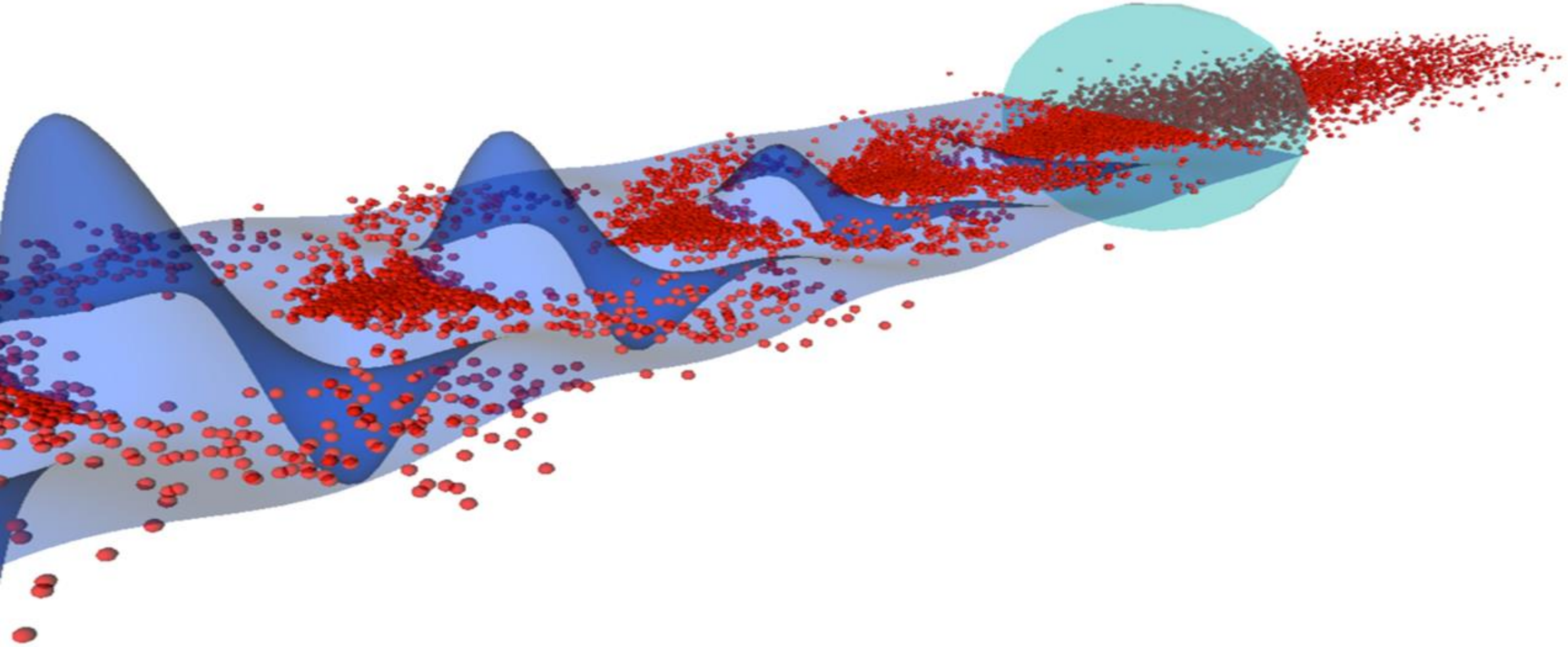


Plasma Wakefield Acceleration

AWAKE Experiment at CERN

Marlene Turner

Outline

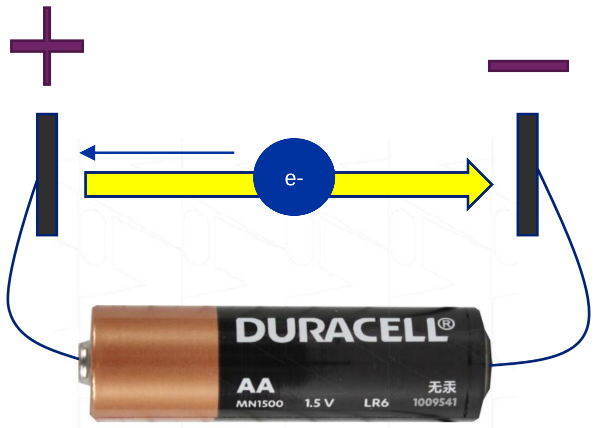
- What are plasma wakefields and why are they interesting?
- How to accelerate charged particles using plasma wakefields?
    - Underlying physics concepts, state-of-the-art results
- What is the AWAKE experiment, and why is it important?
- The AWAKE experimental setup
- Latest AWAKE results
    - Ideas and plans for the future

AWAKE

Advanced Proton-Driven Plasma
Wakefield Acceleration **E**xperiment

- Plasma ?
- Proton-driven ?
- Wakefield acceleration ?
- Acceleration ?

Charged Particle Acceleration



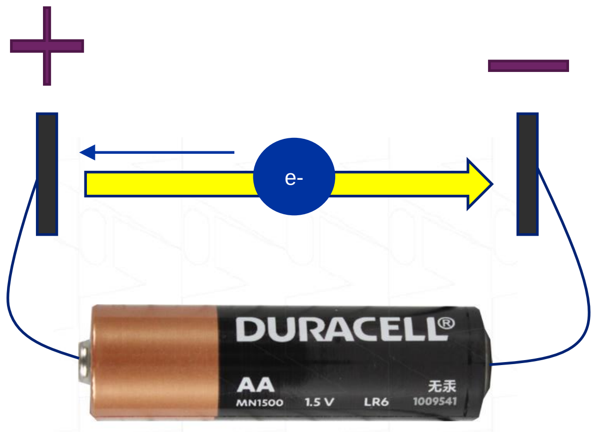
- Acceleration of charged particles requires an electric field
- Charged particle will accelerate as long as it experiences the field

1 TV = 10^{12} V
1 GV = 10^{9} V
1 MV = 10^{6} V
1 kV = 10^{3} V

1.5V with battery length of ~3 cm → 50 V/m

To reach 1 TeV → ~20 000 million km
Distance Earth-Sun ~ 152 million km

Charged Particle Acceleration



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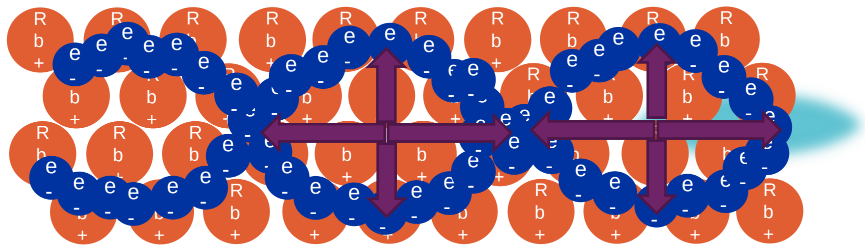
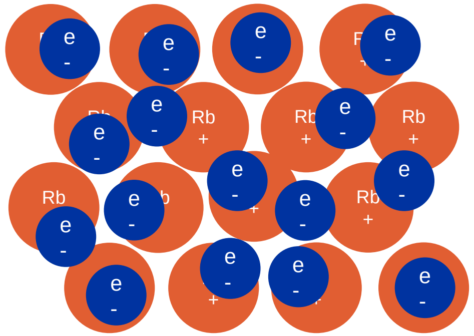


- Even better:
    - Field travels together with the beam

Definition of Plasma and Plasma Wakefield

Plasma

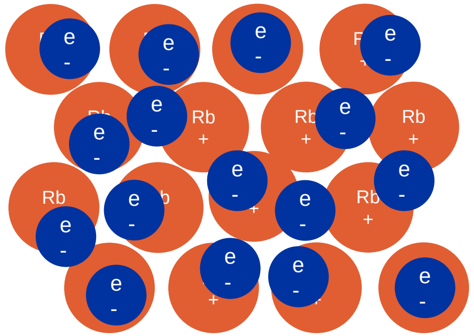


Plasma: ionised gas (4th state of matter)

- **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.

Definition of Plasma and Plasma Wakefield

Plasma



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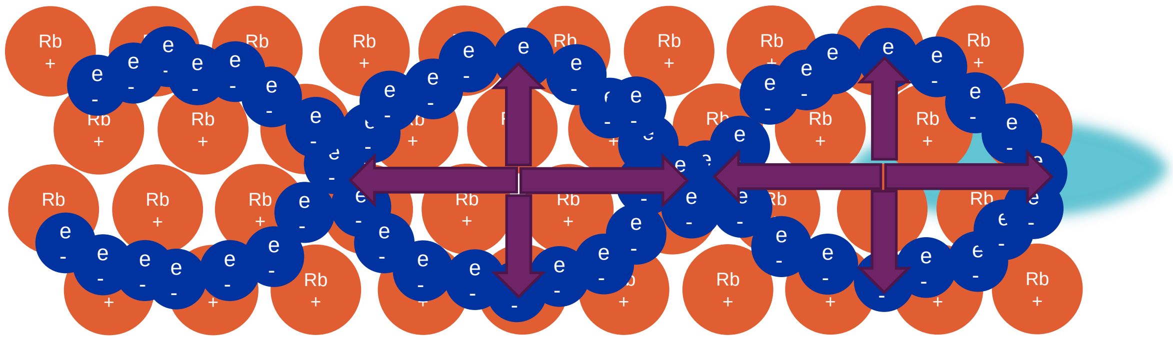
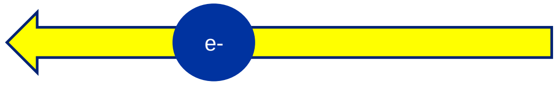
Plasma Wakefields



Plasma Wakefields:

- are the **fields** created/sustained by collective motion of plasma particles.

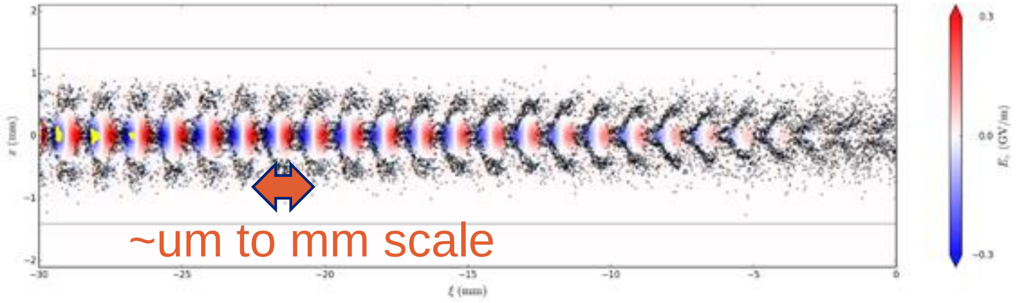


Why use Plasmas for Charged Particle Acceleration?

Conventional technology:
metallic radiofrequency (RF) cavities

LHC cavities

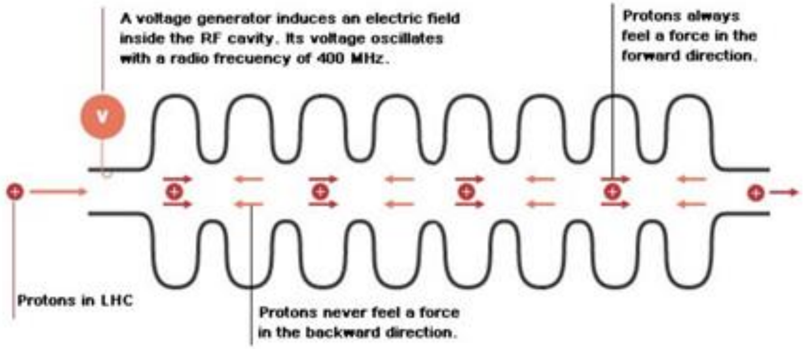
New concept:
plasma wakefields acceleration
→ transient structures in plasma



Accelerating Gradient

RF cavities

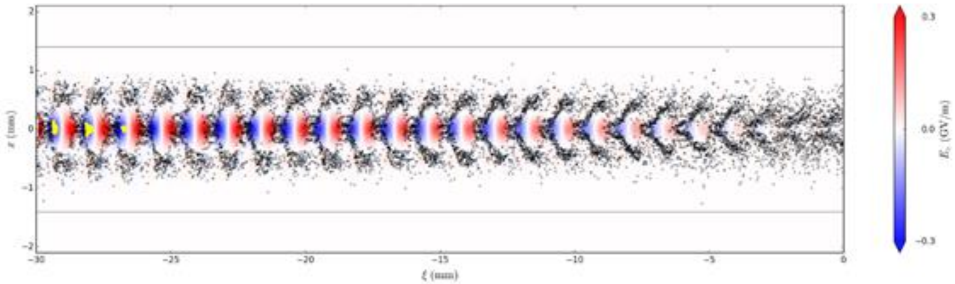
Limited to ~100 MV/m due to electric breakdowns (ionization).



Plasma Wakefields

Plasma is already ionized or "broken-down" and can sustain electric fields ~100 GV/m.

$$eE_{max} = 1\left[\frac{eV}{cm}\right] \cdot n^{1/2}[cm^{-3}]$$



Accelerating Gradient

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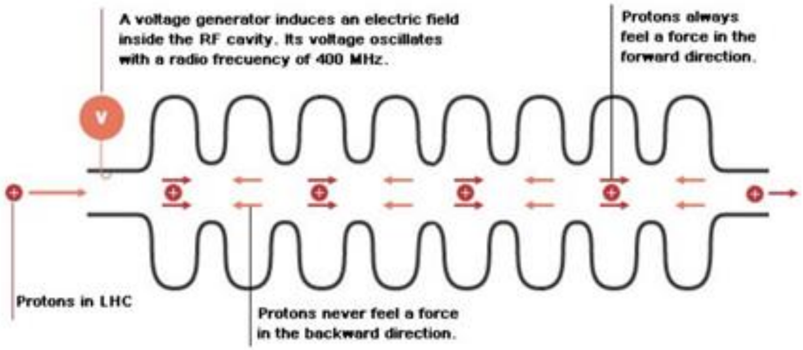
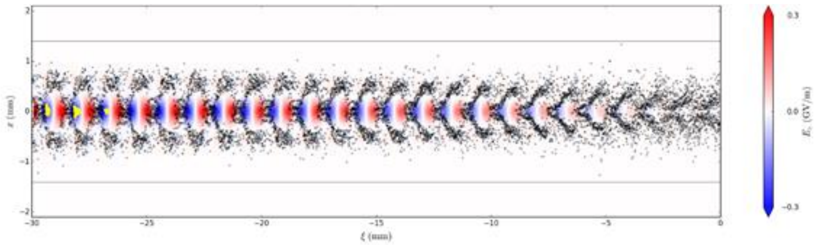


➔ Plasma wakefields can sustain order of magnitude higher fields

Plasma Wakefields

Plasma is already ionized or “broken-down” and can sustain electric fields ~100 GV/m.

$$eE_{max} = 1\left[\frac{eV}{cm}\right]\cdot n^{1/2}[cm^{-3}]$$

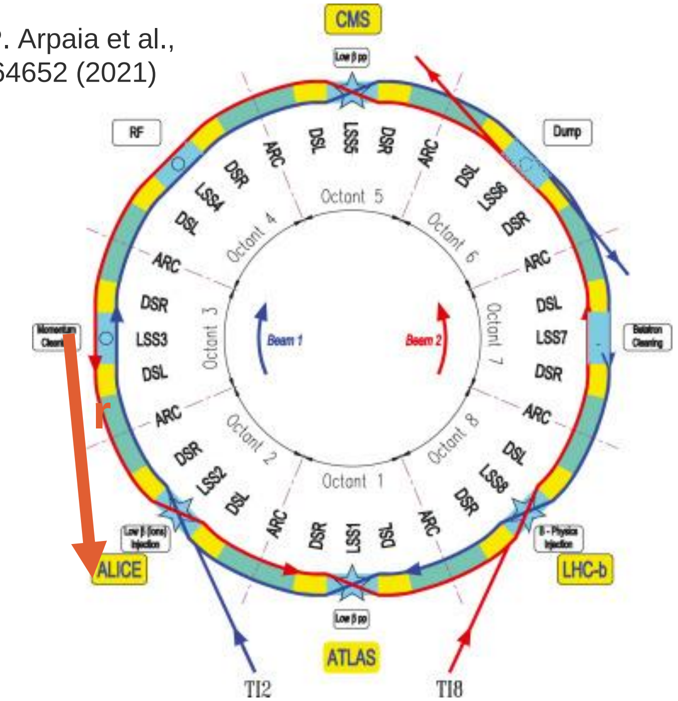


Structure exists only for a very short amount of time!

Circular and Linear Accelerators

Circular accelerators

Image from P. Arpaia et al.,
NIMA 985, 164652 (2021)

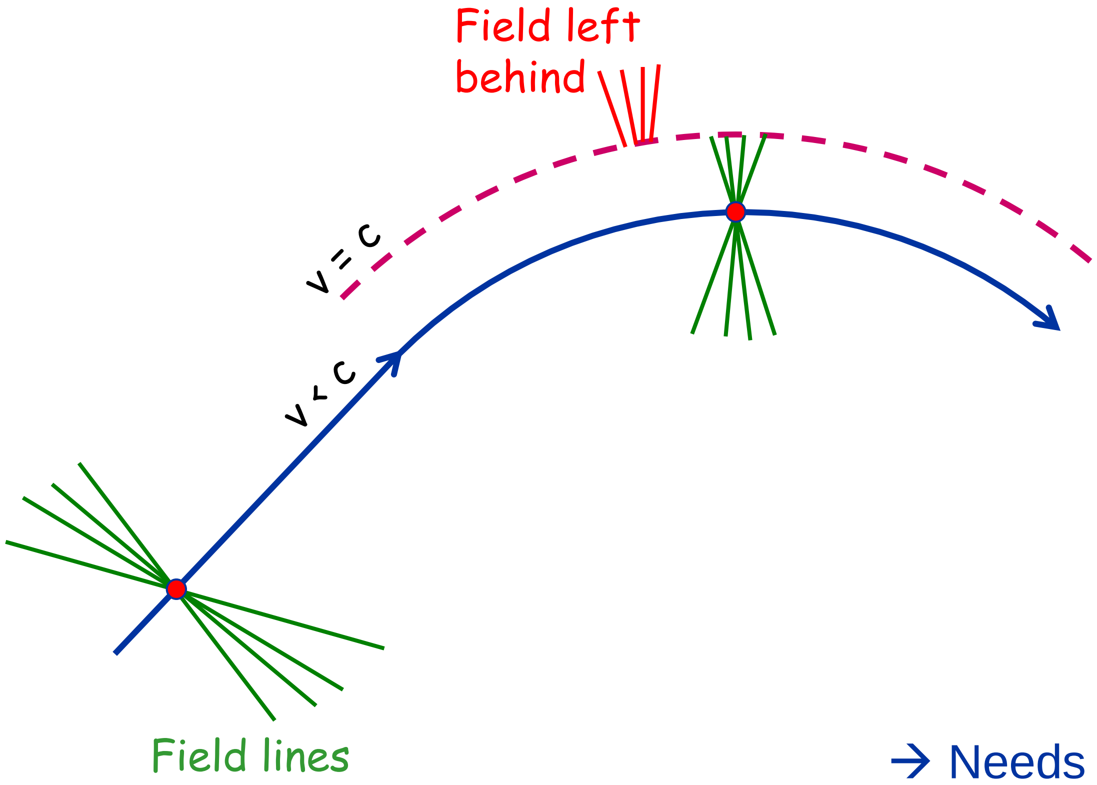


- Beam passes acceleration section multiple times.
- Max. energy (E) limited by synchrotron radiation losses
  $\propto E^4/(r^2m^4)$

- Advantage: beam passes accelerating section many times
- Disadvantage: synchrotron radiation losses

LHC tunnel:
p+p+ → 14 TeV
e+e- → 209 GeV

Synchrotron Radiation



Synchrotron radiation is caused by leaving part of fields behind
when the beam moves along the curve.

