MAX-PLANCK-GESELLSCHAFT

AWAKE

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

STATUS OF THE AWAKE EXPERIMENT

Allen Caldwell
Max-Planck-Institut für Physik

1. Motivation - reminder
2. The AWAKE project
    A. Collaboration Matters
    B. Infrastructure & Beamlines
    C. Plasma Cell
    D. Laser system
    E. Diagnostics
    F. Planning & Beam request

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	[illegible]	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	[illegible]	[illegible]

The most important tool for this development was the particle accelerator

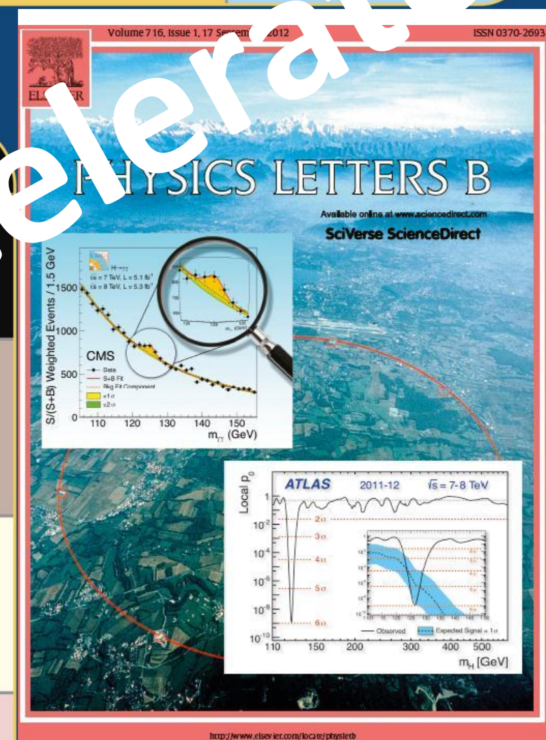
FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c²	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

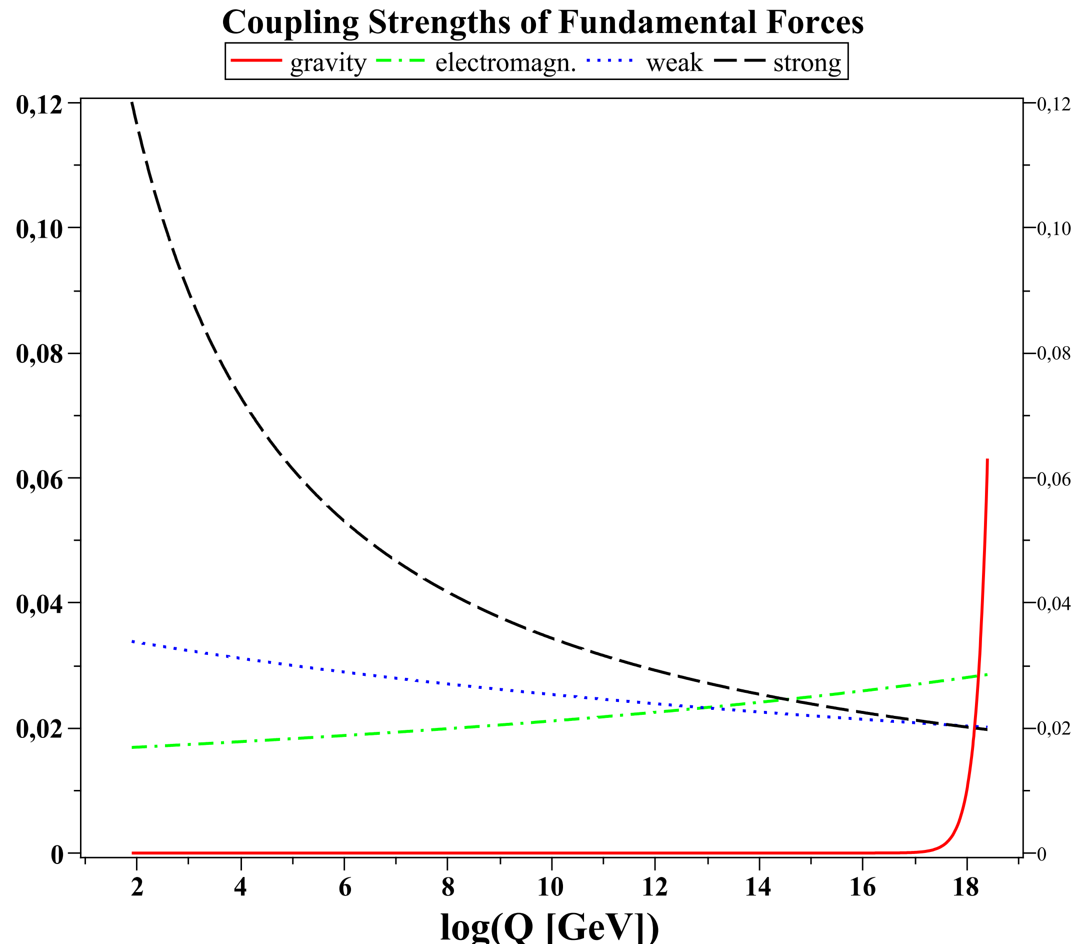
Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3



Particle physicists are convinced there are more discoveries to come:

Many things not explained in the standard model:

- why three families
- matter/antimatter imbalance
- neutrinos and neutrino mass
- hierarchy problem/unification
- dark matter
- dark energy
- …



Need to find ways to explore physics at higher energy scales in a laboratory environment.

New acceleration technology !

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

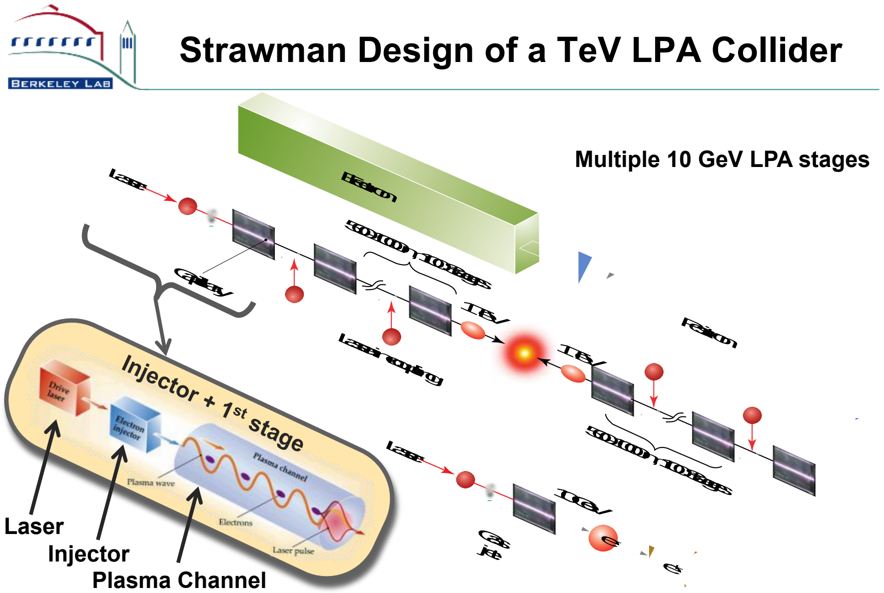
FACET, 30J/bunch

SPS 20kJ/bunch

LHC 300 kJ/bunch

Witness:

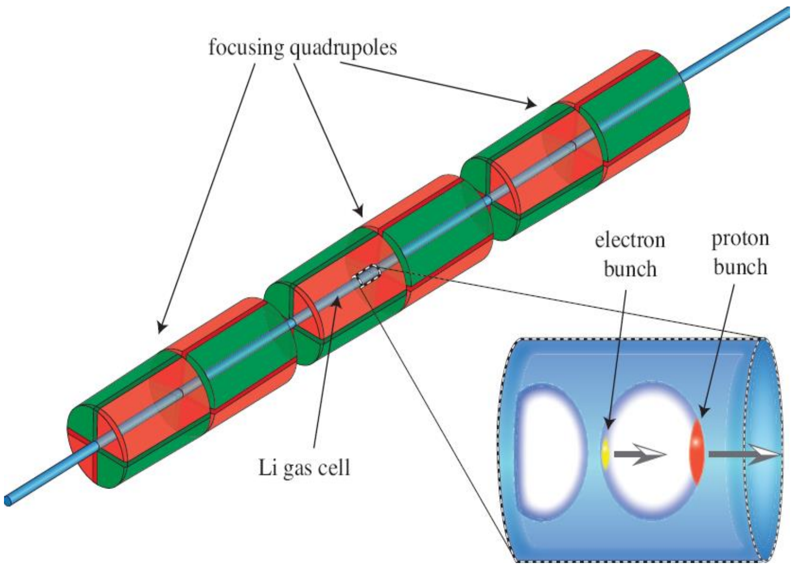
10^{10} particles @ 1 TeV ≈ few kJ

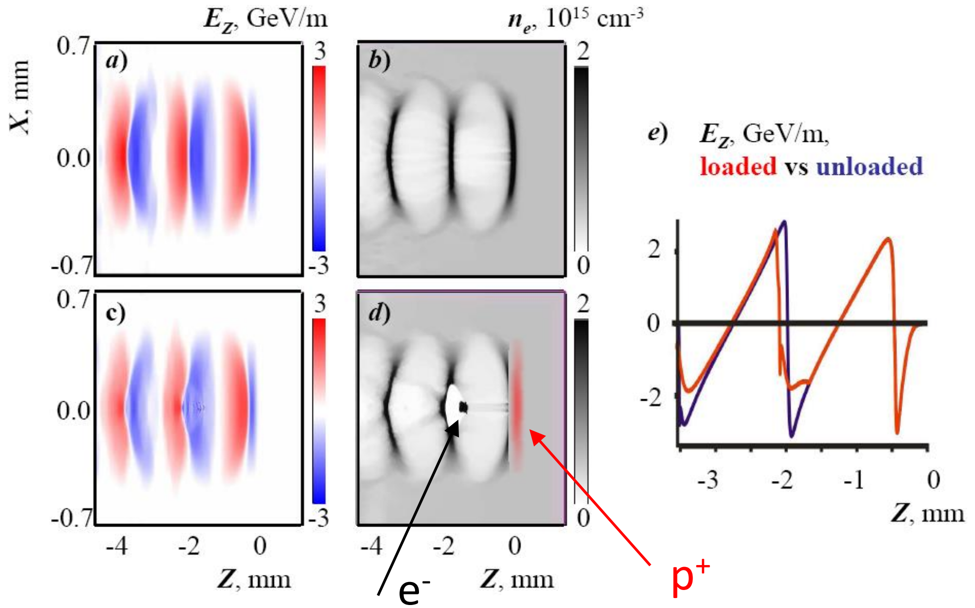


Leemans & Esarey, Physics Today, March 2009

Energy content of driver allows to consider single stage acceleration

Simulation Results





Drive beam: p^+

$E=1$ TeV, $N_p=10^{11}$

$\sigma_z=100$ µm, $\sigma_r=0.43$ mm

$\sigma_\theta=0.03$ mrad, $\Delta E/E=10\%$

Witness beam: e^-

$E_0=10$ GeV, $N_e=1.5\times10^{10}$

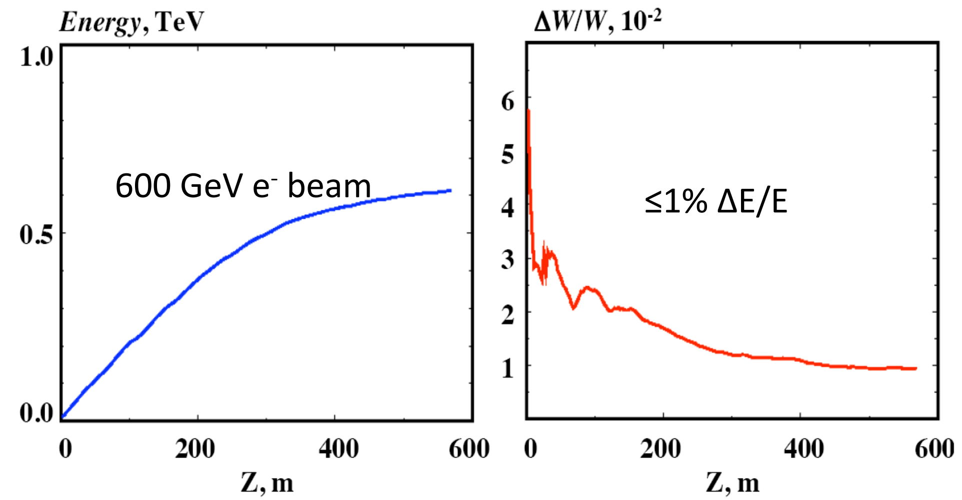
Plasma: Li^+

$n_p=6\times10^{14}$cm^{-3}

External magnetic field:

Field gradient: 1000 T/m

Magnet length: 0.7 m

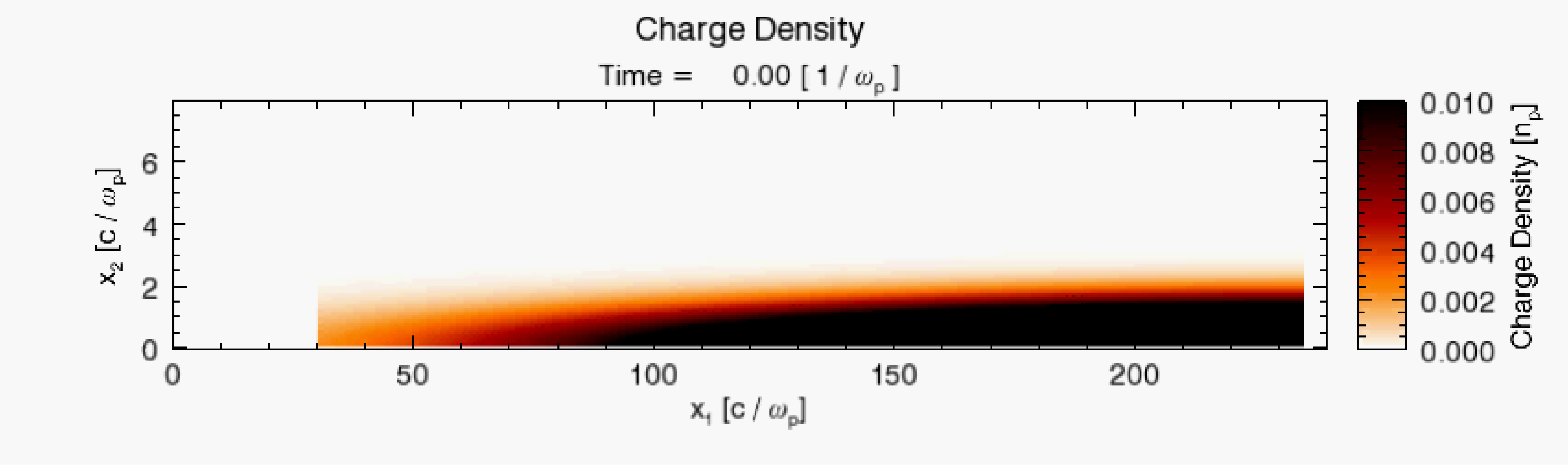


A. Caldwell, K. Lotov, A. Pukhov, F. Simon, Nature Physics 5, 363 (2009).

Modulated Proton Beam

The 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.

