Plasma Wakefield Acceleration and the AWAKE Experiment

Basic CERN Accelerator School
20 May 2021

Edda Gschwendtner, CERN

Outline

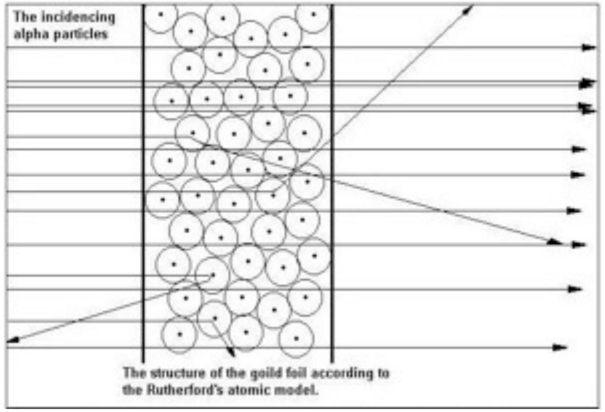
- Motivation
- Introduction to Plasma Wakefield Acceleration
- State of the Art
- The AWAKE Experiment
- Outlook

Motivation: Increase Particle Energies

What are the smallest building blocks of matter?

- Increasing particle energies probe smaller and smaller scales of matter
  - **1910:** Rutherford: scattering of MeV scale alpha particles revealed structure of atom
  - **1950ies:** scattering of GeV scale electron revealed finite size of proton and neutron
  - **Early 1970ies:** scattering of tens of GeV electrons revealed internal structure of proton/neutron, ie quarks.

Pattern of scattered high energy particles → structure of the atom.



Optical Microscope:	**10^{-6} m**
Radioactive Source:	**10^{-14} m**
LHC:	**$<10^{-21}$ m**

Motivation: Increase Particle Energies

Study smallest building blocks of matter with high energy particle colliders and production of new massive particles is connected:

$$E = mc^2$$

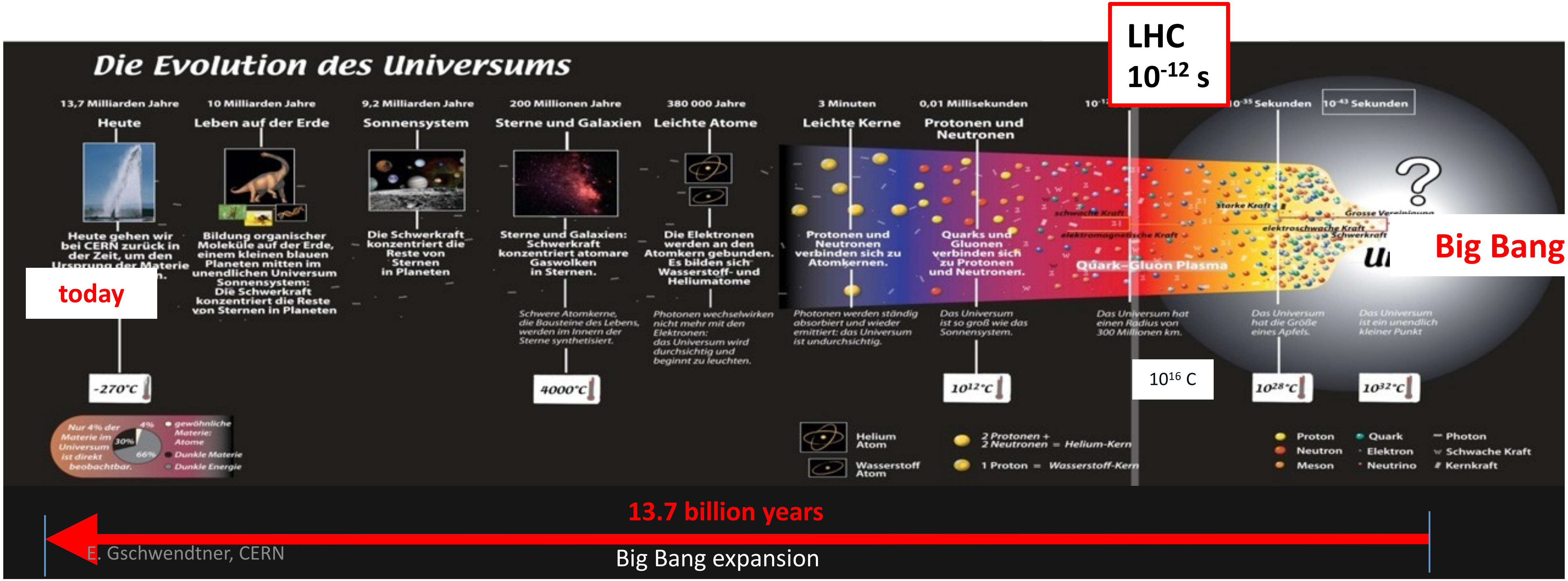
- Increasing energies **makes particles of larger and larger mass accessible**
  - GeV type masses in 1950ies, 60ies (Antiproton, Omega, hadron resonances…
  - Up to 10 GeV in 1970ies (J/Psi, Ypsilon…)
  - Up to ~100 GeV since 1980ies (W, Z, top, Higgs…)

Higgs Particle discovery in 2012 at CERN
Nobel Prize 2013

Motivation: Increase Particle Energies

What is the origin of the universe?

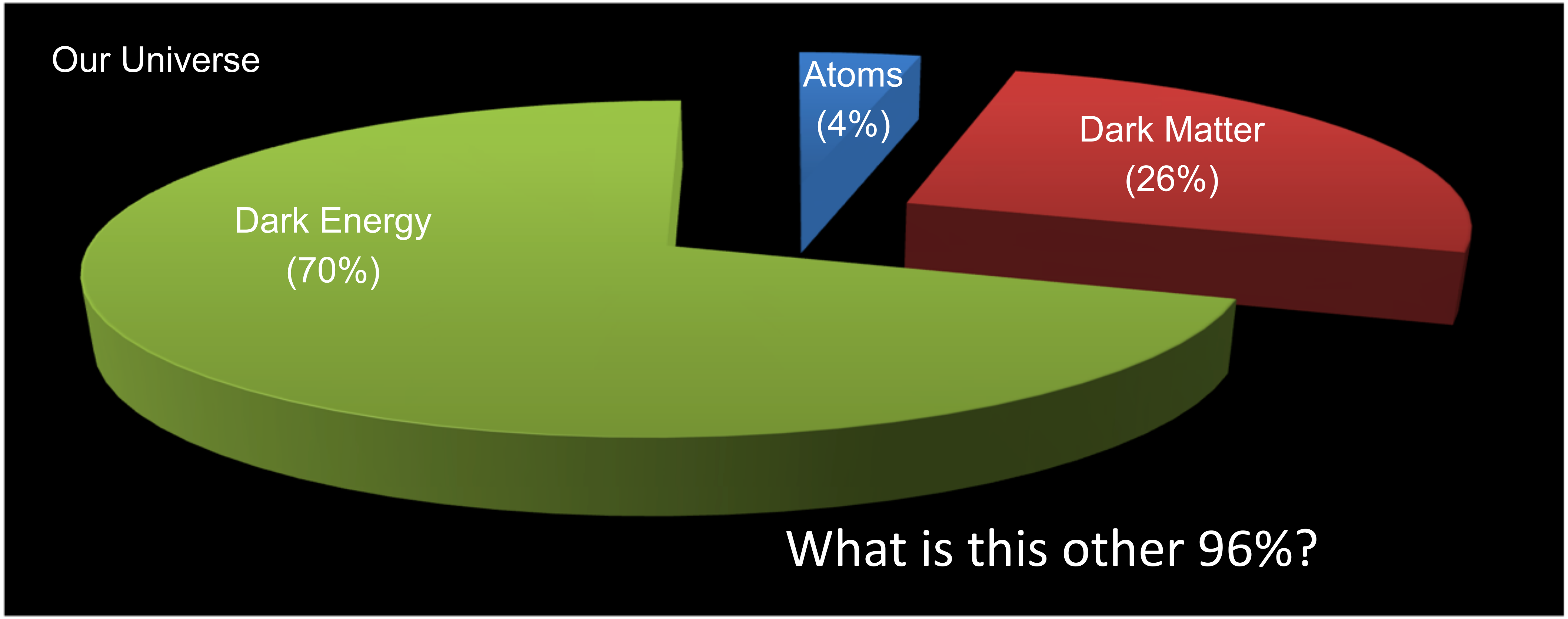
- Increasing particle energies probe earlier times in the evolution of the universe.
  - Temperatures at early universe were at levels of energies that are achieved by particle accelerators today
  - Understand the origin of the universe



E. Gschwendtner, CERN

Motivation: High Energy Accelerators

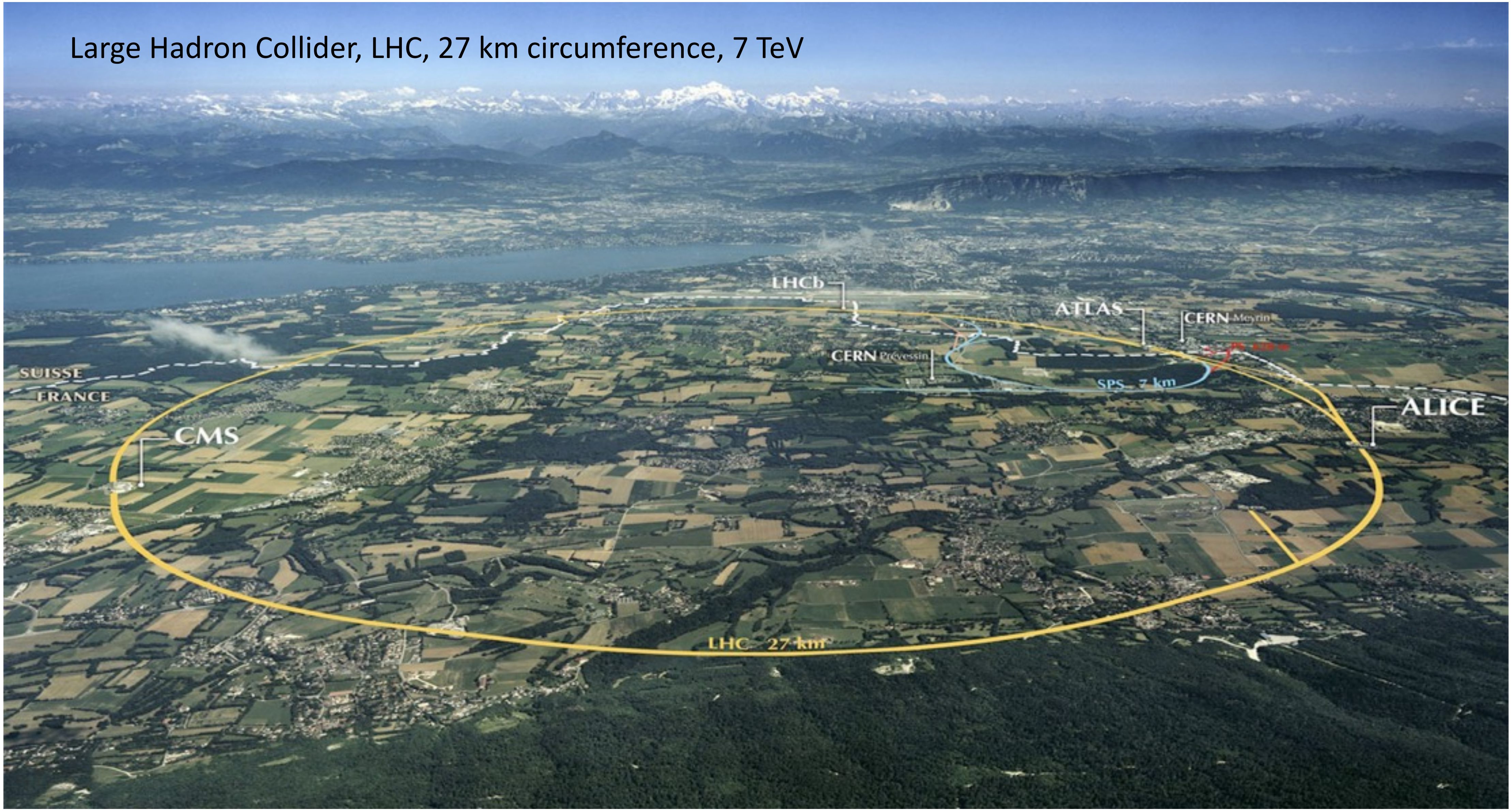
- Large list of unsolved problems:
  - What is dark matter made of? What is the reason for the baryon-asymmetry in the universe? Etc…



➔ **Need particle accelerators with new energy frontier**

LHC

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

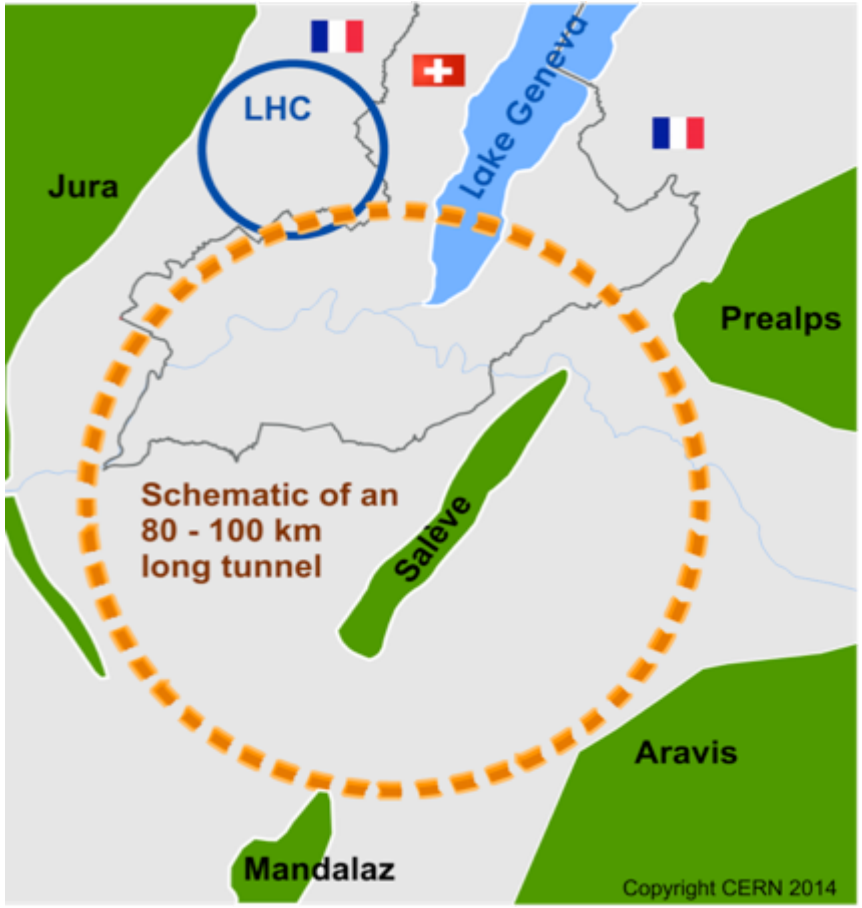


Discover New Physics

Accelerate particles to even higher energies

→ **Bigger accelerators: circular colliders**

Future Circular Collider: FCC



Limitations of conventional circular accelerators:

