PhD Defence

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University of Oslo
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Thesis Title

Beam Loading in a Proton Driven Plasma Wakefield Accelerator

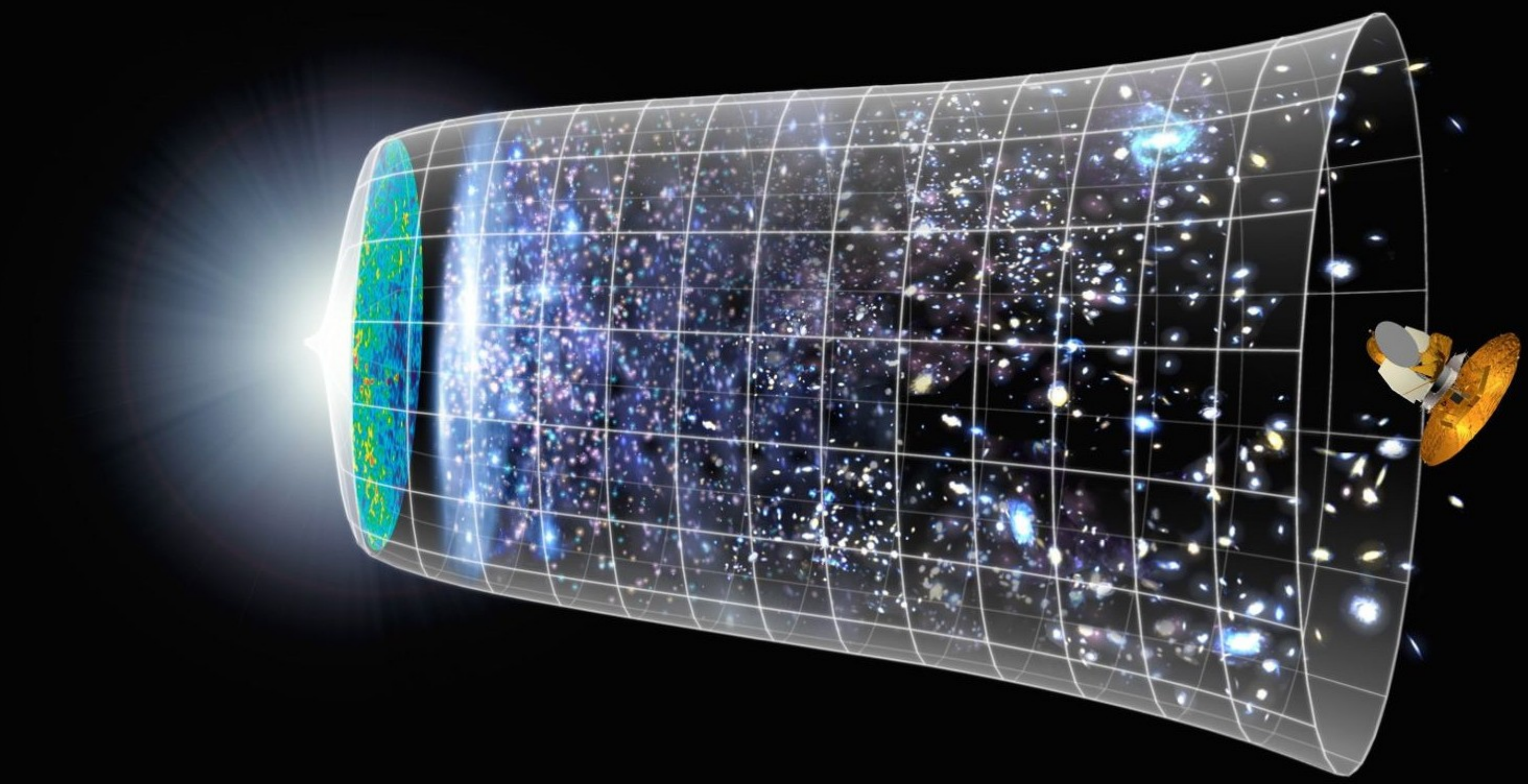
Thesis Advisors

Erik Adli – University of Oslo

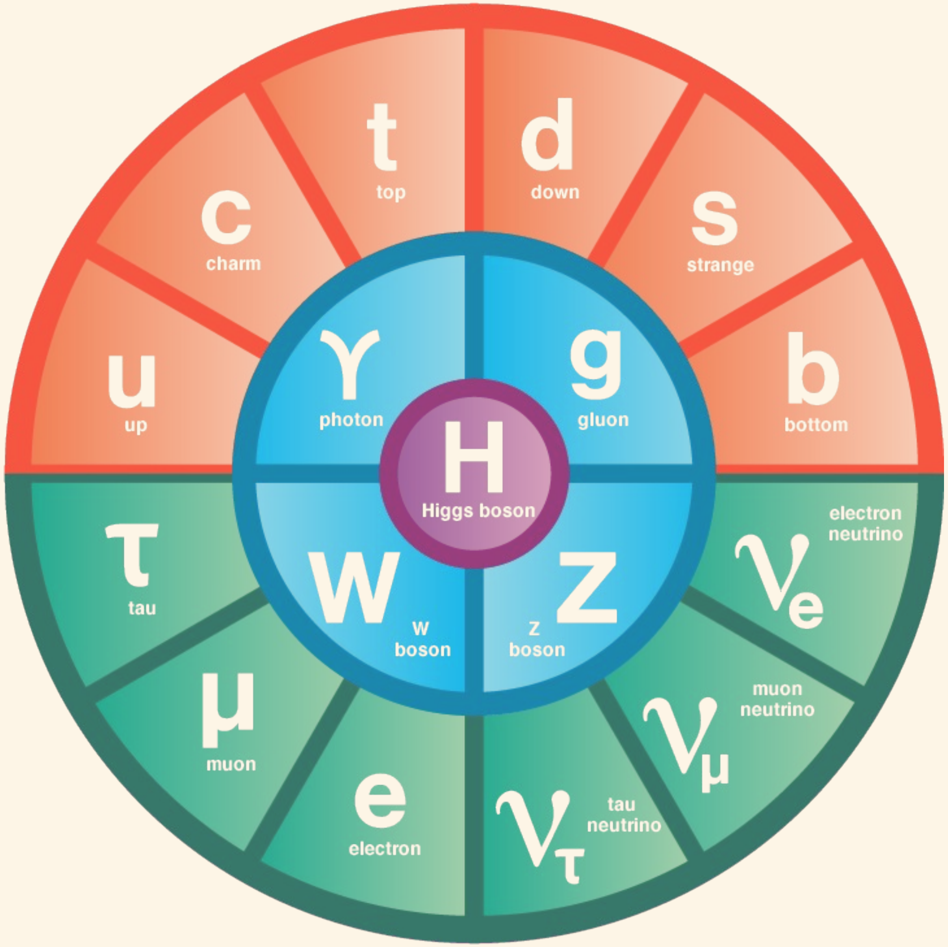
Patric Muggli – Max Planck and CERN

High Energy Physics
… and Why We Study It

High Energy Physics is the study of the universe at very high energies ...



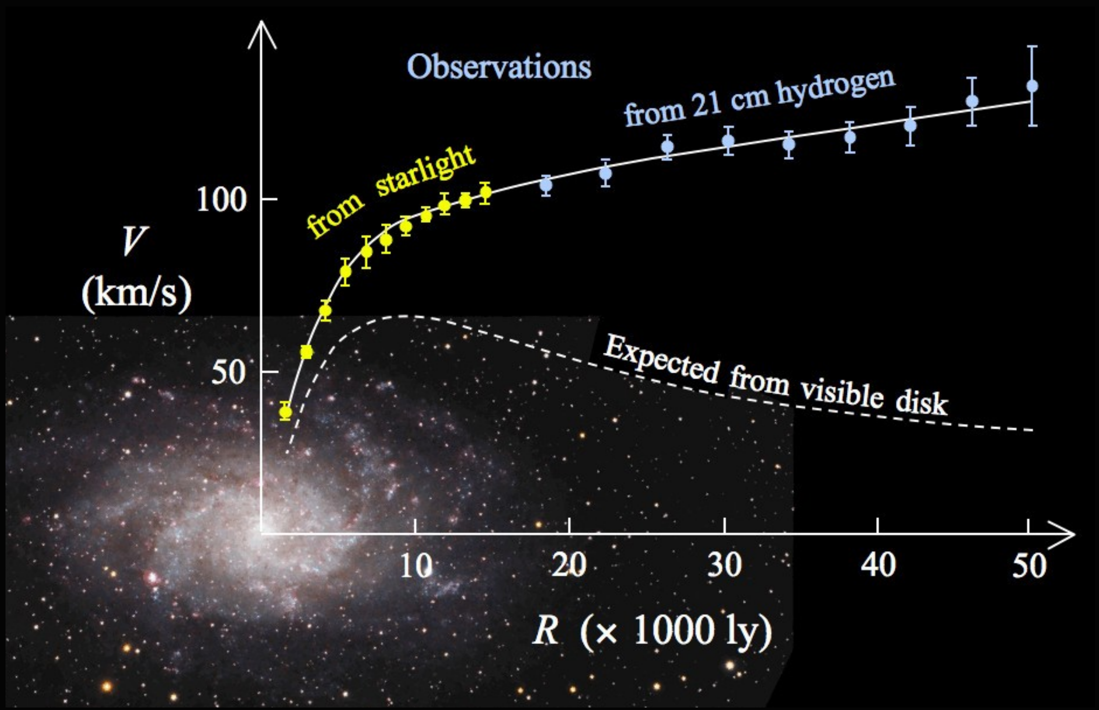
... like the conditions at the very beginning



We study the universe by looking at the smallest building blocks we know of.

The Standard Model of Particle Physics describes the building blocks of the matter we see around us every day.

But there is more ...



The galaxies in our universe are spinning faster than we first expected.

Implication: They are heavier than we thought, and may contain matter we cannot see or measure directly.

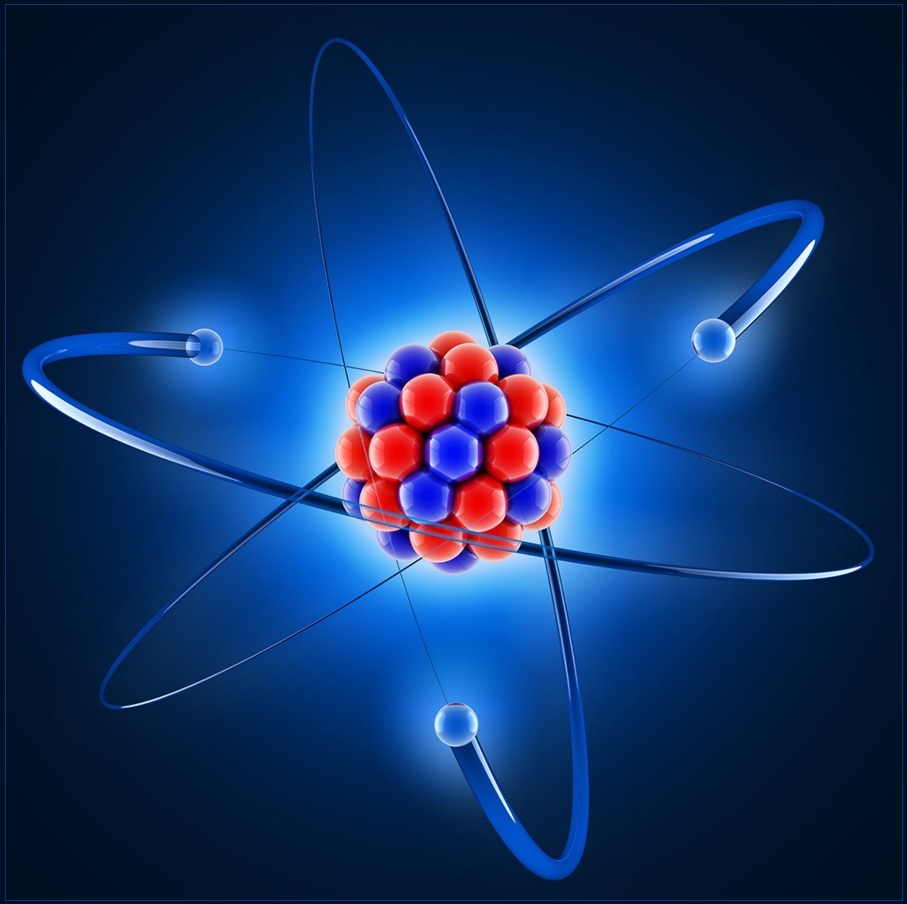
Vera Rubin, Kent Ford and Ken Freeman showed this by measuring the rotation of galaxies in the 1960s and 1970s.

