Particle Driven Acceleration Experiments

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CAS, Plasma Wake Acceleration 2014


STOP
DREAMING
AND
SNAP BACK
TO REALITY

Outline

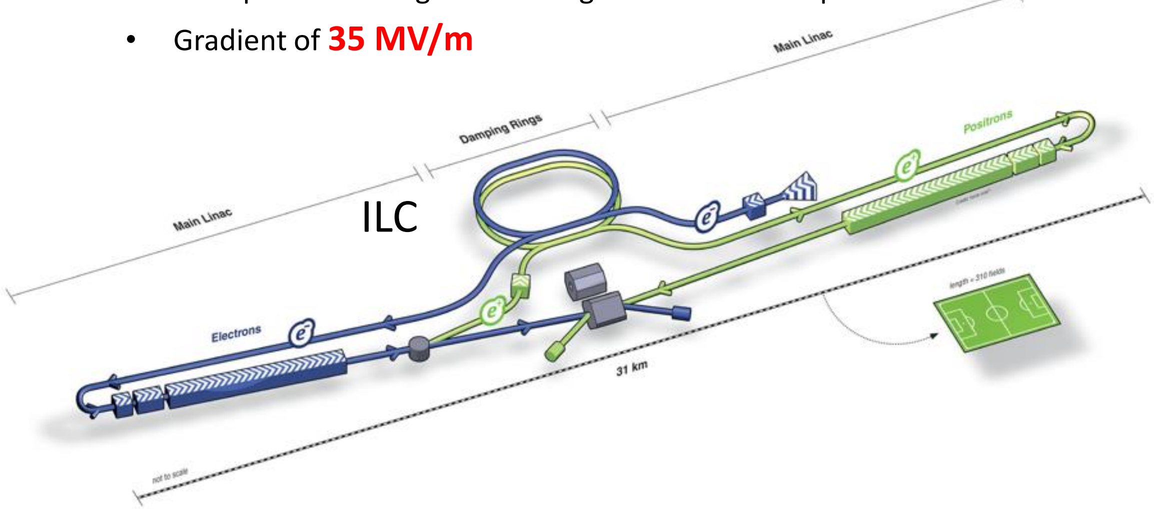
- Introduction
  - Motivation for Beam Driven Plasmas Wakefield Acceleration Experiments
  - Electron and proton driven PWA
- Overview table of experiments
- The example AWAKE
  - Which components are required for a Beam Driven PWA Experiment
    - Drive beam
    - Plasma cell
    - Diagnostics
    - Witness beam
    - Diagnostics
  - Put the pieces together
- Other beam driven PWA experiments
  - DESY-PITZ
  - Flash-Forward
  - FACET
- Summary

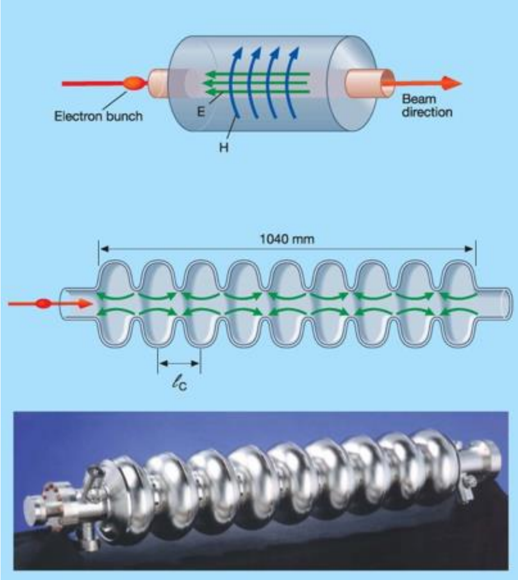
Main Driver for PWFA: Linear Collider

➔ Build a High energy collider at TeV range!

Linear collider based on RF cavities:

- Accelerating field **limited to <100 MV/m**
  - Several tens of kilometers for future linear colliders
  - For example ILC:
    - **31km long**
    - 500 GeV electrons
    - 16 superconducting accelerating cavities made of pure niobium
    - Gradient of **35 MV/m**





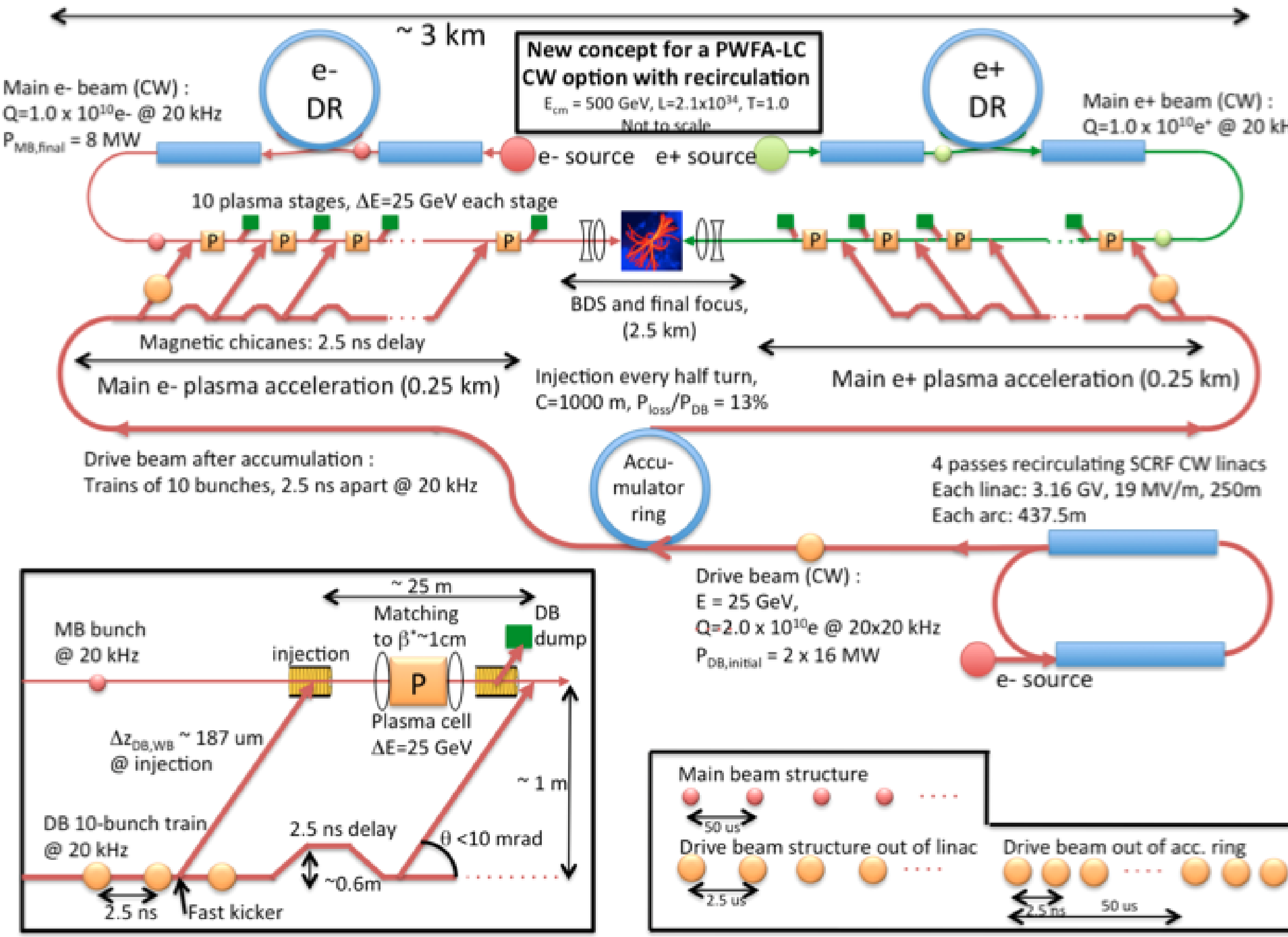
Linear collider based on plasma wakefield acceleration:

- Plasma can sustain up to **three orders of magnitude higher gradient**

  → Much shorter linear colliders!

Main Driver for PWFA research: Linear Collider

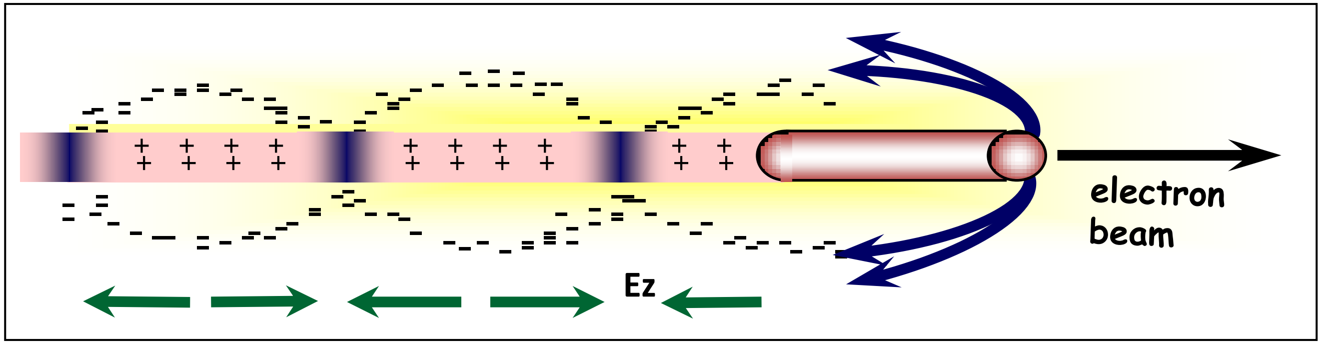
Aim to reach accelerators in the TeV range!



Main parameters		
E_{CM} GeV	500	3000
Effective gradient [MV/m]	1,000	1,000
Number of bunches [1×10^{10}]	1	1
Bunch spacing (CW) [μs]	50	100
Main beam power per beam [MW]	8	24
Linac length [km]	0.25	1.5
Overall facility length km	3	8
IP parameters		
σ_x [μm]	0.47	0.19
σ_y [nm]	2.7	1.1
β_x [cm]	1.1	1.1
β_y [cm]	0.01	0.01
σ_z [μm]	20	20
Total L [$\times 10^{34}$/cm^2/s]	2.1	6.3
$L_{1\%}$ [$\times 10^{34}$/cm^2/s]	1.3	3.8
Efficiency and power		
Drive to witness bunch efficiency [%]	50	50
# of plasma stages per linac	10	60
Drive linac bunch rep. freq. [kHz]	400	1200
Drive beam power per beam [MW]	16.2	48.6
Total wall plug power [MW]	150	297
Beam acceleration efficiency [%]	21	23
Wall plug to main beam efficiency [%]	11	16

* J.P.Delahaye, E. Adli et al., White Paper input to US Snowmass Process 2013

Electron Beam Driven PWA

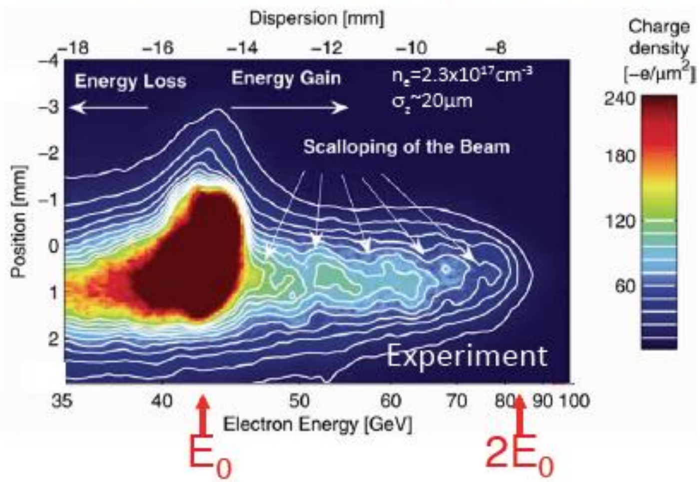


Electric fields can accelerate, decelerate, focus, defocus

- Test key performance parameters for the witness bunch acceleration:
  - Gradient
  - Efficiency
  - Energy spread
  - Emittance

➔ Experimental results show success of PWFA and its research
  - For example SLAC beam:
    - 42 GeV, 3nC @ 10 Hz, σ_x = 10μm, 50 fs

Blumenfeld, Nature 445, 741 (2007)



42 => 84GeV in 85cm! 50GeV/m

Electron Beam Driven PWA

- There is a limit to the energy gain of a witness bunch in the plasma:

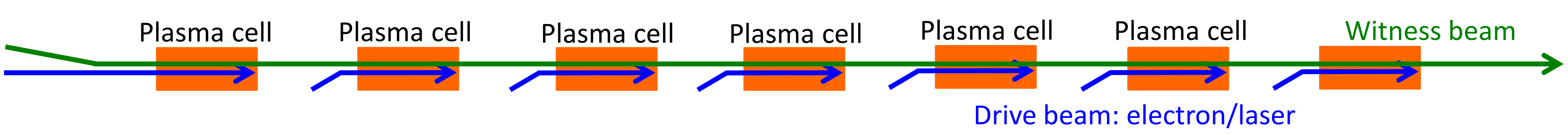
  $\Delta E_{witness} = R\, E_{drive}$ $R = 2 - N_{witness}/N_{drive}$

  → for $N_{witness} << N_{drive}$ → $\Delta E_{witness} = 2\, E_{drive}$

  → Energy gain of the witness beam can never be higher than 2 times the drive beam

  → Today's electron beams usually < 100 J level.

- To reach TeV scale with electron driven PWA: also need several stages, but need to have
  - relative timing in 10's of fs range
  - many stages
  - effective gradient reduced because of long sections between accelerating elements….



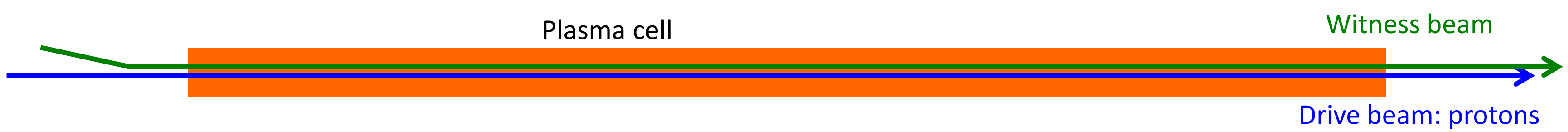
Proton Beam Driven PWA

Proton beams carry much higher energy:

- 19kJ for 3E11 protons at 400 GeV/c.
  - Drives wakefields over much longer plasma length, only 1 plasma stage needed.

Simulations show that it is possible to gain 600 GeV in a single passage through a 450 m long plasma using a **1 TeV p+** bunch driver of **10e11 protons** and an rms bunch length of **100 μm**.

A. Caldwell, K. Lotov, Physics of Plasma, 18,103101 (2011)



Protons are positively charged.

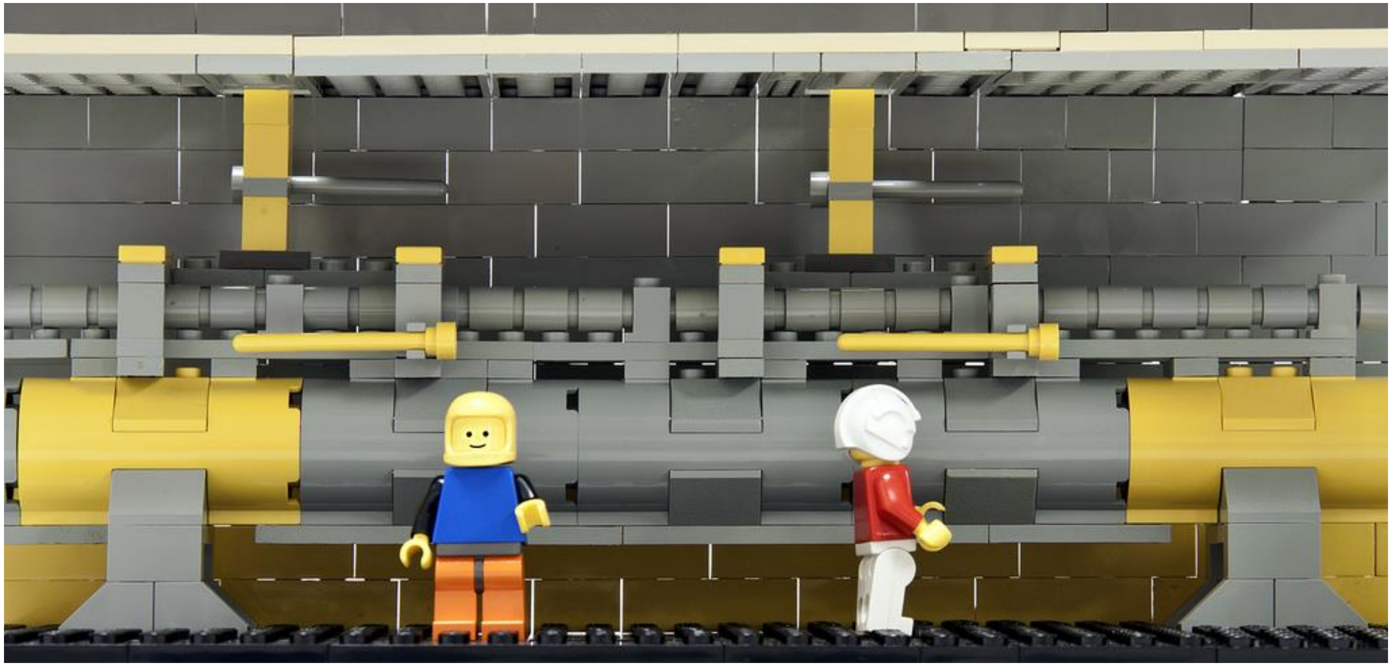
- They don't blow out the plasma electrons, they suck them in.
- The general acceleration mechanism is similar.

