically less ~12 hrs)
  - Ask to be removed from super cycle when not using beam for >1hr.

Note that 2024 will be the last AWAKE run before a 3-year stop
(due to CNGS dismantling and LS3 installation)
→ 2024 proton run is crucial

Run 2c Preparations

Separation between self-modulator and accelerator



Preparing for AWAKE Run 2c,2d → CNGS Dismantling

Q4 2024 – mid 2026

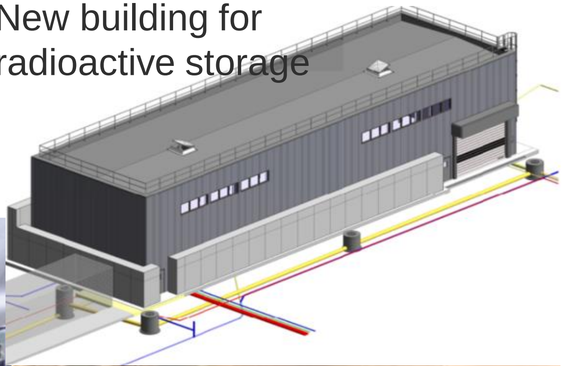
Area content (~600 m³) will be emptied:

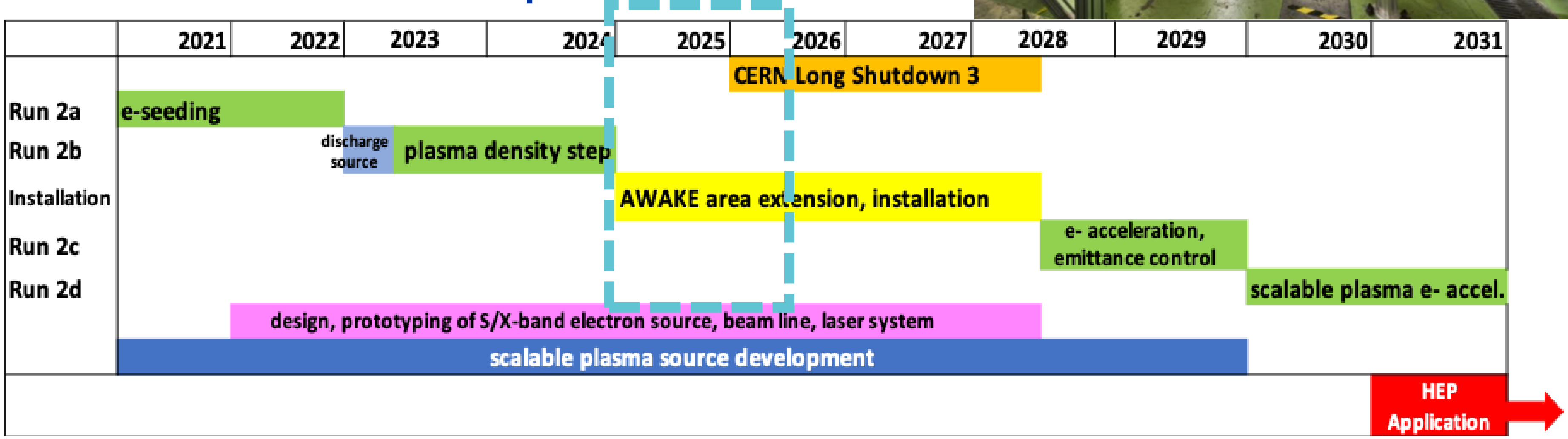
- ~500 large shielding blocks (0,05-0,6 mSv/h)
- a few high dose-rate elements (2-20mSv/h)
- 70-meter-long aluminum He-tank
- Various supports, ducts…

Requires dismantling of the current AWAKE experiment.

Wall separating AWAKE and CNGS target cavern.

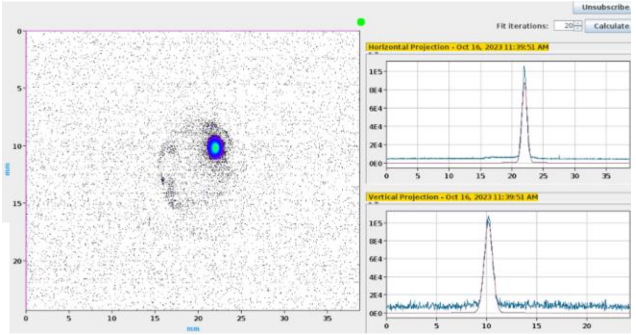
New building for radioactive storage





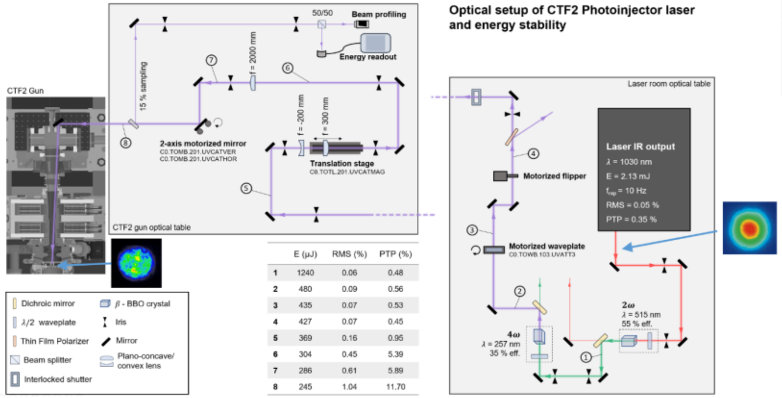
Additional Run 2c, 2d Preparations

- New electron source
  - Successful commissioning of the prototype RF-gun with beam