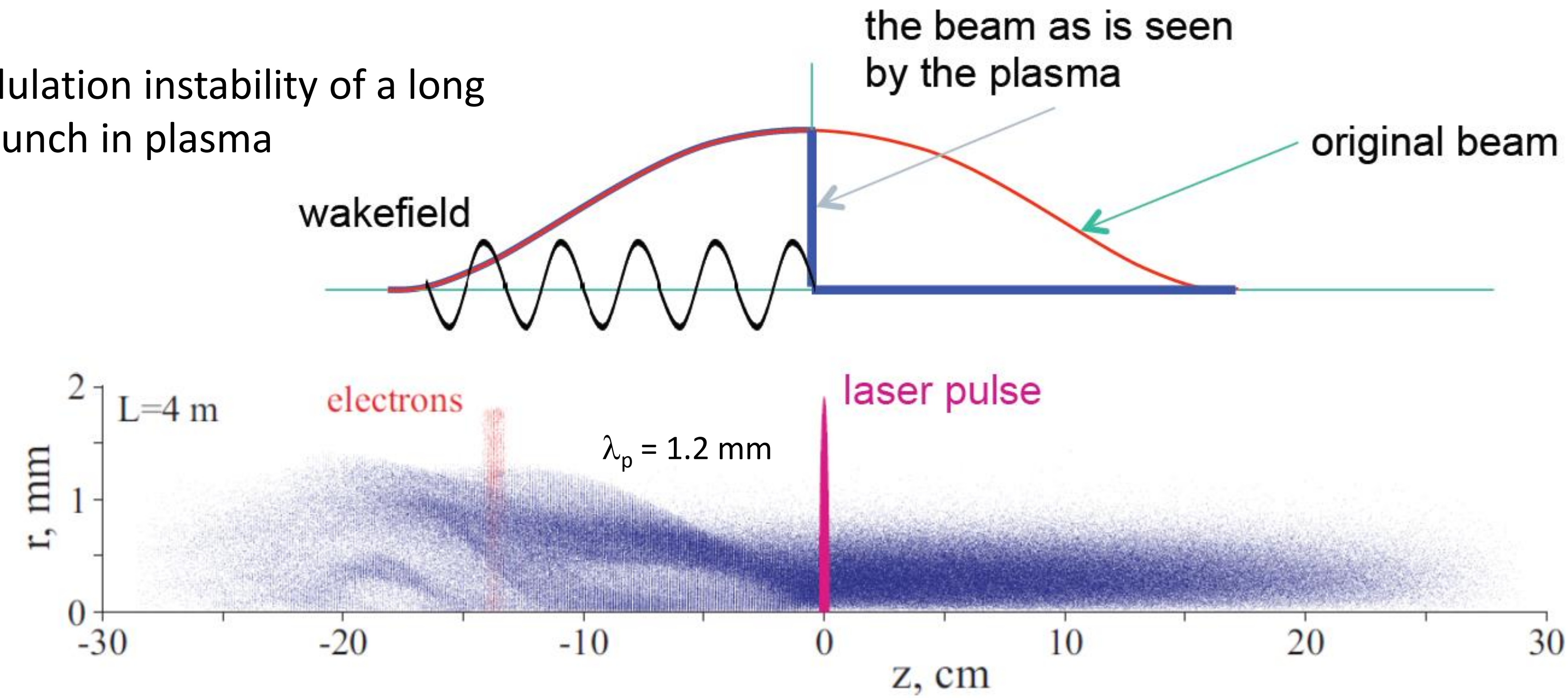
N. Kumar, A. Pukhov, and K. V. Lotov, Phys. Rev. Lett. **104**, 255003 (2010)



Propagation of a ‘cut’ proton bunch in a plasma. From Wei Lu, Tsinghua University

Modulated Proton Bunch

Self-modulation instability of a long proton bunch in plasma



Self-modulated proton bunch resonantly driving plasma wakefields.

AWAKE

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
University of Oslo
University of Strathclyde

Requests under consideration:
Ulsan National Institute of Science and Technology (UNIST), Korea
Wigner Institute, Budapest
Swiss Plasma Center group of EPFL

Further groups have also expressed their interest to join AWAKE.

New since 2014 SPSC report

Cost and Schedule Review April 28, 2015

- The AWAKE plan to complete Phases I,II before LS2 of the LHC was fully endorsed

- The committee recommended making resources available at CERN to meet this goal. This included extra funding at CERN of 2.6MCHF. The funding recommendation was approved very recently in the scientific council.

- AWAKE was tasked with producing a baseline design document for the experiment as it is to be built, and to produce design change requests for any future modifications to the design. We are now preparing the engineering specifications for all WPs.

Further Funding News …

- The Max Planck Institute for Physics was granted a Large Equipment Grant of 1.5MEur in April

- other funding requests are either nearing approval (UK) or need resubmission (Korea).

In the News

CERN Accelerating science

CERN

TEDxCERN

x = independently organized TED event

Videos | Speakers | Attend | Programme | Interactive story | Participate

Edda Gschwendtner

Edda Gschwendtner, physicist, is the project leader of CERN's plasma wakefield ac

Süddeutsche Zeitung

Presseartikel

Ritt auf der Plasma-Welle

Teilchenphysiker haben ein Problem

The Economist | World politics | Business & finance | Economics | Science & technology | Cultu

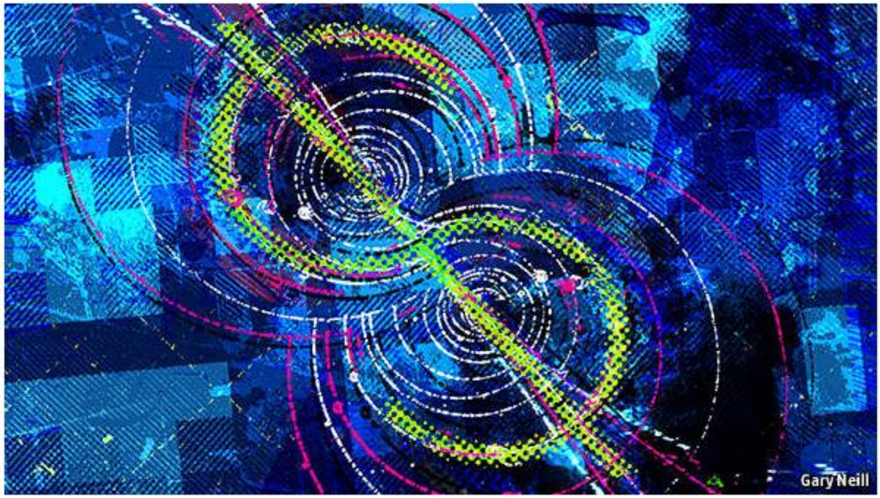
Particle physics

A new awakening?

Accelerators are getting bigger and more expensive. There may be a way to make them smaller and cheaper

Jan 31st 2015 | From the print edition

Timekeeper | Like 515 | Tweet 85



Gary Neill

nature International weekly journal of science

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Archive > Volume 526 > Issue 7572 > News > Article

NATURE | NEWS

CERN prepares to test revolutionary mini-accelerator

Machines that 'surf' particles on electric fiel

Elizabeth Gibney

07 October 2015

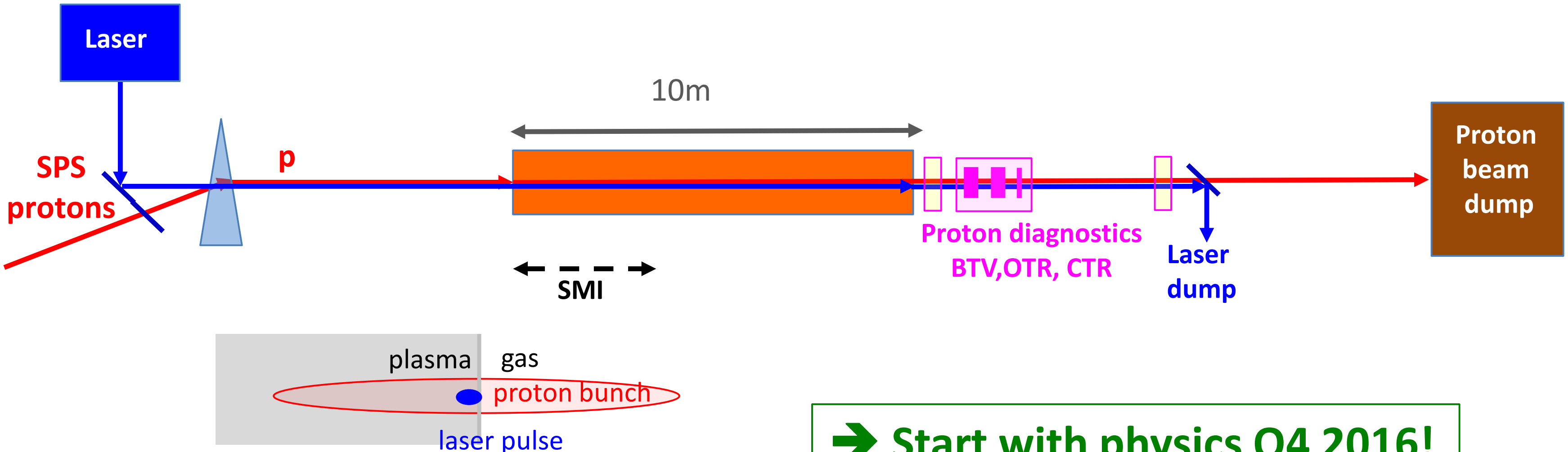
AWAKE: Platz 5 der SPIEGEL Bestsellerliste DVD (TV & Hobby)

SPIEGEL ONLINE KULTUR

Just kidding – but there was a Spiegel article!

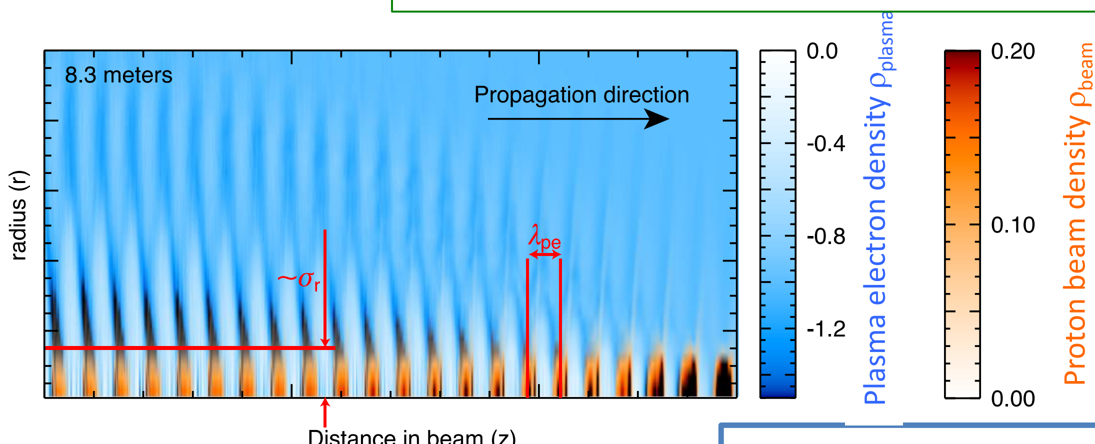
AWAKE: Experimental Program

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



➔ Start with physics Q4 2016!

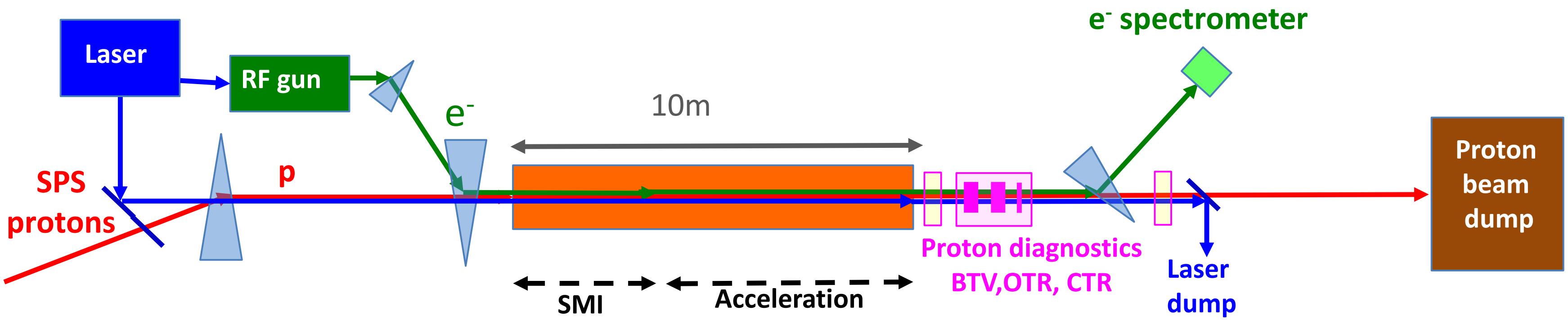
Self-modulated bunch resonantly driving plasma wakefields.

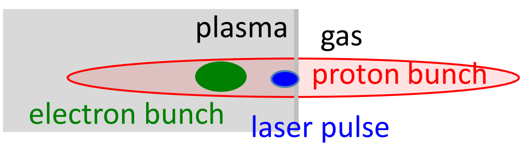


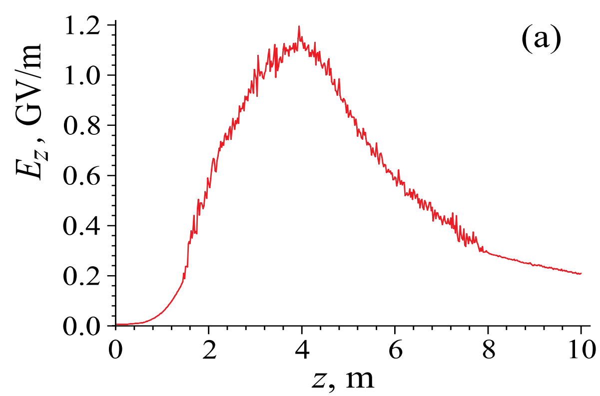
J. Vieira et al PoP 19063105 (2012)

AWAKE Experimental Program

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



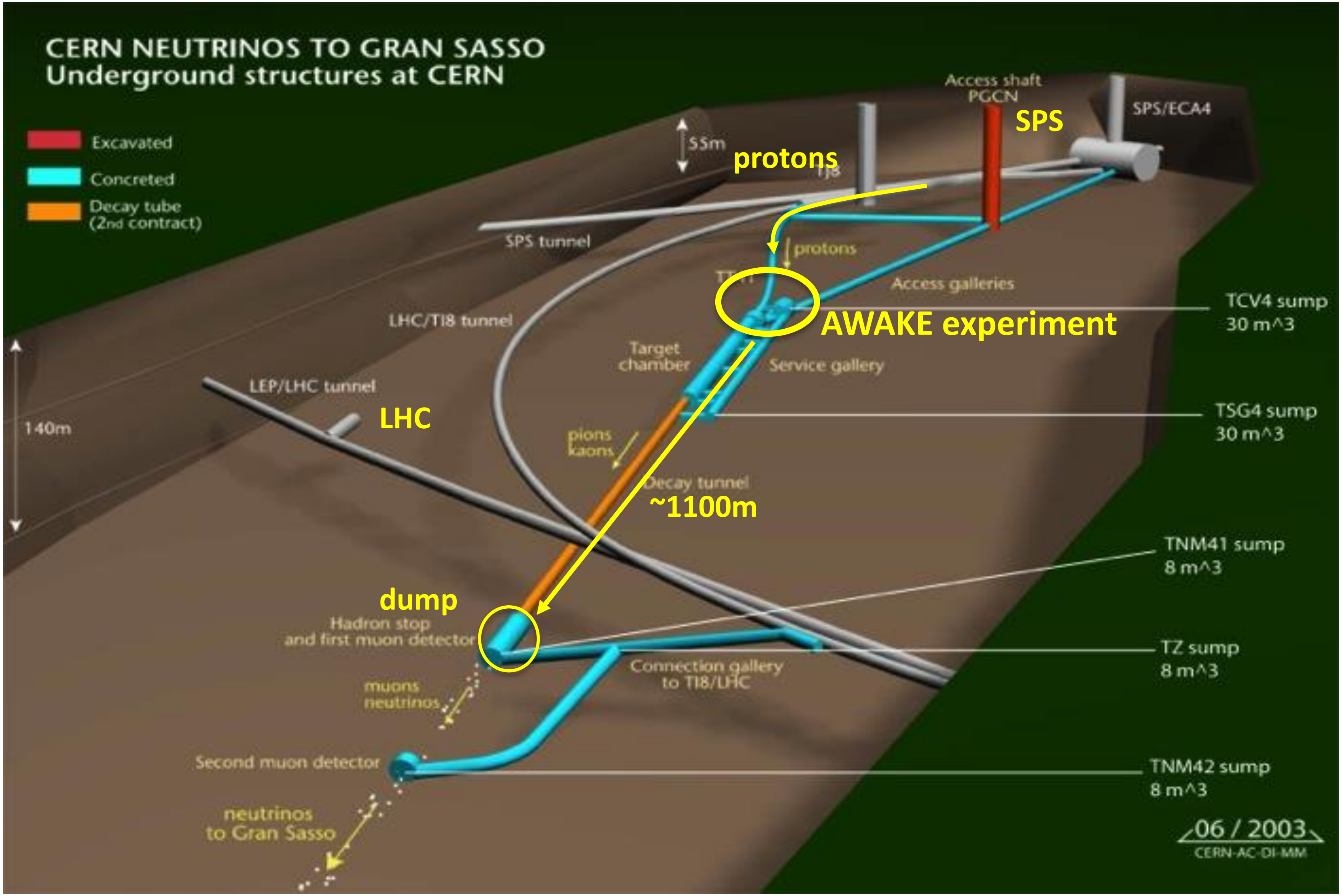




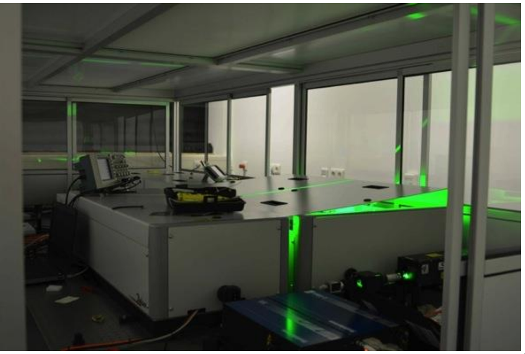
Demonstrate GeV scale gradients with proton driven wakefields.

