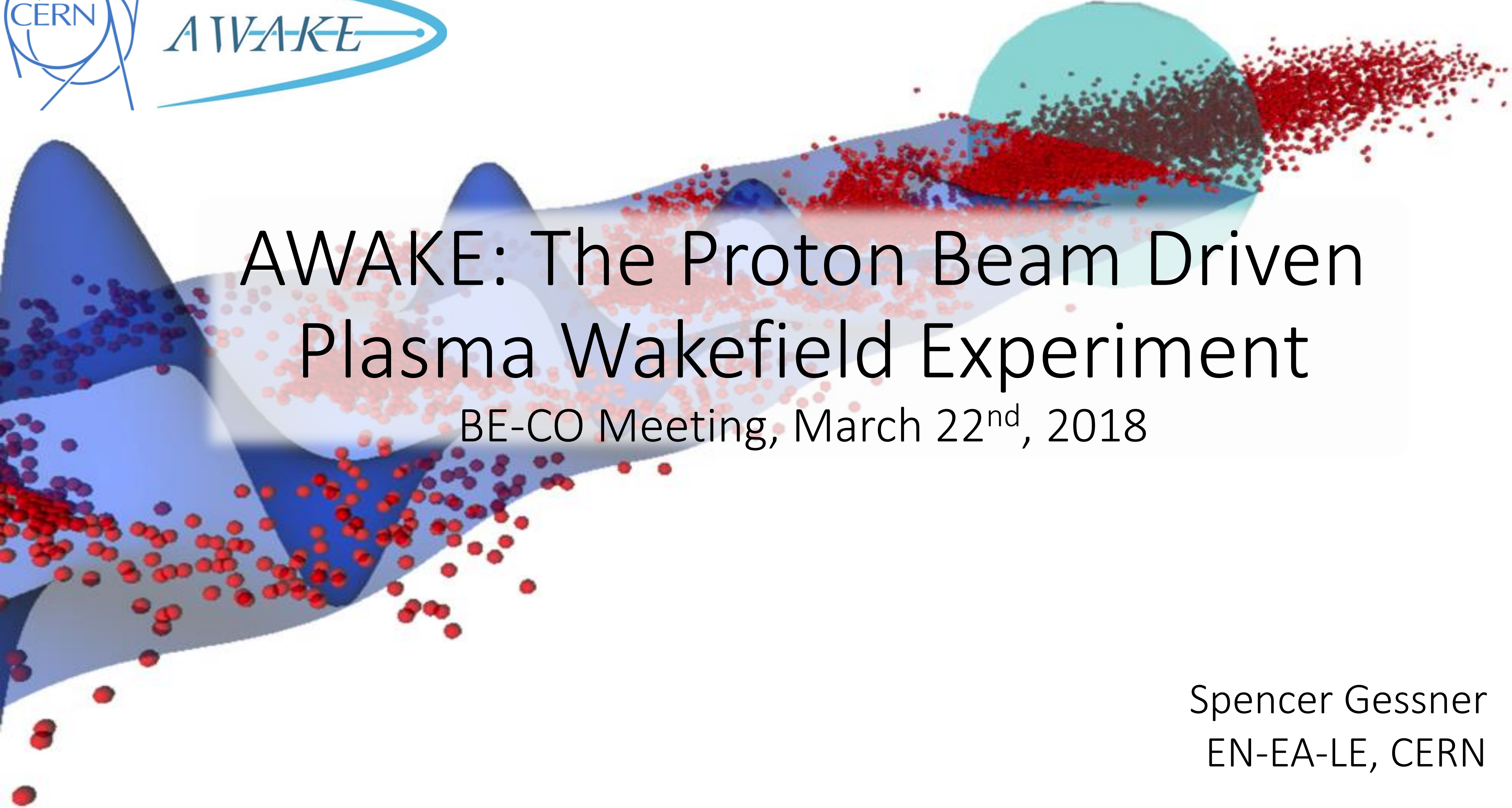


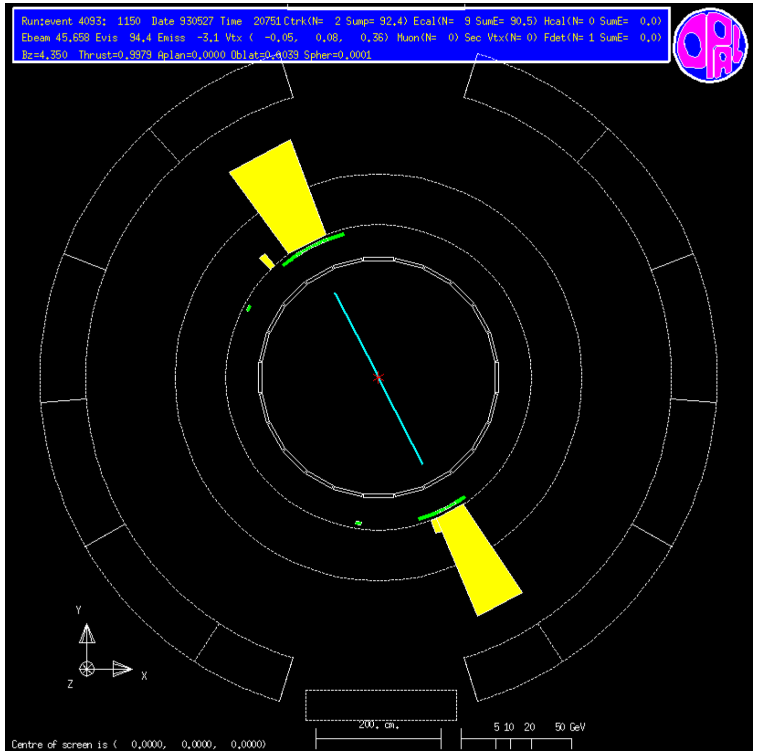
AWAKE: The Proton Beam Driven Plasma Wakefield Experiment

BE-CO Meeting, March 22nd, 2018

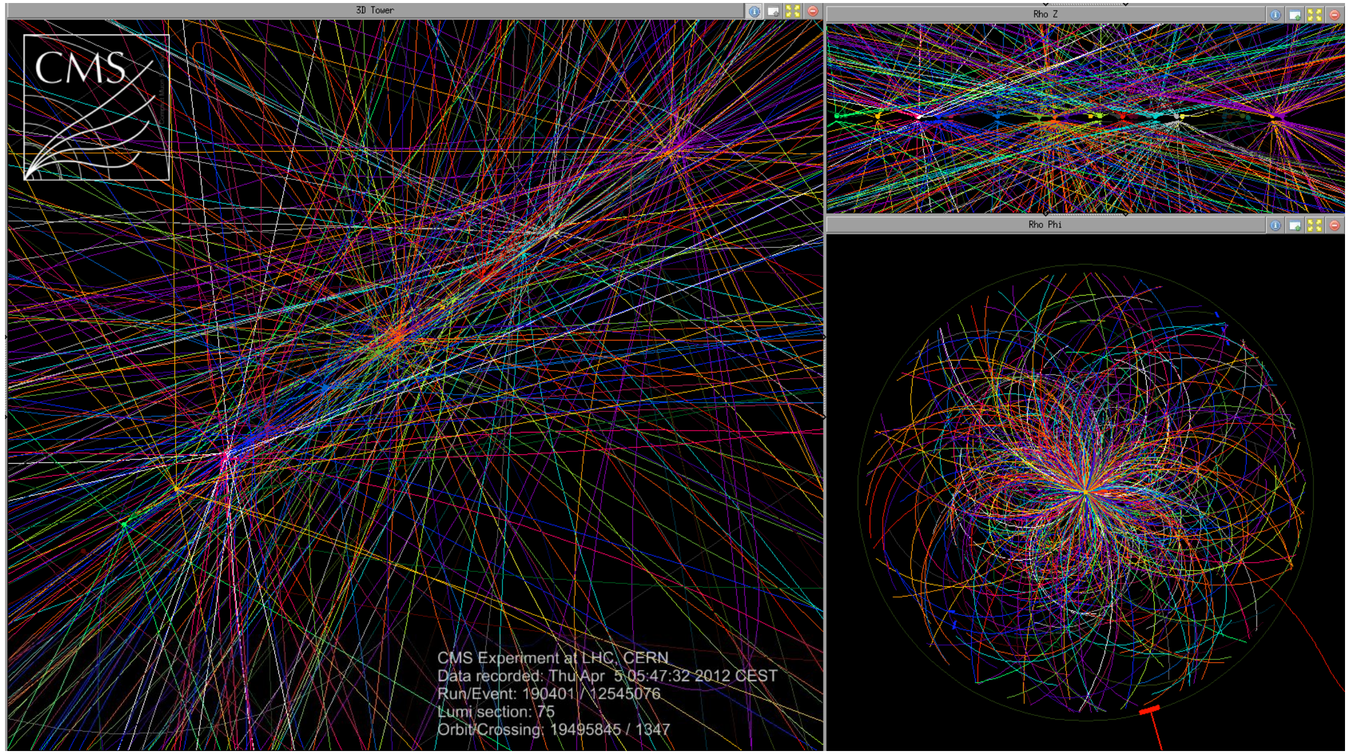
Spencer Gessner
EN-EA-LE, CERN

LEP: 1989-2000

Why build an Electron-Positron Collider?



$e^+ e^-$ collision (1993)

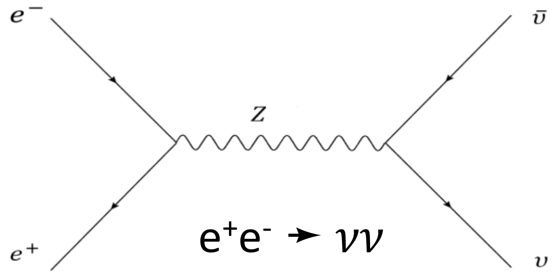


pp collision (2012)

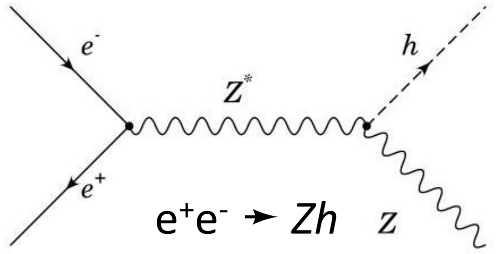
Electron-Positron collisions are “clean” compared to Proton-Proton collisions. They allow us to make precise measurements of the standard model.

The Large Electron-Positron Collider

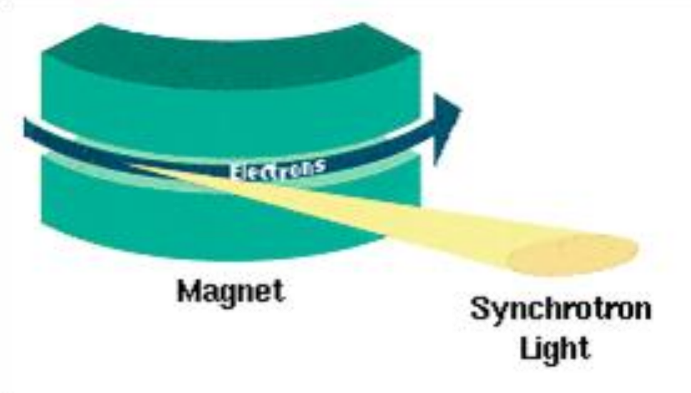
LEP started at a center-of-mass (CM) energy of 90 GeV in 1989.