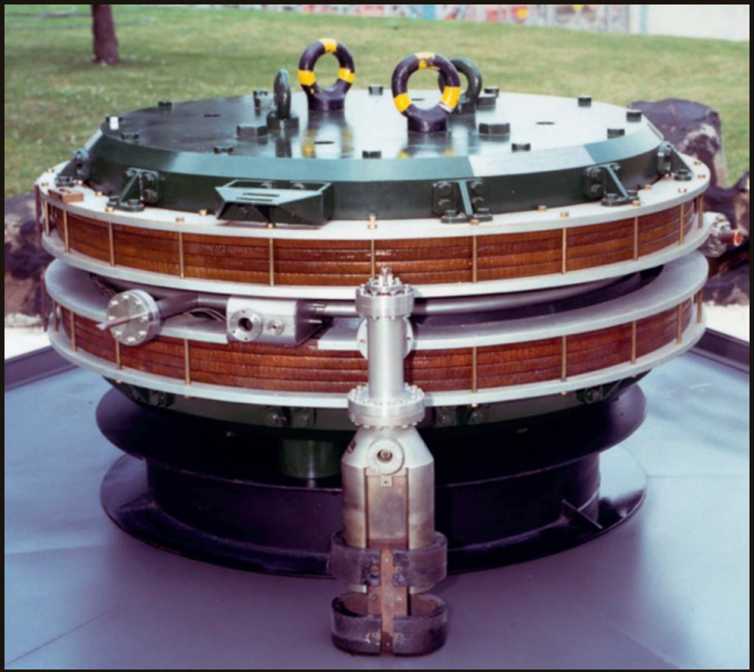
Ordinary matter is made of the lightest and most stable fundamental particles.

Heavier particles can be created by colliding lighter particles at high energies ...

… because energy and matter are connected:

$$E = mc^2$$

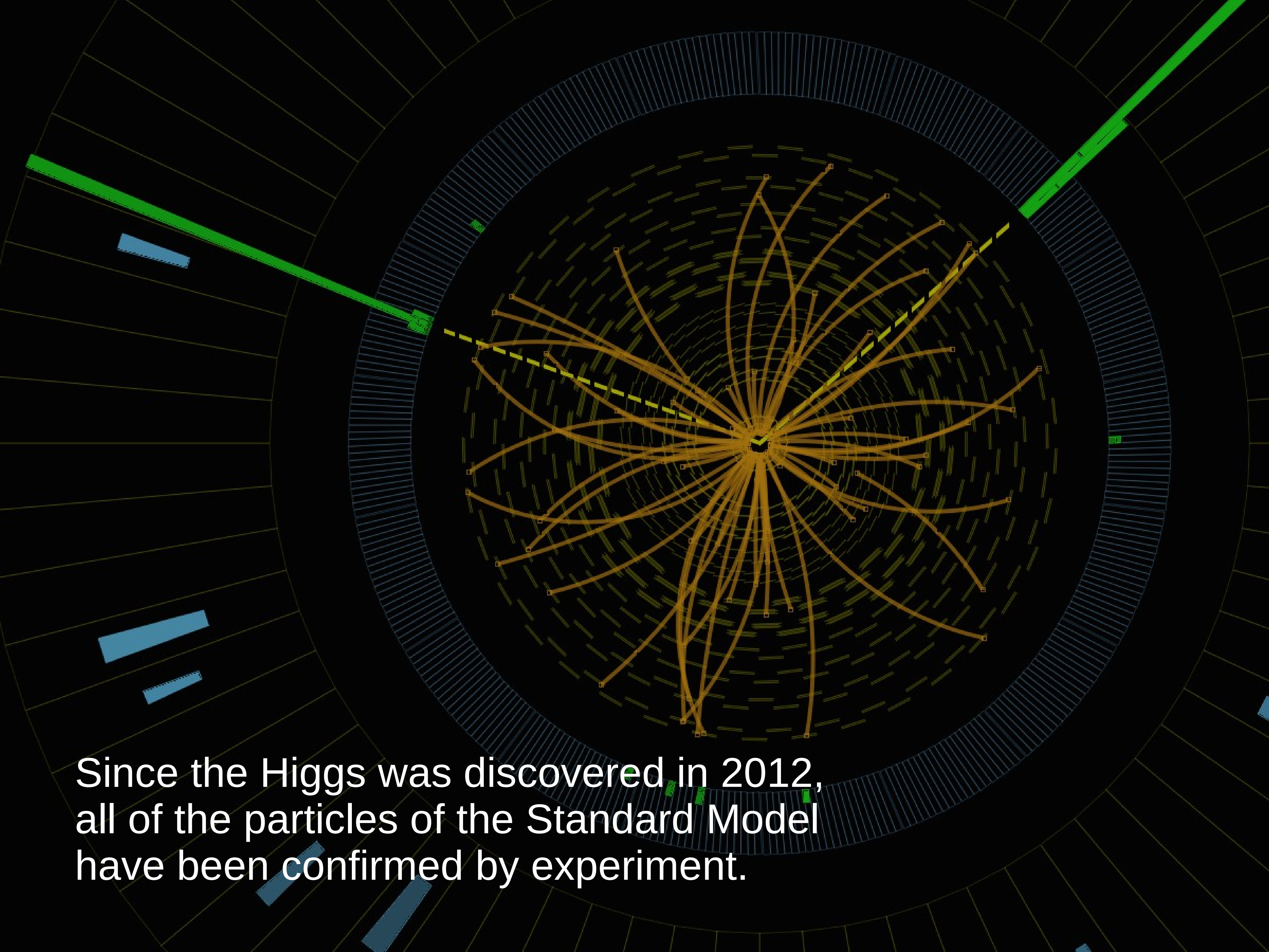




From the 4 m AdA electron–positron collider at LNF in Frascati, Italy in 1961 ...

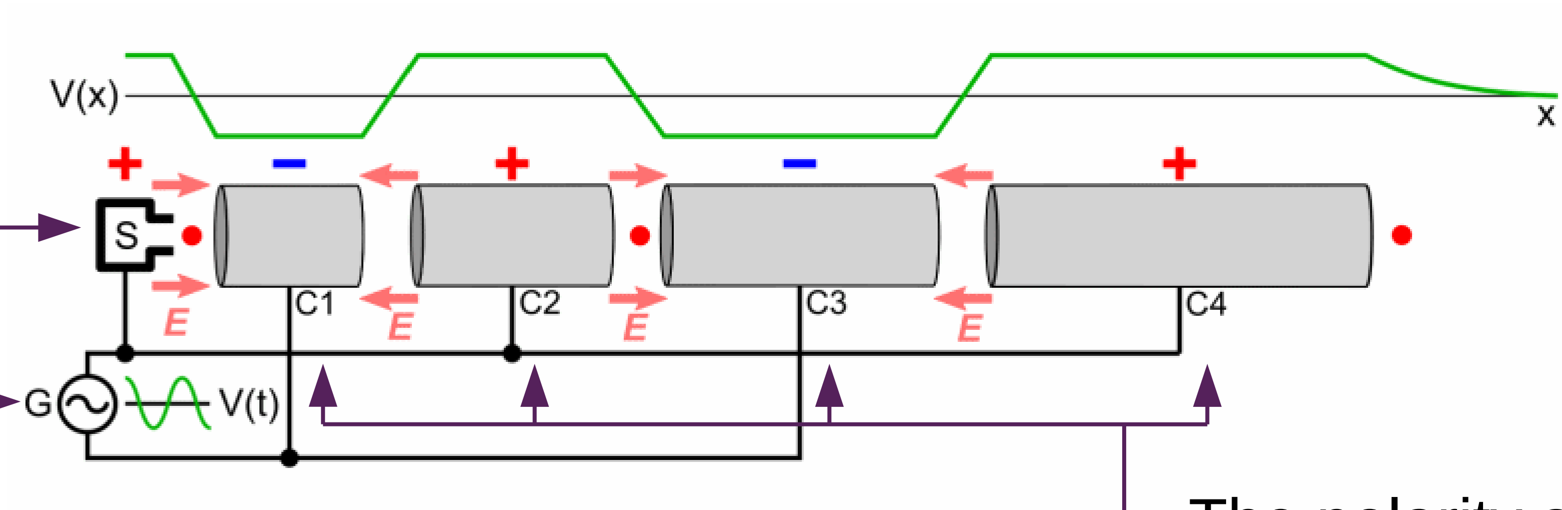
… to the 27 km Large Hadron Collider (LHC) at CERN completed in 2008 ...

… we have been building increasingly larger particle colliders.


Since the Higgs was discovered in 2012,
all of the particles of the Standard Model
have been confirmed by experiment.

A Brief Introduction to Accelerator Physics

The Principles of a Simple Linear Accelerator



A proton source

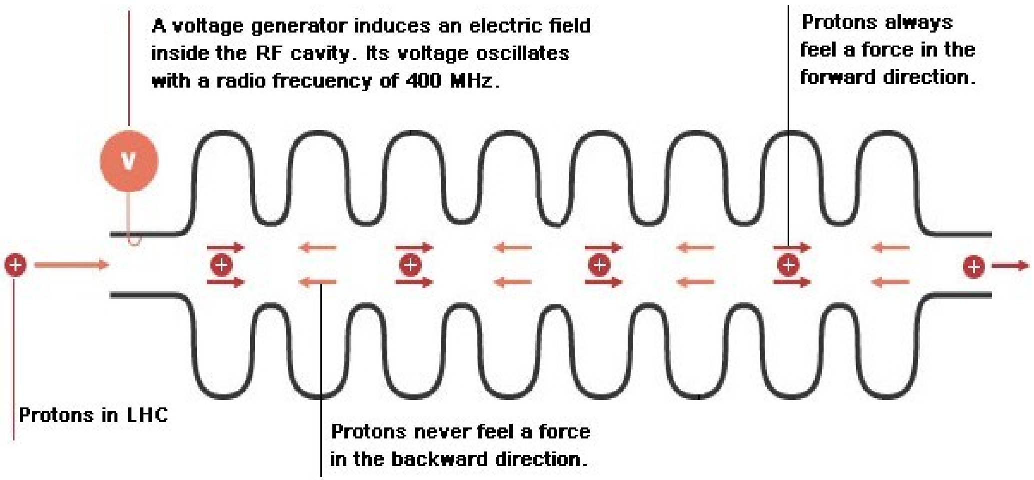
An alternating power source

Electrodes with alternating polarity

The polarity shifts at a frequency that ensures a particle, or bunch of particles, always sees an accelerating field.

