MAX-PLANCK-GESELLSCHAFT

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AWAKE - a Proton Driven Plasma Wakefield Acceleration Experiment at CERN

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1. Brief Introduction
2. The AWAKE project
   - Collaboration
   - Program Run I
   - First beam !
   - Planning for Run II
3. Brief comment on particle physics applications

AWAKE

Proton Drivers for PWFA

Proton bunches as drivers of plasma wakefields are interesting because of the very large energy content of the proton bunches.

Drivers:

PW lasers today, ~40 J/Pulse

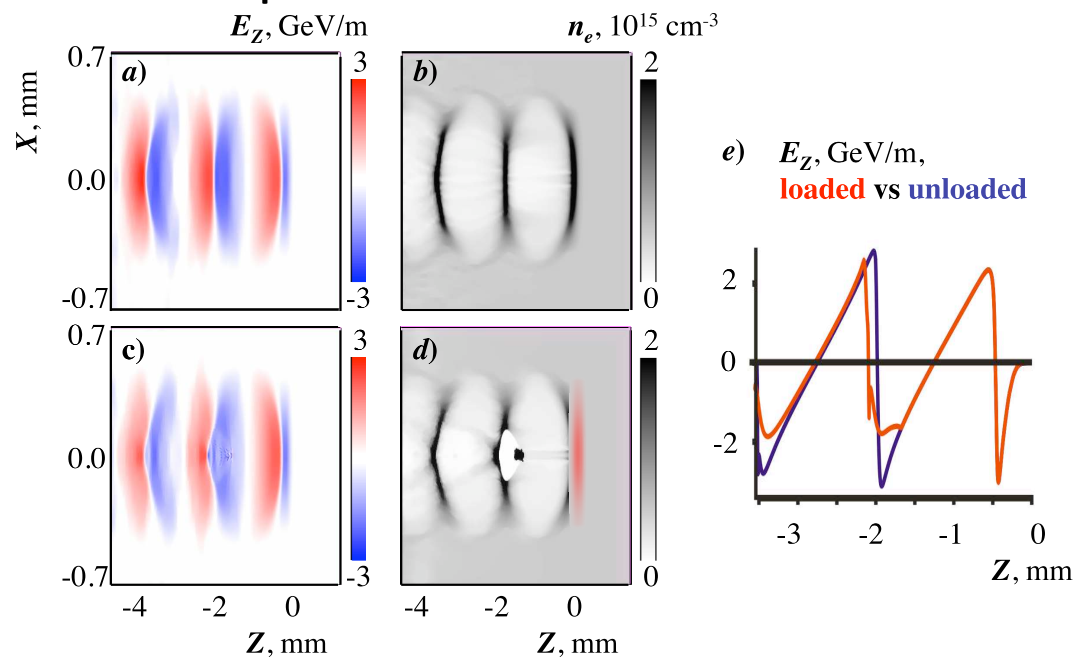
FACET, 30J/bunch

SPS 20kJ/bunch

LHC 300 kJ/bunch

Witness:

10^{10} particles @ 1 TeV ≈ few kJ



$$\lambda_p \approx 1 \text{ mm} \sqrt{\frac{1 \cdot 10^{15} \text{cm}^{-3}}{n_p}}$$

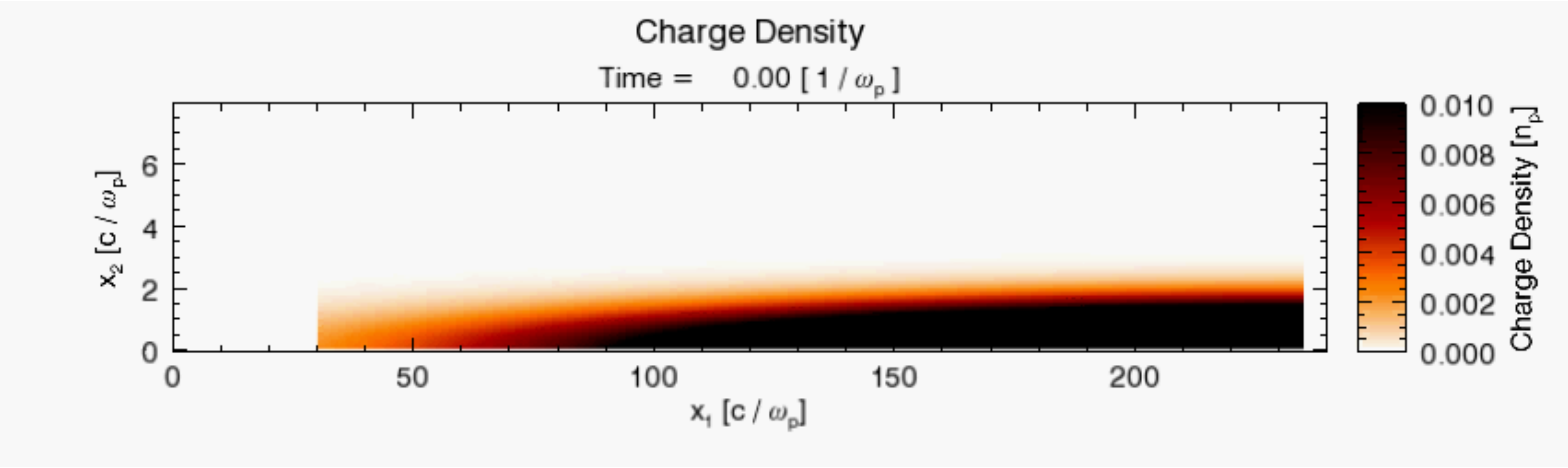
Energy content of driver allows to consider single stage acceleration

Self-modulation Instability

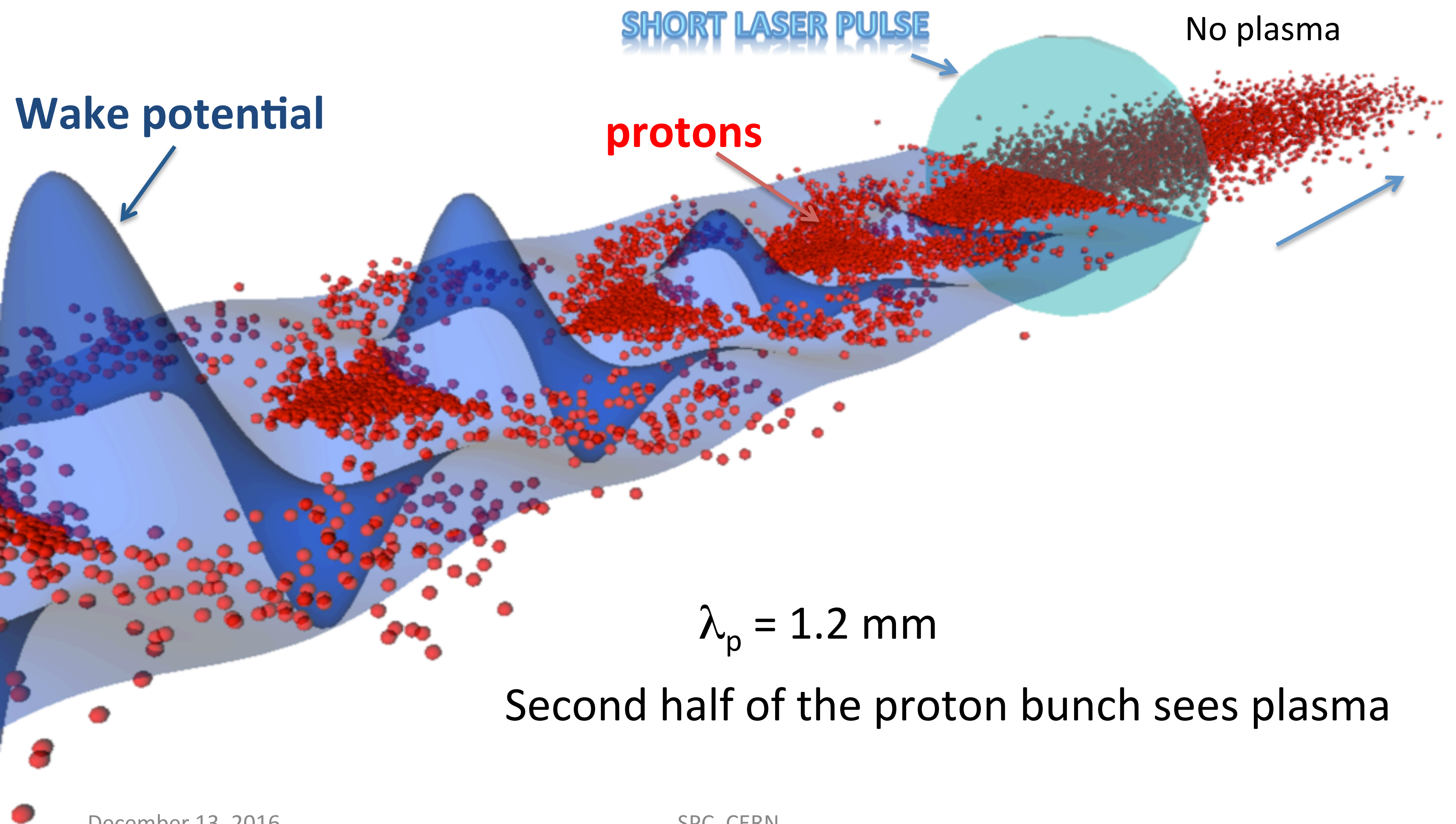
$$E_{z,\max} \approx 2\ \mathrm{GeV/m} \cdot \left(\frac{N_b}{10^{10}}\right) \cdot \left(\frac{100\ \mu\mathrm{m}}{\sigma_z}\right)^2$$

Need very short proton bunches for strong gradients. Today's proton beams have $\sigma_z \approx 10 - 30\ \mathrm{cm}$

Microbunches are generated by a transverse modulation of the bunch density (transverse two-stream instability). The microbunches are naturally spaced at the plasma wavelength, and act constructively to generate a strong plasma wake. Investigated both numerically and analytically.



Seeded self-modulation instability of a long proton bunch in plasma



λ_p = 1.2 mm

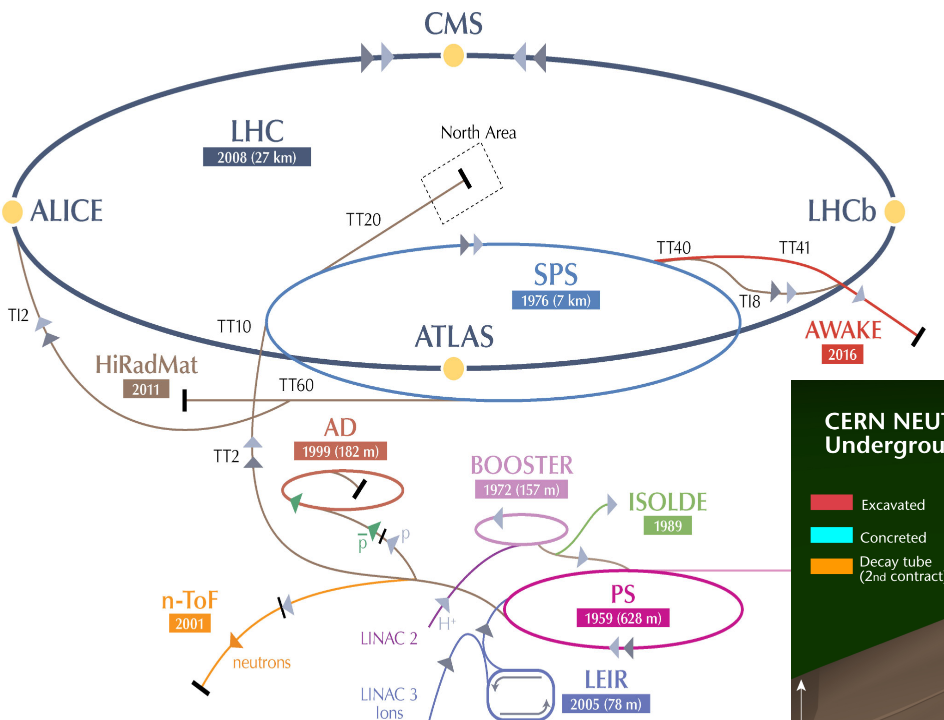
Second half of the proton bunch sees plasma

AWAKE

- AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment
  - Use SPS proton beam as drive beam (Single bunch 3e11 protons at 400 GeV)
  - Inject electron beam as witness beam
- Proof-of-Principle Accelerator R&D experiment at CERN
  - First proton driven plasma wakefield experiment worldwide
  - First beam in 2016 (just happened !)
- AWAKE Collaboration: 16 Institutes world-wide:

John Adams Institute for Accelerator Science,
Budker Institute of Nuclear Physics & Novosibirsk State University
CERN
Cockroft 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
Univesity of Oslo
University of Strathclyde

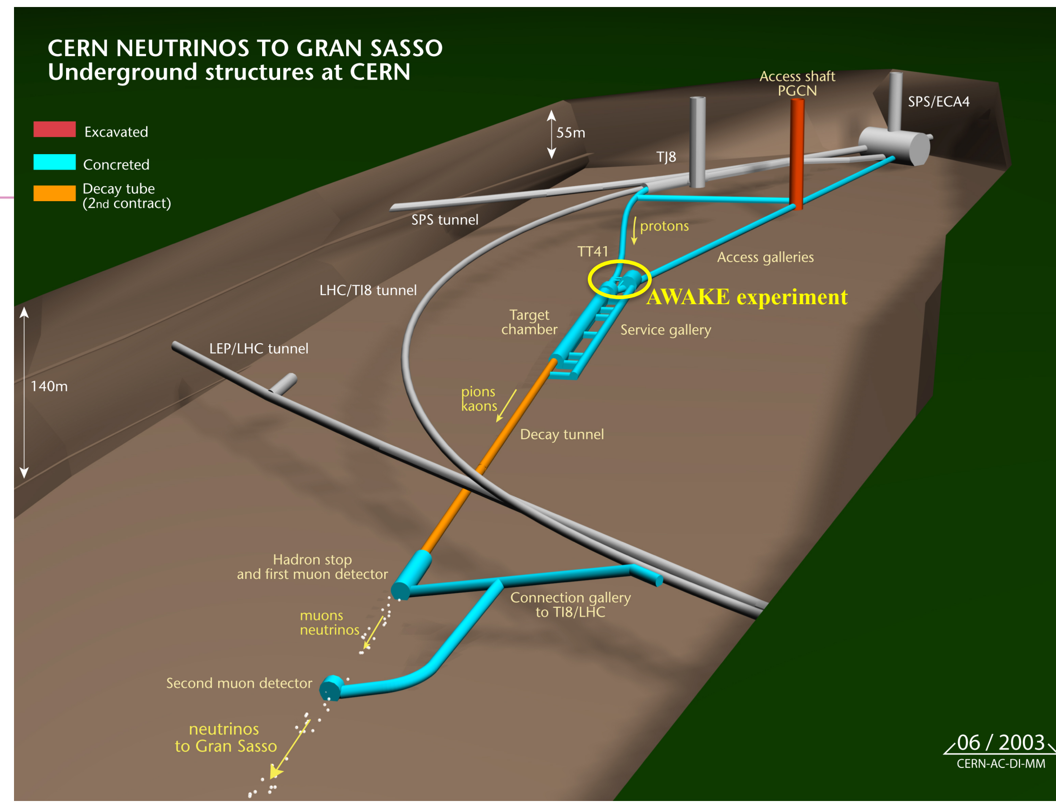
AWAKE at CERN



AWAKE is installed in

CNGS Facility (CERN Neutrinos to Gran Sasso)

