AWAKE
The Proton Driven Plasma Wakefield Acceleration Experiment

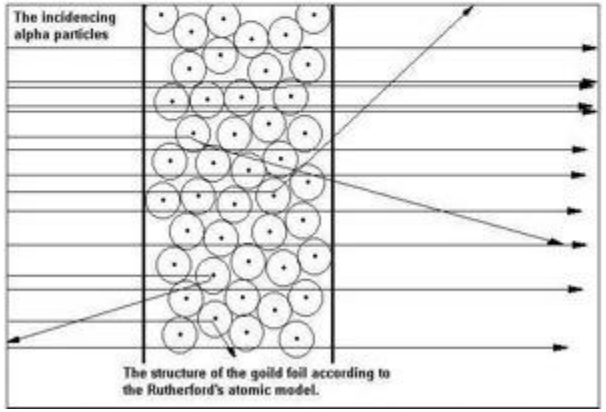
Edda Gschwendtner, CERN

Outline

- Motivation
- Plasma Wakefield Acceleration
- Plasma Wakefield Acceleration Experiments
- Outlook

Motivation: Increase Particle Energies

- 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.

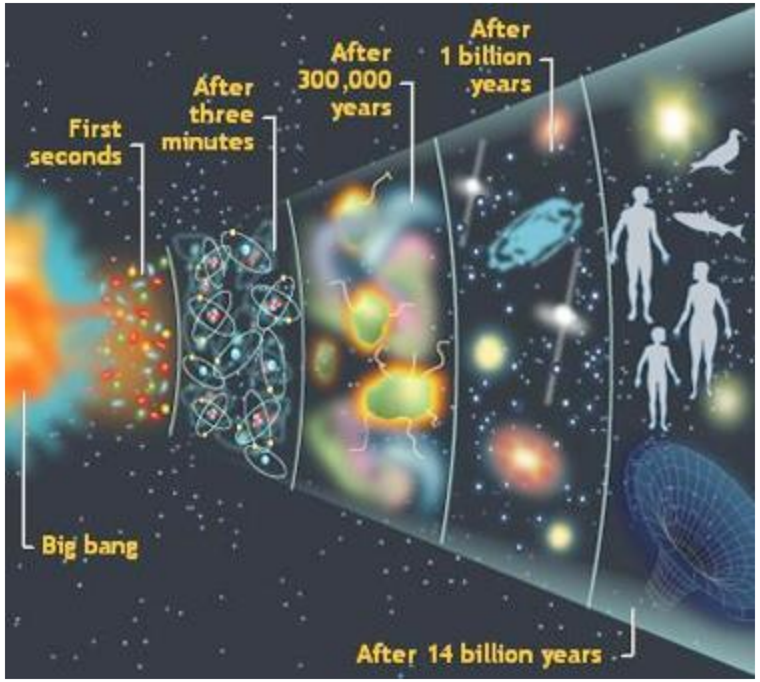


- Increasing energies makes particles of larger and larger mass accessible
  - GeV type masses in 1950ies, 60ies (Antiproton, Omega, hadron resonances…
  - Up to 10 GeV in 1970ies (J/Psi, Ypsilon…)
  - Up to ~100 GeV since 1980ies (W, Z, top, Higgs…)

- Discoveries went hand in hand with theoretical understanding of underlying laws of nature

  → **Standard Model** of particle physics

- 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



Motivation: High Energy Accelerators

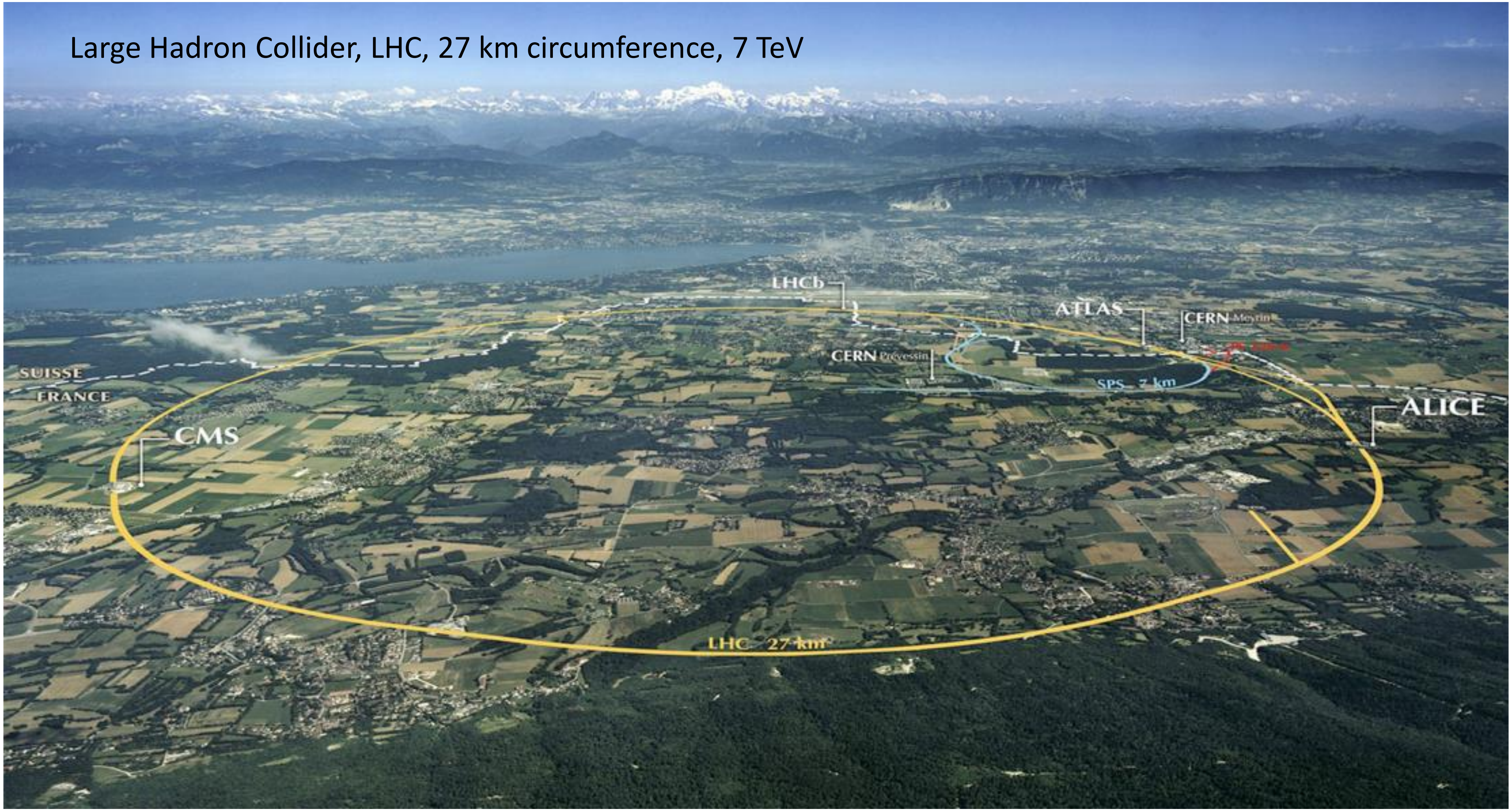
- Large list of unsolved problems:
  - What is dark matter made of? What is the reason for the baryon-asymmetry in the universe? What is the nature of the cosmological constant? How does quantum gravity fit into the picture?

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

➔ **30'000 accelerators worldwide!**

Also application of accelerators outside particle physics in medicine, material science, biology, etc…

LHC

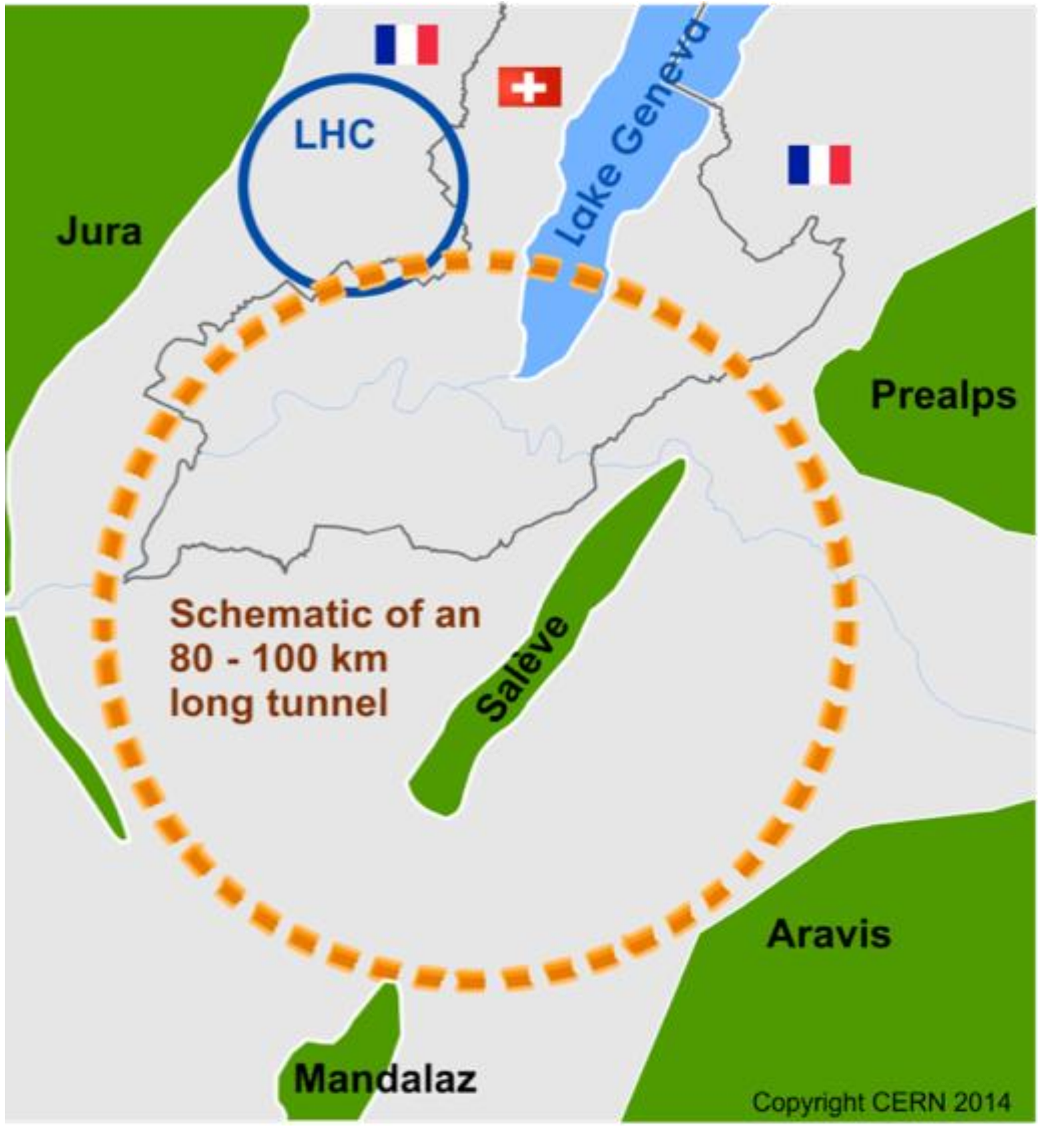

Large Hadron Collider, LHC, 27 km circumference, 7 TeV
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

Circular Collider

FCC, Future Circular Collider

80 – 100 km diameter
100 TeV (pp)
>350 GeV (e^+e^-)

20 T dipoles

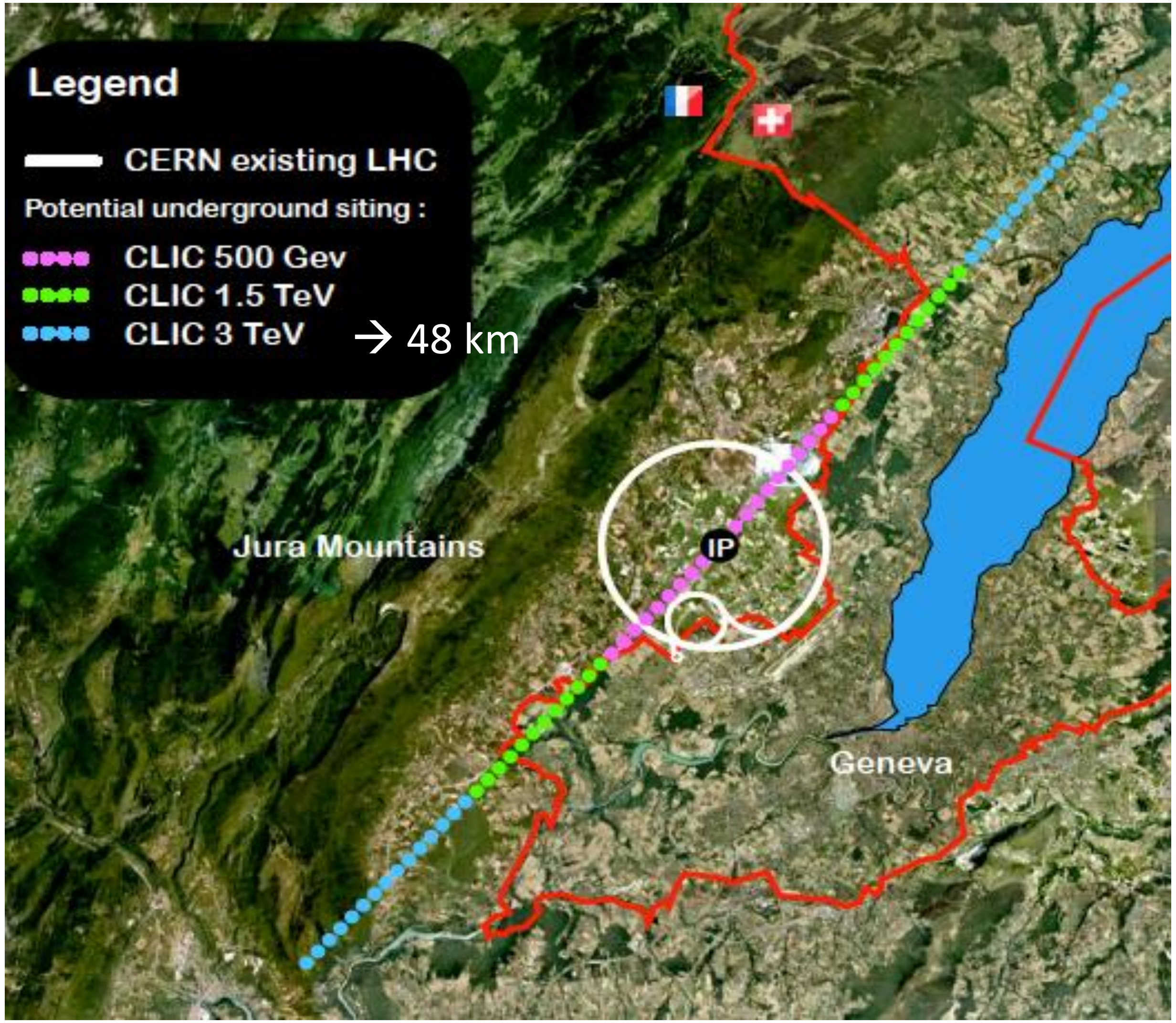


Linear Colliders

CLIC

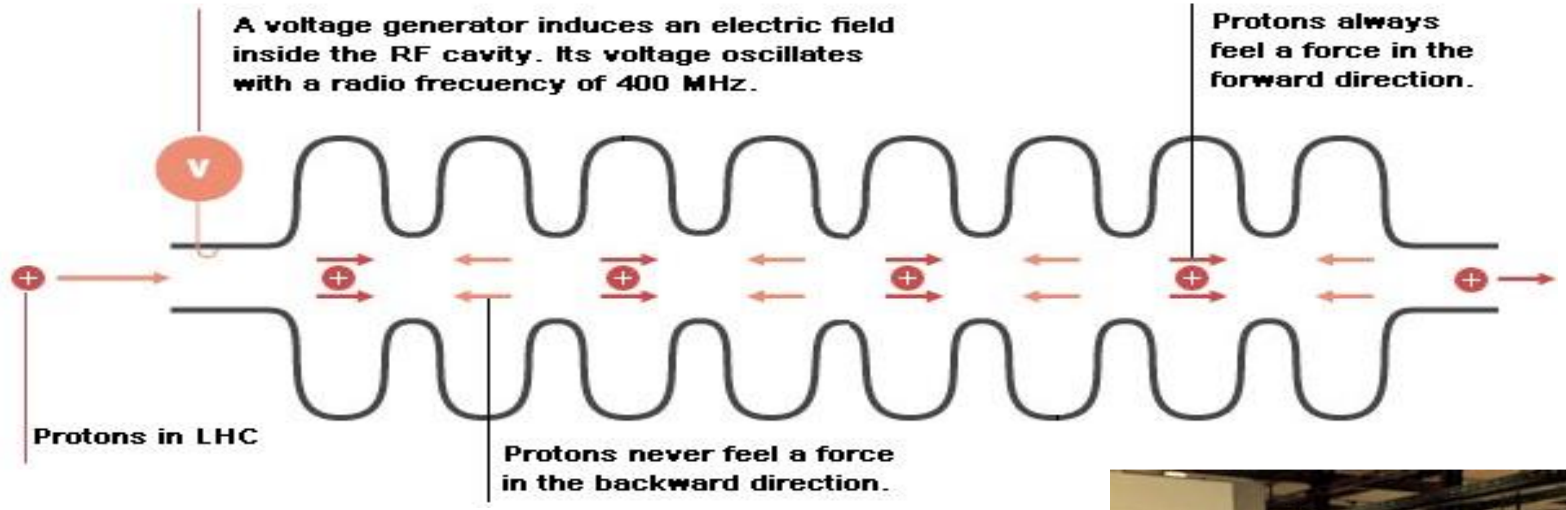
48 km length
3 TeV (e^+e^-)