Beam-Driven Wakefield Acceleration: Landscape

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

Let's Build a Beam Driven Plasma Wakefield Accelerator Experiment

The Example AWAKE



The Example AWAKE

- AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment
  - First proton driven wakefield experiment worldwide
  - Proof-of-Principle Accelerator R&D experiment
  - final goal: pave the way for high-energy linear collider

- AWAKE Program
  - Study the Self-Modulation Instability (SMI)
  - Accelerate externally injected electrons
  - Demonstrate scalability of the acceleration scheme

Components for a Particle Driven Plasma Wakefield Acceleration Experiment

1. Drive beam
2. Plasma source system
   a. Plasma source
   b. Laser beam
3. Drive beam diagnostics

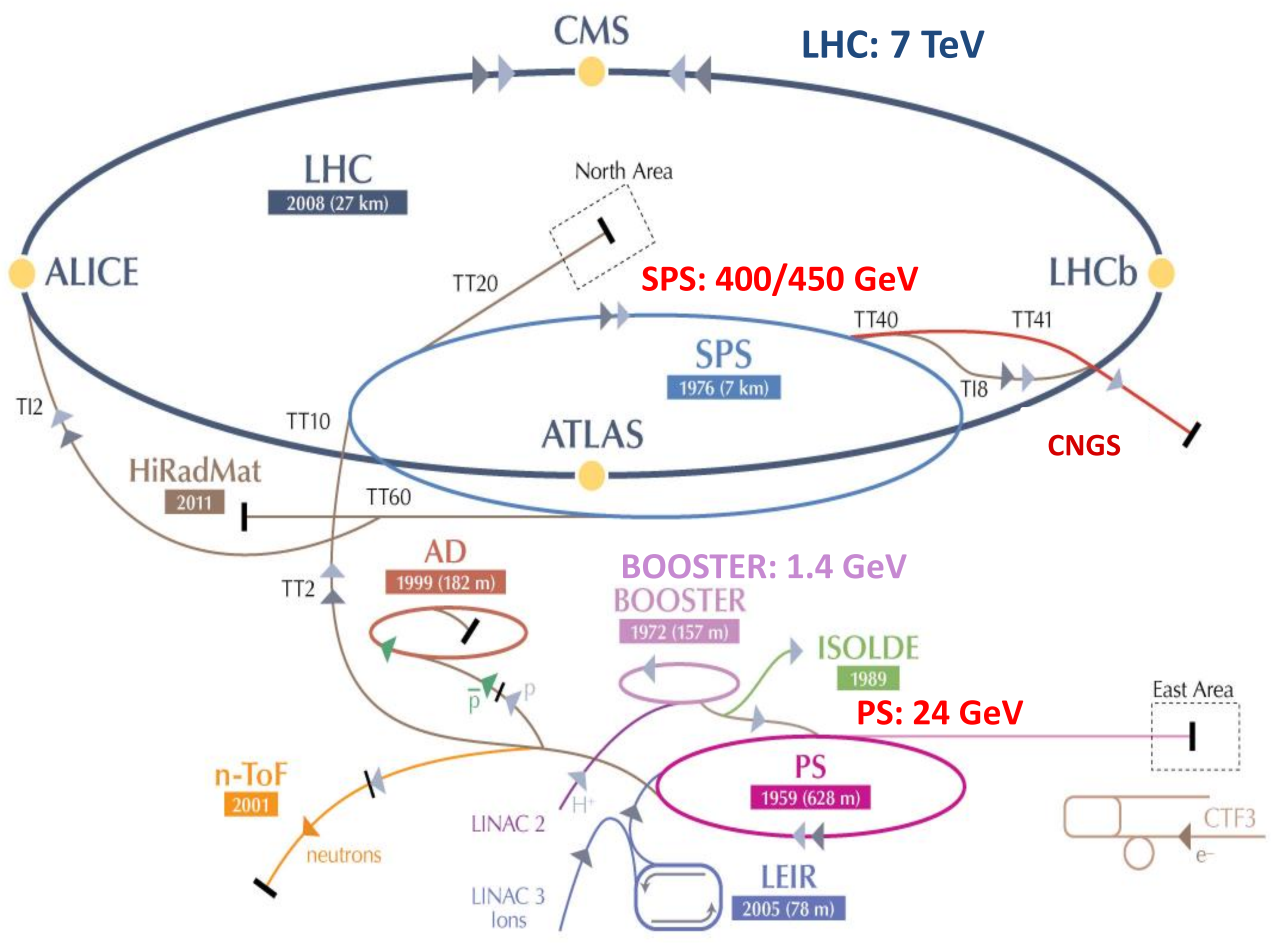
4. Witness beam
5. Witness beam acceleration diagnostics

1. Drive Beam: CERN Accelerator Scheme

In 2011:

5.3 10^{16} protons to LHC

1.37 10^{20} protons to CERN's Non-LHC Experiments and Test Facilities

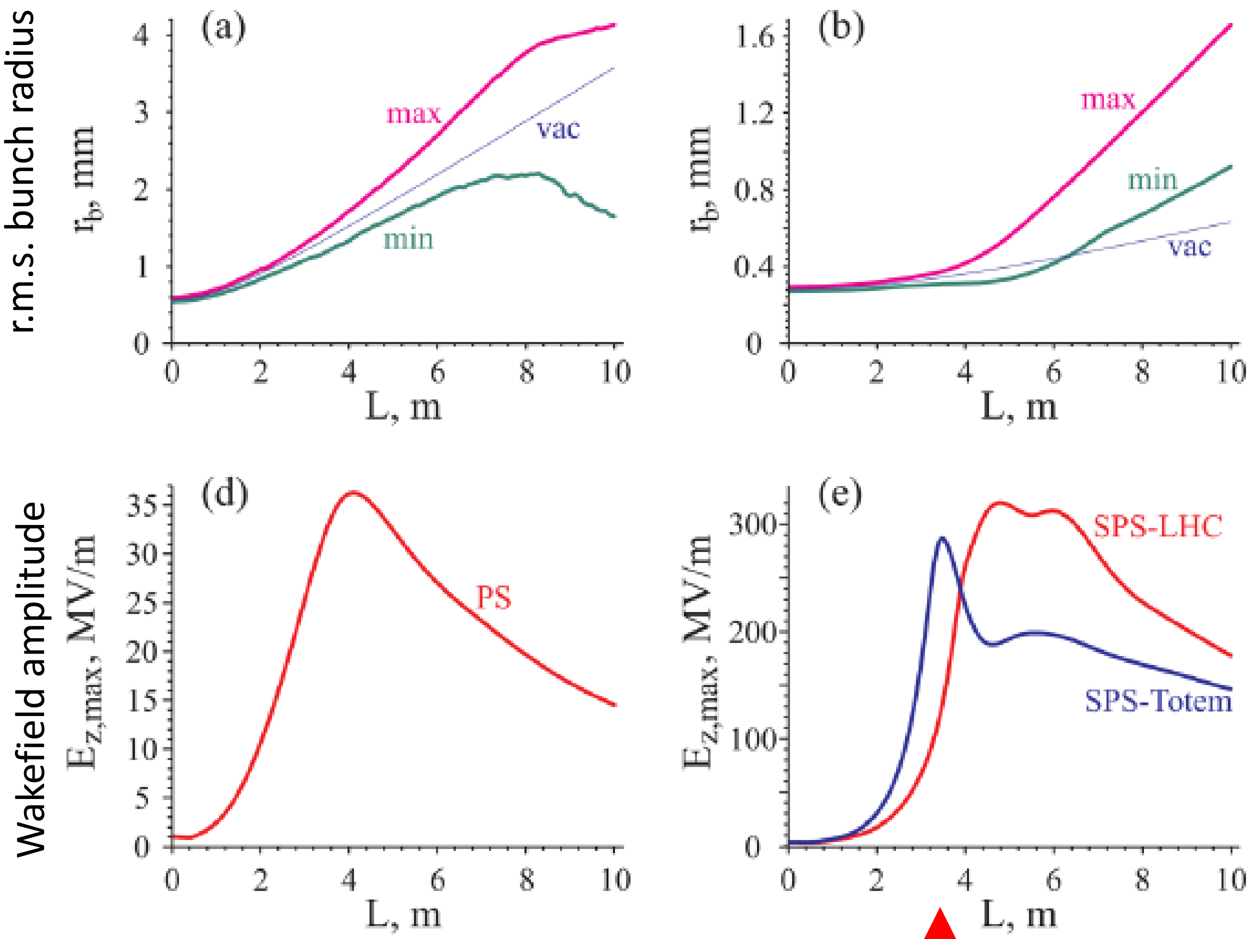


1. Drive Beam: Which Proton Beam Energy?

PS (24 GeV,1.3 E11 p)

SPS-LHC (450GeV, 1.15E11 p)

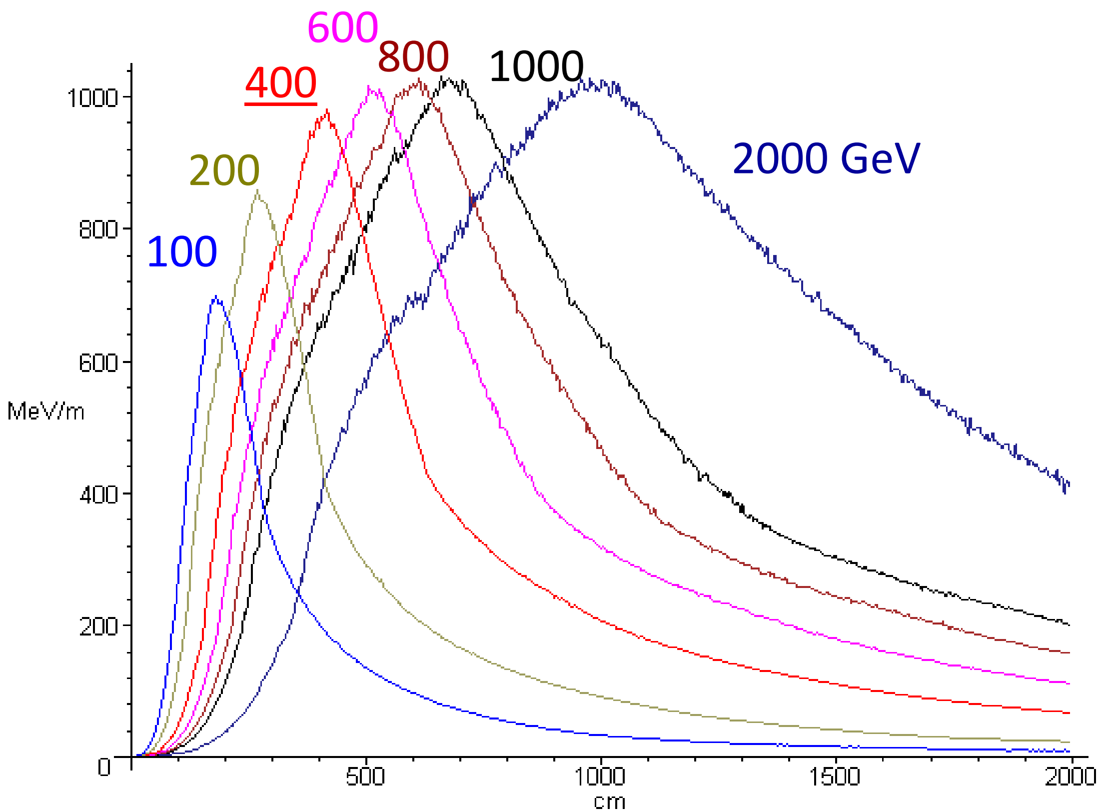
SPS-Totem (450GeV,0.3E11 p)



A. Caldwell, K. Lotov, Physics of Plasma, 18,103101 (2011)

SPS Beam

1. Drive Beam: Which Proton Energy?

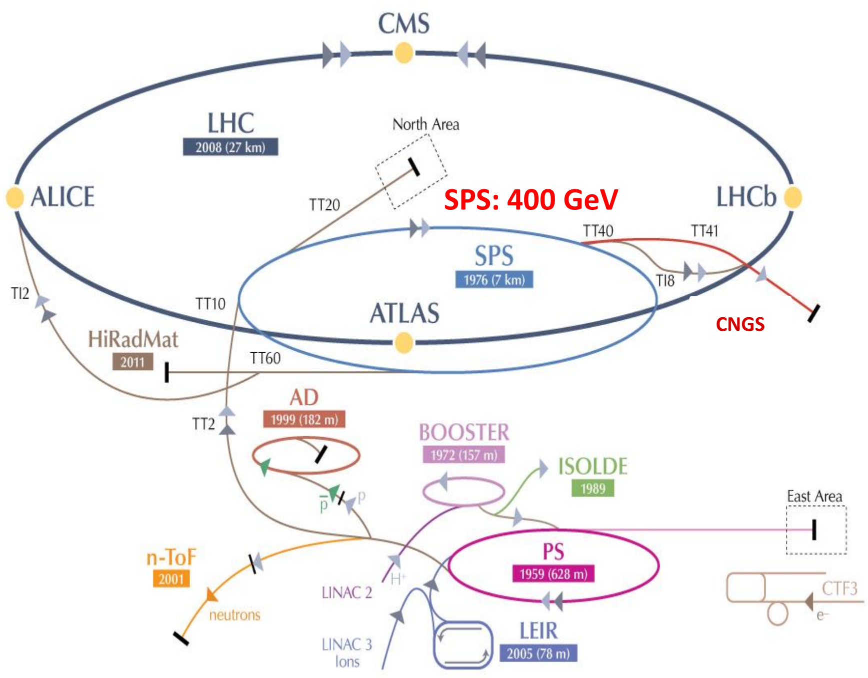


Variation of driver energy at constant normalized emittance

SPS-AWAKE parameters

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

1. Drive Beam: SPS Proton Beam



→ SPS Beam at 400 GeV/c

AWAKE will be installed in the CNGS, CERN Neutrinos to Gran Sasso, experimental facility.
CNGS physics program finished in 2012.

→ Proton beam for AWAKE requires:

- High charge
- Short bunch length
- Small emittance

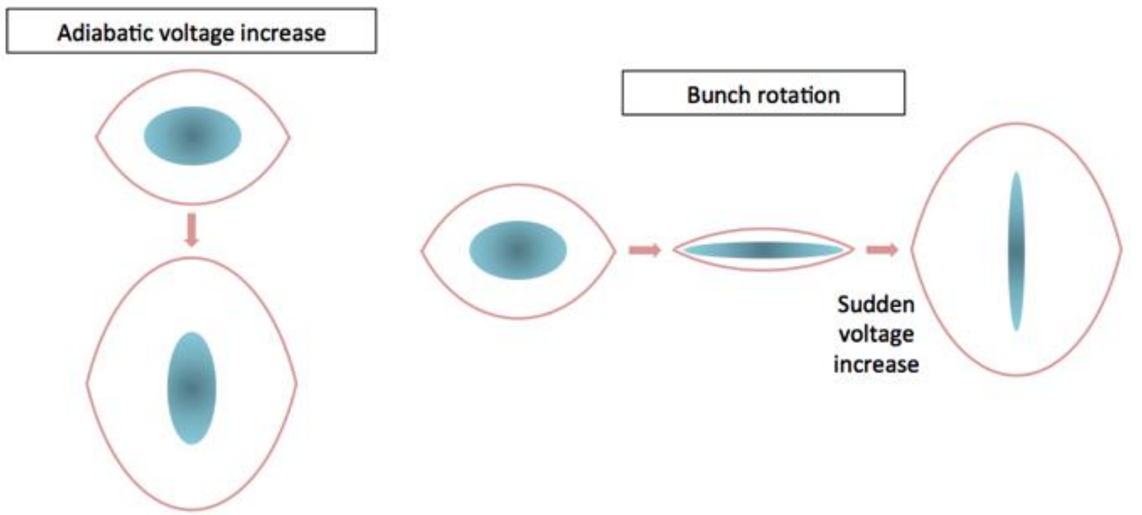
$$E_{z,\max} \approx 2\ \mathrm{GeV/m} \cdot \left(\frac{N_b}{10^{10}}\right) \cdot \left(\frac{100\ \mu\mathrm{m}}{\sigma_z}\right)^2$$

1. Drive Beam: SPS Proton Beam Optimization

In the SPS:

Use bunch rotation in longitudinal phase space instead of adiabatic voltage increase

→ bunches can be made shorter for the same voltage

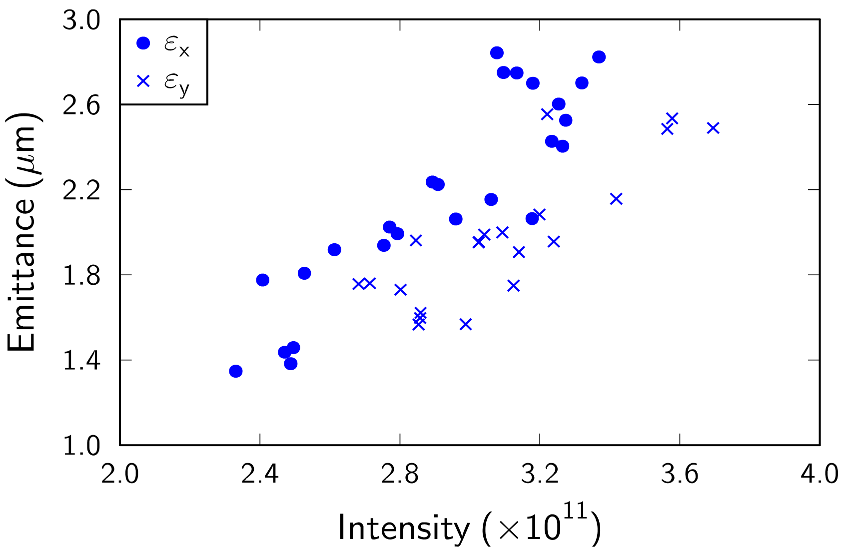


→ Main limitations for the proton beam:

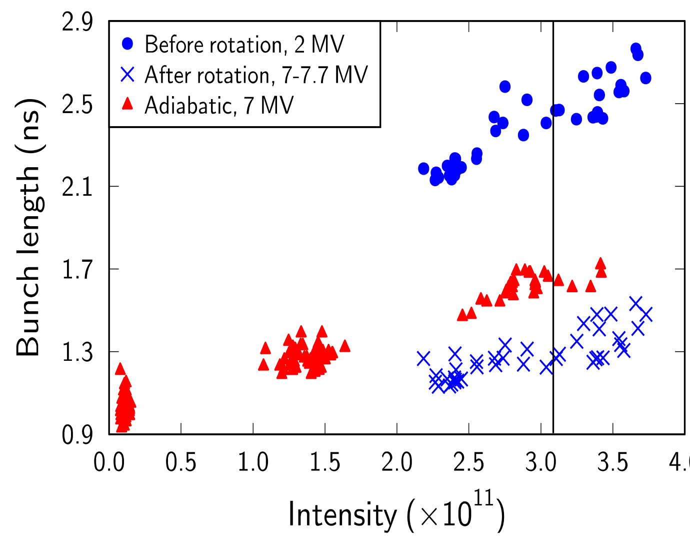
- The desired AWAKE intensities are significantly higher than the operational intensity
    - currently 1.6×10^{11} protons/bunch for the 50 ns spaced LHC beam
- Limited RF voltage in the SPS
- Intensity effects: beam-induced voltage, instability leading to uncontrolled emittance blow-up, Space-charge effect in SPS injectors and SPS flat bottom

1. Drive Beam: SPS Proton Beam Optimization

Transverse emittance at SPS flat top.



Flat top bunch length (4σ) before and after rotation.



E. Shaposhnikova, H. Timko et al, BE-RF

Results: SPS proton beam optimization:

→ 3 E 11 protons/bunch

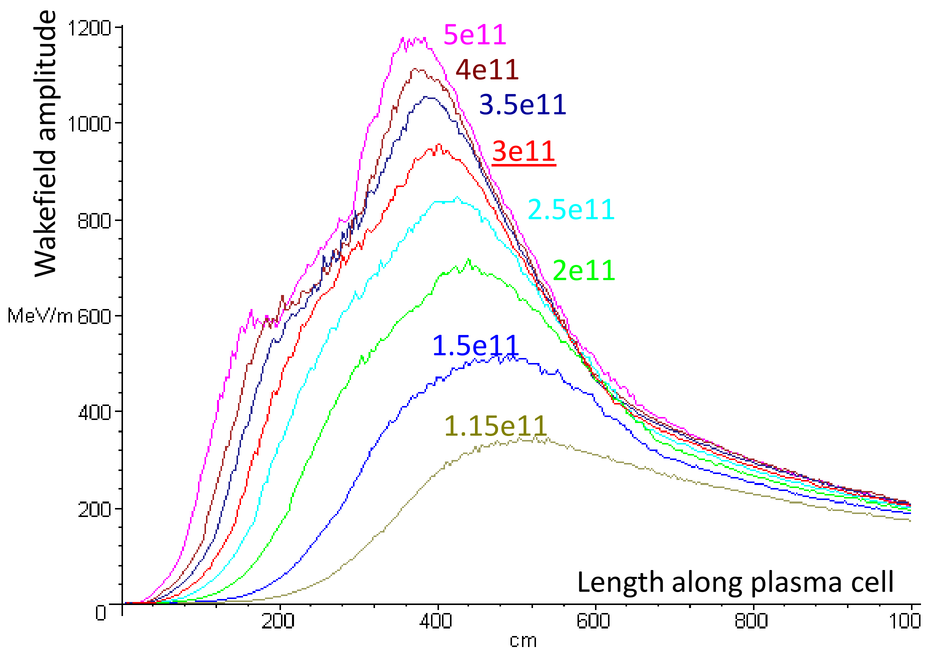
→ normalized transverse emittance of 1.7 mm mrad

→ r.m.s. bunch length of 9 cm (0.3ns)

→ Peak current of 60 A

1. Drive Beam: Proton Beam Sensitivity

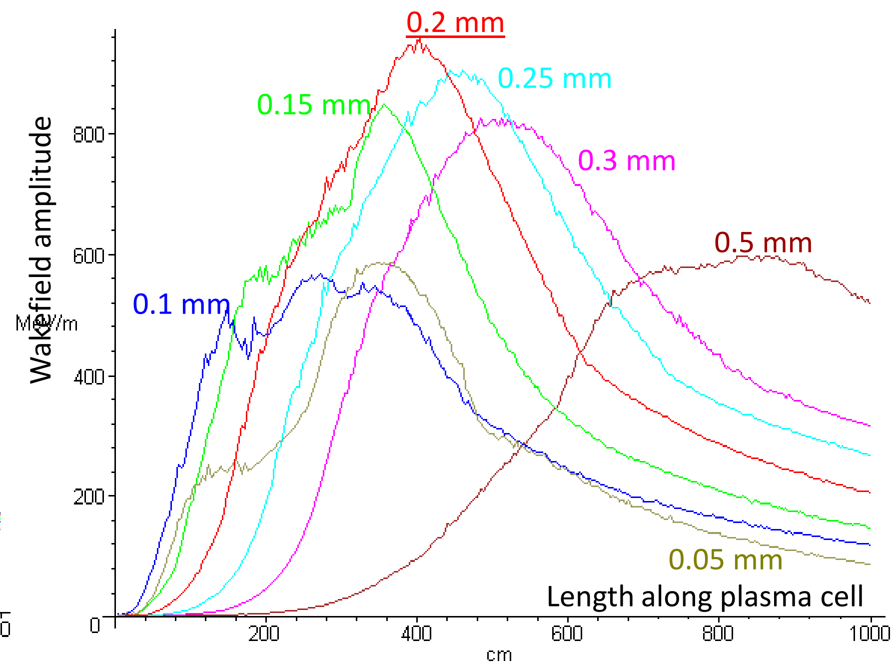
Proton beam population



The baseline regime is close to the limit (~40% of wave-breaking field)

Further increase of population does not result in proportional field growth.

