Overview of the AWAKE Experiment at CERN

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on behalf of AWAKE Collaboration

LA^{3}NET Novel Accelerators Workshop
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What is AWAKE?

AWAKE - is an international collaboration formed to carry on a Proton Driven Plasma Wake Field Acceleration Experiment at CERN site with SPS proton bunches.

AWAKE Structure:

Spokesperson:	Allen Caldwell	(MPP)
Deputy Spokesperson:	Matthew Wing	(UCL)
Technical Coordinator:	Edda Gschwendtner	(CERN)
Physics and Experiment Coordinator:	Patric Muggli	(MPP)
Simulation Coordinator:	Konstantin Lotov	(BINP)

Some useful links:

AWAKE web-page:	http://awake.web.cern.ch/awake/
AWAKE INDICO web-page:	http://indico.cern.ch/category/4278/
AWAKE Design Report:	http://cds.cern.ch/record/1537318

AWAKE at a glance

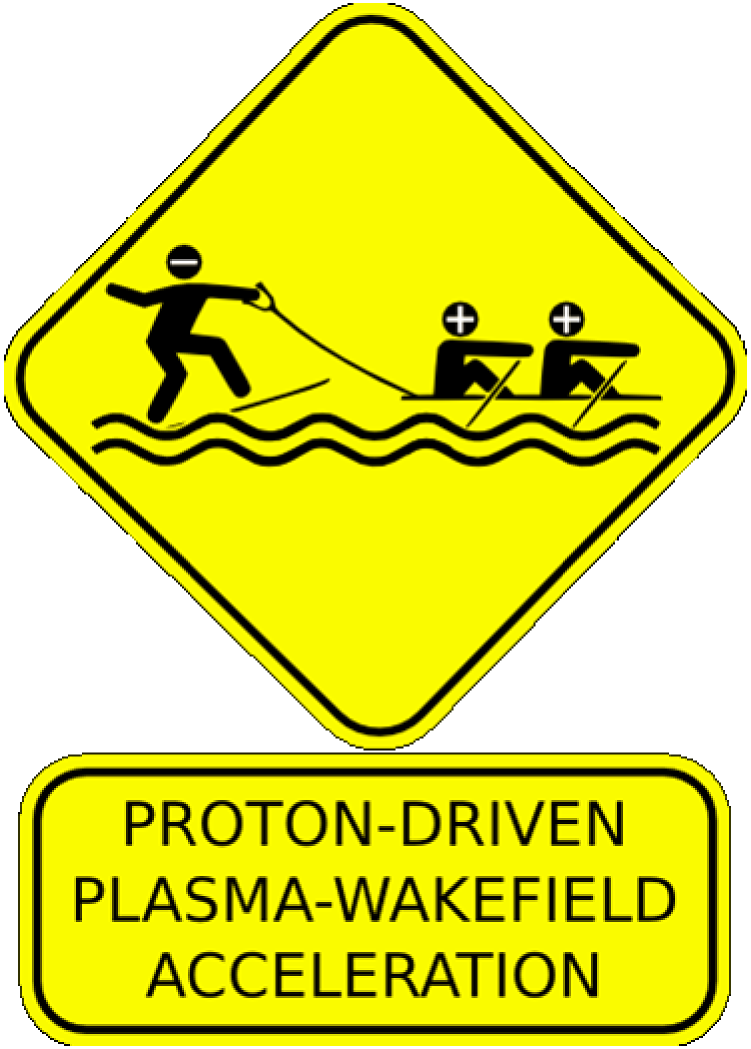
Four Ingredients:

- **Protons (from SPS, 400 GeV)**
  ← energy source

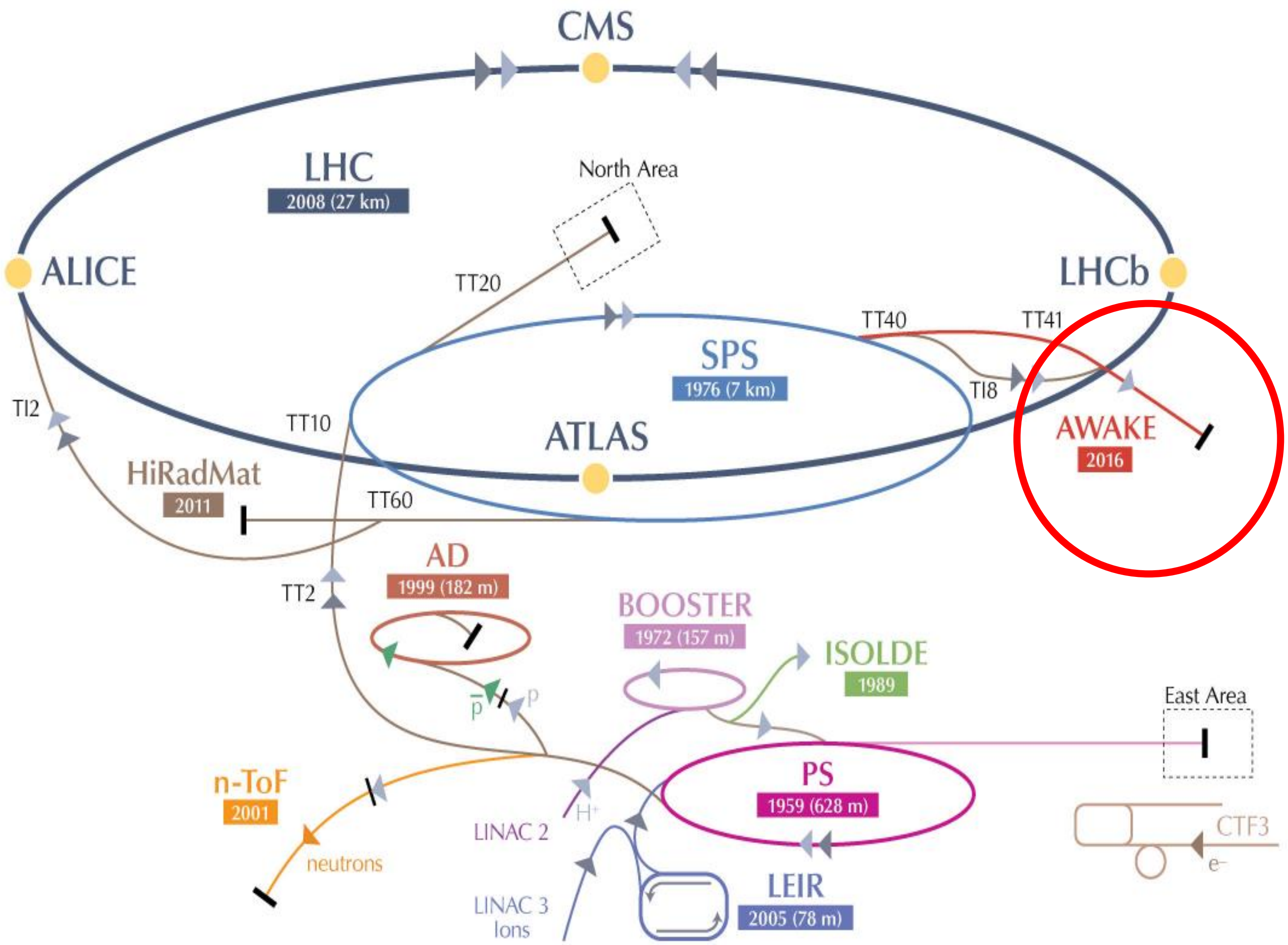
- **Rubidium vapor / plasma wake**
  ← transformer to an E-field
  (a few GV/m)