Accelerating elements:
Cavities: 100 MV/m



Conventional Acceleration Technology

Radiofrequency Cavities



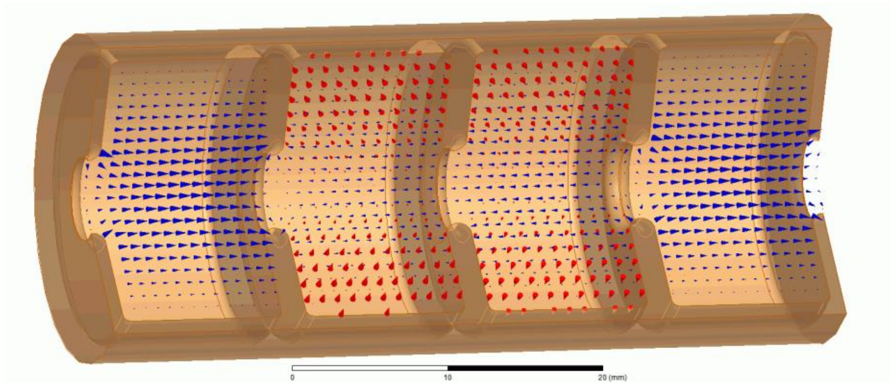
(invention of Gustav Ising 1924 and Rolf Wideroe 1927)

LHC Cavity

Conventional Accelerating Technology

Today's RF cavities or microwave technology:

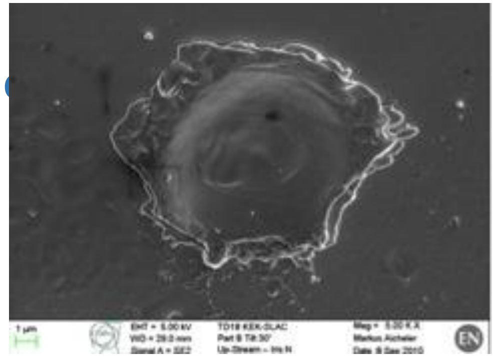
- Very successfully used in all accelerators (hospitals, scientific labs,…) in the last 100 years.



- Typical gradients:
    - LHC: 5 MV/m
    - ILC: 35 MV/m
    - CLIC: 100 MV/m

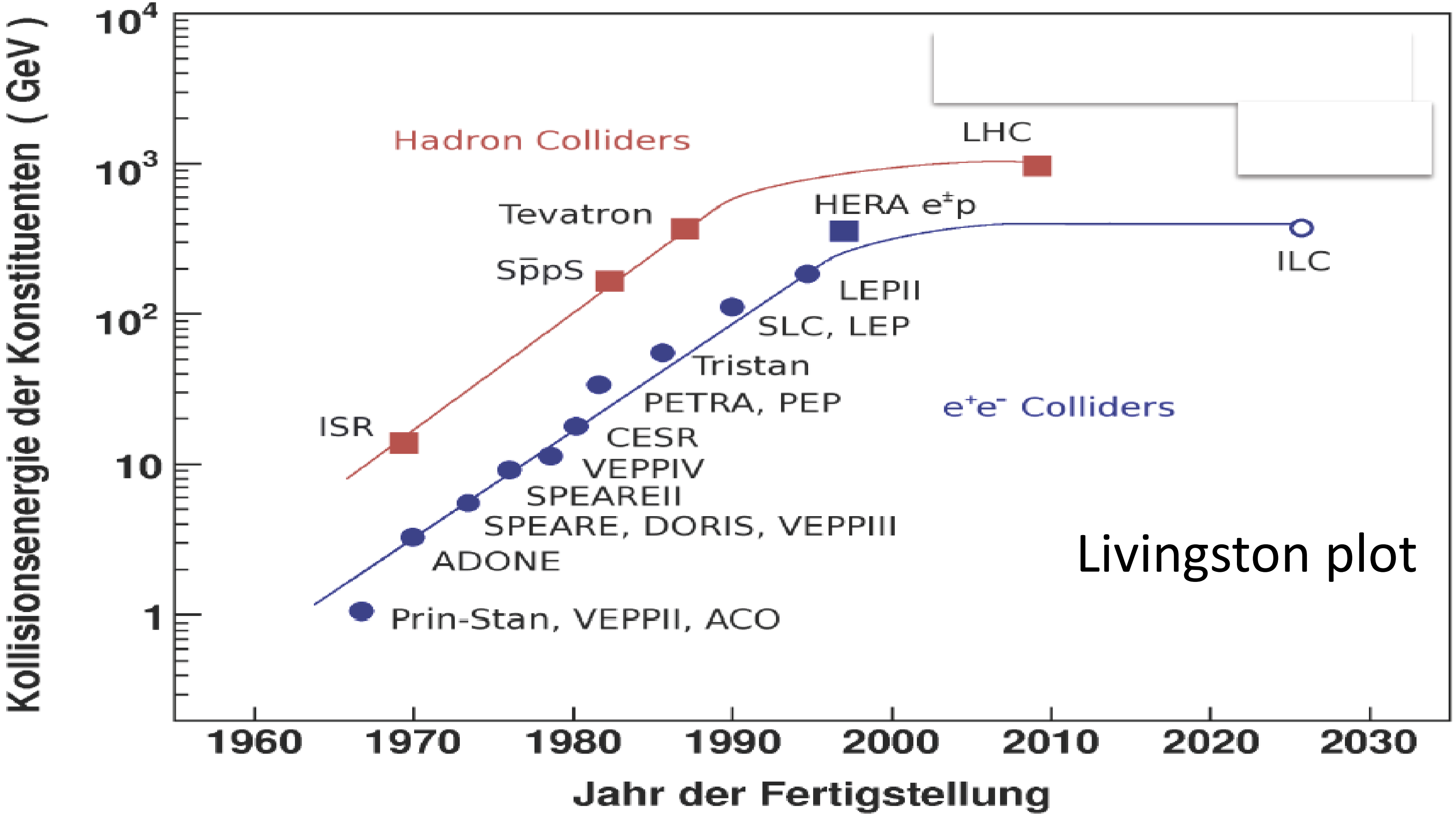
However:

- accelerating fields are limited to <100 MV/m
    - In metallic structures, a too high field level leads to break down of surfaces, creating discharge.
    - Fields cannot be sustained, structures might be damaged.



- several tens of kilometers for future linear colliders

Saturation at Energy Frontier for Accelerators



➔ **Project size and cost increase with energy**

Motivation

New directions in science are launched by new tools much more often than by new concepts.

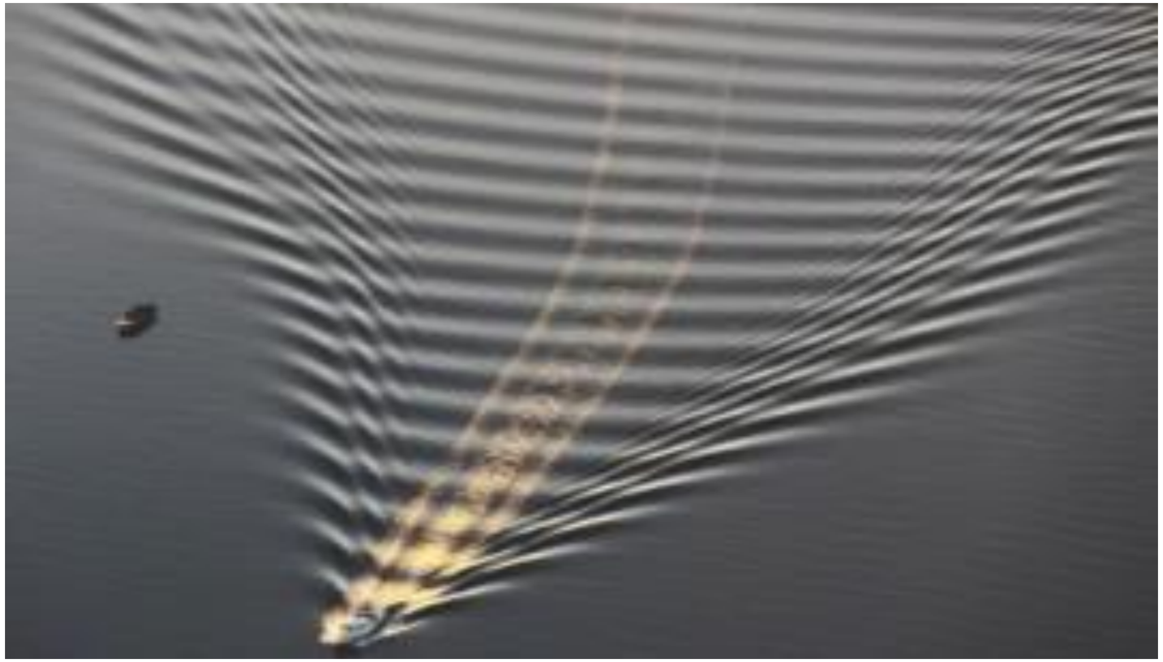
The effect of a concept-driven revolution is to explain old things in new ways.

The effect of a tool-driven revolution is to discover new things that have to be explained.

From Freeman Dyson ‘Imagined Worlds’

Plasma Wakefield Acceleration

Wakefield excitation

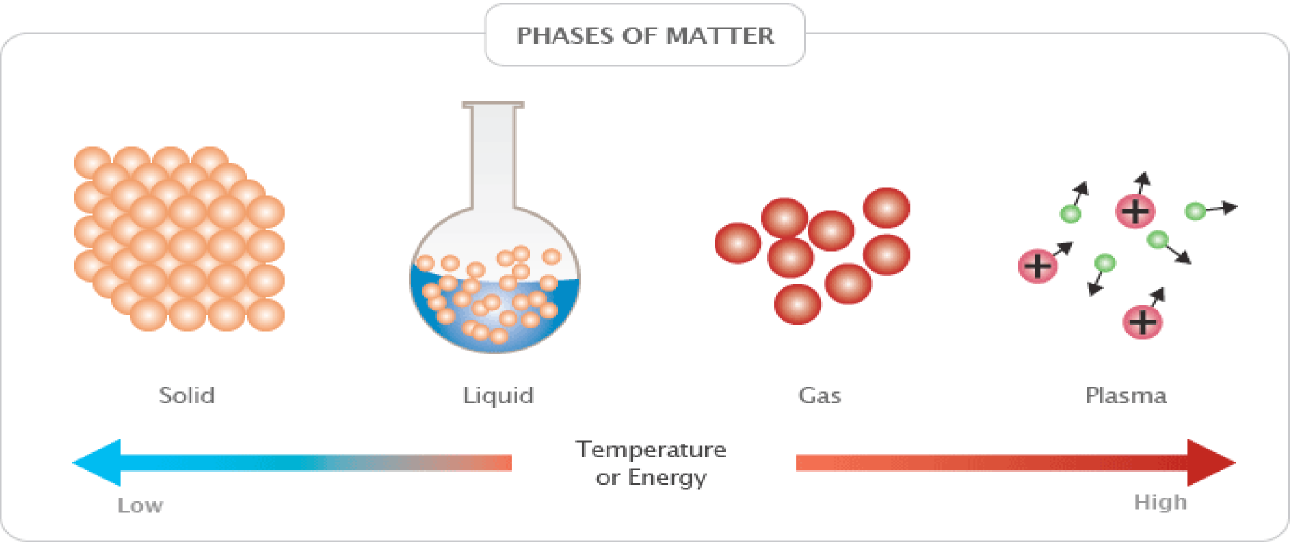


Particle acceleration

Why is Plasma Interesting?

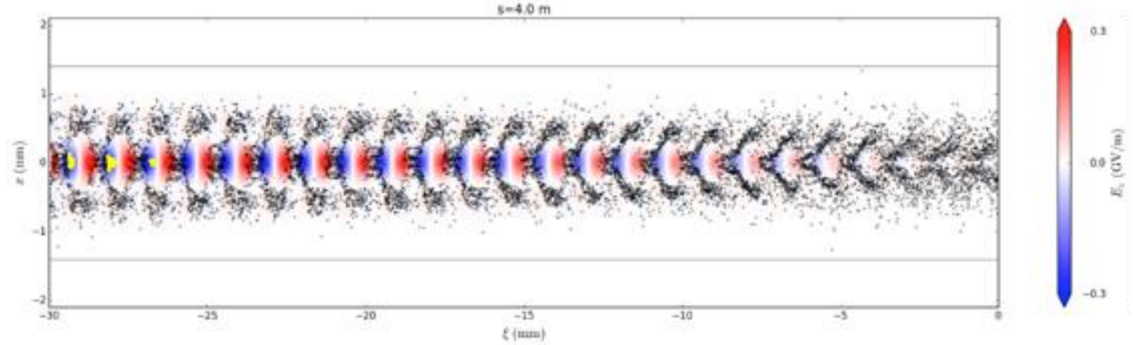
Plasma Wakefield Acceleration

Plasma is already ionized or “broken-down” and can sustain **electric fields up to three orders of magnitude higher gradients** → order of **100 GV/m.**



→ Use plasma as ‘cavity’

$$eE_{max} \approx 1[\mathrm{eV/cm}] \cdot \mathrm{n}^{1/2}[\mathrm{cm}^{-3}]$$



→ Much shorter linear colliders

Cavities vs. Plasma

- ILC Cavity: 35 MV/m

1000 mm

- Plasma cell: 35 GV/m → **35 MV/mm!!**

1 mm (Not to scale!)

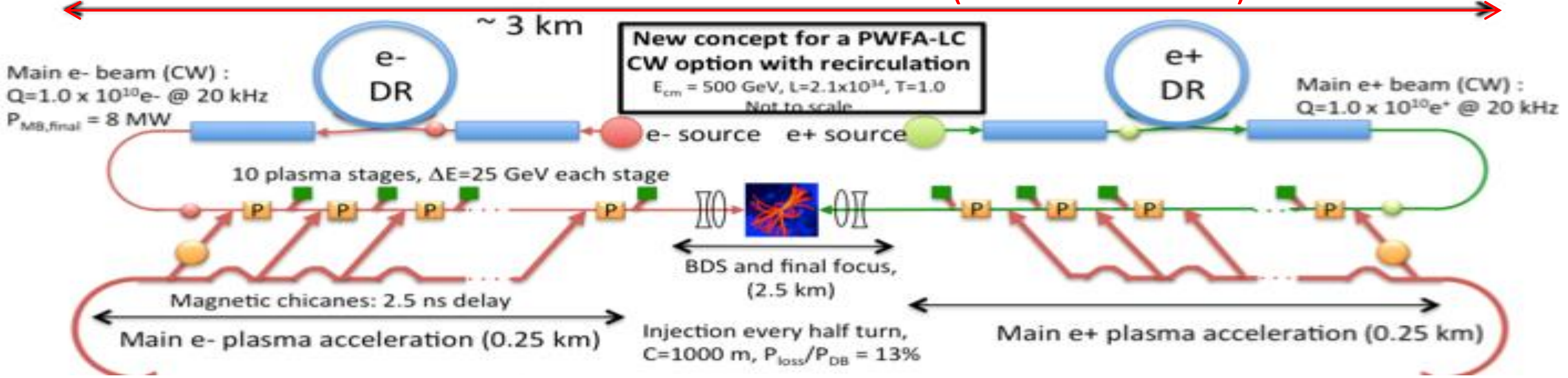
With this new technology:
No magnets, no RF, no vacuum needed

Linear Colliders

ILC

Plasma based Linear Collider

500 GeV: 3 km (3000 GeV: 8 km)



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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.