By the time LEP turned off in 2000, it had reached a CM energy of 209 GeV.



It could have gone further were it not for synchrotron radiation.



The radiated power increased from 0.6 MW at 90 GeV CM to 18 MW at 209 GeV CM.

$$P_\gamma(GeV/s) = \frac{c}{2\pi}\frac{c_\gamma E_b^4}{\rho^2}$$

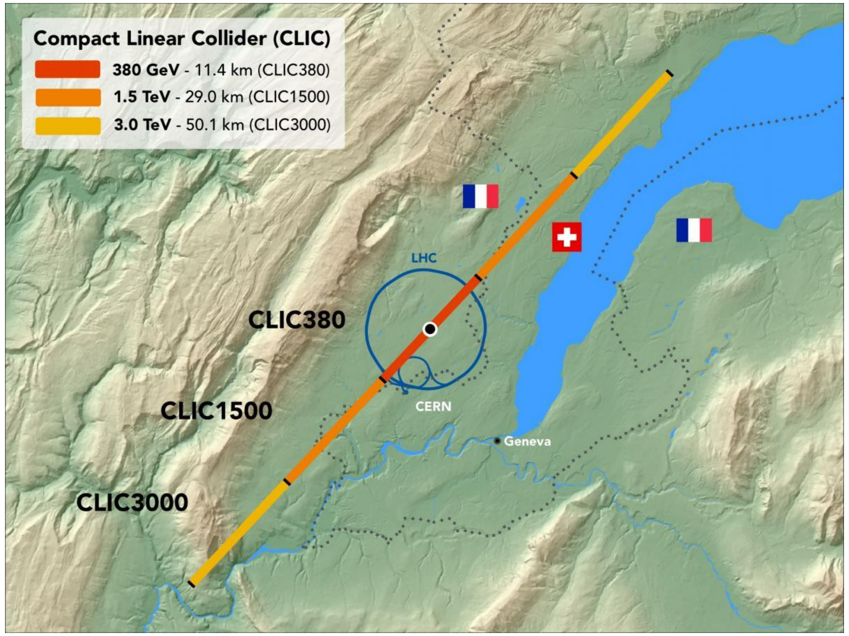
We know now that LEP would have seen the Higgs if it had reach 250 GeV CM, but that would have required 37 MW of power!

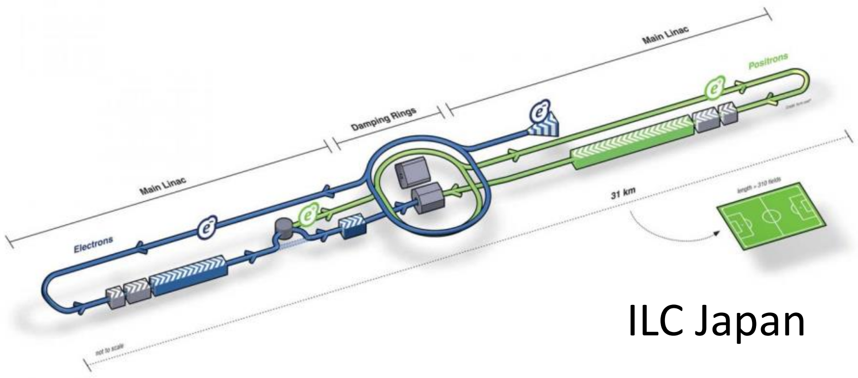
Linear Colliders

Linear Colliders do not lose energy to synchrotron radiation because the particles are not bent by magnets.

Instead, the particles are accelerated to the highest possible energy in a single pass and focused towards a collision point.

The length of the linear collider is determined by the *accelerating gradient*: the amount of energy added to the particles in a given distance.





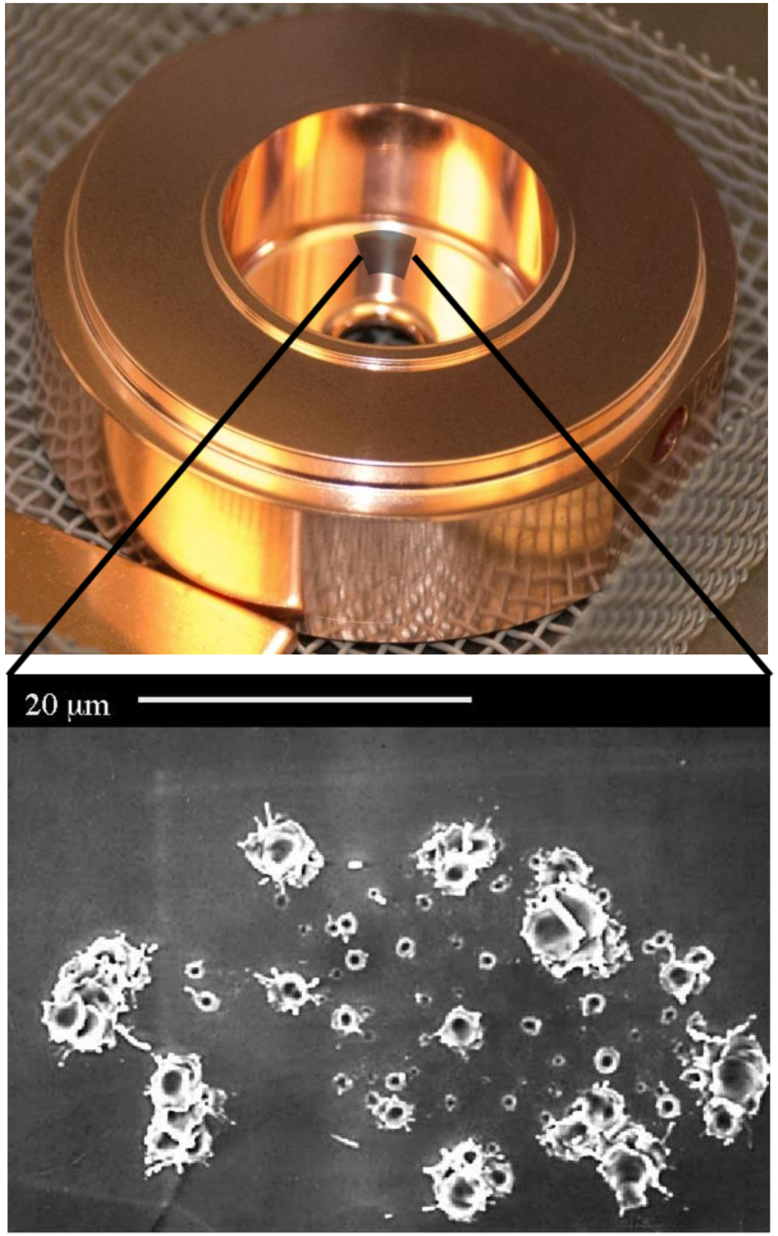
ILC Japan

RF Accelerators

Traditional RF cavities are made from materials like copper. They can produce accelerating fields up to 100 MV/m.

Beyond this field strength, RF-breakdown occurs. In a breakdown event, plasma forms at the surface of the cavity.

Plasma is the *natural* state of matter at very large fields.



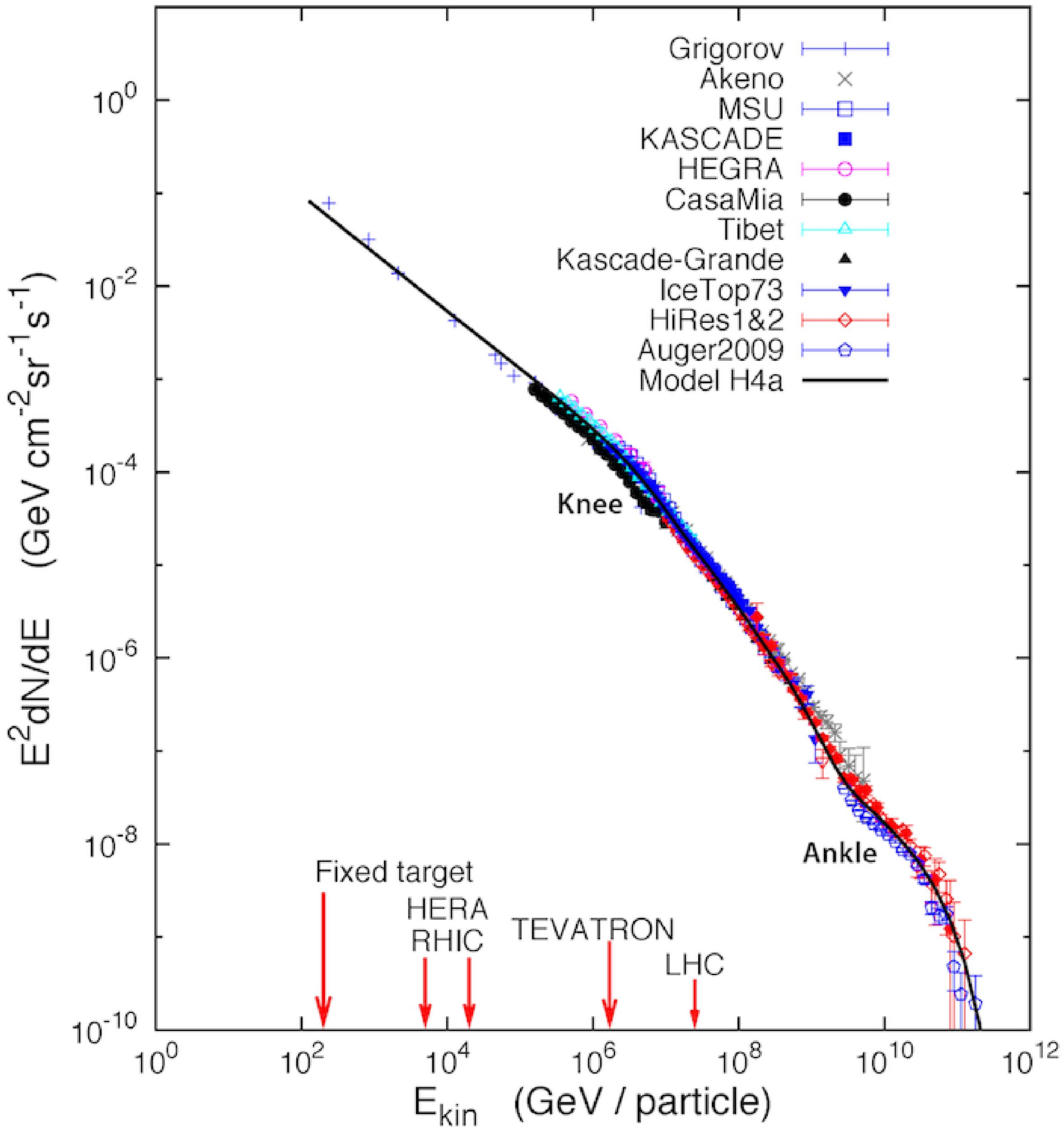
Why Plasma?

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 that plasma shockwaves from exploding supernova were responsible.