- **Laser (short intense pulse)**
  ← to ionize Rb vapor
  ← to seed an instability of p^+ bunch

-**Electrons (from photo-gun, 20 MeV)**
  ← to probe a wake fields

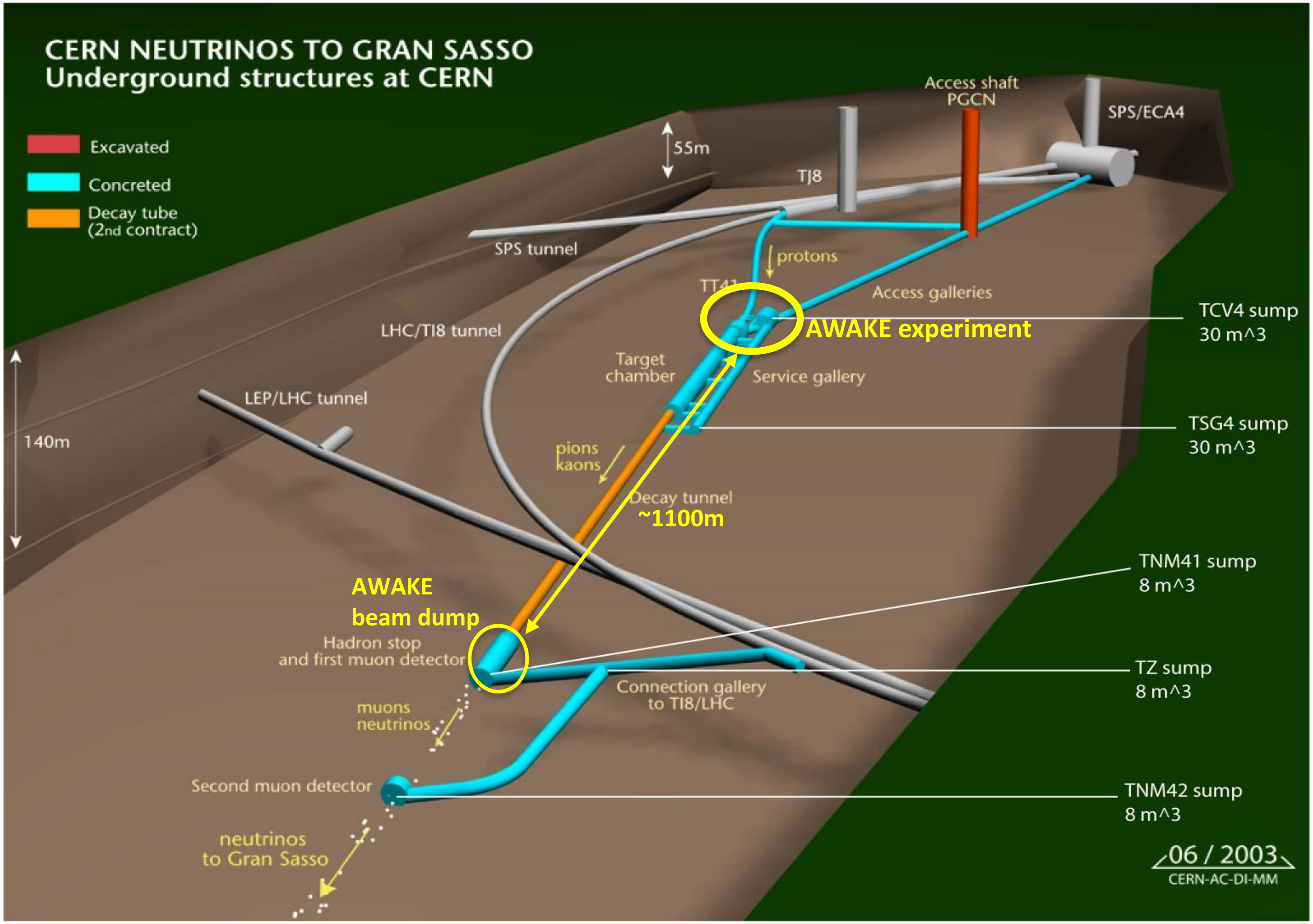


AWAKE at CERN



AWAKE at CERN

~100 meters deep underground, former CNGS facility

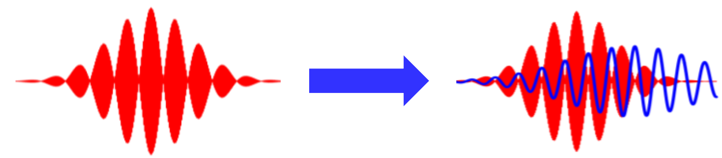


AWAKE Baseline Parameters

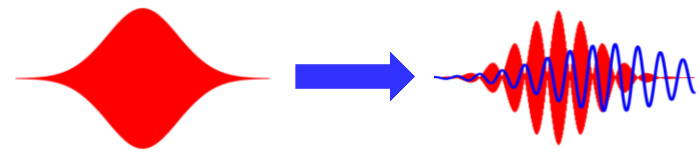
Plasma	Rb plasma density	$10^{14} \div 10^{15}$ cm^{-3} $7 \cdot (10^{-3} \div 10^{-2})$ mBar at 500°K
	Uniformity	<0.1%
	Length	10 meters
Proton bunch	Energy	400 GeV → 64 nJ/p^{+} → 19.2 kJ/bunch
	Charge	$3 \cdot 10^{11}$ particles → 48 nC
	Length, σ_z	12 cm → 400 ps
	Radius, σ_r	200 μm
Electron bunch	Energy	20 MeV → 3.2 pJ/e^{-} → 4 mJ/bunch
	Charge	$1.25 \cdot 10^{9}$ particles → 200 pC
	Length, σ_z	0.25 cm → 8 ps
	Radius, σ_r	200 μm
Laser	Energy	up to 450 mJ
	Pulse duration	120 fs
	Beam size at Rb vapor (focused from 40m)	a few mm
	Focused intensity	> 50 TW/cm2