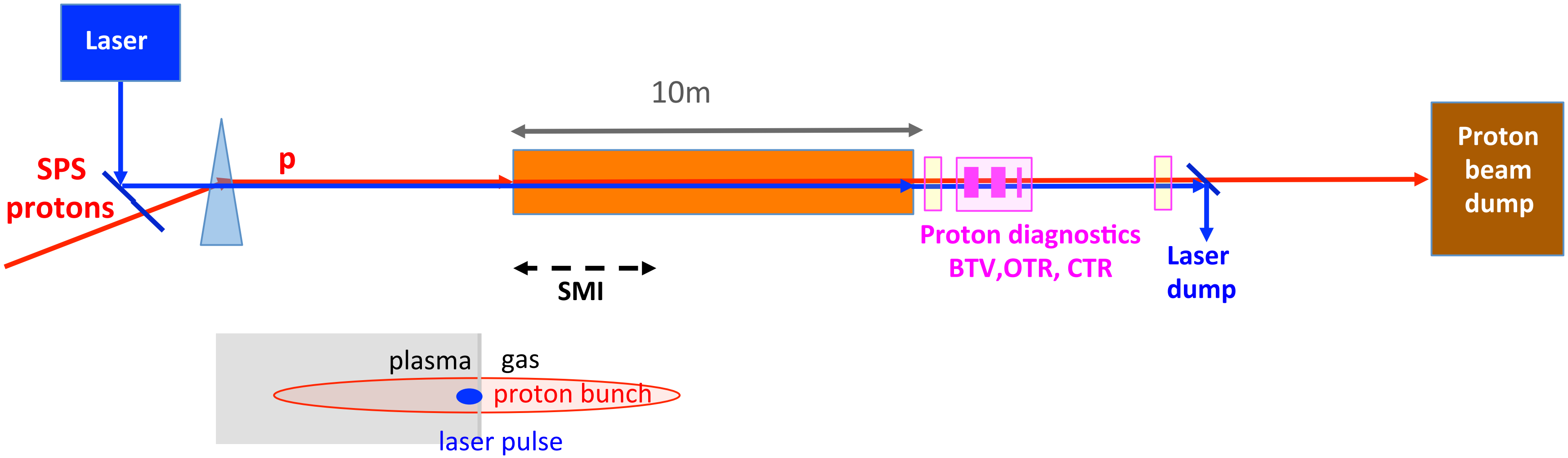
→ CNGS physics program finished in 2012



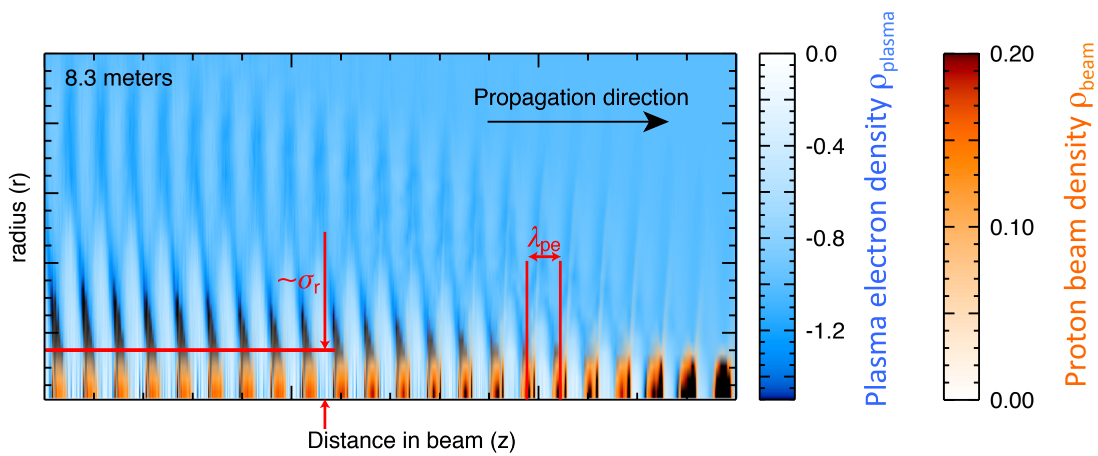
A. Caldwell et al., "Path to AWAKE: Evolution of the concept", Nucl. Instrum. Meth. A829 (2016) 3-16; E. Gschwendtner et al. [AWAKE Collaboration], "AWAKE, The Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN," Nucl. Instrum. Meth. A829, 76 (2016).

AWAKE: Experimental Program

Phase 1: Understand **the physics of self-modulation instability.**

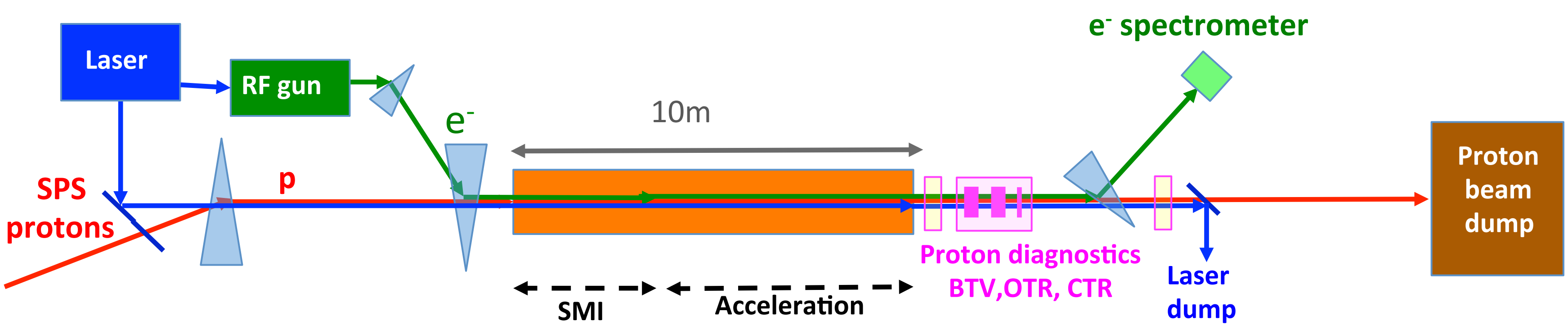


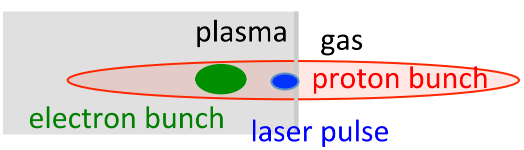
Self-modulated proton bunch resonantly driving plasma wakefields.



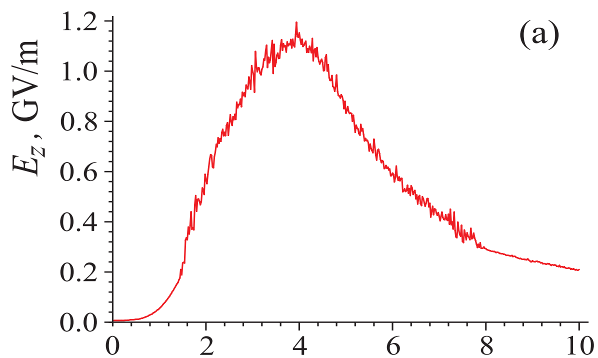
AWAKE Experimental Program

- Phase 1: Understand **the physics of self-modulation instability**.
- Phase 2: **Probe the accelerating wakefields** with externally injected electrons.





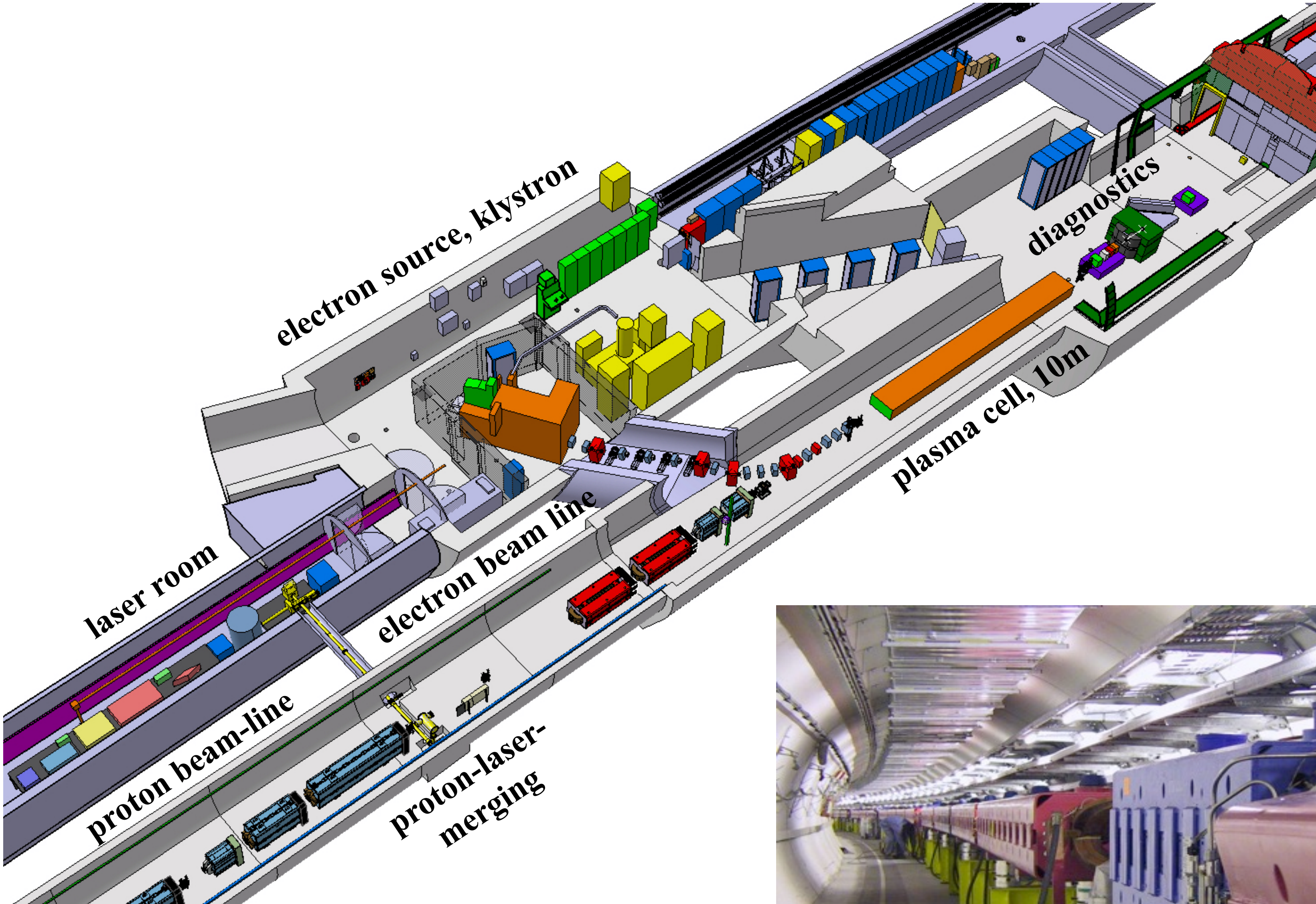
➔ **Start with electron acceleration studies Q4 2017**



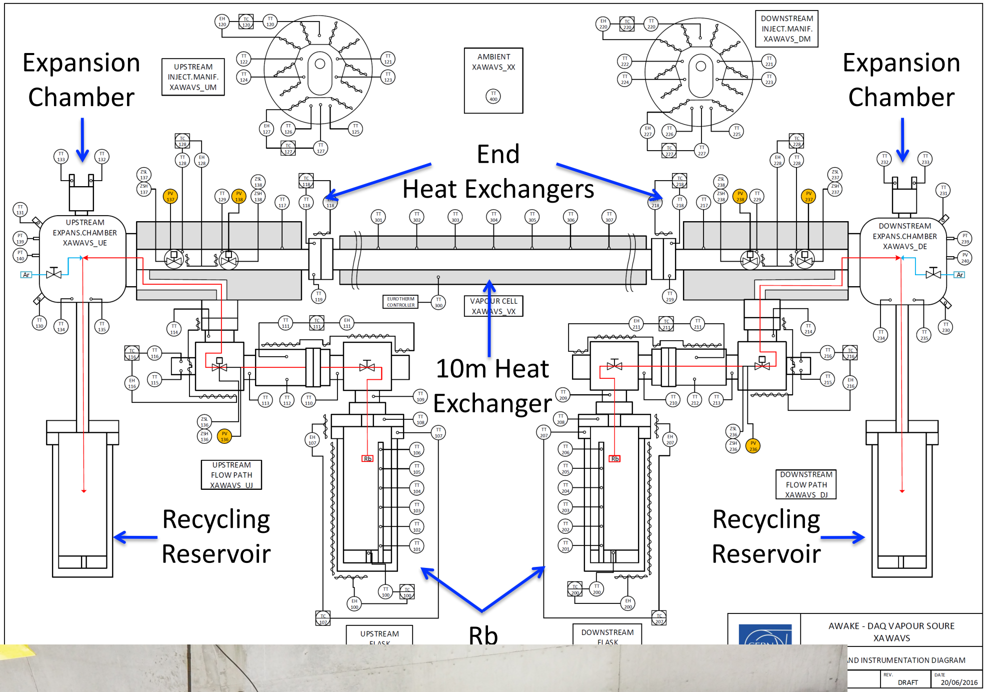
Demonstrate GeV scale gradients with proton driven wakefields.

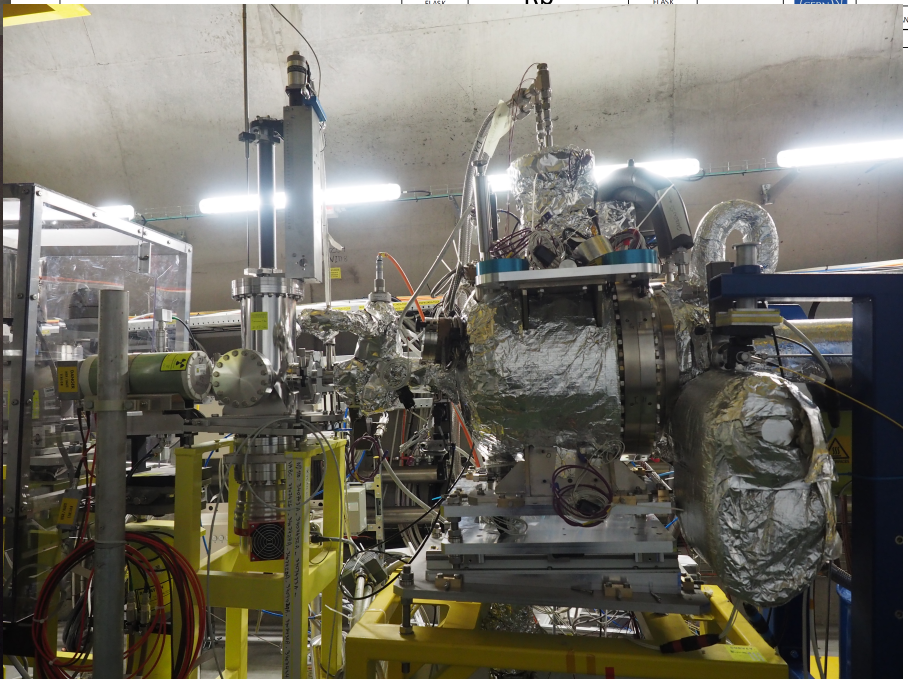
Maximum amplitude of the **accelerating field E_z** as a function of position along the plasma. Saturation of the SMI at ~4m.

