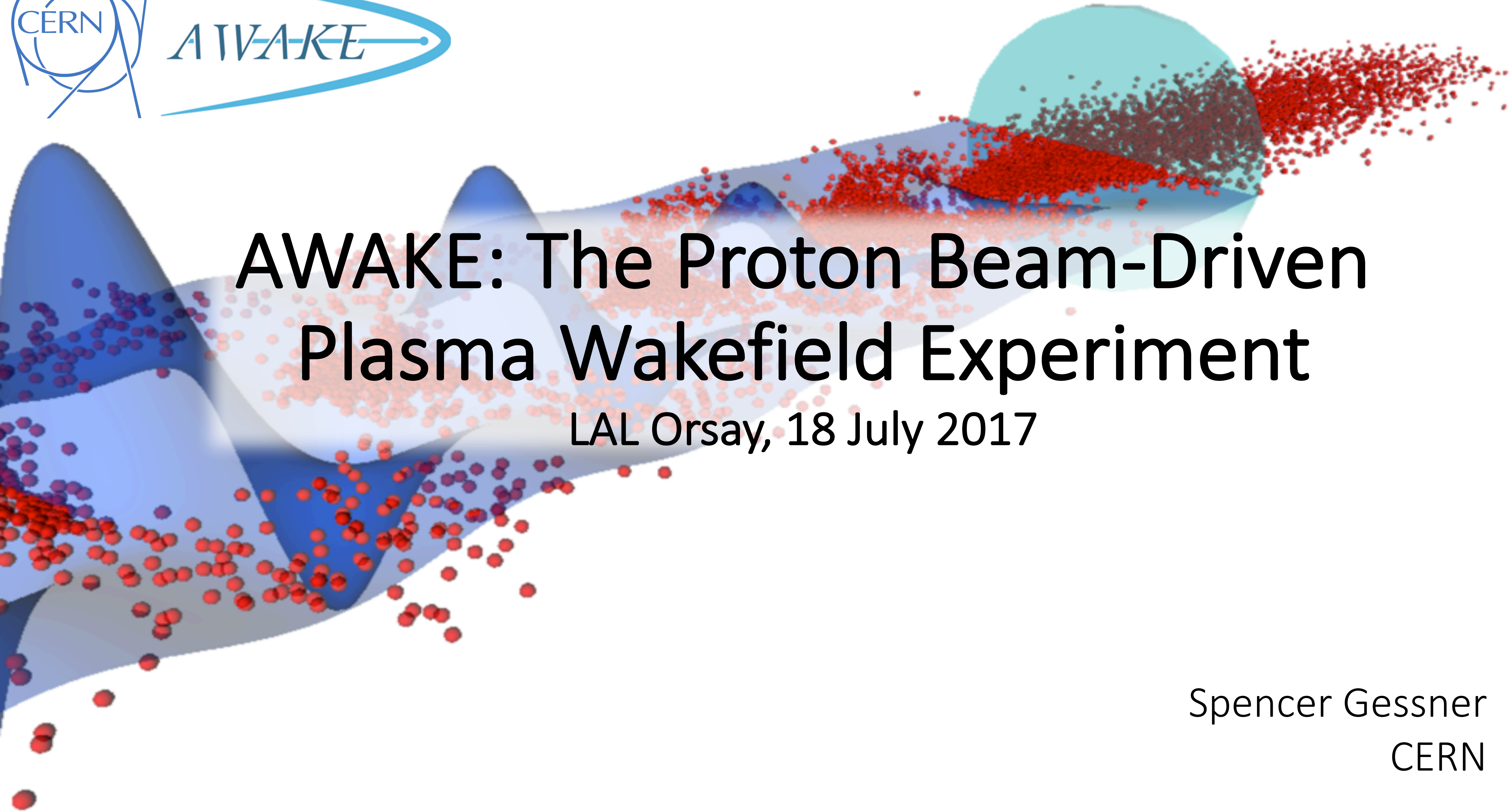
# AWAKE: The Proton Beam-Driven Plasma Wakefield Experiment

LAL Orsay, 18 July 2017



Spencer Gessner
CERN

# Outline

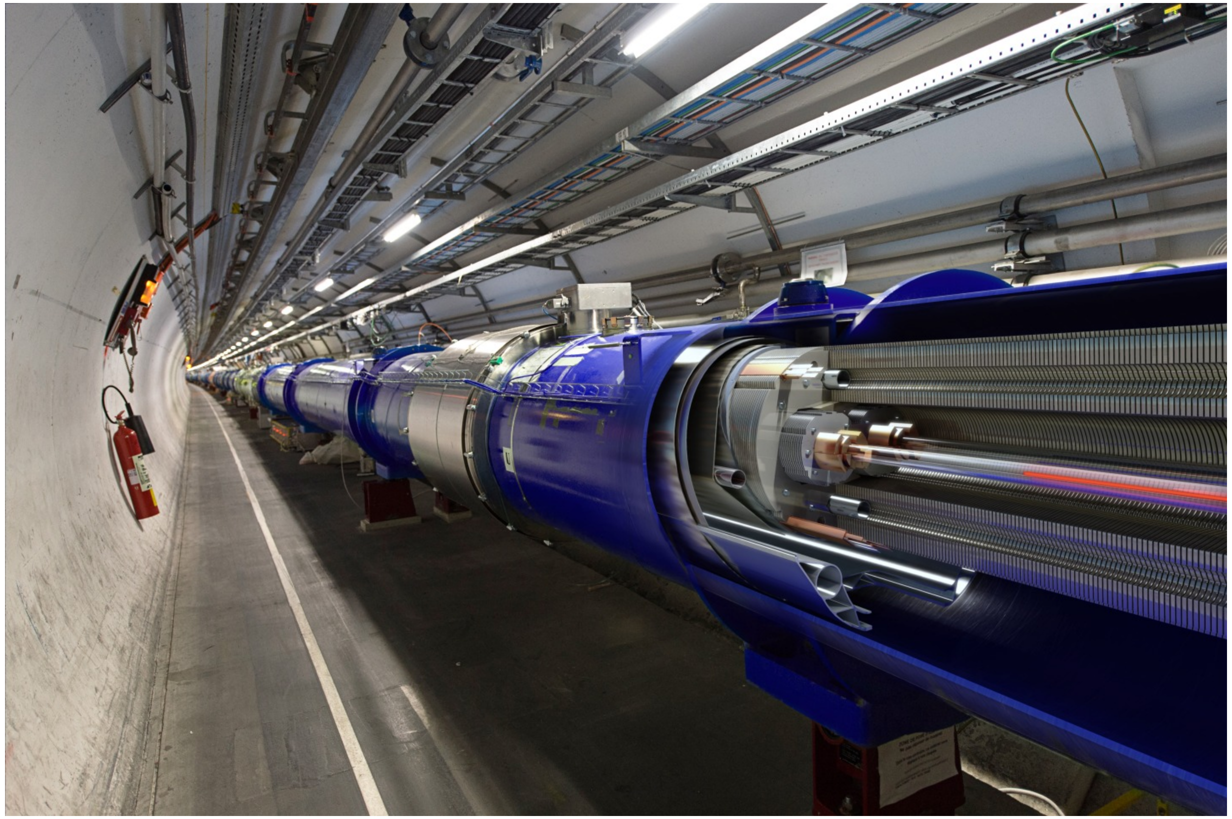
1. Recipe for a High Energy Collider
2. Why Plasma?
3. Self-Modulation and Plasma Wakefield Acceleration with Proton Beams
4. The AWAKE Experiment
5. First Results!
6. Future Plans for AWAKE

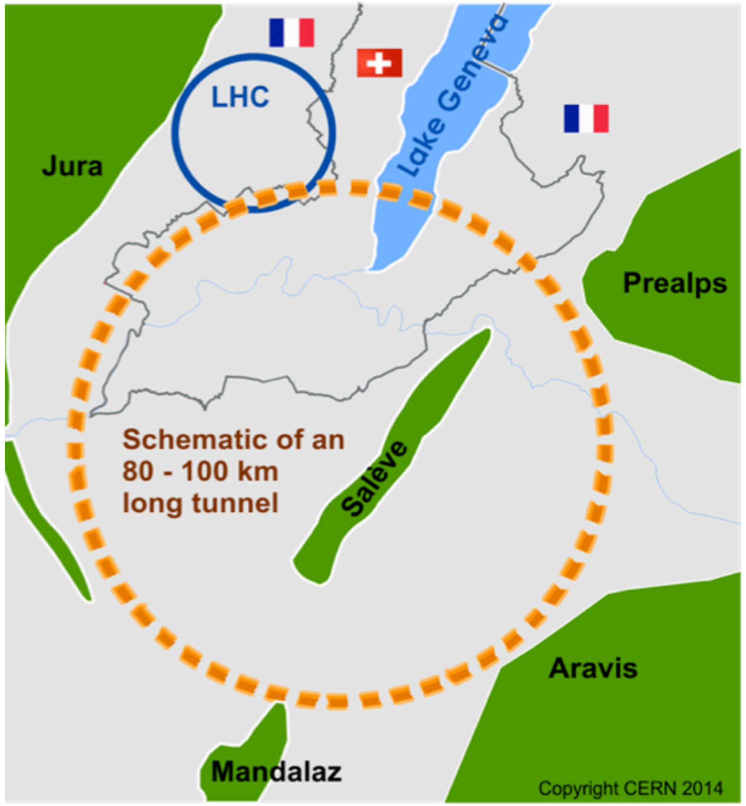
# Recipe for a High Energy Collider

1. Achieve the highest possible energy
2. Achieve the highest possible luminosity
3. Minimize cost (shrink facility)
4. Maximize efficiency

$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)$$

# Limitations of conventional machines



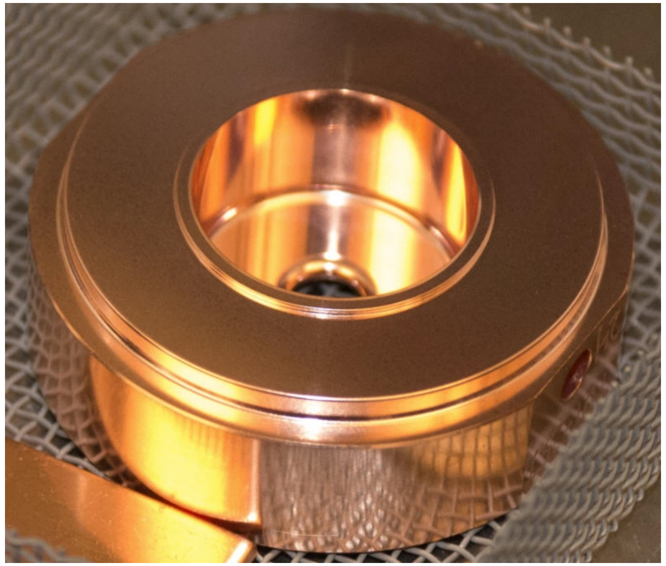



Circular machines are limited by synchrotron radiation in the case of positron colliders. There is wide agreement that these machines are unfeasible beyond $E_{cm}$ ~ 250 GeV.

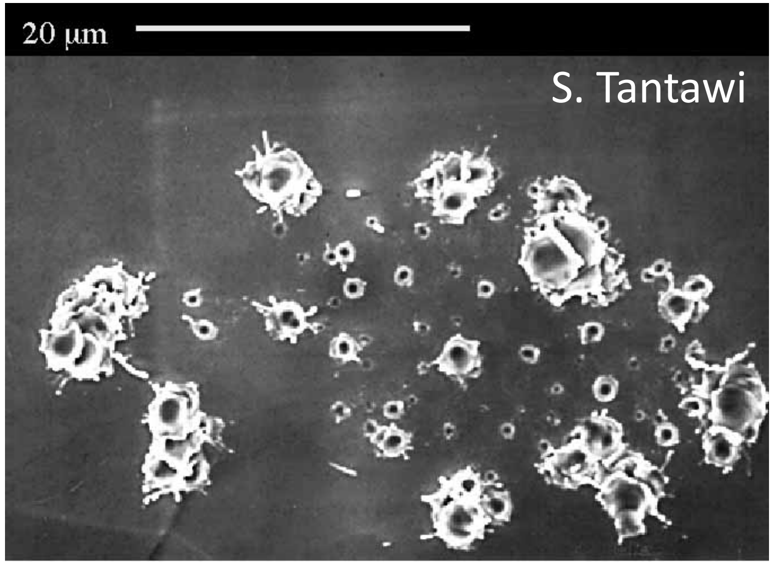
For hadron colliders, the limitation is magnet strength. Ambitious plans like the FCC call for 16 T magnets in a 100 km tunnel.

# Limitations of conventional machines

New RF Copper Cell



Surface of Copper Cell After Breakdown Events




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. Fields above this value lead to "breakdown" of the copper cavities.