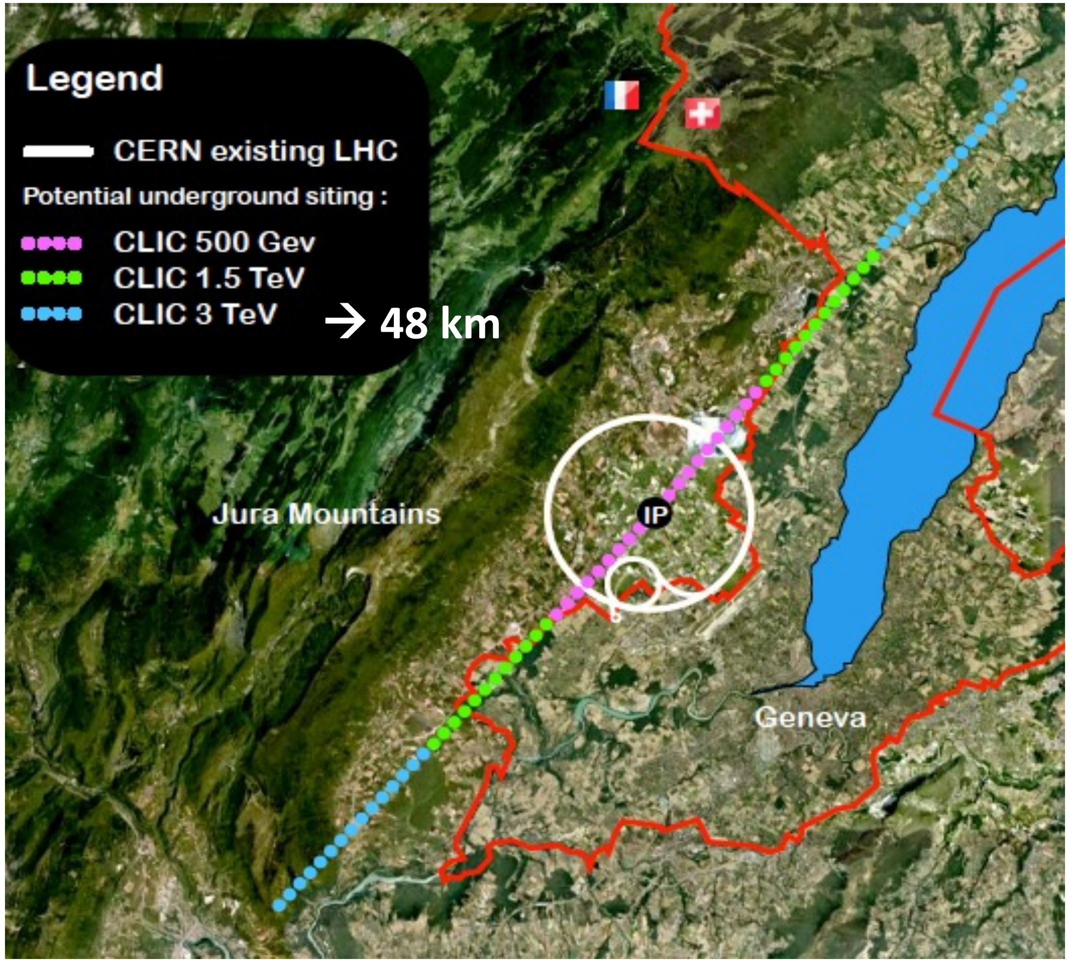
- For **hadron colliders**, the limitation is **magnet strength**. Ambitious plans like the FCC call for 16 T magnets in a 100 km tunnel to reach **100 TeV** proton-proton collision energy.
- For **electron-positron colliders**: Circular machines are limited by **synchrotron radiation** in the case of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

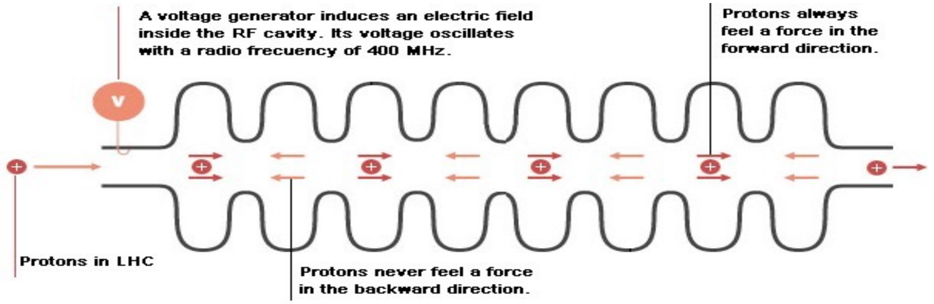


Limitations of linear colliders:

- 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.

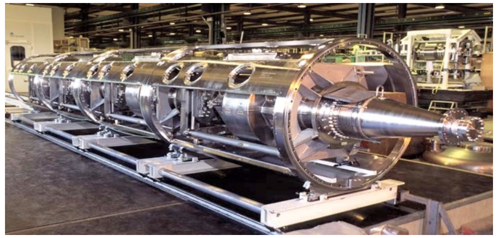
Why Plasma Wakefield Acceleration?

Conventional Acceleration Technology: Radiofrequency Cavities

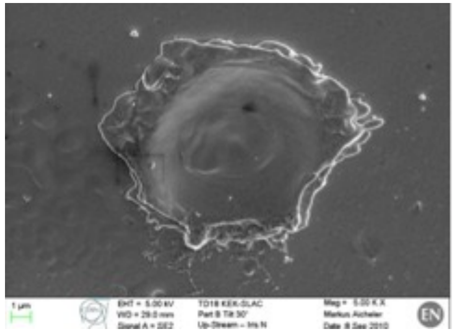


(invention of Gustav Ising 1924 and Rolf Wideroe 1927)

LHC Cavity



- 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.



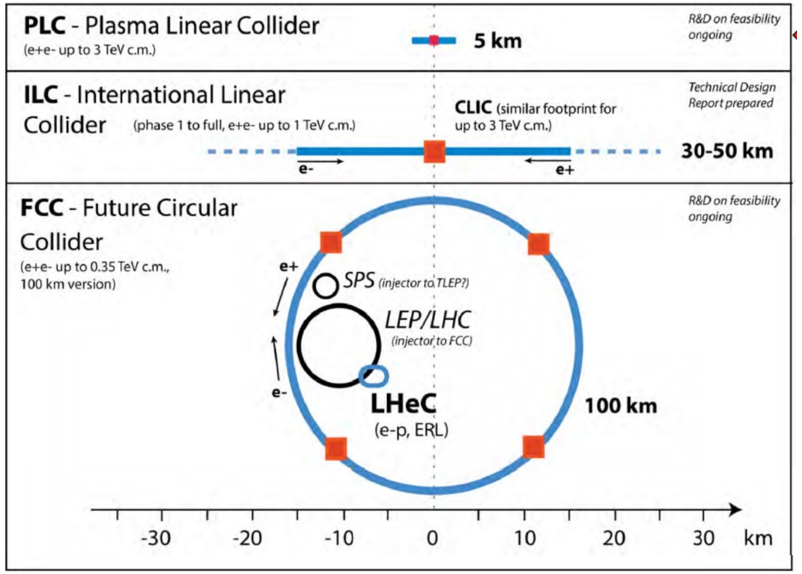
- several tens of kilometers for future linear colliders

Discover New Physics

Accelerate particles to even higher energies:

Plasma Wakefield Acceleration

➔ Obtain ~1000 factor stronger acceleration with same size of machine.



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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.

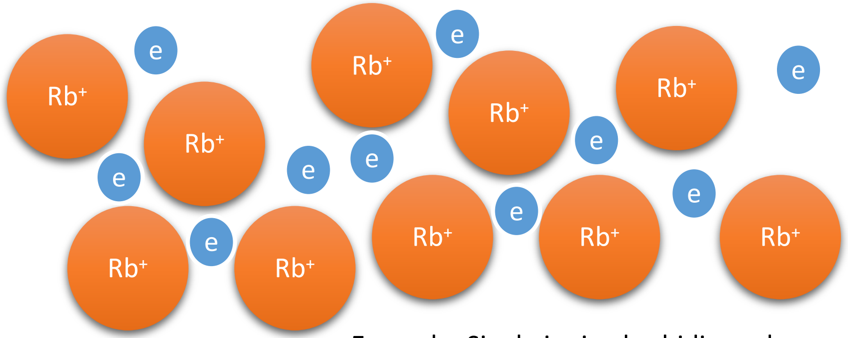
the wavelength of the plasma waves in the wake:

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

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

Plasma Wakefield

What is a plasma?



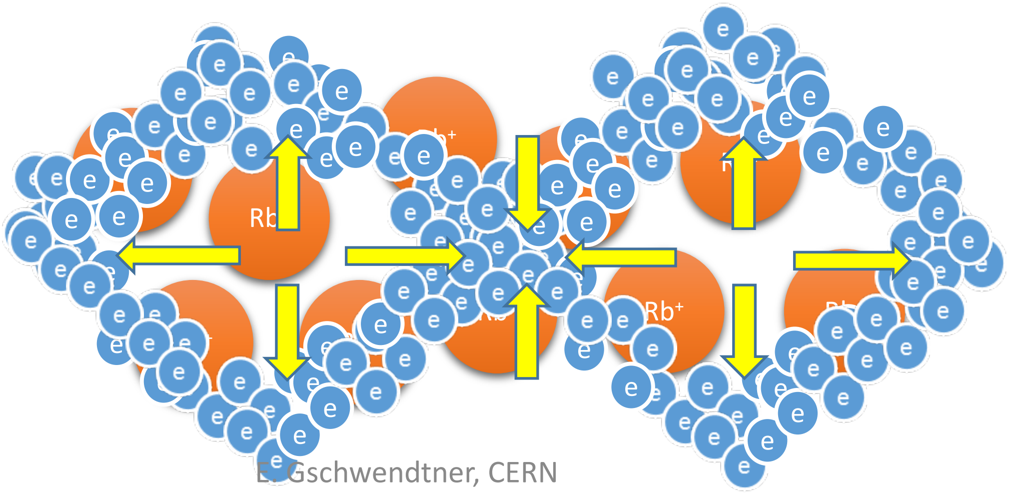
Example: Single ionized rubidium plasma

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?

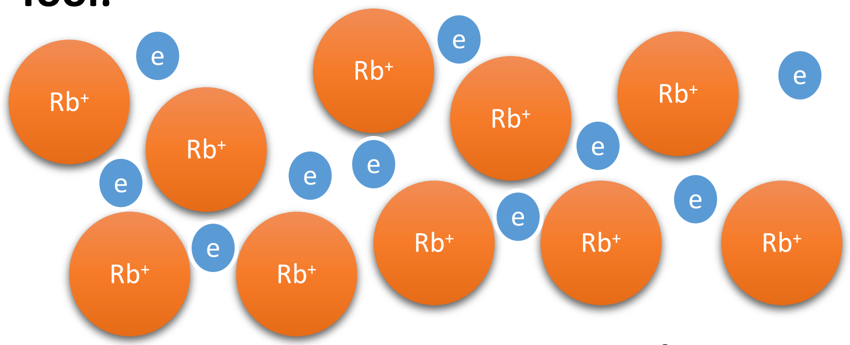


Fields created by collective motion of plasma particles are called plasma wakefields.

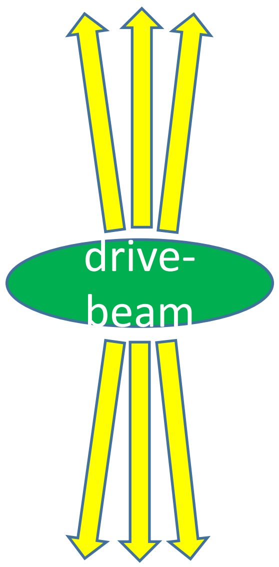
How to Create a Plasma Wakefield?

What we want:
Longitudinal electric field to accelerate charged particles.

Our Tool:



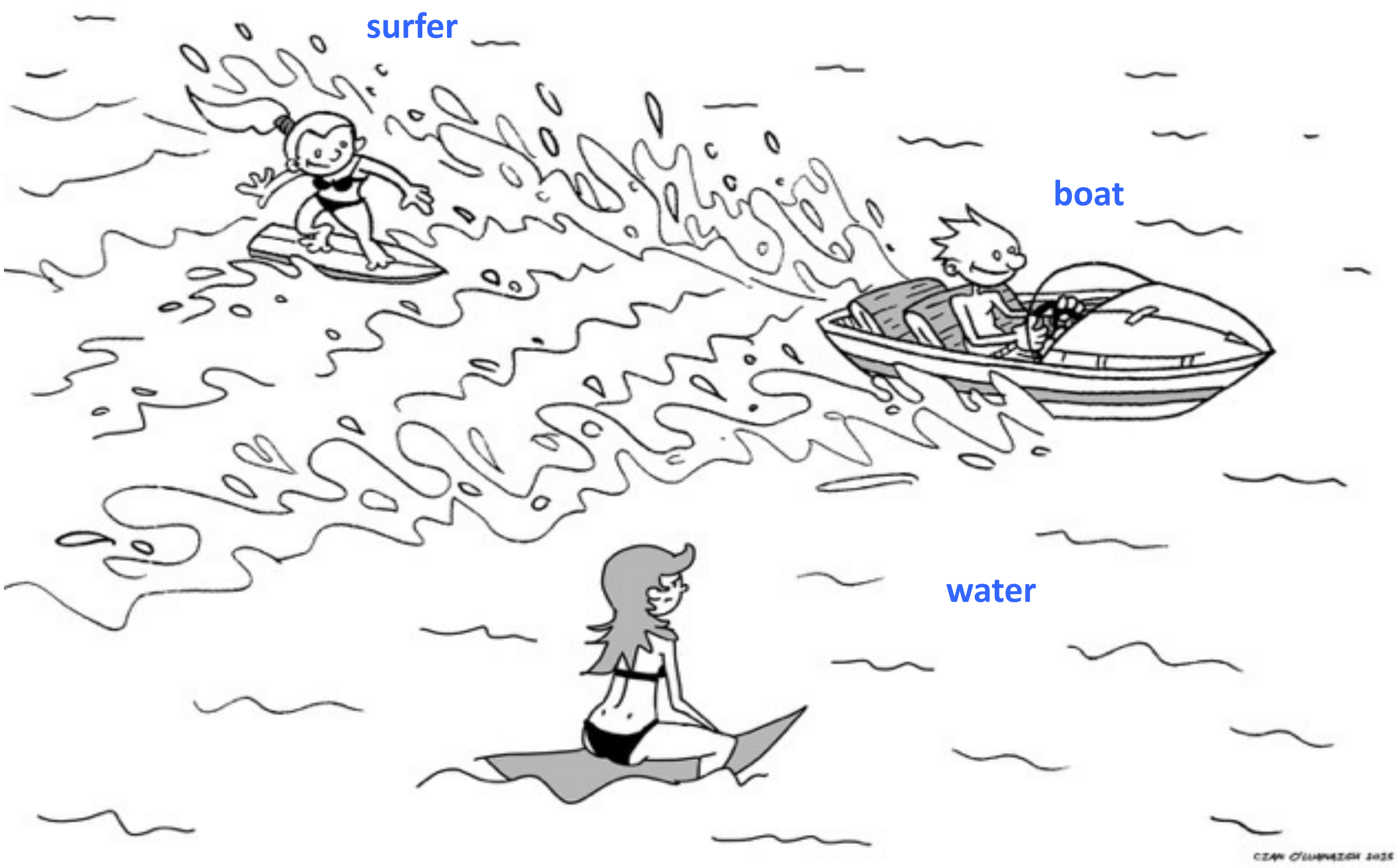
Single ionized rubidium **plasma**



Charged particle bunches carry almost purely transverse Electric Fields.

Using plasma to convert **the transverse electric field** of the drive bunch into a **longitudinal electric field in the plasma.** The more energy is available, the longer (distance-wise) these plasma wakefields can be driven.

How to Create a Plasma Wakefield?