$\propto E^4/(r^2m^4)$

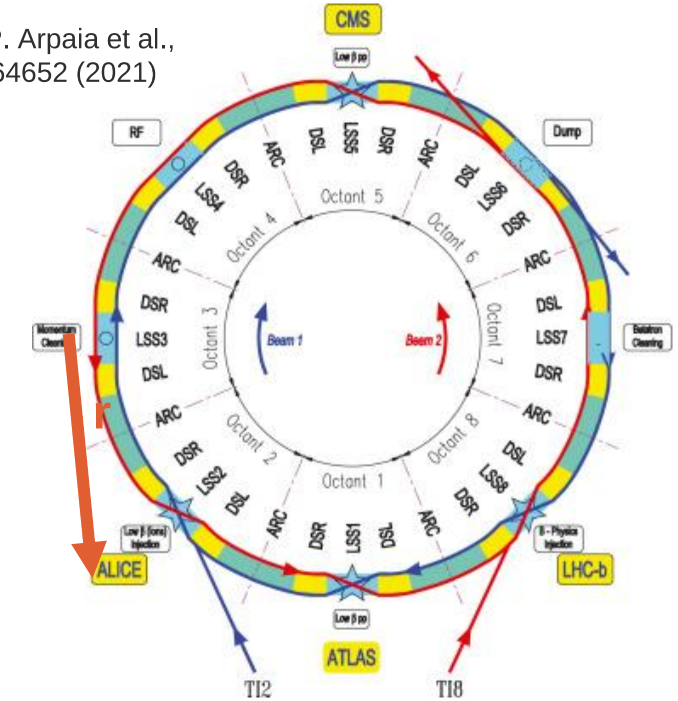
Particle energy
Bending radius
Mass of the particle

→ Needs to be taken into account when accelerated charged particles are deflected in the radial direction.

Circular and Linear Accelerators

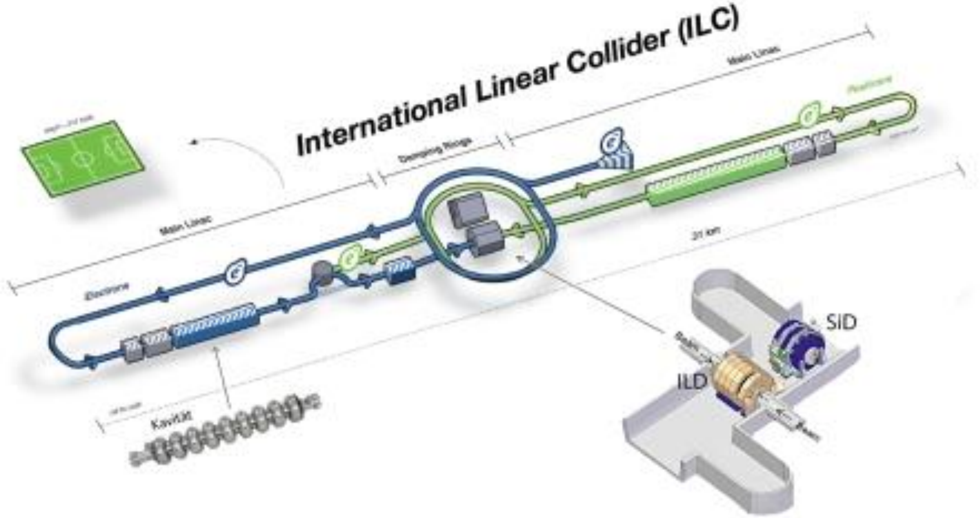
Circular accelerators

Image from P. Arpaia et al.,
NIMA 985, 164652 (2021)



- Beam passes acceleration section multiple times.
- Max. energy (E) limited by synchrotron radiation losses
  $\propto E^4/(r^2 m^4)$

Linear accelerators



- Beam passes acceleration section multiple times.
- Negligible synchrotron radiation losses
- Accelerator length and accelerating gradient define final beam energy.

e.g. to accelerate electrons to 1 TeV (10^{12} eV):
100 MeV/m x 10000 m or
100 GeV/m x 10 m

Let Us Repeat…

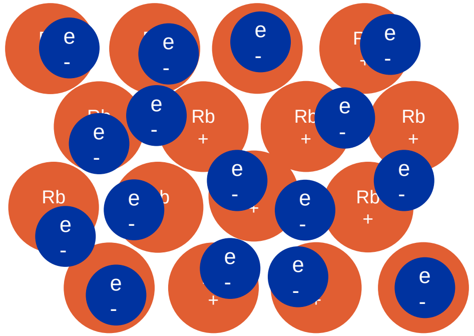
- Plasma wakefields allow to accelerate charged particles with ~ 1-100 GeV/m

- High gradients are important when using linear accelerators (e.g. for light particles) to minimize synchrotron radiation losses
  - For linear accelerators, their length defines the final beam energy

How to Create Plasma Wakefields?

Two ingredients

Plasma
(Medium)



Relativistic charged particle beam or
Short intense laser pulse
(Energy source)

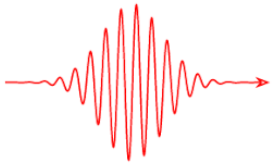
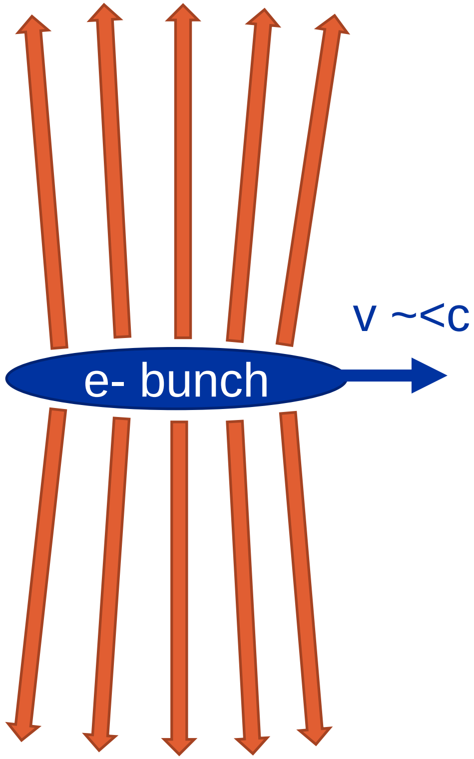


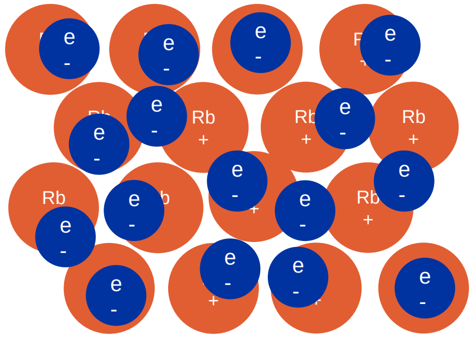
Image from https://revbalance.com/improving-balance-for-wakesurfing/

Energy Source: The Driver

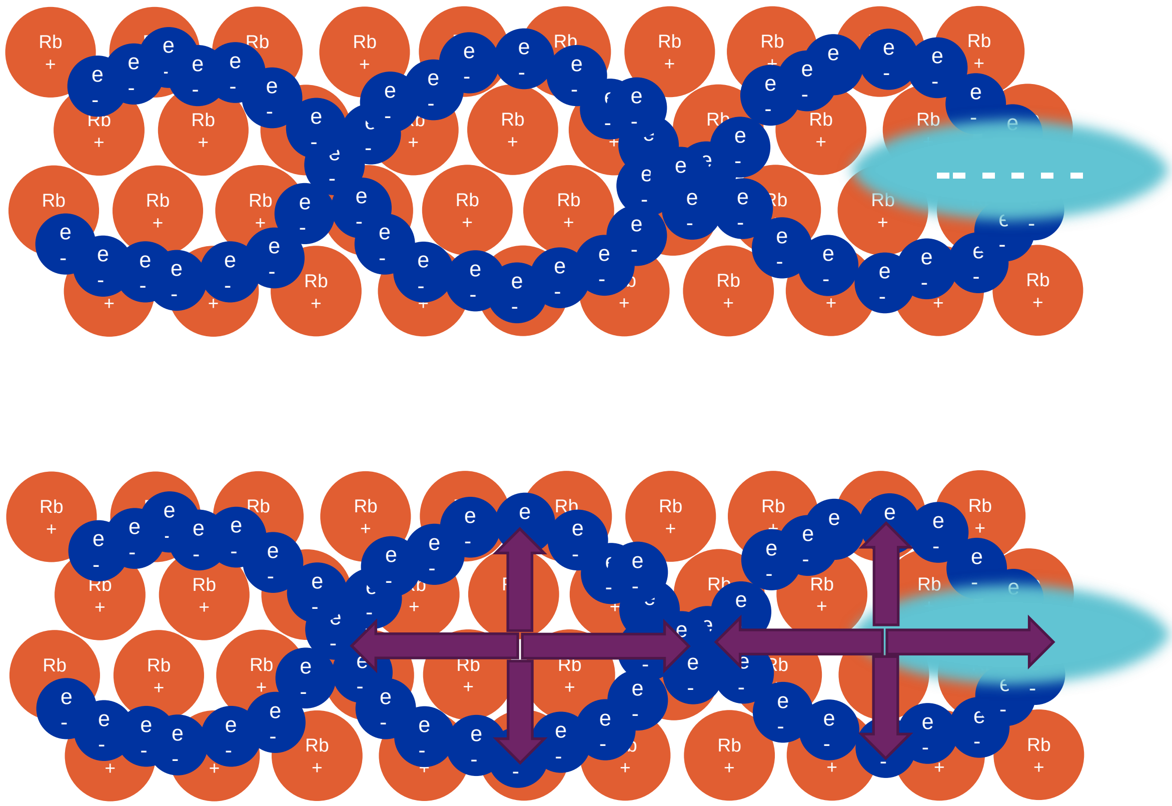


- Relativistic charged particle bunches or laser pulses
  - → Relativistic charged particle bunches carry almost purely **transverse electric** fields
- What we need → longitudinal electric field to accelerate charged particles

Trick:
- Use plasma to convert the transverse electric field of the proton bunch into a longitudinal electric field in the plasma.
- The more energy is available, the longer (distance-wise) these plasma wakefields can be sustained



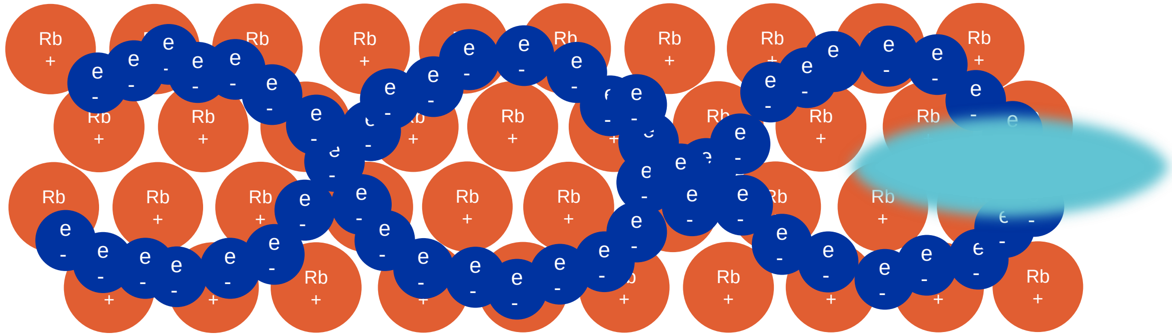
How to Drive a Plasma Wave



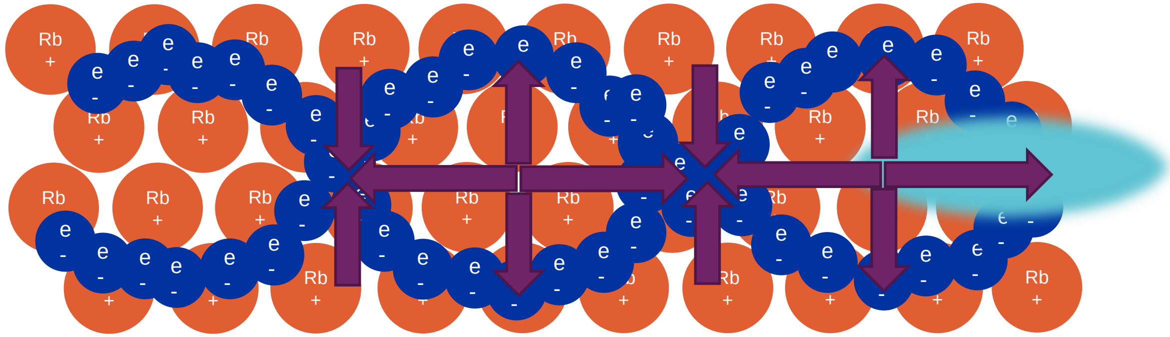
Important to understand

- Plasma electron motion is mostly **transverse**
- Electrons do not move significantly longitudinally
- Rb ions are heavy and do not move significantly on the timescale of the electrons

How to Drive a Plasma Wave

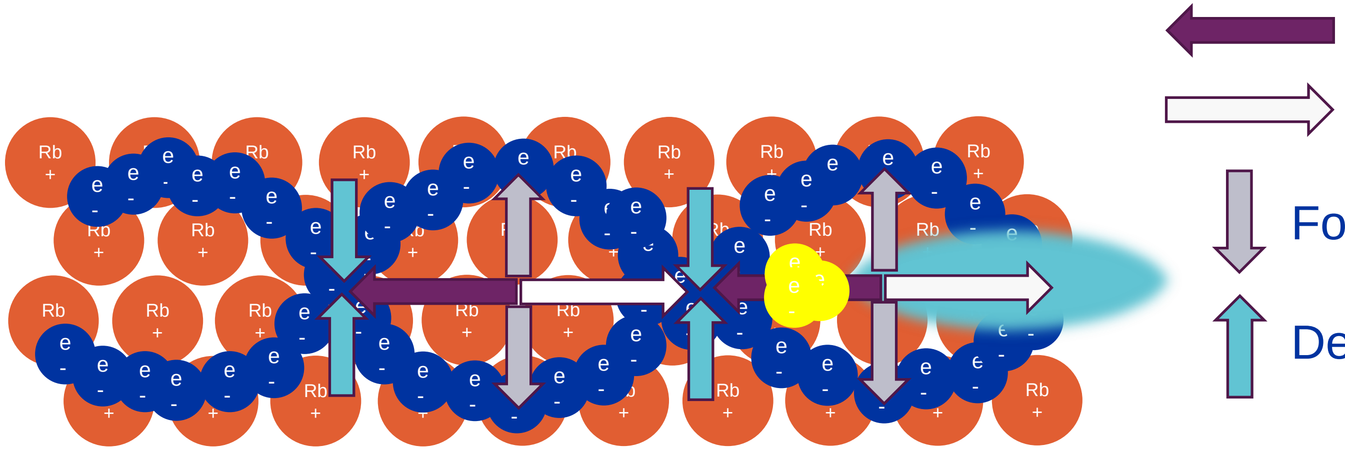


Charge separation → electric field (longitudinal and transverse)



Where should we place an electron bunch to be accelerated?

Plasma Wakefields



Accelerating for negatively charged particles

Decelerating for negatively charged particles

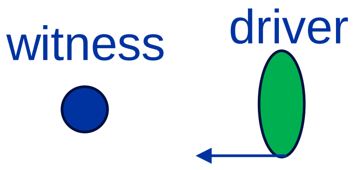
Focusing for negatively charged particles

Defocusing for negatively charged particles

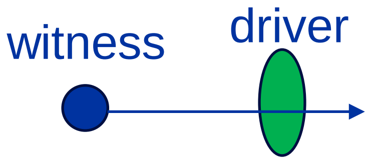
Plasma Acts As a Transformer

Driver deposits energy, witness gains energy

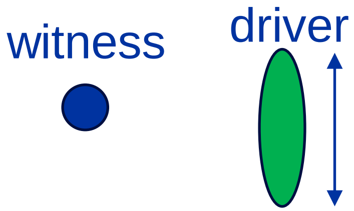
Acceleration distance typically limited by either



Depletion: The drive bunch/pulse running out of energy. Solution: couple in a new driver or use a more energetic driver



Dephasing: The witness bunch outruns the driver. Solution: couple in a new driver or shape the plasma density



Diffraction: Drive beam evolution. Solution: Guiding or use a more rigid driver

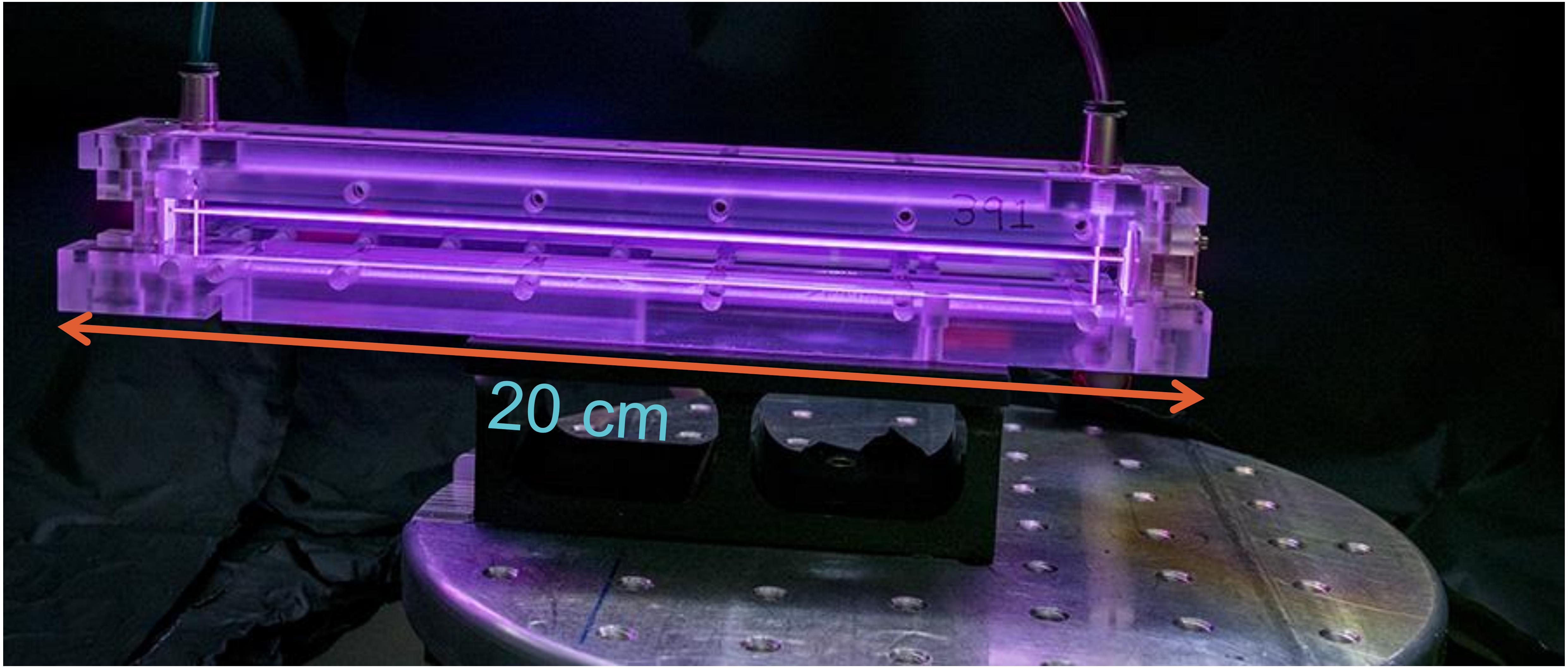
Let Us Repeat…

- Plasma wakefields require: plasma, energy source (driver)
  - Place a particle beam (witness) to be accelerated