# Why Plasma?

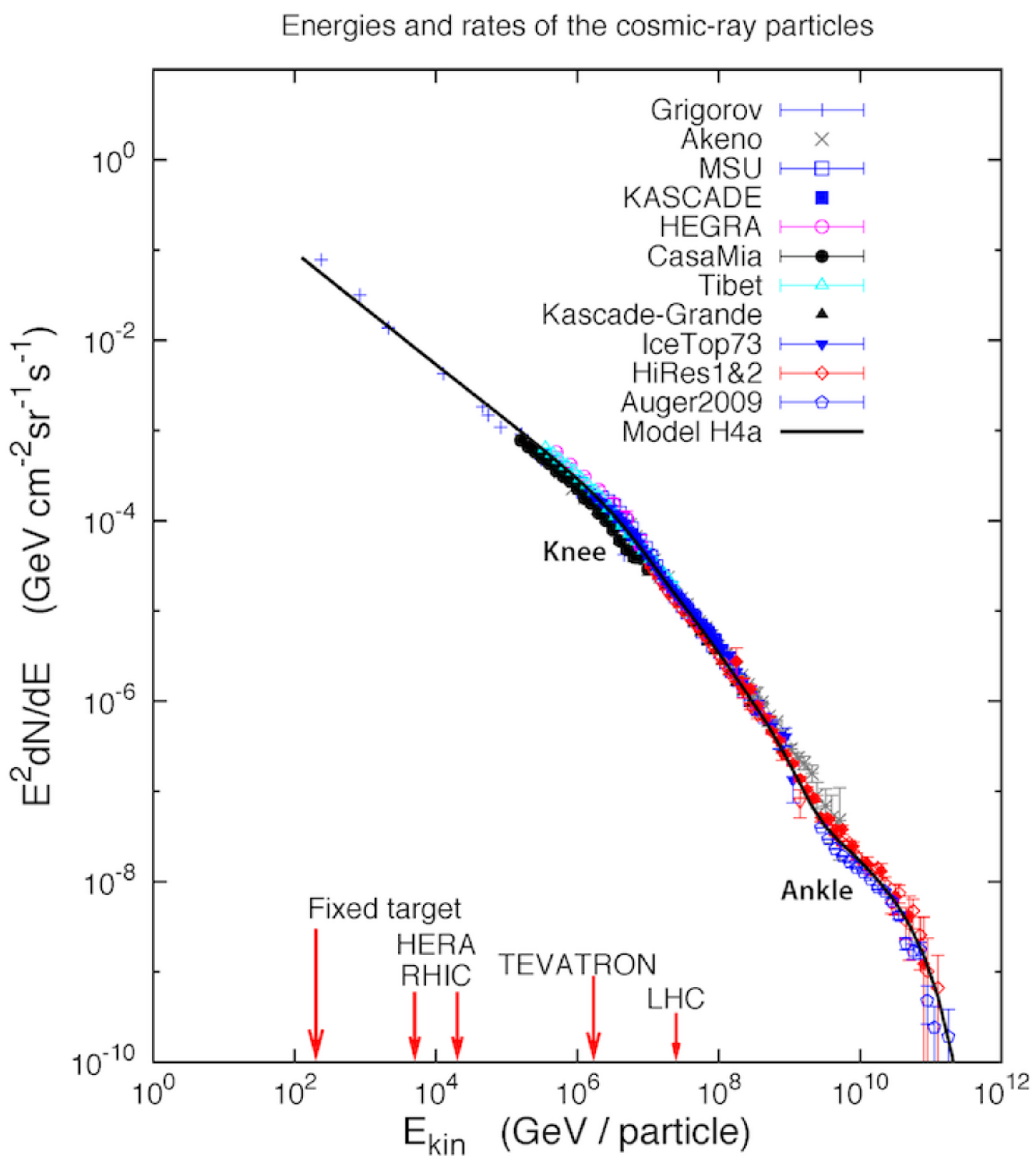
# Why Plasma?

The highest energy particles detected on Earth are not made in a machine. They come from space!

How do they acquire one million times the energy of an LHC proton?

In 1949, Fermi proposed the plasma shockwaves were responsible.

Years later, in 1979, Tajima and Dawson realized that intense lasers could be used to drive high amplitude waves in plasma.



# Properties of Plasmas

$$\omega_p = \sqrt{\frac{4\pi e^2 n_0}{m_e}} \qquad E \approx 100\sqrt{n\ (10^{18}\ \mathrm{cm}^{-3})}\ [\mathrm{GV/m}]$$

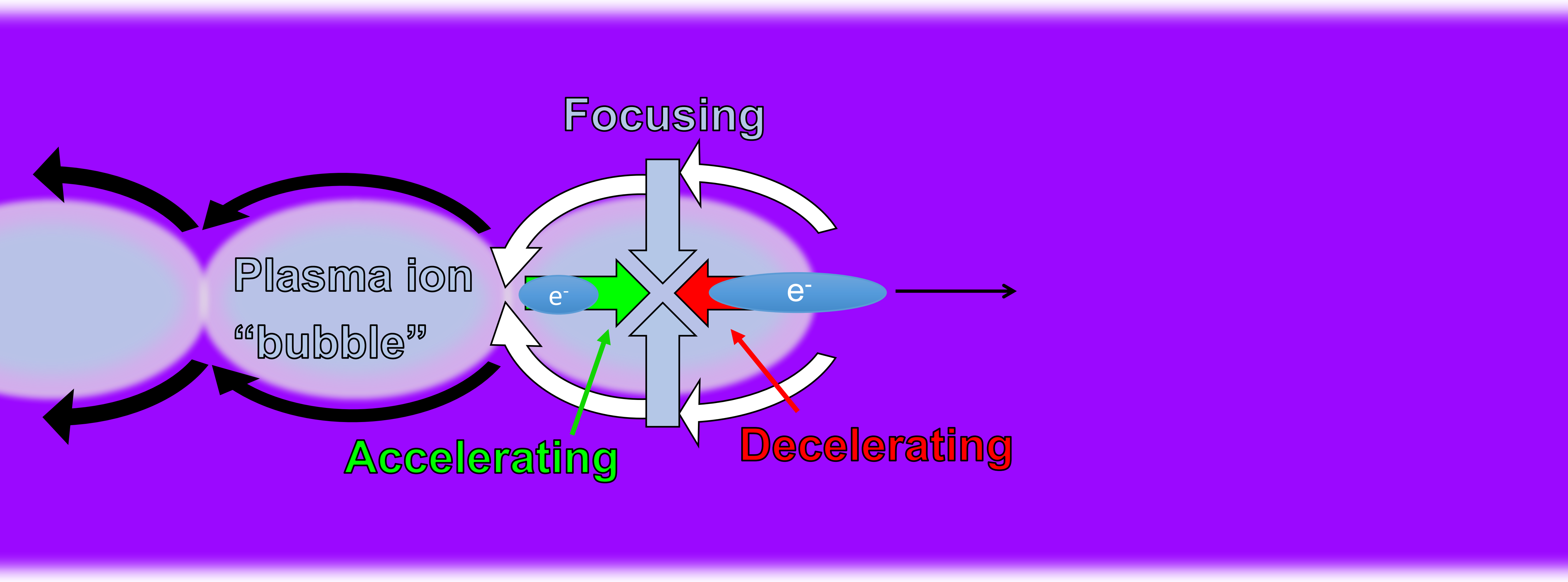
Particle beams and laser pulses can be used to excite waves in plasmas (called *wakes*).

The frequency and amplitude of the waves depend on the plasma density *n*.

Laser-plasma accelerators typically use densities greater than $10^{18}$ cm$^{-3}$, which corresponds to a wavelength of roughly 30 microns and accelerating fields of 100 GV/m (about 1000 times the acceleration of state-of-the-art copper cavities).

Beam-driven plasma accelerators typically operate at densities below $10^{17}$ cm$^{-3}$, but the accelerating gradients are still enormous and the size of the plasma wave still much smaller than that of a traditional RF accelerator.

# Creating a wake with a short drive beam




**The field is accelerating in the back half of the bubble. Beam electrons can extract energy from the plasma wake in this region.**

# Creating a Wake with a Long Driver

$$eE_{\mathrm{linear}} \cong 100\,\mathrm{GeV/m}\left(\frac{N}{2\times 10^{10}}\right)\left(\frac{20}{\sigma_z(\mu\mathrm{m})}\right)^2 \ln\sqrt{\frac{2.5\times 10^{17}(\mathrm{cm}^{-3})}{n_{\mathrm{p}}}\,\frac{10(\mu\mathrm{m})}{\sigma_r}}$$

Accelerating field created by drive beam

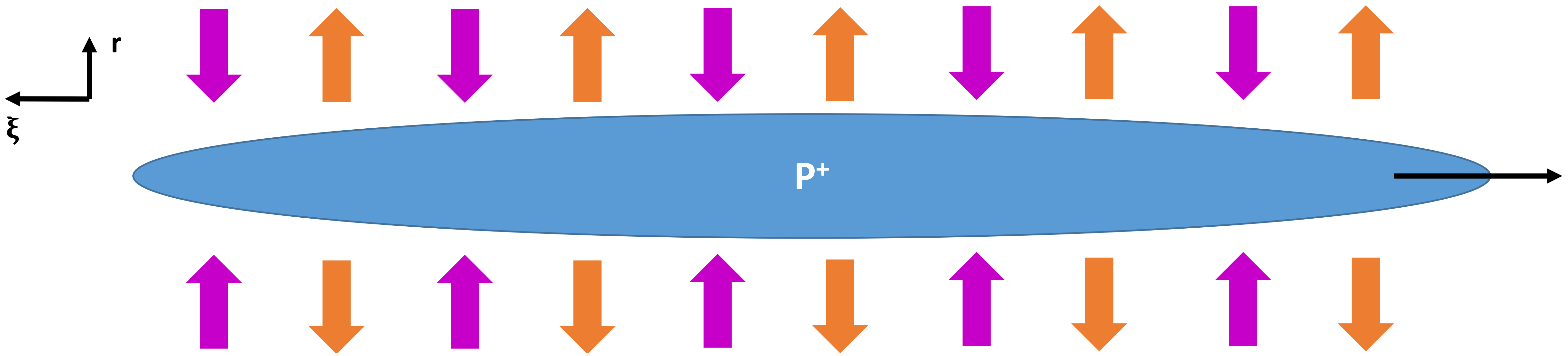
Accelerating field created by drive beam

The plasma supports charges oscillations at the plasma frequency. Short bunches can excite these oscillations, but long bunches do not.

The CERN proton beam is much longer than the plasma wavelength. Can we use it to drive high amplitude wakes?

# The Self-Modulation Instability

Kumar, et al, PRL 104.255003 (2010)




$$W_\perp(r,\xi) = -4\pi\rho_0 \int_0^{\xi} r_b(\xi')I_1\{k_p r(\xi')\}K_1\{k_p r_b(\xi')\}f(\xi')$$

$$k_p \sin k_p(\xi - \xi')d\xi',$$

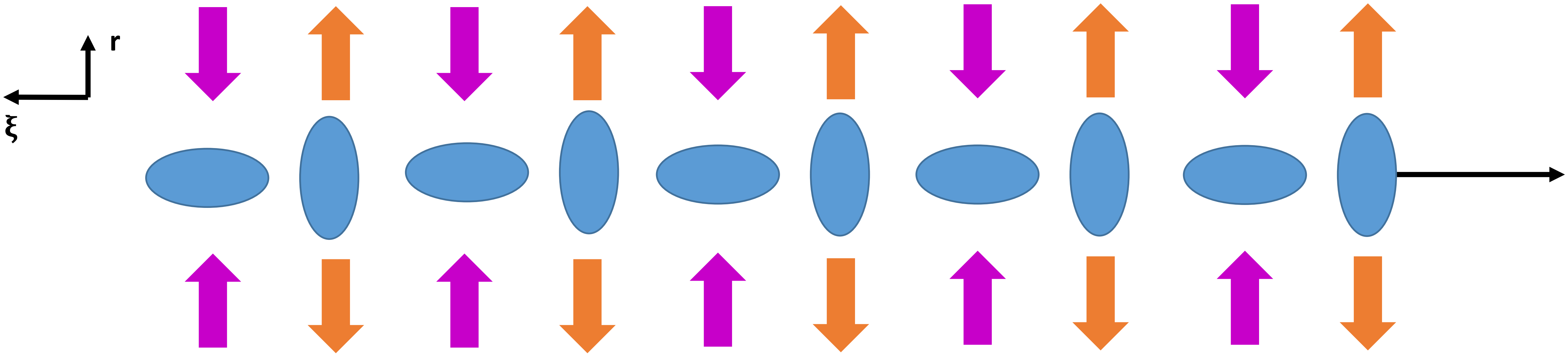
Transverse force along the bunch

Focusing oscillates along bunch

The transverse force felt by a particle in the proton bunch varies along the bunch at the plasma frequency.