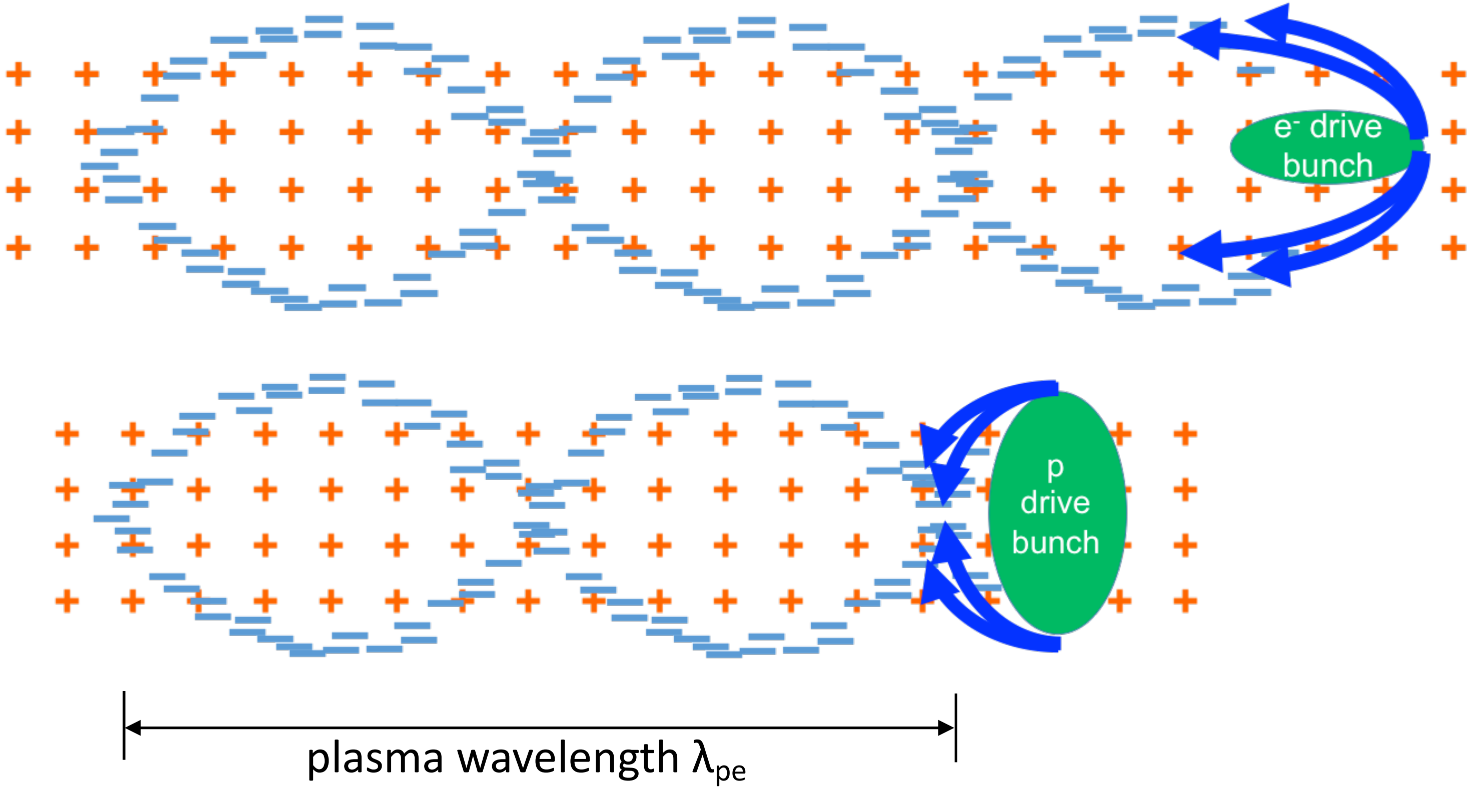
Analogy:
water → plasma

Boat → particle beam (drive beam)

Surfer → accelerated particle beam (witness beam)

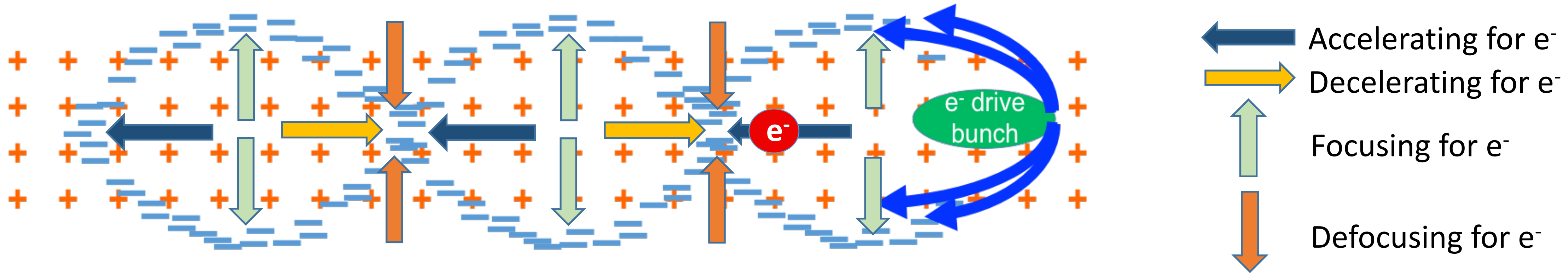
Principle of Plasma Wakefield Acceleration

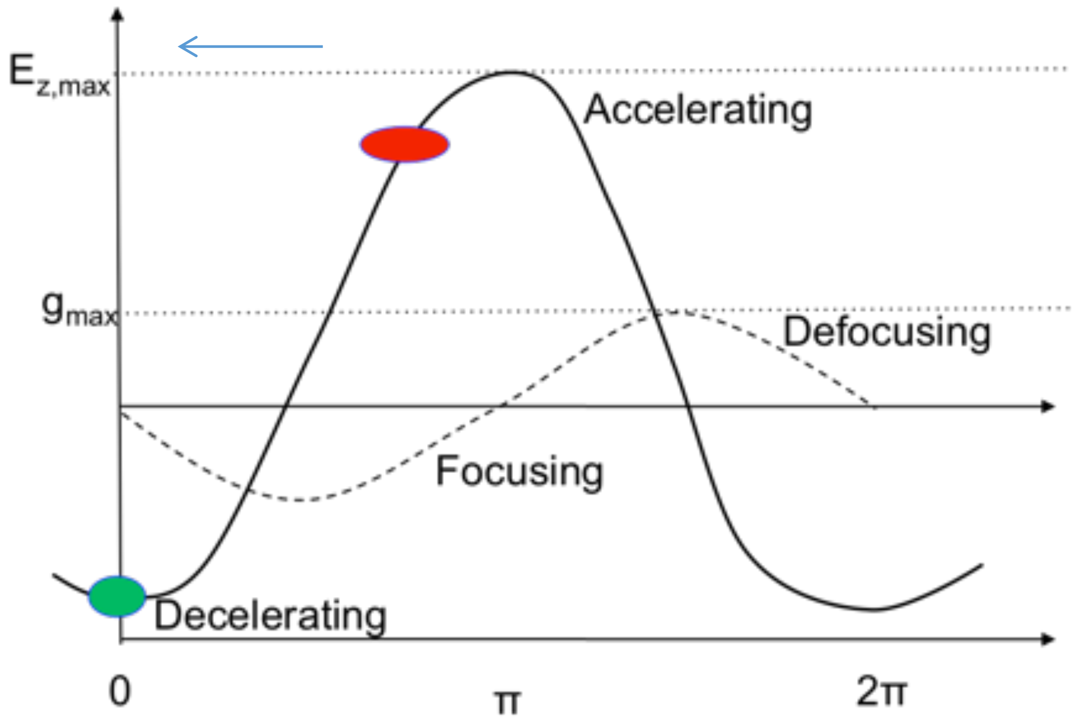
- Laser drive beam
  - ➔ Ponderomotive force
- Charged particle drive beam
  - ➔ Transverse space charge field
  - Reverses sign for negatively (blow-out) or positively (suck-in) charged beam



- Plasma wave/wake excited by relativistic particle bunch
- Plasma e^- are expelled by space charge force
- Plasma e^- rush back on axis
- Ultra-relativistic driver – ultra-relativistic wake → no dephasing
- Acceleration physics identical for LWFA, PWFA

Where to Place the Witness Beam (Surfer)?





Plasma Baseline Parameters

- A plasma of density n_{pe} is characterized by the plasma frequency

$$\omega_{pe} = \sqrt{\frac{n_{pe}\, e^2}{m_e\, \varepsilon_0}} \quad \rightarrow \quad \frac{c}{\omega_{pe}} \text{ ... unit of plasma [m]} \qquad k_{pe} = \frac{\omega_{pe}}{c}$$

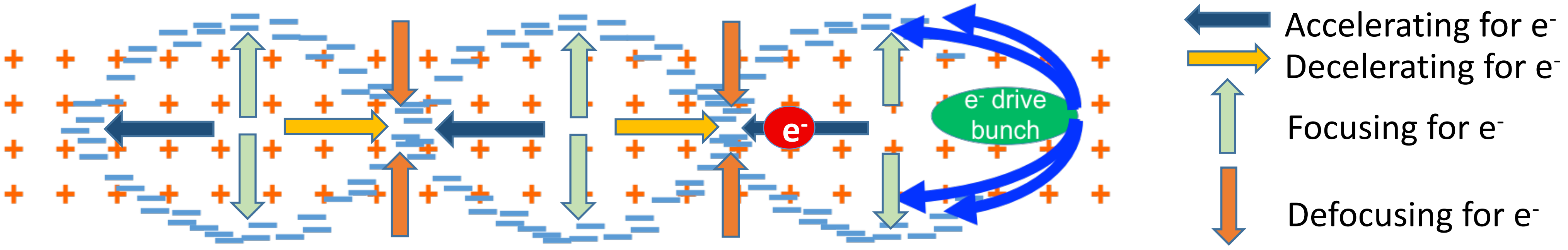
Example: n_{pe} = 7x10^{14} cm^{-3} (AWAKE) → ω_{pe} = 1.25x10^{12} rad/s → $\frac{c}{\omega_{pe}}$ **= 0.2mm** → k_{pe} = 5 mm^{-1}

- This translates into a wavelength of the plasma oscillation

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

$\boxed{\lambda_{pe} = 1.2\text{ mm}}$ → **Produce cavities with mm size!**

Wakefields



How strong can the fields be?

- The plasma oscillation leads to a longitudinal accelerating field. The maximum accelerating field (wave-breaking field) is:

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

- The ion channel left on-axis, where the beam passes, induces an **ultra-strong focusing field:**

$$g = 960\,\pi\,\frac{n_{pe}}{10^{14}\,cm^{-3}}\,\frac{T}{m}$$

Example: n_{pe} = 7x10^{14} cm^{-3} (AWAKE) ➔ eE$_{WB}$ = 2.5 GV/m ➔ g = 21kT/m
Example: n_{pe} = 7x10^{17} cm^{-3} ➔ eE$_{WB}$ = 80 GV/m ➔ g = 21MT/m

Plasma Wakefield, Linear Theory

(R. D. Ruth, P. Chen, SLAC-PUB-3906, 1986)

When drive beam density is smaller than plasma density ($n_b << n_p$) → **linear theory.**

- Peak accelerating field in plasma resulting from drive beam with Gaussian distribution:

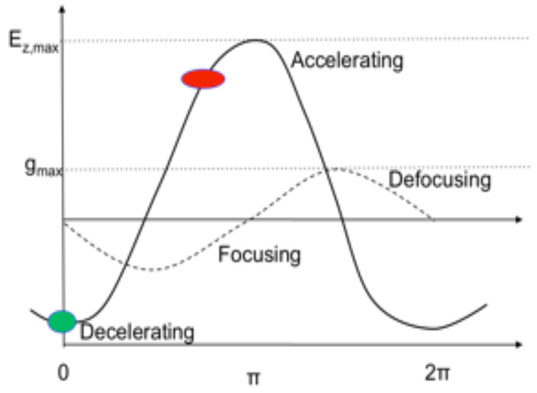
$$eE_z = \sqrt{n_p}\,\frac{n_b}{n_p}\,\frac{\sqrt{2\pi}\,k_p\sigma_z e^{-k_p^2\sigma_z^2/2}}{1+\frac{1}{k_p^2\sigma_r^2}}\sin k_p(z-ct) \quad (eV/cm)$$

B.E. Blue 2003

$\boxed{\Rightarrow eE_z \approx N/\sigma_z^2}$

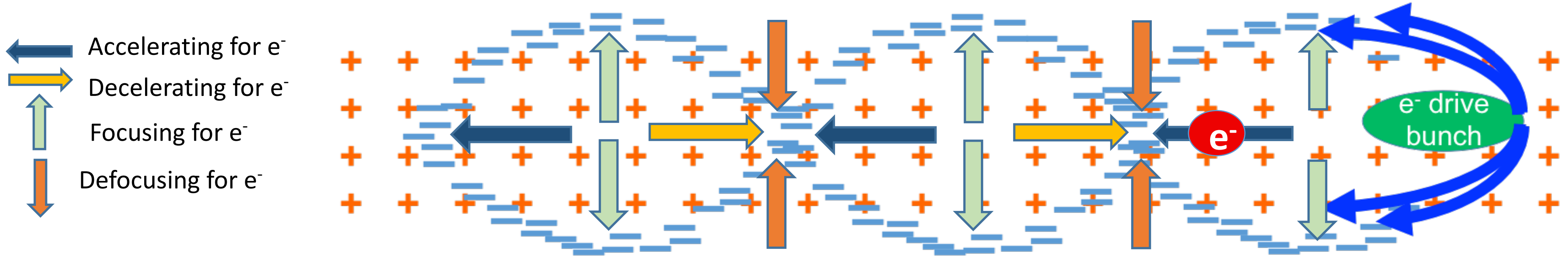
- **Wakefield** excited by bunch oscillates **sinusoidally** with frequency determined by plasma density
- **Accelerating gradient** increases linearly with $\mathbf{N/\sigma_z}$
- Fields excited by electrons and protons/positrons are **equal in magnitude but opposite in phase**
- The **accelerating field is maximized** for a value of

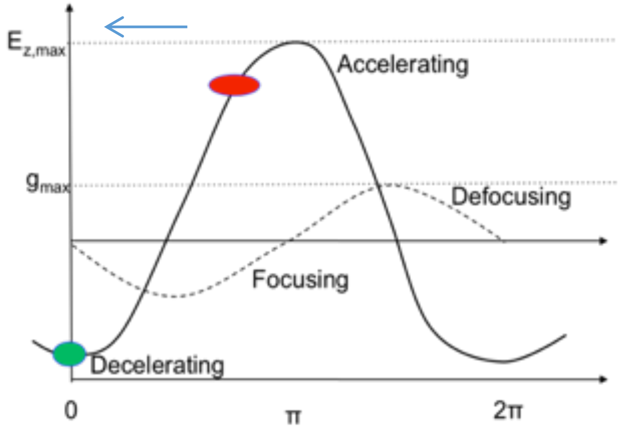
$$\boxed{\begin{array}{l} k_{pe}\,\sigma_z \approx \sqrt{2} \\ k_{pe}\,\sigma_r \leq 1 \end{array}}$$



Example: $n_{pe} = 7\times10^{14}\ cm^{-3}$ **(AWAKE)**, $k_{pe} = 5\ mm^{-1}$ ➔ **drive beam:** $\sigma_z = 300\mu m$, $\sigma_r = 200\mu m$

Plasma Wakefield, Linear Theory





Linear Theory: Maximum accelerating electric field reached with drive beam of N and σ_z:

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

← Driver must be short compared to plasma wavelength, easy for laser and electron bunches.

