# AWAKE
# The Proton Driven Plasma Wakefield Acceleration Experiment

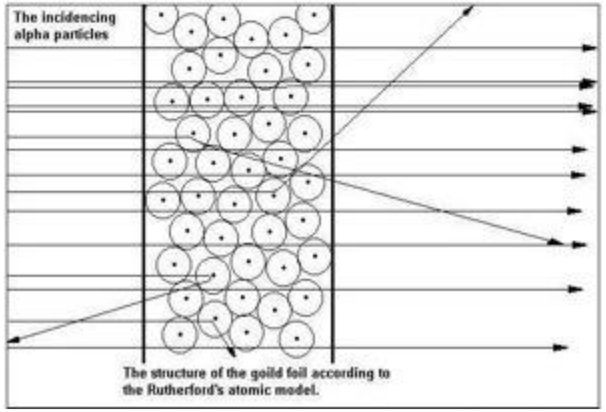
Edda Gschwendtner, CERN

# Outline

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

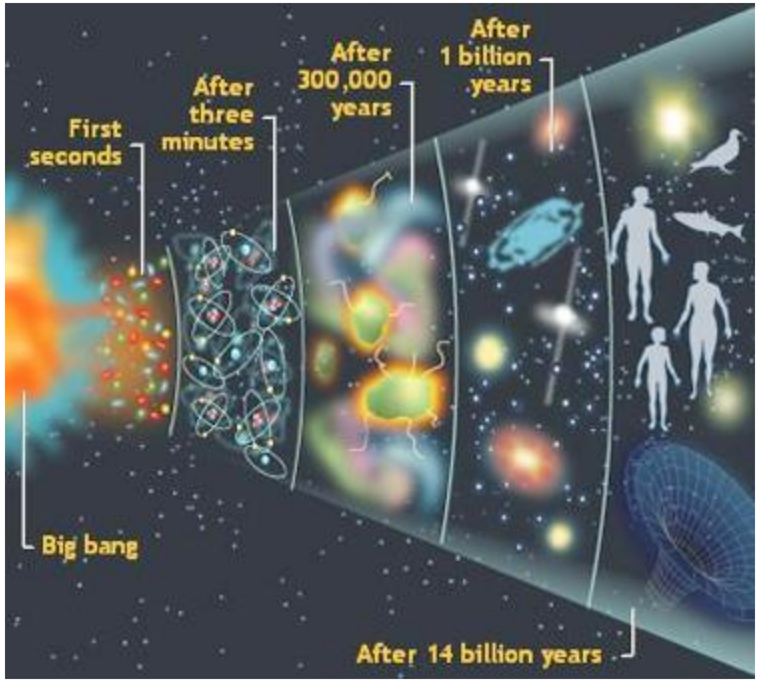
# Motivation: Increase Particle Energies

- 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…)

- 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




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

  → **Standard Model** of particle physics

# 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

# Circular Collider

Electron/positron colliders:
→ limited by synchrotron radiation

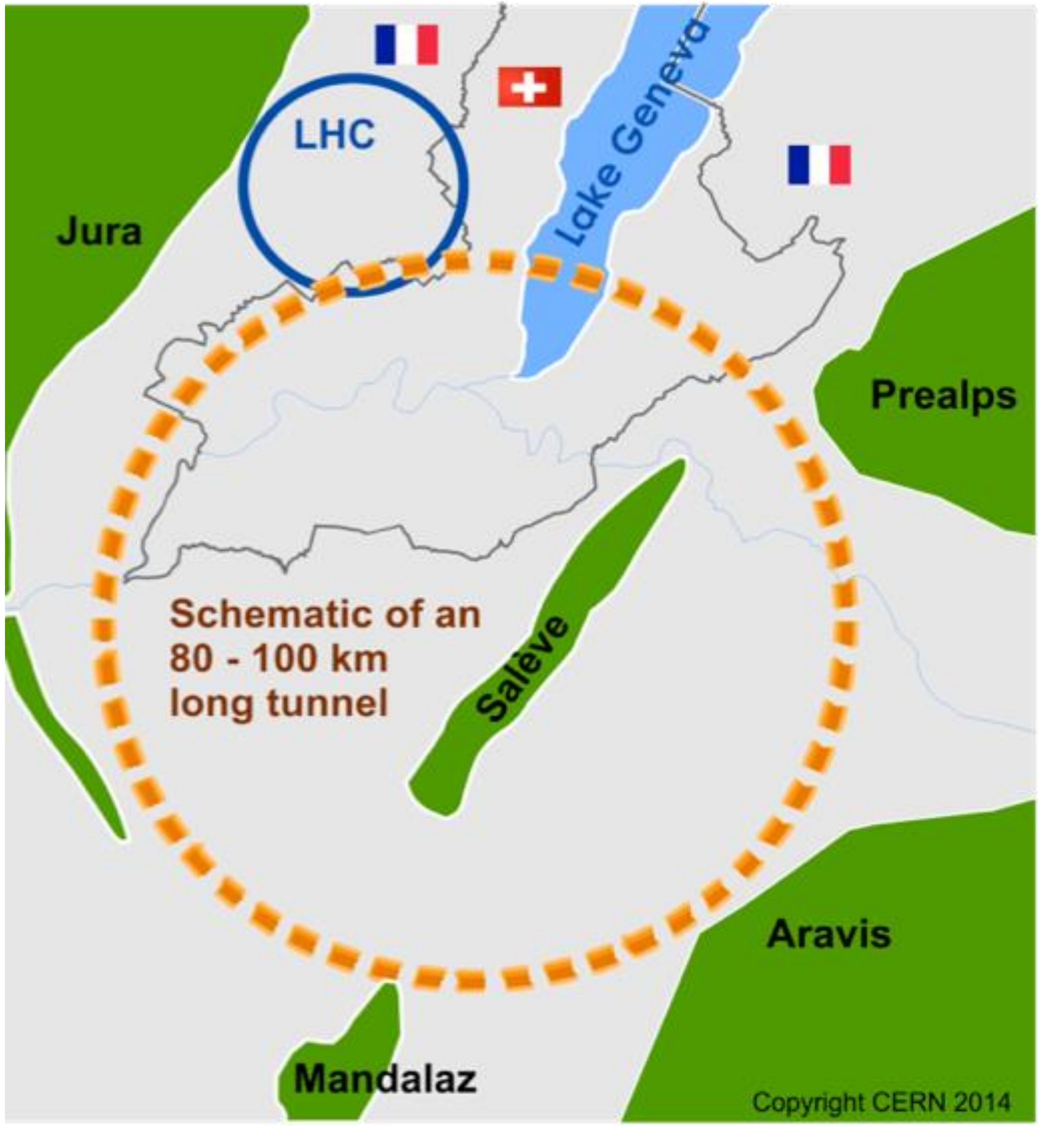
Hadron colliders:
→ limited by magnet strength

## FCC, Future Circular Collider

80 – 100 km diameter

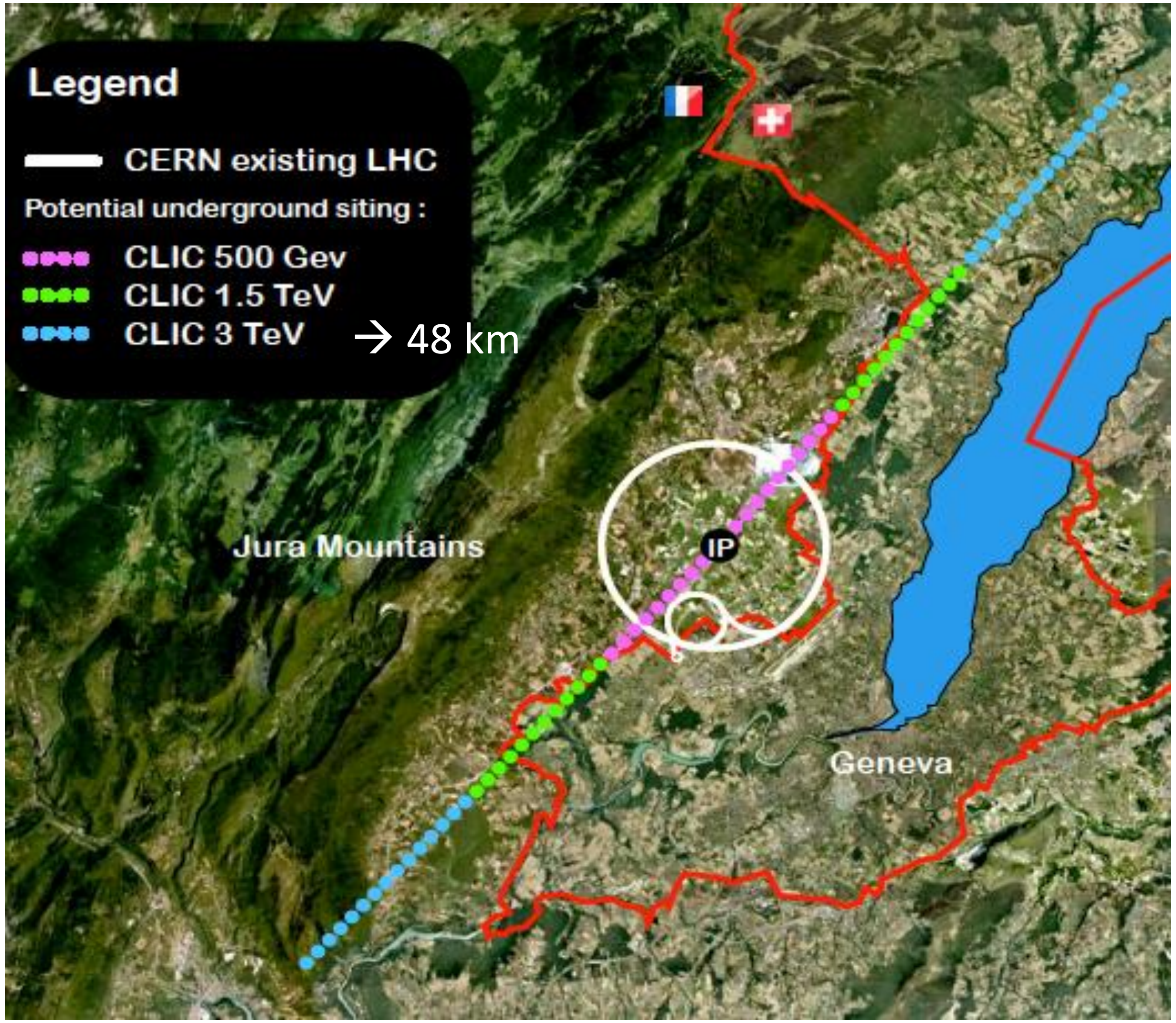
Electron/positron colliders:
→ 350 GeV

Hadron (pp) collider:
→ 100 TeV
→ → 20 T dipole magnets.



# Linear Colliders

Particles are accelerated in a single pass.
Amount of acceleration achieved in a given distances is the 'accelerating gradient'.
→ Limited by accelerating field.



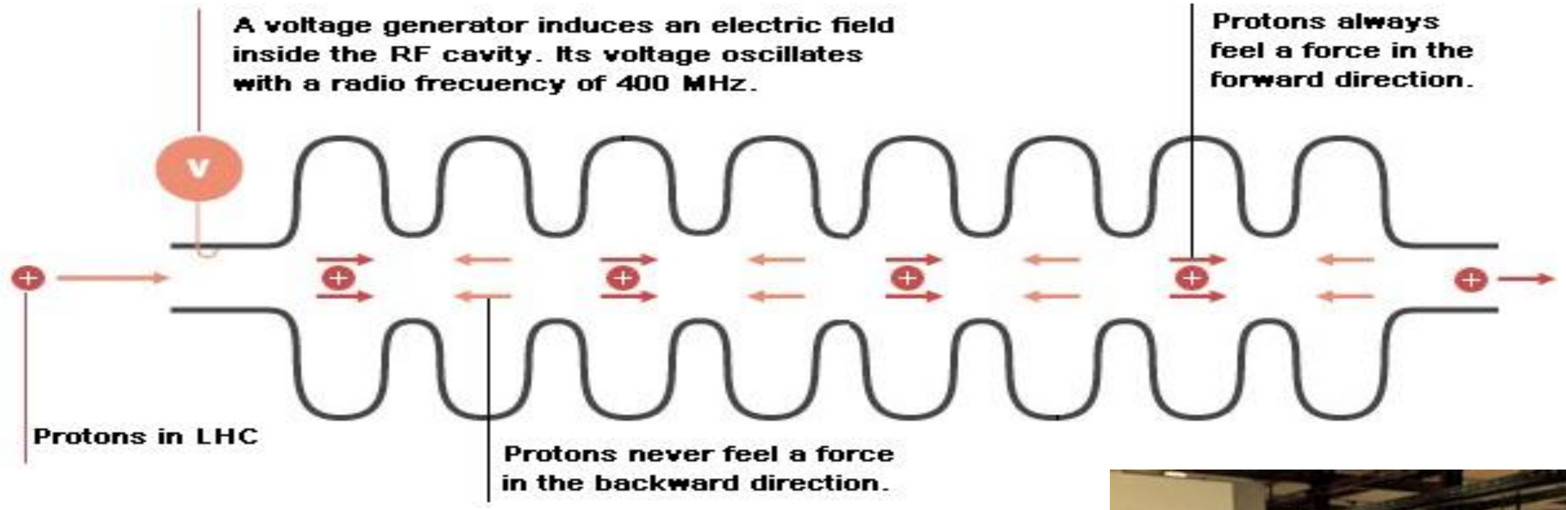

## CLIC

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

Accelerating elements:
Cavities: 100 MV/m

# Conventional Acceleration Technology

Radiofrequency Cavities



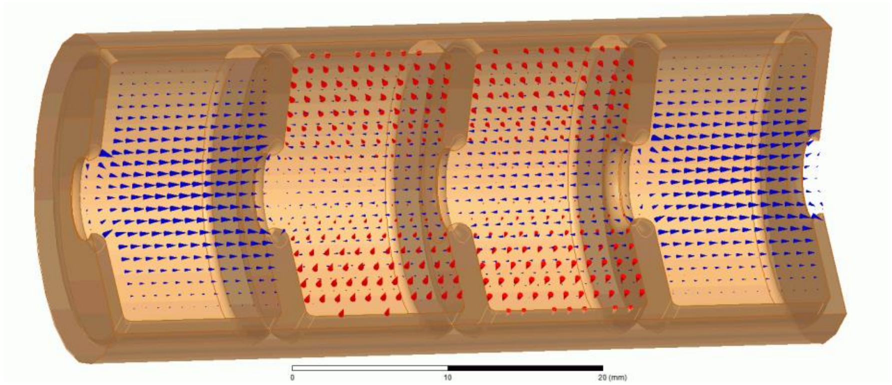

(invention of Gustav Ising 1924 and Rolf Wideroe 1927)

LHC Cavity

# Conventional Accelerating Technology

**Today's RF cavities or microwave technology:**

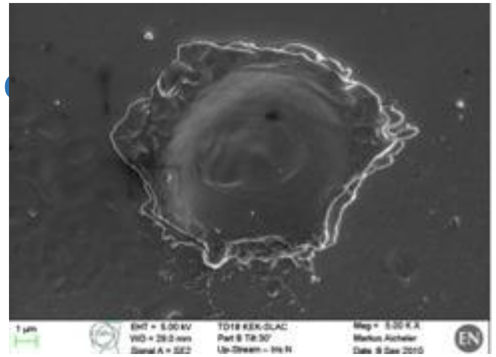
- Very successfully used in all accelerators (hospitals, scientific labs,…) in the last 100 years.