- Plasma acts as a transformer
  - Drive beam energy is transferred to the witness bunch

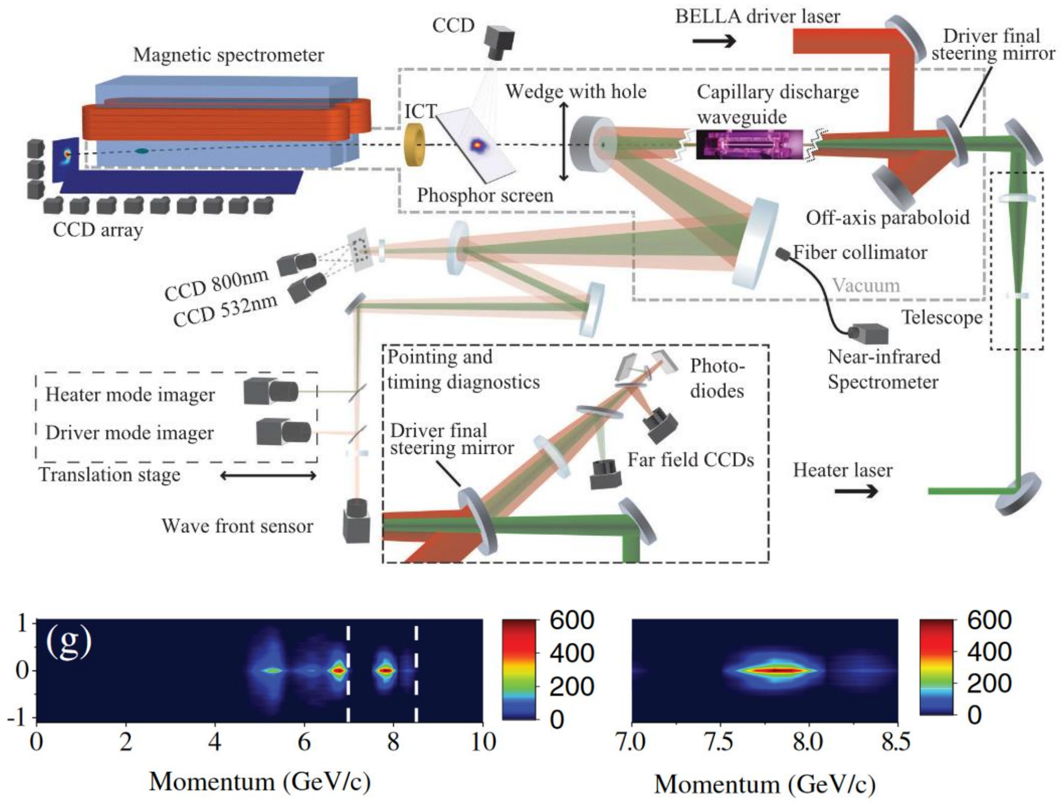
- What limits the energy gain:
  - Depletion: Driver runs out of energy
  - Dephasing: Accelerating bunch outruns the driver
  - Diffraction: Driver no longer intense enough

State-of-the-Art Results

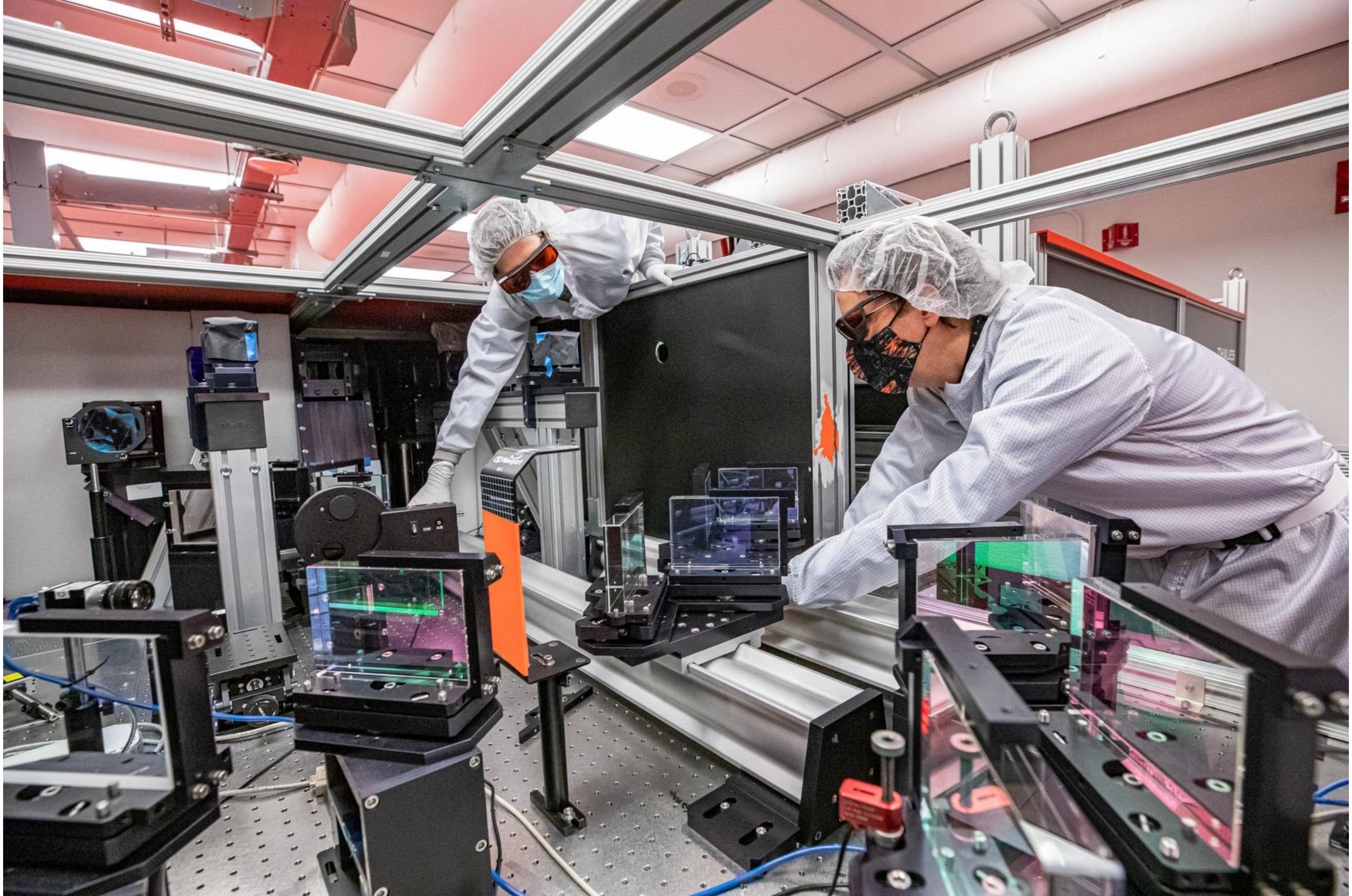

20 cm
391

State-of-the-Art Results

BELLA (Berkeley, California)

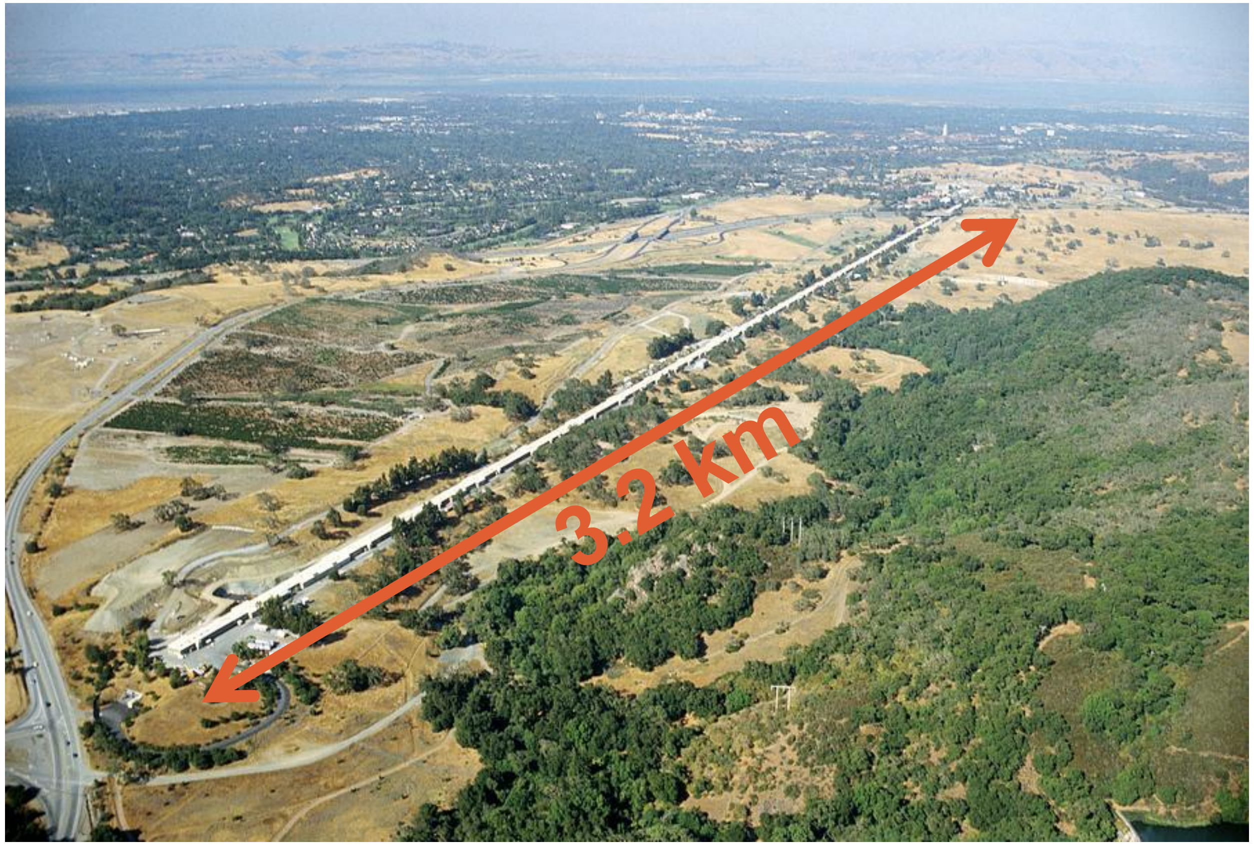


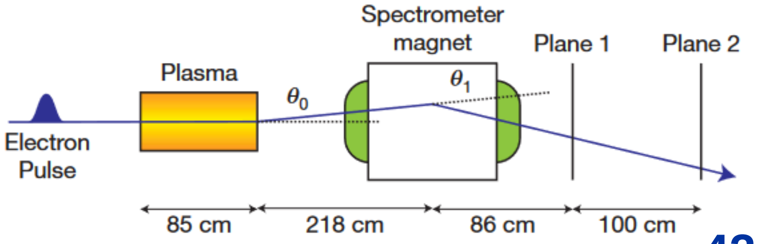
Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide
A. J. Gonsalves et al., Phys. Rev. Lett. 122, 084801



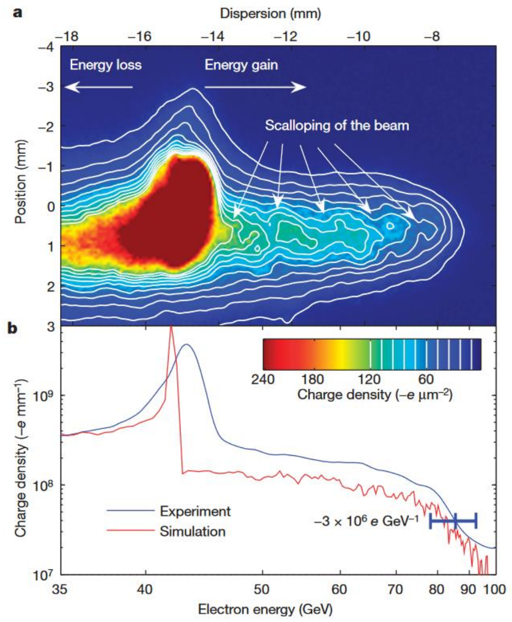
State-of-the-Art Results

SLAC (Stanford, California)



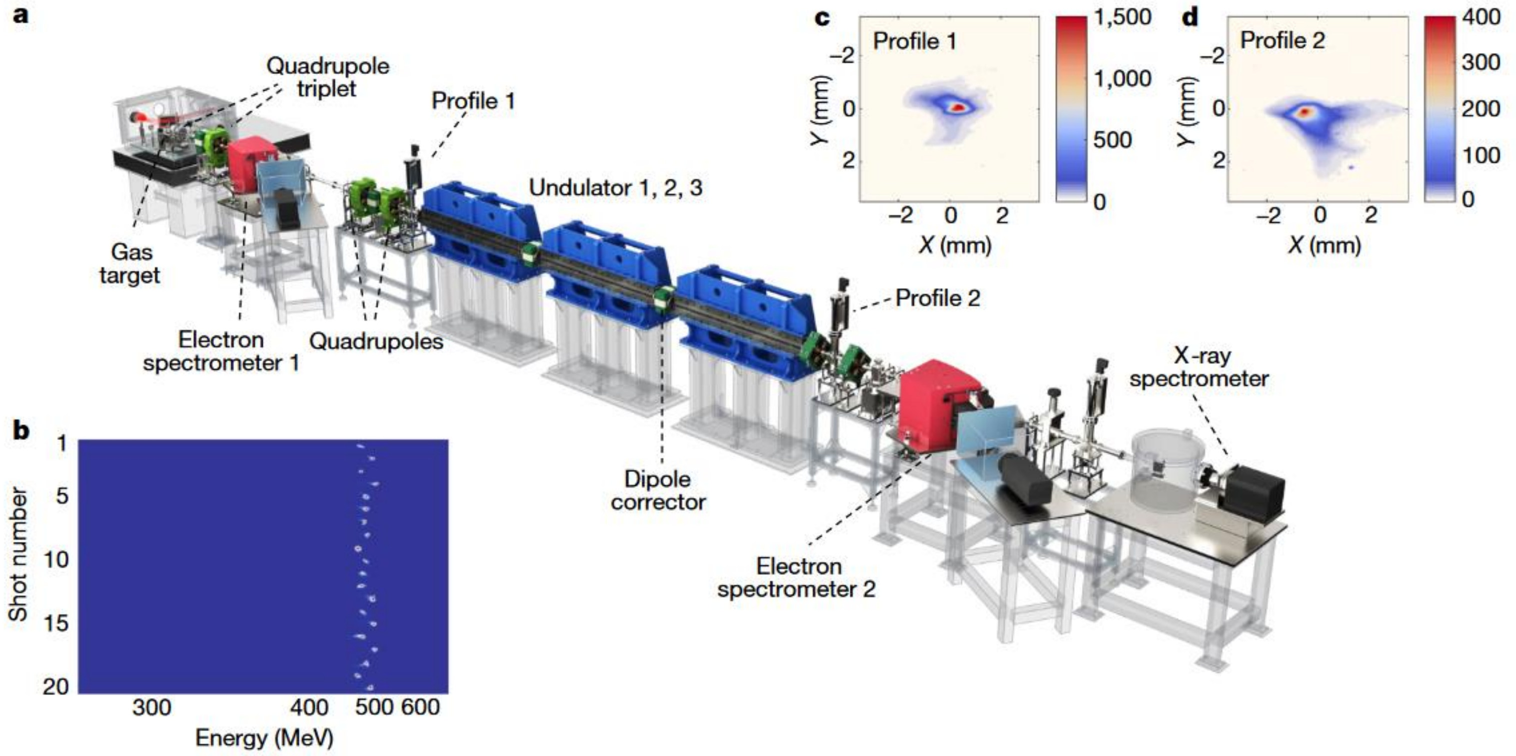


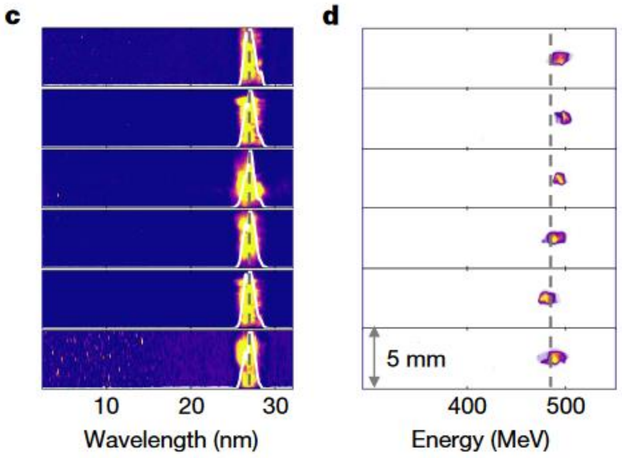
42 GeV energy gain in 85 cm of plasma



Blumenfeld, I., Clayton, C., Decker, FJ. *et al.* Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator. *Nature* **445**, 741–744 (2007).

