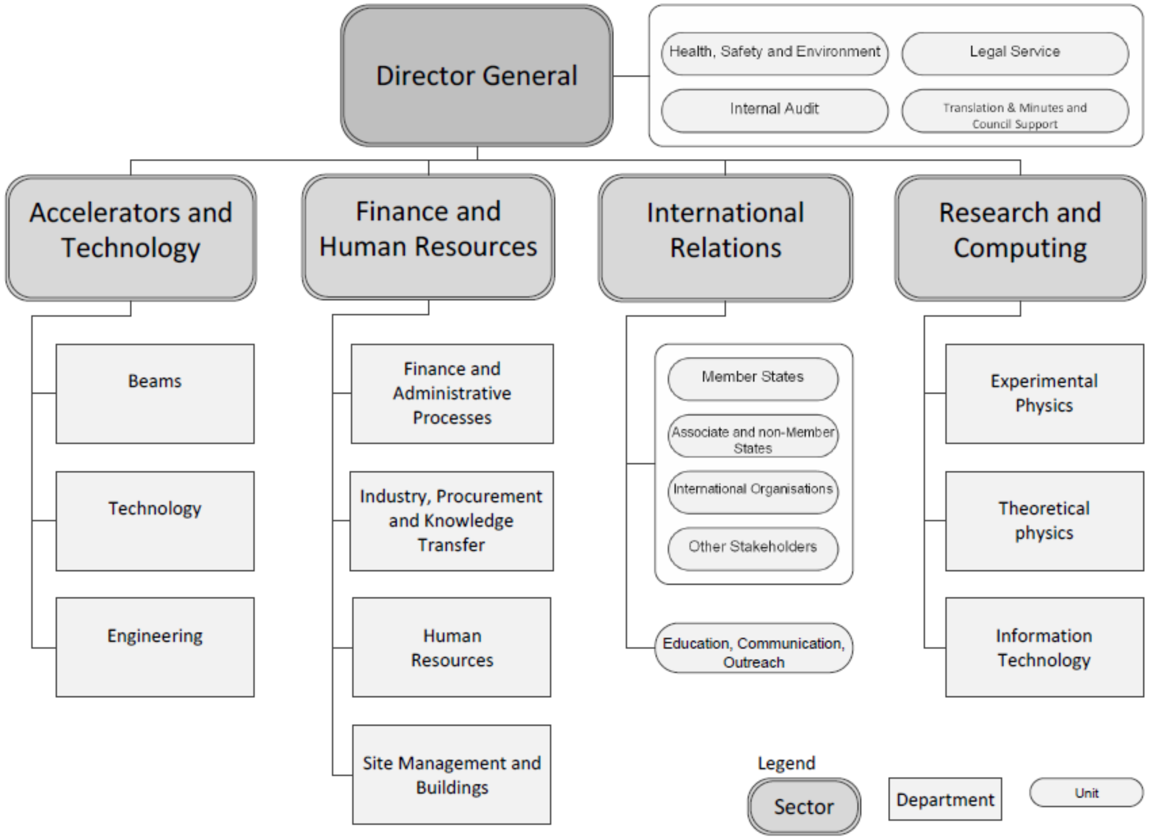
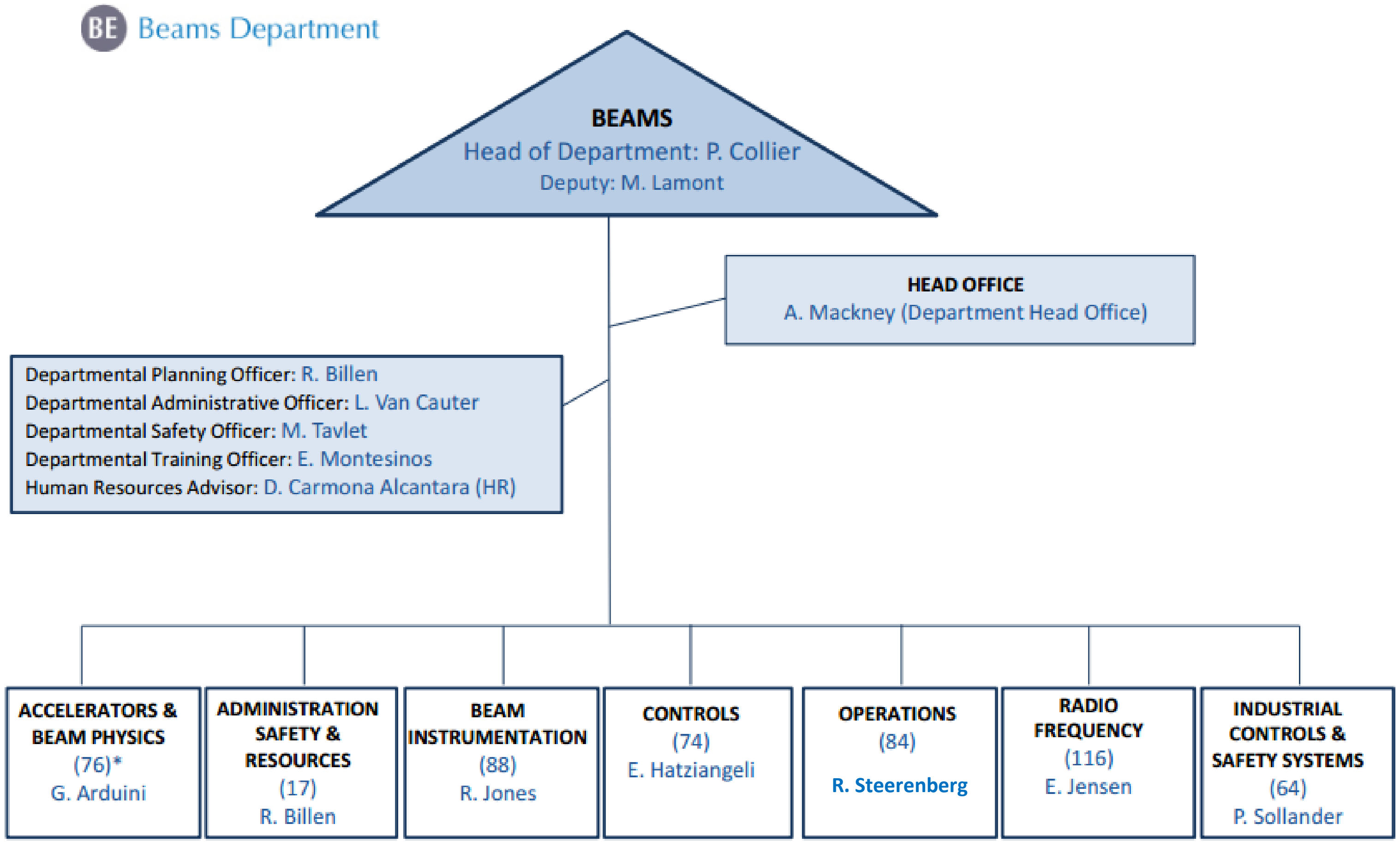

# An introduction to CERN

# CERN structure

- Fabiola Gianotti DG for 2016-2021
- CERN organized in **four** sectors



# CERN beams department

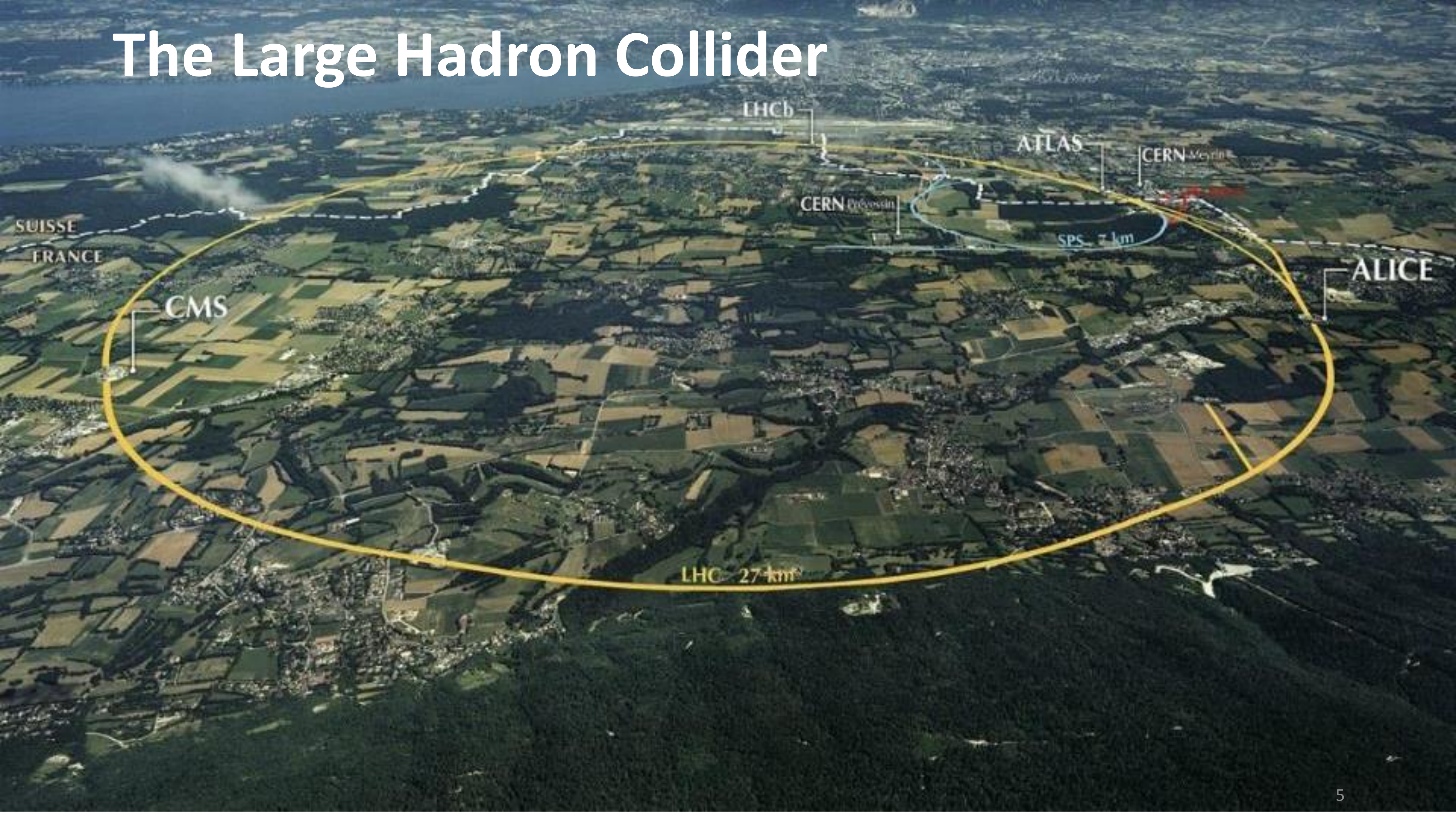


# CERN Beam instrumentation

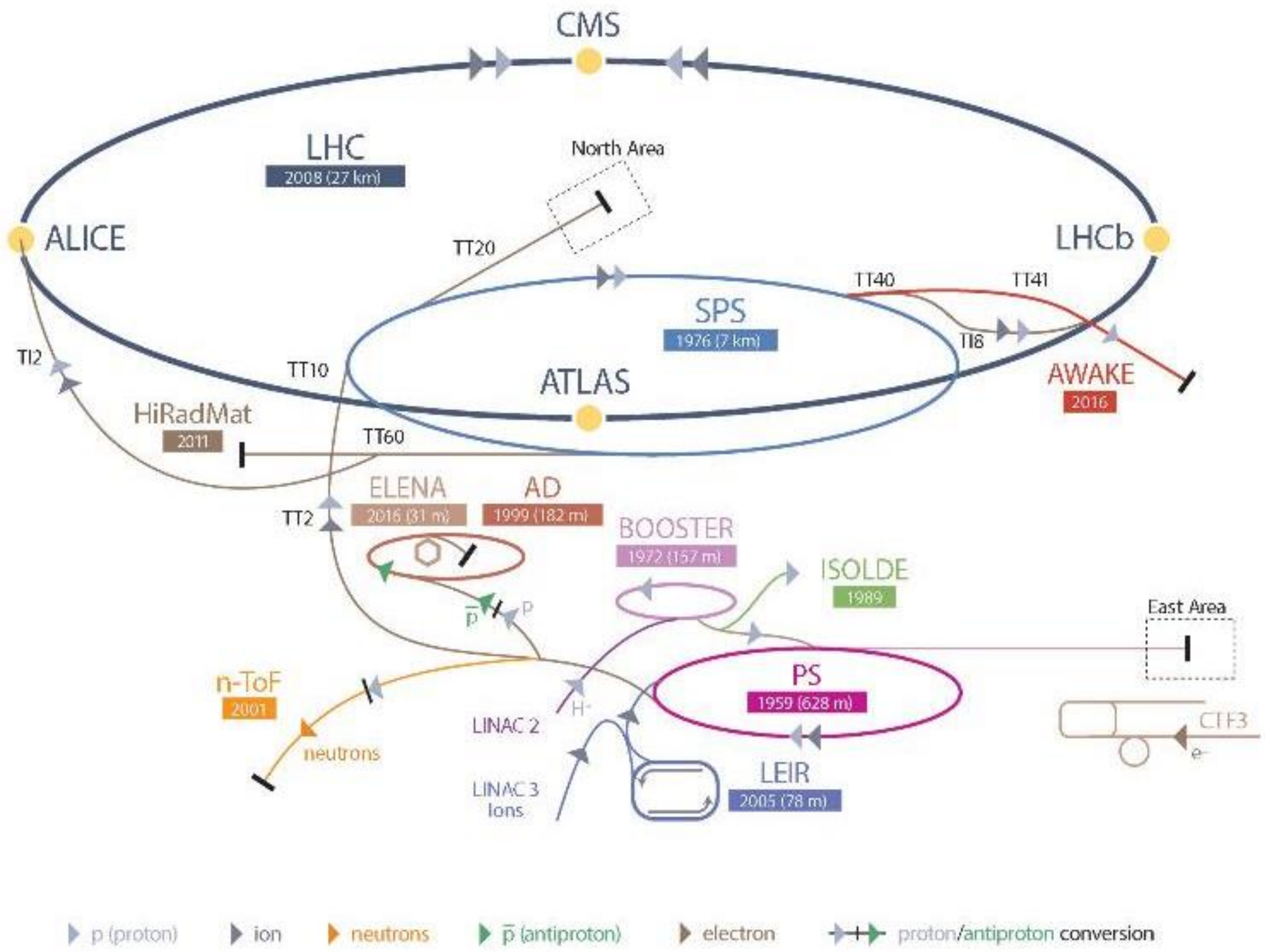
- CERN BI group responsible for instrumentation of LHC complex (Linac, booster, PS, SPS, LHC + transfer lines), experiments (AWAKE, HiRadMAt, ISOLDE) and R&D projects.
- Personnel: more than 100 in 7 sections. Group leader: Rhodri Jones
- Wide range of instruments:
  - Beam position to control location of beam in the accelerator
  - Beam Intensity to measure operational efficiency
  - Beam loss to ensure safe operations
  - Transverse beam profile
  - Longitudinal beam profile

} to optimize operations

# The Large Hadron Collider



# CERN accelerator complex



# AWAKE, the Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN

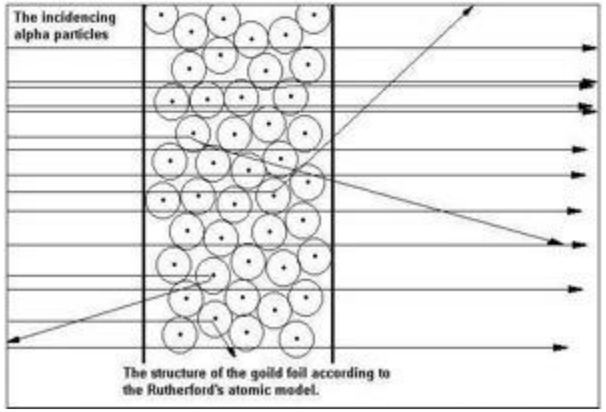
Edda Gschwendtner, CERN
for the AWAKE Collaboration