Proton beam radius



Wide beams are not dense enough to drive the wave to the limiting field.
Narrow beams are quickly diverging due to the transverse emittance.

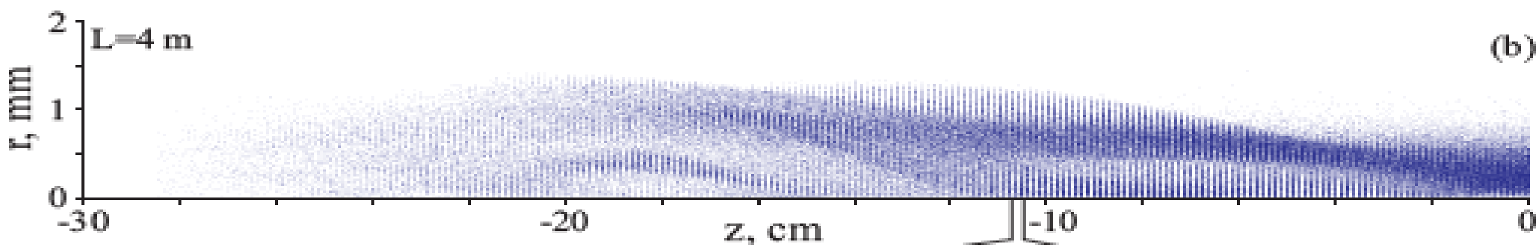
➔ Baseline radius is the optimum one for this emittance.

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

1. Drive Beam: Proton Beam Specifications

Nominal SPS Proton Beam Parameters	
Momentum	400 GeV/c
Protons/bunch	$3\ 10^{11}$
Bunch length	σ_z = 0.4 ns (12 cm)
Bunch size at plasma entrance	$\sigma^*_{x,y}$ = 200 μm
Normalized emittance (r.m.s.)	3.5 mm mrad
Relative energy spread	$\Delta p/p$ = 0.35%

Long proton beam σ_z = 12cm! ←→Compare with plasma wavelength of λ = 1mm.
→ Experiment based on Self-Modulation Instability!



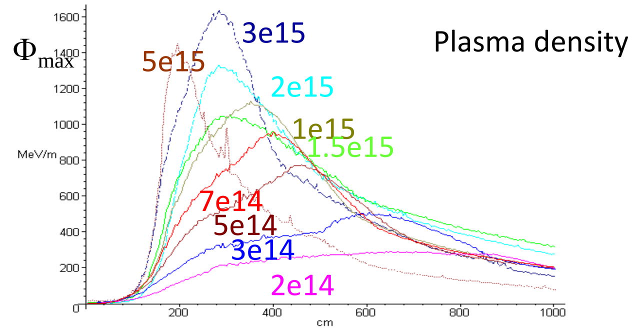
Self-modulation instability of the proton beam: modulation of a long (SPS) beam in a series of 'micro-bunches' with a spacing of the plasma wavelength.

1. Drive Beam: Summary

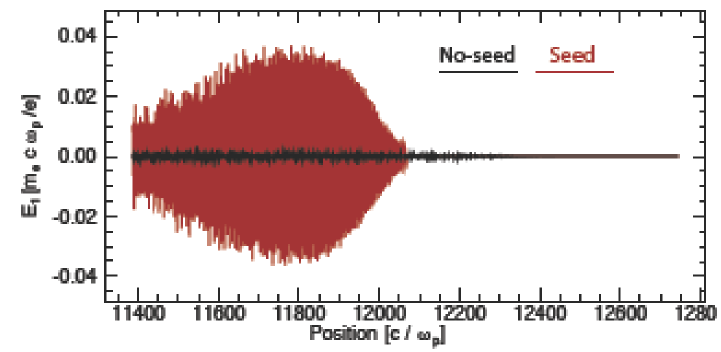
- Use 400 GeV/c SPS proton beam as drive beam for the AWAKE experiment
- SPS beam is optimized, however longitudinal beam size (σ_z = 12 cm) is much longer than plasma wavelength (λ = 1mm)
- Experiment is based on self-modulation instability
  - Modulate long bunch to produce a series of 'micro-bunches' in a plasma with a spacing of plasma wavelength λ_p.
    - → Strong self-modulation effect of proton beam due to transverse wakefield in plasma
    - → Starts from any perturbation and grows exponentially until fully modulated and saturated.

2a. Plasma Source: Requirements

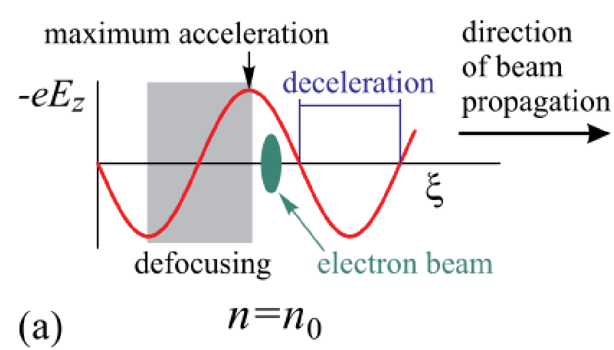
- Reach a strong wakefield
  - $E_z \ \alpha \ (n_e)^{-1/2}$



- Seeding of the SMI is necessary
  - Seeding shortens the length in the plasma
    - → until the SMI reaches saturation.
  - Fixes the phase of the wakefields
    - → deterministically inject the witness electron beam.
  - **➔ Seeding**



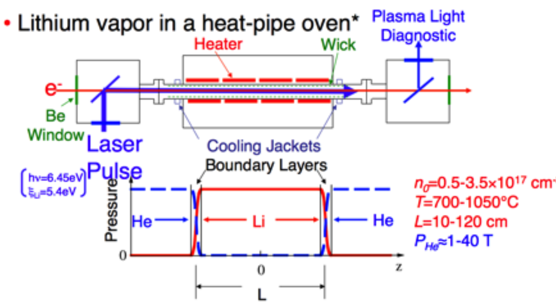
- Witness beam: very sensitive to the wakefield phase.
  - If λ_p changes locally, the witness electrons will be defocussed
  - → Wakefield phase is determined by the plasma density:
  - → Density must be constant with an accuracy of $\lambda_{pe}/4\sigma_z$
  - **➔ $\Delta n/n \leq 0.002$**



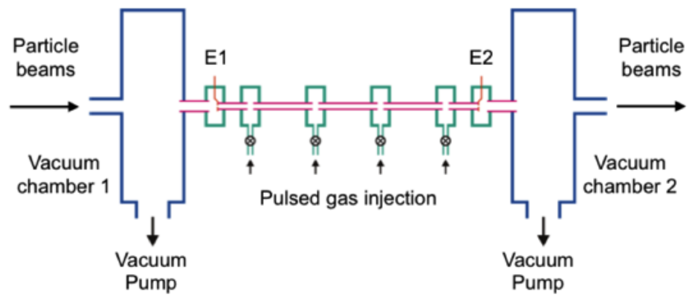
2a. Plasma Source: Different Types

- Metal Vapor Source (Li, Cs, Rb) → SLAC experiments
  - Very uniform, very well known
  - Ionization with laser. Scaling to long lengths?

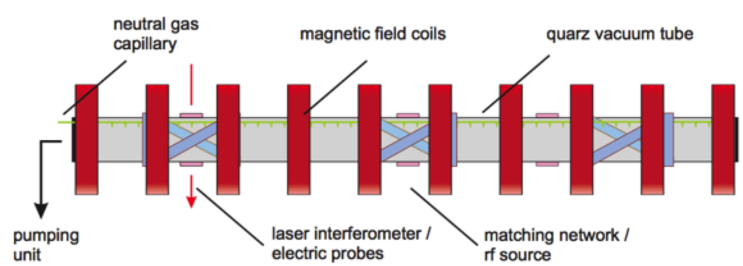
P. Muggli *et al.*, IEEE Trans. on Plasma Sci. 27, 791 (1999).



- Discharge plasma source
  - Simple, scalable
  - Uniformity? Density?

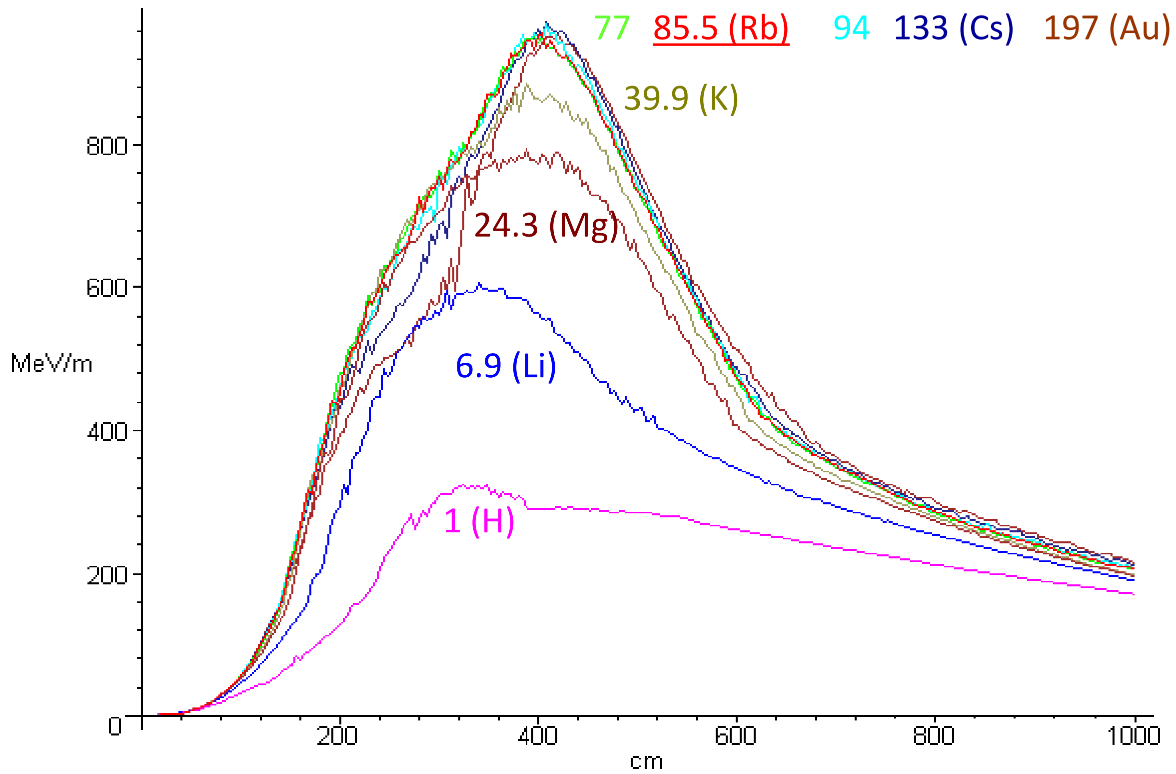


- Helicon source
  - Scalable, density recently achieved.
  - Uniformity?



2a. Plasma Source: Density Variations

Maximum wakefield amplitude vs ion mass



Rubidium is heavy enough to have no problems with ion motion

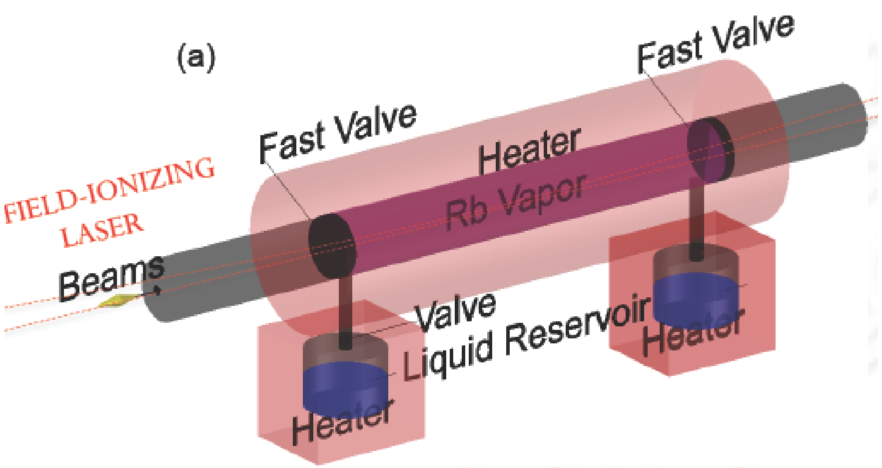
2a. Plasma Source: Rubidium Vapor Source

- Density adjustable from $\mathbf{10^{14} – 10^{15}\ cm^{-3}}$
- 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



Required:
$\Delta n/n = \Delta T/T \leq 0.002$

2a. Plasma Source: Rubidium Vapor Source

- Fast valves at both ends
  → separation of plasma from SPS beam vacuum.
  → Must be opened when laser/electron/proton passes through.

2a. Plasma Source: Summary

- Rubidium Vapor Source is used
  - Ionization with laser beam
- Density uniformity of 0.2% required
- Seeding of SMI is needed in the plasma cell
  - Use laser beam for seeding

2b. Laser Beam

- Laser intensity must exceed ionization intensity at the plasma end (L=10m) over a plasma radius of $r > 3\sigma = 600\ \mu m$.

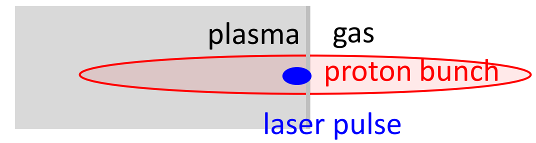
Laser Beam	
Laser type	Fiber Ti:Sapphire
Pulse wavelength	$\lambda_0 = 780$ nm
Pulse length	100-120 fs
Pulse energy (after compr.)	**450 mJ**
Laser power	4.5 TW
Focused laser size	$\boldsymbol{\sigma_{x,y} = 1}$ **mm**
Rayleigh length Z_R	5 m
Energy stability	±1.5% r.m.s.
Repetition rate	10 Hz

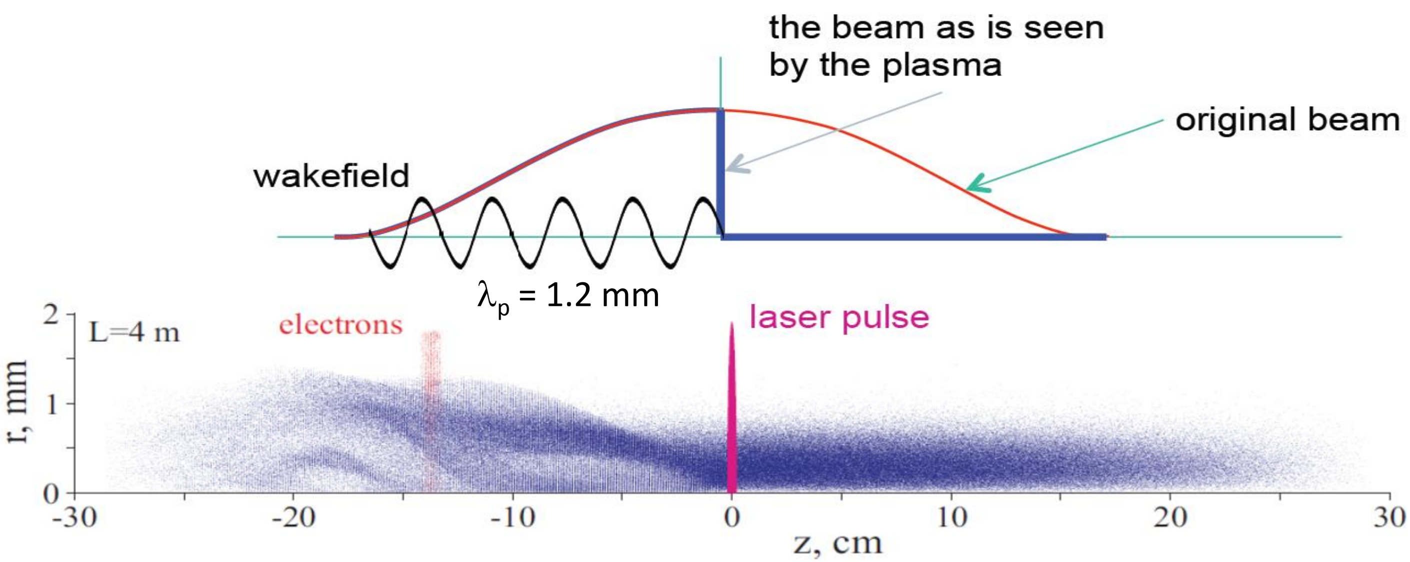
- Summary: ➔ 4.5 TW Laser for ionization and seeding

Combination 1.) 2a.) 2b.): Proton Bunch Modulation

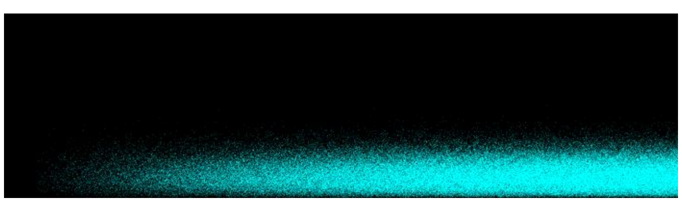
Self-Modulation Instability (SMI):

- Laser beam co-moving within the proton bunch effectively seeds the SMI
  - Laser pulse creates the ionization front
  - Ionization front acts as if long proton bunch is sharply cut
  - Laser pulse excites wakes to directly seed the self-modulation instability
  - grows exponentially until fully modulated and saturated.





