Pushing to New Particle Energy Frontiers with Plasma Wakefield Acceleration

Physics Colloquium
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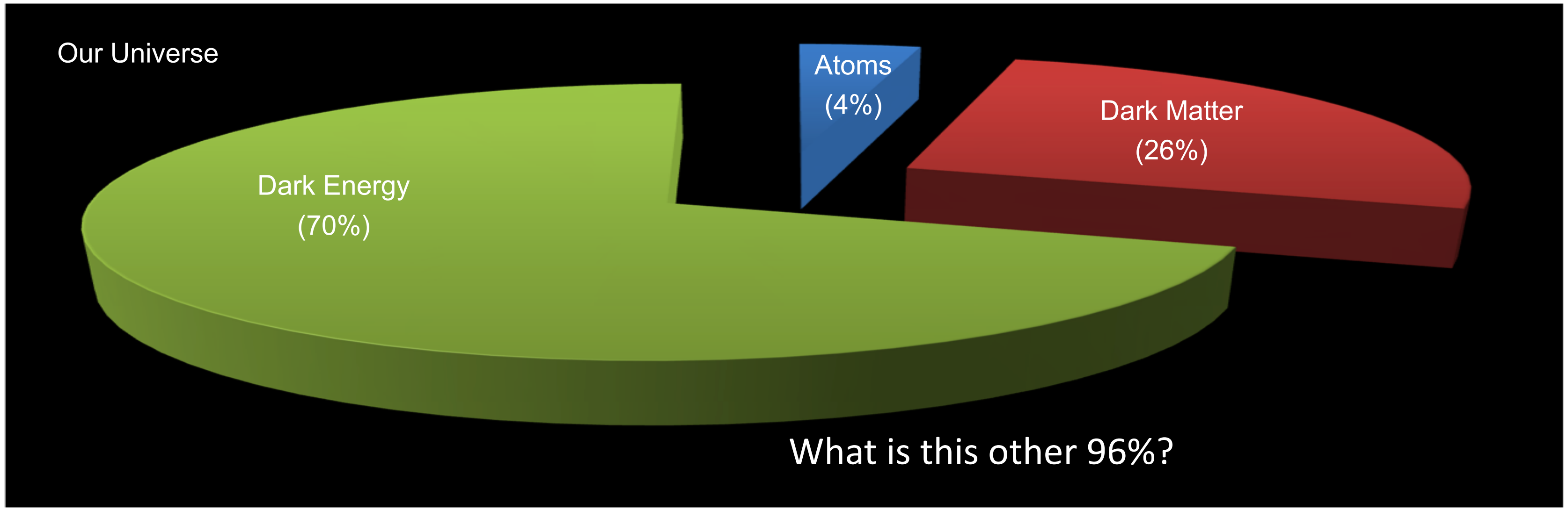
Outline

- Motivation
- Introduction to Plasma Wakefield Acceleration
- State of the Art
- The AWAKE Experiment
  - Results of AWAKE Run 1
  - AWAKE Run 2
- Applications with AWAKE-Like Scheme
- Outlook

Motivation: High Energy Accelerators

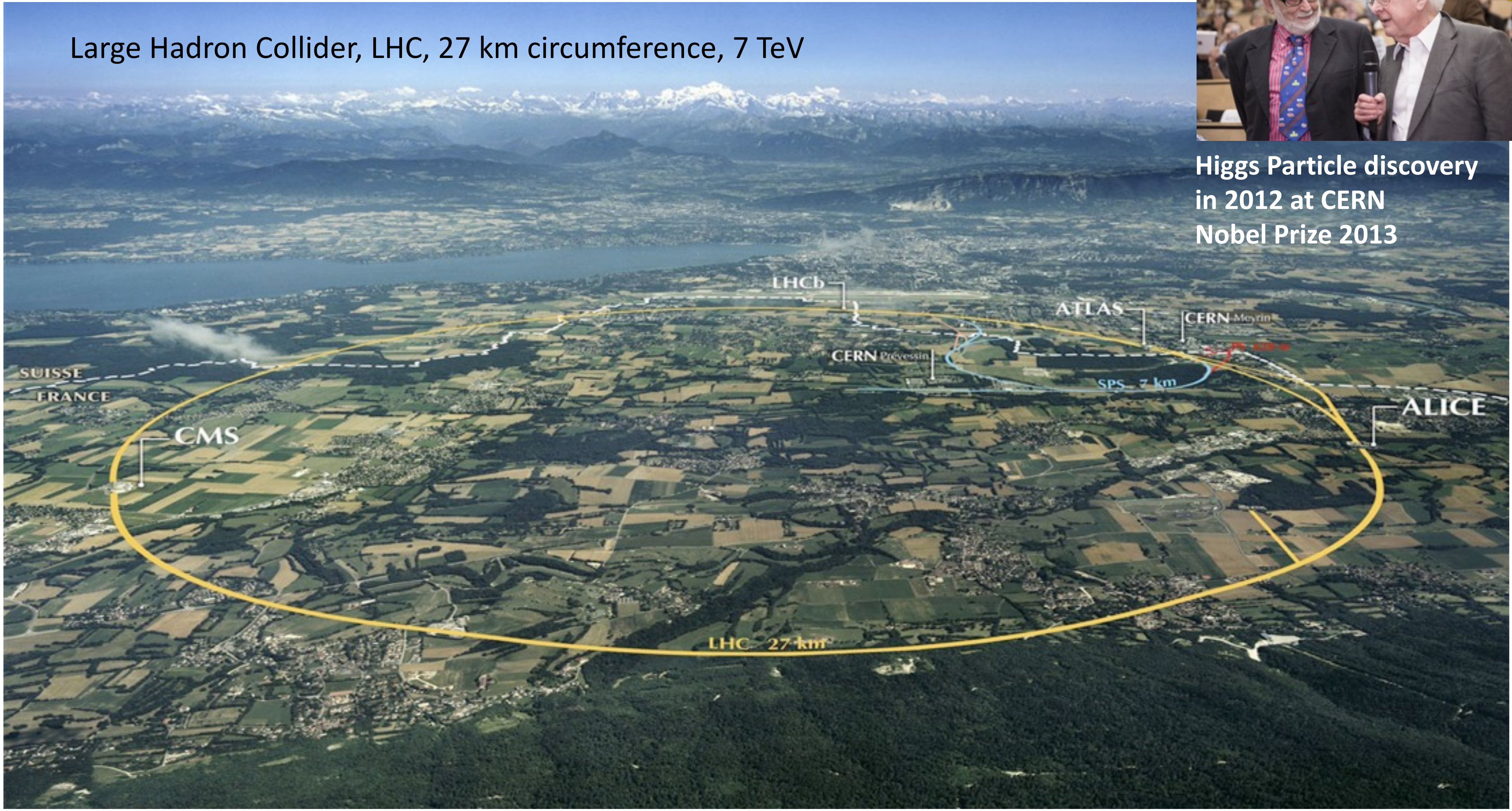
- **Large list of unsolved problems:**
  - Understand the origin of the universe
    - What is dark matter made of? What is the reason for the baryon-asymmetry in the Universe? etc…
    - ➔ With increasing particle energies, we can probe earlier times in the evolution of the Universe.



➔ Need particle accelerators with new energy frontier

LHC

Large Hadron Collider, LHC, 27 km circumference, 7 TeV



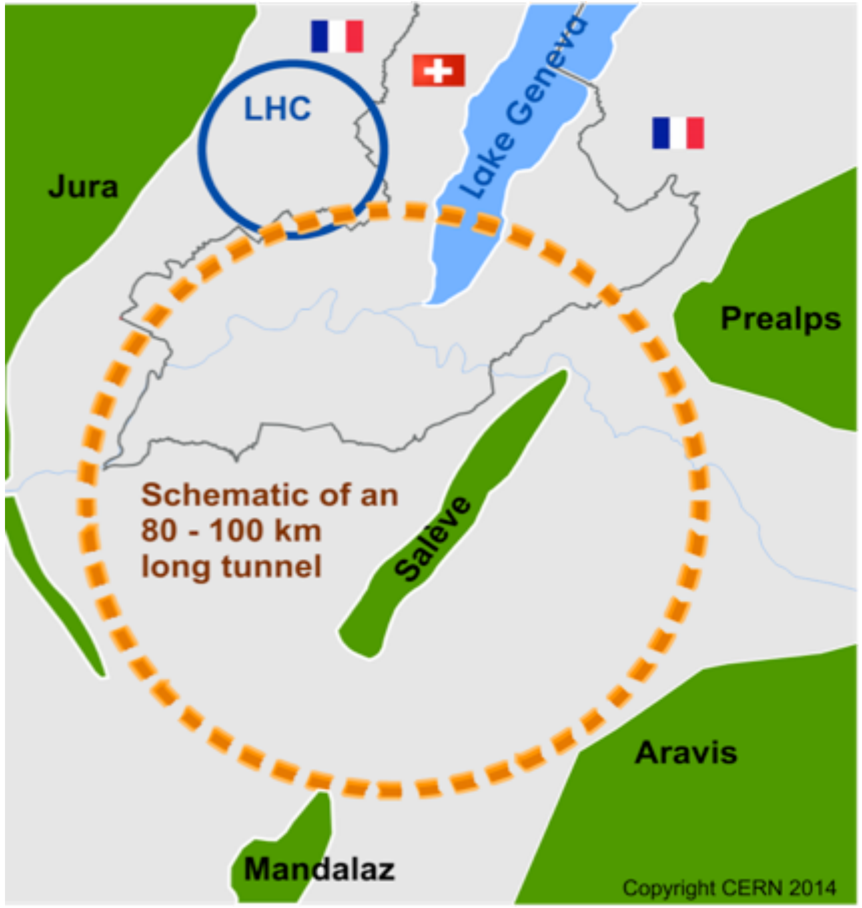
Higgs Particle discovery in 2012 at CERN
Nobel Prize 2013

Discover New Physics

Accelerate particles to even higher energies

→ **Bigger accelerators: circular colliders**

Future Circular Collider: FCC



Limitations of conventional circular accelerators:

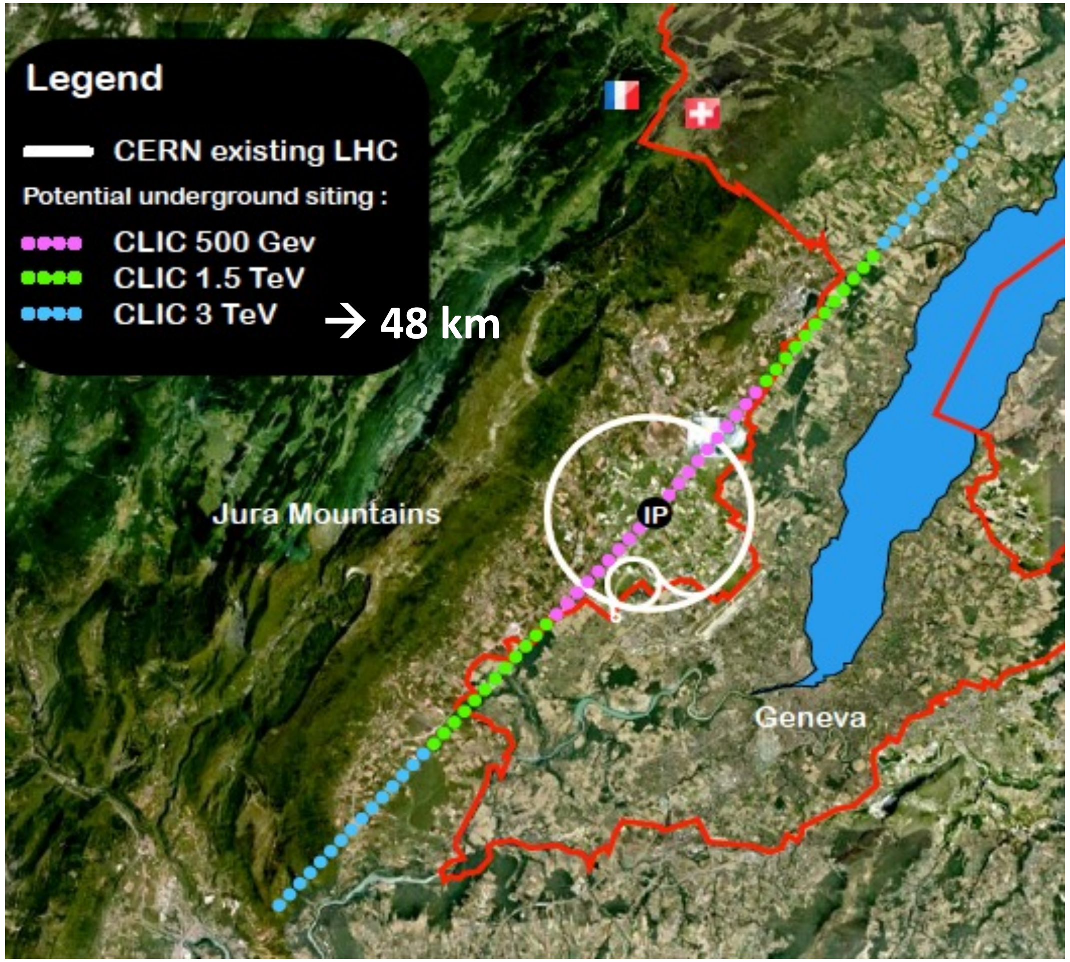
- For **hadron colliders**, the limitation is **magnet strength**. Ambitious plans like the FCC call for 16 T magnets in a 100 km tunnel to reach **100 TeV** proton-proton collision energy.
- For **electron-positron colliders**: Circular machines are limited by **synchrotron radiation** in the case of positron colliders. These machines are unfeasible for collision energies beyond **~350 GeV**.

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

Discover New Physics

Linear colliders are favorable for acceleration of low mass particles to high energies.

CLIC, electron-positron collider with 3 TeV energy

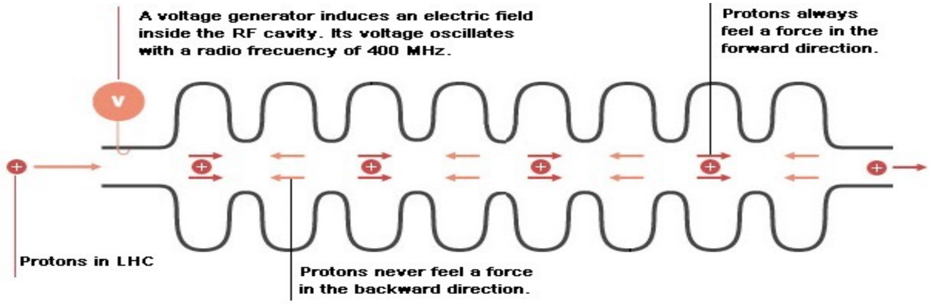


Limitations of linear colliders:

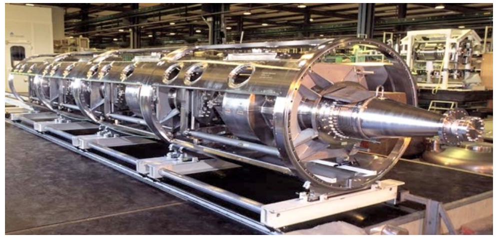
- Linear machines accelerate particles in a **single pass.** The amount of acceleration achieved in a given distance is the ***accelerating gradient***. This number is **limited to 100 MV/m** for conventional copper cavities.

Why Plasma Wakefield Acceleration?

Conventional Acceleration Technology: Radiofrequency Cavities

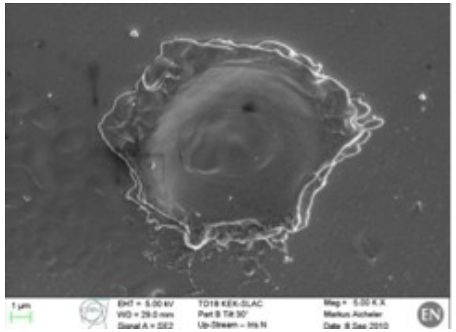


LHC Cavity



(invention of Gustav Ising 1924 and Rolf Wideroe 1927)

- Very successfully used in all accelerators (hospitals, scientific labs,…) in the last 100 years.
- Typical gradients:
  - LHC: 5 MV/m
  - ILC: 35 MV/m
  - CLIC: 100 MV/m
- However, accelerating fields are limited to <100 MV/m
  - In metallic structures, a too high field level leads to break down of surfaces, creating electric discharge.
  - Fields cannot be sustained; structures might be damaged.



- several tens of kilometers for future linear colliders

Plasma Wakefield Acceleration

➔Acceleration technology, which obtains ~1000 factor stronger acceleration than conventional technology.

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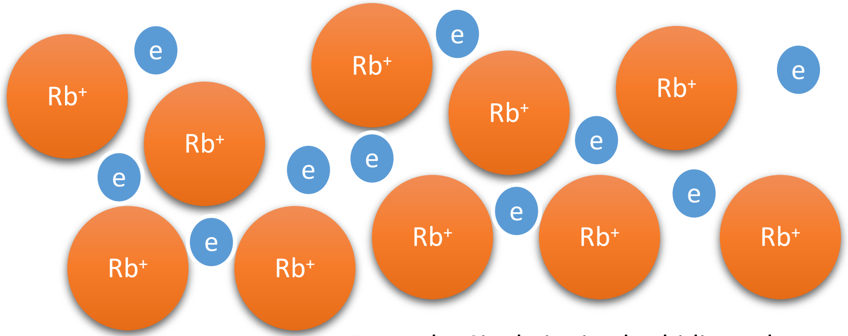
Plasma Wakefield

What is a plasma?



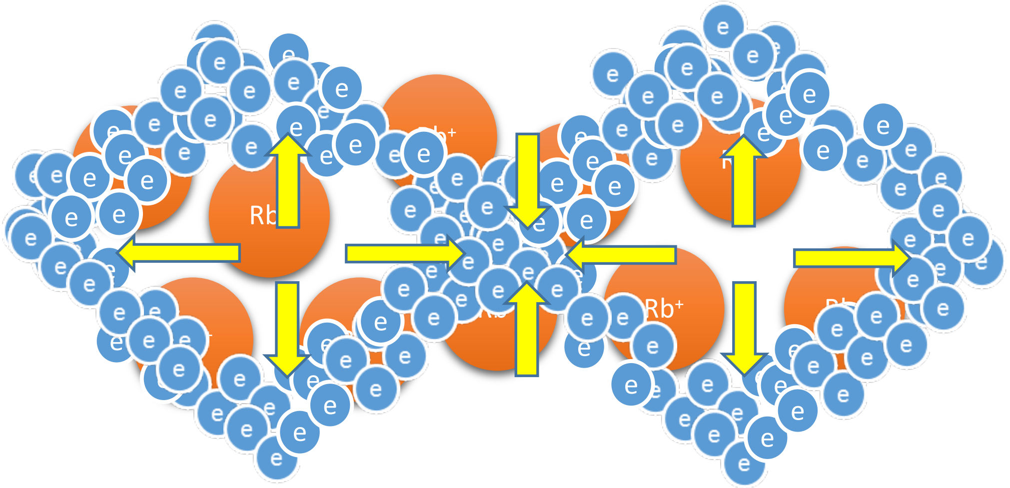
Example: Single ionized rubidium plasma

Quasi-neutrality: the overall charge of a plasma is about zero.

Collective effects: Charged particles must be close enough together that each particle influences many nearby charged particles.

Electrostatic interactions dominate over collisions or ordinary gas kinetics.

What is a plasma wakefield?



Fields created by collective motion of plasma particles are called plasma wakefields.