# Outline

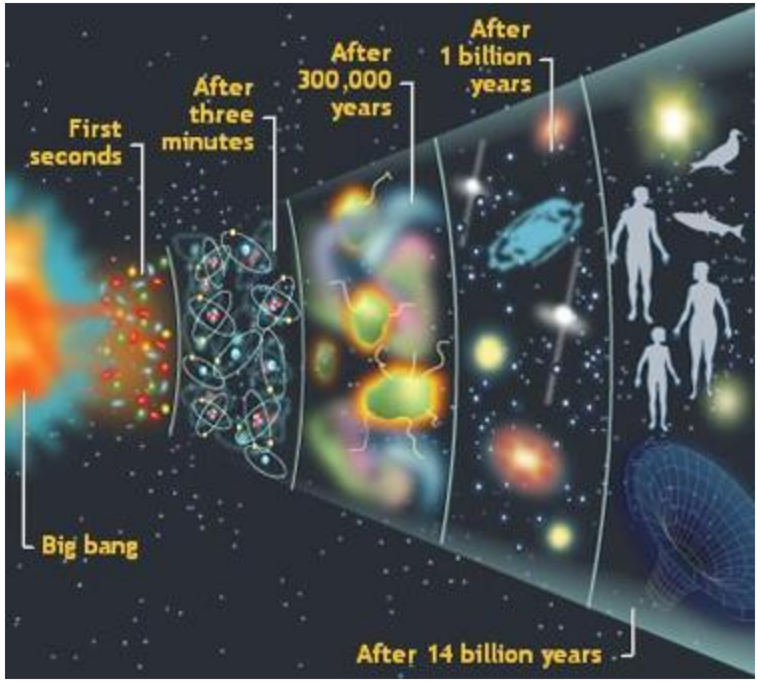
- Motivation
- Plasma Wakefield Acceleration
- AWAKE
- Outlook

# 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

# Circular Collider

Electron/positron colliders:
→ limited by synchrotron radiation

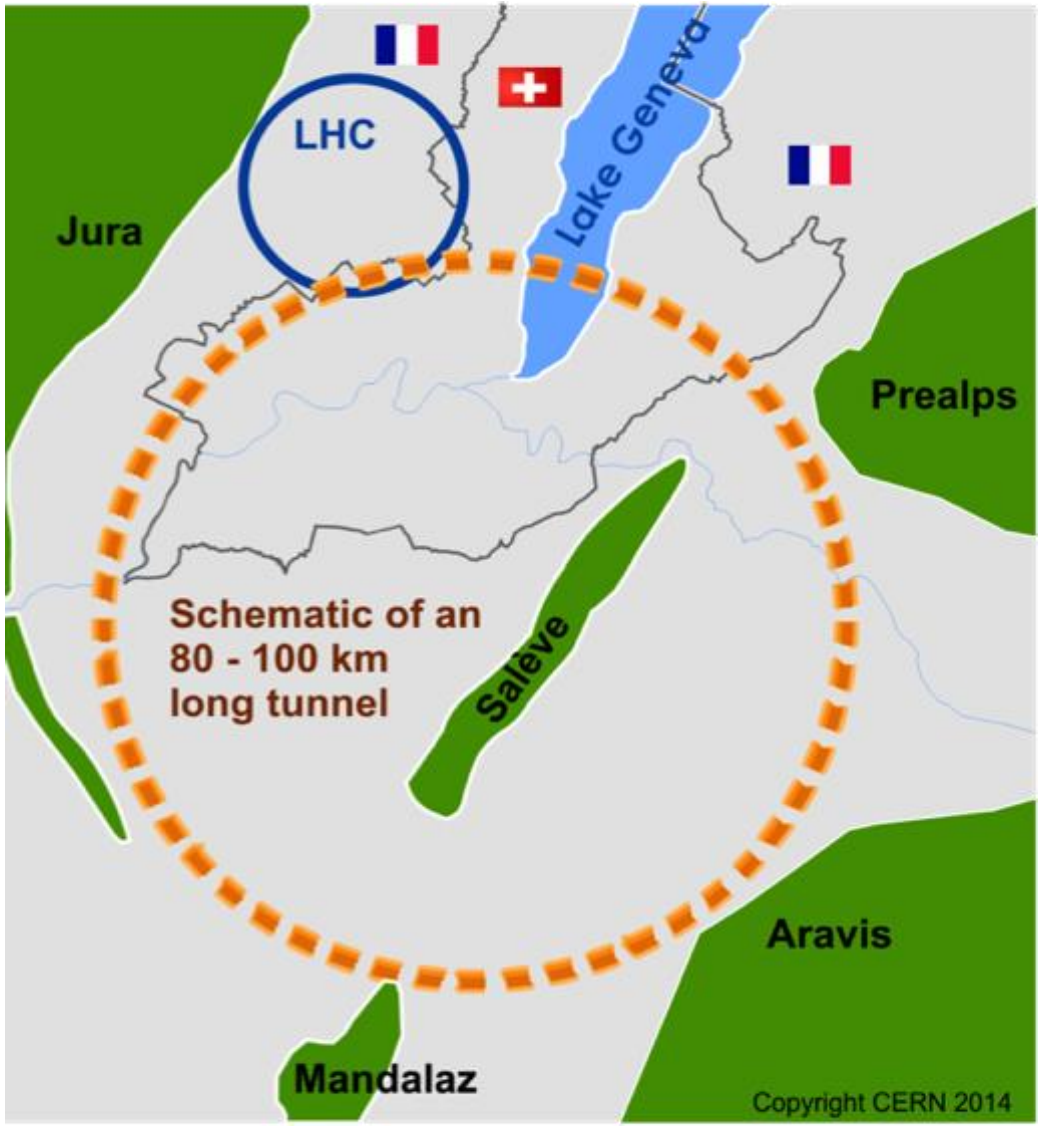
Hadron colliders:
→ limited by magnet strength

## FCC, Future Circular Collider

80 – 100 km diameter

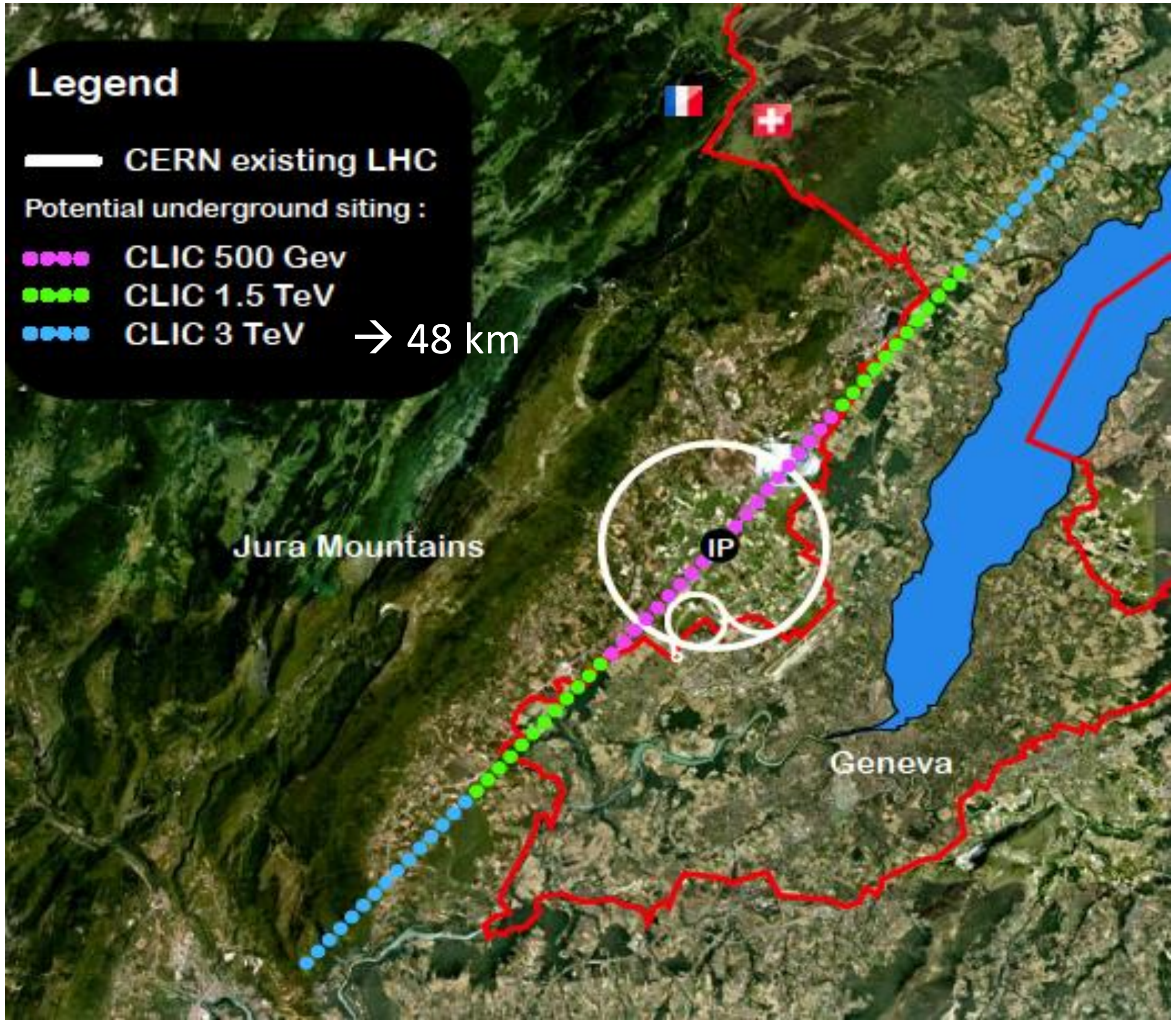
Electron/positron colliders:
→ 350 GeV

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

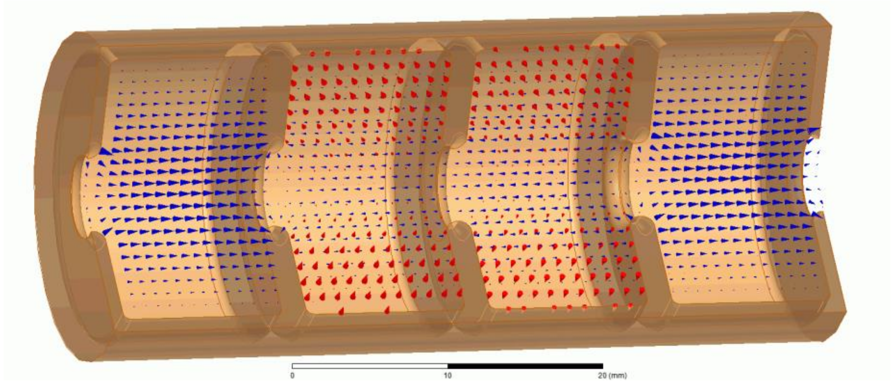
48 km length
3 TeV ($e^+e^-$)

Accelerating elements:
Cavities: 100 MV/m

# Conventional Accelerating Technology

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

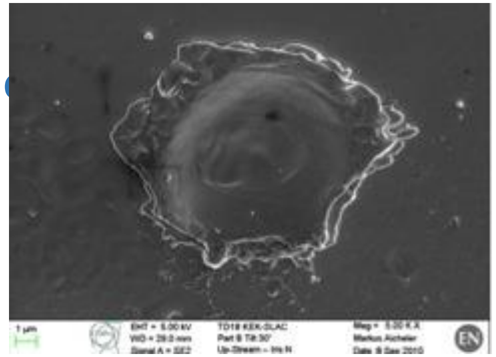
- Very successfully used in all accelerators (hospitals, scientific labs,…) in the last 100 years.



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

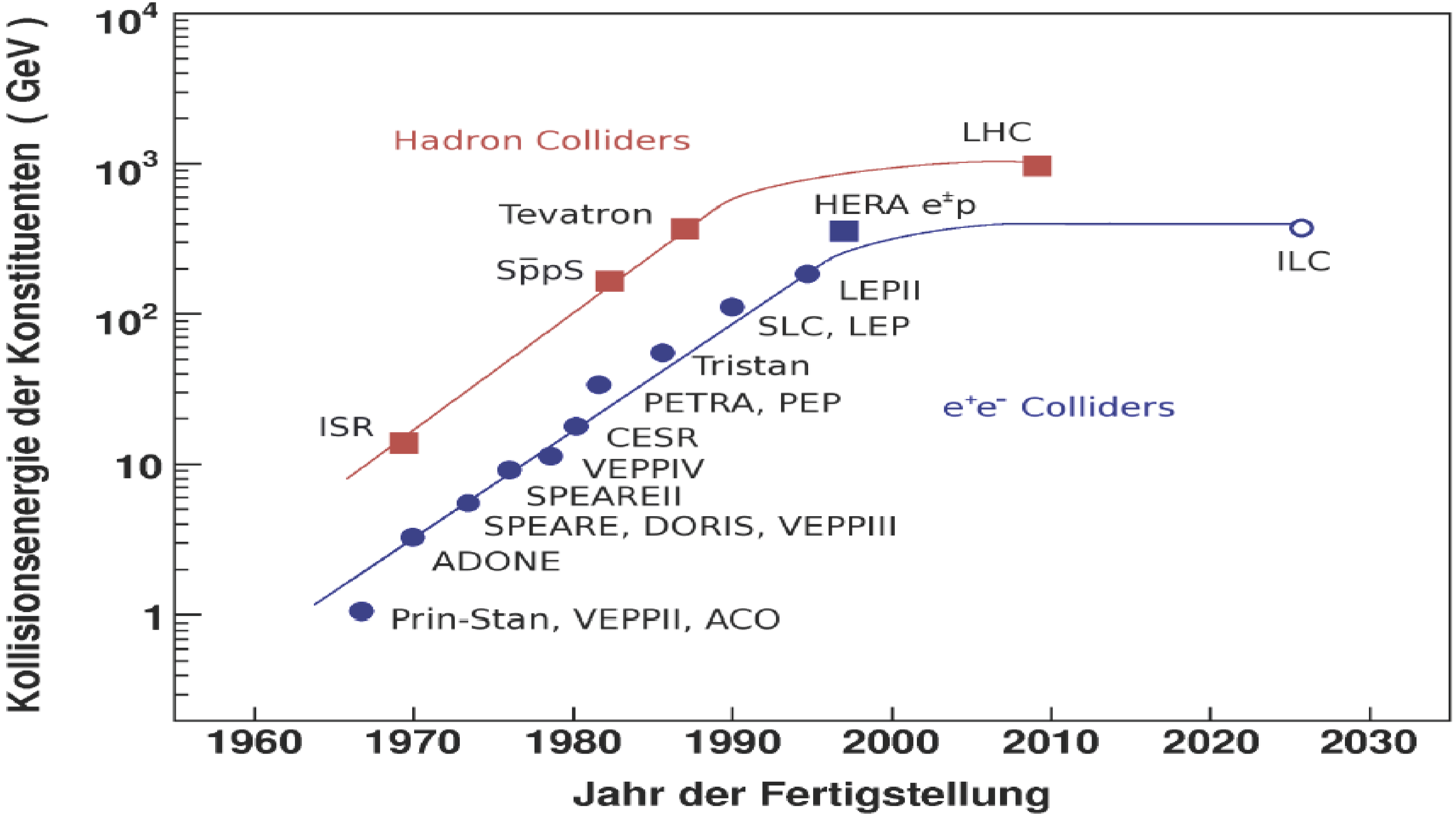
However:

- 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**

# Outline

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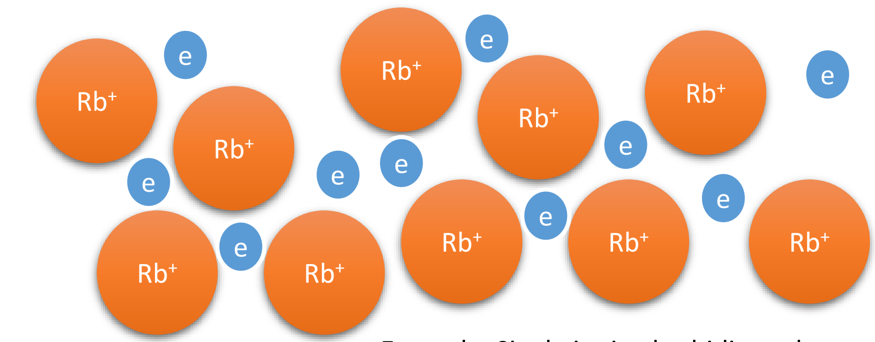
- Plasma Wakefield Acceleration
- AWAKE
- Outlook

# Plasma Wakefield

## What is a plasma?




Example: Single ionized rubidium plasma

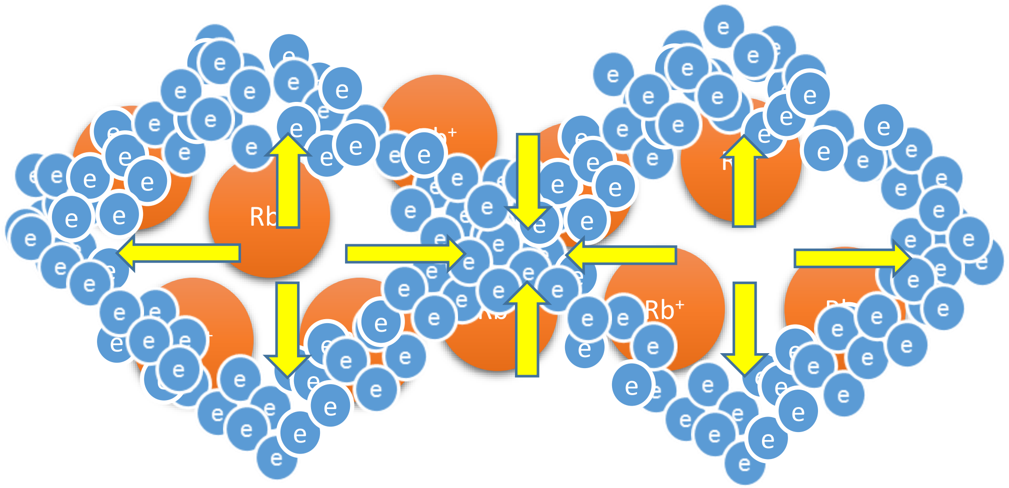
Plasma is already ionized or "broken-down" and can sustain **electric fields up to three orders of magnitude higher gradients** → order of **100 GV/m.**

**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.

# Plasma Baseline Parameters

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

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

**Example: $n_{pe}$ = $7\text{x}10^{14}$ $cm^{-3}$ (AWAKE)** → $\omega_{pe}$ = $1.25\text{x}10^{12}$ rad/s → $\frac{c}{\omega_{pe}}$ **= 0.2mm** → $k_{pe}$ = 5 $mm^{-1}$

- This translates into a wavelength of the plasma oscillation

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

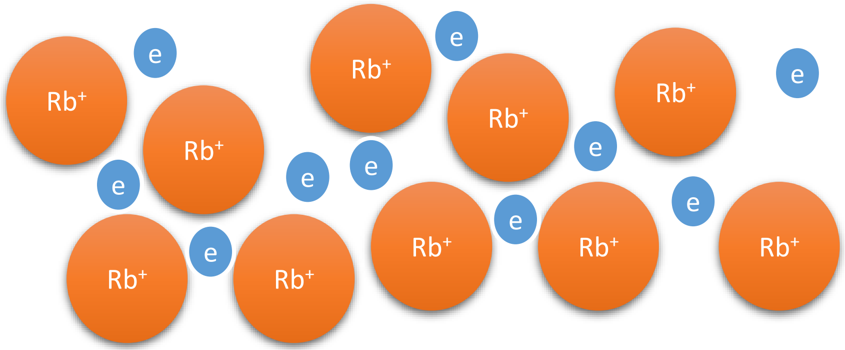
**$\lambda_{pe}$ = 1.2 mm**

→ **Produce cavities with mm size!**

# How to Create a Plasma Wakefield?

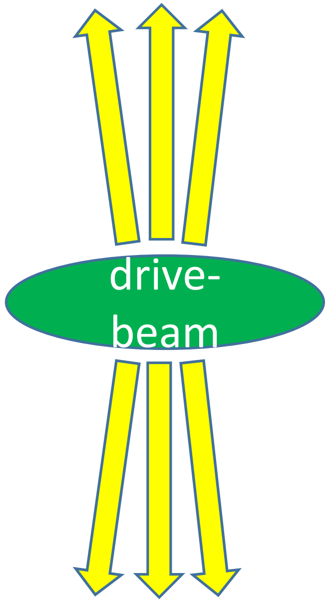
**What we want:**
Longitudinal electric field to accelerate charged particles.


**Our Tool:**



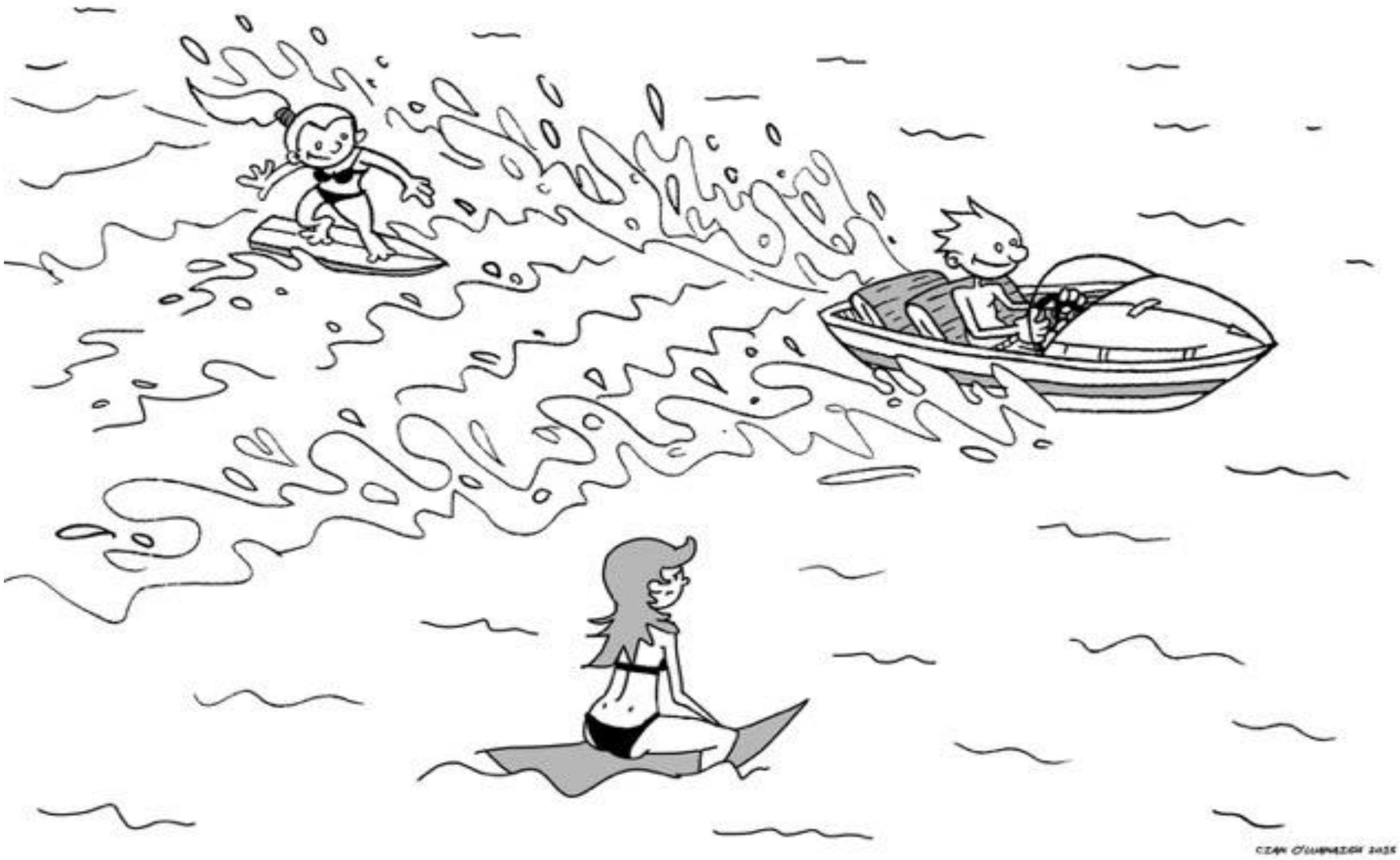

Single ionized rubidium **plasma**

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



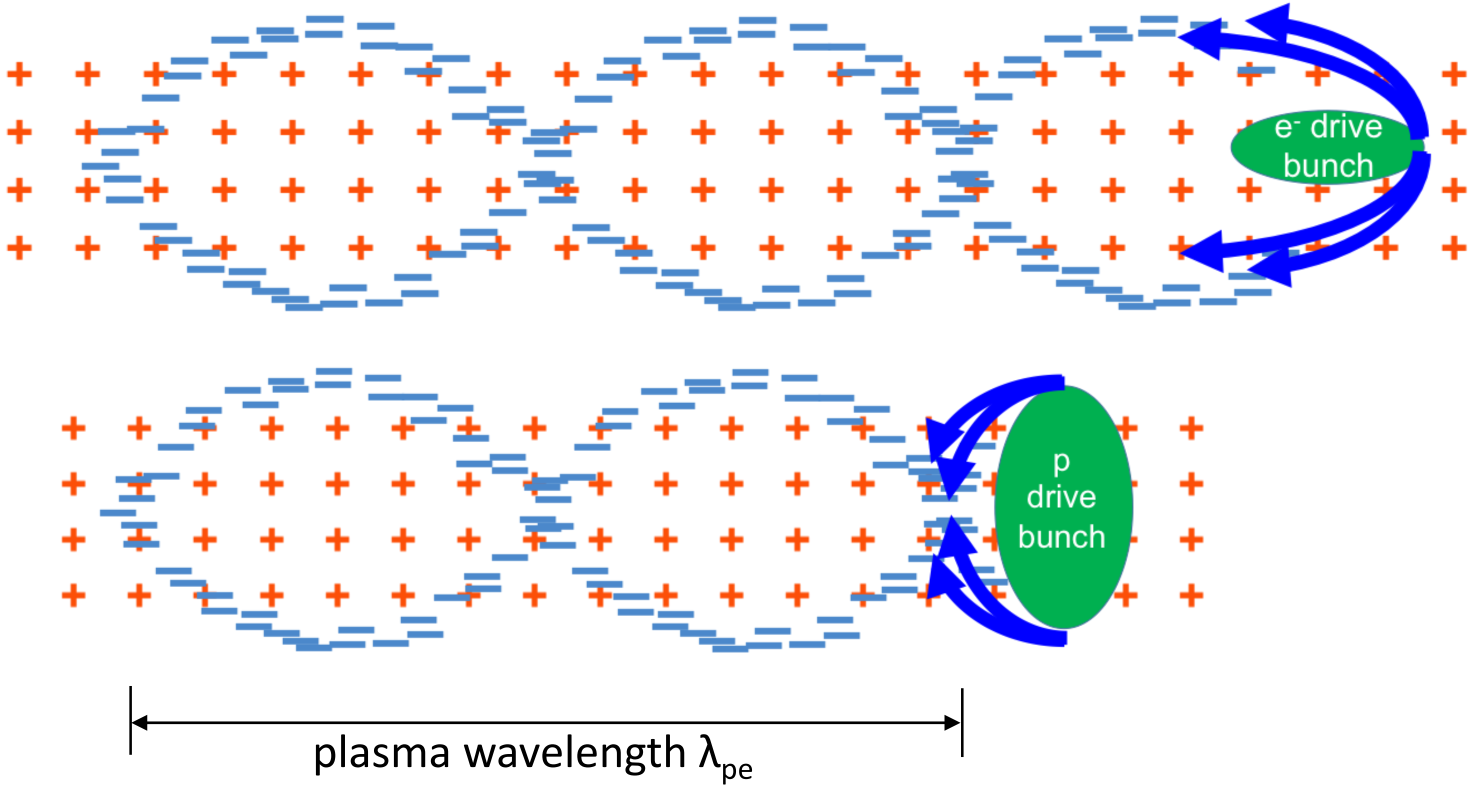

Using plasma to convert **the transverse electric field** of the drive bunch into a **longitudinal electric field in the plasma.** The more energy is available, the longer (distance-wise) these plasma wakefields can be driven.

# How to Create a Plasma Wakefield?



# Principle of Plasma Wakefield Acceleration

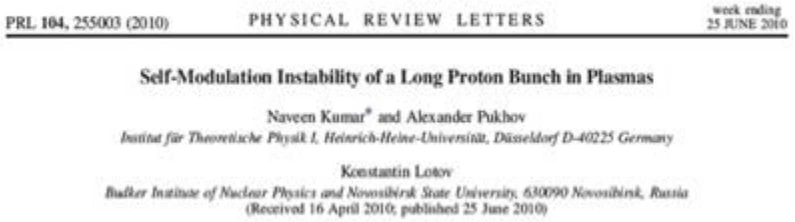
- **Laser drive beam**
  - ➔ Ponderomotive force
- **Charged particle drive beam**
  - ➔ Transverse space charge field
  - Reverses sign for negatively (blow-out) or positively (suck-in) charged beam




- 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

# 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)**

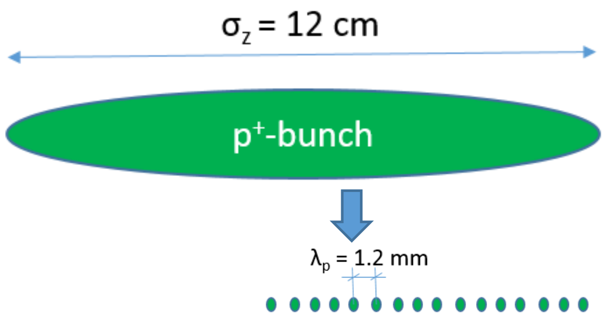

PRL 104, 255003 (2010) PHYSICAL REVIEW LETTERS week ending 25 JUNE 2010

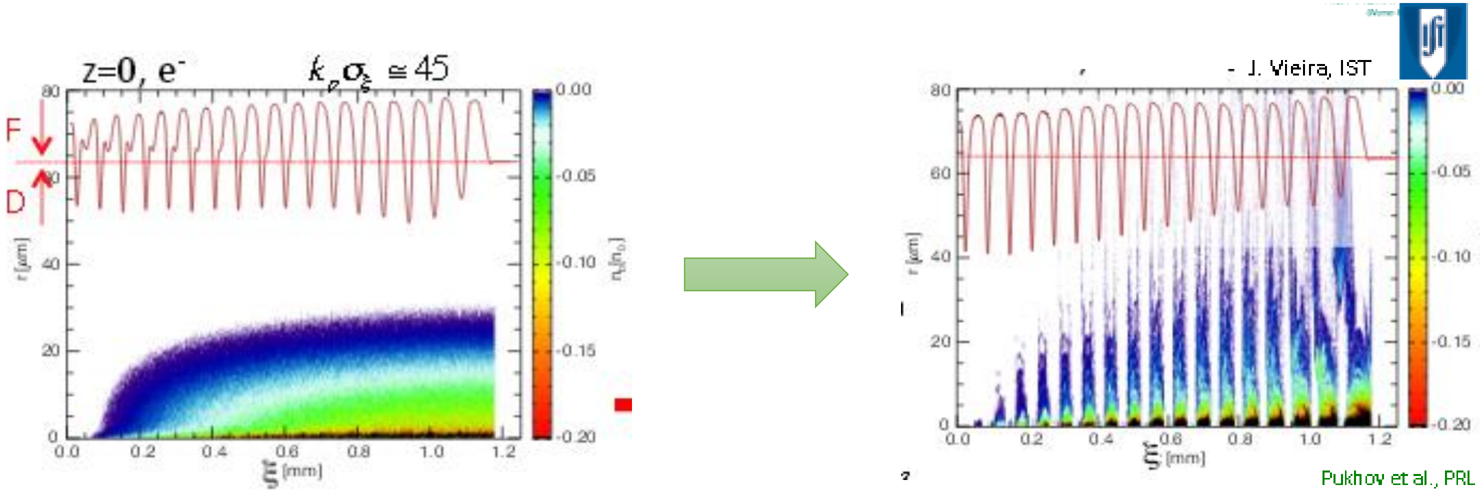
**Self-Modulation Instability of a Long Proton Bunch in Plasmas**

