AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN

NGACDT Annual Conference

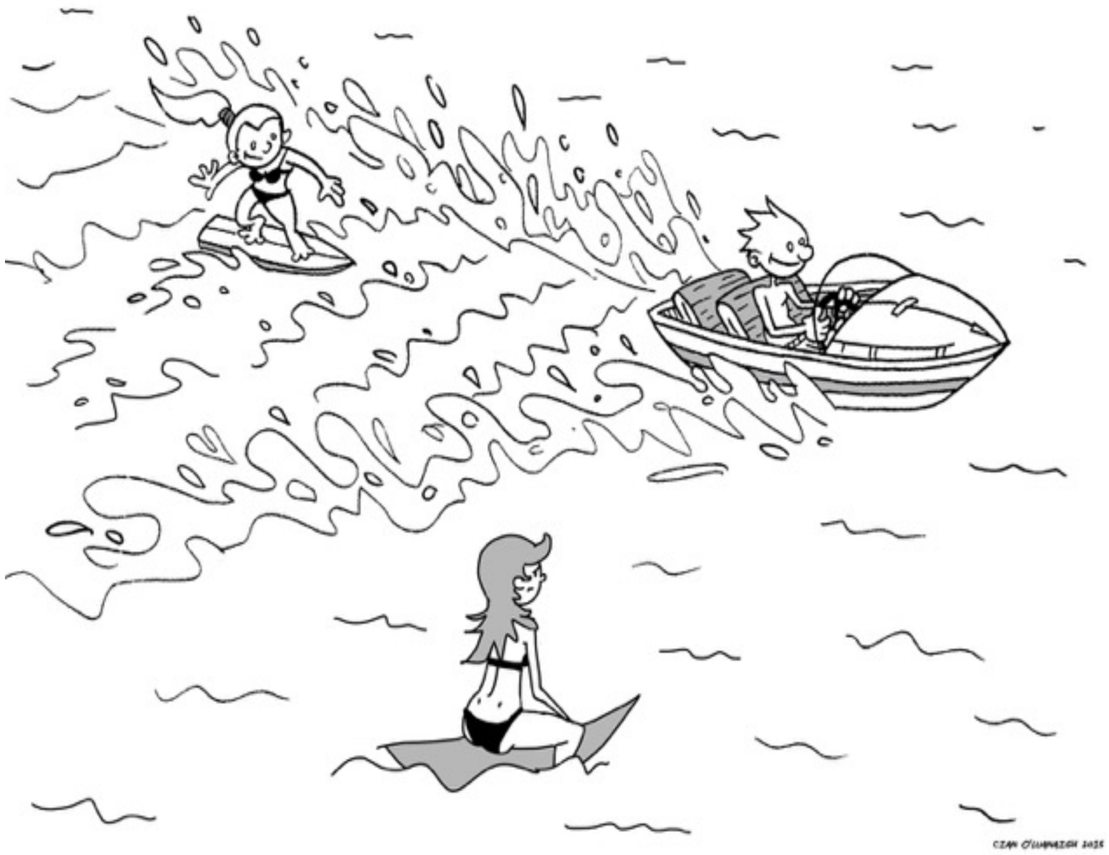
CERN, Nov. 2015

Janet Schmidt

CERN TE-ABT-BTP

Outline

1. Introduction: AWAKE and plasma wake field acceleration
2. AWAKE at CERN
    - Experimental Phase 1
    - Experimental Phase 2
3. Status of AWAKE



E. Gschwendtner, TEDxCERN 2015 https://youtu.be/5Ryp6UTCeUo

AWAKE – Who We Are?

- Proton driven plasma wake field acceleration of electrons
  - First proof of principle experiment worldwide
- 16 institutes in the collaboration
- Approved in Aug. 2013
- First beam planned in 2016

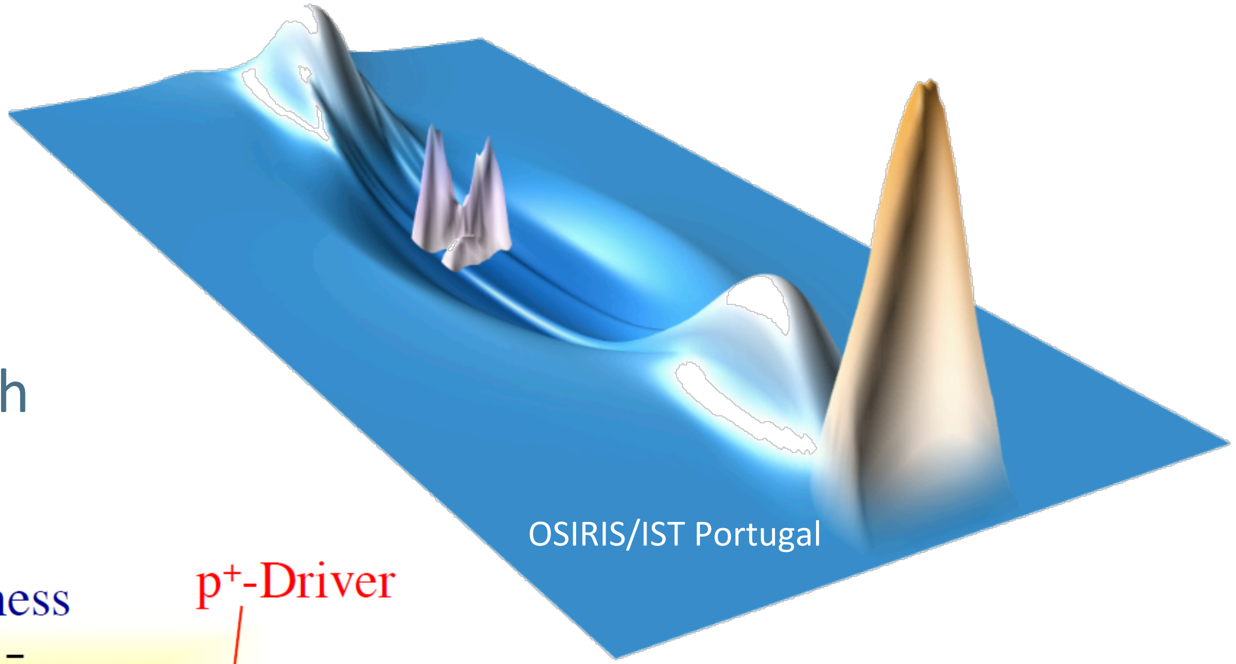
AWAKE

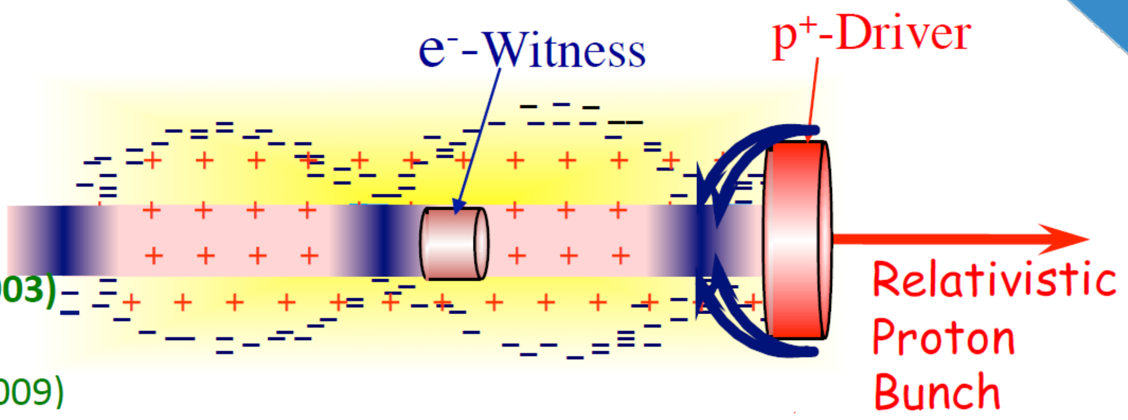
Beam Driven Wakefield Experiments

Facility	Where	Drive (D) beam	Witness (W) beam	Start	End	Goal
AWAKE	CERN, Geneva, Switzerland	400 GeV **protons**	Externally injected electron beam (PHIN 15 MeV)	2016	2020+	**Use for future high energy e-/e+ collider.** - Study Self-Modulation Instability (SMI). - Accelerate externally injected electrons. - Demonstrate scalability of acceleration scheme.
SLAC-FACET	SLAC, Stanford, USA	20 GeV **electrons** and **positrons**	Two-bunch formed with mask (e^-/e^+ and e^--e^+ bunches)	2012	Sept 2016	- Acceleration of witness bunch with high **quality and efficiency** - Acceleration of positrons - FACET II proposal for 2018 operation
DESY-Zeuthen	PITZ, DESY, Zeuthen, Germany	20 MeV **electron** beam	No witness (W) beam, only D beam from RF-gun.	2015	~2017	- Study Self-Modulation Instability **(SMI)**
DESY-FLASH Forward	DESY, Hamburg, Germany	X-ray FEL type **electron** beam 1 GeV	D + W in FEL bunch. Or independent W-bunch (LWFA).	2016	2020+	- **Application (mostly) for x-ray FEL** - Energy-doubling of Flash-beam energy - Upgrade-stage: use 2 GeV FEL D beam
Brookhaven ATF	BNL, Brookhaven, USA	60 MeV **electrons**	Several bunches, D+W formed with mask.	On going		- **Study quasi-nonlinear PWFA regime.** - Study PWFA driven by multiple bunches - Visualisation with optical techniques

Protons as Drive Beam

- Drivers:
  - PW lasers today, ~40 J/Pulse
  - FACET, 30J/bunch
  - SPS 20kJ/bunch ➔ LHC 300 kJ/bunch





Blue
PRL, 90, 214801 (2003)
Caldwell
Nat. Phys. 5, 363 (2009)

Protons as Drive Beam

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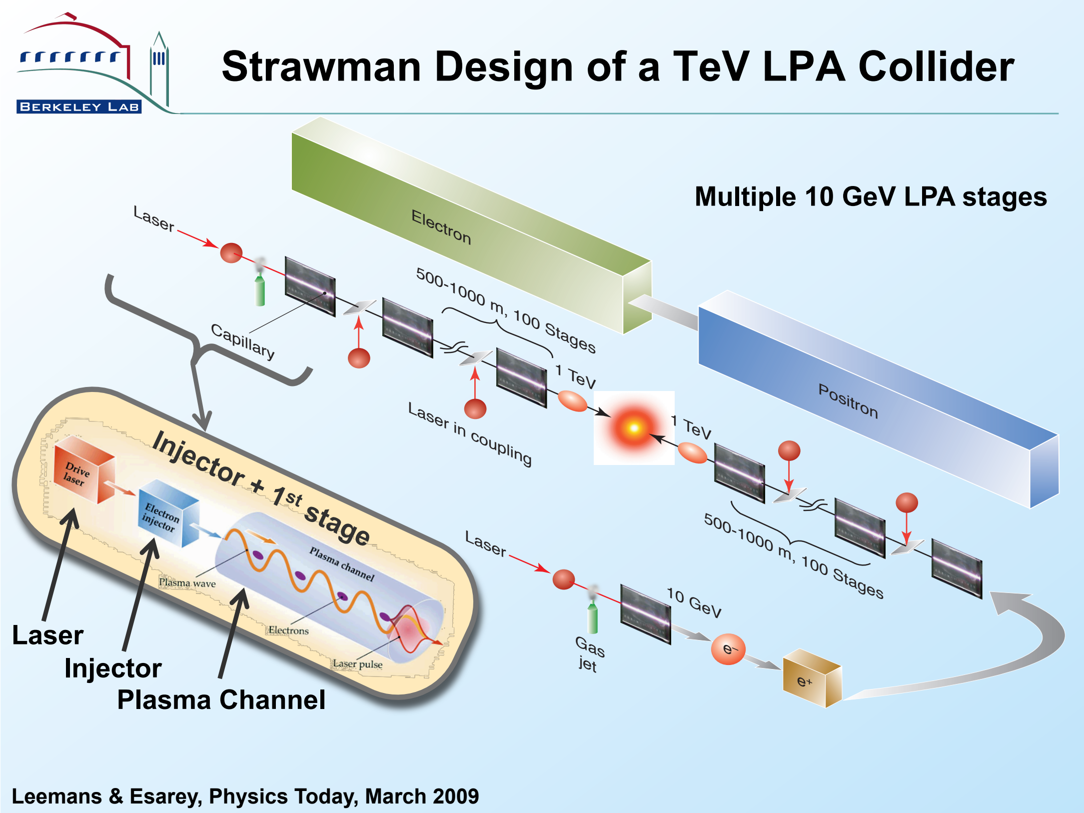
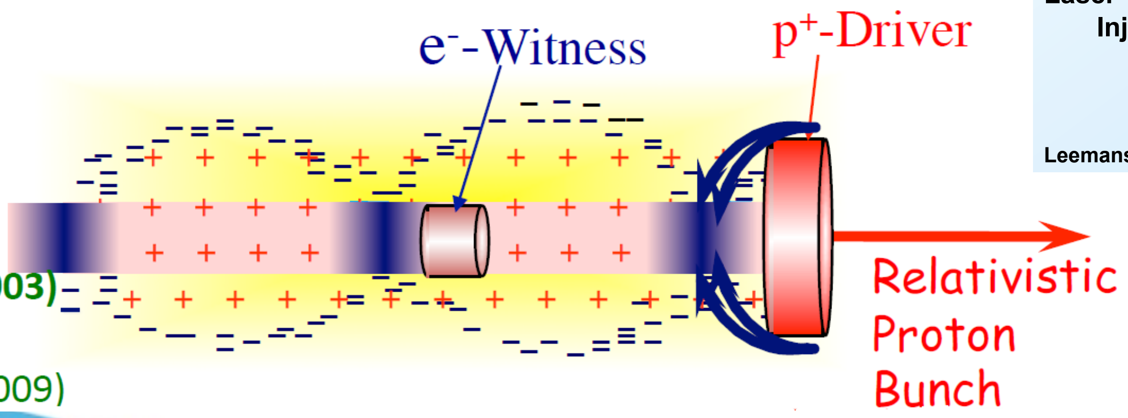




Blue
PRL, 90, 214801 (2003)
Caldwell
Nat. Phys. 5, 363 (2009)