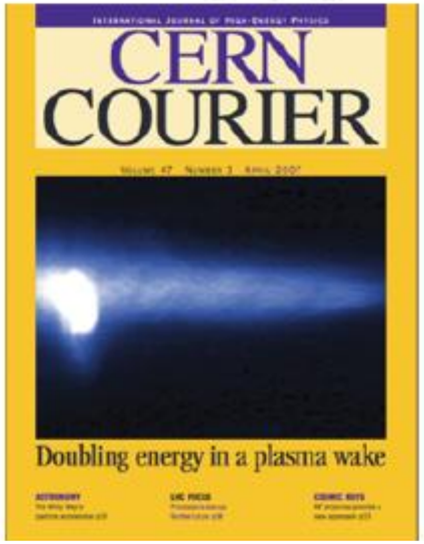
Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective 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

Since Then…


CERN COURIER
Doubling energy in a plasma wake


nature
FULL SPEED AHEAD

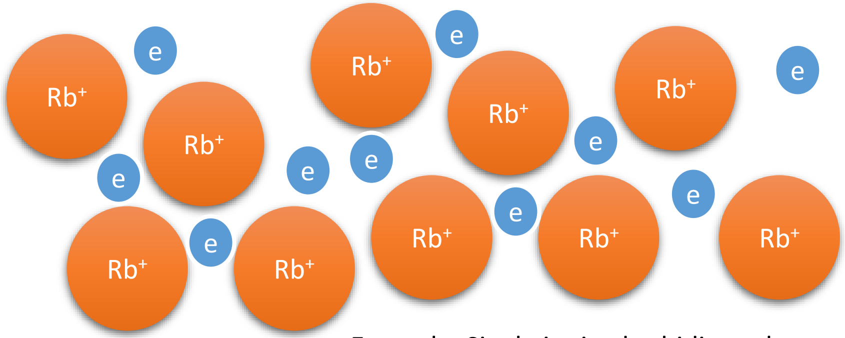

nature
Dream beam
The dawn of compact particle accelerators


Monoenergetic beams of relativistic electrons from intense laser–plasma interactions
High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding
A laser–plasma accelerator producing monoenergetic electron beams


NBC NEWS
Not-So-Large Colliders Could Revolutionize Physics
LETTER
High-efficiency acceleration of an electron beam in a plasma wakefield accelerator
SCIENTIFIC AMERICAN
Plasma-Surfing Mini-Accelerator
Science
LATEST NEWS
Ebola
THE AGING BRAIN
Physicists crank up current in new type of accelerator
Voice of America
US Scientists Build the Sma
Accelerator
Scienze
Gli acceleratori di particelle saranno più "piccoli" e low cost
welt der physik
Fortschritte in der Kielfeld-Beschleunigung
COMILLAS
ciencia plus.com
Proyectan aceleradores de partículas con plasma de bajo coste
TEDxCERN
g wakefields to create smaller
rators
CERN

Plasma Wakefield

What is a plasma?



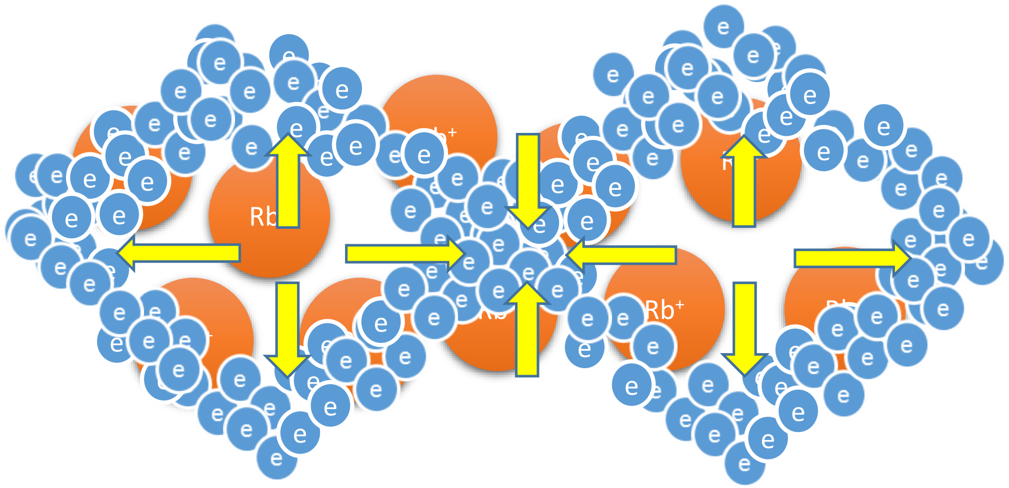
Example: Single ionized rubidium plasma

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?

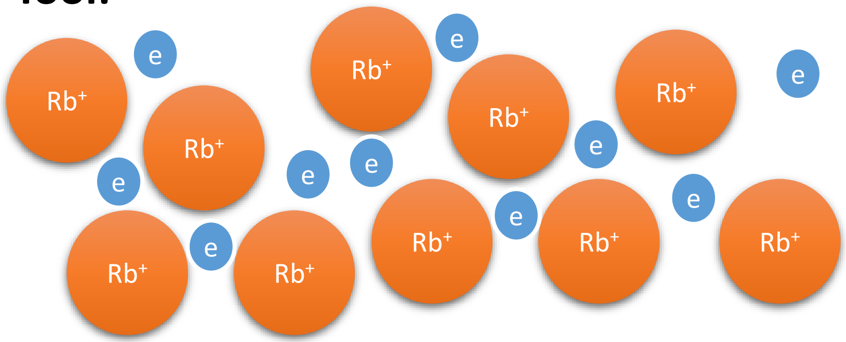


Fields created by collective motion of plasma particles are called plasma wakefields.

How to Create a Plasma Wakefield?

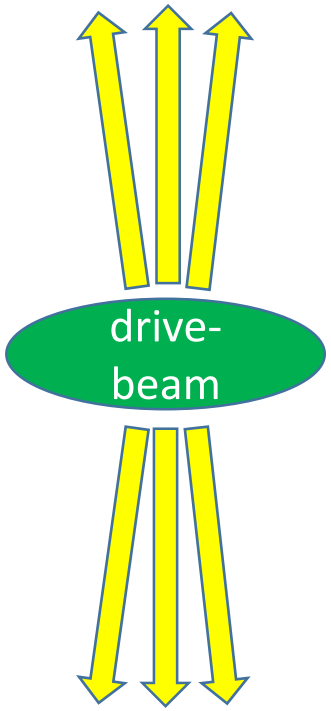
What we want:
Longitudinal electric field to accelerate charged particles.

Our Tool:



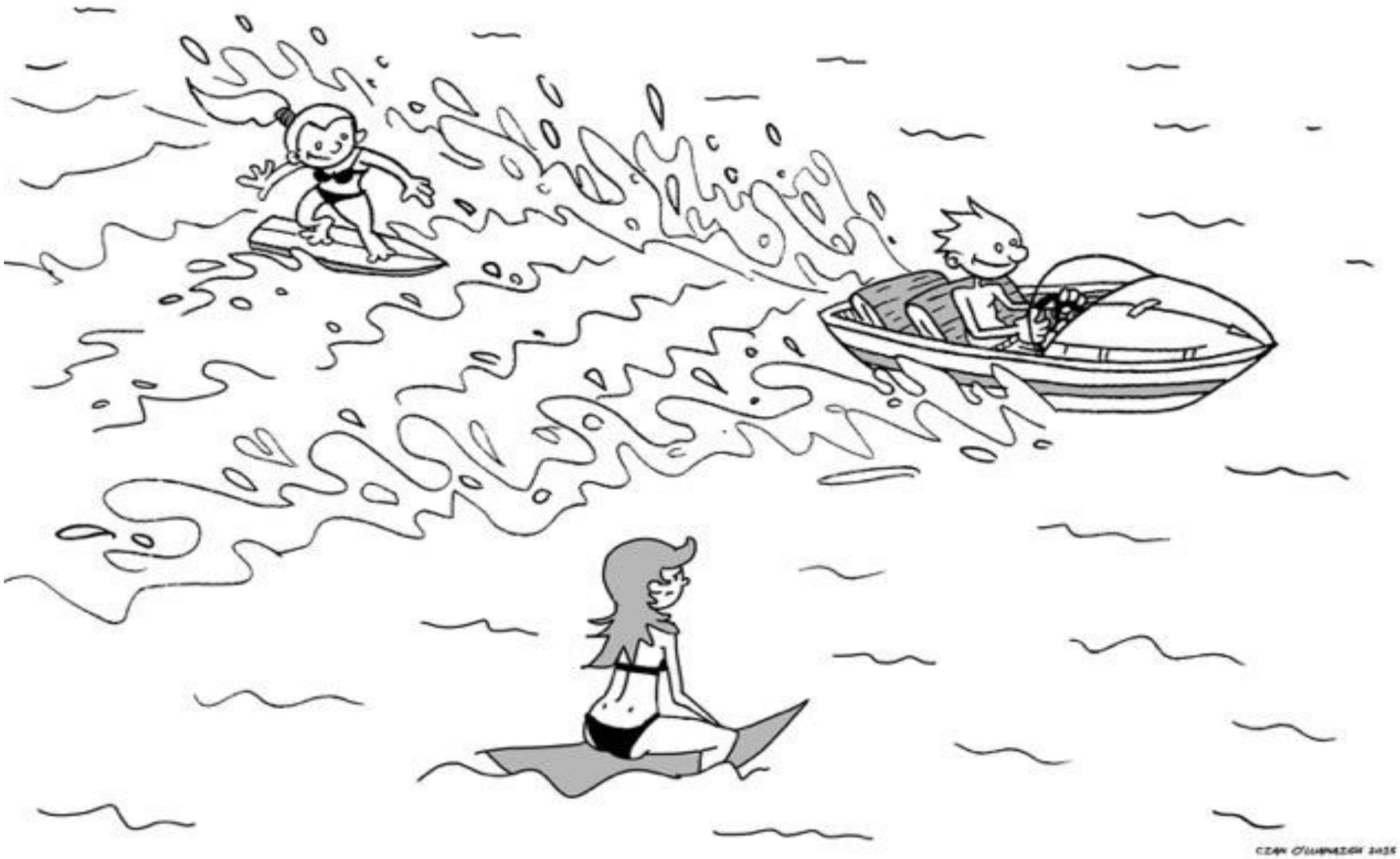
Single ionized rubidium **plasma**

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.

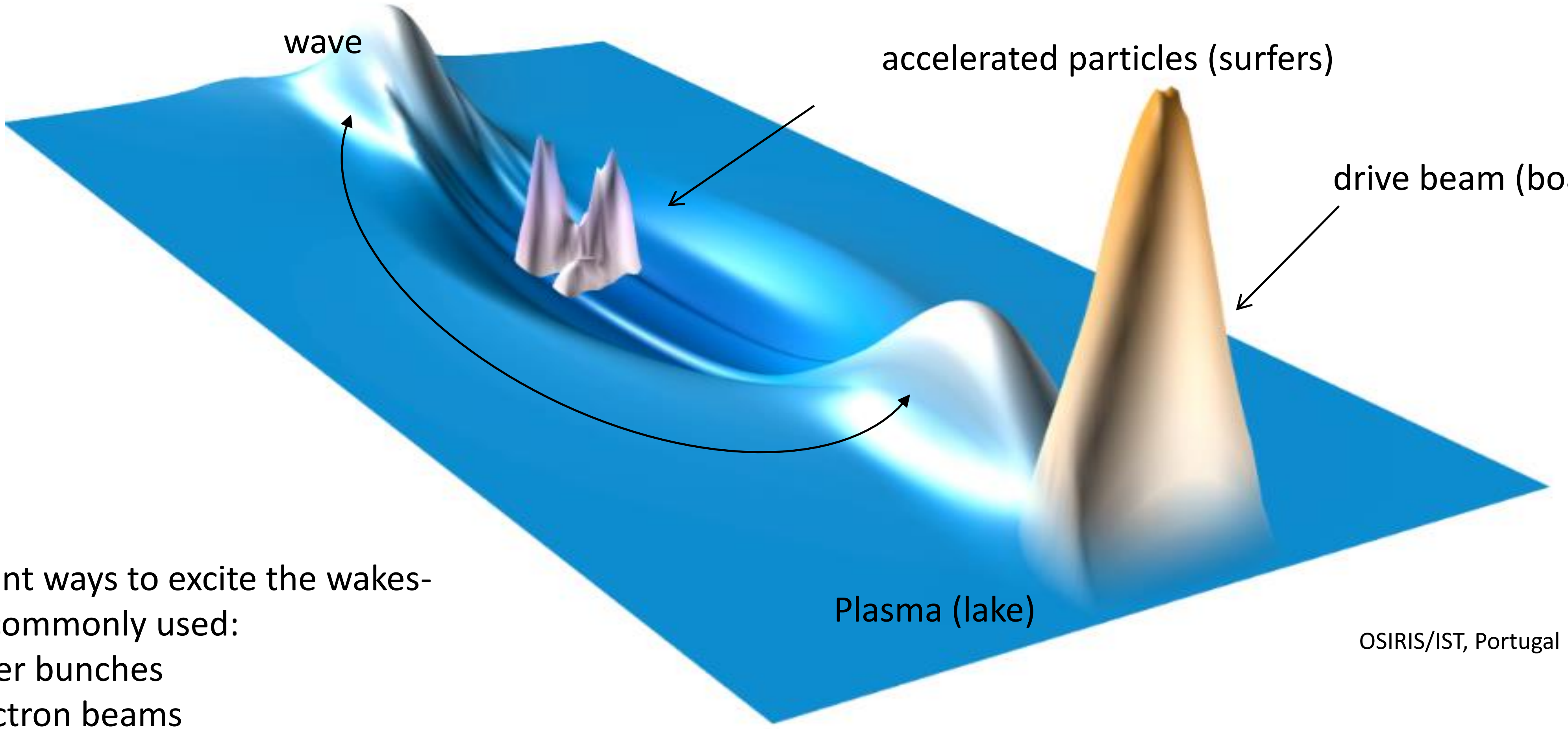


Charged particle bunches carry almost purely transverse Electric Fields.

How to Create a Plasma Wakefield?



How to Create a Plasma Wakefield?



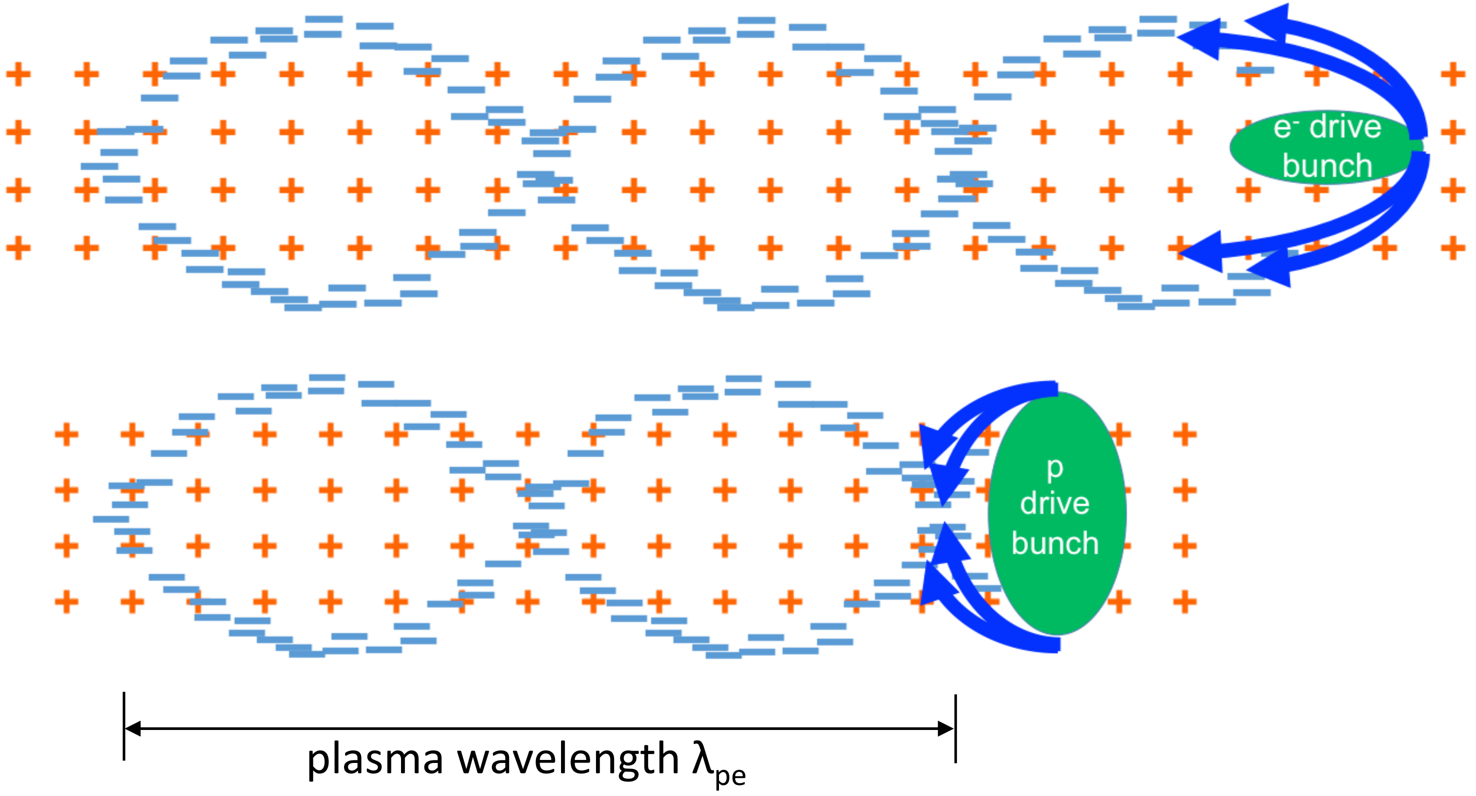
OSIRIS/IST, Portugal

Different ways to excite the wakes-
Most commonly used:

- Laser bunches
- Electron beams
- Protons bunches (first time to be done at CERN)

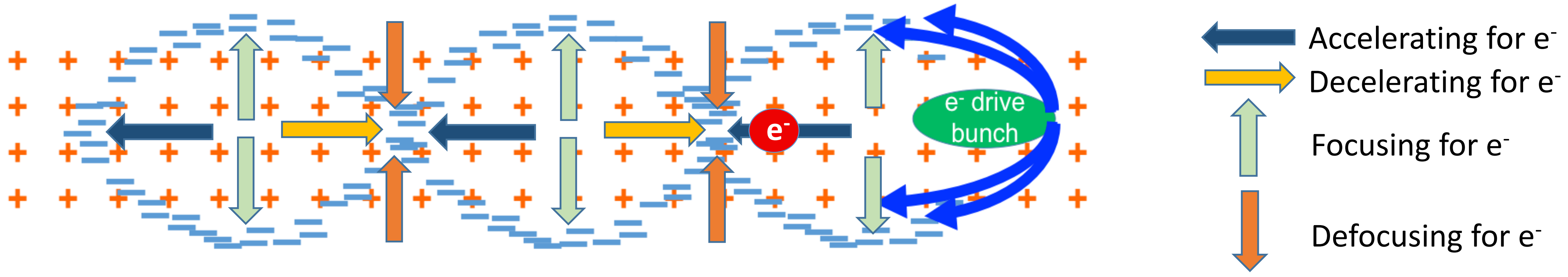
Principle of Plasma Wakefield Acceleration

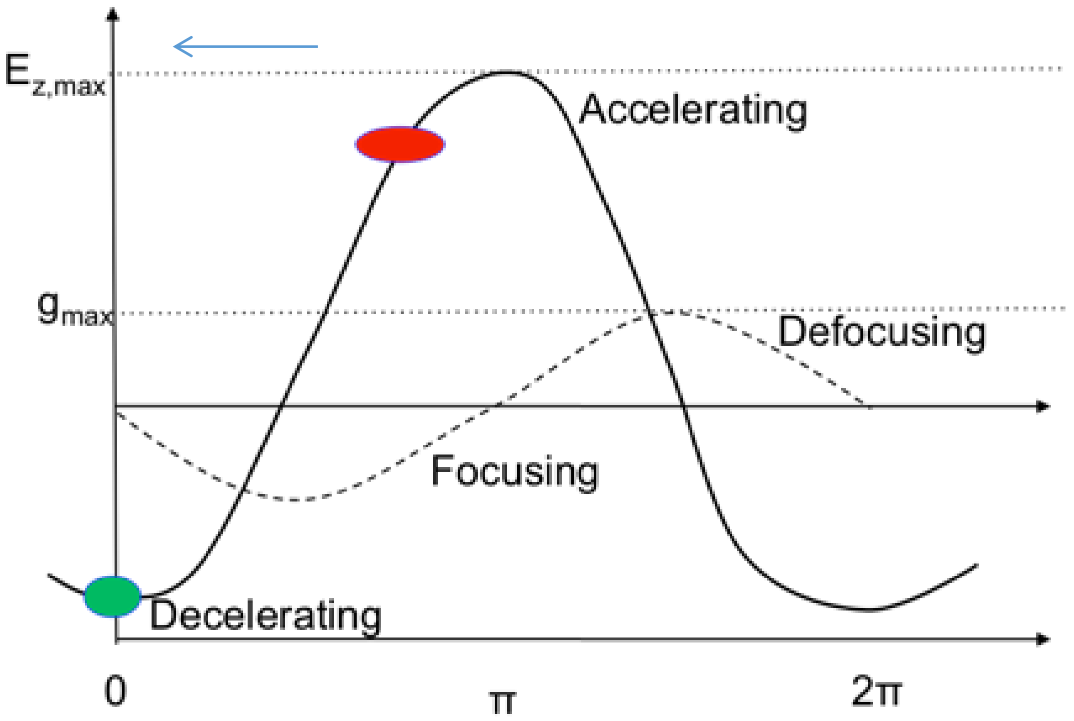
- Laser drive beam
  ➔ Ponderomotive force
- Charged particle drive beam
  ➔ Transverse space charge field
  - Reverses sign for negatively (blow-out) or positively (suck-in) charged beam



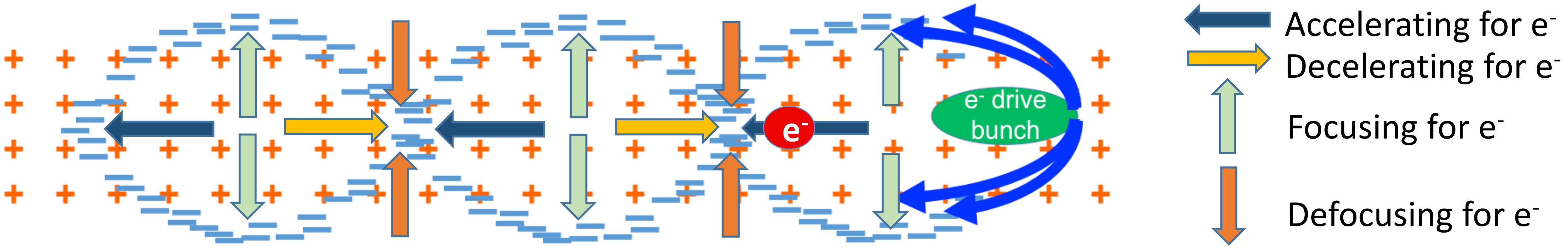
- Plasma wave/wake excited by relativistic particle bunch
- Plasma e^- are expelled by space charge force
- Plasma e^- rush back on axis
- Ultra-relativistic driver – ultra-relativistic wake → no dephasing
- Acceleration physics identical for LWFA, PWFA

Where to Place the Witness Beam (Surfer)?





Wakefields



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

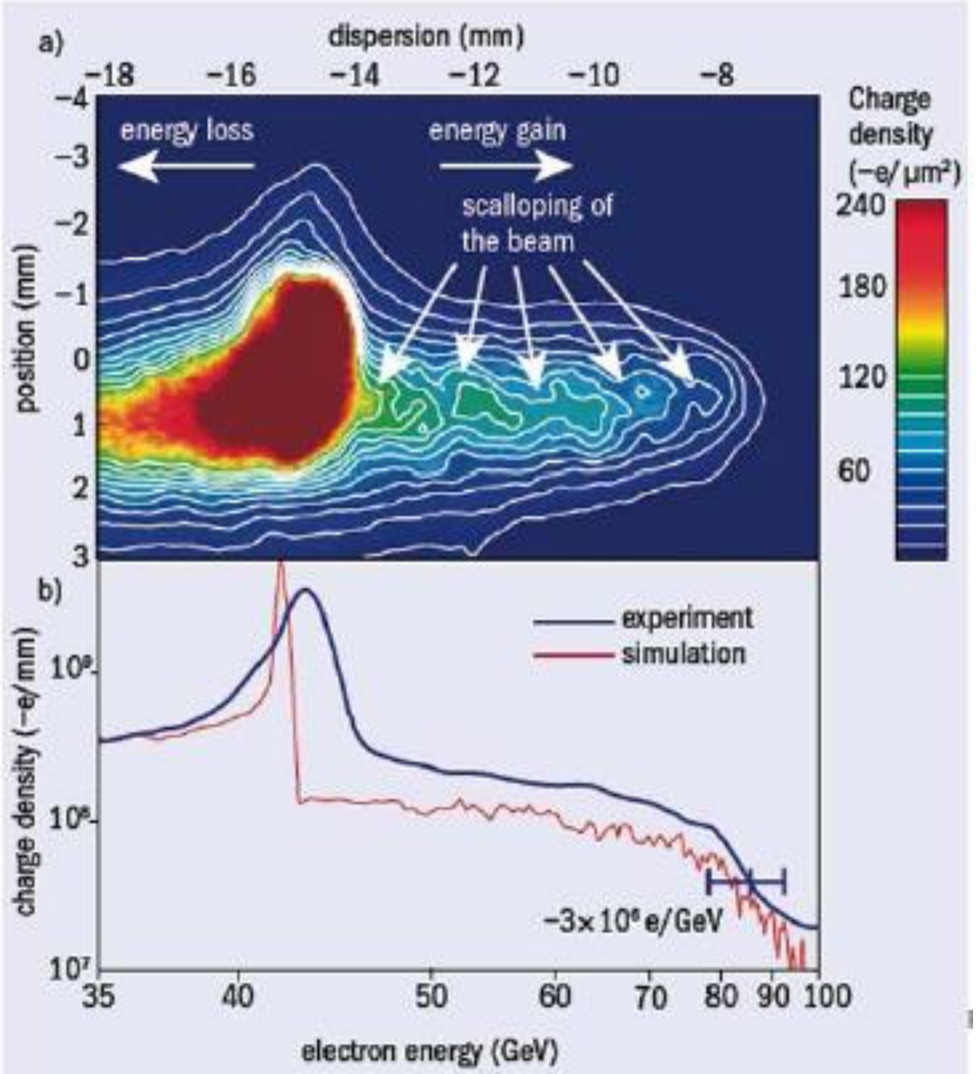
$$e\,E_{WB} = 96\,\frac{V}{m}\sqrt{\frac{n_{pe}}{cm^{-3}}}$$

Example: n_{pe} = 7x10^{14} cm^{-3} (AWAKE) → eE_{WB} = 2.5 GV/m
Example: n_{pe} = 7x10^{17} cm^{-3} → eE_{WB} = 80 GV/m

Record Acceleration: 42 GeV

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

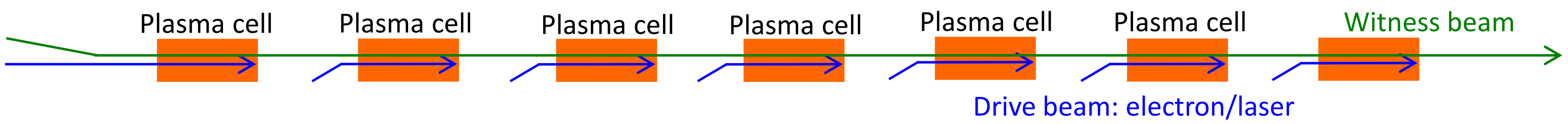
- Gaussian electron beam with 42 GeV, 3nC @ 10 Hz, σ_x = 10µm, 50 fs
- **Reached accelerating gradient of 50 GeV/m**
- Accelerated electrons from 42 GeV to 85 GeV in 85 cm.



Building Accelerators Based on PWA

Lasers: ~40 J/pulse
Electron drive beam: 30 J/bunch
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

- To reach TeV scale with 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….



- Proton drivers: large energy content in proton bunches → interesting for plasma wakefield accelerators → to reach high energies of a witness beam possible in few stages.
- But: need short bunches → self-modulation instability

Self-Modulation Instability

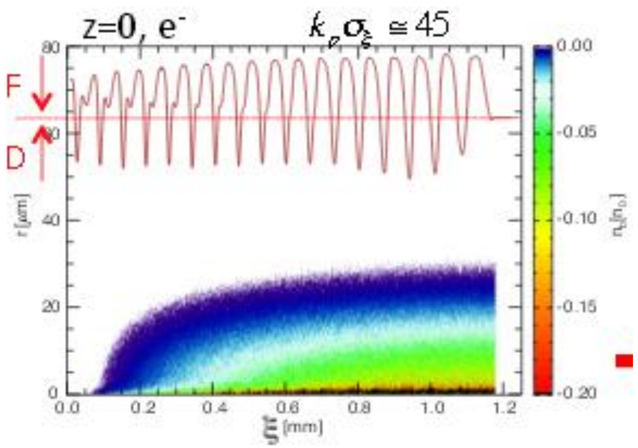
- In order to create plasma wakefields efficiently, the drive bunch length has to be in the order of the plasma wavelength.
- **CERN SPS proton bunch: very long!**
- Longitudinal beam size (**σ_z = 12 cm**) is much longer than plasma wavelength **(λ = 1mm**)

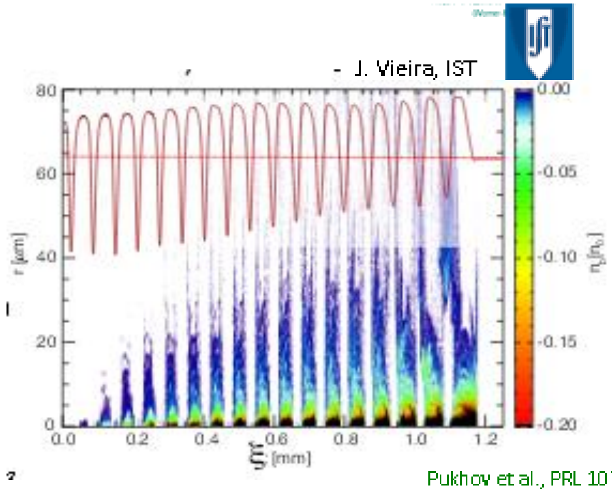
Self-Modulation Instability of the proton beam

- Modulate long bunch to produce a series **of ‘micro-bunches’ in a plasma with a spacing of plasma wavelength λ_p.**

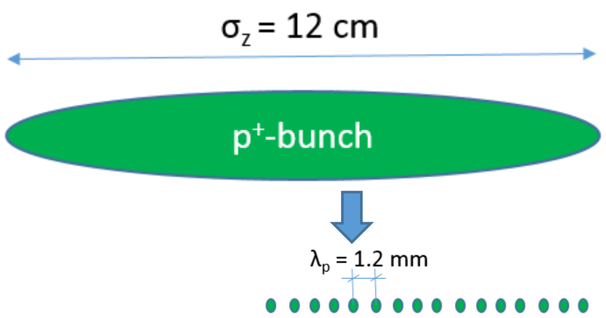
  →Strong self-modulation effect of proton beam due to transverse wakefield in plasma

  →**Resonantly drives the longitudinal wakefield**





Pukhov et al., PRL 107, 145003 (2011)
Schroeder et al., PRL 107, 145002 (2011)