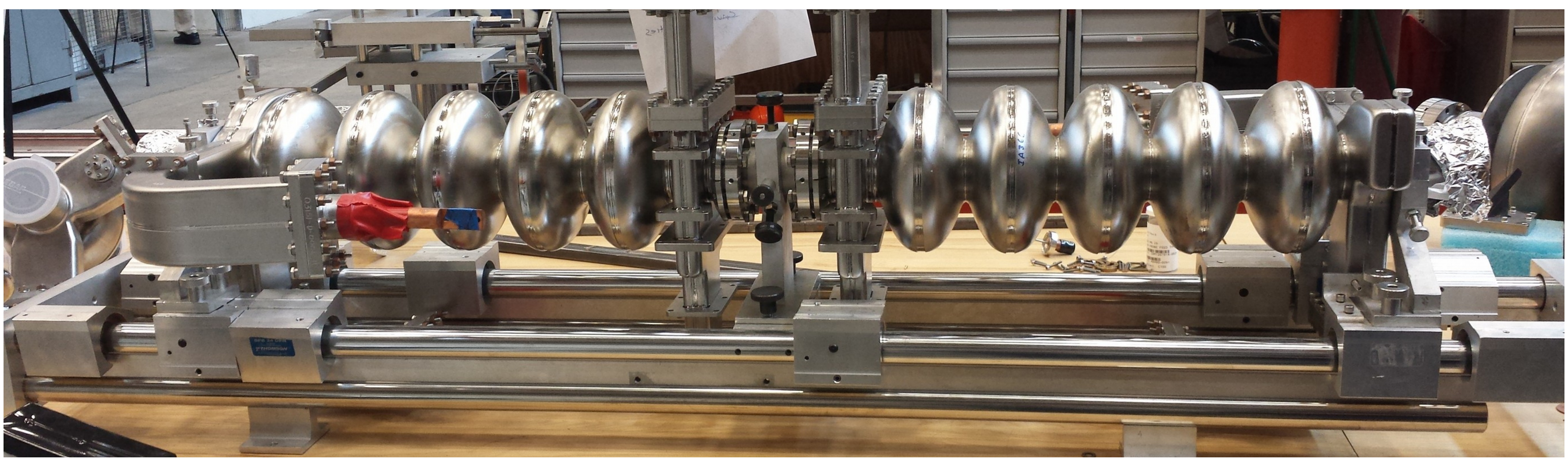
The original concept was developed by Norwegian physicist Rolf Widerøe in the 1920s, building on work by Gustav Ising.

Radiofrequency Cavities



Modern accelerators use RF cavities, which is an electro-magnetic resonator.

It produces standing microwaves that can be used to accelerate particles.

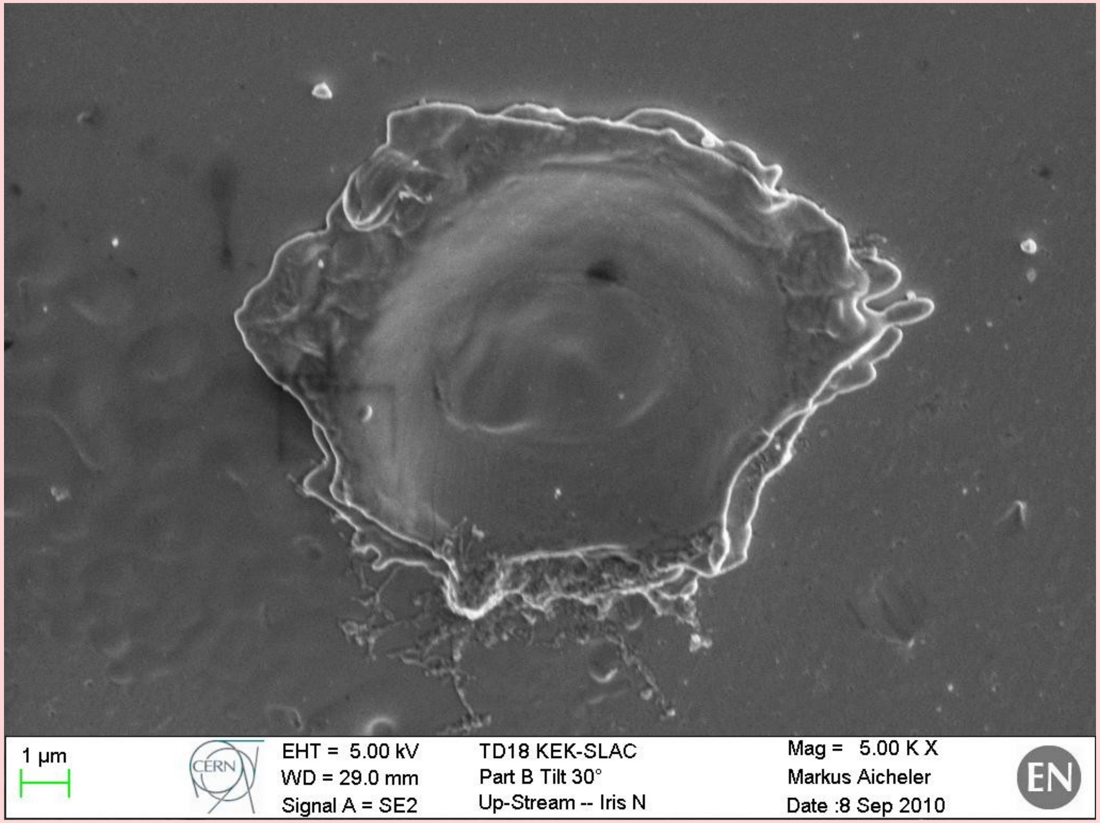


Production of RF Cavities at Jefferson Labs in Virginia, USA.

Radiofrequency Cavities

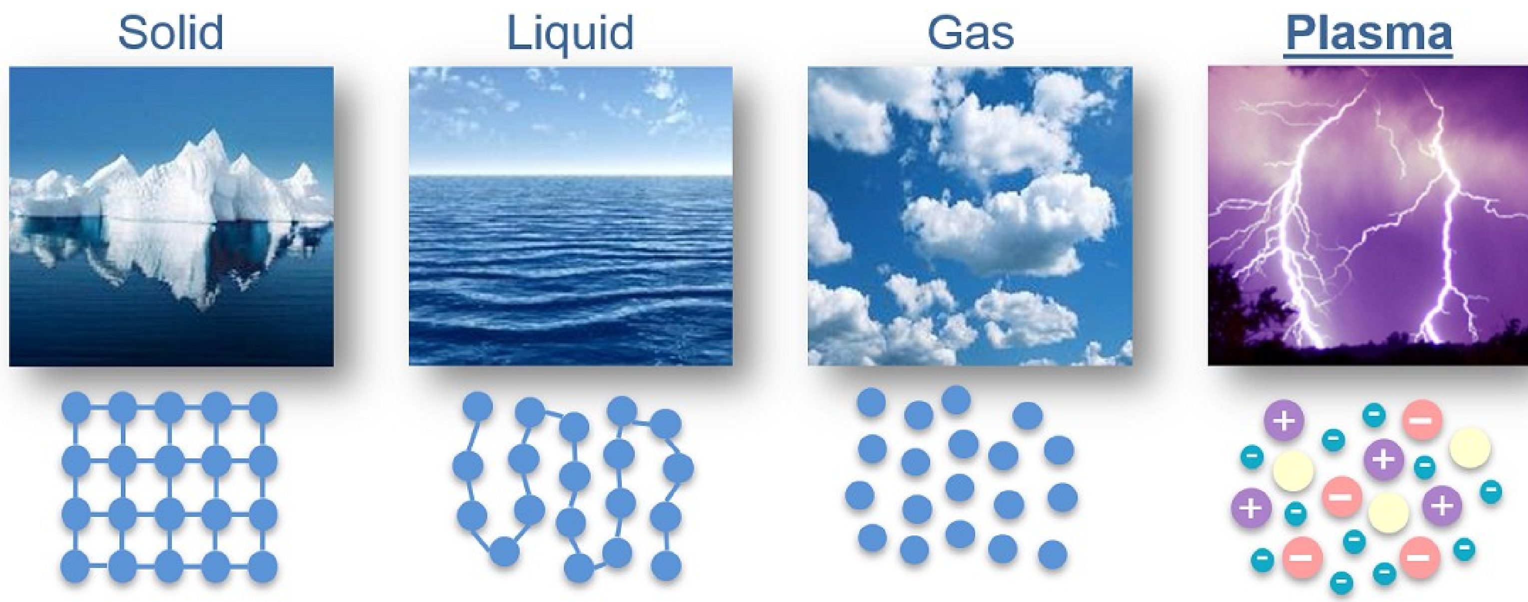
At very high voltages, the RF technology runs into problems with break downs via electric discharge.

This can cause damage in accelerators and must therefore be kept at a minimum.



The upper limit is ≈ 100 MV/m.

Making Waves with Plasma Wakefield Acceleration



What is plasma?

Plasma is the fourth state of matter where atoms are split into ions and electrons. In other words an ionized gas.

Collective motion of plasma particles can generate strong wakefields.