Naveen Kumar* and Alexander Pukhov
*Institut für Theoretische Physik I, Heinrich-Heine-Universität, Düsseldorf D-40225 Germany*
Konstantin Lotov
*Budker Institute of Nuclear Physics and Novosibirsk State University, 630090 Novosibirsk, Russia*
(Received 16 April 2010; published 25 June 2010)

## Self-Modulation Instability

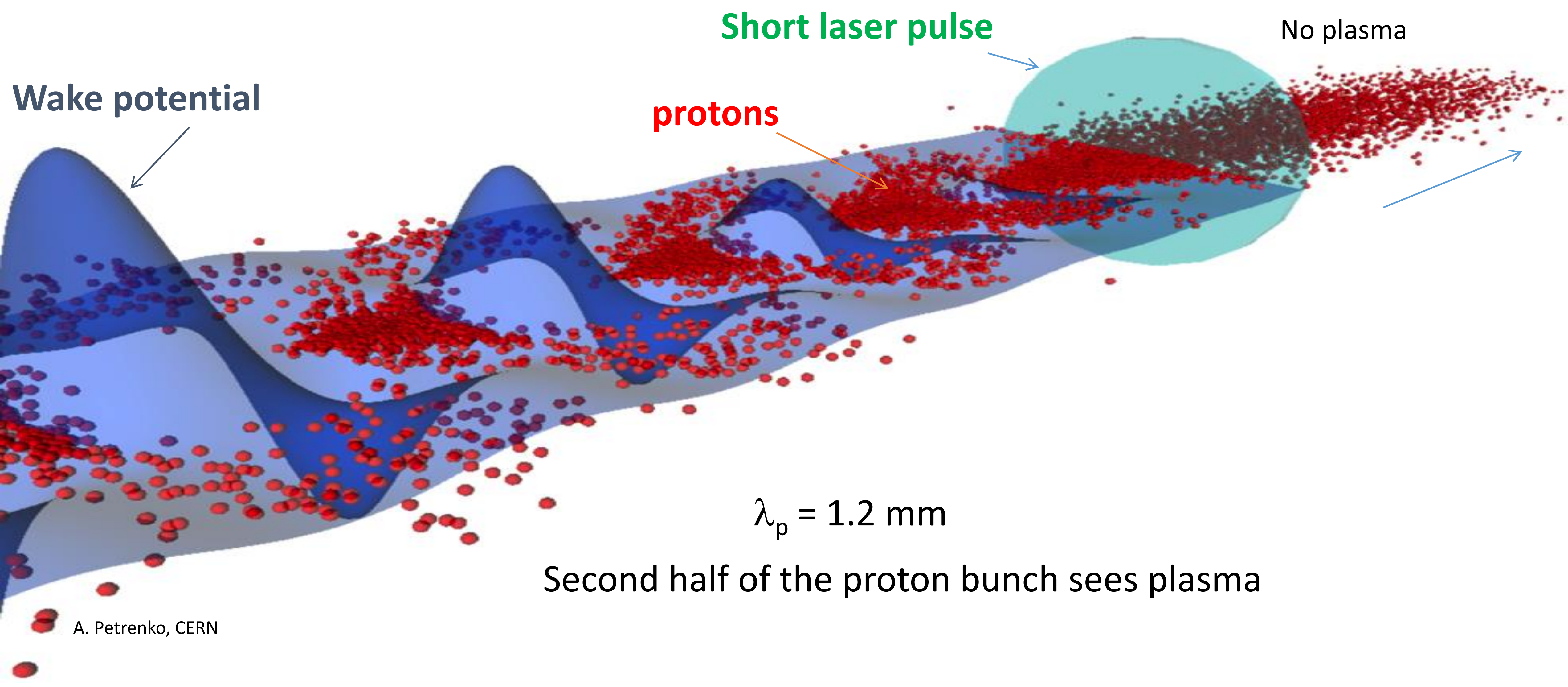
- Modulate long bunch to produce a series **of 'micro-bunches' in a plasma with a spacing of plasma wavelength $\lambda_p$.**
  →Strong self-modulation effect of proton beam due to transverse wakefield in plasma
  →**Resonantly drives the longitudinal wakefield**




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

# Seeded Self-Modulation of a Long Proton Bunch in Plasma




$\lambda_p = 1.2$ mm

Second half of the proton bunch sees plasma

A. Petrenko, CERN

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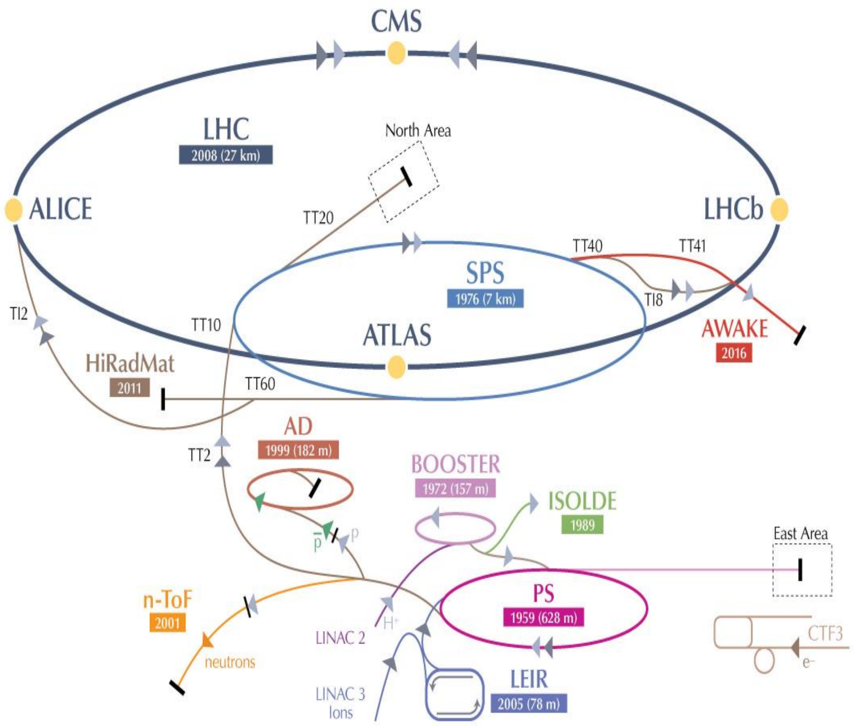
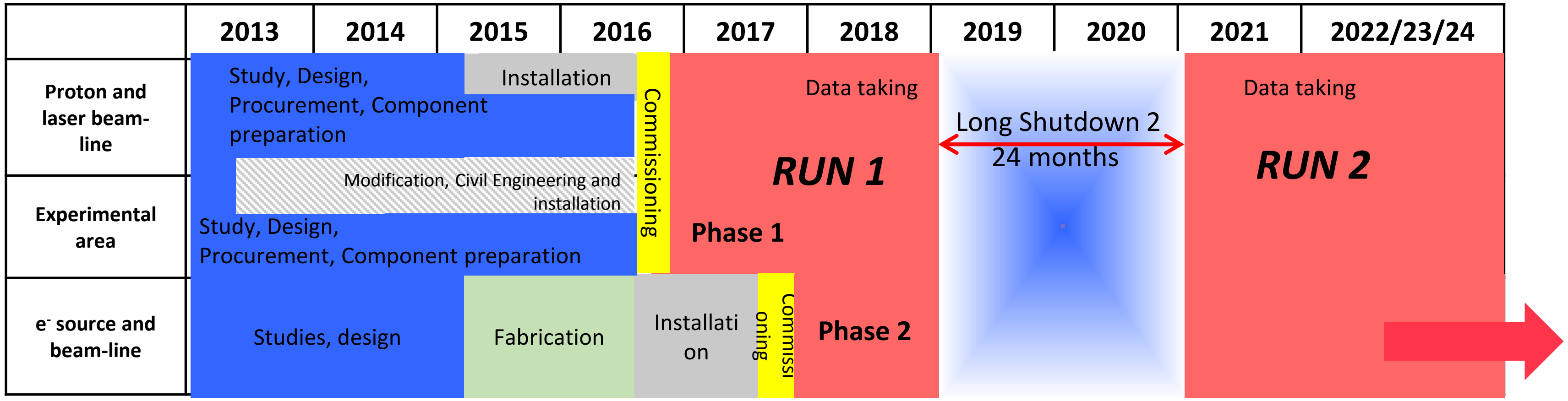
# AWAKE at CERN




**Advanced Proton Driven Plasma Wakefield Acceleration Experiment**

- Proof-of-Principle Accelerator R&D experiment at CERN
- Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.
- AWAKE Collaboration: 16 institutes + 3 associate

- Approved in August 2013
- First beam end 2016

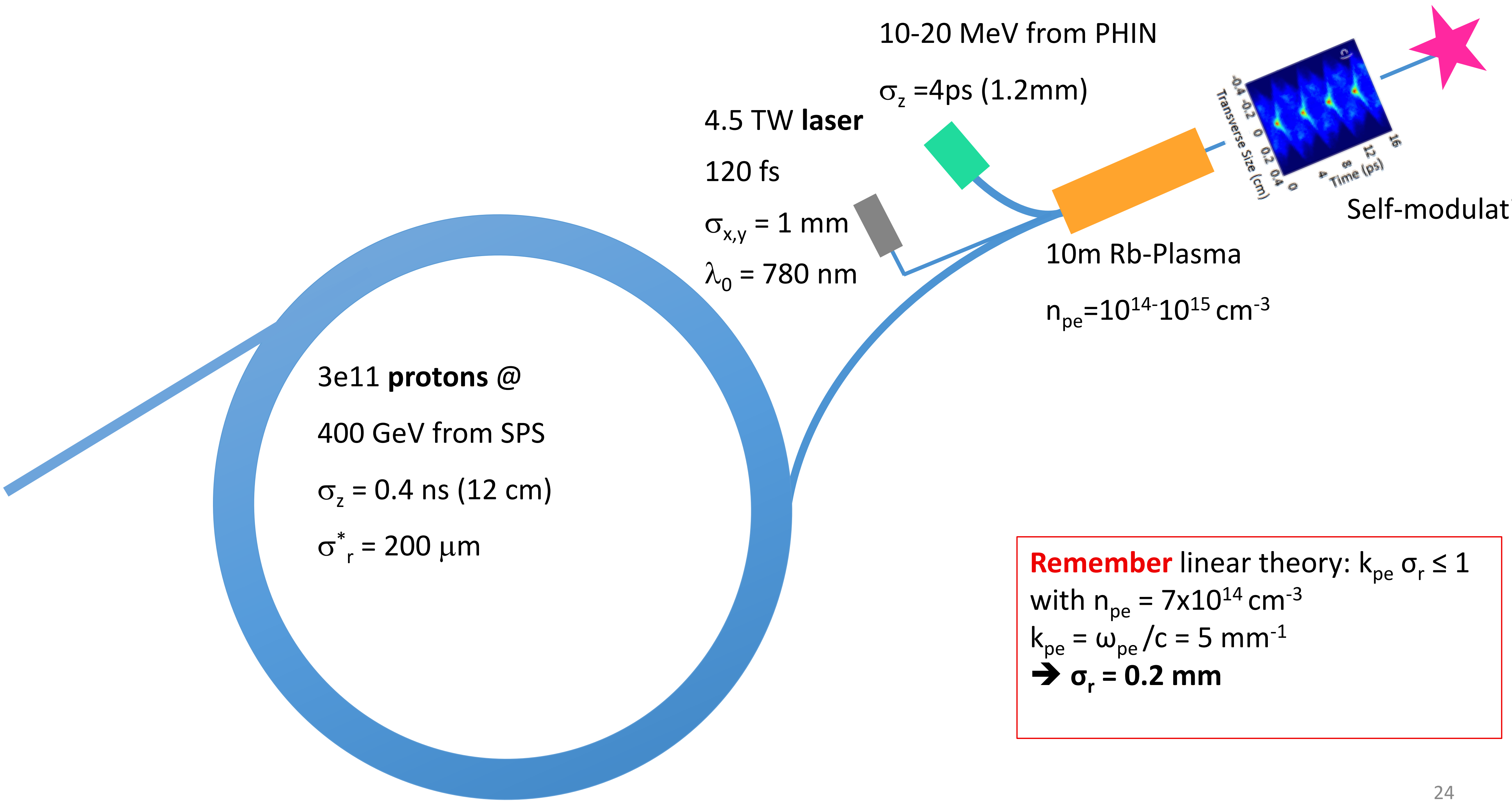



Run 1 – until LS2 of the LHC.

After LS2 – proposing Run 2 of AWAKE (during Run 3 of LHC)

After Run 2 – kick off particle physics driven applications

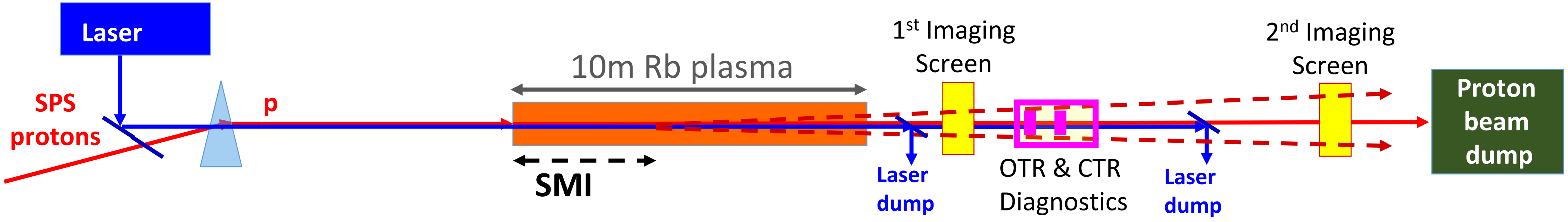
# The AWAKE Facility



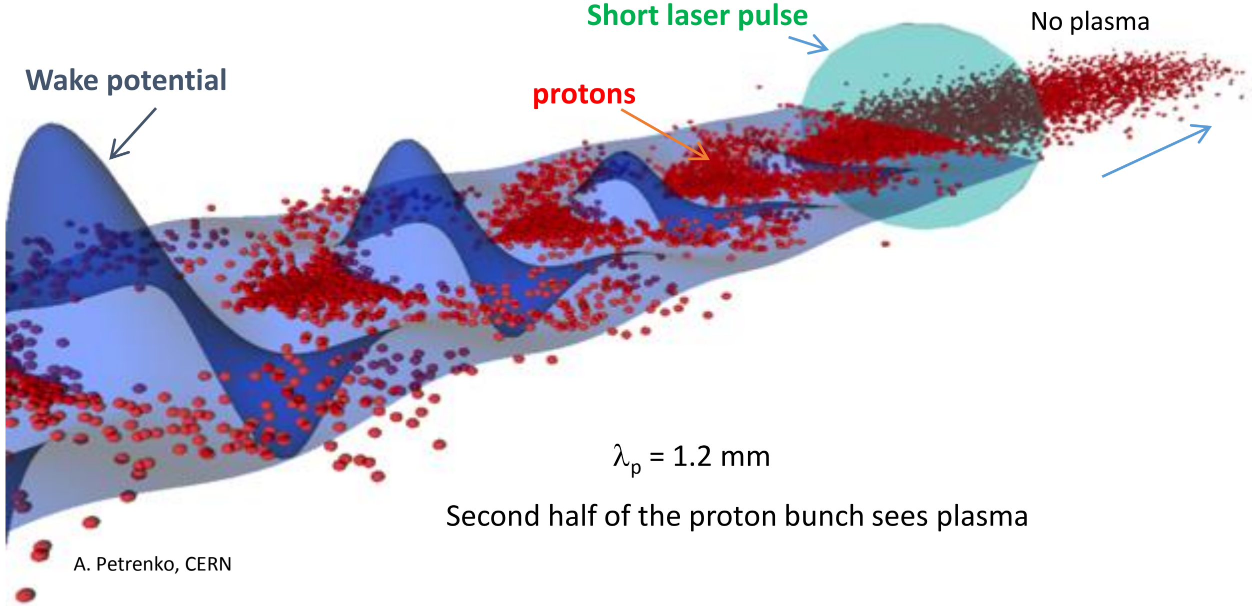

**Remember** linear theory: $k_{pe}\,\sigma_r \leq 1$
with $n_{pe} = 7\text{x}10^{14}$ cm$^{-3}$
$k_{pe} = \omega_{pe}/c$ = 5 mm$^{-1}$
➔ $\boldsymbol{\sigma_r}$ **= 0.2 mm**