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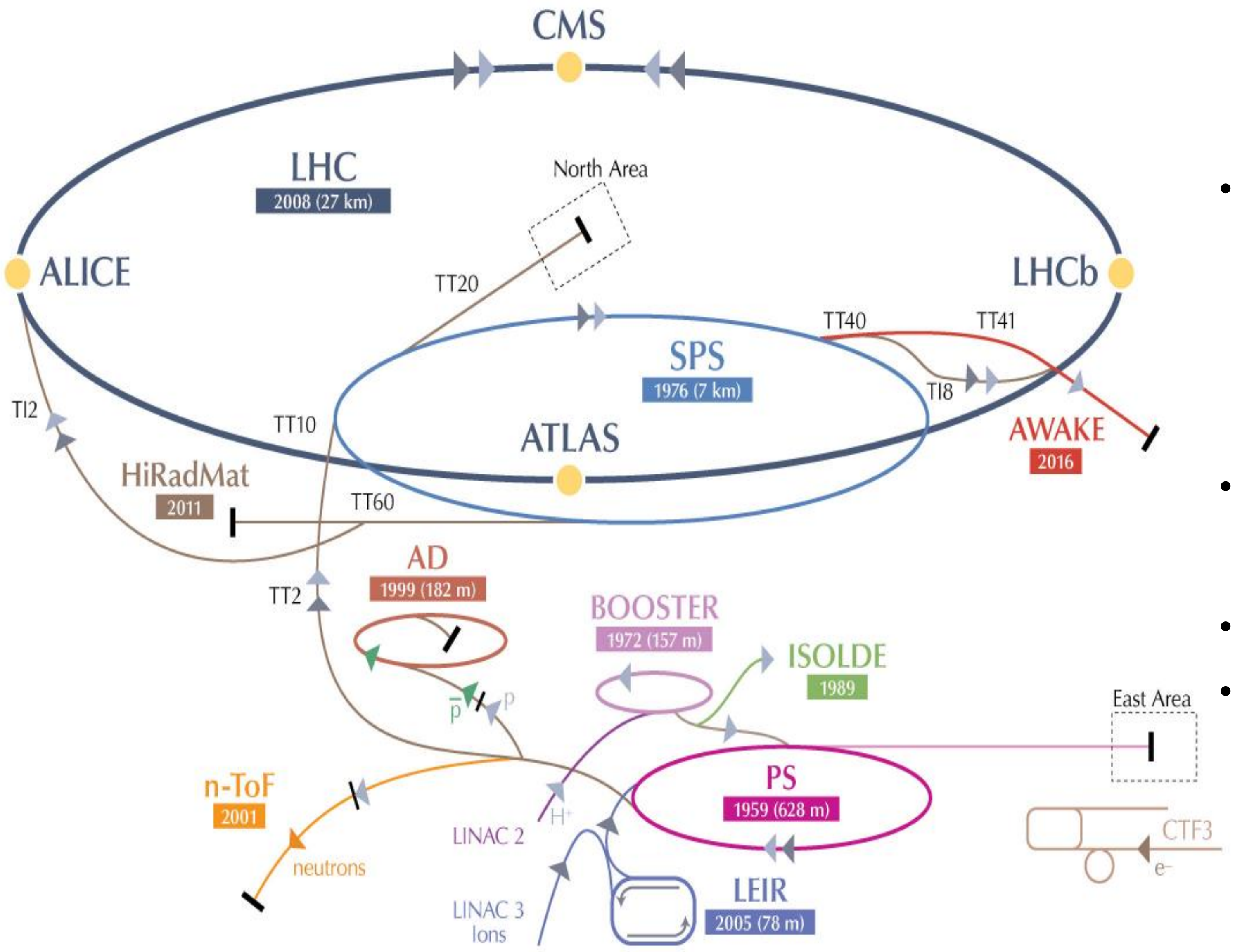
Beam-Driven Wakefield Acceleration: Landscape

Facility	Where	Drive (D) beam	Witness (W) beam	Start	End	Goal
AWAKE	CERN, Geneva, Switzerland	400 GeV **protons**	Externally injected electron beam (PHIN 15 MeV)	2016	2020+	**Use for future high energy e-/e+ collider.** - Study Self-Modulation Instability (SMI). - Accelerate externally injected electrons. - Demonstrate scalability of acceleration scheme.
SLAC-FACET	SLAC, Stanford, USA	20 GeV **electrons** and **positrons**	Two-bunch formed with mask (e^-/e^+ and e^--e^+ bunches)	2012	Sept 2016	- Acceleration of witness bunch with high **quality and efficiency** - Acceleration of positrons - FACET II preparation, starting 2018
DESY-Zeuthen	PITZ, DESY, Zeuthen, Germany	20 MeV **electron** beam	No witness (W) beam, only D beam from RF-gun.	2015	~2017	- Study Self-Modulation Instability **(SMI)**
DESY-FLASH Forward	DESY, Hamburg, Germany	X-ray FEL type **electron** beam 1 GeV	D + W in FEL bunch. Or independent W-bunch (LWFA).	2016	2020+	- **Application (mostly) for x-ray FEL** - Energy-doubling of Flash-beam energy - Upgrade-stage: use 2 GeV FEL D beam
Brookhaven ATF	BNL, Brookhaven, USA	60 MeV **electrons**	Several bunches, D+W formed with mask.	On going		- **Study quasi-nonlinear PWFA regime.** - Study PWFA driven by multiple bunches - Visualisation with optical techniques
SPARC Lab	Frascati, Italy	150 MeV	Several bunches	On going		- Multi-purpose user facility: includes laser- and beam-driven plasma wakefield experiments

AWAKE at CERN



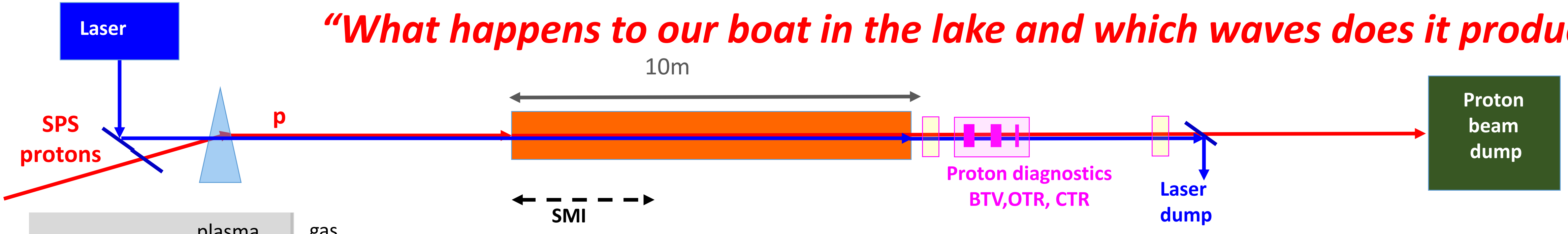
- **Advanced Proton Driven Plasma Wakefield Acceleration Experiment**
  - Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.
- Proof-of-Principle Accelerator R&D experiment at CERN
- Approved in August 2013
- First beam end 2016

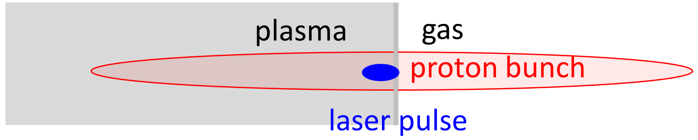
AWAKE Experimental Program, 2016/17

Phase 1: Understand **the physics of self-modulation instability** processes in plasma.

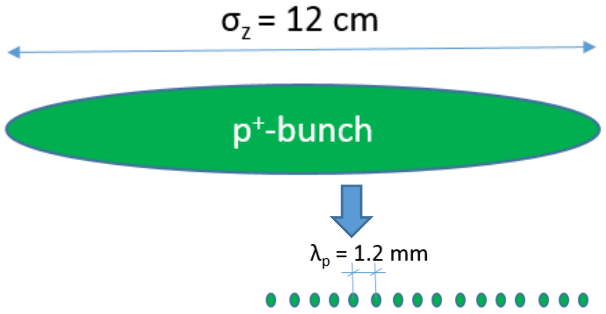
➔ start Q4 2016

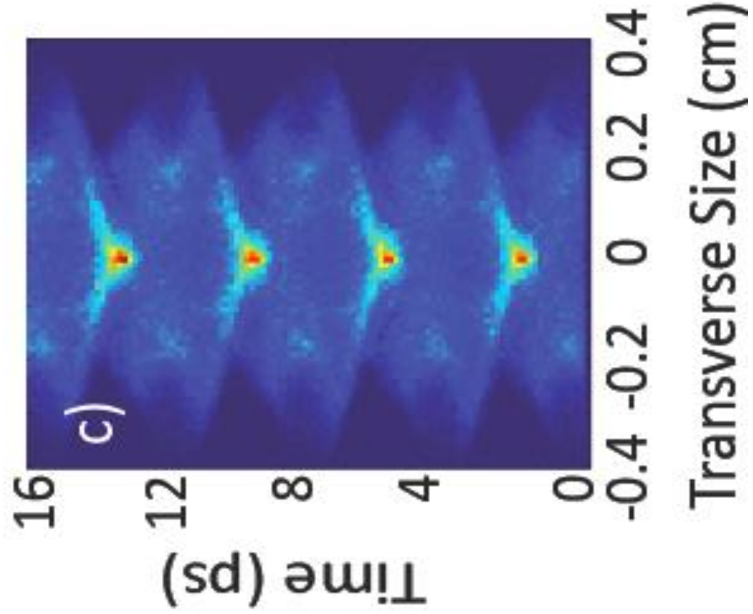
"What happens to our boat in the lake and which waves does it produce?"





Self-modulated proton bunch resonantly driving plasma wakefields.

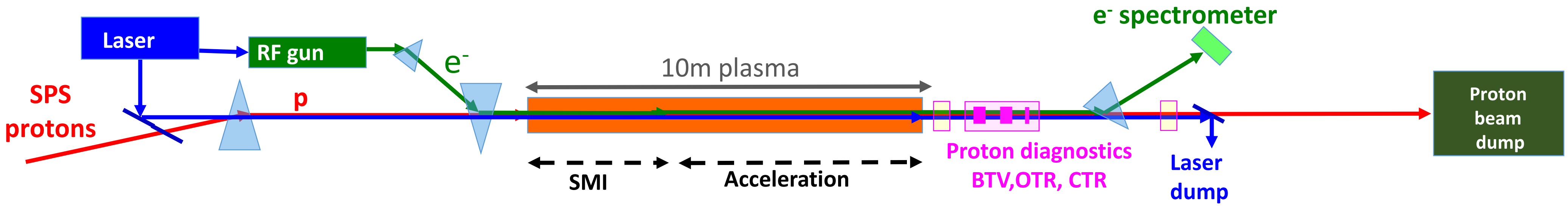


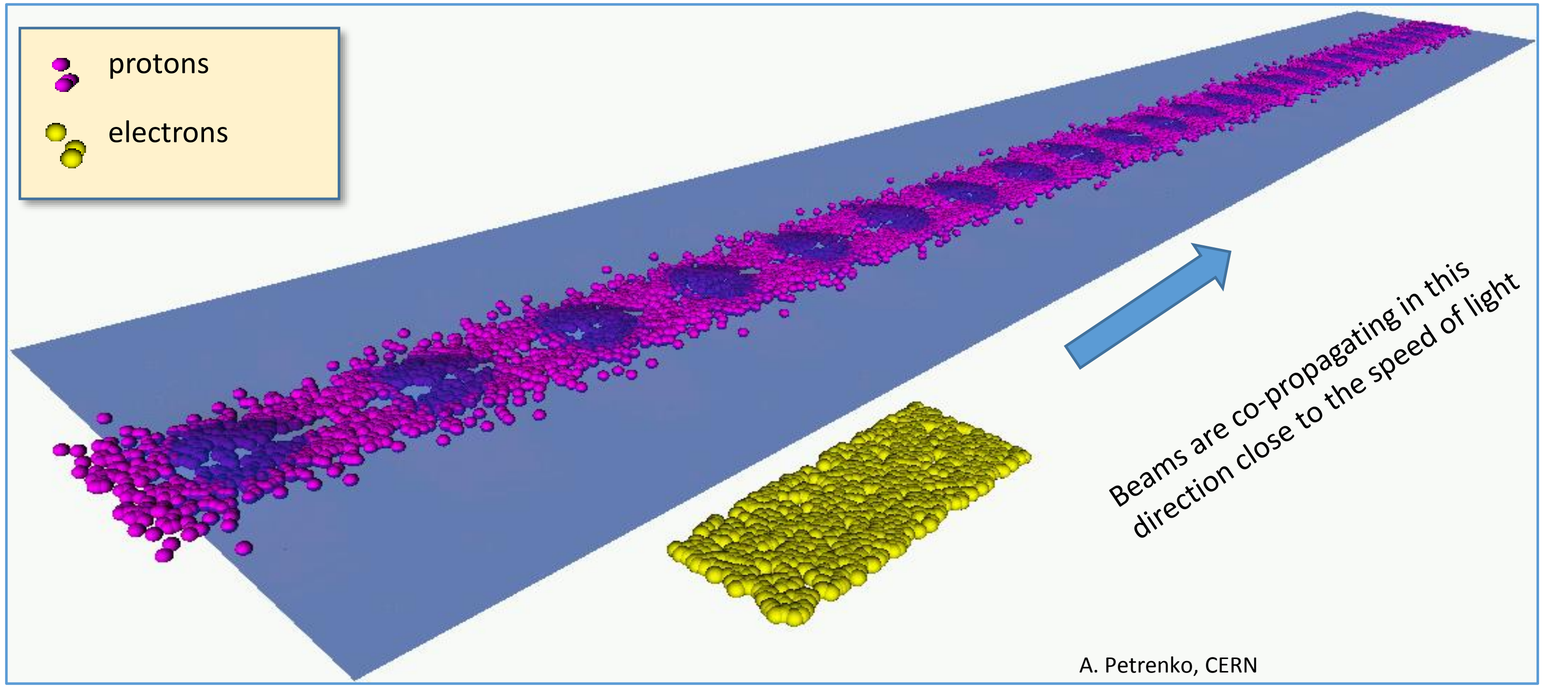


AWAKE Experimental Program 2017/18

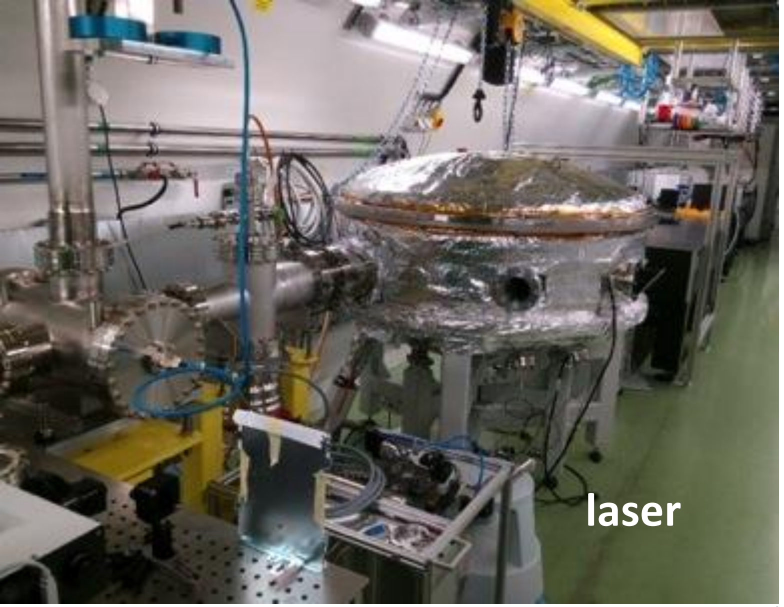
- **Phase 1:** Understand **the physics of self-modulation instability** processes in plasma.
- **Phase 2: Probe the accelerating wakefields** with externally injected electrons. ➔ start Q4 2017
  - Demonstrate GeV scale gradients with proton driven wakefields

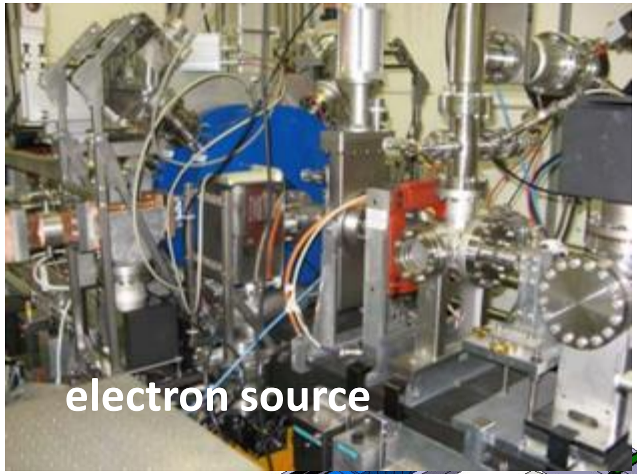
"How fast get our surfers?"