AWAKE Overview



AWAKE Overview





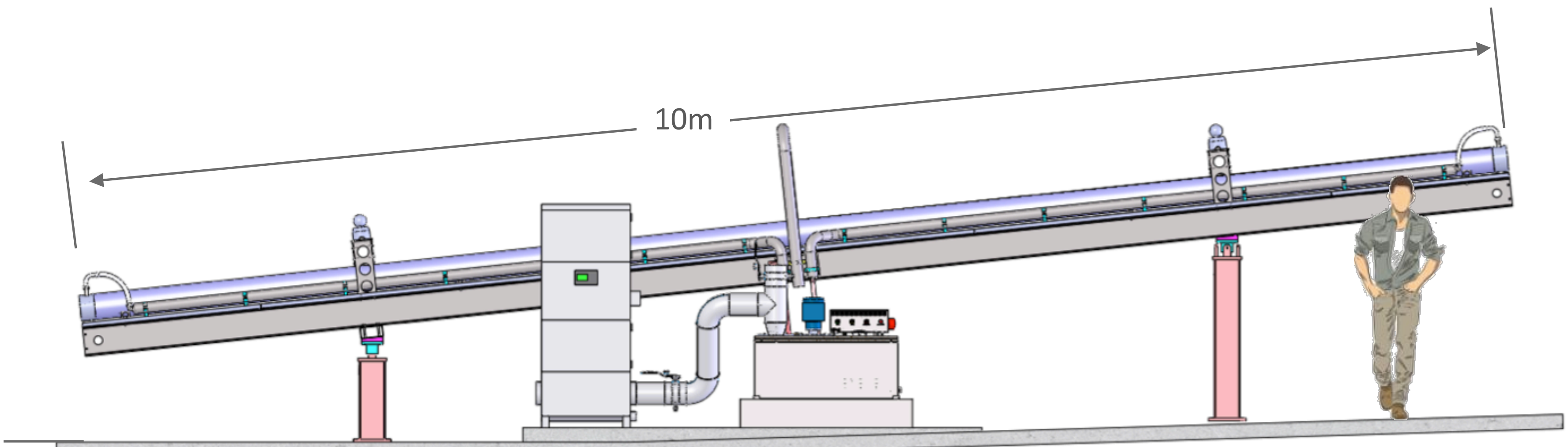
AWAKE: Plasma Source

- Density adjustable from **$10^{14} – 10^{15}$ cm^{-3}**
- 10 m long, 4 cm diameter

- Plasma formed by field ionization of Rb
  - Ionization potential Φ_{Rb} = 4.177eV
  - above intensity threshold (I_{ioniz} = 1.7 x 10^{12}W/cm^2) 100% is ionized.

- Plasma density = vapor density

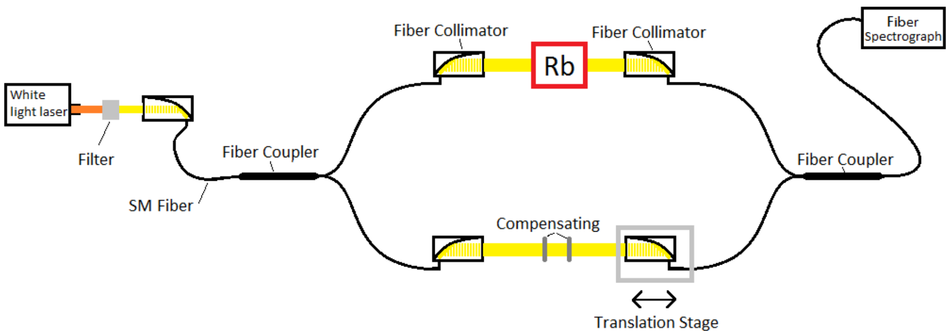
- System is oil-heated: 150˚ to 200˚ C
  - → keep temperature uniformity
  - → Keep density uniformity



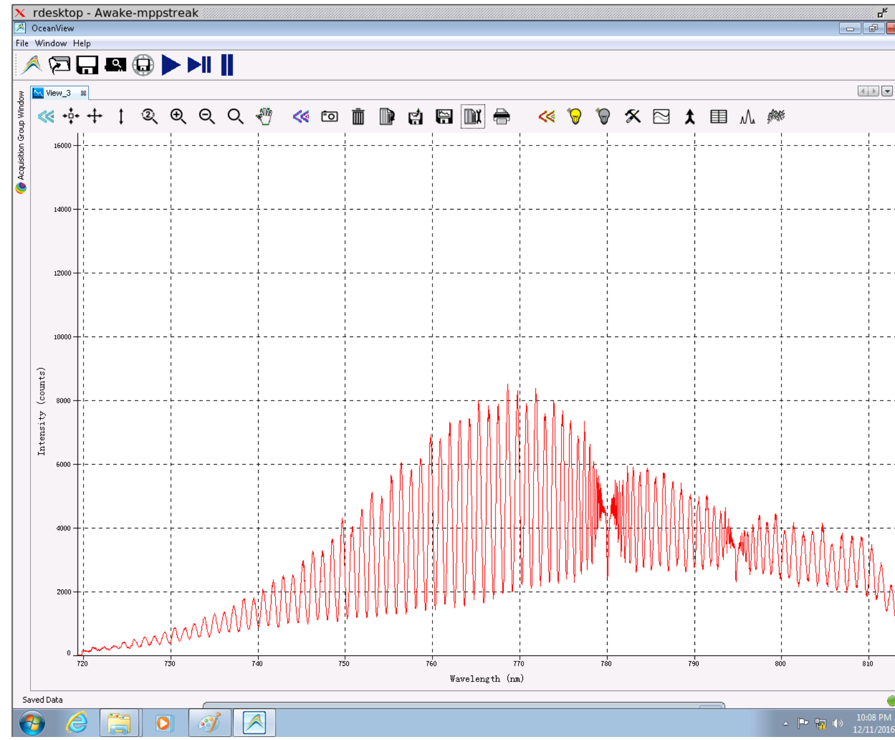
Grant Instruments

Diagnostics

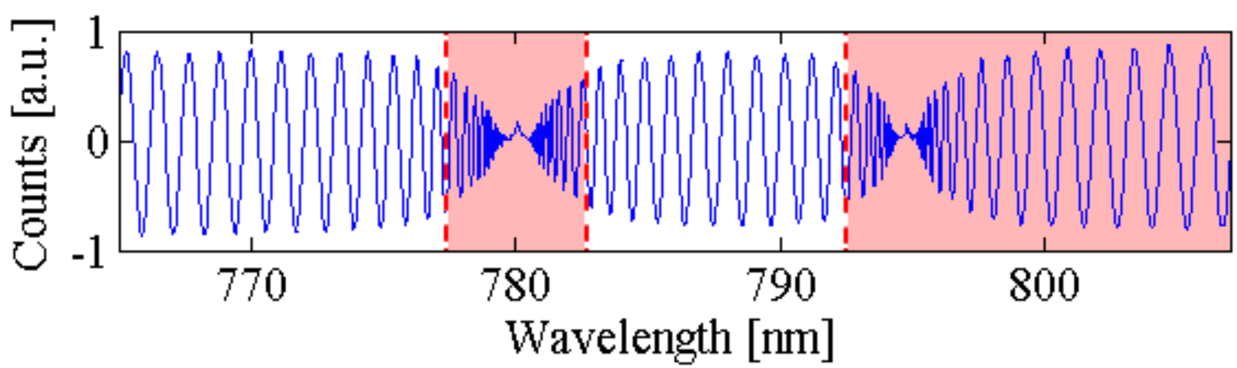
Rubidium vapor density measurement



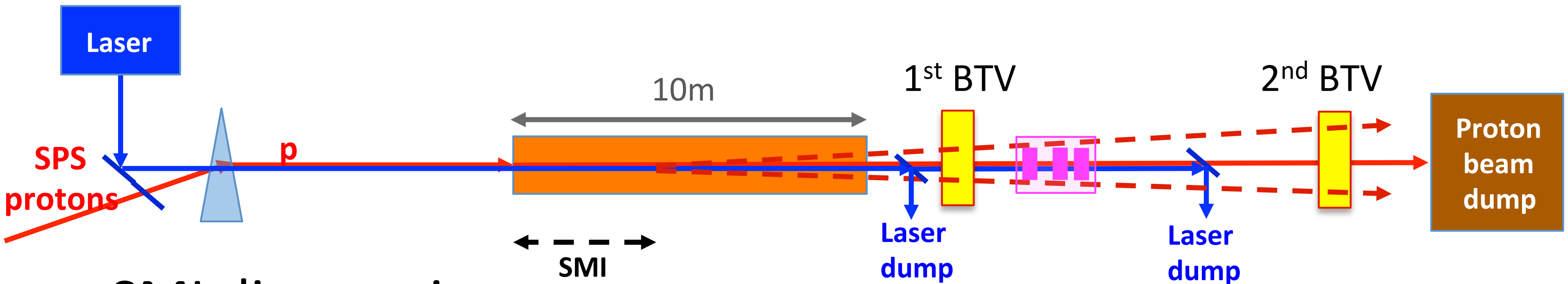
$$S(\lambda) = A\cos\left(\frac{2\pi}{\lambda}\left[\frac{n_{Rb} l r_0 f_1 \lambda_1^3}{4\pi(\lambda-\lambda_1)} + \frac{n_{Rb} l r_0 f_2 \lambda_2^3}{4\pi(\lambda-\lambda_2)} \pm \xi\right]\right)$$



After subtracting reference & normalizing – fit with functional form to get Rb density.



Diagnostics

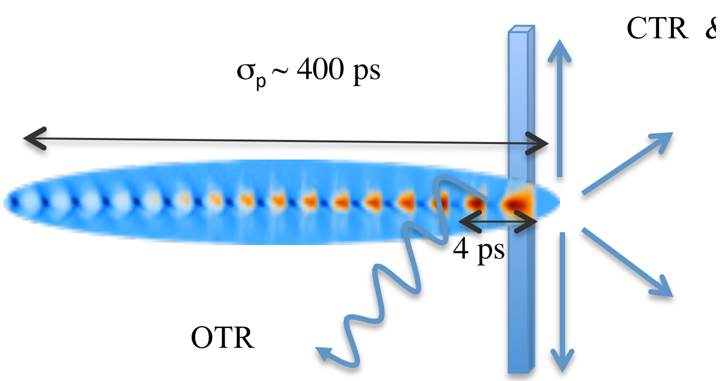


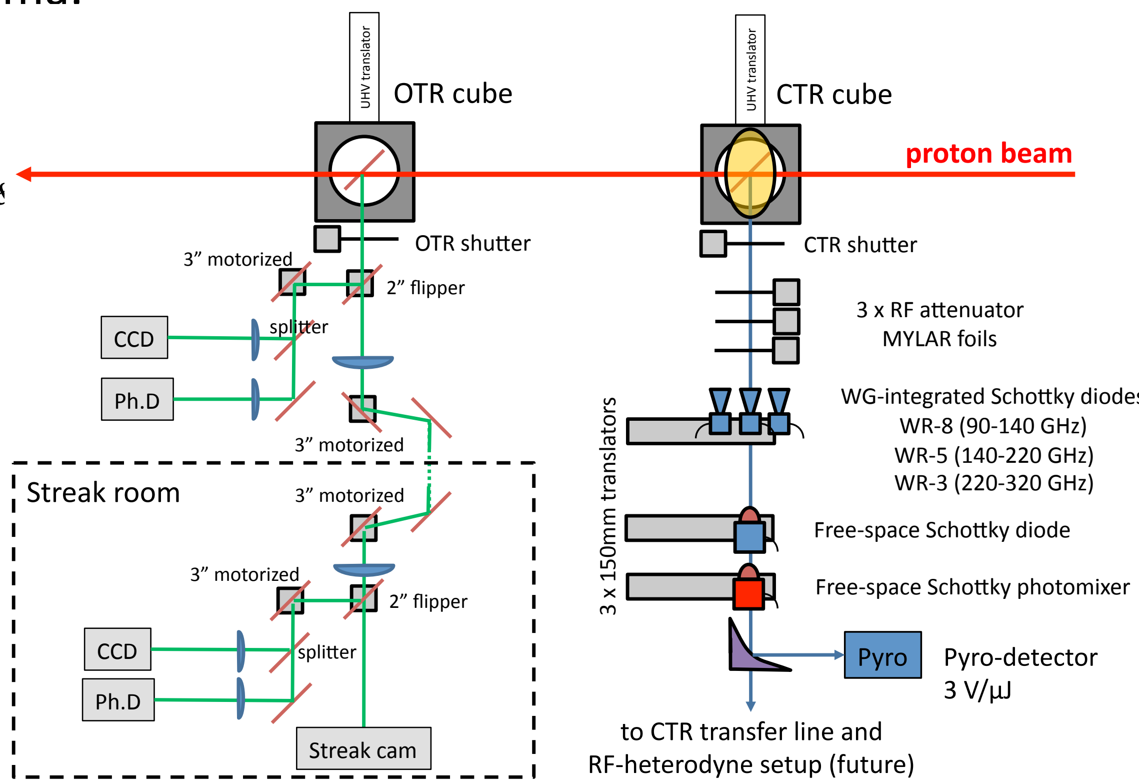
Indirect SMI diagnostic:

Compare transverse size of beam with and without plasma. Growth of tails governed by the transverse fields in the plasma.

Direct SMI diagnostic:

Measure frequency of modulation

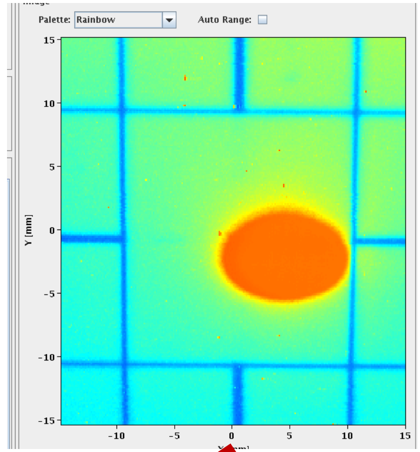




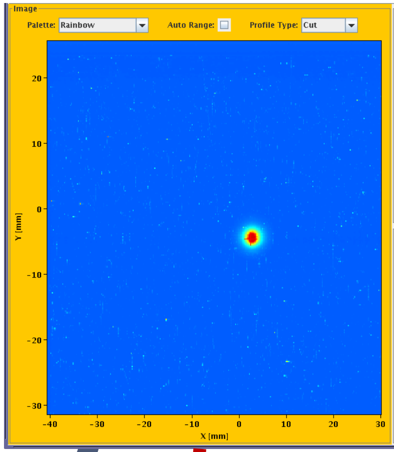
Commissioning

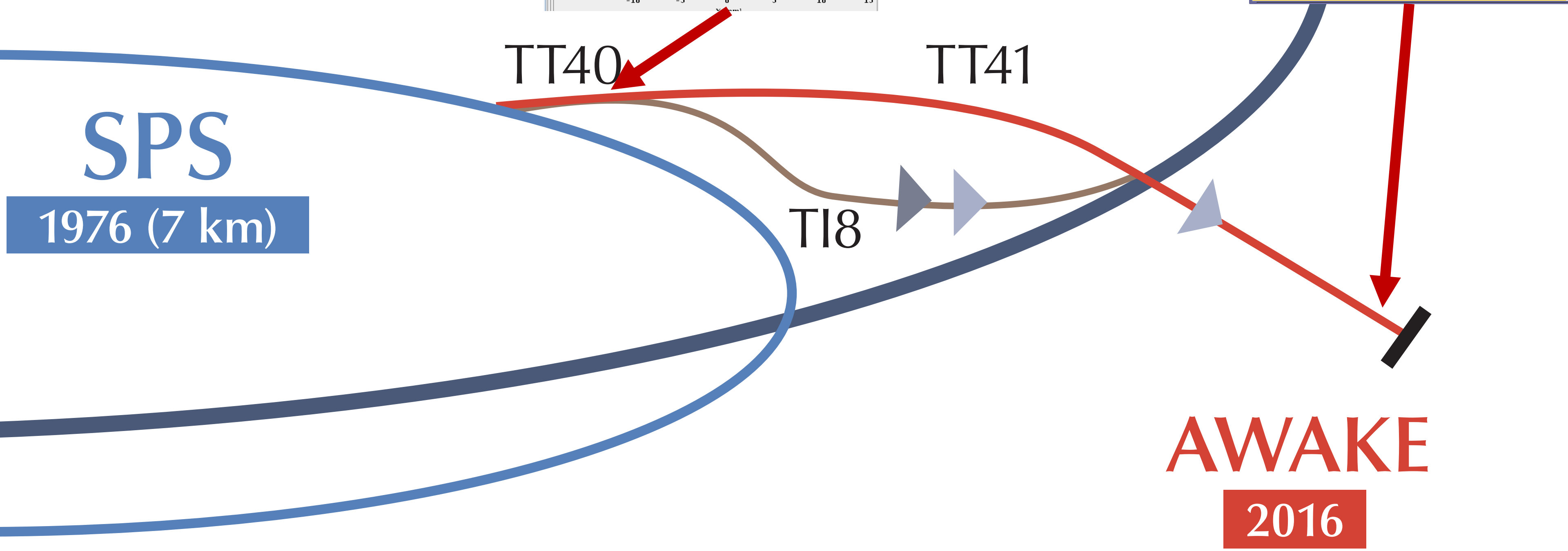
Proton beam commissioning run June 2016

BTV.400343
15.6.2016
1st AWAKE cycle extraction from SPS



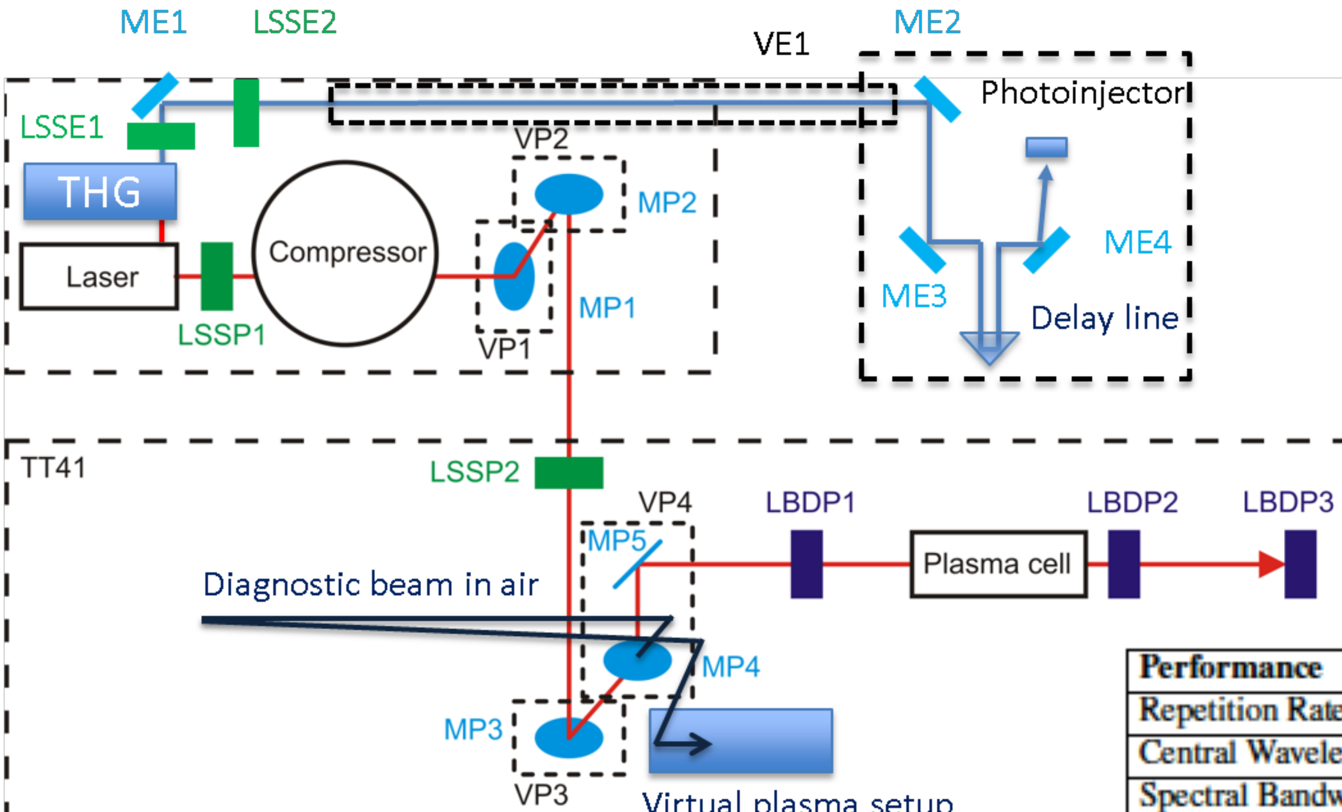
BTV.412442
16.6.2016
1st AWAKE beam in TT41



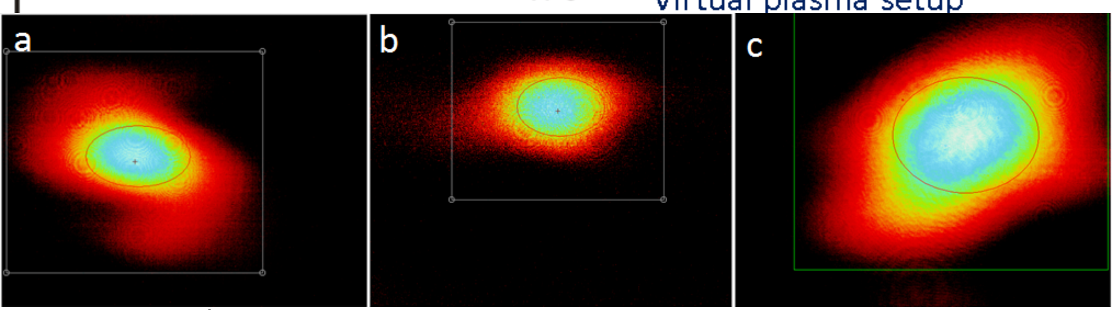


Commissioning

Proton & laser beam commissioning run September 2016



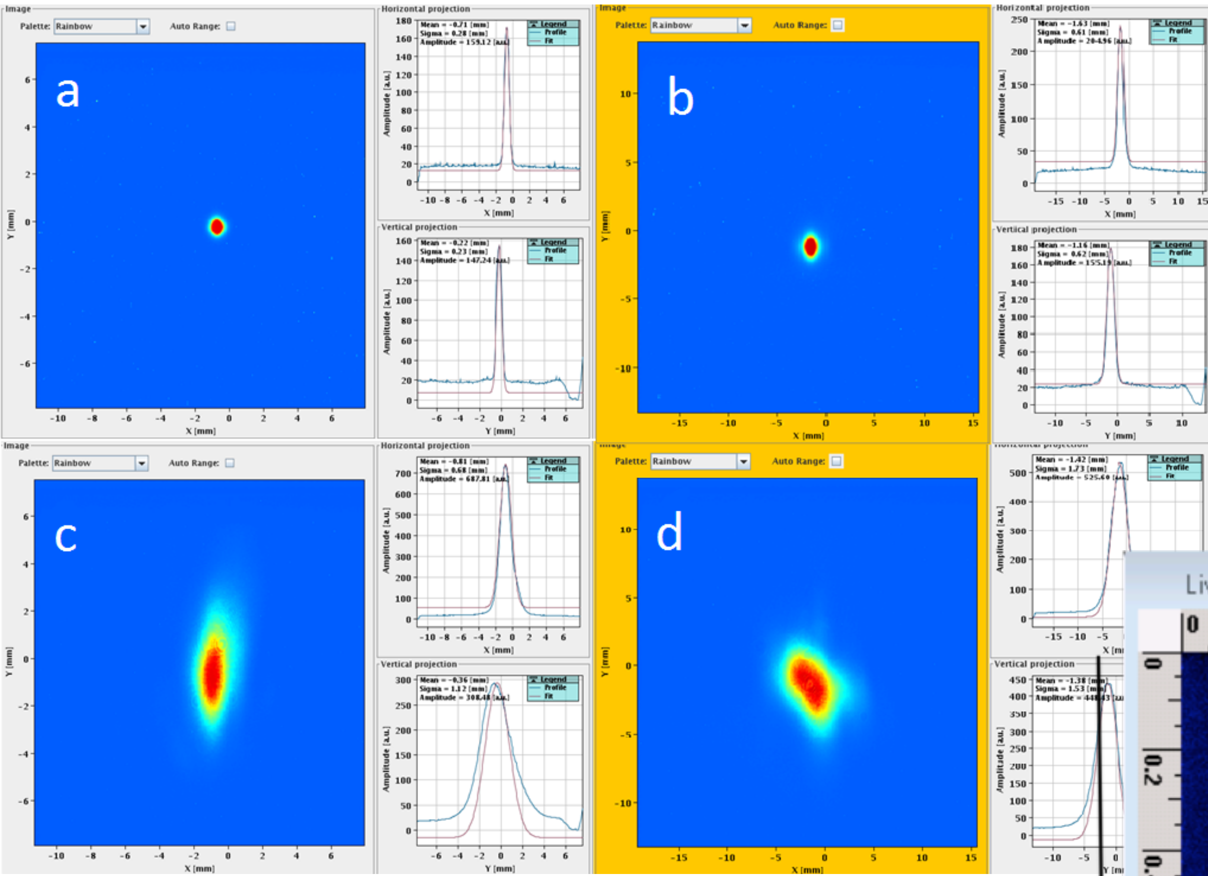
Laser beam setup – includes a 'virtual plasma cell' line for commisisoning & monitoring laser.



Performance	Measured Value
Repetition Rate	10 Hz
Central Wavelength	780–785 nm
Spectral Bandwidth	24 nm
Pulse duration	120 fs
Output Energy (uncompressed)	663 mJ
Output Energy (after compression)	500 mJ
Secondary output (uncompressed)	3 mJ
Energy stability	1.02%
Beam pointing stability	4.2 μrad
Temporal intensity contrast	2×10^{-7}
Polarization (linear)	250:1

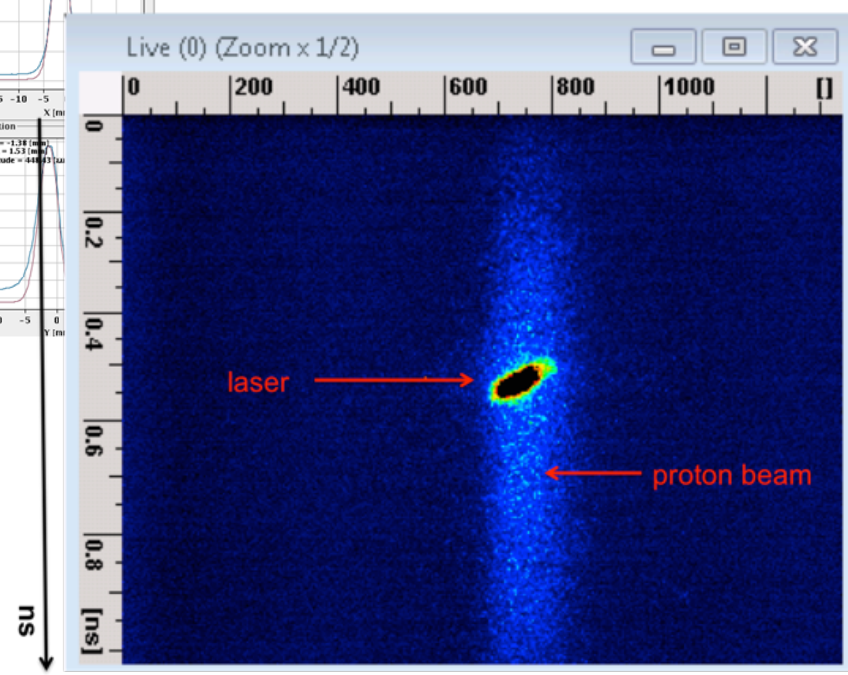
Commissioning

Proton & laser beam commissioning run September 2016



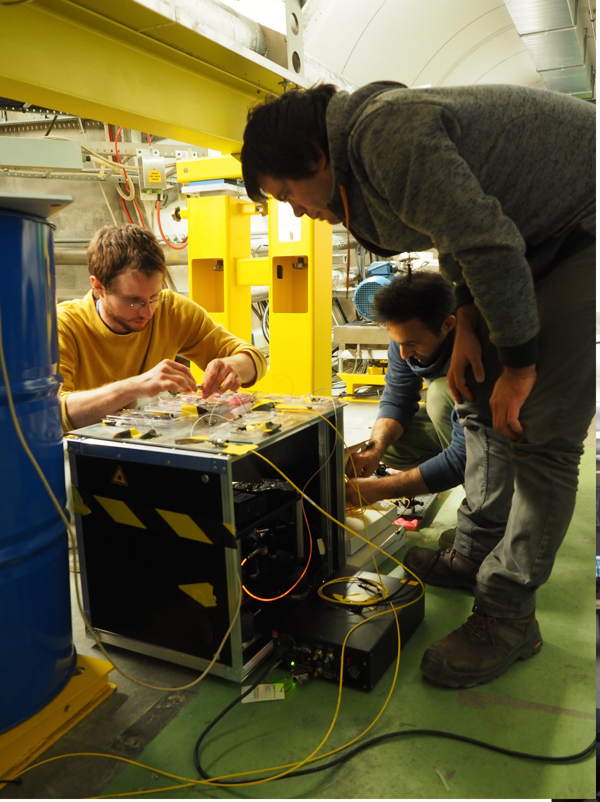
Spatial and temporal overlap of the proton and laser beams achieved.

Beam properties (size, jitter, etc. as expected)