# The Self-Modulation Instability

Kumar, et al, PRL 104.255003 (2010)




Transverse beam size

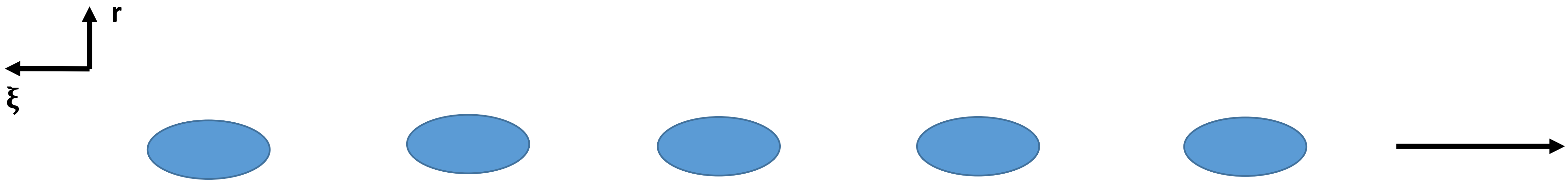
$$\frac{\partial^2 r_b}{\partial \tau^2} - \frac{\mathcal{M}^2}{r_b^3} = -\frac{\omega_b^2}{\gamma_0} \int_0^{\xi} r_b(\xi^{'}) I_1\{k_p r_b(\xi^{'})\} K_1\{k_p r_b(\xi^{'})\} f(\xi^{'})\, k_p \sin k_p(\xi - \xi^{'}) d\xi^{'},$$

Radial beam evolution

Transverse force felt by bunch

The radial evolution of the bunch depends on the local radius of the bunch -> instability.

# The Self-Modulation Instability




$$eE_{\text{linear}} \cong 100\,\text{GeV/m}\left(\frac{N}{2\times10^{10}}\right)\left(\frac{20}{\sigma_z(\mu\text{m})}\right)^2 \ln\sqrt{\frac{2.5\times10^{17}(\text{cm}^{-3})}{n_\text{p}}\,\frac{10(\mu\text{m})}{\sigma_r}}$$

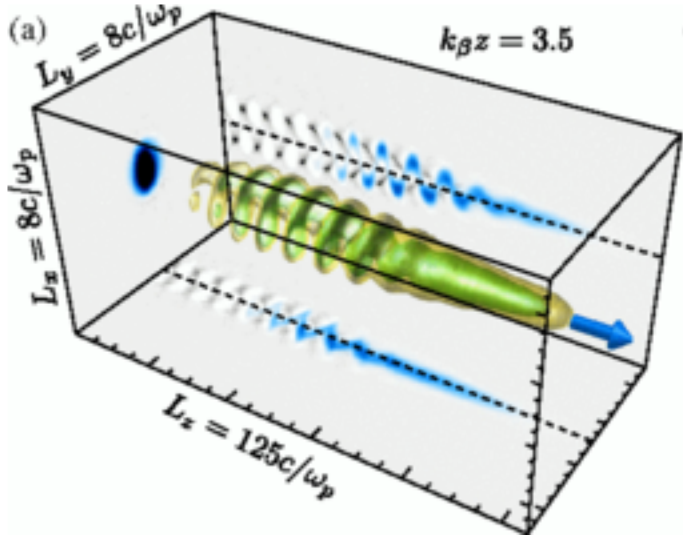
The remaining microbunches have half the charge, but 1/100$^{th}$ the bunch length.

This leads to a huge increase in the accelerating field because the microbunches couple to and excite the plasma wake.

# Other Instabilites?

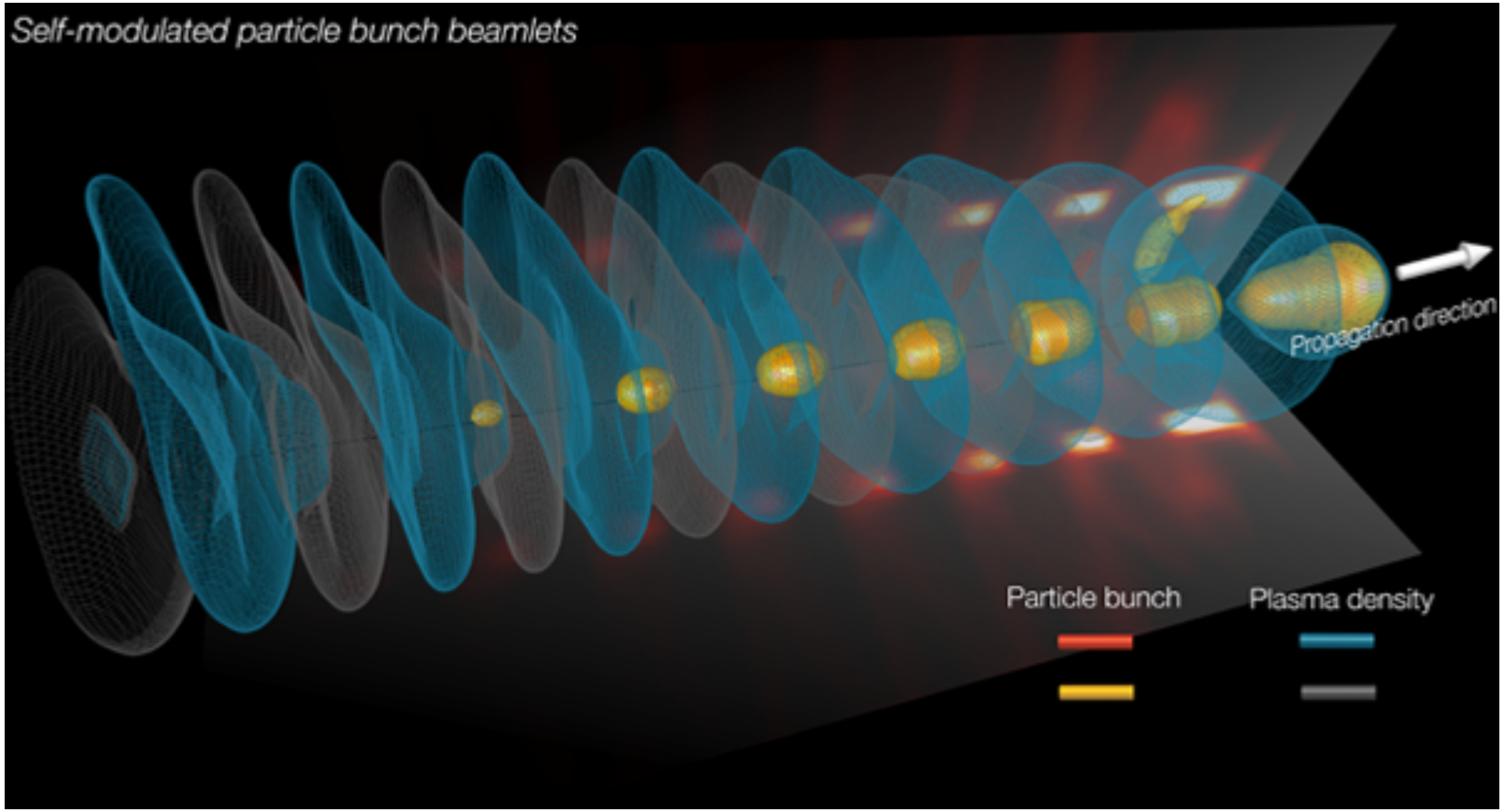
Are we “lucky” to find an instability that allows us to drive high amplitude wakes in a plasma starting from a long bunch? Or is this just one of several instabilities that can occur?

Hosing is the most prominent instability that “competes” with SMI. We need to suppress the hosing instability in order to generate long trains of microbunches that can drive a wake.




Hosing Instability Suppression in Self-Modulated Plasma Wakefields
J. Vieira, W. B. Mori, and P. Muggli
Phys. Rev. Lett. **112**, 205001 – Published 21 May 2014