AWAKE

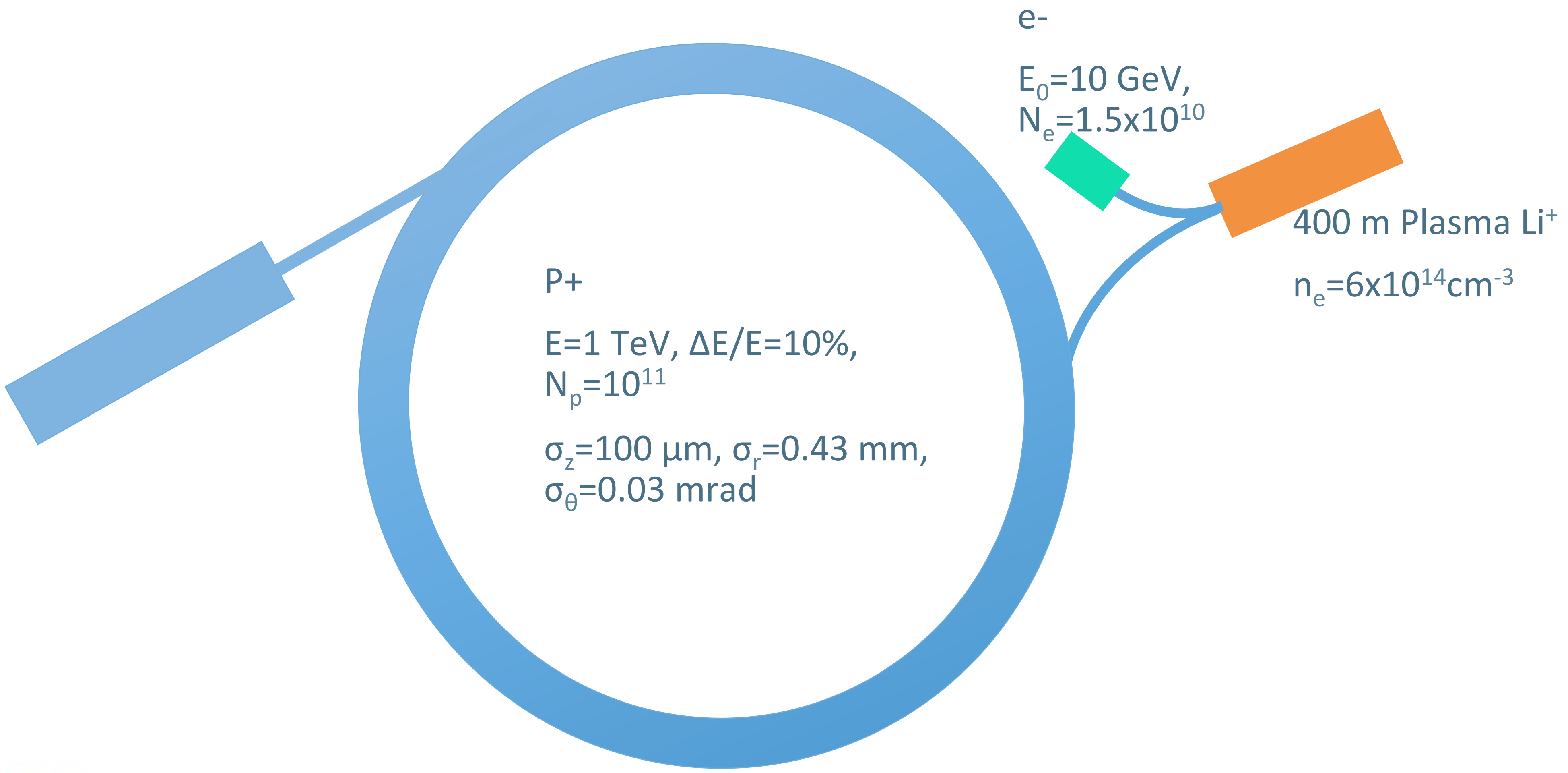
Protons as Drive Beam

P+

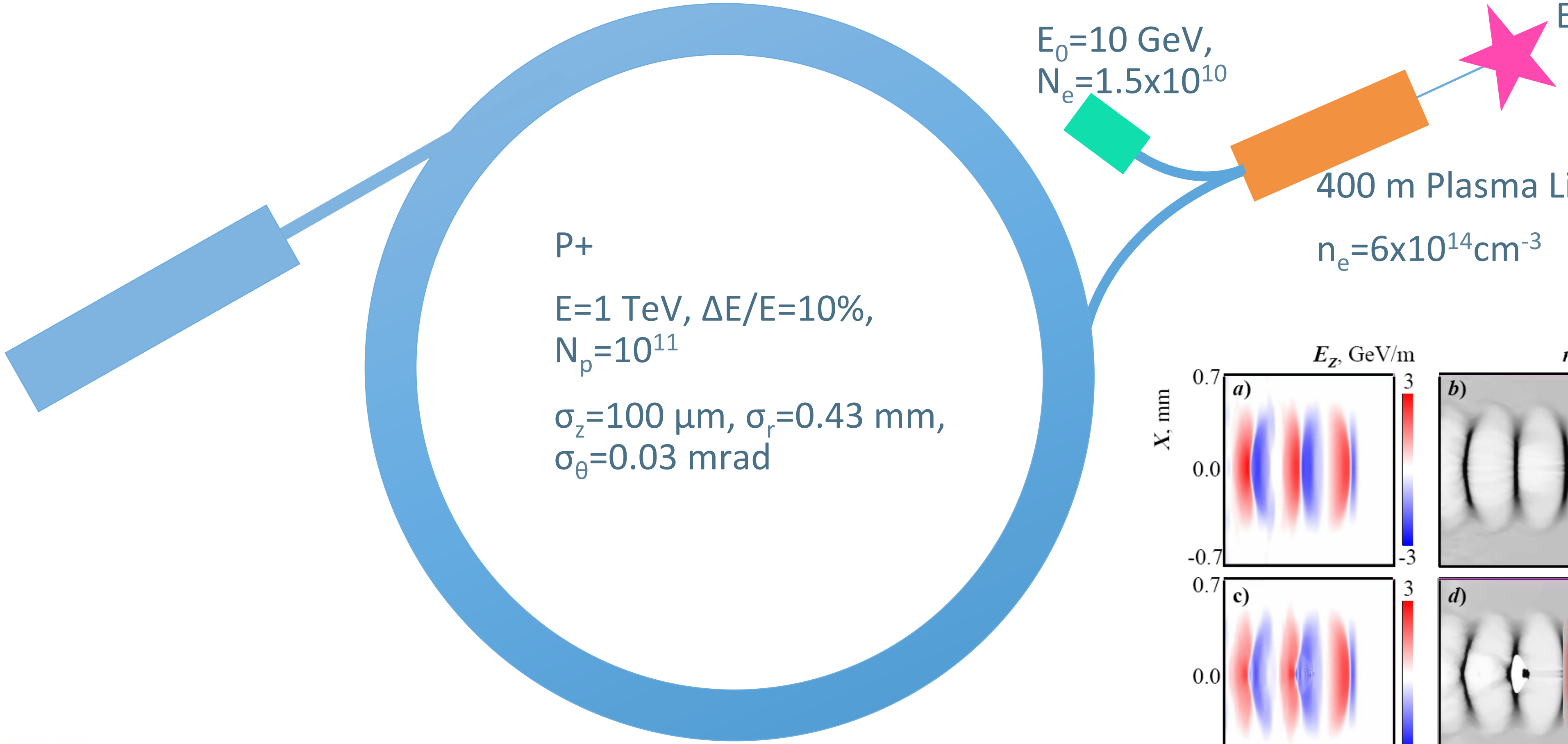
E=1 TeV, $\Delta E/E=10\%$, $N_p=10^{11}$

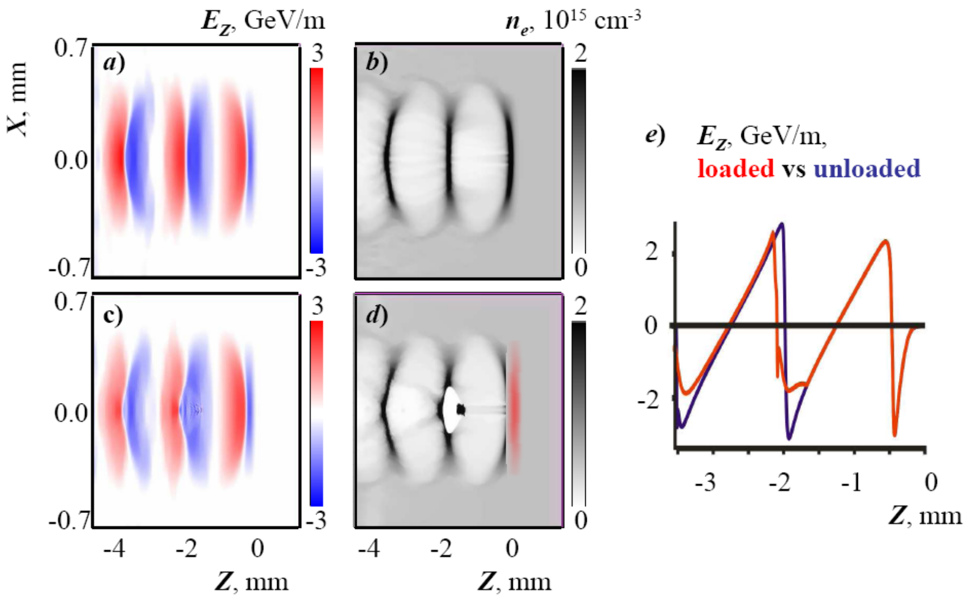
$\sigma_z=100\ \mu m$, $\sigma_r=0.43$ mm, $\sigma_\theta=0.03$ mrad

Protons as Drive Beam



Protons as Drive Beam

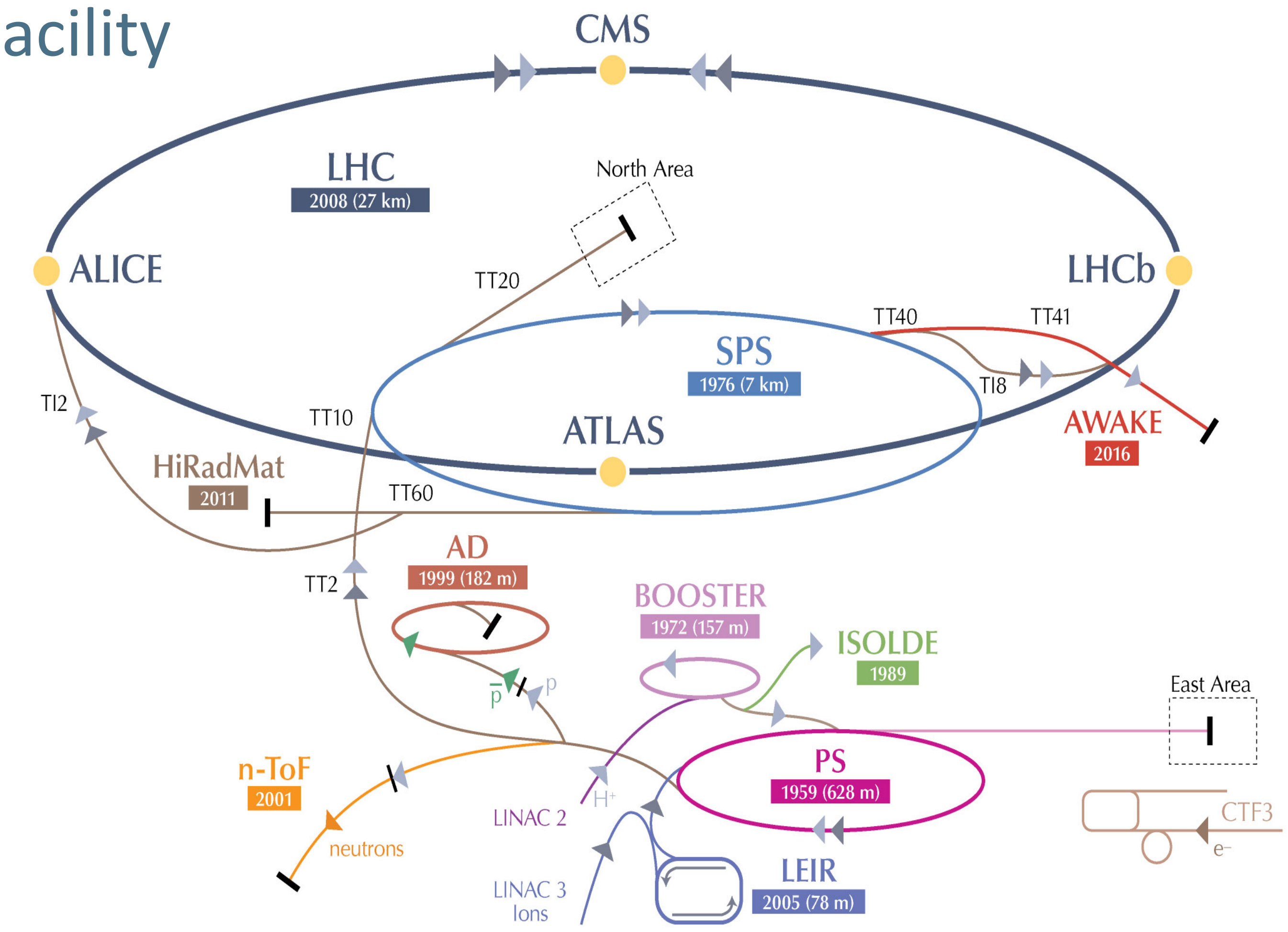




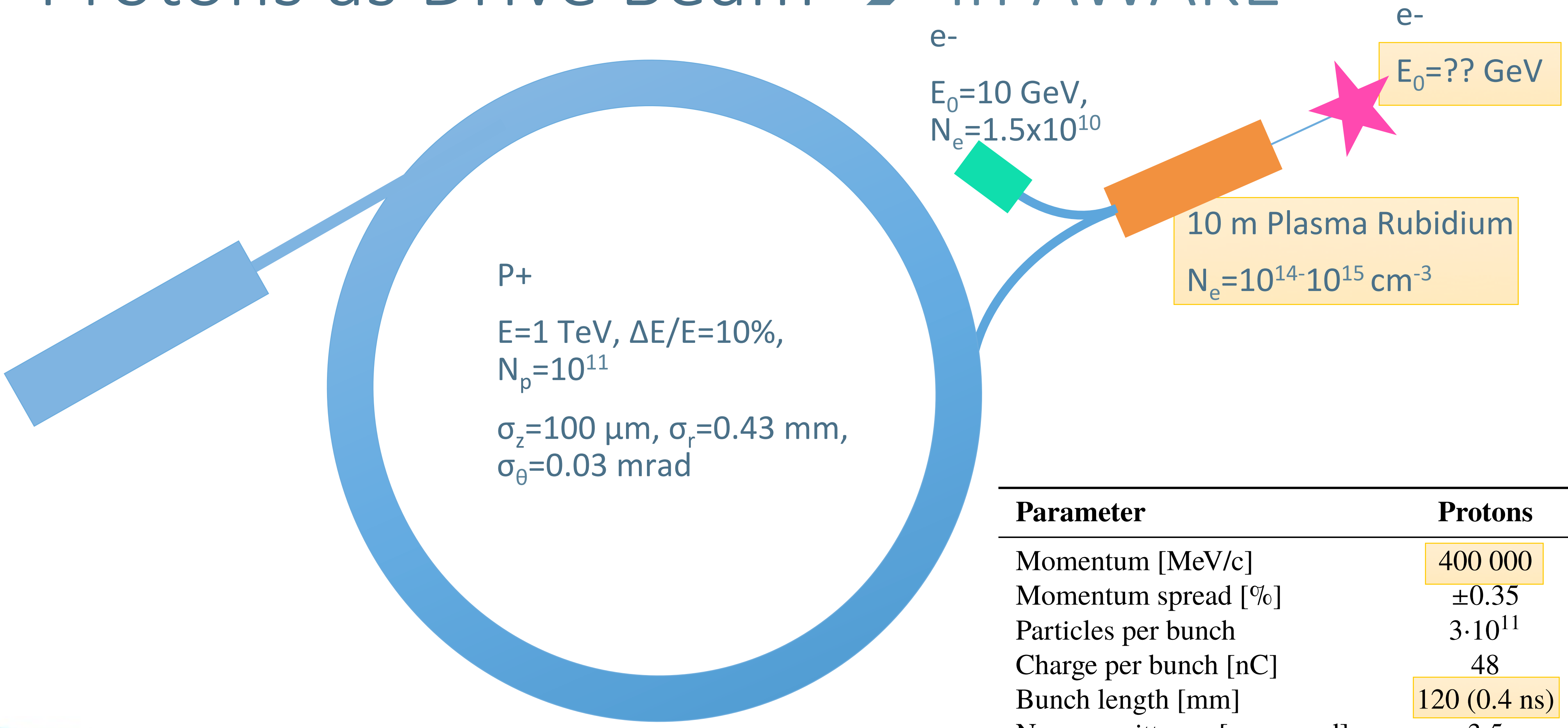
A. Caldwell, K. Lotov, A. Pukhov, F. Simon, Nature Physics 5, 363 (2009).

The Facility at CERN

- Installation @ former CNGS Facility
- Phase 1 in 2016
- Phase 2 in 2017
- 3-4 year physics program
- 4* 2weeks per year run



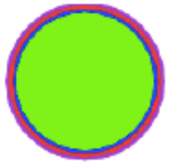
Protons as Drive Beam → in AWAKE



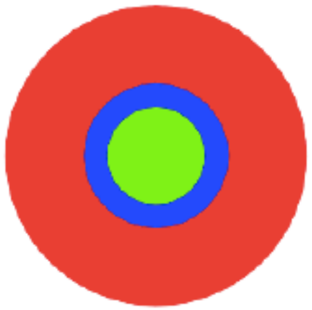
Parameter	Protons	Electrons
Momentum [MeV/c]	400 000	10-20
Momentum spread [%]	±0.35	±0.5
Particles per bunch	$3\cdot10^{11}$	$1.25\cdot10^{9}$
Charge per bunch [nC]	48	0.2
Bunch length [mm]	120 (0.4 ns)	1.2 (4ps)
Norm. emittance [mm·mrad]	3.5	2
Repetition rate [Hz]	0.033	10

The Self-Modulation Instability

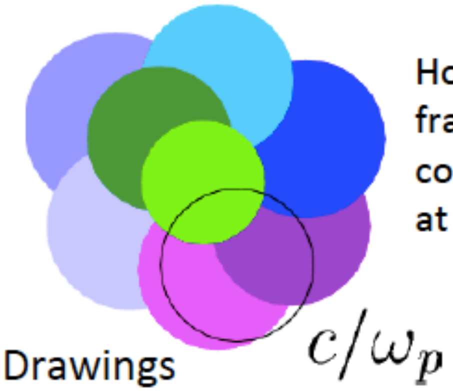
Spontaneous instability



Original beam
(front view)

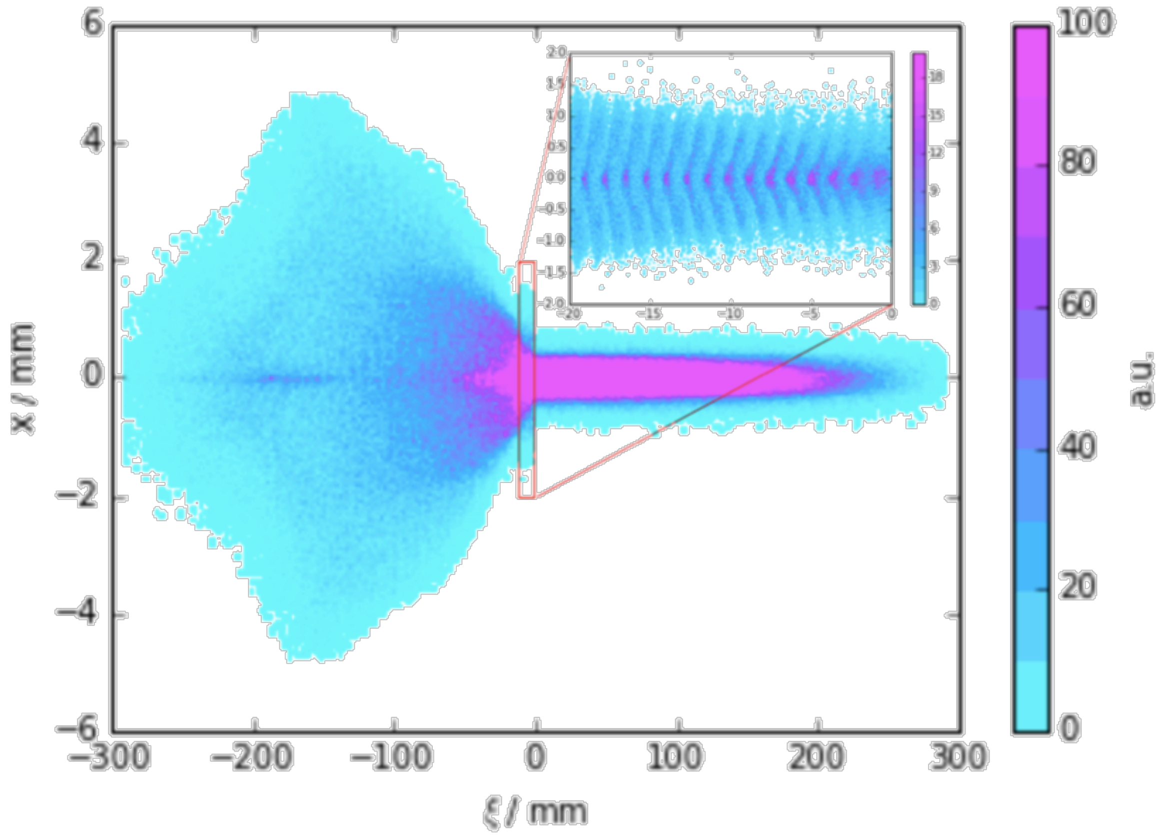


Axisymmetric mode
(half of the beam
contributes to on-axis
field excitation)