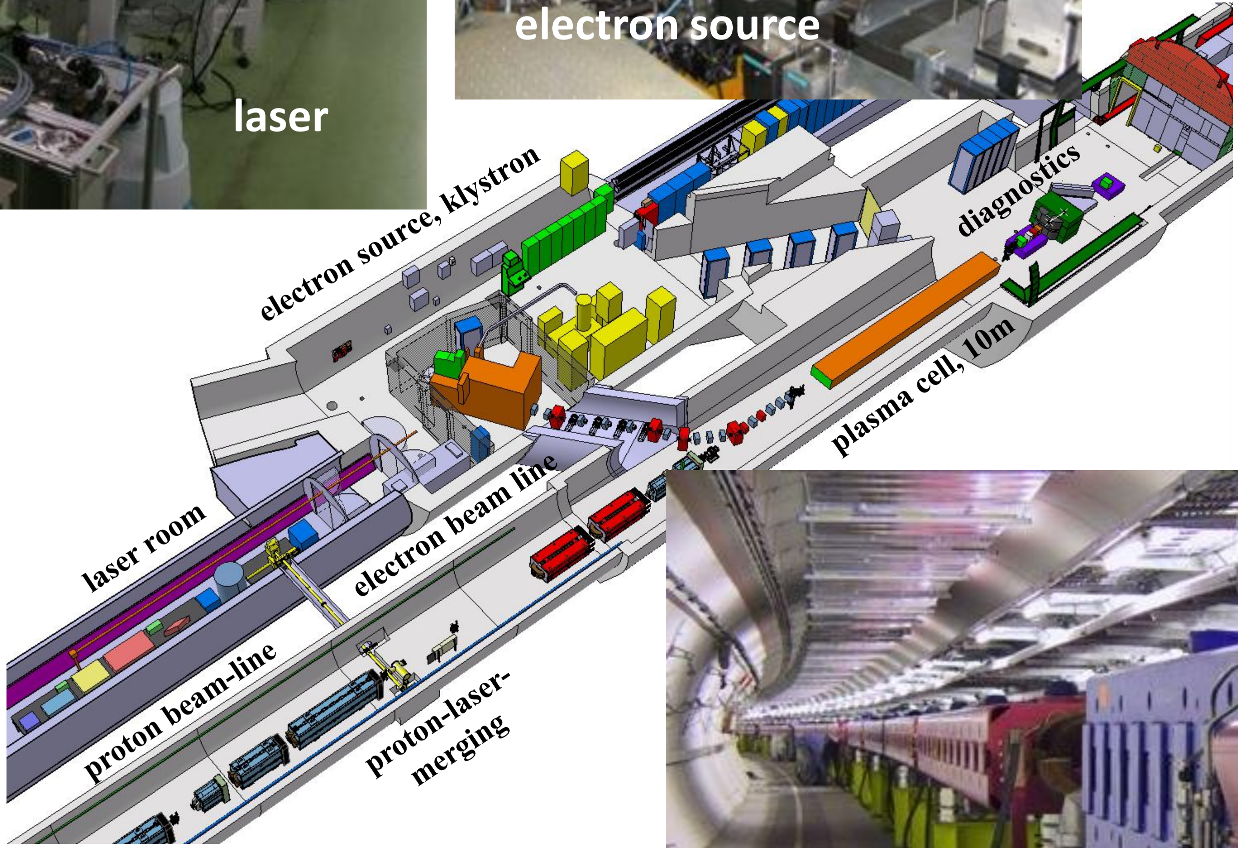


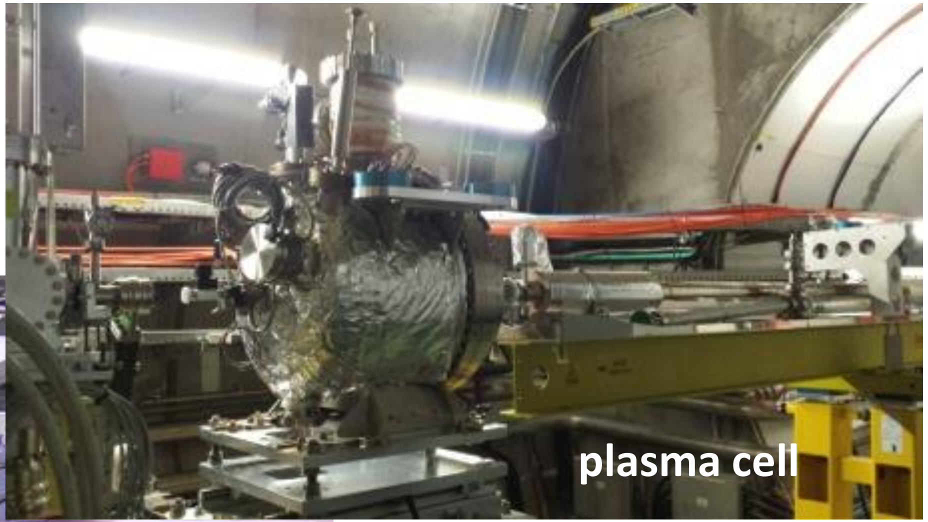


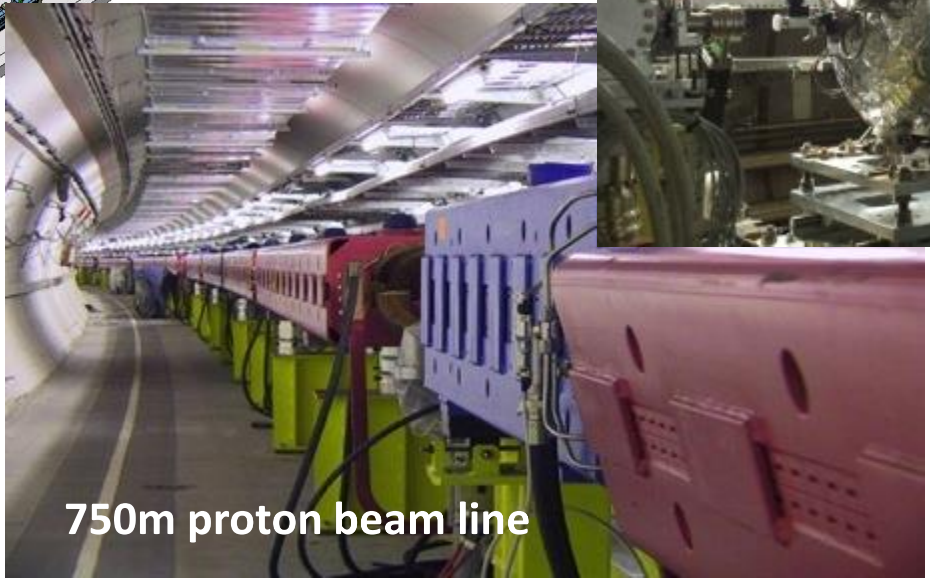
AWAKE Impressions





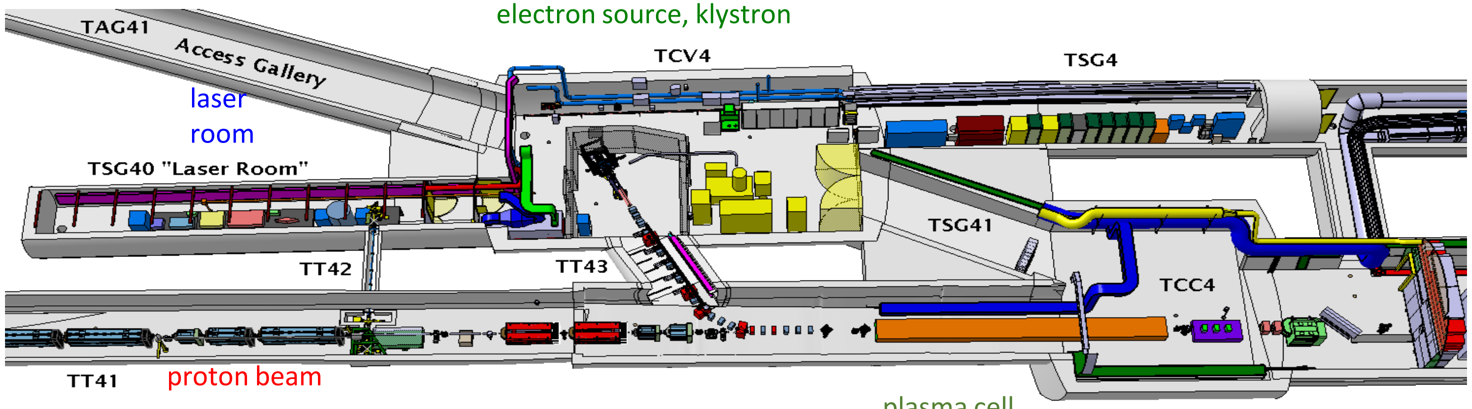


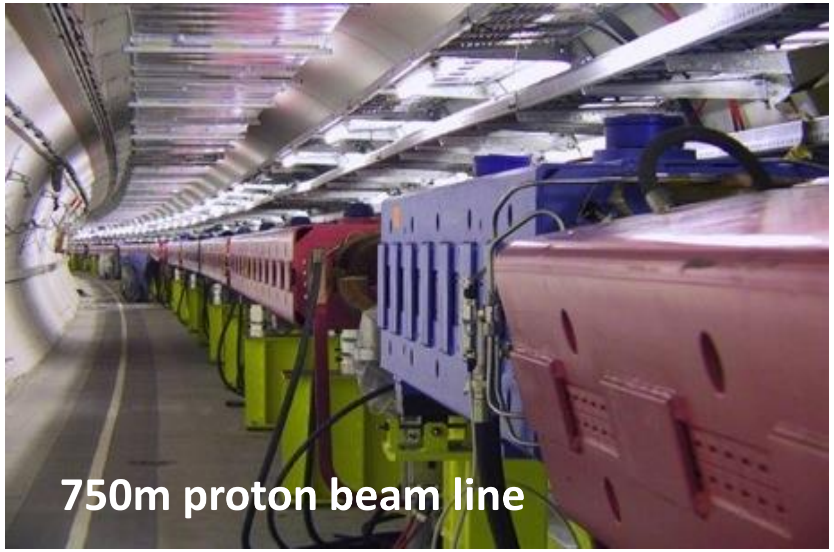


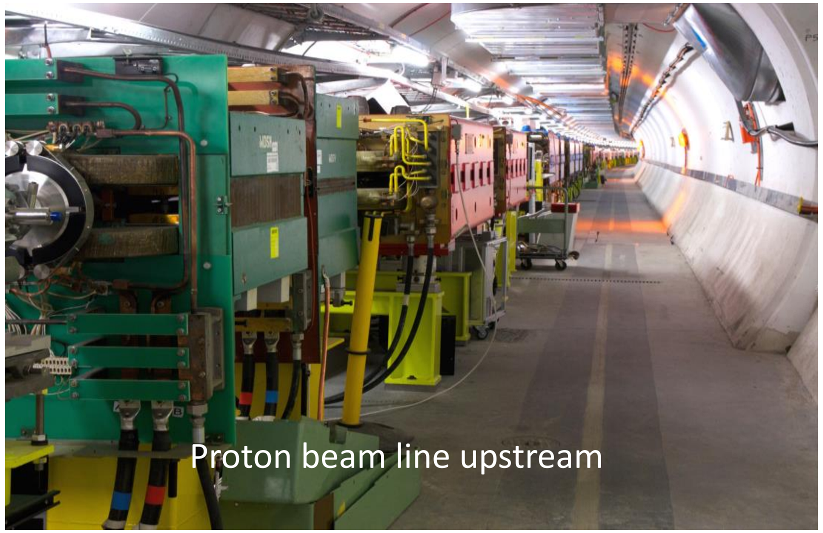


AWAKE Proton Beam Line

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

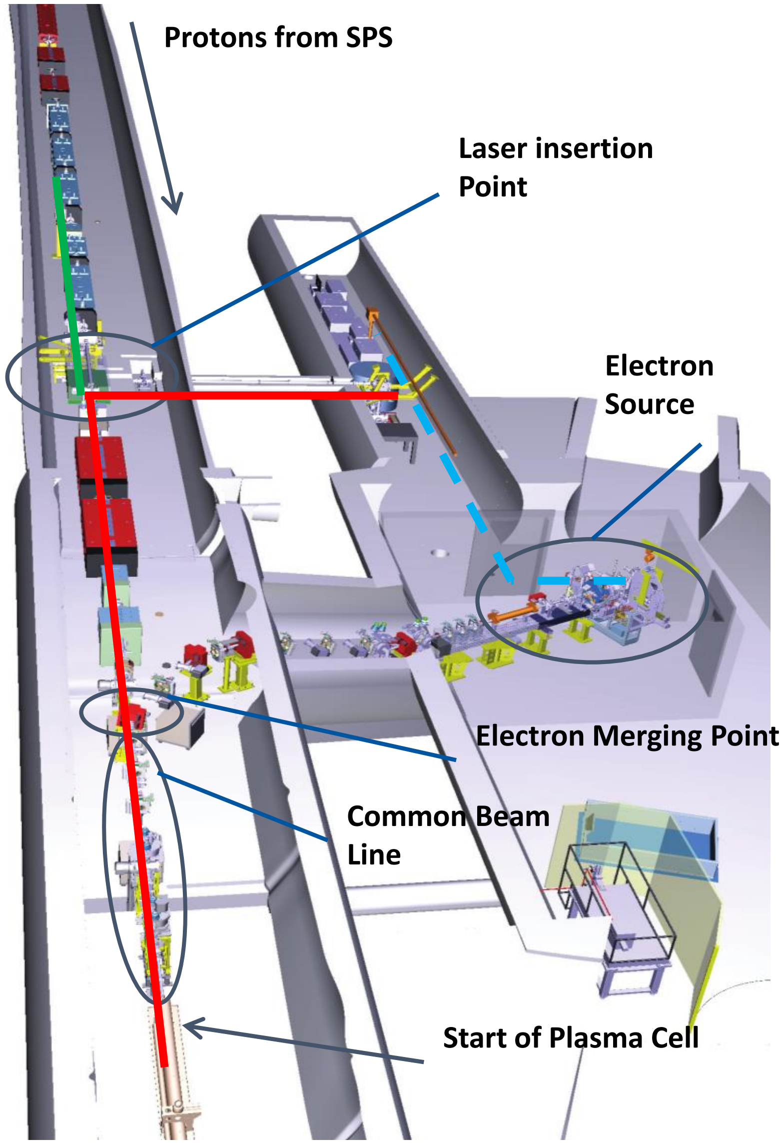


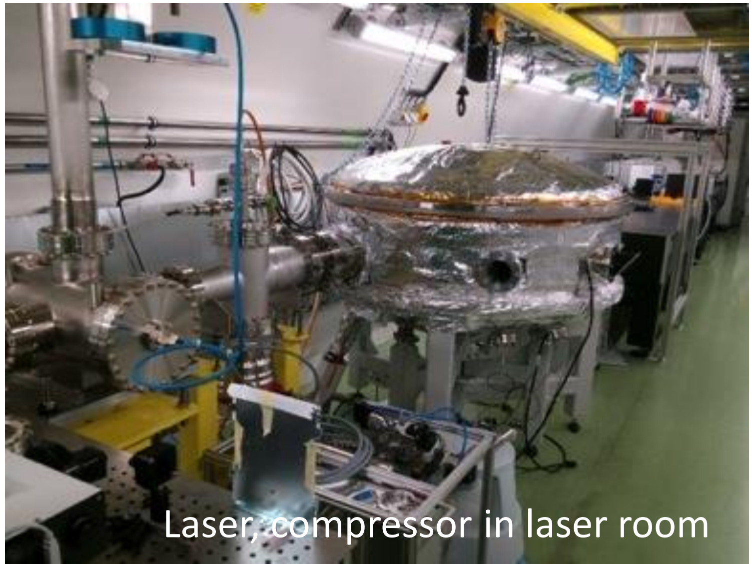




Laser and Laser Line

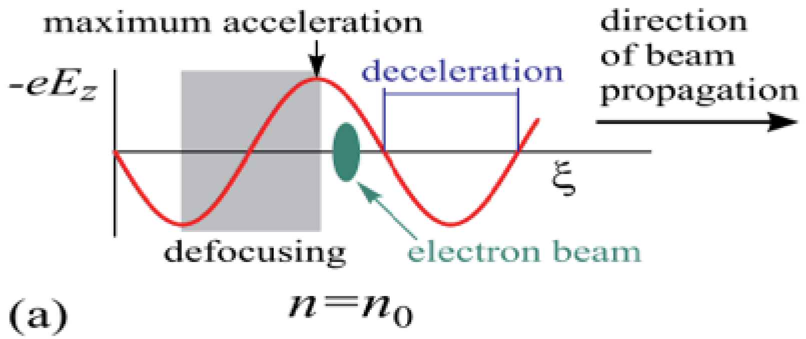
- **Laser beam line to plasma cell**
  - λ = 780 nm
  - t pulse = 100-120 fs
  - E = 450 mJ