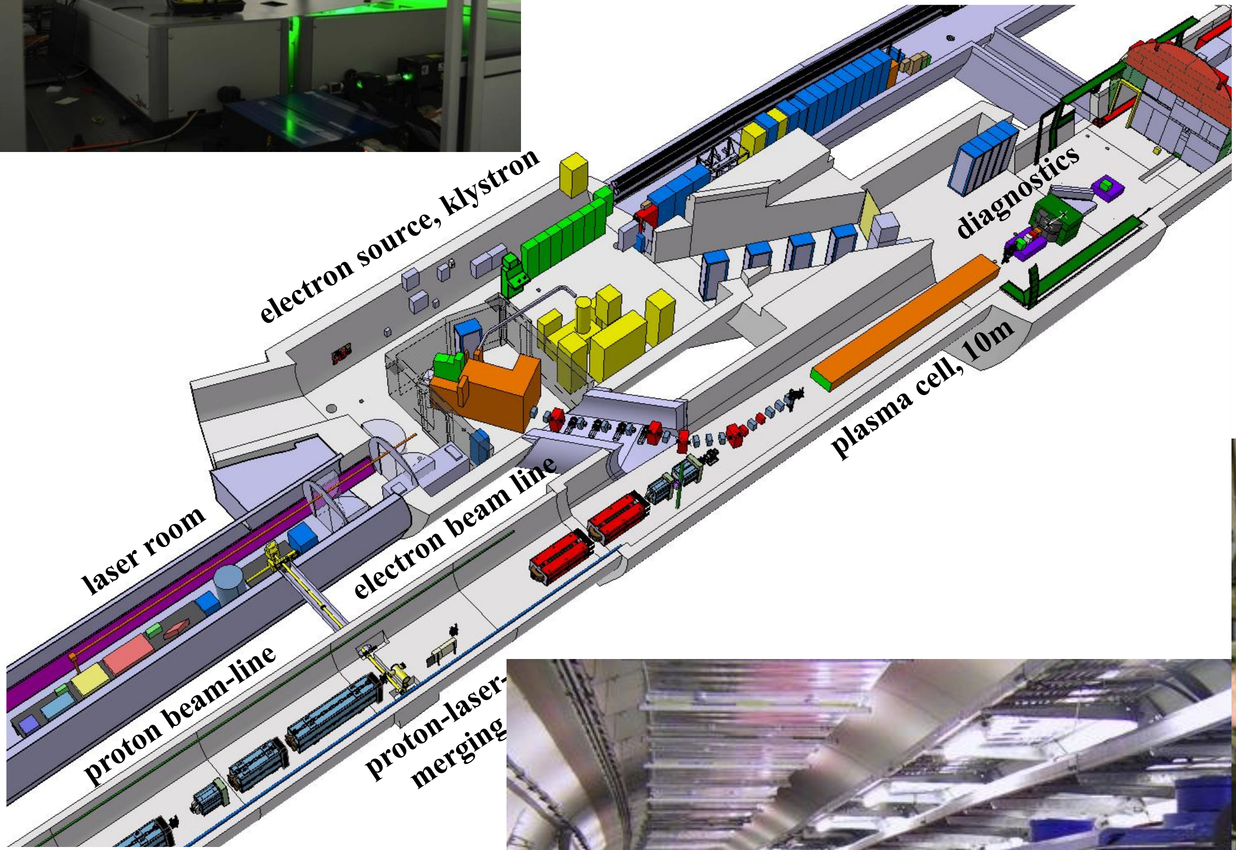
Maximum amplitude of the **accelerating field E_z** as a function of position along the plasma. Saturation of the SMI at ~4m.

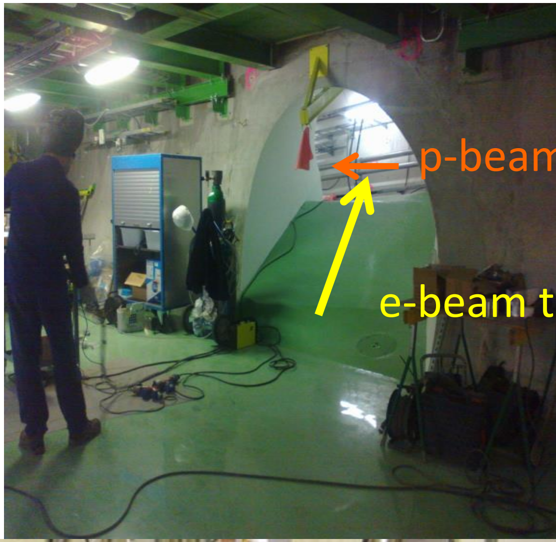
AWAKE Installation



AWAKE Overview

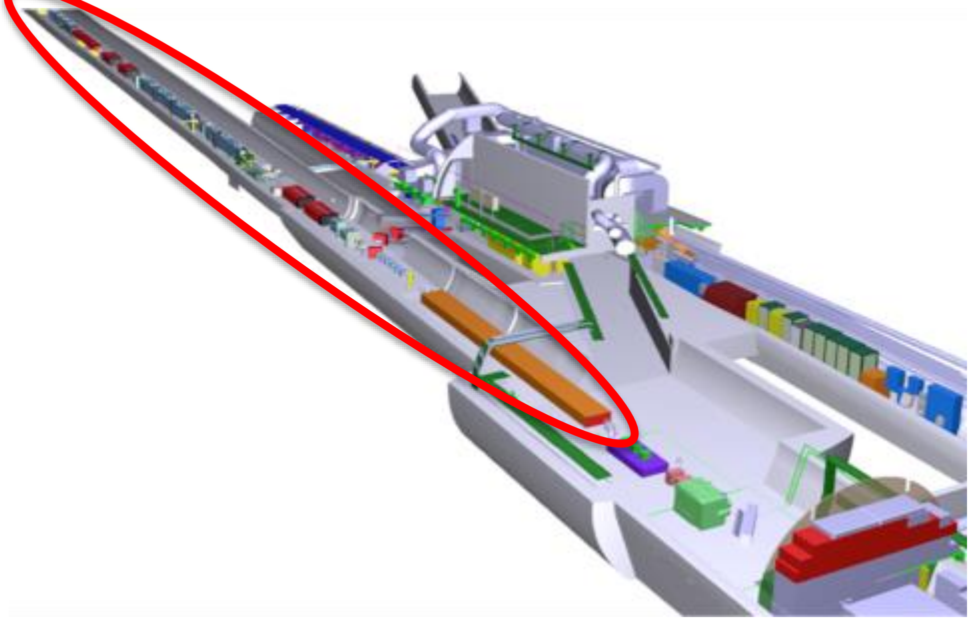




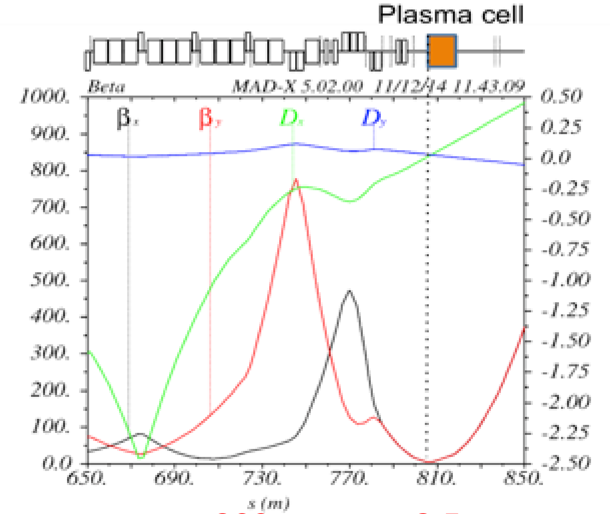


Proton Beam Line

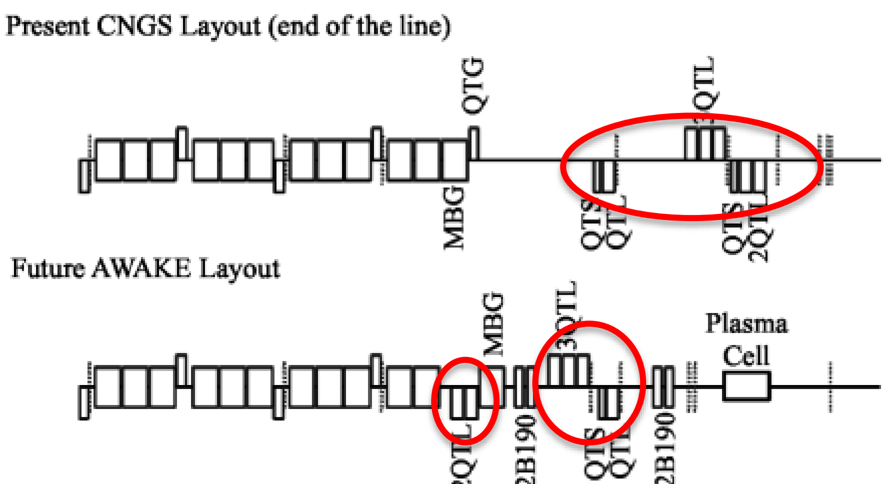
Proton beam line



Displace **existing CNGS magnets** of **final focusing** to fulfill optics requirements at the entrance of the plasma cell (**DONE** !)

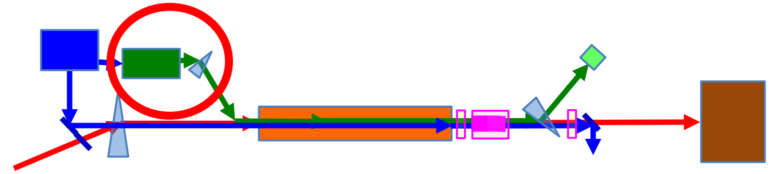


$\sigma_{x,y}$ = 200 µm, ε_n = 3.5 mm mrad



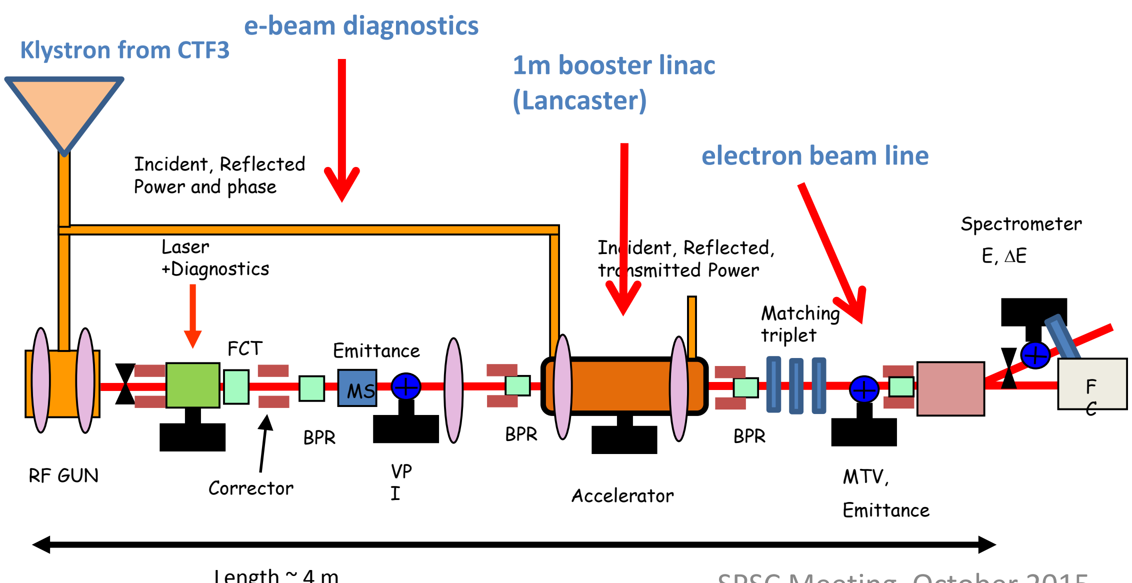
Electron Source

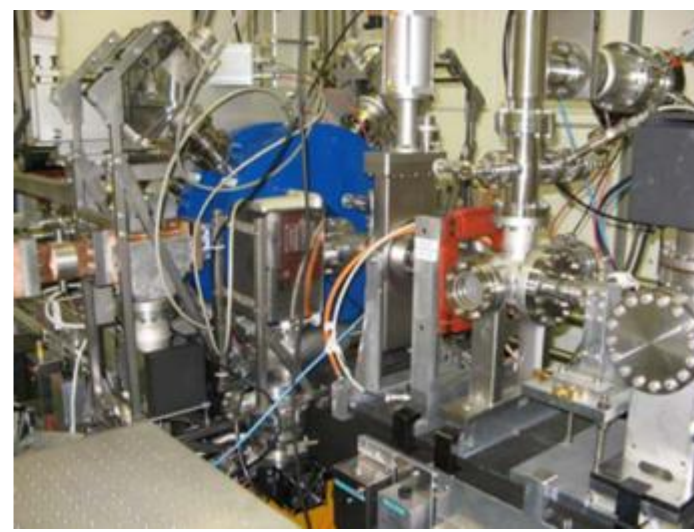
Electron beam for AWAKE	Baseline	Range for upgrade phase
Momentum	16 MeV/c	10-20 MeV
Electrons/bunch (bunch charge)	1.25 E9	0.6 – 6.25 E9
Bunch charge	0.2 nC	0.1 – 1 nC
Bunch length	σ_z =4ps (1.2mm)	0.3 – 10 ps
Bunch size at focus	$\sigma^*_{x,y}$ = 250 μm	0.25 – 1mm
Normalized emittance (r.m.s.)	2 mm mrad	0.5 – 5 mm mrad
Relative energy spread	$\Delta p/p$ = 0.5%	<0.5%



PHIN Photo-injector for CTF3/CLIC:

→ **Program will stop end 2015** ➔ Fits to requirements ➔ use for AWAKE

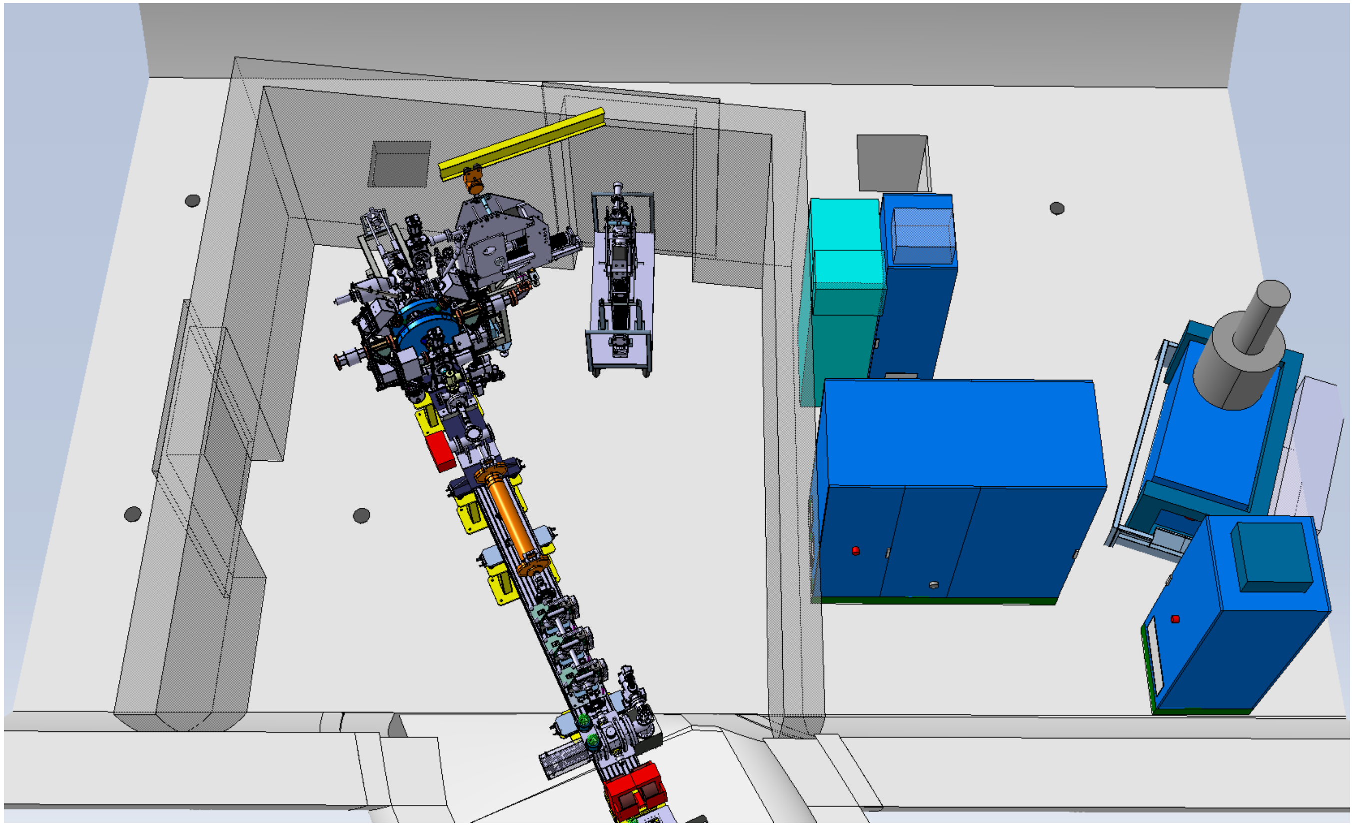




Electron Source

Challenging integration of the electron source

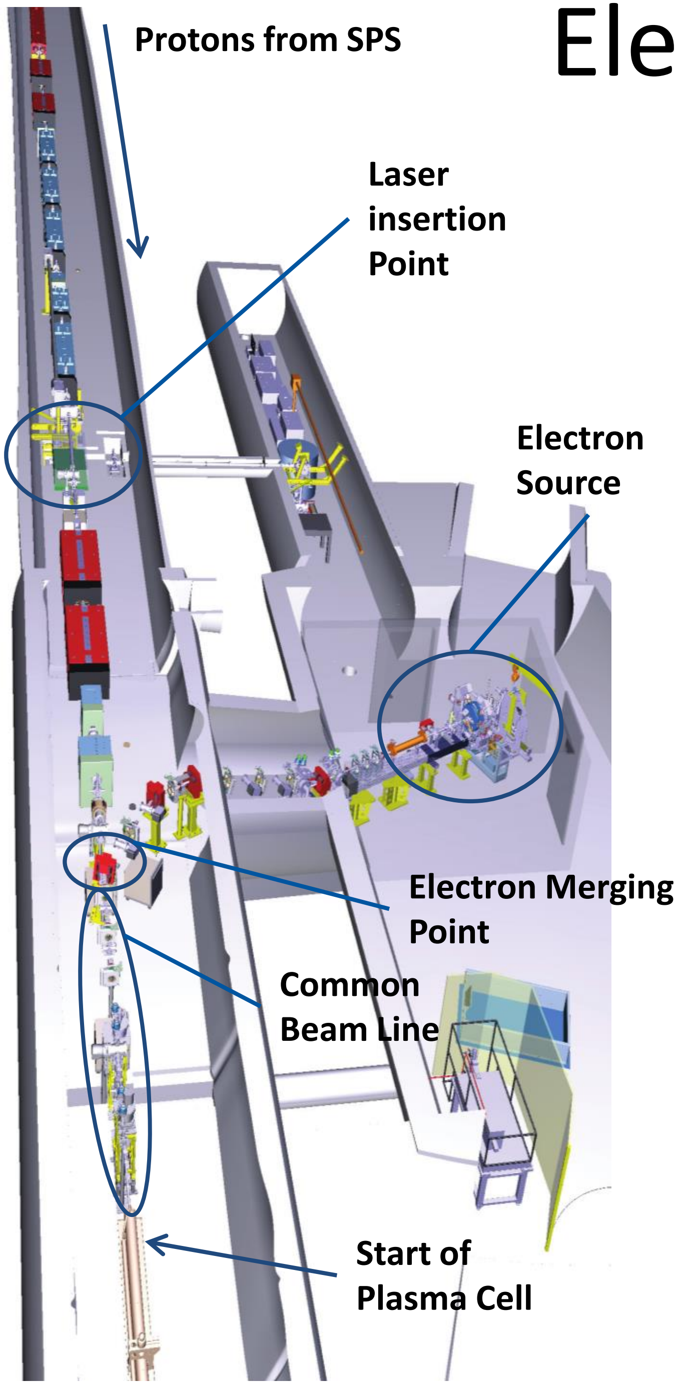
Use load lock cathode system to allow for different types of cathodes



Klystron

PHIN RF-gun

Electron Beam Line



Plasma Source

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

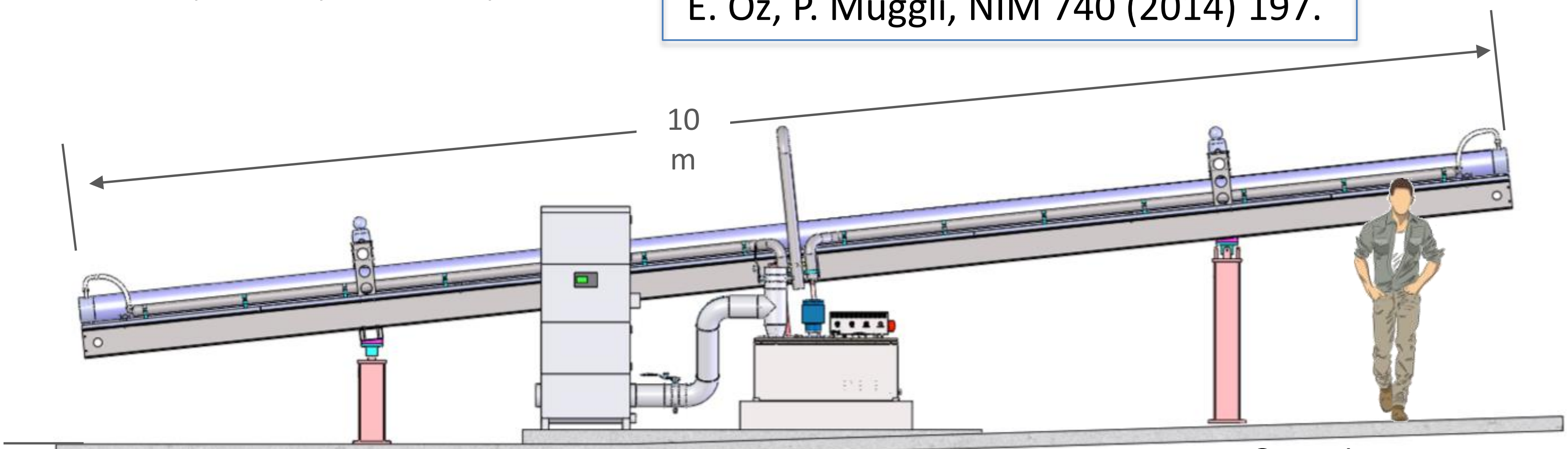
- Plasma formed by field ionization of Rb
  - Ionization potential Φ_{Rb} = 4.177eV
  - above intensity threshold (I_{ioniz} = 1.7 x 10^{12}W/cm^2) 100% is ionized.

- Plasma density = vapor density

- System is oil-heated ~ 200˚ C
  - → keep temperature uniformity
  - → Keep density uniformity

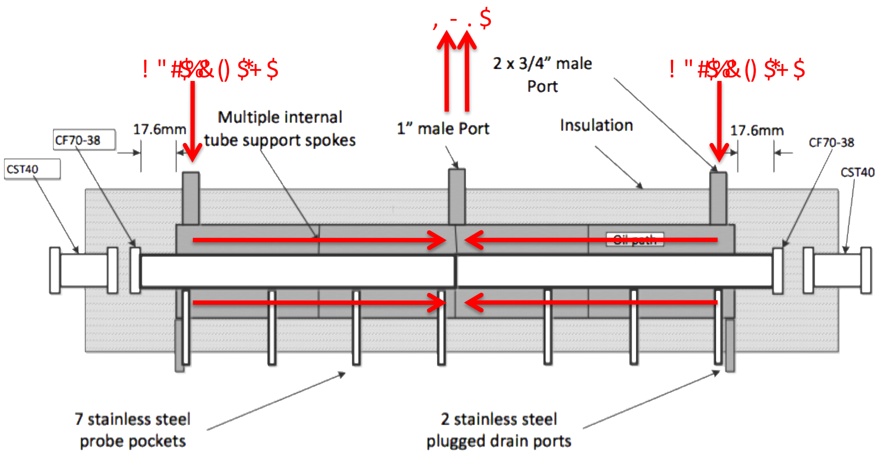
(2) 10m heat exchangers @ CERN

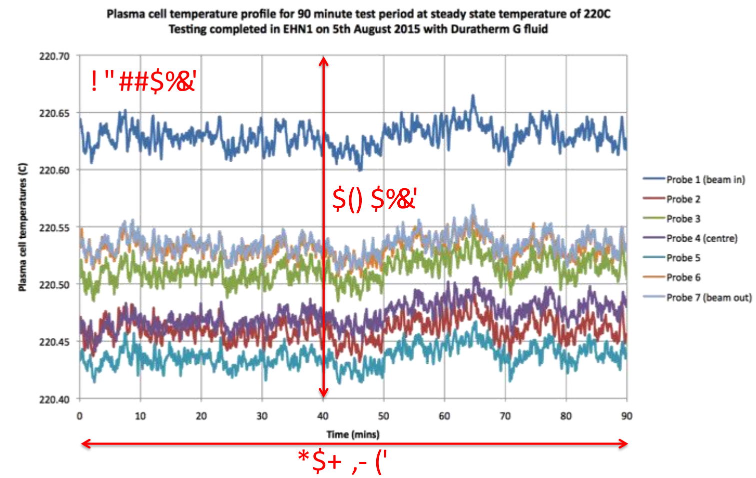
E. Öz, P. Muggli, NIM 740 (2014) 197.

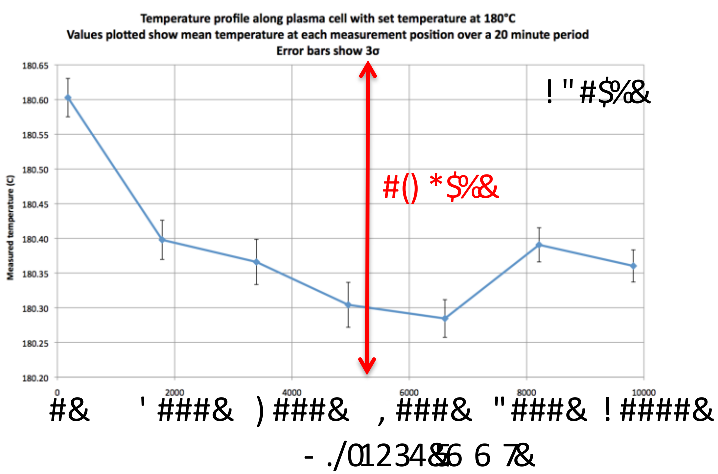


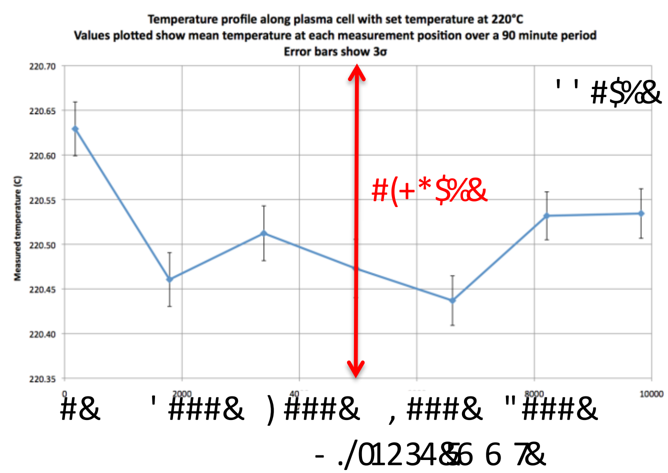
Grant Instruments

Plasma Source



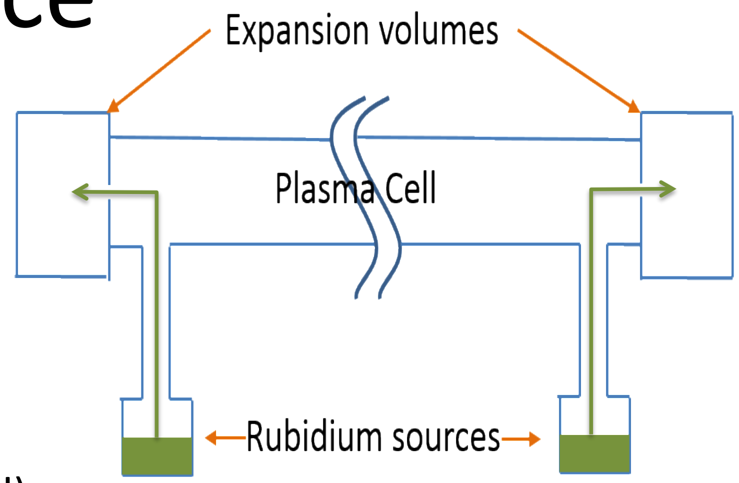






Heat exchanger satisfies (exceeds) all requirements !