First Demonstration of a Free Electron Laser Driven by a Plasma Wakefield Accelerator





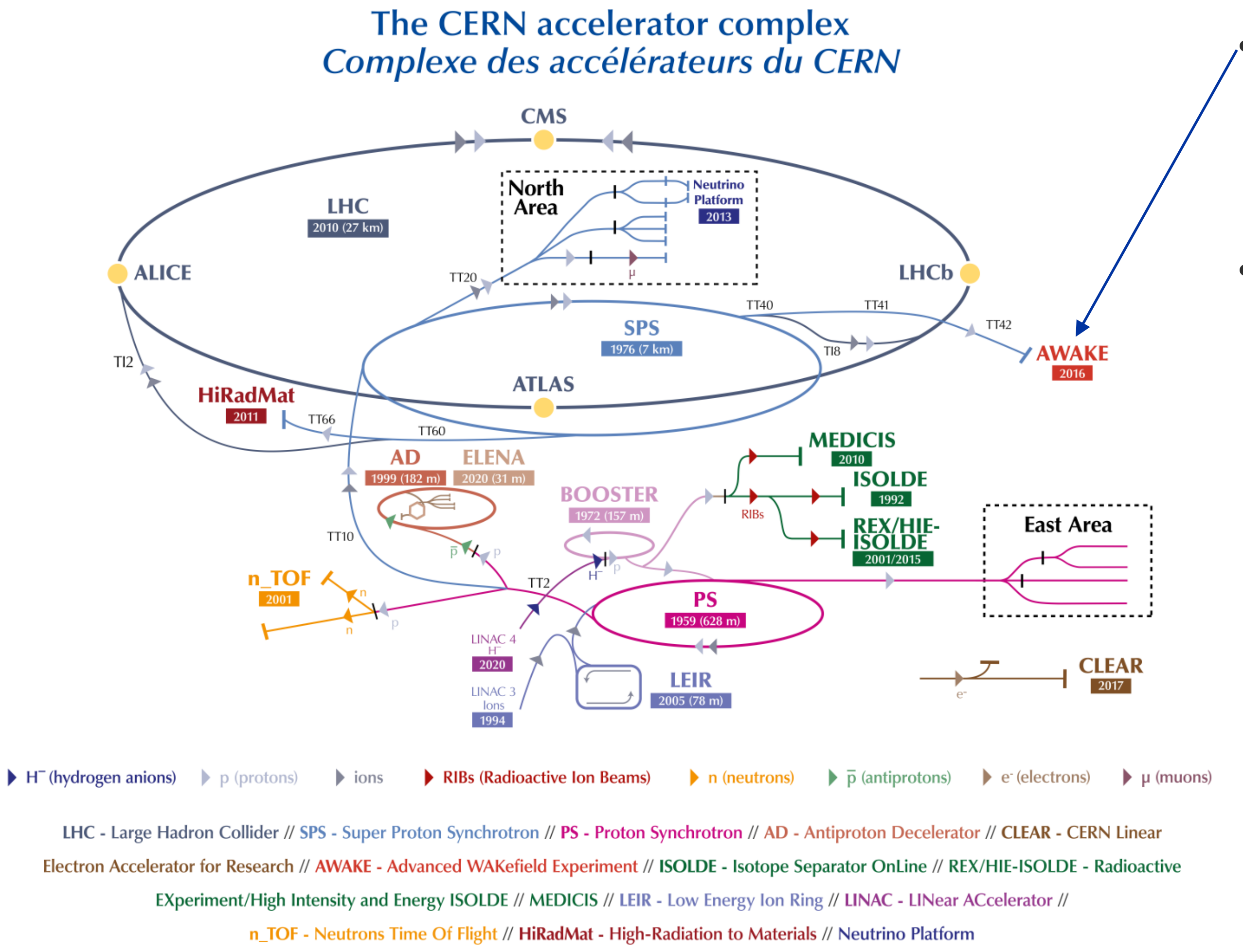
Free-electron lasing at 27 nanometres based on a laser wakefield accelerator
Wentao Wang et al., *Nature* **volume 595**, pages 516–520 (2021)

Let Us Repeat…

- Plasma wakefields acceleration has been demonstrated experimentally:
  - ~8 GeV in 20 cm of plasma
  - 42 GeV in 85 cm of plasma
  - First laser-plasma wakefield driven free electron laser

The AWAKE Experiment @CERN

Plasma Wakefield Physics @ CERN



- CERN has very high energetic proton bunches available.
- Idea: use energy stored in the proton bunches to accelerate lighter particles e.g. electrons

19 kJ
400 GeV

→ however, they are too long to excite wakefields

AWAKE Requires Microbunching of p+ Bunch

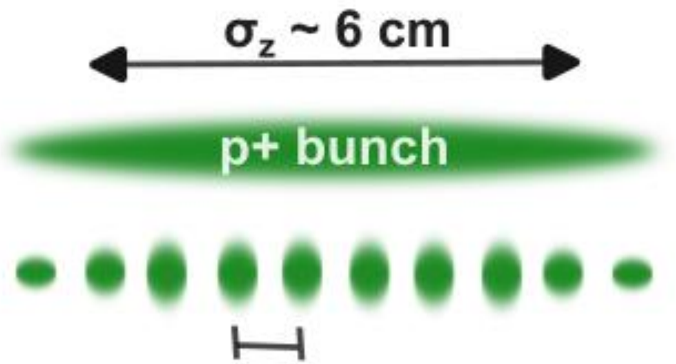
To effectively excite wakefields:

- The drive bunch length has to be on the order of the plasma wavelength

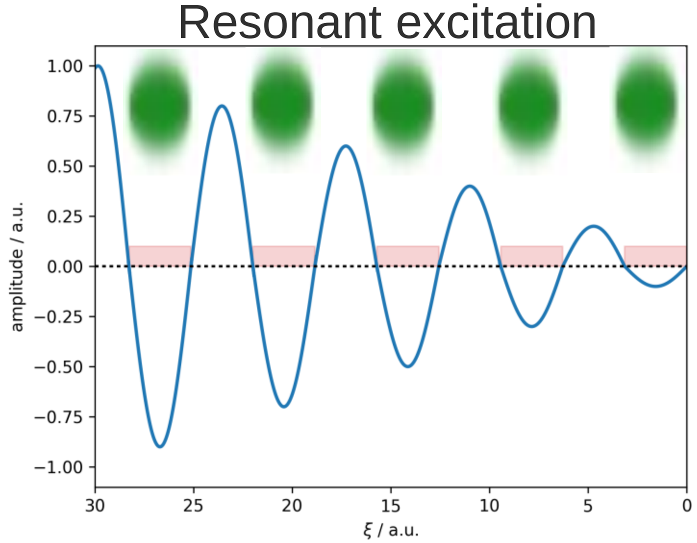
For AWAKE → mm-scale bunch length

CERN SPS proton bunch length is ~6 cm

⇒ Plasma process: Self-Modulation Instability (SMI), can be seeded (SSM)



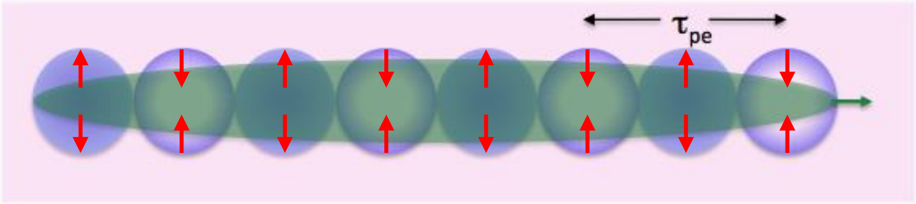
(7x10^14 cm^-3)



- Wakefields driven resonantly to large amplitude
- Self-modulation necessary to drive ~GV/m accelerating fields in 10^{14} cm^{-3} density plasma

Self-Modulation Process

Long driver (p^+), dense plasma,
$\sigma_t >> 1/\omega_{pe}$, $\sigma_r \sim c/\omega_{pe}$

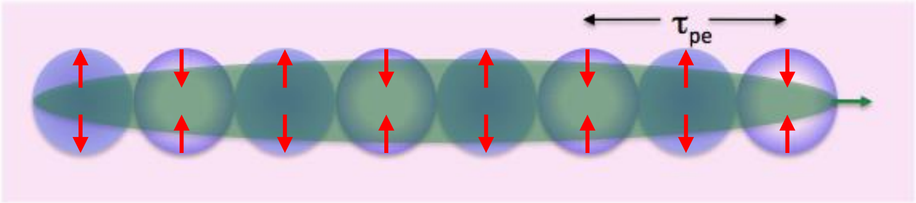


Growth mechanism:

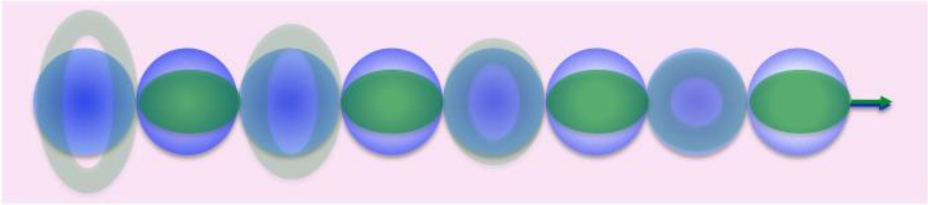
Initial (transverse) wakefields

Self-Modulation Process

Long driver (p^+), dense plasma,
$\sigma_t >> 1/\omega_{pe}$, $\sigma_r \sim c/\omega_{pe}$



Self-modulation



Growth mechanism:

Initial (transverse) wakefields

Periodic focusing/defocusing

Self-Modulation Process

Long driver (p^+), dense plasma,
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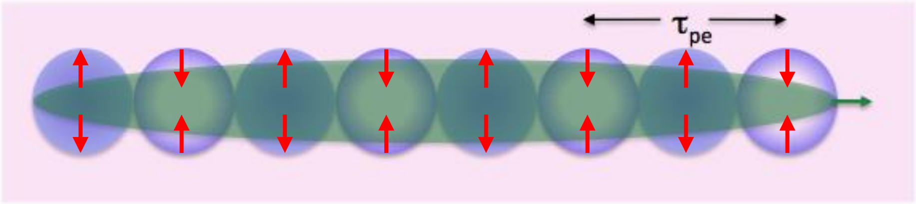
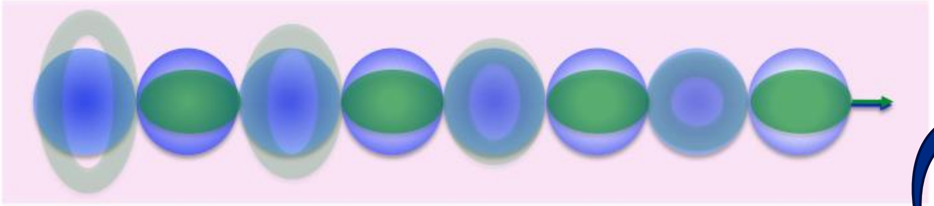


Self-modulation



Self-modulated bunch

Growth mechanism:

↓

Initial (transverse) wakefields

↓

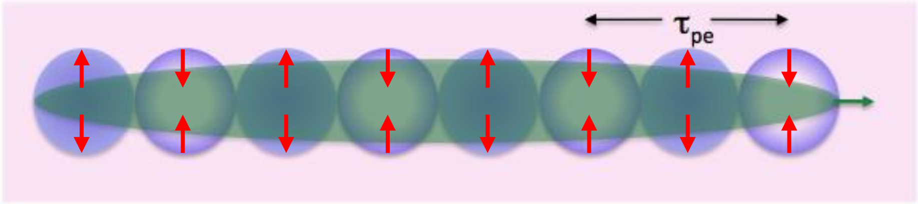
Periodic focusing/defocusing

↓

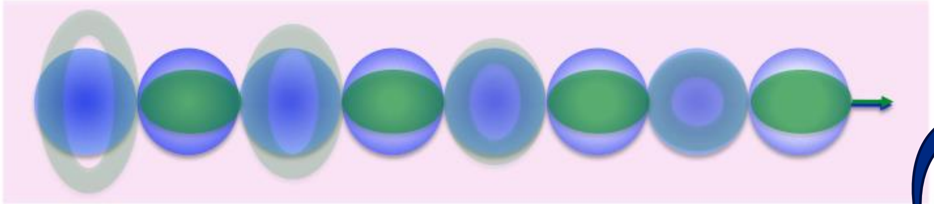
Density modulation

Self-Modulation Process

Long driver (p^+), dense plasma,
$\sigma_t >> 1/\omega_{pe}$, $\sigma_r \sim c/\omega_{pe}$

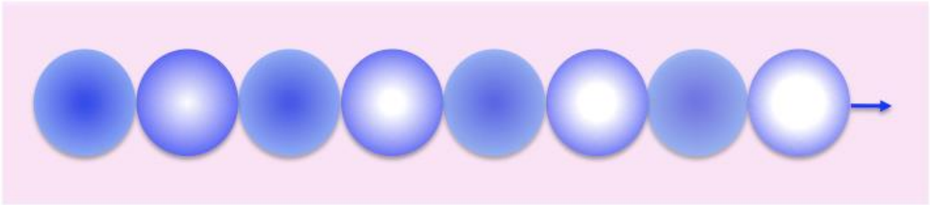


Self-modulation



Self-modulated bunch

Plasma wakefields



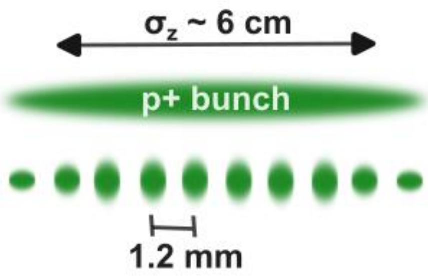
Growth mechanism:

Initial (transverse) wakefields

Periodic focusing/defocusing

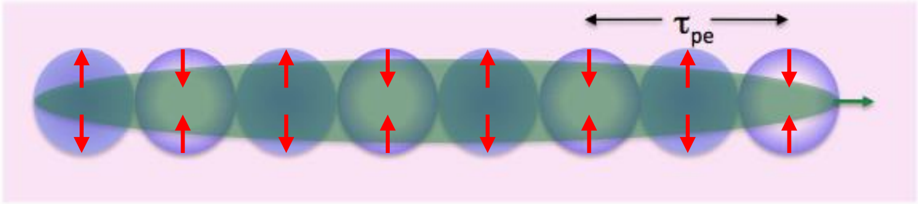
Density modulation

Full modulation – bunch train

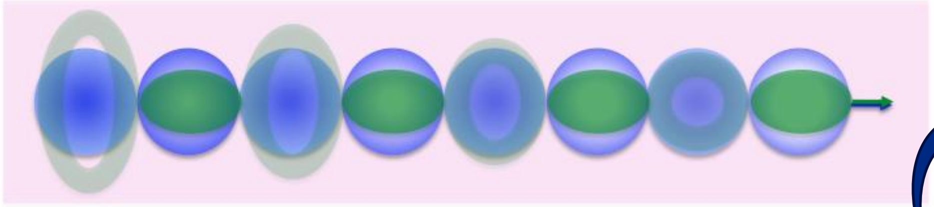


Self-Modulation Process

Long driver (p^+), dense plasma,
$\sigma_t >> 1/\omega_{pe}$, $\sigma_r \sim c/\omega_{pe}$

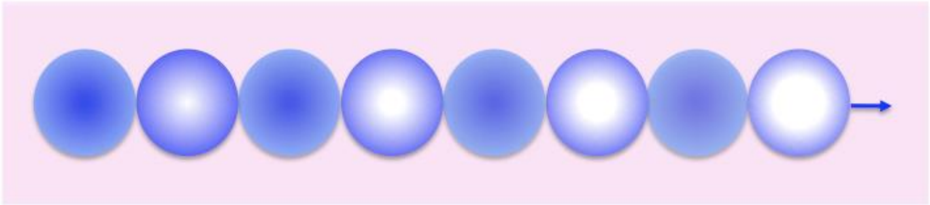


Self-modulation



Self-modulated bunch

Plasma wakefields



Growth mechanism:

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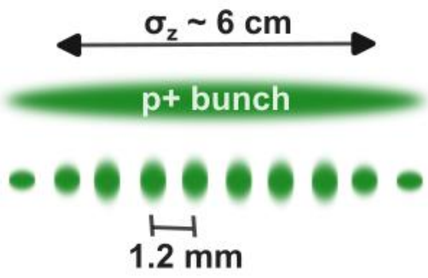
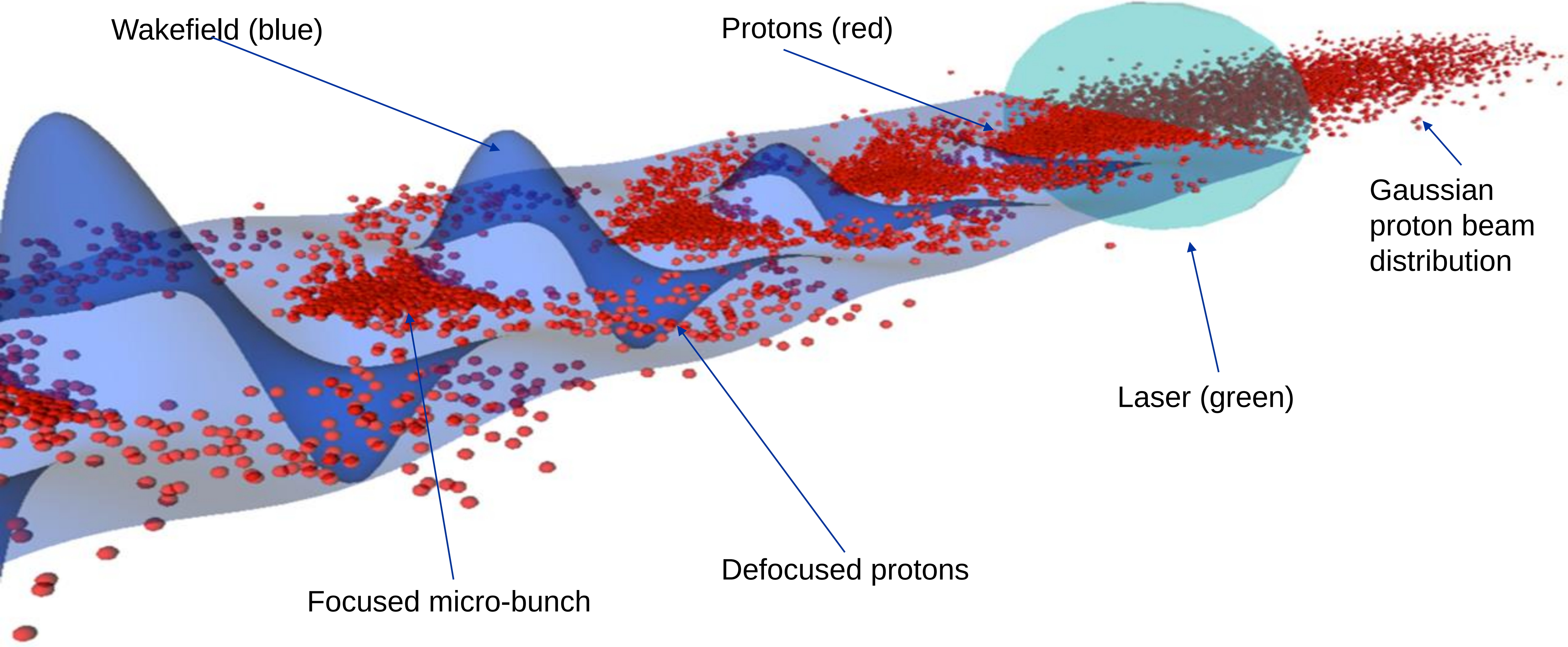
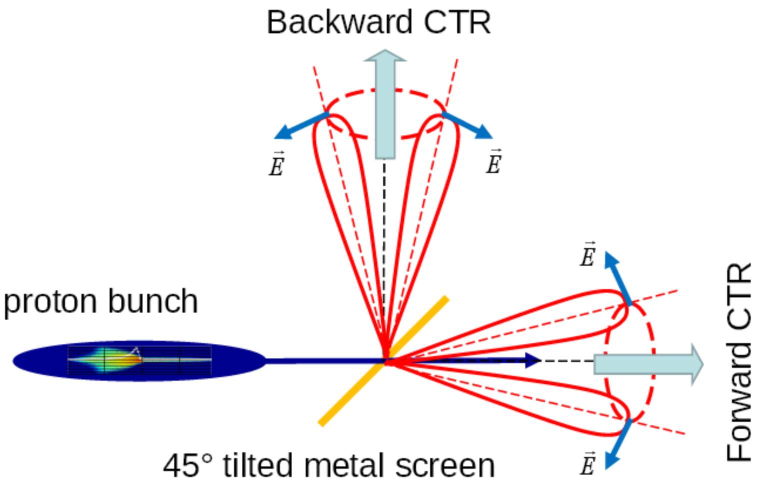