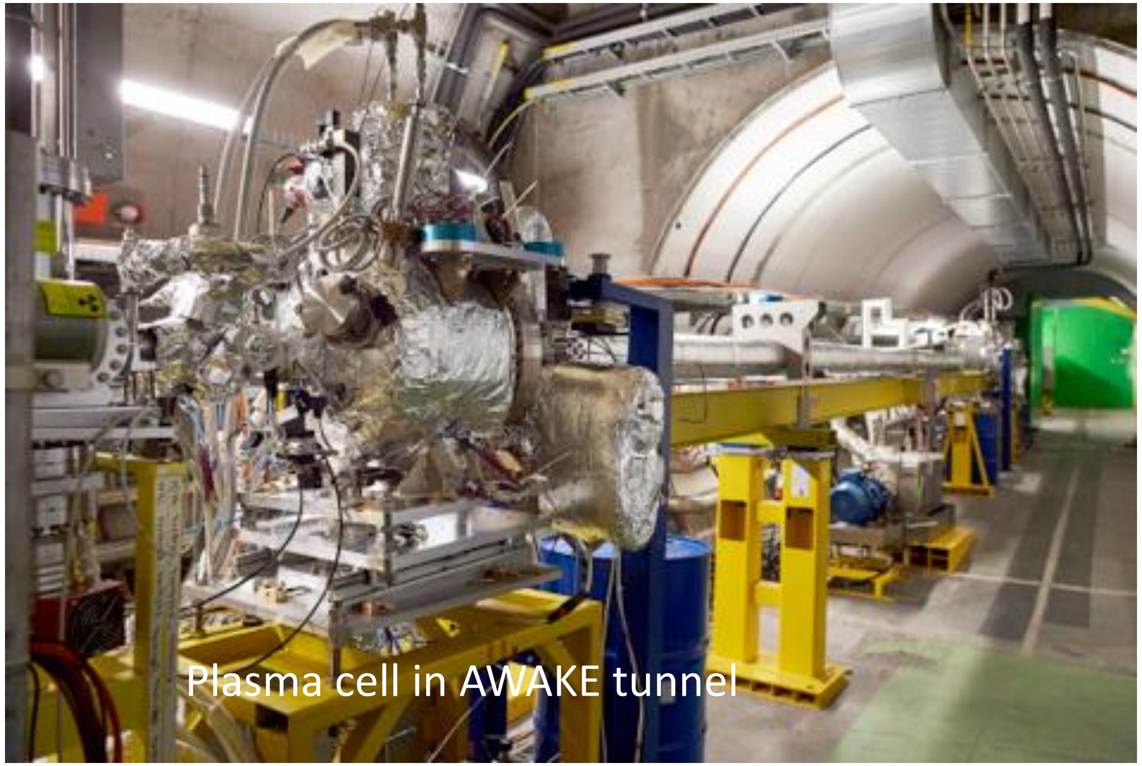


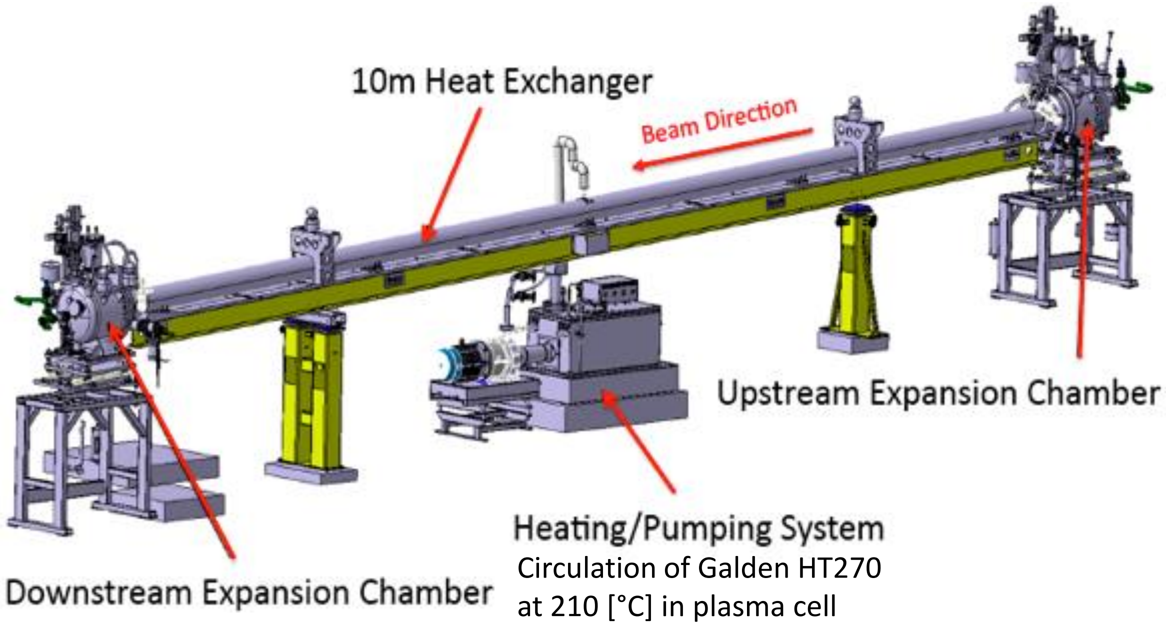


The AWAKE Plasma Cell

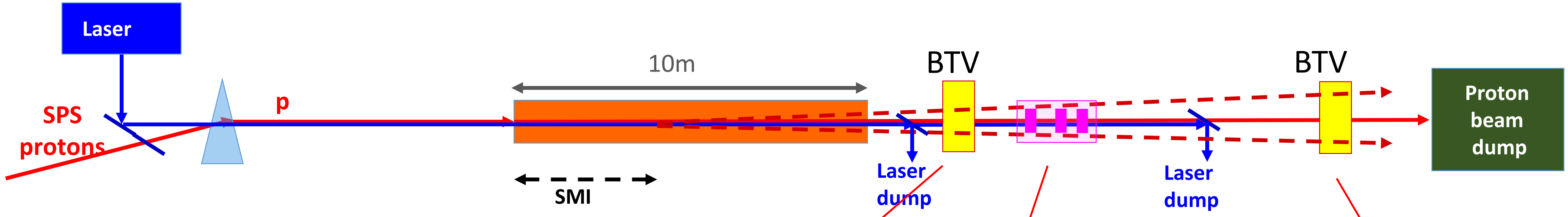
- **10 m long**, 4 cm diameter,
- Rubidium vapor, field ionization threshold ~10^{12} W/cm^2
- Density adjustable from $10^{14} – 10^{15}$ cm^{-3} ➔ **7x 10^{14} cm^{-3}**
  - **Requirement: uniformity better than 0.2%**
- Fluid-heated system (˜220 deg)



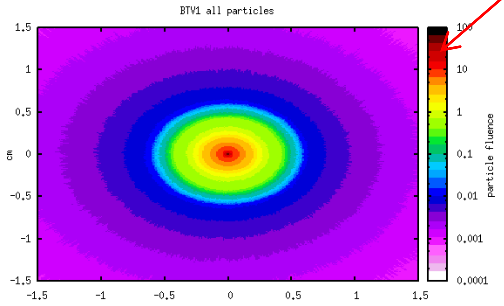


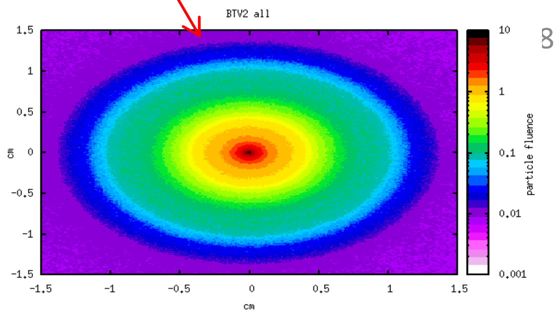


AWAKE Self-Modulation Instability Measurements

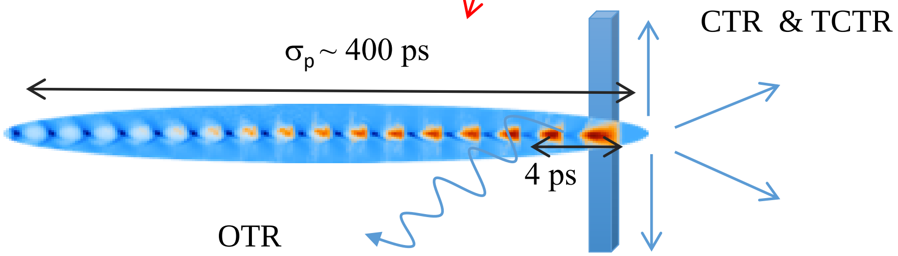


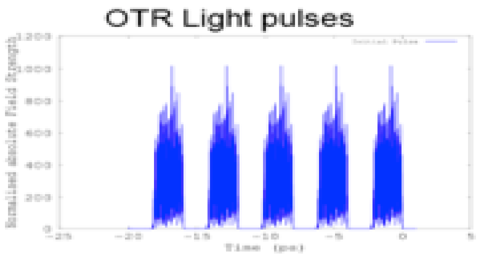
Indirect SMI Measurement:
Defocusing of the proton beam





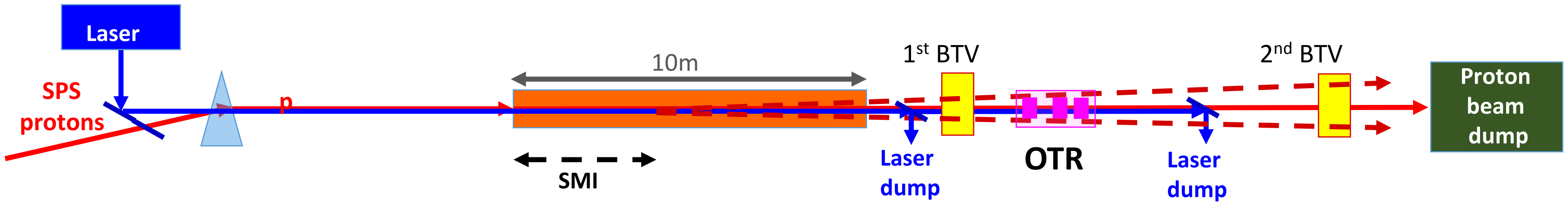
Direct SMI Measurement:
Radiation emitted by bunch when traversing dielectric material
→ Streak camera





Self-Modulation Instability: 1st Measurements!!!

"What happens to our boat in the lake and which waves does it produce?"



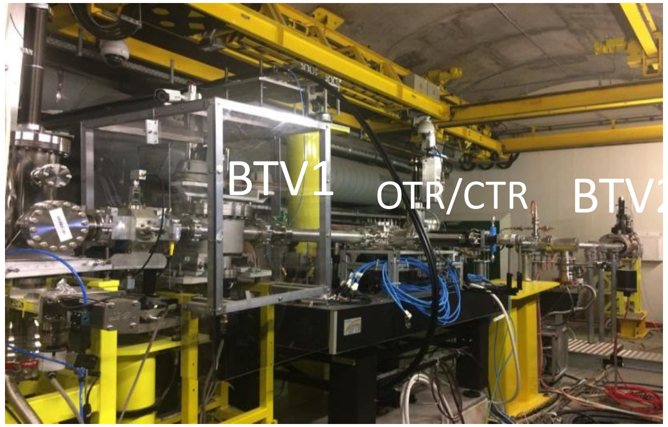
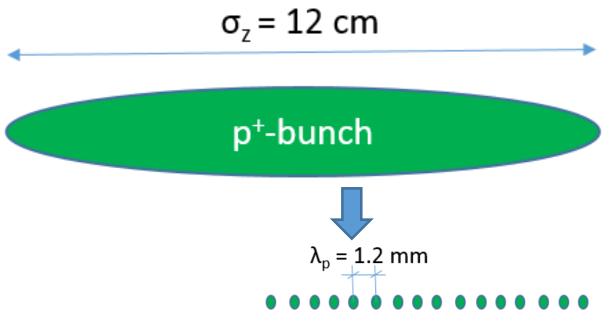
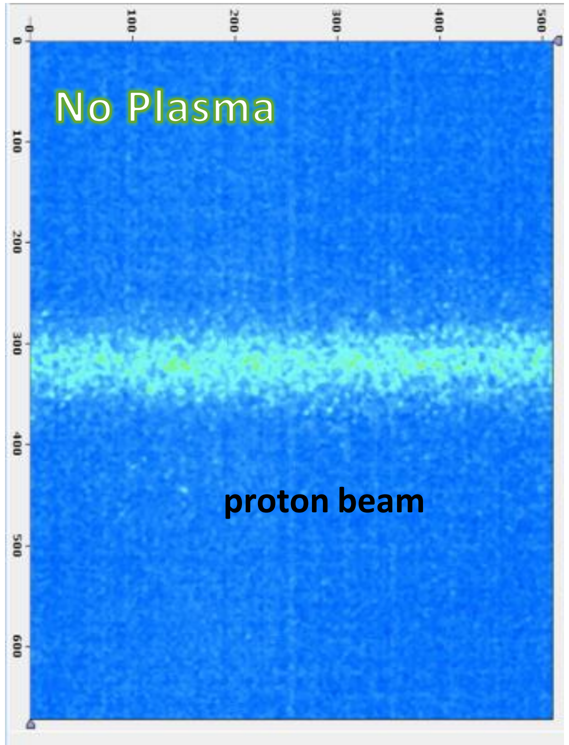
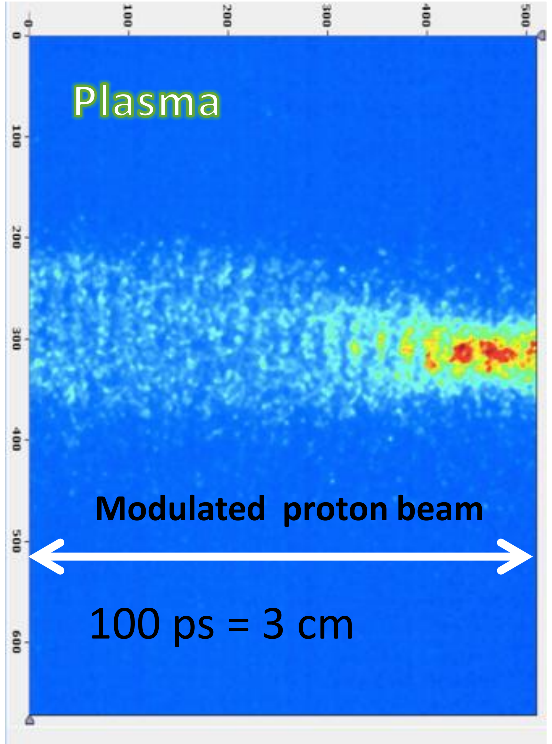


Image of proton beam measured with OTR and a streak camera



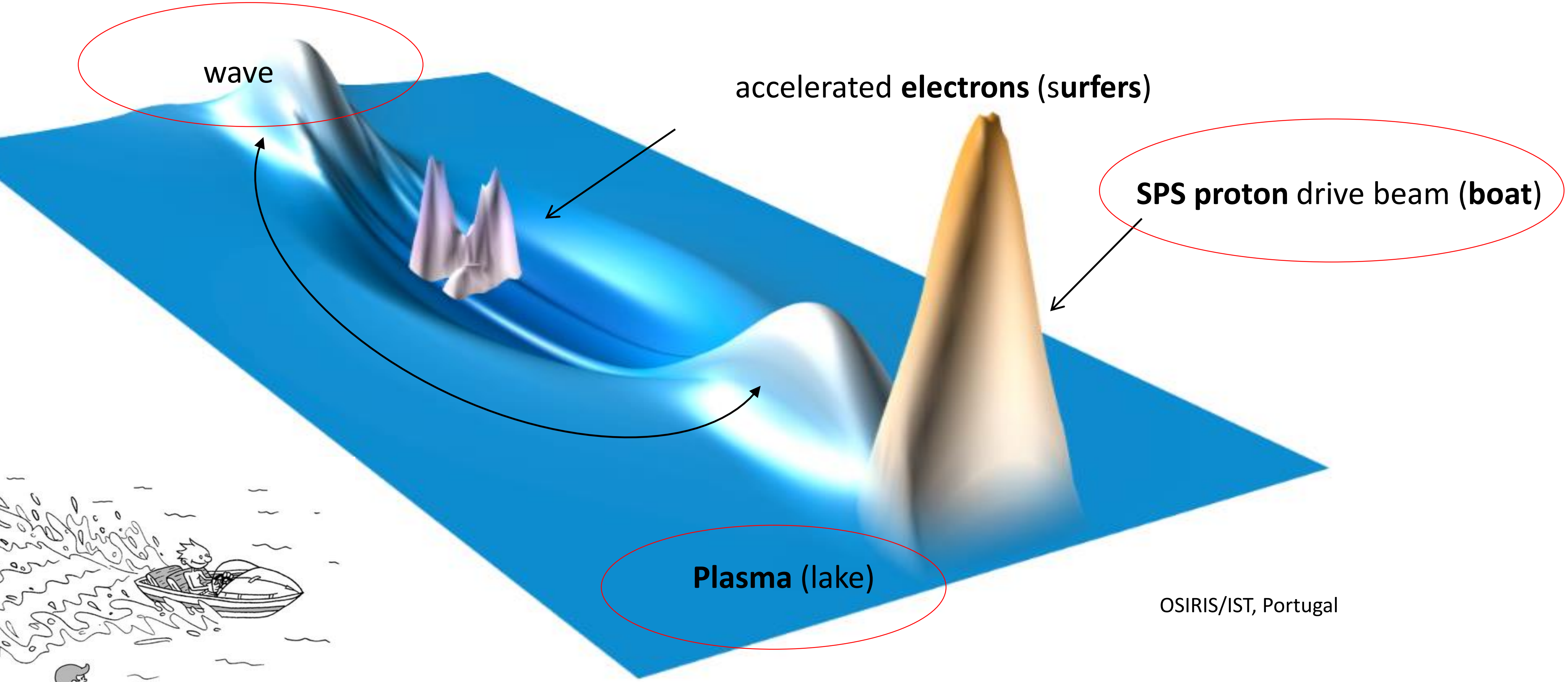




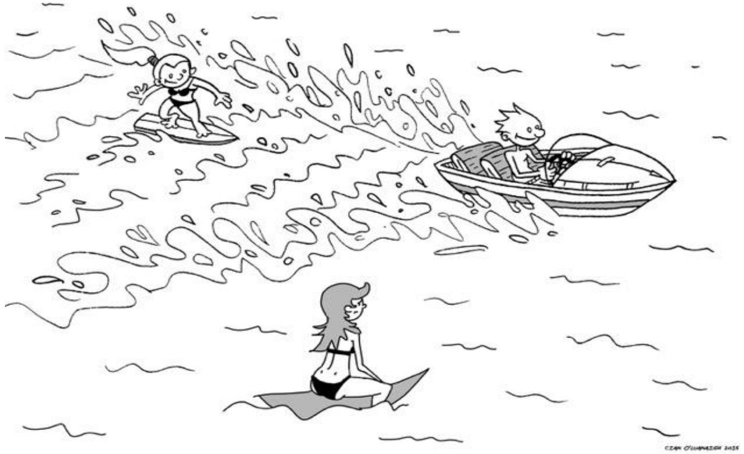
K. Rieger, MPP

2016/2017

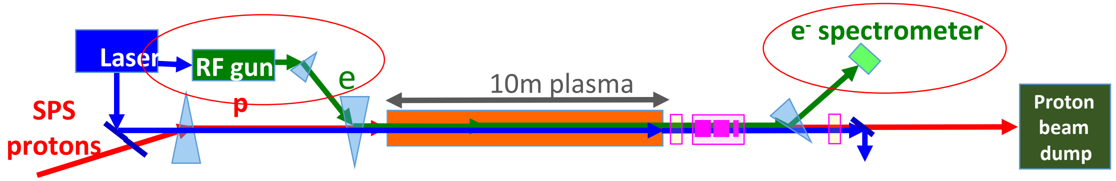
This Means:



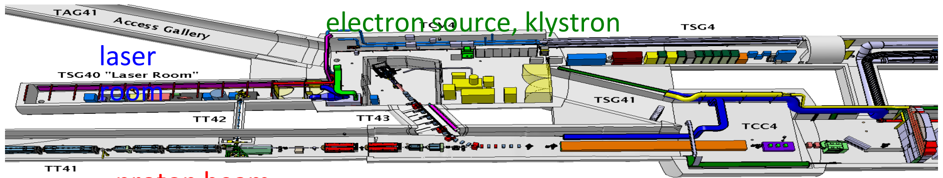
OSIRIS/IST, Portugal



Electron Source and Electron Beam Line



"How fast get our surfers?"



Electron beam line tunnel

Klystron system

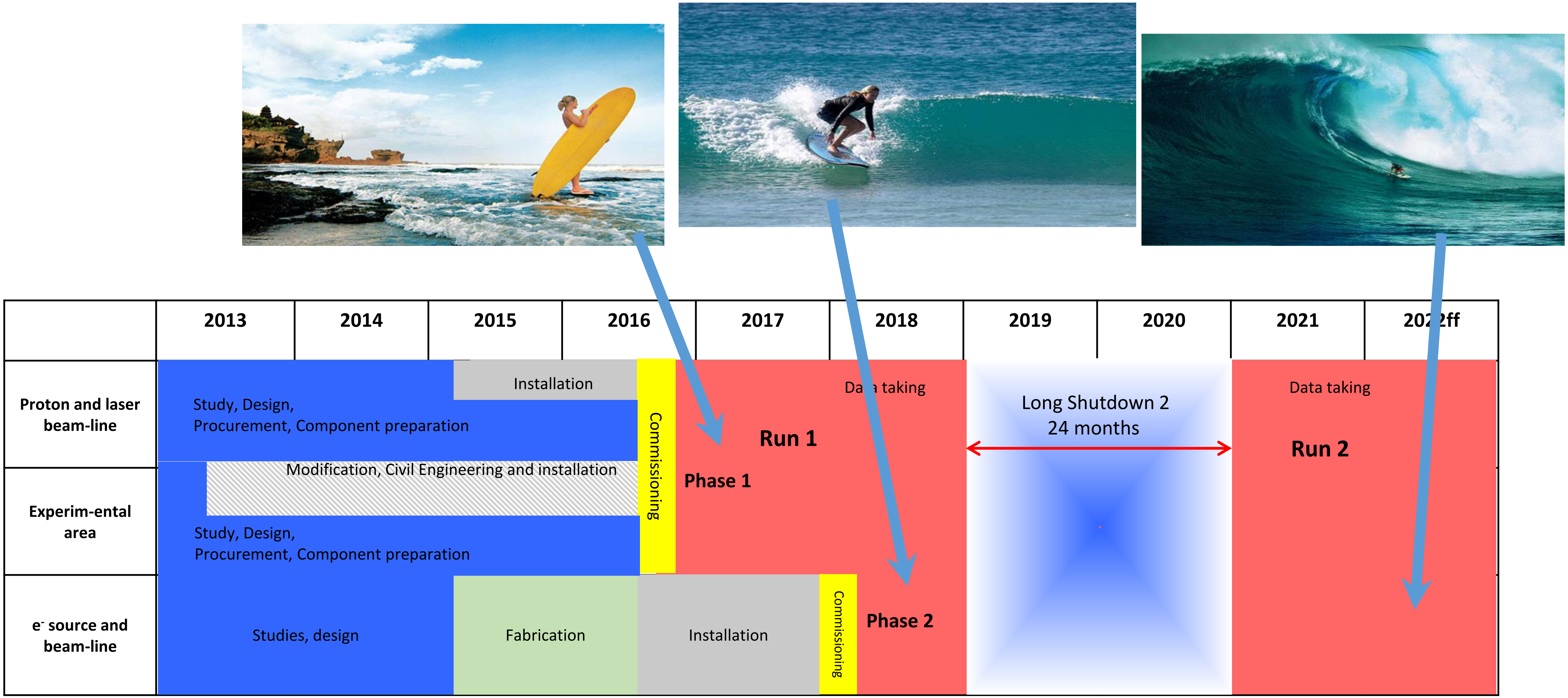
PHIN electron source

Electron spectrometer to measure the accelerated electrons

8.5 ton, 1.2 T, 1.3 Tm, L=1.6 m, W=1.3 m

→ **Start in 2018**

AWAKE Time Line



Outline

- Motivation
- Plasma Wakefield Acceleration
- Plasma Wakefield Acceleration Experiments
- Outlook

What is the Future of the PWA Technology?

Short term perspective (< 10 years):

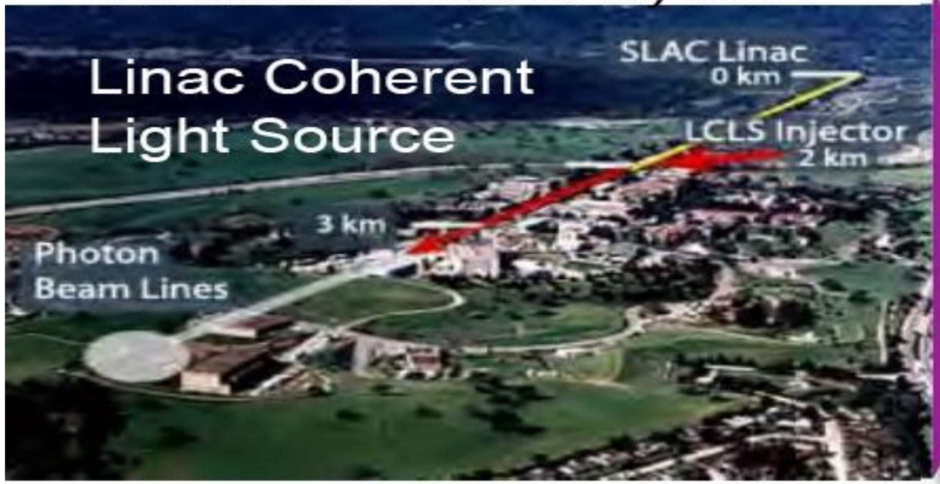
- Applications in medicine, radiobiology, material science Compact FEL , Compact X-ray source are rather close: generating light sources for fine-scale imaging, producing radioactive isotopes for medical use, creating gamma ray and THz radiation for material testing.

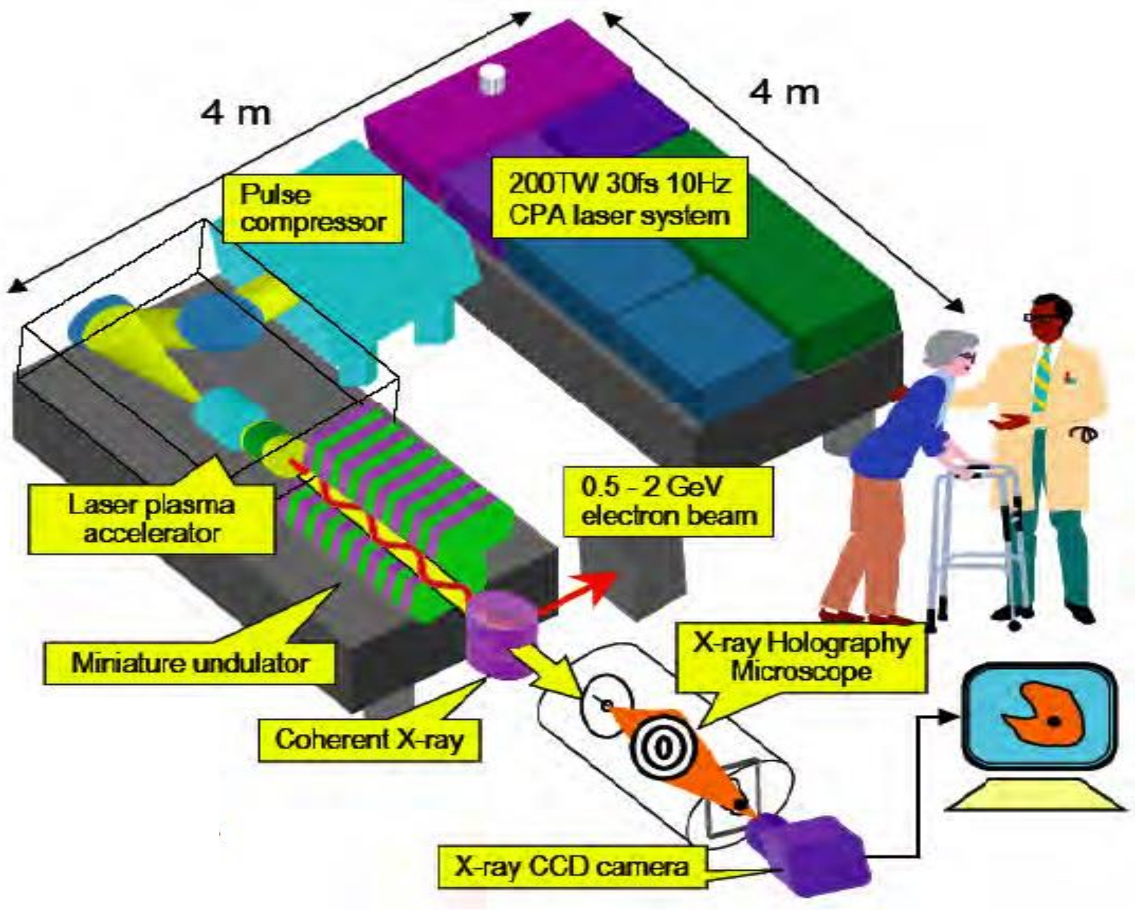
Long term perspective (>20 years):

- High energy physics applications depend on progress in multistage design, acceleration of positrons, laser technology, beam quality…

Photon Science XFEL

Kilometer-scale X-ray FEL





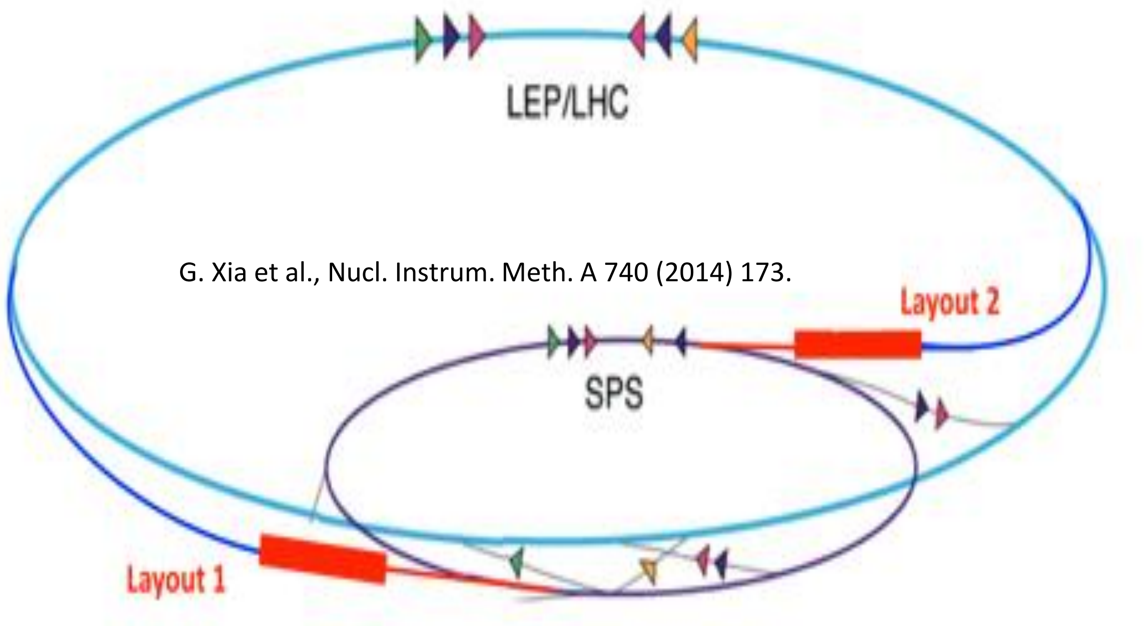
Visualization by T. Tajima, 2010

XFEL

Photon Science

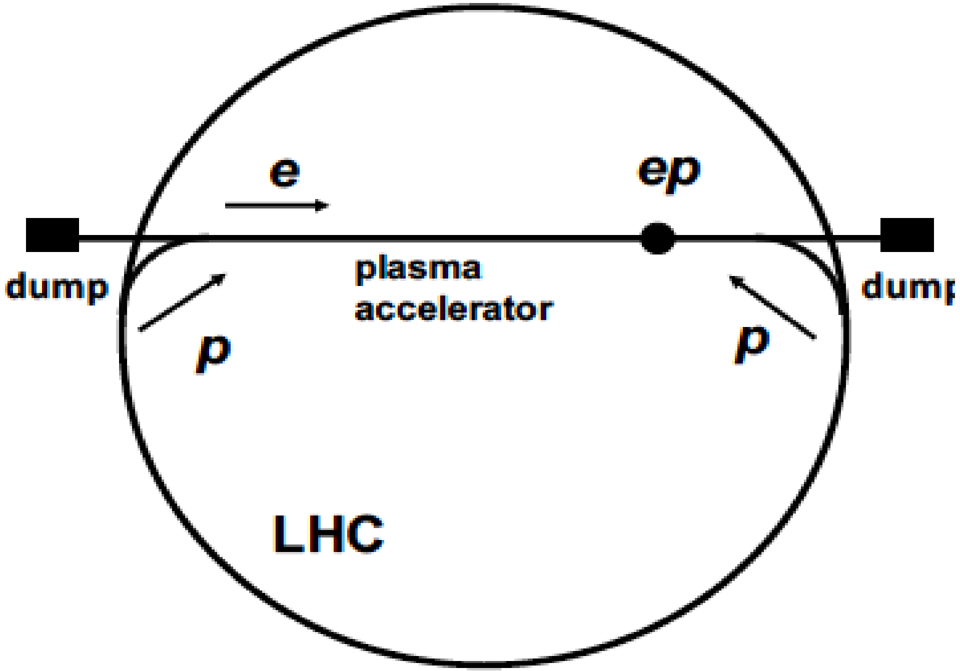
Possible Application of Wakefield Acceleration Technology

Physics with an Electron-Proton or Electron-Ion Collider, LHeC-like



G. Xia et al., Nucl. Instrum. Meth. A 740 (2014) 173.

Create ~50 GeV electron beam within 50–100 m of plasma driven by SPS protons, But luminosity < 10^{30} cm^{-2} s^{-1}.



VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

One proton beam used for acceleration of **electrons to 3 TeV** to then collide with other **proton beam at 7 TeV.**

Summary

Many encouraging result in plasma wakefield acceleration technology.

The future is bright!

Plasma wakefield acceleration is an exciting and growing field with a huge potential.