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

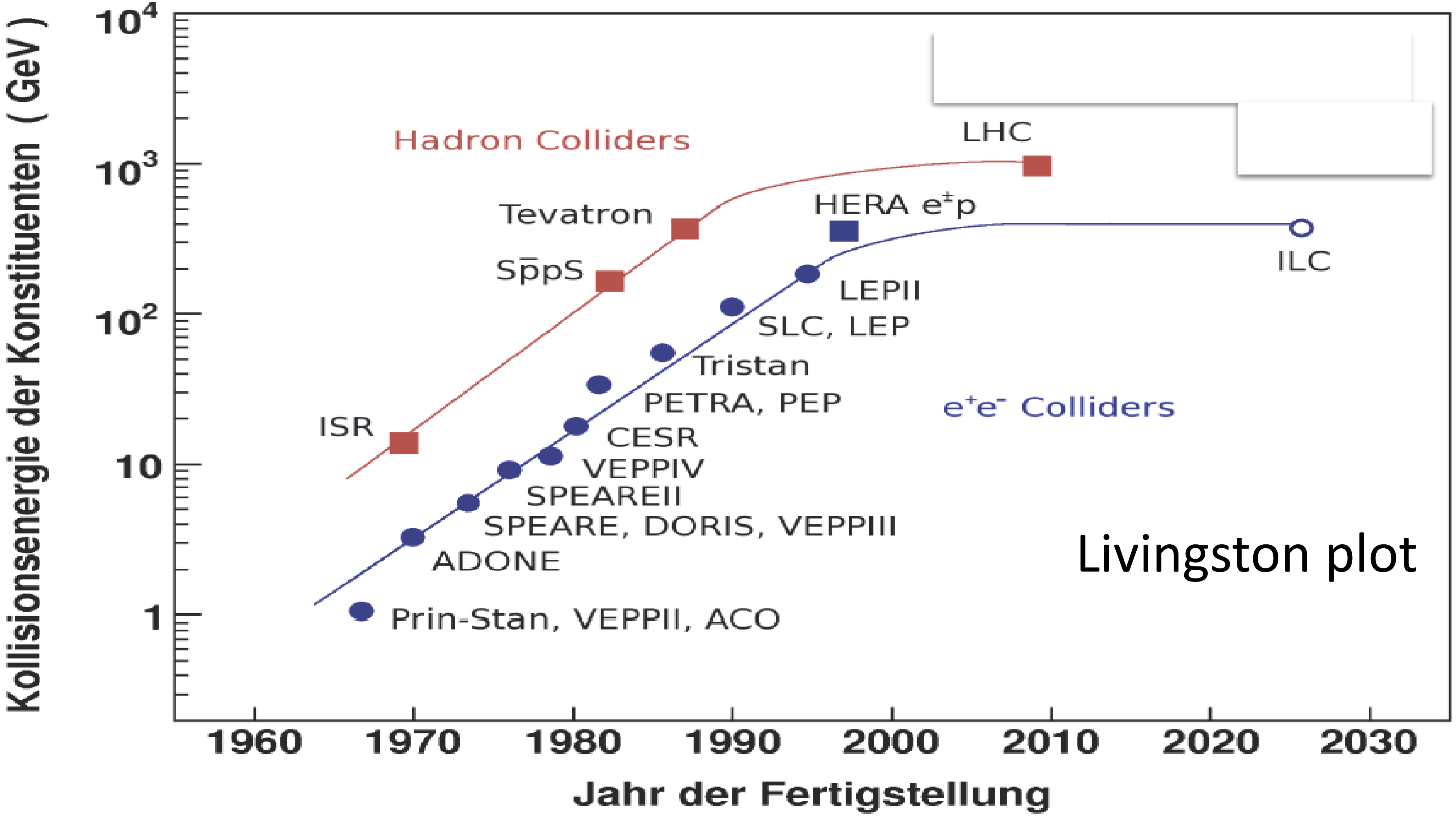
However:

- 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




Livingston plot

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

# Motivation

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

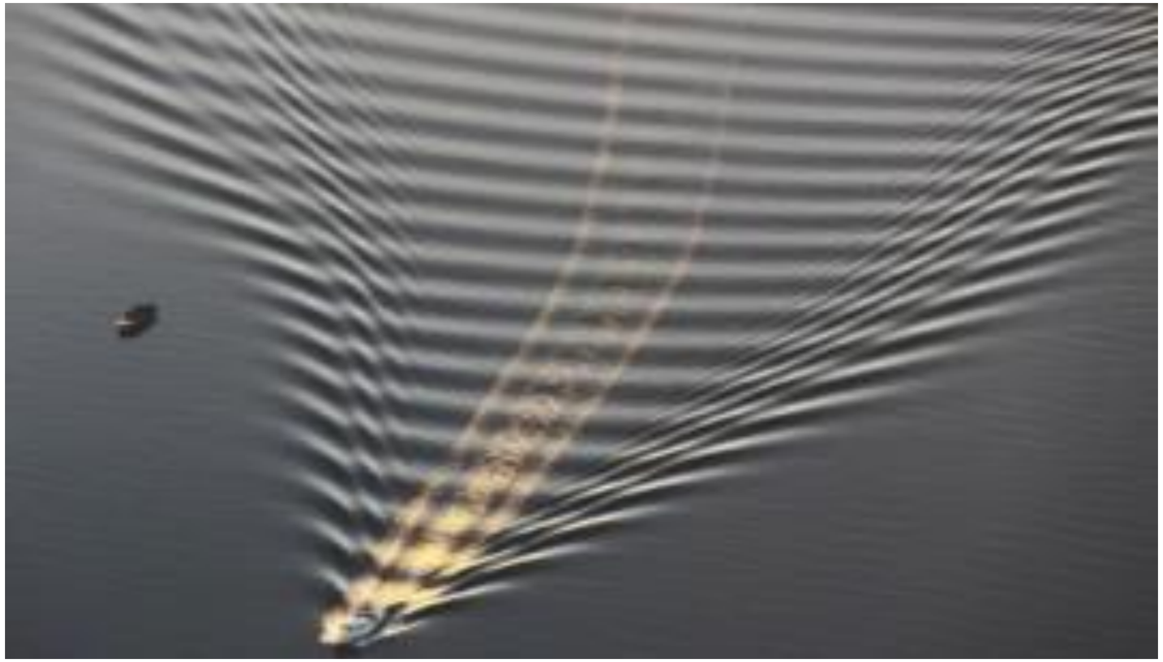
**The effect of a concept-driven revolution is to explain old things in new ways.**

**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

# Cavities vs. Plasma

- ILC Cavity: 35 MV/m


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

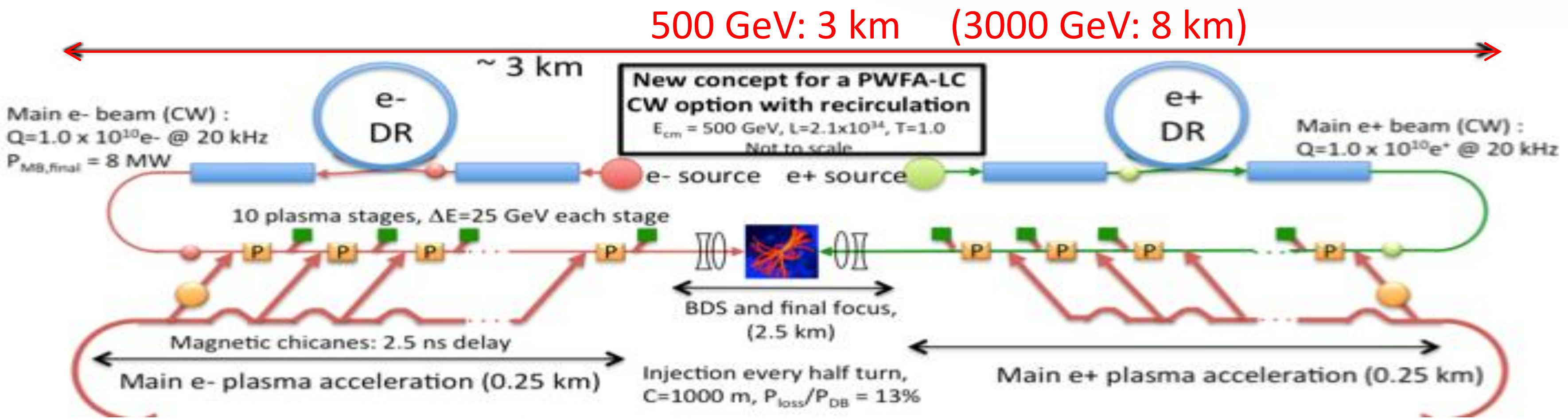

(Not to scale!)

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

# Linear Colliders

**ILC**


**Plasma based Linear Collider**



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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.

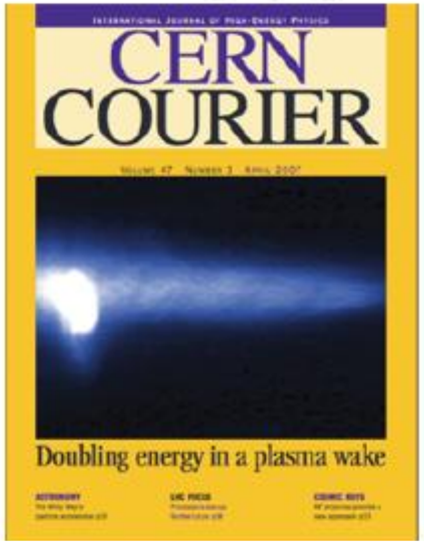
Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective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

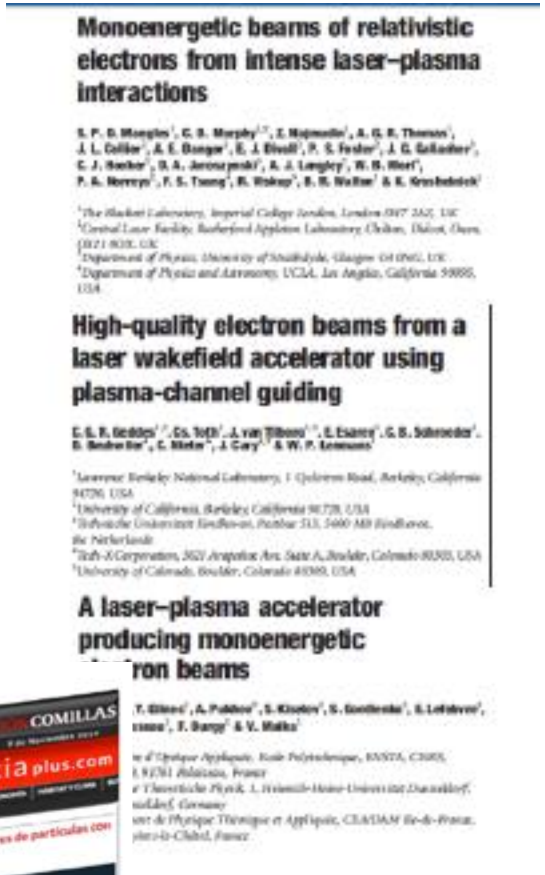
# Since Then…



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


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
COMILLAS
ciencia plus.com
Proyectan aceleradores de partículas con plasma de bajo coste


EDxCERN
g wakefields to create smaller
rators
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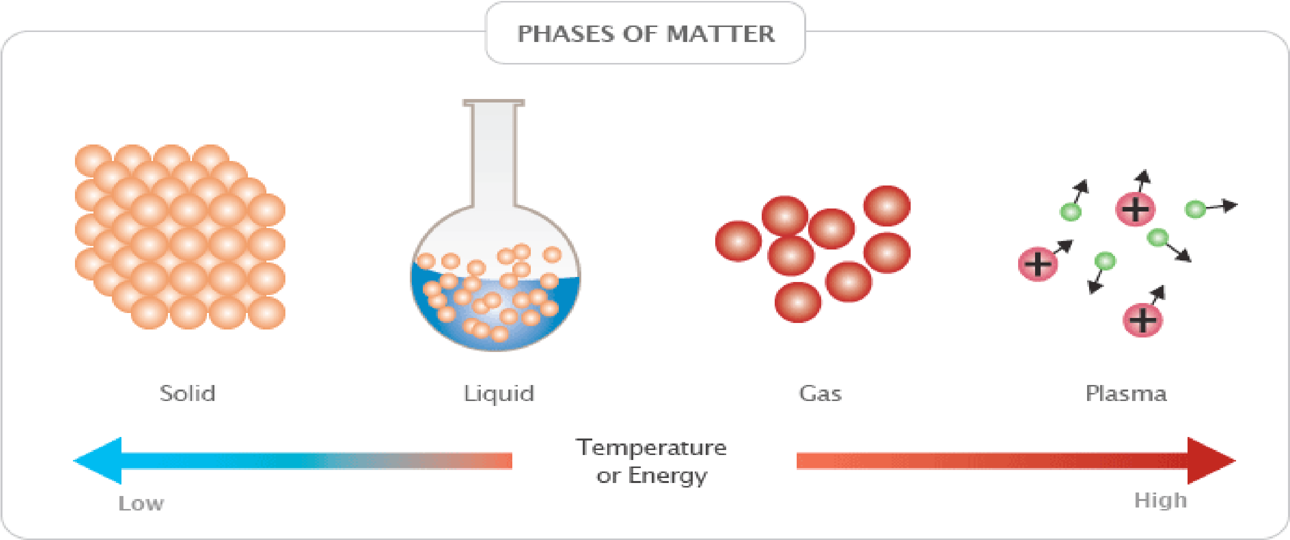
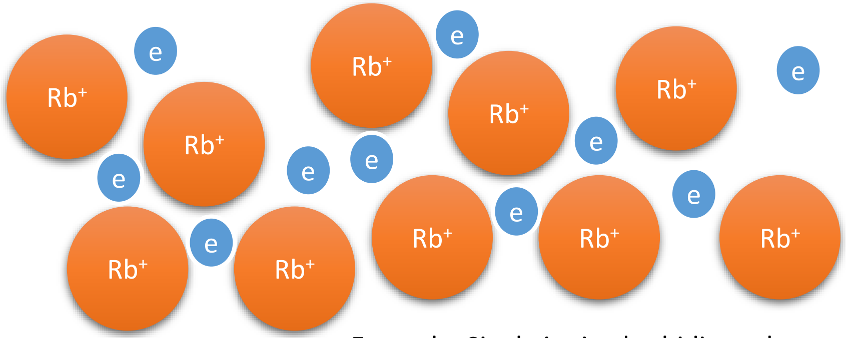
# Why is Plasma Interesting?

## What is a plasma?

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.**



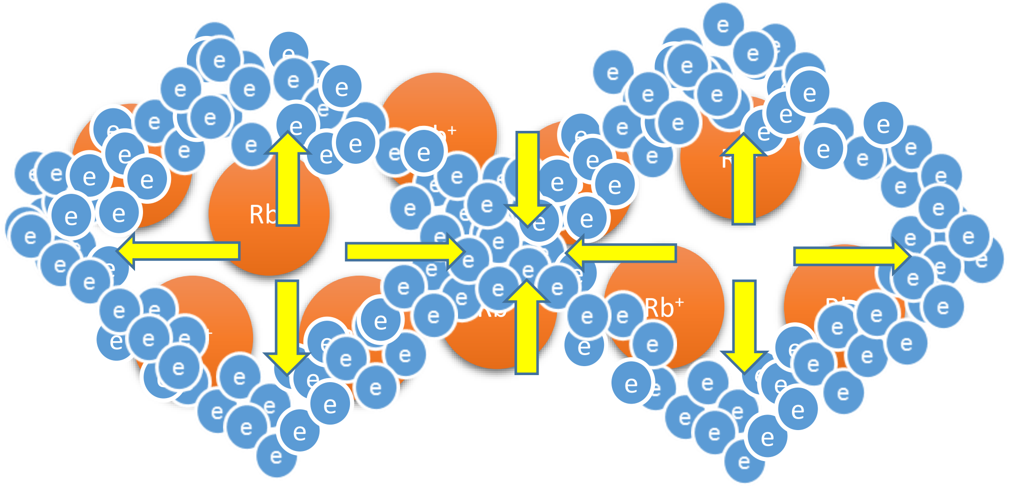

Example: Single ionized rubidium plasma

**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.

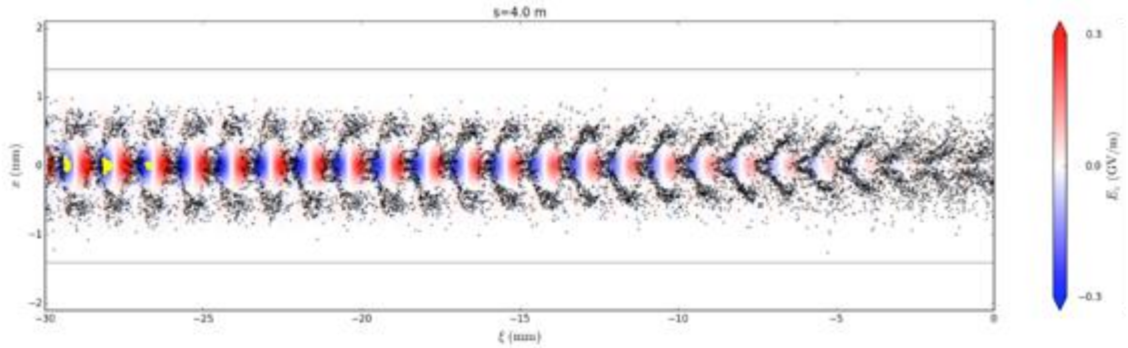
**Electrostatic interactions dominate** over collisions or ordinary gas kinetics.