Seminal Paper 1979, T. Tajima, J. Dawson

Use a plasma to convert the transverse space charge force of a beam driver into a longitudinal electrical field in the plasma

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

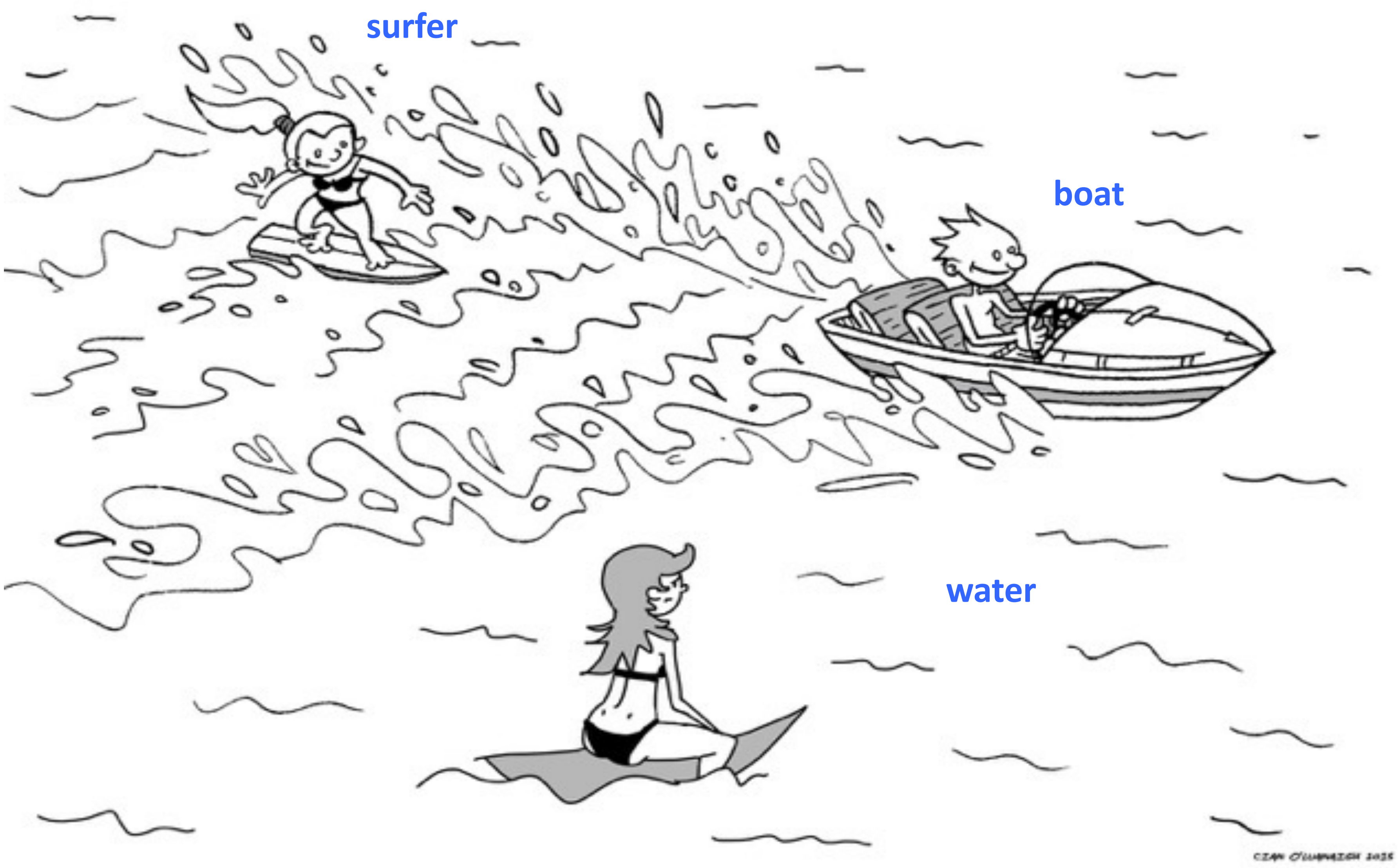
Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective accelerators, present-day electron beams[3] yield electric fields of ~10^7 V/cm and power densities of 10^{13} W/cm^2.

the wavelength of the plasma waves in the wake:

$$L_t = \lambda_w/2 = \pi c/\omega_p . \qquad (2)$$

An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes $2\pi c/\omega_p$. The mechanism for generating the wakes can be simply seen by the following approximate

How to Create a Plasma Wakefield?

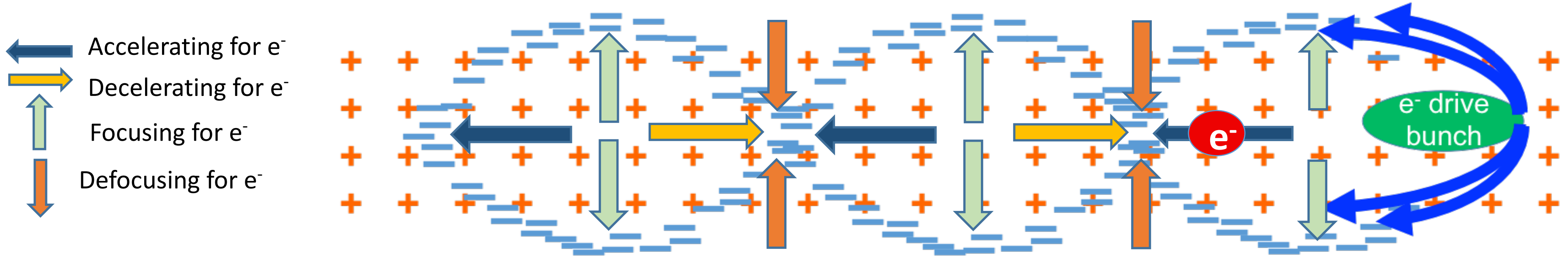


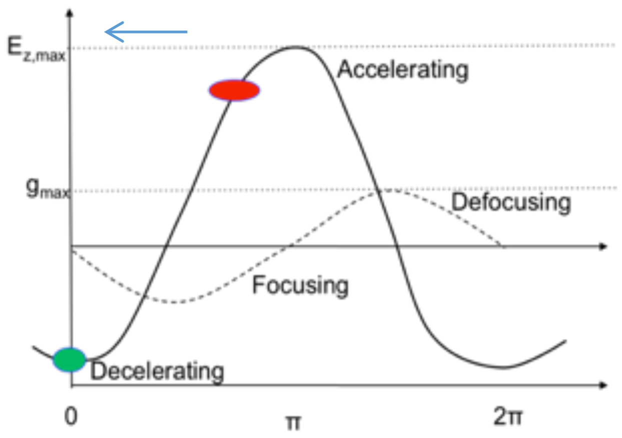
Analogy:
water → plasma

Boat → particle beam (drive beam)

Surfer → accelerated particle beam (witness beam)

Plasma Wakefield, Linear Theory





➔ **Drive beam: *electron* or *laser* or *proton* beam**

$$\omega_{pe} = \sqrt{\frac{n_{pe}\, e^2}{m_e\, \varepsilon_0}} \rightarrow \lambda_{pe} = 2\pi \frac{c}{\omega_{pe}} \rightarrow \lambda_{pe} \approx 1\text{ mm} \sqrt{\frac{10^{15}\text{ cm}^{-3}}{n_{pe}}}$$

plasma frequency   plasma wavelength

Example: $n_{pe} = 7\times10^{14}$ cm^{-3} (AWAKE) → $\omega_{pe} = 1.25\times10^{12}$ rad/s ➔ $\frac{c}{\omega_{pe}}$ **= 0.2mm** → $k_{pe} = 5$ mm^{-1}

λ_{pe} = 1.2 mm → **Produce cavities with mm size!**

$n_{pe} = 10^{16}$ cm^{-3} → λ_{pe} = 0.3 mm

Introduction – Accelerating Field, Energy in PWA

The maximum accelerating field (wave-breaking field) is:

$$e\,E_{WB} = 96\ \frac{V}{m}\sqrt{\frac{n_{pe}}{cm^{-3}}}$$

Example: $n_{pe} = 10^{16}\ cm^{-3} \rightarrow E_{WB} = 10GV/m$

Increase gradient by increasing density.

➔ Advantage of beam-driven PWFA

➔For LWFA: **dephasing**: laser group velocity depends on plasma density, is slower than c.

- Electron energy reach is limited by dephasing: → move to lower densities and longer accelerators
- Lower density needs higher laser power (Significant progress since Chirped Pulse Amplification, CPA, Nobel Prize 2018 to D. Strickland & G. Mourou)

Drive beams:

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

$$E_{acc} = 110\ \frac{MV}{m}\ \frac{N/(2 \times 10^{10})}{(\sigma_z / 0.6mm)^2}$$

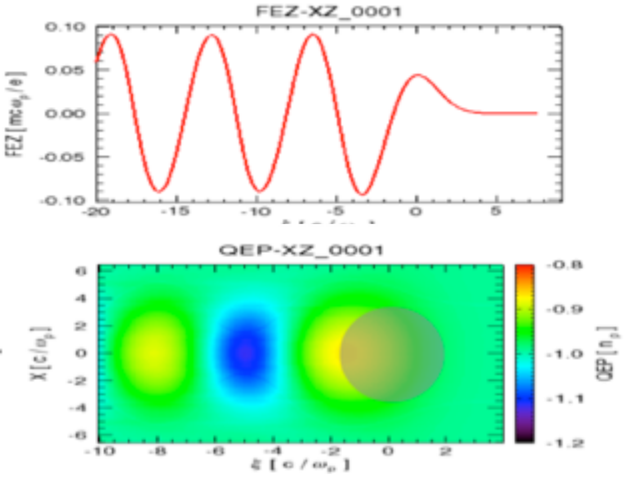
→ Relatively easy for **Laser** and **Electron** bunches.

→ **Proton** beam relies on Self-Modulation.

Introduction – Beam Quality in PWA

Different regimes:

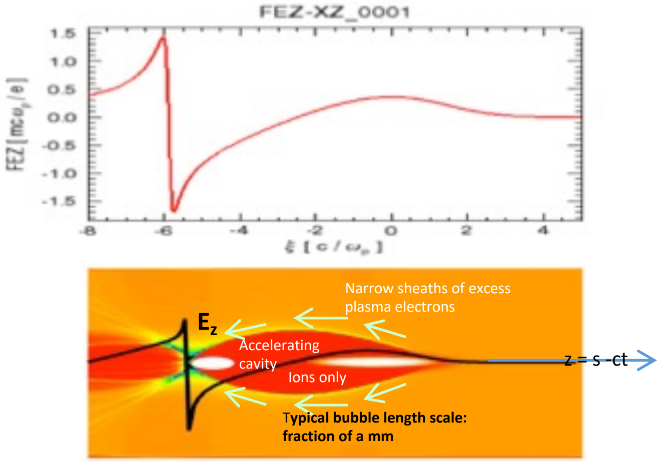
Linear regime: $n_{beam} << n_{pe}$



- *lower wakefields*
- *transverse forces not linear in r*

+ Symmetric for positive and negative witness bunches
+ Well described by theory

Blow-out regime: $n_{beam} >> n_{pe}$

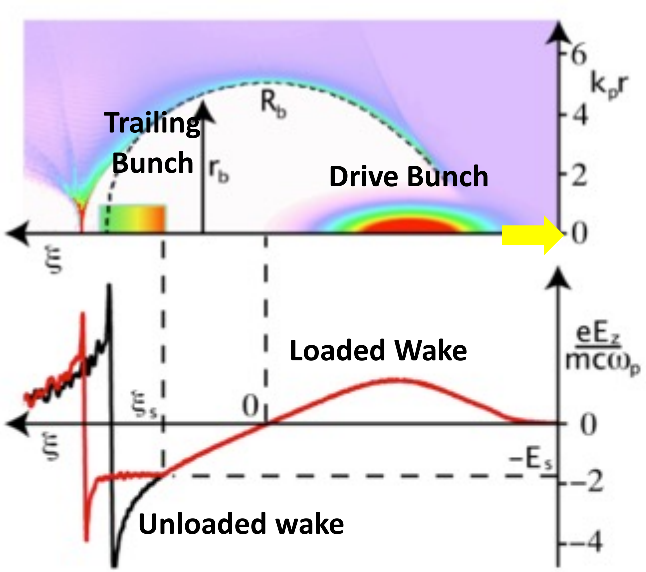


+ Higher wakefields
+ transverse forces linear in r (emittance preservation)
+ High charge witness acceleration possible

- *Requires more intense drivers*
- *Not ideal for positron acceleration*

Beam loading

Blown Out Wake



Sufficient charge in the witness bunch to flatten the accelerating field
→ **reduce energy spread**

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Laser-Driven Plasma Acceleration Facilities

ALEGRO

Advanced LinEar collider study GROup

Table 2.2: Laser facilities (≳100 TW) performing LWFA R&D in Europe.

Facility	Institute	Location	Energy (J)	Peak power (PW)	Rep. rate (Hz)
ELBE [16]	HZDR	Dresden, Ge	30	1	1
GEMINI [17]	STFC, RAL	Didcot, UK	15	0.5	0.05
LLC [18]	Lund Univ	Lund, Se	3	0.1	1
Salle Jaune [19]	LOA	Palaiseau, Fr	2	0.07	1
UHI100 [20]	CEA Saclay	Saclay, Fr	2	0.08	1
CALA* [21]	MPQ	Munchen, Ge	90	3	1
CILEX* [22]	CNRS-CEA	St Aubin, Fr	10-150	1-10	0.01
ELIbeamlines* [23]	ELI	Prague, TR	30	1	10
ILIL* [24]	CNR-INO	Pisa, It	3	0.1	1
SCAPA* [25]	U Strathclyde	Glasgow, UK	8	0.3	5
ANGUS	DESY	Hamburg, Ge	5	0.2	5

Table 2.3: Laser facilities (≳ 100 TW) performing LWFA R&D in Asia

Facility	Institute	Location	Energy (J)	Peak power (PW)	Rep. rate (Hz)
CLAPA	PKU	Beijing, PRC	5	0.2	5
CoReLS [28]	IBS	Gwangju, Kr	20-100	1-4	0.1
J-Karen-P* [29]	KPSI	Kizugawa, Jn	30	1	0.1
LLP [30]	Jiao Tong Univ	Shanghai, PRC	5	0.2	10
SILEX*	LFRC	Myanyang, PRC	150	5	1
SULF* [31]	SIOM	Shanghai, PRC	300	10	1
UPHILL [32]	TIFR	Mumbai, In	2.5	0.1	
XG-III	LFRC	Myanyang, PRC	20	0.7	

Table 2.1: US laser facilities (>100 TW) performing LWFA R&D.

Facility	Institute	Location	Gain media	Energy (J)	Peak power (PW)	Rep. rate (Hz)
BELLA [7]	LBNL	Berkeley, CA	Ti:sapphire	42	1.4	1
Texas PW [8]	U. Texas	Austin, TX	Nd:glass	182	1.1	single-shot
Diocles [9]	U. Nebraska	Lincoln, NE	Ti:sapphire	30	1	0.1
Hercules [10]	U. Michigan	Ann Arbor, MI	Ti:sapphire	9	0.3	0.1
Jupiter [11]	LLNL	Livermore, CA	Nd:glass	150	0.2	single-shot

Beam-Driven Plasma Acceleration Facilities

Table 3.1: Overview of PWFA facilities

	AWAKE	CLEAR	FACET-II	FF>>	SparcLAB	EuPR@Sparc	CLARA	MAX IV
operation start	2016	2017	2019	2018	2017 PWFA, LWFA	2022	2020	tbd
unique contribution	protons	rapid access and operation cycle	high energy peak-current electrons, positrons	MHz rep rate 100kW average power 1 fs resolution bunch diagn. FEL gain tests	PWFA with COMB beam, LWFA external injection, test FEL	PWFA with COMB beam, X-band Linac LWFA ext. inj. test FEL	ultrashort e^- bunches	low emittance, short pulse, high-density e^- beam
research topic	HEP	instrumentation irradiation AA technology	high intensity e^-, e^+ beam driven exp.	high average power e^- beam driven exp.	PWFA LWFA FEL	PWFA, LWFA, FEL, other applications	FEL	PWFA, Soft X-FELs
user facility	no	yes	yes	no	no	yes	partially	no
drive beam driver energy ext. inject. witness energy	p^+ 400 GeV yes 20 MeV	e^- 200 MeV no na	e^- 10 GeV no/yes tb ugraded	e^- $0.4-1.5$ GeV yes?? $0.4-1.5$ GeV	e^- 150 MeV no 150 MeV	e^- 600 MeV no 600 MeV	e^- 240 MeV no na	e^- 3 GeV no 3 GeV
plasma density [cm^{-3}] length plasma tapering	Rb vapour 1-10E14 10 m yes	Ar, He capillary 1E16-1E18 5-20 cm na	Li oven 1E15-1E18 10-100 cm yes	H, N, noble gases 1E15-1E18 1-30 cm yes	H, capillary 1E16-1E18 3 cm yes	H, capillary 1E16-1E18 >30 cm yes	He, capillary 1E16-1E18 10-30 cm	H, gases 1E15-1E18 10-50cm yes
acc. gradient exp. E gain	1 GeV/m average 1+ GeV	na na	10+ GeV/m peak $\approx$10 GeV	10+ GeV/m peak $\approx$1.5 GeV	>1 GeV/m?? 40 MeV ??	>1 GeV/m?? > 500 MeV	na na	10+ GeV/m peak 3 GeV

FACET, SLAC, US – Electrons as Driver

Premier R&D facility for PWFA: Only facility capable of e^+ acceleration

- **Timeline:**
  - Commissioning (2011)
  - Experimental program (2012-2016)
- **Key PWFA Milestones:**
  - ✓ Mono-energetic e^- acceleration
  - ✓ High efficiency e^- acceleration
  - ✓ First high-gradient e^+ PWFA
  - ✓ Demonstrate required emittance, energy spread

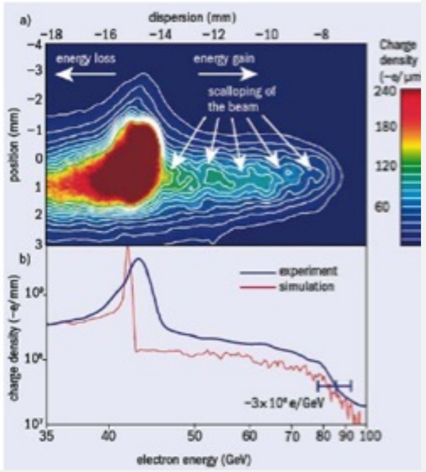
➔ **FACET-II starts in 2021**

- Facility hosted more than 200 users, 25 experiments
- One high profile result a year
- Priorities balanced between focused plasma wakefield acceleration research and diverse user programs with ultra-high fields
- Unique opportunity to develop future leaders

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

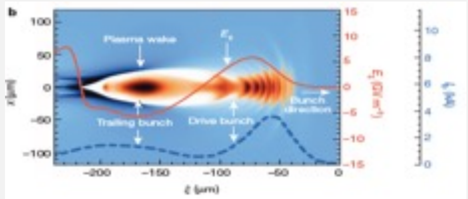
*I. Blumenfeld et al, Nature 455, p 741 (**2007**)*