The Zoo of Plasma Wake-field Accelerators

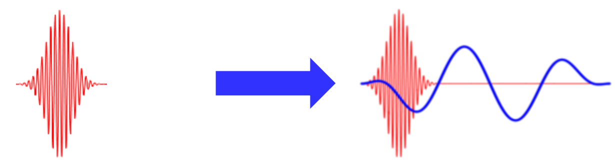
Laser Beat-Wave WFA (~1 ns)
Two frequencies laser pulse (pulse train)



Self-Modulated Laser WFA (~1 ns)
Raman forward scattering instability in a long laser pulse

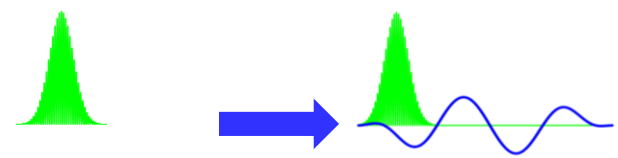


Laser WFA (~0.1 ps)
Short intense laser pulse

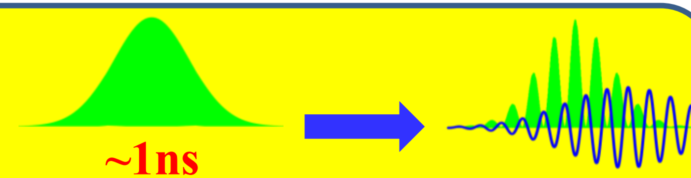


Particle Bunch WFA
Short intense particle bunch

~1ps proton bunch does not exist !

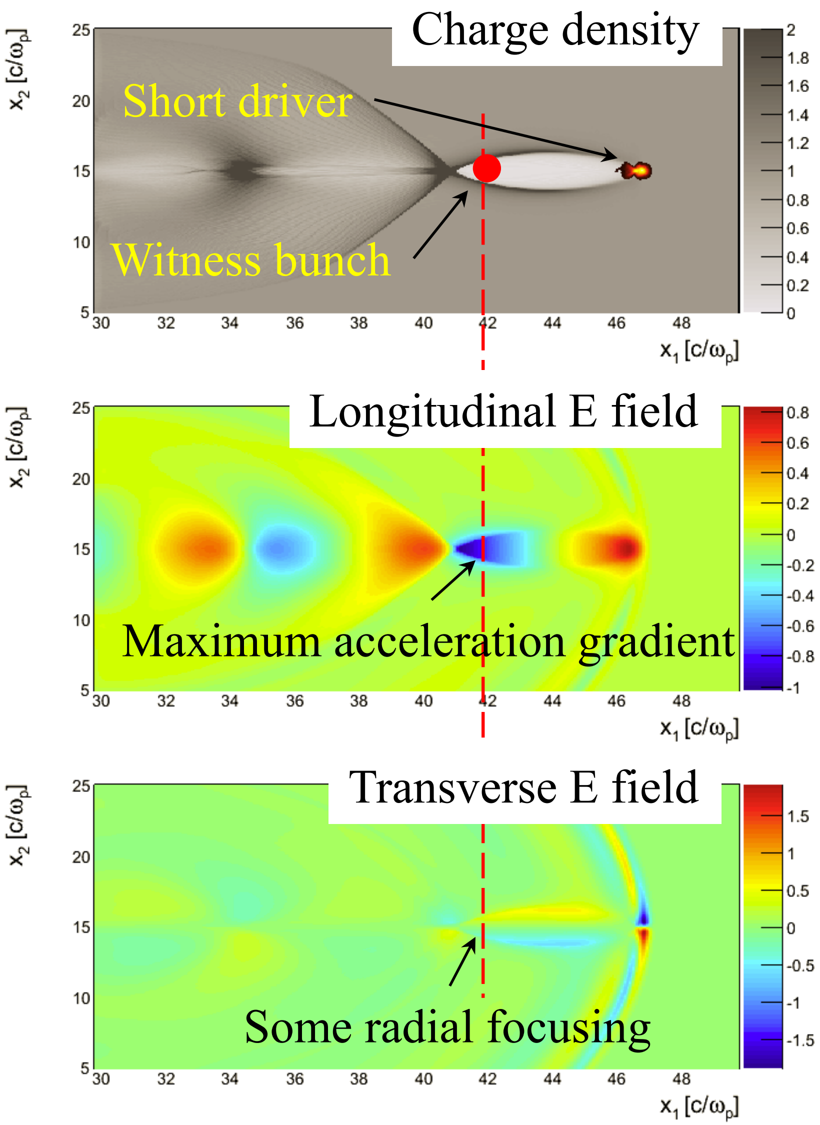


Self-Modulated Particle Bunch WFA
Long bunch experience transverse self-modulation instability



Scope of AWAKE proof-of-principle experiment

Plasma Wake Field. Short Driver



As a short driver:

- Focused powerful fs-laser pulse
- High energy particle bunch (p^+, e^-)

Simulation done by Alberto Martinez de la Ossa

$n_e = 2\ 10^{15}\ cm^3$ $\nu_{pe} = 402$ GHz

$\lambda_{pe} = 750\ \mu m$ $E_{0max} = 4.3$ GV/m

Taken from the talk by Matthias Gross
at Proton-Driven PWA Meeting
Lisbon, 22 June 2012

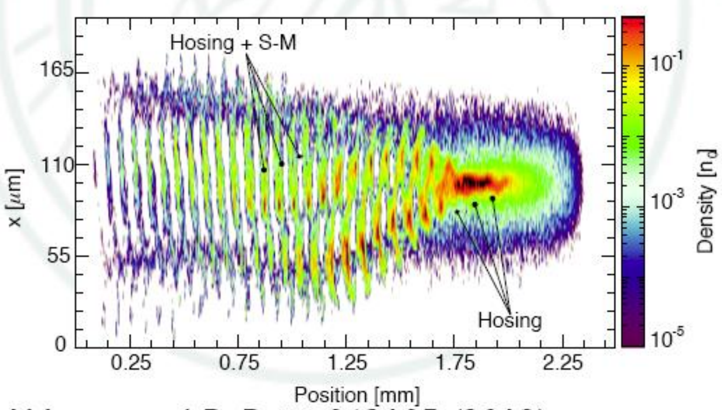
Plasma Wake Field: Long Particle Bunch Driver

If the driving bunch is long – no efficient wake excitation.
But … **there are instabilities**!