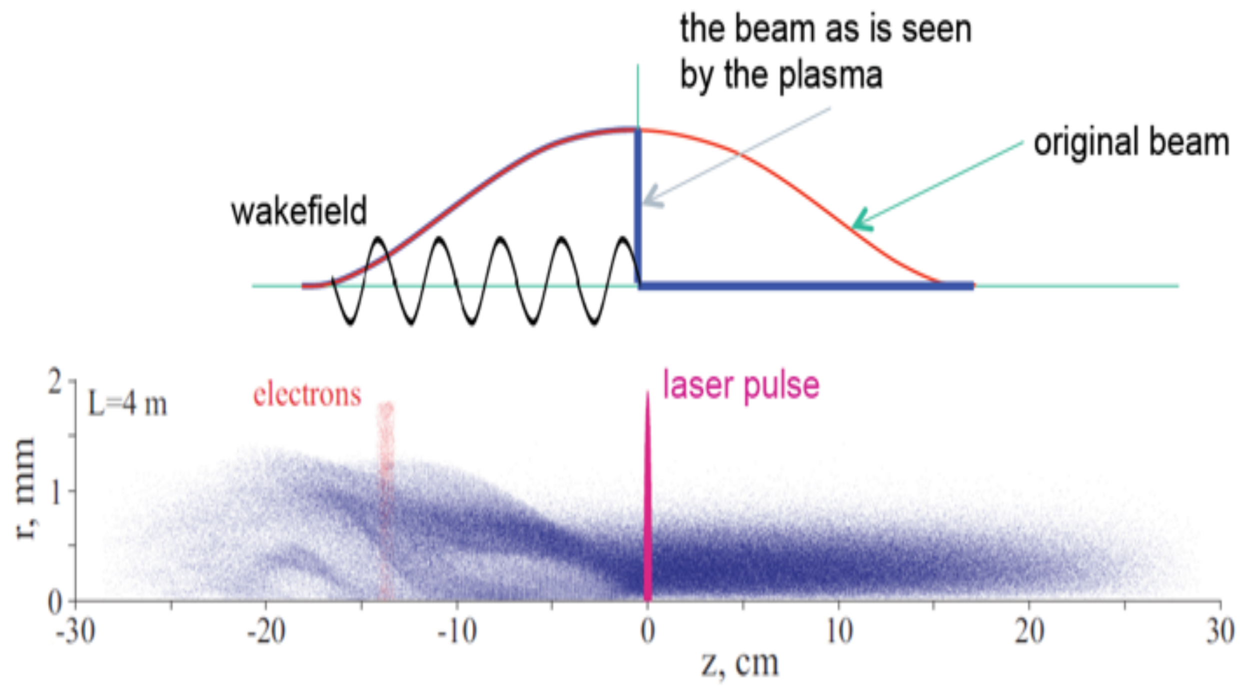
Hosing mode (small
fraction of the beam
contributes to the field
at a given point)

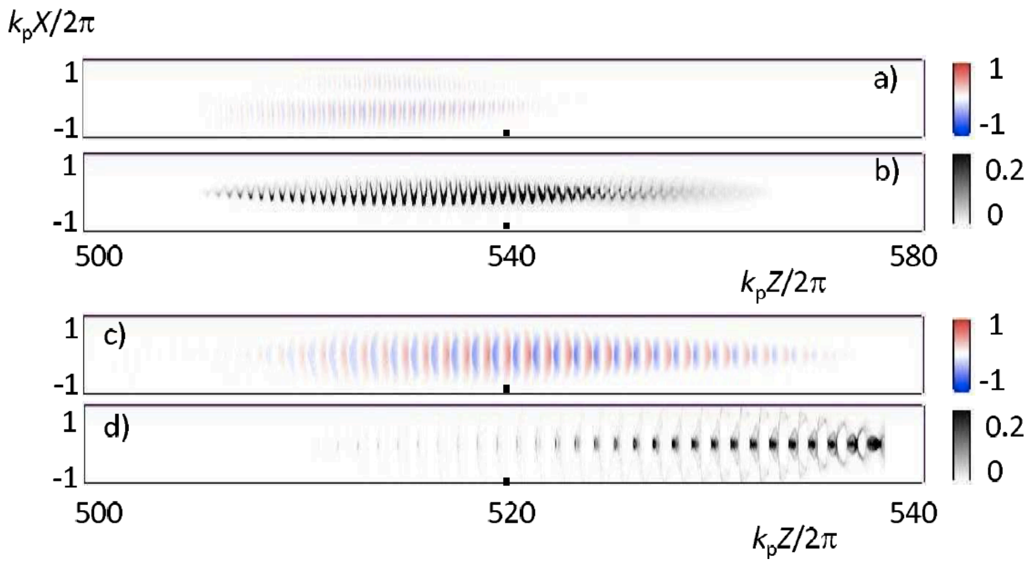
Drawings
from K. Lotov

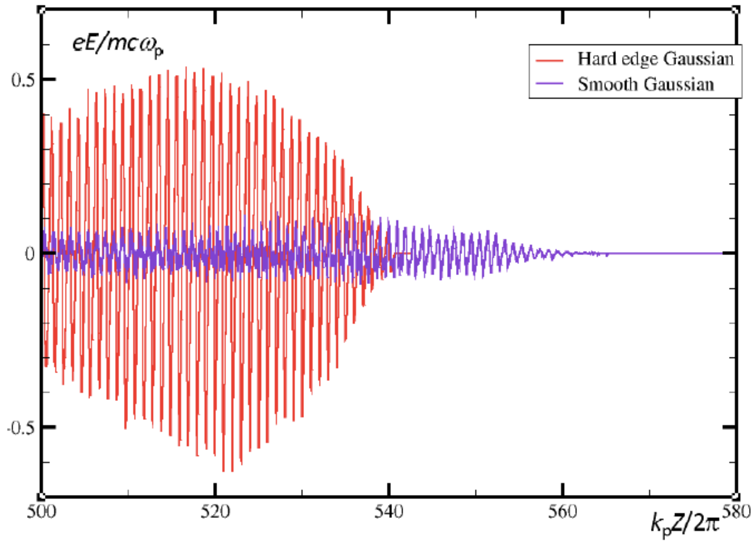


M. Cooper

Seeding of Self-Modulation Instability

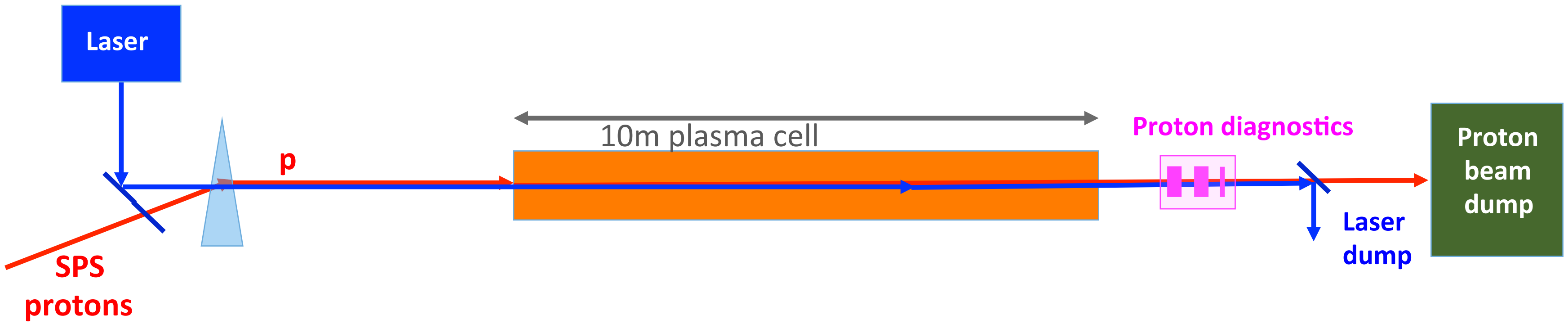


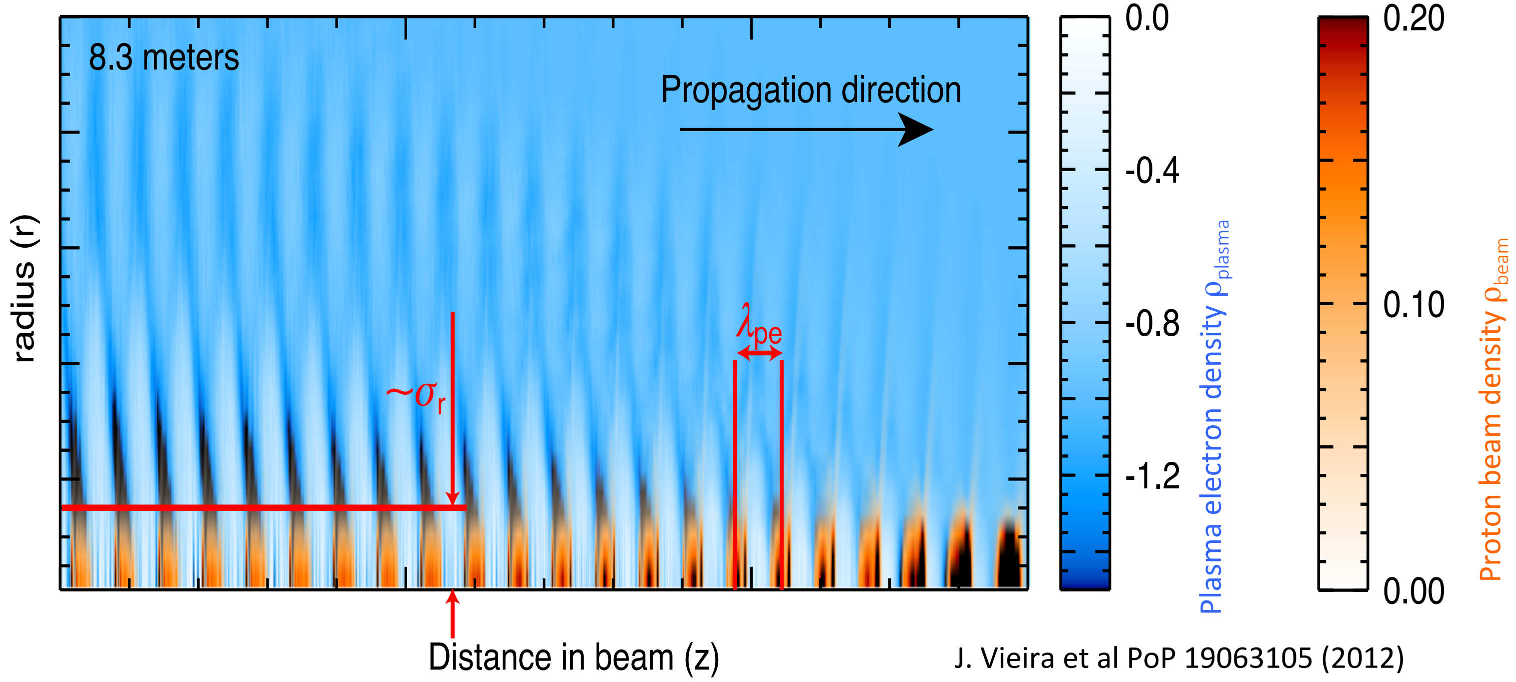




N. Kumar, A. Pukhov, and K. V. Lotov, Phys. Rev. Lett. **104**, 255003 (2010)

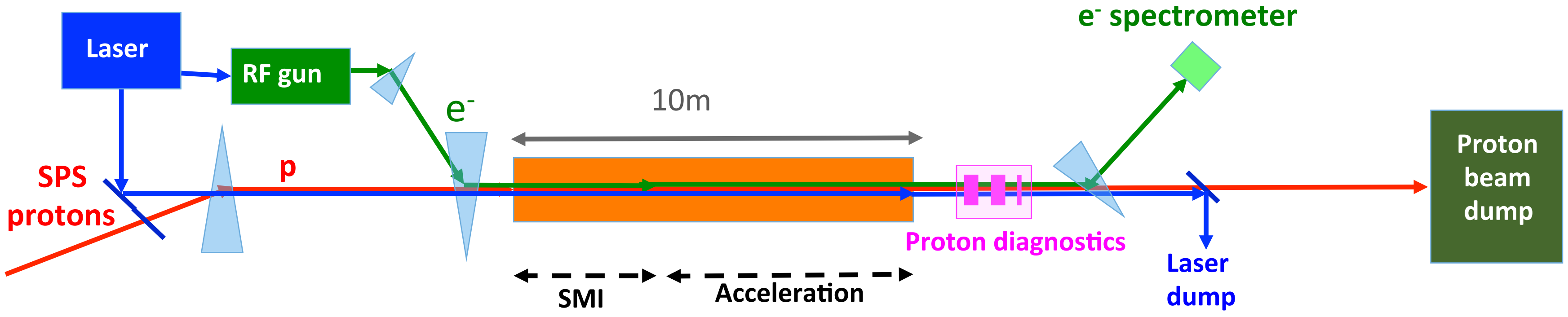
Phase 1 - the Self-Modulation Instability



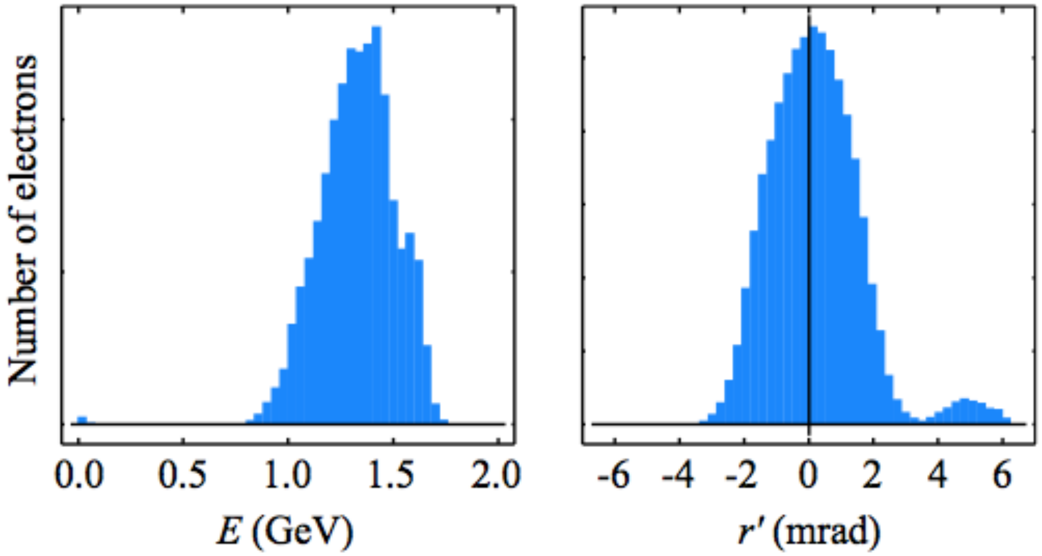


J. Vieira et al PoP 19063105 (2012)

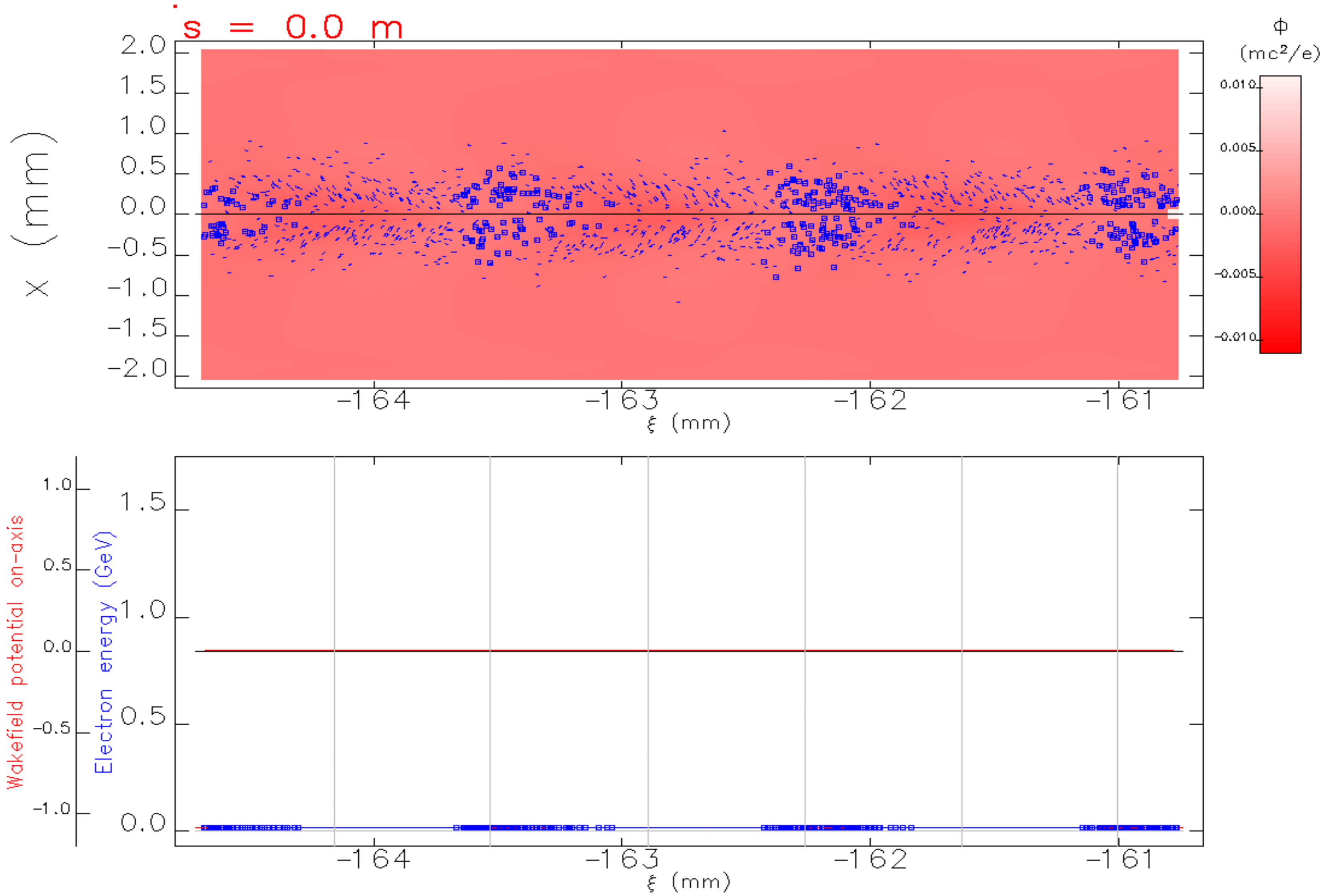
Phase 2 – Electron Acceleration



- Trapping efficiency: 10-15% (high sensitivity diagnostics)
- Average energy gain: 1.3 GeV
- Energy spread: ± 0.4 GeV
- Angular spread up to ± 4 mrad