- Beam instrumentation upgrade

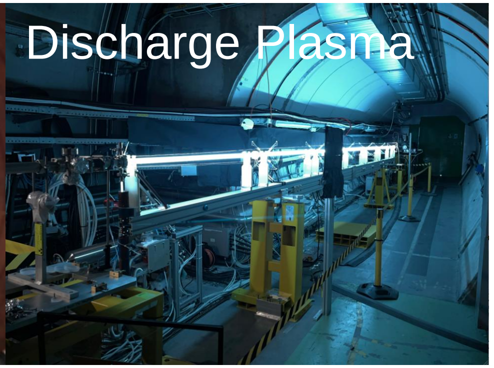
- Beam transport line upgrades
  - Electron, laser and proton



	E (μJ)	RMS (%)	PTP (%)
1	1240	0.06	0.48
2	480	0.09	0.56
3	435	0.07	0.53
4	427	0.07	0.45
5	369	0.16	0.95
6	304	0.45	5.39
7	286	0.61	5.89
8	245	1.04	11.70

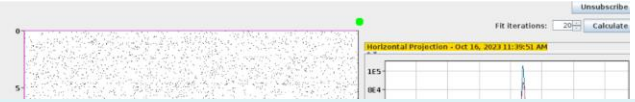
- Simulation studies

- Scalable plasma source R&D
  - Review was organized (CERN, IST Lisbon, IC London, EPFL-SPC, IPP/Madison)



Additional Run 2c, 2d Preparations

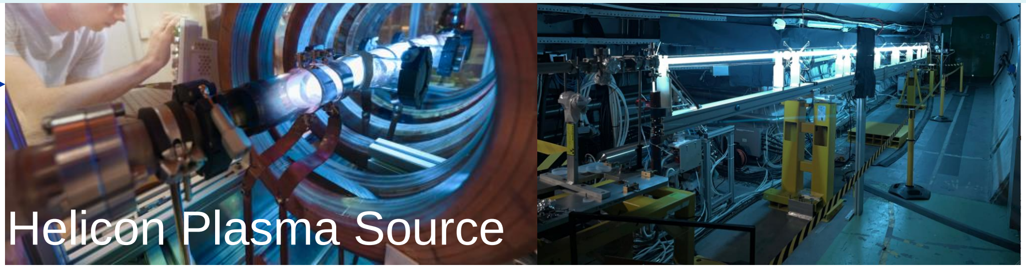
- New electron source



- CERN management requested **external review**, with external plasma experts to assess the scientific and technology challenges of Run 2c as input for next year's MTP discussion

- Works for Run 2c are ongoing already
  - This is important to keep the timeline of starting with Run 2c in 2028

- Scalable plasma source R&D
  - Review was organized (CERN, IST Lisbon, IC London, EPFL-SPC, IPP/Madison)



Summary

Publications & Prizes

- Nechaeva, et al. (AWAKE Collaboration), Hosing of a long relativistic particle bunch in plasma, arXiv:2309.03785 (2023)
- L. Verra, et al. (AWAKE Collaboration), Development of the Self-Modulation Instability of a Relativistic Proton Bunch in Plasma, Phys. Plasmas 30, 083104 (2023)
- M. Martinez-Calderon, et al., Fabrication and rejuvenation of high quantum efficiency caesium telluride photocathodes for high brightness and high average current photoinjectors, Submitted (2023)
- E. Senes, et al., Selective electron beam sensing through coherent Cherenkov diffraction radiation, Submitted (2023)
- G. Demeter, et al., Generation of 10-m-lengthscale plasma columns by resonant and off-resonant laser pulses, Optics and Laser Technology, Volume 168, 109921 (2023)
- M. Granetzny, et al., Overview of the Madison AWAKE Prototype - A High Density Helicon Experiment, arXiv:2212.11401 (2022)
- H. Saberi, et al., Radiation reaction and its impact on plasma-based energy-frontier colliders, Phys. Plasmas 30, 043104 (2023)
- F. Velotti, et al., Towards automatic setup of 18 MeV electron beamline using machine learning, Mach. Learn.: Sci. Technol. 4 025016 (2023)
- R. Ramjiawan, et al. Design and operation of transfer lines for plasma wakefield accelerators using numerical optimizers, Phys. Rev. Accel. Beams 25, 101602 (2022)

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

The work and achievements in AWAKE is well recognized, in 2023:

- Livio Verra: EPS Plasma Physics Division PhD Award
- Marlene Turner: Simon Van der Meer Early Career Award in Novel Accelerators

Summary

- Successful Run with the **discharge plasma source** (DPS)
  - Demonstrated self-modulation and a large variety of physics studies

- Successful installation and commissioning with the **new Rb vapor source**
  - Observed clear effect of density step
  - First tests are promising
- Beam request for 2024 to optimize the density step and define self-modulator plasma design for Run 2c

- Continue clear plan for applications to particle physics in 2030's
  - Clear scientific program
    - Run 2b: plasma density step
    - Run 2c: external injection of e-bunch in second plasma, quality
    - Run 2d: operation with acceleration in scalable plasma source