Propagation of long bunches in plasmas - instability competition

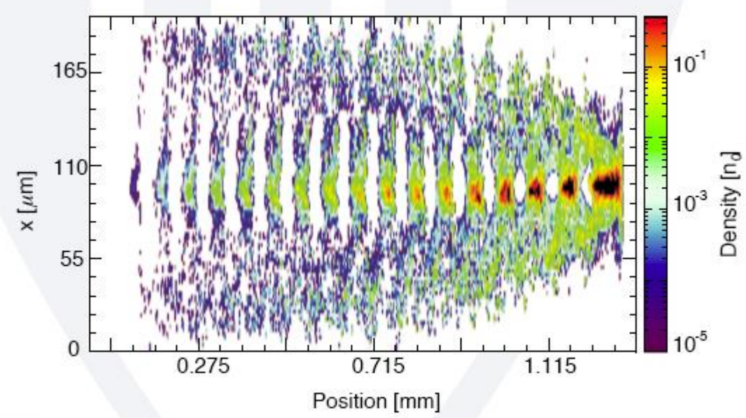
- self-modulation instability: generation of large amplitude wakefields
- hosing instability or beam break up instability: prevent generation of large amplitude wakefields

No seeding



J.Vieira et al PoP **19** 063105 (2012).

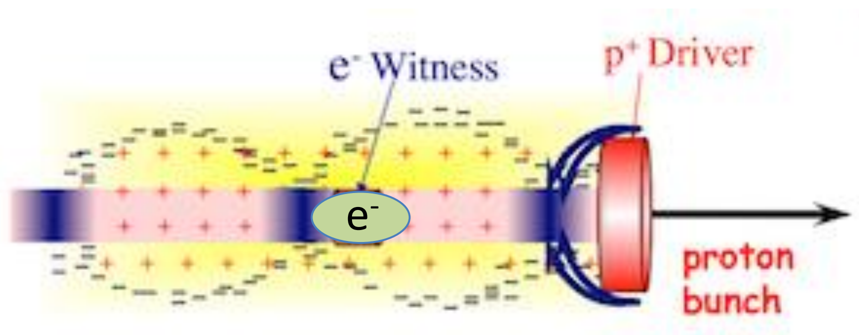
With seeding



Presented by J. Vieira, 8 March 2013, CERN, Geneva
at AWAKE Collaboration Meeting

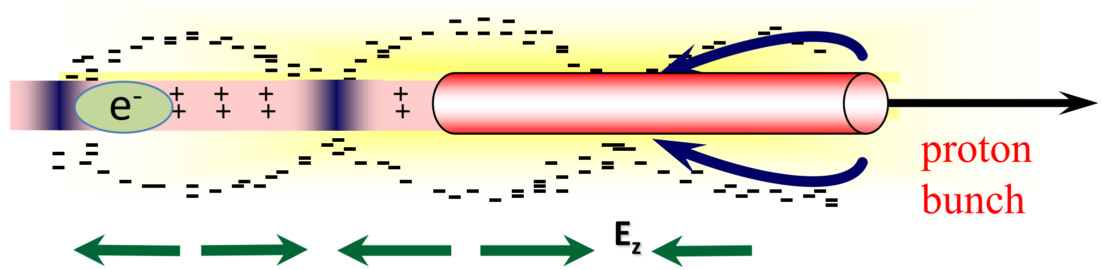
Self Modulation Instability

Short proton bunch driver
No SMI



→ Space charge of drive beam displaces plasma electrons.
→ Plasma ions exert restoring force.