Key plasma parameters

$$\omega_{pe} = \sqrt{\frac{e^2 n}{\varepsilon_0 m_e}}$$

frequency

$$k_{pe} = \frac{\omega_{pe}}{c}$$

wave number

$$\lambda_{pe} = \frac{2\pi}{k_{pe}}$$

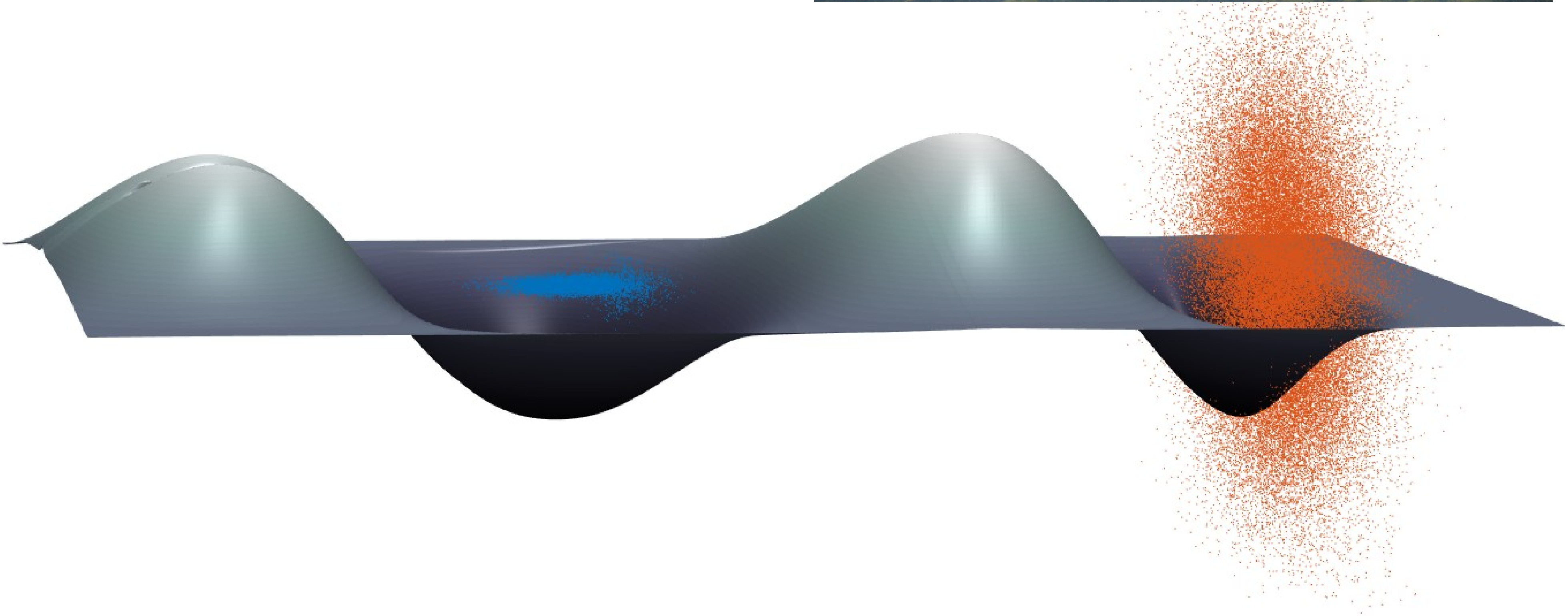
wave length

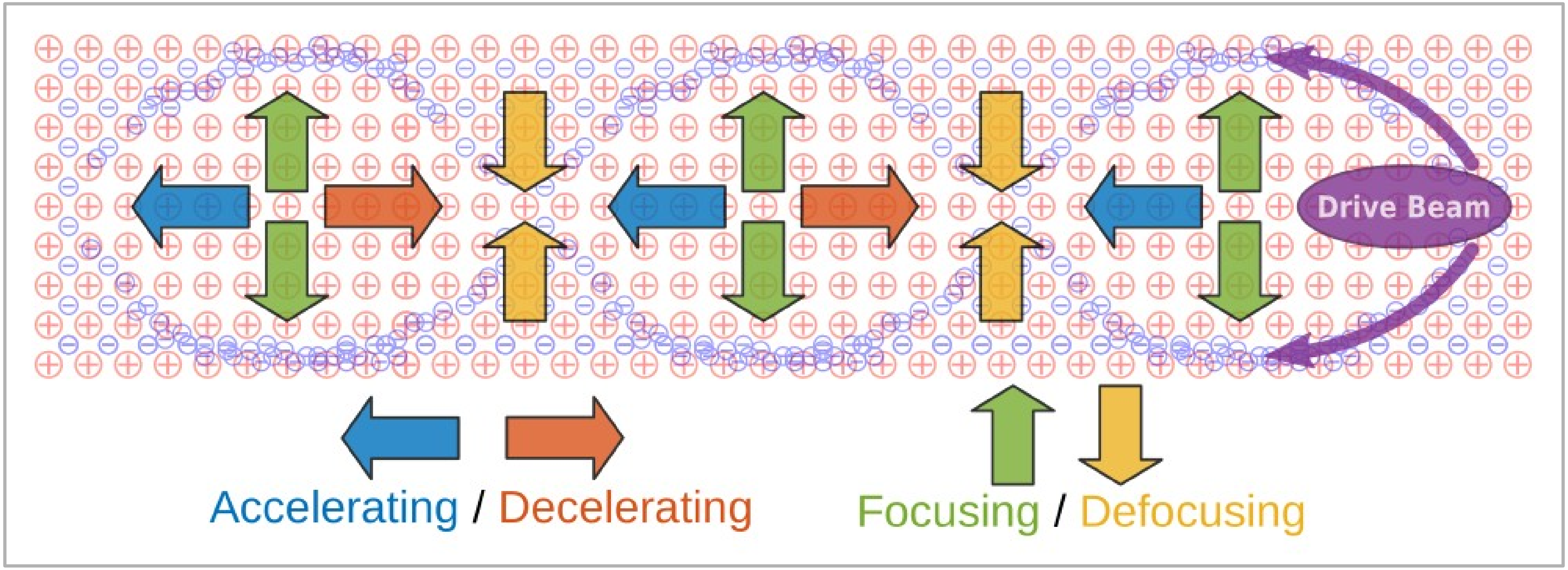
Plasma is already ionized or “broken down”, and can therefore sustain much higher field gradients than RF structures. On the order of 100 GV/m.

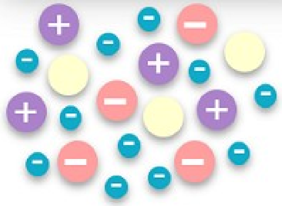
What is a Wakefield?

A beam at high energy, travelling through a plasma, will crate a strong electric field in its wake, analogous to objects in water.

These waves can hold a lot of energy, and this energy can be extracted again by other objects.



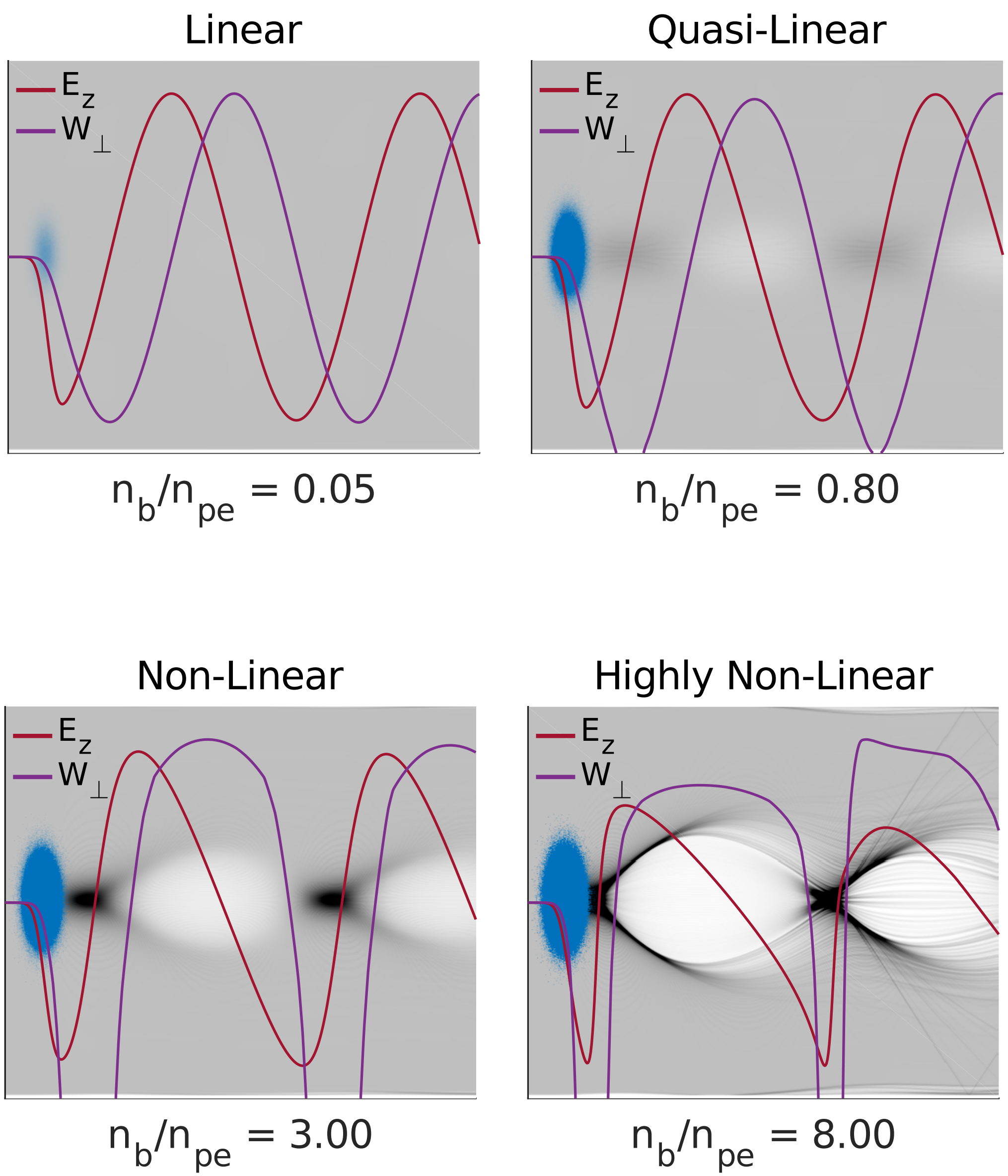




A beam of electrons push away plasma electrons, but heavy ions are more or less stationary.

The plasma electrons are then drawn back to the centre, and start oscillating.

This process can generate very strong electric fields.



Linear Plasma Regime

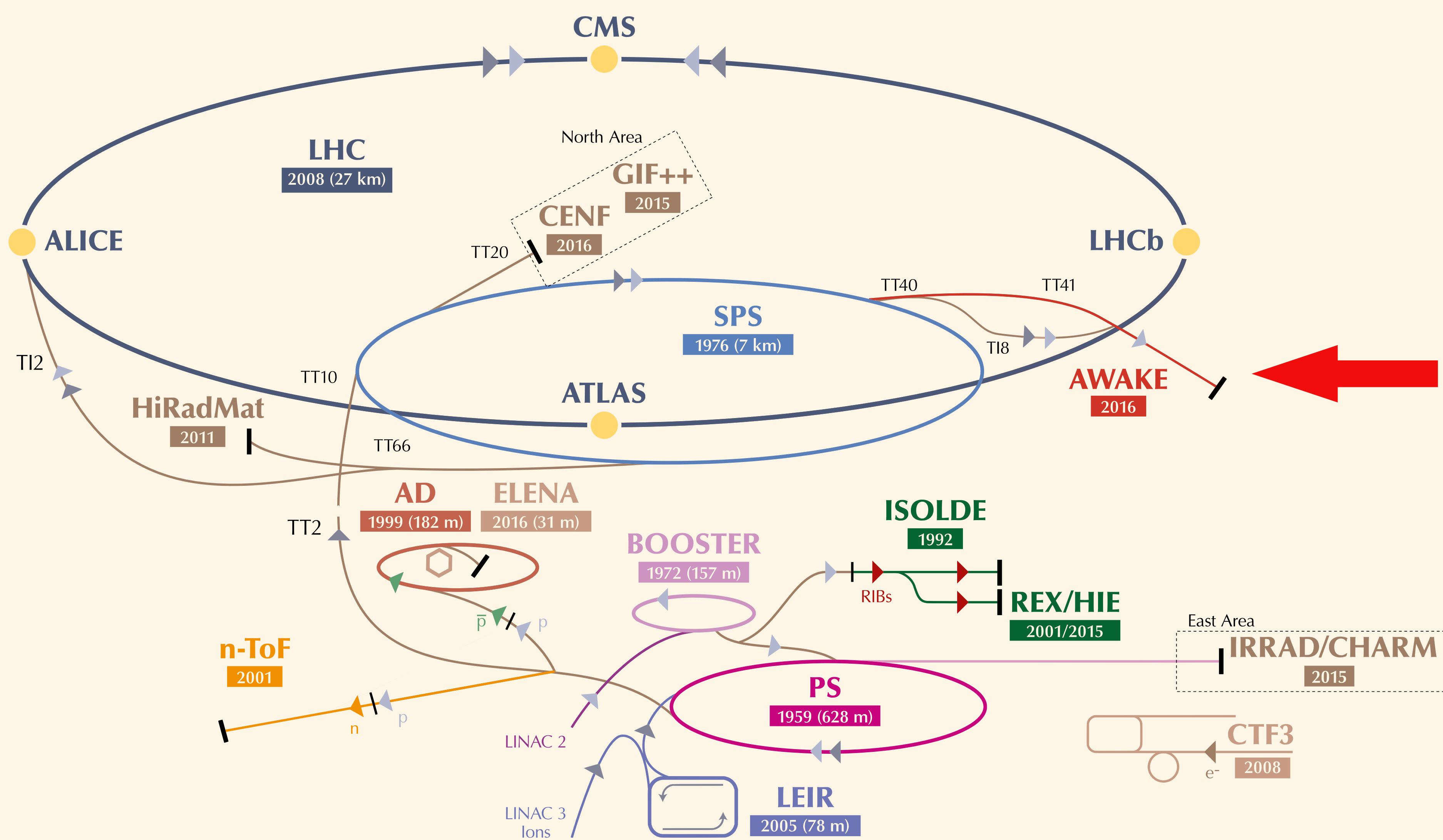
- + Well defined theoretically
- + Can be used for positrons
- − Weak accelerating fields, dropping with radius
- − Focusing is not uniform