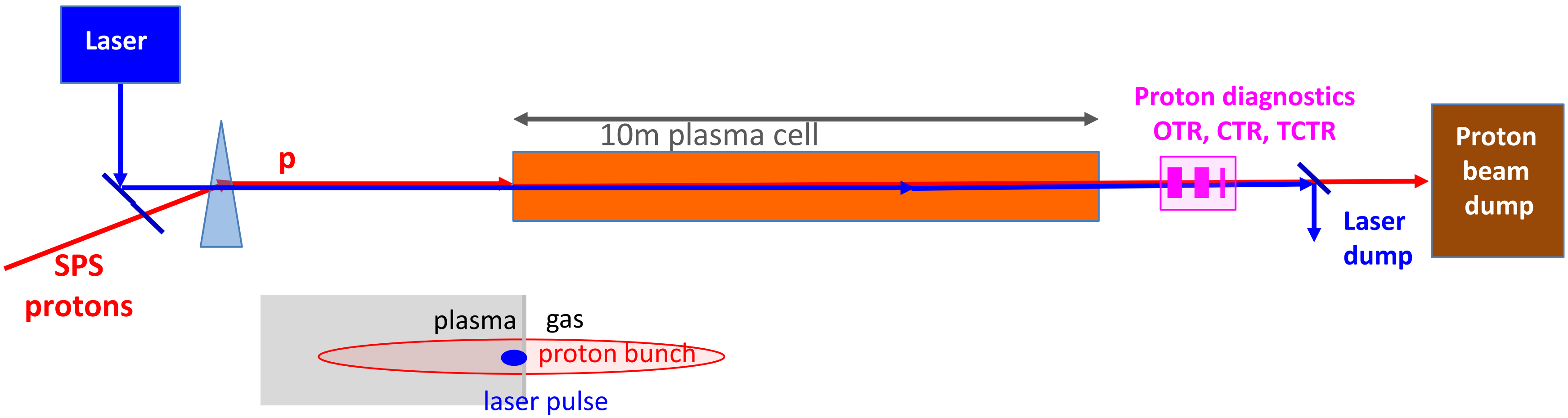
N. Kumar, A. Pukhov, K. Lotov, Phys. Rev. Letters (2010):



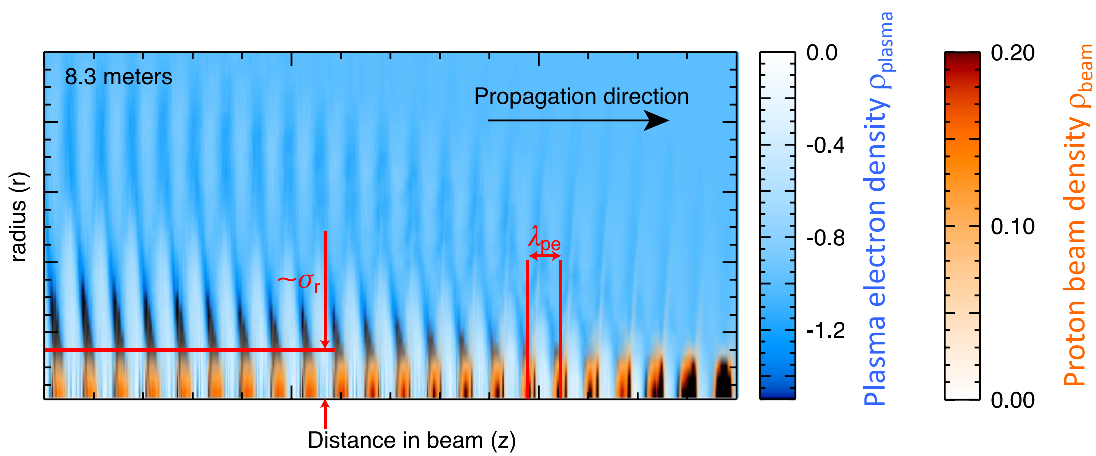
Self-modulated proton bunch resonantly driving plasma wakefields.

AWAKE: 1st Experimental Phase

- Perform **benchmark experiments using proton bunches** to drive wakefields for the first time ever.
- Understand **the physics of self-modulation instability** processes in plasma.



Self-modulated proton bunch resonantly driving plasma wakefields.



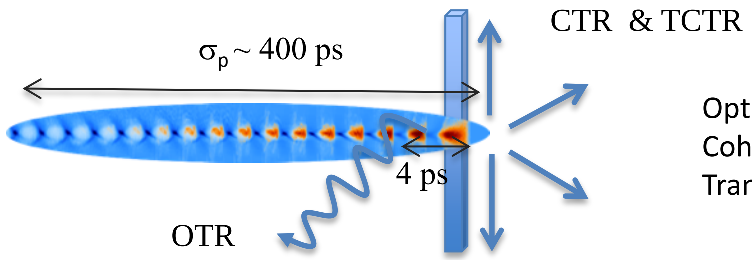
J. Vieira et al PoP 19063105 (2012)

3. Drive Beam Diagnostics

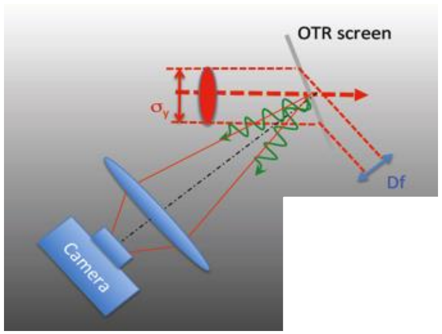
Direct Measurement of self-modulation instability of the proton beam

→ **results in radial modulation of the proton beam (micro-bunches)**

– Measured by using the radiation emitted by the bunch when traversing a dielectric interface or by directly sampling the bunch space charge field. → streak-camera.

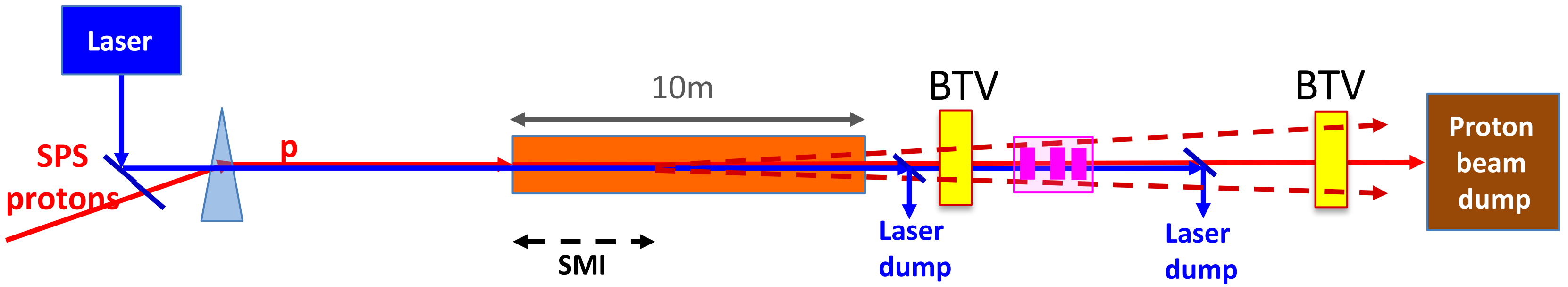


Optical Transition Radiation (OTR)
Coherent Transition Radiation (CTR)
Transverse Coherent Transition Radiation (TCTR)



Indirect Measurement by observing the proton bunch defocusing downstream the plasma

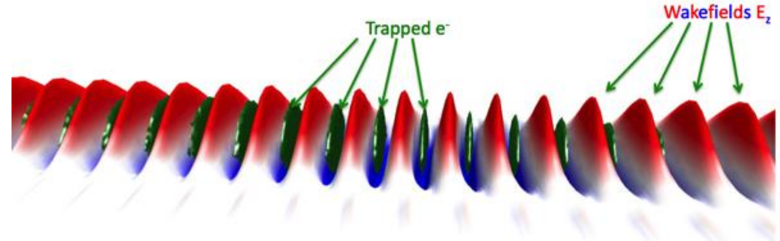
→ **Proton bunch: 1mrad divergence**

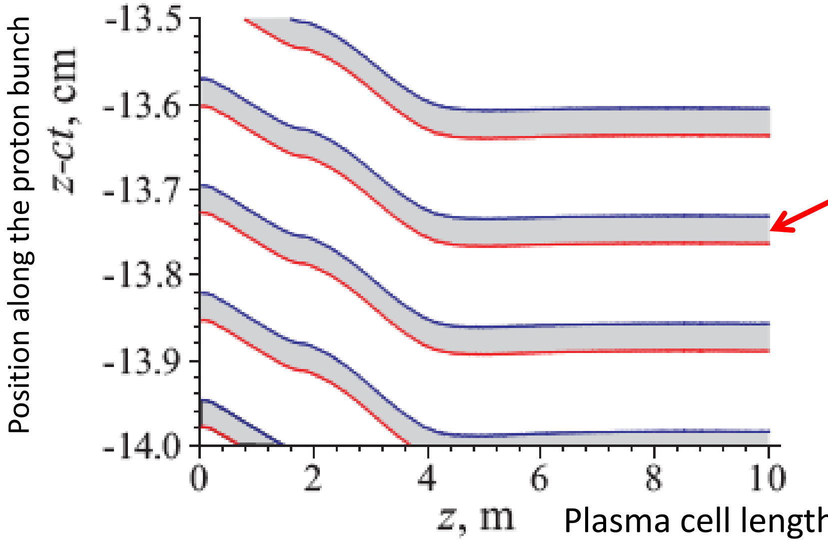


4. Witness Beam: Beam Characteristics

Externally injected electron beam

→ **Which energy?**





Area (grey) where wakefields are both accelerating and focusing for the witness electrons

→ Electrons must be trapped in the accelerating/focusing wakefield

SMI: grows in the first ~4 m and is then fully developed.

- Wakefield phase velocity is slower than that of the drive beam.
- Approaches light velocity at z ~4m.

4. Witness Beam: Beam Characteristics

→ Optimal electron energy is 10-20 MeV

- Electron energy = wakefield phase velocity at self-modulation stage.
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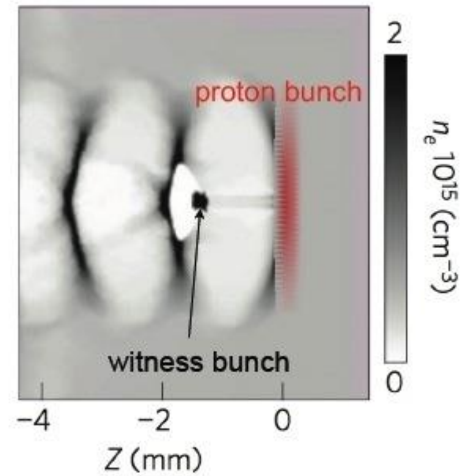


→ Electron bunch length:

- Should be small to be in phase with high field region.

→ Electron beam should have small enough size and angular divergence to fit into high capture efficiency region.

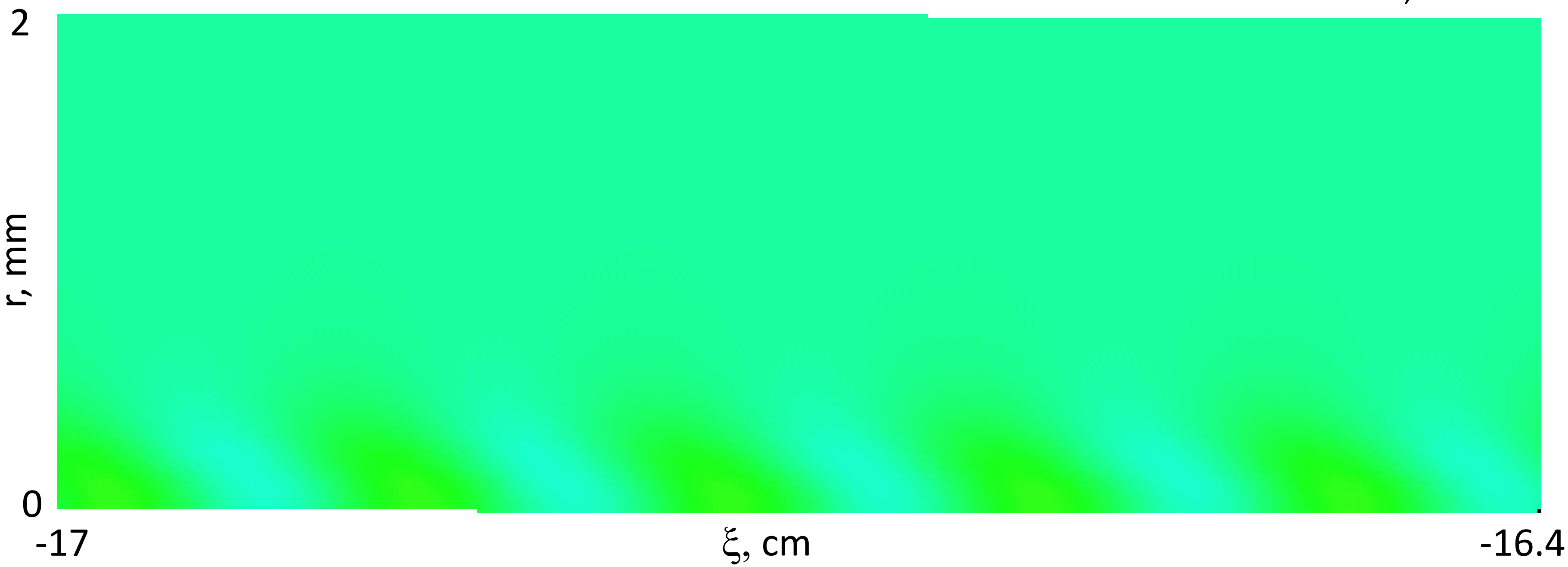
→ Electron beam intensity: get good signal in diagnostics!

Electron beam	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%

4. Witness Beam: Electron Trapping and Acceleration

black points – injected electrons, false colors – wakefield potential

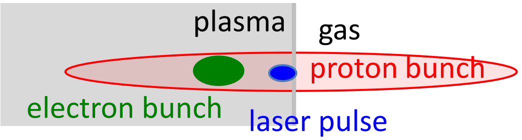
K. Lotov, LCODE



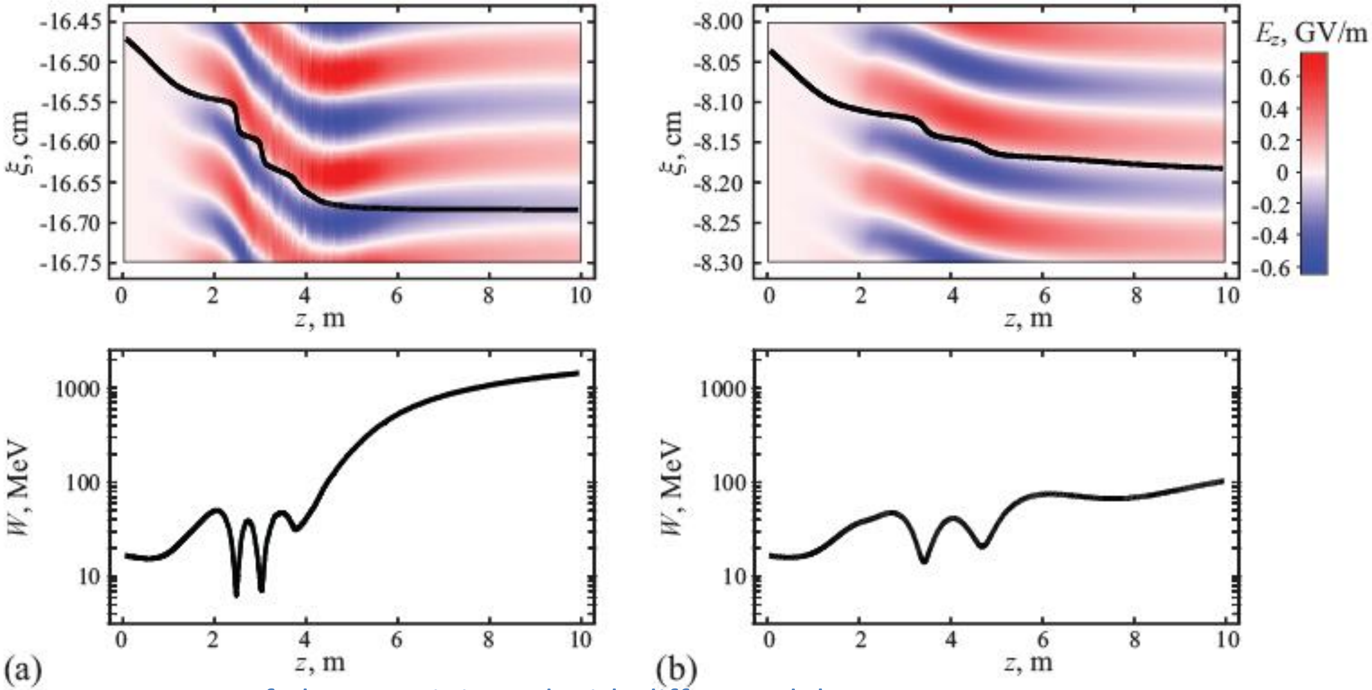
- Electrons are trapped from the very beginning by the wakefield
- Trapped electrons make several synchrotron oscillations in their potential wells
- After z=4 m the wakefield moves forward in the light velocity frame

4. Witness Beam: Electron Beam Optimization

Electron beam injection delay optimization



Co-moving coordinate for electrons injected with different delays.



Energy of electrons injected with different delays.

K. Lotov et al., arXiv: 1408.4448

4. Witness Beam: Electron Source

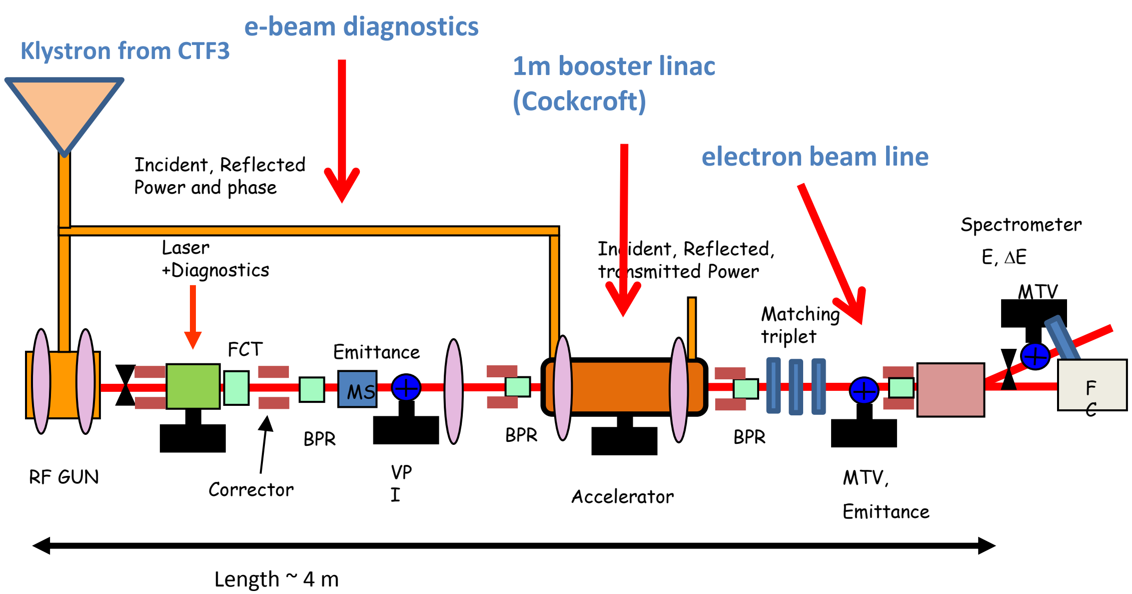
PHIN Photo-injector for CTF3/CLIC:

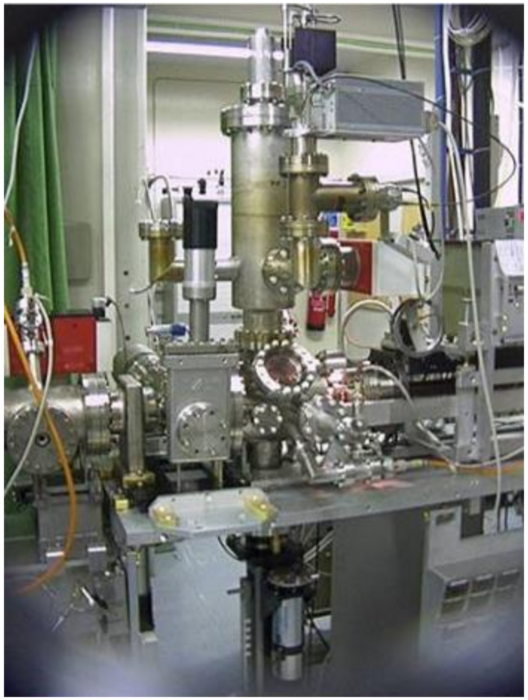
- Charge/bunch: 2.3 nC
- Bunch length: 10 ps
- 1800 bunches/train, 1.2μs train-length
- → Program will stop end 2015

→ Fits to requirements of AWAKE

→ Photo-injector laser derived from low power level of plasma ionization laser system.