First Run

December 9-12, 2016

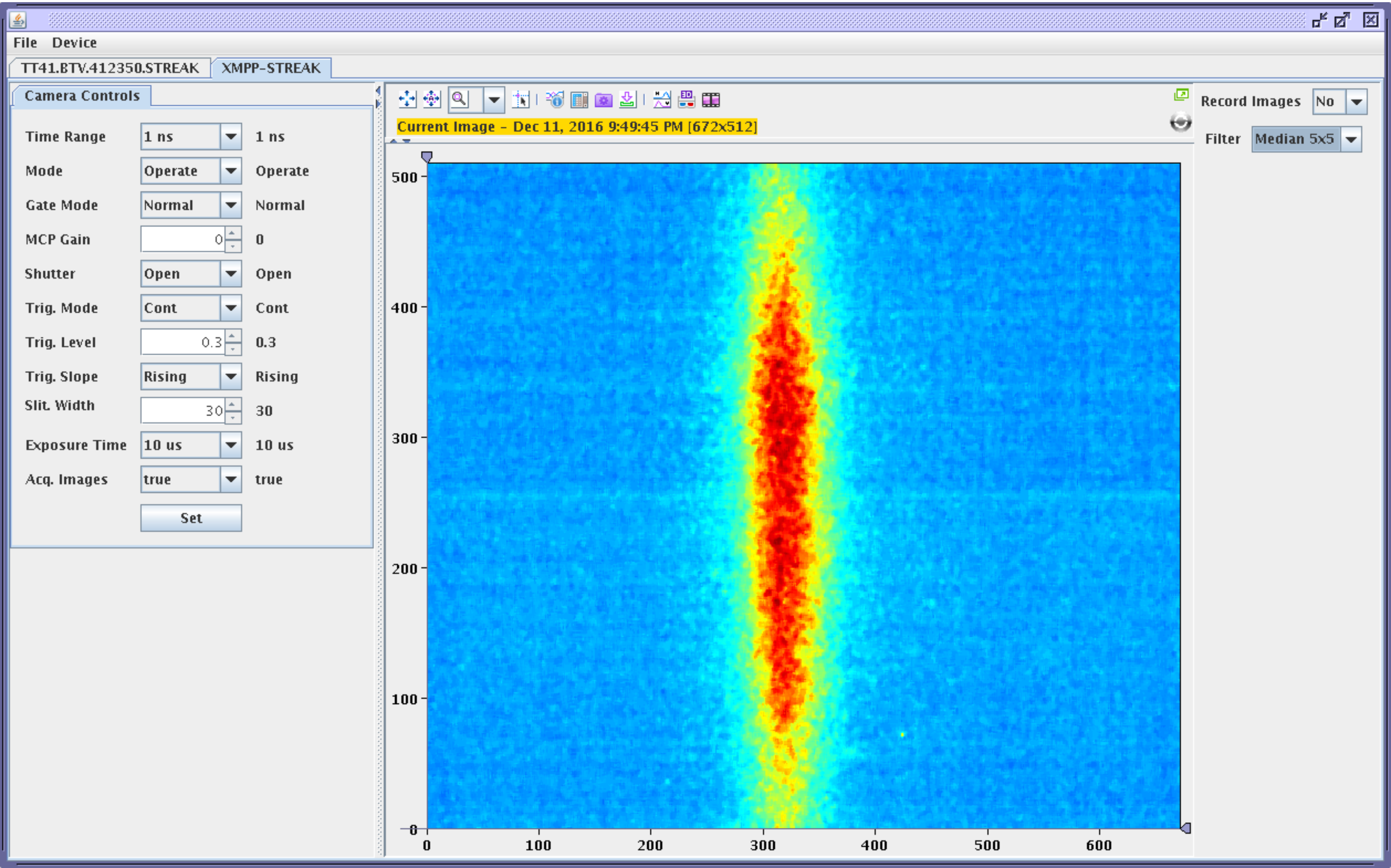




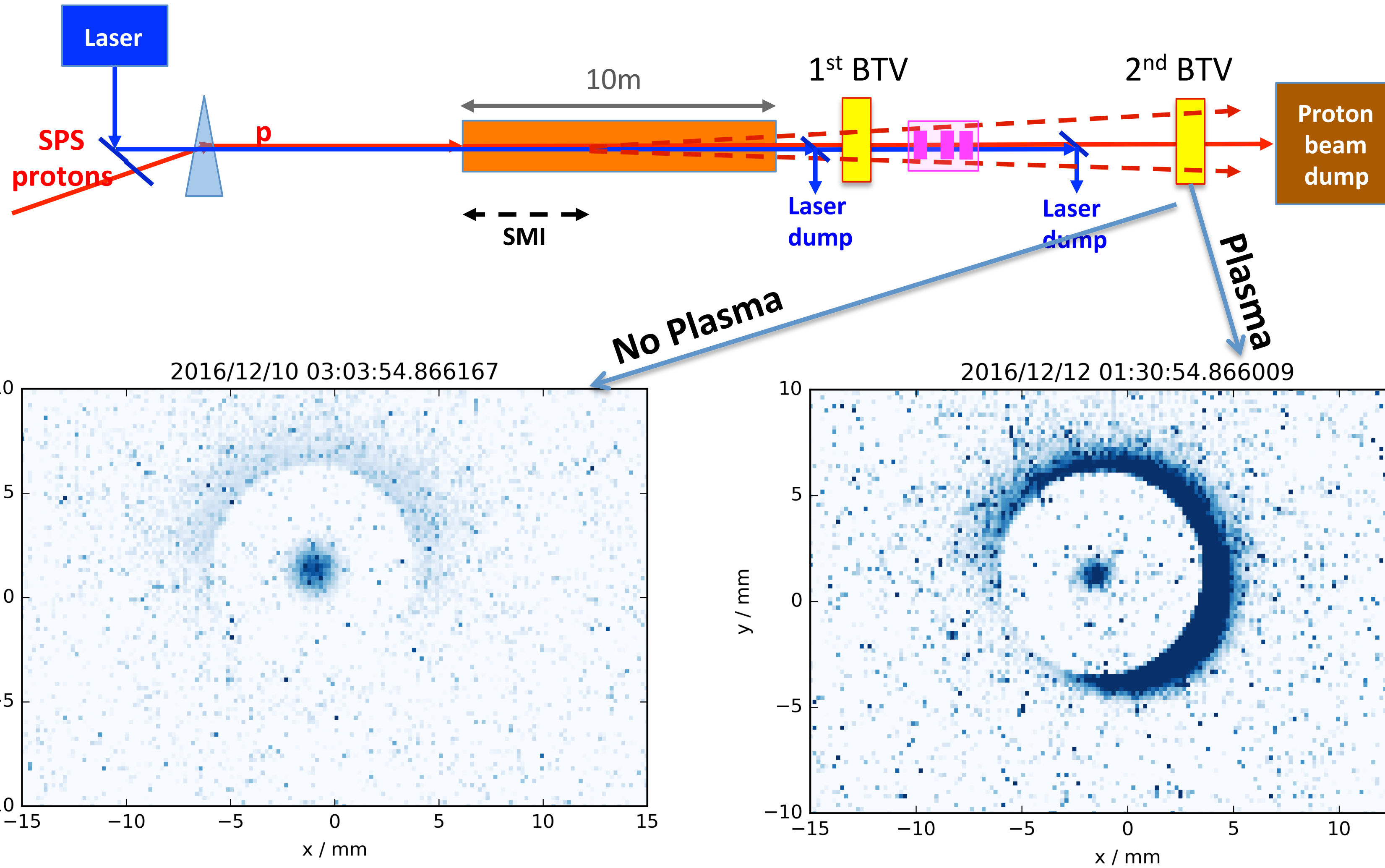


First Run December 9-12, 2016

$3\ 10^{11}$ Protons seen in optical transition radiation using streak camera



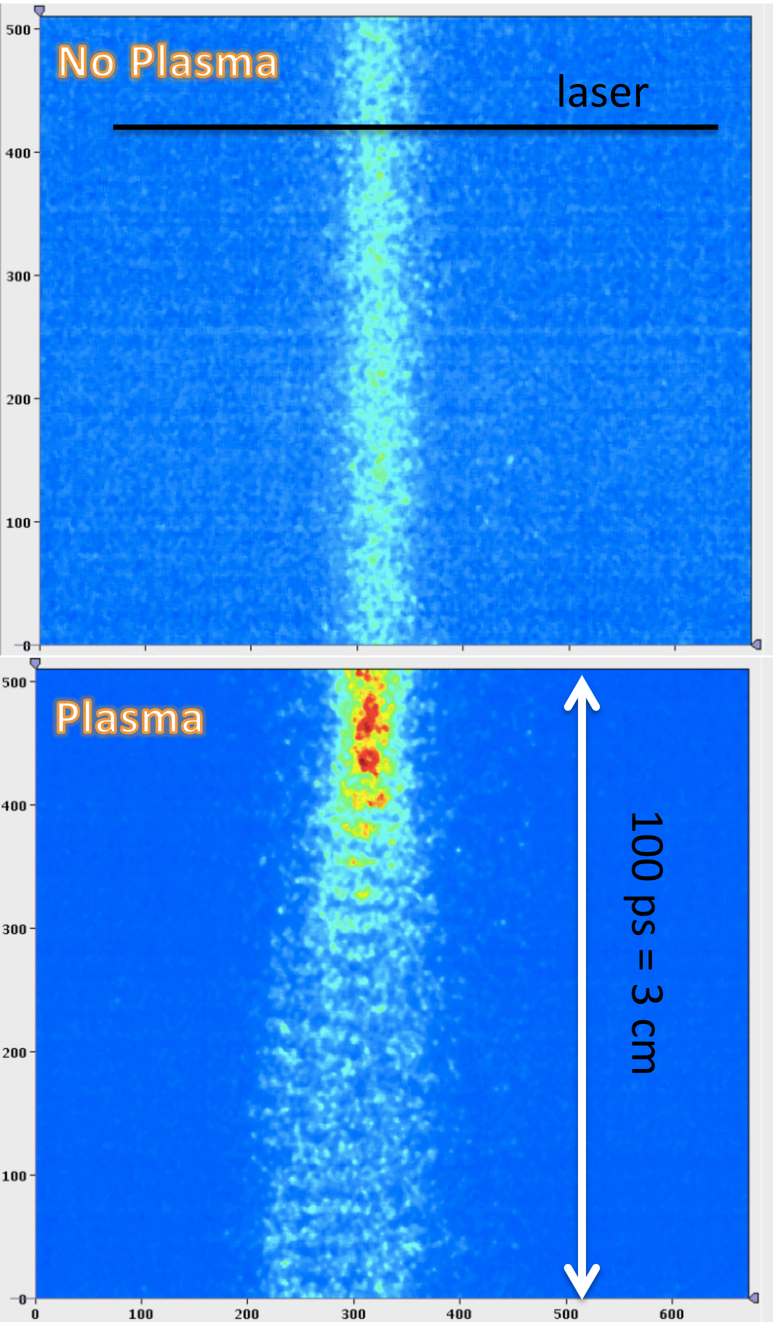
Success !

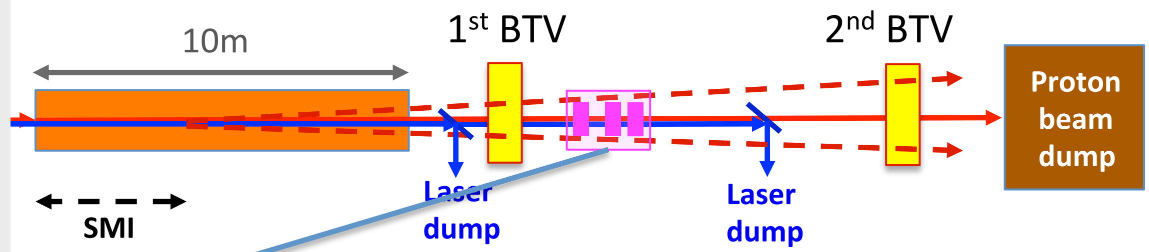


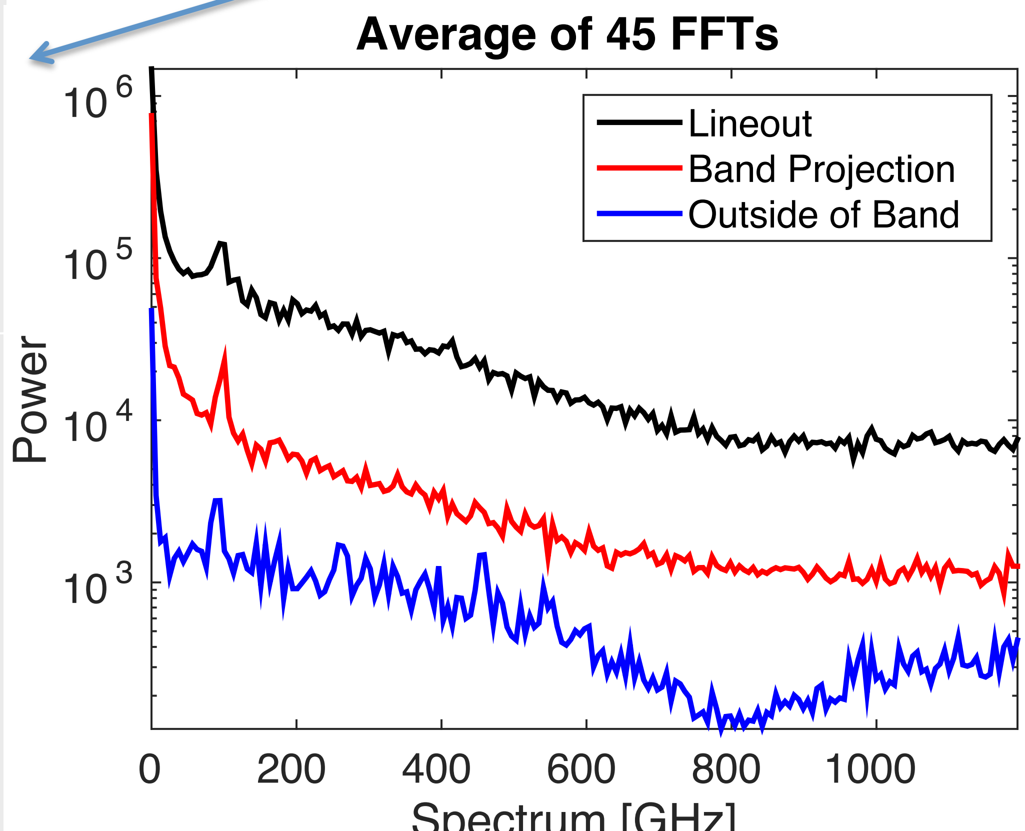
Clearly see the transverse blow-up of the proton beam. Only possible with very strong electric fields !

Success !

Optical Transition Radiation Diagnostic



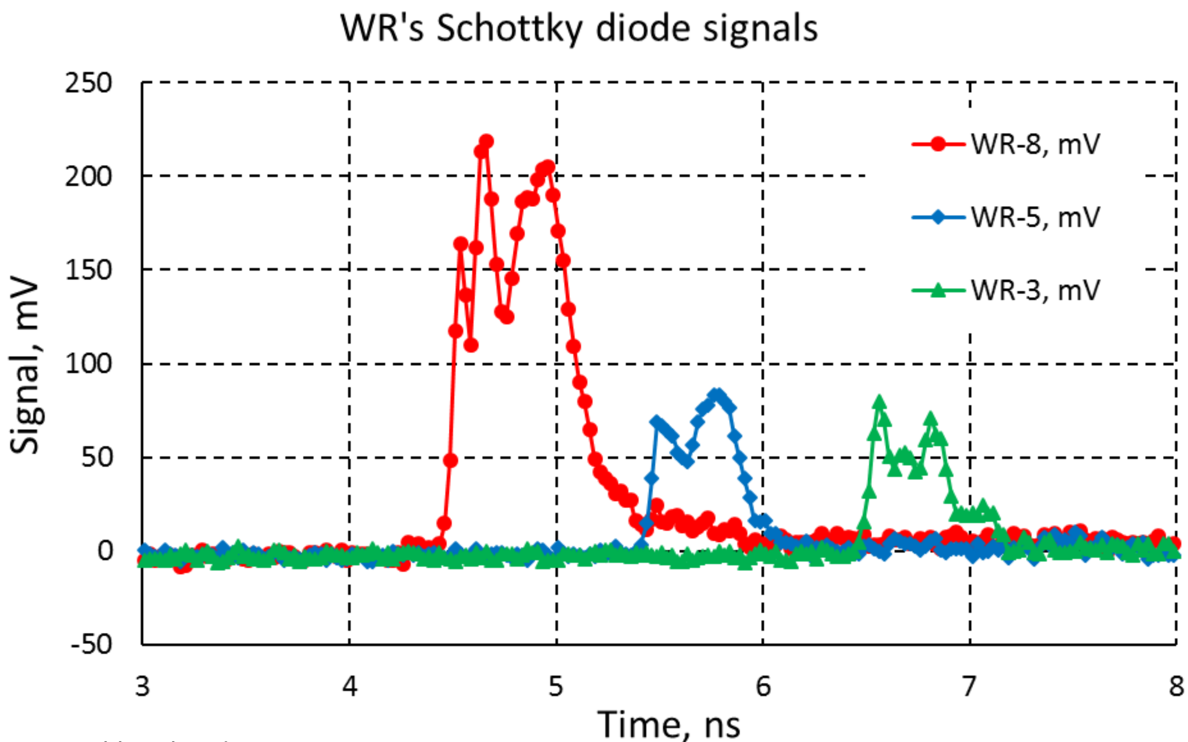




Fourier transform -> see modulation frequency

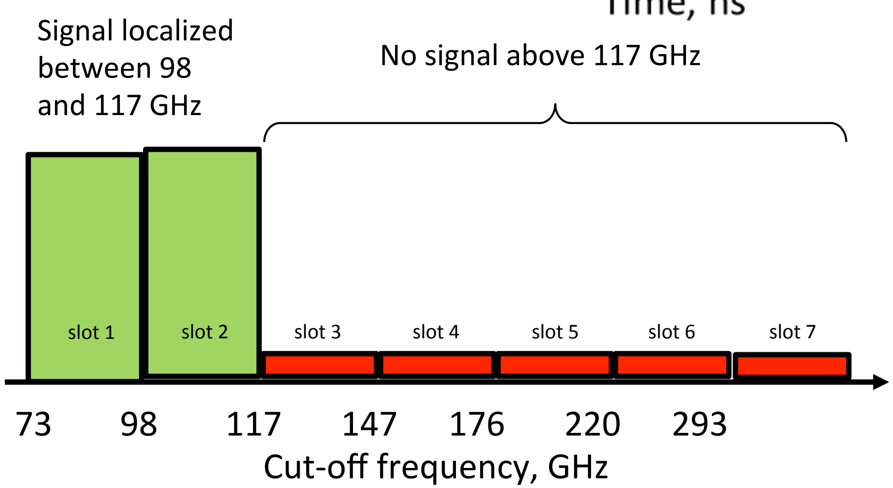
SPC, CERN

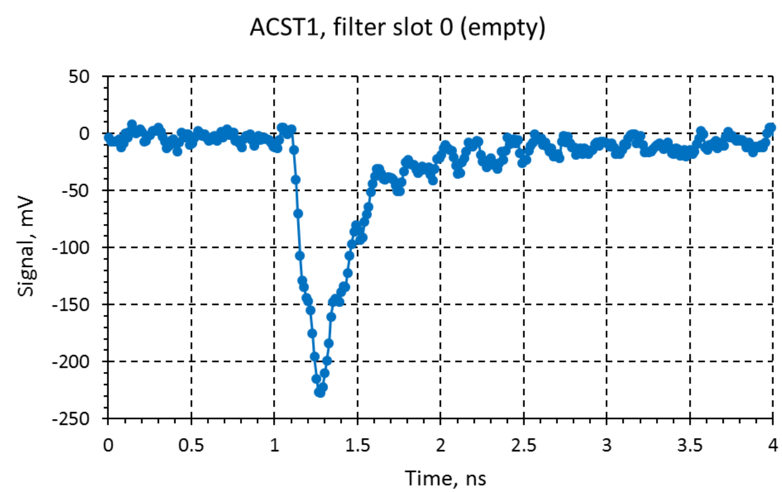
Success !