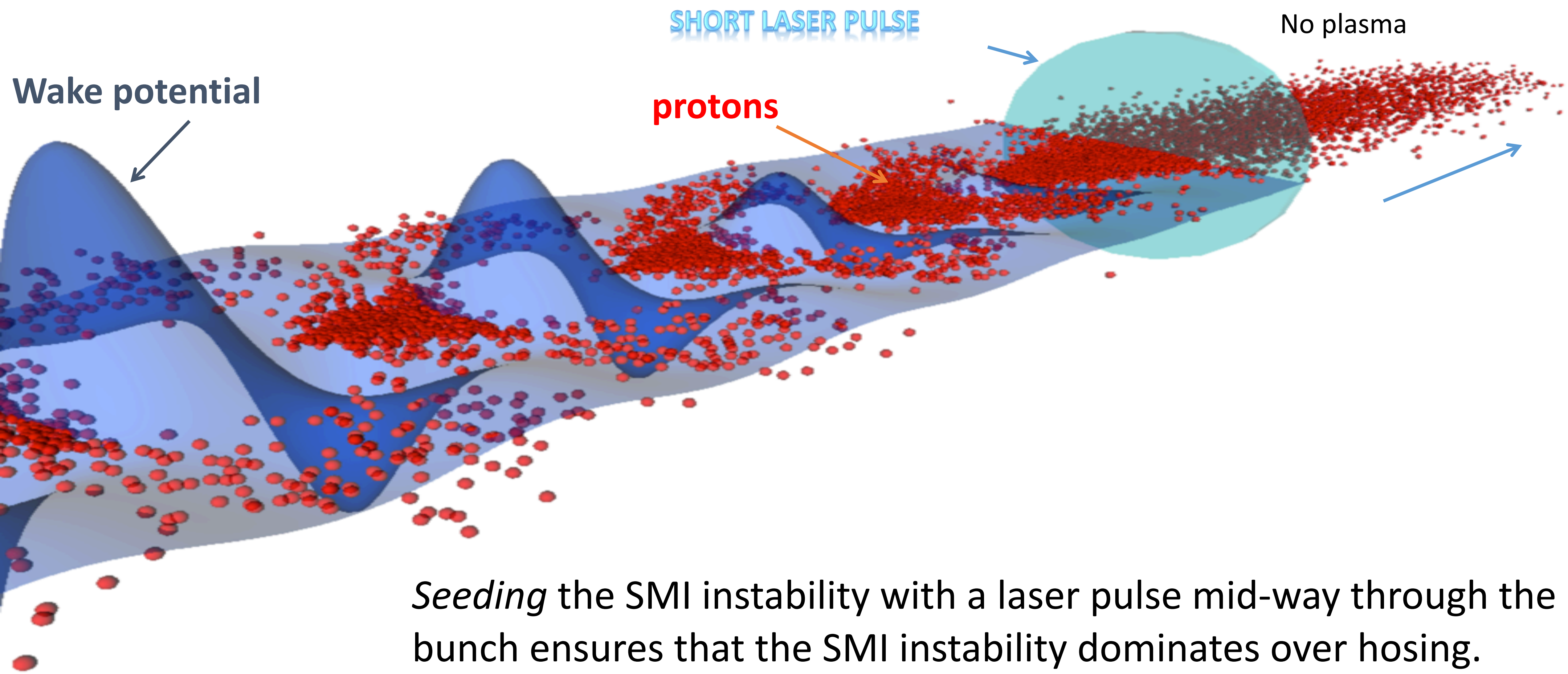
# Competition of instabilities




J. Viera, IST

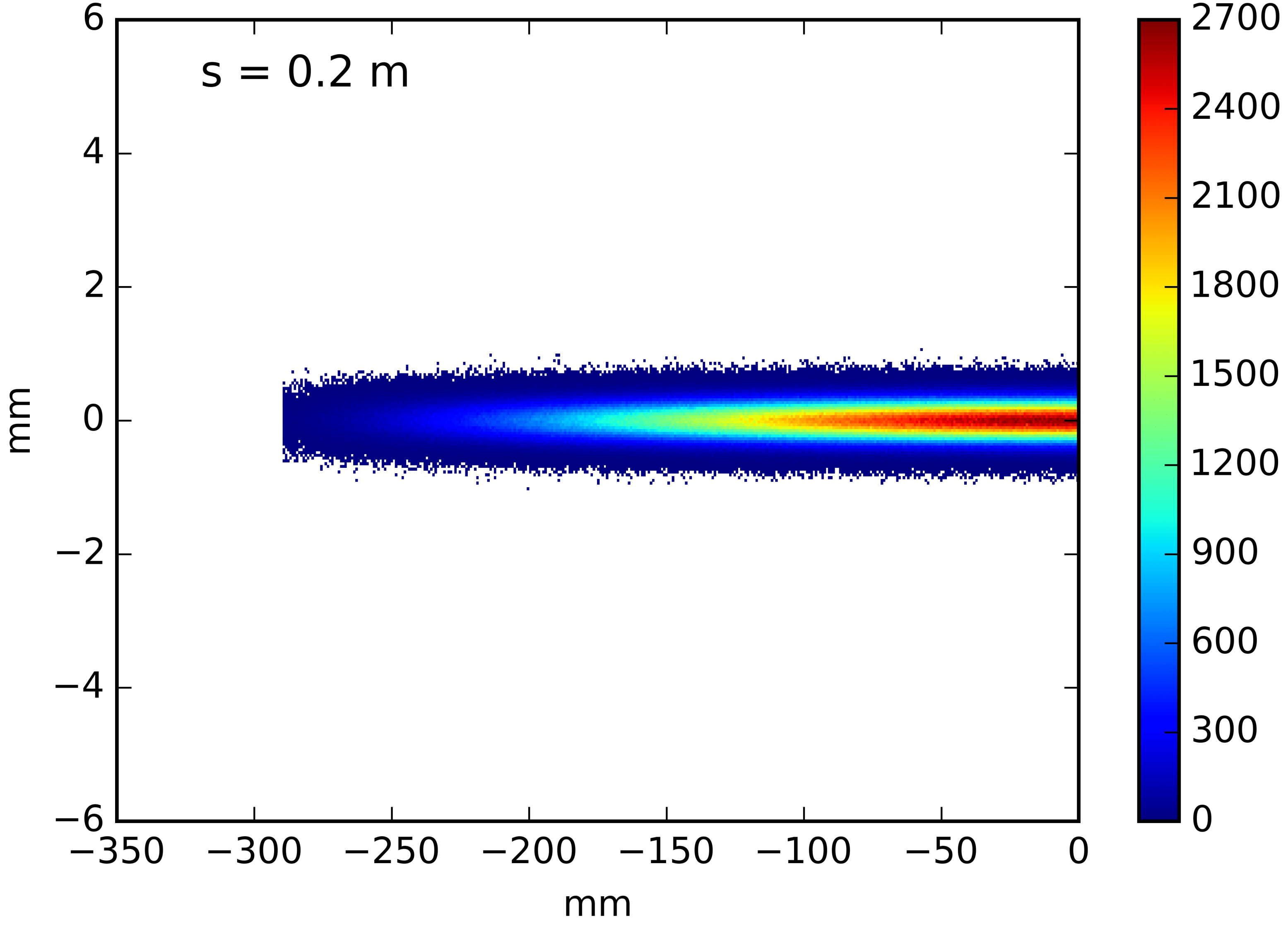
# SMI Seeding

A. Petrenko, CERN




*Seeding* the SMI instability with a laser pulse mid-way through the bunch ensures that the SMI instability dominates over hosing.

# SMI Growth




M. Turner, CERN

# AWAKE


Novosibirsk, Russia. March, 2017

# The AWAKE Collaboration

## AWAKE Collaboration: 16+3 Institutes world-wide:

**Collaboration members:**

- John Adams Institute for Accelerator Science
- Budker Institute of Nuclear Physics & Novosibirsk State University
- CERN
- Cockcroft Institute
- DESY
- Heinrich Heine University, Düsseldorf
- Instituto Superior Tecnico
- Imperial College
- Ludwig Maximilian University
- Max Planck Institute for Physics
- Max Planck Institute for Plasma Physics
- Rutherford Appleton Laboratory
- TRIUMF
- University College London
- University of Oslo
- University of Strathclyde

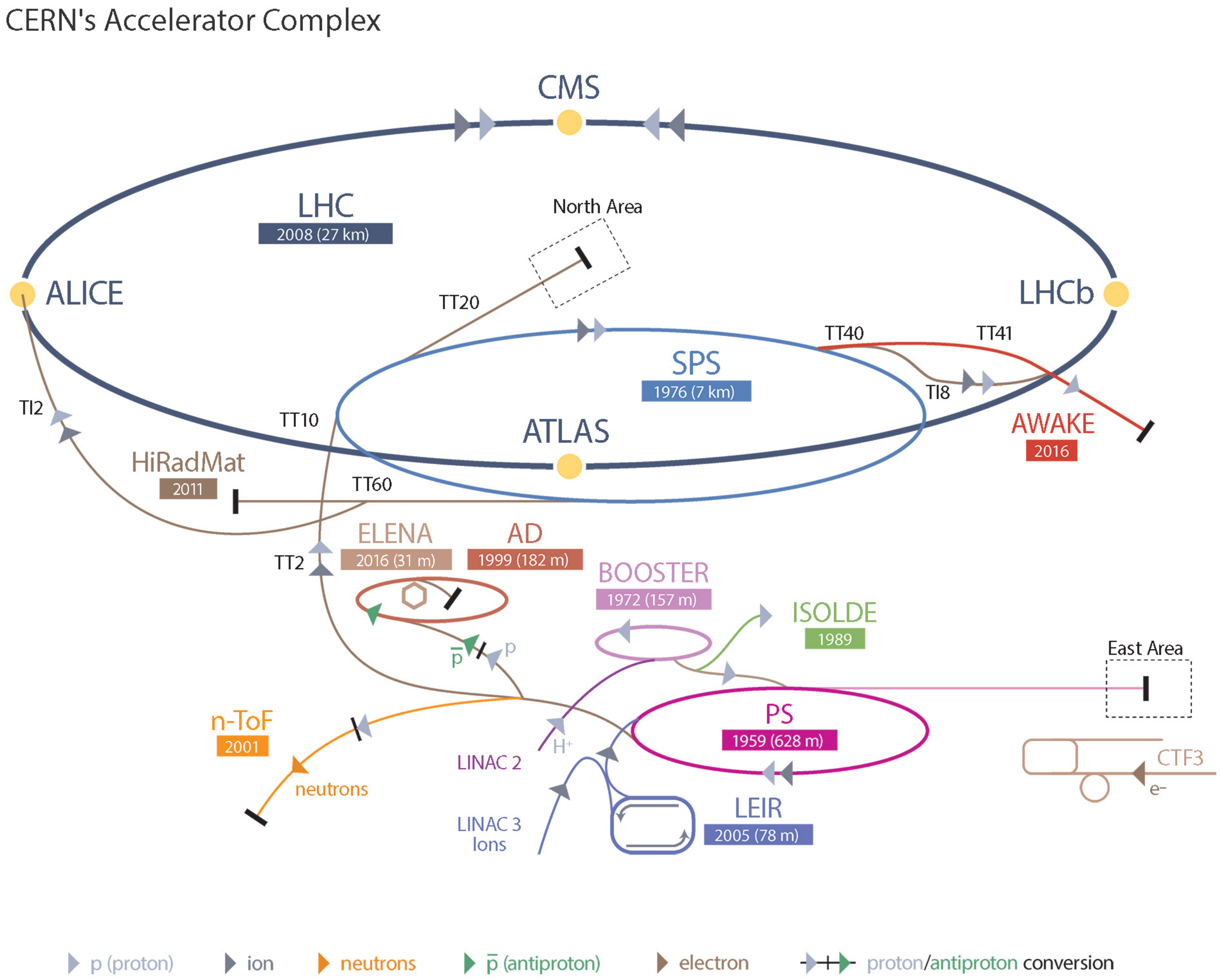

**Associated members:**

- Ulsan National Institute of Science and Technology (UNIST), Korea
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL

# AWAKE@CERN

The AWAKE experiment occupies the former CNGS target area, about 120 m underground.

The SPS sends a 400 GeV beam to AWAKE roughly once every 30 seconds.



# The AWAKE Beamline

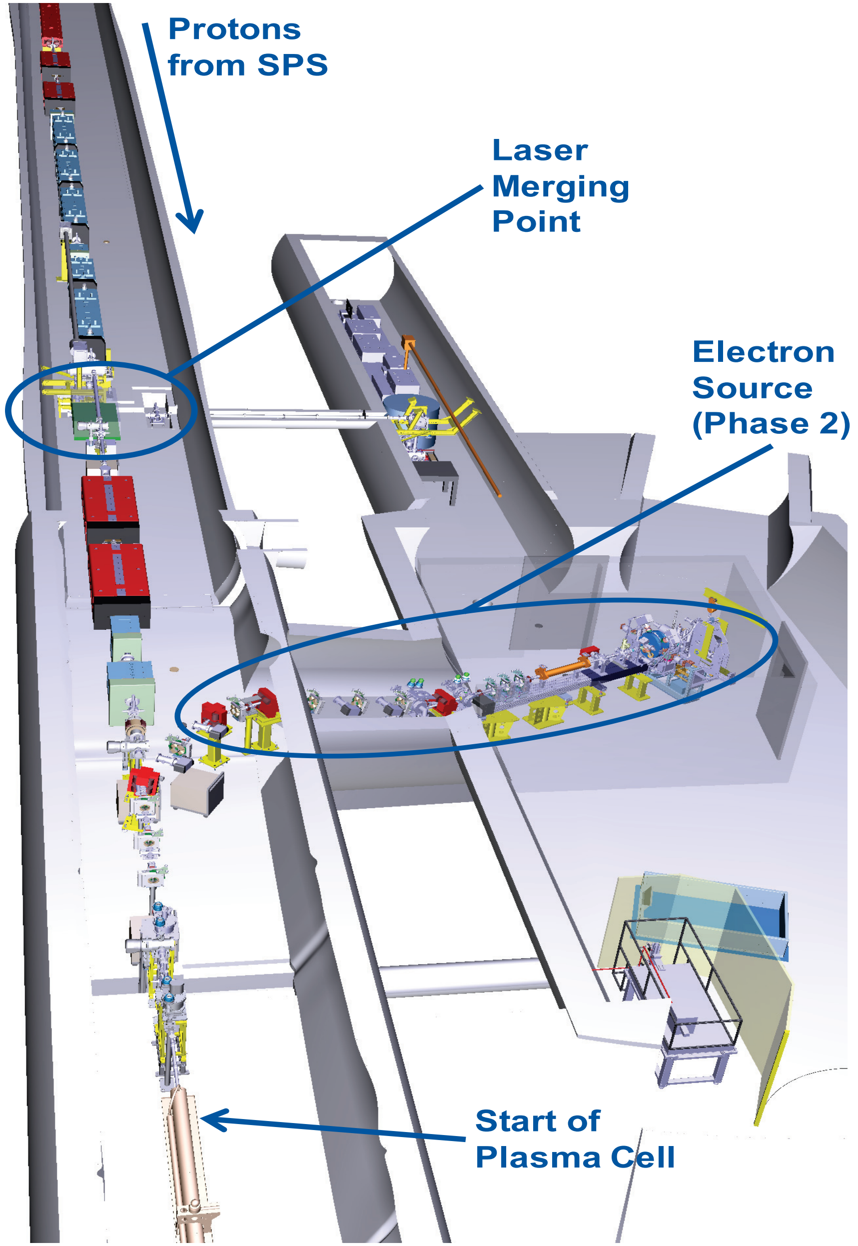
The AWAKE beamline is designed to deliver a high-quality beam to the experiment.

The proton beam must be steered around a mirror which couples a terawatt-class laser into the beamline.

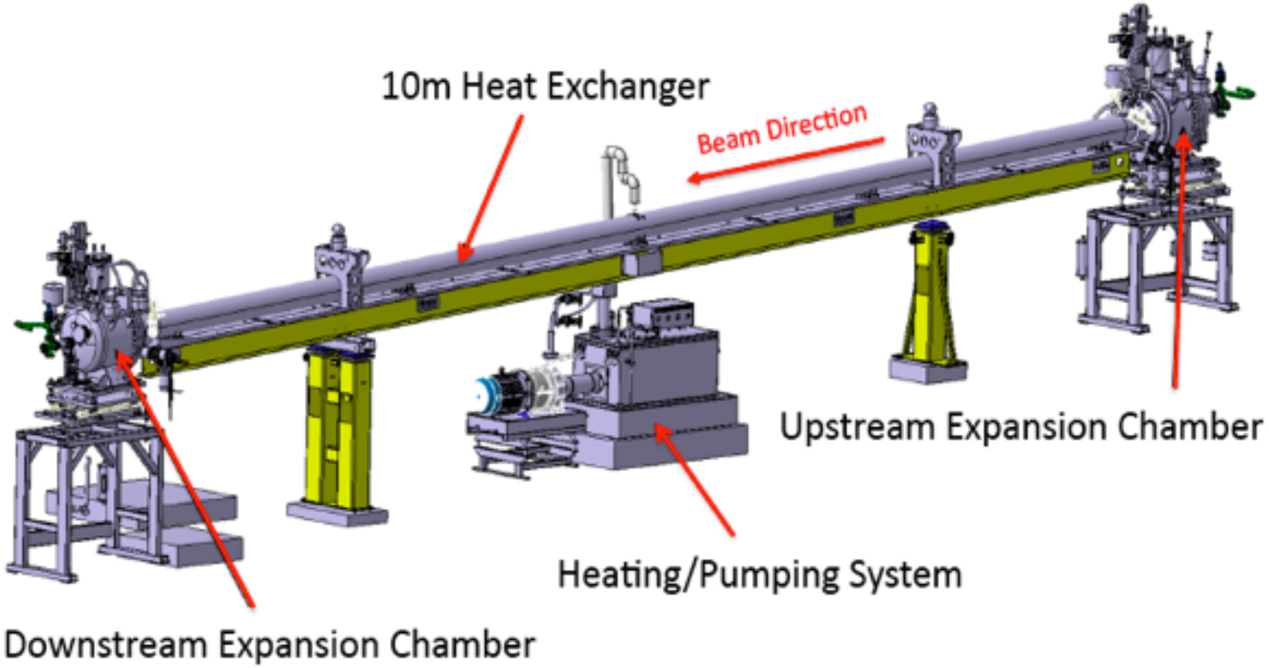
Further downstream, a trailing electron beam will injected into the same beamline.