Laser beam for electron source	
Laser type	Ti:Sapphire Centaurus
Pulse wavelength	λ_0 = 260 nm
Pulse length	10 ps
Pulse energy (after compr.)	500 μJ
Electron source cathode	Copper
Quantum efficiency	3.00 E-5
Energy stability	±2.5% r.m.s.

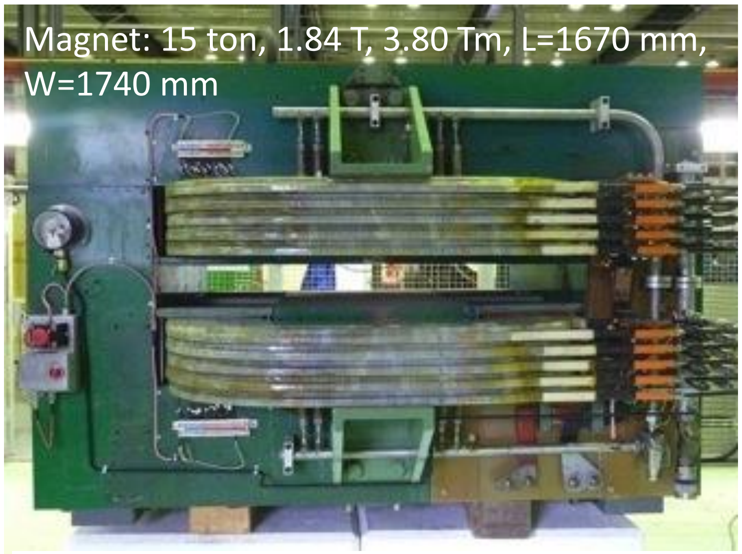


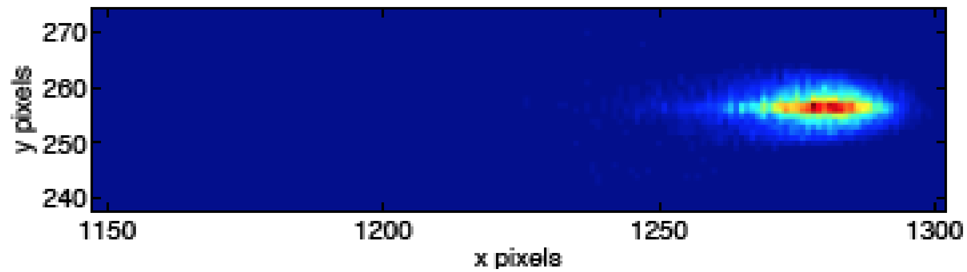


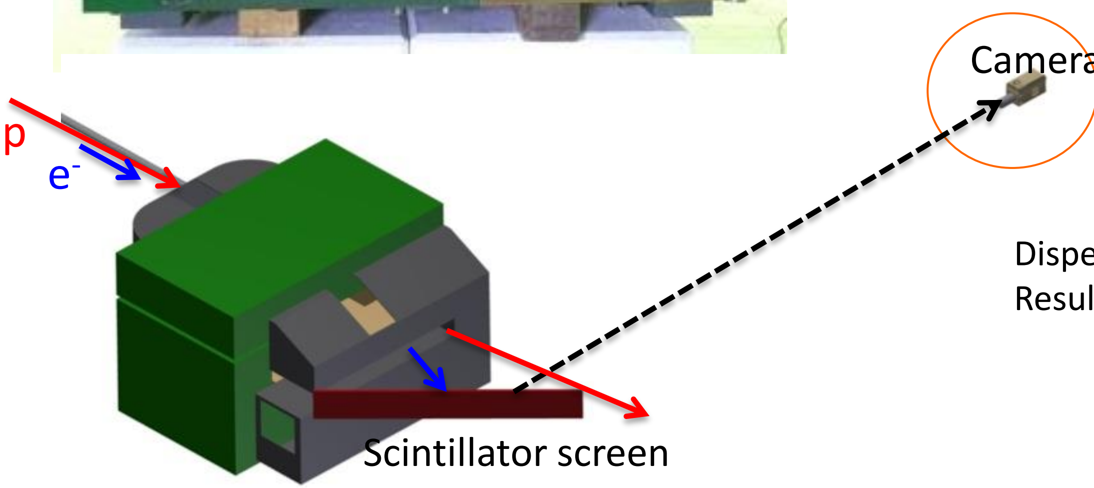
5. Witness Beam Acceleration Diagnostics

Probe the accelerating wakefields with externally injected electrons
→ Electron spectrometer

- Measure **peak energy and energy spread** of electrons.
- Spectrometer magnet separates electrons from proton beam-line.







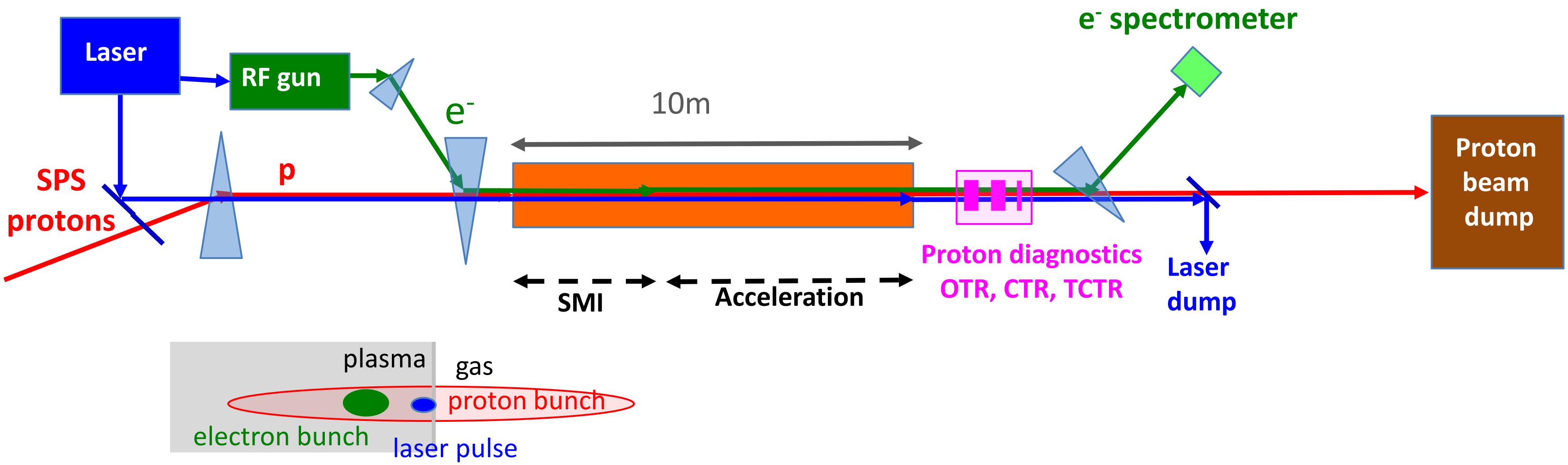
Dispersed electron impact on scintillator screen.
Resulting light collected with intensified CCD camera.

4./5. Witness Beam and Diagnostics Summary

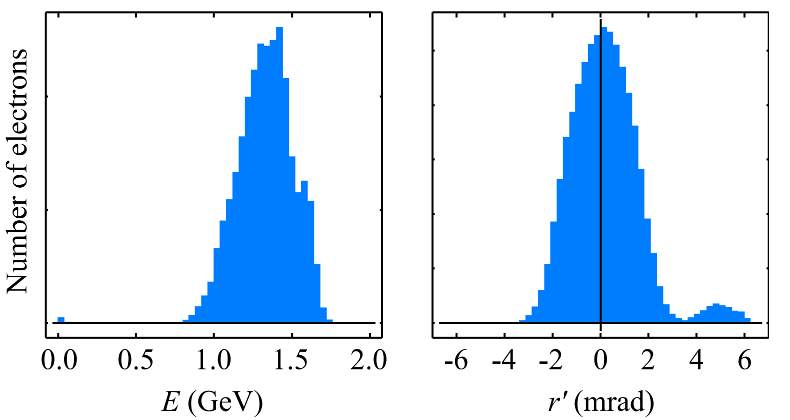
- Externally injected electrons
- Electron energy: 10 – 20 MeV
- Energy and number of accelerated electrons depend on injection delay into wakefield
- Use the Photo-injector PHIN from CLIC
- Photo injector laser derived from low power level of the plasma source ionizing system.
- Electron spectrometer is used to probe the accelerating wakefields.

AWAKE: 2^{nd} Experimental Phase

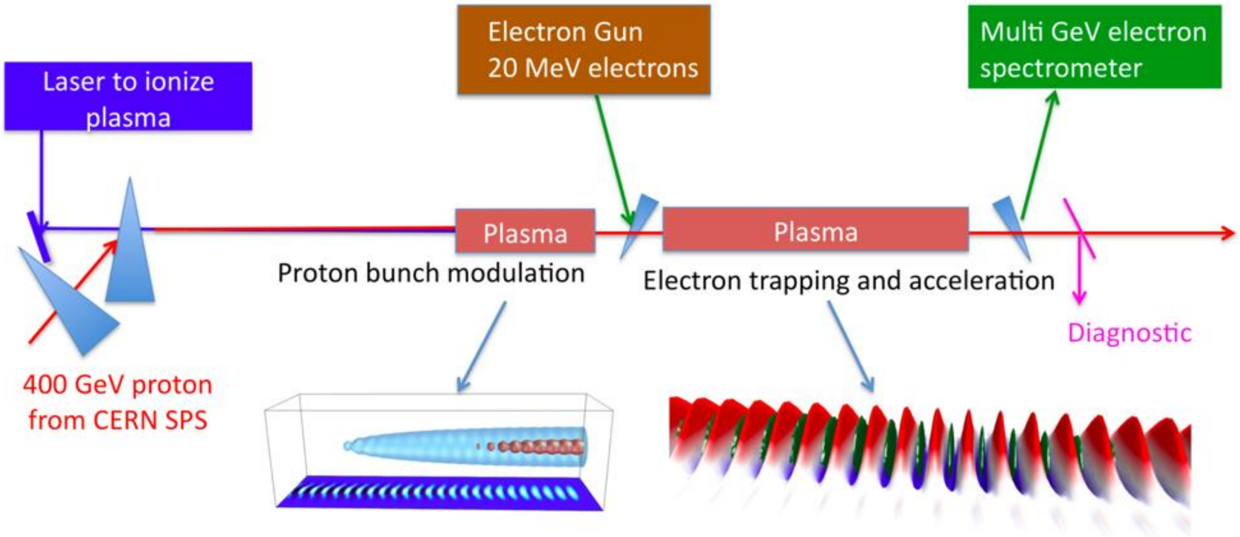
Probe the accelerating wakefields with externally injected electrons, including energy spectrum measurements for different injection and plasma parameters.



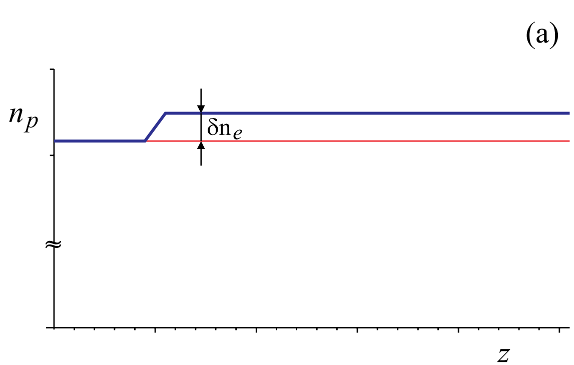
- Trapping efficiency: **10 – 15 %**
- Average energy gain: **1.3 GeV**
- Energy spread: ± 0.4 GeV
- Angular spread up to ± 4 mrad



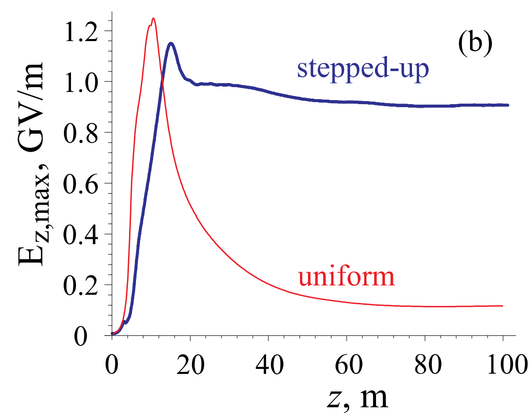
Next Steps (Phase 3)