Non-Linear Plasma Regime

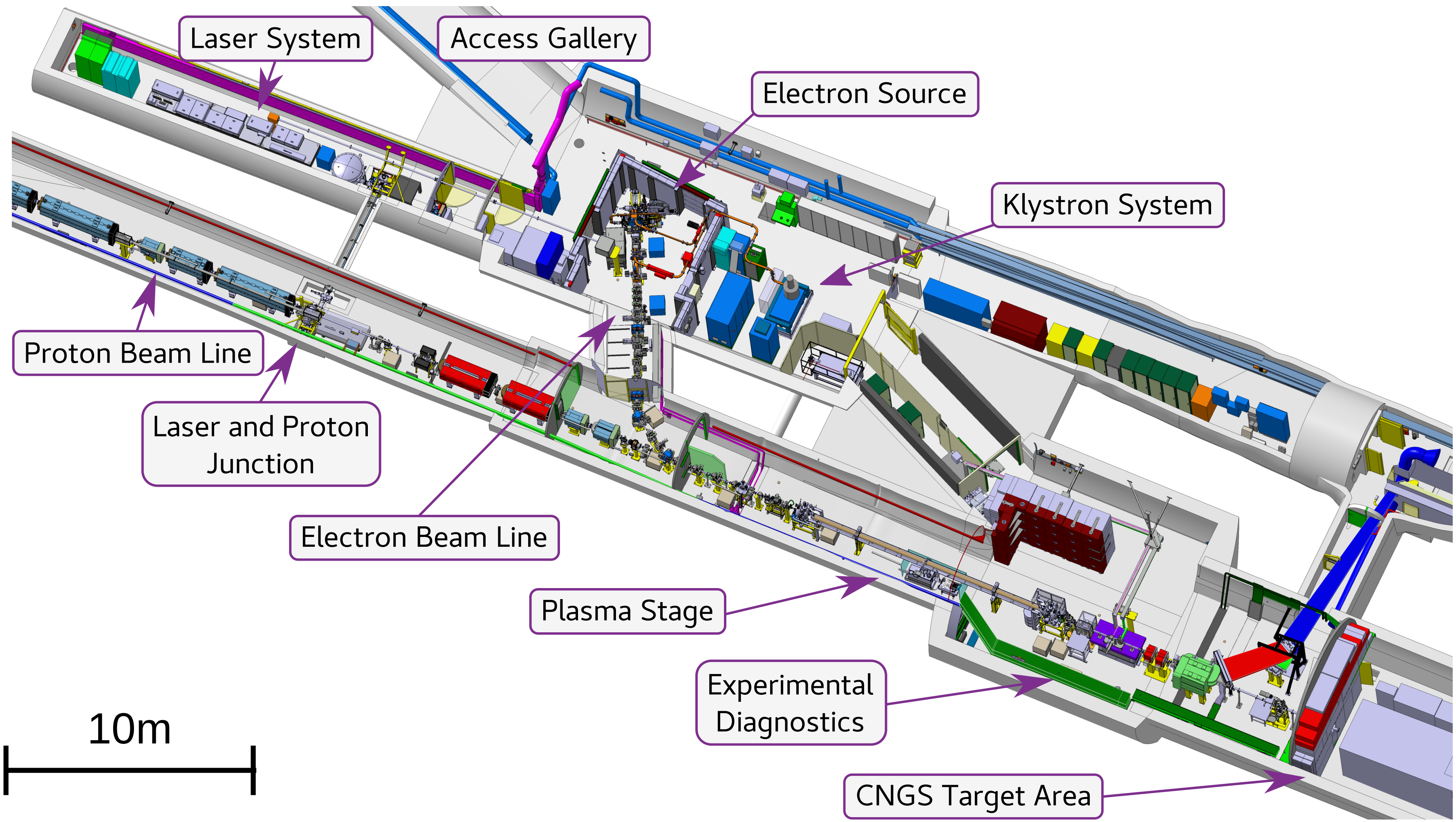
- + Strong, linear focusing
- + Strong and uniform accelerating field in bubble
- − Cannot be used for accelerating positrons

The Advanced Wakefield Experiment (AWAKE)

An overview of the CERN Accelerator Complex



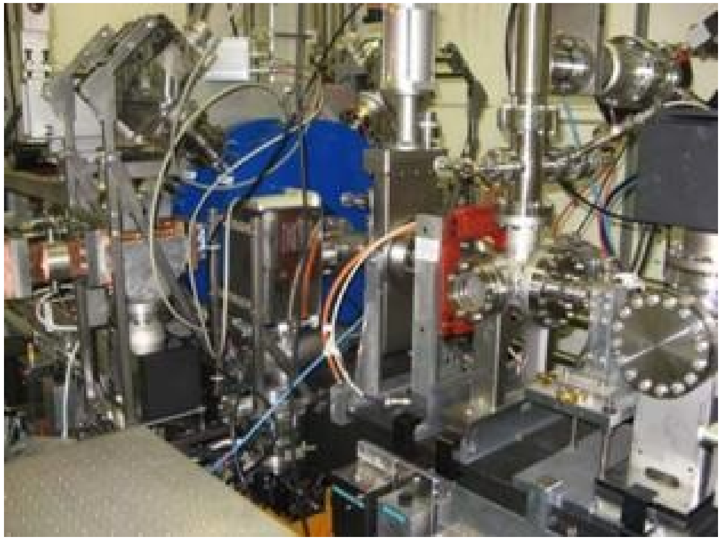
An overview the AWAKE experimental area



Photos from the AWAKE Experiment in the Tunnel

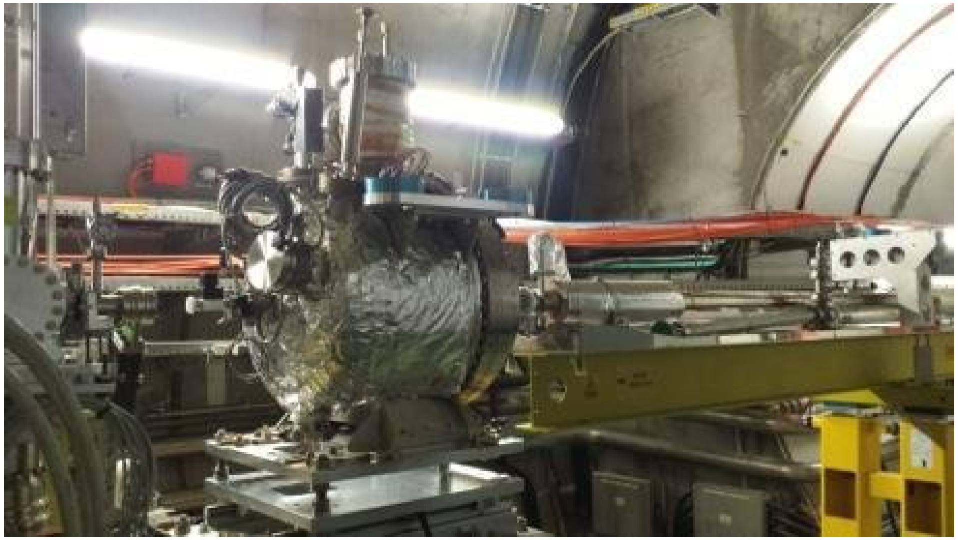
SPS Proton Beam Line.