Trapping and Acceleration of the Electrons



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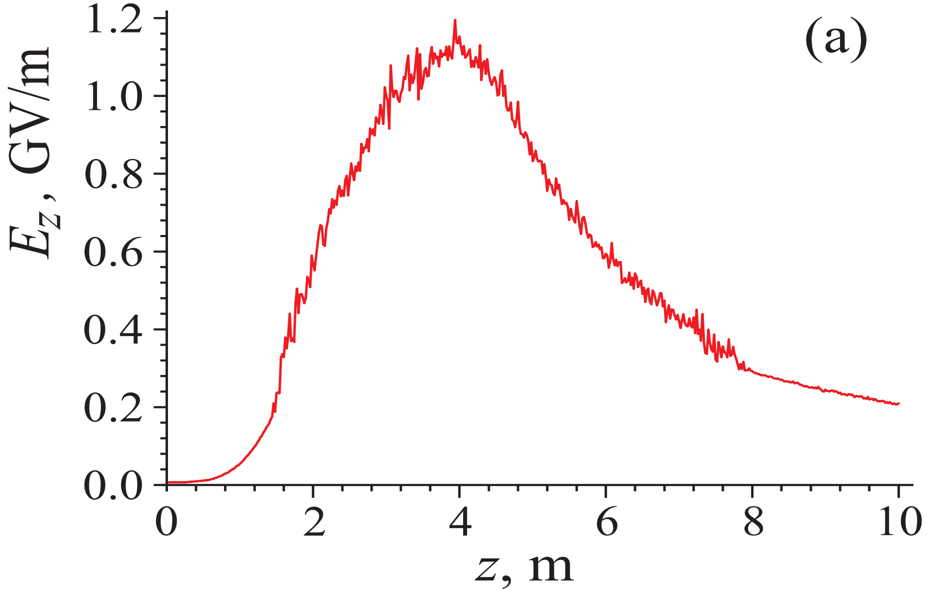
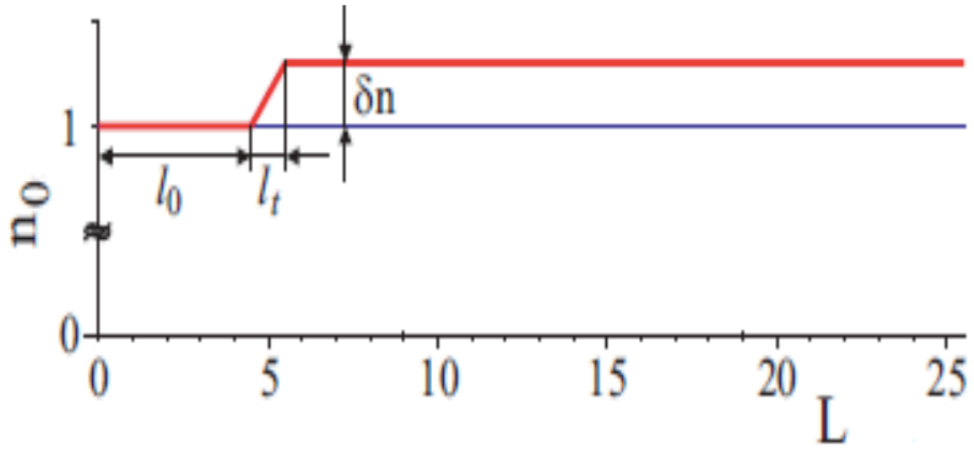
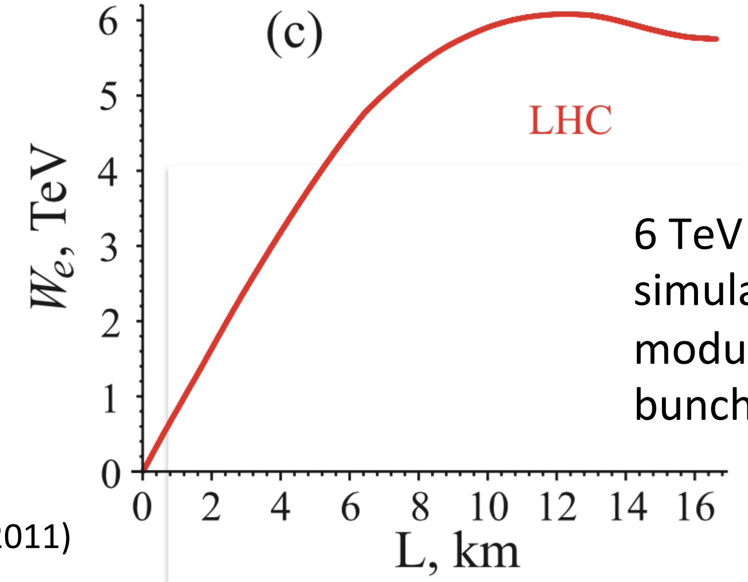
Stabilization of Peak Electric Fields





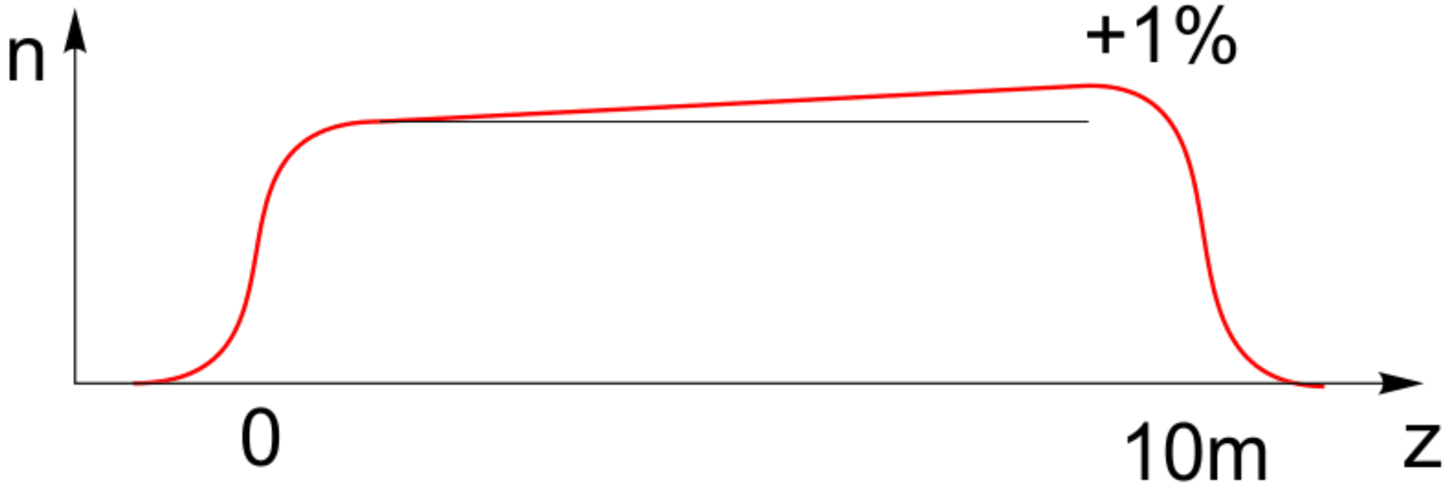


6 TeV electrons simulated with modulated LHC bunch

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

Simulations on Plasma Distribution with Gradient and Density Ramp

- Realistic simulation need to include density distributions at plasma edges
- Implementation of density gradient can be used to optimize capture efficiency

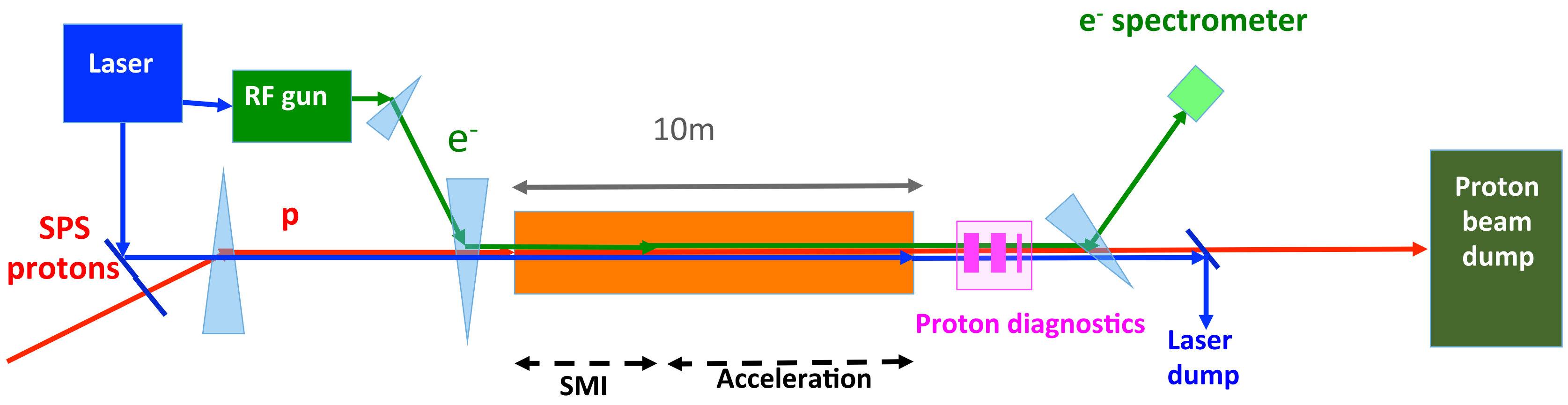


Low slowly increasing density → Fast growing density → 1% density gradient → Fast decreasing density → Low slowly decreasing density

A. Gorn

The Experimental Setup

- Plasma cell
- Laser beam
- Proton beam
- Electron beam
- Diagnostics



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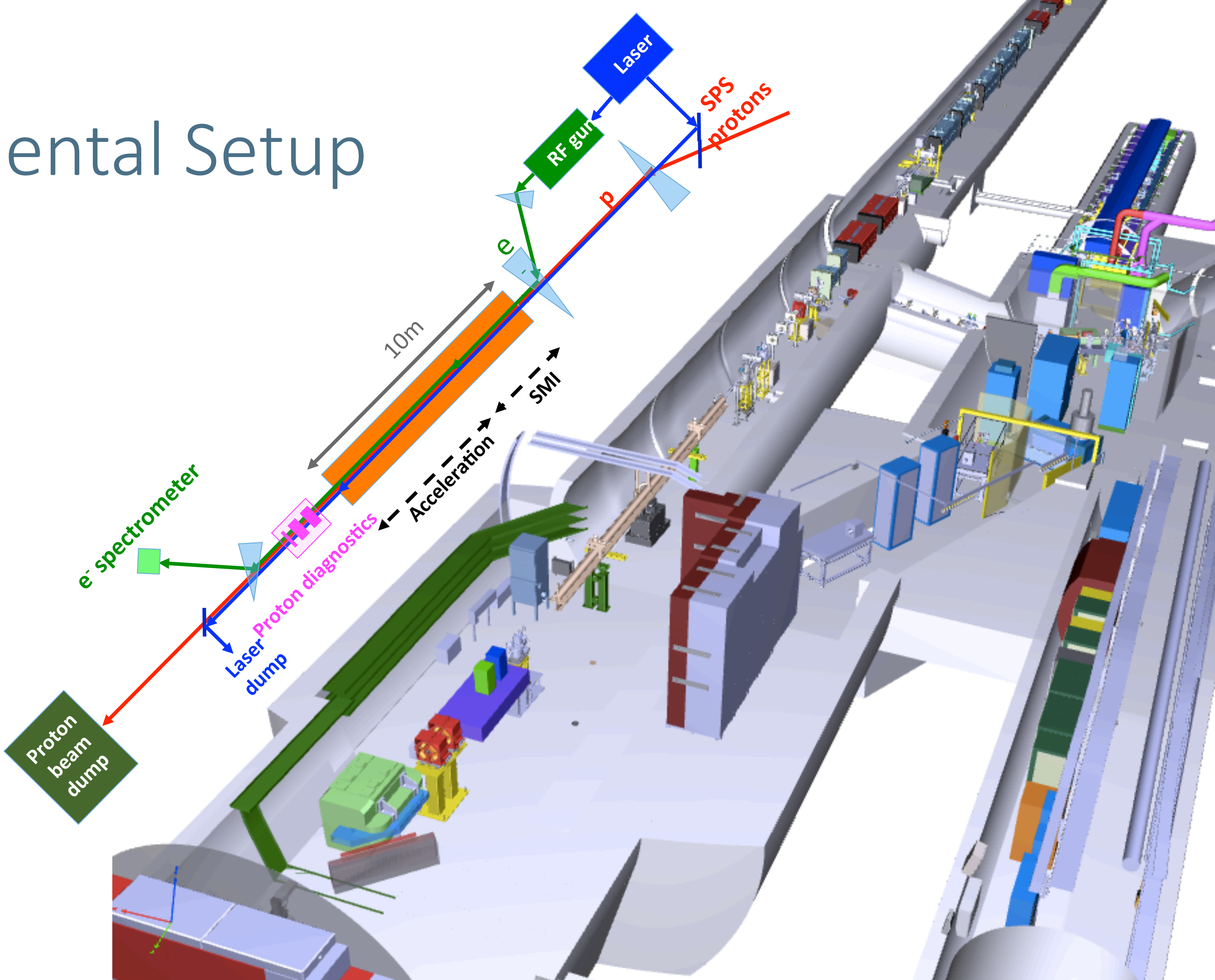
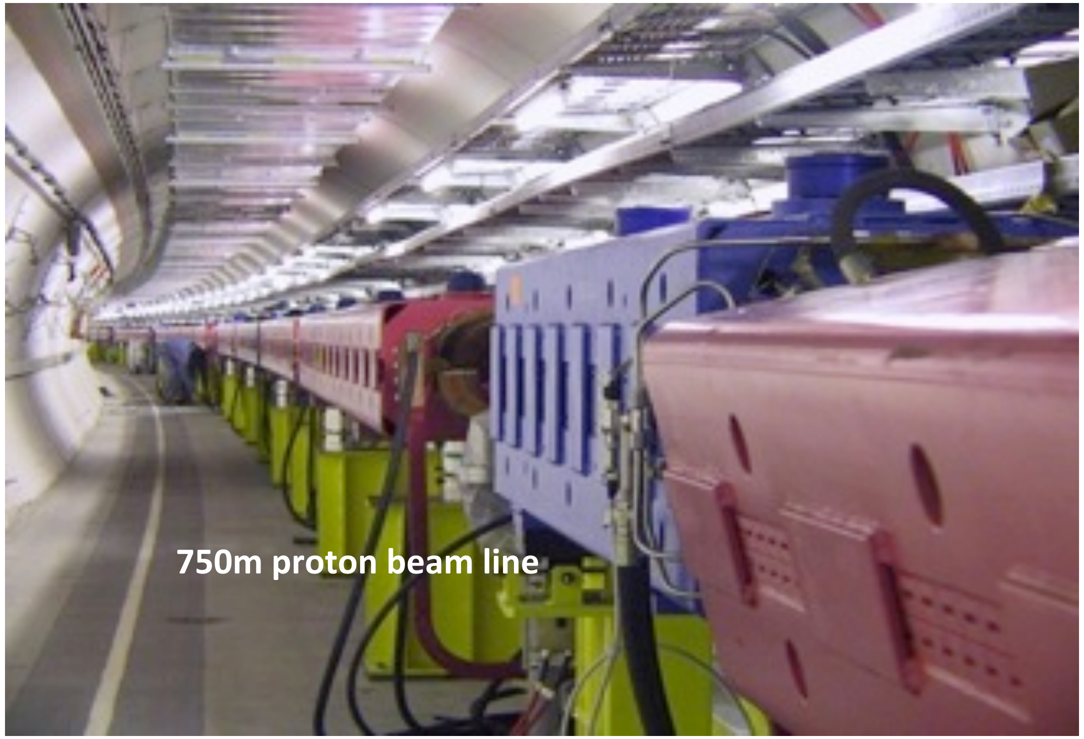
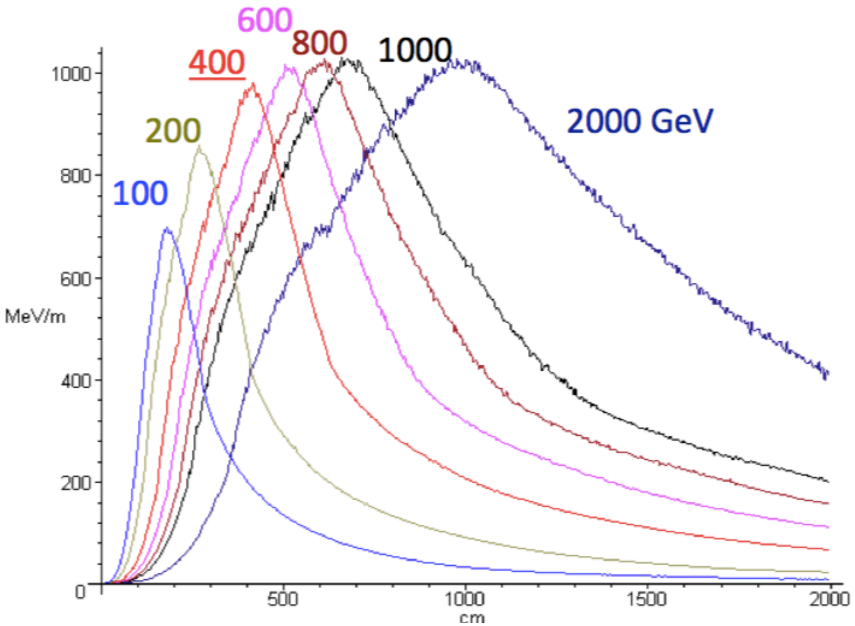
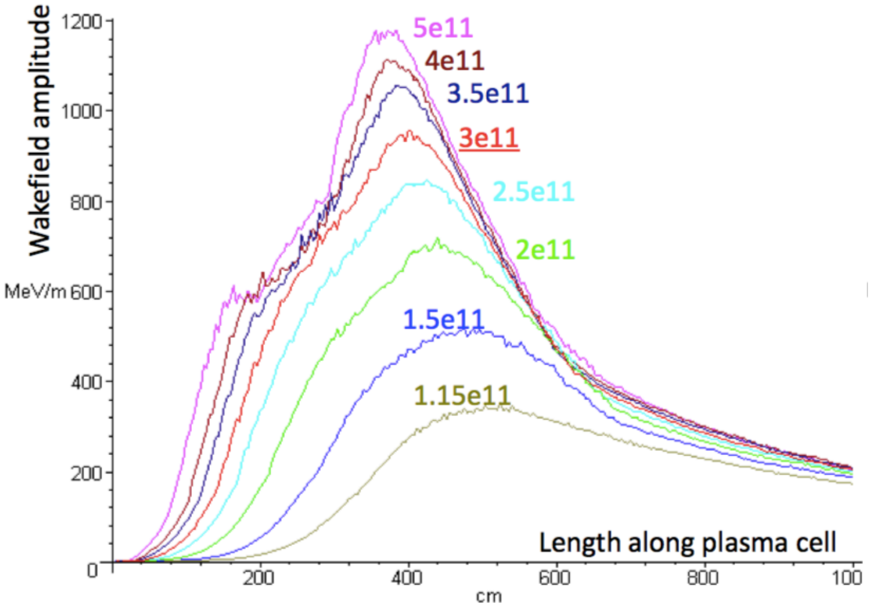