Coherent Transition Radiation diagnostic

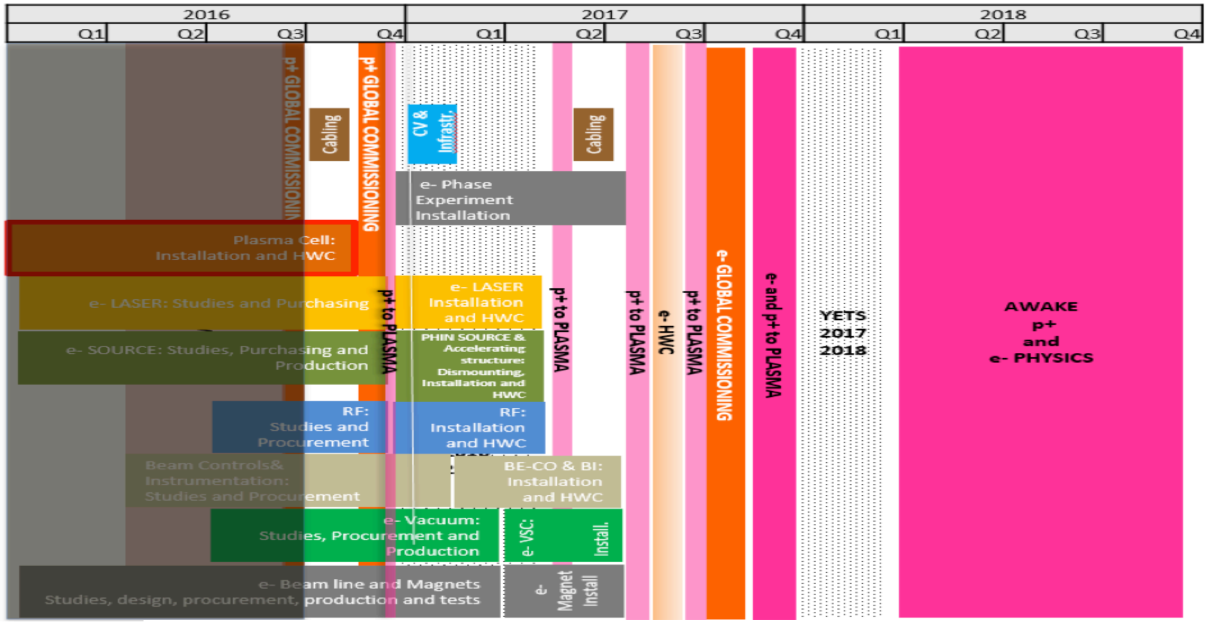
WR-8, 90-140 GHz
WR-5, 140-220 GHz
WR-3, 220-320 GHz





AWAKE Run Team

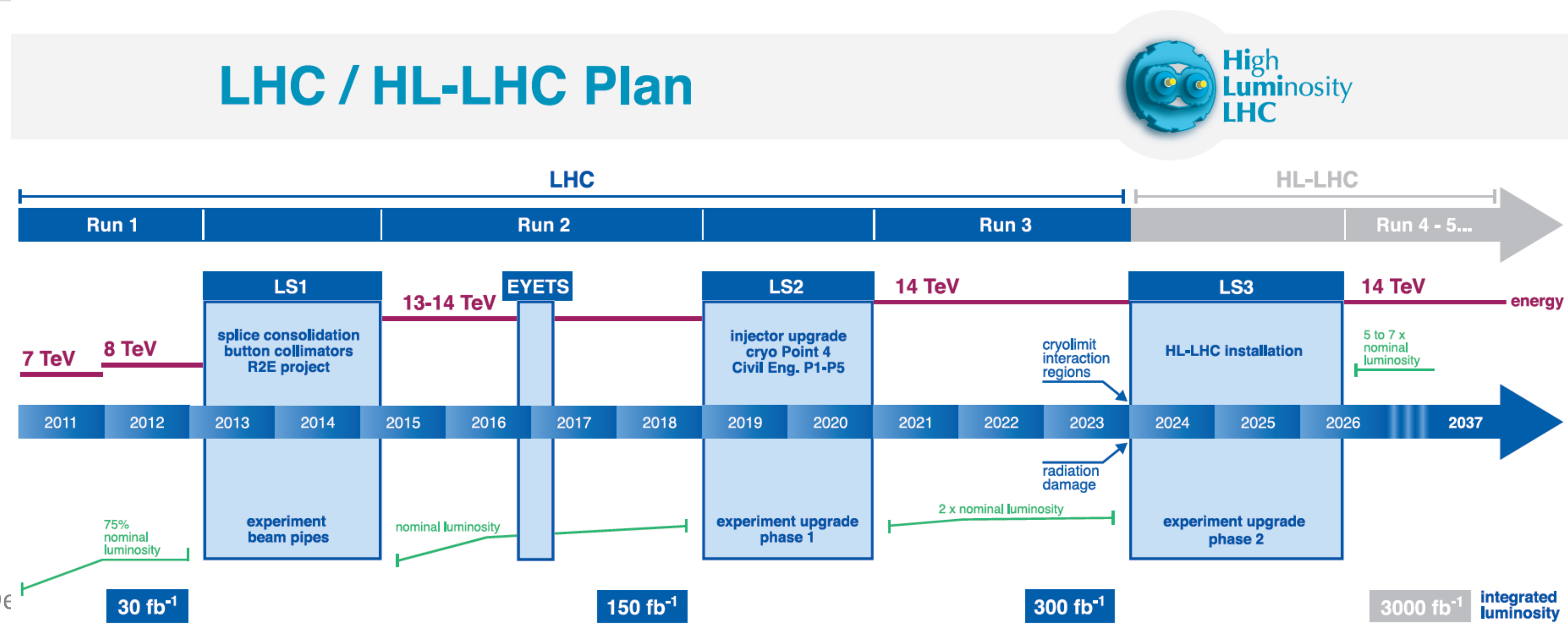
Schedule



AWAKE Planning for Run I – until LS2 of the LHC.

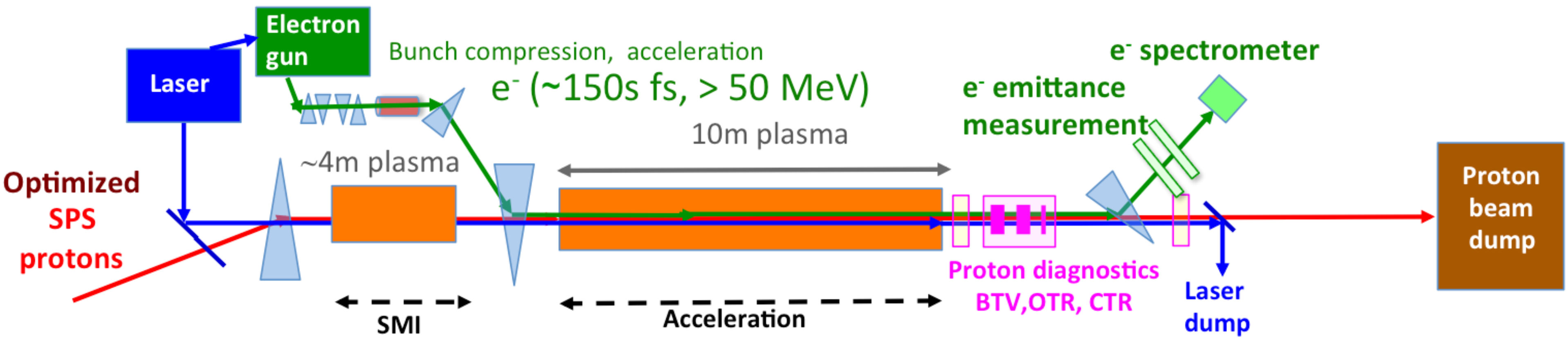
After LS2 – proposing Run II of AWAKE (during Run 3 of LHC)

After Run II – particle physics driven applications



Run II

Goals:
- stable acceleration of bunch of electrons with high gradients over long distances
- 'good' electron bunch emittance at plasma exit



Require:
- Compressed proton beam in SPS
- Short electron bunch with higher energy for loading wakefield
- Density step in plasma for freezing modulation
- Alternative plasma cell developments

Preliminary Run 2 electron beam parameters

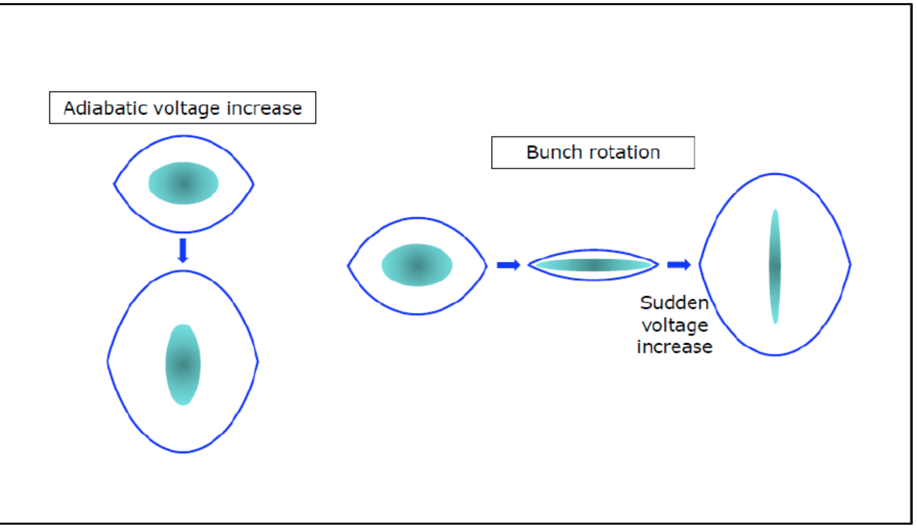
Parameter	Value
Acc. gradient	>0.5 GV/m
Energy gain	10 GeV
Injection energy	$\gtrsim$ 50 MeV
Bunch length, rms	40–60 μm (120–180 fs)
Peak current	200–400 A
Bunch charge	67–200 pC
Final energy spread, rms	few %
Final emittance	$\lesssim$ 10 μm

Run II

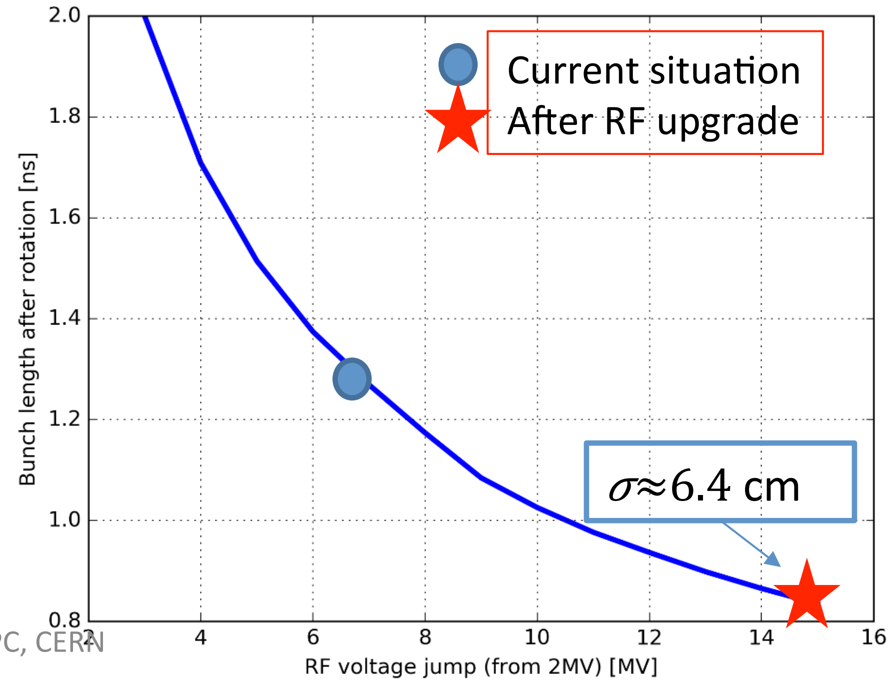
Proton beam:

Three important upgrades for the High Luminosity-LHC project that are also relevant for AWAKE:

- 200 MHz and 800 MHz RF upgrade in the SPS (800 MHz is done already)
- Impedance reduction in the SPS
- Increase of the injection kinetic energies in PS Booster (from 50 MeV to 160 MeV) and PS (from 1.4 GeV to 2 GeV)
    - ➢ Good for space charge limitation => smaller transverse emittance



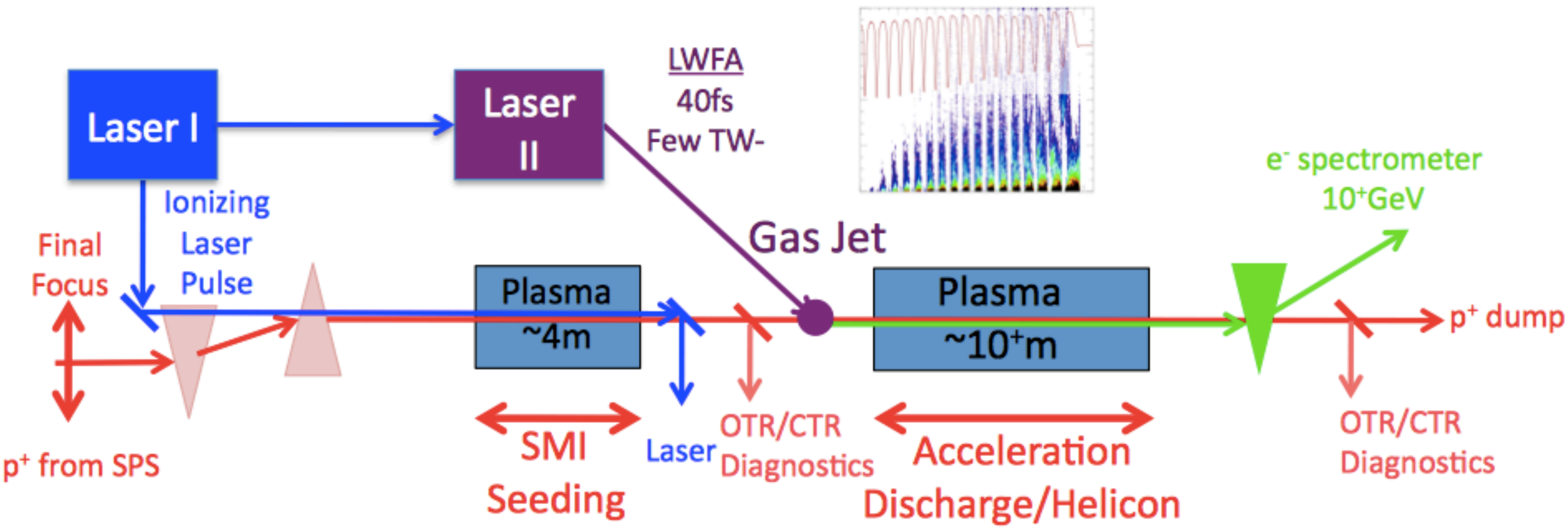
More studies required



Run II

Electron Injectors:

- **S-band gun**: cannot provide parameters in available space (bunch length, peak current)
- **X-band gun**: interesting technology, 50 MeV electrons in few meter. Expensive to "re-develop" a new gun.
- **LWFA** :

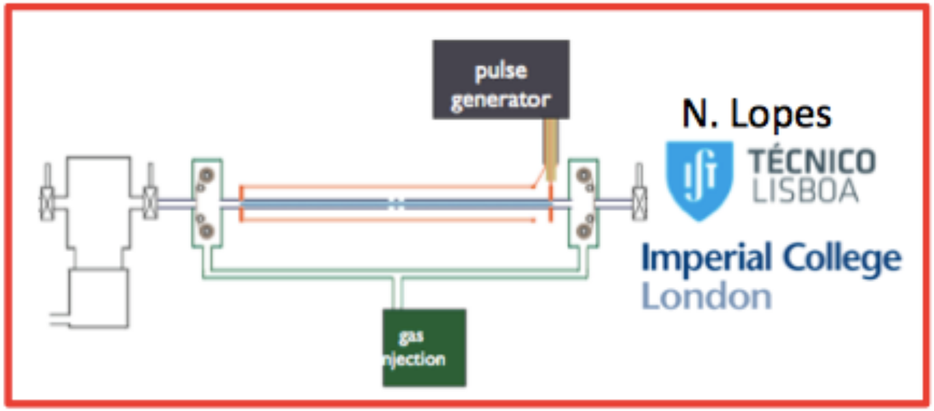


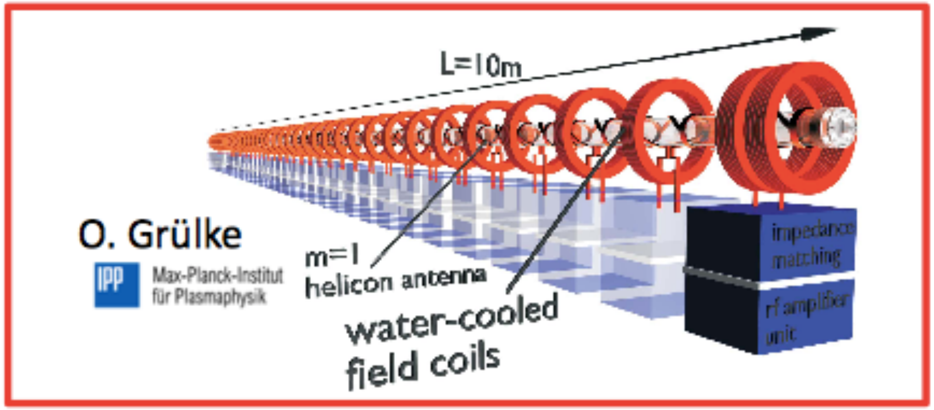
- **Ionization injection** : preliminary studies – fields need to be strong; still in linear regime ?