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



Characteristic Plasma Scales

The characteristic field strength of the plasma is typically measured in GV/m.

$$E \approx 100\sqrt{n\ (10^{18}\ \mathrm{cm}^{-3})}\ [\mathrm{GV/m}]$$

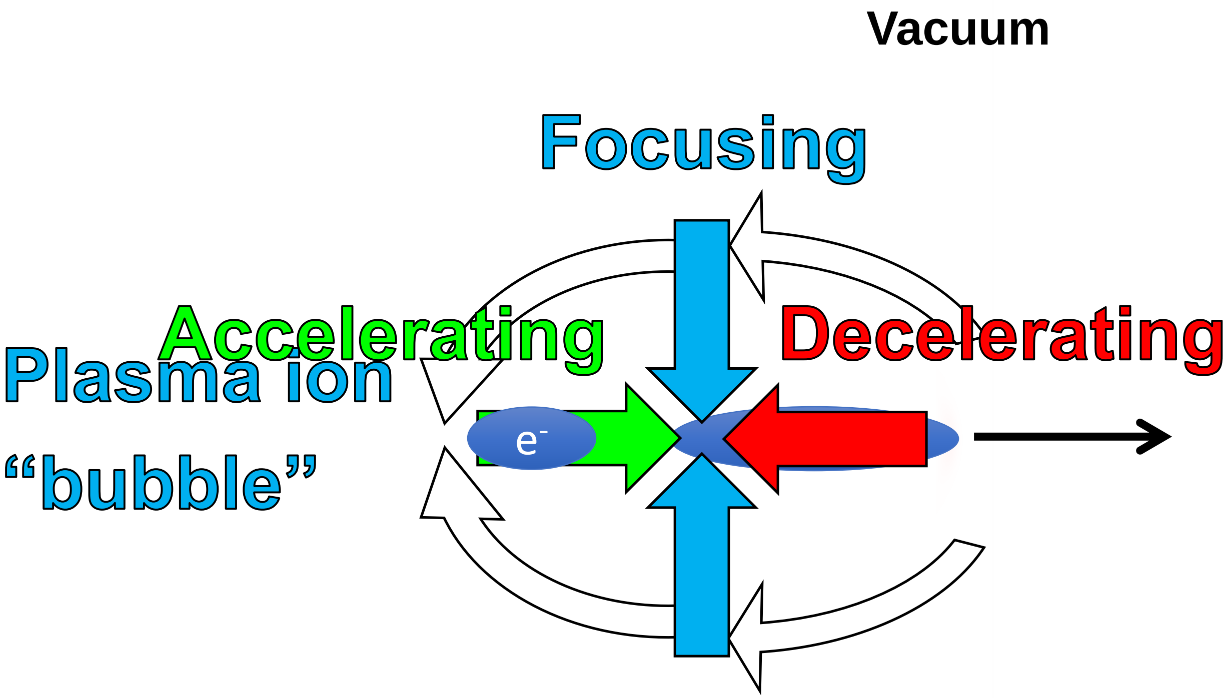
Compare that to the CLIC RF cavities which provide 100 MV/m.

But there is a “cost”. The plasma wavelength between a micron and a millimeter in length. The wavelength of the SLAC cavities is 10 cm.

$$\lambda \approx 33\sqrt{\frac{1}{n\ (10^{18}\ \mathrm{cm}^{-3})}}\ [\mu\mathrm{m}]$$

That means we have to control the particle beam on micron/femtosecond scales.

Creating a wake with a short drive beam



Can we drive a wake with a proton beam?

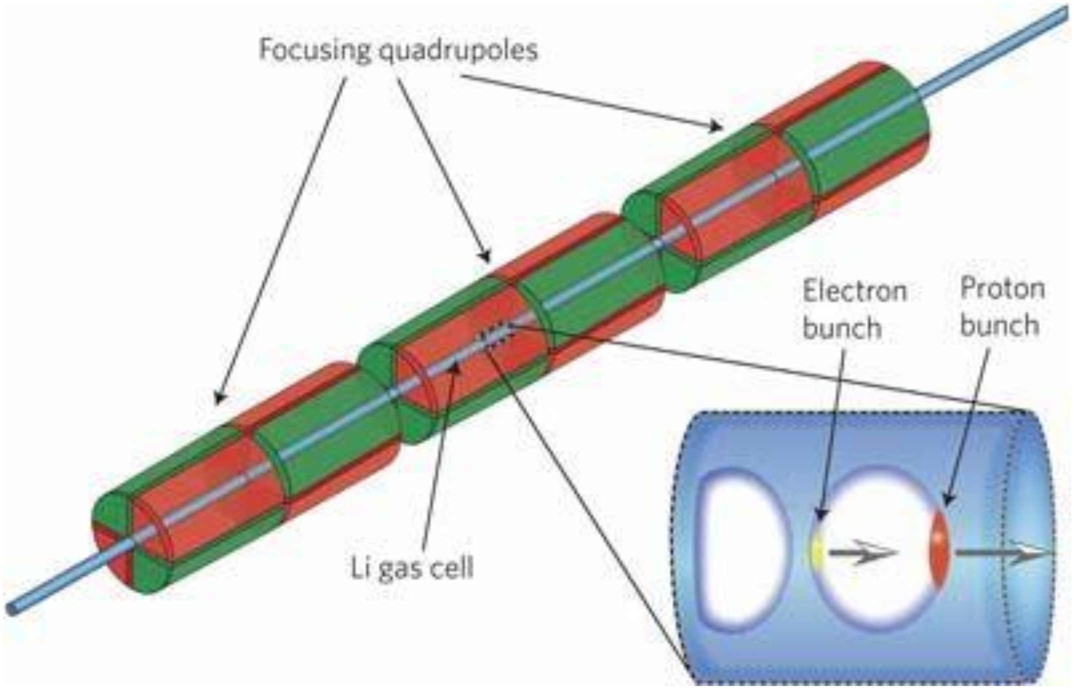
Proton beams store tremendous amounts of energy:

- Petawatt Laser Pulse ≈ 50 J
- FACET Electron Beam ≈ 65 J
- CERN SPS Proton Bunch ≈ 20,000 J

If we can transfer a significant amount of this energy to a trailing electron beam, we can create a simple, single-stage, plasma accelerator.

But there's a catch!

The proton beam is much longer than the plasma wavelength . . .



A. Caldwell, et. al. *Nat. Phys.* **5**, 363 - 367 (2009)

Creating a Wake with a Long Drive Beam

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

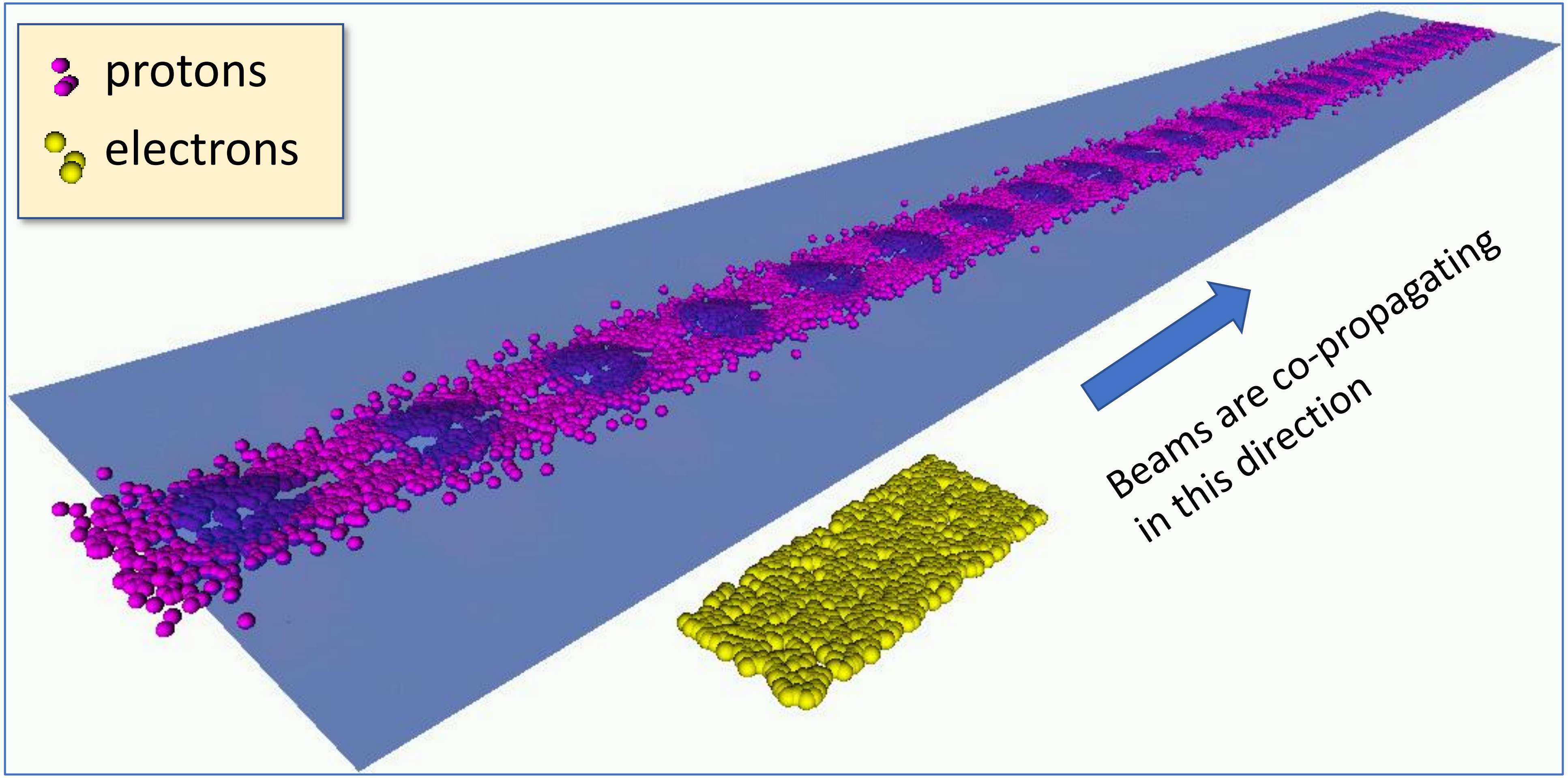
Accelerating field created by drive beam

Length of the drive beam

The plasma supports charge 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?

Physics of AWAKE



The plasma wakefield forms via seeded self-modulation. In this process, roughly half of the protons are defocused by the plasma. The remaining protons form “micro-bunches” spaced at the plasma frequency.