SPS Proton Beam

- LHC type proton beam



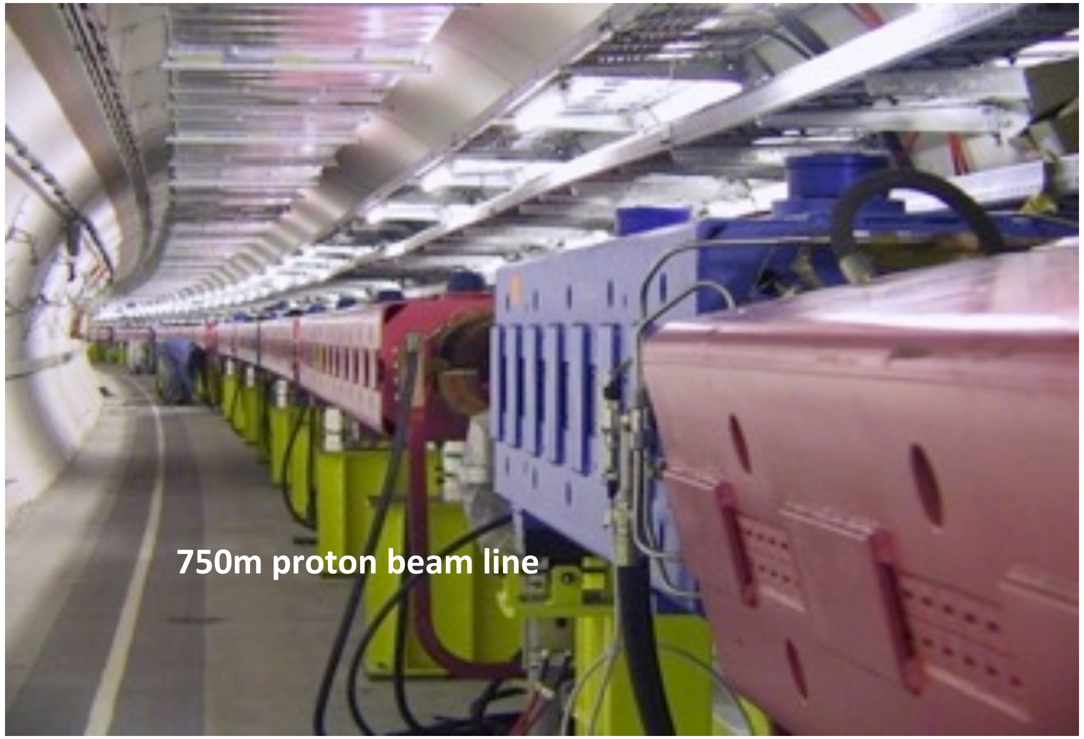


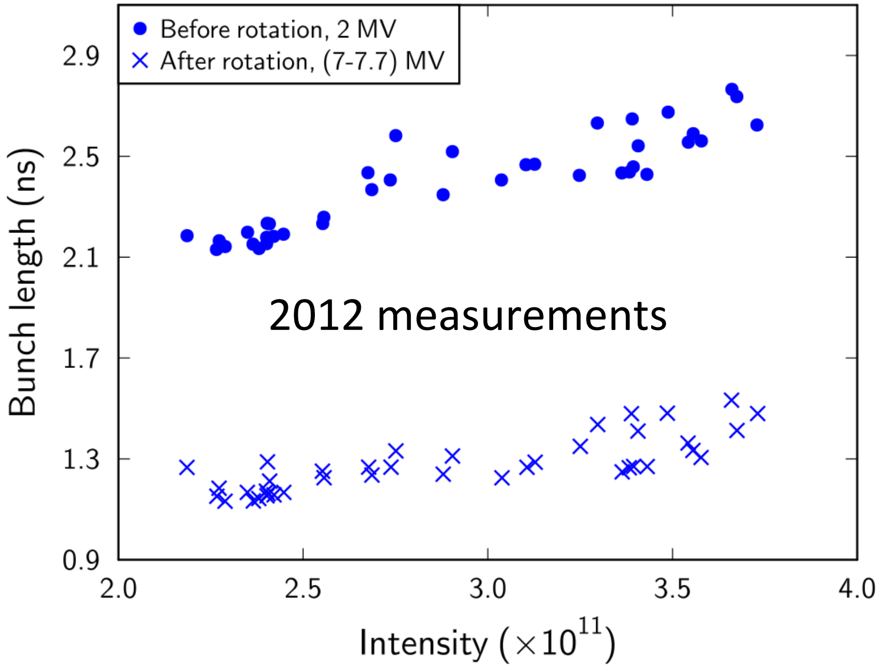


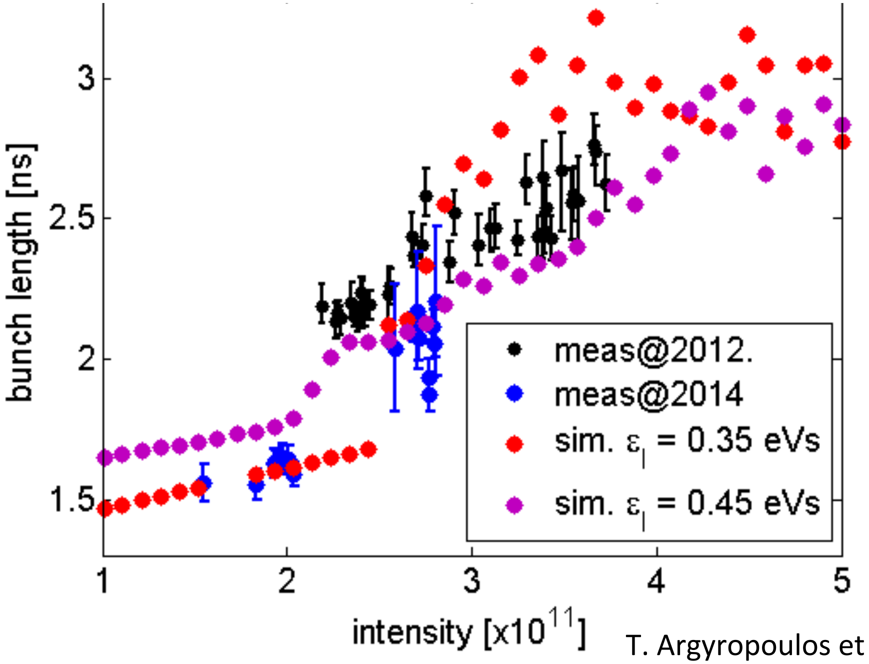
K. Lotov et al., Physics of Plasma, 21, 083107 (2014)

SPS Proton Beam

- LHC type proton beam



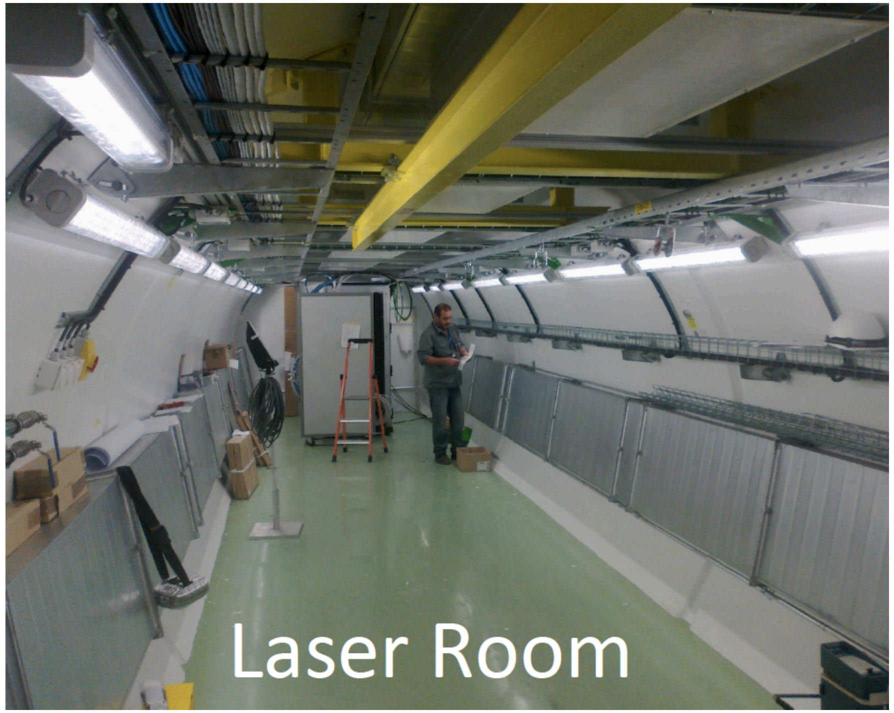




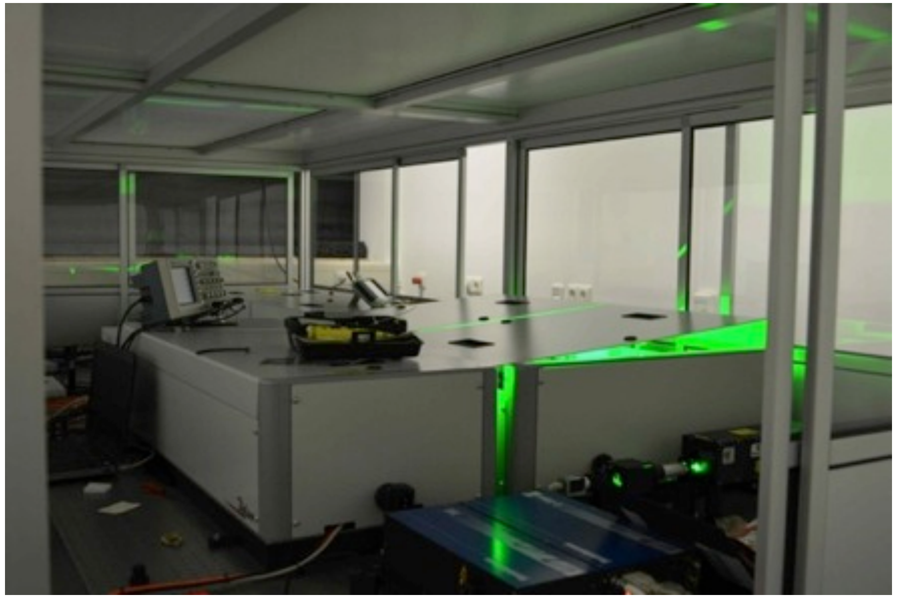
T. Argyropoulos et al

The Laser Beam

- Ionizing the rubidium
- Seeding the self-modulation instability
- Driving the electron gun



Laser Beam	
Laser type	Fiber Ti:Saphire
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



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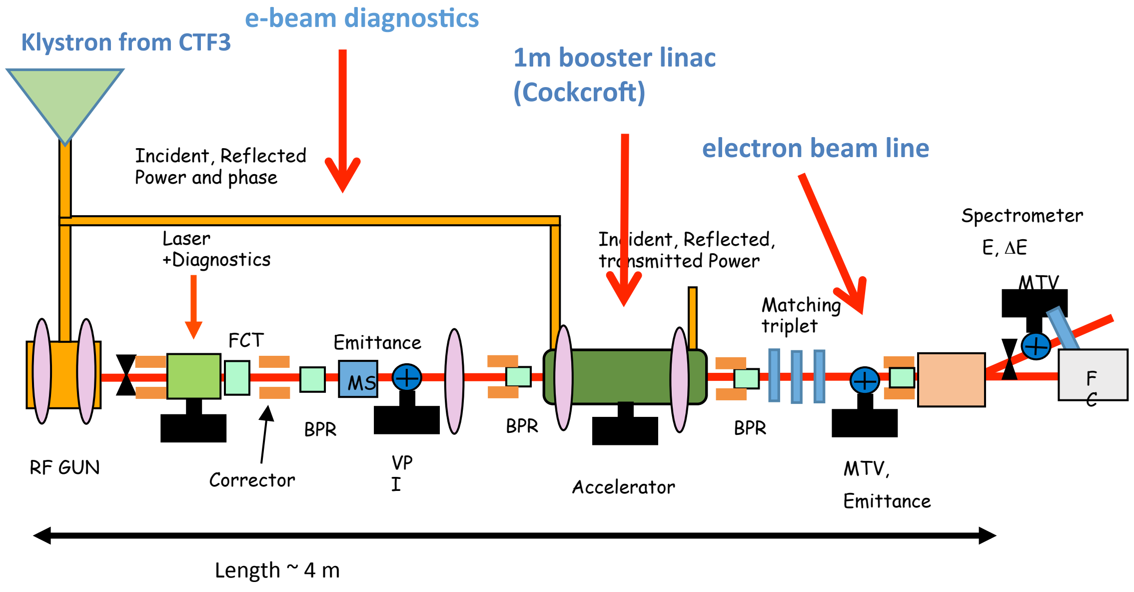
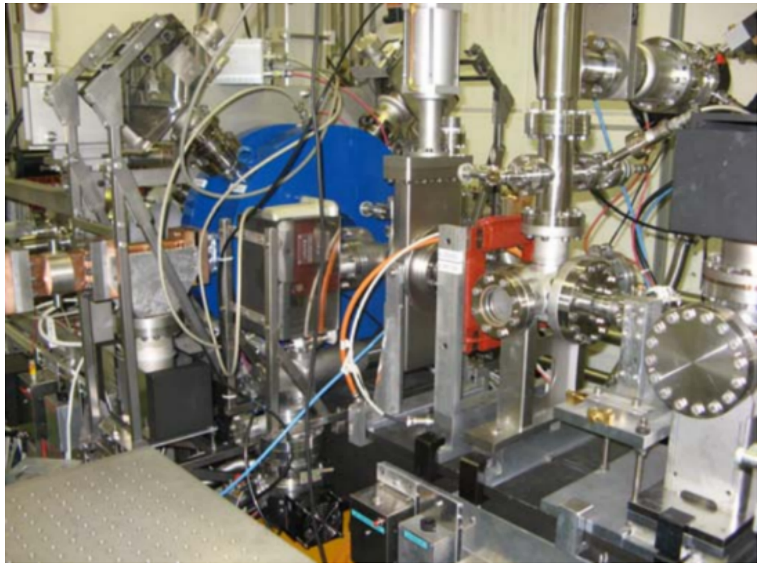
Electron Beam

- Reuse of the PHIN photo-injector (from CTF3/CLIC)
- 14m transfer line
- Diagnostic of acceleration with spectrometer magnet





Courtesy of S. Doebert

Electron beam	
Momentum	16 MeV/c
Electrons/bunch (bunch charge)	1.2 E9 (0.2 nC)
Bunch length	σ_z =4ps (1.2mm)
Bunch size at focus	$\sigma^*_{x,y}$ = 250 μm
Normalized emittance (r.m.s.)	2 mm mrad
Relative energy spread	$\Delta p/p$ = 0.5%
Beta function	$\beta^*_x = \beta^*_y$ = 0.4 m
Dispersion	$D^*_x = D^*_y$ = 0

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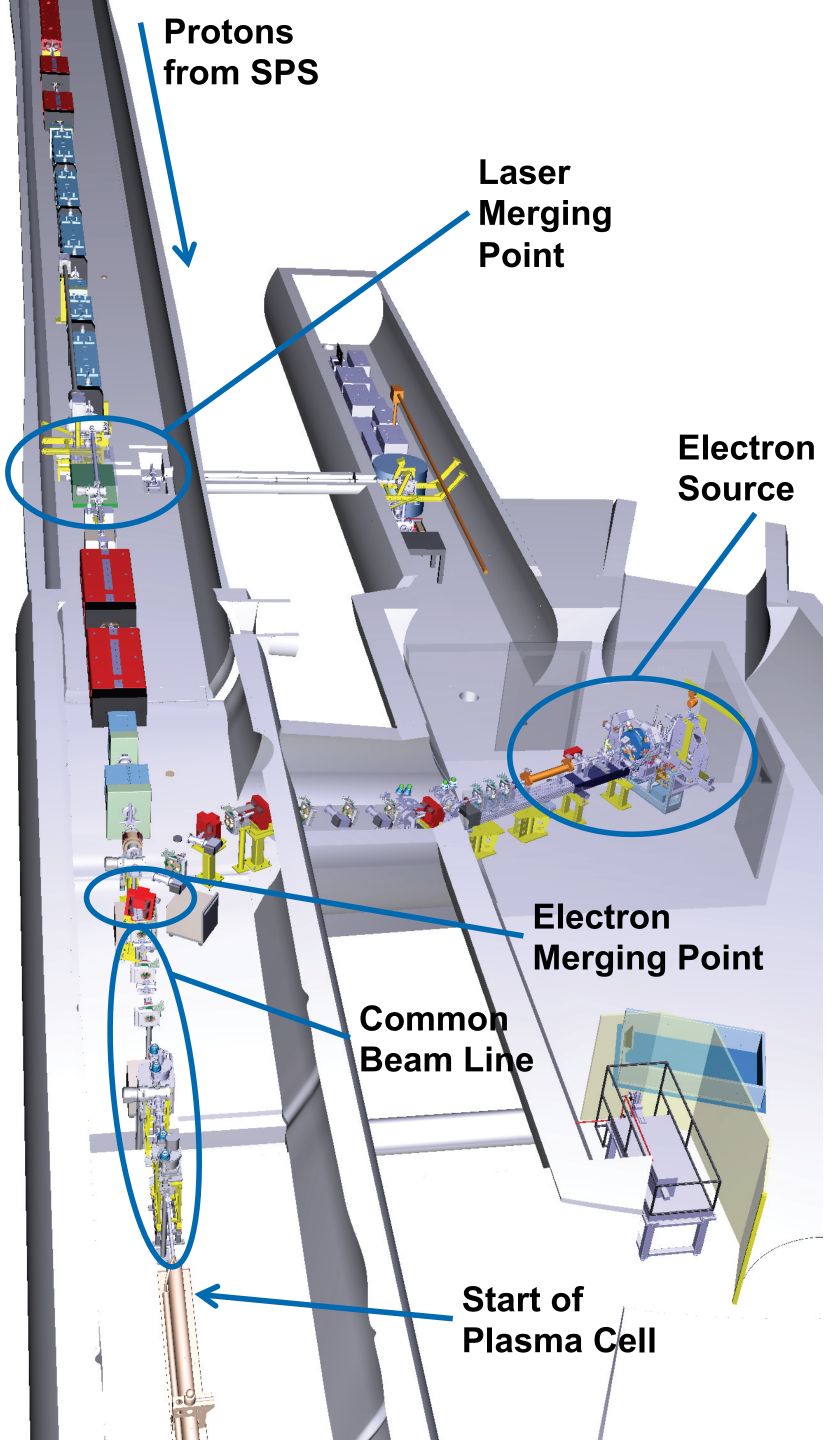
Transfer Lines