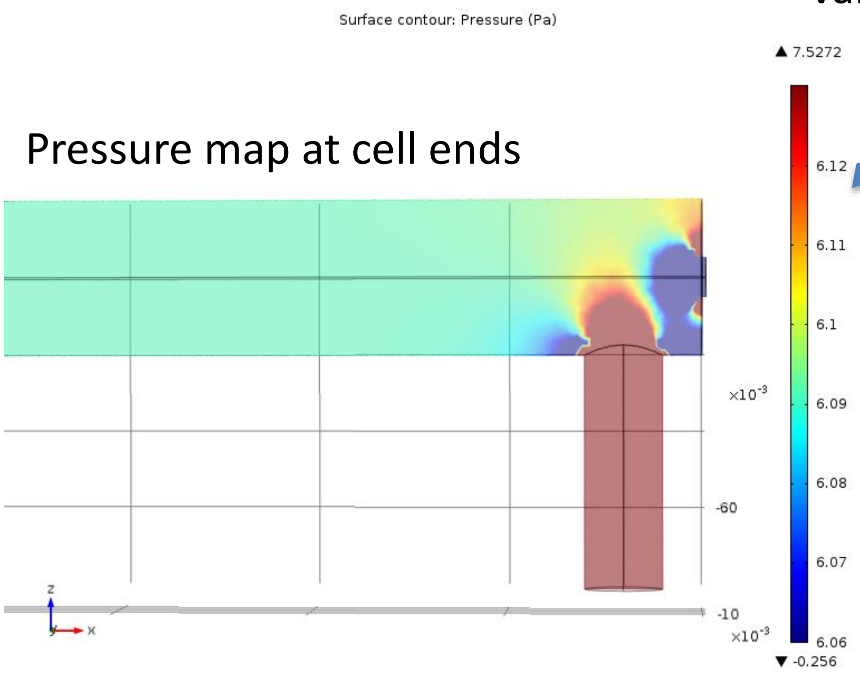
Plasma Source

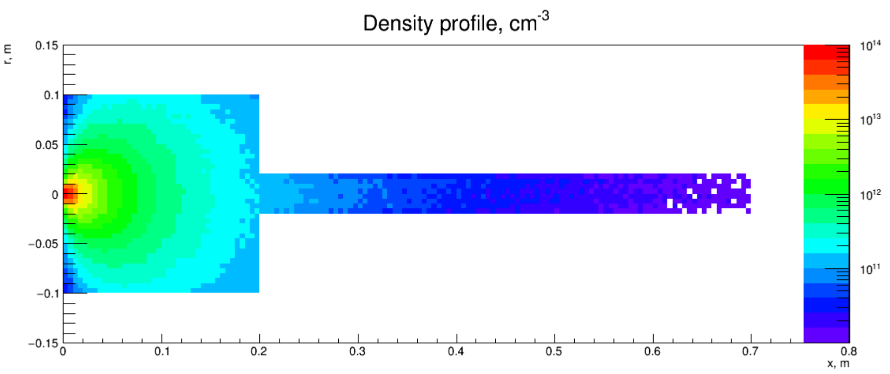


Revised solution for source ends
Valves resulted in long Rb density ramp and slow refill time.
New solution: continuous flow through small aperture
Result of intense brainstorming & simulation campaign

Note scale: small variations (<% level)

Pressure map at cell ends

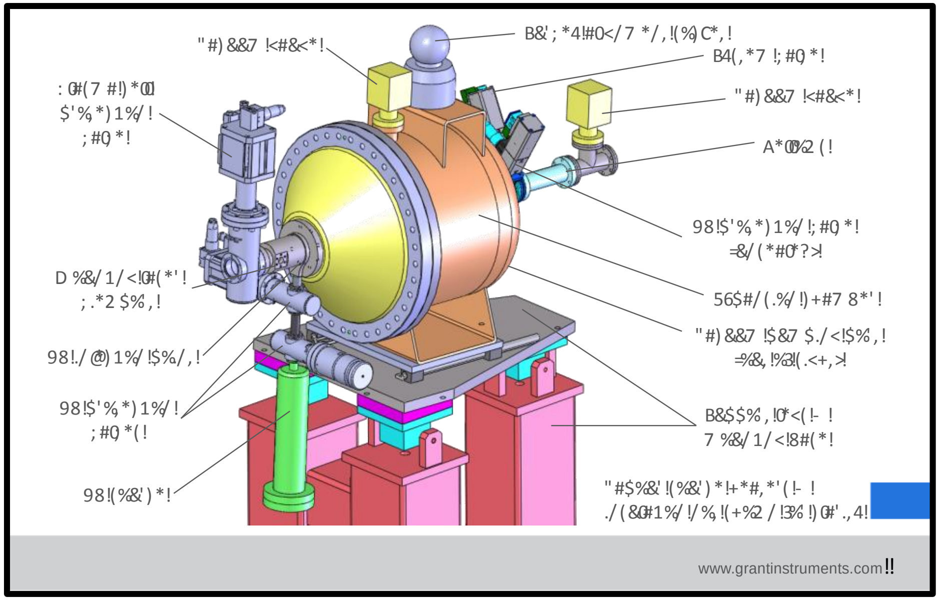


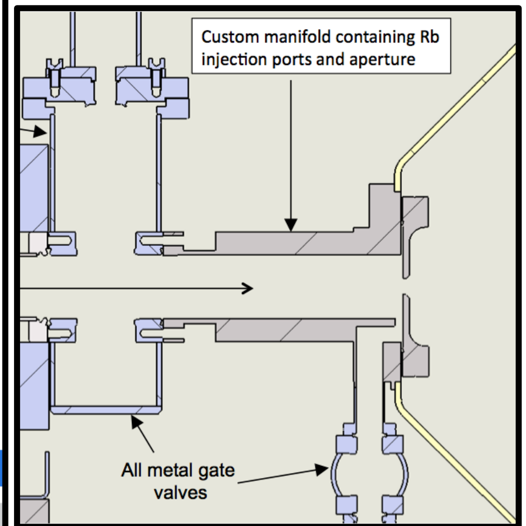


Where does the Rb go ?
Density profile after the aperture

Density drop-off on axis ~$1/x^2$;

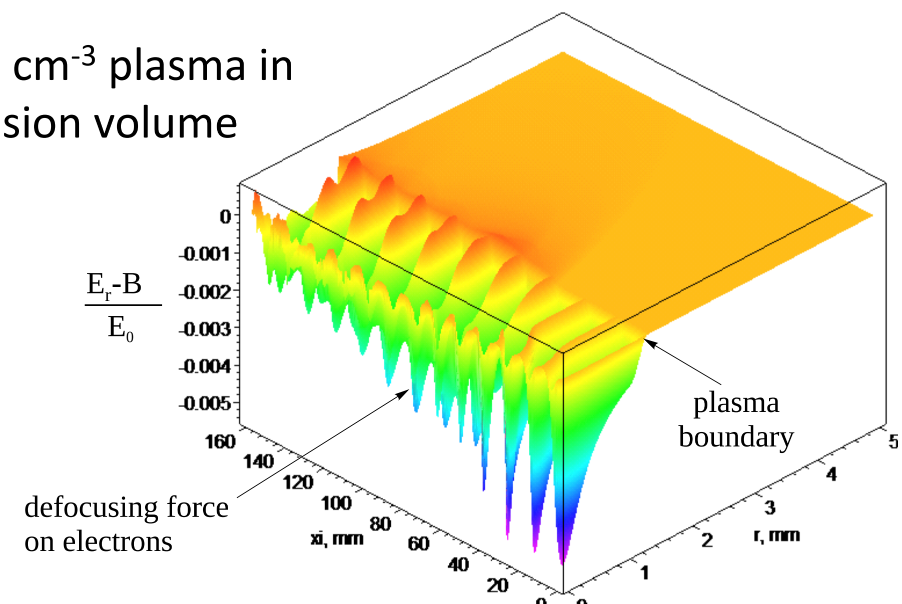
Plasma Source





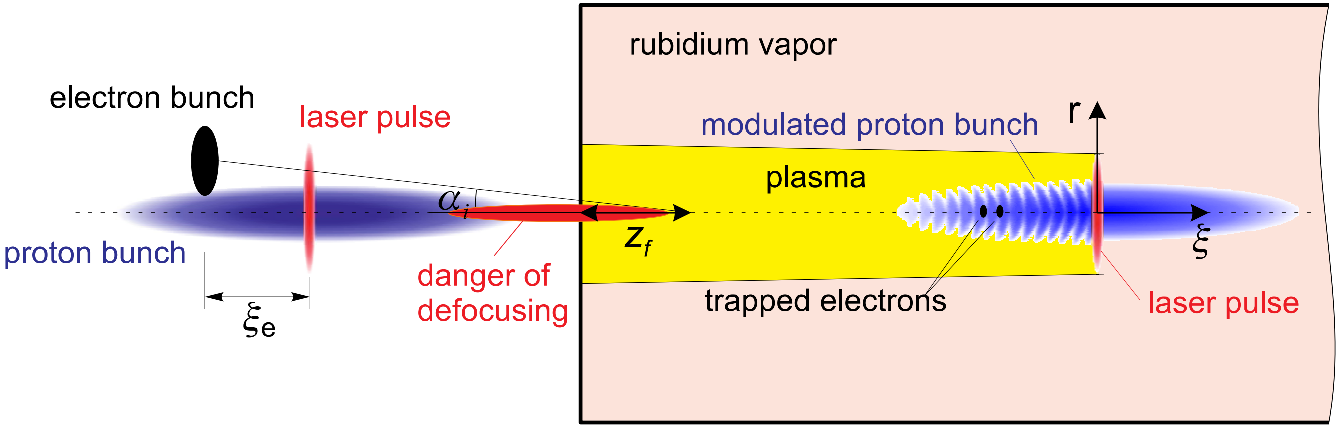
First design study completed. Working on detailed design and component tests

$4\ 10^{12}\ cm^{-3}$ plasma in expansion volume



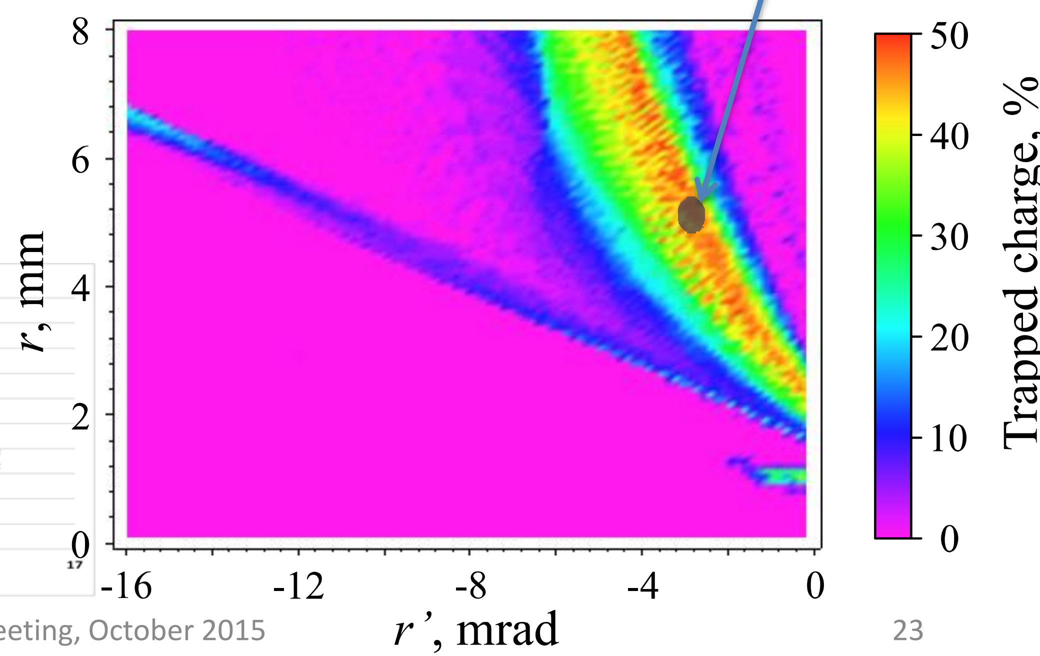
Want to stay outside low density plasma to avoid wakefields that defocus electrons

Plasma Source

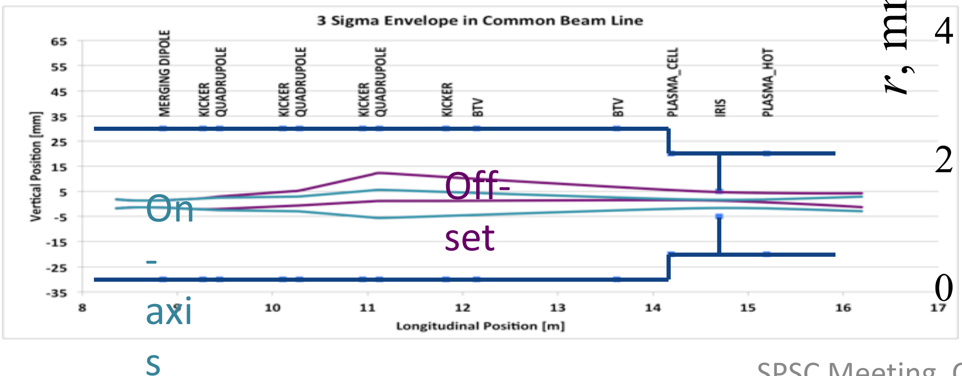


Simulations: oblique injection best for capture

Optimal injection

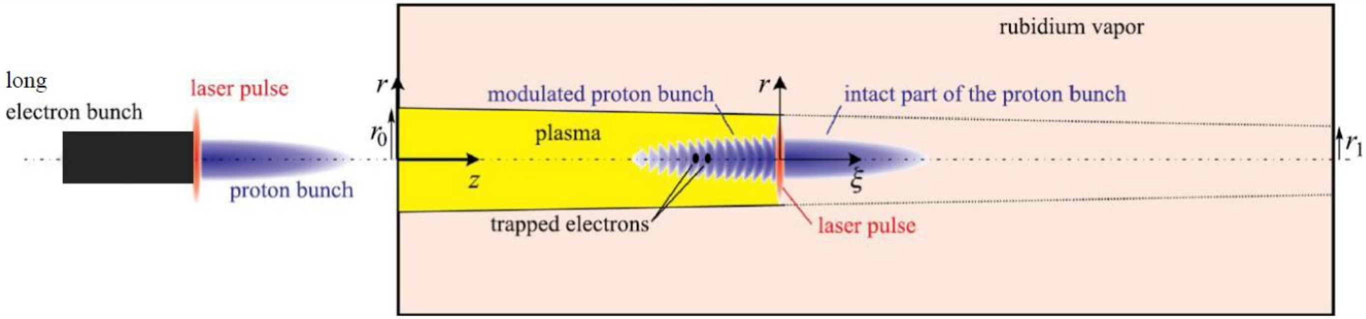


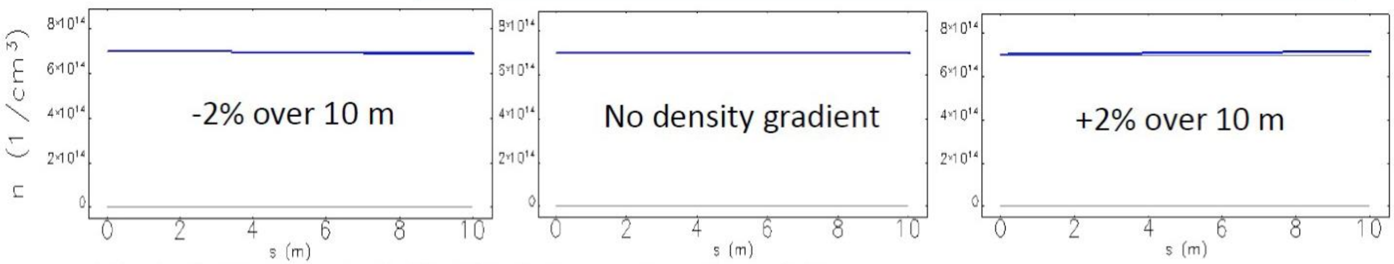
Electron source optics provide great flexibility in offset, angle, focus



Density & Energy Gain

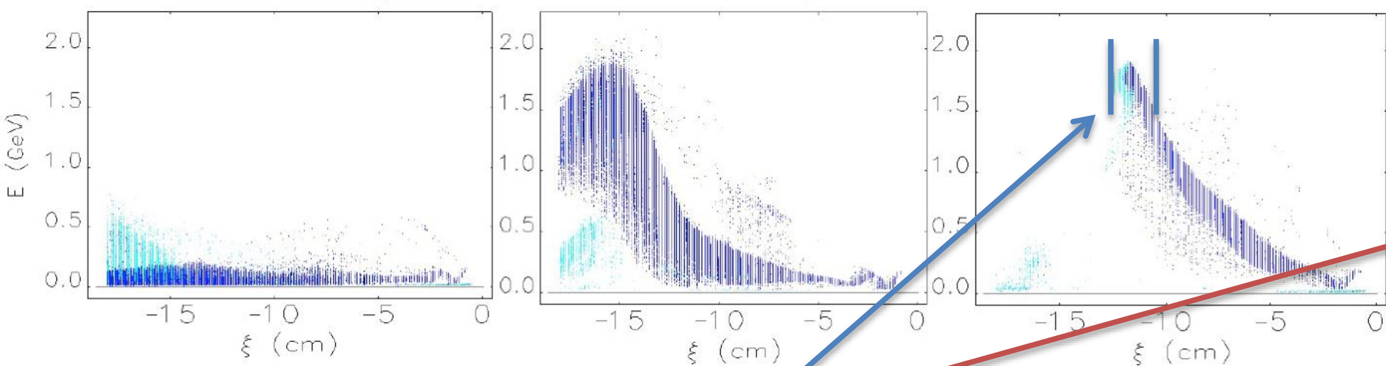
Design allows for density gradient along the 10m cell