A. Petrenko

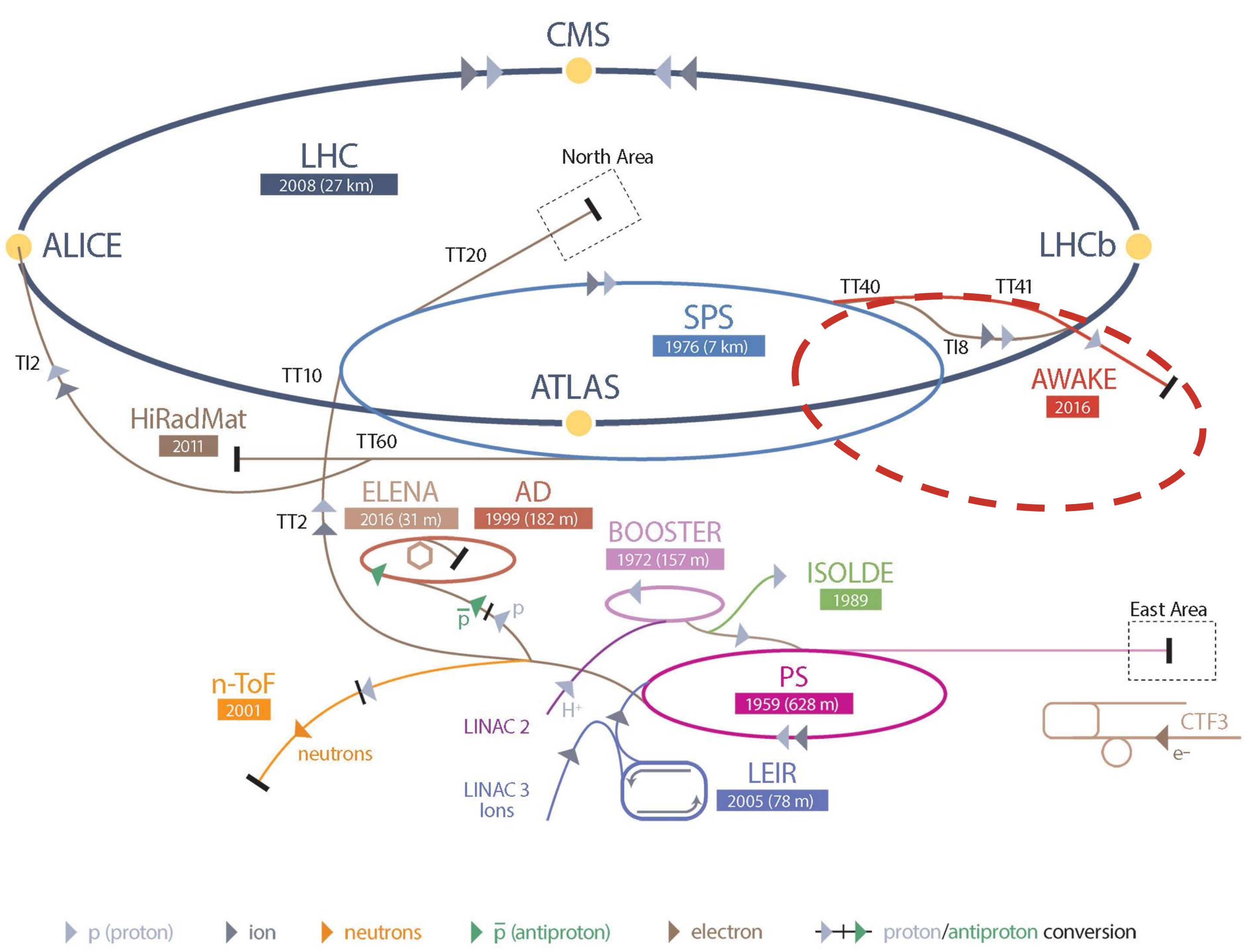
AWAKE @ CERN

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

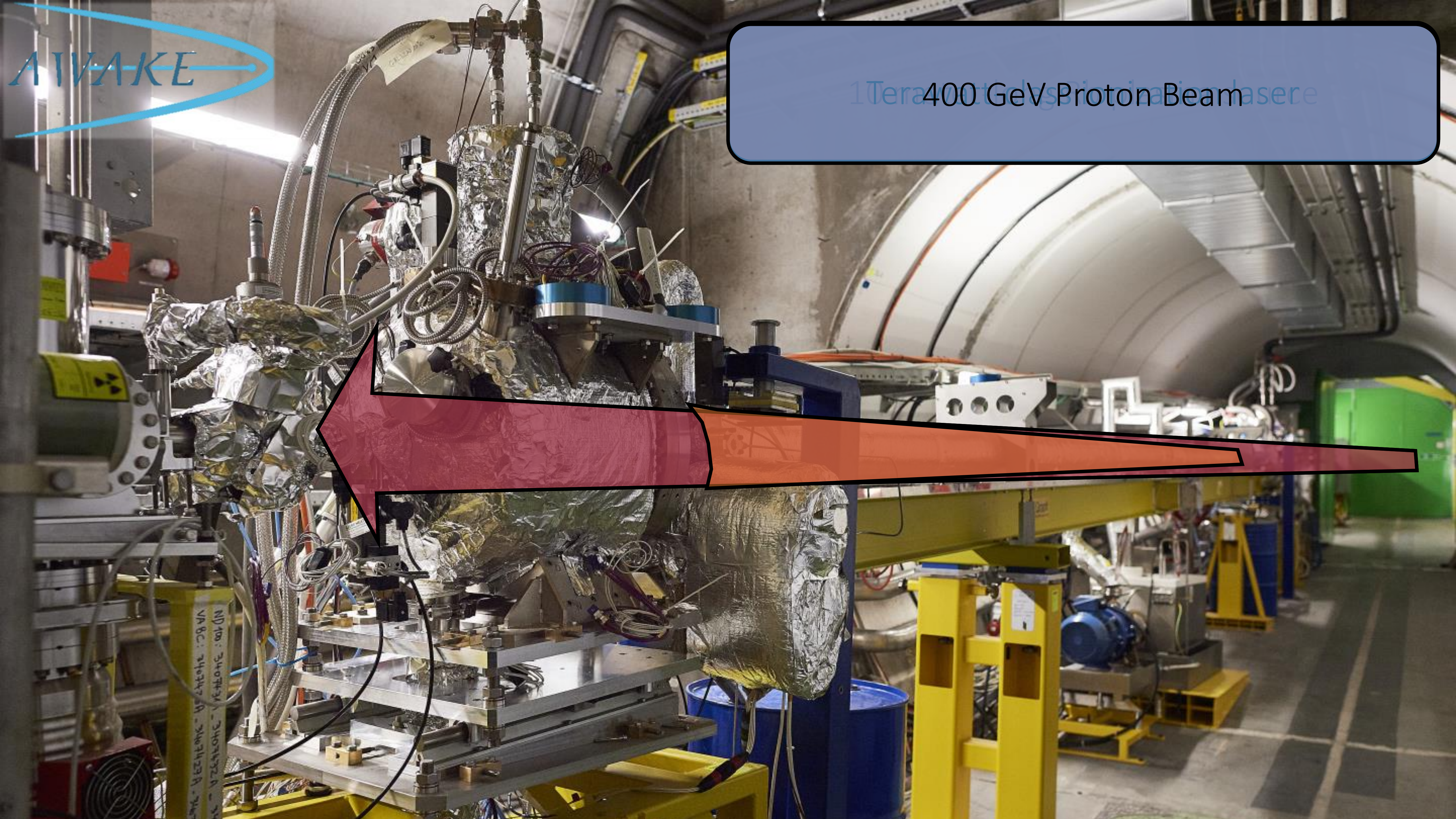
The SPS sends a 400 GeV beam to AWAKE roughly once every 30 seconds.

The proton beam is approximately 12 cm long.