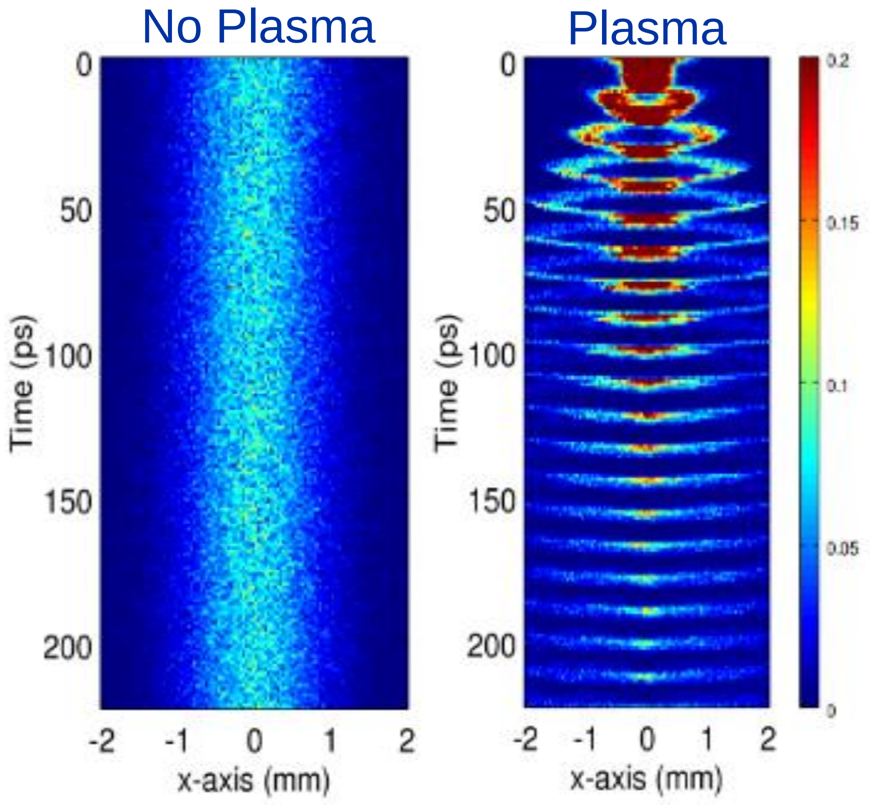
Simulation Result



Self-Modulation Diagnostics

Streak camera measurement

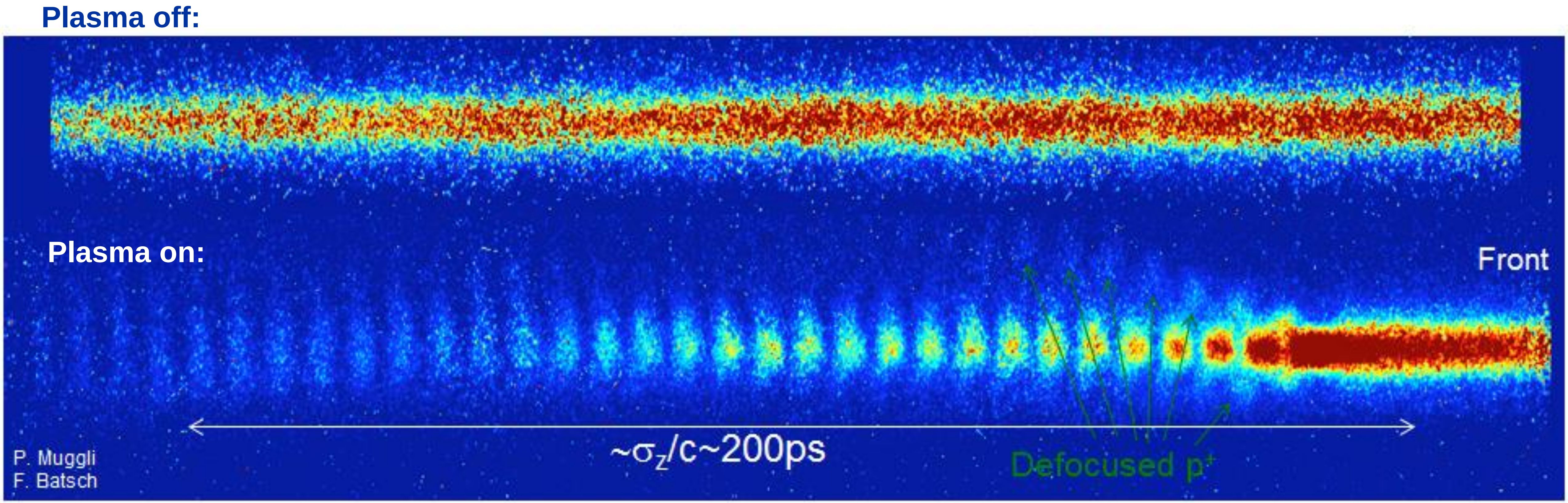




Foil emits waves up to the plasma wavelength of the foil including:

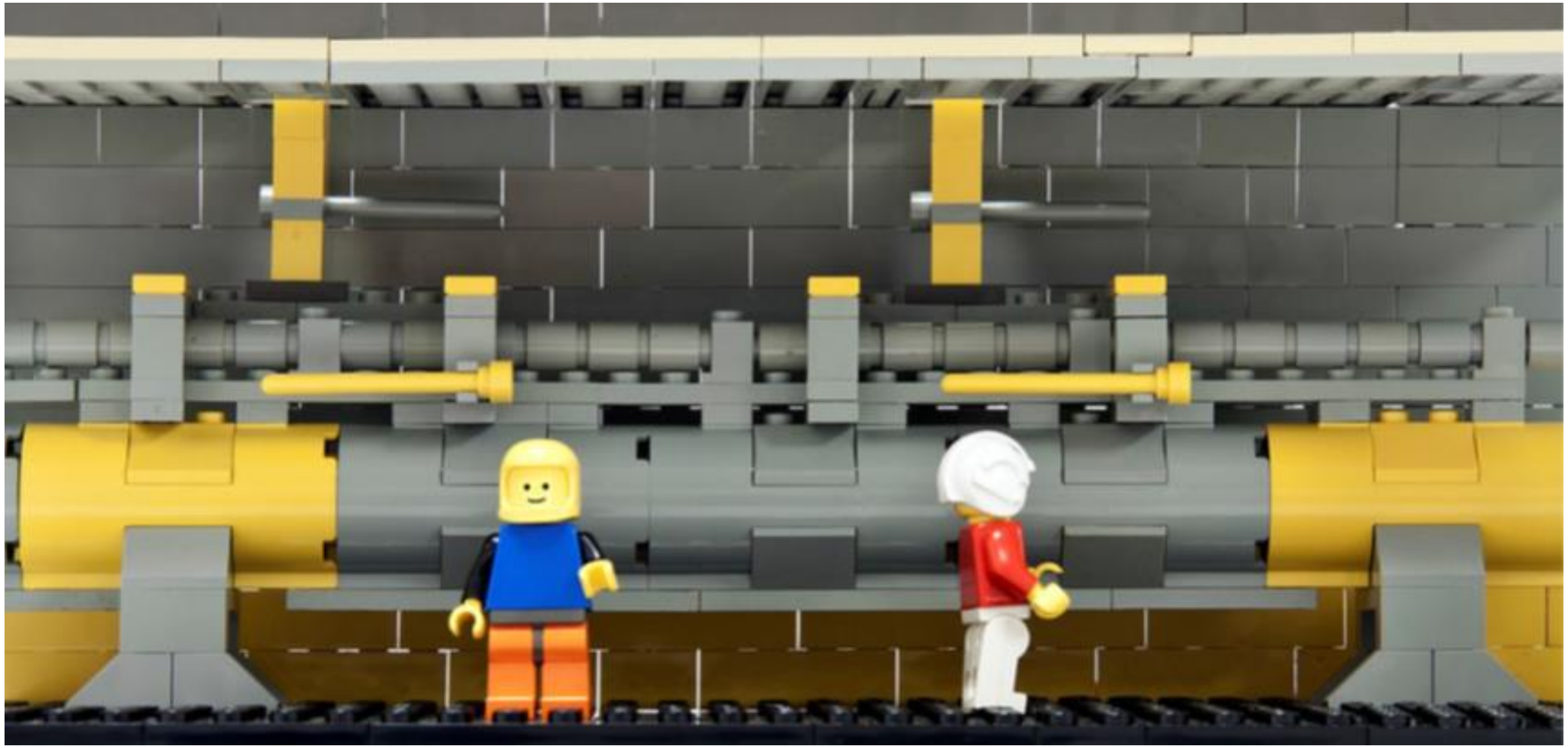
- radiation in the optical range (OTR).
- Coherent radiation (CTR) for wavelengths bigger than the structure of the micro-bunches

Self-Modulation Measurement Results



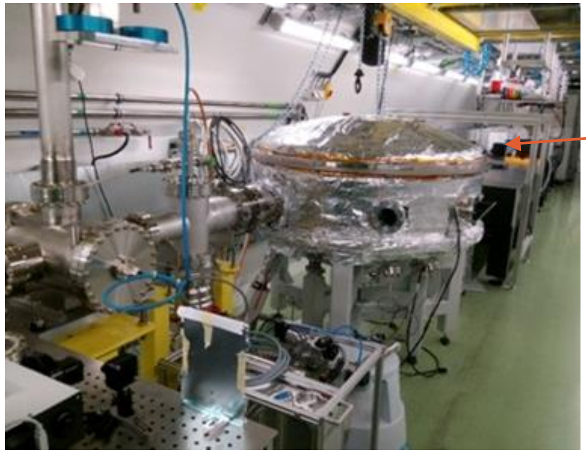
Shortly after we have observed the Seeded-Self Modulation for the first time!

Experimental Realization @CERN
→ AWAKE Experiment



From a concept and an idea to reality !

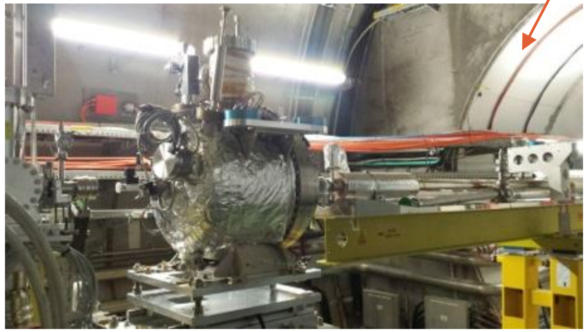
AWAKE Components



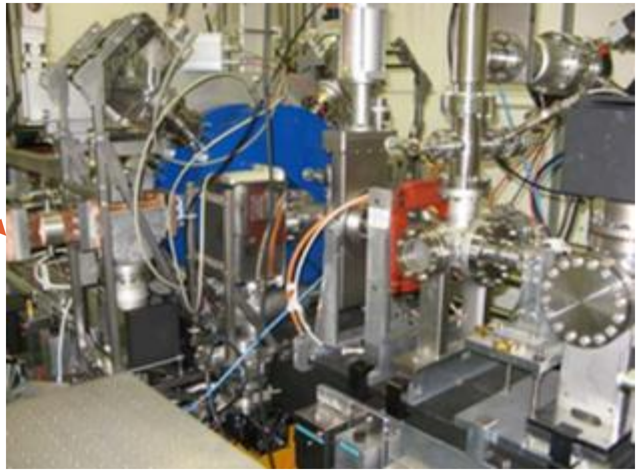
Plasma
- Laser
- Rubidium vapor

Drive Bunch
- Proton beam (400 GeV/c)

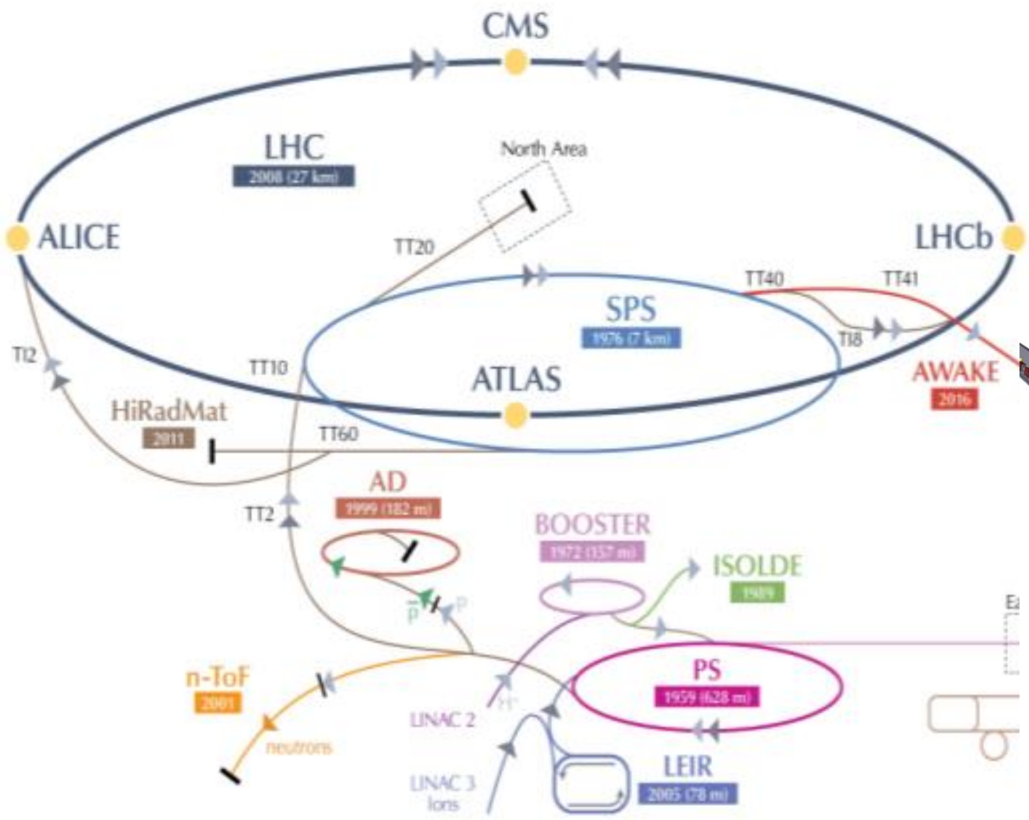
Witness Bunch
- Electron beam (10-20 MeV)

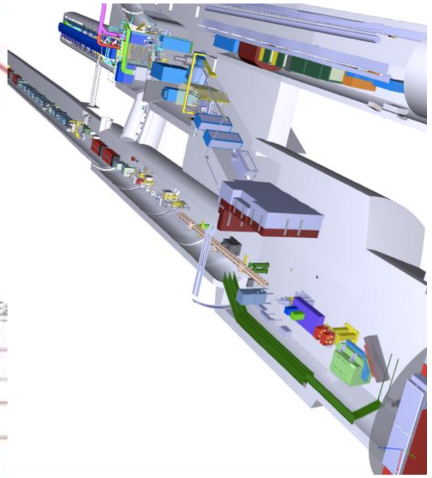


Diagnostics:
- Proton
- Laser
- Electron



Protons Delivered by CERN SPS

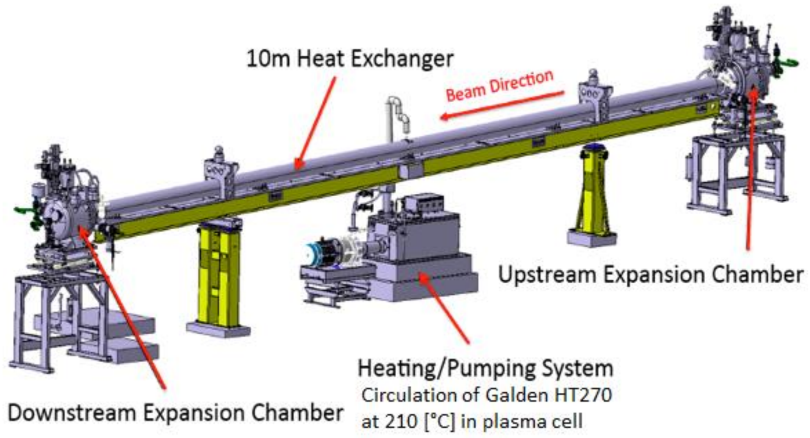


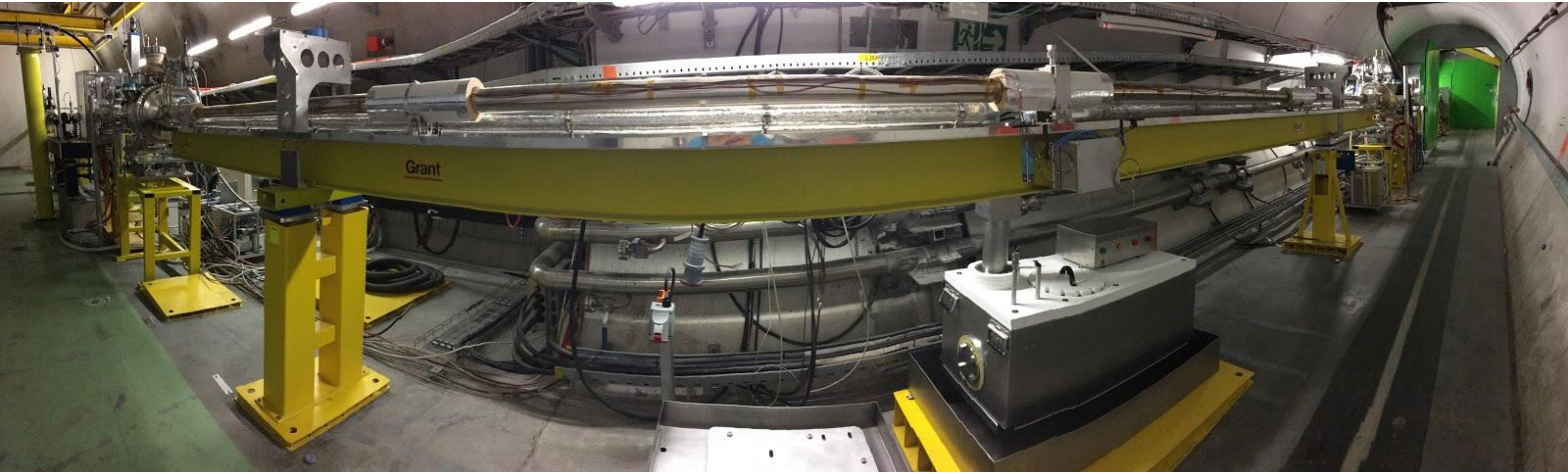


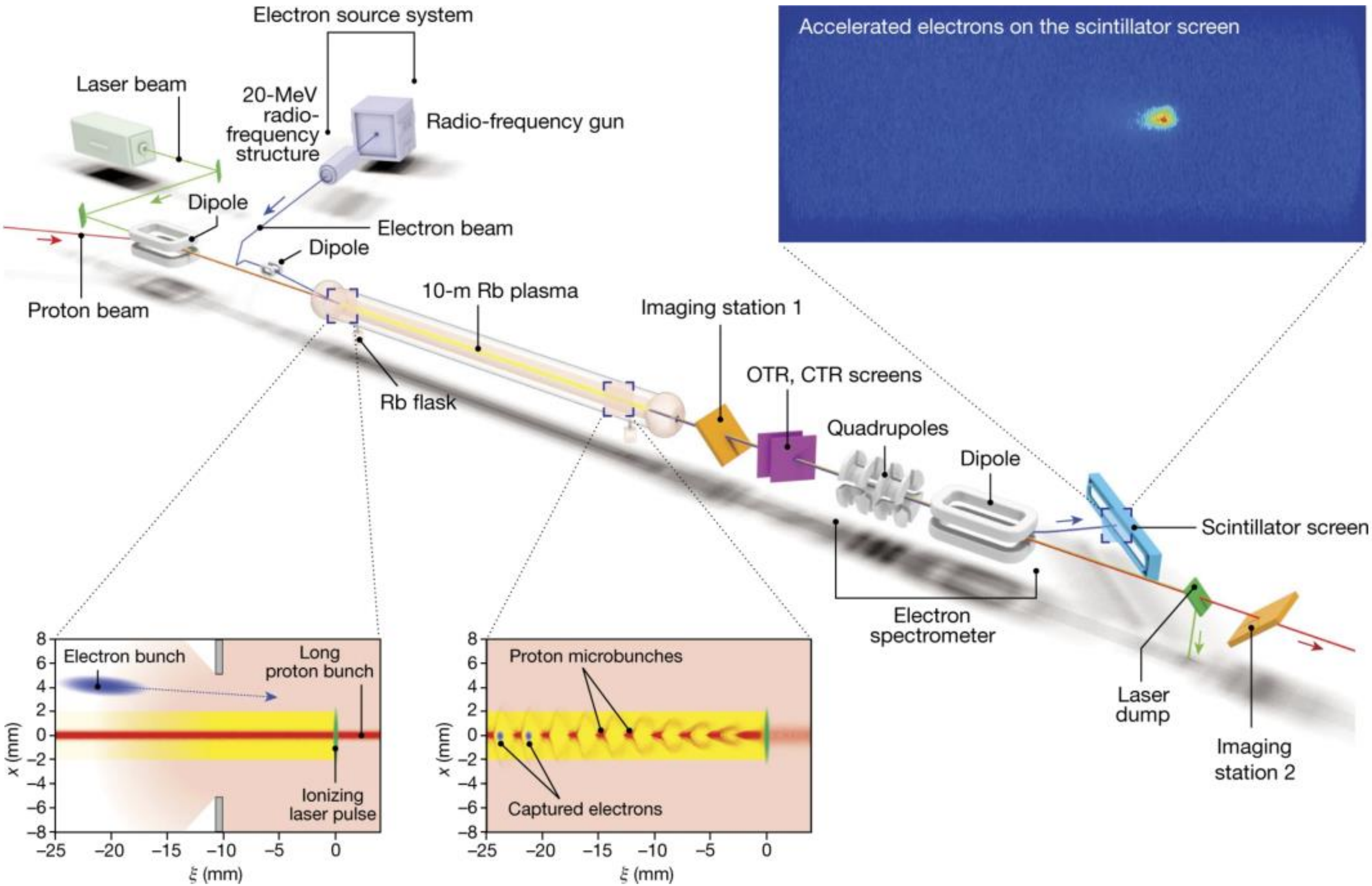
- Proton bunch momentum: 400 GeV/c
- $3x10^{11}$ protons/bunch
- Bunch length: σ_z = ~10 cm
- Radial bunch size at plasma entrance: σ_r = 0.2 mm

The AWAKE Plasma

Rubidium vapour cell.
The laser **ionizes** the outermost electron of each rubidium atom.
Desired **plasma density**: ~1-10x10^{14} electrons/cm^3.