Electron source

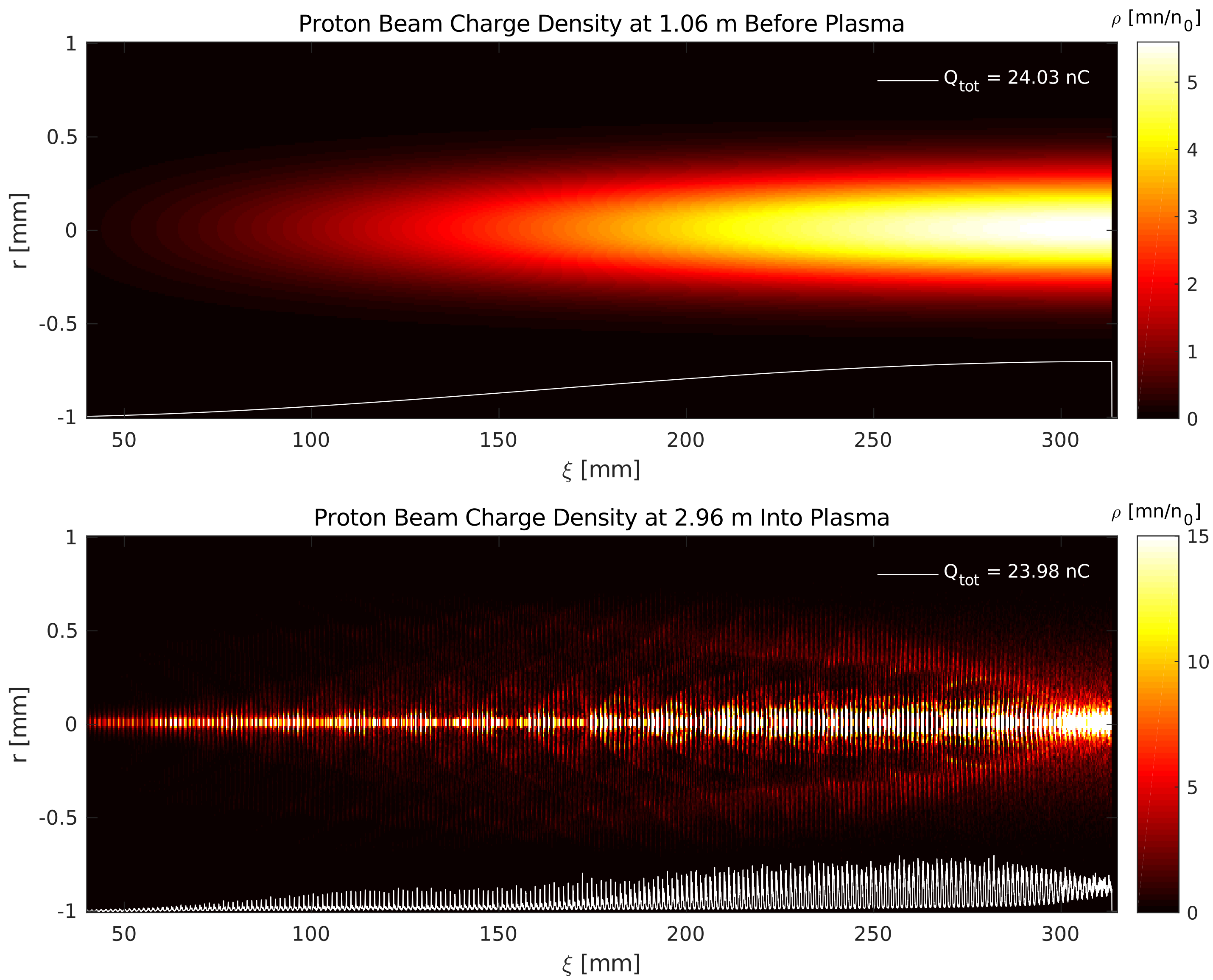


Laser

Plasma stage

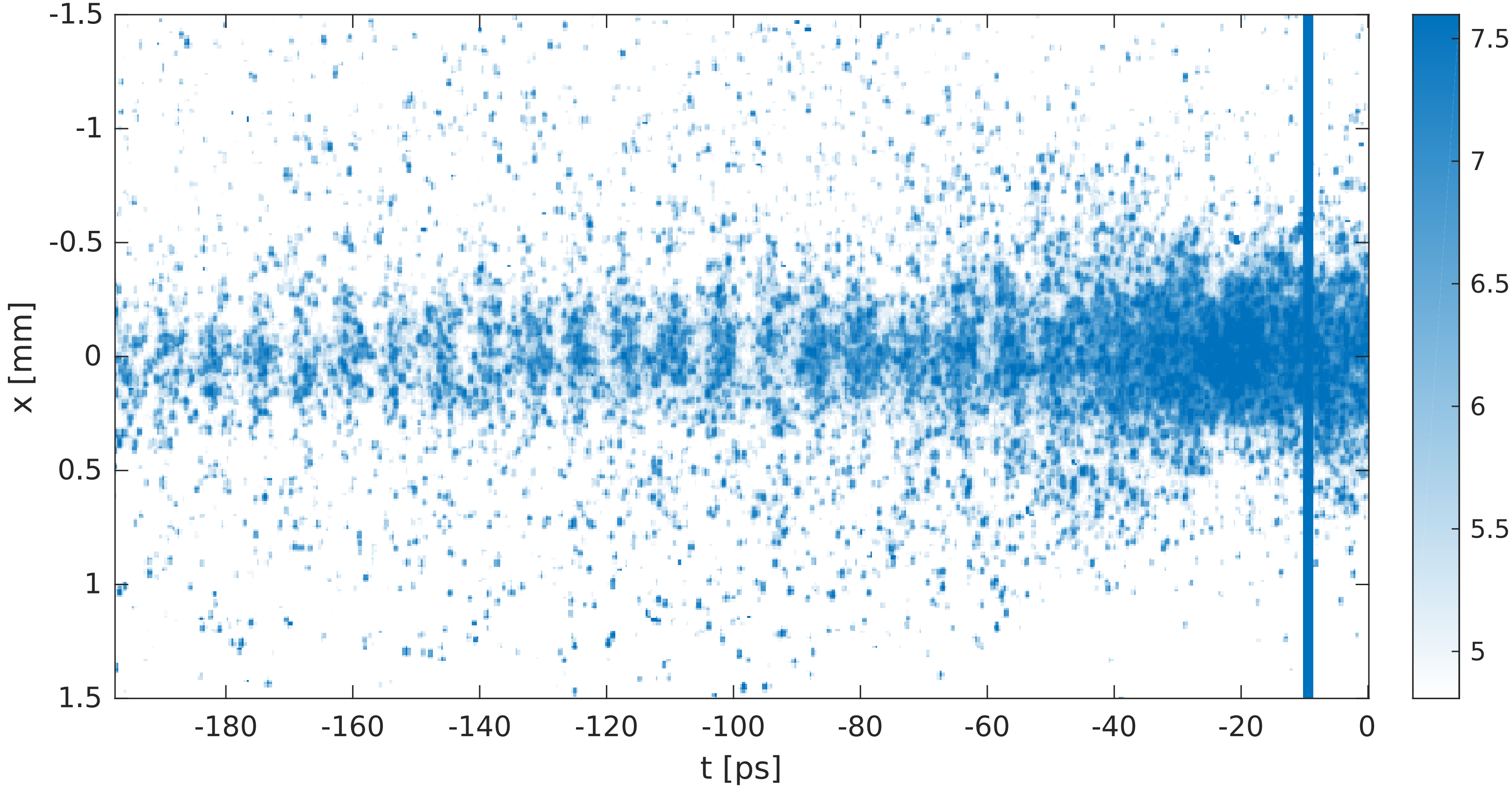


The proton beam delivered to AWAKE from the SPS is far too long.



However, due to an effect called self-modulation, the beam is transformed into a train of short bunches by the plasma.

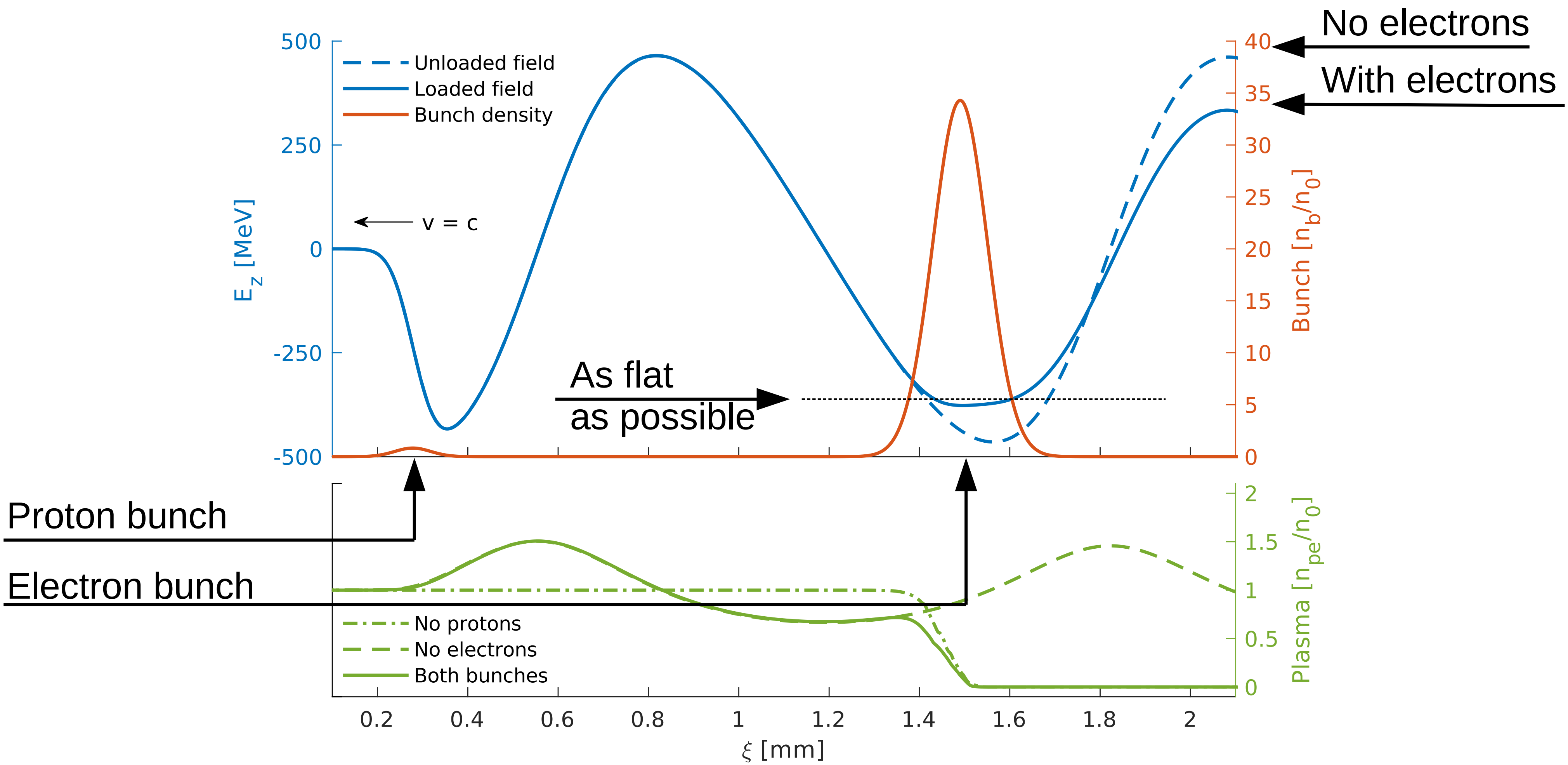
Self-Modulation in the Real World!



In this figure we see real experimental data of a self-modulated SPS proton bunch in AWAKE. The data was recently published by the collaboration: Phys. Rev. Lett. 122, 054802 (2019)

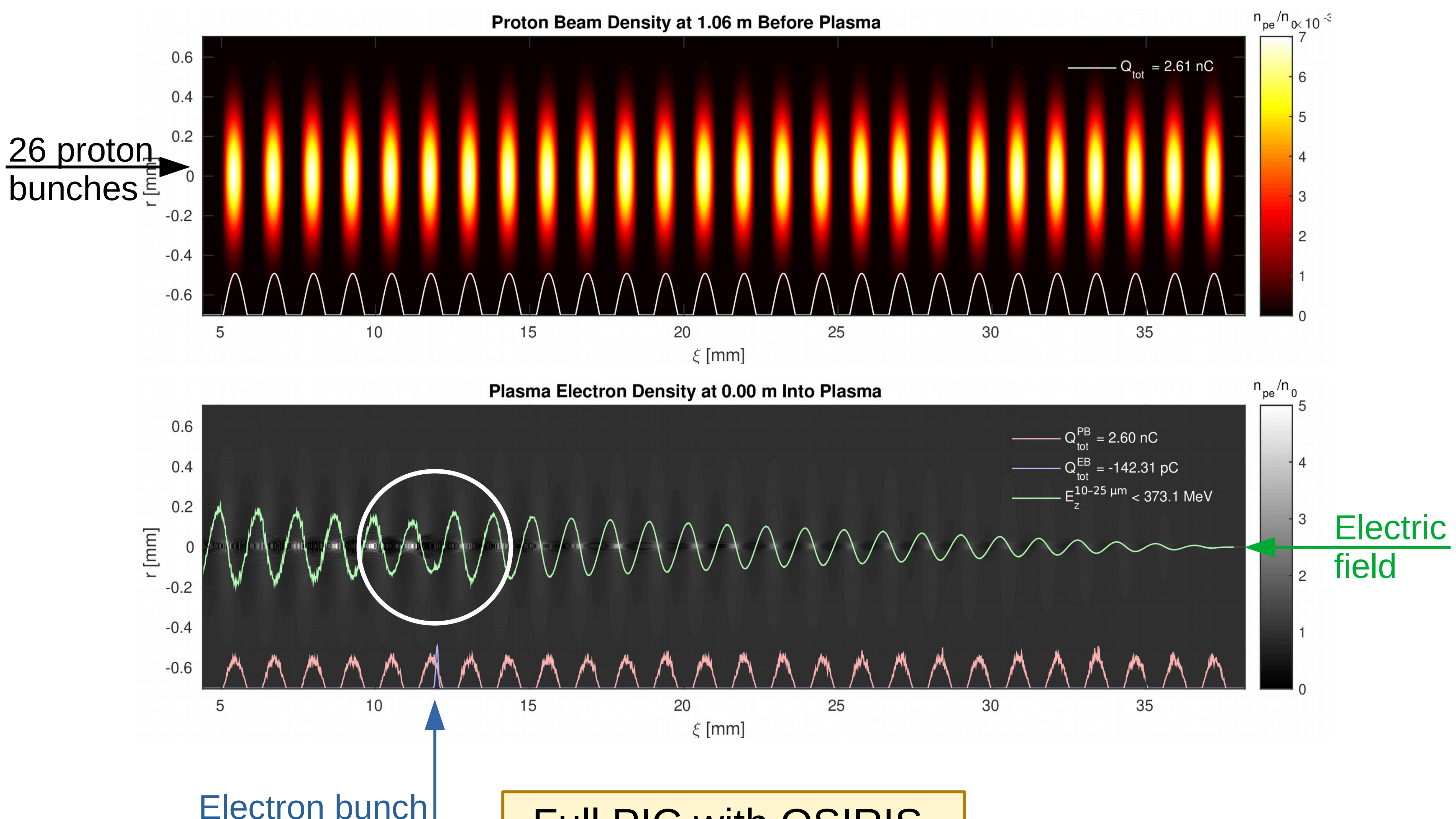
Plasma Wakefield Computer Simulations

What is Beam Loading?