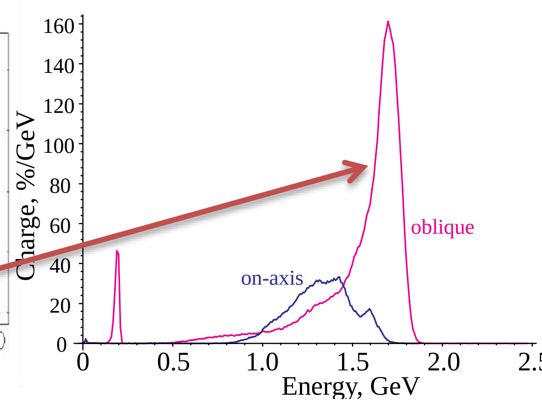




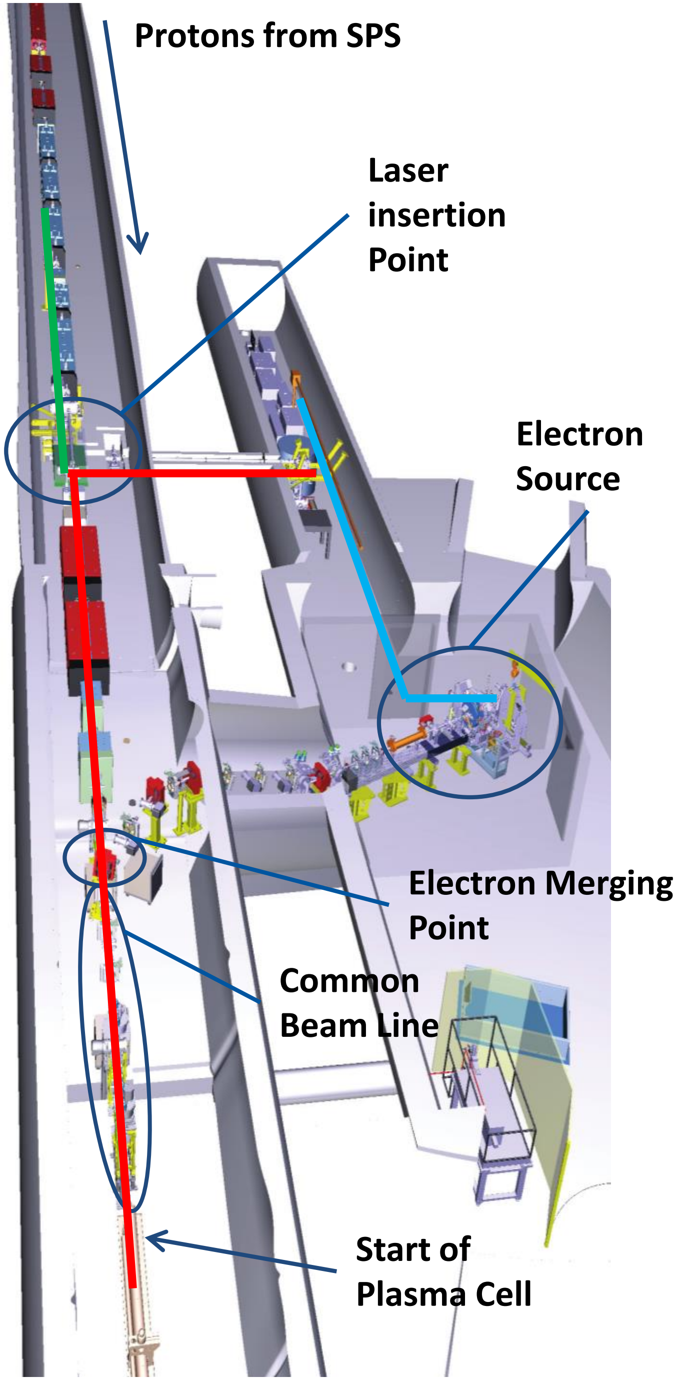
Best results expected for oblique injection with small density gradient; 40% of electrons trapped and accelerated.

Final electron energy distribution as a function of ξ:





Short injected bunch -> narrow energy spread



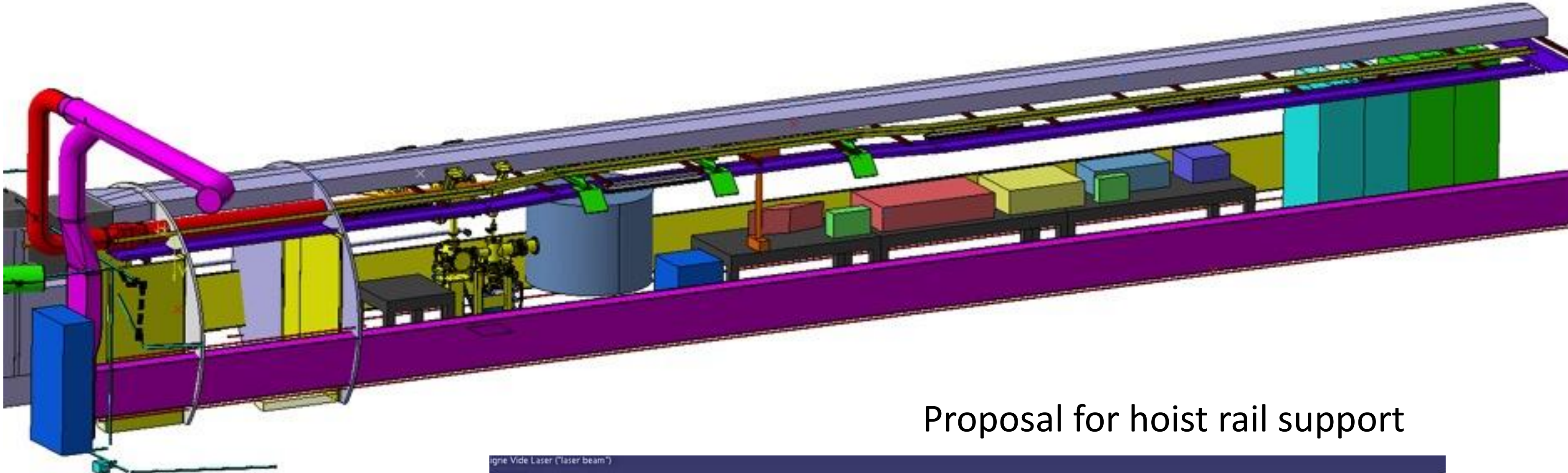
Laser Line

- **Laser beam line to plasma cell**
  - λ = 780 nm
  - t pulse = 100-120 fs
  - E = 450 mJ
- **Diagnostic beam line ("virtual plasma")**
  - λ = 780 nm
  - t pulse = 100-120 fs,
  - E ≈ 5 mJ
- **Laser beam line to electron gun**
  - λ = 260 nm
  - t pulse = 0.3-10 ps
  - E = 0.5 mJ

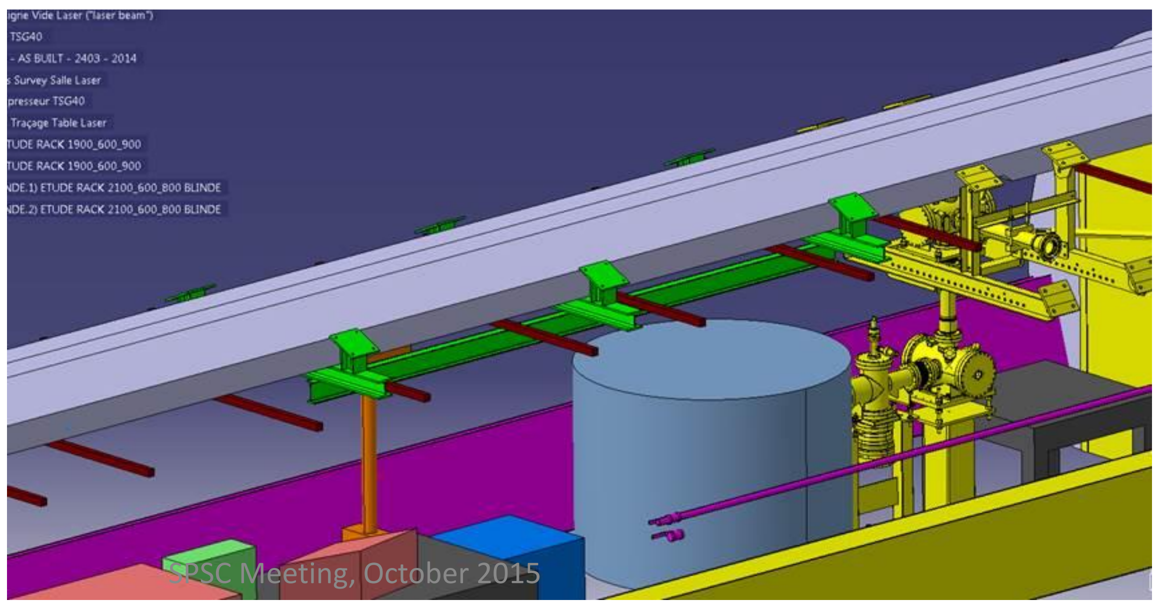
Laser Integration

Racks for laser control and RF equipment

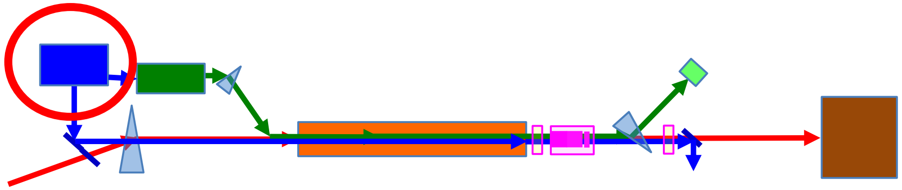
Latest version of laser room integration

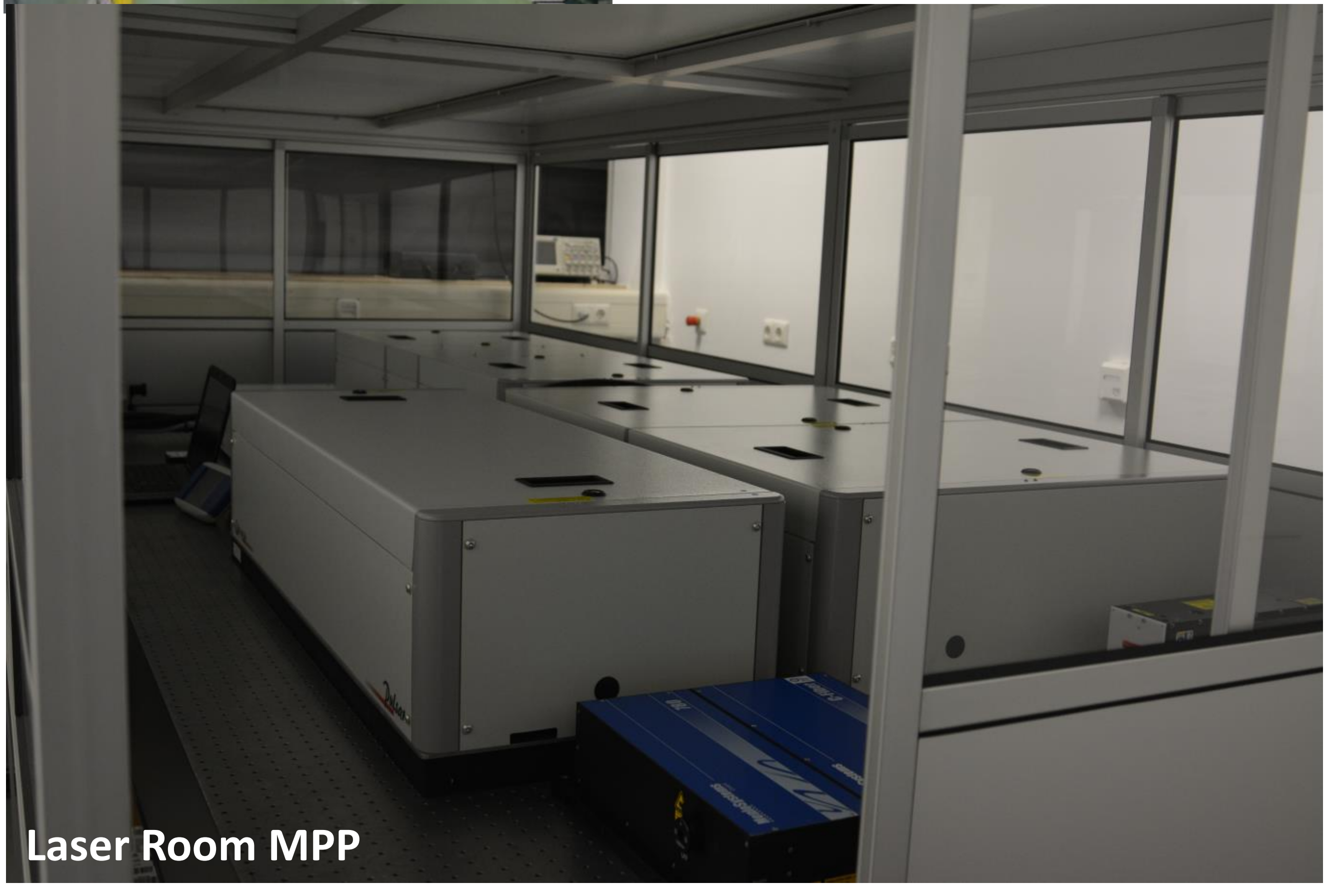


Proposal for hoist rail support



Laser

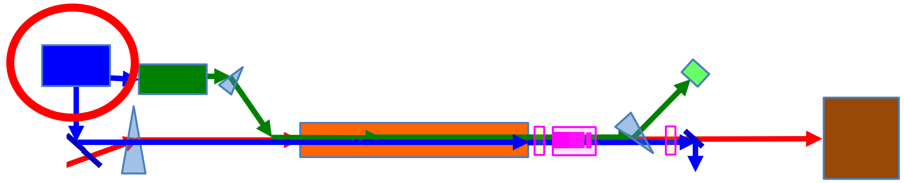




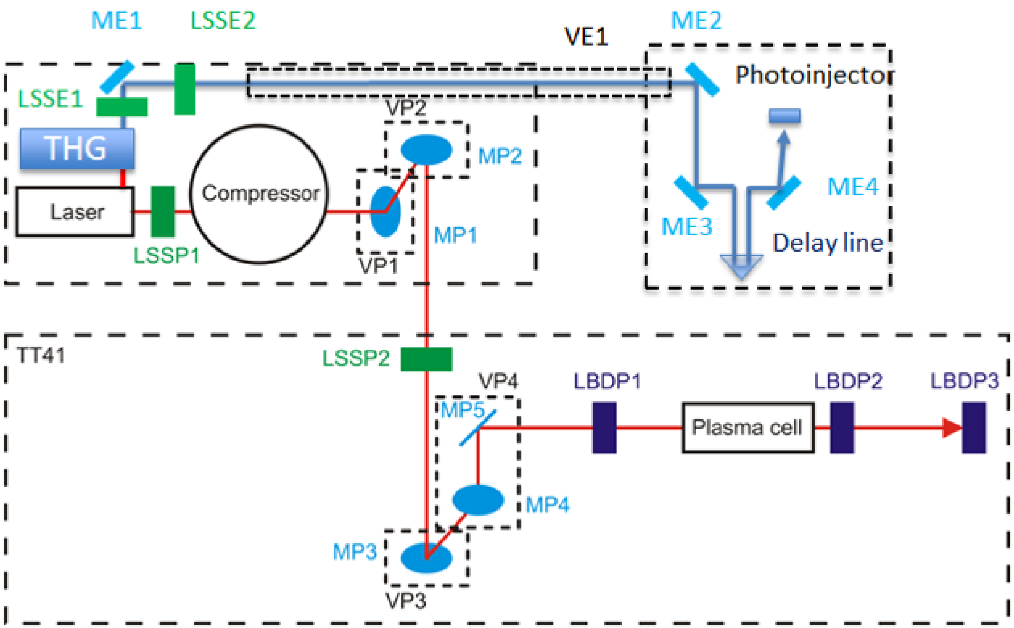
Laser Beam	
Laser type	Fiber Ti:Sapphire
Pulse wavelength	λ_0 = 780 nm
Pulse length	100-120 fs
Pulse energy (after compr.)	**450 mJ**
Laser power	**4.5 TW**
Focused laser size	$\sigma_{x,y}$ **= 1 mm**
Rayleigh length Z_R	5 m
Energy stability	±1.5% r.m.s.
Repetition rate	10 Hz

Laser installed & operating at MPP since fall 2014. Will move to CERN early 2016.