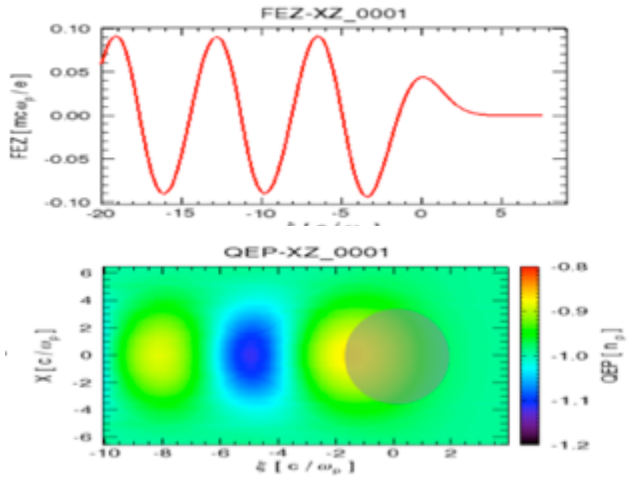
Examples of accelerating fields for different beam parameters and plasma parameters fields:

$N = 3x10^{10}$, $\sigma_z = 300\mu m$, $n_{pe} = 7x10^{14}$ cm^{-3} ➔ **E_{acc} = 600 MV/m**
$N = 3x10^{10}$, $\sigma_z = 20\mu m$, $n_{pe} = 2x10^{17}$ cm^{-3} ➔ **E_{acc} = 15 GV/m**

Beam Quality in Plasma Wakefield Acceleration

Different regimes:

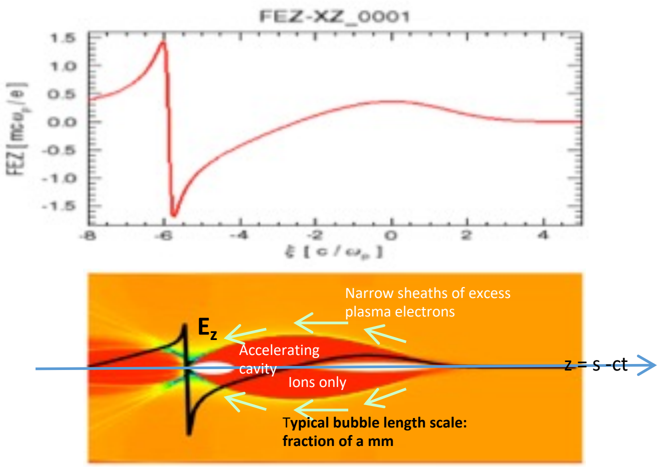
Linear regime: $n_{beam} << n_{pe}$



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

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

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

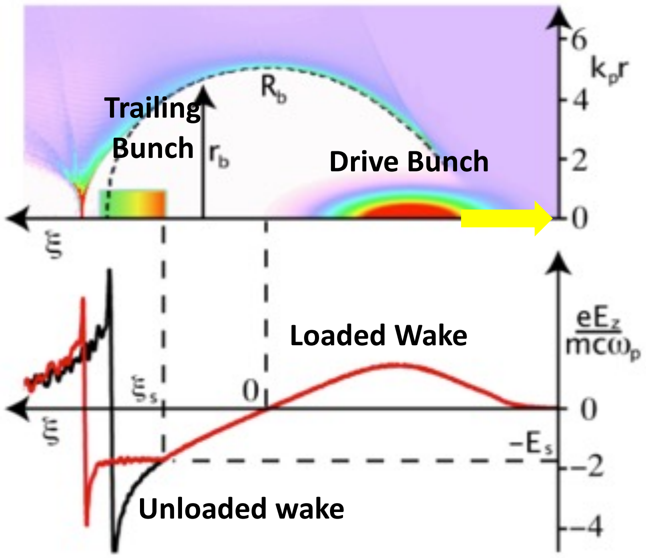


+ Higher wakefields
+ transverse forces linear in r (emittance preservation)
+ High charge witness acceleration possible

- *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**

➔ **Challenges**: emittance preservation, stability, reproducibility, beam matching, positron acceleration, witness beam injection, independent shaped drive and witness bunch, etc…

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Many, Many Electron and Laser Driven Plasma Wakefield Experiments…!

Now first Proton Driven Plasma Wakefield Experiment

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

ALEGRO
Advanced LinEar collider study GROup

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
current status	running	running	construction	commissioning	commissioning	CDR ready??	construction	design
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	p^+	e^-	e^-	e^-	e^-	e^-	e^-	e^-
driver energy	400 GeV	200 MeV	10 GeV	$0.4-1.5$ GeV	150 MeV	600 MeV	240 MeV	3 GeV
ext. inject.	yes	no	no/yes	yes??	no	no	no	no
witness energy	20 MeV	na	tb ugraded	$0.4-1.5$ GeV	150 MeV	600 MeV	na	3 GeV
plasma	Rb vapour	Ar, He capillary	Li oven	H, N, noble gases	H, capillary	H, capillary	He, capillary	H, gases
density [cm^{-3}]	1-10E14	1E16-1E18	1E15-1E18	1E15-1E18	1E16-1E18	1E16-1E18	1E16-1E18	1E15-1E18
length	10 m	5-20 cm	10-100 cm	1-30 cm	3 cm	>30 cm	10-30 cm	10-50cm
plasma tapering	yes	na	yes	yes	yes	yes		yes
acc. gradient	1 GeV/m average	na	10+ GeV/m peak	10+ GeV/m peak	>1 GeV/m??	>1 GeV/m??	na	10+ GeV/m peak
exp. E gain	1+ GeV	na	≈10 GeV	≈1.5 GeV	40 MeV ??	> 500 MeV	na	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

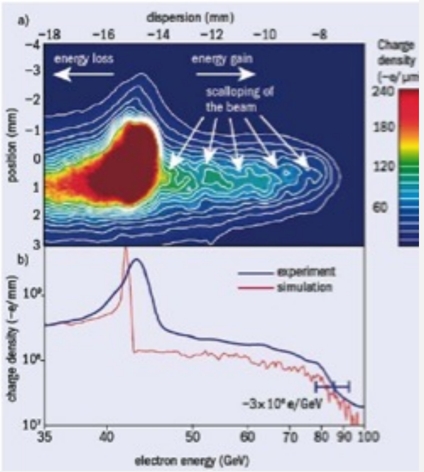
➔ **FACET-II starts in 2021**

- 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

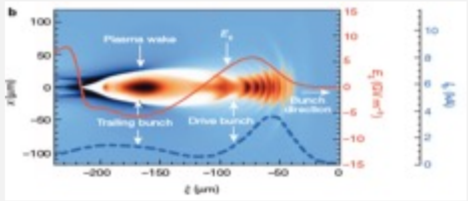
*I. Blumenfeld et al, Nature 455, p 741 (**2007**)*

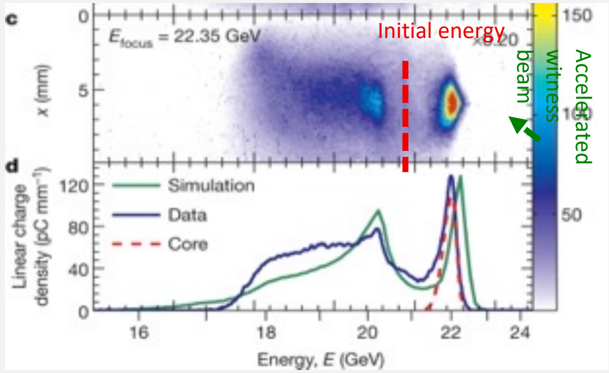
→ **gradient of 52 GV/m**



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*

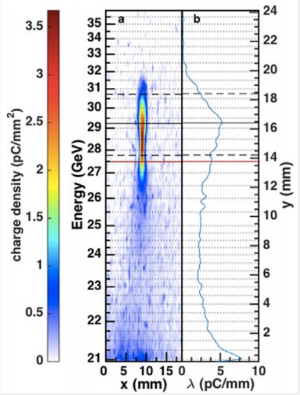




70 pC of charge accelerated, 2 GeV energy gain, 5 GeV/m gradient ➔ **Up to 30% transfer efficiency, ~2% energy spread**

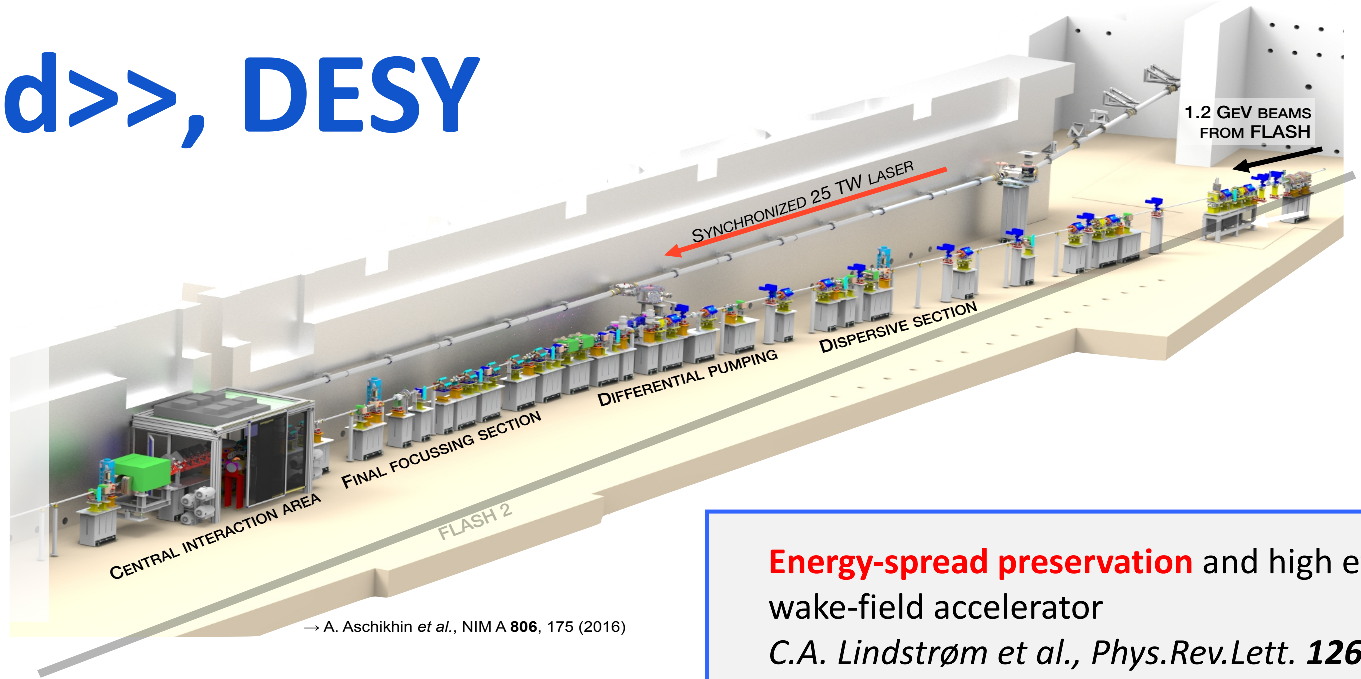
9 GeV energy gain in a beam-driven plasma wakefield accelerator

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

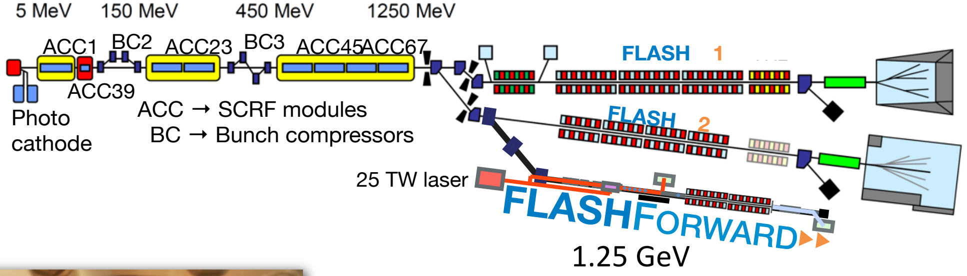


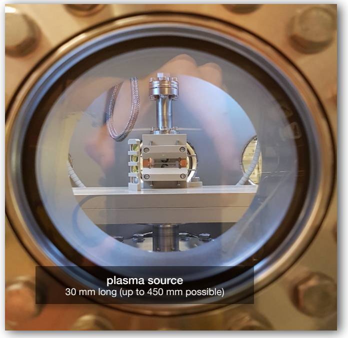
FLASHForward>>, DESY

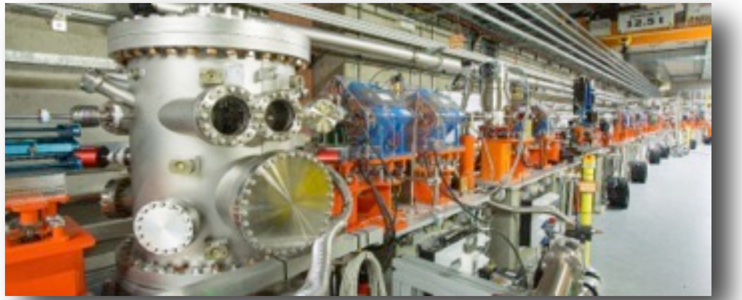
→ unique FLASH facility features for PWFA
- FEL-quality drive and witness beams
- up to 1 MHz repetition rate
- 3rd harmonic cavity for phase-space linearization → tailoring of beam current profile
- differentially pumped, windowless plasma sources
- *2019*: X-band deflector of 1 fs resolution post-plasma (collaboration with FALSH 2, SINBAD, CERN & PSI)
- *Future:* up to 800 bunches (~MHz spacing) at 10 Hz macro-pulse rate, few 10 kW average power.



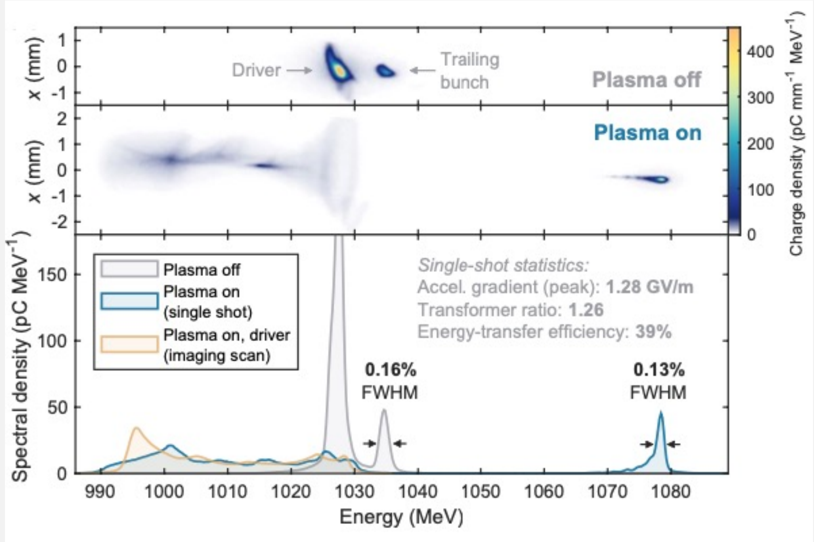
→ A. Aschikhin *et al.*, NIM A **806**, 175 (2016)







Energy-spread preservation and high efficiency in a plasma-wake-field accelerator
C.A. Lindstrøm et al., Phys.Rev.Lett. ***126****, 014801 (****2021****)*

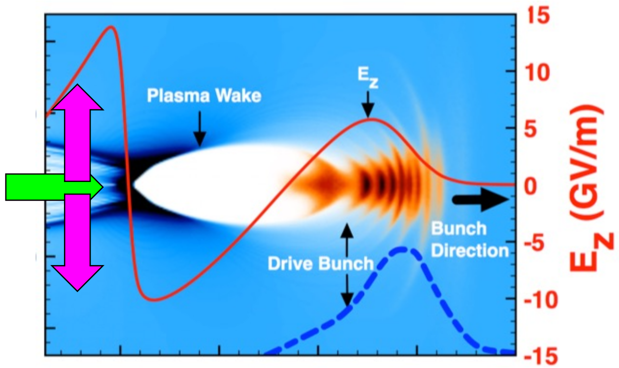


Transfer efficiency **42+/-4%** with **0.2% energy spread**,
Up to **70%** when allowing energy spread increase

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.