# First Experiment: Seeded Self-Modulation

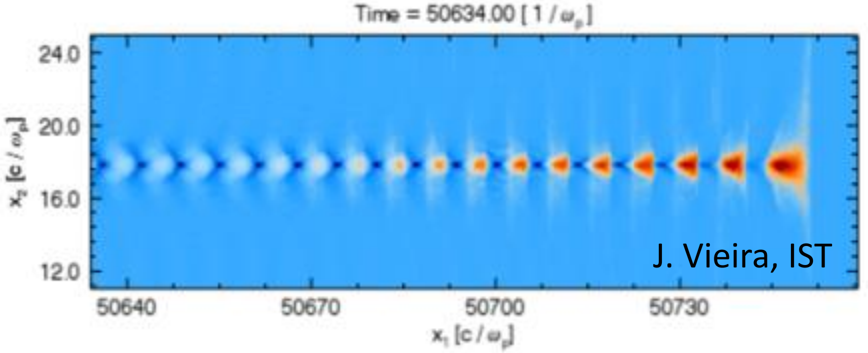
Phase 1: 2016/17: Understand **the physics of the seeded self-modulation** processes in plasma.




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

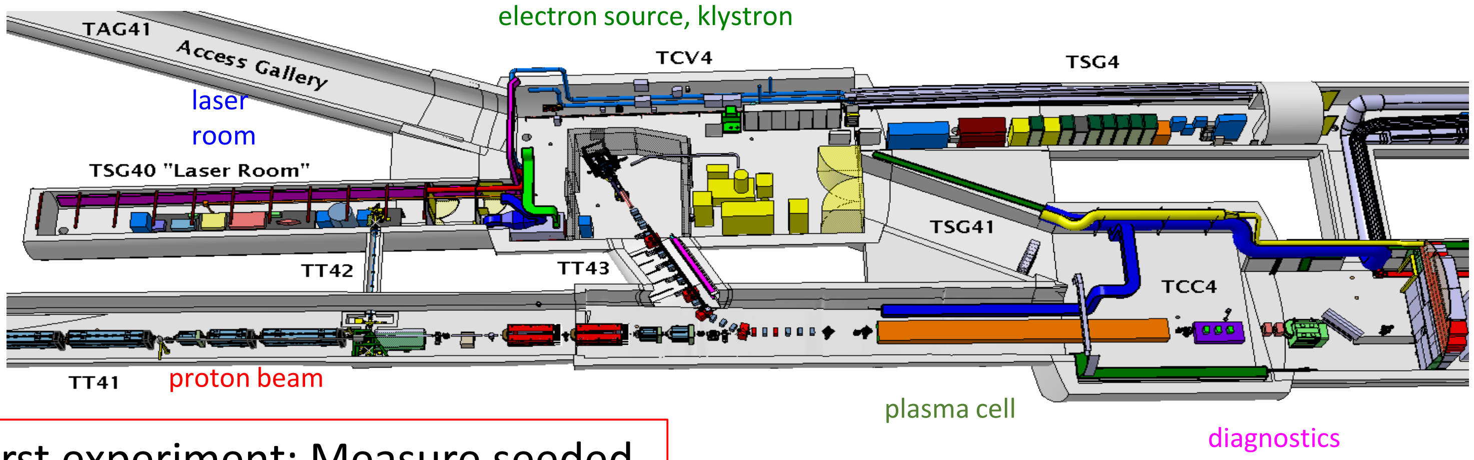



What we want to see in the diagnostics:

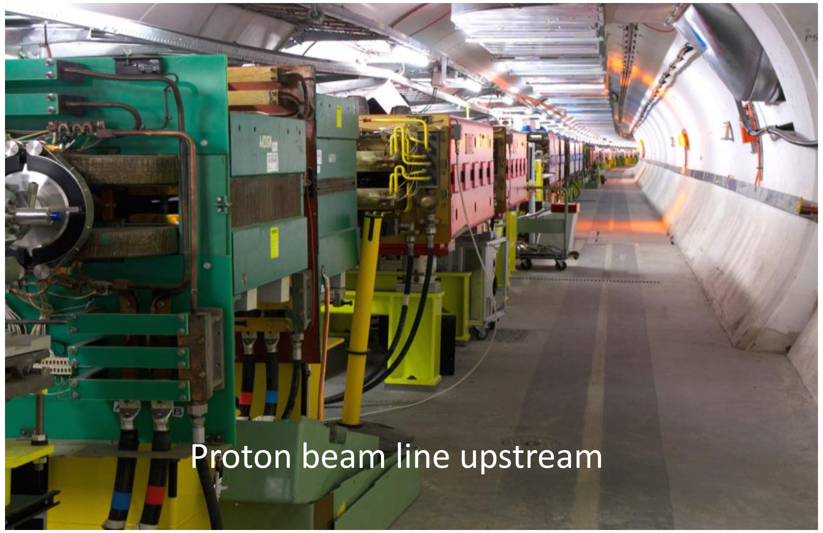


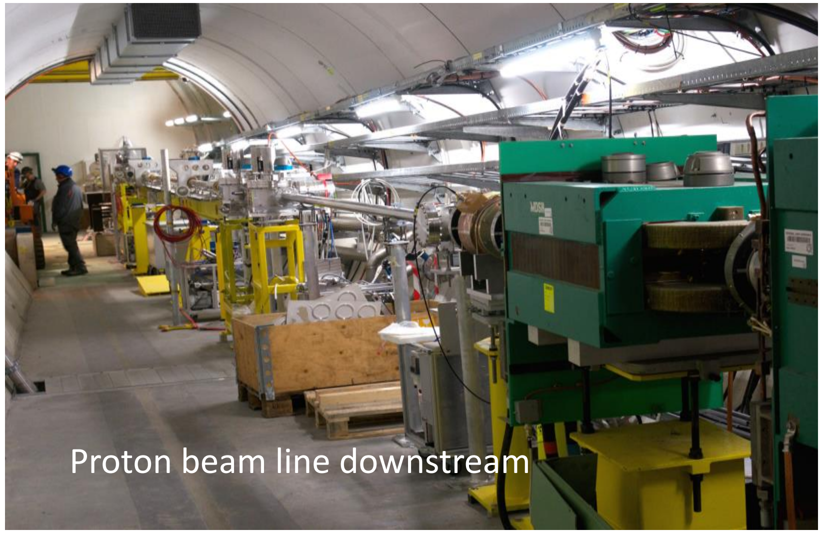
# AWAKE Proton Beam Line

| 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 |



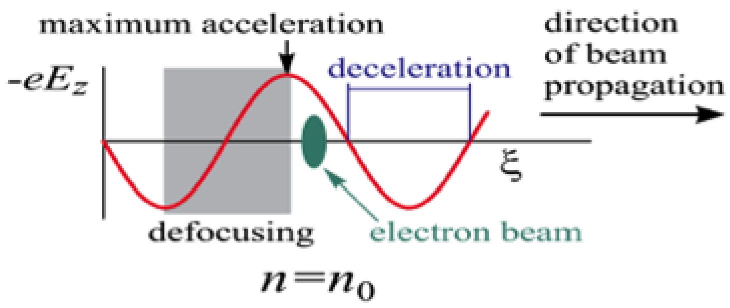

First experiment: Measure seeded self-modulation!

# The AWAKE Plasma Cell

F. Batsch, F. Braunmueller, E. Oez, P. Muggli, (MPP, Munich)
R. Kerservan (CERN), G. Plyushchev (EPFL)




→10 m long, 4 cm diameter

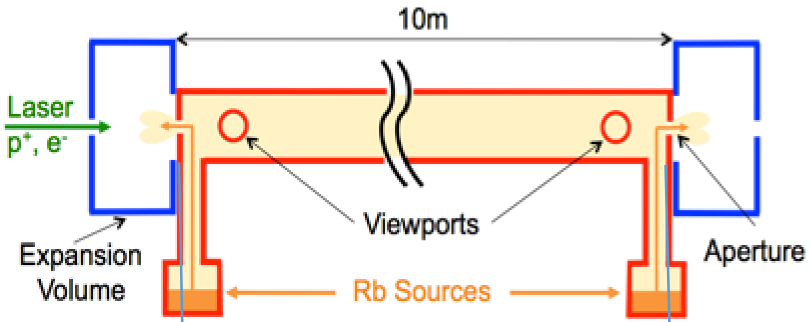
→Rubidium vapor

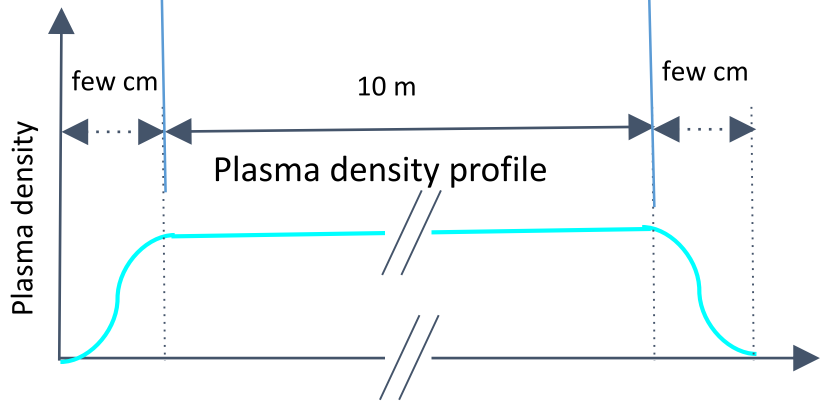
→Laser field ionization: threshold ~$10^{12}$ W/cm$^2$

→Rb density measured with 0.3% accuracy using white light interferometry

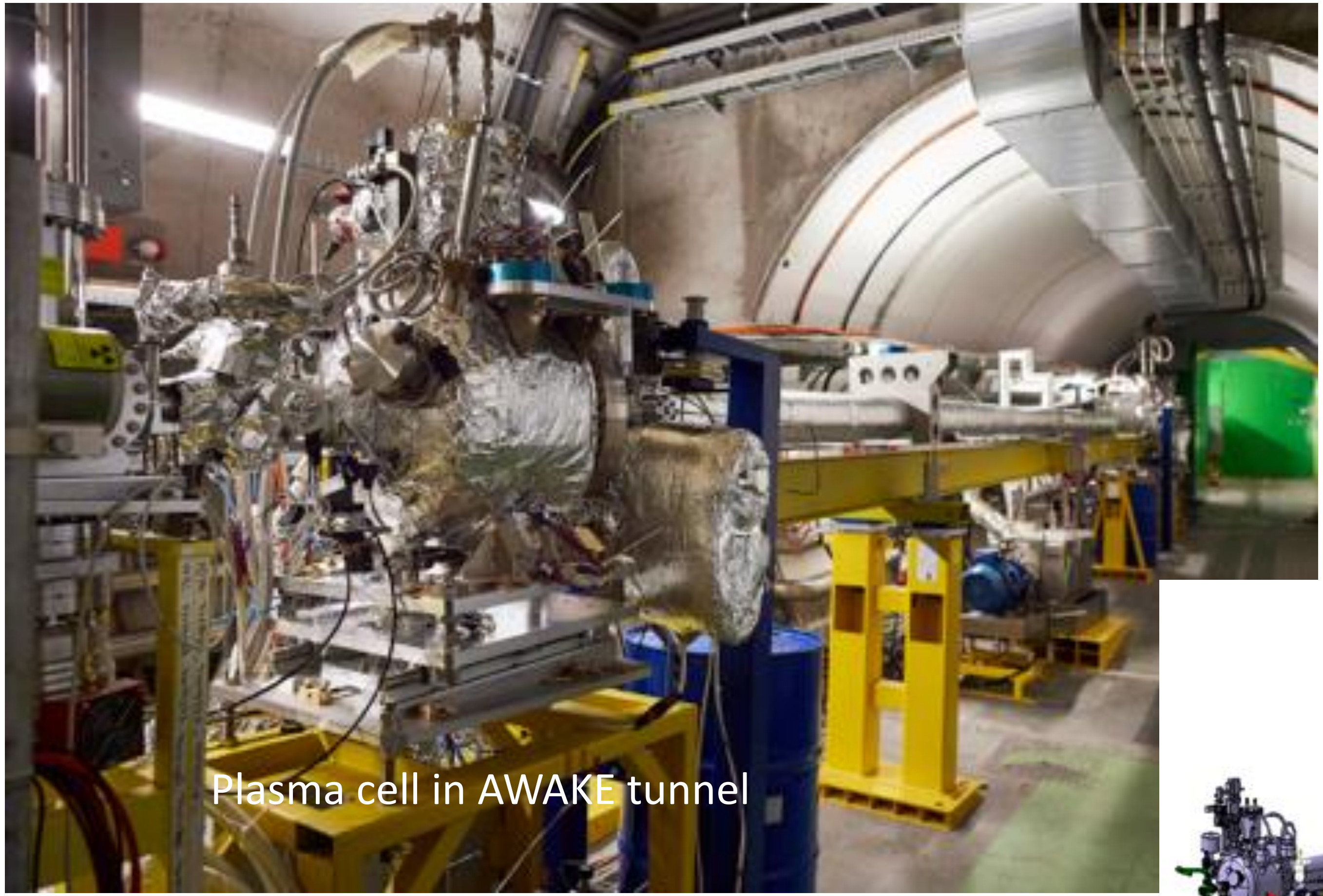
**Requirements:**

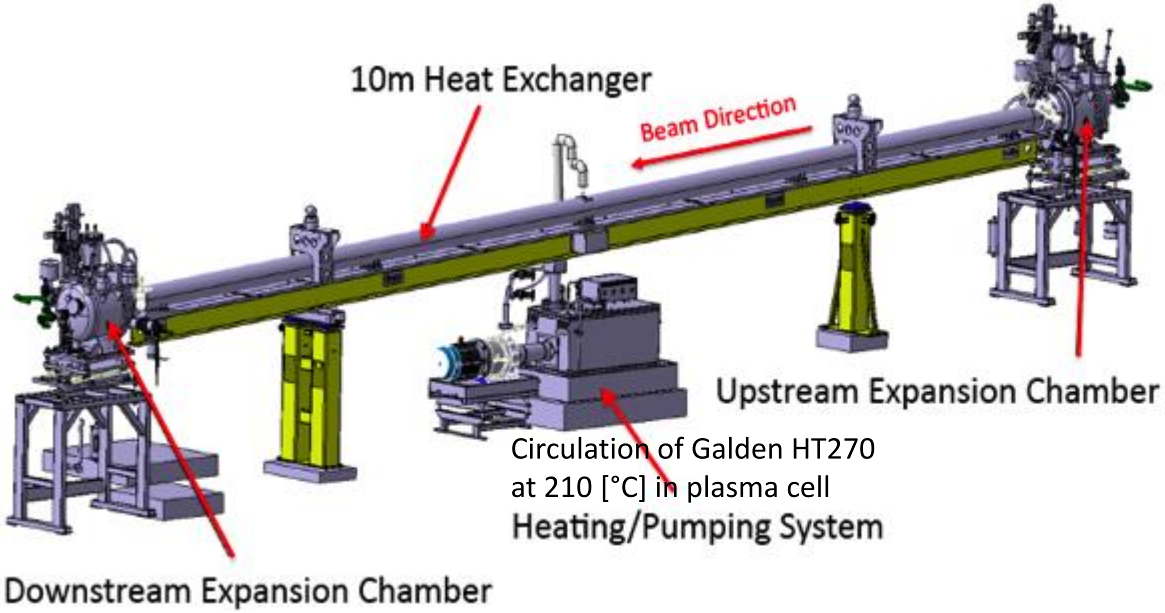
- Density adjustable from $10^{14}$ – $10^{15}$ cm$^{-3}$ (7x$10^{14}$ cm$^{-3}$)
- $\Delta n_e/n_e$ density uniformity better than 0.2%
  - Impose very uniform T: → Fluid-heated system (~220 deg)
  - Complex control system: 79 Temperature probes, valves → measured ΔT/T ~0.1%
- few cm $n_e$ ramp: transition between plasma and vacuum as sharp as possible
  - Rb vapor expands into vacuum and sticks to cold walls
  - Scale length ~ diameter aperture: 1cm