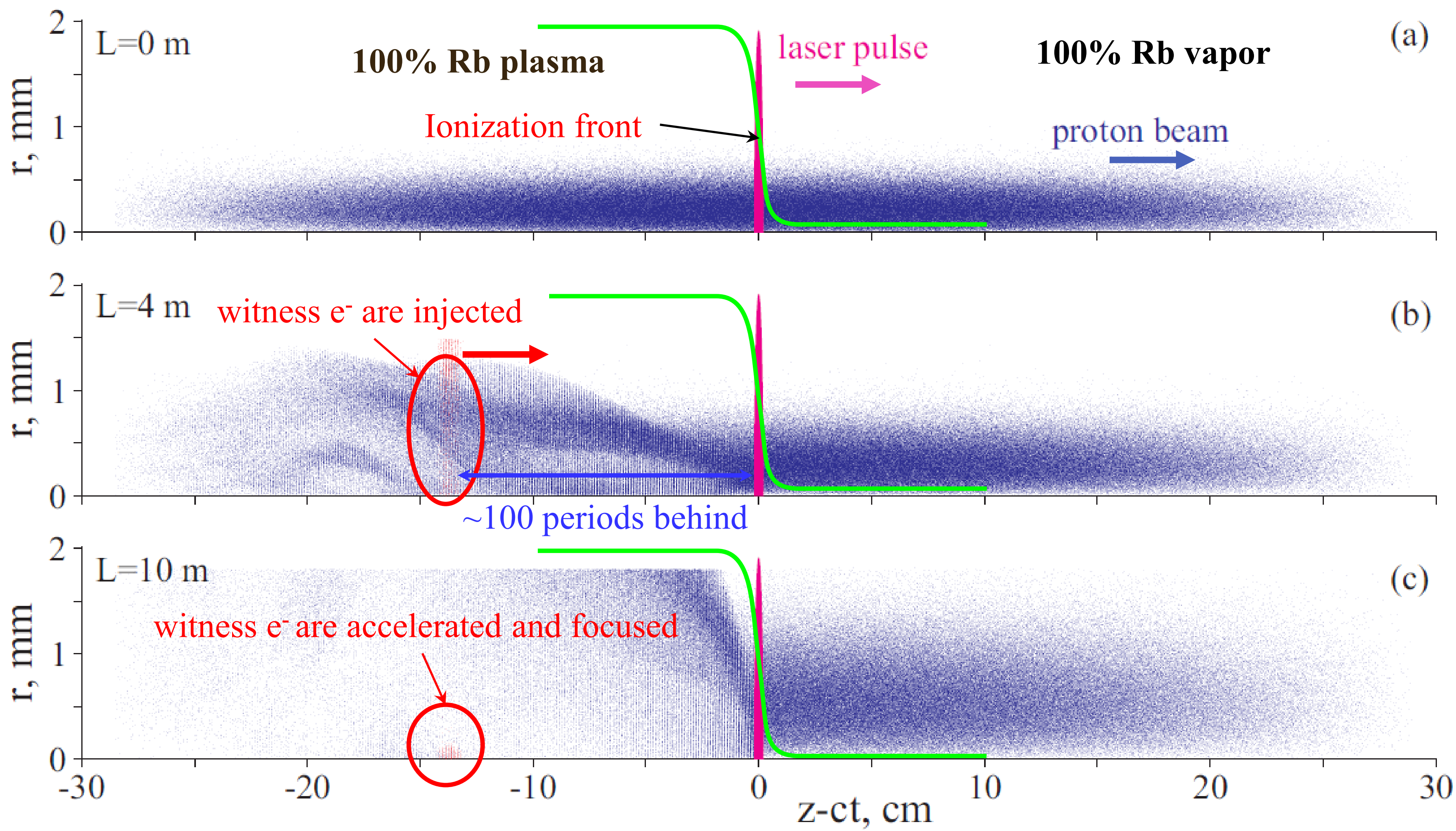
Long proton bunch driver
SMI develops



AWAKE Physics: Principle

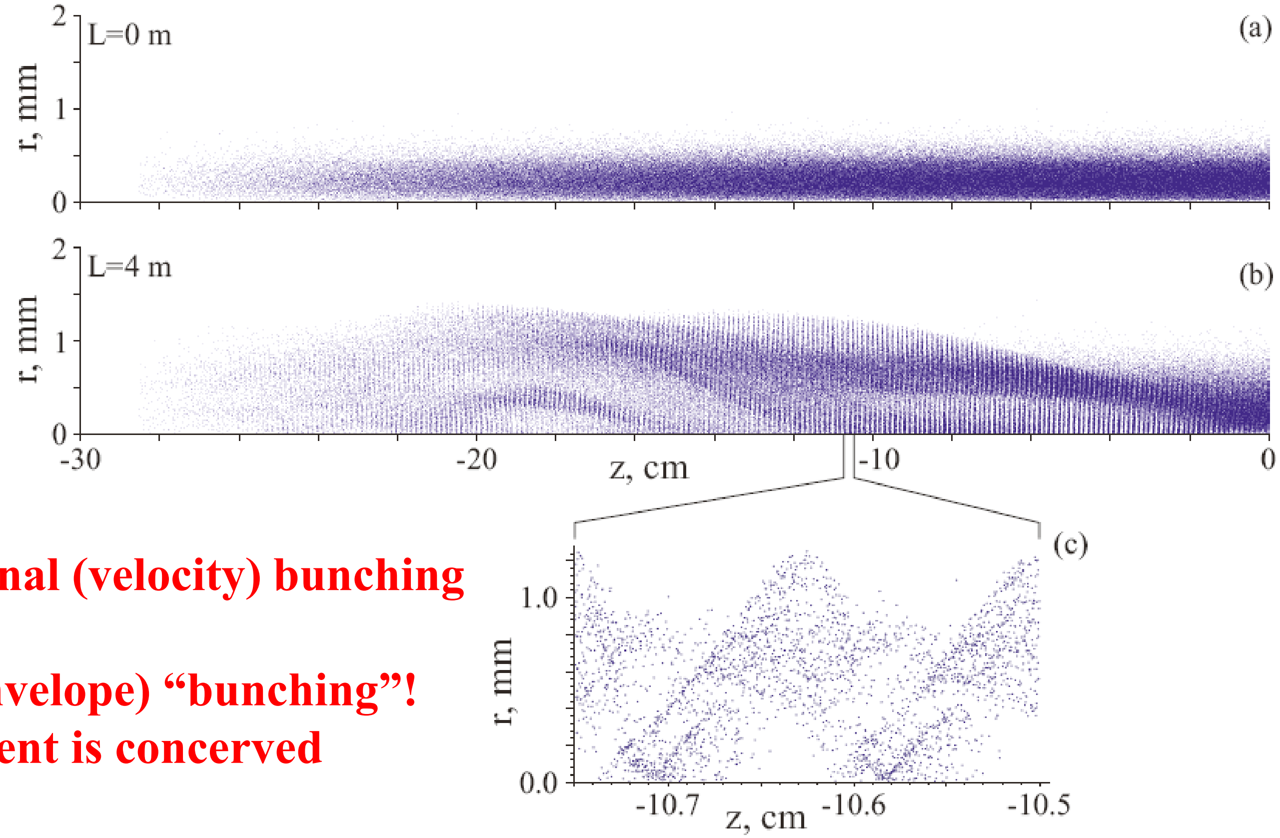
Ionization front is co-propagating with a short laser pulse and seeds Self Modulation Instability (SMI)

$\tau_{laser} \sim 100$ fs $\ll$ $\tau_{wake} \sim 3$ ps



Picture taken from AWAKE CDR, CERN 2013

AWAKE Physics: SMI details



NB! No longitudinal (velocity) bunching

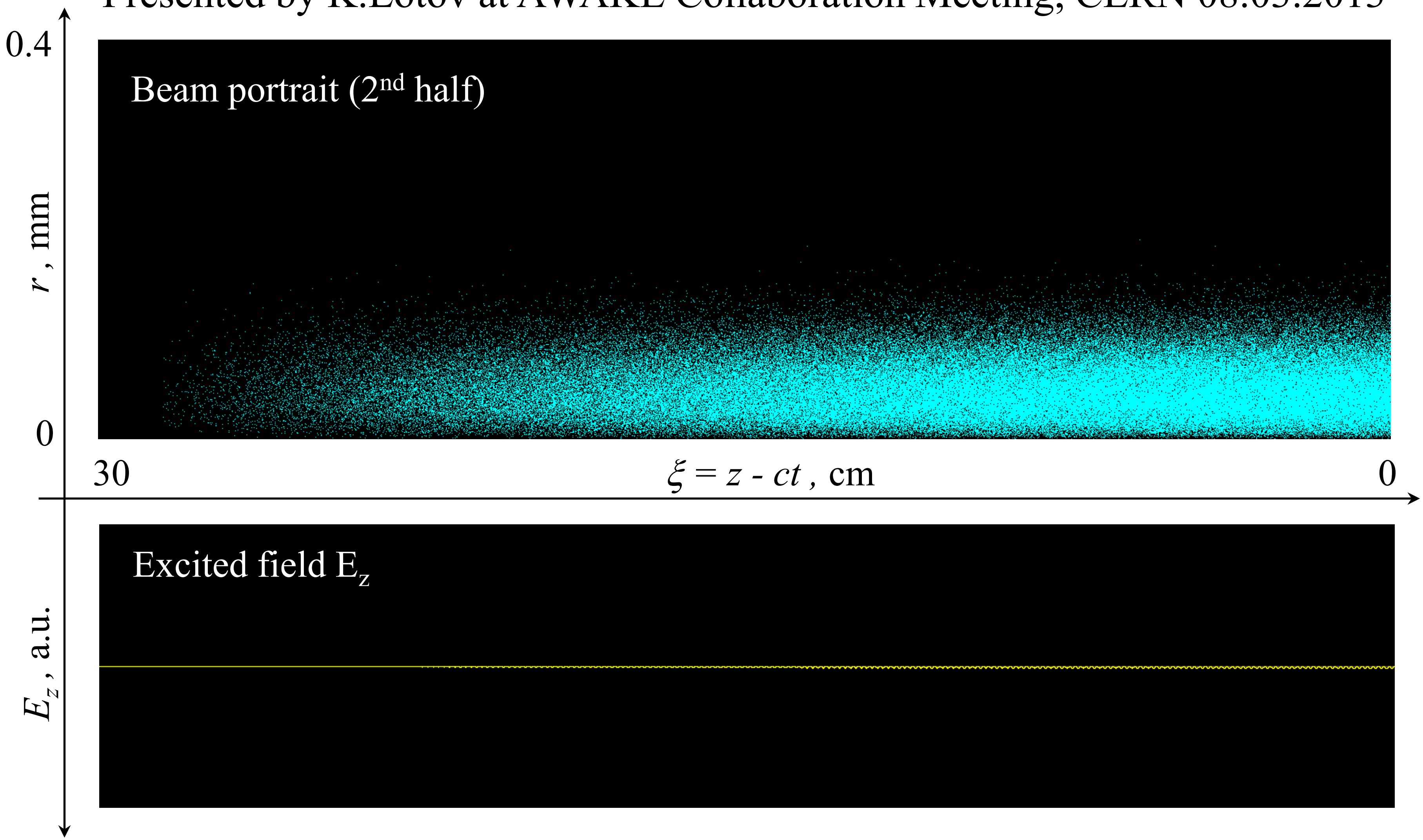
Only radial (envelope) "bunching"!
Total current is concerved