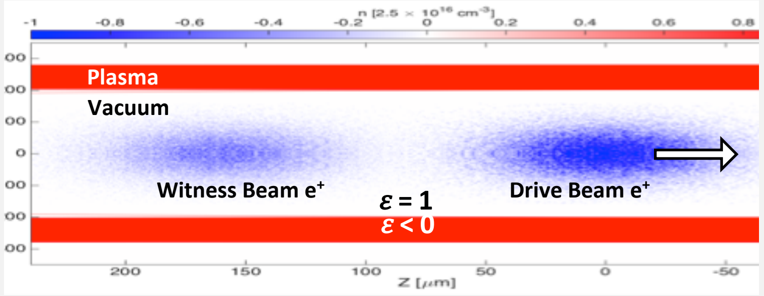
First demonstration of positron acceleration in plasma (FFTB)

*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)*

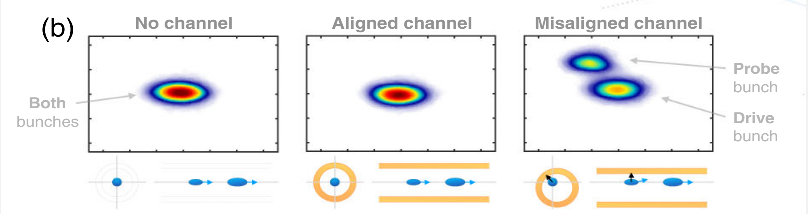
Hollow plasma channel: positron propagation, wake excitation, acceleration in 30 cm channel.
S. Gessner et. al. Nat. Comm. 7, 11785 (2016)



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

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**).*



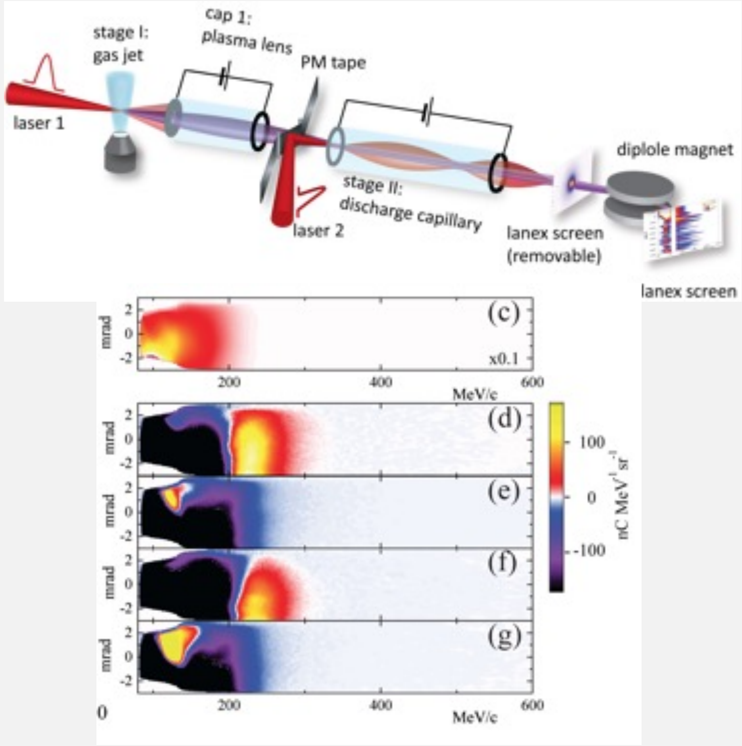
➔ **Emittance blow-up is an issue!** → Use hollow-channel, so no plasma on-axis, no complicated forces from plasma electrons streaming through the plasma → but then strong transverse wakefields when beams are misaligned.

BELLA, Berkeley Lab, US– Laser as Driver

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

Multistage coupling of independent laser-plasma accelerators

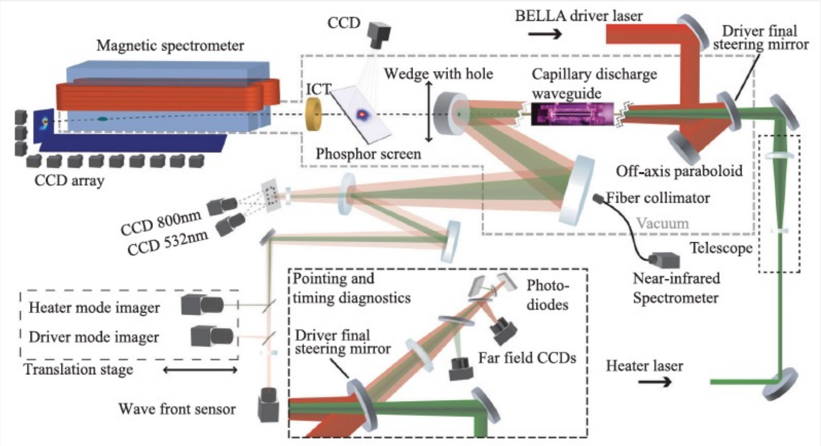
*S. Steinke, Nature **530**, 190 (2016)*



Staging demonstrated at 100MeVs level.

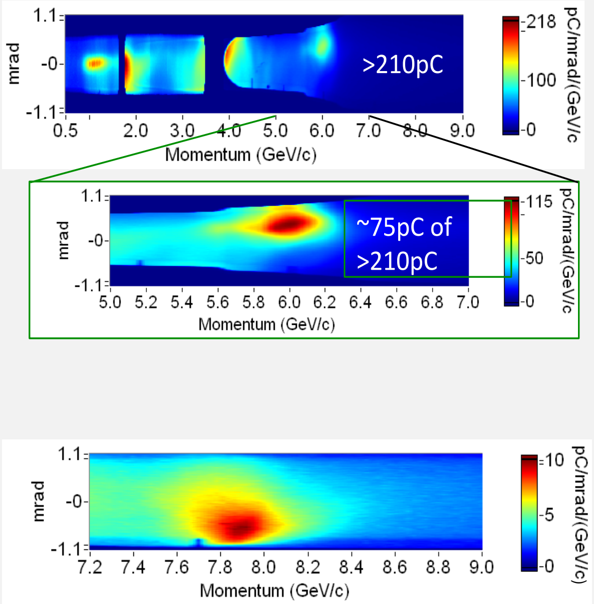
Petawatt laser guiding and electron beam **acceleration to 8 GeV** in a laser-heated capillary discharge waveguide

*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

State of the Art and Goals for HEP Collider

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

Many new/upgraded facilities:

- FACET-II
- SPARCLab
- BELLA
- FLASHForward>>
- KALDERA
- EUPRAXIA
- AWAKE Run 2
- ….

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

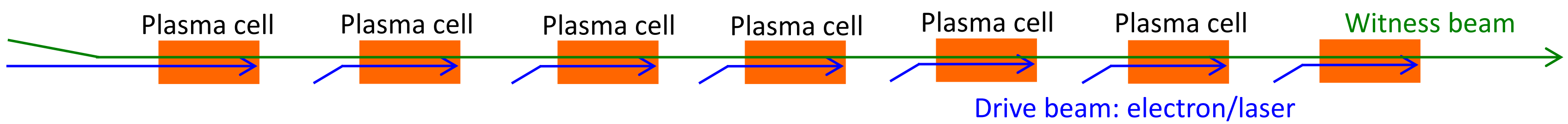
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

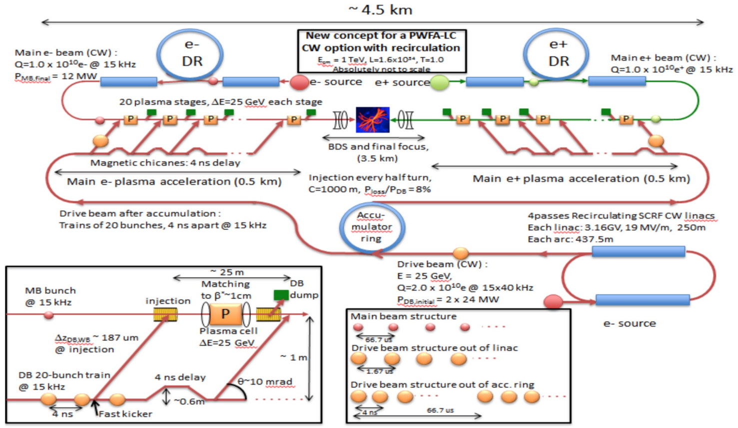
Witness beams:

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

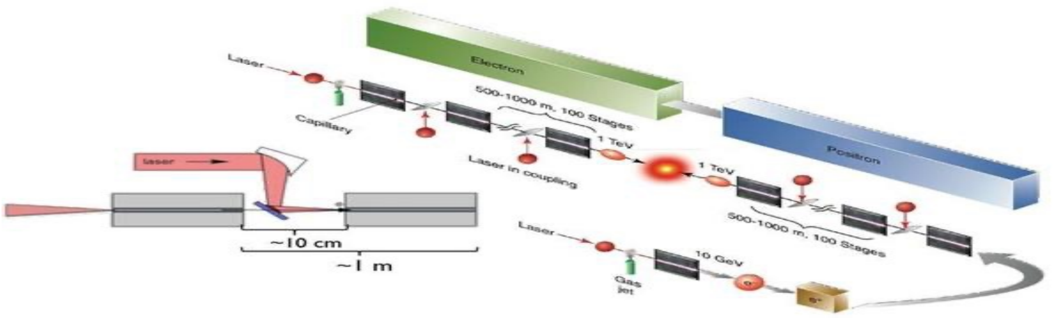
To reach TeV scale:

- **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

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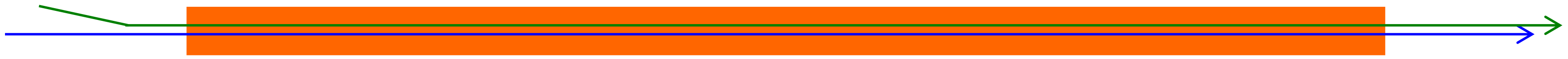
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

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

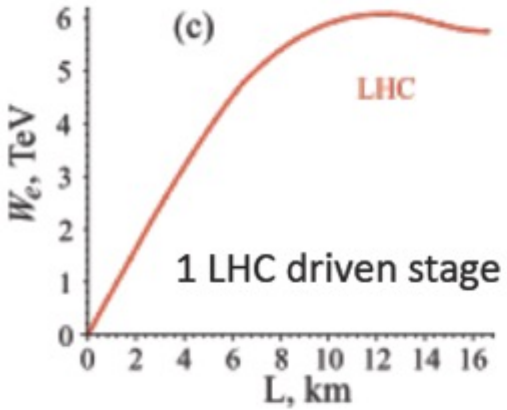
- **Proton drivers**: large energy content in proton bunches → allows to consider single stage acceleration:
  - A single SPS/LHC bunch could produce an ILC bunch in a single PDWA stage.



Dephasing:

SPS: ~70 m
LHC: ~few km

FCC: ~ ∞



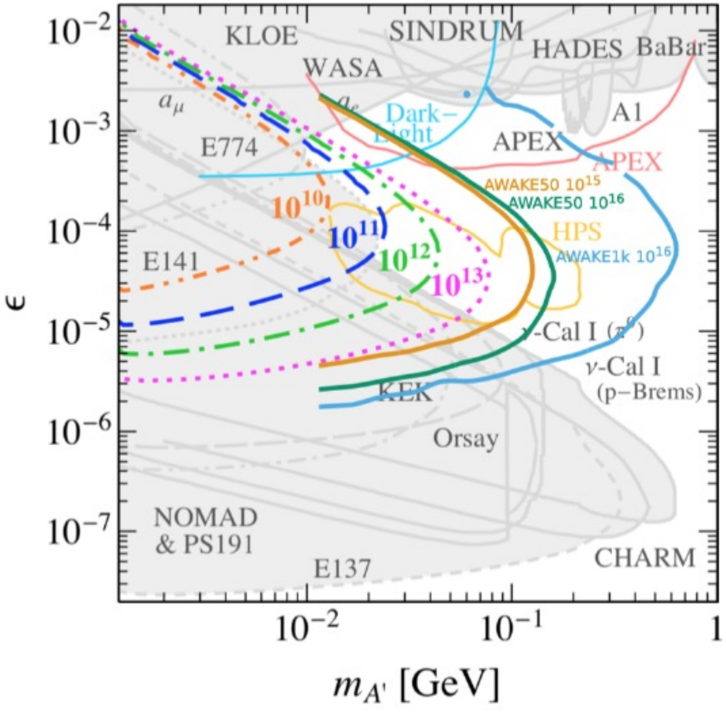
Applications with AWAKE-Like Scheme

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

First Application:

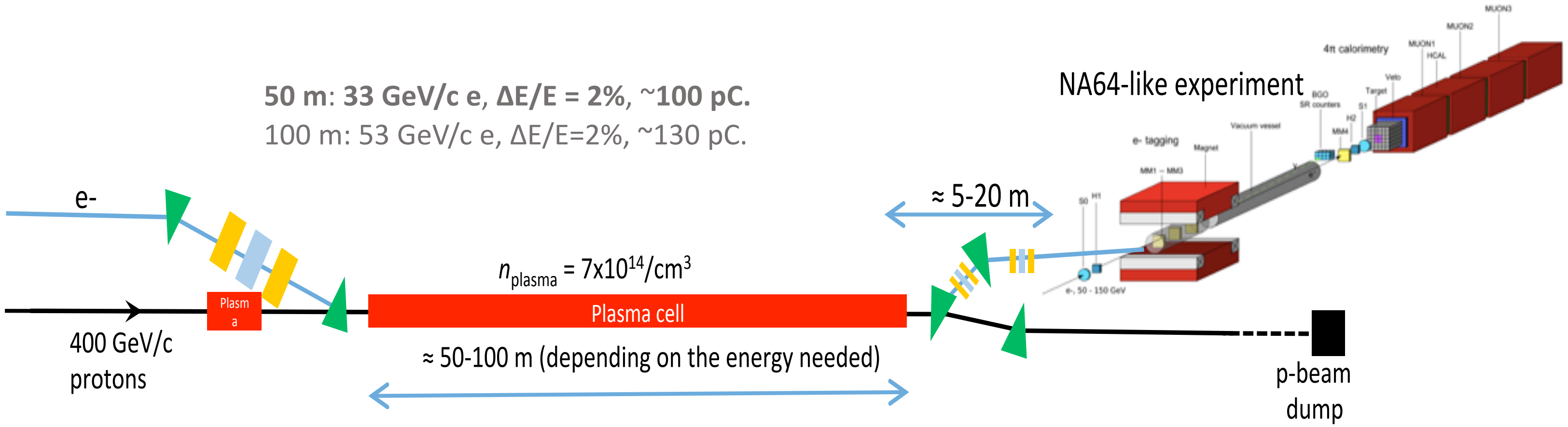
→ **Fixed target test facility**: Use bunches from SPS with 3.5 E11 protons every ~5sec, → electron beam of up to O (50GeV), **3 orders of magnitude increase in electrons** (compared to NA64)

→ deep inelastic scattering, non-linear QED, **search for dark photons a la NA64**



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

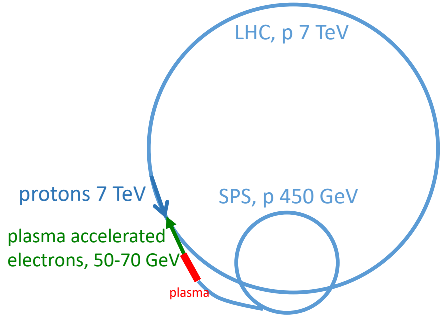
→ Decay of dark photon into visible particles (e.g. e+/e-)
→ Energy and flux is important
→ Relaxed parameters for emittance



Applications with AWAKE-Like Scheme

Electron-proton and electron-ion physics → Focus on QCD:

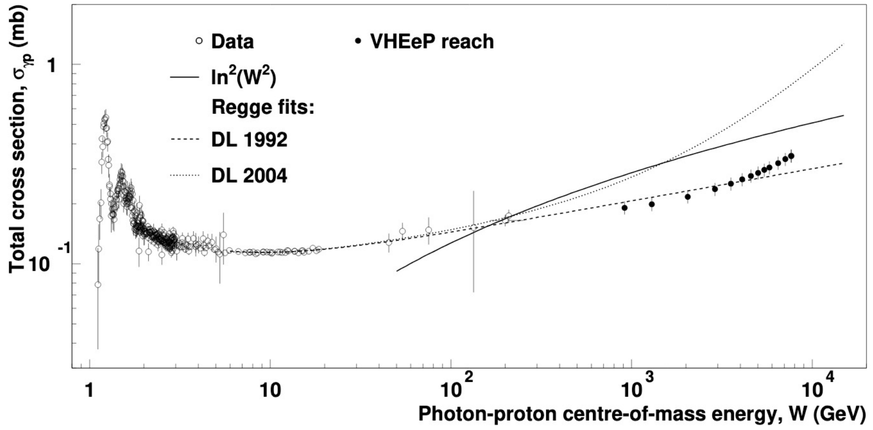
PEPIC: use the SPS to drive electron bunches to 50 GeV and collide with protons from LHC with 7 TeV
→ Modest luminosity → only interesting should the LHeC not go ahead.