- Proton, laser and electron beam transferred to plasma cell
- Parallel operation ➔ diagnostic
- As flexible as possible

Parameter	Protons	Electrons
Momentum [MeV/c]	400 000	10-20
Momentum spread [%]	±0.35	±0.5
Particles per bunch	$3 \cdot 10^{11}$	$1.25 \cdot 10^{9}$
Charge per bunch [nC]	48	0.2
Bunch length [mm]	120 (0.4 ns)	1.2 (4ps)
Norm. emittance [mm·mrad]	3.5	2
Repetition rate [Hz]	0.033	10
1σ spot size at focal point [μm]	200 ±20	<250
β-function at focal point [m]	5	0.4
Dispersion at focal point [m]	0	0



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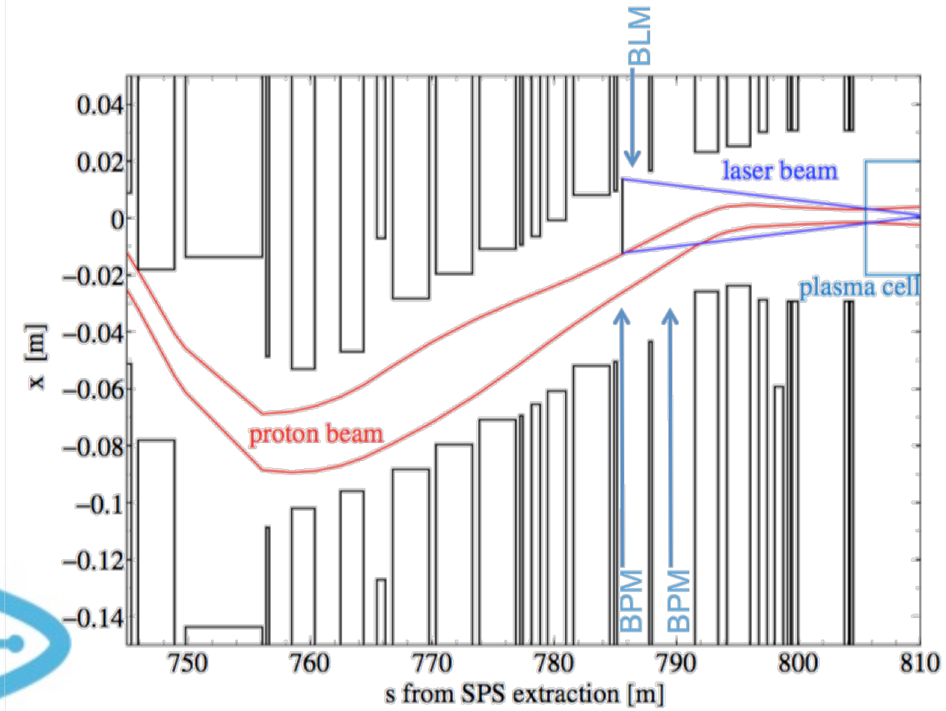
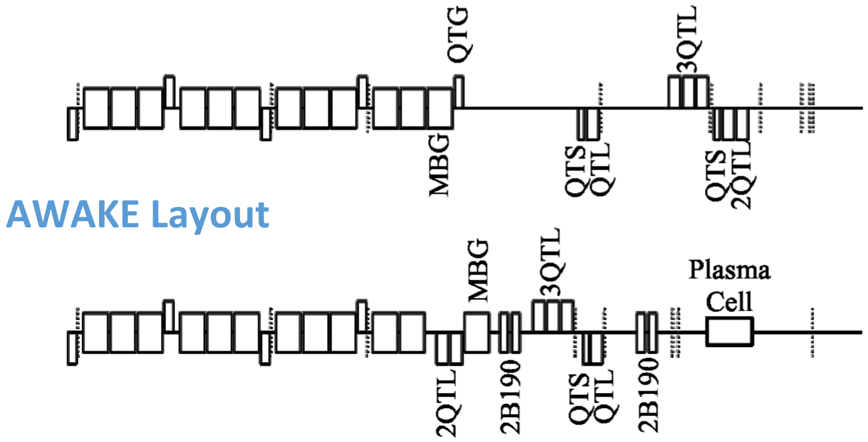
Proton Beam Transfer

- σ_z=12cm $\sigma_{x,y}$=200µm
- Created chicane to merge laser beam
- Synchronization with laser beam @ 100 ps level

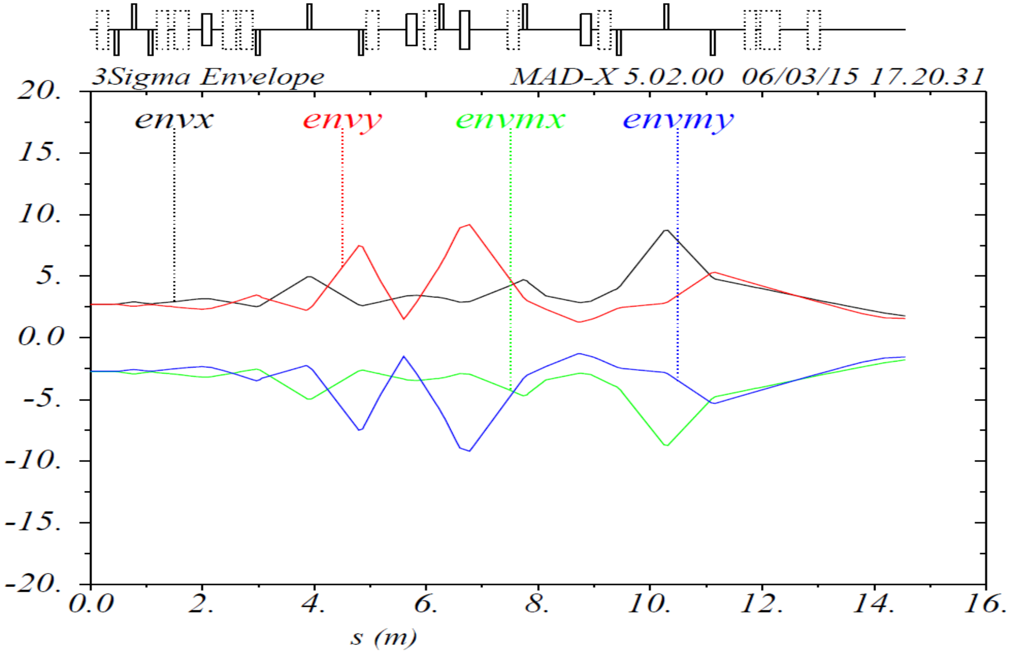


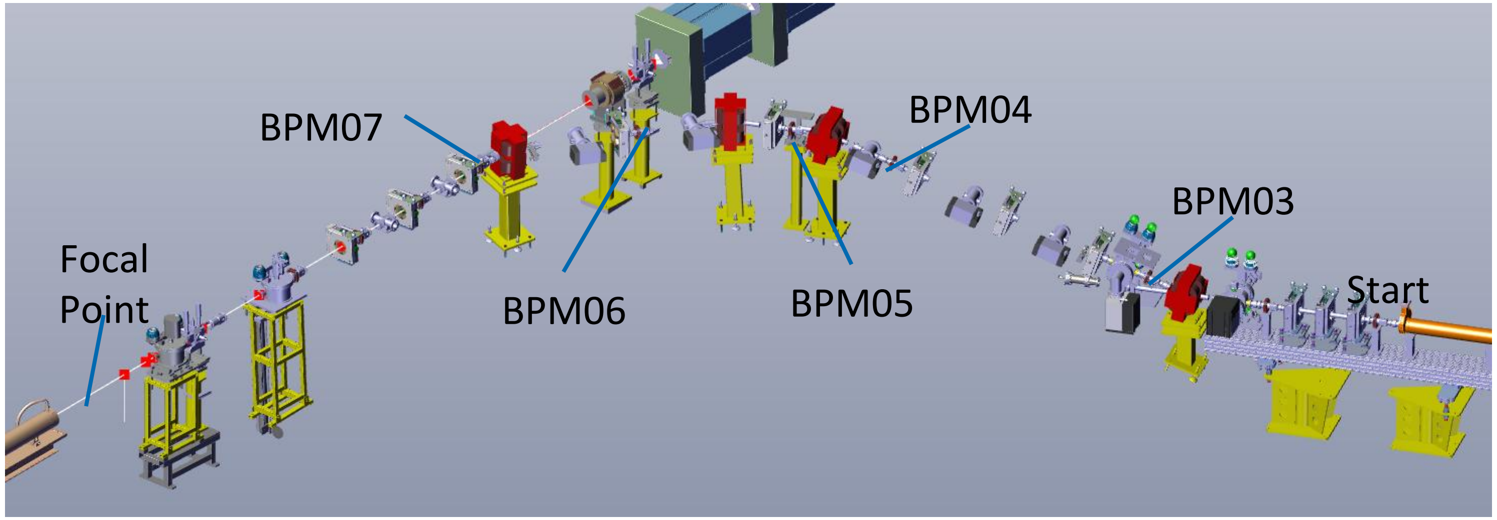


The Electron Transfer Line

- Transport the electron beam from source level up to the plasma source level
- Merge electron beam with proton beam
- Provide a flexible focus point with

  $\sigma_{x,y} \leq 250\mu m$
  - 3 - 4.5m after last quadrupole

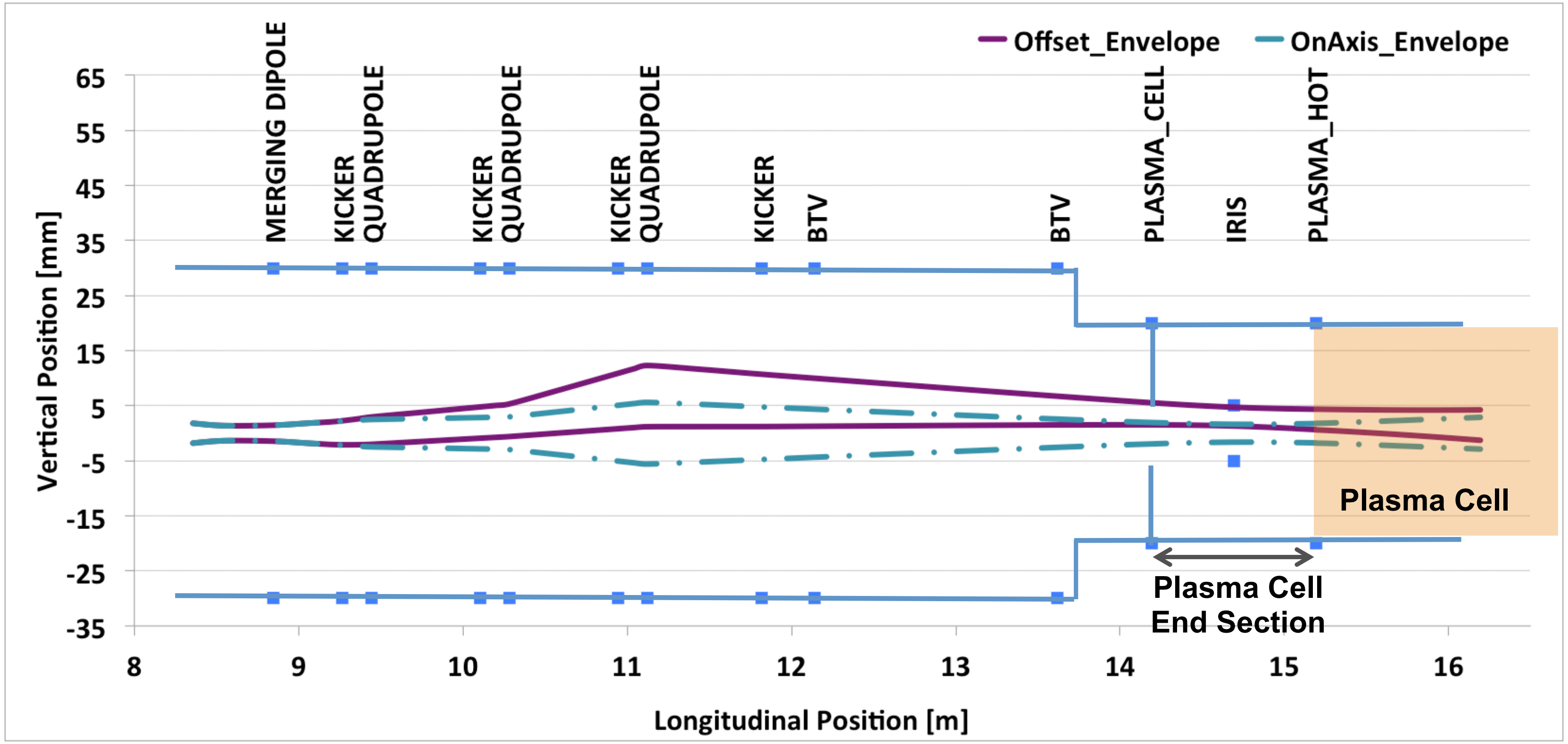




Common Beam Line

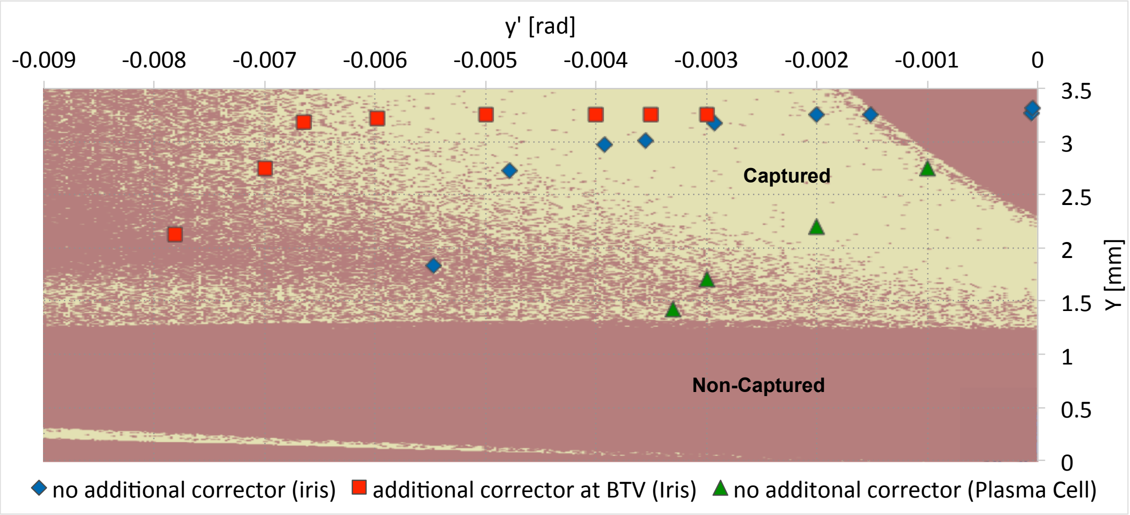
1. Introduce an offset in the common beam line

2. Introduce an offset and angle at the focal point of the electron beam

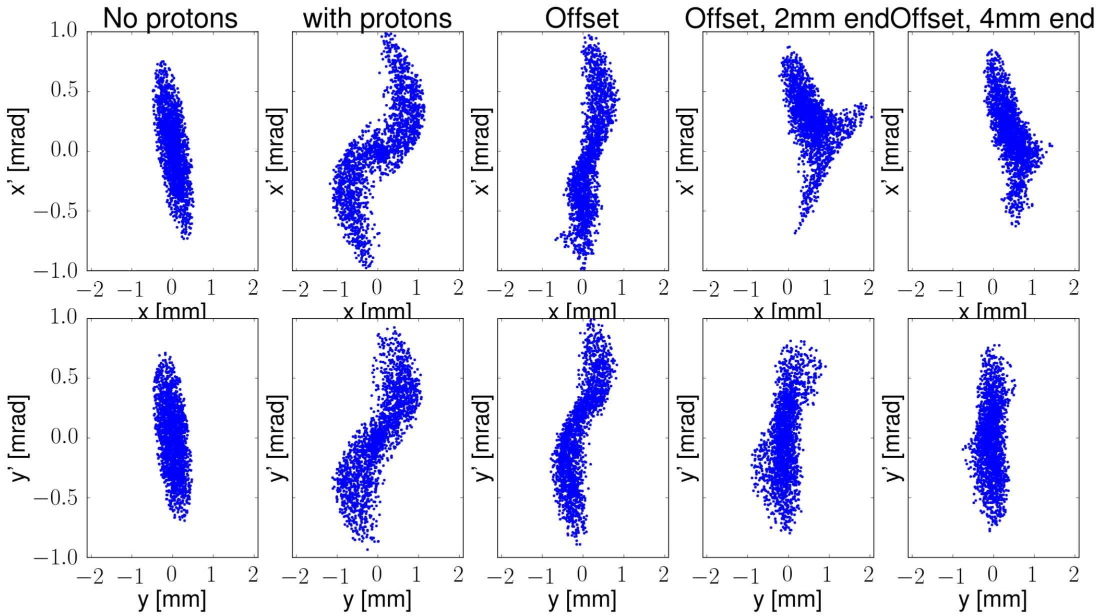


Common Beam Line

1. Introduce an offset in the common beam line
   - reduce beam-beam effects
2. Introduce an offset and angle at the focal point of the electron beam
   - scan transverse phase space to optimize trapping efficiency