# What is a Plasma Wakefield?




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

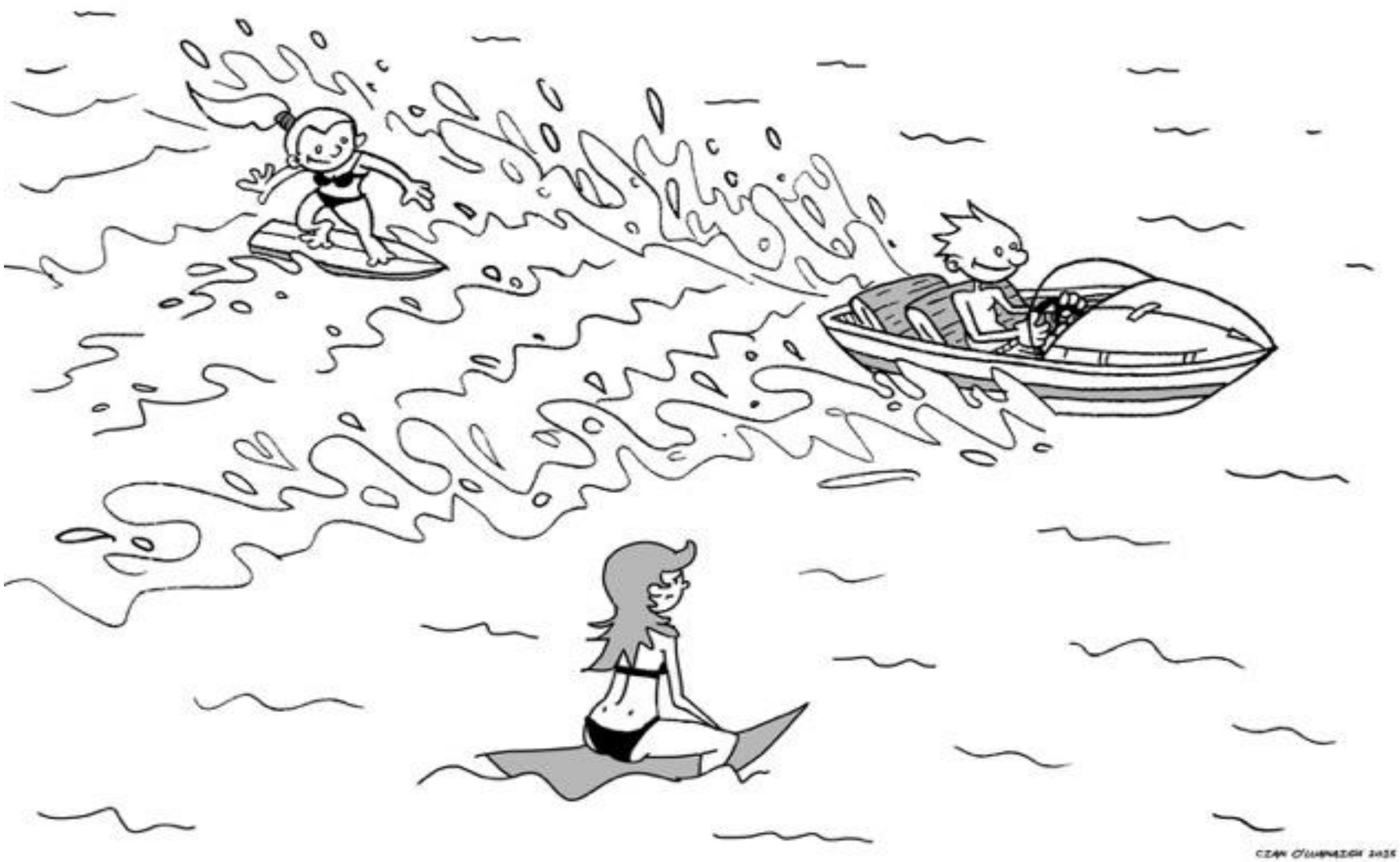
$$eE_{max} \approx 1[\mathrm{eV/cm}] \cdot \mathrm{n}^{1/2}[\mathrm{cm}^{-3}]$$



➔ **Use plasma as 'cavity'**

➔ **Much shorter linear colliders**

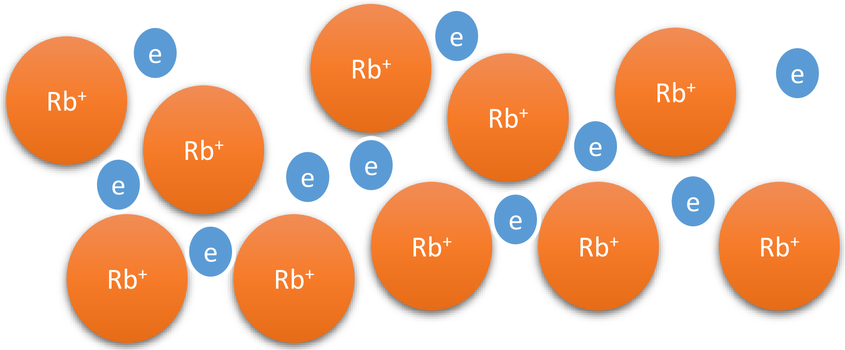
# How to Create a Plasma Wakefield?



# How to Create a Plasma Wakefield?

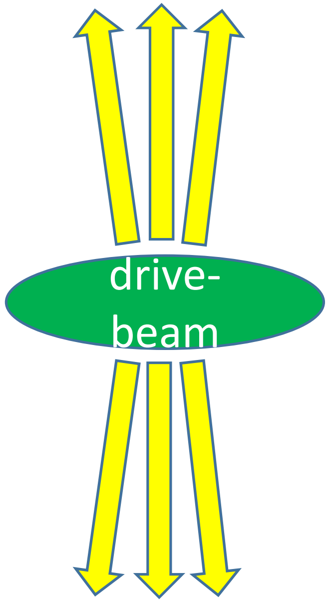
**What we want:**
Longitudinal electric field to accelerate charged particles.


**Our Tool:**




Single ionized rubidium **plasma**

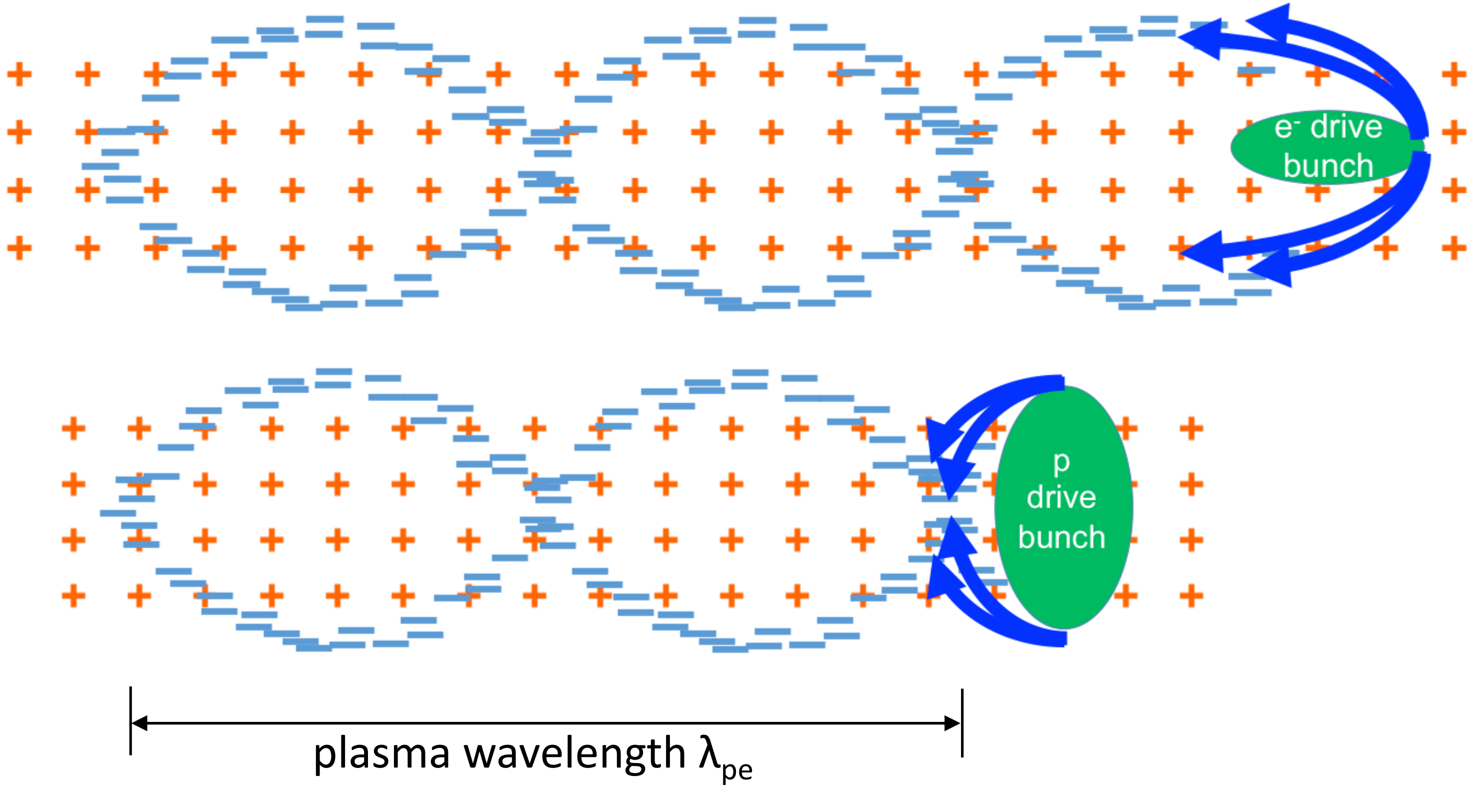
**Charged particle bunches** carry almost purely transverse electric fields.




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.

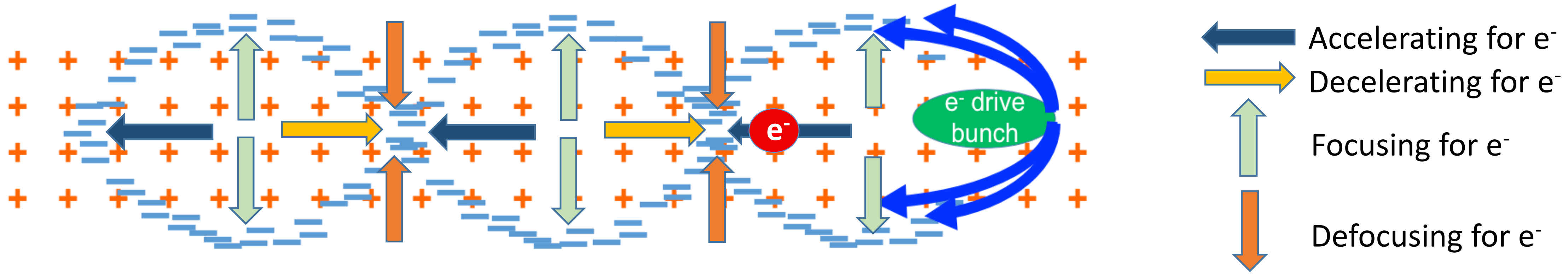
# Principle of Plasma Wakefield Acceleration

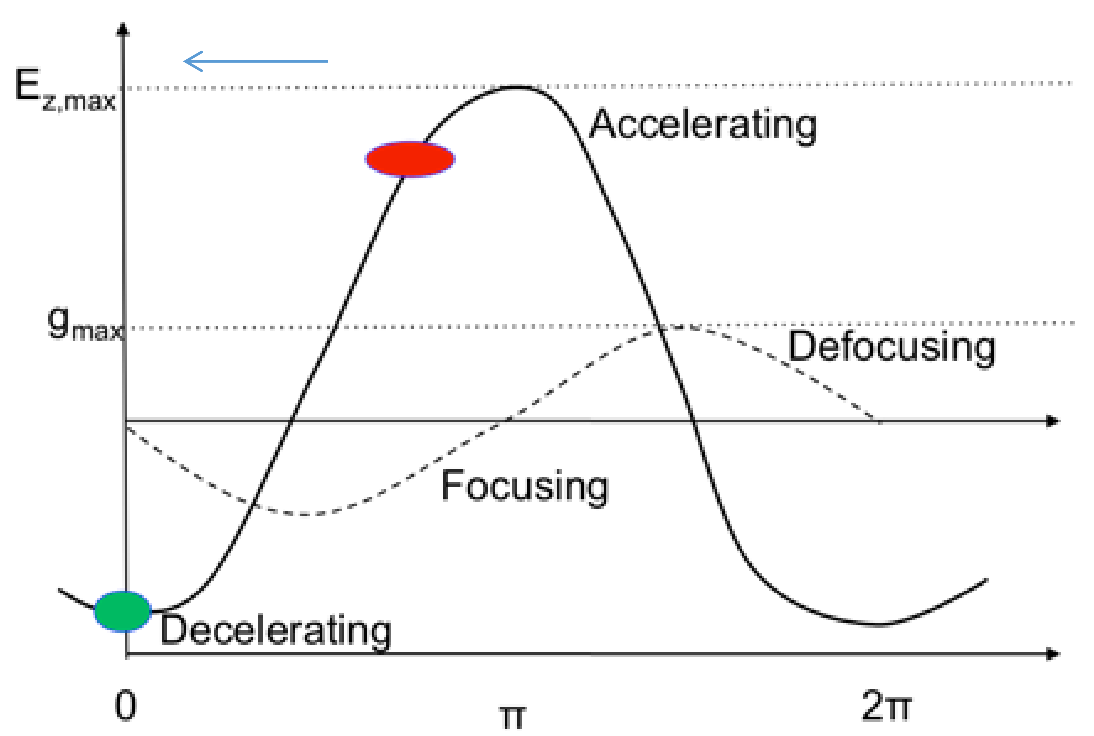
- Laser drive beam
  - ➔ Ponderomotive force
- Charged particle drive beam
  - ➔ Transverse space charge field
  - Reverses sign for negatively (blow-out) or positively (suck-in) charged beam