- **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



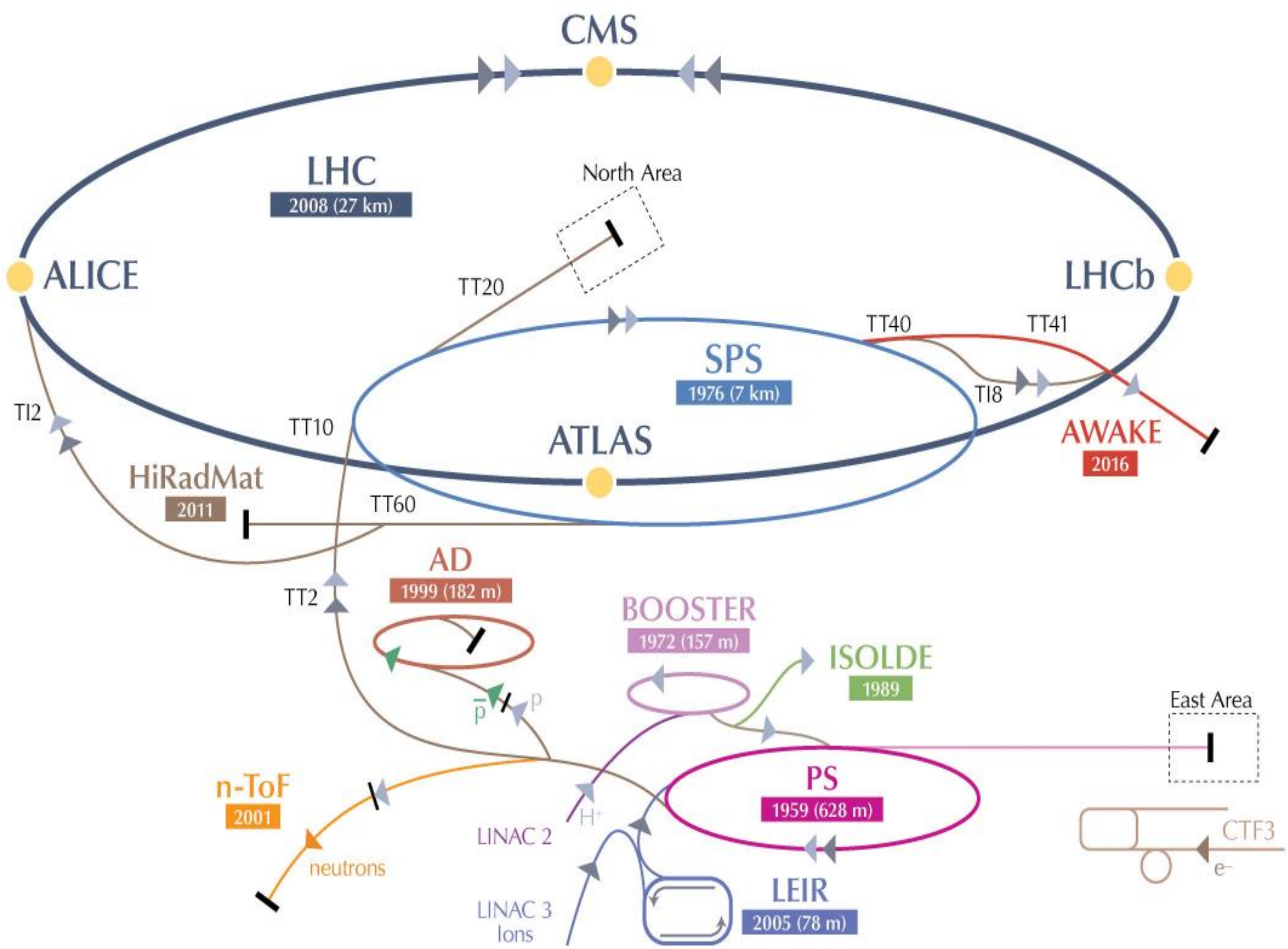
Plasma density profile

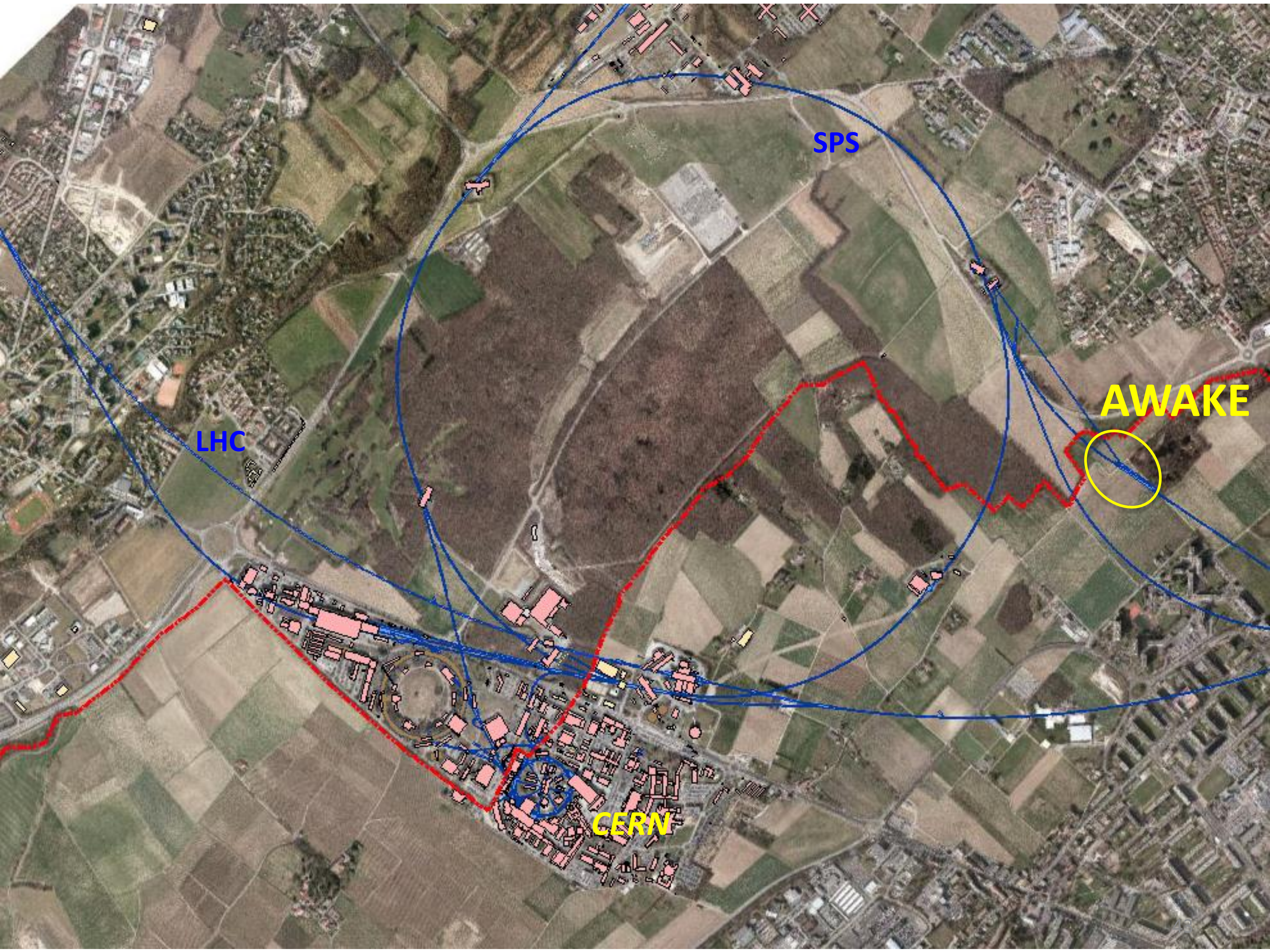


Maximum wakefield amplitude

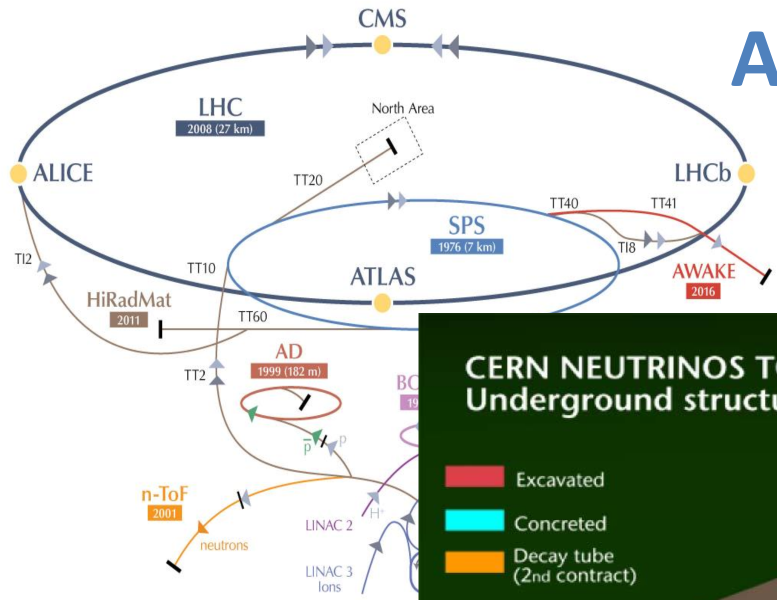
Putting the Pieces Together

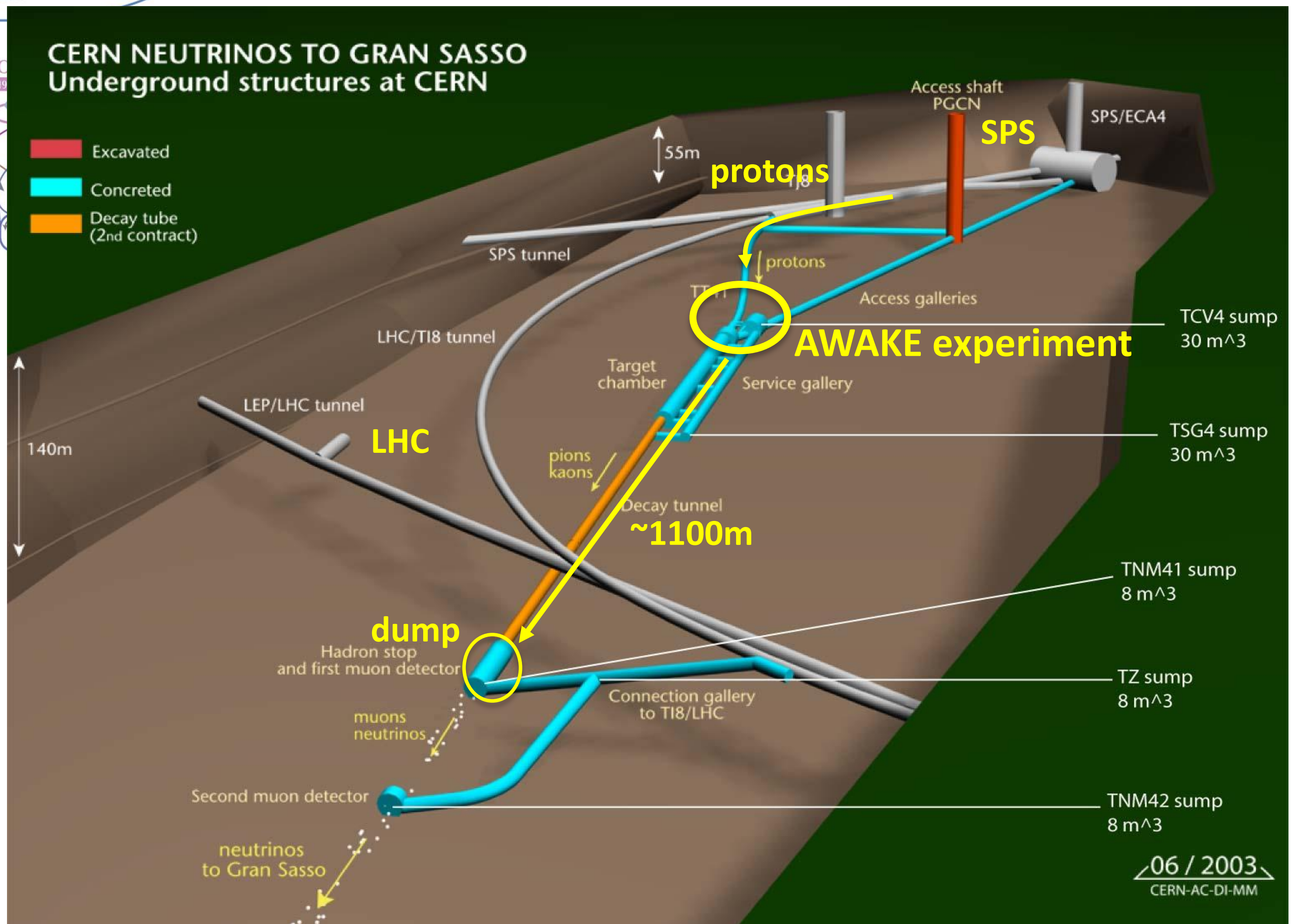
AWAKE at CERN



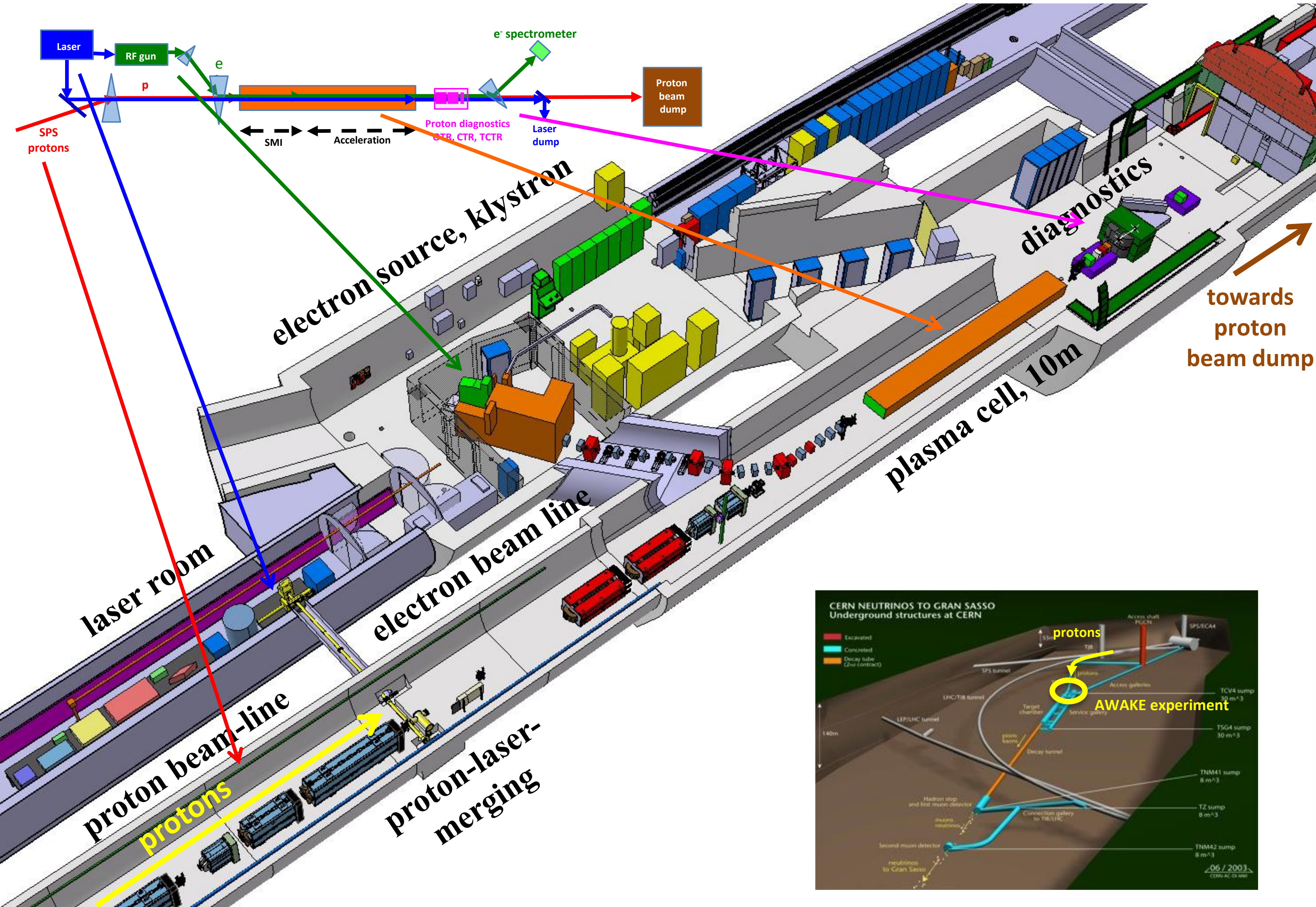

SPS
LHC
AWAKE
CERN

AWAKE at CERN



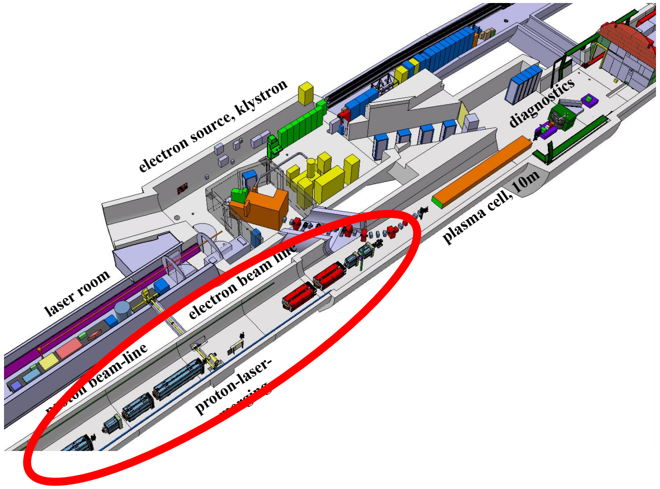


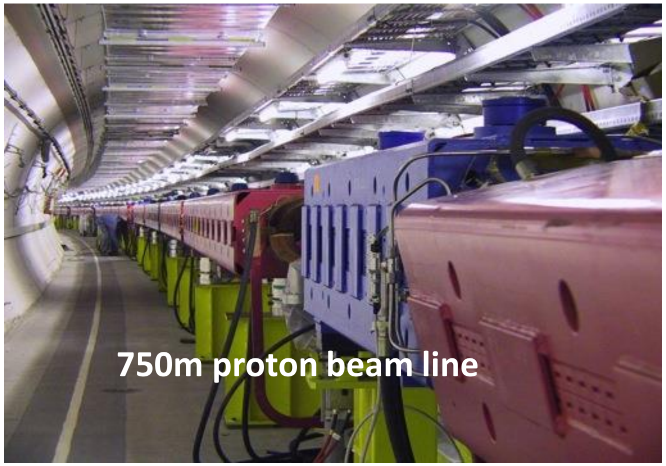
AWAKE Experimental Facility at CERN



Proton Beam Line

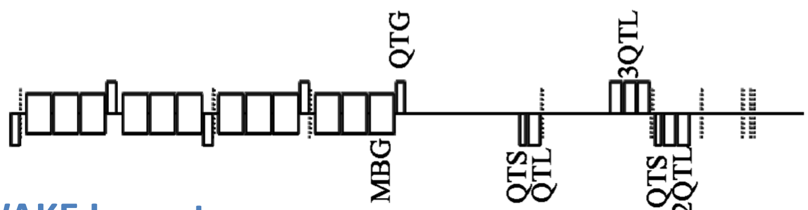
Change of the proton beam line only in the **downstream part (~80m)**



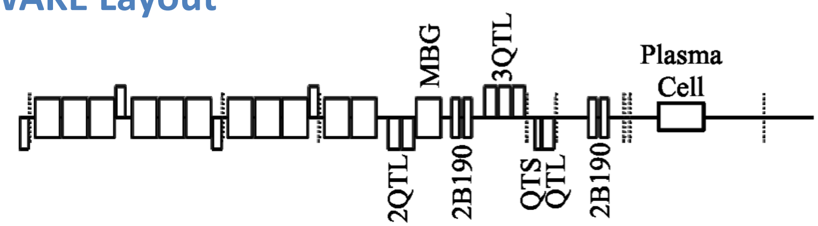


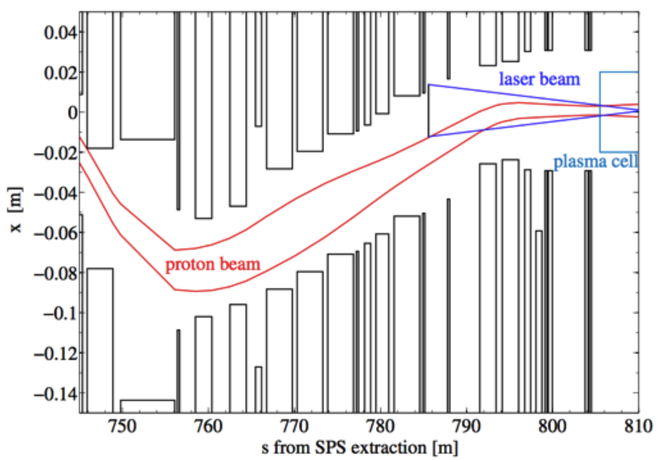
→ **Displace existing magnets** of the final focusing to fulfill optics requirements at plasma cell

CNGS Layout



AWAKE Layout

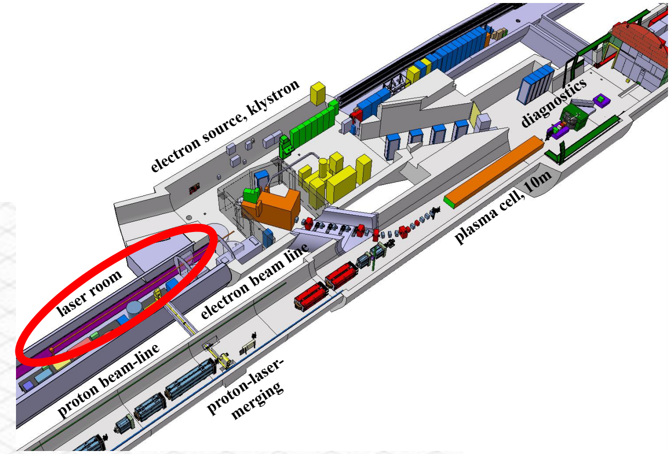


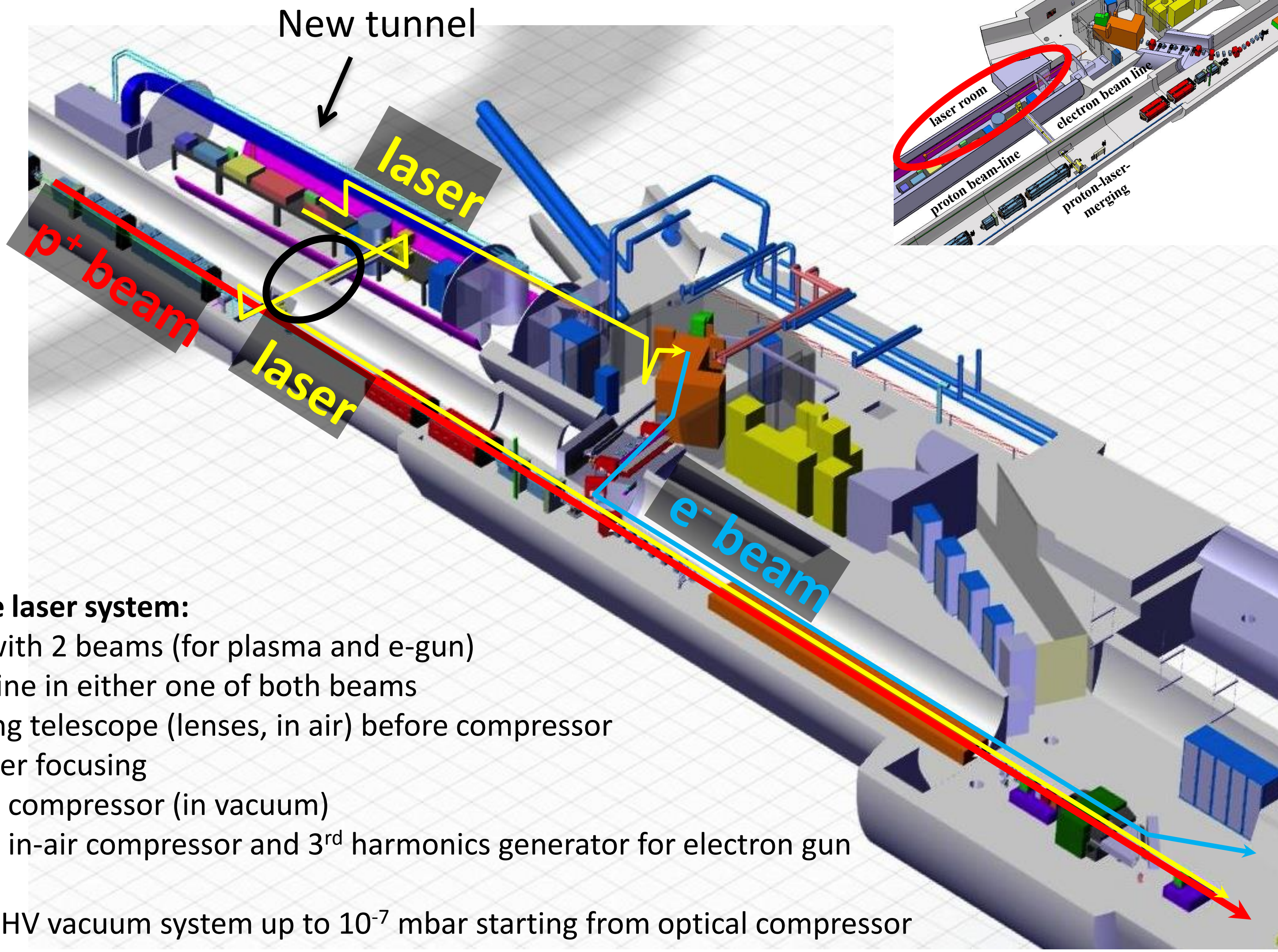


Laser-proton merging 20m upstream the plasma cell

→ Move existing dipole and **4 additional dipoles** to create a **chicane for the laser mirror** integration.