# The AWAKE Plasma Cell



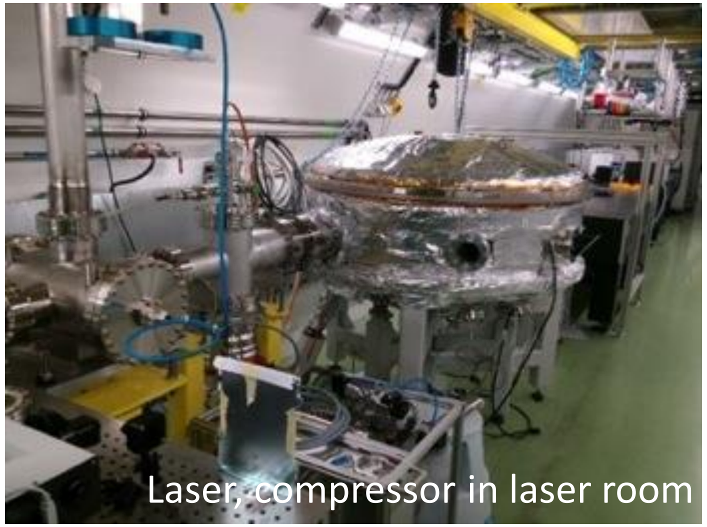



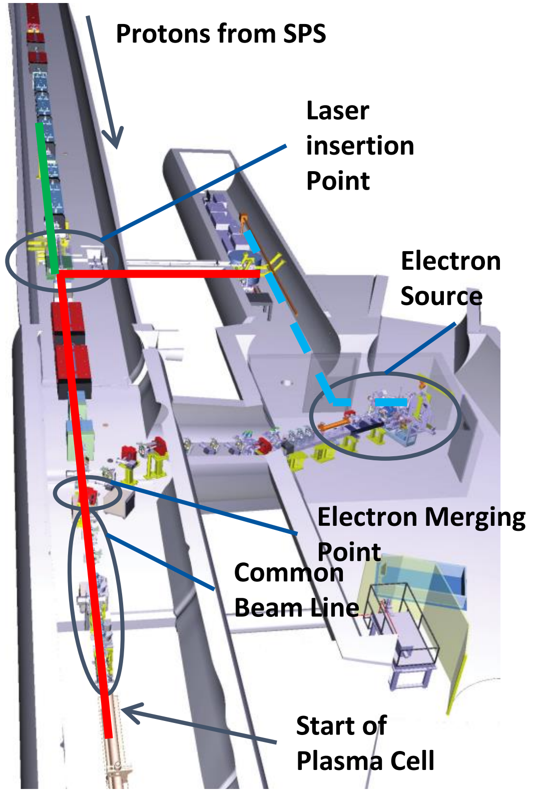
# Laser and Laser Line

V. Fedosseev, F. Friebel, CERN
J. Moody, M. Huether, A. Bachmann, MTP

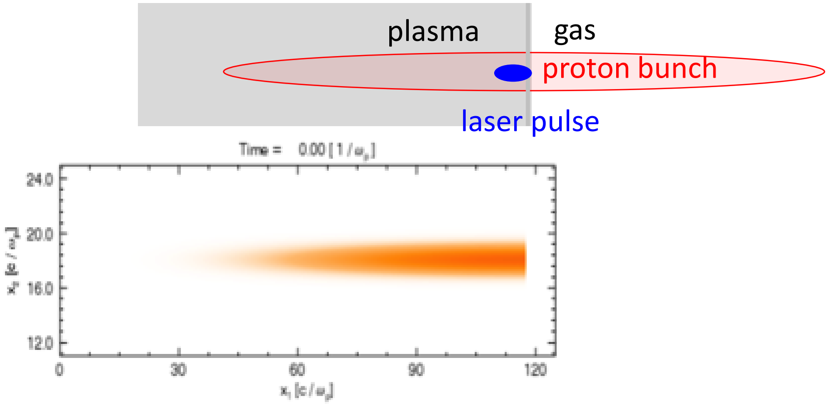
**Fiber/Ti-Sapphire laser**

- **Laser beam line to plasma cell**
  - $\lambda$ = 780 nm, $t_{pulse}$ = 100-120 fs, E = 450 mJ
- Diagnostic beam line ("virtual plasma")
- *Laser beam line to electron gun (installed in 2017)*

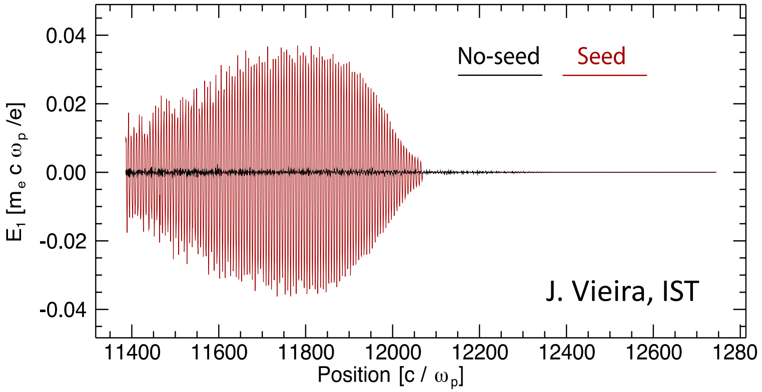


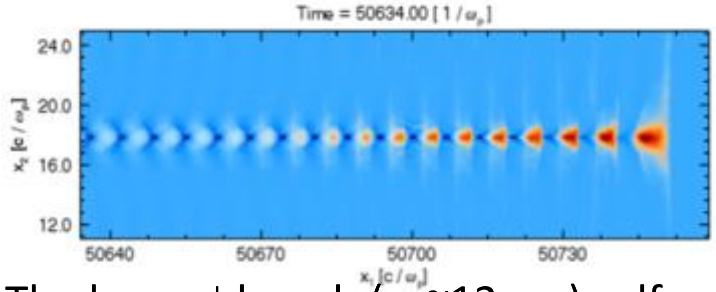

**→ Short laser pulse creates the plasma, which seeds the self-modulation**




Sharp start of beam/plasma interaction
→ Seeding with ionization front




No seed no SM (over 10m)

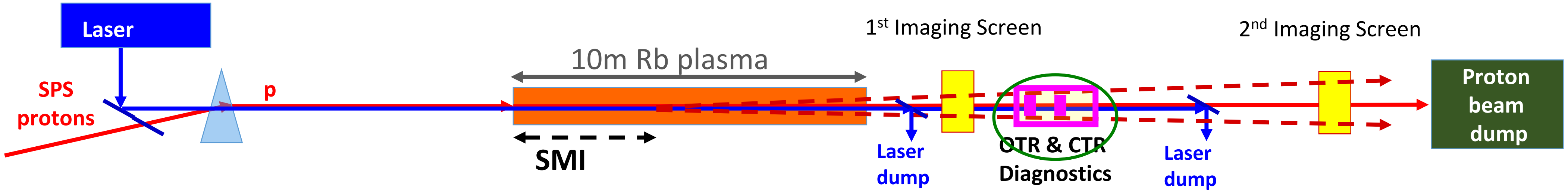



The long $p^+$ bunch ($\sigma_z$~12cm ) self modulates with period $\lambda_{pe}$~1.2mm,
→ $100\lambda_{pe}$ per $\sigma_z$

# Outline

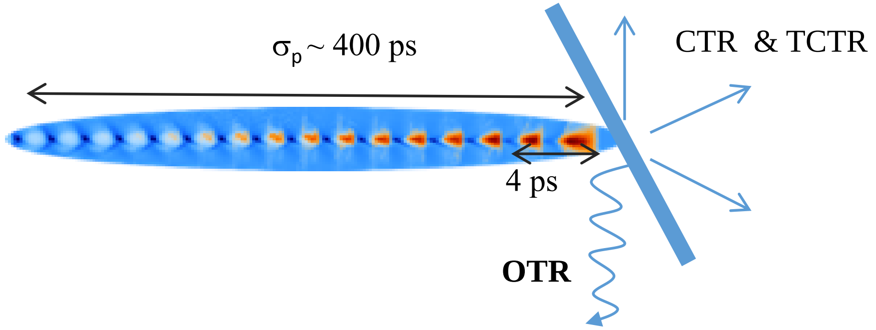
- Motivation
- Plasma Wakefield Acceleration
- AWAKE → First Results
- Outlook

# Seeded Self-Modulation Diagnostics I



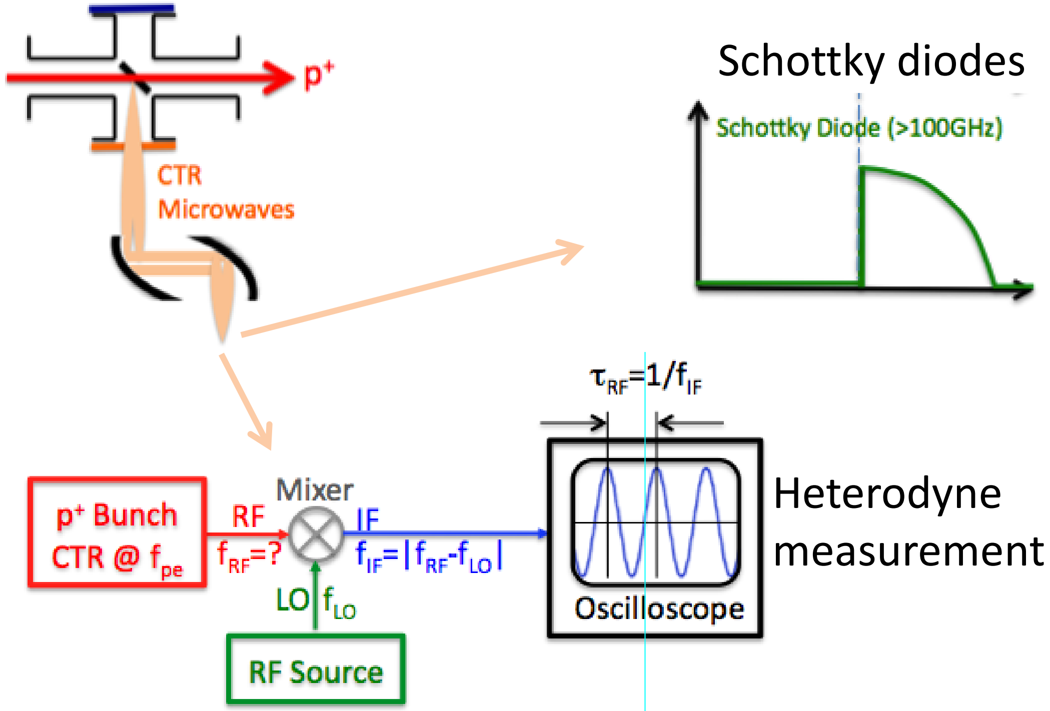

**Direct SSM diagnostic: Measure frequency of modulation.**

**OTR: Optical Transition Radiation:** Temporal intensity of the OTR carries information on bunch longitudinal structure.

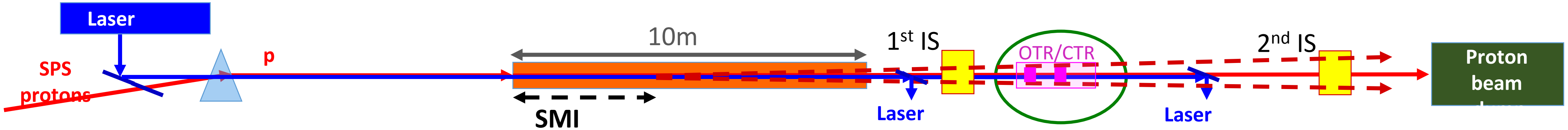



Streak Camera

**CTR: Coherent Transition Radiation:** Radiation is coherent for wavelengths bigger than the structure of the micro-bunches (90-300GHz).



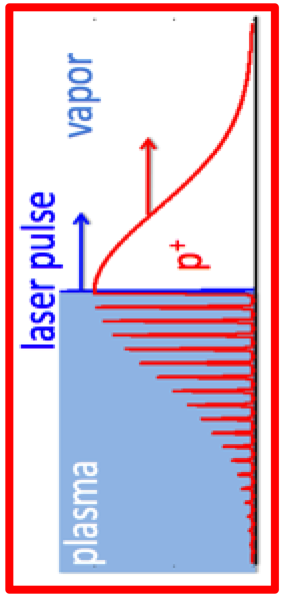
# Direct Seeded Self-Modulation Results

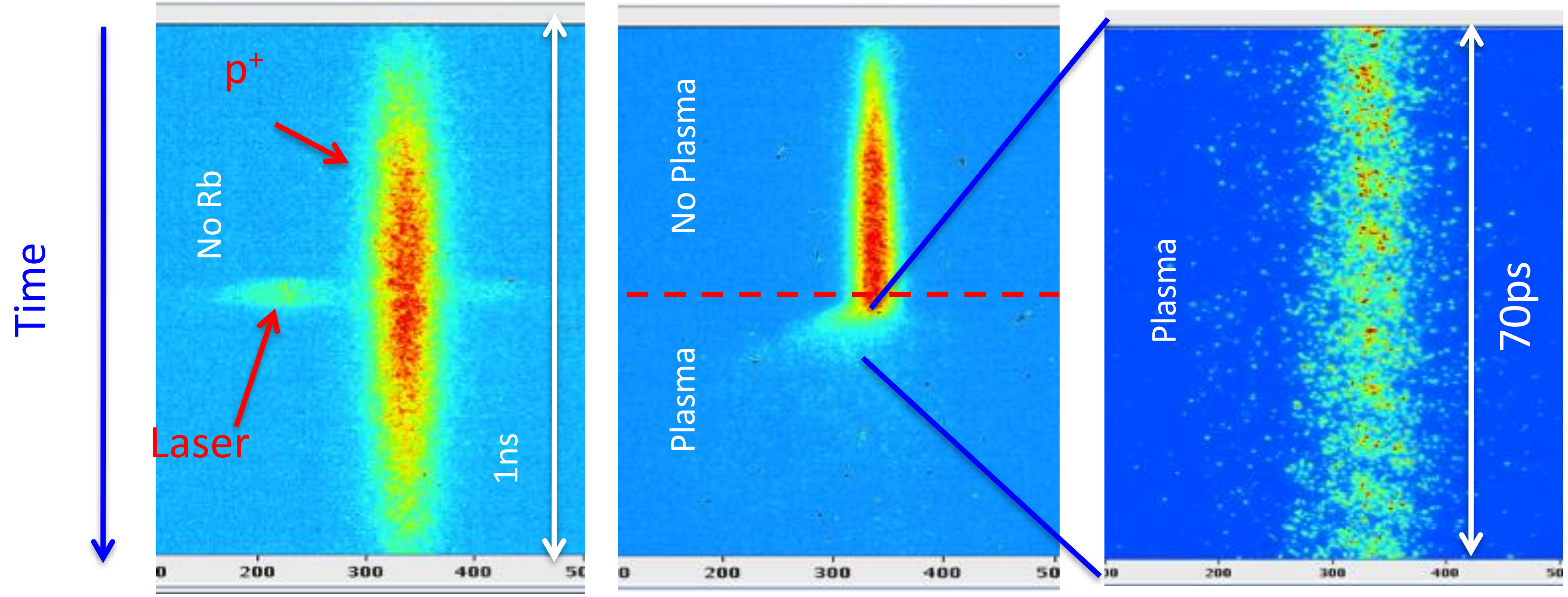



K. Rieger, MPP

OTR

Streak camera Images



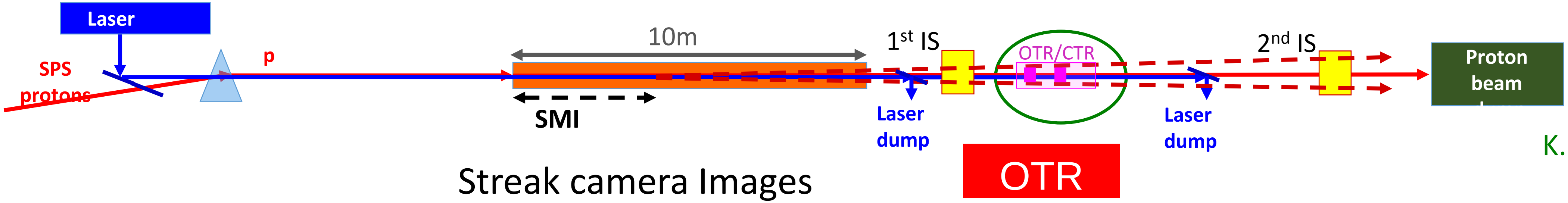

Preliminary!!!