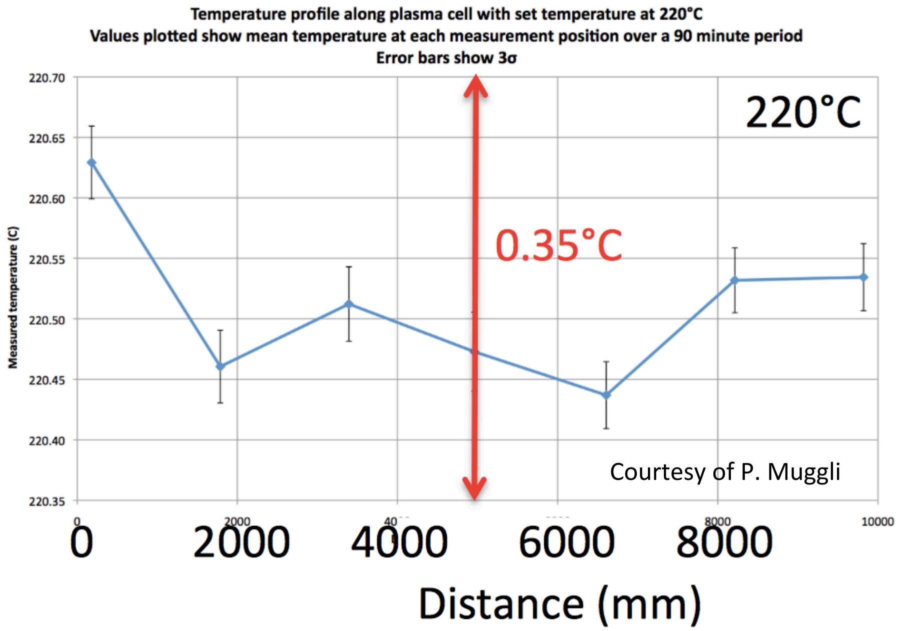
Acceptance simulation by A. Petrenko



Courtesy of U. Dorda

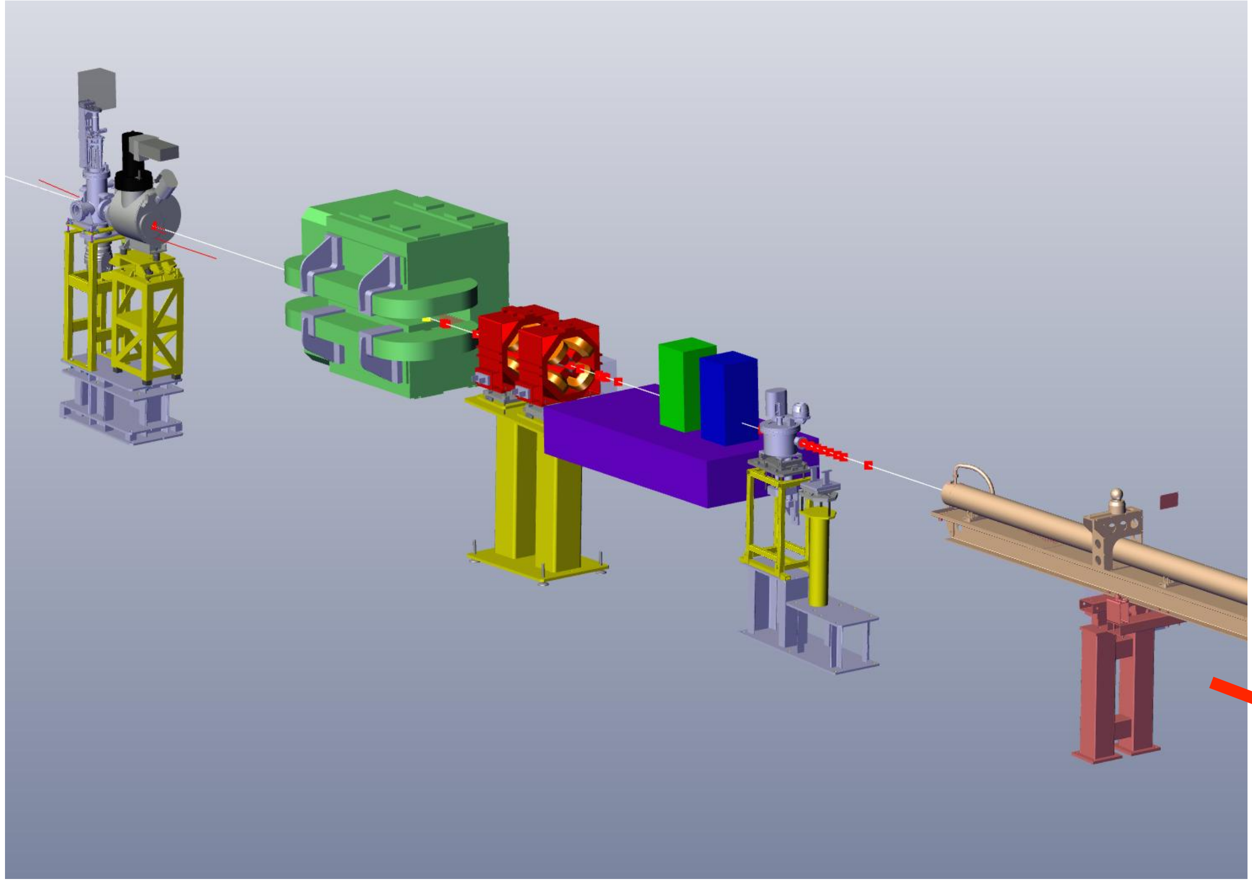
The Plasma Cell – Rubidium Vapor Source

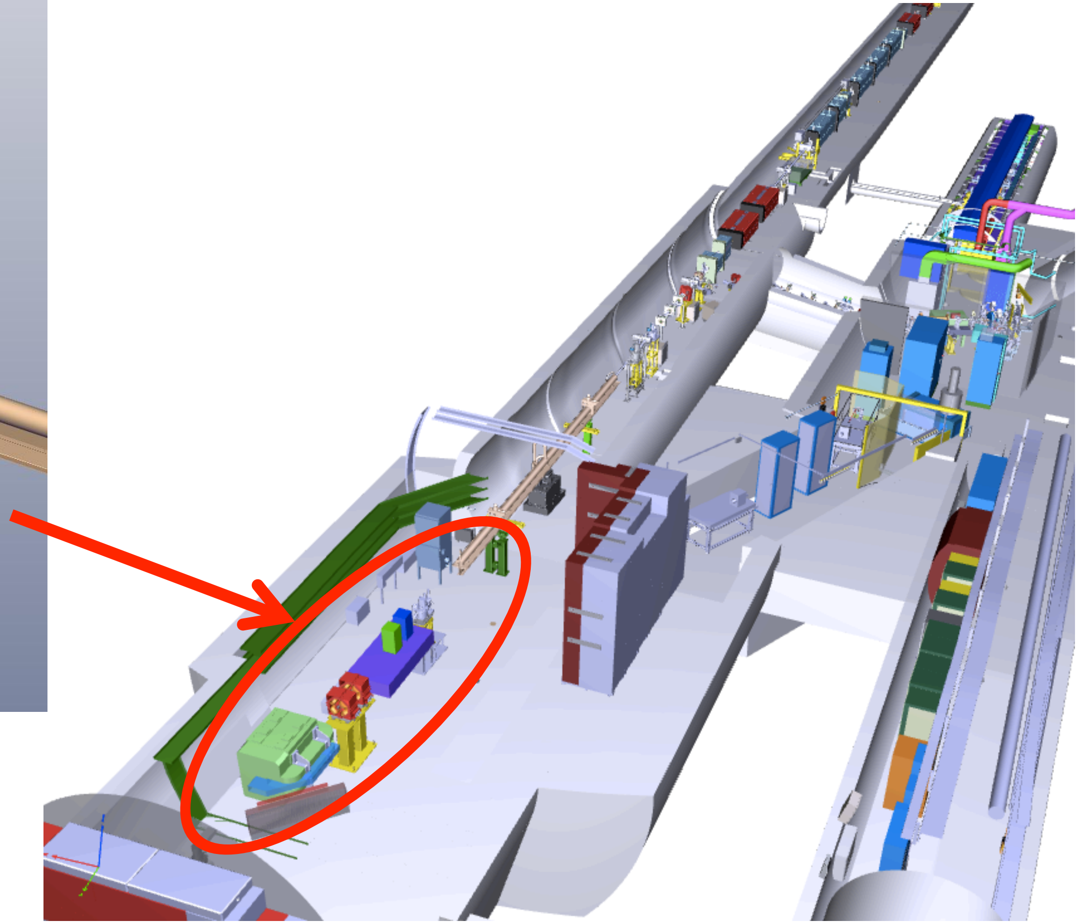
- Density adjustable from 10^{14} – 10^{15} cm^{-3}
  - Requirement: uniformity better than 0.2%
- 10 m long, 4 cm diameter
- Oil-heated system



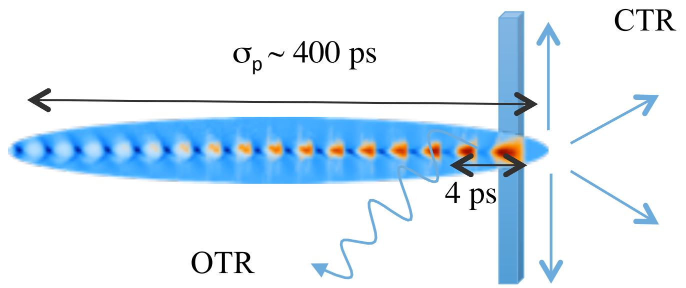
10 m long plasma cell prototype in the AWAKE test area at CERN

Diagnostic Section



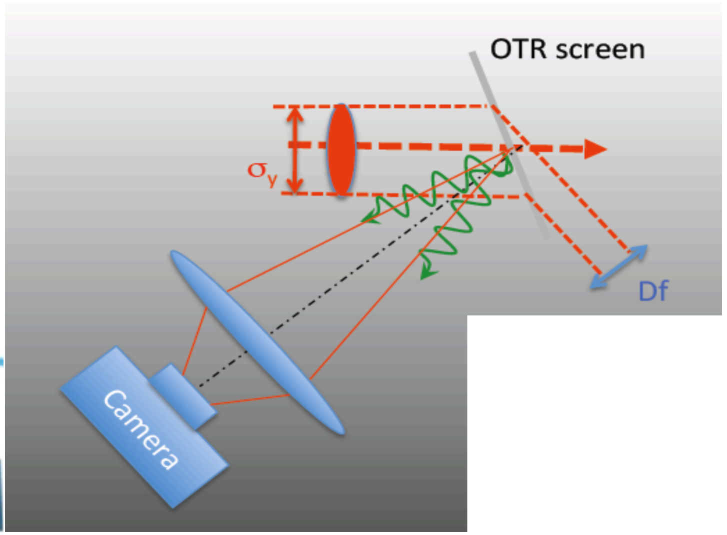


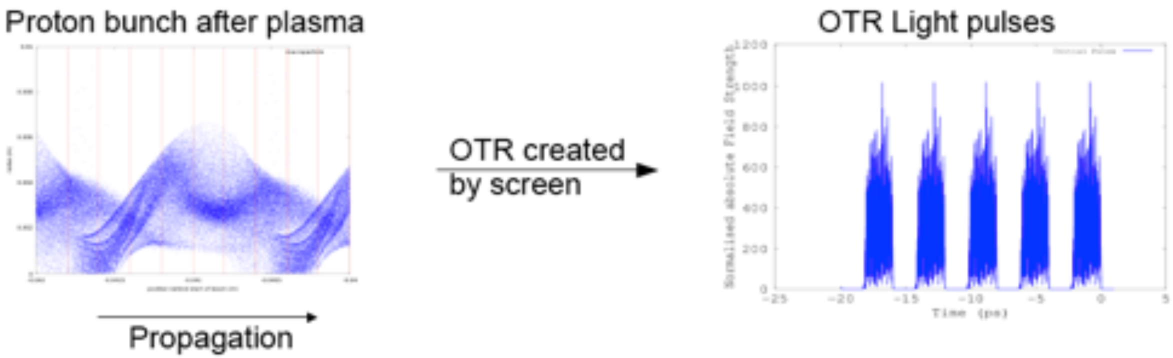
Direct Self-Modulation Diagnostic



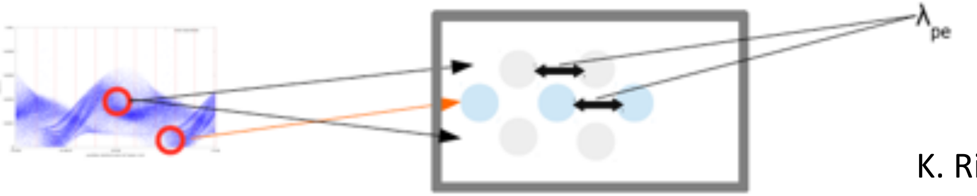
→ transforming the charge distribution information into a radiation distribution using transition radiation

→ Measured radiation emitted by the bunch when traversing a dielectric interface or by directly sampling the bunch space charge field.





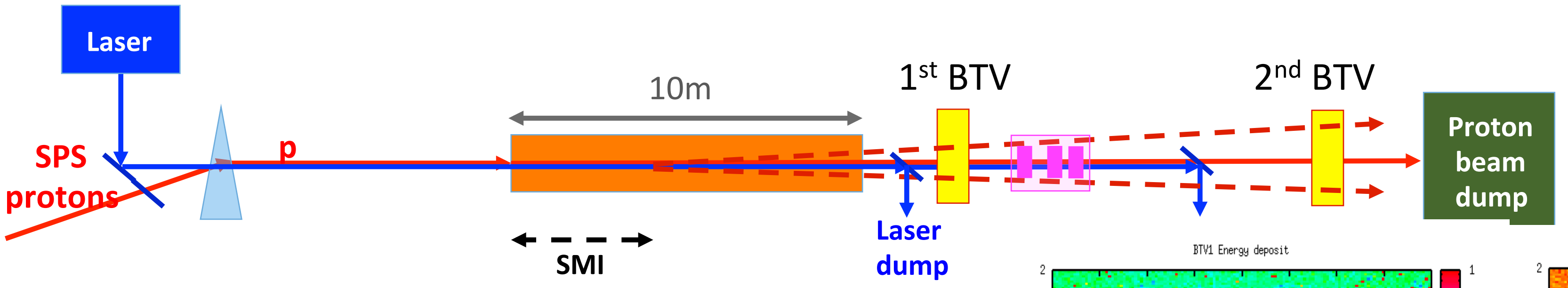
- Measure the OTR Light pulse with a streak camera (~ps resolution) while imaging:



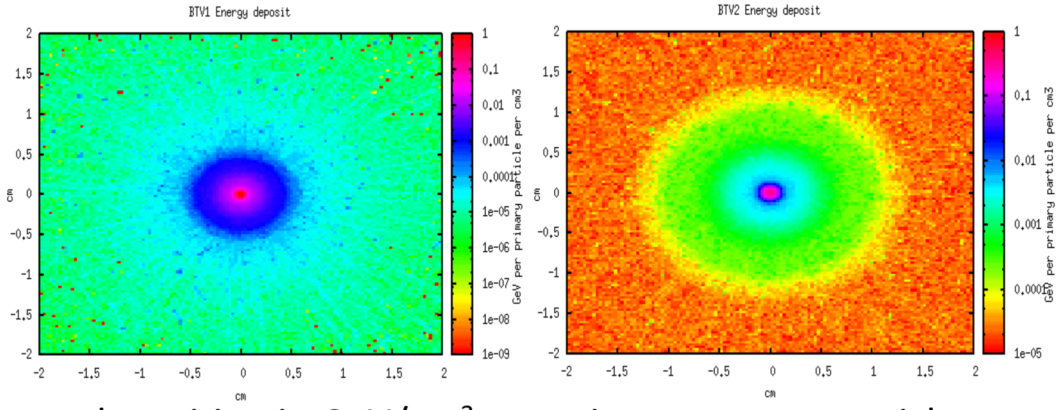
K. Rieger, M. Martyanov

Indirect Self-Modulation Diagnostic

- SMI causes angular divergence of the proton beam at the order of ~1 mrad.
- → Measure bunch profile at two different scintillator screens at a distance of ~8m



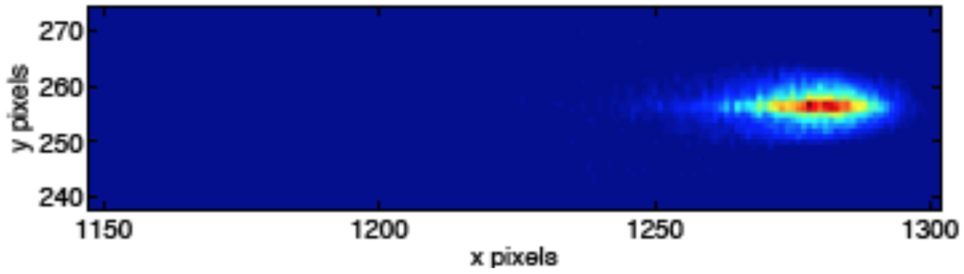
Measure saturation point of SMI at a 2% level.



Energy deposition in GeV/cm^3 per primary proton particle.

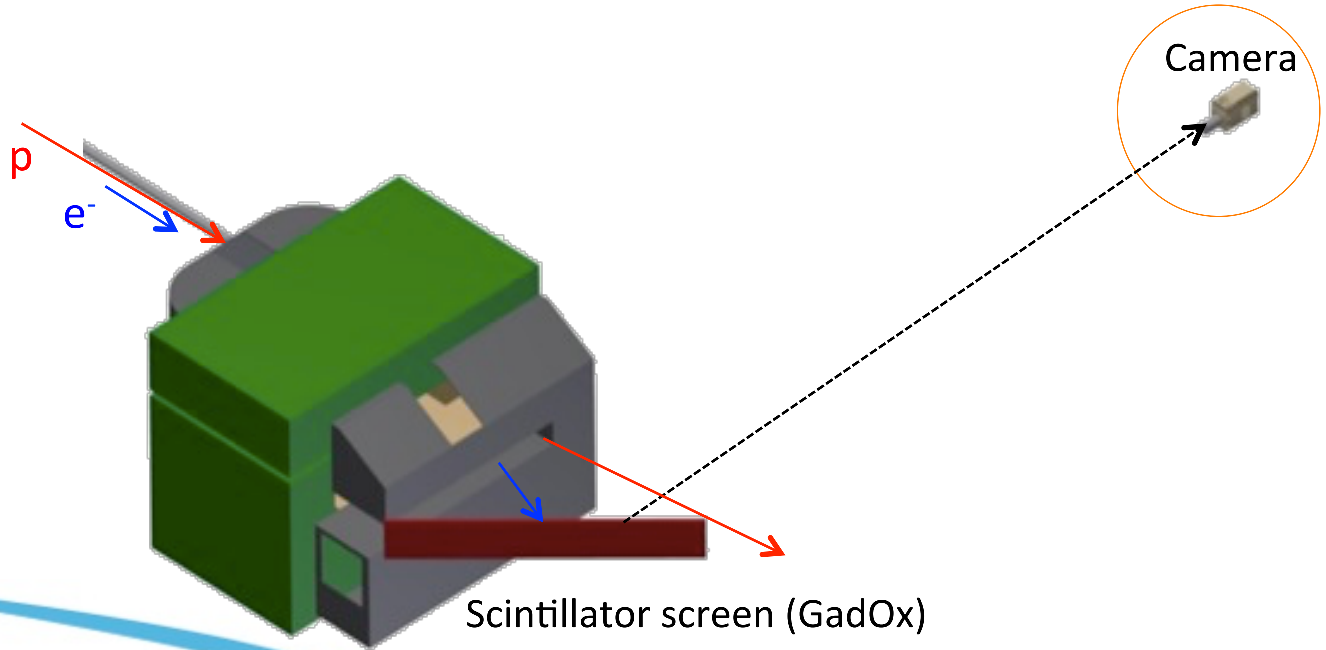
Electron Energy Spectrometer

- Be able to measure electron beam energies from 0-5 GeV

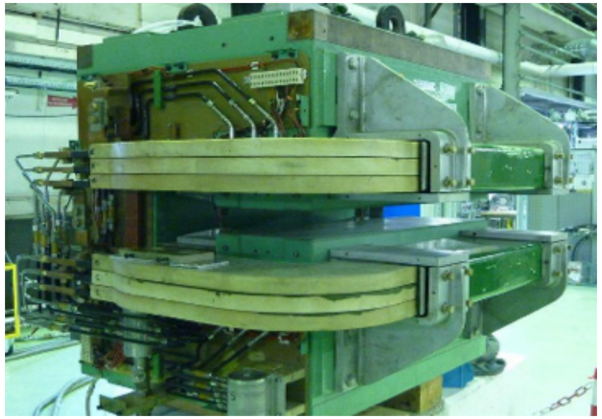


Dispersed electron impact on scintillator screen.
Resulting light collected with intensified CCD camera.