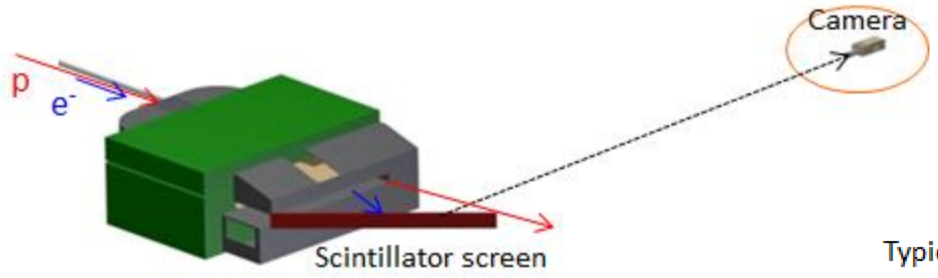




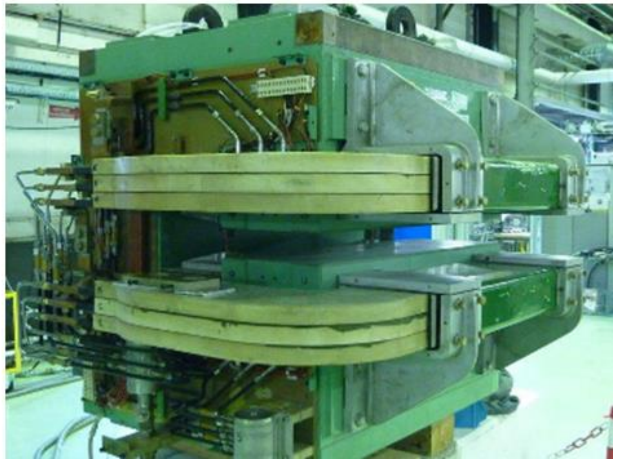

Electron source system
Laser beam
20-MeV radio-frequency structure
Radio-frequency gun
Dipole
Electron beam
Dipole
Proton beam
10-m Rb plasma
Rb flask
Imaging station 1
OTR, CTR screens
Quadrupoles
Dipole
Scintillator screen
Electron spectrometer
Laser dump
Imaging station 2
Accelerated electrons on the scintillator screen
Electron bunch
Long proton bunch
Ionizing laser pulse
x (mm)
ξ (mm)
Proton microbunches
Captured electrons
8
6
4
2
0
−2
−4
−6
−8
−25
−20
−15
−10
−5
0

Accelerated Electron Energy Measurement

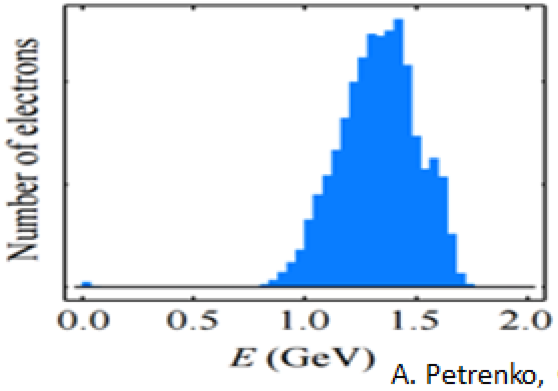
- Electrons will be injected with an energy around 10-20 MeV.
- Accelerated electrons are sent through a **dipole magnet** and deposit energy on a scintillating screen which is imaged by a camera.



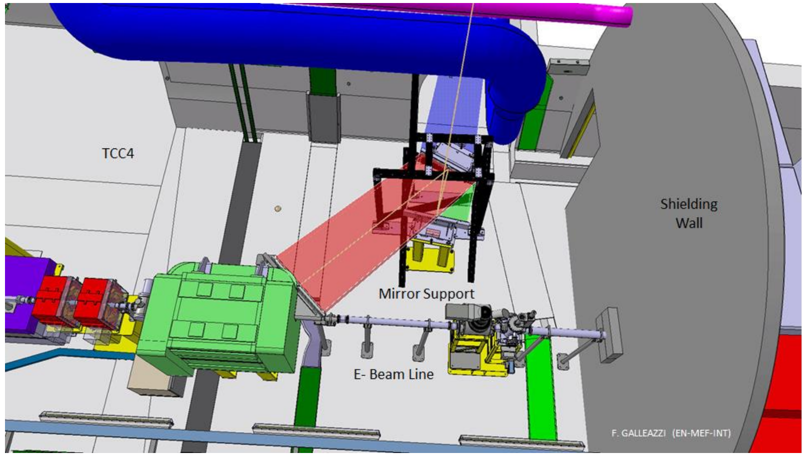
8.5 ton, 1.2 T, 1.3 Tm, L=1.6 m, W=1.3 m

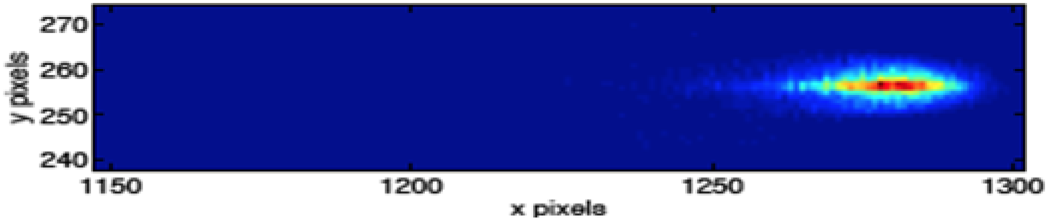


Typical final energy distribution of the accelerated electron beam after 10 m plasma:

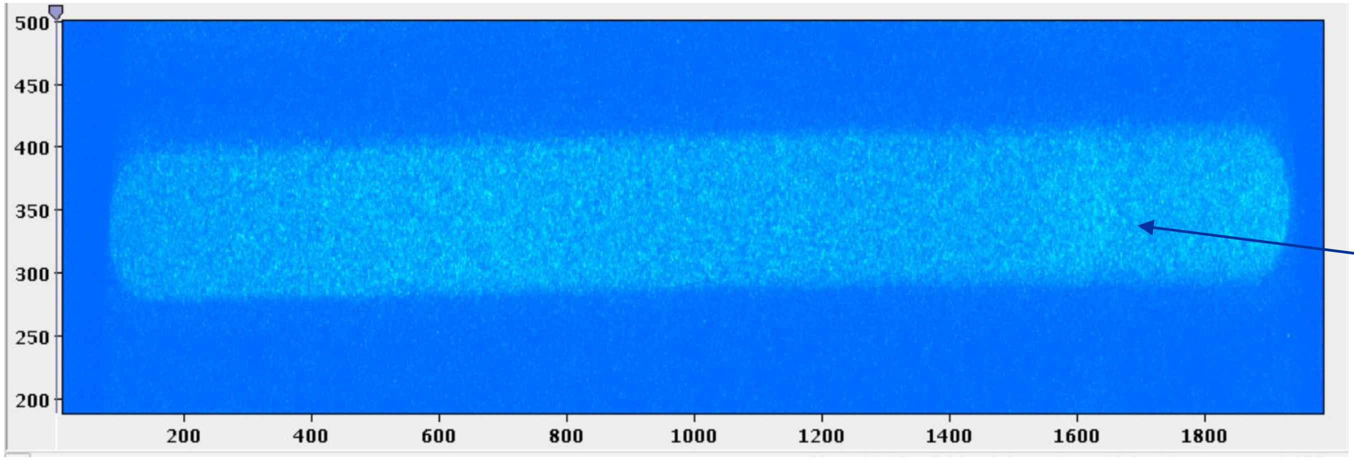


A. Petrenko, CERN

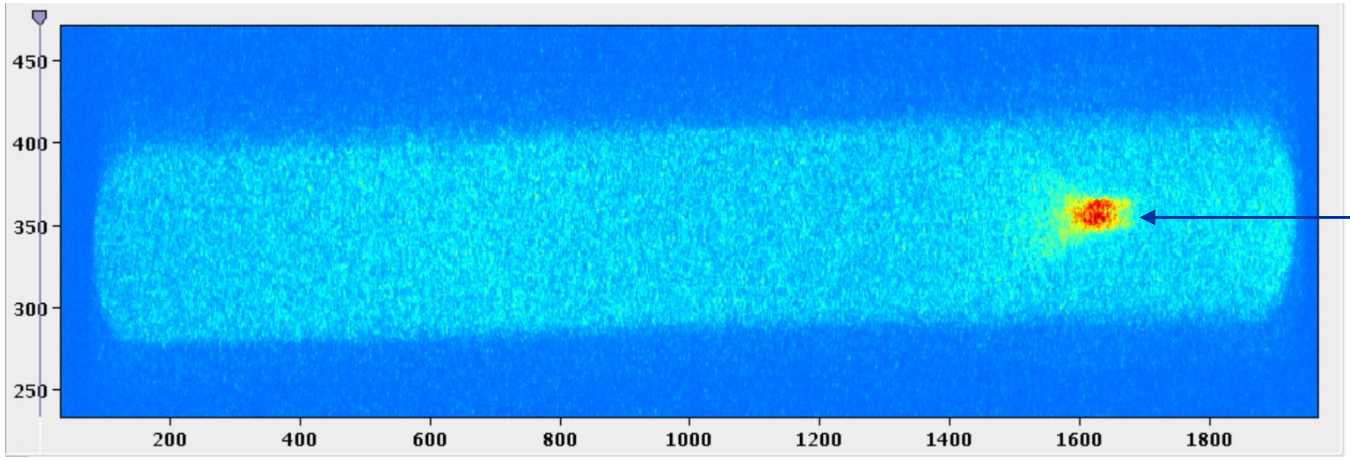




First Electron Acceleration

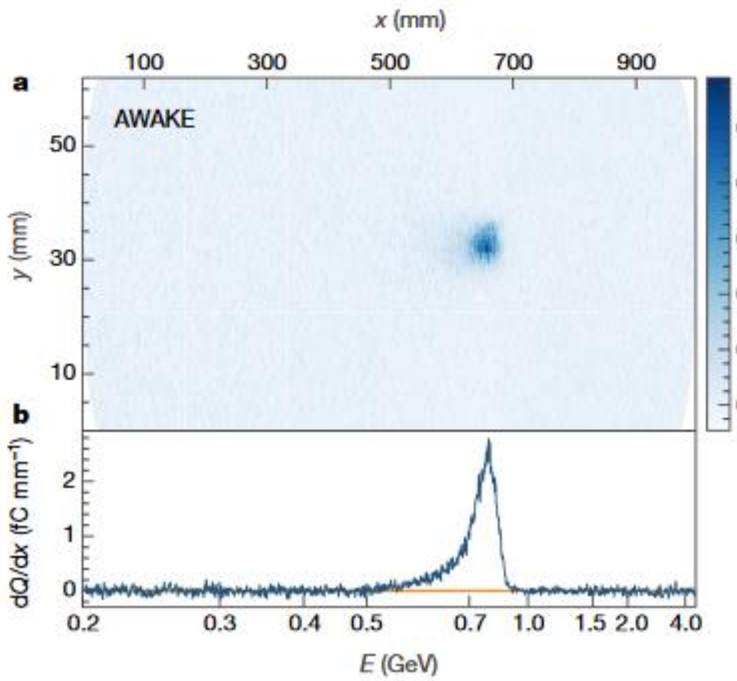


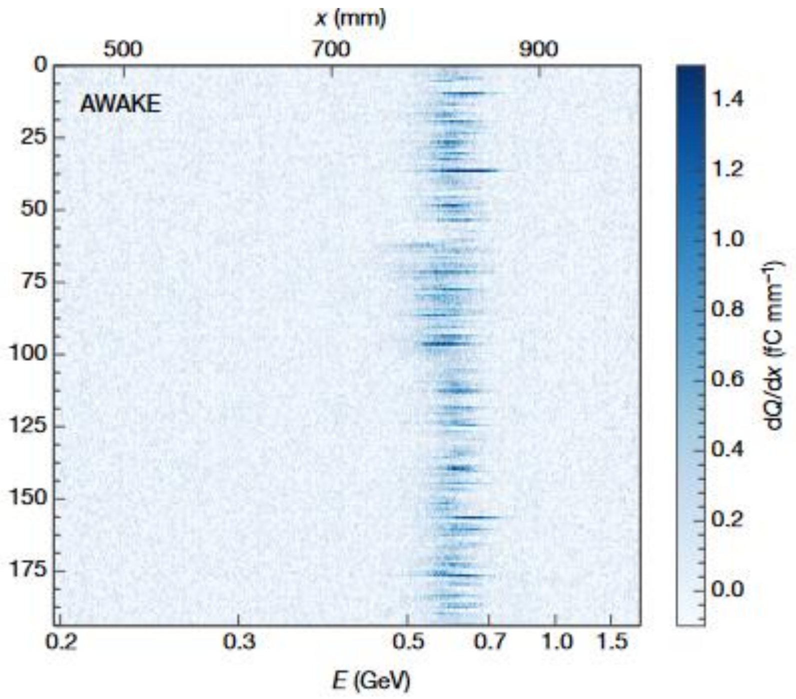
No electrons accelerated.

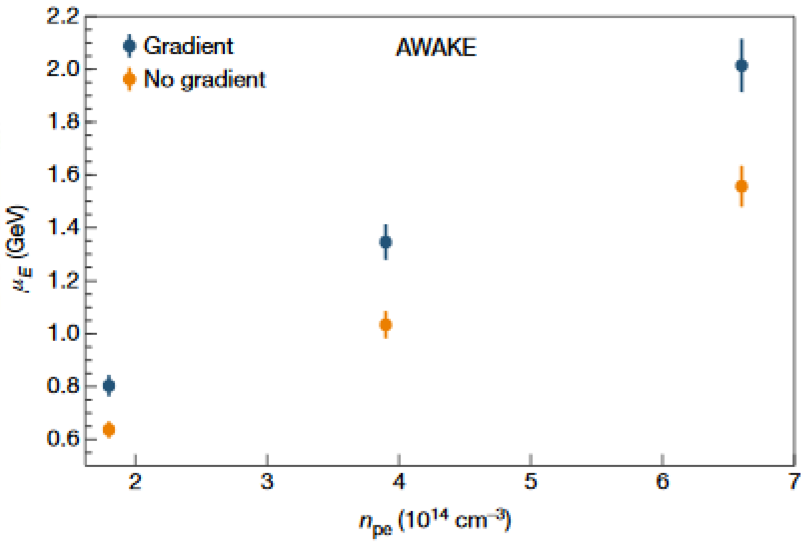


Accelerated electrons.

Electron Acceleration Results







AWAKE Collaboration, *Nature* **volume 561**, pages 363–367 (2018)

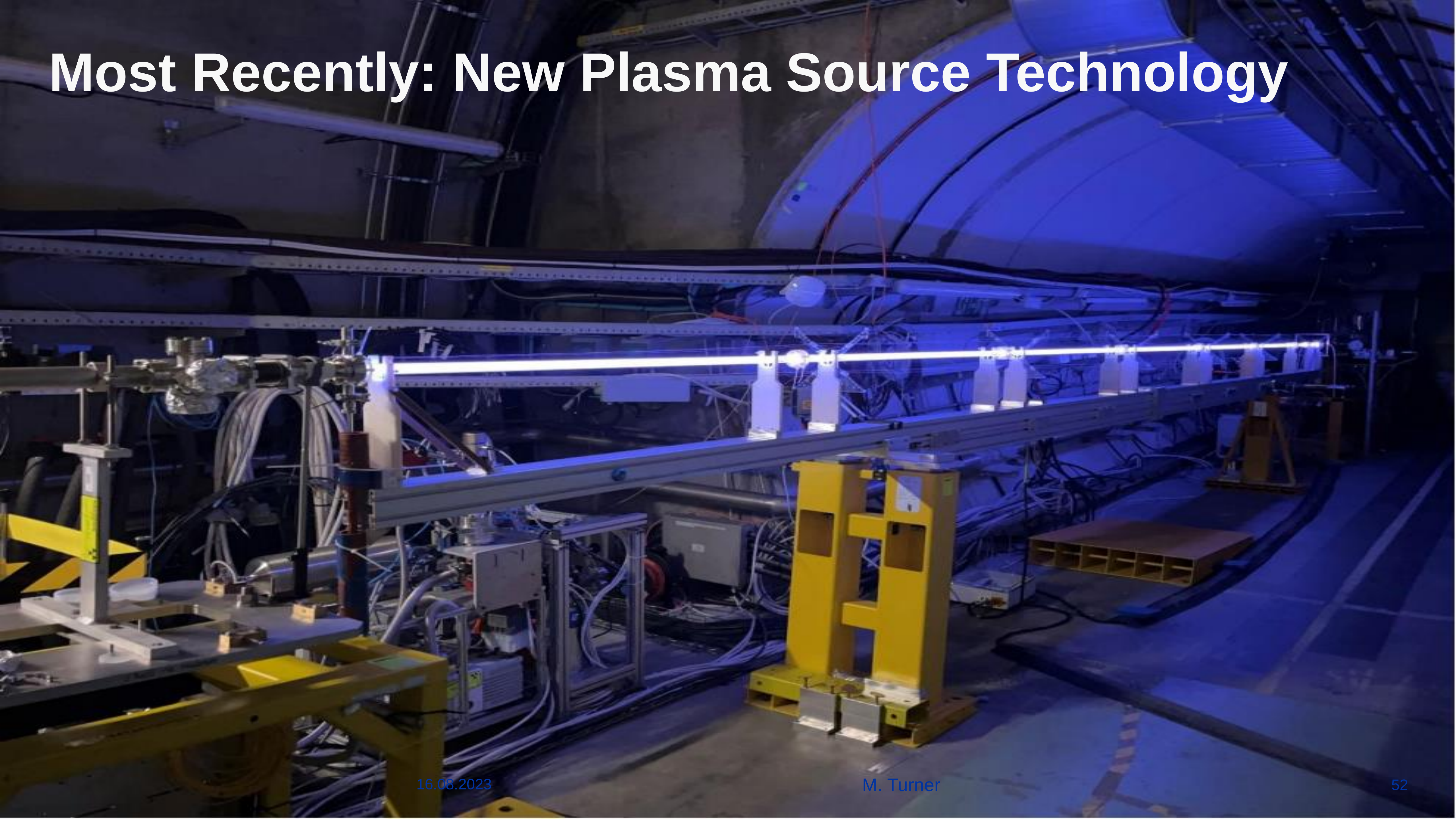
Shortly after we have observed electron acceleration for the first time!