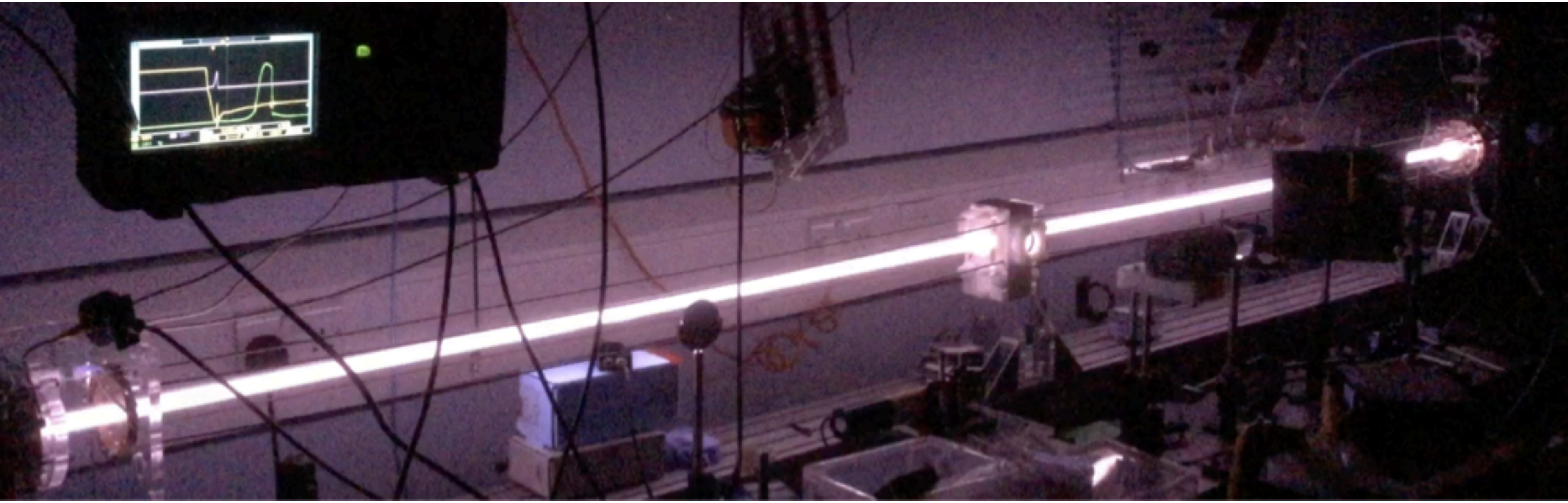
Run II

Scalable Plasma sources :

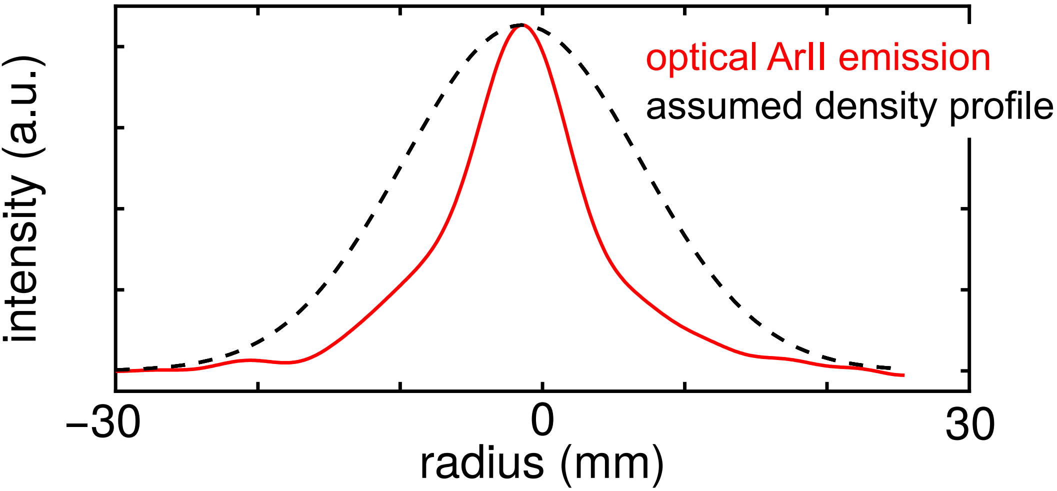
- CERN-MPP-SPC **helicon initiative**
- **Discharge source technology,** 10 m cell, is being further developed at UCL.

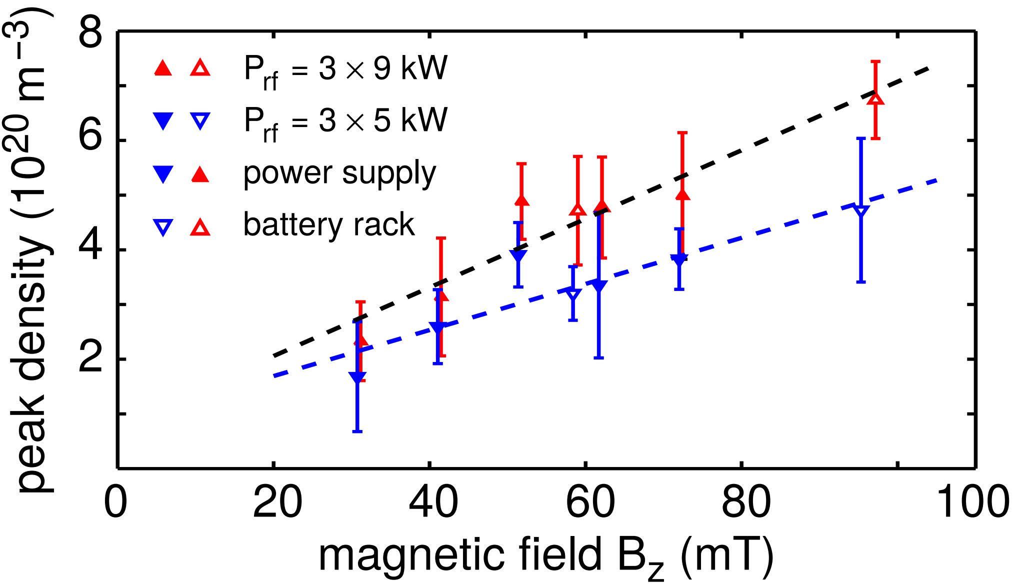






Helicon cell





1m prototype in regular operation (B. Buttenschön, O. Grülke, IPP Greifswald)

Target density achieved

Uniformity under study.

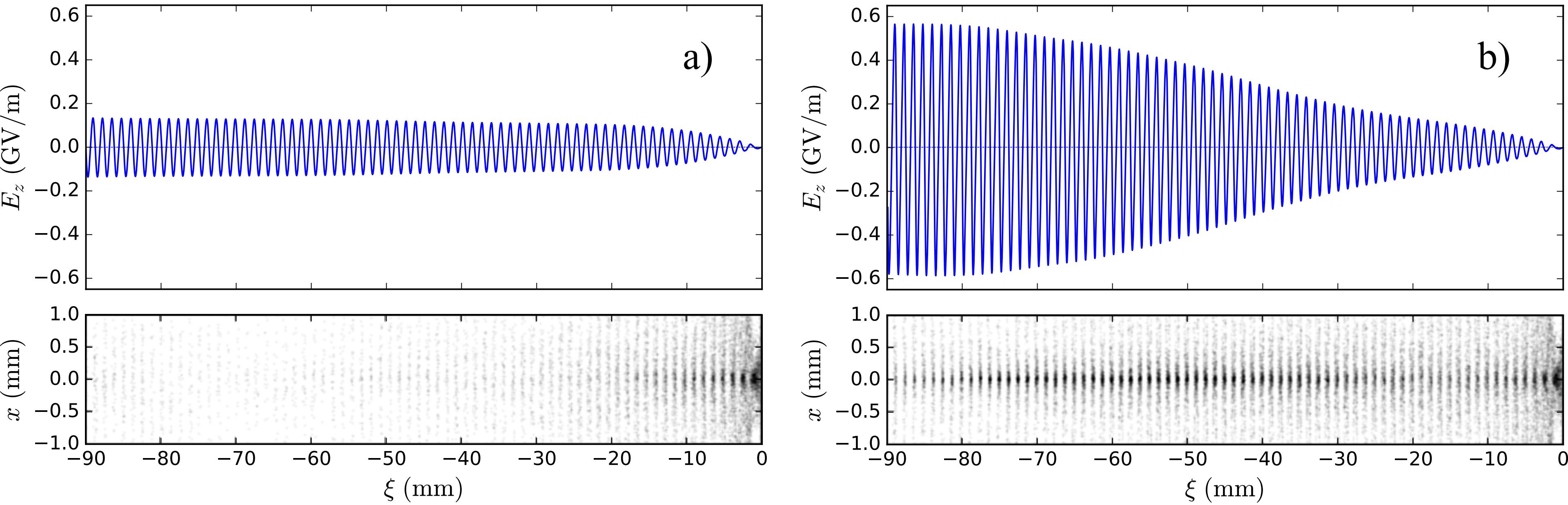
New effort CERN - IPP – SPC @CERN under consideration

Run II

Simulation studies:

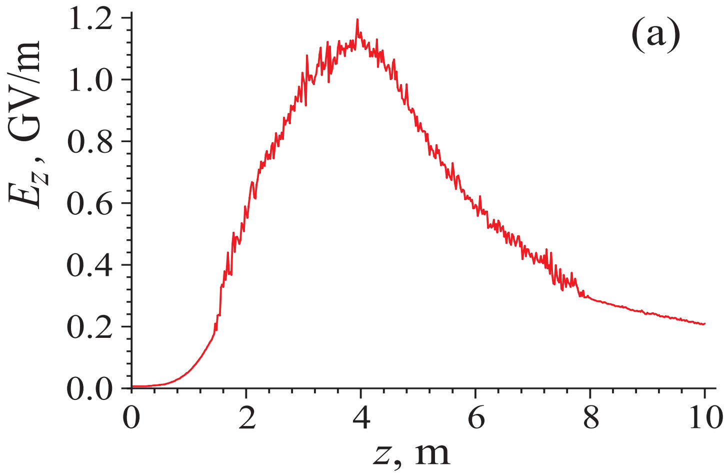
- **Staging**: issue - length of gap allowed between plasma cells, length of cells
- **Beam loading**: study loading as function charge versus bunch length (on-going)
- **Emittance preservation:** optimal location for injection, parameters of electron bunch
- **Tolerances:** input to plasma source development
- **Density step:** optimal location, parameters

No density step | With density step



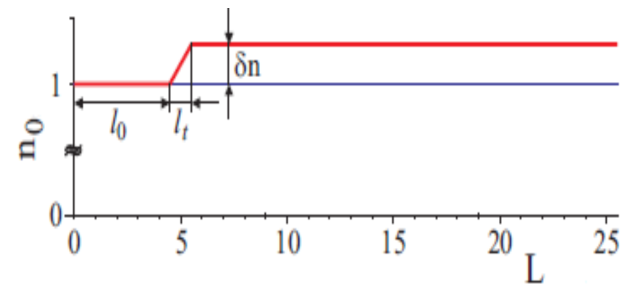
Intense simulation campaign will be launched

Freezing the Modulation

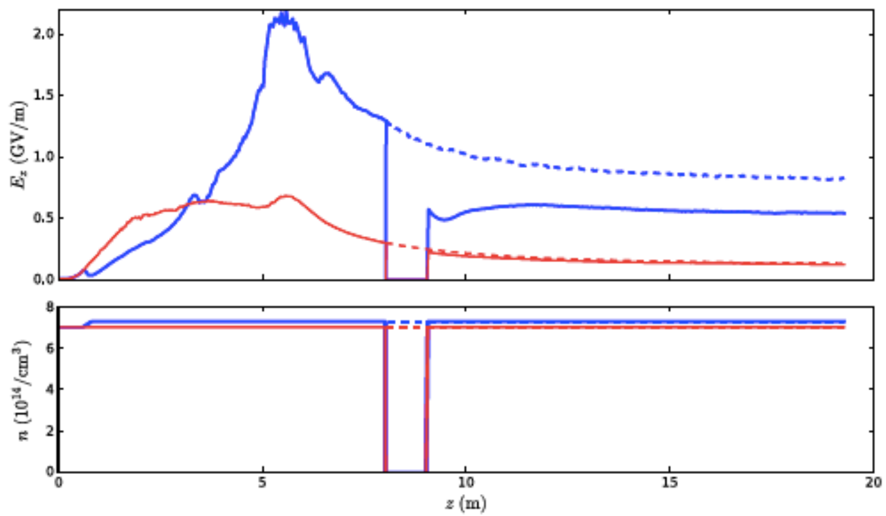


... wakefield amplitude quickly drops after the beam gets modulated.

Reason: defocusing regions keep on moving along the beam and destroys the bunches.



Remedy: control of the wave phase by the plasma density profile. Very promising:



Run II simulations
'Mind the gap'

Particle Physics Perspectives

Started considering:

- **Physics with a high energy electron beam**
  - E.g., search for dark photons

- **Physics with an electron-proton or electron-ion collider**
  - Low luminosity version of LHeC
  - Very high energy electron-proton, electron-ion collider

Are there fundamental particle physics topics for high energy but low luminosity colliders ?

I believe – yes ! Particle physicists will be interested in going to much higher energies, even if the luminosity is low.

In general – start investigating the particle physics potential of an AWAKE-like acceleration scheme.

Summary

Proton-driven plasma wakefield acceleration interesting because of large energy content of driver.

Modulation process means existing proton machines can be used.

Goal for AWAKE run I: demonstrate modulation process and proton-driven acceleration of electrons before LS2 of the LHC. **First data show the modulation – now need to study in detail !**

Run II proposal developing: goals are demonstration of stable acceleration and good electron bunch properties.