VHEeP : use the LHC to drive electron bunches to 3 TeV and collide with protons from LHC with 7 TeV
→ Yields centre-of-mass energy of 9 TeV! Luminosity is relatively modest ~10^{28} – 10^{29} cm^{-2} s^{-1} , i.e. $1pb^{-1}$/yr.
→ Reach in (high) Q^2 and (low) Bjorken x etended by ~1000 compared to HERA.

Energy dependence of hadronic cross-sections not understood and needs new experimetnal results.

W=6TeV corresponds to ~20PeV photons on fixed target
→ Extends into regions of ultra-high energy cosmic rays!

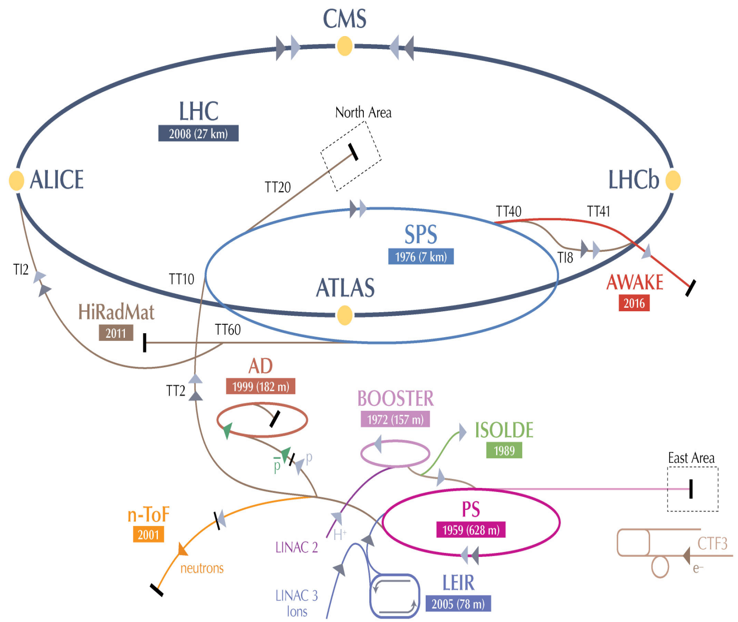


Fixed target variants with these electron beams
Physics beyond Standard Model: e.g. search of new particles with both lepton and quark quantum numbers

Outline

- Motivation
- Introduction to Plasma Wakefield Acceleration
- State of the Art
- The AWAKE Experiment
- Outlook

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)

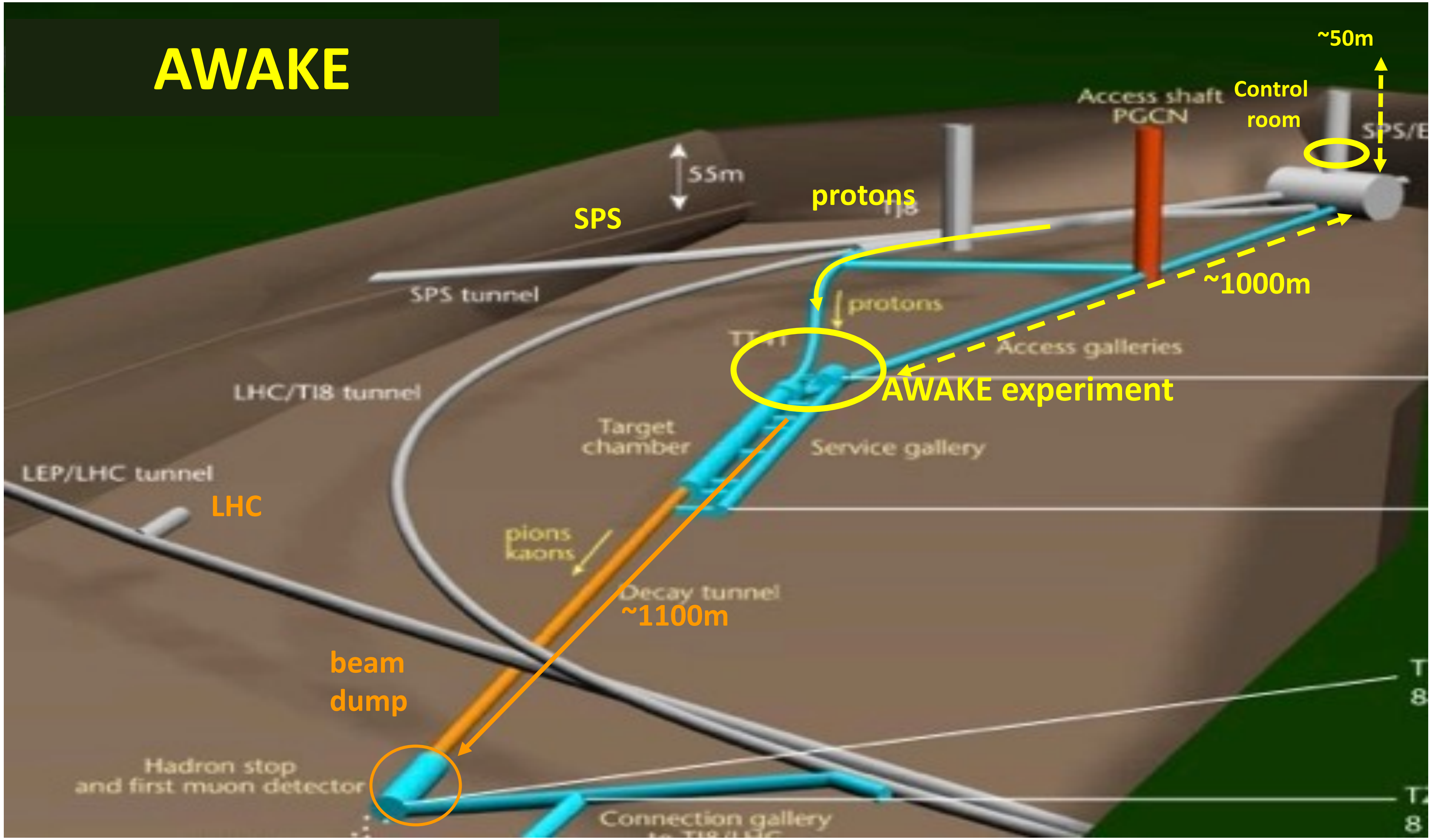
AWAKE Run 2 (2021 – ~2028):

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.

After 2028: First application of the AWAKE-like technology:

Once AWAKE Run 2 demonstrated: fixed target experiments for e.g. dark photon search.

AWAKE at CERN



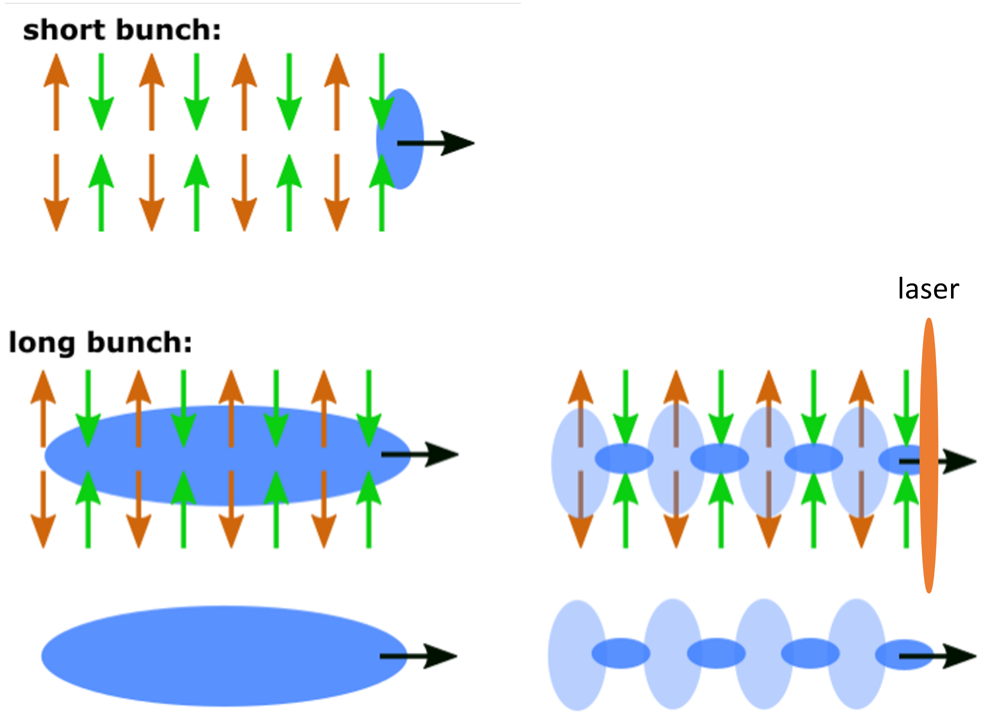
AWAKE installed in CERN underground area

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**.

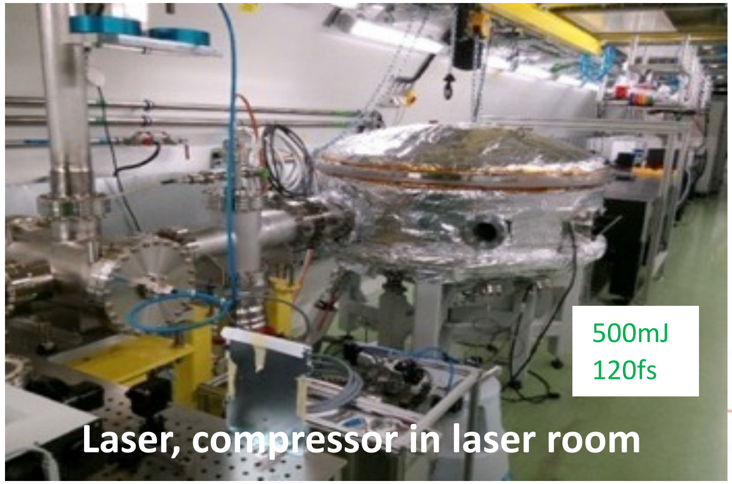
- Micro-bunches separated by plasma wavelength λ_{pe}.
- drive wakefields resonantly.

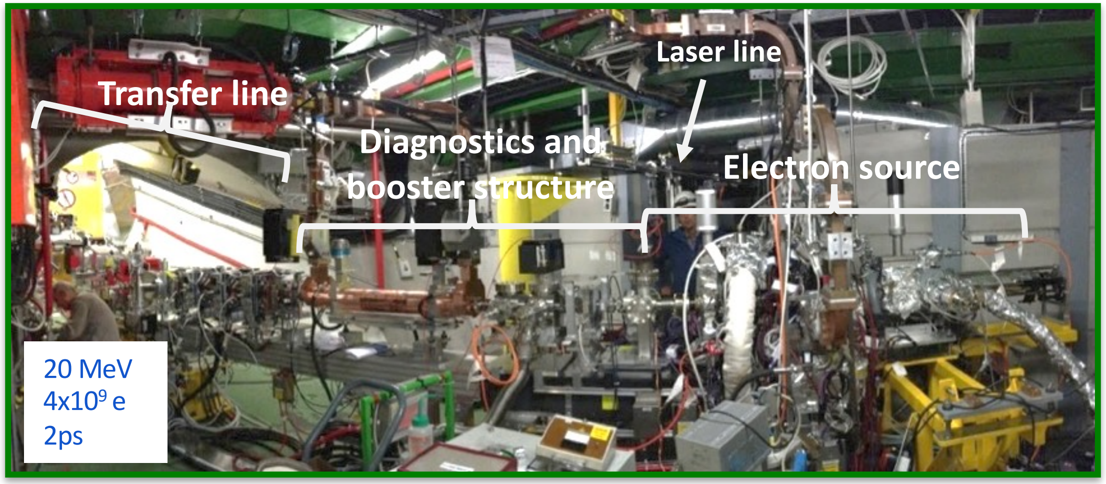
AWAKE: Seeding of the instability by

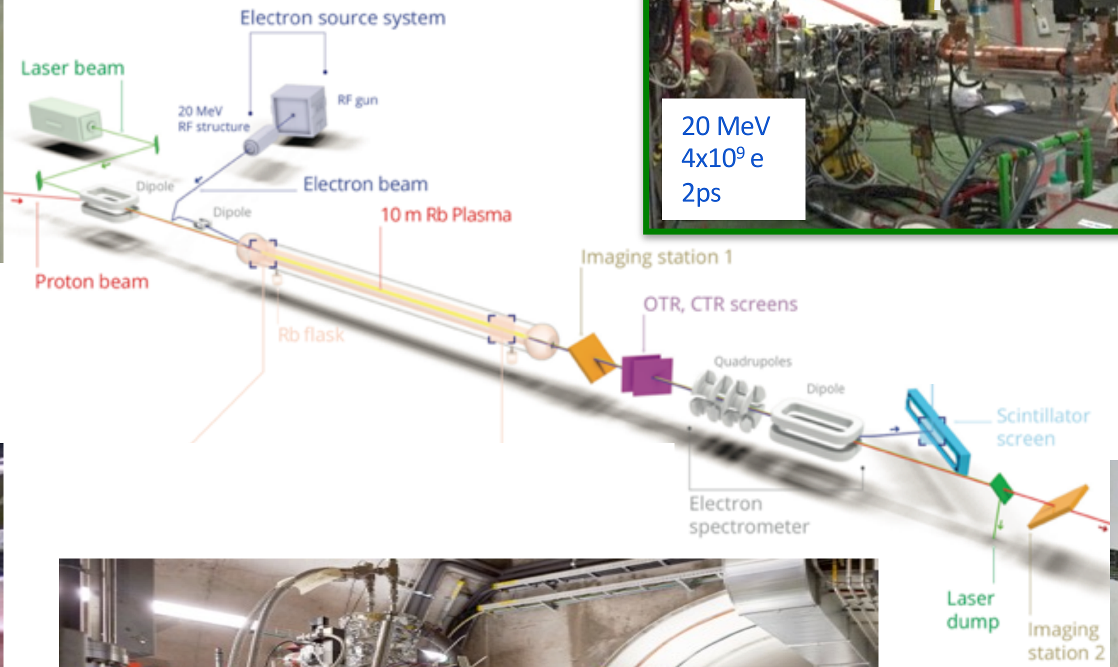
- Placing a laser close to the center of the proton bunch
- Laser ionizes vapour to produce plasma
- Sharp start of beam/plasma interaction
- → Seeding with ionization front