Fig. 11: Simulation result showing (a) the incoming uniform bunch and (b) the self-modulated bunch after 4 m of plasma. (c) Zoomed region of the self-modulated proton bunch, as could be measured using the OTR–streak camera system. The z coordinate is converted to time by the streak camera. The period of the self-modulation is ~ 1.2 mm or ~ 4 ps. The r direction is along the camera slit.

Picture taken from AWAKE CDR, CERN 2013

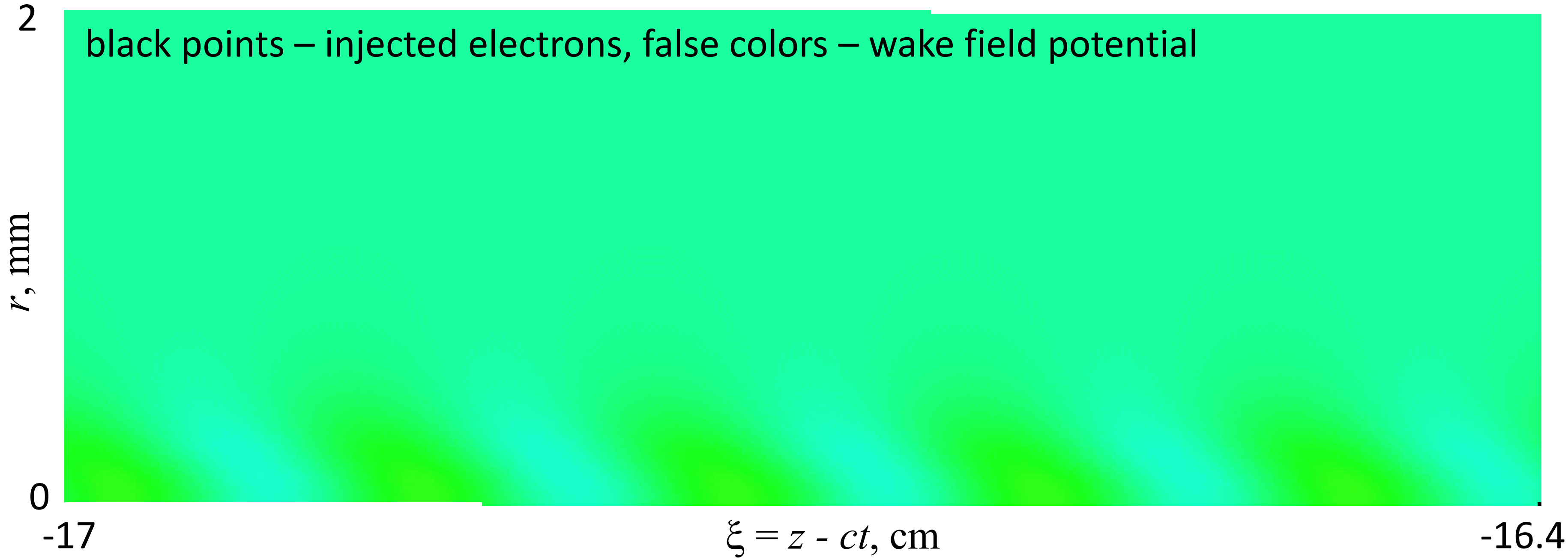
Proton bunch evolution

Presented by K.Lotov at AWAKE Collaboration Meeting, CERN 08.03.2013



On-axis e^- injection: trapping and acceleration

Presented by K.Lotov at AWAKE Collaboration Meeting, CERN 10.04.2014



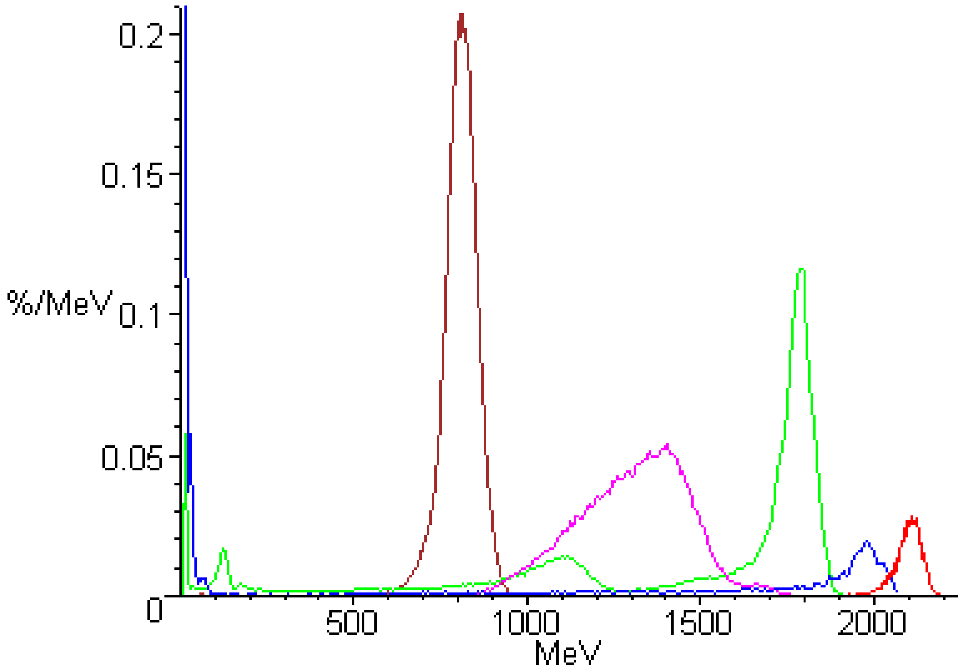
Plasma density must be very uniform $\Delta n/n \sim 0.1\%$

since an e- injection occurs at ~100 periods behind driver (“accordeon”) !