CERN's Accelerator Complex

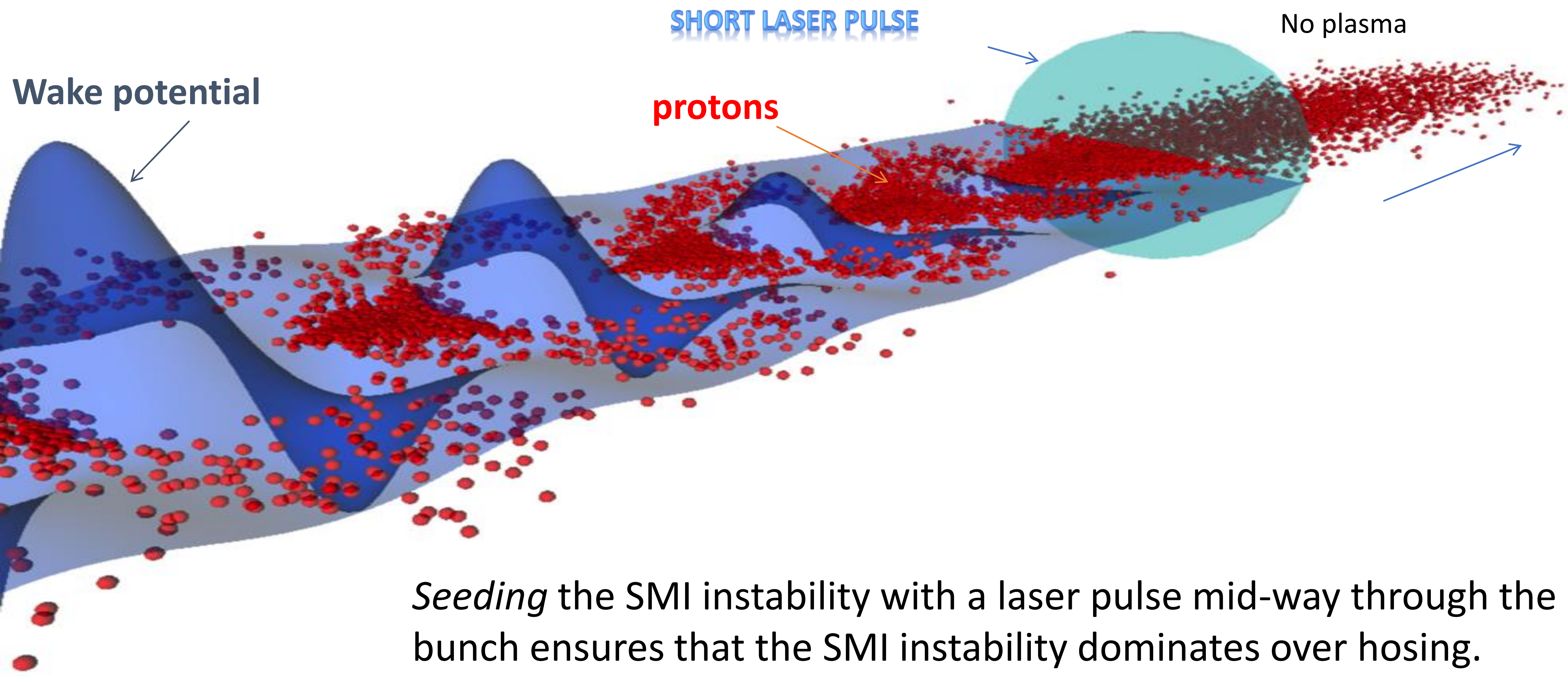


E. Gschwendtner, et. al. *NIM A.* **829**, 76-82(2016)


AWAKE
400 GeV Proton Beam

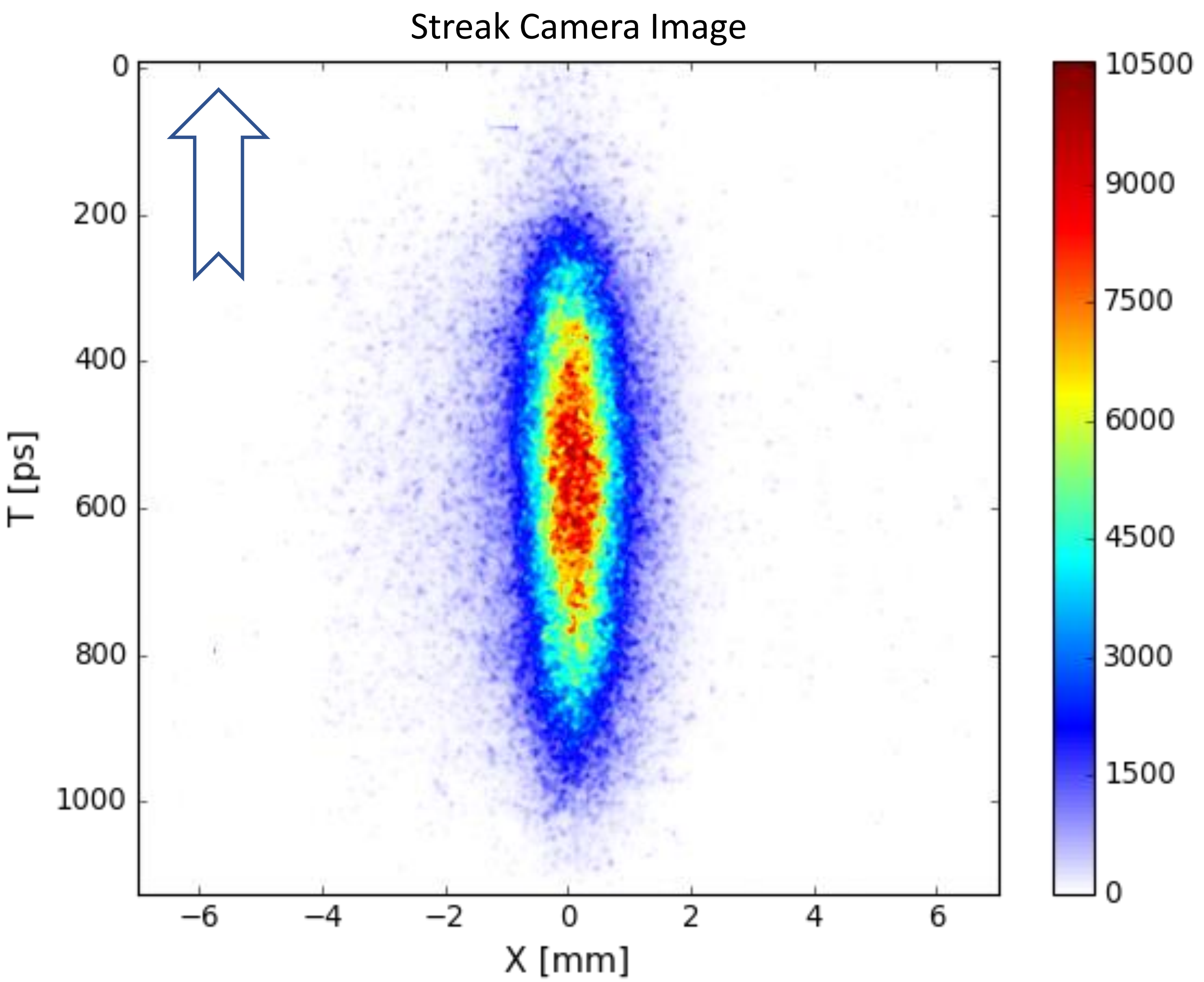
Seeded Self-Modulation

A. Petrenko



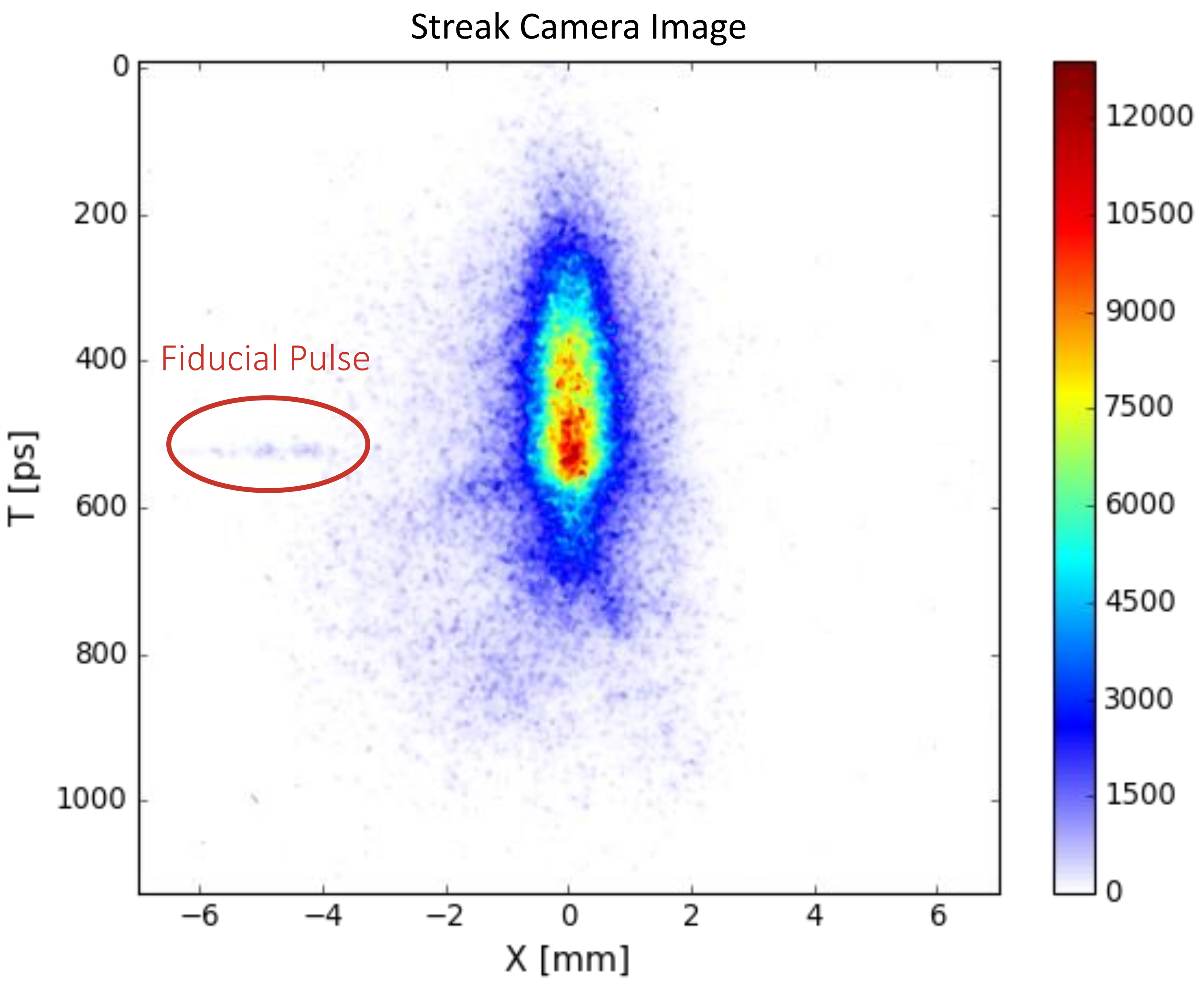
Seeding the SMI instability with a laser pulse mid-way through the bunch ensures that the SMI instability dominates over hosing.