Laser System



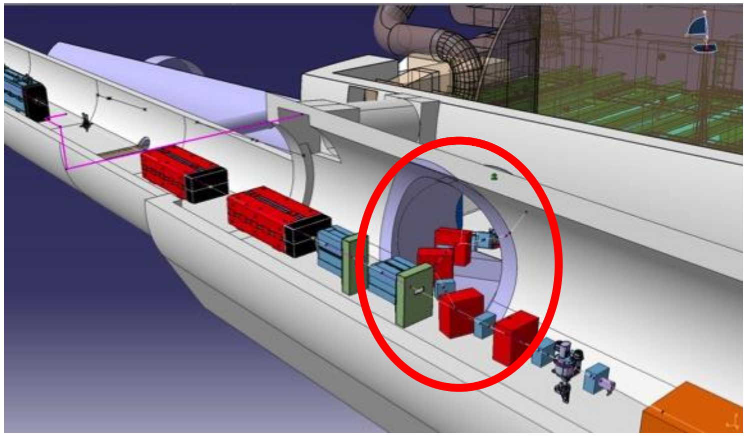


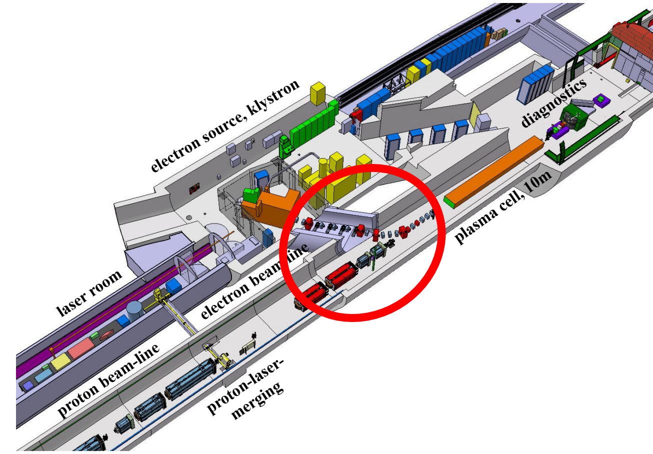
Ti: Sapphire laser system:

- Laser with 2 beams (for plasma and e-gun)
- Delay line in either one of both beams
- Focusing telescope (lenses, in air) before compressor
- 35 meter focusing
- Optical compressor (in vacuum)
- Optical in-air compressor and 3rd harmonics generator for electron gun

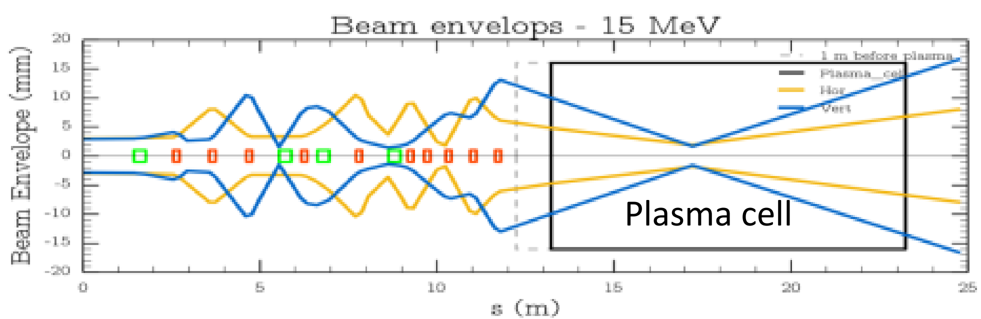
Complete UHV vacuum system up to 10^{-7} mbar starting from optical compressor

Electron Beam Line



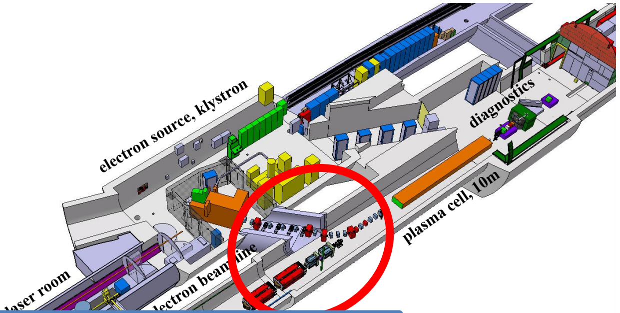


- Completely **new beam line and tunnel**:
  - Horizontal angle of 60 deg,
  - 20% slope of the electron tunnel → 1m level difference
  - 7.2% slope of the plasma cell
  - ~5 m common beam line between electron and proton
- **Common diagnostics** for proton (high intensity, 3E11 p) and electron beam (low intensity, 1.2E9 e)
- **Flexible electron beam optics**: focal point can be varied by up to 6 m inside the plasma cell



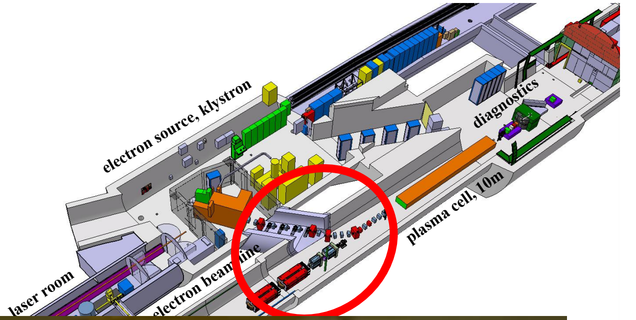
Electron beam envelope (H, V)

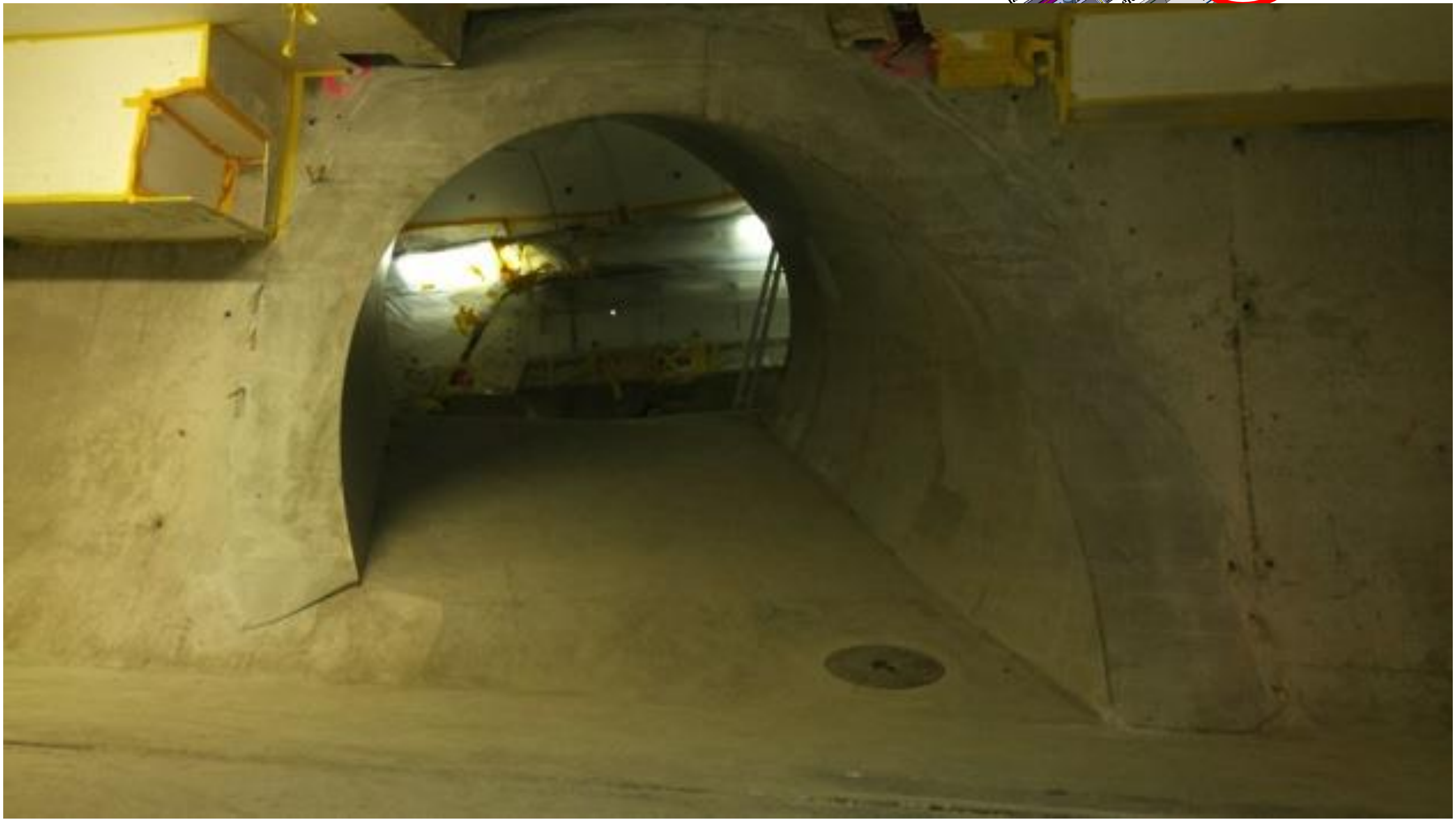
Electron Beam Line



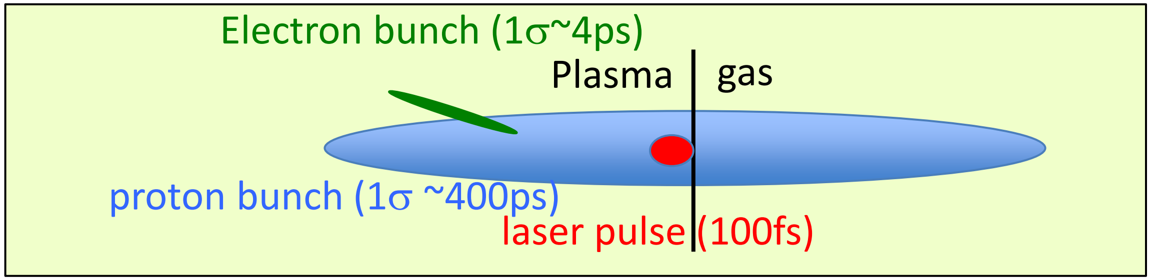
Excavation June – October 2014

Electron Beam Line





Proton/Electron/Laser Synchronization

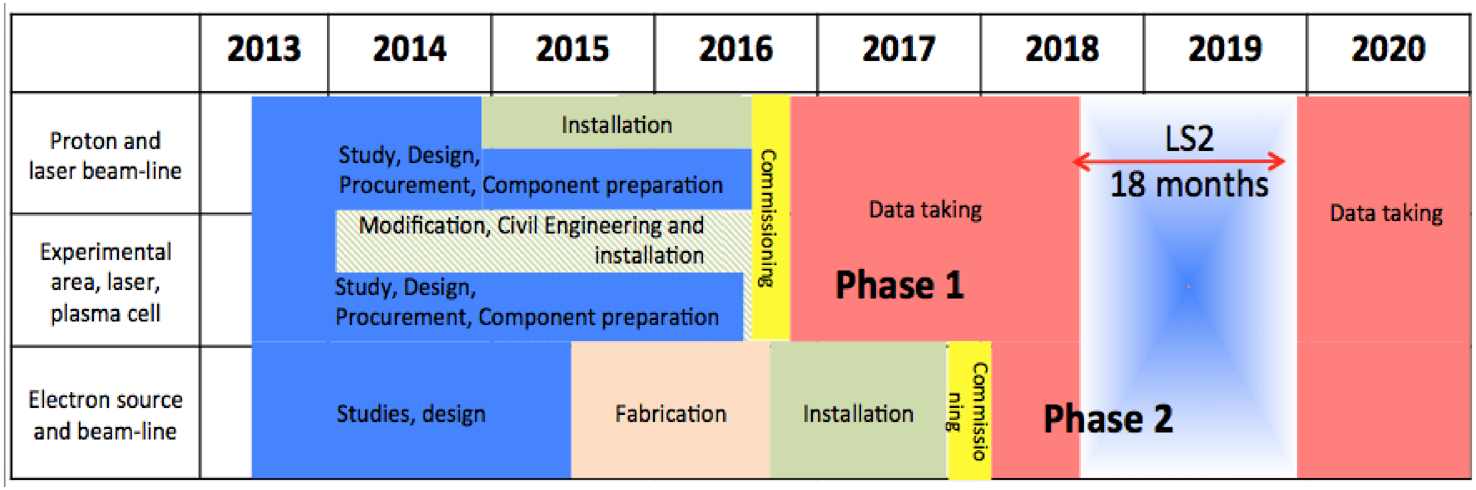


- Synchronization between proton beam and laser pulse: ~ 100 ps (cf. proton bunch length 1σ~400ps).
  - SPS beam must synchronize to the AWAKE reference just before extraction.

- Synchronization between electron beam and laser pulse: ~ 100 fs (cf. plasma period ~4ps)
  - For deterministic injection of e- bunch into plasma wakefields
  - Achieved by driving the RF-gun of the electron source with a laser pulse derived from same laser system as used for plasma ionization.

- Exchange of synchronization signals on ~3 km long fibres between the AWAKE facility and SPS RF Faraday Cage in the control room

AWAKE Timeline



2016 Phase 1: Self-Modulation Instability physics
2017-18 Phase 2: Electron acceleration physics

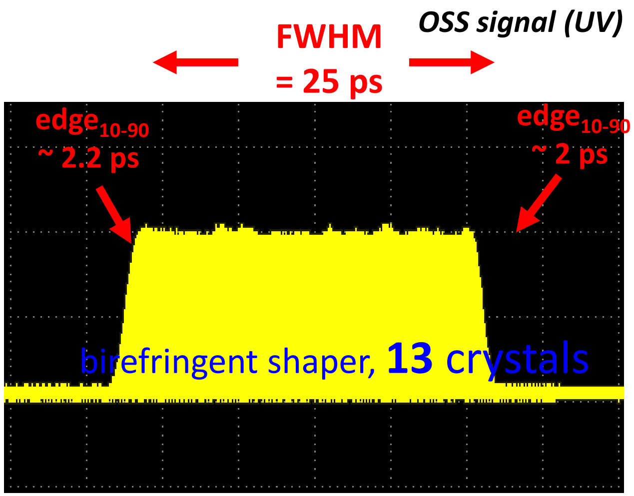
Beam-Driven Wakefield Acceleration: Landscape

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

DESY PITZ

Facility	Where	Drive (D) beam	Witness (W) beam	Start	End	Goal
DESY-Zeuthen	PITZ, DESY, Zeuthen, Germany	20 MeV electron beam	**Only D beam from RF-gun, no witness (W) beam.**	2015	~2017	- **Study Self-Modulation Instability (SMI)**

Study the Self-Modulation Instability



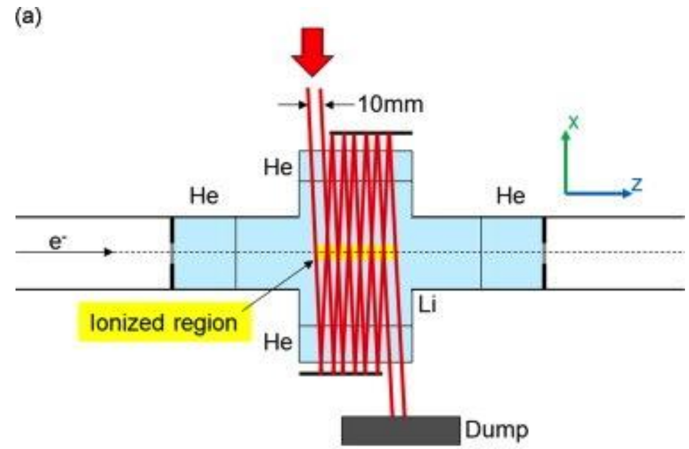
PITZ: Photo-Injector Test Facility at DESY, Zeuthen.

- Pure R&D facility
- Unique laser system (pulse shaper)
- Well developed diagnostics (longitudinal phase space measurement setup: transverse deflecting cavity and high resolution electron spectrometer)

Start: 2015

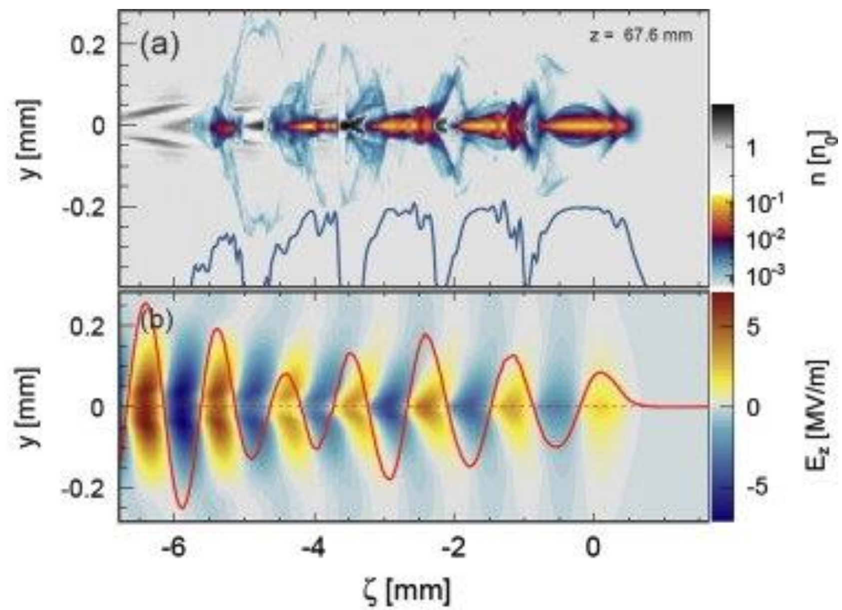
DESY PITZ

- Lithium Plasma Source:
  - Evaporate Lithium to 700˚ C
  - Lithium zone defined with steep temperature gradient and Helium buffer gas
  - Ionize Lithium gas with laser (Ti:Sapphire, 1TW)
  - → 1mm diameter, 58mm length plasma
  - Inject particle beam for PWA experiment



- Electron beam parameters:
  - 0.1 nC
  - FWHM: 22ps (5.93mm)
  - 21.5 MeV/c
  - σ_x = 42 µm

- PIC simulations:
  - After 67.6mm the self-modulation has completely developed in a plasma with density of 10^{15} cm^{-3}.