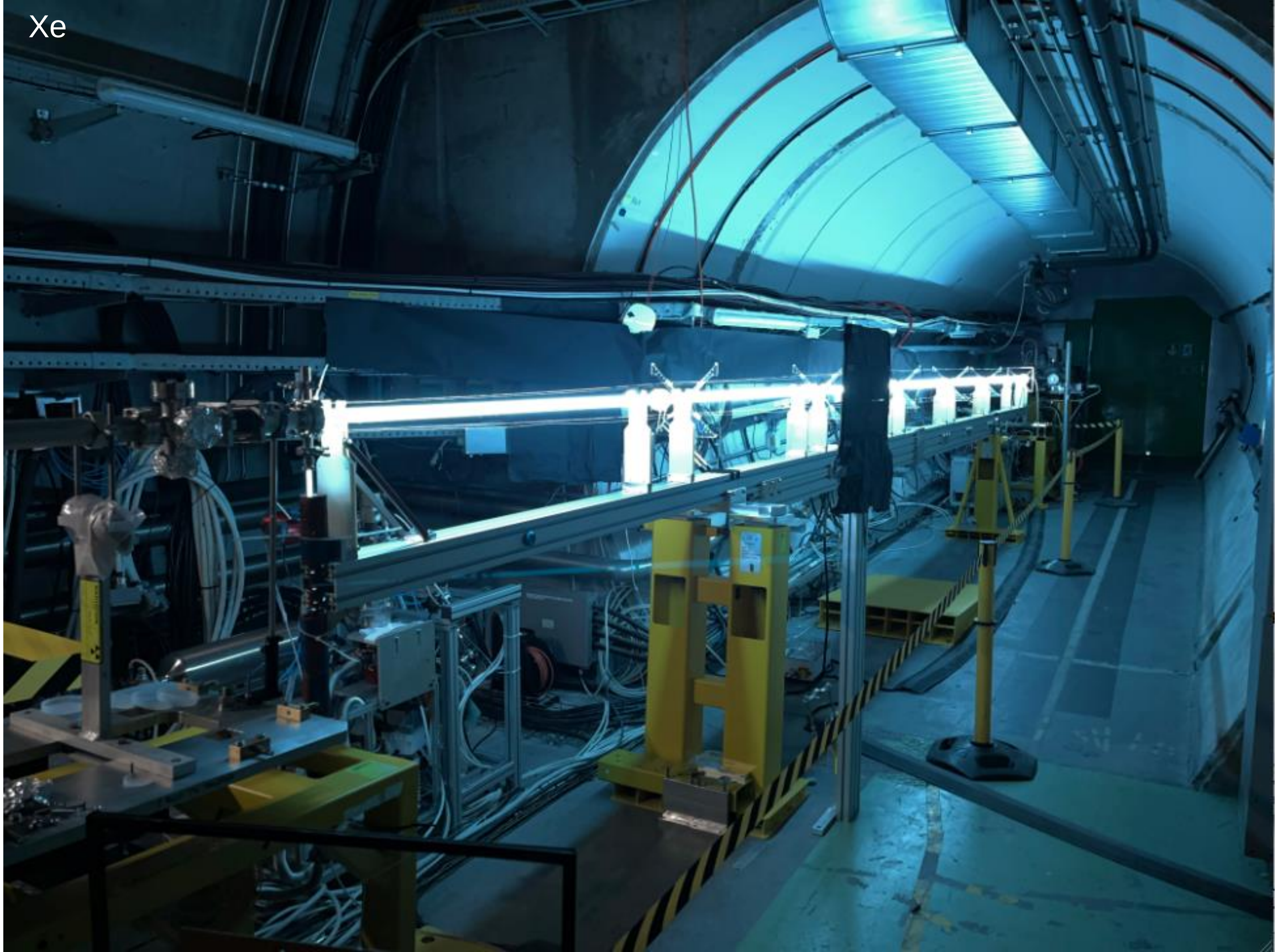
Let Us Repeat…

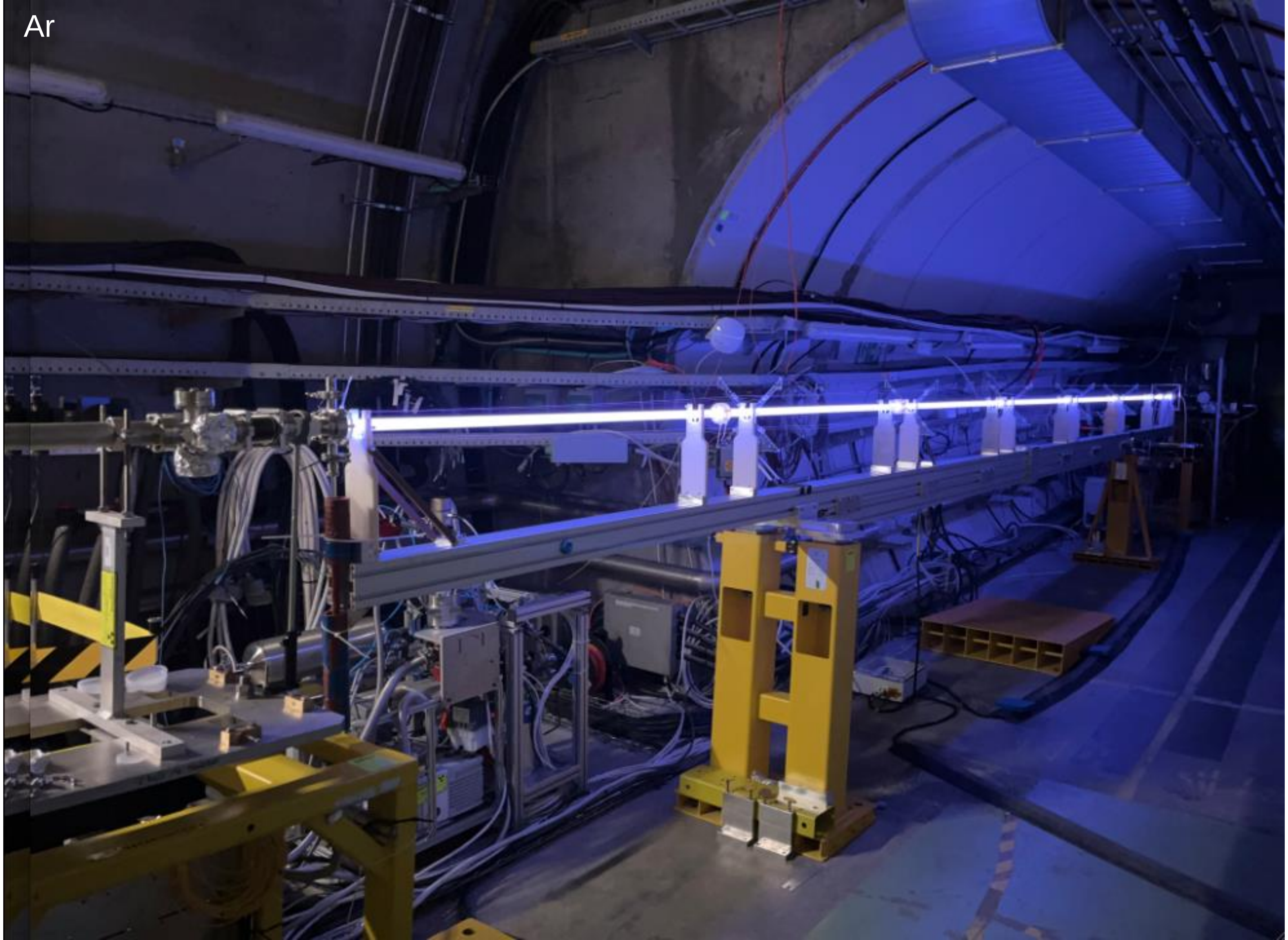
- To realize the AWAKE experiment at CERN, we need:
  - Plasma (vapor source + laser)
  - Proton bunch (wakefield driver)
  - Electron bunch (witness – to be accelerated)

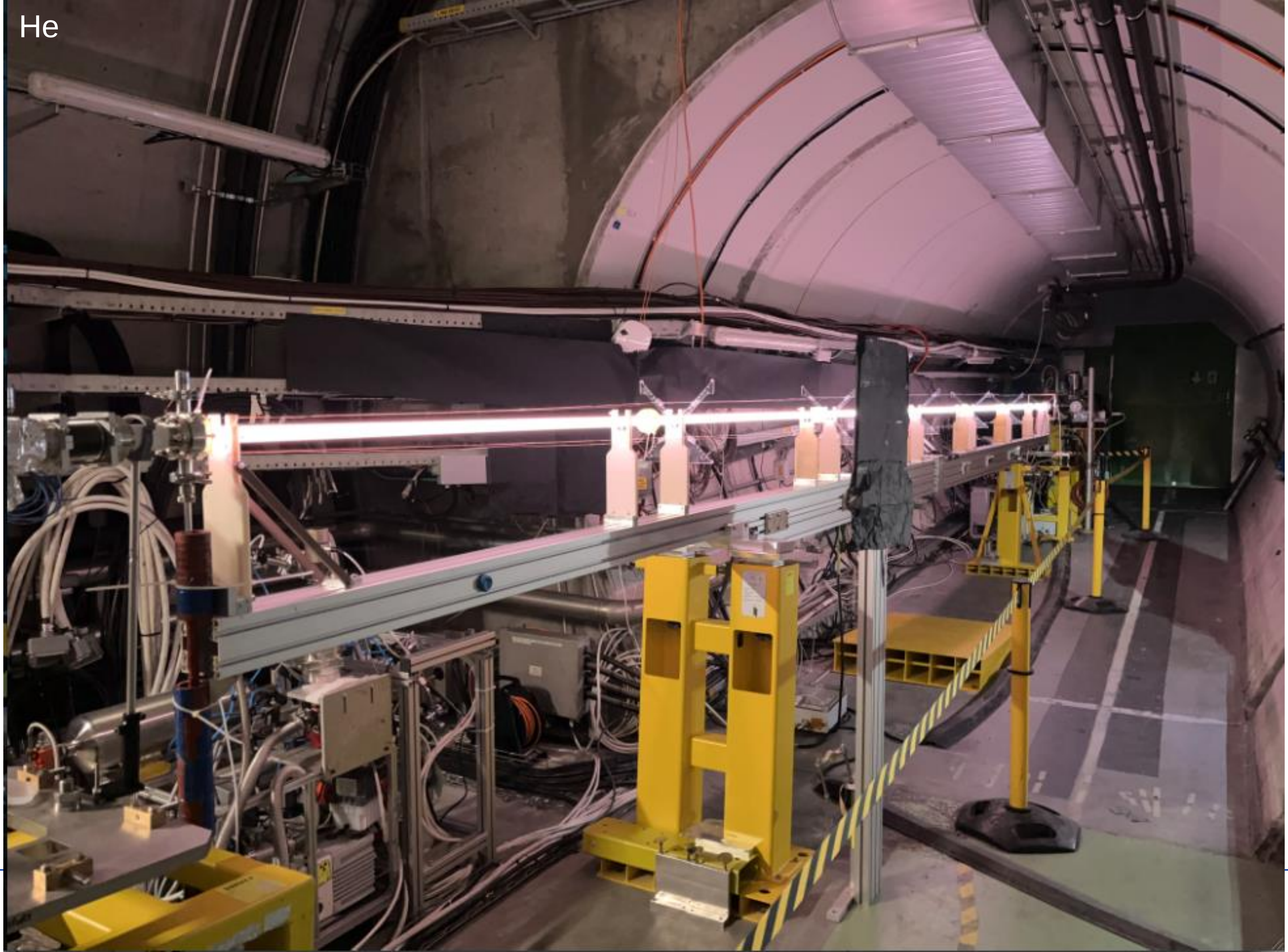
- Diagnostics are key to a successful measurement
  - AWAKE diagnostics include:
    - Screens + Streak camera (to know beam positions and verify that SSM was successful)
    - Electron spectrometer (energy of the accelerated witness bunch)