Demonstration of Seeded Self-Modulation



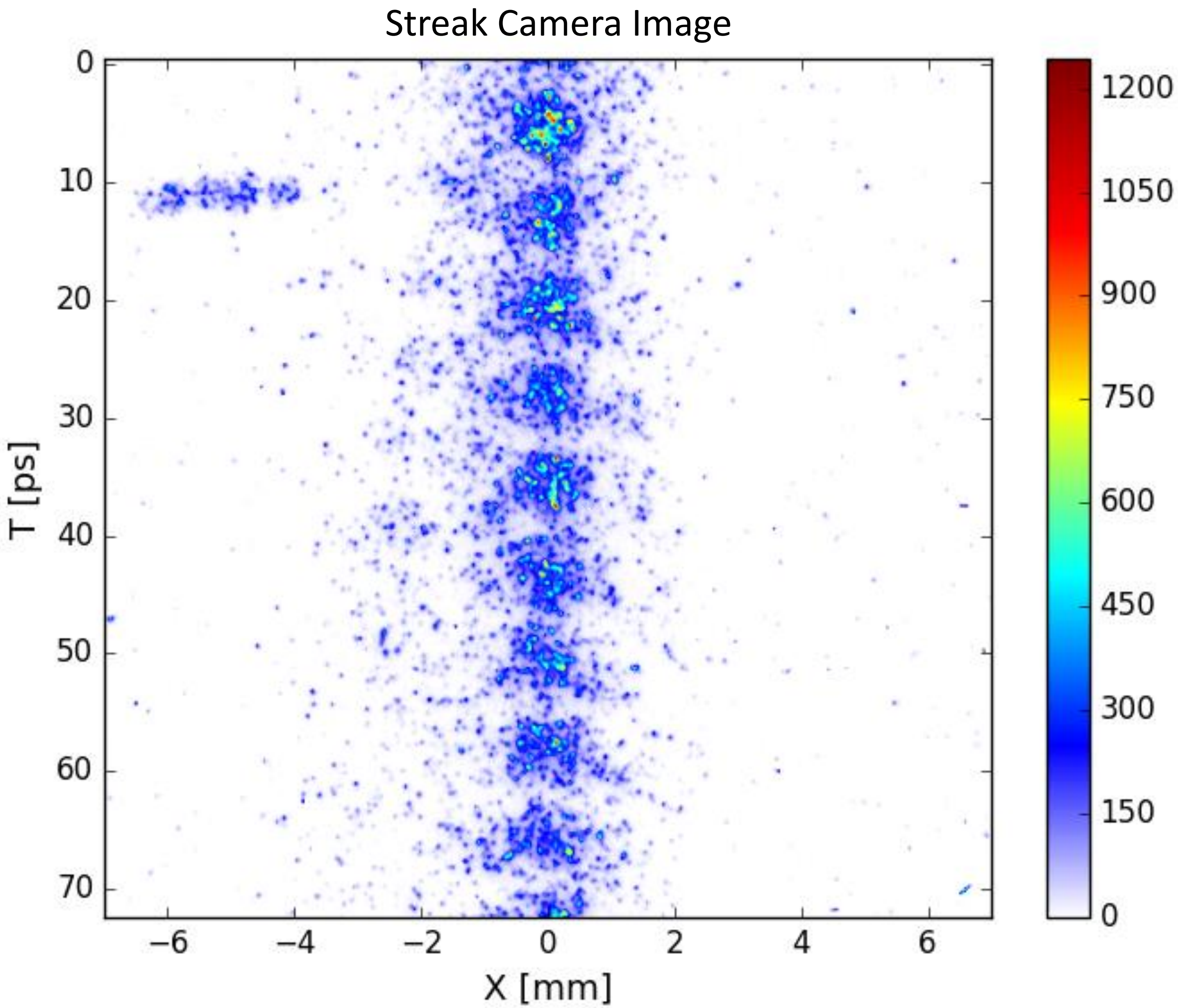
K. Rieger, M. Martyanov

Demonstration of Seeded Self-Modulation



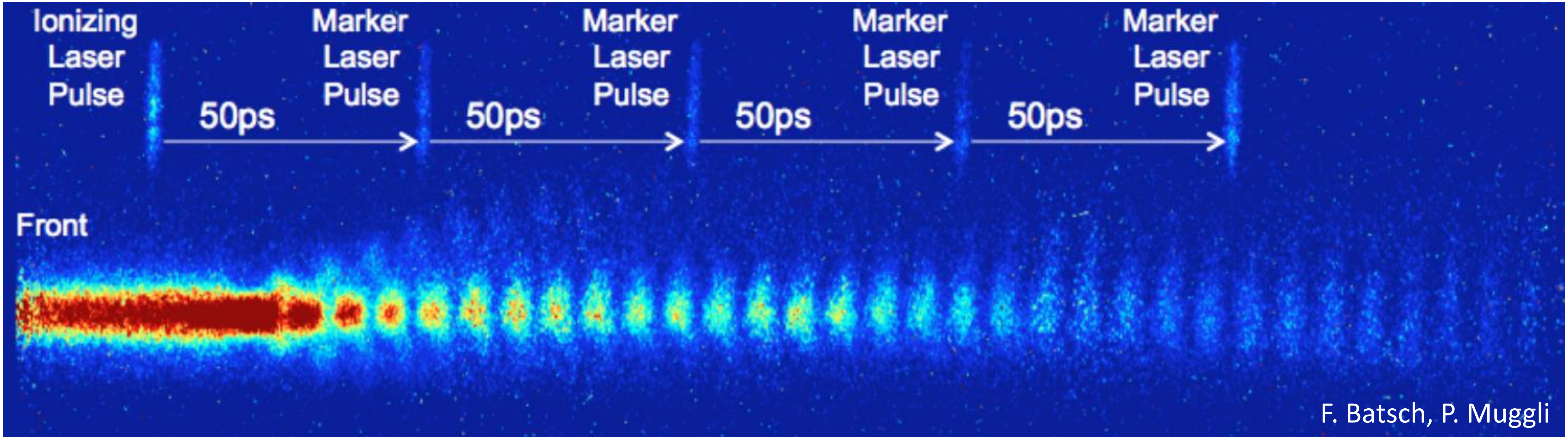
K. Rieger, M. Martyanov

Demonstration of Seeded Self-Modulation



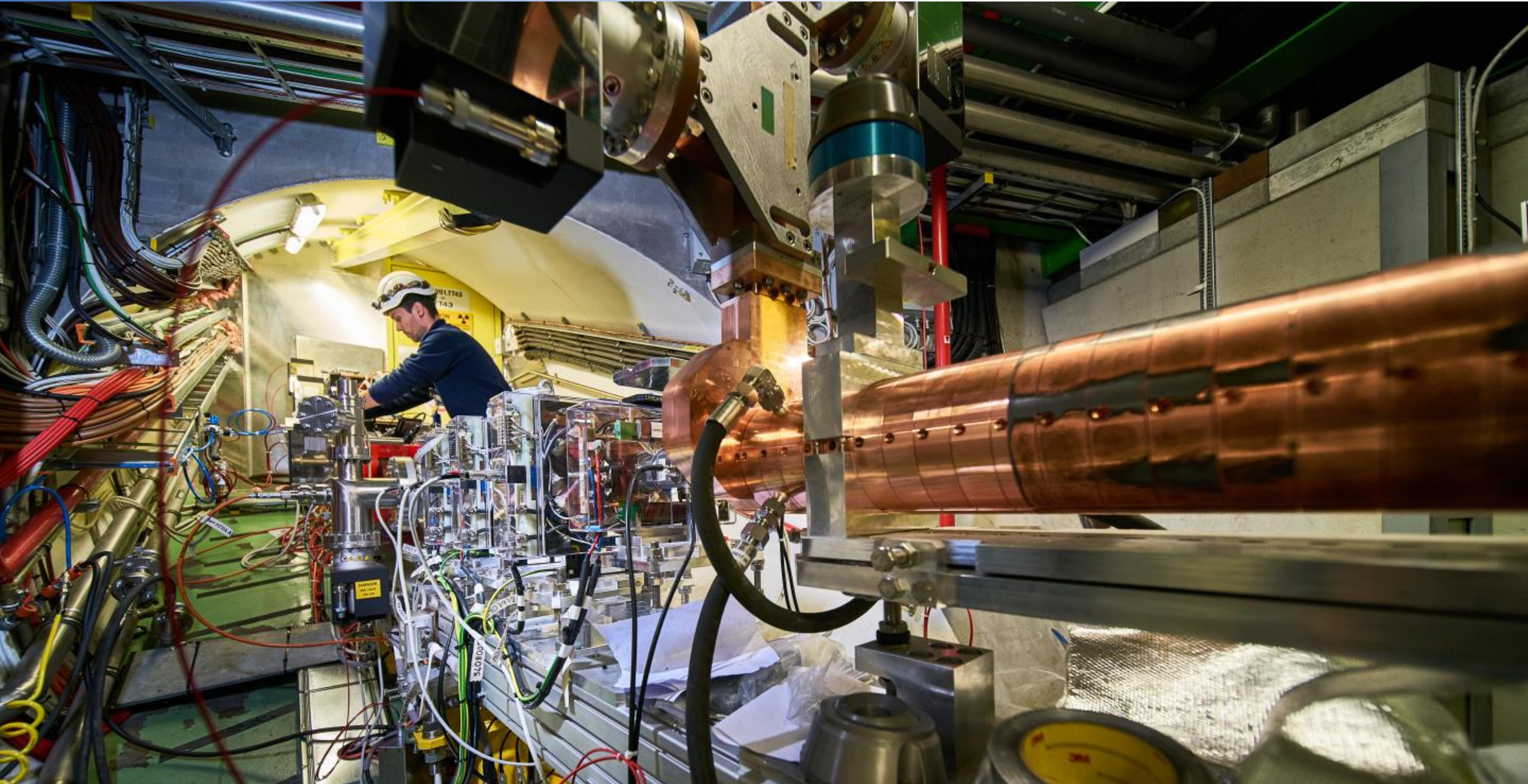
K. Rieger, M. Martyanov

Demonstration of Seeded Self-Modulation

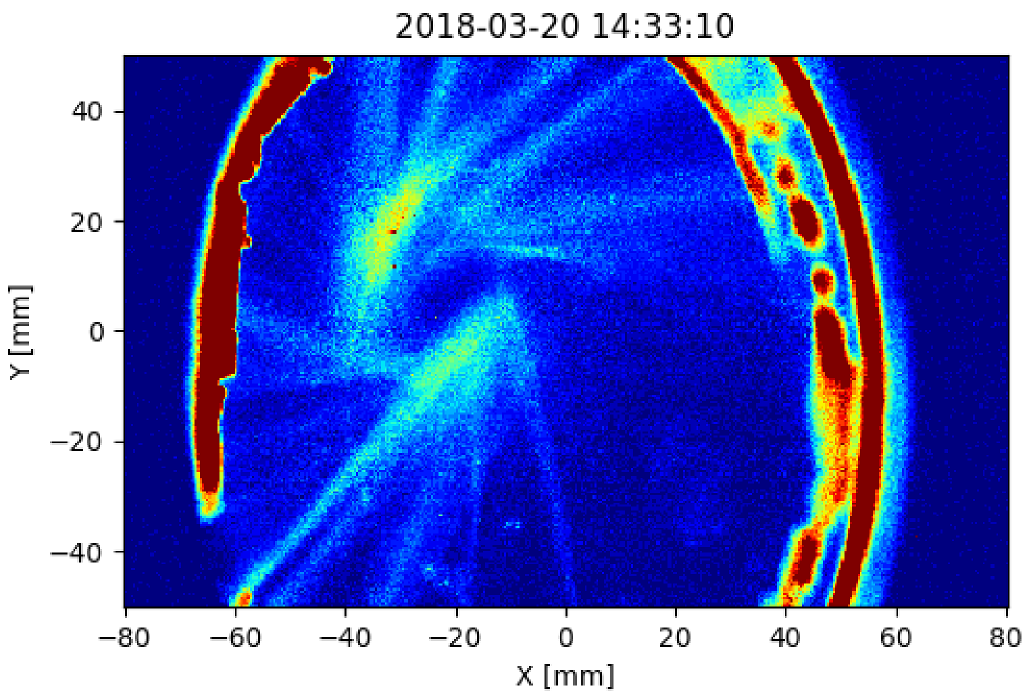


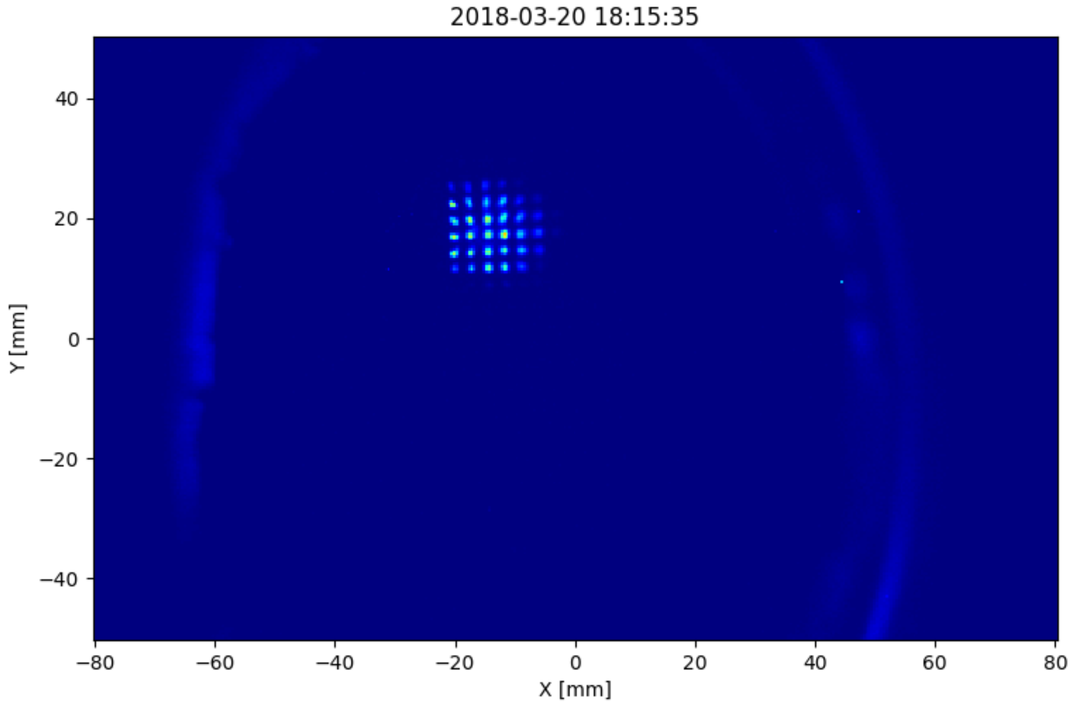
By "stacking" images together, we demonstrate that the proton bunch modulation is persistent and stable.

Future Plans: Acceleration of Electrons



Beam Commissioning is Underway!