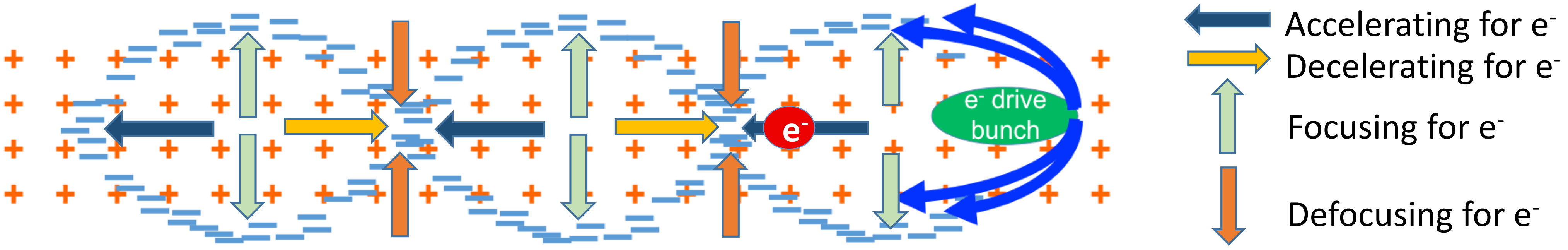

- Plasma wave/wake excited by relativistic particle bunch
- Plasma $e^-$ are expelled by space charge force
- Plasma $e^-$ rush back on axis
- Ultra-relativistic driver – ultra-relativistic wake → no dephasing
- Acceleration physics identical for LWFA, PWFA

# 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:

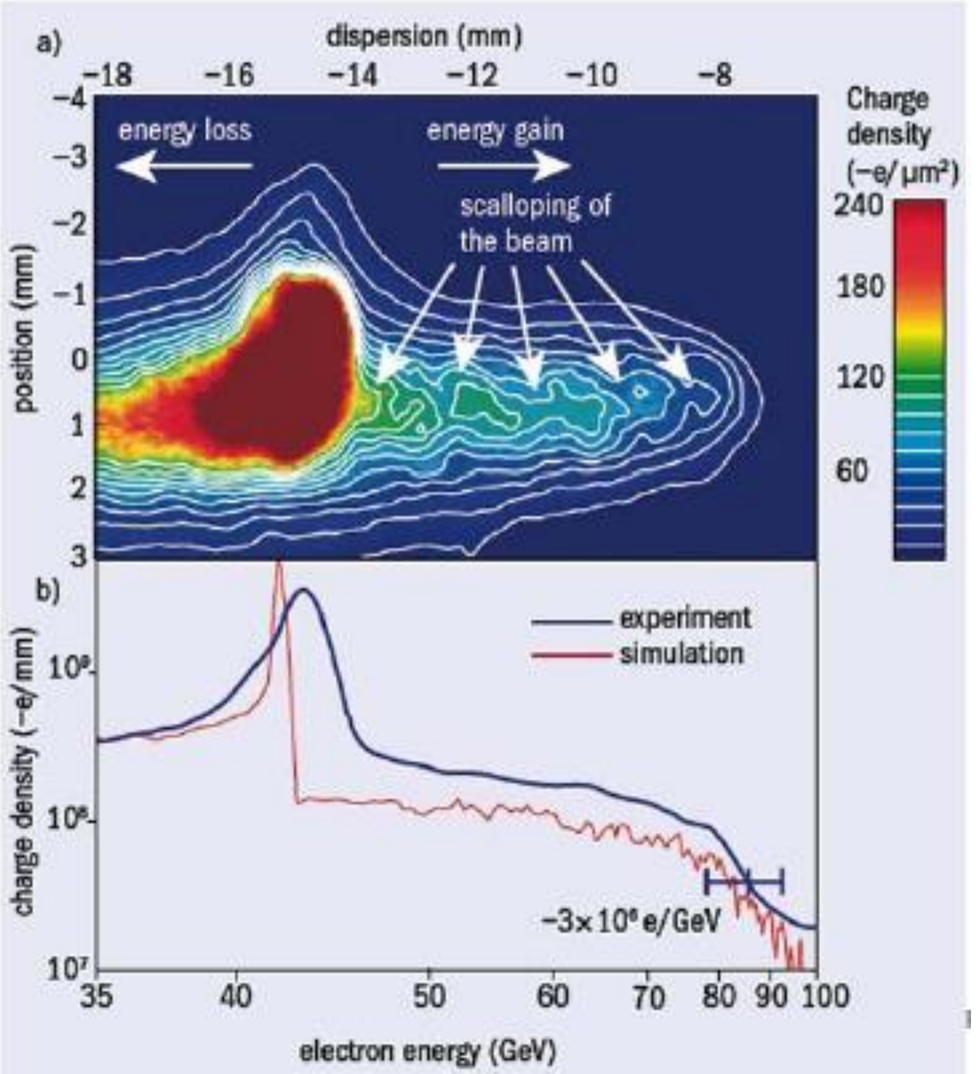
$$e\,E_{WB} = 96\,\frac{V}{m}\sqrt{\frac{n_{pe}}{cm^{-3}}}$$

**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)

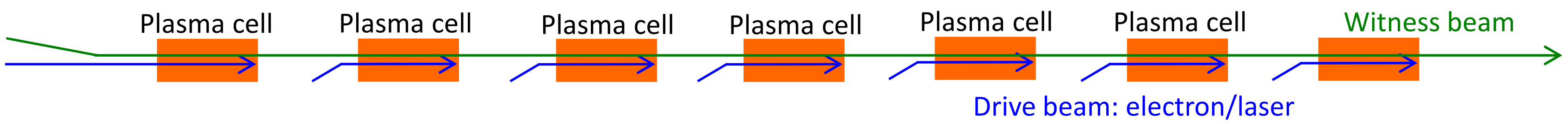
- Gaussian electron beam with 42 GeV, 3nC @ 10 Hz, $\sigma_x$ = 10µm, 50 fs
- **Reached accelerating gradient of 50 GeV/m**
- Accelerated electrons from 42 GeV to 85 GeV in 85 cm.



# 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….



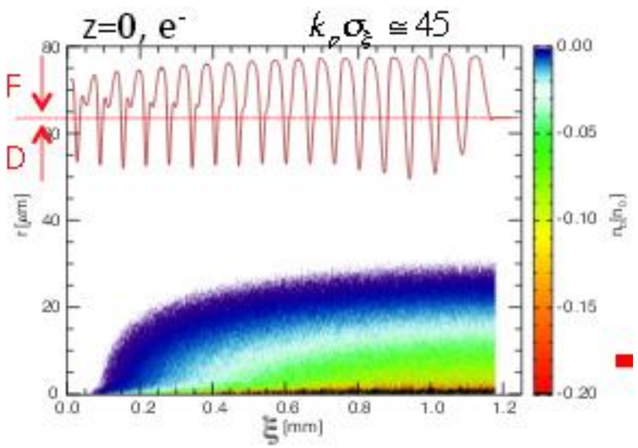

- Proton drivers: large energy content in proton bunches → interesting for plasma wakefield accelerators → to reach high energies of a witness beam possible in few stages.
- But: need short bunches → self-modulation instability

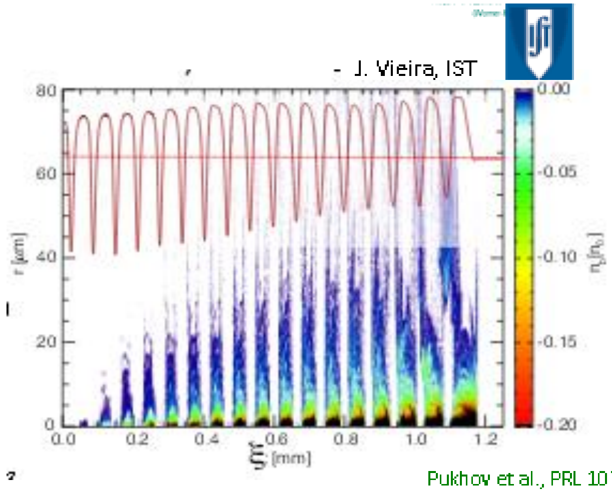
# Self-Modulation Instability

- 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 (**$\sigma_z$ = 12 cm**) is much longer than plasma wavelength **($\lambda$ = 1mm**)

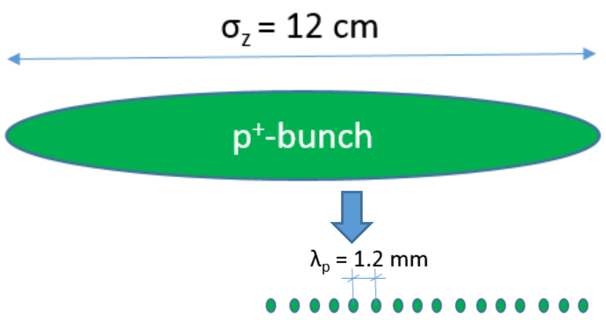
## Self-Modulation Instability of the proton beam

- Modulate long bunch to produce a series **of 'micro-bunches' in a plasma with a spacing of plasma wavelength $\lambda_p$.**
  - →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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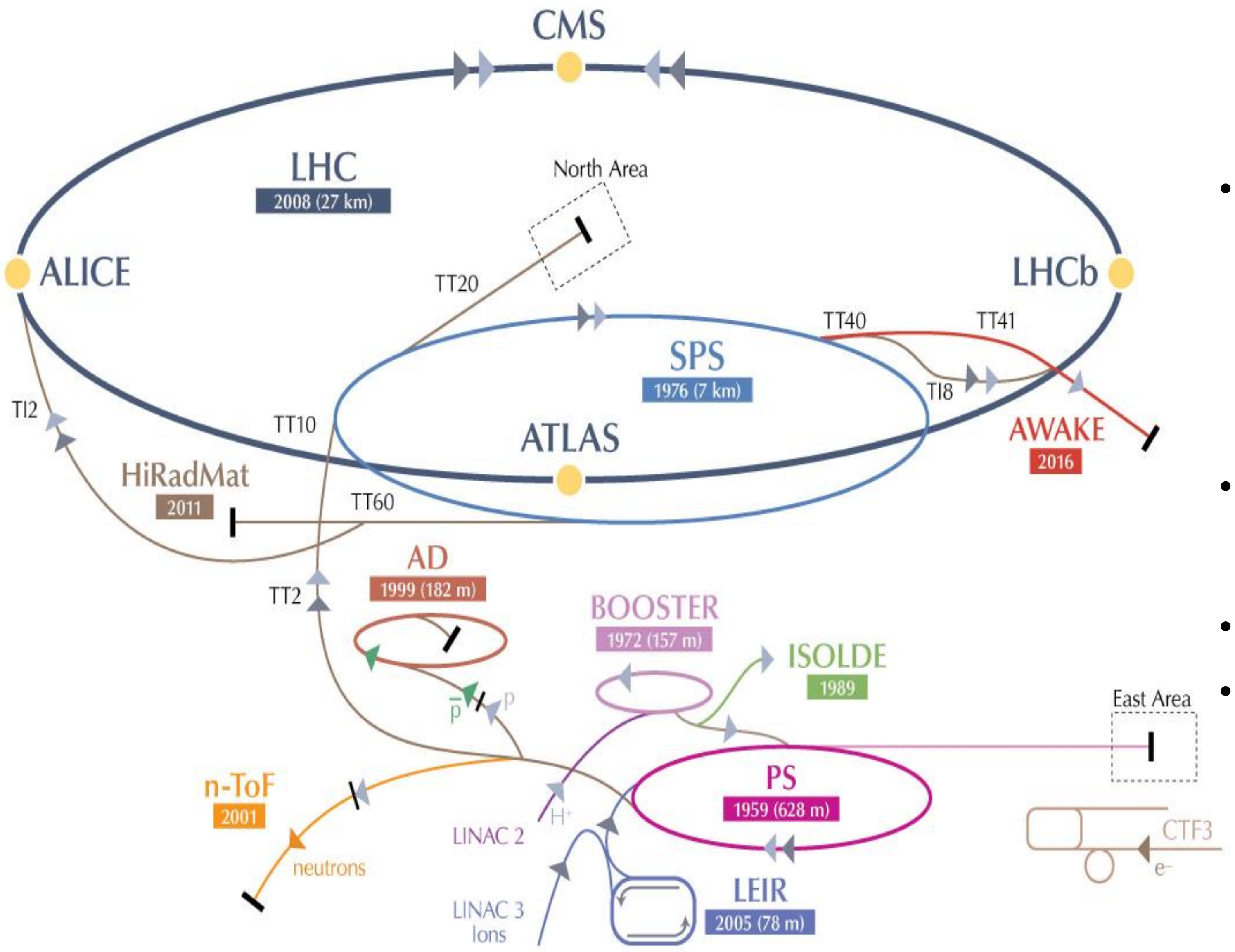
# Beam-Driven Wakefield Acceleration: Landscape

| 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.**<br>- Study Self-Modulation Instability (SMI).<br>- Accelerate externally injected electrons.<br>- 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**<br>- Acceleration of positrons<br>- 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**<br>- Energy-doubling of Flash-beam energy<br>- 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.**<br>- Study PWFA driven by multiple bunches<br>- 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



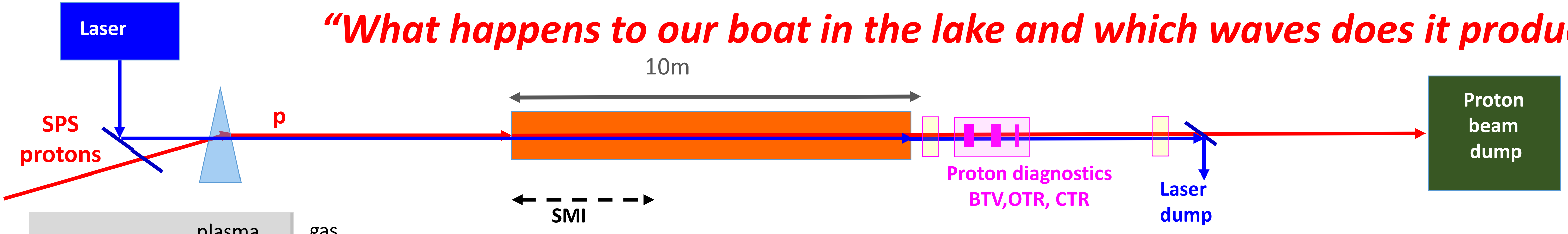

- **Advanced Proton Driven Plasma Wakefield Acceleration Experiment**
  - Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.
- Proof-of-Principle Accelerator R&D experiment at CERN
- Approved in August 2013
- First beam end 2016

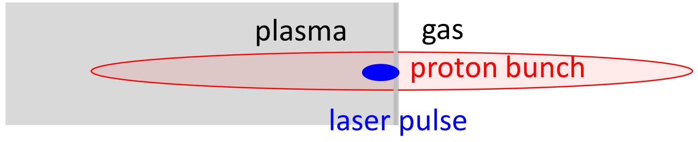
# AWAKE Experimental Program, 2016/17

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

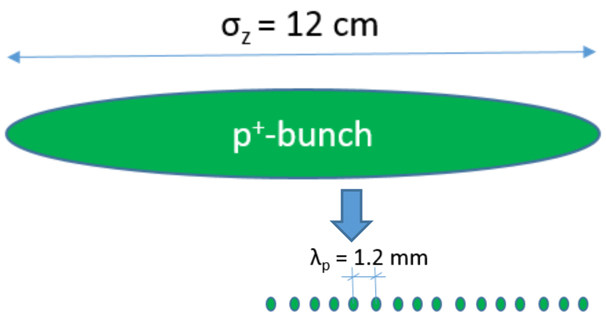
➔ start Q4 2016

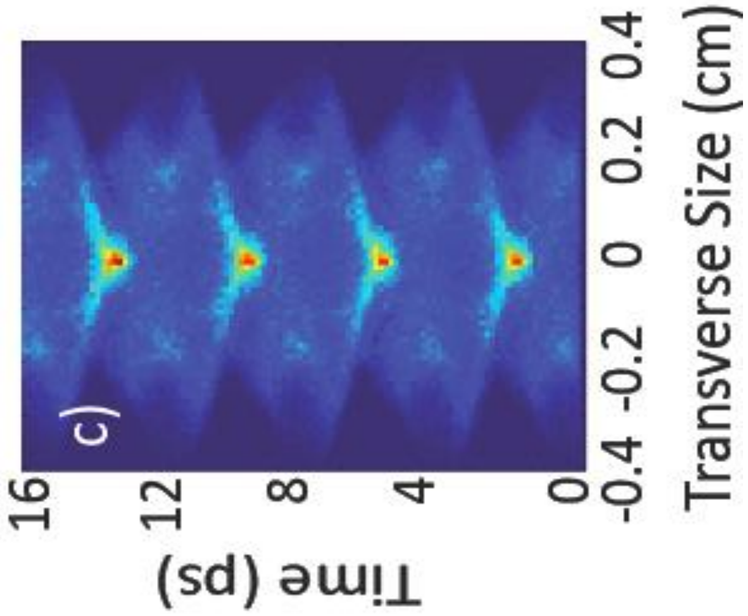
***"What happens to our boat in the lake and which waves does it produce?"***