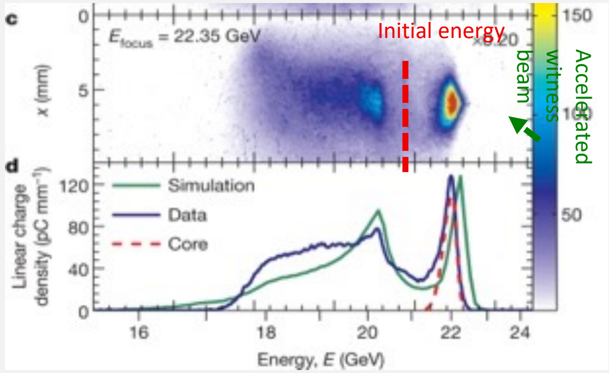
→ **gradient of 52 GV/m**



High-Efficiency acceleration of an electron beam in a plasmas wakefield accelerator, 2014

*M. Litos et al., doi, Nature, 6 Nov **2014**, 10.1038/nature 13882*

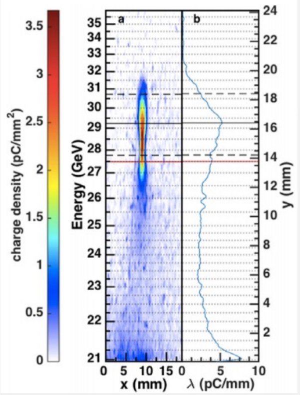




70 pC of charge accelerated, 2 GeV energy gain, 5 GeV/m gradient ➔ **Up to 30% transfer efficiency, ~2% energy spread**

9 GeV energy gain in a beam-driven plasma wakefield accelerator

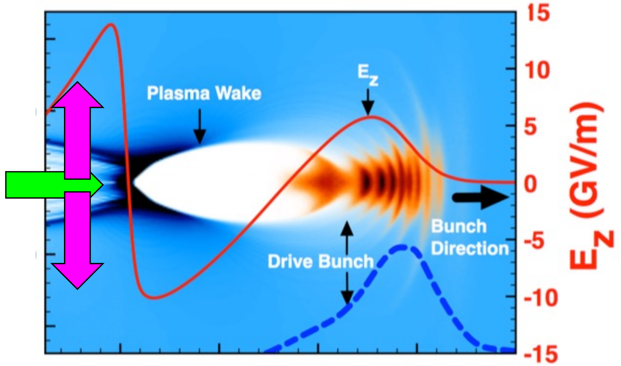
*M Litos et al **2016** Plasma Phys. Control. Fusion 58 034017*



Positron Acceleration, FACET

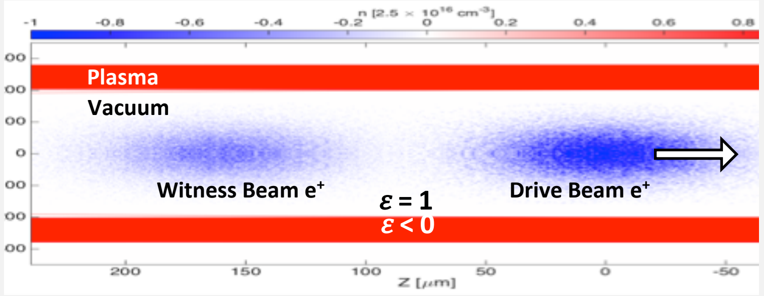
Positrons for high energy linear colliders: **high energy, high charge, low emittance**.

Electron-driven blowout wakes:



But the field is defocusing in this region.

Hollow plasma channel: positron propagation, wake excitation, acceleration in 30 cm channel.
S. Gessner et. al. Nat. Comm. 7, 11785 (2016)



There is no plasma on-axis, and therefore no complicated forces from plasma electrons streaming through the beam.

First demonstration of positron acceleration in plasma (FFTB)

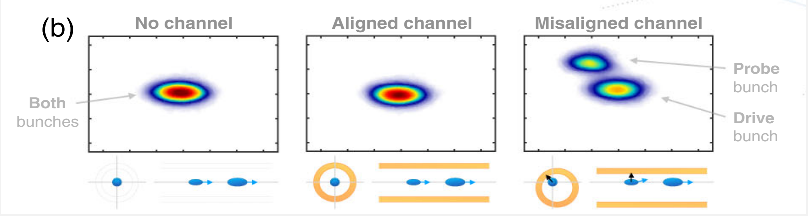
*B.E. Blue et al., Phys. Rev. Lett. 90, 214801 (**2003**)*
M. J. Hogan et. al. Phys. Rev. Lett. 90 205002 (2003).

Energy gain of 5 GeV. Energy spread can be as low as 1.8% (r.m.s.).

*S. Corde et al., Nature **524**, 442 (2015)*

Measurement of **transverse wakefields in a hollow plasma** channel due to off-axis drive bunch propagation.

*C. A. Lindstrøm et. al. Phys. Rev. Lett. 120 124802 (**2018**).*



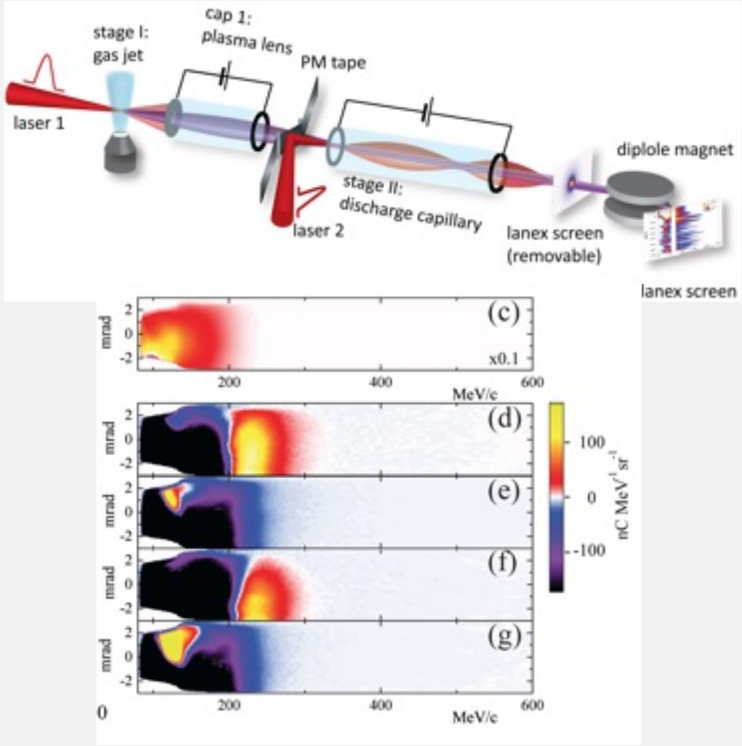
→ **Emittance blow-up is an issue!** → Use hollow-channel, so no plasma on-axis, no complicated forces from plasma electrons streaming through the plasma → but then strong transverse wakefields when beams are misaligned.

BELLA, Berkeley Lab, US– Laser as Driver

Laser Driven Plasma Wakefield Acceleration Facility: Today: PW laser!

Multistage coupling of independent laser-plasma accelerators

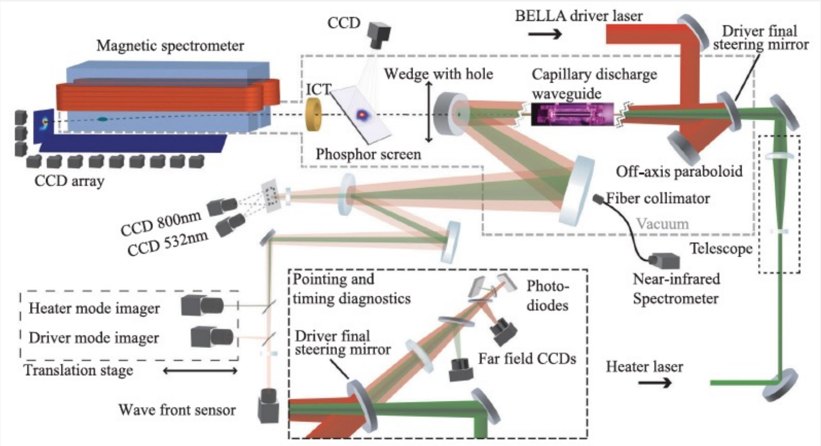
*S. Steinke, Nature **530**, 190 (2016)*



Staging demonstrated at 100MeVs level.

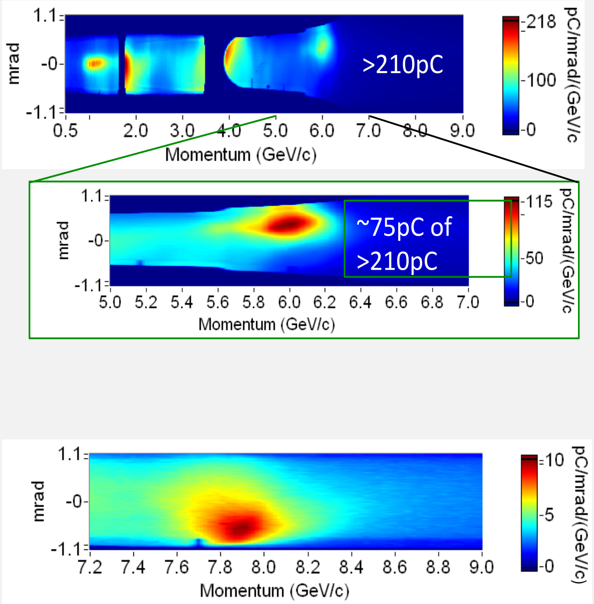
Petawatt laser guiding and electron beam **acceleration to 8 GeV** in a laser-heated capillary discharge waveguide

*A.J.Gonsalves et al., Phys.Rev.Lett. **122**, 084801 (2019)*



Laser heater added to capillary

Electron spectra, up to 6- 8 GeV



→ path to 10 GeV with continued improvement of guiding in progress

FLASHForward>>, DESY

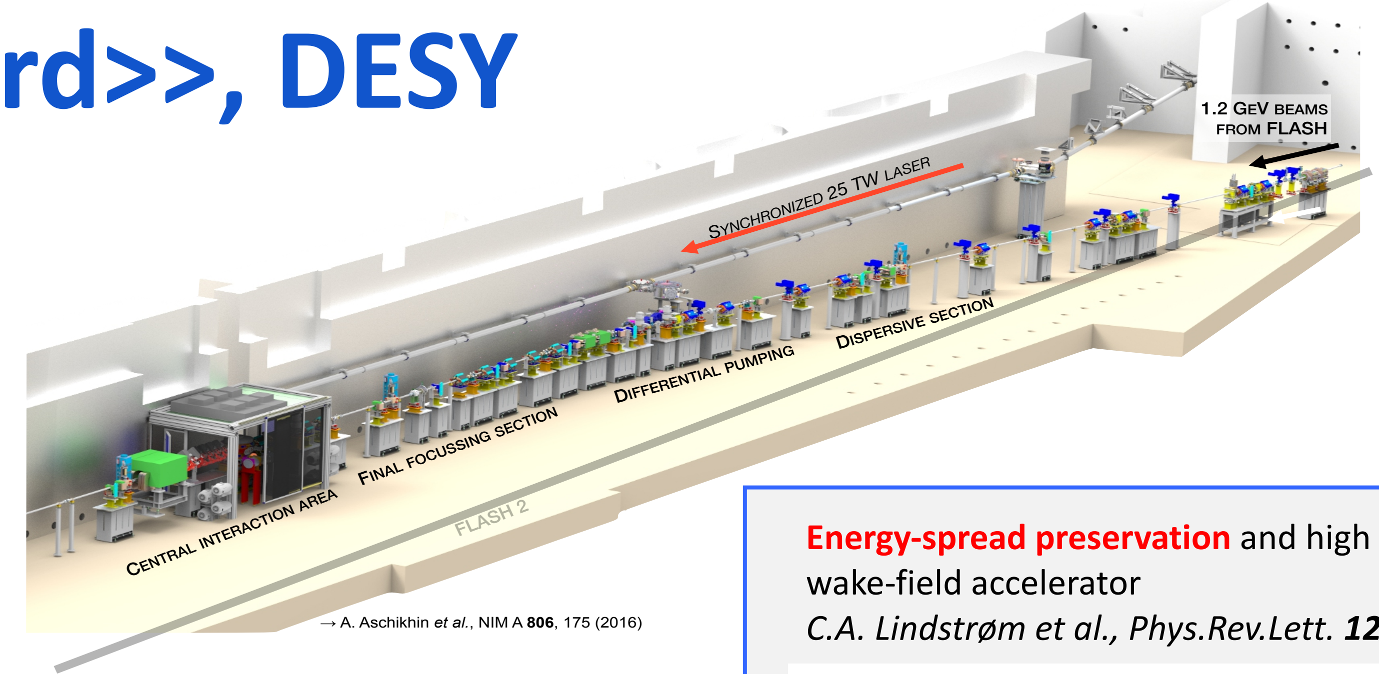
→ **FLASH** is an FEL user facility

- 10% of beam time dedicated to generic accelerator research and development

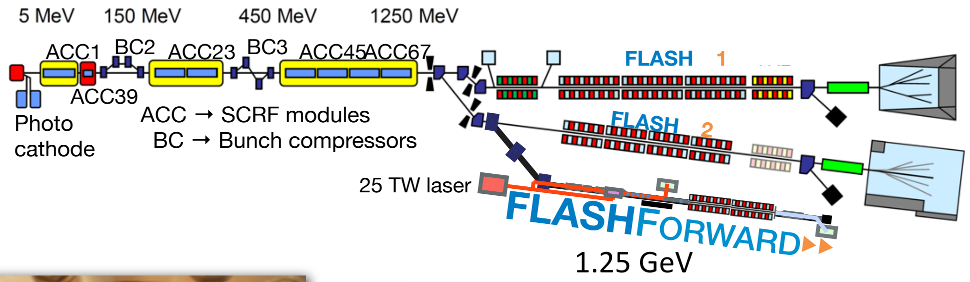
→ **FLASH**Forward▸▸ is a beam line for PWFA research

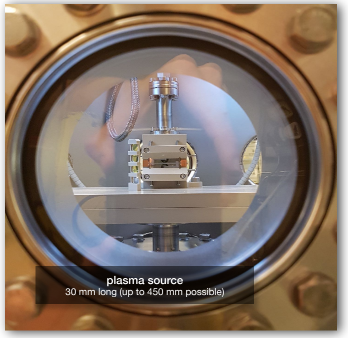
→ Both share the same superconducting accelerator based on ILC/XFEL technology. Typical electron beam parameters:

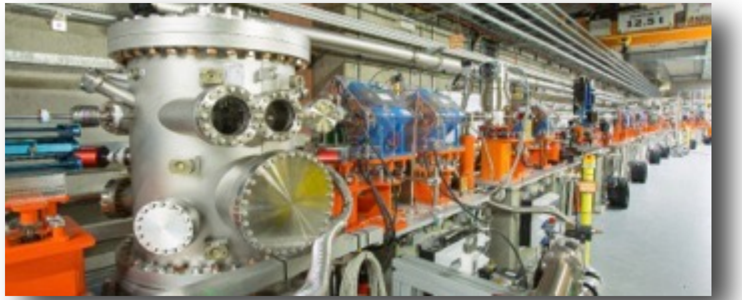
- ≲ **1.25 GeV energy** with a few **100 pC at ~100 fs** rms bunch duration, up to 1MHz repetition rate, few kW average power



→ A. Aschikhin *et al.*, NIM A **806**, 175 (2016)

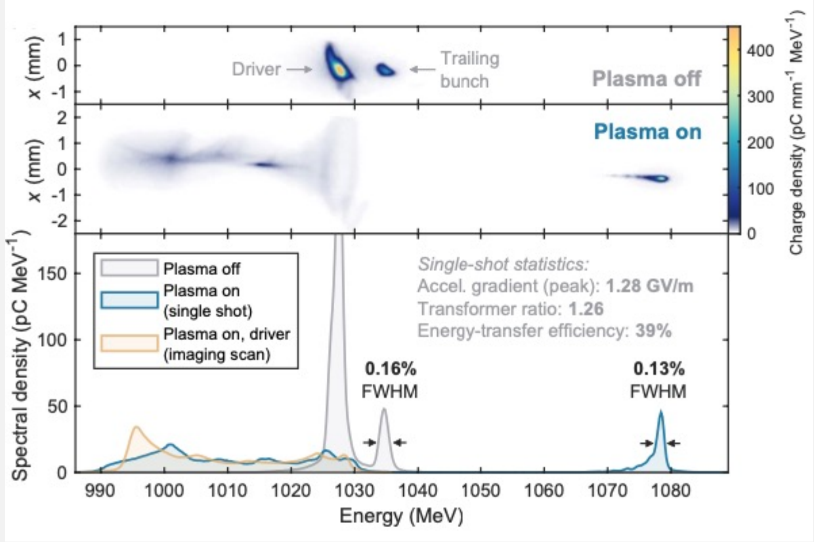






Energy-spread preservation and high efficiency in a plasma-wake-field accelerator

C.A. Lindstrøm et al., Phys.Rev.Lett. ***126****, 014801 (****2021****)*



Transfer efficiency **42+/-4%** with **0.2% energy spread**,
Up to **70%** when allowing energy spread increase

What about a proton beam as a driver?