We restarted electron beam this week for the first time since December of last year.

On the left, we vary the strength of our solenoid to determine the center of the cathode.

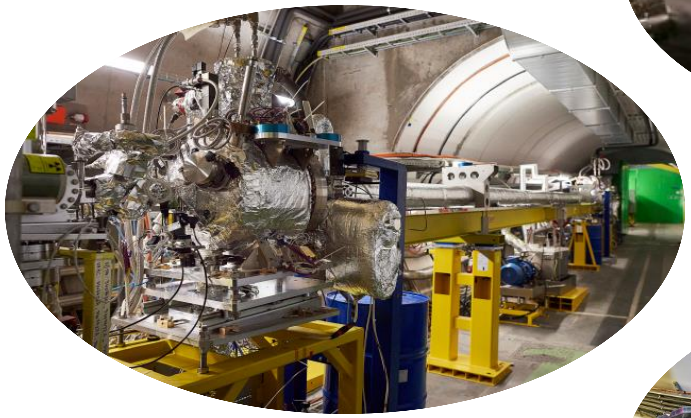
On the right, we send the electron beam through a fine mesh to measure its emittance.

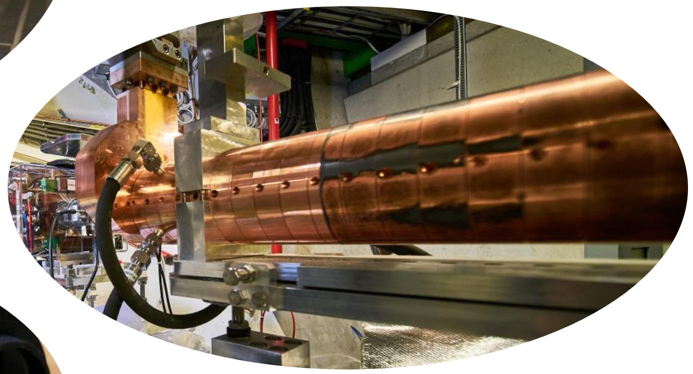
Controls @ AWAKE

Systems at AWAKE

AWAKE is composed of 5 critical systems:

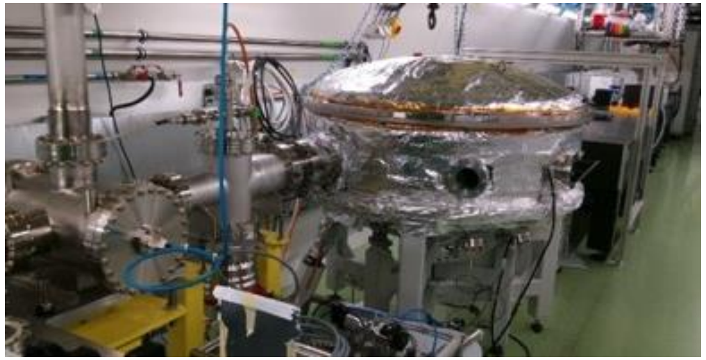
- Proton Beam Line (BE-OP-SPS)
- High-Power Laser (MPP + EN-STI)
- Plasma Cell (MPP + EN-CV)
- Electron Beam Line (BE-RF + TE-ABT)
- Diagnostics (MPP + EN-EA + BE-BI)

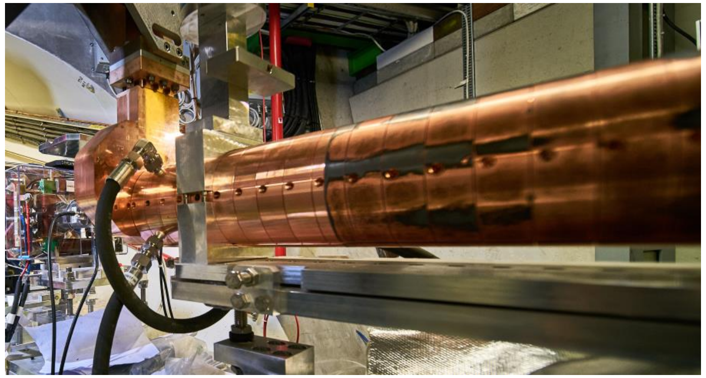




Timing Challenges

0.033 Hz





10 Hz

AWAKE receives the proton beam from the SPS once every 30 seconds.

But the laser and electron beam fire at 10 Hz. Our diagnostics and controls need to function on both timescales!

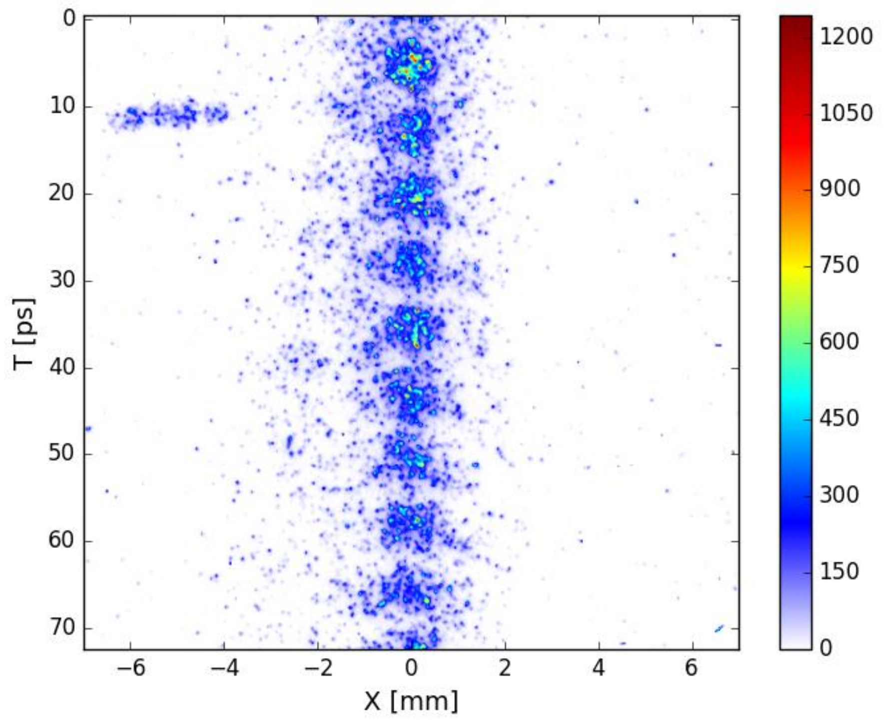
Data Challenges

Data from a single image is between 1-10 Megabytes.

The data rate is measured in Gbps (Gigabits per second).

One Megabyte is approximately 10 Megabits.

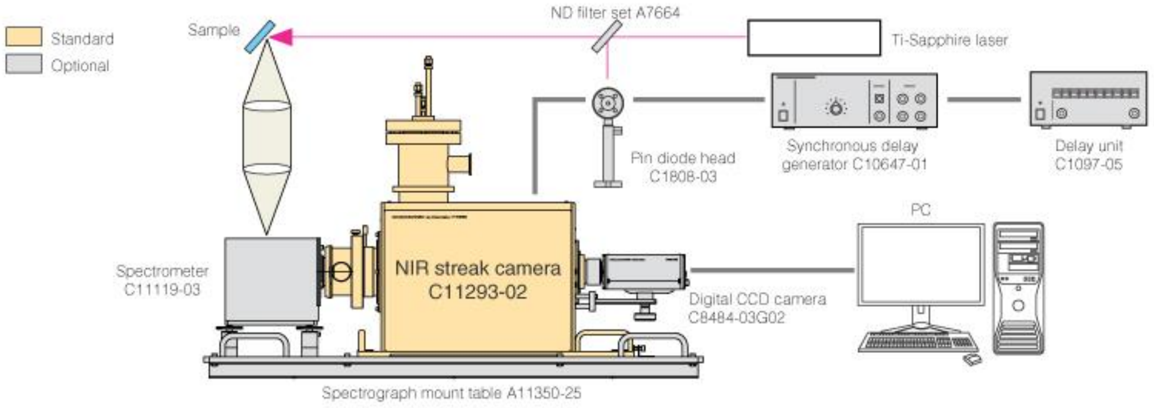
Therefore, a 10 Megabyte image (MB) streamed at 10 Hz works out to roughly 1 Gbps.



Data from a *single camera* at 10 Hz is enough to overwhelm the network.

We have approximately 30 cameras in operation at AWAKE.

Integration Challenges



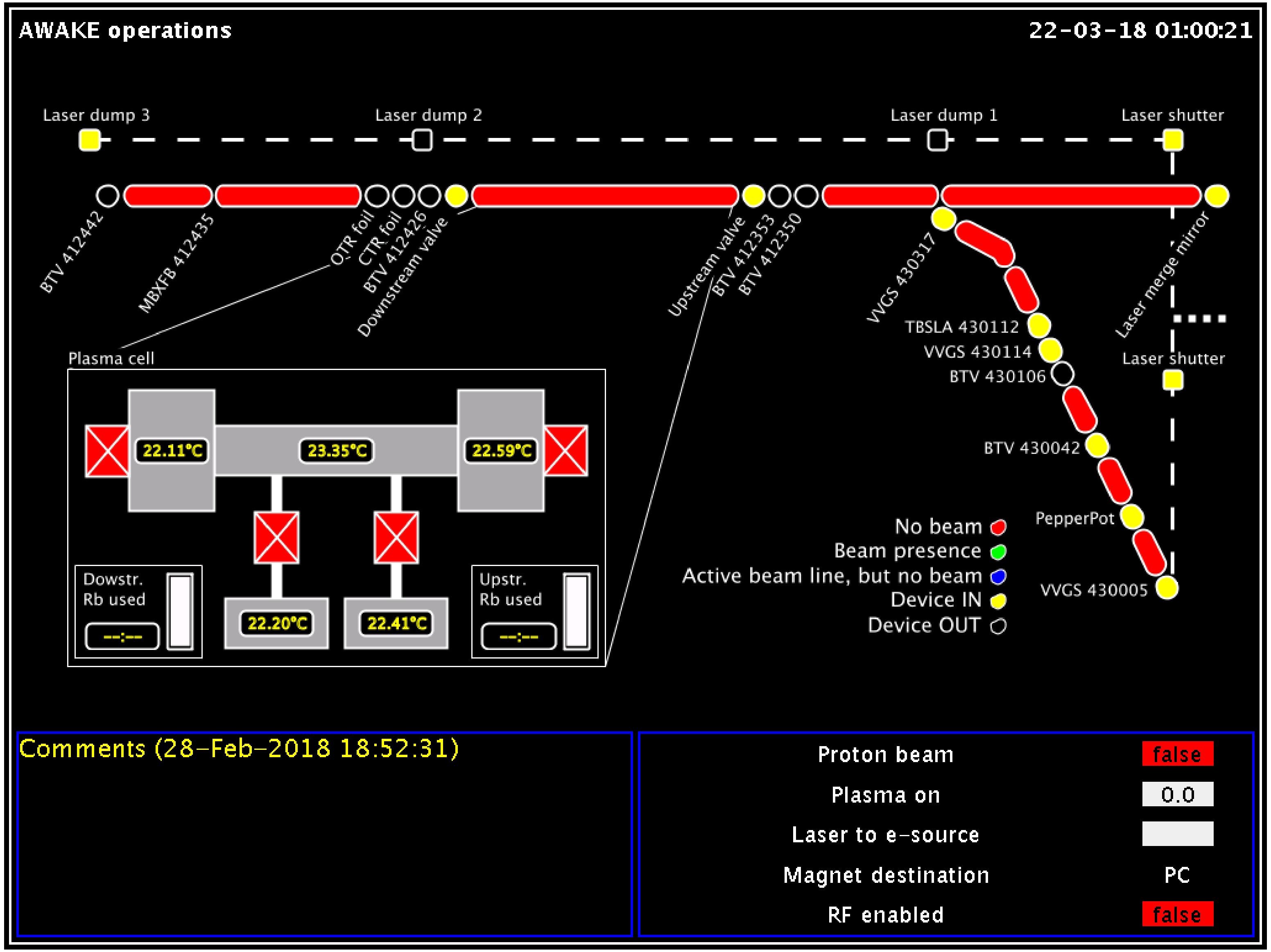
AWAKE uses special diagnostics like streak cameras, spectrometers, and RF heterodyne systems that come with proprietary software. Some of these devices cannot be directly controlled by FESA classes.