| 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 |

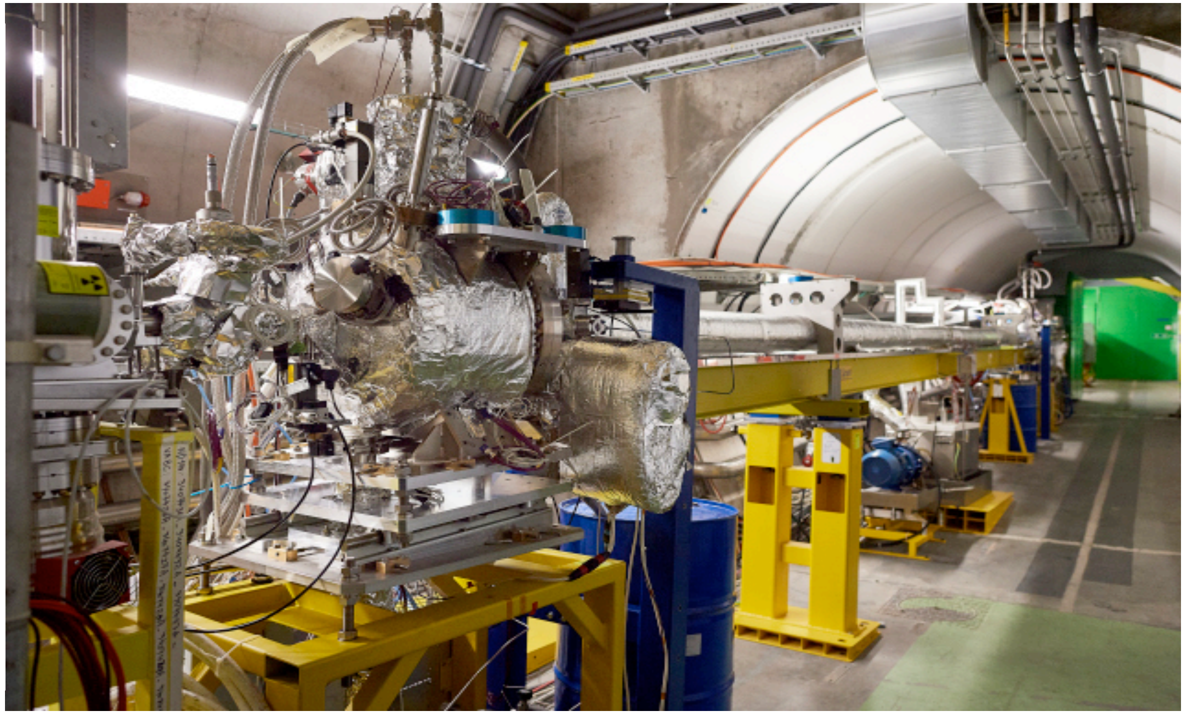
750m proton beam line



# The AWAKE Plasma Cell




**Plasma cell in AWAKE tunnel**

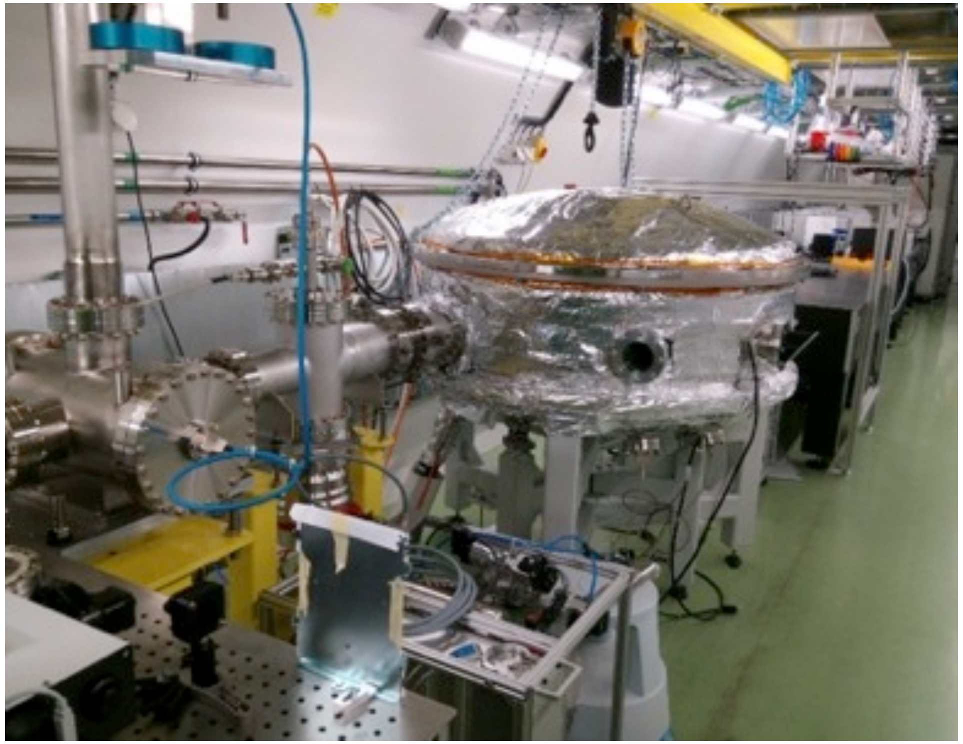


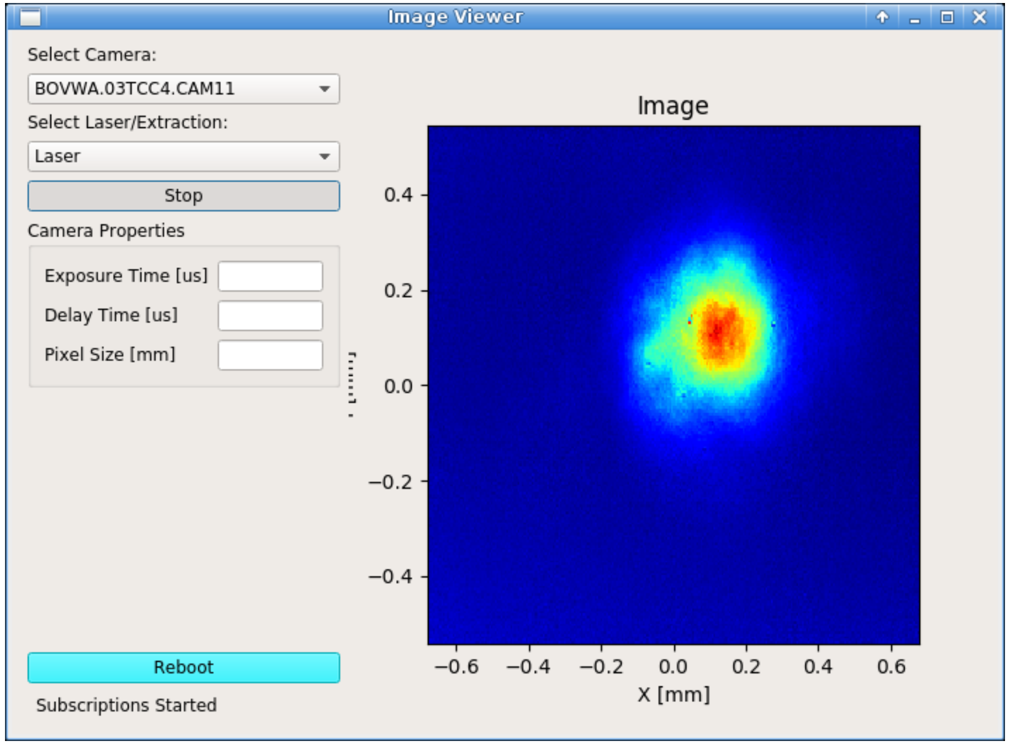
The AWAKE experiment requires a long plasma source that allows for the SMI to develop and subsequently, for the modulated proton beam to sustain a high-gradient wakefield in the plasma.

The 10 meter long Rubidium vapor cell at AWAKE is the longest plasma source for wakefield experiments in the world. The device requires a complex thermal feedback system in order to maintain constant vapor density throughout the cell.

E. Oz, F. Braunmuller, P. Muggli, MPP

# The AWAKE Laser System



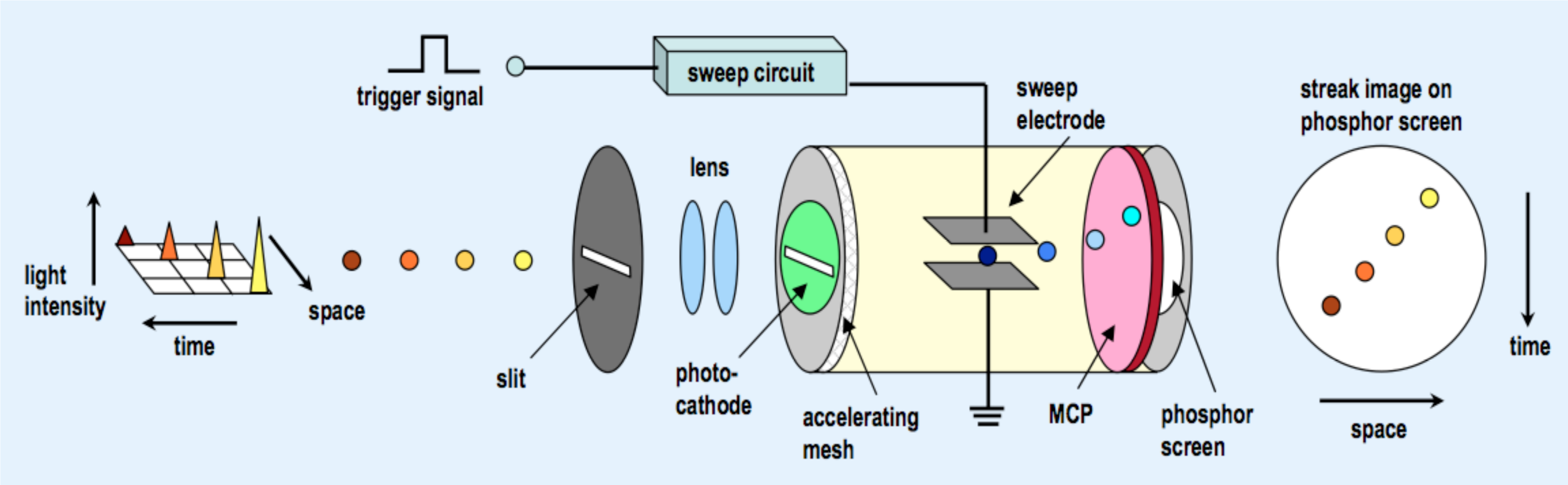



AWAKE uses a short-pulse Titanium:Sapphire laser to ionize the rubidium source. The laser can deliver up to 500 mJ in a 120 fs pulse envelope.

J. Moody, MPP

# Measuring SMI: Streak Camera

R. Ishbeck, PSI

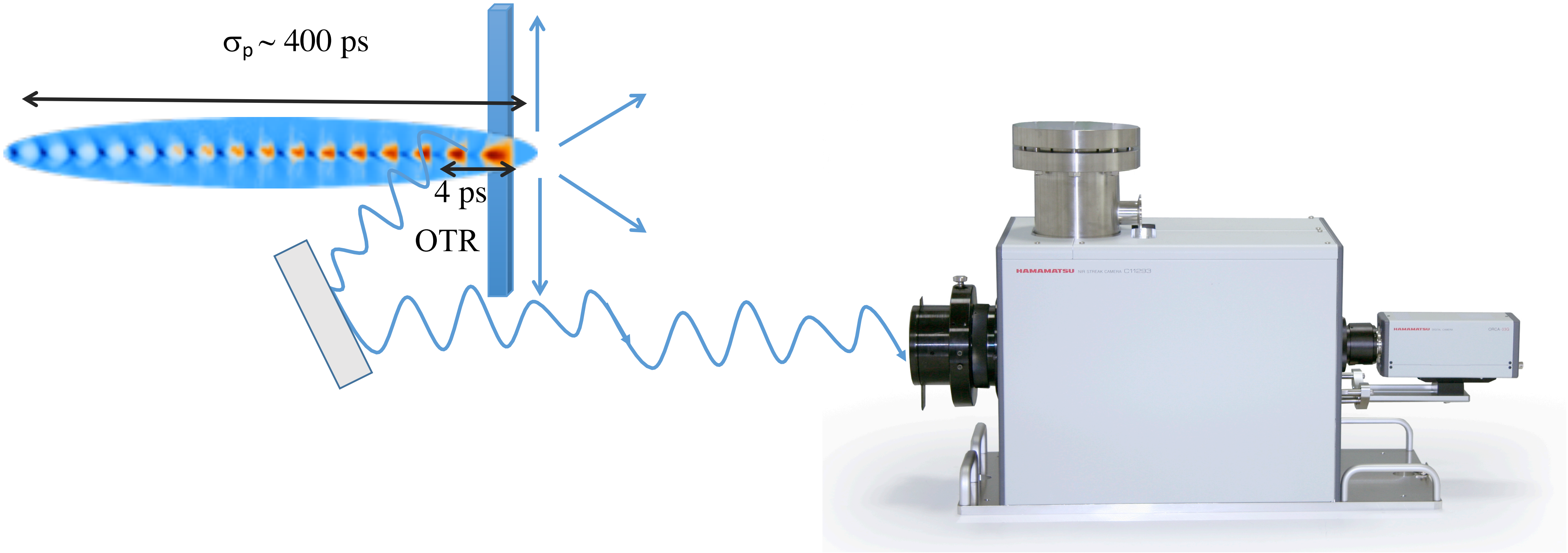



AWAKE uses plasma densities in the range of 1E13-1E15 cm$^{-2}$. The corresponding plasma frequencies are in the range of 30-300 GHz -> too fast to be measured by an oscilloscope.