Energy Budget for High Energy Plasma Wakefield Accelerators

Drive beams:

Lasers: ~40 J/pulse

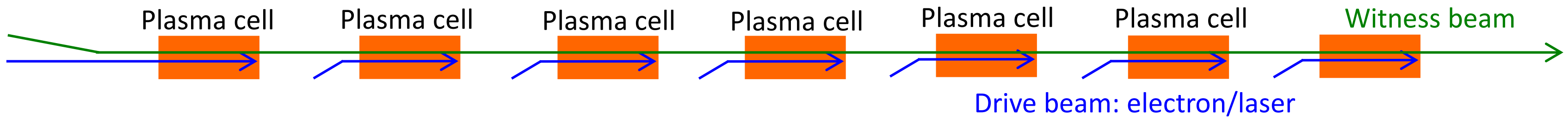
Electron drive beam: 30 J/bunch

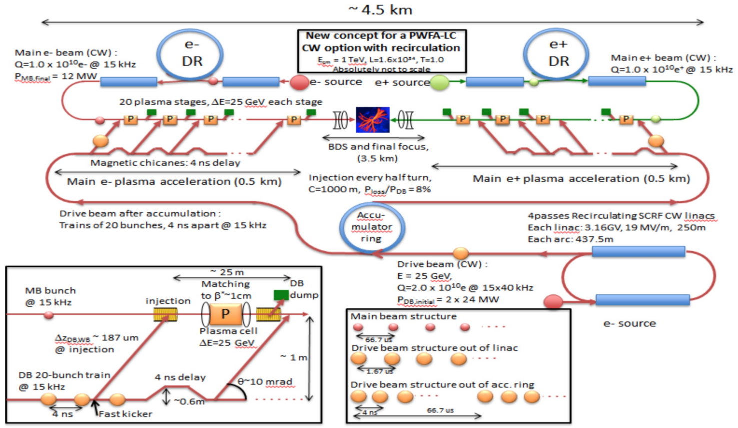
Witness beams:

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

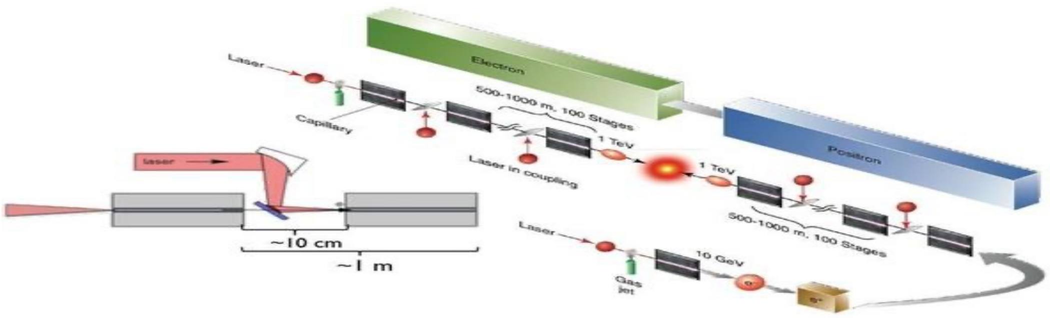
To reach TeV scale:

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





E. Adli *et. al*.,arXiv:1308.1145 [physics.acc-ph]



C. B. Schroeder *et. al*. Phys. Rev. ST Accel. Beams **13**, 101301

Energy Budget for High Energy Plasma Wakefield Accelerators

Drive beams:

Lasers: ~40 J/pulse

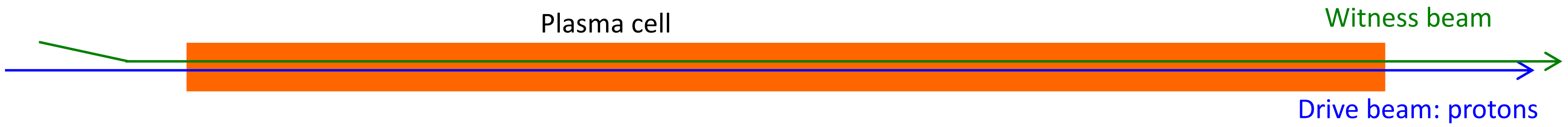
Electron drive beam: 30 J/bunch

Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

Witness beams:

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

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

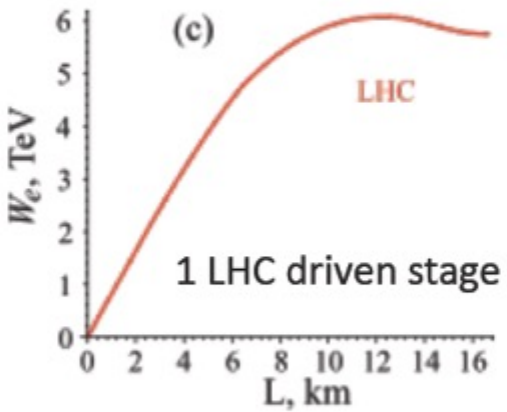


Dephasing:

SPS: ~70 m

LHC: ~few km

FCC: ~ ∞



State of the Art and Goals for HEP Collider

	Current	FEL (Intermediate Goal)	Collider (Final Goal)
Charge (nC)	0.01 – 0.1	0.01 – 0.1	0.1– 1
Energy (GeV)	9	0.1 – 10	1000
Energy spread (%)	0.1	0.1	0.1
Emittance (um)	>50-100 (PWFA), 0.1 (LFWA)	0.1– 1	0.01
Staging	single, two	single, two	multiple
Wall plug efficiency (%)	0.1	<0.1 - 10	10
Rep Rate (Hz)	10	10^1 - 10^6	10^4 - 10^5
Avg. beam power (W)	10	10^1 - 10^6	10^6
Acc. Distance (m)/stage	1	1	1 – 5
Continuous run	24/1	24/1 – 24/7	24/365
Parameter stability	1%	0.1%	0.1%
Simulations	days	days - 10^7	improvements by 10^7
Positron acceleration	acceleration		emittance preservation
Plasma cell (p-driver)	10 m		100s m
Proton drivers	SSM, acceleration		emittance control

Various important milestones have been and will be achieved in internationally leading programmes at:
CERN, CLARA, CNRS, DESY, various centres and institutes in the Helmholtz Association, INFN, LBNL, RAL, Shanghai XFEL, SCAPA, SLAC, Tsinghua University and others.

New European research infrastructures involving lasers and plasma accelerator technology have been driven forward in recent years, namely ELI and EuPRAXIA, both placed on the ESFRI roadmap.

The distributed RI EuPRAXIA as well as the aforementioned internationally leading programmes **will pursue several important R&D milestones and user applications for plasma accelerators.**

ESPP Roadmap for Accelerator R&D

- As an outcome of the European Strategy for Particle Physics 2020**, CERN Council has mandated the Laboratory Directors Group (LDG) to define and maintain a prioritised accelerator R&D roadmap towards future large-scale facilities for particle physics**.
- **Expert Panels are convened**, which are steered by the 'Extended Laboratories Directory Group (LDG)'.
- In **autumn 2021**: prepare a report on the strategic roadmap for the **Council meeting in December 2021.**

European Strategy for Particle Physics - Accelerator R&D Roadmap
Final Report

Editor: N. Mounet[a]

Steering committee: D. Newbold[b,] (Chair), S. Bentvelsen[c], F. Bossi[d], N. Colino[e], A.-I. Etienvre[f], F. Gianotti[a], K. Jakobs[g], M. Lamont[a], W. Leemans[h], J. Mnich[a], E. Previtali[i], L. Rivkin[j], A. Stocchi[k], E. Tsesmelis[a]*

Expert panel chairs: R. Assmann[d,h], S. Bousson[k], M. Klein[l], D. Schulte[a], P. Védrine[f]

Expert panel editors: R. Assmann[d,h], B. Baudouy[f], L. Bottura[a], E. Gschwendtner[a], M. Klein[l], R. Ischebeck[j], C. Rogers[b], D. Schulte[a]

CERN Yellow Reports: Monographs, CERN-2021-XXX

Expert Panel
3 High-gradient Plasma and Laser Accelerators

Editors: R. Assmann[a,b], E. Gschwendtner[c], R. Ischebeck[d]

Panel members: R. Assmann[a,b,] (Chair), E. Gschwendtner[c] (Co-Chair), K. Cassou[e], S. Corde[f], L. Corner[g], B. Cros[h], M. Ferrario[b], S. Hooker[i], R. Ischebeck[d], A. Latina[c], O. Lundh[j], P. Muggli[k], P. Nghiem[l], J. Osterhoff[a], T. Raubenheimer[m], A. Specka[n], J. Vieira[o], M. Wing[p]*

Associated members: C. Geddes[q], M. Hogan[m], W. Lu[r], P. Musumeci[s]

- **Proposed delivery plan for the required R&D roadmap :**
  - Minimal plan: Plasma Collider and Particle Physics Facility **Feasibility and Pre-CDR Study** and **four Experimental Demonstration** of highly Important Technical R&D Milestones
  - Aspirational plan: **Four additional highly important experimental demonstrations** of R&D Milestones
  - **Ongoing projects and facilities**

Panel selected **8 out of 56** experimental demonstrations

"The expert panel considers those activities of very high priority and fully endorses them."

ESPP R&D Roadmap Delivery Plan

Feasibility and Pre-CDR Study

	Due	Title	Description
DEL2.1	6/24	Report Electron High Energy Case Study	Plasma accelerator from 175 GeV to 190 GeV, including full lattice, in/out-coupling, all magnetic elements, correctors, diagnostics, collective effects, synchrotron radiation, estimate of realistic performance, estimate of realistic footprint, estimate of realistic benefits in cost and size, understanding of scaling with beam energy for different technologies (laser-driven, electron-driven, proton-driven, DLA/THz).
DEL2.2	6/24	Physics Case of an Advanced Collider	Report from common study group with particle physicists on physics cases of interest at the energy frontier ($e^+ - e^-$ collider, $\gamma\gamma$) and at lower beam energies ($e^- p$ collider, dark matter search, ...).
DEL2.3	6/25	Report Positron High Energy Case Study	Equivalent to 2024 report on electron accelerator (see above).
DEL2.4	6/25	Report Low Energy Study Cases for Electrons and Positrons	Assessing the low energy regime around 15-50 GeV, achievable performance, foot print and cost, schemes and designs for first particle physics experiments with novel accelerators, needed R&D demonstration topics for low energy design and needed test facilities. Includes studies on a low energy, high charge plasma injector.
DEL2.5	12/25	Pre-CDR and Collider Feasibility Report	Input for decision point of European strategy, brings together work/reports achieved (see earlier). Complemented by report on Technical Readiness Levels (TRL report) for collider components and systems. Comparison of performance and readiness for different technologies (laser, electron, proton driven plasma, DLA/THz) for a possible focus on the most promising path for particle physics. Design of a staging experiment. Report on intermediate steps and need for a dedicated facility. Project plan for a CDR of an advanced collider.

4 Exp. Demo. of R&D Milestones

DEL3.1	12/25	High-Repetition Rate Plasma Accelerator Module	At least 1 kHz characterised, robust lifetime ($> 10^9$ shots), only the plasma cell, without full repetition rate beam test, include cooling and power handling assessment. Long-term goal: 15 kHz repetition rate.
DEL4.1	12/25	High-Efficiency, Electron-Driven Plasma Accelerator Module with High beam Quality	Beam demonstration of high efficiency PWFA module. 50% transfer efficiency from stored energy beam driver to stored energy beam witness
DEL5.1	12/25	Scaling of DLA/THz Accelerators	Staged dielectric laser/THz accelerator with 10 MeV energy gain, with transverse and longitudinal focusing with at least two stages. Long-term goal: Massively scale-able design printed on a chip.
DEL6.1	12/25	Spin-Polarised Beams in Plasma Accelerators	Demonstration of polarised electron beams from plasma with 10...20% polarization fraction. Long-term goal: Polarization 85%.

4 Additional Exp. Demo. of R&D Milestones

Topic	Milestones to be achieved by 2025	Far term goal
Scalable plasma source	Several metres long prototype with required plasma density and stability	10s to 100s metres of plasma source
High-charge, high-quality plasma accelerator module driven by laser pulses	Detailed specification of the parameters for a self-consistent demo remain to be finalised	Accelerator module with 1 nC high quality beam (outcome feasibility study)
Stable low-emittance electron source	Electron beam extracted with 50-250 MeV, 10-100 Hz, sub-micron emittance, 30-100 pC	15 kHz, >500 pC, <100nm emittance, fs bunch length, sub % energy spread
High-rep rate, high peak power laser	Demonstration of kW average power (e.g. 100Hz, 10J, <100fs or 1kHz, 1J , <100fs or another combination/scheme) Ti:sapp laser pulse	15 kHz rep rate, >100 Tera-Watt, 30% wall plug efficiency

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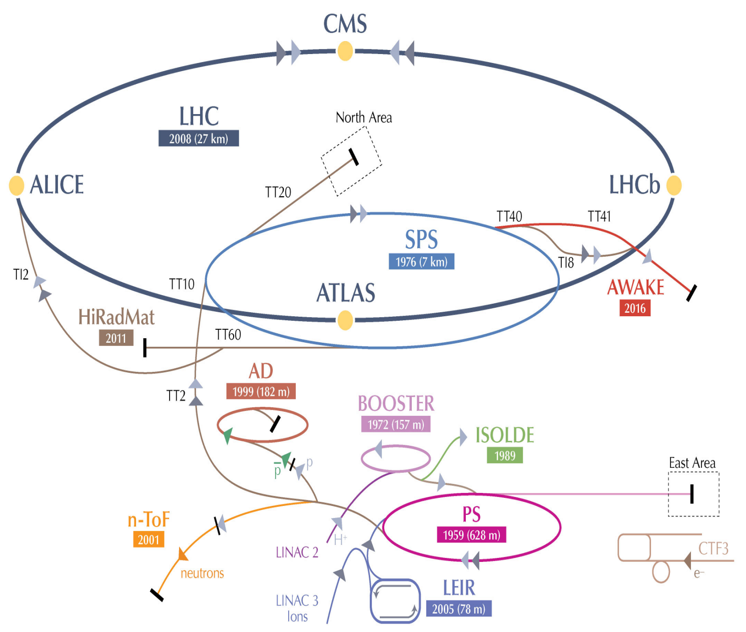
AWAKE at CERN



Advanced WAKEfield Experiment

- Proof-of-Principle Accelerator R&D experiment at CERN to study proton driven plasma wakefield acceleration.
- Collaboration of 23 institutes world-wide
- Approved in August 2013

AWAKE Run 1 (2016-2018):

✓ 1st milestone: Demonstrate seeded self-modulation of the proton bunch in plasma (2016/17)

✓ 2nd milestone: Demonstrate electron acceleration in plasma wakefield driven by a self-modulated proton bunch. (2018)

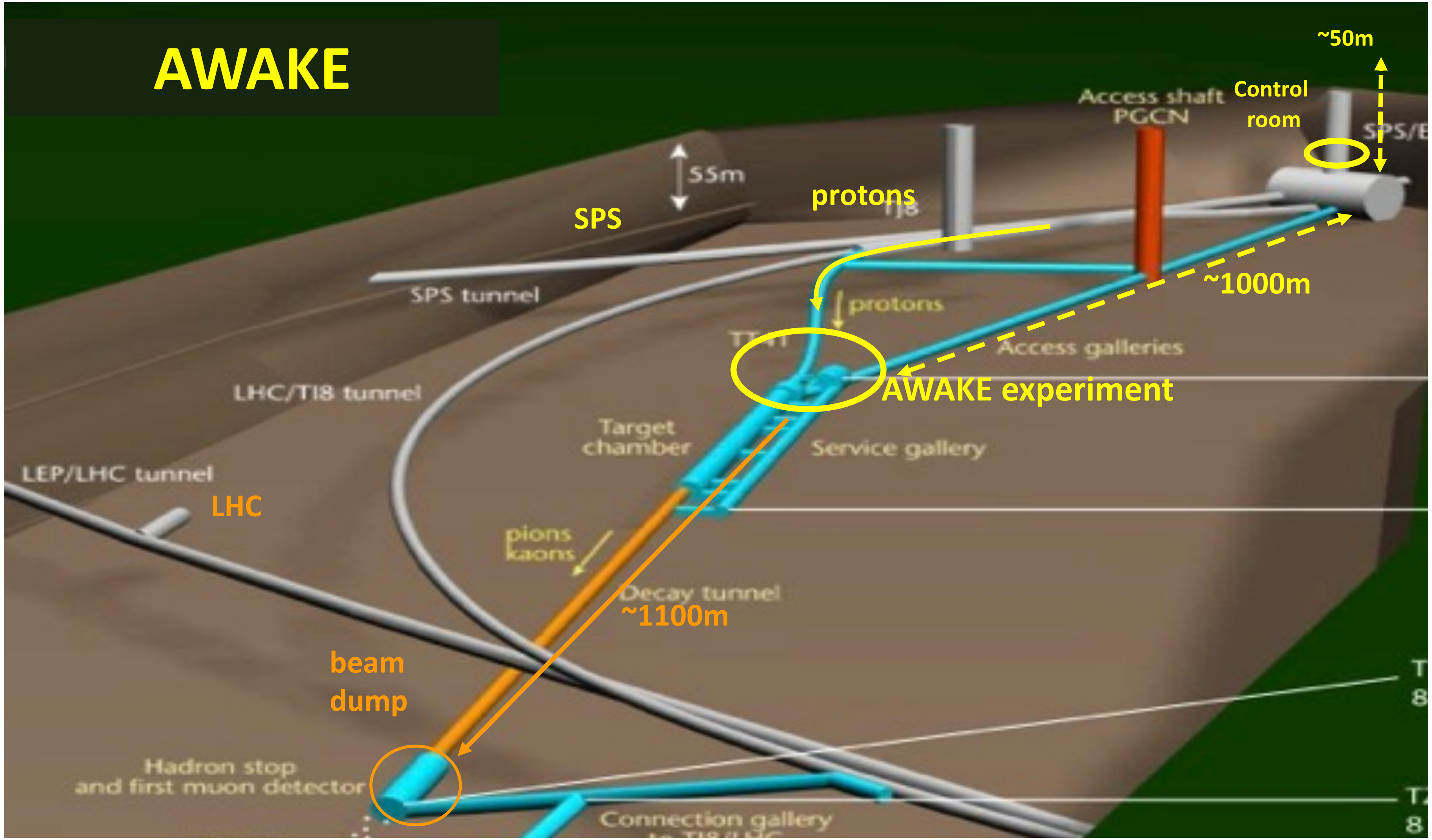
AWAKE Run 2 (2021 – ~2029):

Accelerate an electron beam to high energies (gradient of 0.5-1GV/m) while preserving the electron beam quality and demonstrate scalable plasma source technology.

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

Fixed target experiments for e.g. dark photon search.

AWAKE at CERN



AWAKE installed in CERN underground area

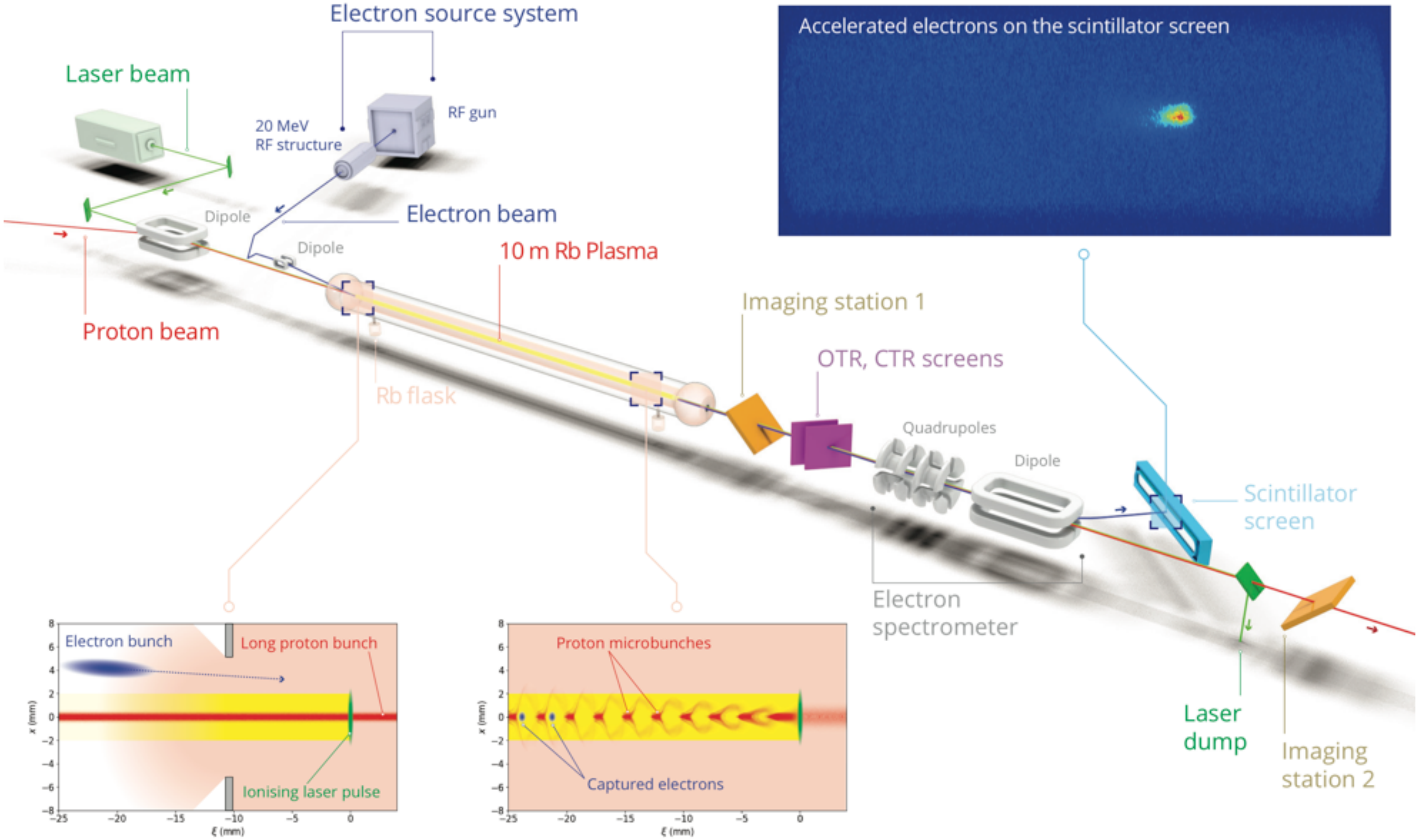
AWAKE

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-University of Düsseldorf, Düsseldorf, Germany
- University of Liverpool, Liverpool, UK
- ISCTE - Instituto Universitéario de Lisboa, Portugal
- Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
- Novosibirsk State University, Novosibirsk, Russia
- GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
- TRIUMF, Vancouver, Canada
- Ludwig-Maximilians-Universität, Munich, Germany
- University of Wisconsin, Madison, US
- Uppsala University, Sweden
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL, Lausanne, Switzerland