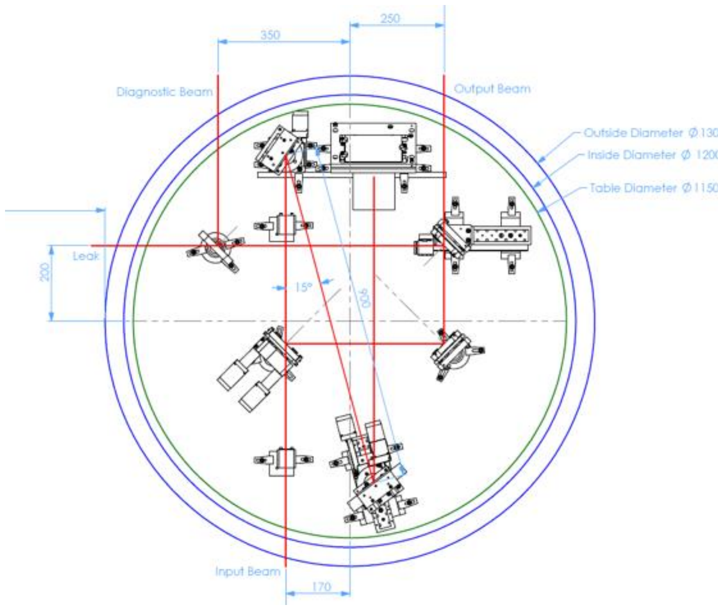
Laser



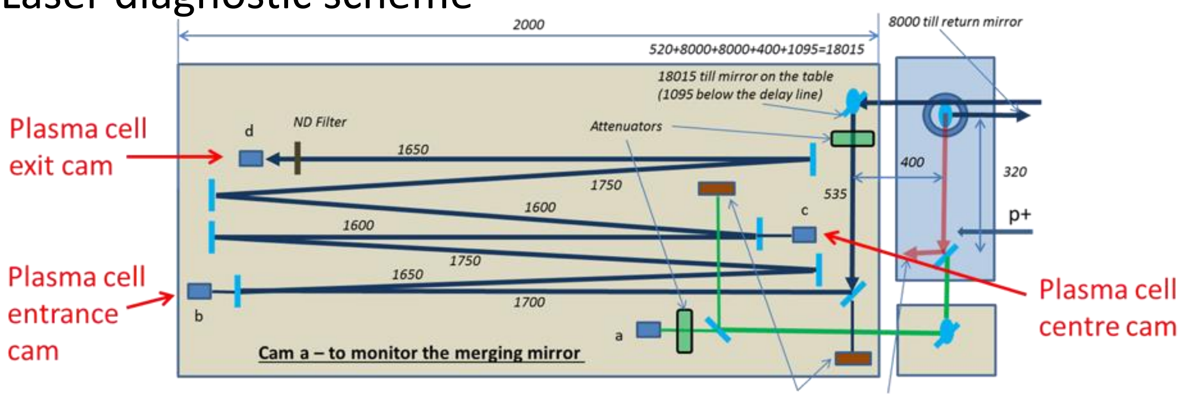
Laser overview



Compressor optics

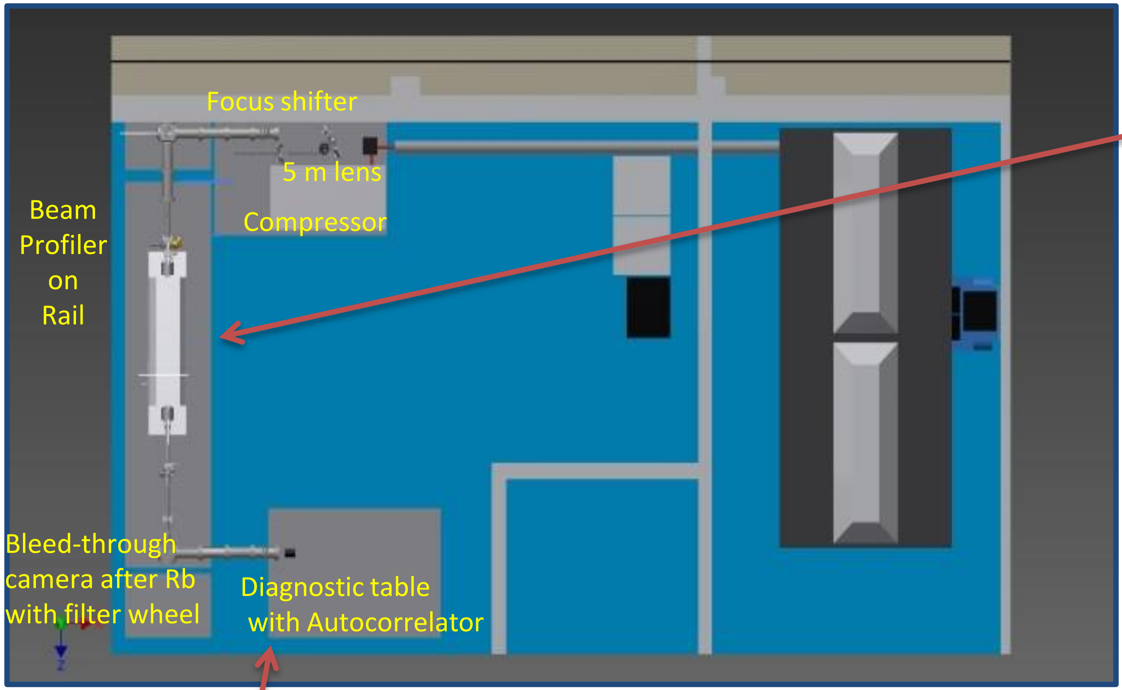


Laser diagnostic scheme



Compressor design finalized and ordered summer 2015; will be installed early 2016

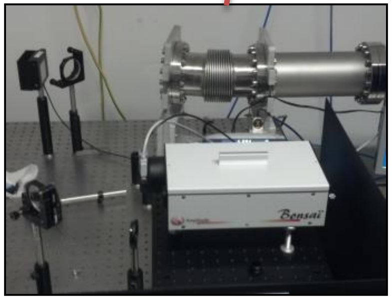
Laser Lab MPP



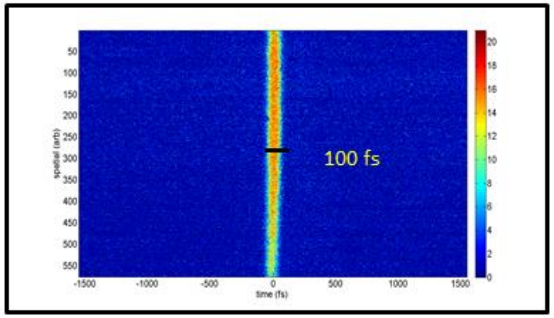
Heat pipe oven

The laser has been operated at the Max Planck Institute with a Rb vapor cell (heat pipe oven)

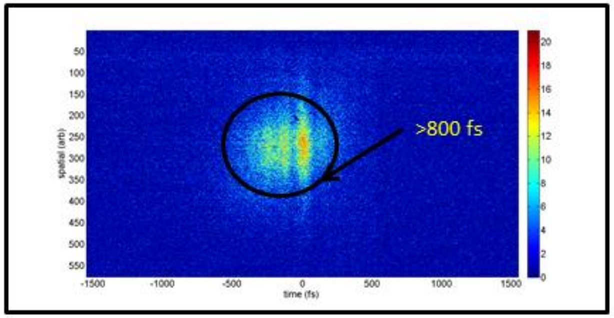
First plasmas seen, results encouraging !



Pulse propagation tests:



Autocorrelation image with focusing

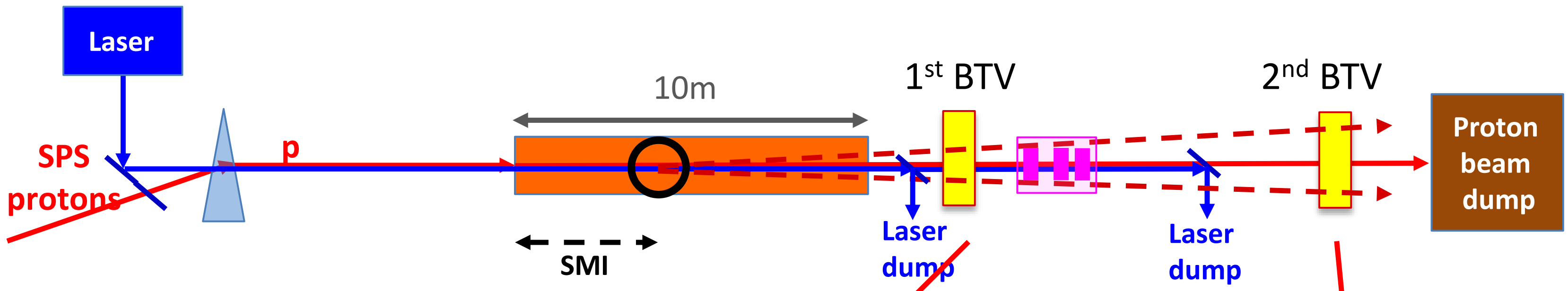


Autocorrelation image no focusing

Indirect Measurement of SMI

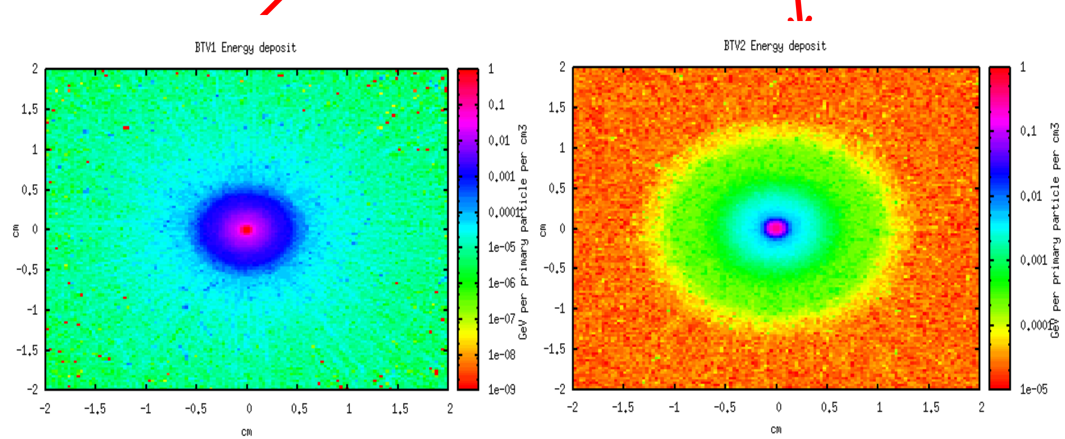
SMI causes angular divergence of the proton beam ofthe order of ~1 mrad.

→ Measure bunch profile at two different scintillator screens at a distance of ~8m.



Measure saturation point of SMI

Growth of tails governed by the transverse fields in the plasma. Will give indication of strong plasma wakefields.



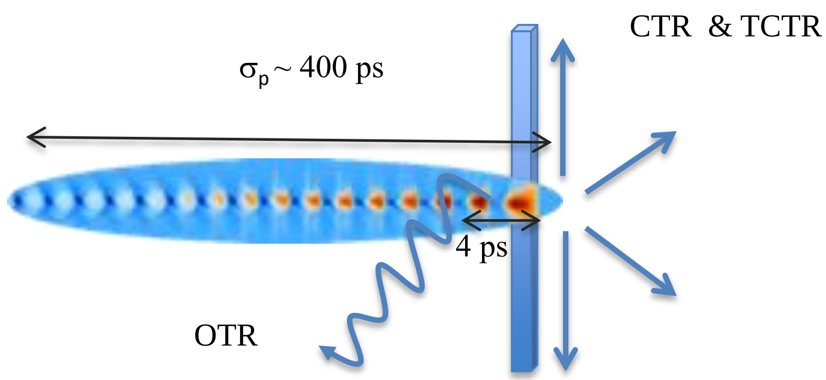
Direct Measurement of SMI

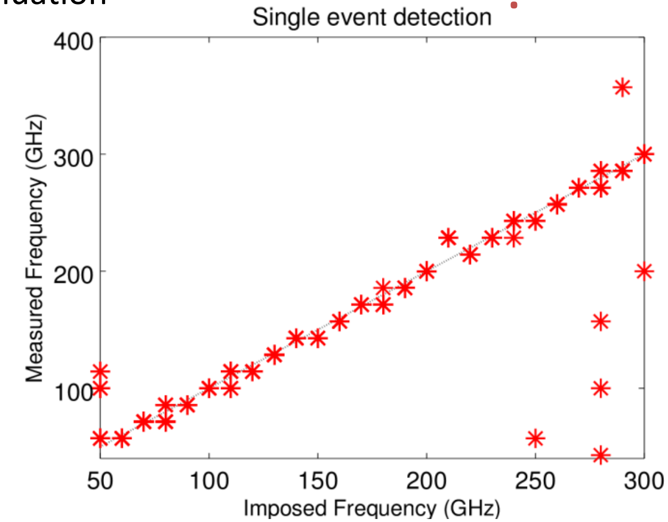
Measure radiation emitted by the bunch when traversing a dielectric interface

Optical Transition Radiation → streak-camera

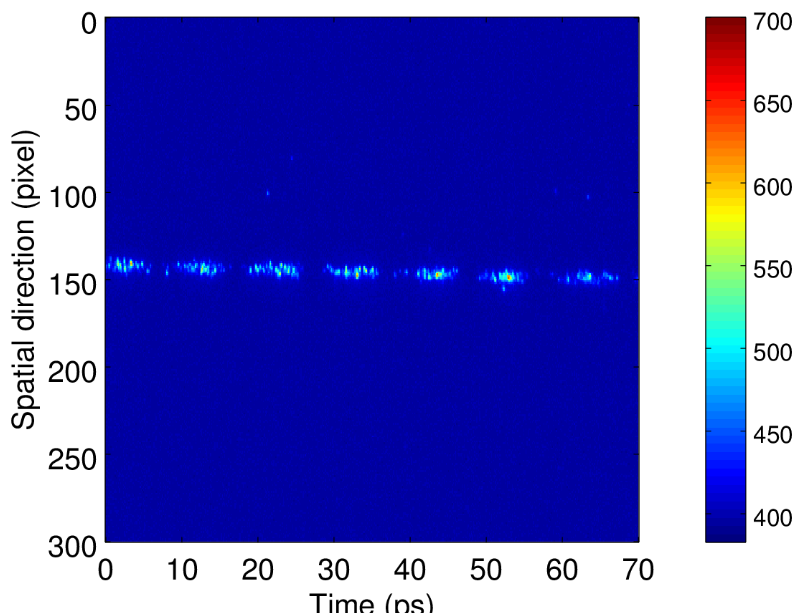
Coherent Transition Radiation → variety of techniques under evaluation

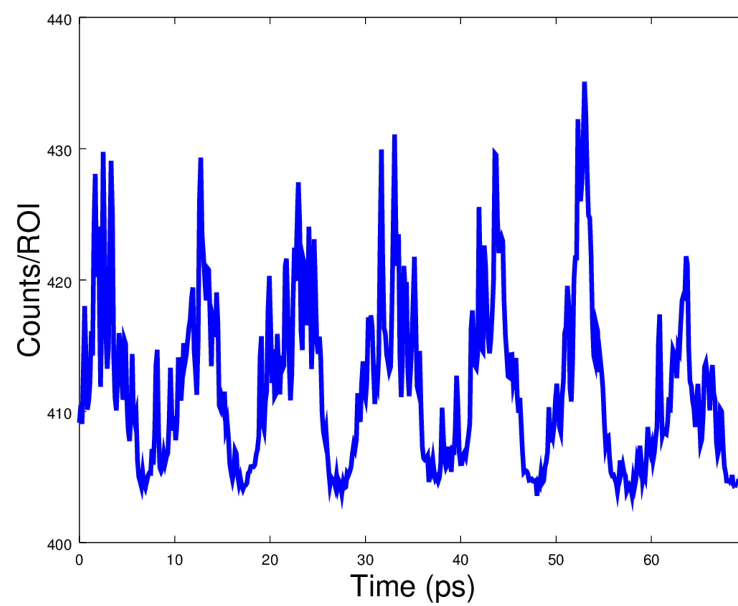
Will work single s
!