F. Hoguin helped us to develop a special FileReader FESA class that allows us to pull data from these devices into the control system

Monitoring

There are many components to AWAKE and we need a “birds-eye-view” to keep track of things.

J. Batkiewicz developed a number of fixed displays for AWAKE so that we can monitor and optimize our experiment in real time.

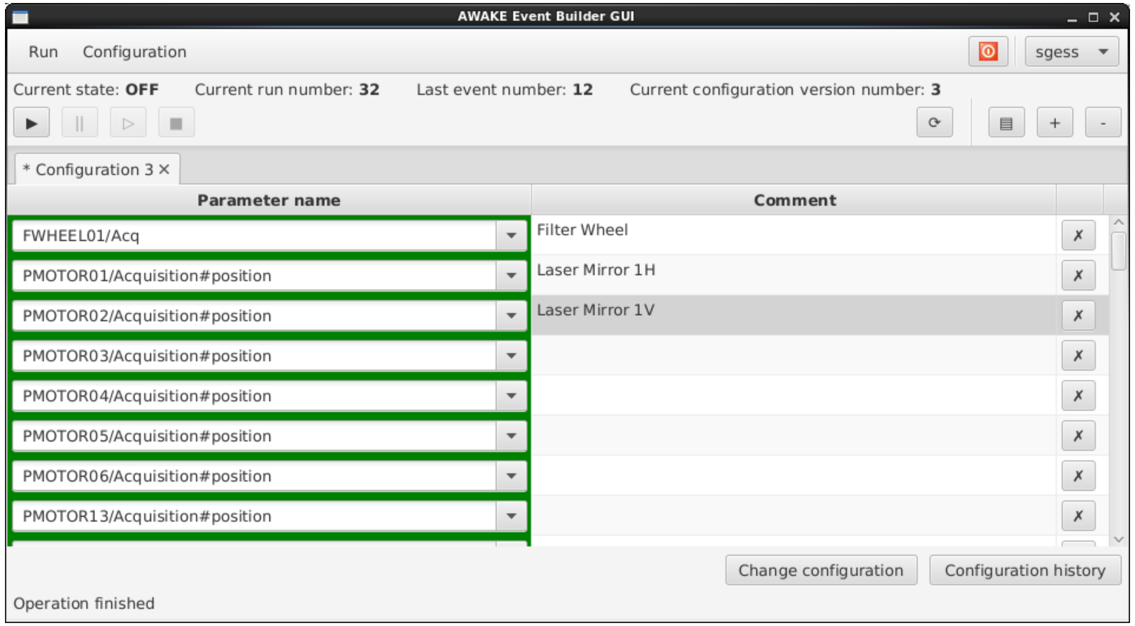


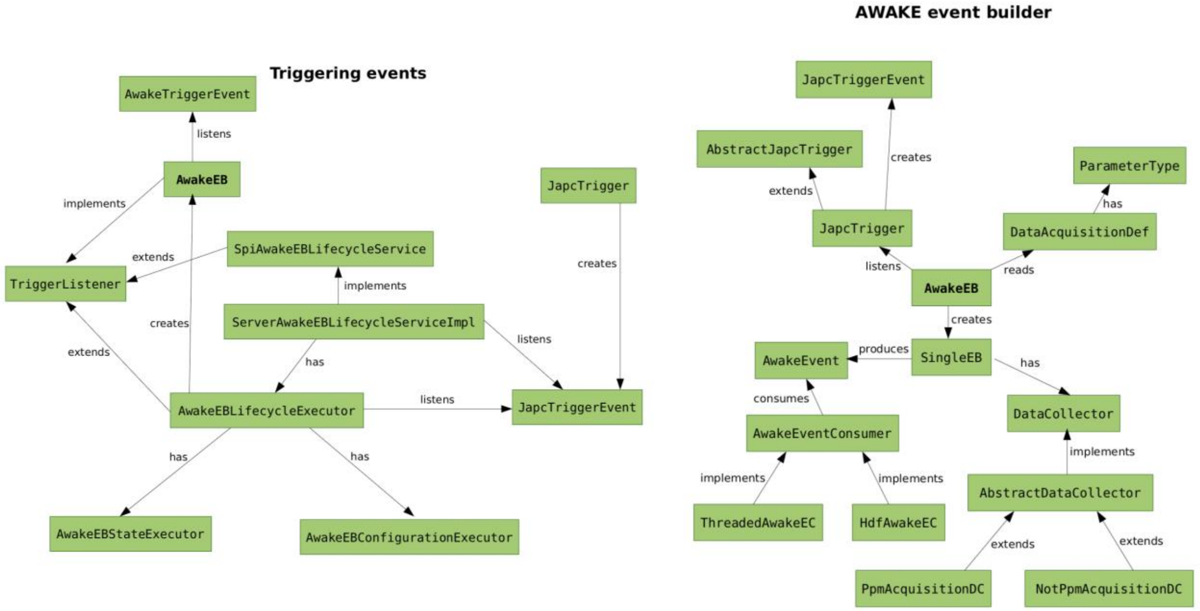
The Event Builder

J. Batkiewicz and R. Gorbonosov created the AWAKE Event Builder.

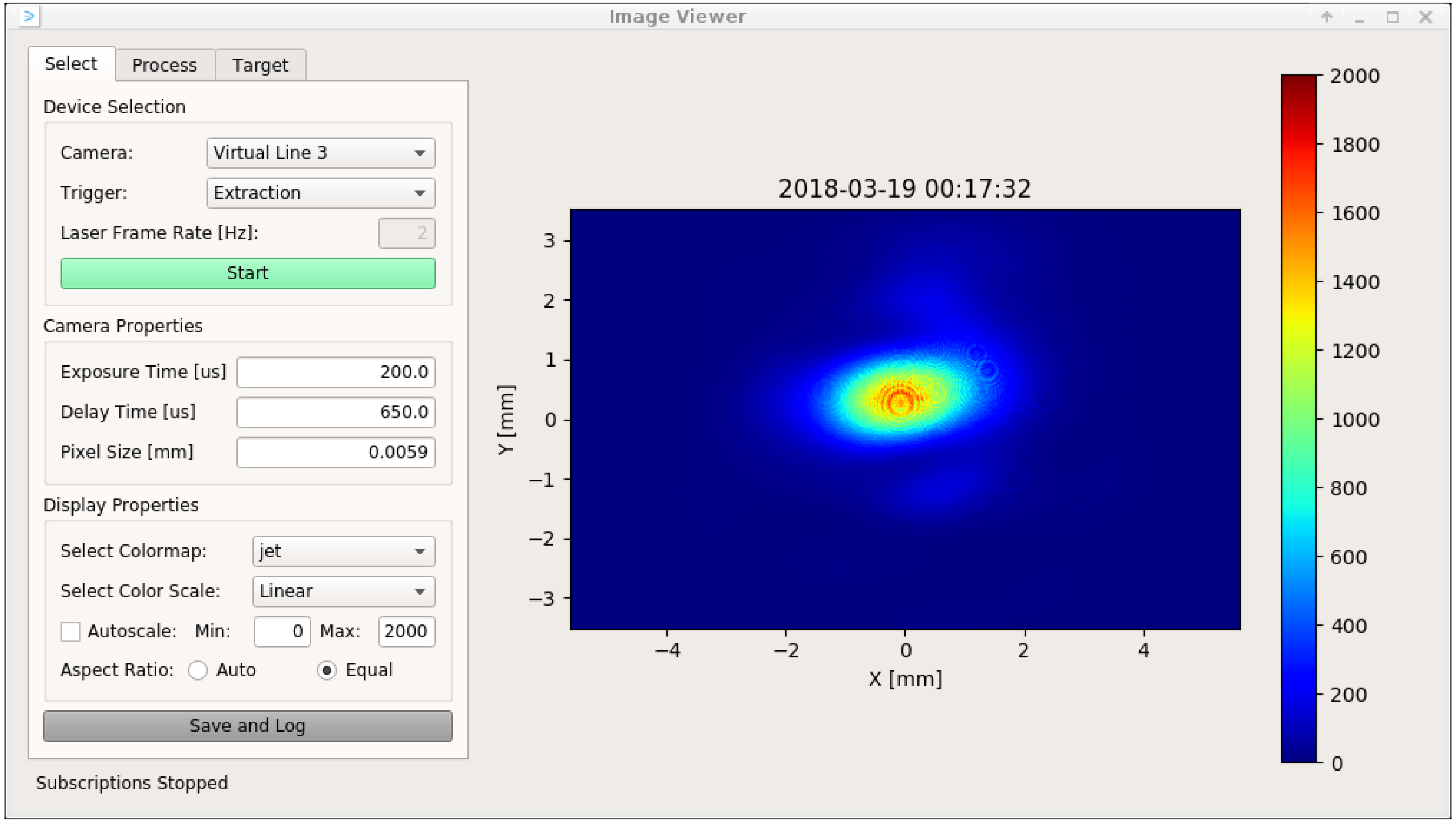
It allows us to acquire PPM and non-PPM data in a synchronized way and organize our data in event-based structures.

Our new technical student A. Ahuja is now taking over the Event Builder and learning the code structure.





PyJAPC



AWAKE uses PyJAPC to tune the experiment in real time. We can quickly write scripts to scan and monitor parameters.

We also use PyJAPC for a few applications like our digital camera viewer.

Conclusion

- AWAKE is the world's first proton beam driven plasma wakefield experiment. We hope to harness the enormous amount of stored energy in the SPS proton beam to accelerate electrons.

- In 2017, we demonstrated Self-Seeded Modulation: a huge milestone!

- In 2018, our goal is to accelerate electrons.

- Controls are an essential aspect to AWAKE. BE-CO has contributed a lot. We thank you for support and look forward to working with you in the future!

Thank You!

AWAKE Collaboration Meeting, Novisibirsk, 2017

AWAKE Collaboration

AWAKE Collaboration: 18+2 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

New Full members:
- Ulsan National Institute of Science and Technology (UNIST), Korea
- Phillipps-Universitaet Marburg, Germany