AWAKE Experiment

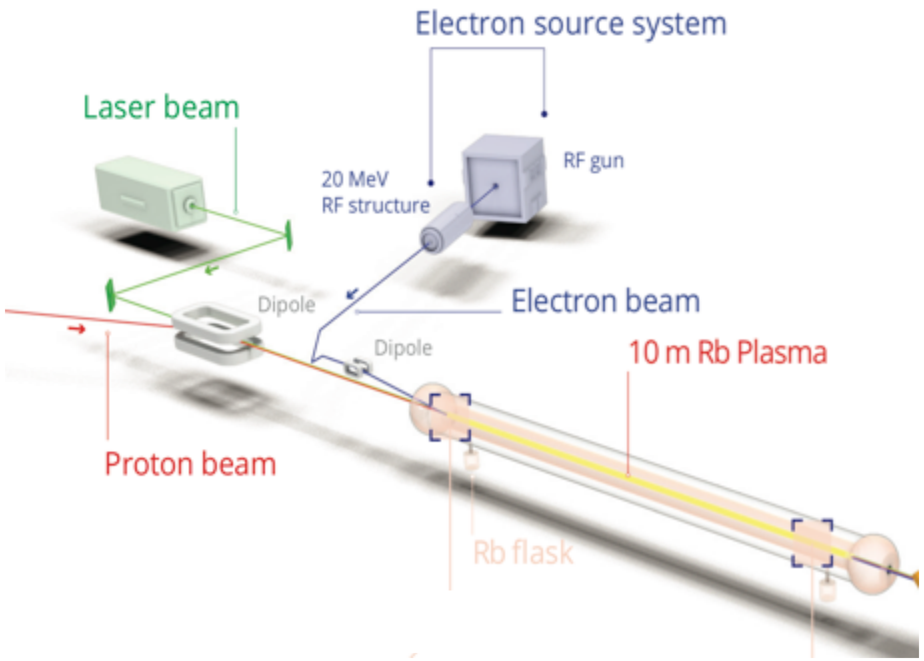
AWAKE Run 1: Proof-of Concept
2016/17: Seeded Self-Modulation of proton beam in plasma
2018: Electron acceleration in plasma

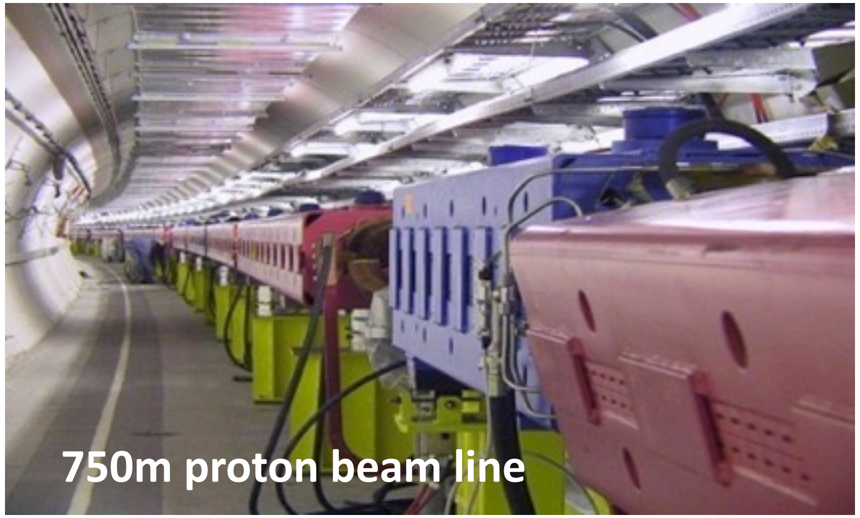


AWAKE Proton Beam Line

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

Plasma linear theory: $k_{pe}\ \sigma_r \leq 1$
With $\boldsymbol{\sigma_r}$ **= 200 μm**
$k_{pe} = \omega_{pe}/c = 5\ \mathrm{mm}^{-1}$
➔ $\mathbf{n_{pe} = 7 \times 10^{14}\ cm^{-3}}$

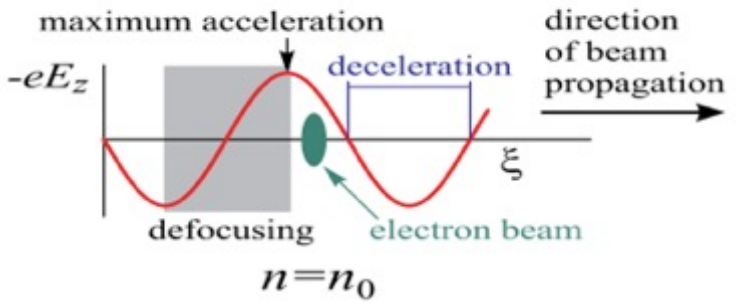


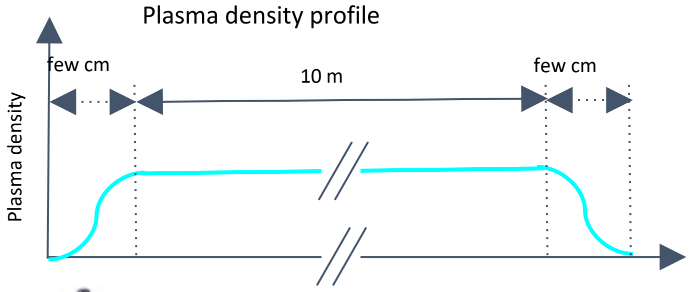


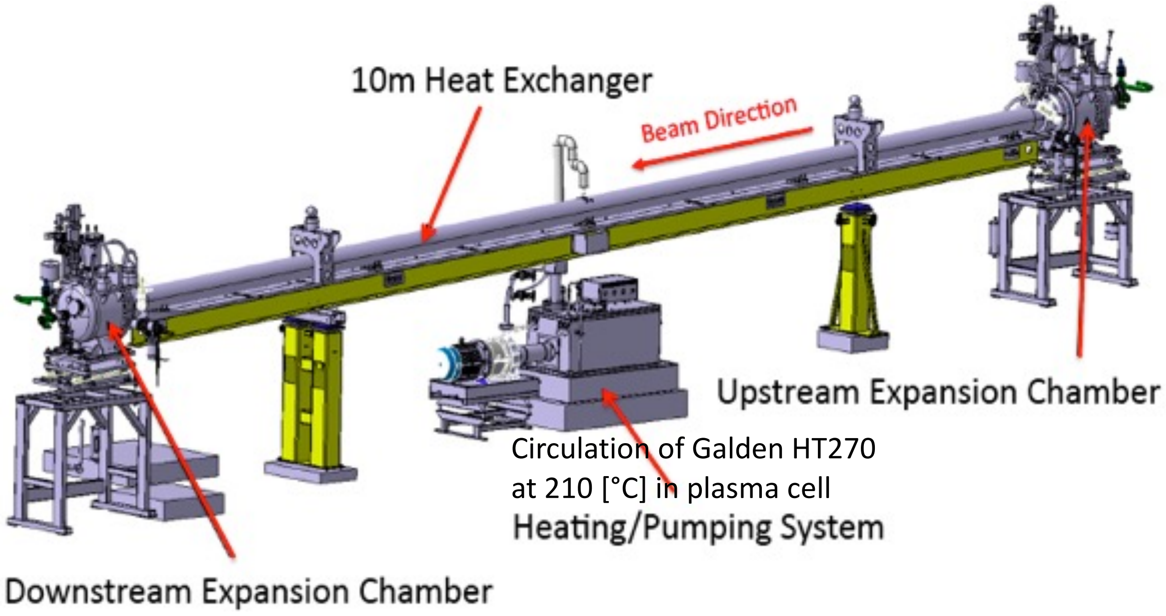
The AWAKE beamline is designed to deliver **a high-quality beam** to the experiment. The proton beam must be steered around a mirror which **couples a terawatt class laser** into the beamline.
Further downstream, the **witness electron beam** will injected into the same beamline.

AWAKE Plasma Cell

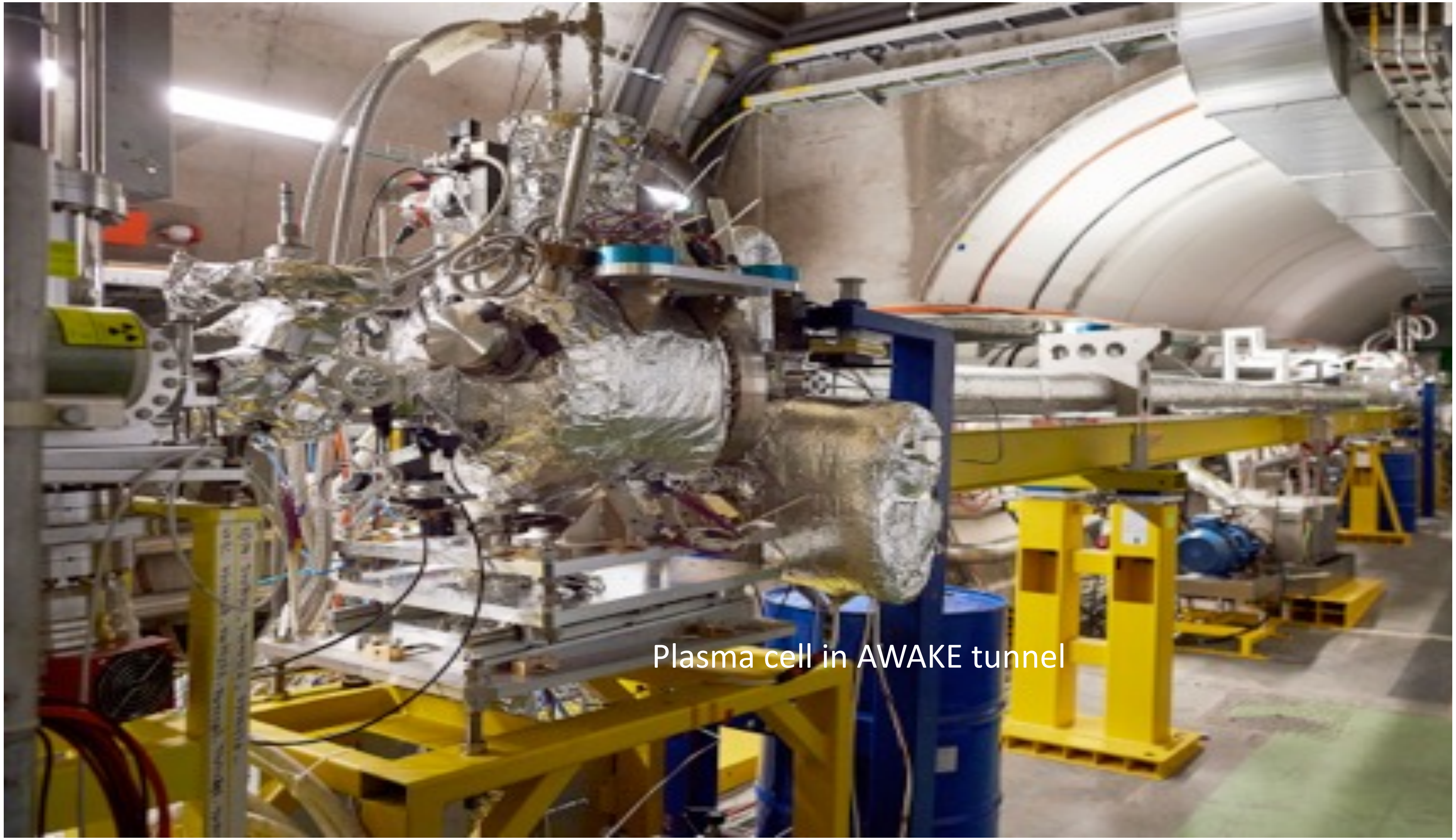
- **10 m long**, 4 cm diameter
- Rubidium vapor, field ionization threshold ~10^{12} W/cm^2
- Density adjustable from 10^{14} – 10^{15} cm^{-3} ➔ **7x 10^{14} cm^{-3}**
- Requirements:
  - **density uniformity better than 0.2%**
    - Fluid-heated system (˜220 deg)
    - Complex control system: 79 Temperature probes, valves
  - **Transition between plasma and vacuum as sharp as possible**