$n_{Rb}=3.7\text{x}10^{14}\text{cm}^{-3}$
→ $\lambda_{Rb\text{-}plasma}$ = 1.8 mm
→ $f_{mod}$~164 GHz

$N_{protons}=3\text{x}10^{11}$

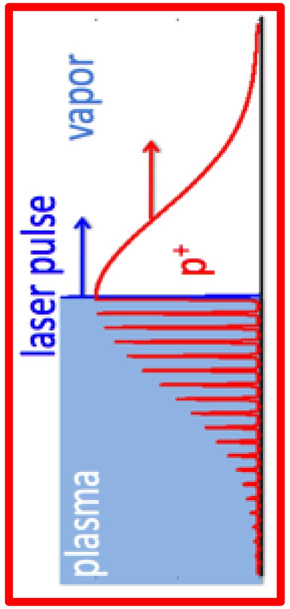
→ Timing at the ps scale
→ Effect starts at laser timing → SM seeding
→ Density modulation at the ps-scale visible

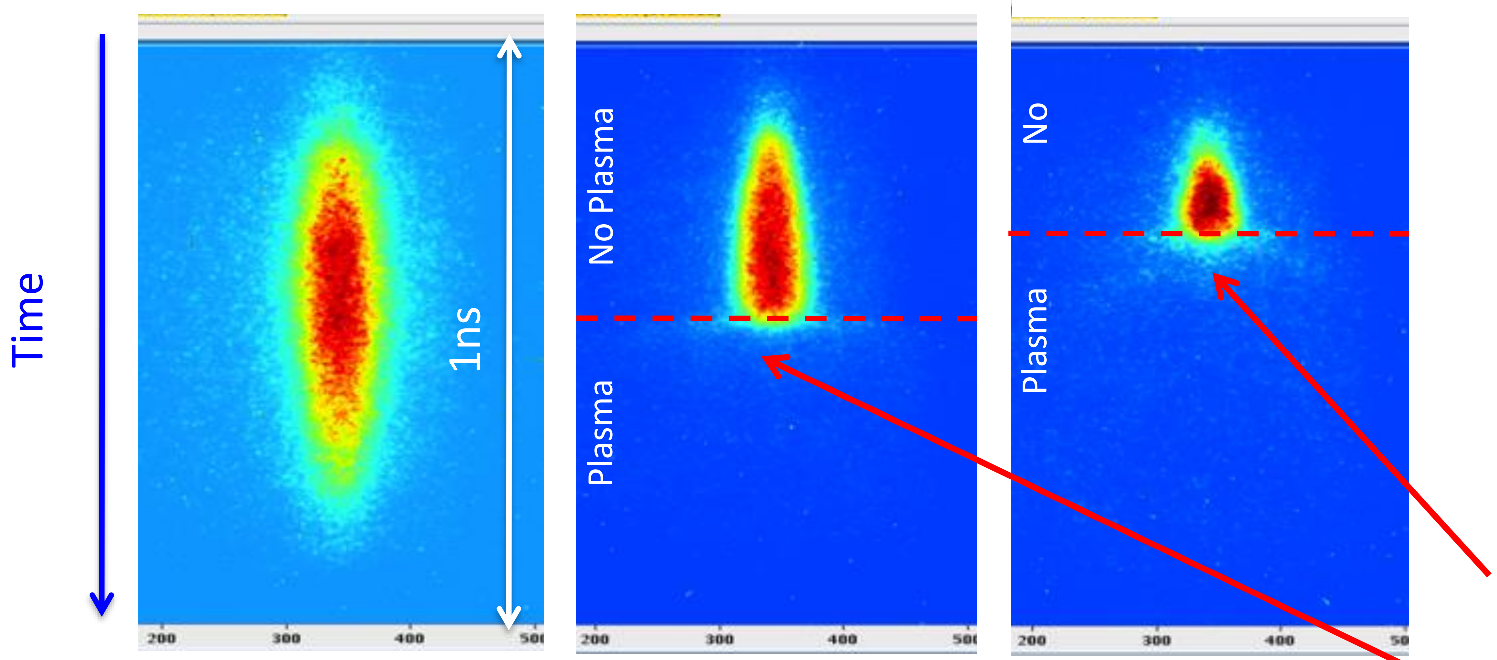
# Direct Seeded Self-Modulation Results




K. Rieger, MPP

Streak camera Images



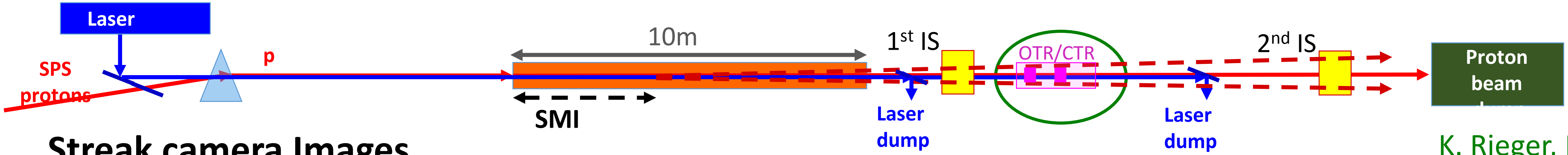

$p^+$ symmetrically defocused by SSM

Preliminary!!!

$n_{Rb}$=2.2x10$^{14}$cm$^{-3}$
N=3x10$^{11}$p$^+$

- → Various seeding position/times
- → Effect starts at laser timing → SM seeding
- → Stronger effects with seed at ¼ than ½

# Direct Seeded Self-Modulation Results



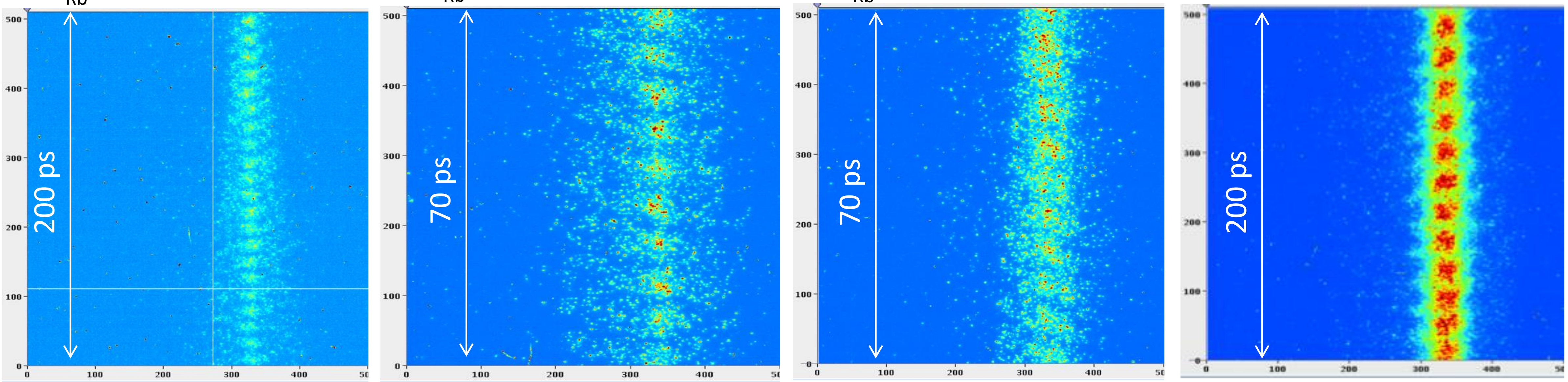

K. Rieger, MPP

Preliminary!!!

**Streak camera Images**

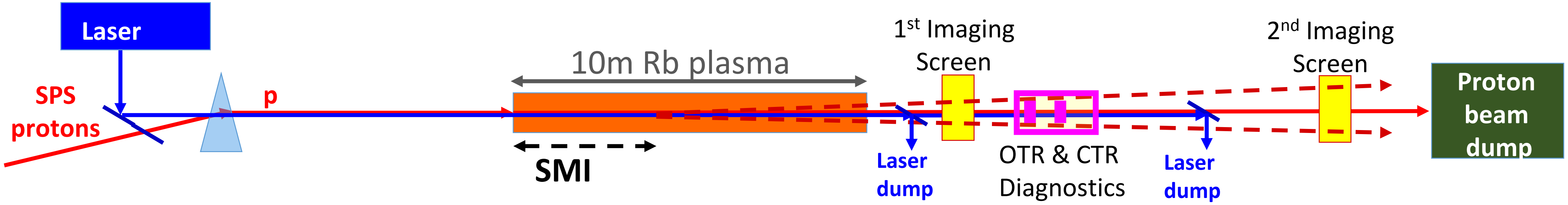
Micro bunches for different plasma densities

$n_{Rb}=1.3x10^{14}cm^{-3}$ $n_{Rb}=2.0x10^{14}cm^{-3}$ $n_{Rb}=2.6x10^{14}cm^{-3}$ $n_{Rb}\sim 0.4x10^{14}cm^{-3}$



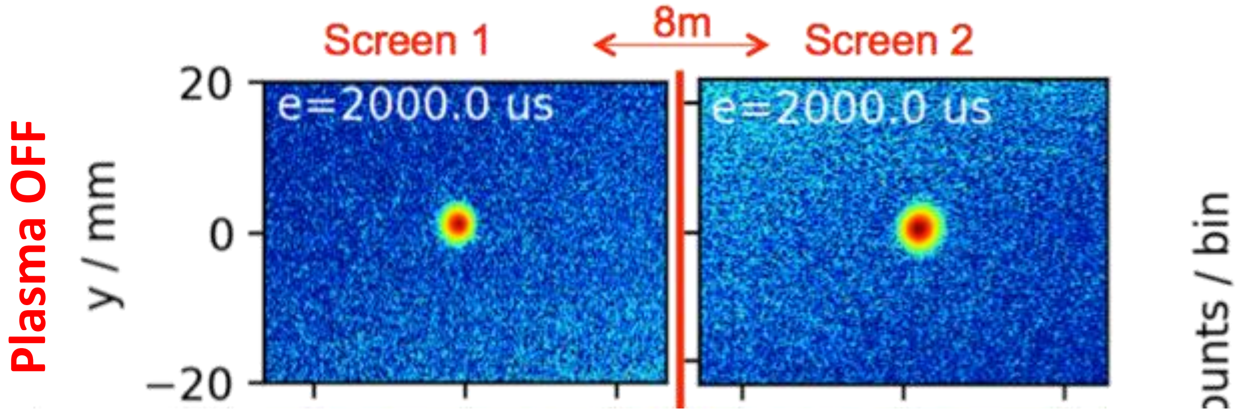

→ Observation of strong, persistent micro bunches for a range of plasma densities
→ Seeding is critical ingredient for producing many periods of micro bunches along the beam

# Seeded Self-Modulation Diagnostics II




**Indirect SSM Measurement: Image protons that got defocused by the strong plasma wakefields.**

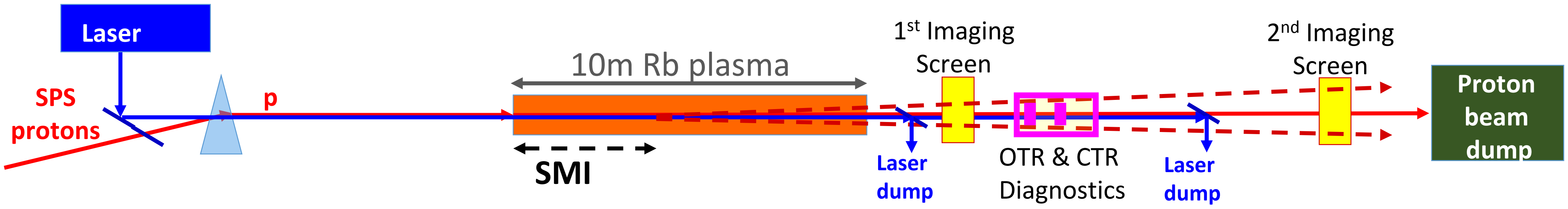

M. Turner, CERN




**Two imaging stations (IS)** to measure the **radial proton beam distribution** 2 and 10 m downstream the end of the plasma.

→ Growth of tails governed by transverse fields in the plasma.