**Self-modulated proton bunch** resonantly driving plasma wakefields.

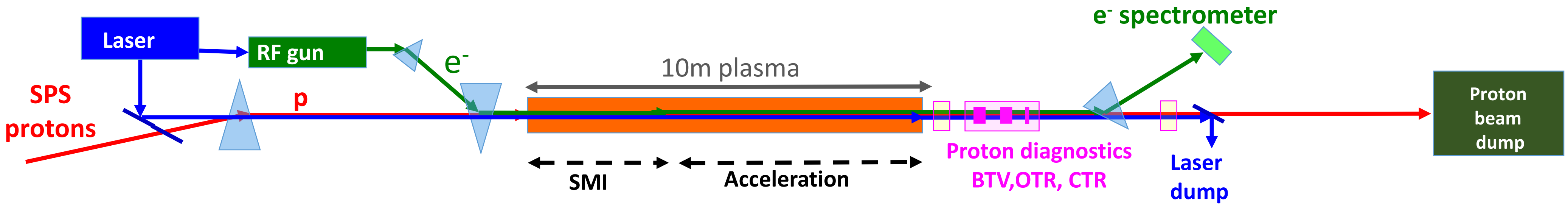


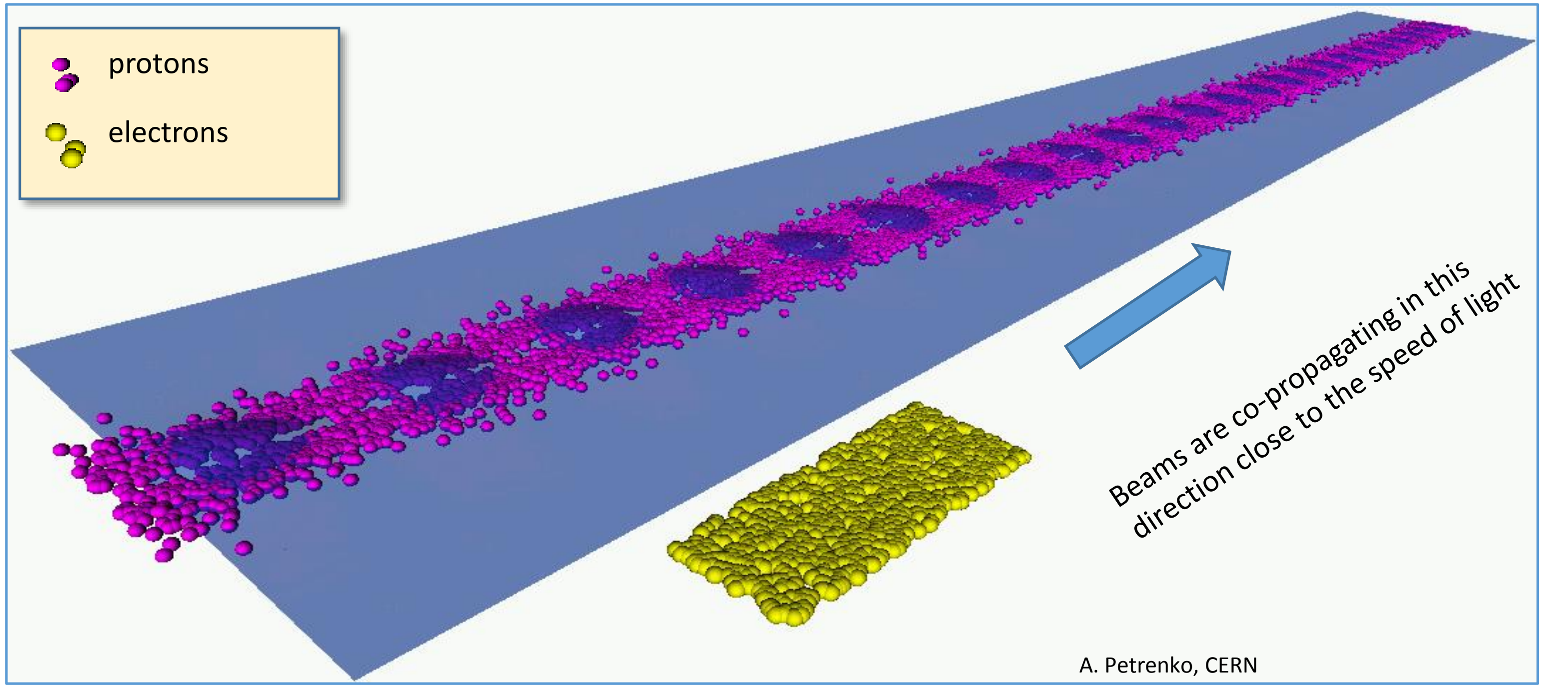



# AWAKE Experimental Program 2017/18

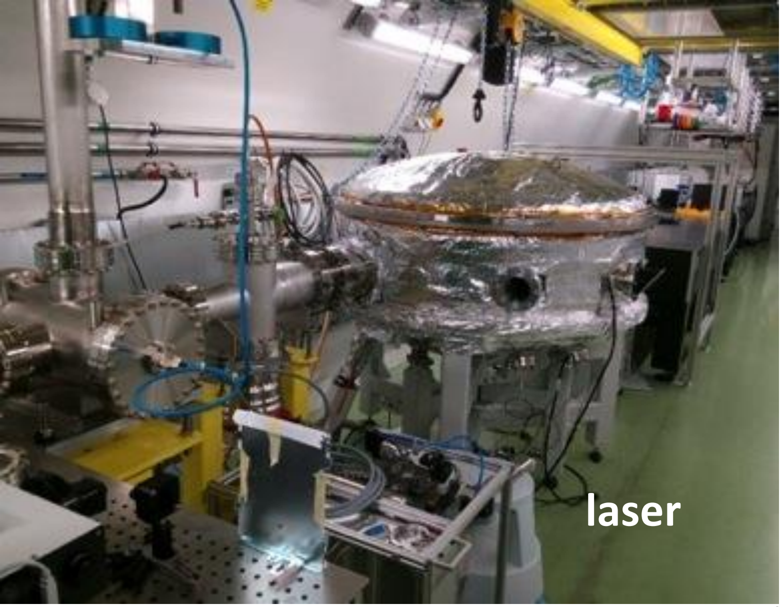
- **Phase 1:** Understand **the physics of self-modulation instability** processes in plasma.
- **Phase 2: Probe the accelerating wakefields** with externally injected electrons. → start Q4 2017
  - Demonstrate GeV scale gradients with proton driven wakefields