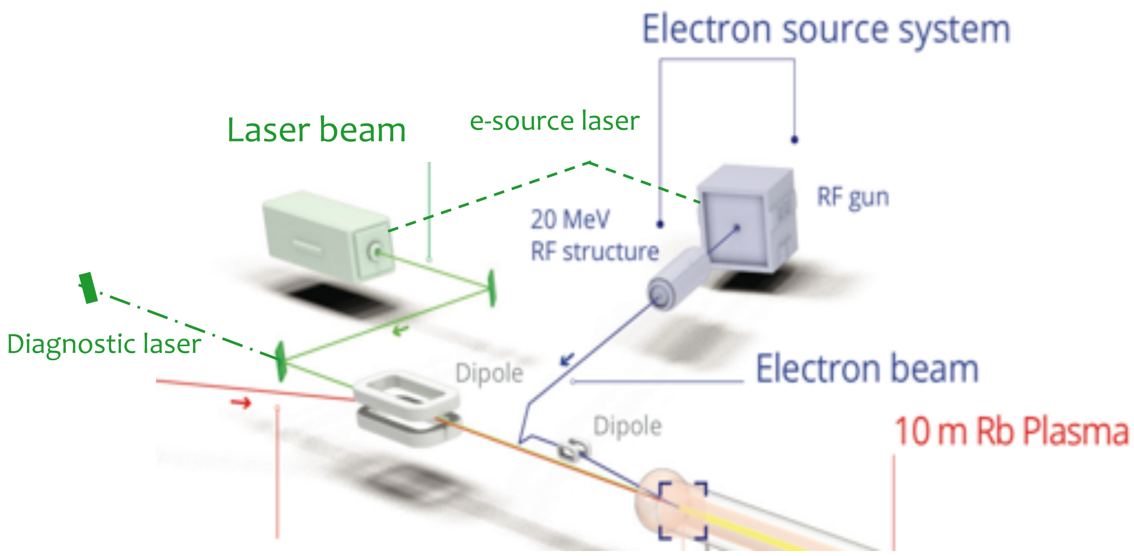


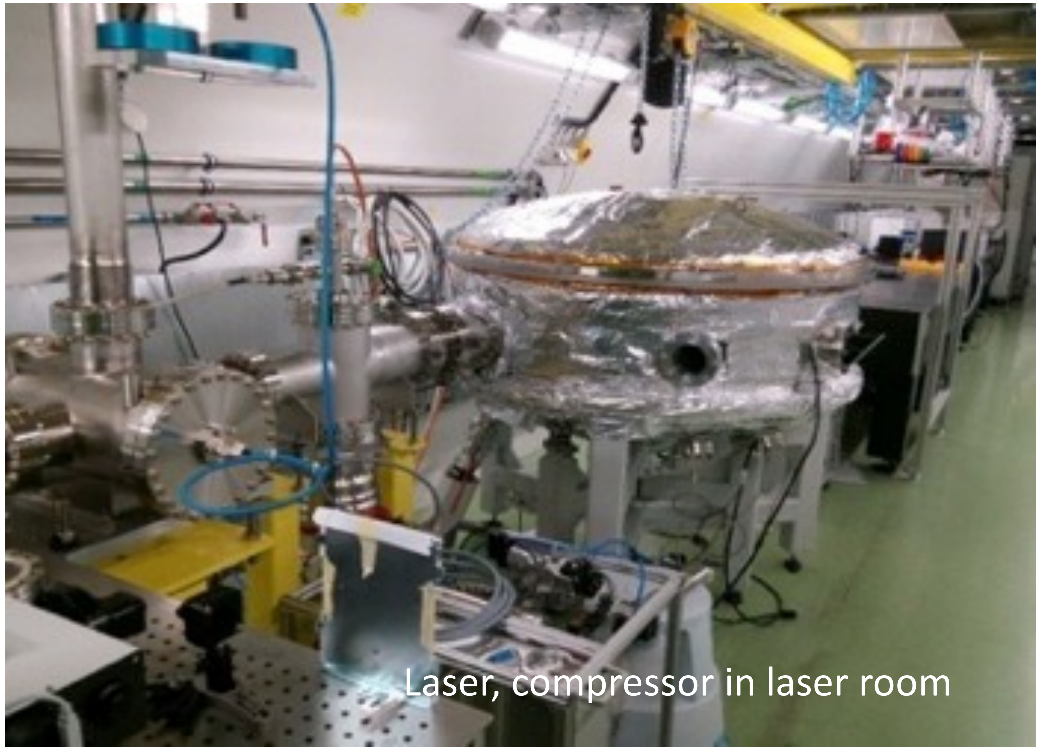
AWAKE Plasma Cell


Plasma cell in AWAKE tunnel

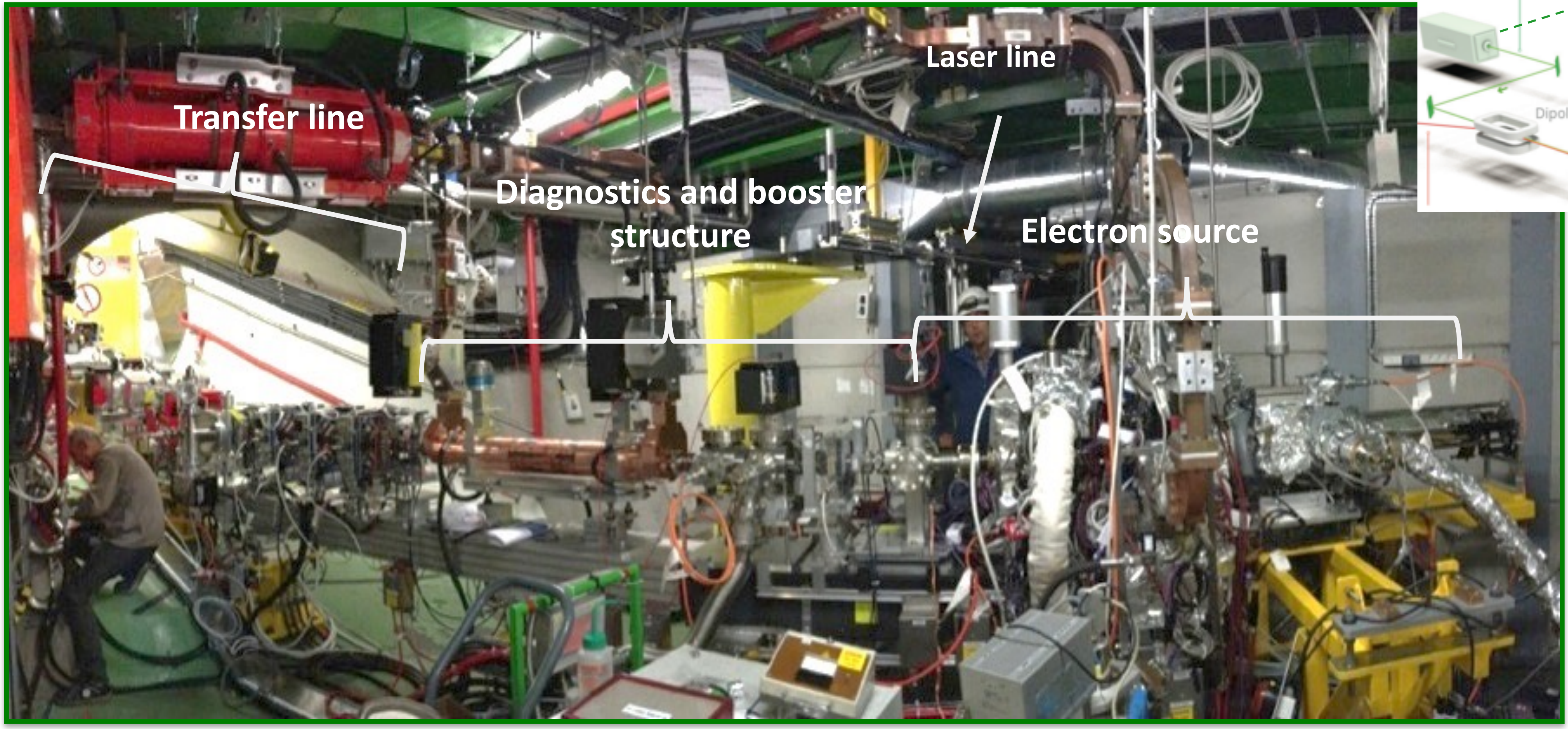
Laser and Laser Line

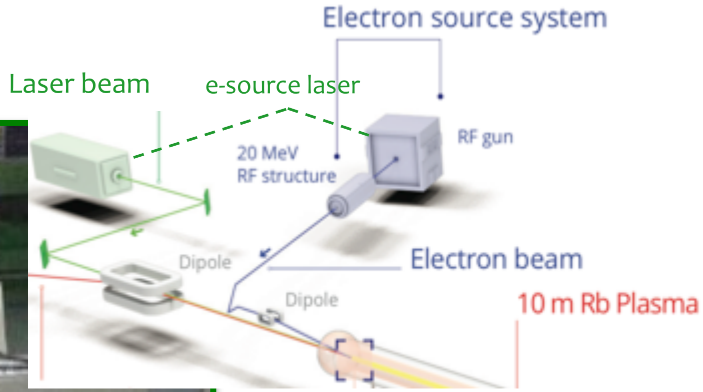
AWAKE uses a short-**pulse Titanium:Sapphire laser** to ionize the rubidium source.
→ Seeding of the self-modulation with the ionization front.
The laser can deliver up **to 500 mJ in a 120 fs pulse envelope**.





Electron Beam System

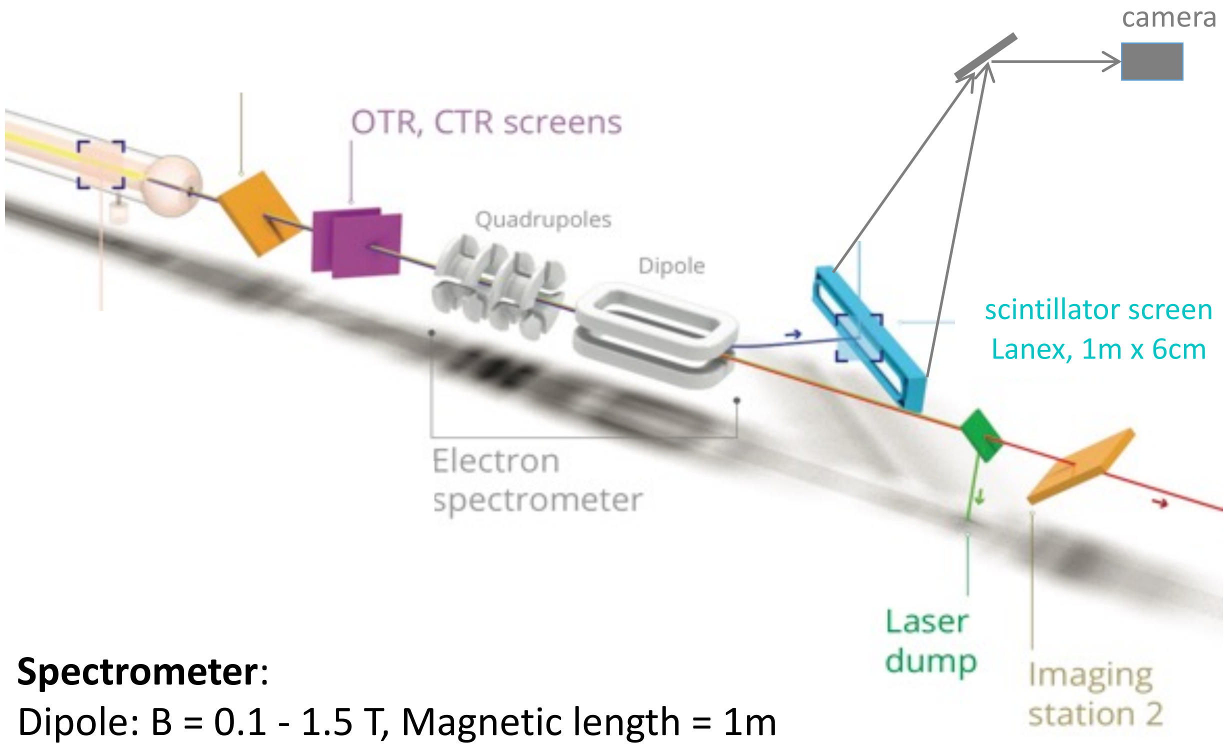




A Photo-injector originally built for a CLIC test facility is now used as electron source for AWAKE producing **short electron bunches at an energy of ~20 MeV/c.**
A **completely new 12 m long electron beam line** was designed and built to connect the electrons from the e-source with the plasma cell.

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

Electron Acceleration Diagnostics



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

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

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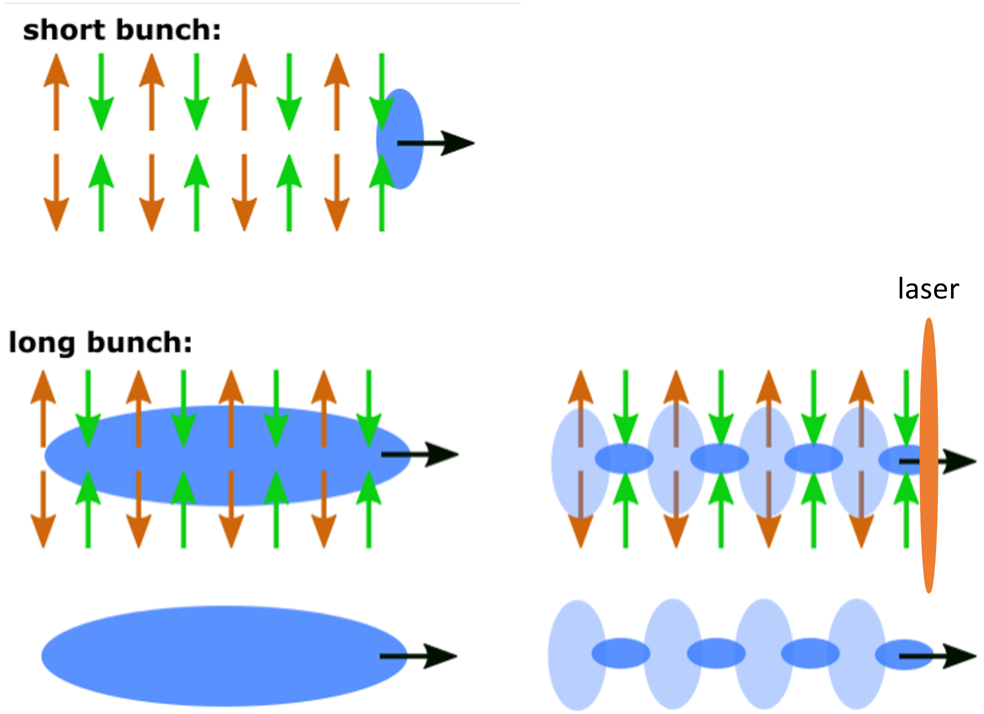
Seeded Self-Modulation of the Proton Beam

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

CERN SPS proton bunch: very long! (σ_z **= 12 cm**) → much longer than plasma wavelength (**λ = 1mm**)

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



Self-Modulation:

a) Bunch drives wakefields at the initial seed value when entering plasma.

- **Initial wakefields act back** on the proton bunch itself. → On-axis density is modulated. → Contribution to the wakefields is $\propto n_b$.

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

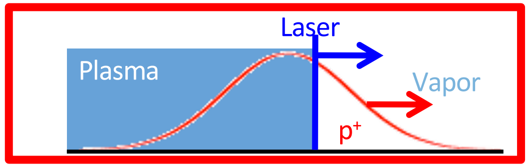
- Micro-bunches separated by plasma wavelength λ_{pe}.
- drive wakefields resonantly.

AWAKE: Seeding of the instability by

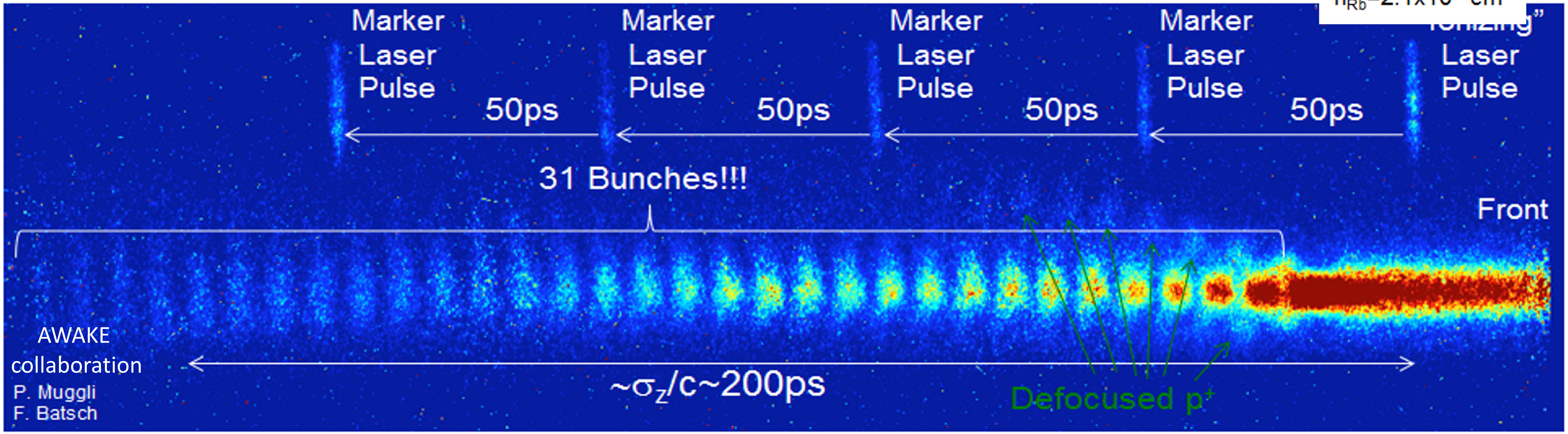
- Placing a laser close to the center of the proton bunch
- Laser ionizes vapour to produce plasma
- Sharp start of beam/plasma interaction
- → Seeding with ionization front

⇒ Seeded self-modulation (SSM)

Results: Direct Seeded Self-Modulation Measurement



n_{Rb}=2.1x10^{14}cm^{-3}

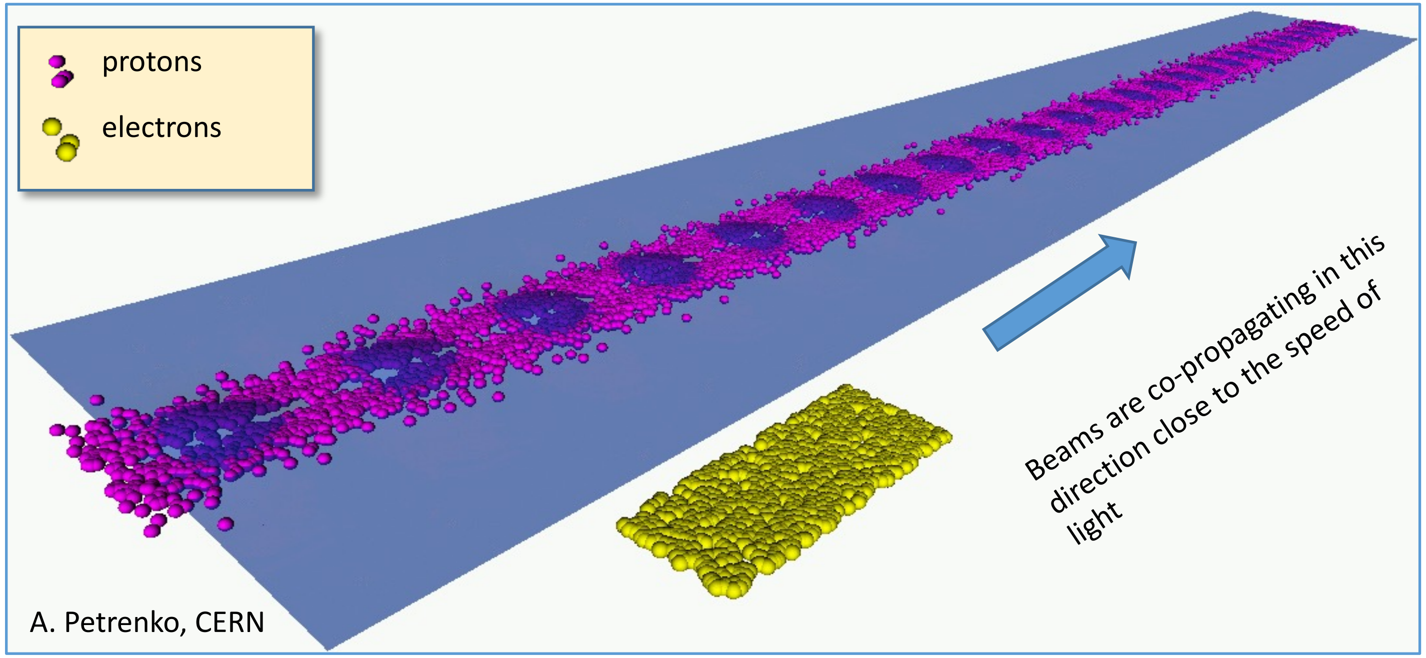


- Effect starts at laser timing → **SM seeding**
- **Density modulation** at the ps-scale visible
- Micro-bunches **present over long time scale** from seed point
- **Reproducibility** of the µ-bunch process against bunch parameters variation
- **Phase stability** essential for e$^-$ external injection.

→ 1st AWAKE Milestone reached

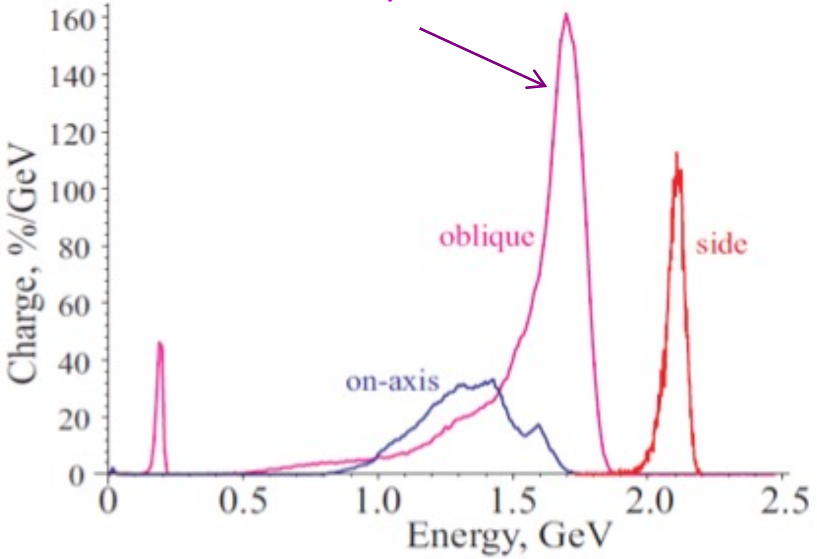
AWAKE Collaboration, Phys. Rev. Lett. 122, 054802 (2019).
M. Turner et al. (AWAKE Collaboration), 'Phys. Rev. Lett. 122, 054801 (2019).
M. Turner, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Accel. Beams 23, 081302 (2020)
F. Braunmueller, T. Nechaeva et al. (AWAKE Collaboration), Phys. Rev. Lett.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

AWAKE Run 1: Electron Acceleration Results



Electron acceleration after 10m:
What we expect with the AWAKE Run 1 setup:

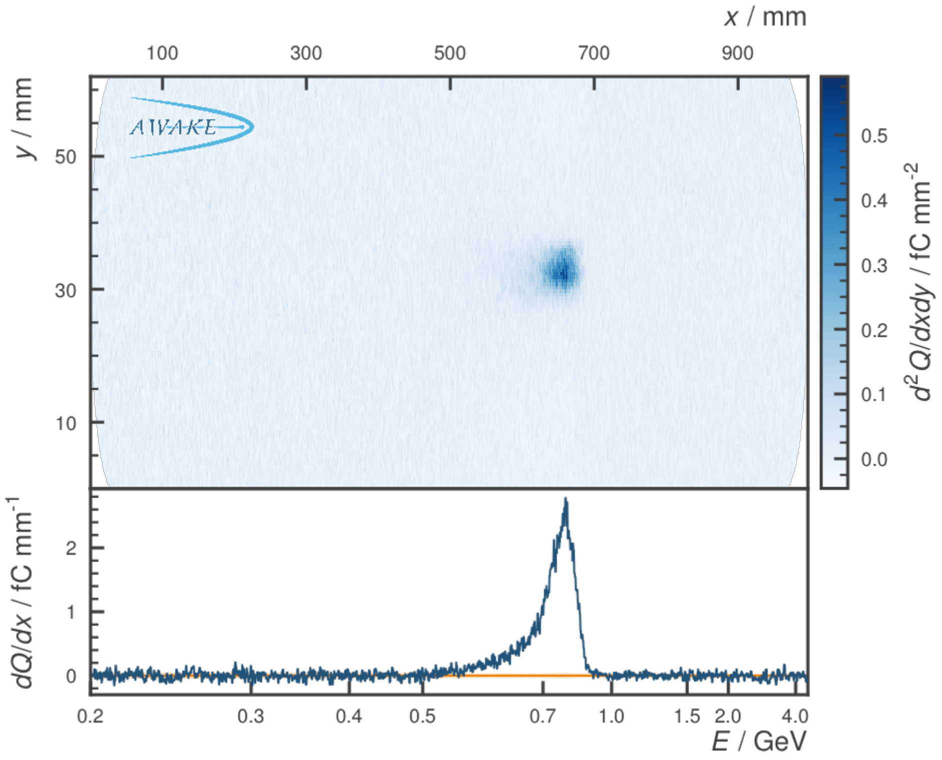
with baseline parameters: ~1.6 GeV



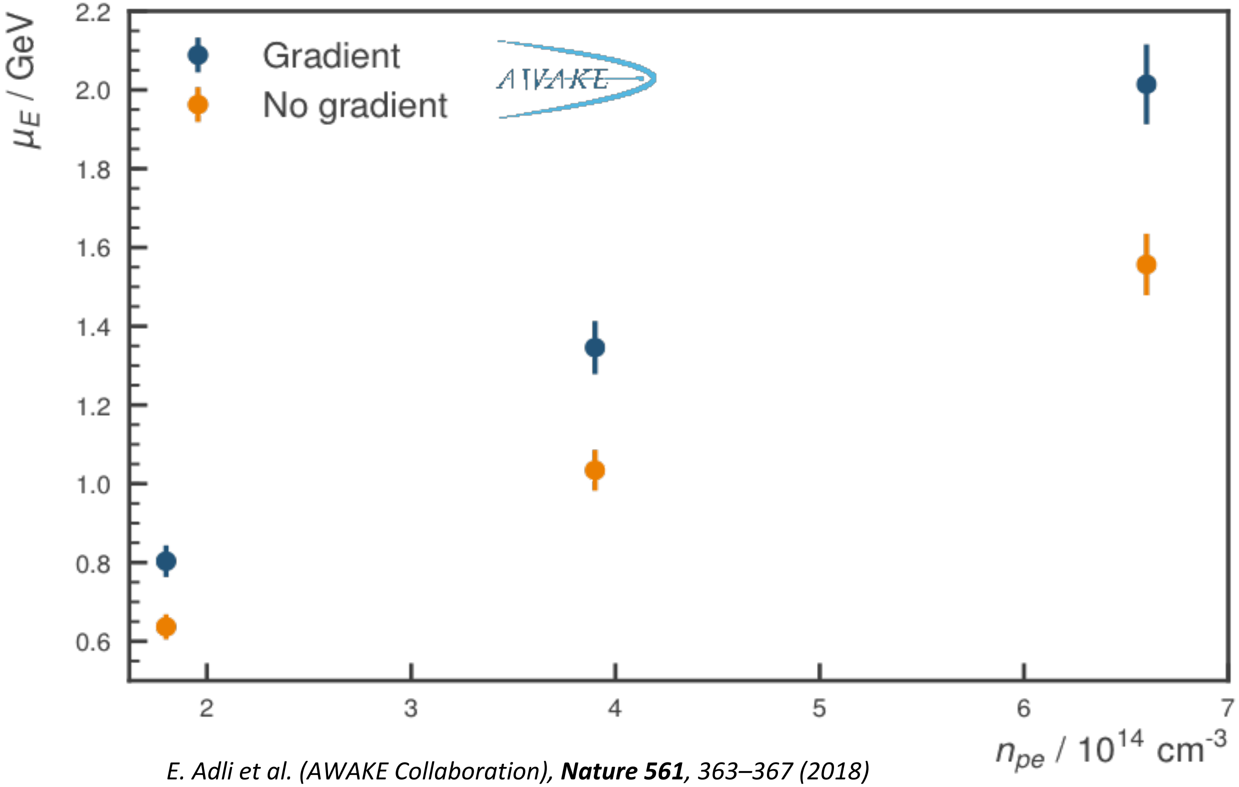
A. Caldwell et al., AWAKE Coll., Nucl. Instrum. A 829 (2016) 3

Electron Acceleration Results

Event at n_{pe} =1.8 x 10^{14} cm^{-3} with 5%/10m density gradient. → Acceleration to 800 MeV.



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



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

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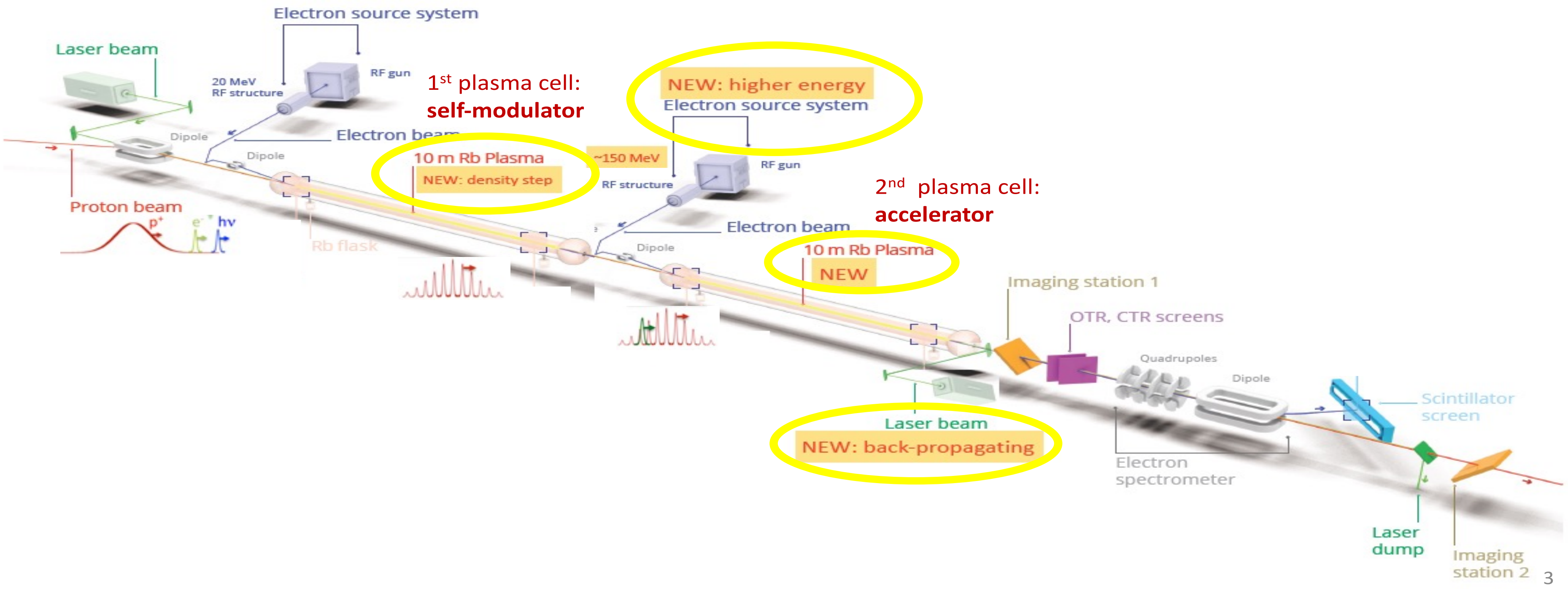
AWAKE Run 2

➔ **Demonstrate possibility to use AWAKE scheme for high energy physics applications in mid-term future!**
➔ **Start 2021, program goes beyond CERN Long Shutdown 3 (2027+)**!



Goals:

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

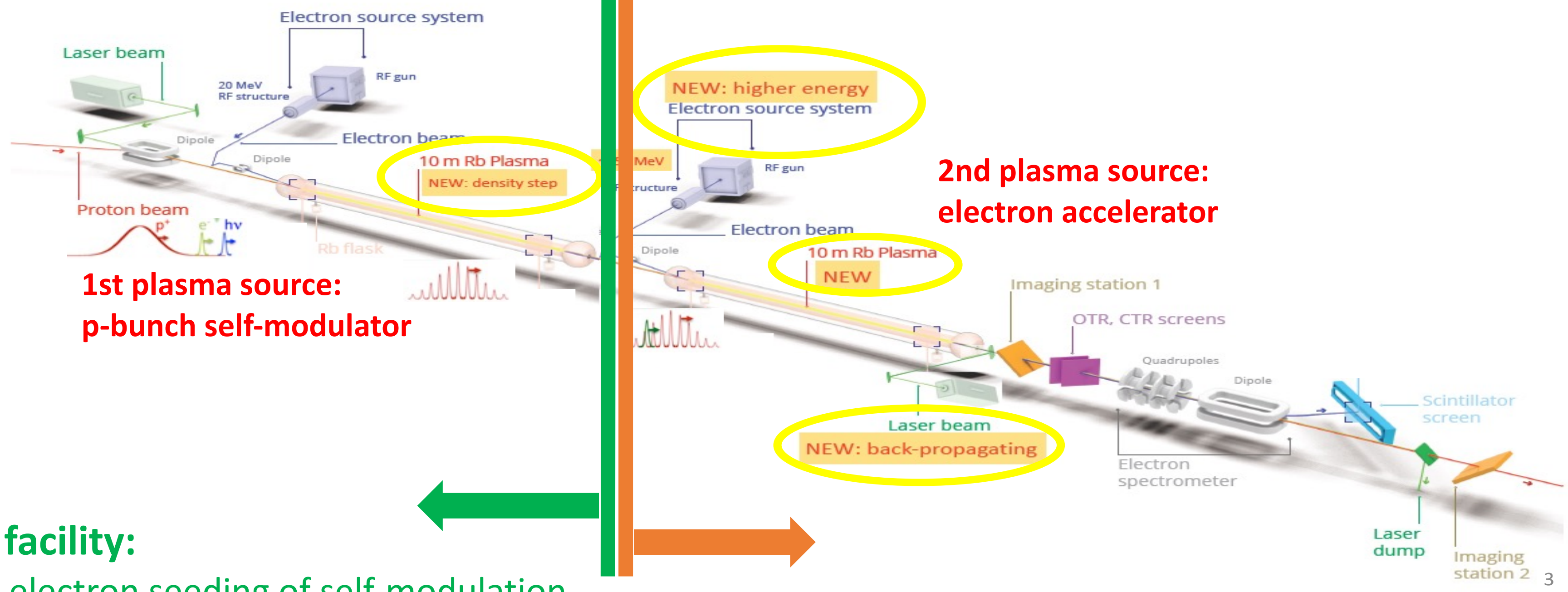
Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)

Demonstrate scalable plasma source technology (e.g. helicon prototype)

AWAKE Run 2 Program

AWAKE Run 2a and Run 2b until LS3 (2025):
Optimize self-modulation of the proton bunch

AWAKE Run 2c and Run 2d after LS3 (2027+) :
Optimize acceleration of electrons in p-driven plasma wakefield



In existing AWAKE facility:

Run 2a: demonstrate electron seeding of self-modulation in first plasma cell (2021/22)

Run 2b: demonstrate the stabilization of the micro-bunches with a density step in the plasma cell (2023/2024)

In extended AWAKE facility: (after LS3 2027+)

Run 2c: demonstrate electron acceleration and emittance preservation

Run 2d: demonstrate scalable plasma sources

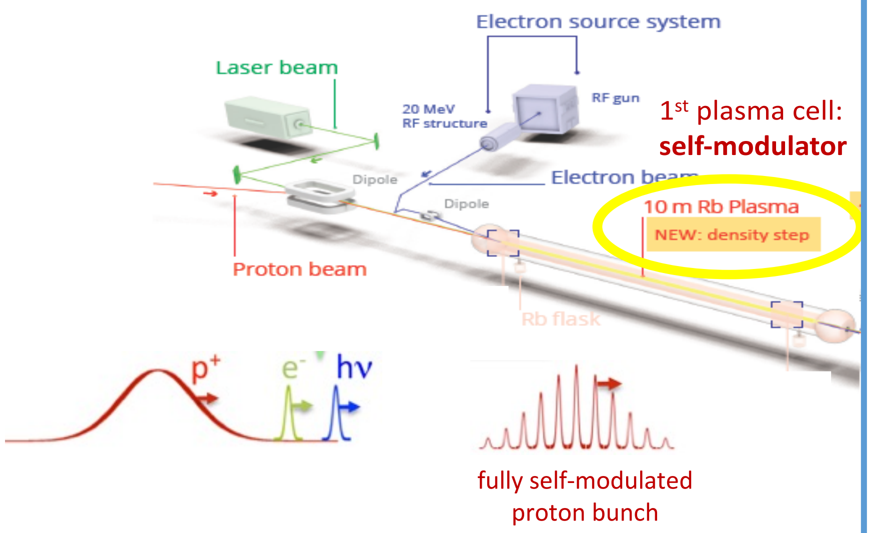
During CERN Long Shutdown 3:
dismantling of CNGS area
Installation of 2nd plasma source, 2nd electron beam system…

AWAKE Run 2a

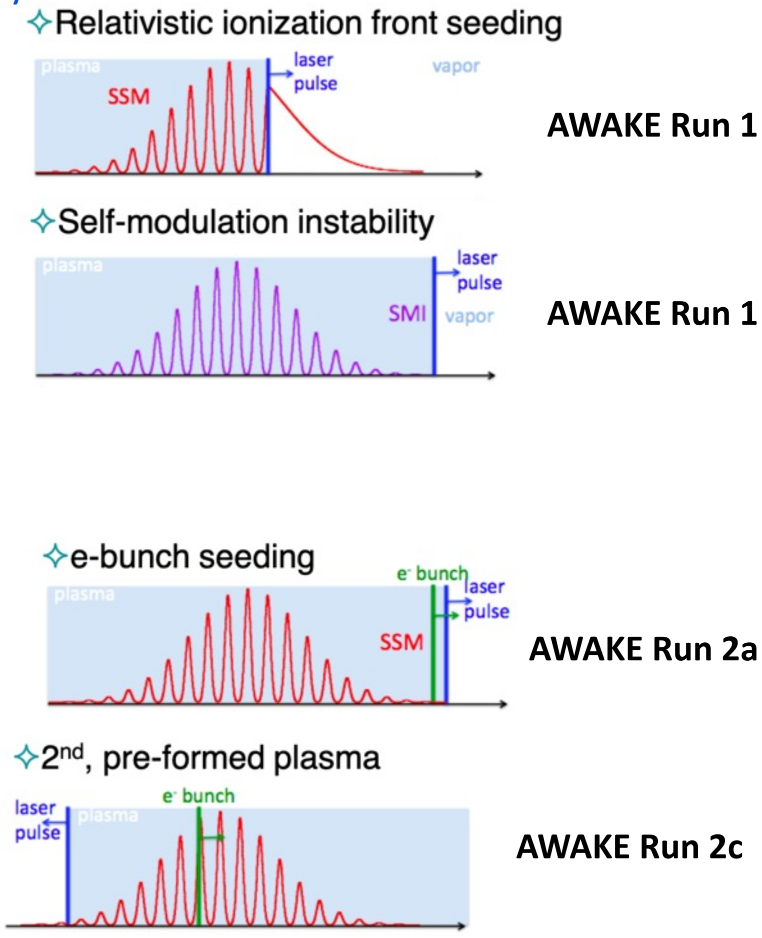
Goal: Electron bunch seeding:

→ Modulates entire proton bunch with phase reproducibility

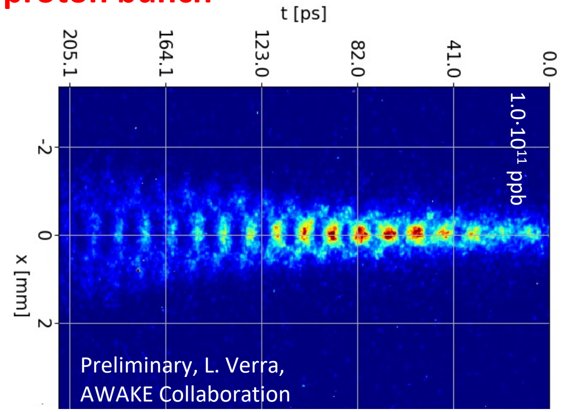
➔ Physics Program 2021/2022



Run 2a: Demonstrate electron seeding of self-modulation in first plasma cell.



Run 2a: experimental demonstration: electron-seeded SSM of the entire proton bunch



Run 1: Front-part of proton beam is not self-modulated

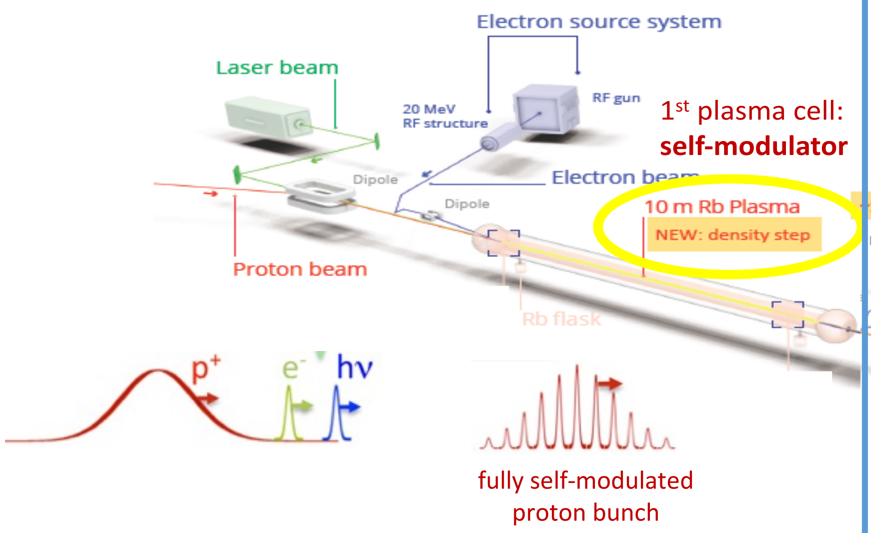
Run 2: → This can cause issues when the proton beam enters into the second plasma source

For Run 2: need fully self-modulated proton bunch

AWAKE Run 2b

- In constant-density plasma, wakefield amplitude decreases after saturation.
- In a plasma with density step within the SM grow: wakefield amplitude **maintains larger** after saturation.

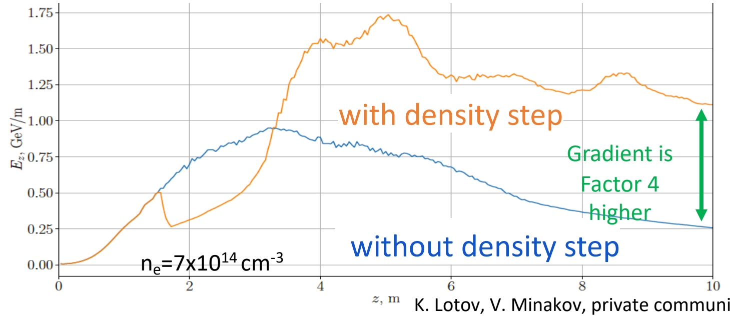
➔ Physics Program 2023/2024



Run 2a: Demonstrate electron seeding of self-modulation in first plasma cell.

Run 2b: Demonstrate the stabilization of the micro-bunches with a density step.