Simulation results: e^- energy and spread

Presented by K.Lotov at AWAKE collaboration meeting, CERN 10.04.2014

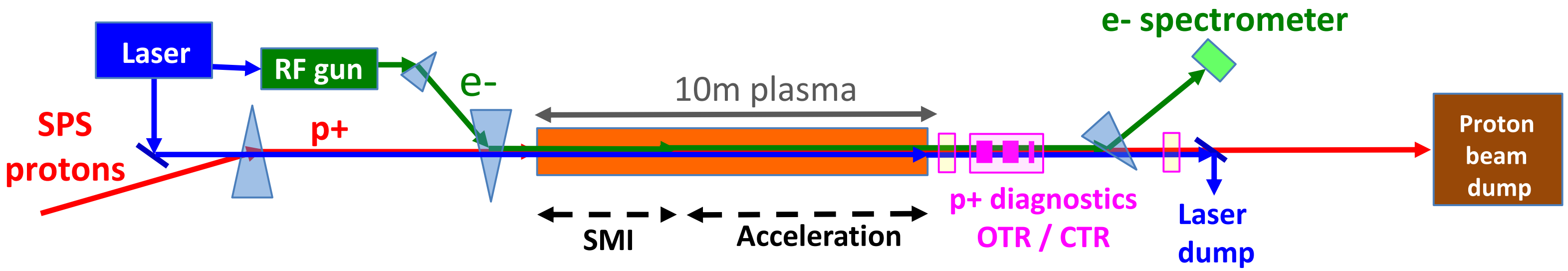
Comparison of best simulation results

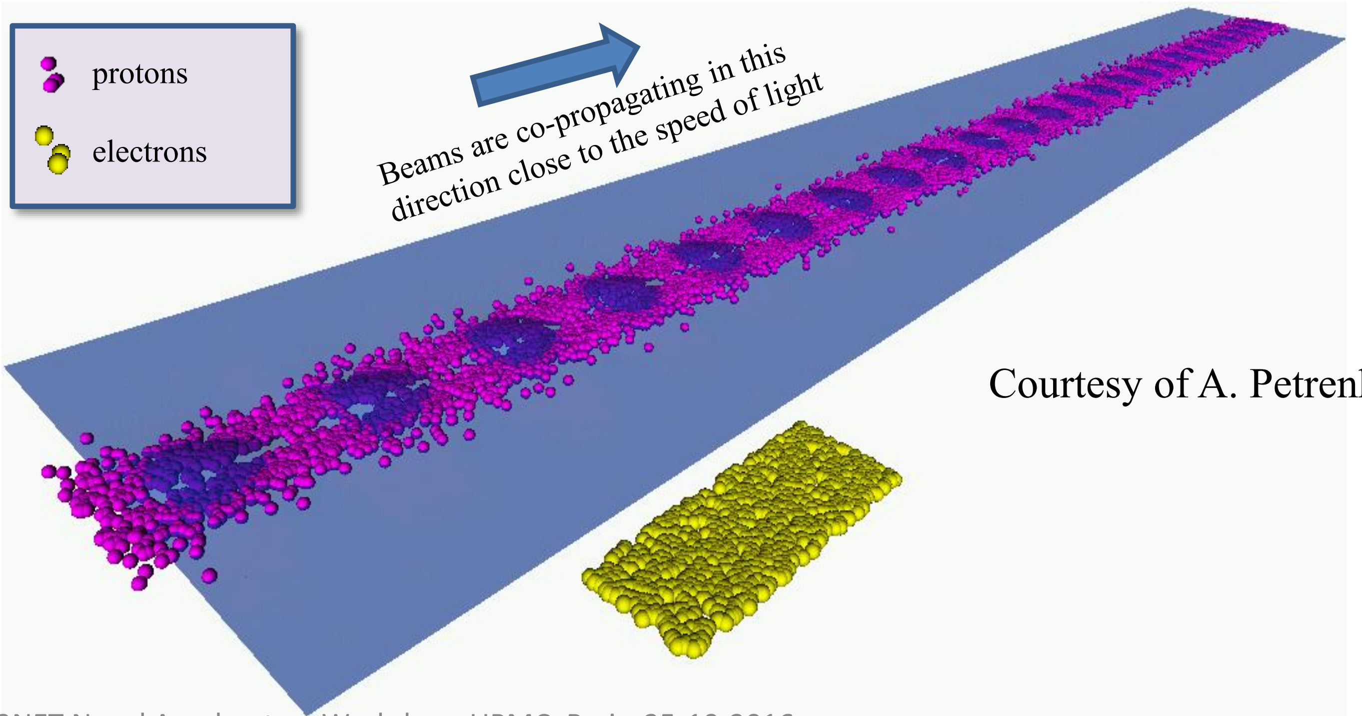


- Side injection (CDR baseline):
  5% trapping, 3% energy spread
- Off-axis injection (collinear electron beam shifted radially by 1.8 mm):
  ~5% in the main spike
- On-axis injection:
  40% trapping, 12% energy spread
- Improved Side injection:
  30% in the main spike, 4% energy spread
  45% trapping, 6.5% energy spread

AWAKE Experiment at CERN

- **Phase 1:** Understand **the physics of self-modulation instability** processes in plasma ➔ start Q4 2016
- **Phase 2: Probe the accelerating wakefields** with externally injected electrons ➔ start Q4 2017