Instead we use a special device called a *streak camera*. The streak camera turns un-measurable temporal phenomena into measurable spatial patters.

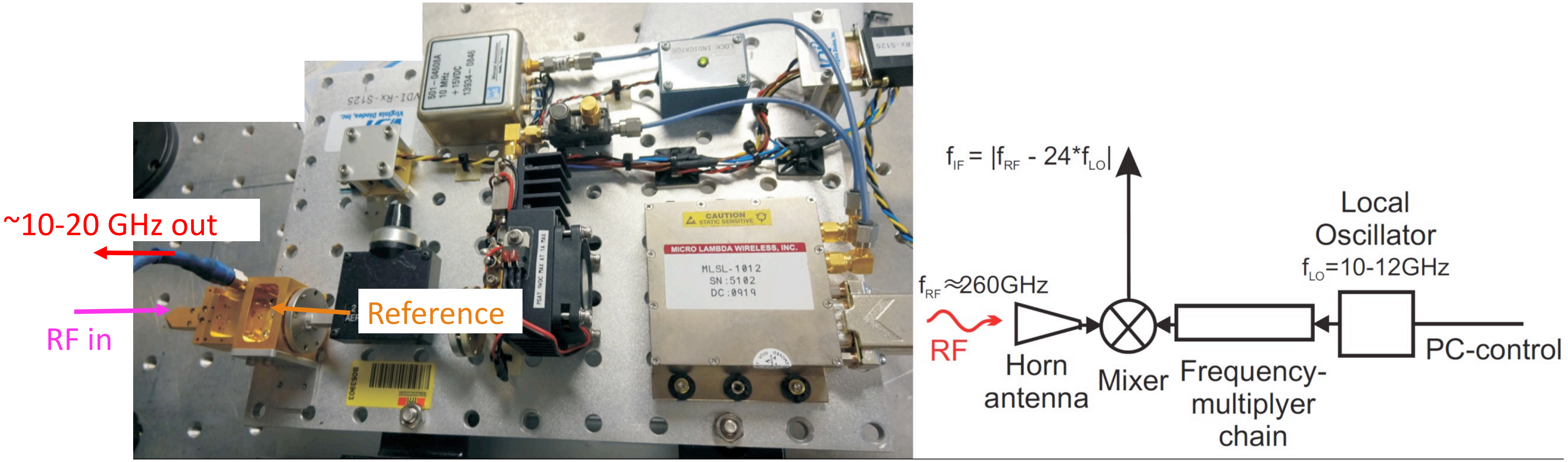
# Measuring SMI: Streak Camera

K. Rieger, MPP




The modulated proton bunch is sent through a metal foil where it generates optical transition radiation (OTR). This radiation is sent to the streak camera.

# Measuring SMI: Coherent Transition Radiation

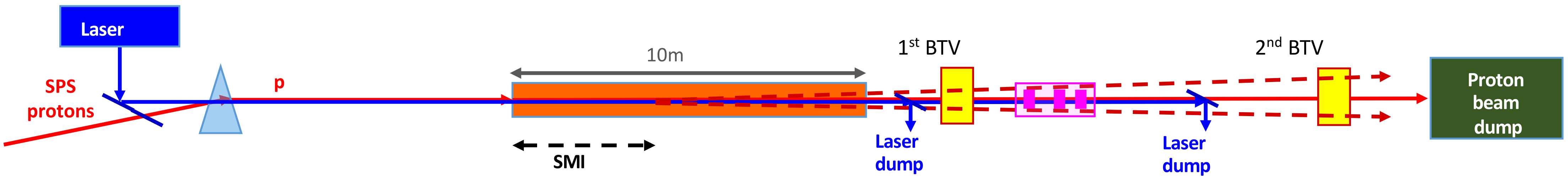



Conventional oscilloscopes cannot measure phenomena above a few tens of GHz. But by mixing the CTR signal with a signal of known (similar) similar frequency, you can measure the resulting beatwave on a normal scope.

This measurement is an excellent complement to the streak camera, which is resolution limited at the highest frequencies.

F. Braunmuller, M. Martyanov, MPP

# Measuring SMI: Indirect Measurement




This schematic of the experiment shows the diagnostics downstream of the plasma cell.

The protons in the defocusing phase of the wake diverge and appear as halos on two of the downstream screens.

By measuring the size of the halos on these screens, we can deduce the kick to the protons, and therefore the strength of the wake.

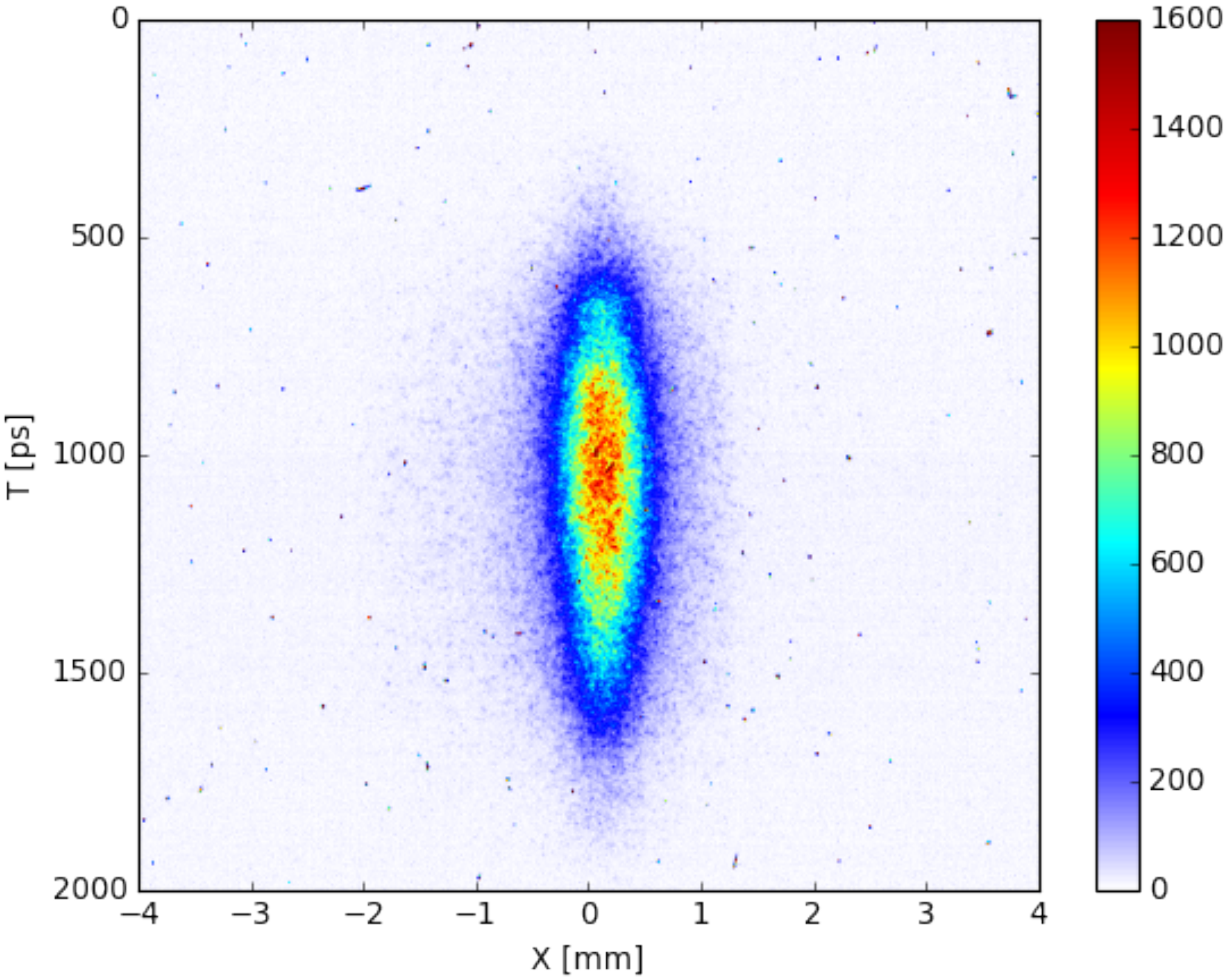
M. Turner, CERN

# Results!

# Nominal Beam

The SPS delivers a 400 GeV proton beam with 3E11 $p^+$, and an rms bunch length of approximately 400 ps (12 cm).

The bunch is typically straight with no visible structure.



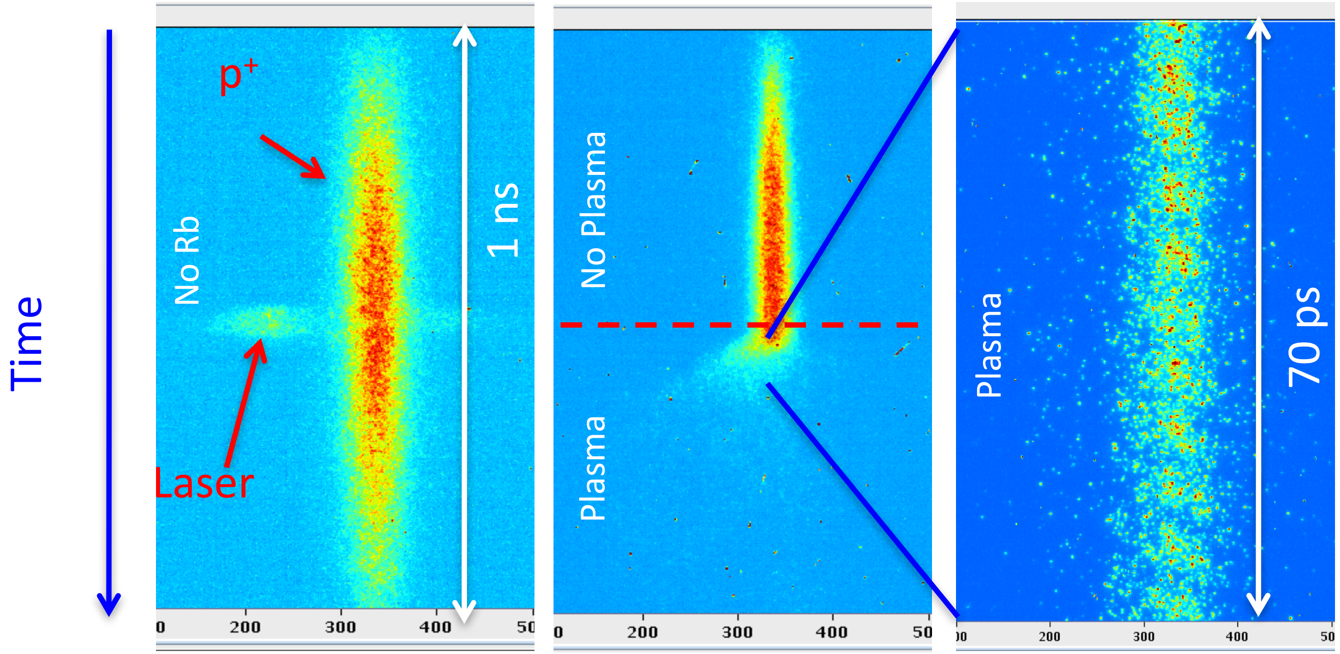
# Observation of Seeded SMI

The laser pulse ionizes the plasma about mid-way through the beam.

The seeded beam undergoes microbunching in the region trailing the plasma.

The microbunching is at the expected plasma frequency.