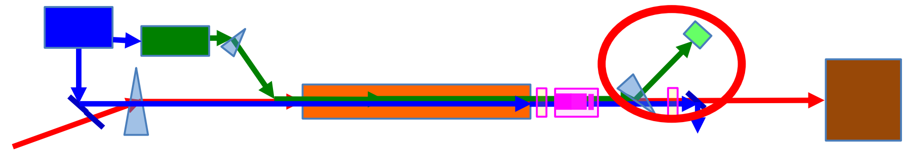
Simulated 100 GHz OTR signal in lab @ MPP





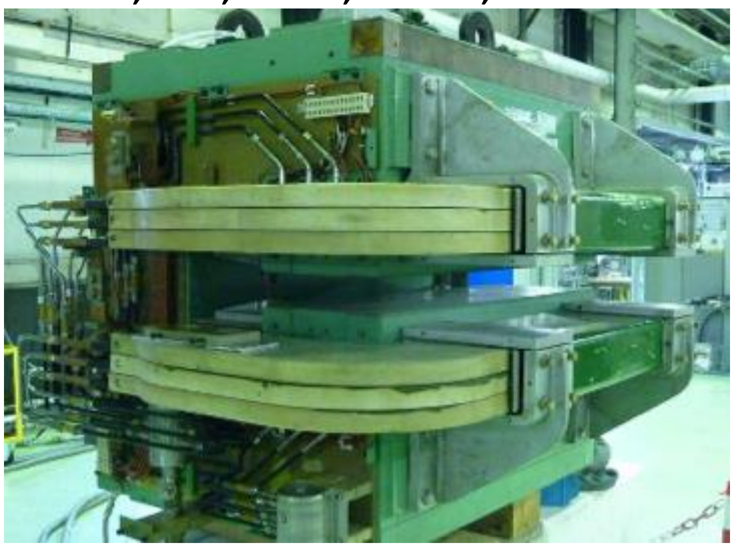
Electron Beam Diagnostics

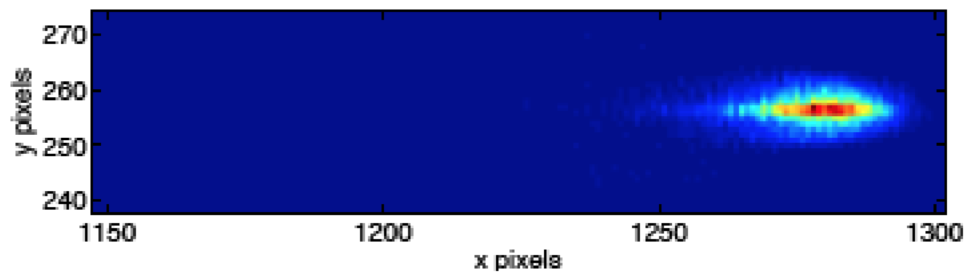
Probe the accelerating wakefields with externally injected electrons → Electron spectrometer

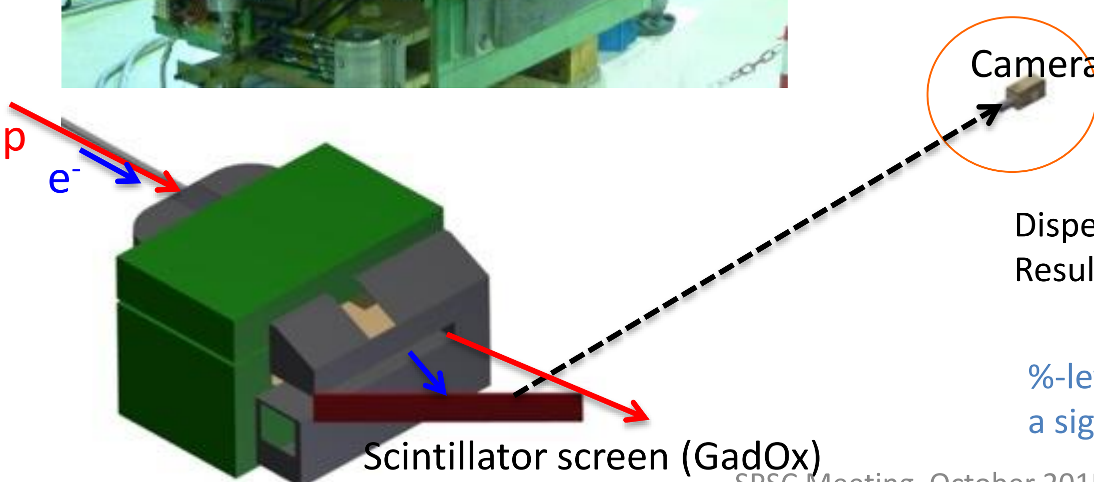


Revised magnet choice since SPSC 2014

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





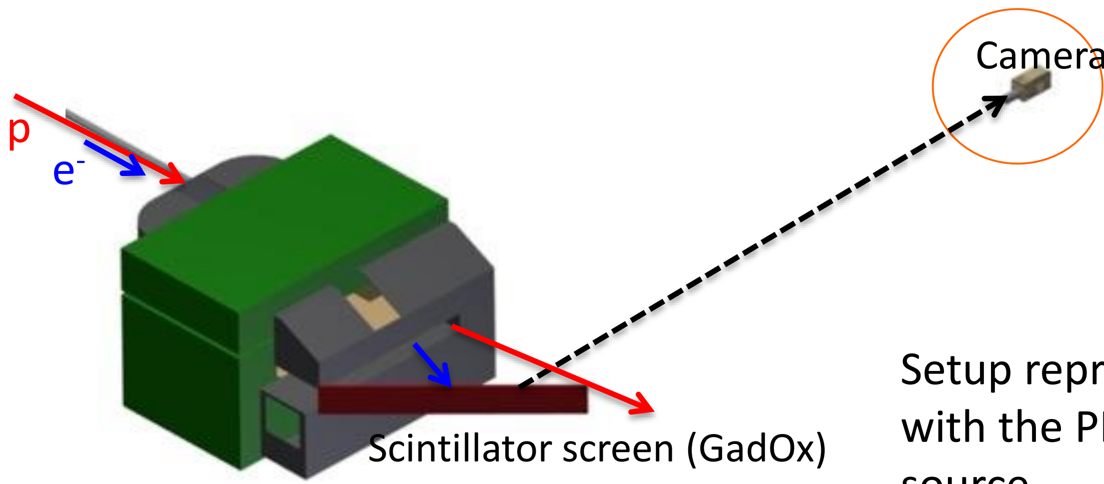


Simulation campaign undertaken to

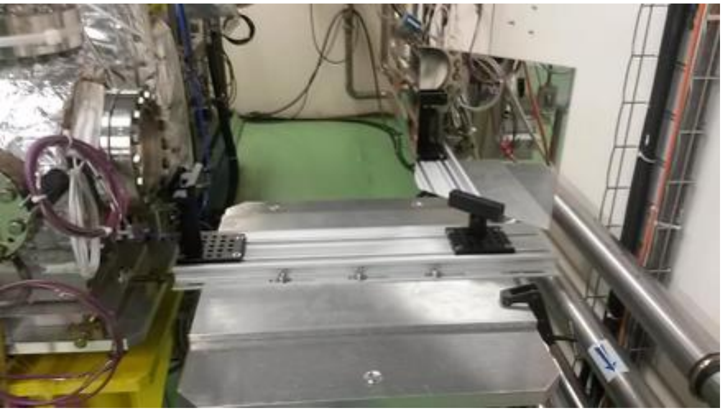
Dispersed electron impact on scintillator screen.
Resulting light collected with intensified CCD camera.

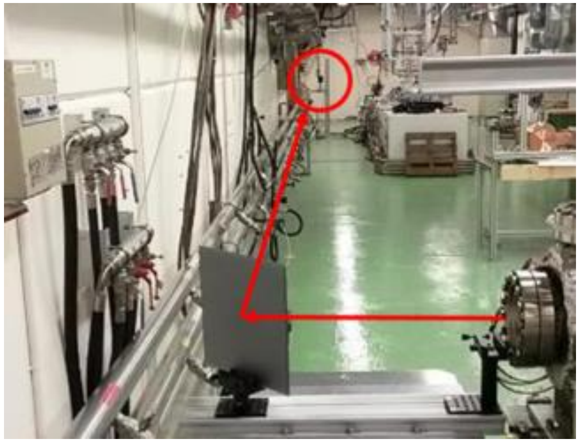
%-level energy resolution can be achieved with a signal to noise ratio larger than 1000:1

Electron Acceleration Diagnostics



Setup reproduced in CTF3 with the PHIN electron source.

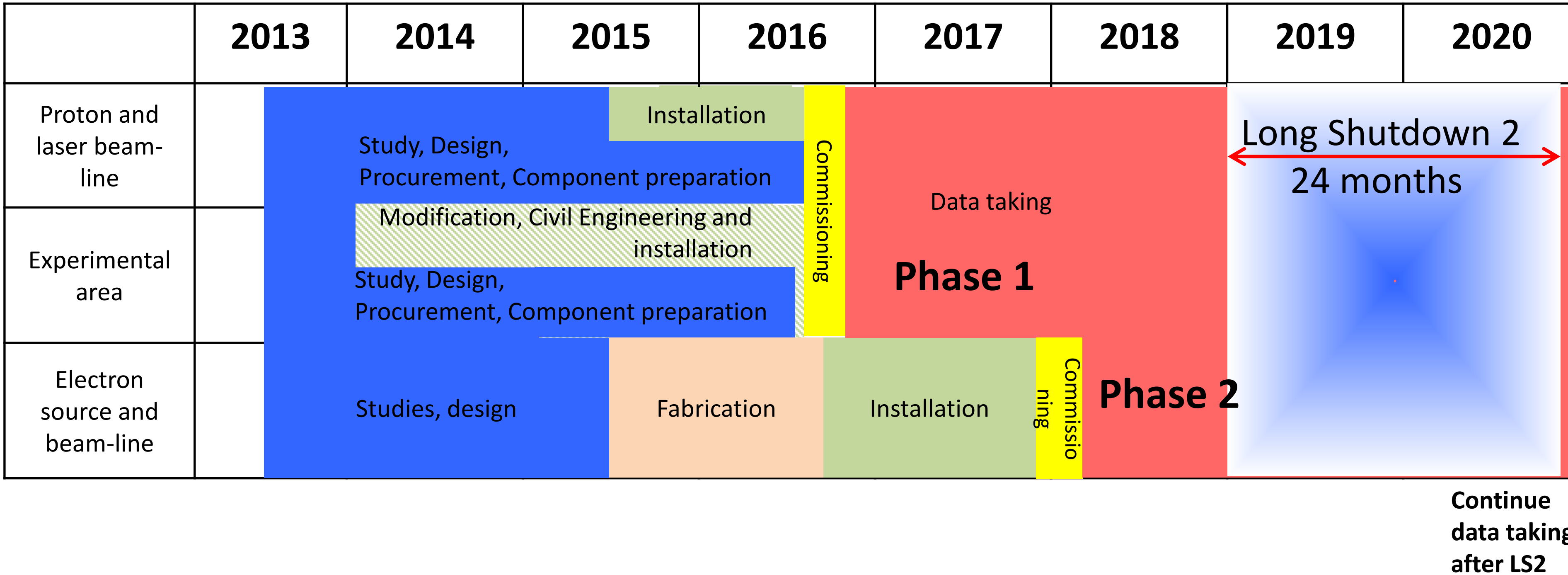




Full length of light transport reproduced.

Confirmed expectation of large signal/noise for electron spectrometer

AWAKE Time Line

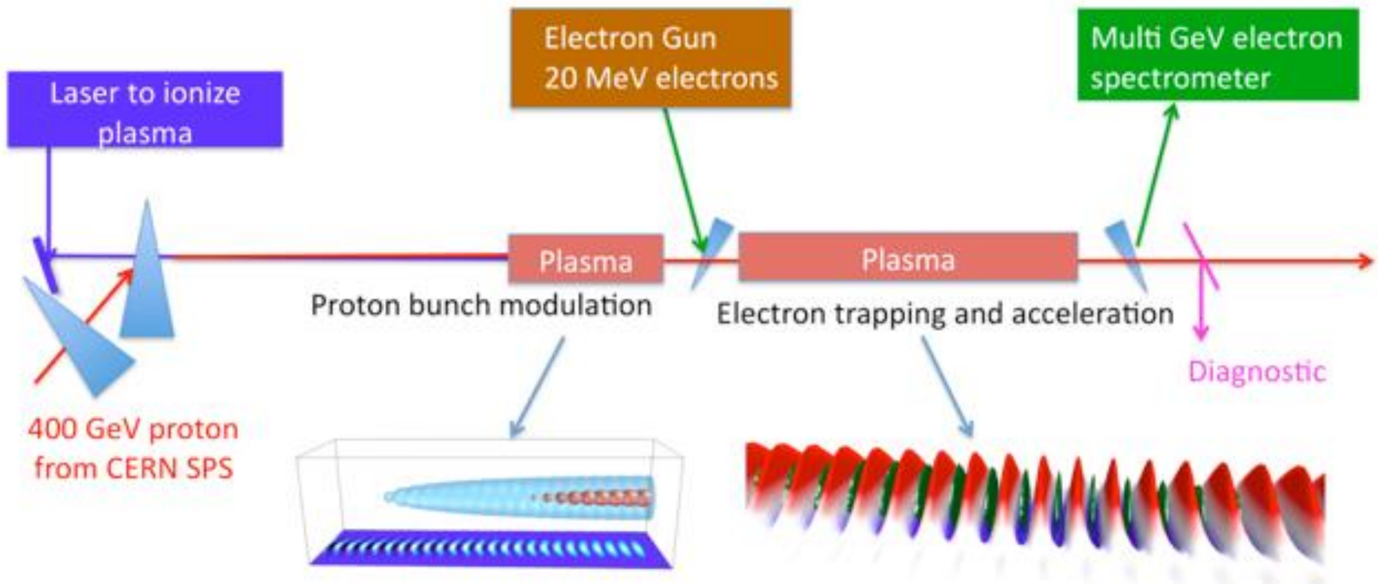


Run request:

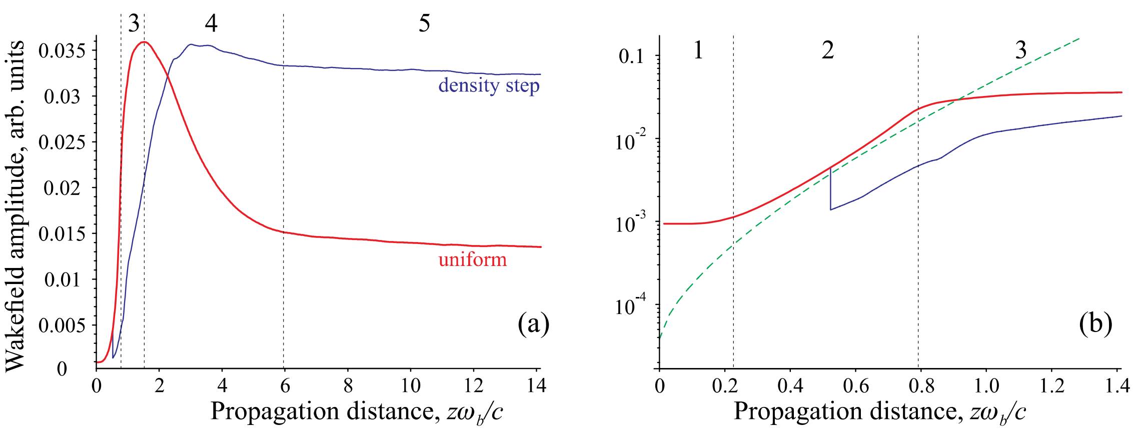
2016: equivalent of 4 weeks continuous running, but upon demand: 2.4 10^{16} protons
+ some running in the summer for proton beam commissioning

2017: equivalent of 8 weeks continuous running, but upon demand: 4.8 10^{16} protons

PHASE 3



- **Split-cell mode**: SMI in 1st plasma cell, acceleration in 2nd one.
- New scalable uniform plasma cells (helicon or discharge plasma cell)
- Step in the plasma density → maintains the peak gradient
- Need ultra-short electron bunches (~ 300fs) → bunch compression → Almost 100% capture efficiency



Density step physics better understood; expect to get electrons of few 10's of GeV using SPS drive beam.

Summary

Progress on all fronts related to Phase I,II

We are on track for commissioning of proton beam next summer, and starting the modulation experiments in the fall