M. Gross et al., NIMA 740 (2014) 74-80

FLASHForward

Facility	Where	Drive (D) beam	Witness (W) beam	Start	End	Goal
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

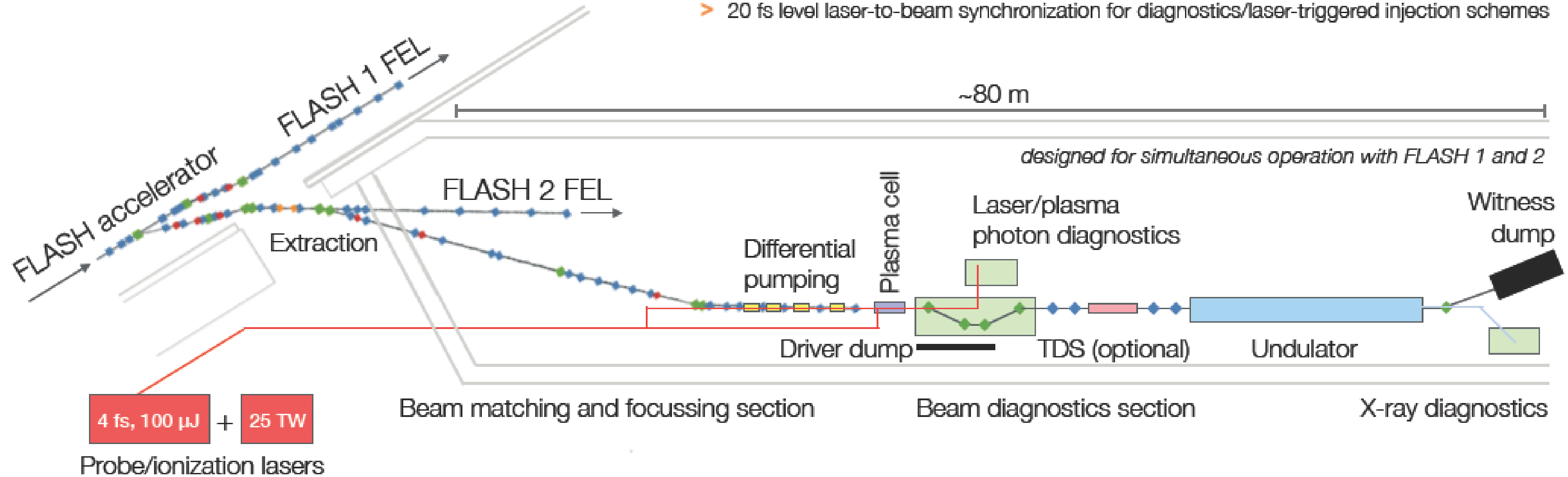
FLASHForward▸▸

Future-oriented wakefield-accelerator research and development at FLASH

Conceptual design concluded, technical design in progress, experiments to start in 2016, run for 4 years+

FLASH capabilities of particular interest for plasma-wakefield studies

- FEL-quality driver beam at 1.25 GeV, post-compression for ~10 kA level peak current
- variable longitudinal beam shape (e.g. triangular)
- 20 fs level laser-to-beam synchronization for diagnostics/laser-triggered injection schemes



Main objectives:

- demonstration of novel beam injection schemes for unprecedented quality from a plasma with *> 2.5 GeV, ~fs duration, ~100 nm norm. emittance, > kA currents, ~‰ uncorrelated energy spread*
- the application of these beams in undulators to test feasibility of FEL gain
- investigation of stability of and control over plasma-accelerated beams

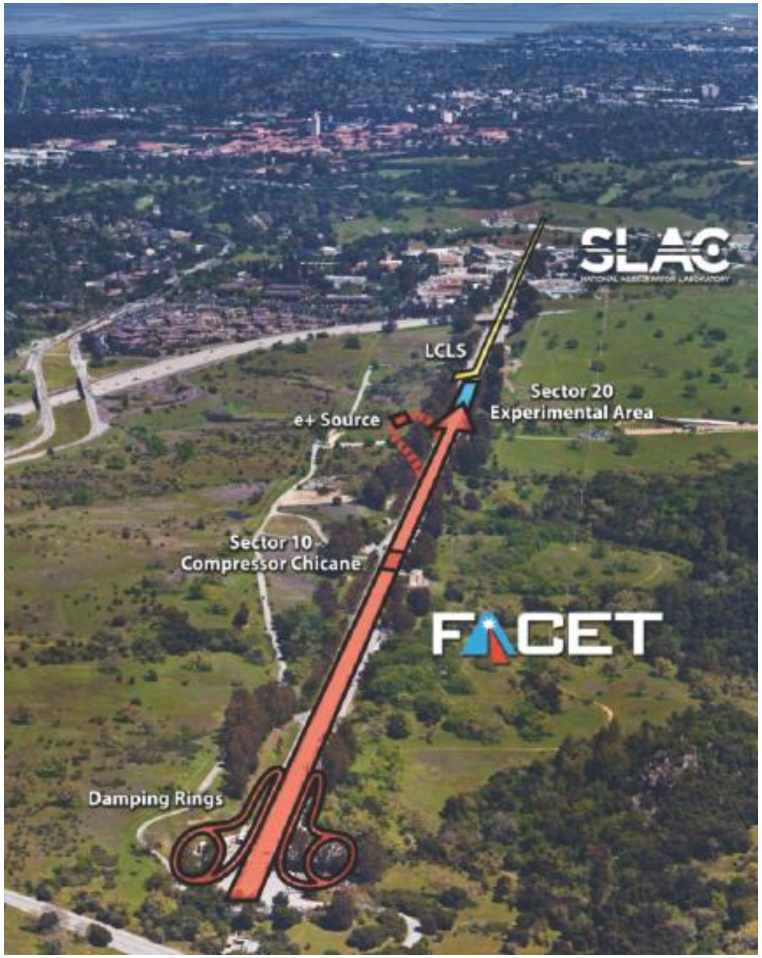
Contact Jens Osterhoff
jens.osterhoff@desy.de
for more details

SLAC – FACET

Facility	Where	Drive (D) beam	Witness (W) beam	Start	End	Goal
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

- Facility for Advanced Accelerator Experimental Tests
- Demonstrate single-stage high-energy plasma accelerator
- Program:
  - Commissioning beam, diagnostics and plasma source (2012)
  - Produce independent drive & witness bunch (2012-2013)
  - Pre-ionized plasmas and tailored profiles to maximize single stage performance: total energy gain, emittance, efficiency (2013-2015)
- First experiments with compressed positrons
  - Identify optimum technique/regime for positron PWFA (2014-2016)

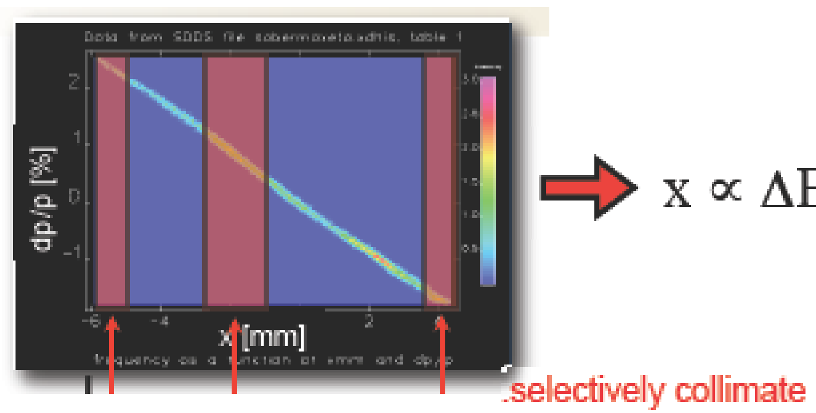
- Facility hosts >150 users, 25 experiments
- ➔ very productive with publishable results!



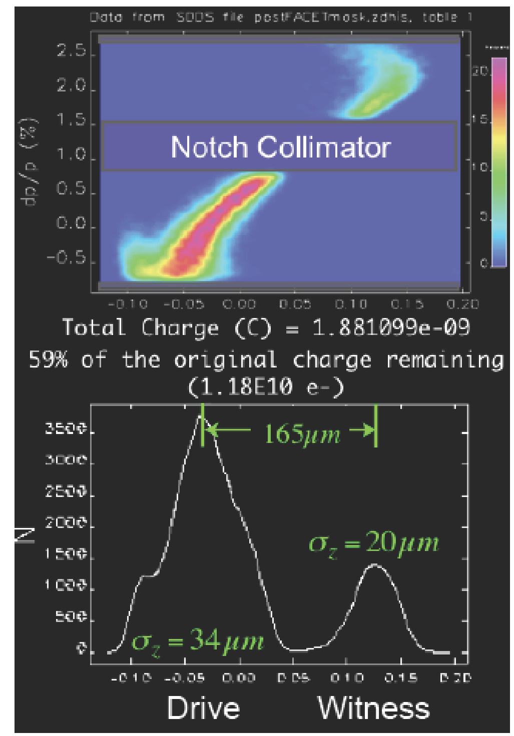
SLAC – FACET

- Beam Parameters:
  - 20 GeV
  - 3 nC
  - σ_z = 17 µm (57 ps)

- Produce Drive beam and Witness Beam:
  - Notch collimator
  - → Bunches are separated by 160 µm



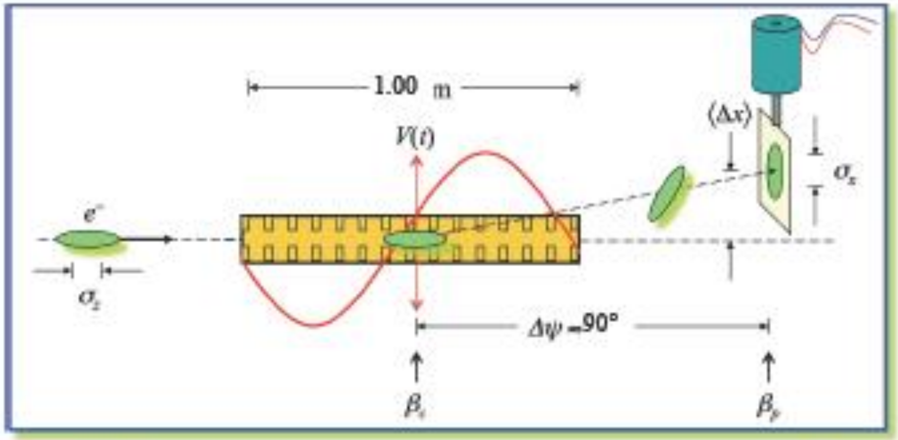
$$x \propto \Delta E/E \propto t$$

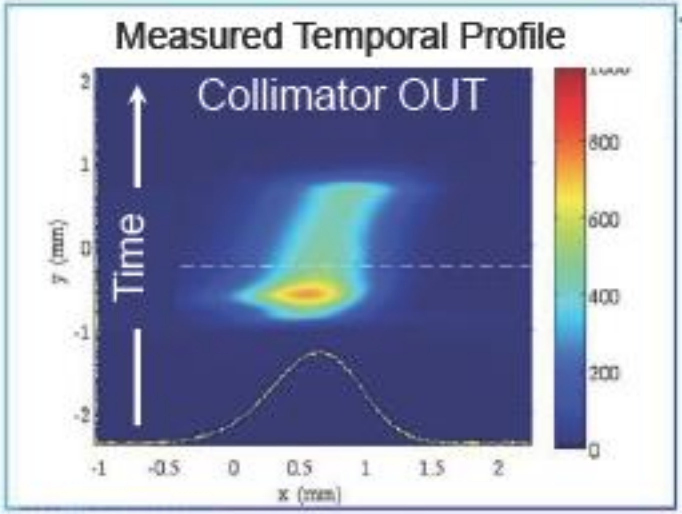


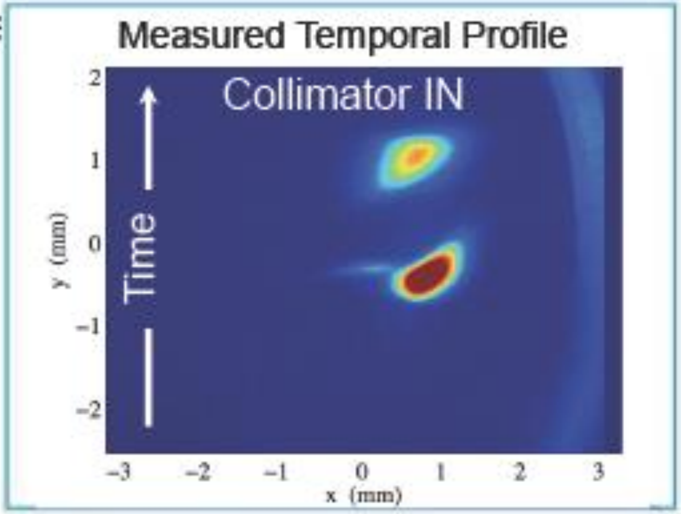
SLAC – FACET

- Measure the beams for the two-bunch PWFA experiments:
  - Transverse deflecting cavity: allows single-shot measurement of the longitudinal profile of the bunch. Deflects bunches transversely according to the longitudinal position in the bunch. Profile monitor.

X-band TCAV installed in Sector 20







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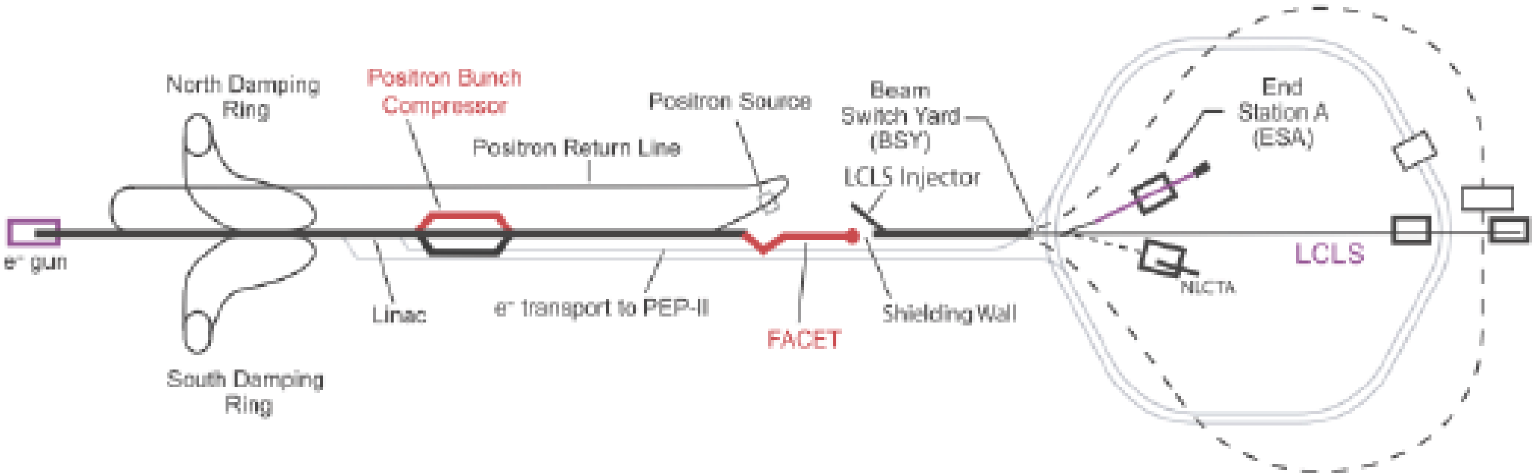
SLAC – FACET

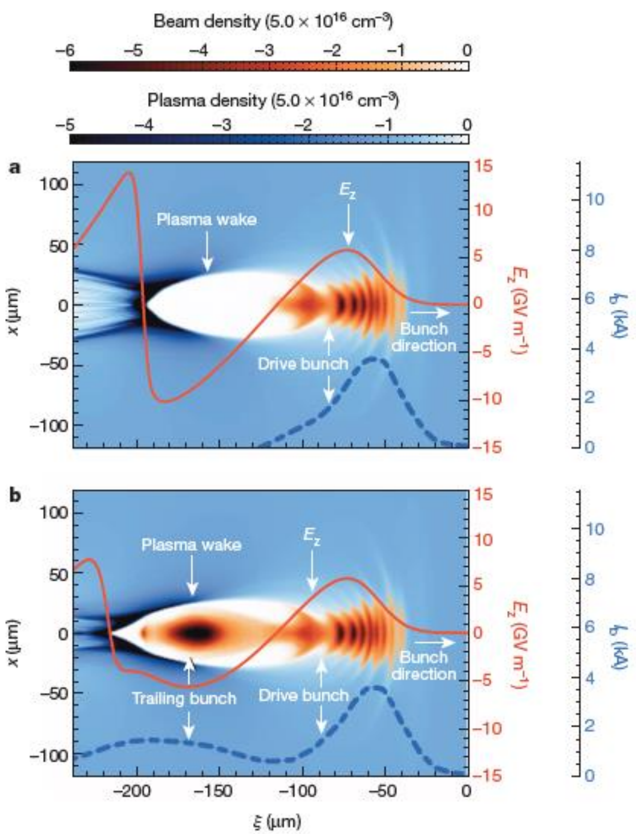


- Plasma sources:
  - Lithium plasma and Rubidium plasma
- Diagnostics:
  - Downstream: Beam profile monitors, OTRs, wire-scanner, energy spectrometer, …

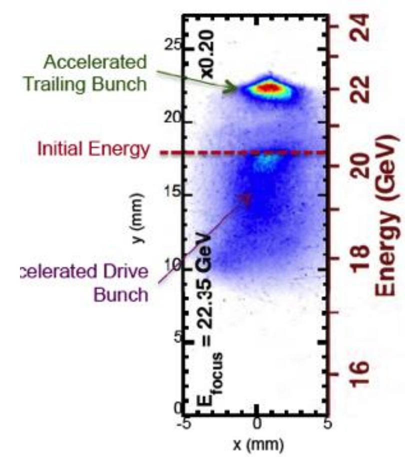
SLAC – FACET: Latest Results

High-Efficiency acceleration of an electron beam in a plasmas wakefield accelerator

M. Litos et al., doi, Nature, 6 Nov 2014, 10.1038/nature 13992

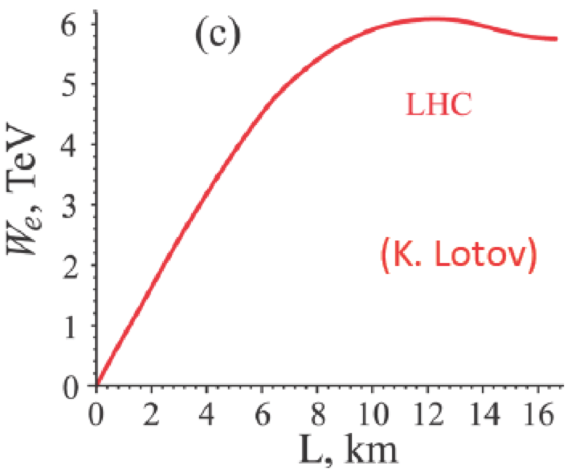


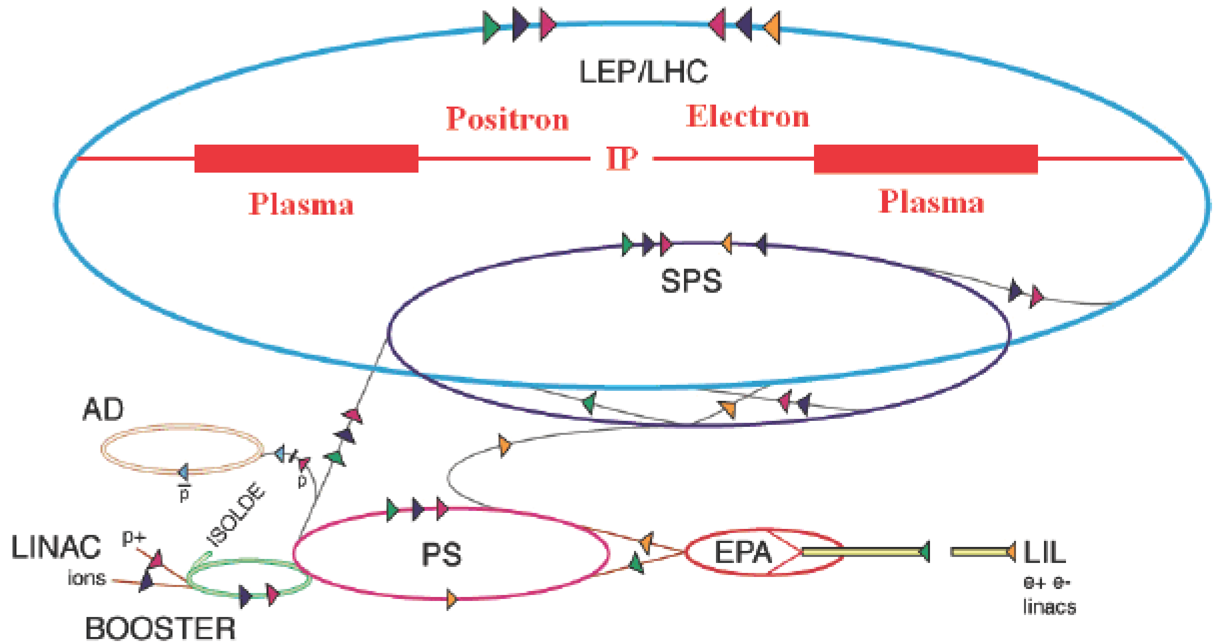
- Laser ionized Lithium vapour plasma cell:
  - 36 cm long, Density: 5 10^{16} cm^{-3}, λ_{π} = 200 µm
- Drive and witness beam:
  - 20.35 GeV, D and W separated by 160 µm
  - 1.02nC (D), 0.78nC (W)
- Result
  - Total efficiency is <29.1%> with a maximum of 50%.
  - Final energy spread of 0.7 % (2% average)



- Electric field in plasma wake is loaded by presence of trailing bunch
- Allows efficient energy extraction from the plasma wake

Back to the Future?!





G. Xia et al, NIMA 740 (2014)173-179

Summary

In the next years, we will have a lot of fun surfing!!