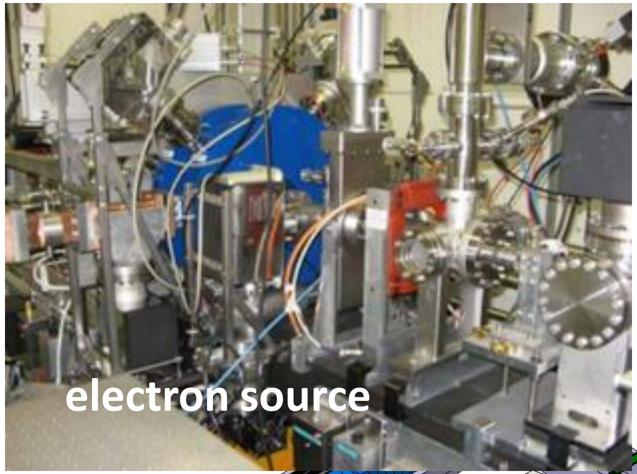
***"How fast get our surfers?"***



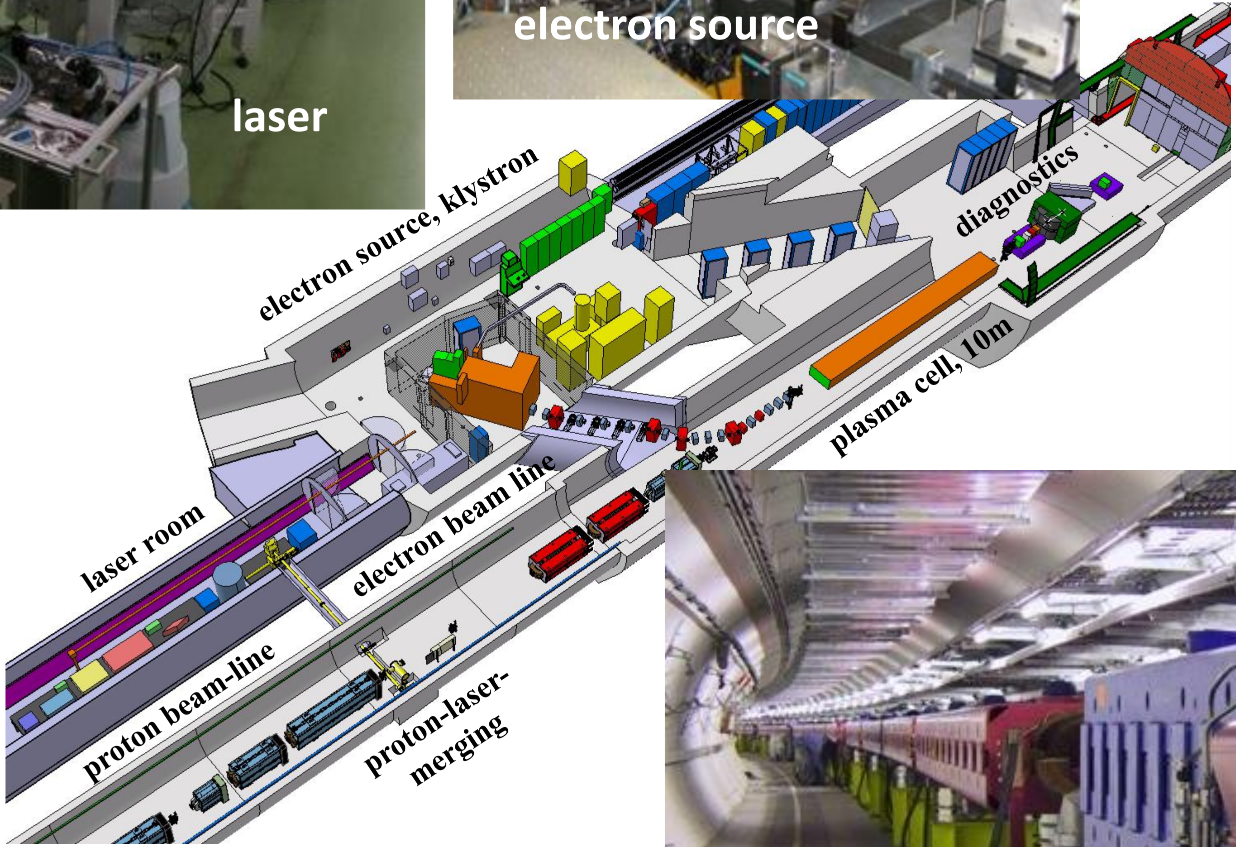



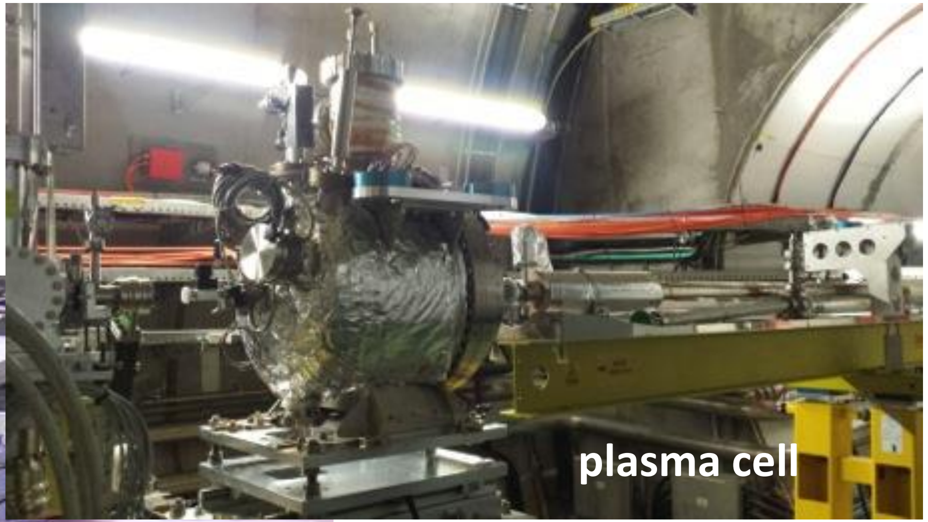
# AWAKE Impressions

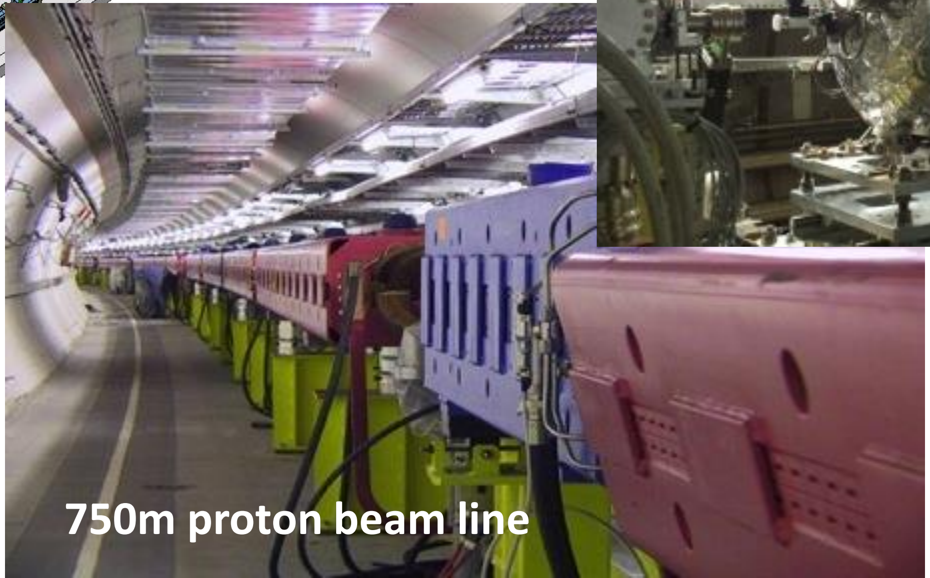




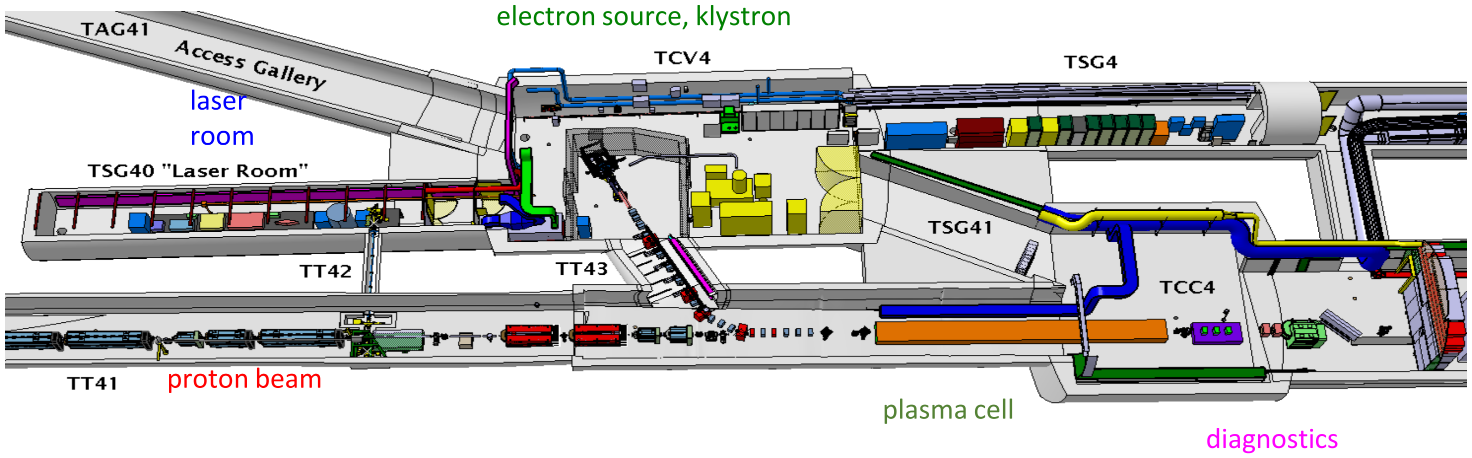


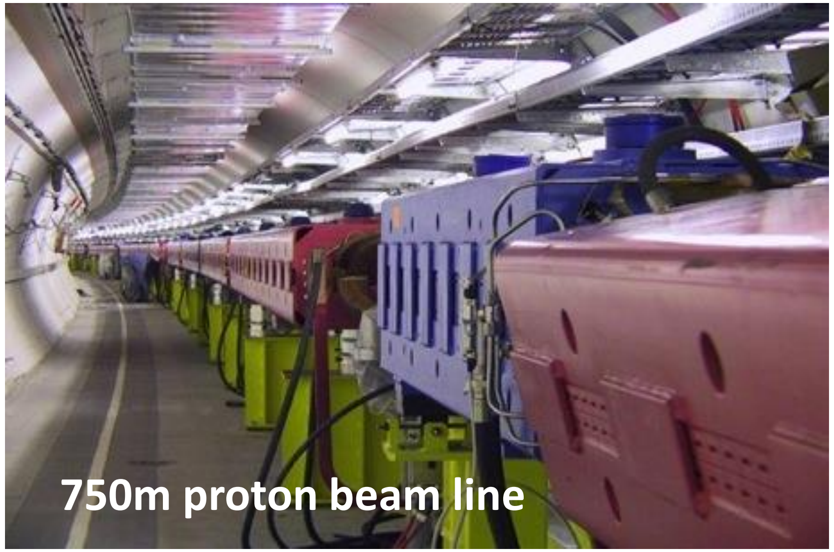



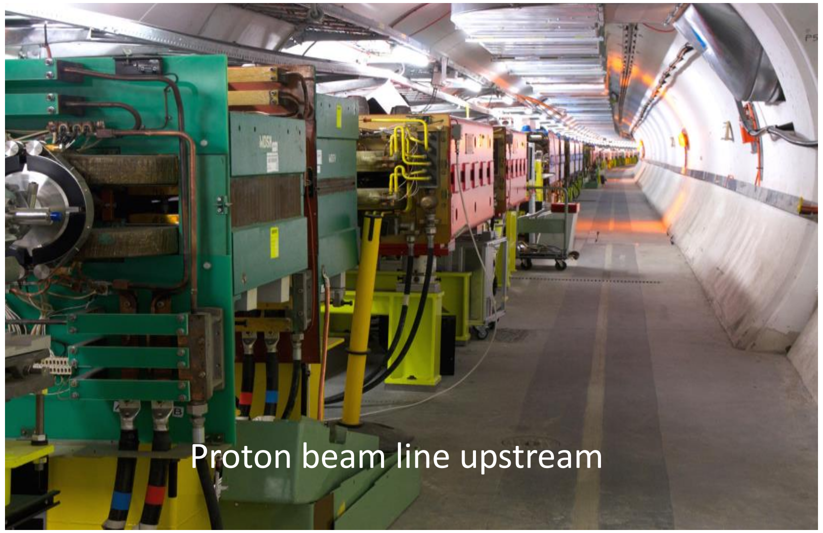



# AWAKE Proton Beam Line

| 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 |
| $1\sigma$ spot size at focal point [$\mu$m] | 200 ±20 |
| $\beta$-function at focal point [m] | 5 |
| Dispersion at focal point [m] | 0 |

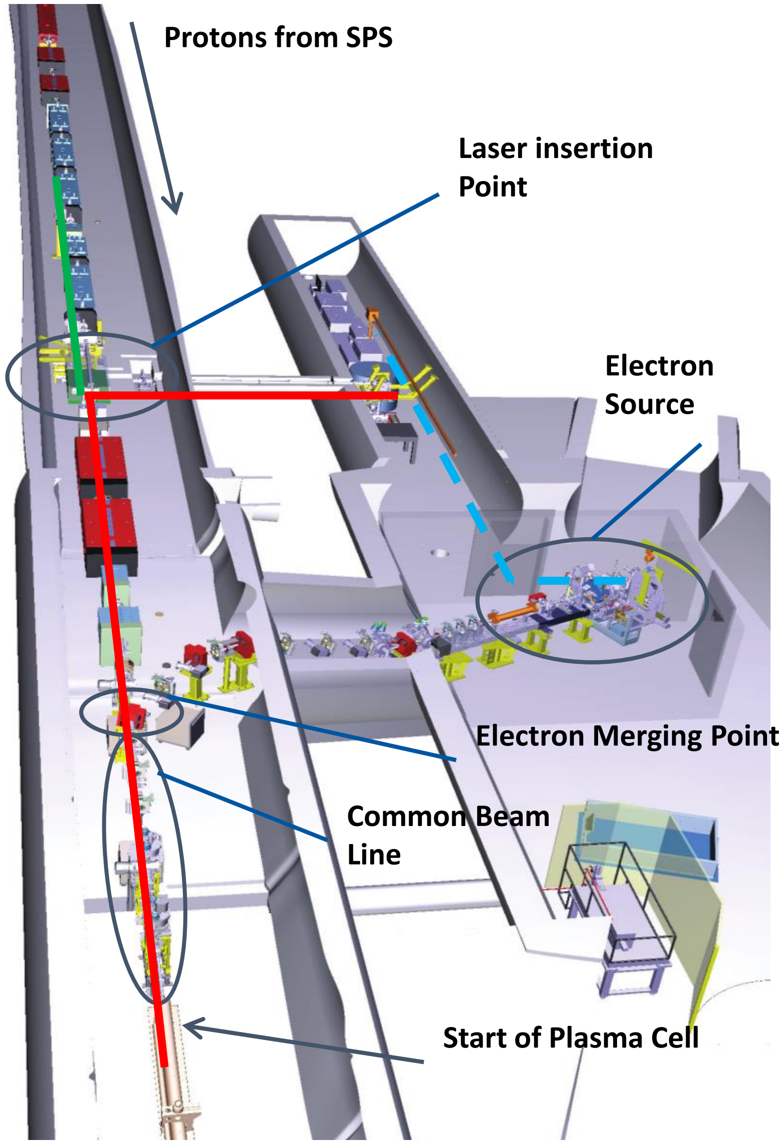


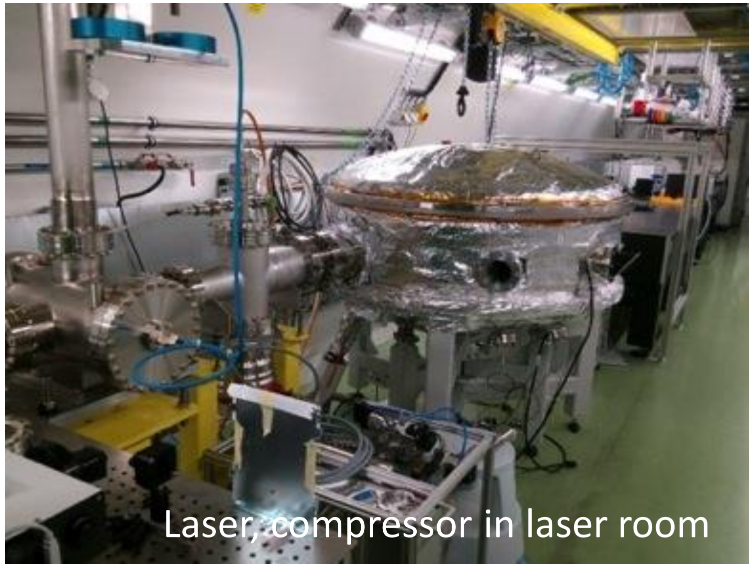




# Laser and Laser Line

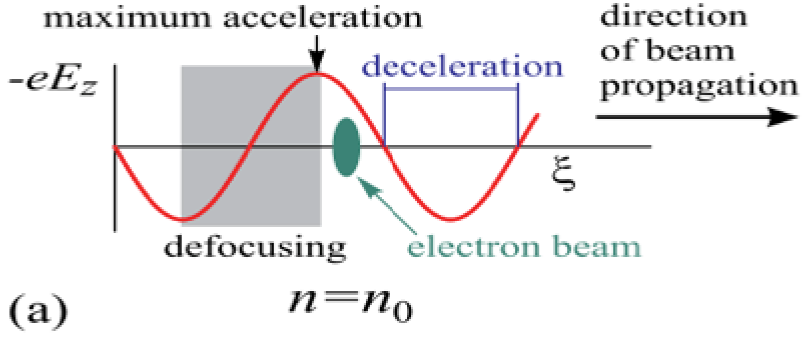
- **Laser beam line to plasma cell**
  - λ = 780 nm
  - t pulse = 100-120 fs
  - E = 450 mJ

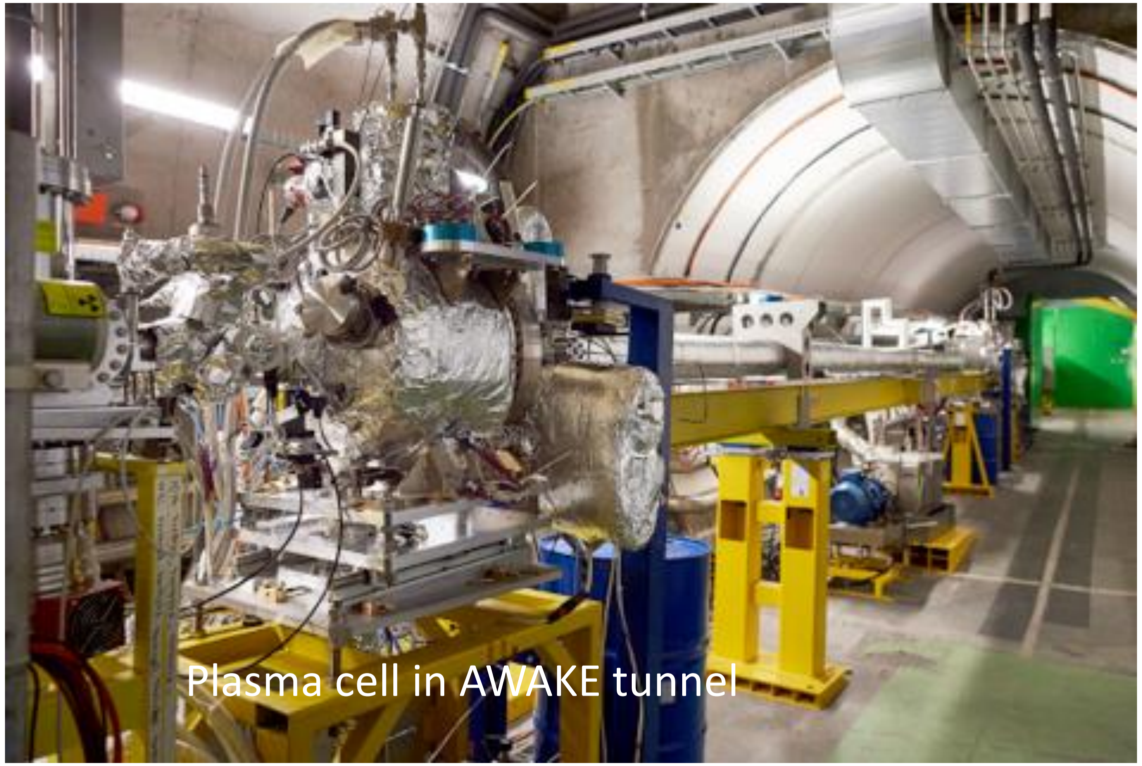


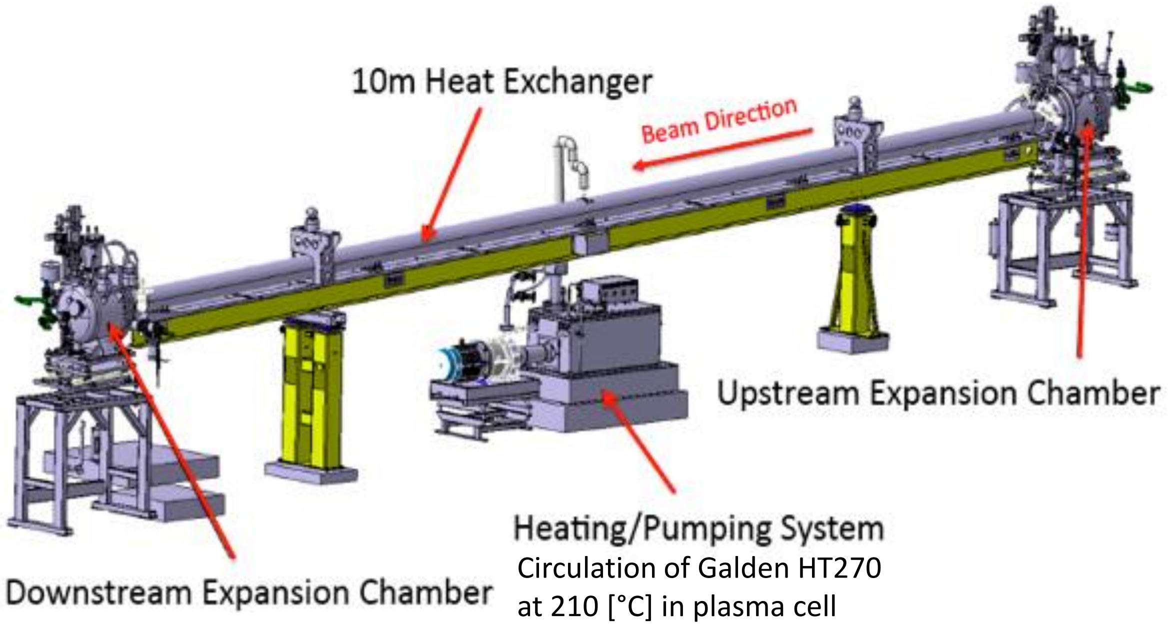



# The AWAKE Plasma Cell

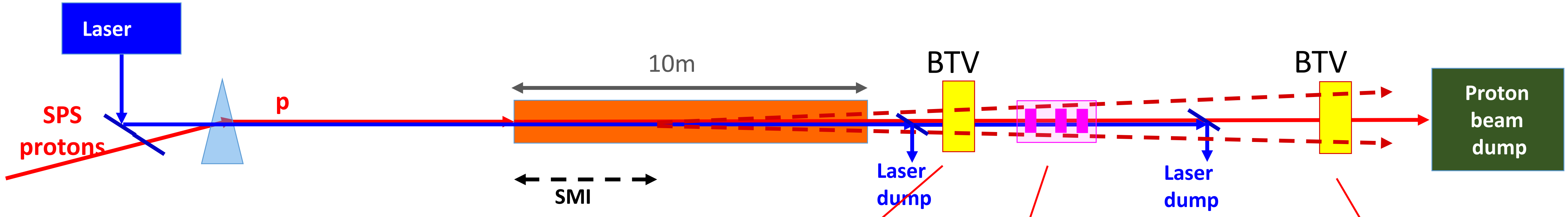
- **10 m long**, 4 cm diameter,
- Rubidium vapor, field ionization threshold ~$10^{12}$ W/cm$^2$
- Density adjustable from $10^{14} - 10^{15}$ cm$^{-3}$ ➔ **7x $10^{14}$ cm$^{-3}$**
  - **Requirement: uniformity better than 0.2%**
- Fluid-heated system (˜220 deg)