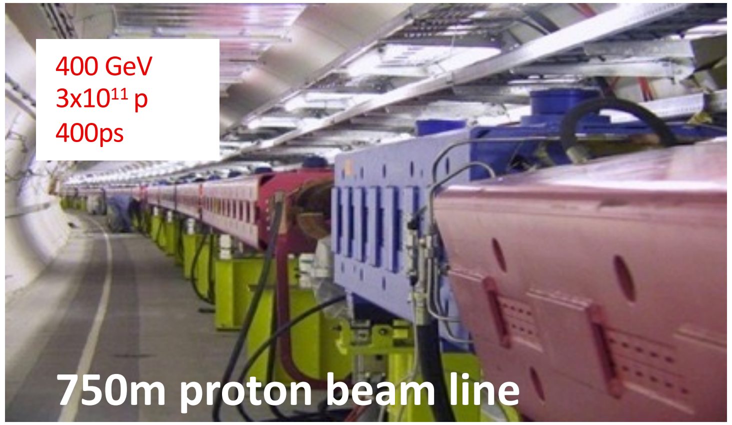
⇒ **Seeded self-modulation (SSM)**

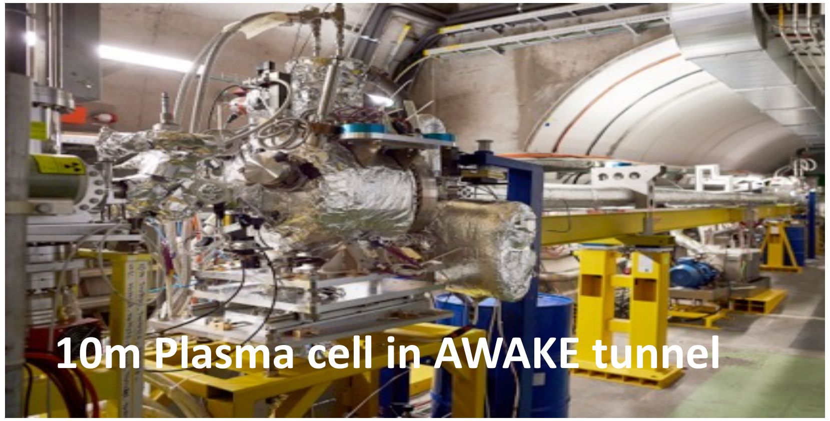
Key Ingredients of AWAKE





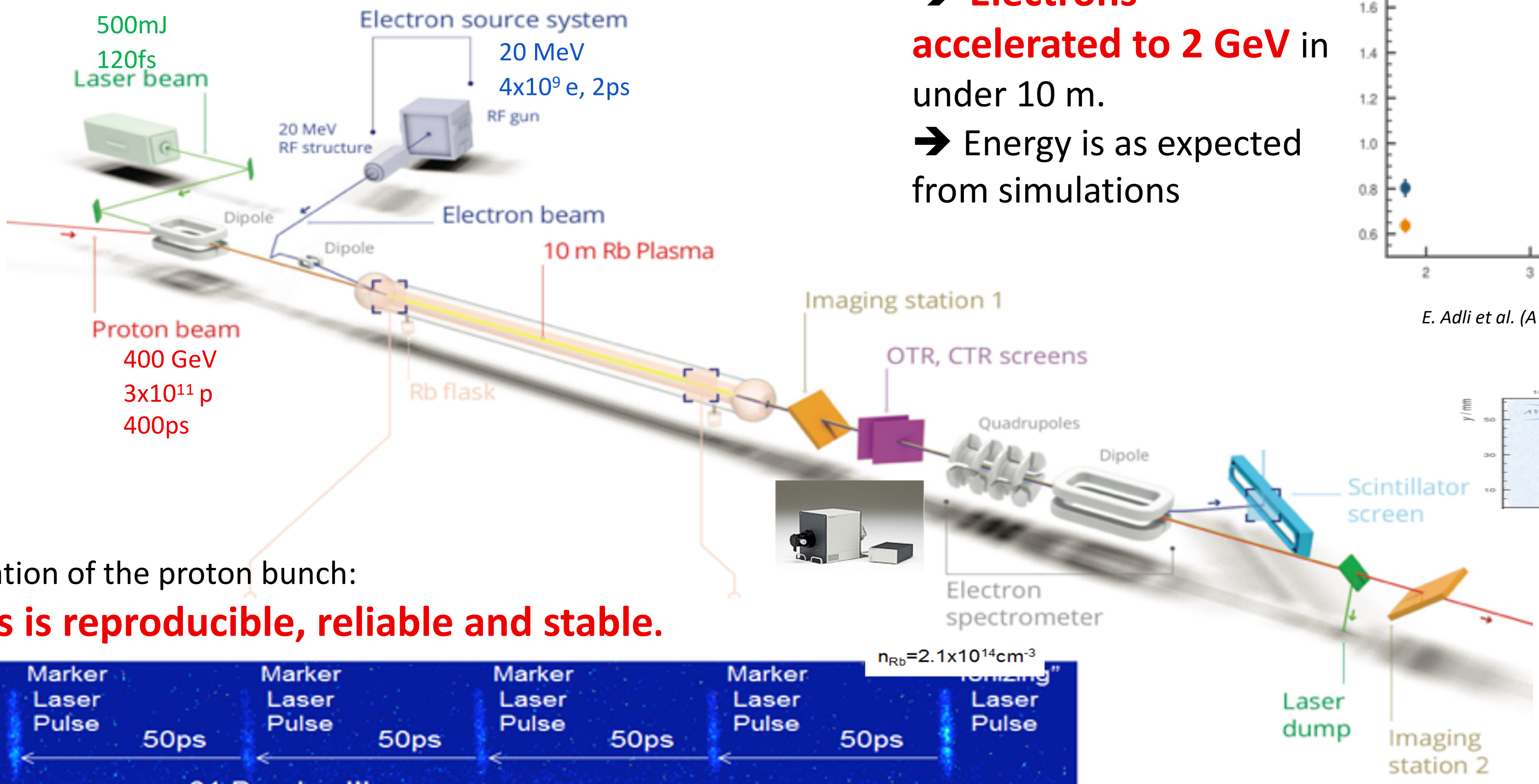






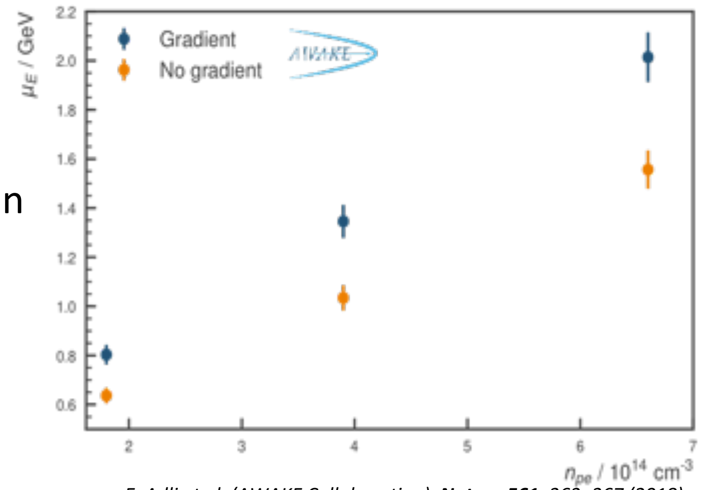
AWAKE Run 1

AWAKE has demonstrated during **Run 1 (2016-2018)** that the seeded self-modulation is a reliable and robust process and that electrons can be accelerated with high gradients.

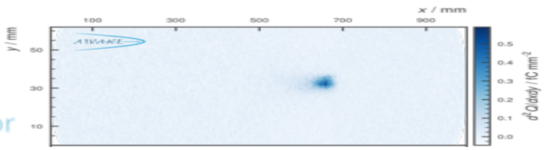


➔ **Electrons accelerated to 2 GeV** in under 10 m.

➔ Energy is as expected from simulations

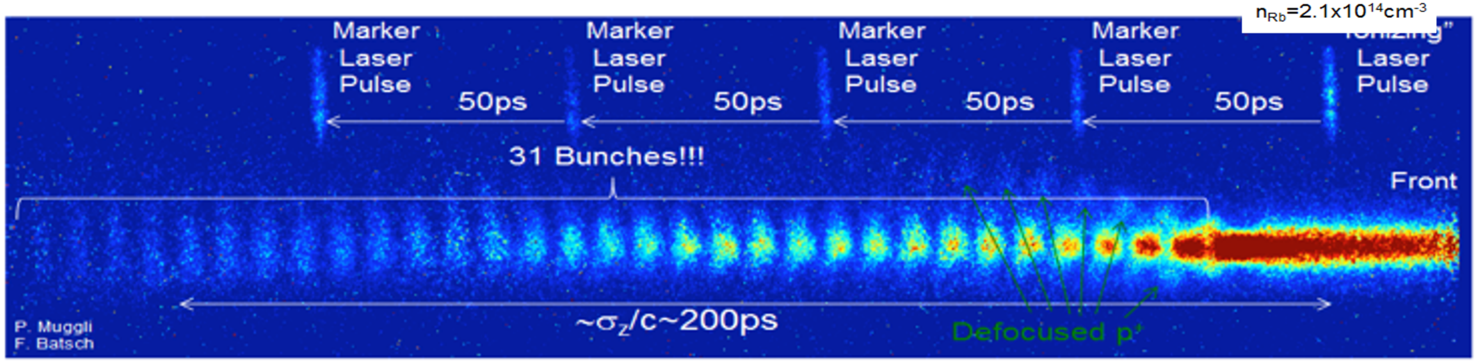


*E. Adli et al. (AWAKE Collaboration), **Nature 561**, 363–367 (2018)*



Seeded self-modulation of the proton bunch:

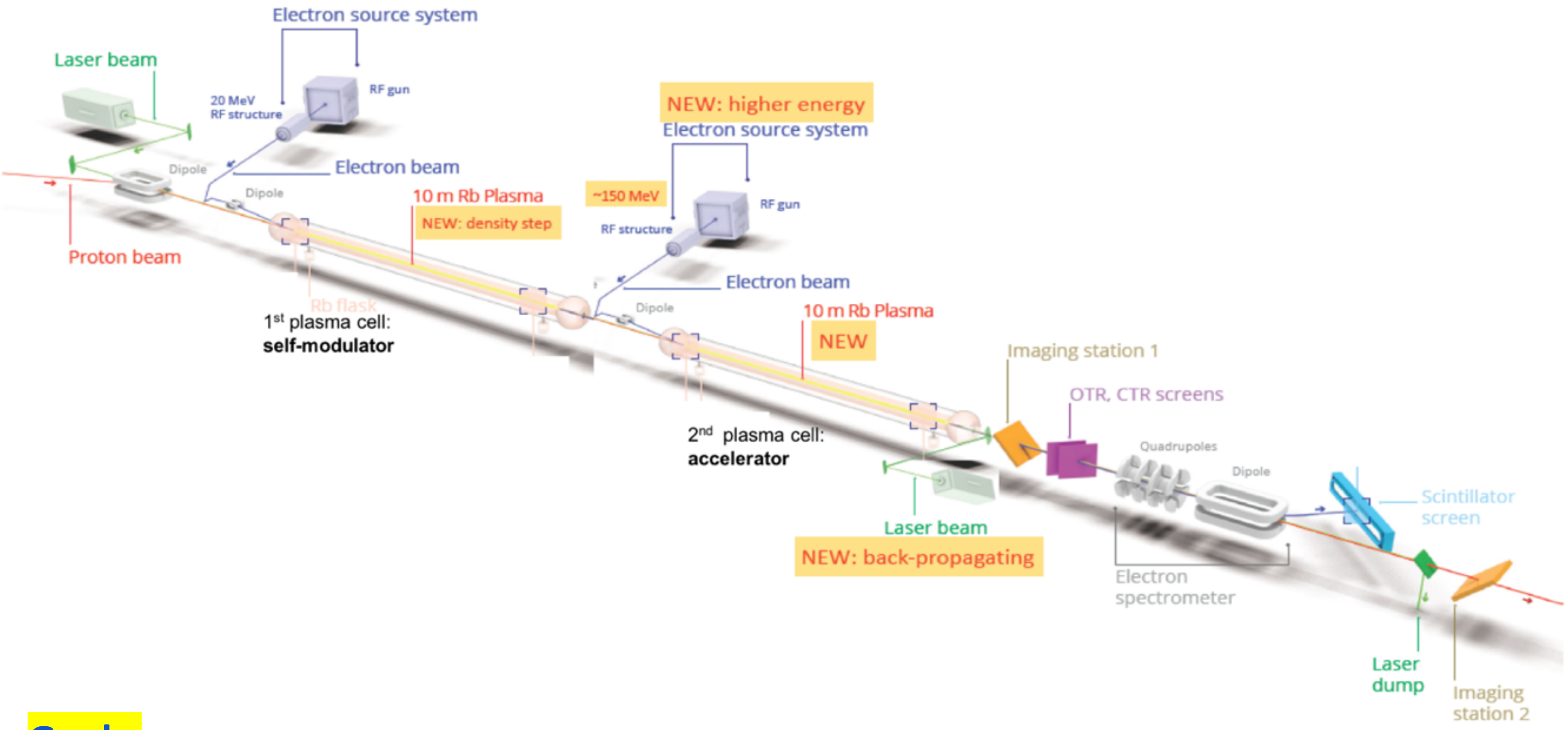
➔ **SSM process is reproducible, reliable and stable.**



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 2

➔ **Demonstrate possibility to use AWAKE scheme for high energy physics applications in mid-term future!**
➔ Start 2021!



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)

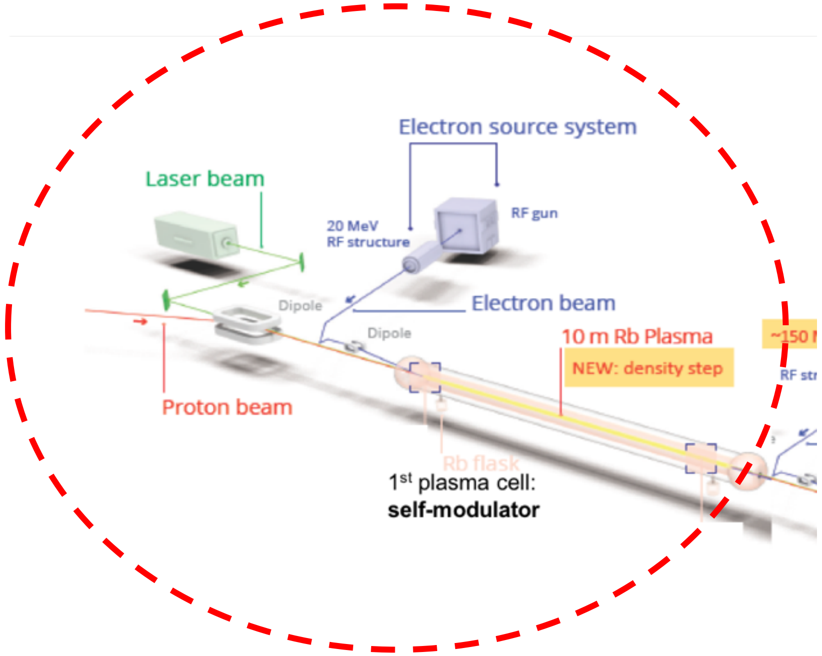
Demonstrate scalable plasma source technology (e.g. helicon prototype)

AWAKE Run 2 Timeline

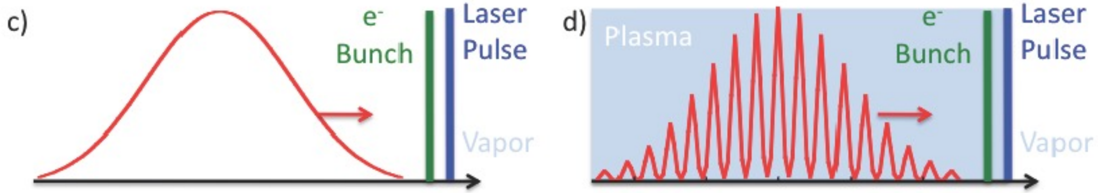
a) Demonstrate electron seeding of self-modulation in first plasma cell
b) Demonstrate the stabilization of the micro-bunches with a density step
c) Demonstrate **electron acceleration to high energies and emittance preservation**
d) Demonstrate scalable plasma sources

➔ first applications to beam dump experiments (e.g. dark photon search) with ~50 GeV electron beam.