$n_{Rb}$=3.7x$10^{14}$cm$^{-3}$, $f_{mod}$~164GHz




**PRELIMINARY!**

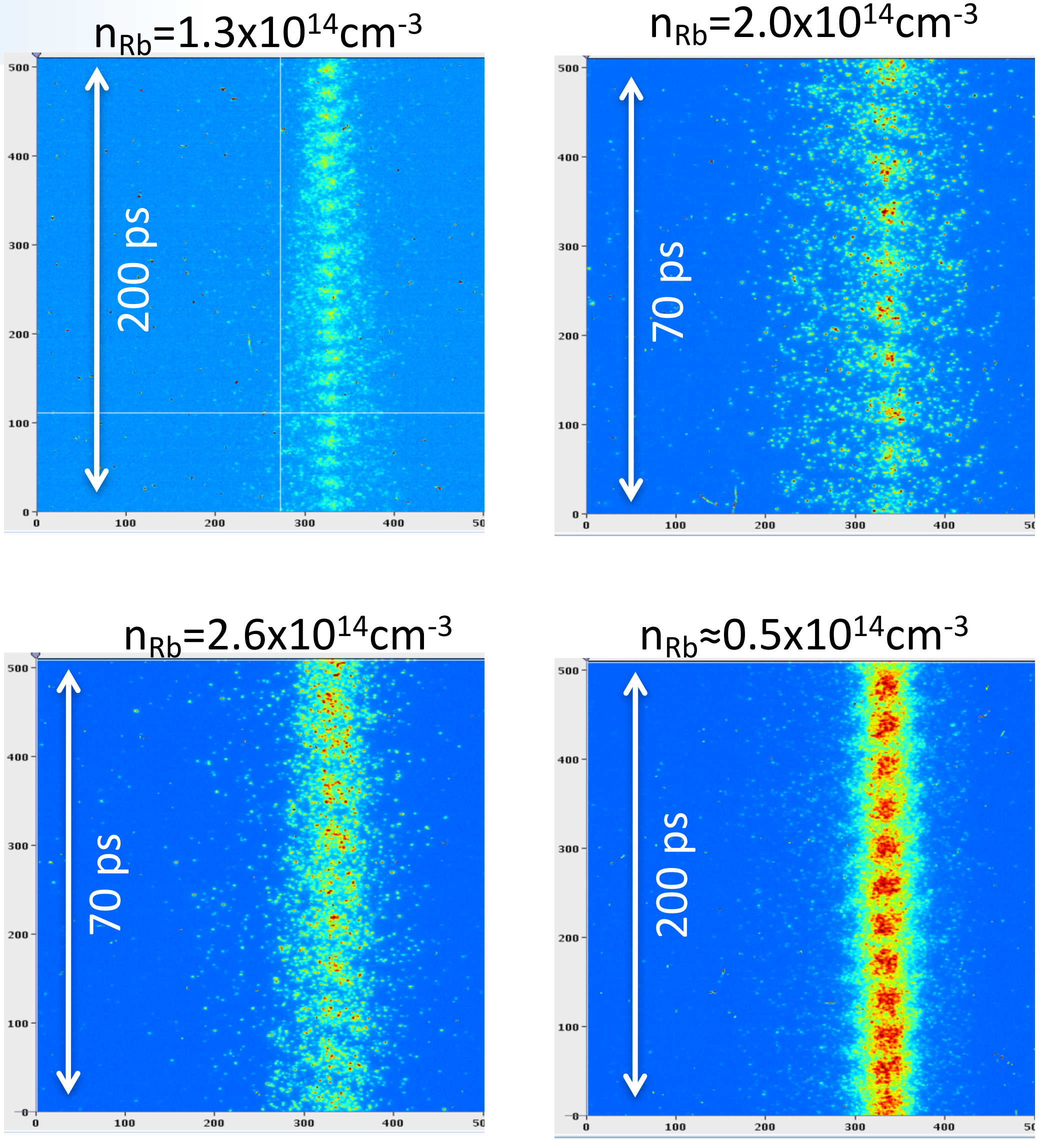
K. Rieger, CERN

K. Rieger, CERN

# Observation of Seeded SMI

We observe strong, persistent microbunching for a range of densities.

Seeding is a critical ingredient for producing many periods of microbunches along the beam.

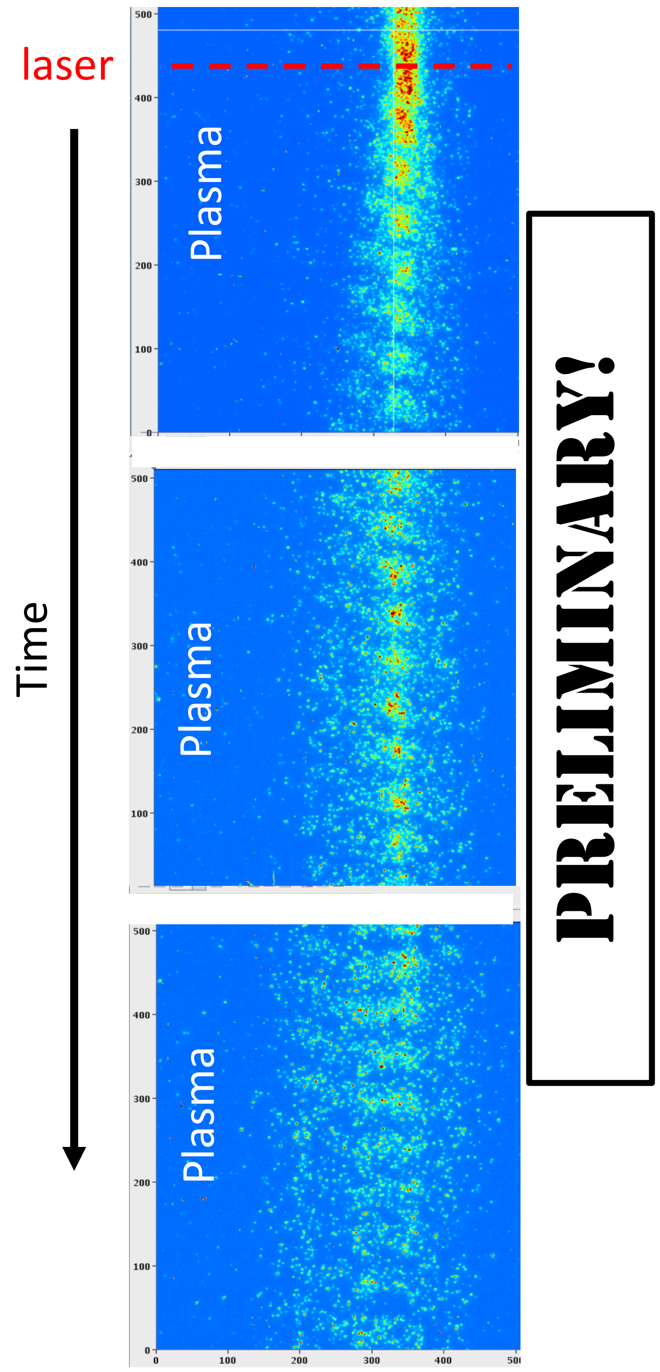



PRELIMINARY!

# Observation of Persistent Microbunching

We scan the timing of the streak camera relative to the position of laser ionizations to attempt to observe the total number of microbunches in the beam.

Persistent microbunching is a good indication that the seeding is working and that a large amount of energy is transferred to the plasma wake.

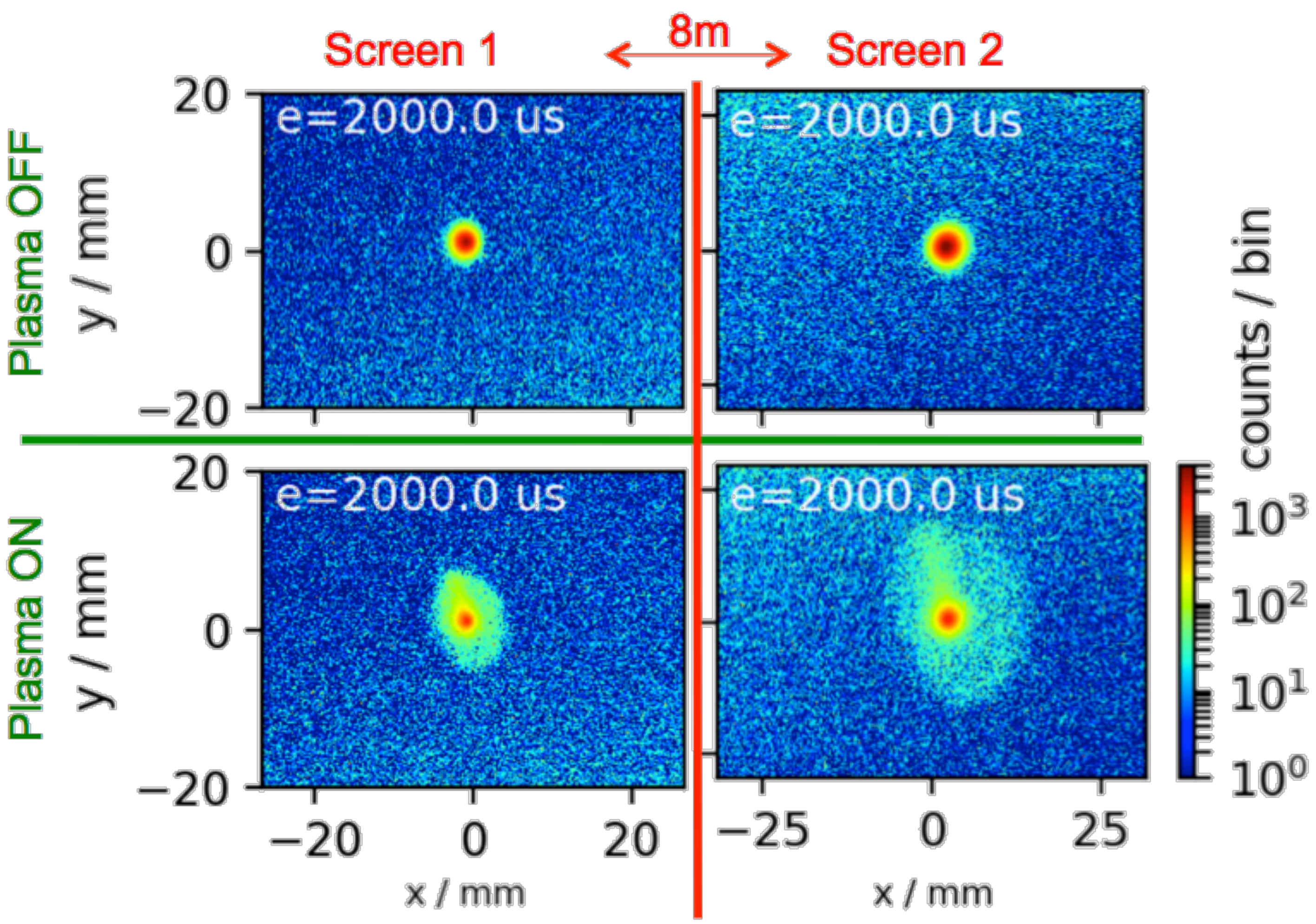



K. Rieger, CERN

# Indirect Observation of SMI

Protons that are defocused by the SMI form a halo around the beam centroid when measured downstream of the plasma.

By measuring the size of the halo, we can deduce the deflection angle, and therefore the strength of the wake in the plasma.