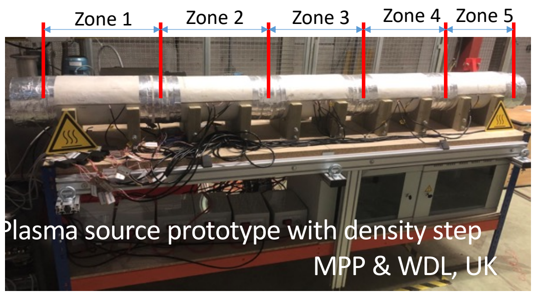
Gradient in 1st plasma source (self-modulator)



K. Lotov, V. Minakov, private communication

➔ new plasma source with density step capability

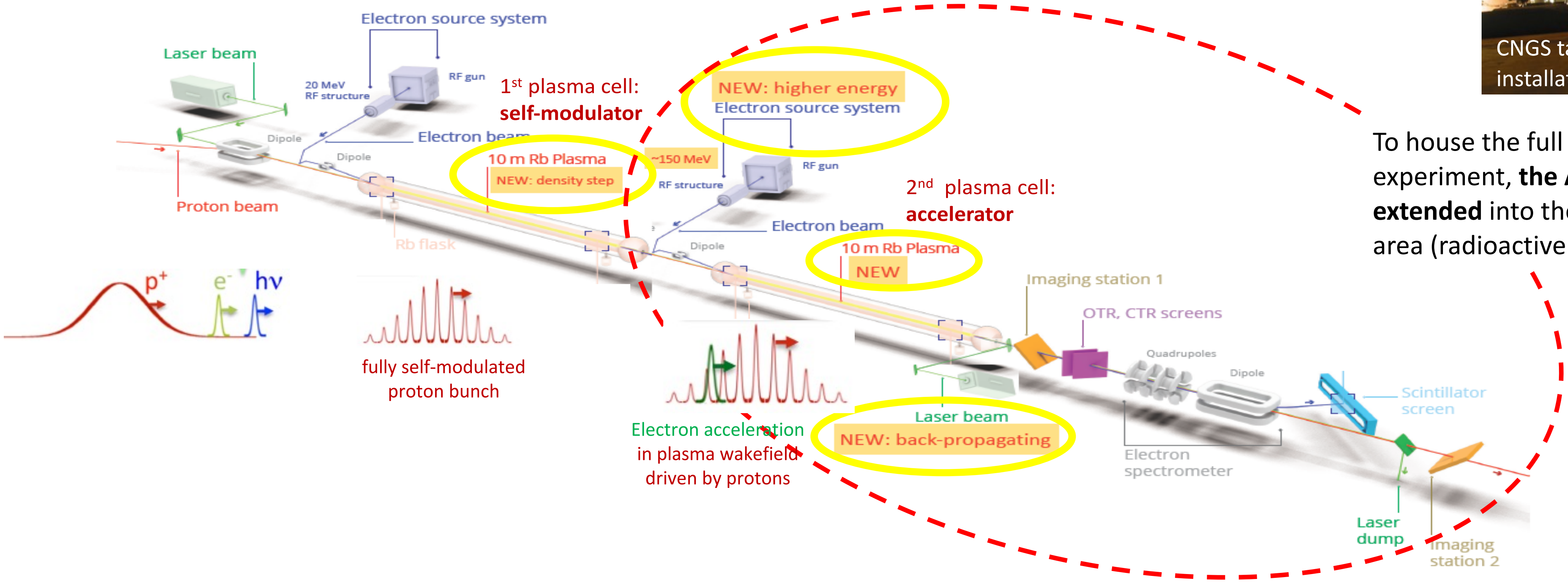
➔ novel plasma diagnostics to allow measurement of plasma 'wave' directly



MPP Munich

AWAKE Run 2c

- Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)
- Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)



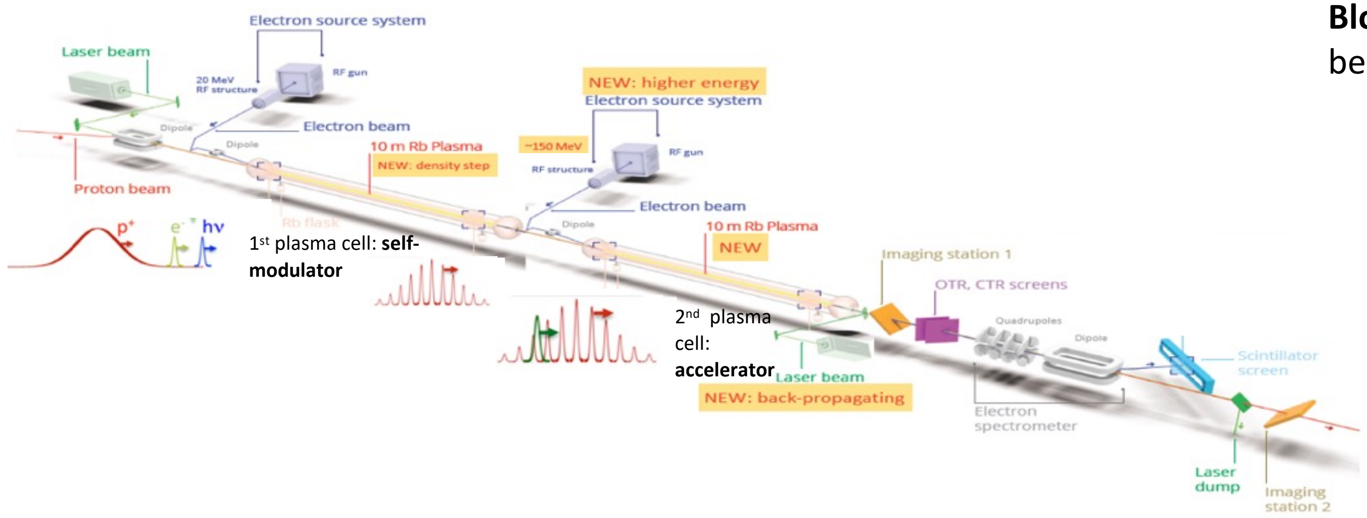
To house the full length of the Run 2 experiment, **the AWAKE area must be extended** into the former CNGS target area (radioactive!)

- New electron source and beam line, reuse run 1 e-source
- New plasma cell (Accelerator cell), reuse 2b self-modulator
- New laser to 2nd plasma cell (back-propagating)
- New diagnostics
- ***Expand the experimental facility (CNGS dismantling)***

➔ **Facility extension and installation: 2025/26/27**

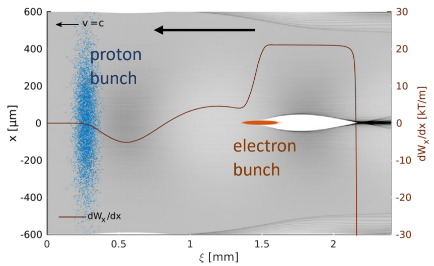
➔ **Physics program: 2027/28/…**

AWAKE Run 2c: Demonstrate Electron Acceleration and Emittance Preservation



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

Blow-out regime: **Beam loading**: reach small ∂E/E , **Match** electron beam transverse properties to the plasma

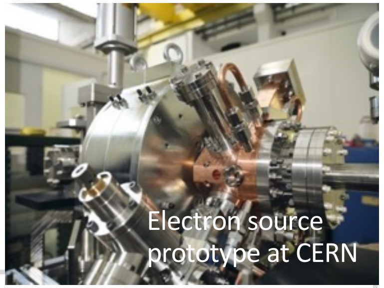


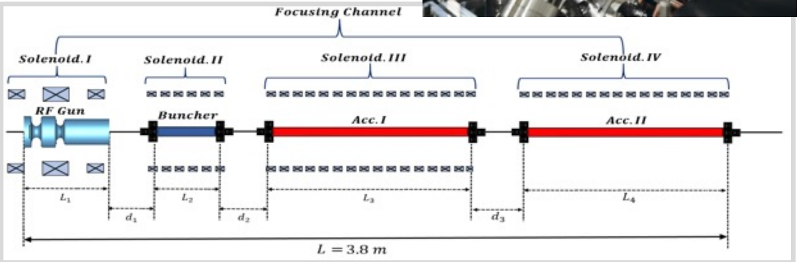
V. Berglyd Olsen, E. Adli, P. Muggli, Phys. Rev. Accel. Beams, 21 (2018) 011301

New electron source:

→ based on X-band

→ Prototyping together with CLEAR





New electron line:

→ Requirement of β = 5 mm at injection.

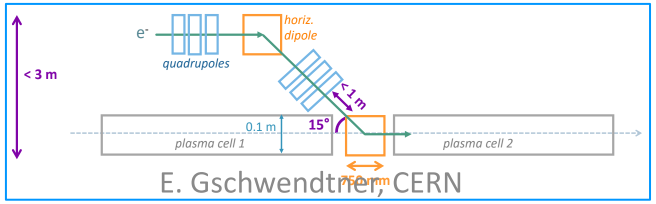
→ Require achromatic module, with no bunch lengthening.

→ Limit of ~ 3m width set by tunnel width

→ Dipole bending angle > 15°

→ Dipole-quadrupole spacing > 1 m

→ Matching conditions at merging: $\sigma = \sqrt{4.87\ \mathrm{mm} \times \epsilon}$



E. Gschwendtner, CERN

New laser system:

IR laser beams to ionize the 2nd rubidium vapour source will be injected from downstream counter-propagating to the p-beam.

UV laser beams for producing two electron beams

New beam instrumentation:

Co-propagating e- and p+ beams: position, size measurement (e- beam).

200 fs electron bunches: bunch length measurement.

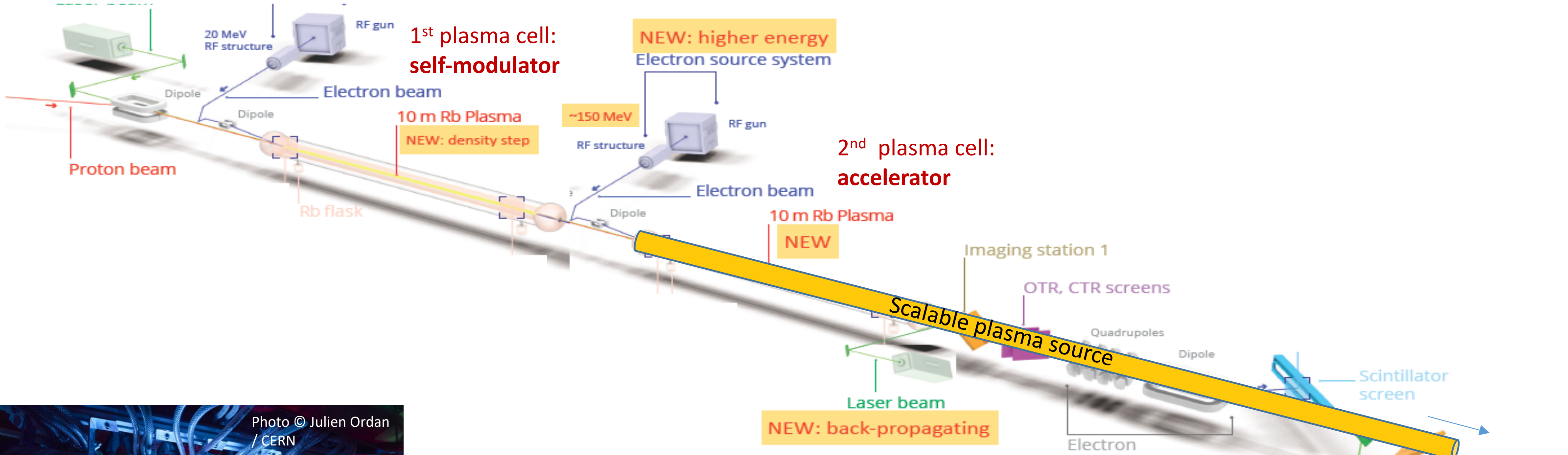
Witness e- beam injected in 2nd plasma cell: measurement of small (6 μm σ) beam in Rb vapour.

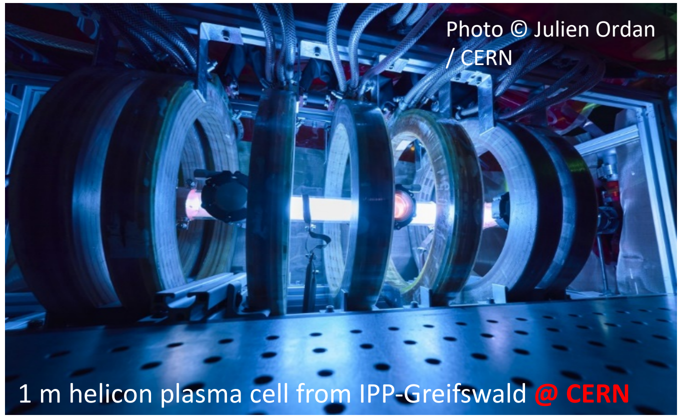
New 2nd plasma cell:

Complex injection region: matching of electron beam to plasma

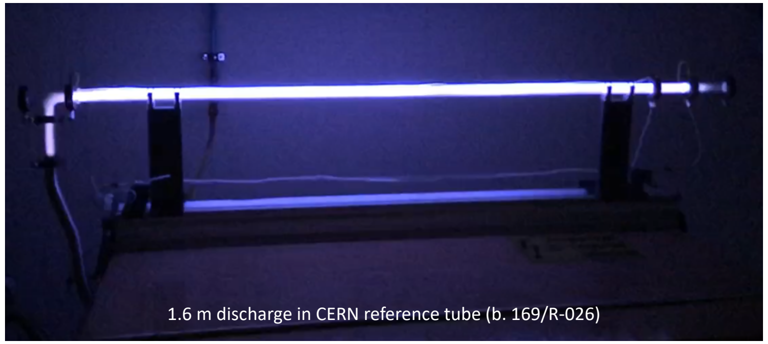
AWAKE Run 2d: Demonstrate Scalable Plasma Sources

Today: Laboratory developments of scalable plasma sources in dedicated plasma labs
Aim: Propose a design for a scalable, several meter-long plasma cell for Run 2d.
Final Goal: Use this technology to build a 50-100m long plasmas source and use it for **first applications (~2029)**





1 m helicon plasma cell from IPP-Greifswald @ CERN


1.6 m discharge in CERN reference tube (b. 169/R-026)

Outline

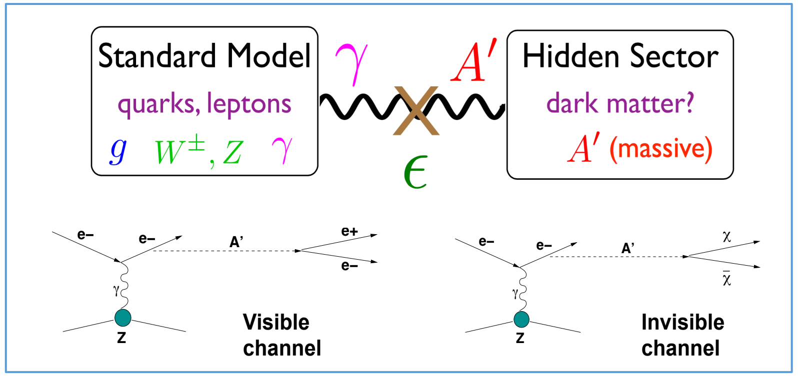
- Motivation
- Introduction to Plasma Wakefield Acceleration
- State of the Art
- The AWAKE Experiment
  - Results of AWAKE Run 1
  - AWAKE Run 2
- Applications with AWAKE-Like Scheme
- Outlook

Applications with AWAKE-Like Scheme

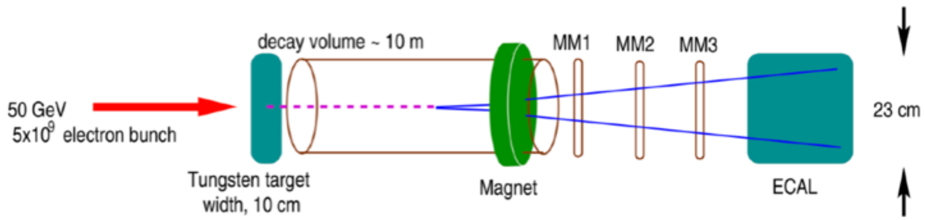
➔ Requirements on emittance are moderate for fixed target experiments and e/p collider experiments, so first experiments in not-too far future!

First Application: Fixed target test facility:

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

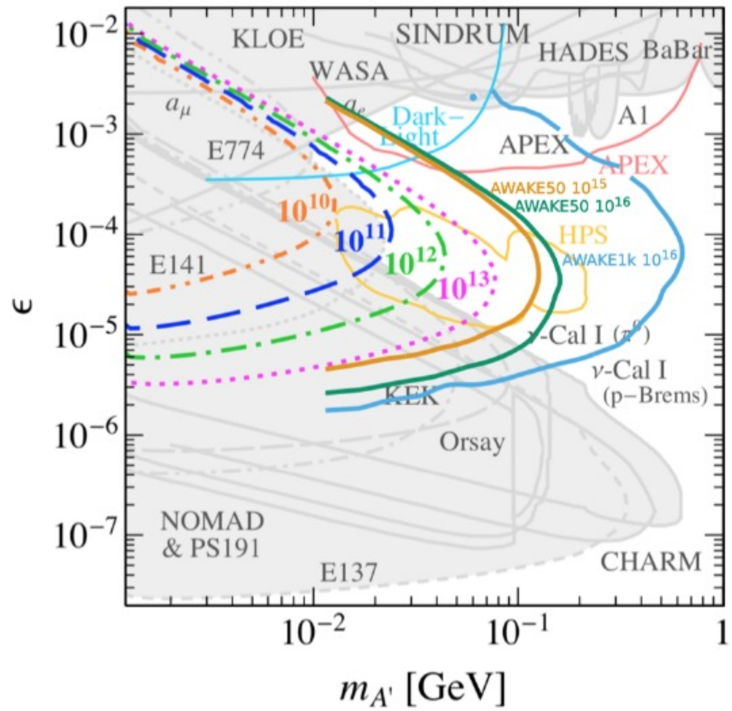


→ Decay of dark photon into visible particles (e.g. e+/e-)
→ Energy and flux is important
→ Relaxed parameters for emittance



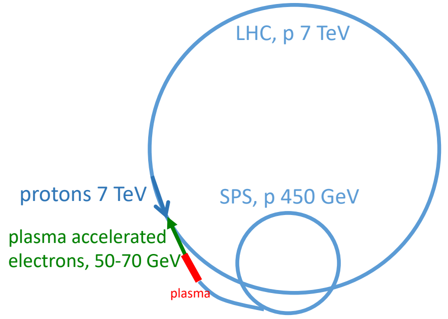
Experimental conditions modeled on NA64 experiment.

→ Use bunches from SPS with 3.5 E11 protons every ~5sec, → electron beam of up to O (50GeV), **3 orders of magnitude increase in electrons** (compared to NA64)



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

Applications with AWAKE-Like Scheme



- **PEPIC:** Low-luminosity version of LHeC (50 GeV electrons)
  - Use the SPS to drive electron bunches to 50 GeV and collide with protons from the LHC
  - Modest luminosity → only interesting should the LHeC not go ahead
- **EIC:**
  - use the RHIC-EIC proton beam to accelerate electron
- **3 TeV VHEeP**
  - use the LHC protons to accelerate electrons to 3 TeV and collide with protons from LHC with 7 TeV
  - Yields centre-of-mass energy of 9 TeV, Luminosity is relatively modest ~1028 – 10^{29} cm^{-2} s^{-1}, i.e. 1bp^{-1}/yr.
  - New energy regime means new physics sensitivity even at low luminosities.
- **Fixed target** variants with these electron beams

Summary and Outlook

→ Plasma wakefield acceleration is an exciting and growing field with many encouraging results and a huge potential.

- → AWAKE: Proton-driven plasma wakefield acceleration interesting because of large energy content of driver. Modulation process means existing proton machines can be used.

→ Current and planned facilities (Europe, America, Asia) explore different advanced and novel accelerator concepts and proof-of-principle experiments and address beam quality challenges and staging of two plasmas.

→ Coordinated R&D program for dedicated international facilities towards addressing HEP challenges are needed over the next 5 to 10 years.

- → As follow-up from the Update of the European Strategy on Particle Physics, the Plasma wakefield acceleration community has prepared a roadmap towards a high-energy collider based on advanced acceleration technologies.

Outlook:

→ **Near-term goals:** the laser/electron-based plasma wakefield acceleration could provide near term solutions for FELs, medical applications, etc.

→ **Mid-term goal:** the AWAKE technology could provide particle physics applications.

→ **Long-term goal:** design of a high energy electron/positron/gamma linear collider based on plasma wakefield acceleration.