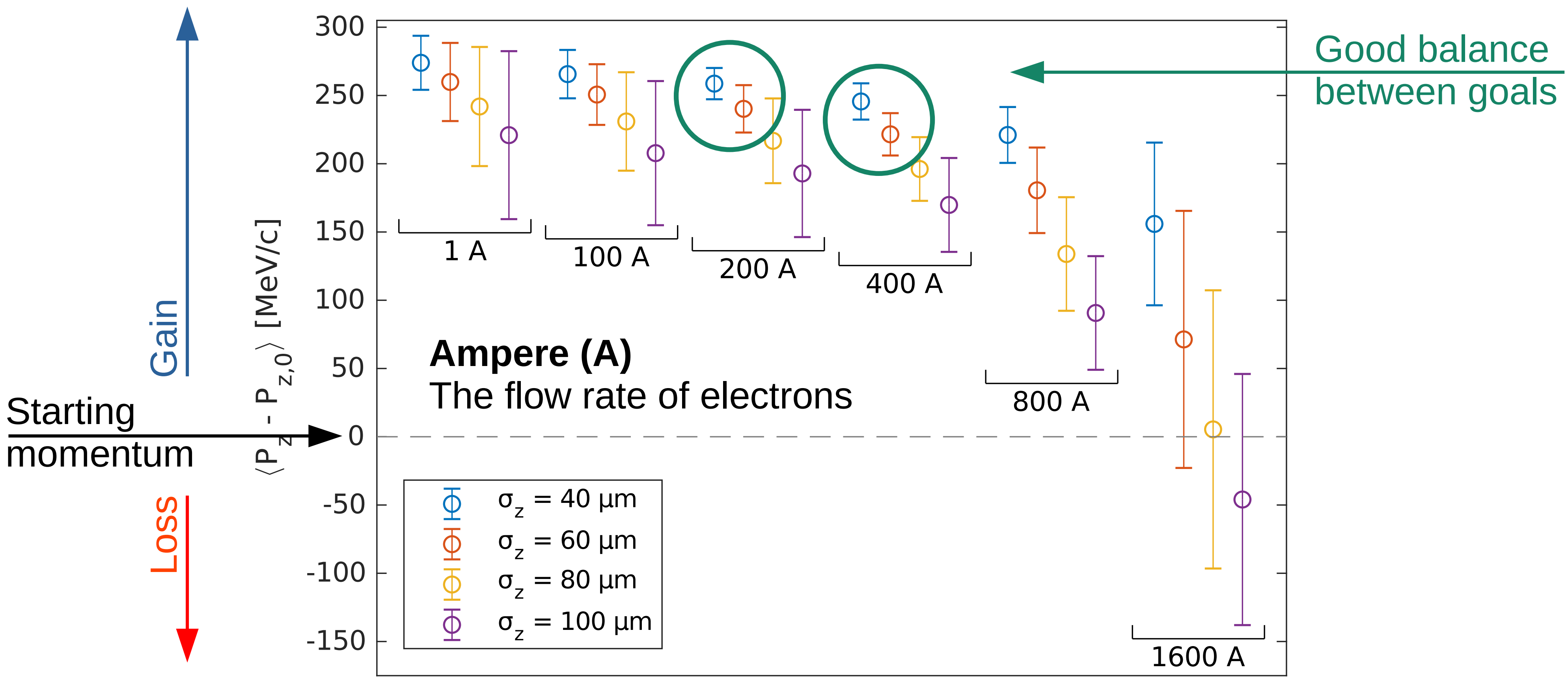
Beam loading is "that which limits the charge and beam quality".

Simulations Case One: Set-up



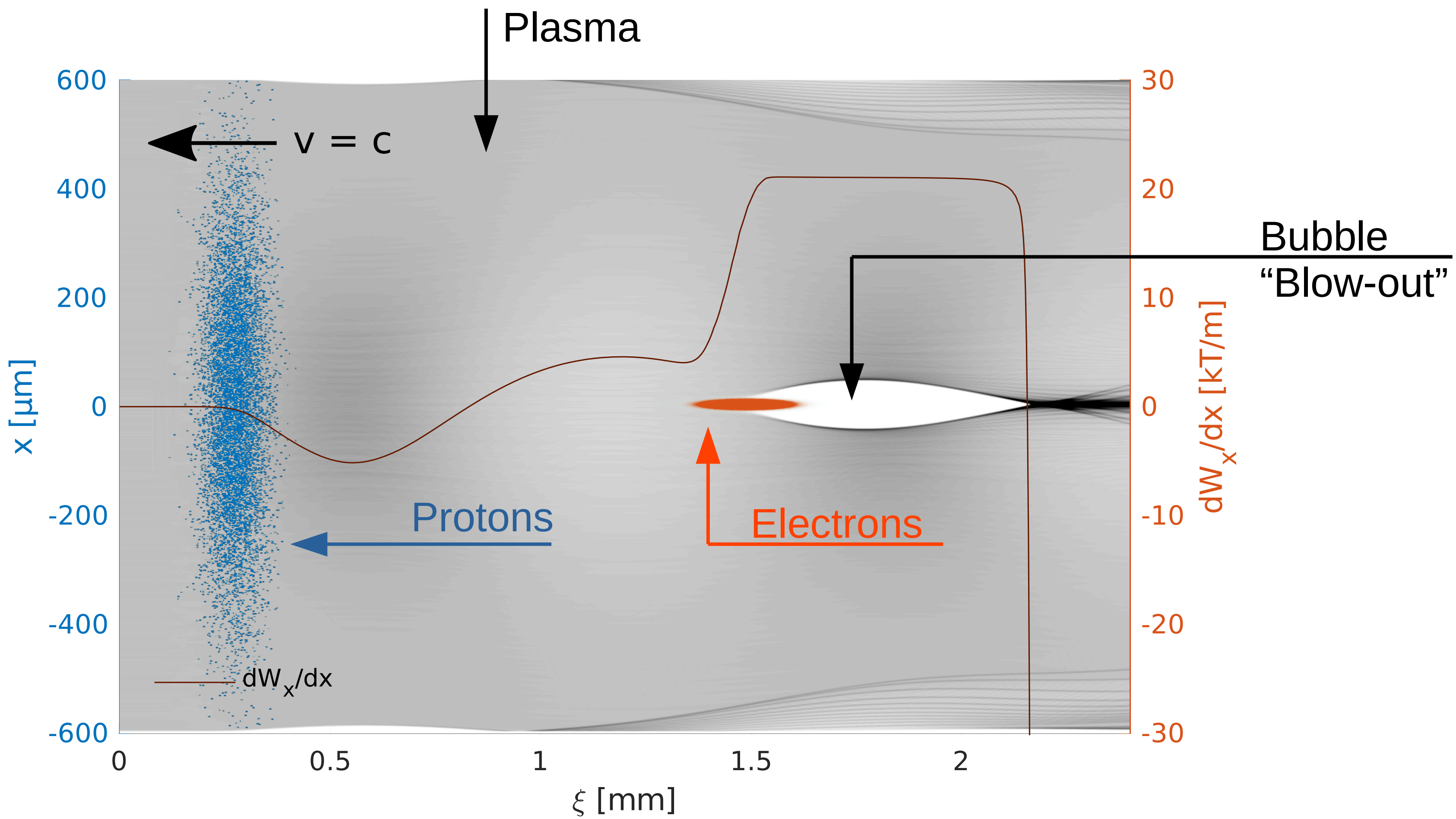
Full PIC with OSIRIS.

Simulations Case One: Main Results



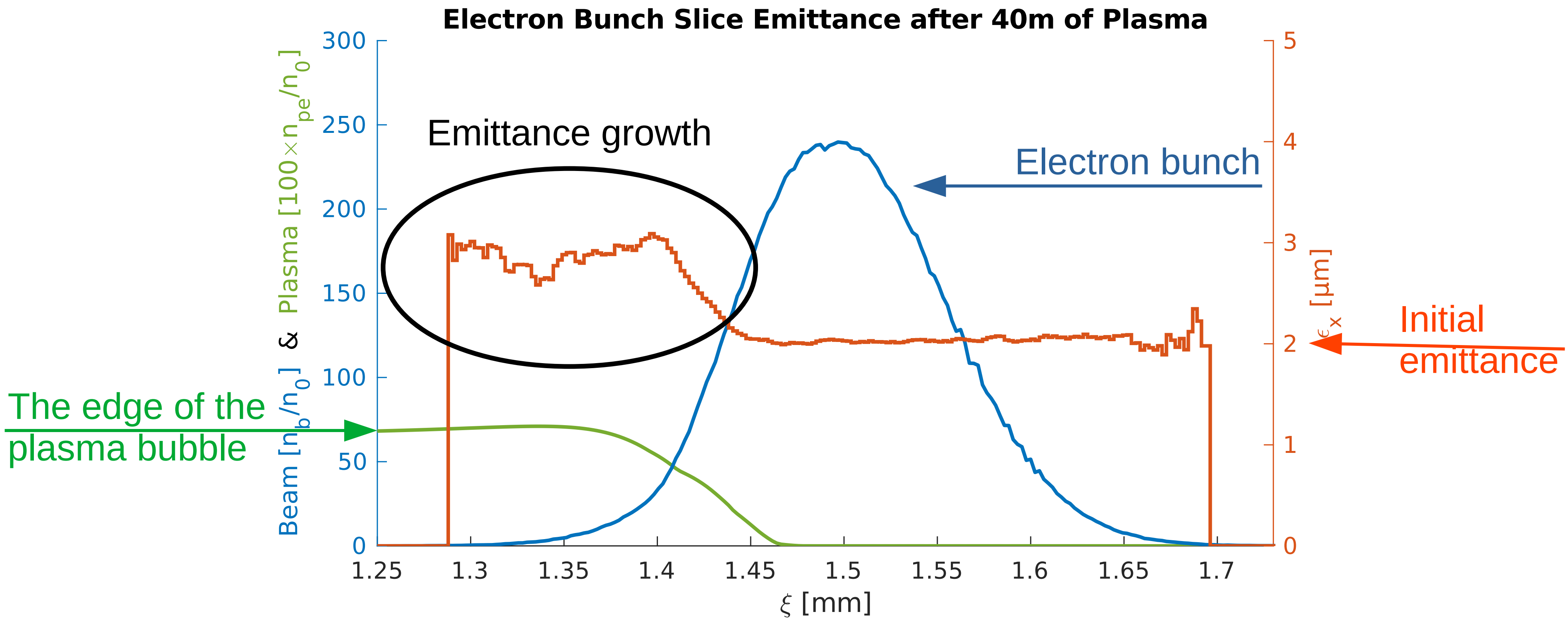
We're interested in how many electrons we can accelerate to as high energy as possible, with as little spread in energy as we can achieve.