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



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



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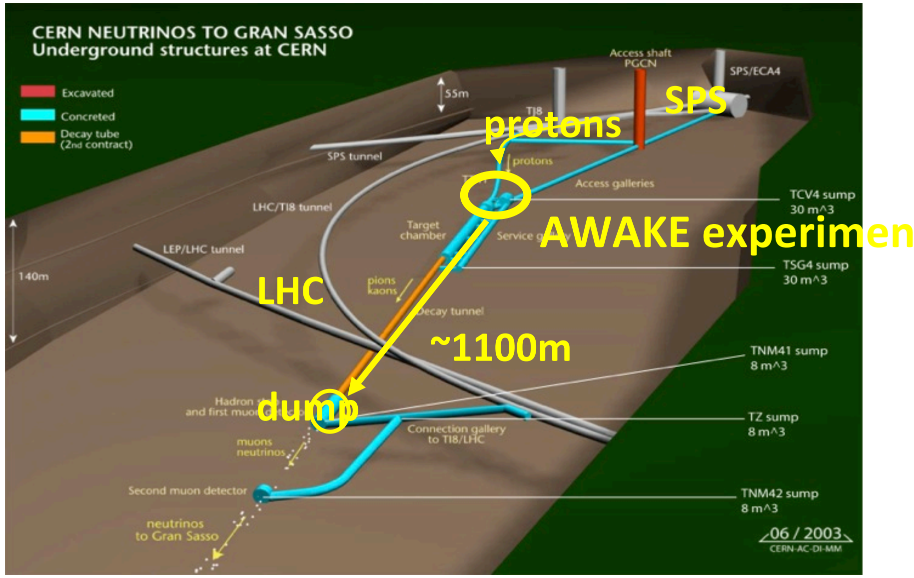
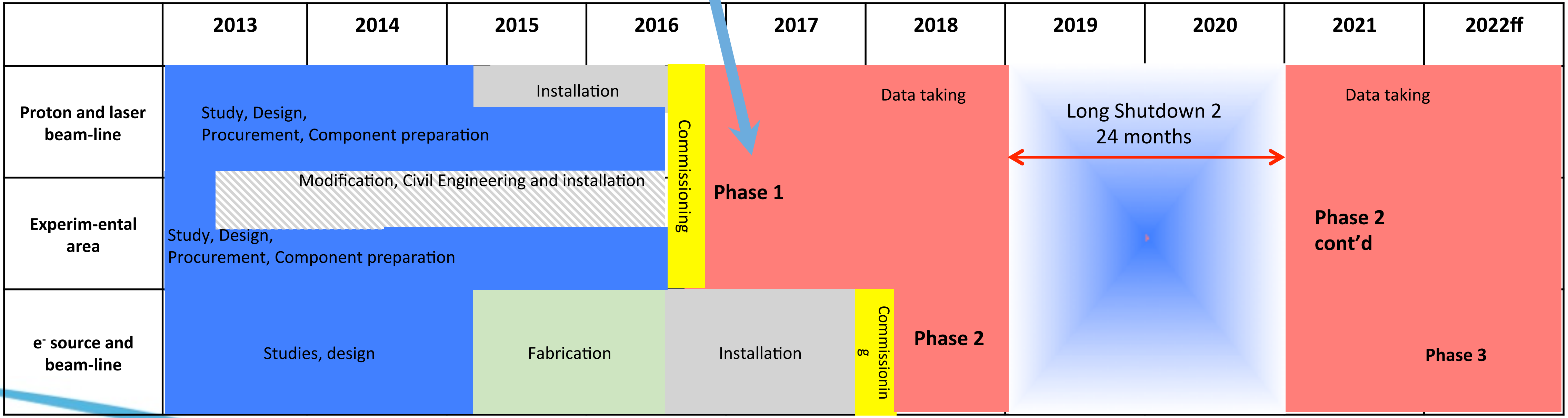
Time Line

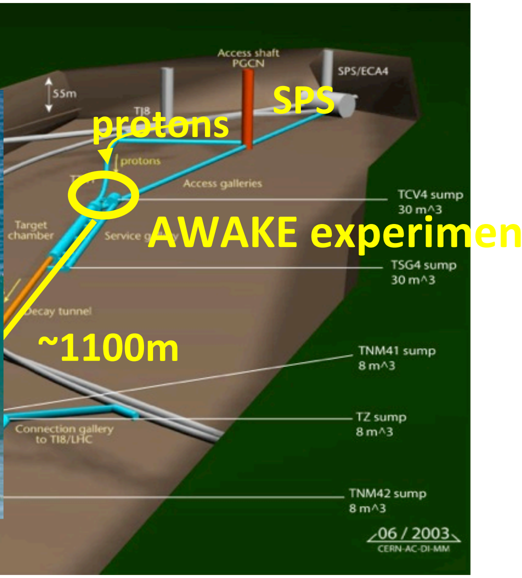


CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
Excavated
Concreted
Decay tube (2nd contract)
protons
SPS
AWAKE experimen
LHC
~1100m
dump
SPS tunnel
LHC/TI8 tunnel
LEP/LHC tunnel
Target chamber
Access galleries
Decay tunnel
TCV4 sump 30 m^3
TSG4 sump 30 m^3
TNM41 sump 8 m^3
TZ sump 8 m^3
TNM42 sump 8 m^3
Connection gallery to TI8/LHC
Second muon detector
neutrinos to Gran Sasso
140m
55m
06 / 2003



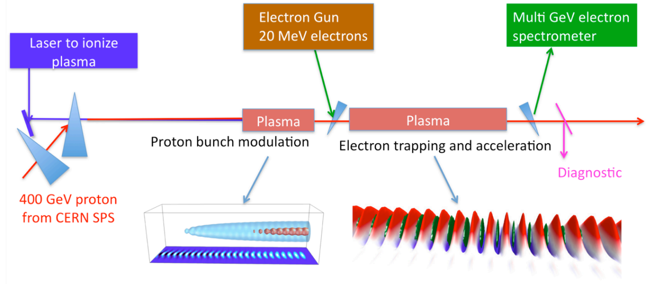
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022ff
Proton and laser beam-line
Experim-ental area
e- source and beam-line
Installation
Study, Design, Procurement, Component preparation
Modification, Civil Engineering and installation
Study, Design, Procurement, Component preparation
Commissioning
Data taking
Phase 1
Long Shutdown 2
24 months
Data taking
Phase 2 cont'd
Studies, design
Fabrication
Installation
Commissioning
Phase 2
Phase 3

Time Line



	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022ff
Proton and laser beam-line	Study, Design, Procurement, Component preparation		Installation	Installation; Commissioning	Data taking; **Phase 1**	Data taking	Long Shutdown 2 24 months		Data taking	
Experim-ental area	Study, Design, Procurement, Component preparation	Modification, Civil Engineering and installation		Commissioning	**Phase 1**				**Phase 2 cont'd**	
e$^-$ source and beam-line	Studies, design		Fabrication	Installation	Installation; Commissioning	**Phase 2**				**Phase 3**

Time Line



	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022ff
Proton and laser beam-line	Study, Design, Procurement, Component preparation		Installation	Installation / Commissioning	**Phase 1**	Data taking	Long Shutdown 2 24 months		Data taking	
Experim-ental area	Study, Design, Procurement, Component preparation	Modification, Civil Engineering and installation		Commissioning	**Phase 1**				**Phase 2 cont'd**	
e^- source and beam-line	Studies, design		Fabrication	Installation	Installation / Commissioning	**Phase 2**				**Phase 3**

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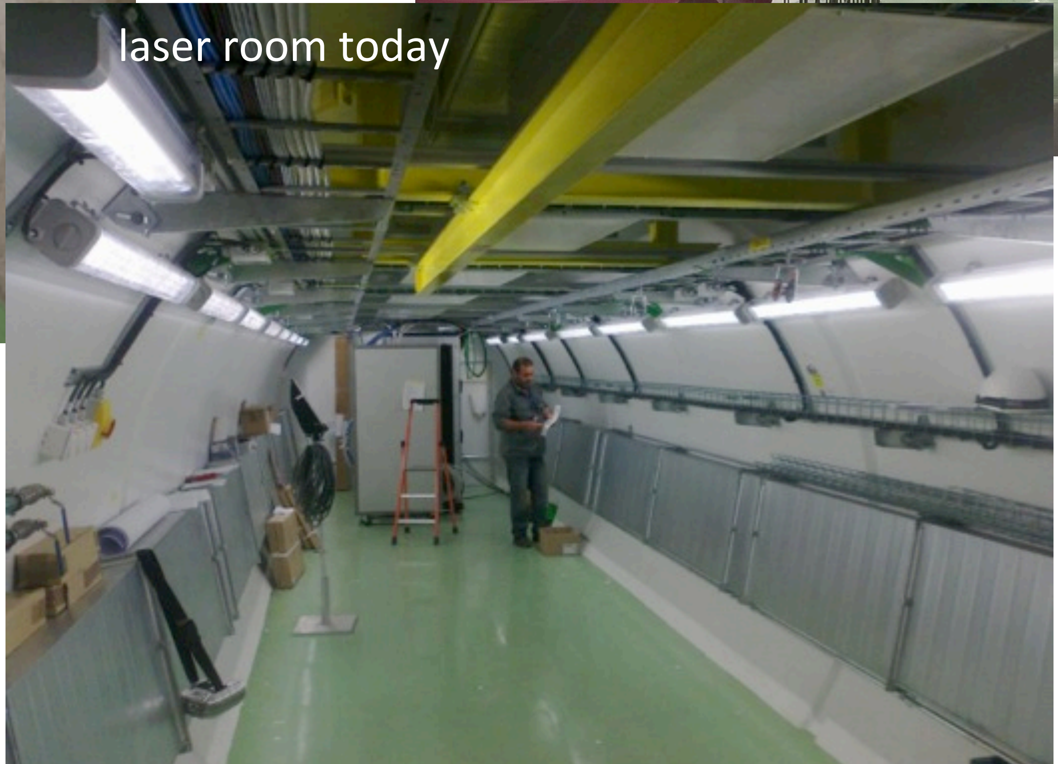
Laser Room



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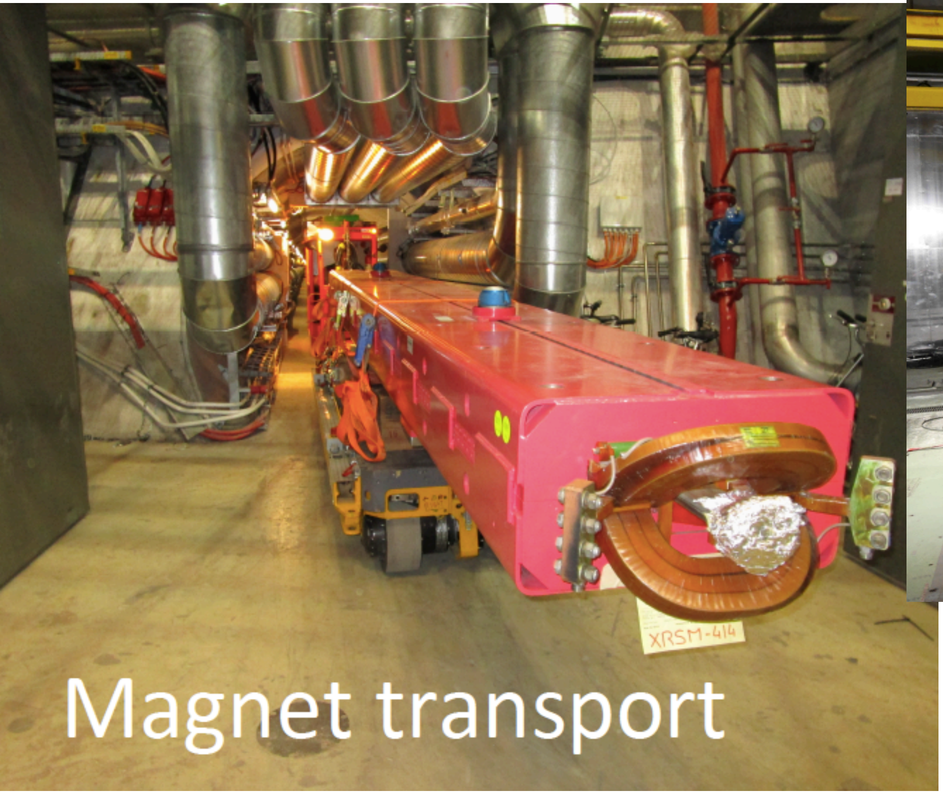
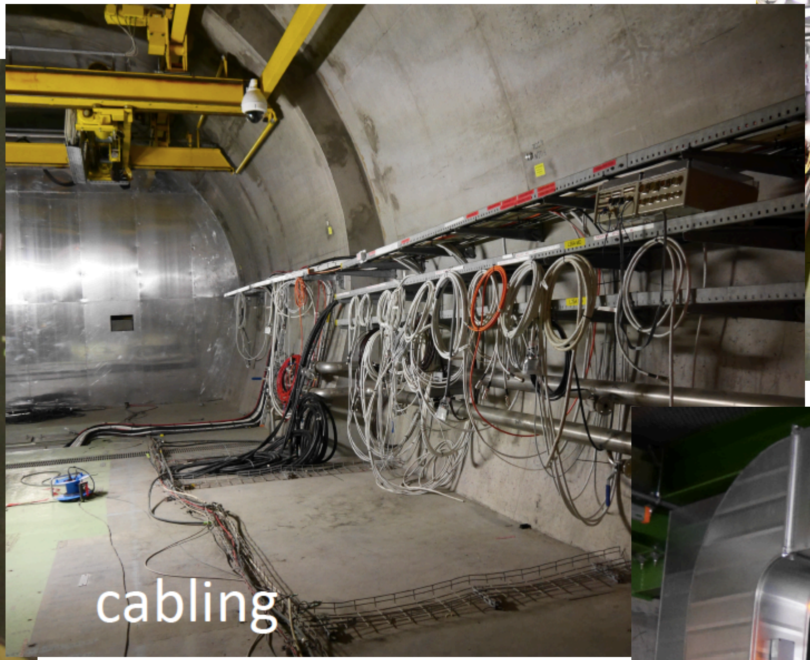
Proton Line and Target Area

General Installation





Ans Pardons

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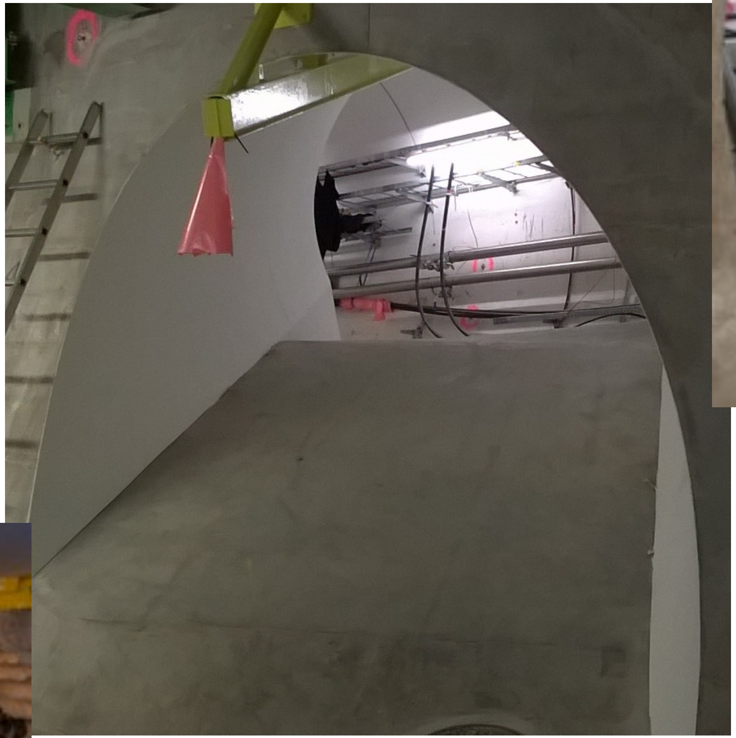
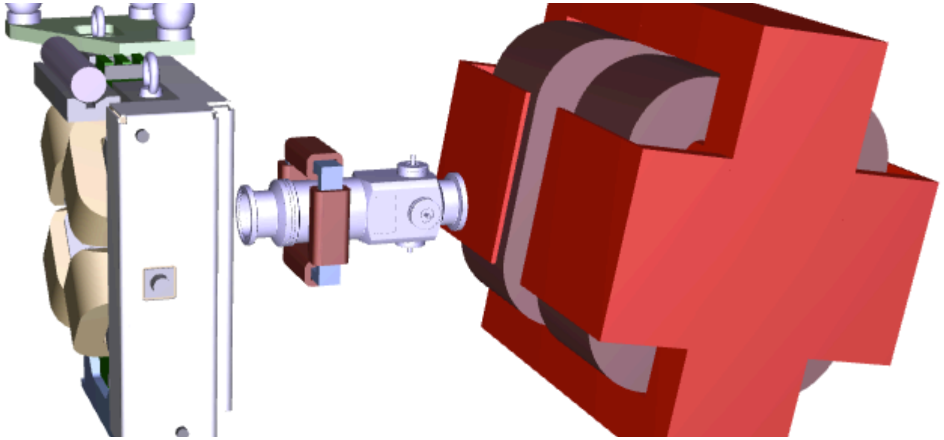
Electron Beam Line





Thank you

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