**PRELIMINARY!**

M. Turner, CERN

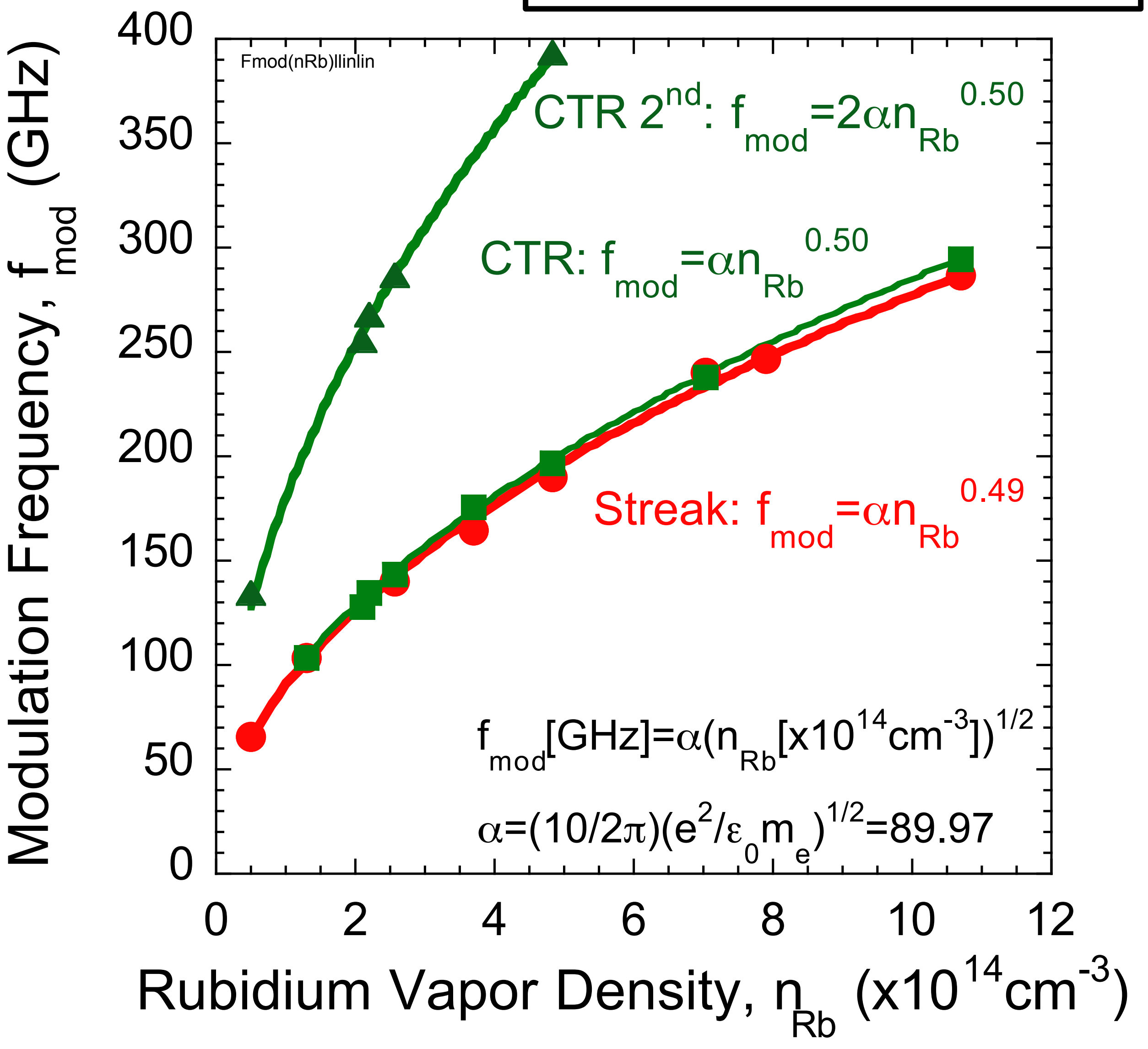
# Measurements of the Plasma Frequency

**PRELIMINARY!**

The Coherent Transition Radiation (CTR) diagnostic measures the oscillating field of the beam as it passes through a thin metal foil.

This diagnostic can measure the frequency of oscillations at the highest densities where the streak camera is less sensitive.

The measurement exactly matches prediction from theory.




F. Braunmuller, M. Martyanov, K. Rieger, MPP

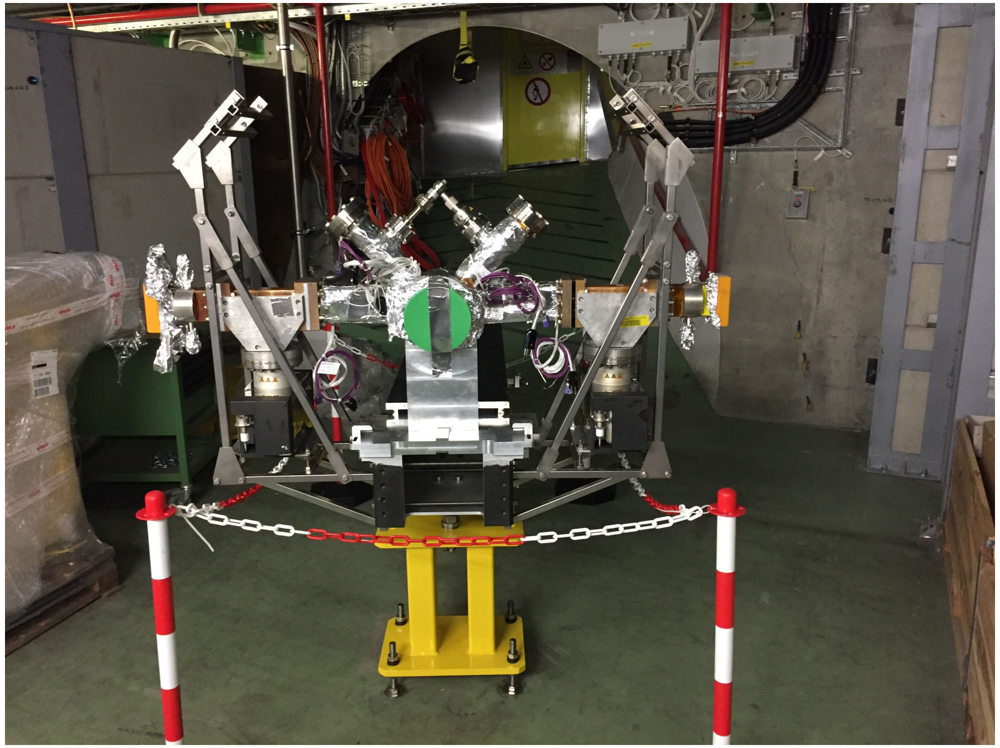
# Results Summary

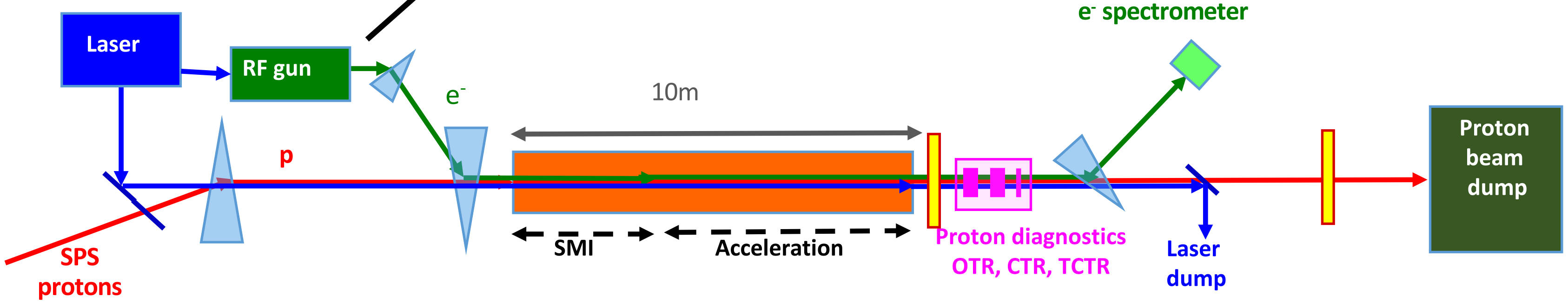
- Successful detection of SMI at AWAKE!
- Effect is present over full range of densities tested and scales with the plasma frequency.
- We also observe the hosing instability, but we are able to suppress it by seeding the SMI instability.
- Under good conditions, we observe microbunching throughout almost all of the beam trailing the laser.
- Next run in August. We will examine optimal conditions and tolerances for microbunching.

# Future Plans: Electron Injector

We are currently installing an RF gun and building up a 20 MeV $e^-$ beamline for transporting electrons to the plasma cell.

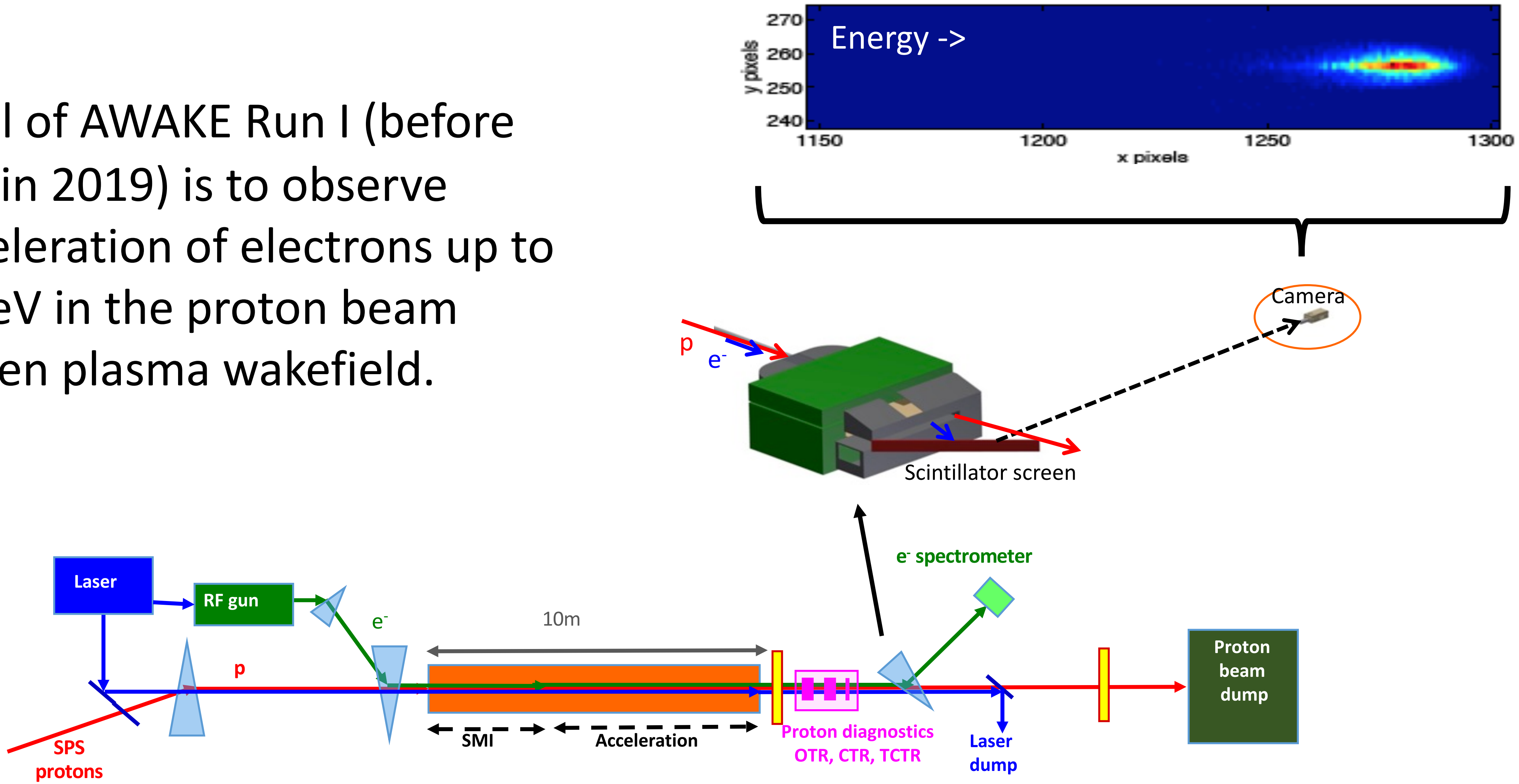
The electron beamline commissioning will take place this fall. The first injection experiments will be next year.



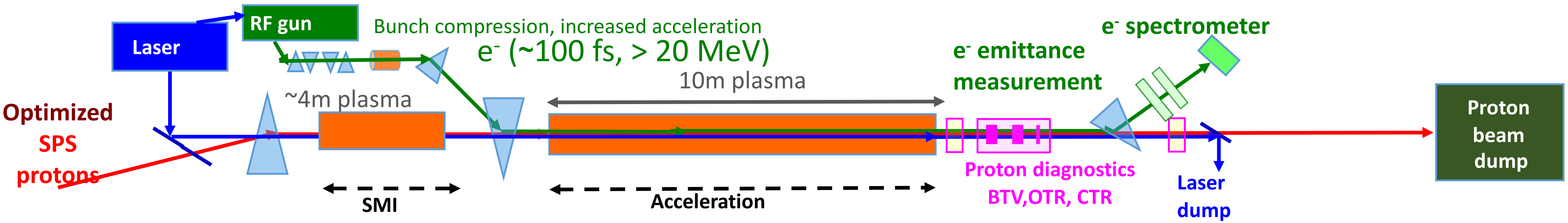


# Future Plans: Acceleration of Electrons

Goal of AWAKE Run I (before LS2 in 2019) is to observe acceleration of electrons up to 1 GeV in the proton beam driven plasma wakefield.



# Future Plans: Pre-Modulate Beam




For AWAKE Run II (following LS2 in 2021) we plan to split the modulation and acceleration stages. This will potentially lead to higher energy, lower emittance electron bunches.

Many concepts still under investigation at the moment.

# Conclusions

- AWAKE is off to a fast start thanks to the hard work of the collaboration.
- We have observed SMI. Now we try to understand optimal seeding parameters and tolerances.
- New electron source is coming online soon.
- AWAKE aims to observe acceleration of electrons in 2018.
- Plans for AWAKE Run II are rapidly evolving as we learn about proton beam-driven SMI.