Most Recently: New Plasma Source Technology

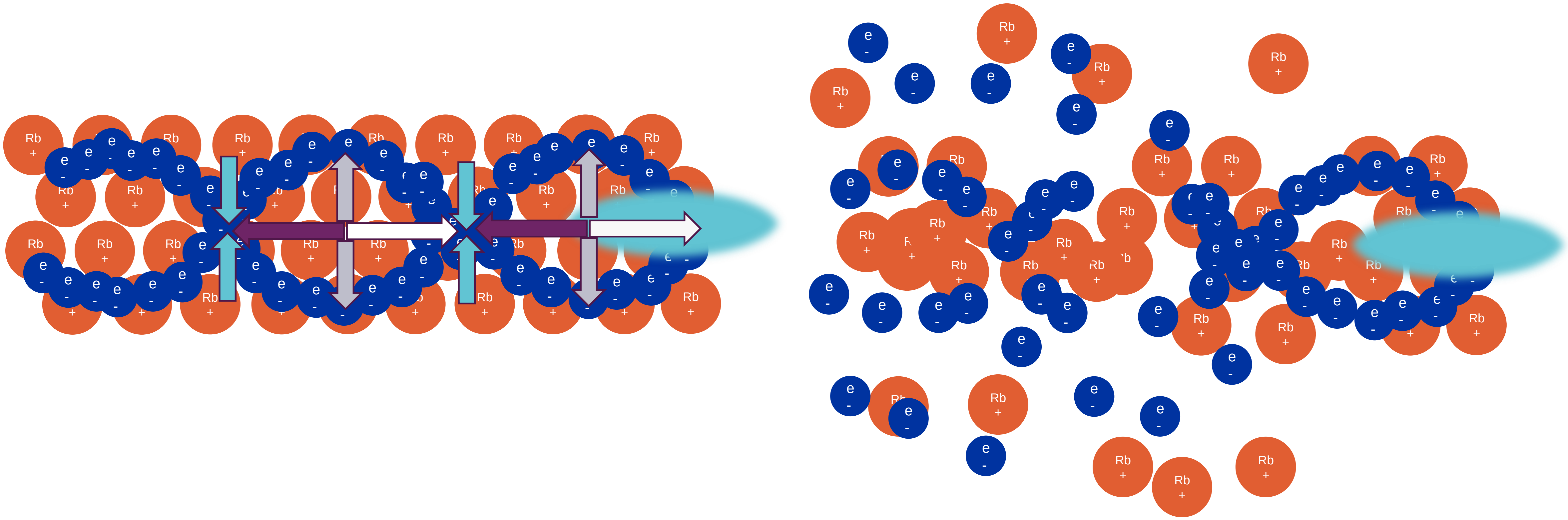



Xe


Ar

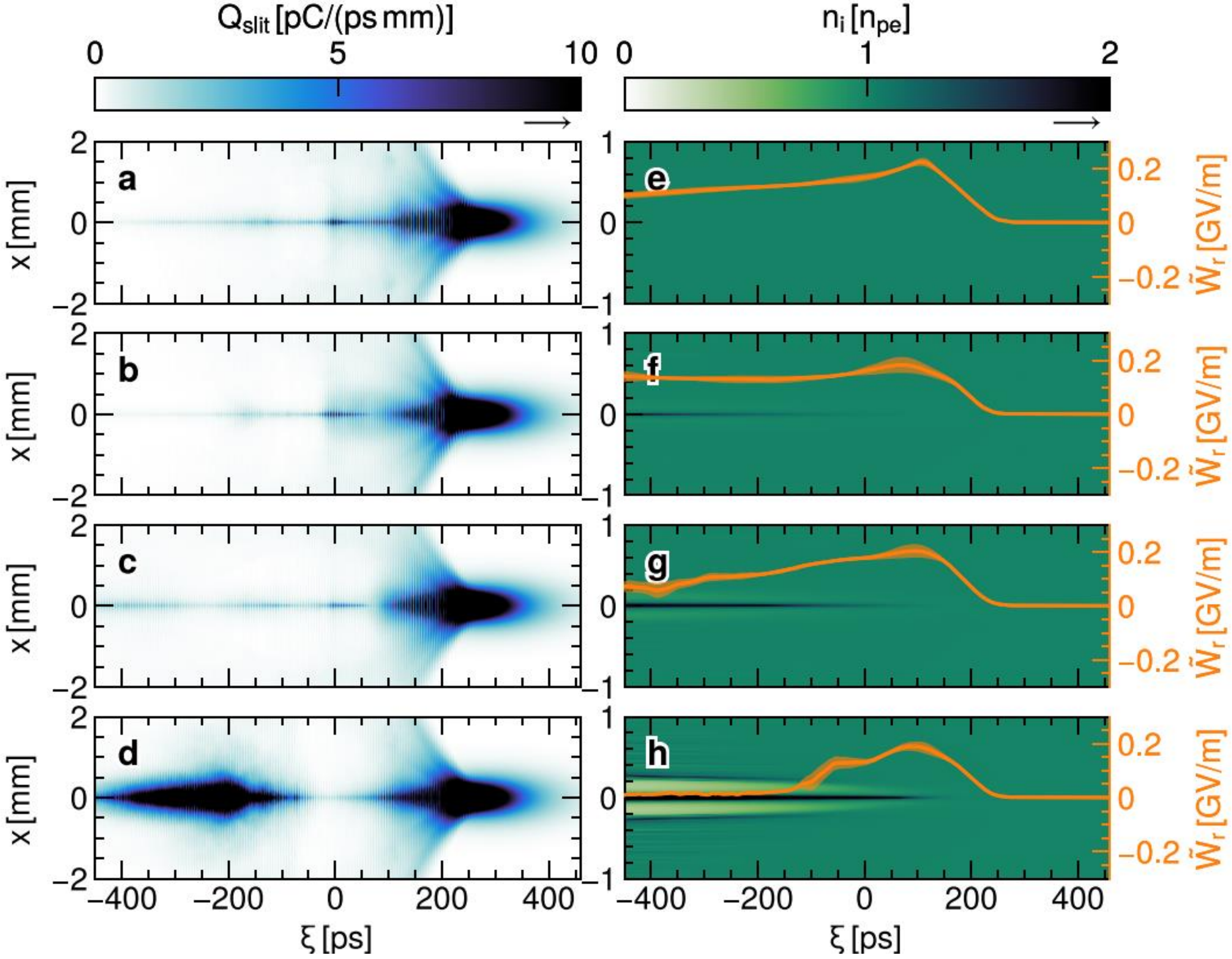

He

Motion of Ions Leads to Decoherence of Plasma Electron Motion

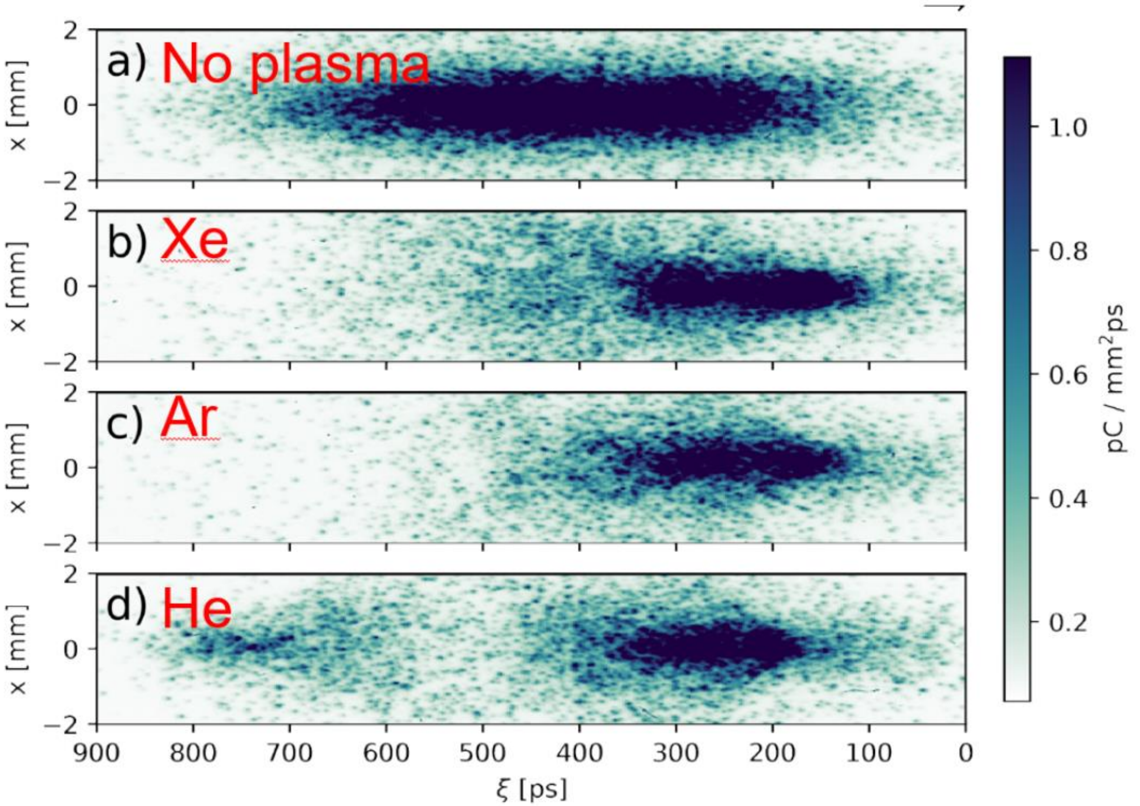


Experimental Observation of Motion of Ions

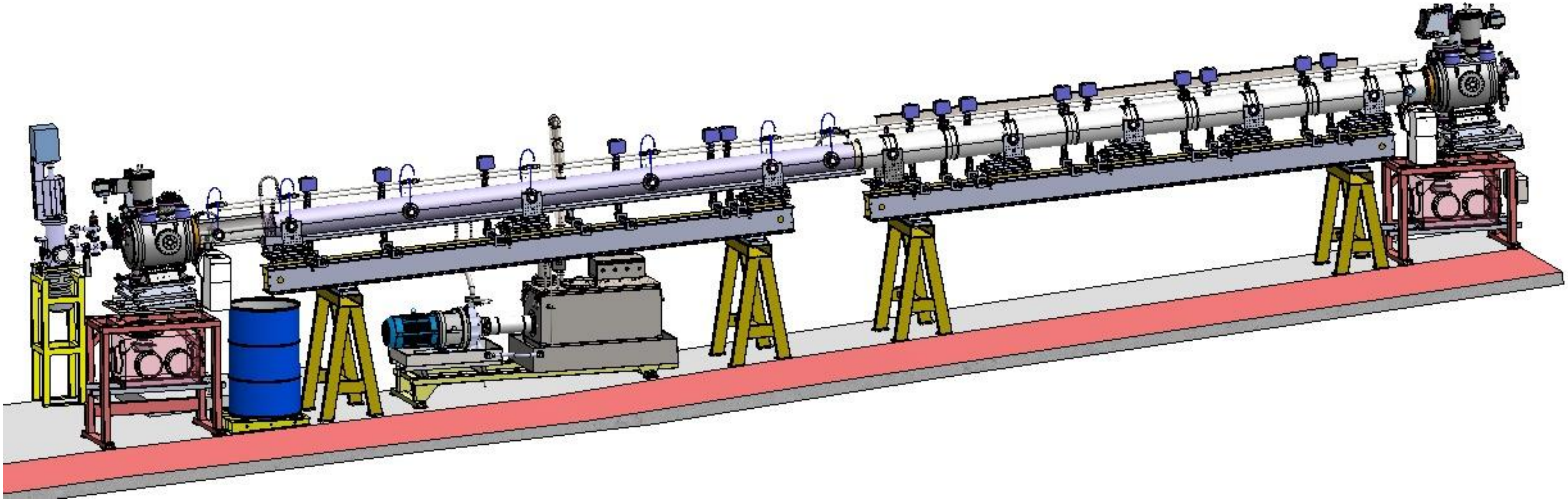
Simulation



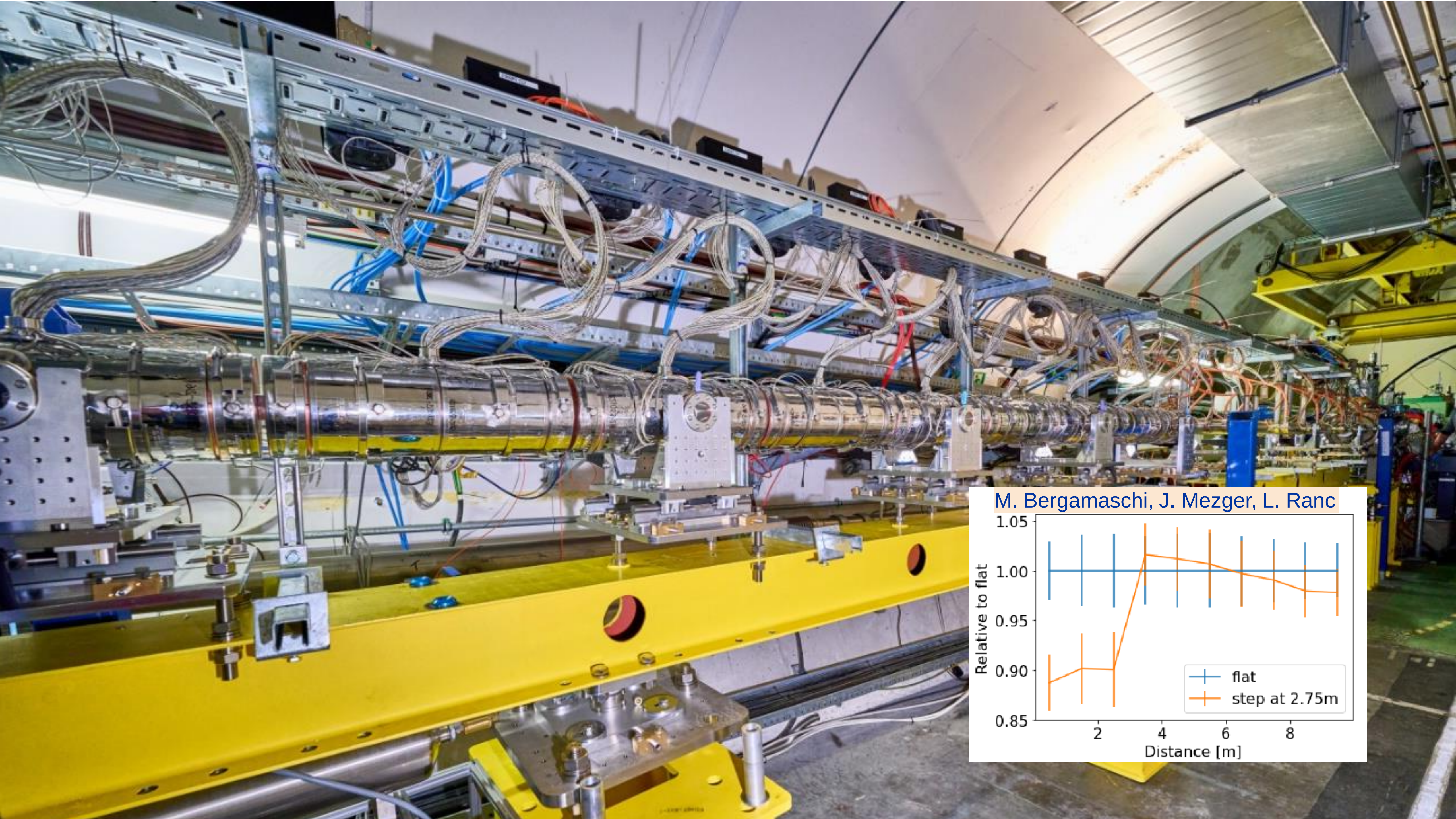
Experiment



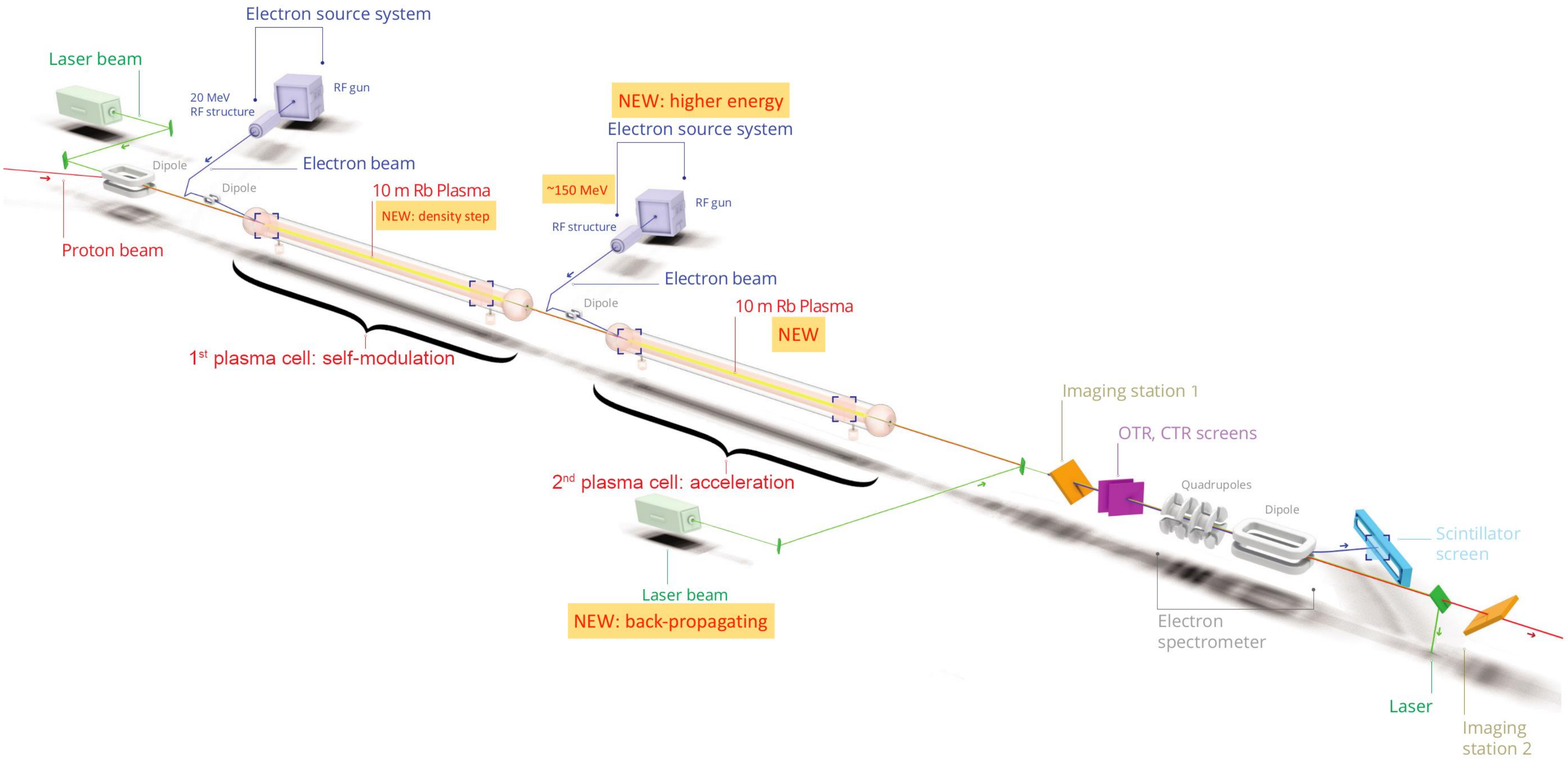
Now in AWAKE: New Plasma Source



- Allows to adjust the plasma density along the 10 m
- More stable SSM, → higher wakefield amplitudes


M. Bergamaschi, J. Mezger, L. Ranc
Relative to flat
1.05
1.00
0.95
0.90
0.85
2
4
6
8
Distance [m]
flat
step at 2.75m

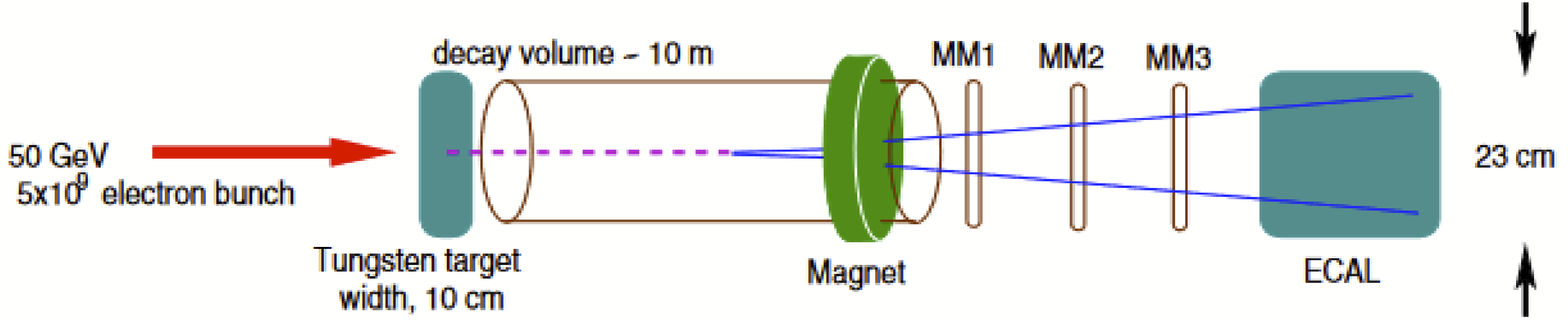
AWAKE until ~2030



First AWAKE Particle Physics Applications
Example I: Dark Matter Experiment

These experiments use the collisions of an electron beam with a fixed-target or a dump to generate the dark photon via Bremsstrahlung (electron and proton beams) or meson production.

The products of the collisions are mostly absorbed in the dump and the dark photon is searched for as a displaced vertex with two opposite charged tracks in the decay volume of the experiment.

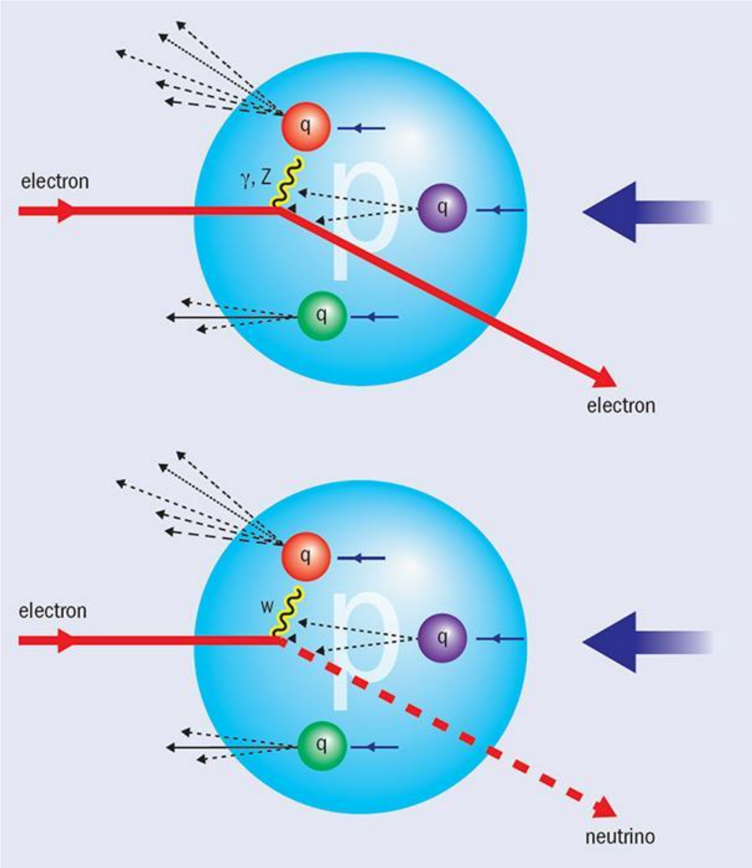


$e^-Z \rightarrow e^-ZA'$

$A' \rightarrow e^+e^-$, etc..

From Caldwell: https://arxiv.org/pdf/1812.11164.pdf

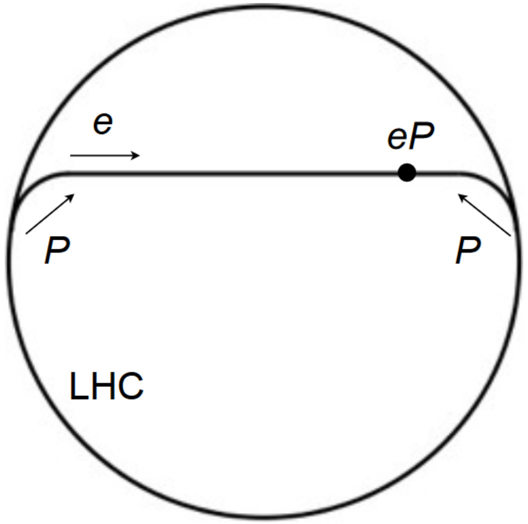
First AWAKE Particle Physics Applications
Example II: Electron-Proton Collisions



Diagrams of neutral-current (top) and charged-current (bottom) deep-inelastic electron–proton scattering processes. Image credit: DESY.

- Collide:
  - 50 GeV electrons with 7 TeV LHC protons
  - ~TeV electrons with 7 TeV LHC protons

Plasma-based collider design



Caldwell, A., Wing, M. VHEeP: a very high energy electron–proton collider. *Eur. Phys. J. C* **76**, 463 (2016). https://doi.org/10.1140/epjc/s10052-016-4316-1

Physics cases:

- Study of the sub-structure and spin structure of the proton and photon
- Determine if partons are fundamental point-like objects
- Clarifying the underlying physics leading to the energy dependence of cross sections
- Leptoquark production: hypothetical particles that would interact with quarks and leptons

Summary and Conclusions

- **Plasma wakefield acceleration** is a novel technique to accelerate charged particles
  - Advantage: Very **high accelerating gradient**, compact accelerators
- Proof of principle acceleration has been demonstrated
  - **Next step**: aim for high beam quality in long plasmas→ First applications

- AWAKE is an accelerator R&D experiment at CERN:
  - Only proton-driven wakefield acceleration experiment worldwide
  - The experiment opens a pathway towards particle physics applications

- **Final Goal**: Design high quality & high energy electron accelerator based on acquired knowledge.

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