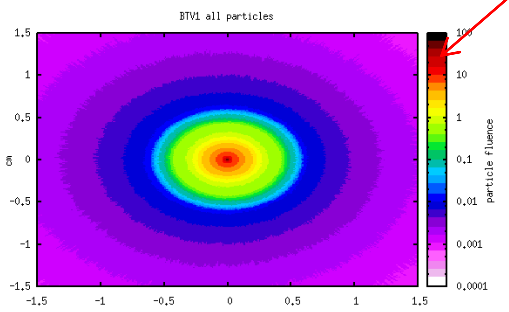



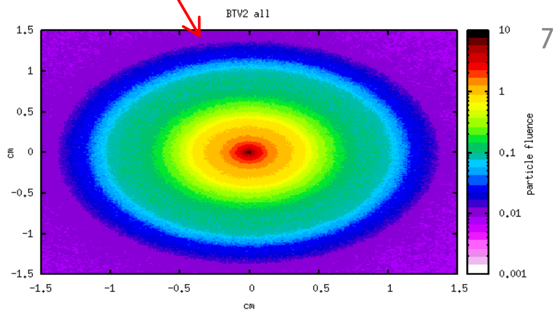



# AWAKE Self-Modulation Instability Measurements

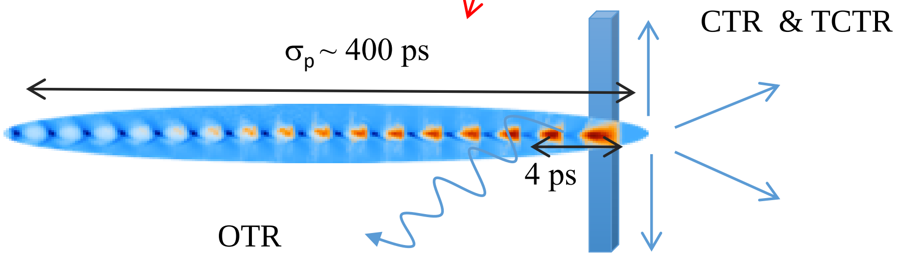


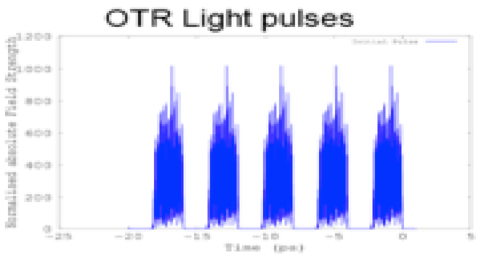

**Indirect SMI Measurement:**
Defocusing of the proton beam



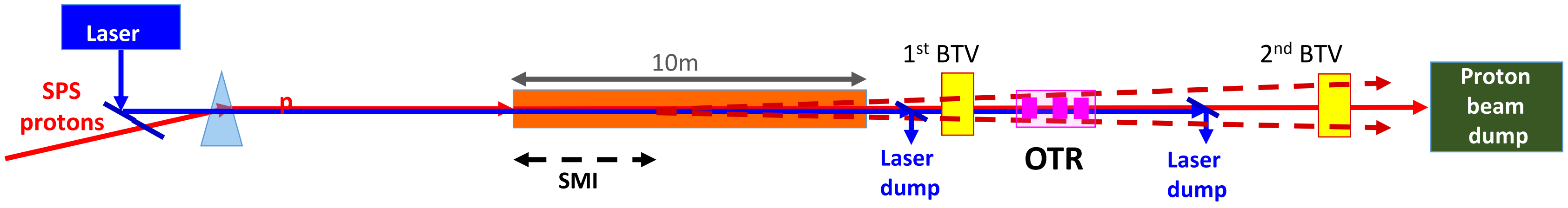

**Direct SMI Measurement:**
Radiation emitted by bunch when traversing dielectric material
→ Streak camera



# Self-Modulation Instability: 1st Measurements!!!

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



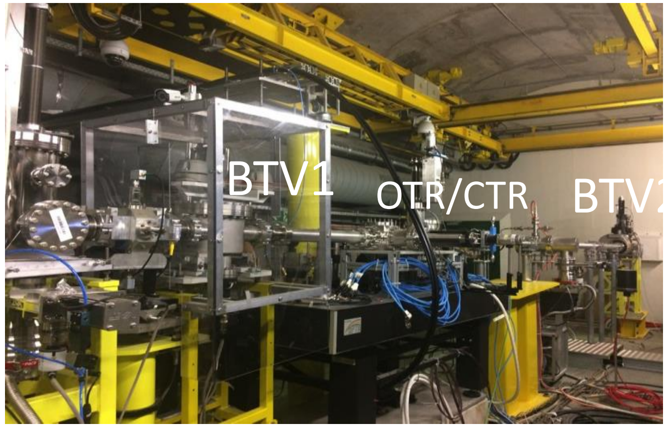
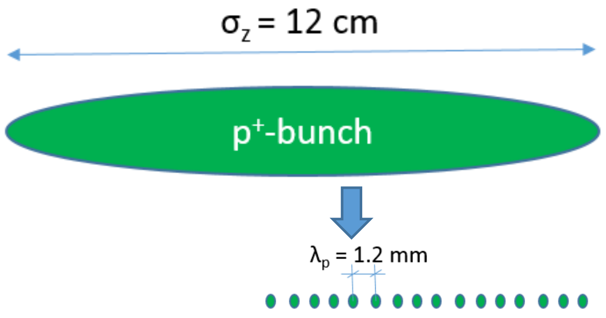
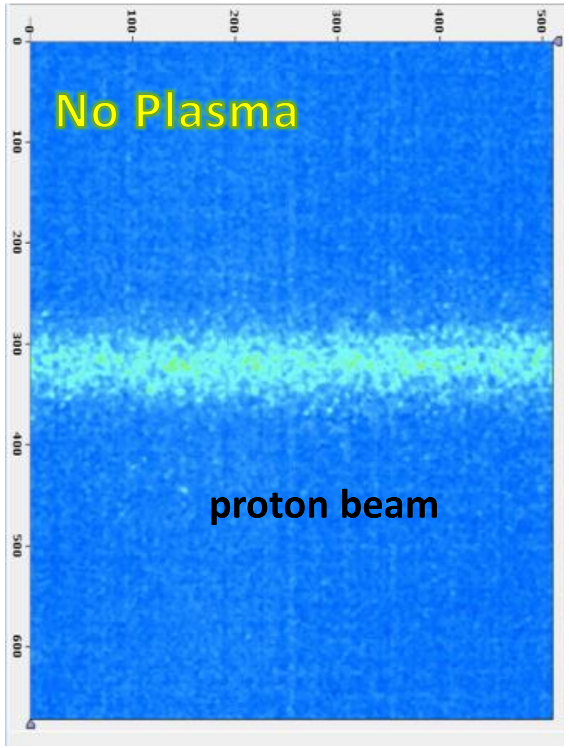
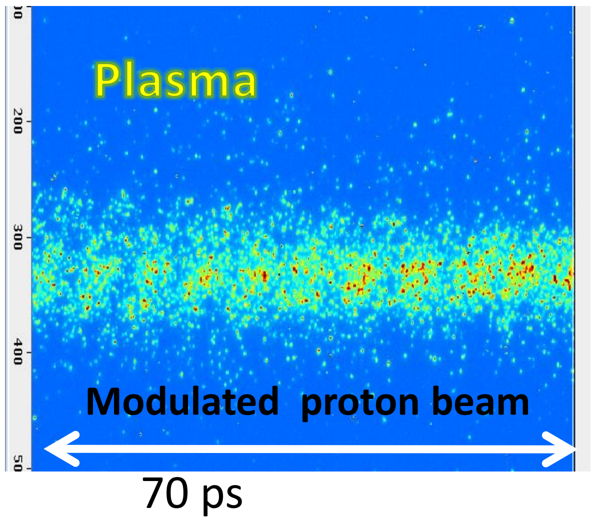




Image of proton beam measured with OTR and a streak camera



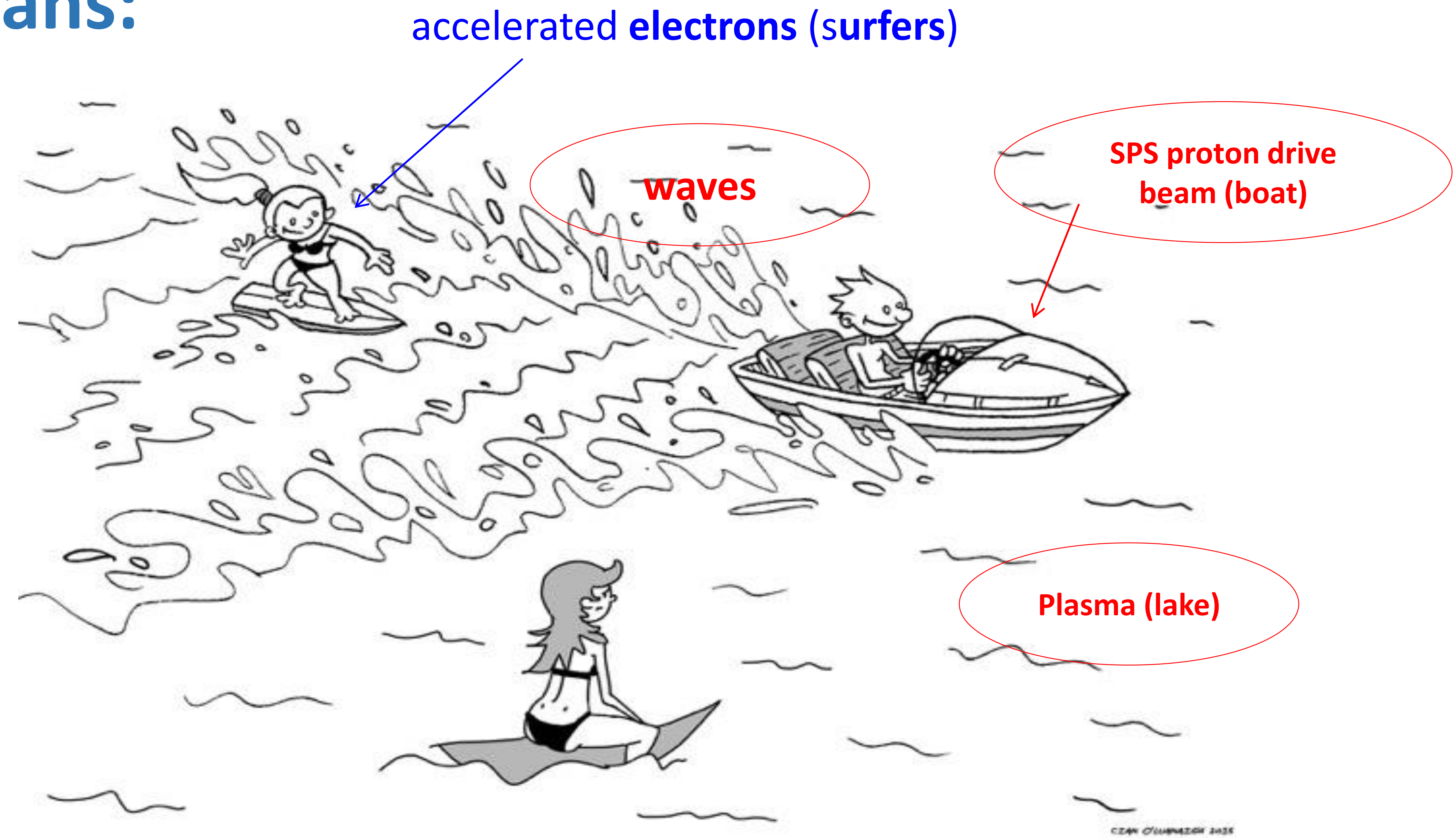



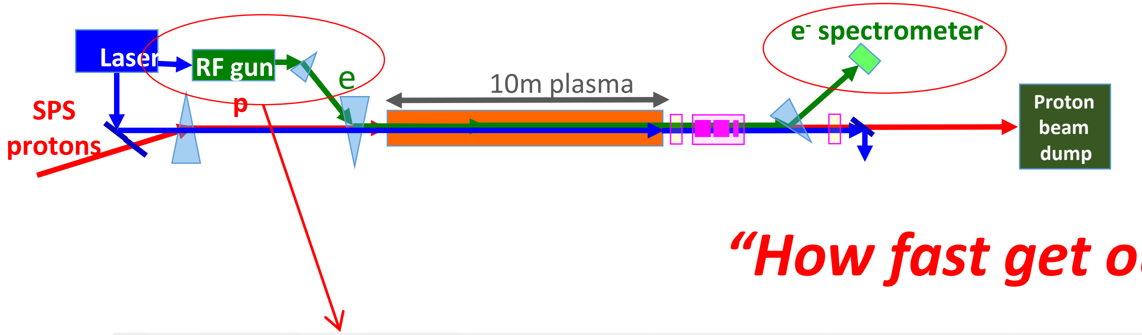

K. Rieger, MPP

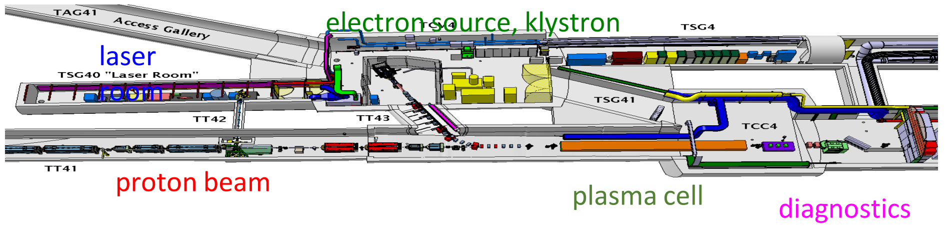
**2016/2017**

# This Means:

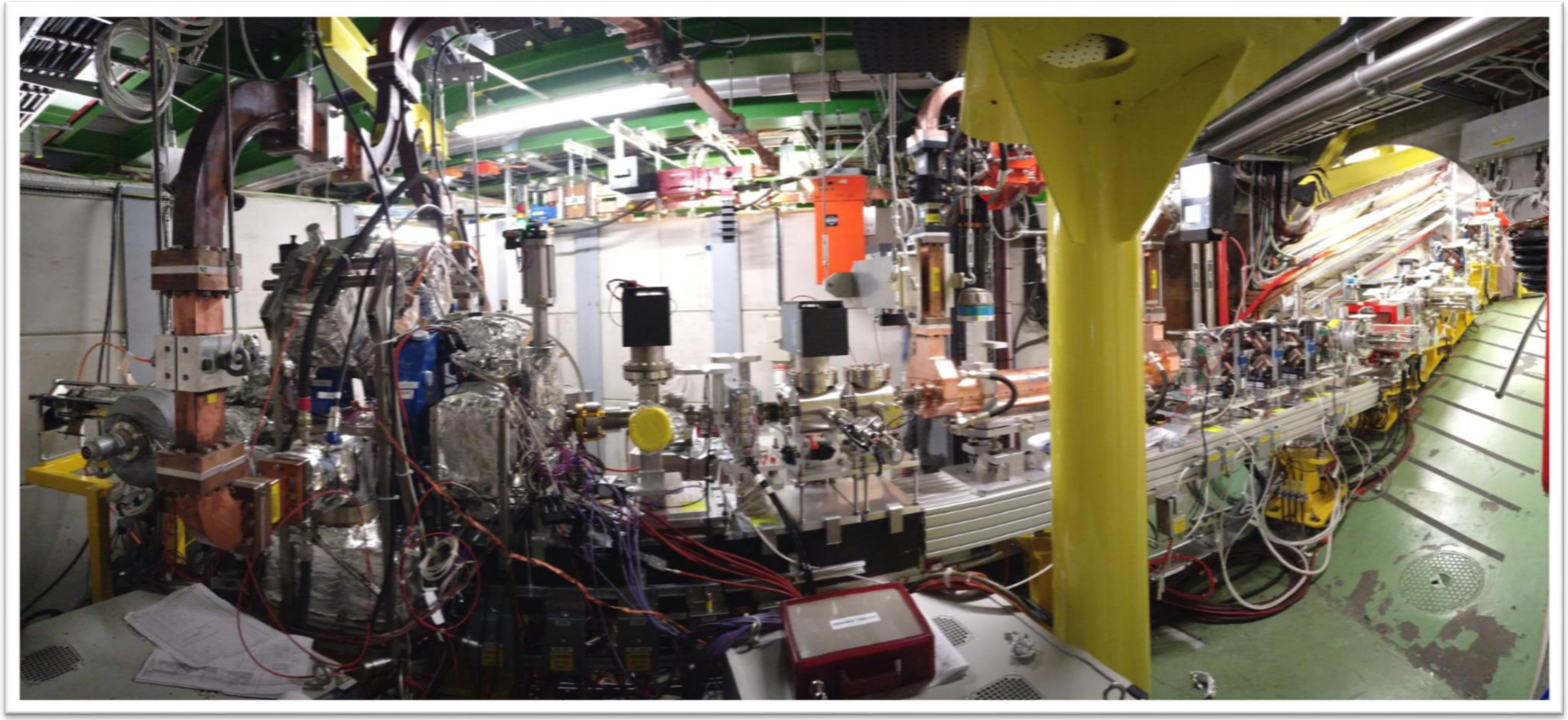

accelerated **electrons** (**surfers**)
waves
SPS proton drive beam (boat)
Plasma (lake)