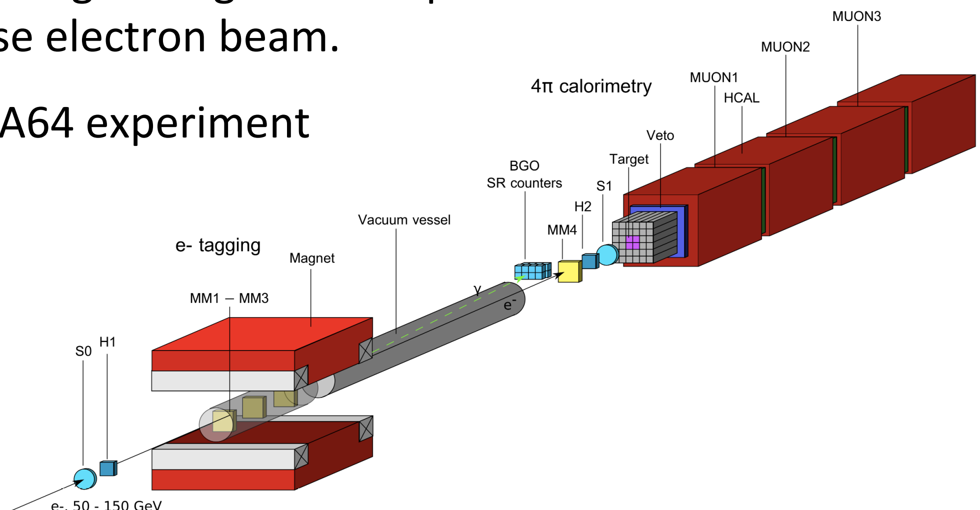
Long term prospects for proton-driven PWA exciting ! Starting to develop particle physics program that could be pursued with an AWAKE-like beam.

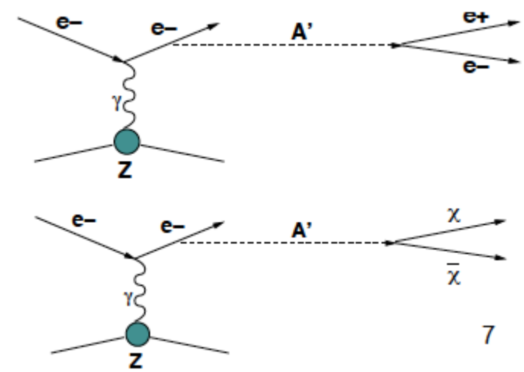
Extra

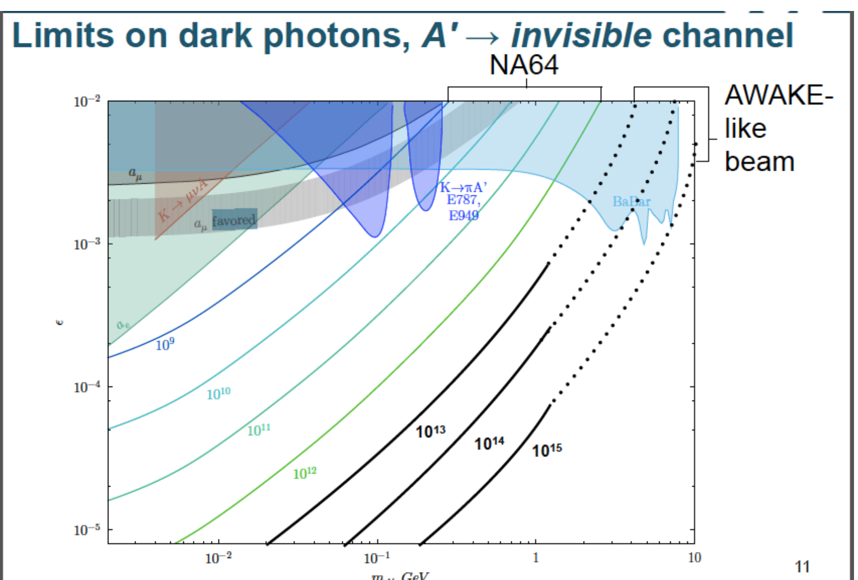
Dark Photon Search

Dark matter – what is it ? So far, no experimental hints on particle nature.
Interest in low-mass particle solutions increasing; e.g., dark photons.
Light shining through walls experiments …
Here, use electron beam.

NA64 experiment







NA64 – expect 10^6 electrons/spill; 10^{12} electrons for 3 months

AWAKE electron beam driven by SPS proton bunch. Assuming 10^9 electrons/bunch, would give 3 orders of magnitude increase.

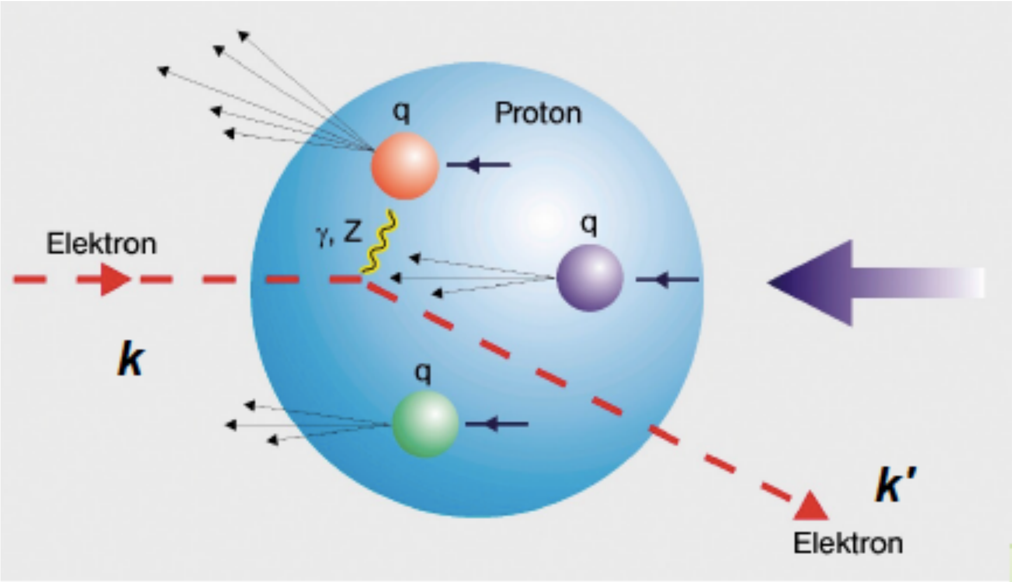
M. Wing, Physics Beyond Colliders Kickoff Workshop, 7/Sep/2016, CERN

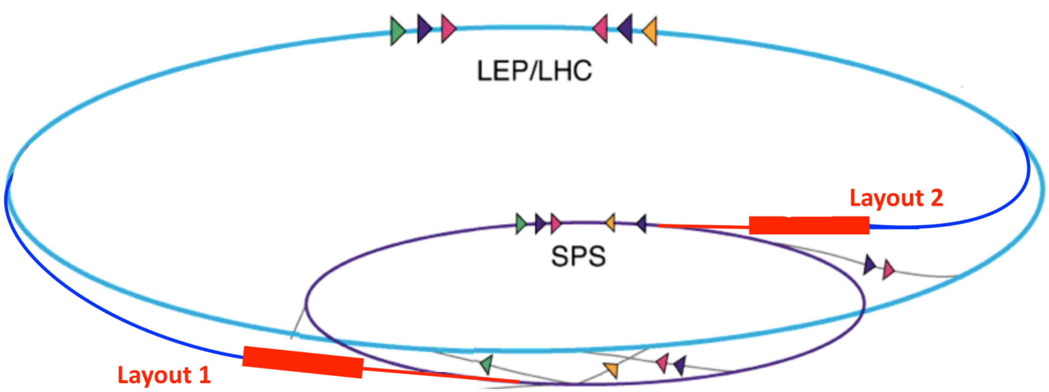
SPC, CERN

LHeC-like

Focus on QCD:

- Large cross sections – low luminosity (HERA level) enough
- Many open physics questions !
- Consider high energy ep collider with Ee up to O(50 GeV), colliding with LHC proton; e.g. Ee = 10 GeV, Ep = 7 TeV, √s = 530 GeV already exceeds HERA cm energy.





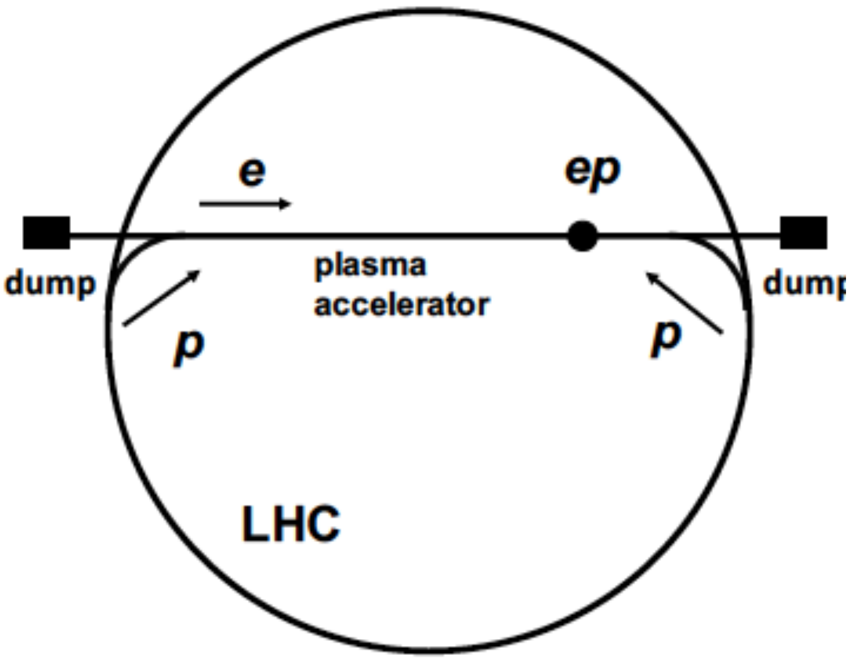
G. Xia et al., Nucl. Instrum. Meth. A 740 (2014) 173.

Create ~50 GeV beam within 50–100 m of plasma driven by SPS protons and have an LHeC-type experiment.

Clear difference is that luminosity currently expected to be $< 10^{30}\ cm^{-2}\ s^{-1}$.

VHEeP

(Very High Energy electron-Proton collider)



One proton beam used for electron acceleration to then collide with other proton beam

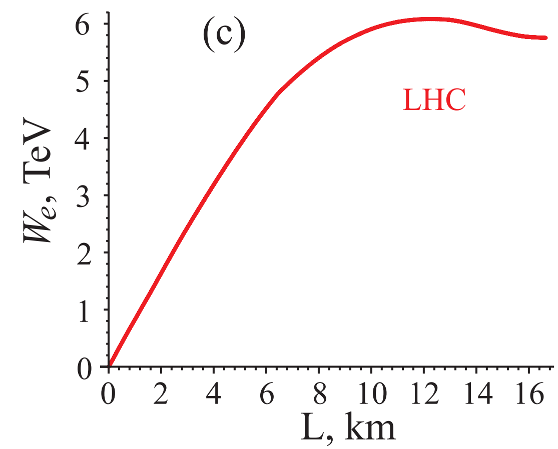
Luminosity ~ 10^{28} – 10^{29} cm^{-2} s^{-1} gives ~ 1 pb−1 per year.

Choose E_e = 3 TeV as a baseline for a new collider with E_P = 7 TeV yields √s = 9 TeV. Can vary.

- Centre-of-mass energy ~30 higher than HERA.
- Reach in (high) Q^2 and (low) Bjorken x extended by ~1000 compared to HERA.
- Opens new physics perspectives

VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

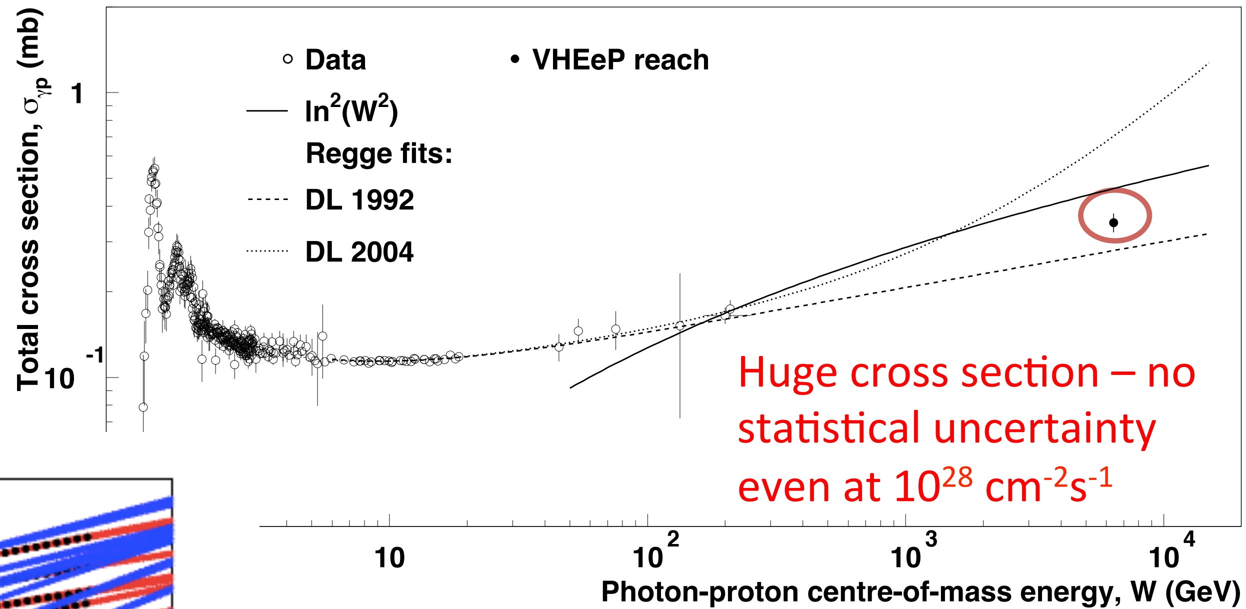
Electron energy from wakefield acceleration by LHC bunch



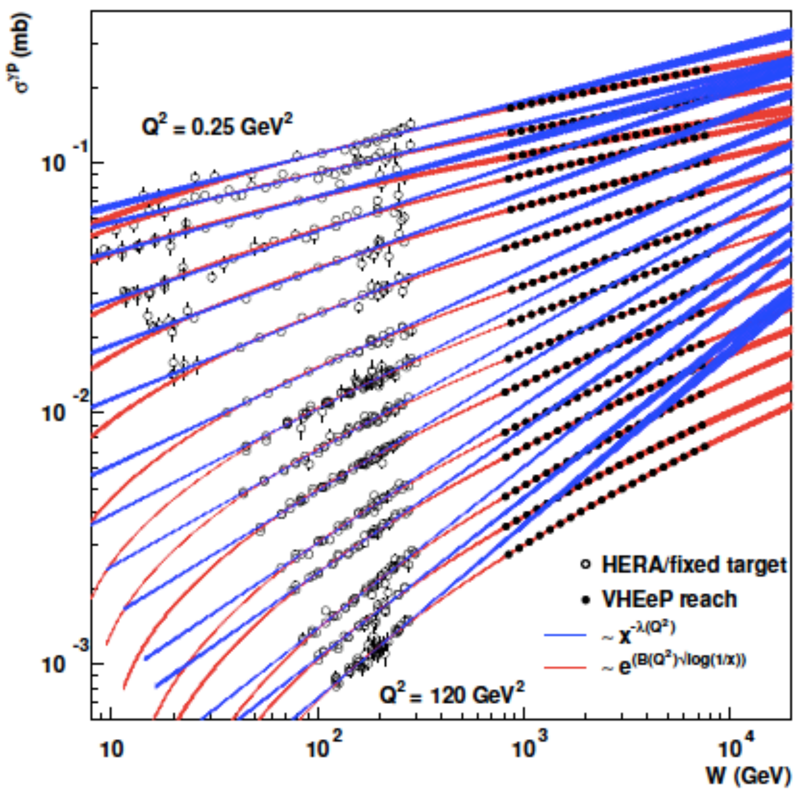
A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

Physics Reach

Total photoproduction cross section – energy dependence ? Fundamental physics question, impact on cosmic ray physics



Huge cross section – no statistical uncertainty even at 10^{28} $cm^{-2}s^{-1}$



Virtual photon cross section – observation of saturation of parton densities ? Would provide information on the fundamental structure of the QCD vacuum.

+ BSM physics such as Leptoquarks, quark substructure, etc.

C, CERN