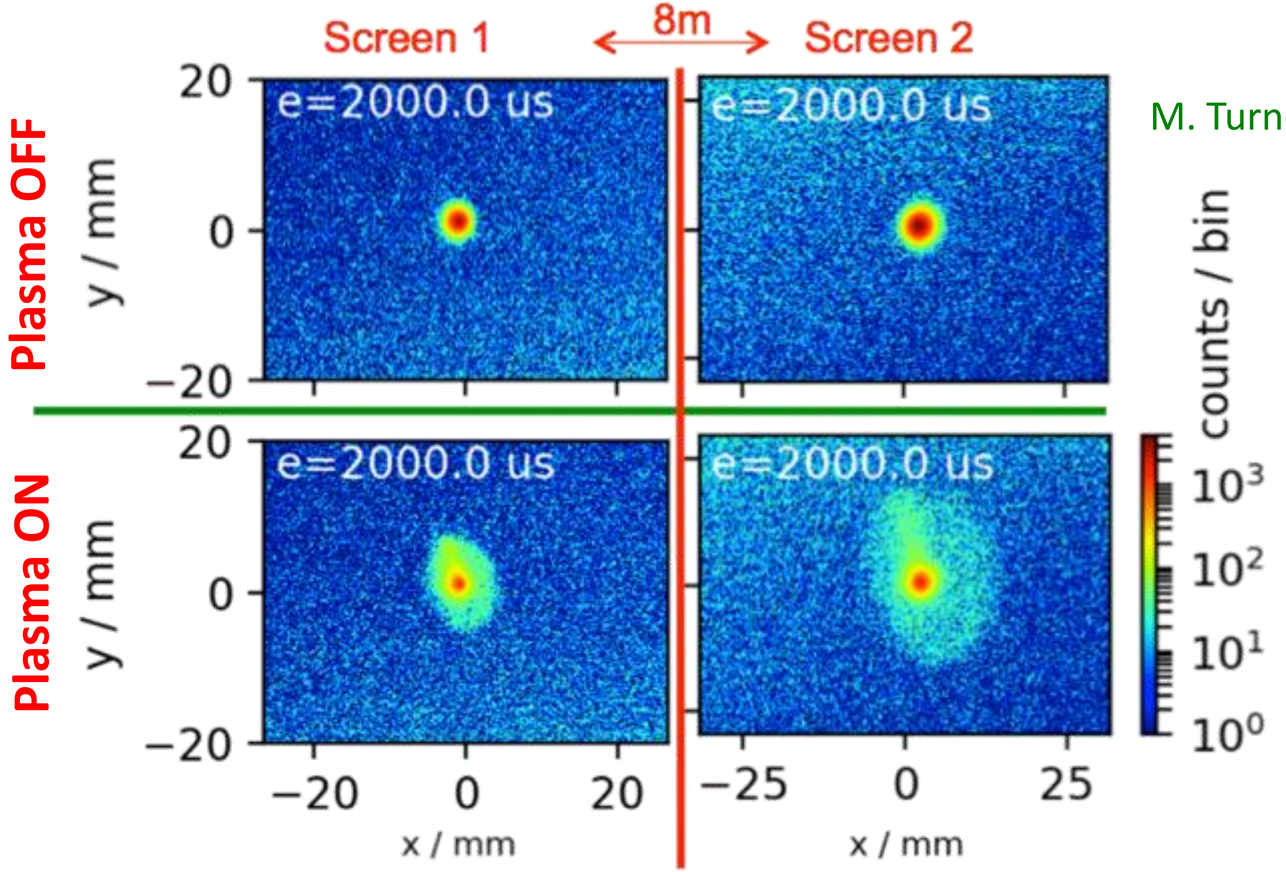
# Indirect Seeded Self-Modulation Results




**Indirect SSM Measurement:** **Image protons that got defocused by the strong plasma wakefields.**

- → $p^+$ defocused by the transverse wakefield (SMI) form a halo
- → $p^+$ focused form a tighter core
- → Estimate of the transverse wakefields amplitude ($\int W_{per} dr$)

Preliminary!!!

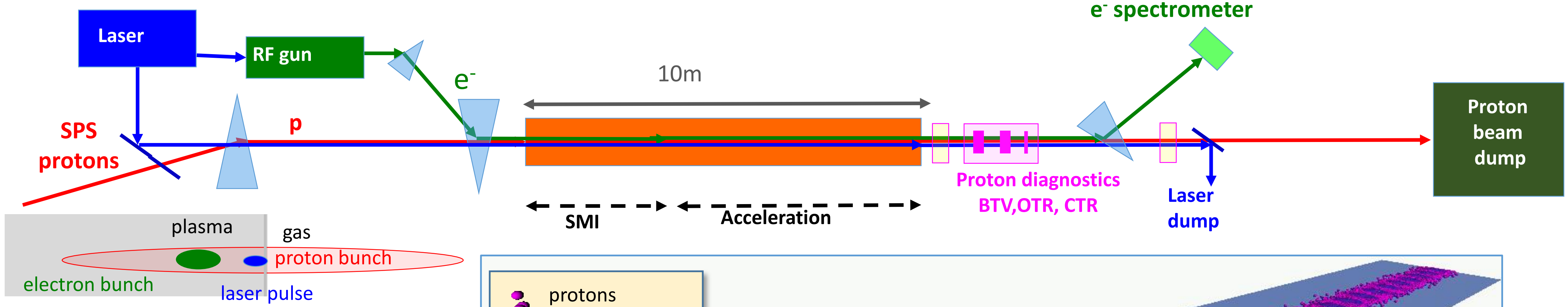


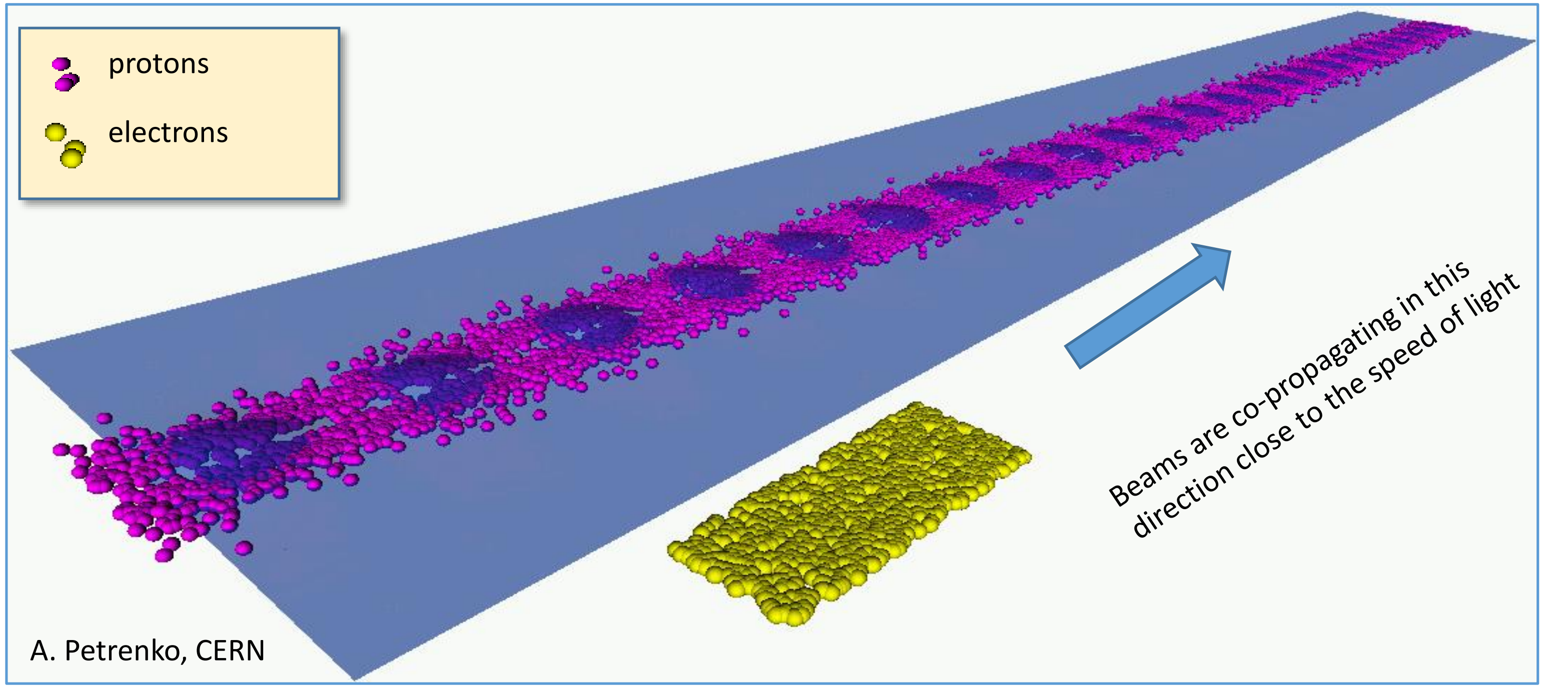

M. Turner, CERN

# AWAKE Experiment: Electron Acceleration 2017/18

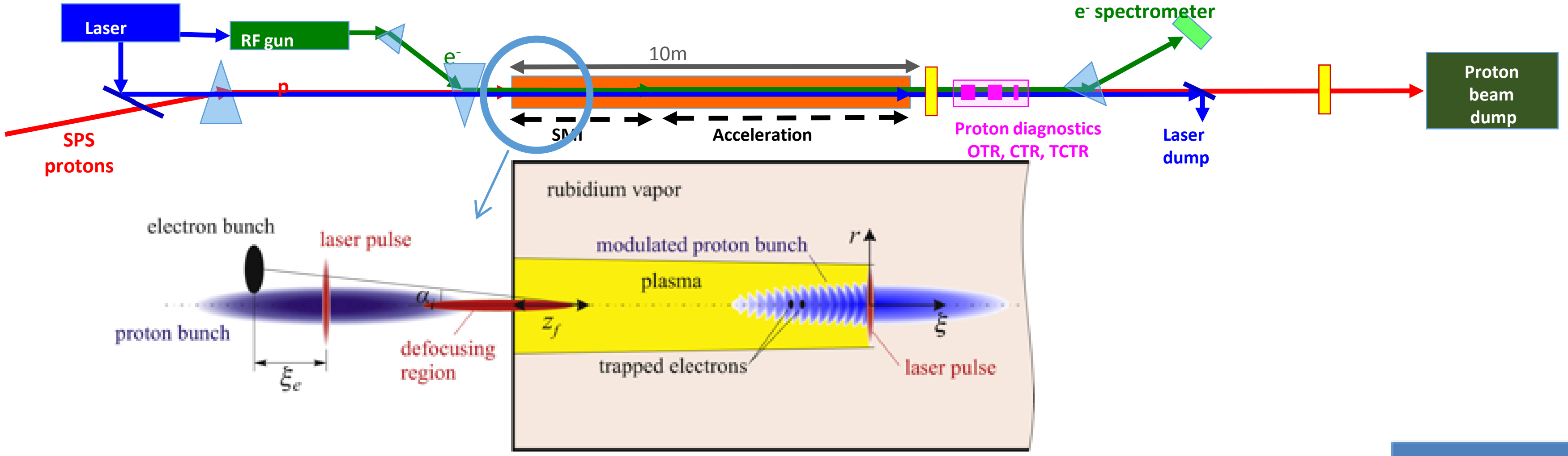
Phase 1: 2016/17: Understand **the physics of the seeded self-modulation** processes in plasma.

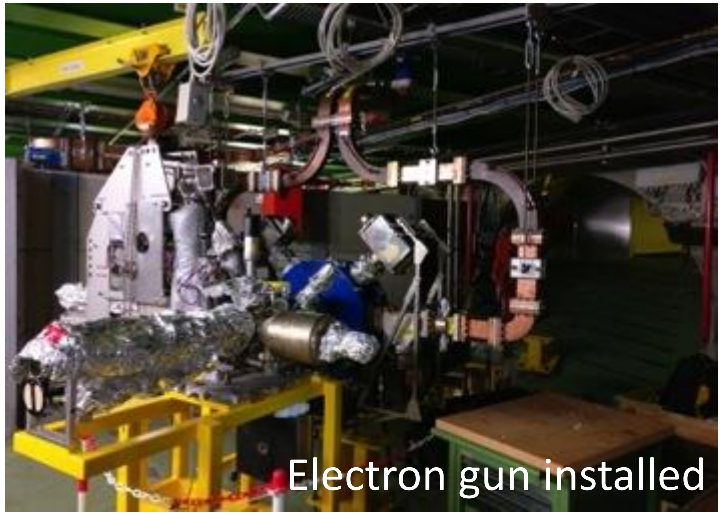
Phase 2: 2017/18: **Probe the accelerating wakefields** with externally injected electrons.

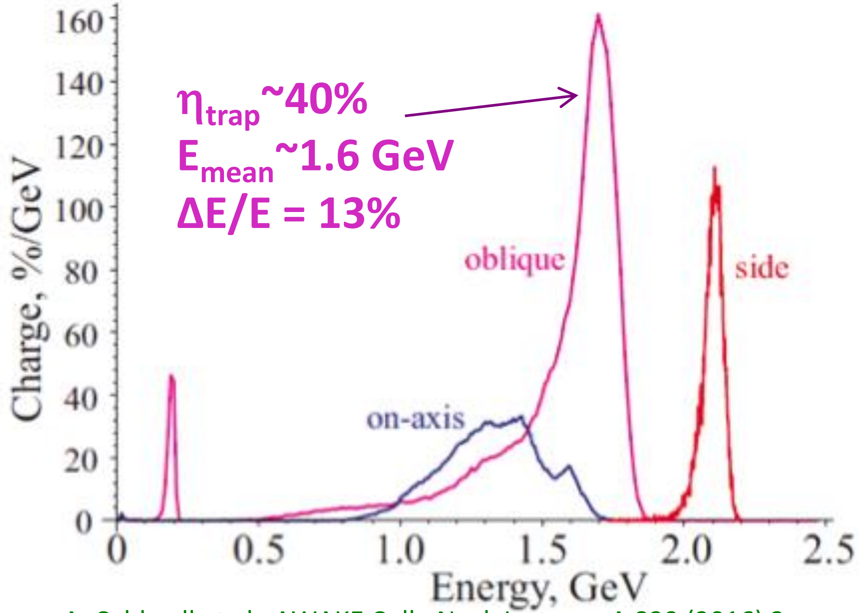


# Electron Acceleration




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

| Electron beam | Baseline |
|---|---|
| Momentum | 16 MeV/c |
| Electrons/bunch (bunch charge) | 1.25 E9 |
| Bunch charge | 0.2 nC |
| Bunch length | $\sigma_z$ =4ps (1.2mm) |
| Bunch size at focus | $\sigma^*_{x,y}$ = 250 μm |
| Normalized emittance (r.m.s.) | 2 mm mrad |
| Relative energy spread | Δp/p = 0.5% |

Externally inject electrons and accelerate $e^-$ to GeV energy with ~GeV/m gradient and finite ΔE/E
→ Start end 2017

# Outline

- Motivation
- Plasma Wakefield Acceleration
- AWAKE
- Outlook

# AWAKE Run 2

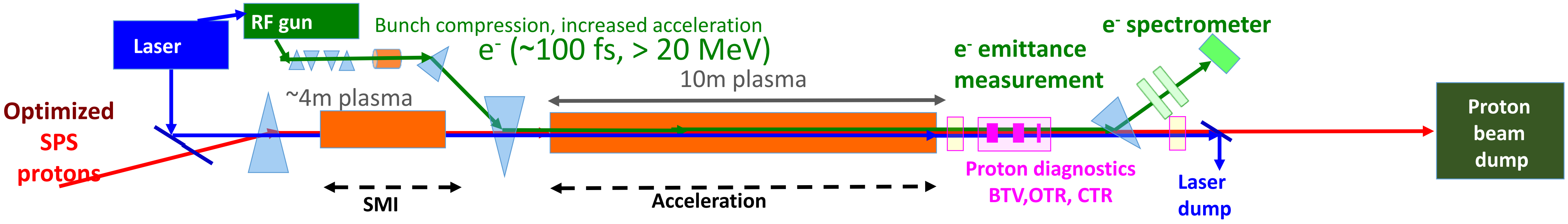
Proposing Run 2 for 2021 after CERN Long Shutdown 2

## Goals:

- **Accelerate an electron beam to high energy**
- **Preserve electron beam quality** as well as possible
- **Demonstrate scalability** of the AWAKE concept

Preliminary Run 2 electron beam parameters

| Parameter | Value |
|---|---|
| Acc. gradient | >0.5 GV/m |
| Energy gain | 10 GeV |
| Injection energy | $\gtrsim$ 50 MeV |
| Bunch length, rms | 40–60 $\mu$m (120–180 fs) |
| Peak current | 200–400 A |
| Bunch charge | 67–200 pC |
| Final energy spread, rms | few % |
| Final emittance | $\lesssim$ 10 $\mu$m |




E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008)

# Summary

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

- Many encouraging results in plasma wakefield acceleration technology.

- AWAKE is the first proton driven plasma wakefield acceleration experiment
  - Successfully observed the seeded Self-Modulation of the proton bunch in AWAKE.
  - Acceleration of electrons in the plasma wakefield driven by proton beam in 2018.
  - Short term prospects: demonstration of stable acceleration and good electron bunch properties.
  - Long term prospects: develop particle physics program that could be pursued with an AWAKE-like beam.