Simulations Case Two: Set-up



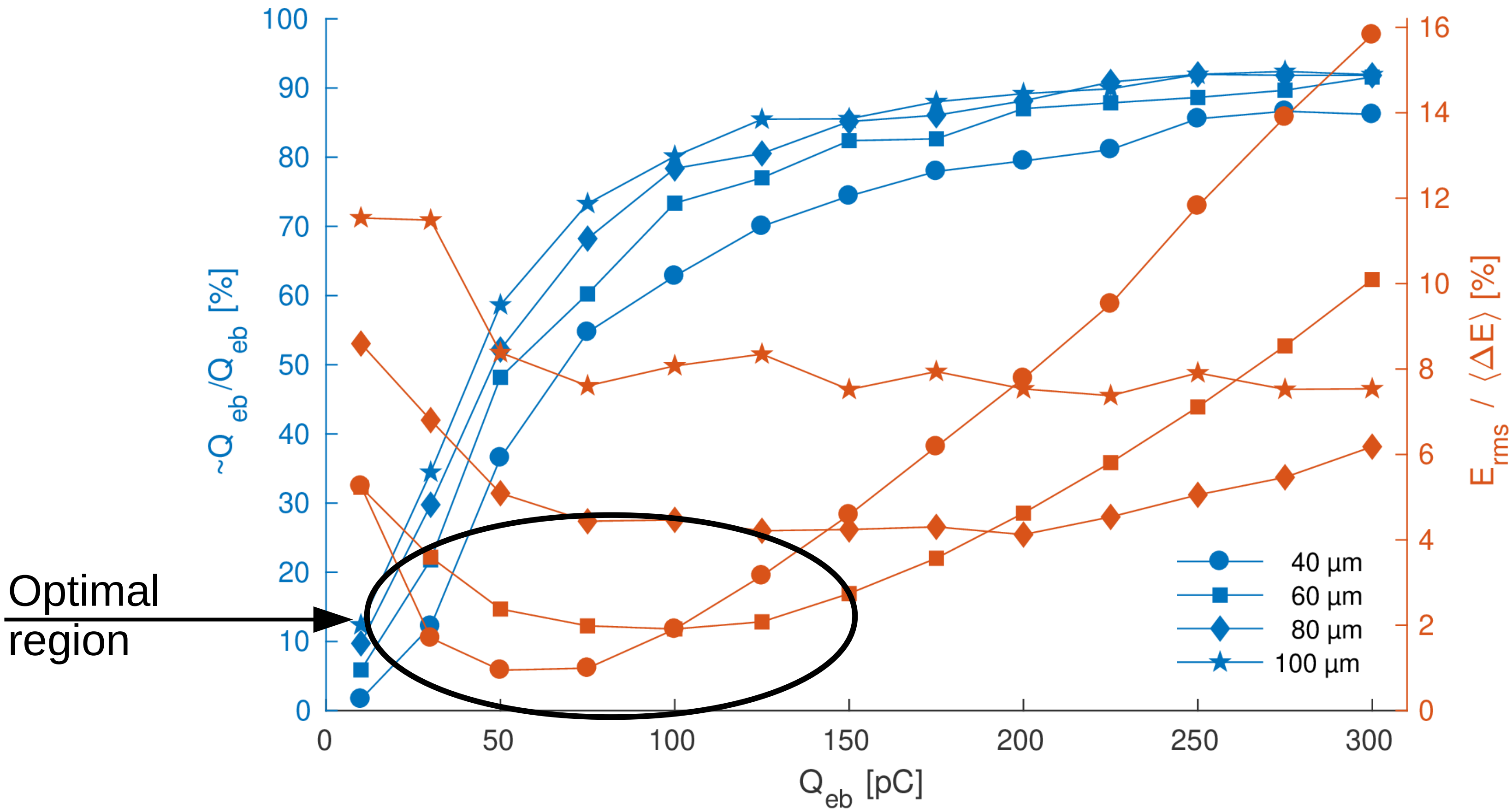
Building on Case One: Reduce complexity, and switch to a different simulation code (QuickPIC) more suitable for further studies.

Simulations Case Two: Emittance



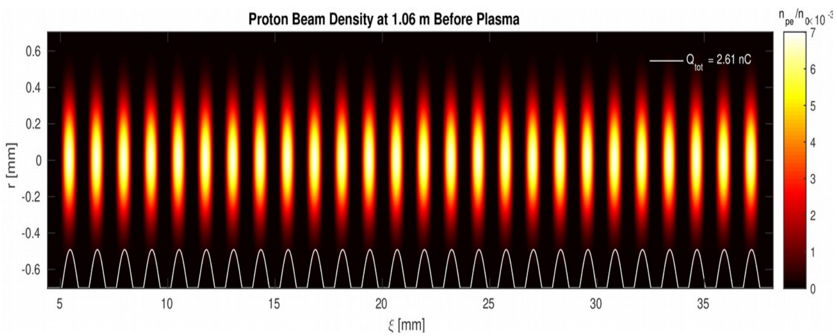
Emittance describes the spread in beam position and in momentum, and is a parameter we need to control and prevent from growing.

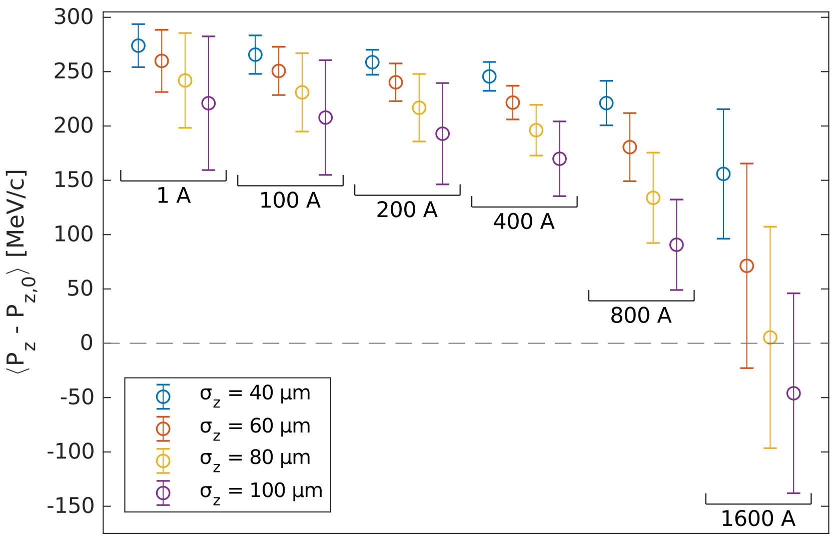
Simulations Case Two: Main Results



We are looking for the combination of high quality (blue axis), low emittance (red axis) and high charge (black axis).

Conclusion of the Studies



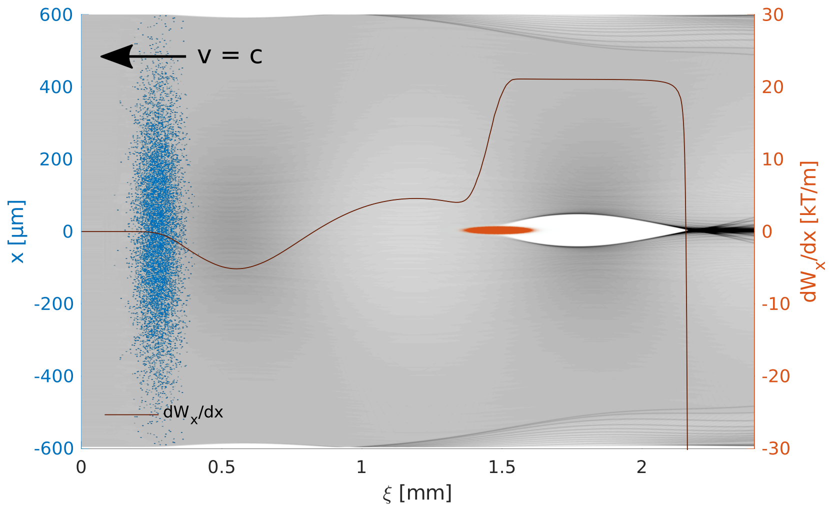


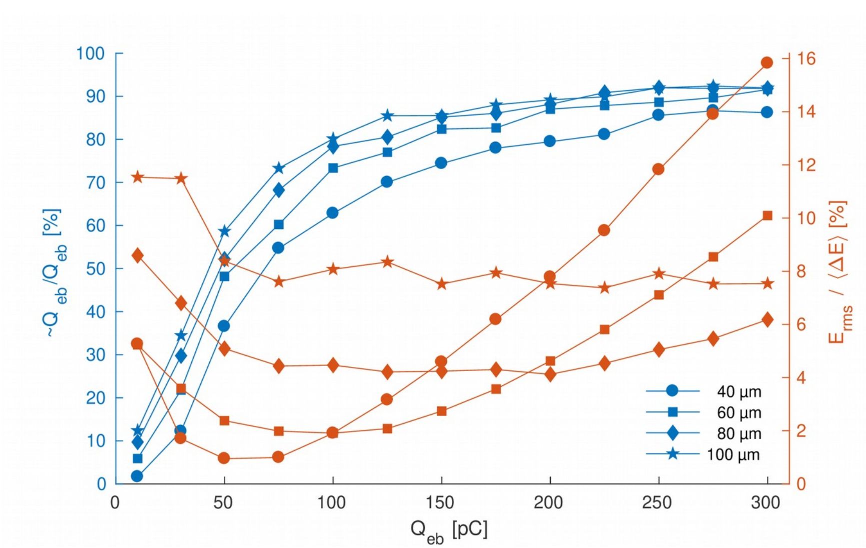
First we studied how much charge, and with what bunch size, electrons could be accelerated in AWAKE.

The aim was to maximise charge and acceleration, while minimising energy spread.

The results of the scan show that bunches of σ_z = 40−60 µm can be accelerated without too much energy spread and at a low cost of loss of final energy. That is, the loading of the field is just enough to make it nearly flat over the length of the bunch.

Conclusion of the Studies





We identified a **new regime** for plasma wakefield acceleration: the quasi-linear + non-linear regime. This creates an **emittance preserving accelerating bubble**.

In excess of 70% of the bunch can be accelerated without significant emittance growth, while the rest is used to drive the non-linear region.

Again, the σ_z = 40−60 μm range performs well. We see a flattening of the accelerating field without overloading until we reach high charges, > 150−200 pC. The different size bunches have their energy spread minima at **≈ 50 pC and ≈ 100 pC**, respectively.

Thanks for listening!

Special thanks to Erik Adli, Patric Muggli,
and the AWAKE Collaboration

Photo from first beam in AWAKE at CERN Control Centre, December 2016.