# Electron Source and Electron Beam Line



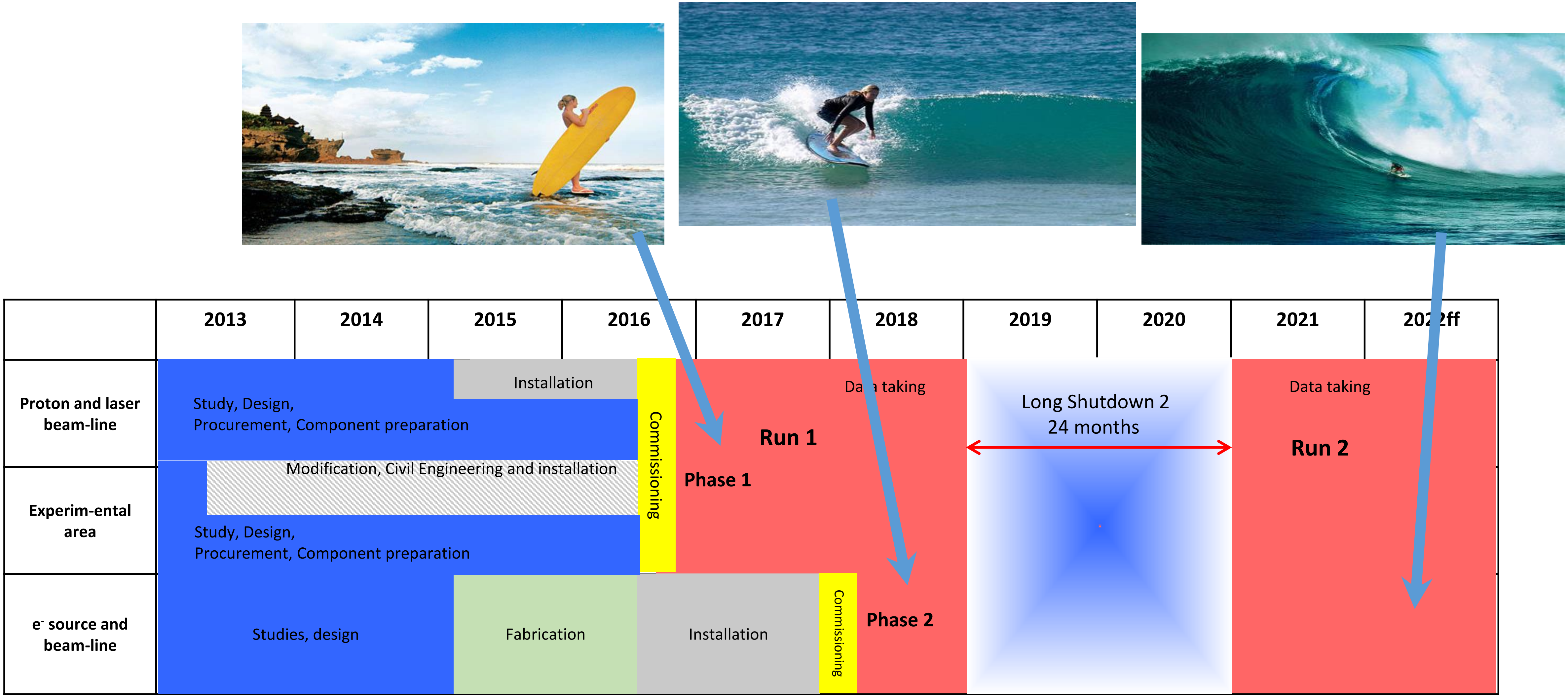




*"How fast get our surfers?"*



→ **Start in 2018**

# AWAKE Time Line



# Outline

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

# What is the Future of the PWA Technology?

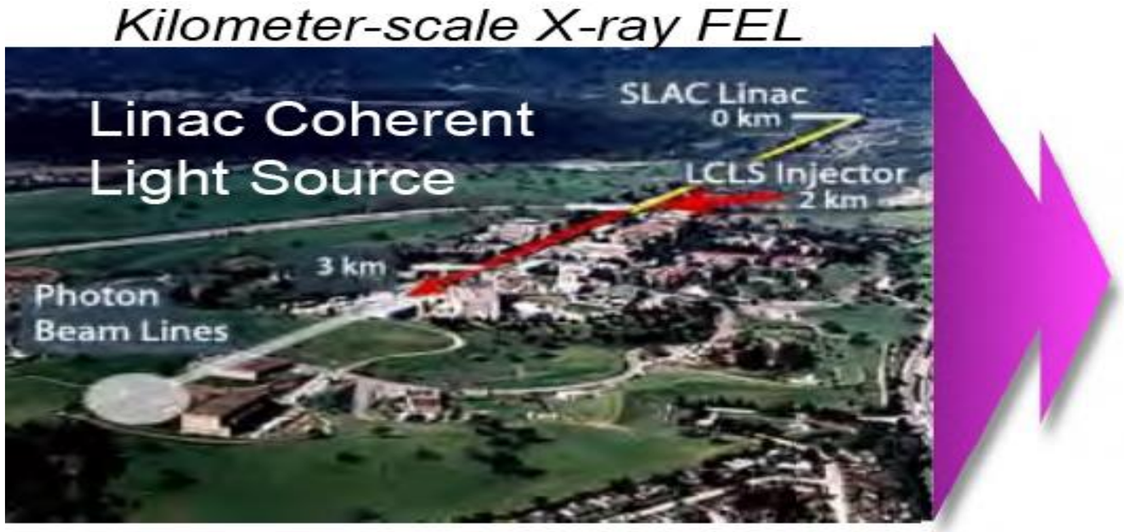
## Short term perspective (< 10 years):

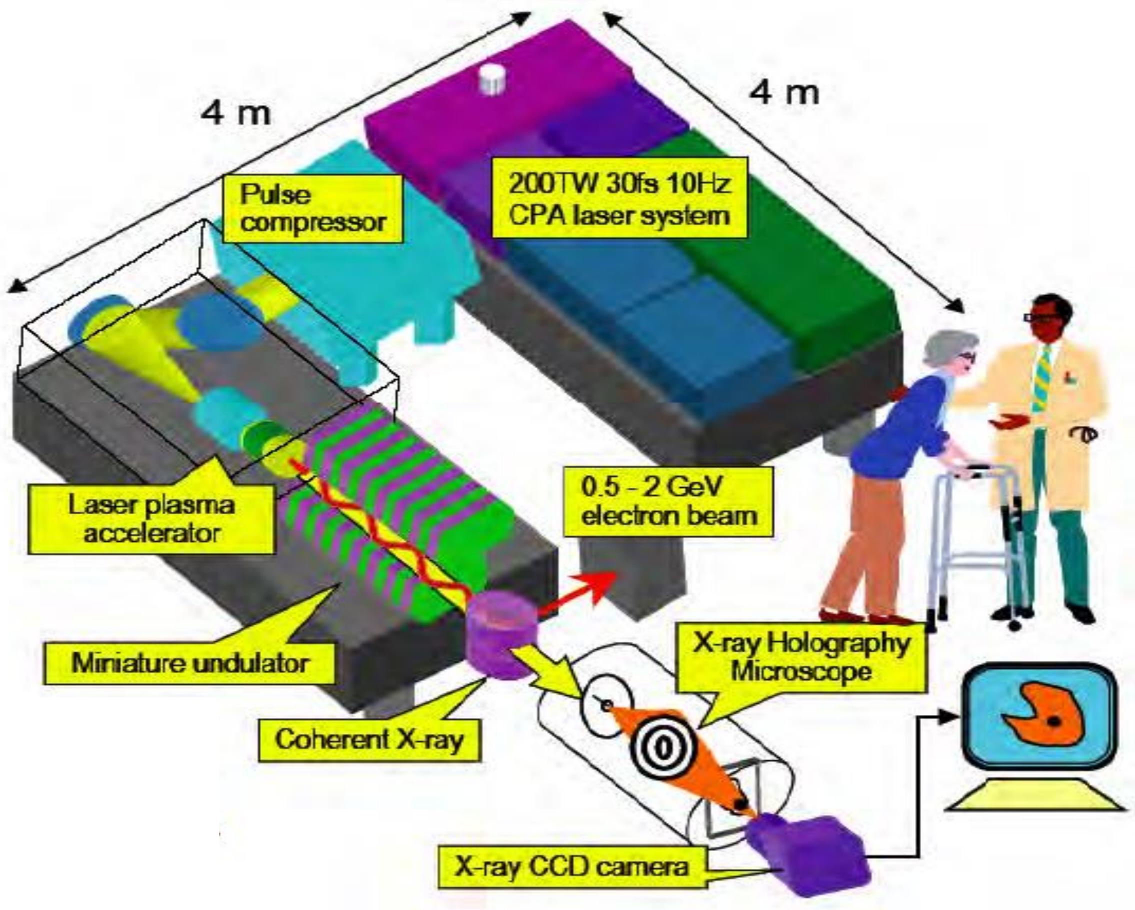
- Applications in medicine, radiobiology, material science Compact FEL , Compact X-ray source are rather close: generating light sources for fine-scale imaging, producing radioactive isotopes for medical use, creating gamma ray and THz radiation for material testing.

## 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



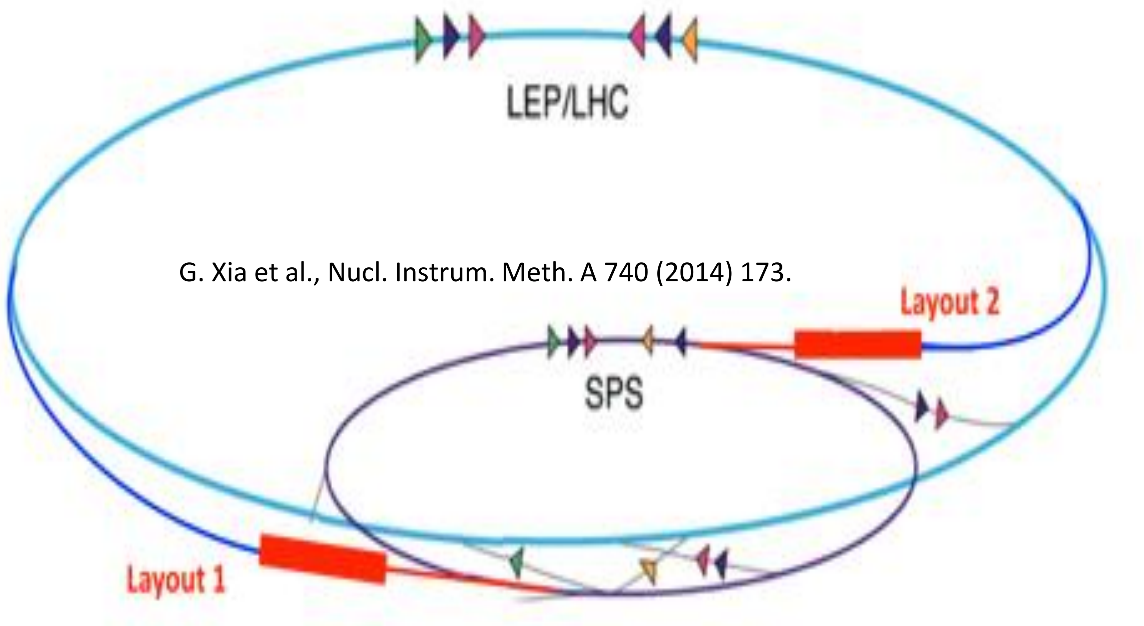

**XFEL**

Photon Science

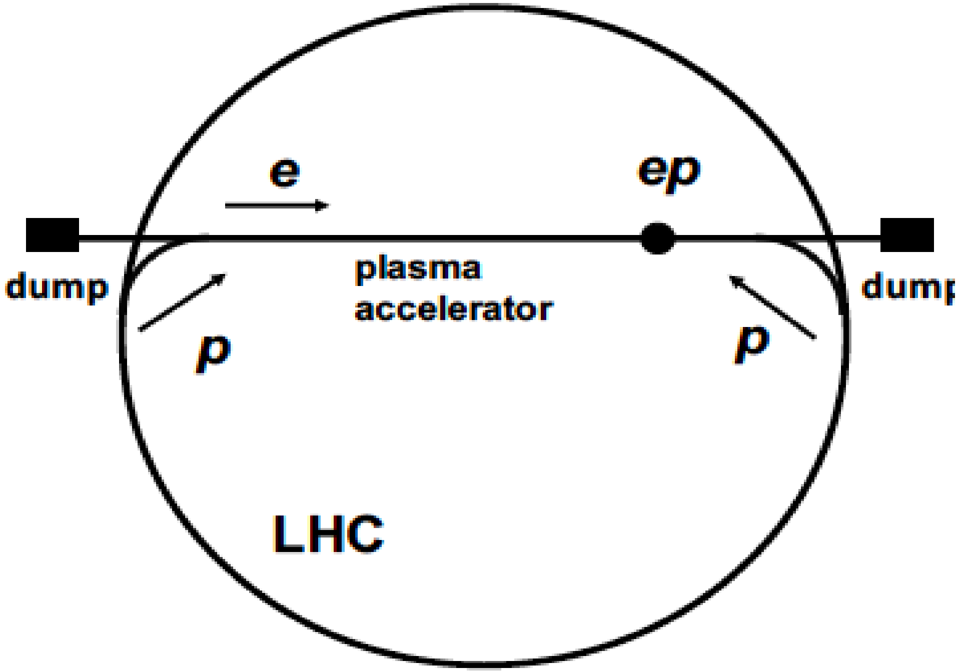
Visualization by
T. Tajima. 2010

# 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.




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

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

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.