AWAKE Run 2a: Demonstrate Electron Seeding of Self-Modulation in First Plasma Cell



Electron bunch seeding:
→ Modulates entire proton bunch with phase reproducibility

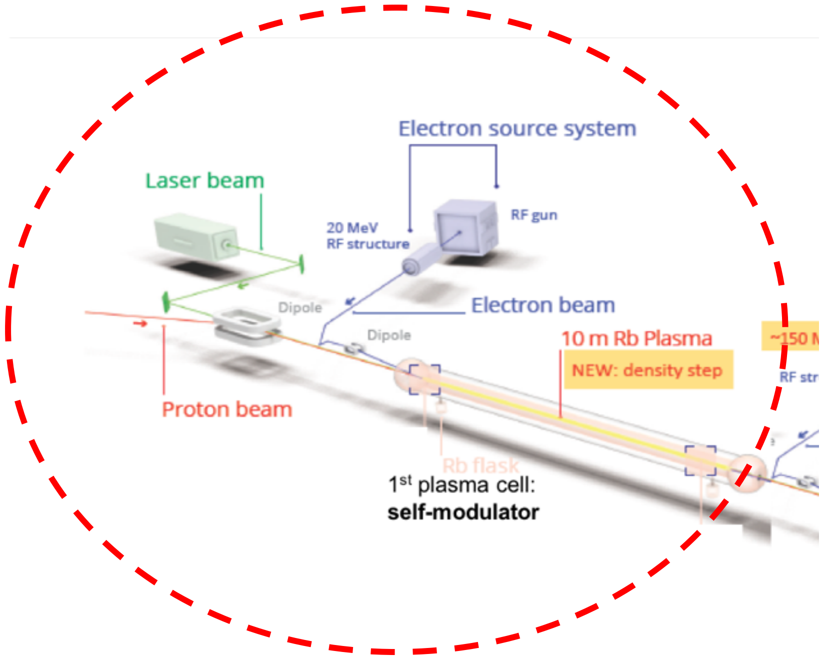


→ Run 2a: use the existing AWAKE Facility

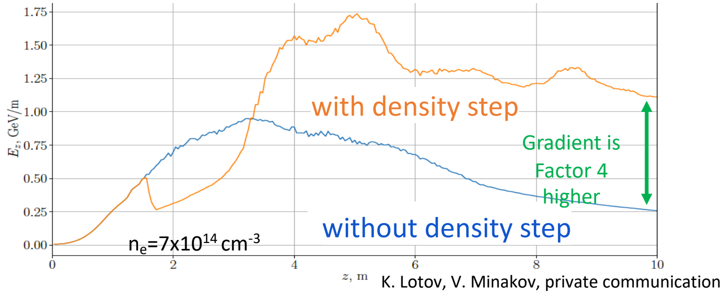
→ **Physics program in ~2021/2022**

AWAKE Run 2b: Demonstrate Stabilization of Micro-Bunches with a Density Step

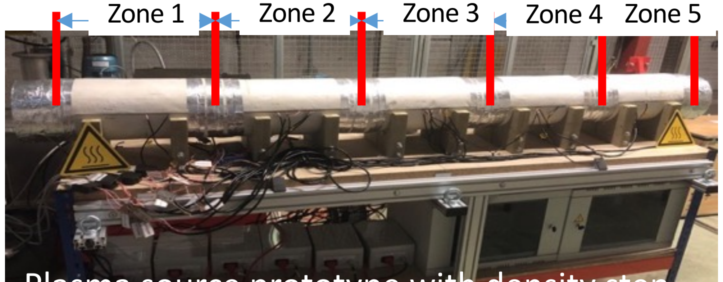
- In constant plasma, wakefield amplitude decreases after saturation.
- In a plasma with density step within the SM grow: wakefield amplitude **maintains larger** after saturation.



Gradient in 1st plasma source (self-modulator)



K. Lotov, V. Minakov, private communication



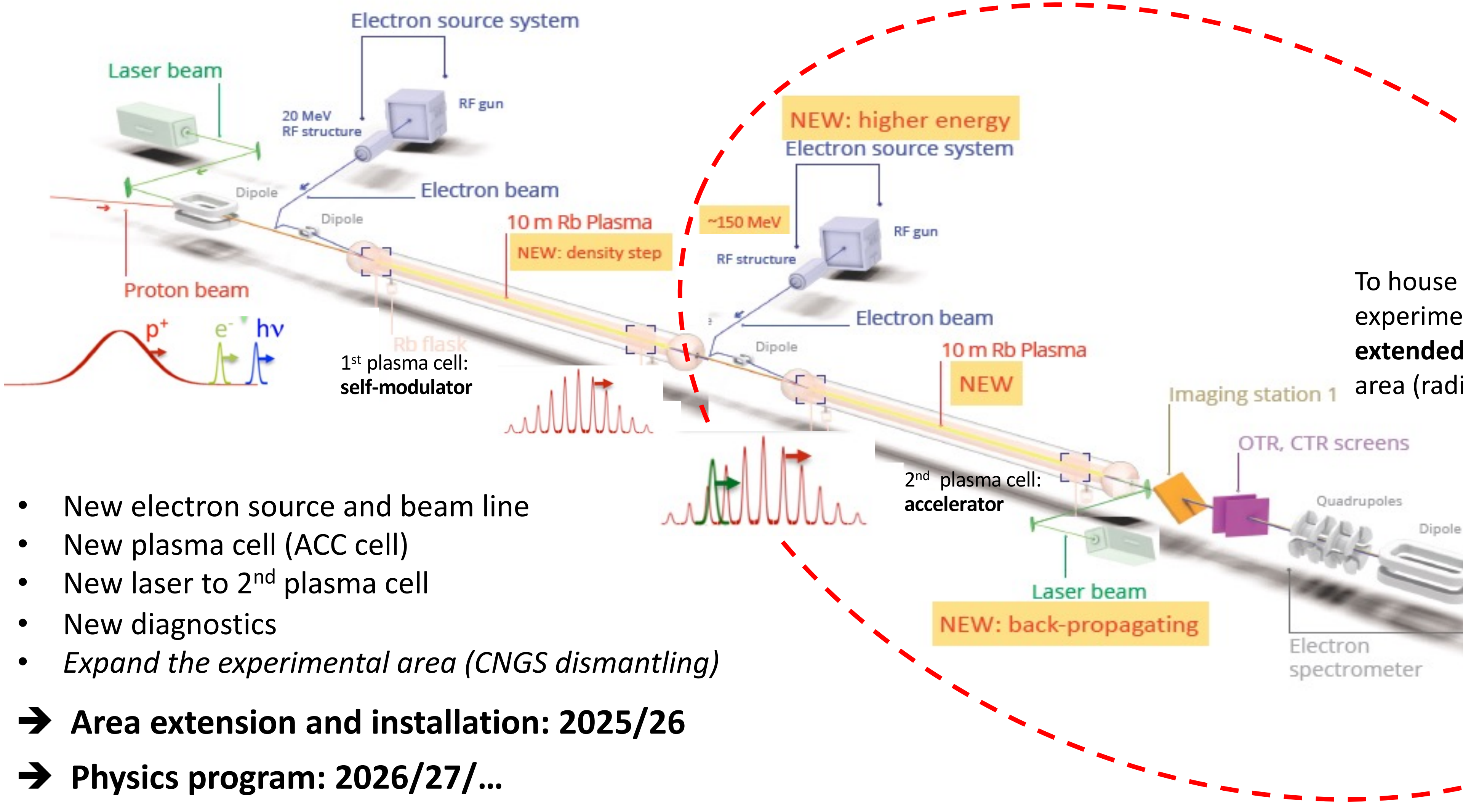
Plasma source prototype with density step

P. Muggli, J.Pucek, MPP & WDL, UK

→ Run 2b: use the existing AWAKE Facility

→ **Physics program in ~2023/2024**

AWAKE Run 2c: Demonstrate Electron Acceleration and Emittance Preservation



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

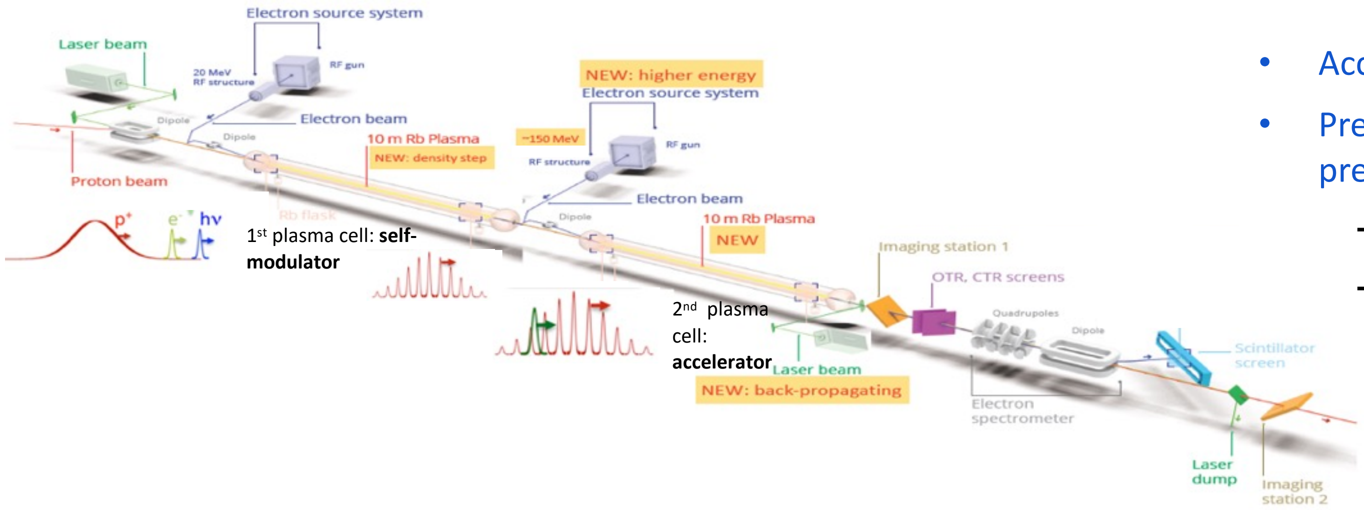
- New electron source and beam line
- New plasma cell (ACC cell)
- New laser to 2nd plasma cell
- New diagnostics
- *Expand the experimental area (CNGS dismantling)*

➔ **Area extension and installation: 2025/26**

➔ **Physics program: 2026/27/…**

AWAKE Run 2c: Demonstrate Electron Acceleration and Emittance Preservation

	Beam Energy	Energy Spread	Energy stability	RMS Bunch Length	Bunch Charge	Emittance	Beam size plasma focus
Injector 1	$18.5\ MeV$	0.5 %	1 x 10^{-2}	$\approx 2-3\ ps$	$100\ - 600\ pC$	2 - 5 μm	$\sim 190\ \mu m$
Injector 2	$\mathbf{150\ MeV}$	$\mathbf{0.2}$ **%**	**1 x 10^{-3} ?**	$\approx \mathbf{200 - 300\ fs}$	$\mathbf{100\ pC}$	$\mathbf{2\ \ \mu m}$	$\mathbf{5.75\ \mu m}$

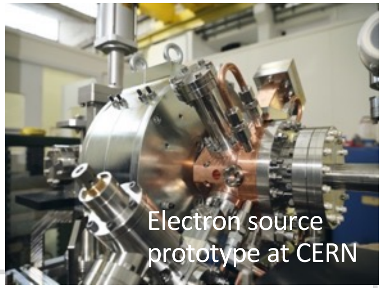


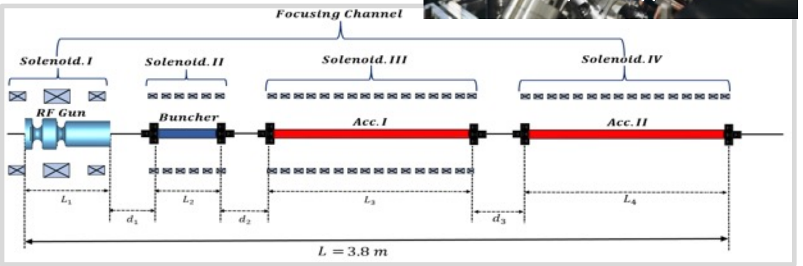
- Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)
- Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)
  - → Need to work in blow-out regime and do beam-loading
  - → New electron beam:150 MeV, 200 fs, 100 pC, σ = 5.75 µm

New electron source:

→ based on X-band

→ Prototyping together with CLEAR





New electron line:

→ Requirement of β = 5 mm at injection.

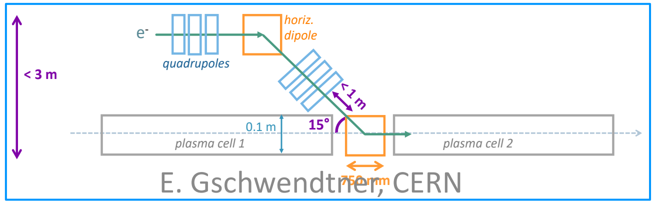
→ Require achromatic module, with no bunch lengthening.

→ Limit of ~ 3m width set by tunnel width

→ Dipole bending angle > 15°

→ Dipole-quadrupole spacing > 1 m

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



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.

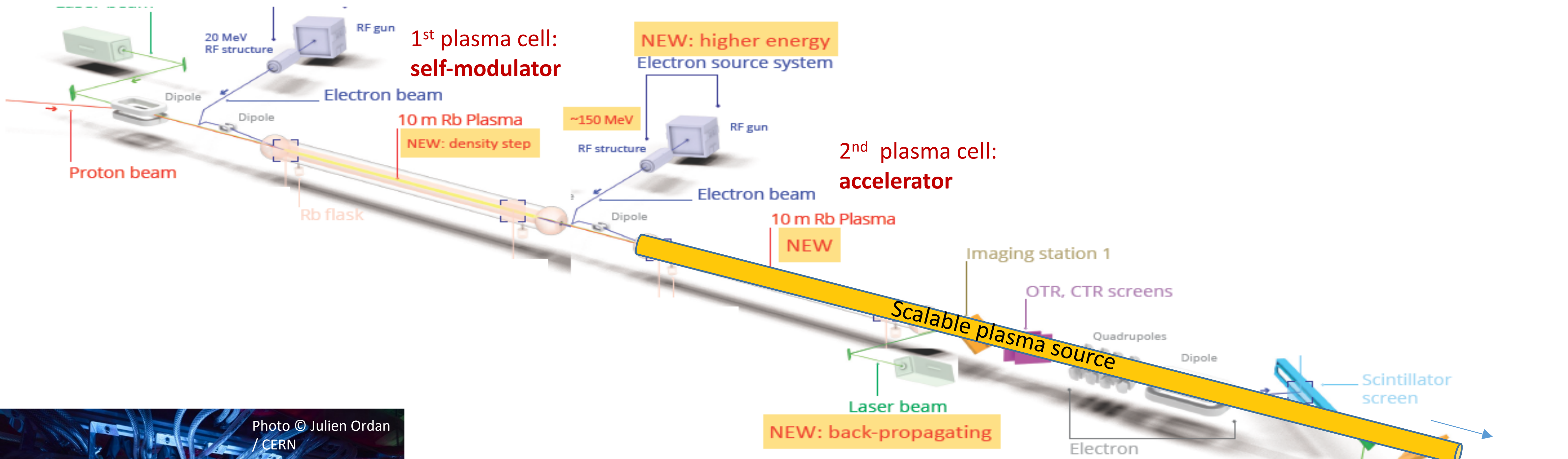
Witness e- beam injected in 2nd plasma cell: measurement of small (6 µm σ) beam in Rb vapour.

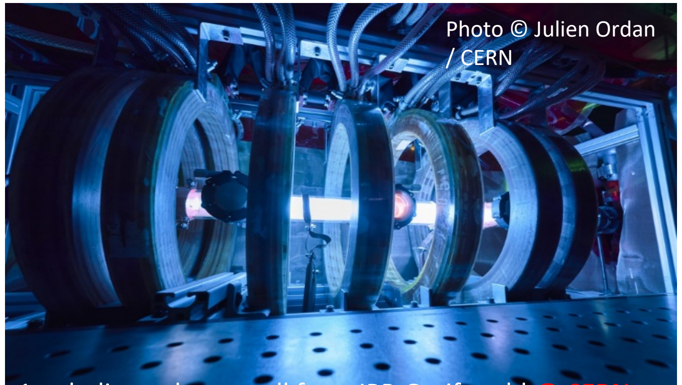
New 2nd plasma cell:

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)

Summary and Outlook

→ Many encouraging results in the plasma wakefield acceleration technology. Plasma wakefield acceleration is an exciting and growing field with 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 prepares 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.