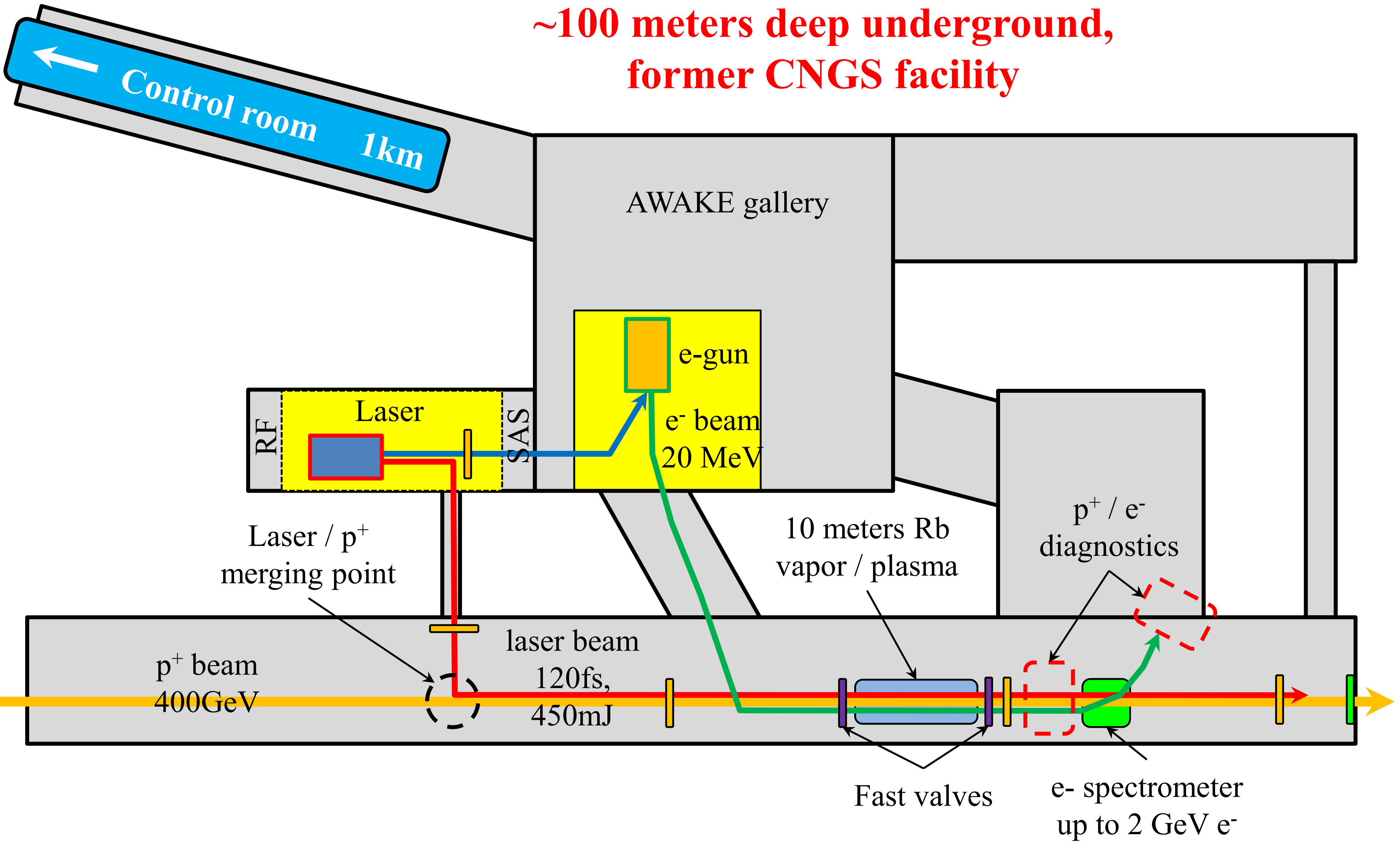




Courtesy of A. Petrenko, CERN

AWAKE Experiment at CERN

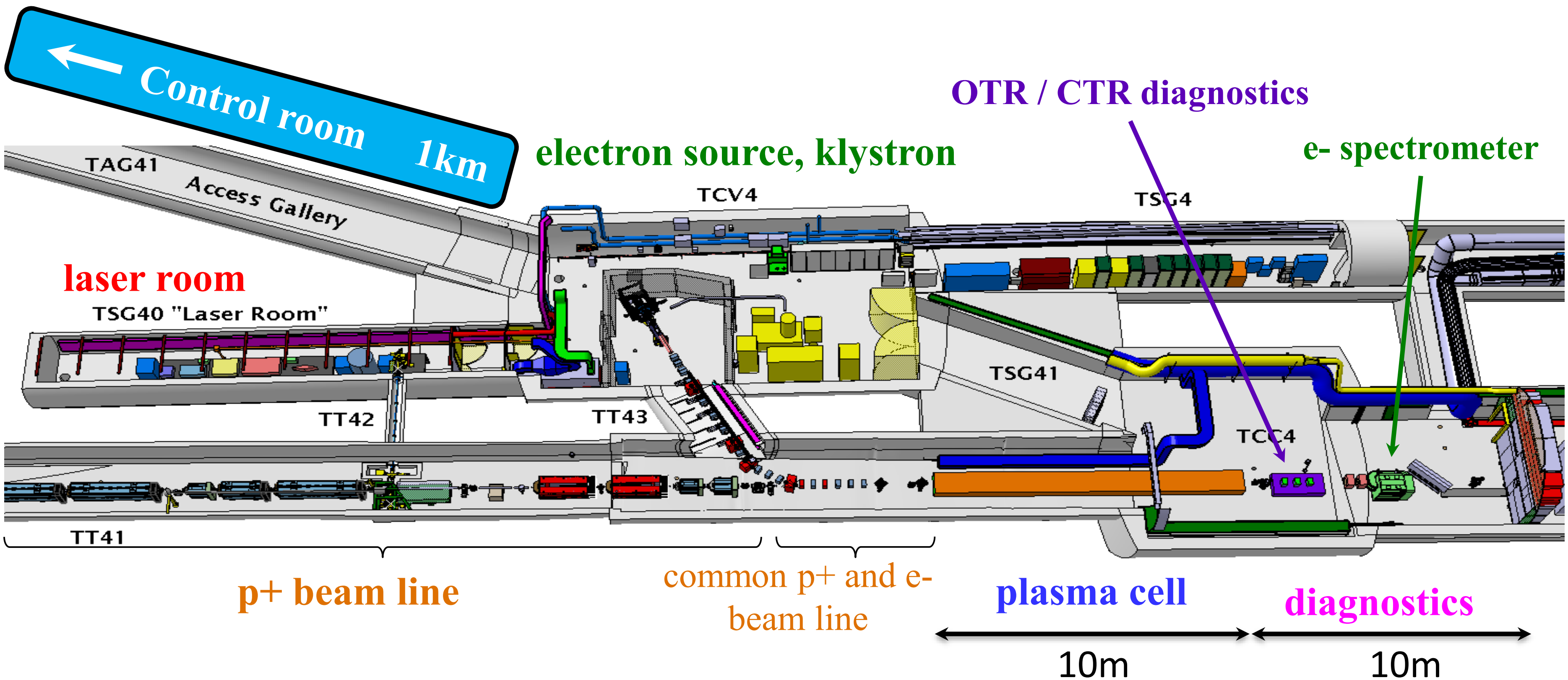
~100 meters deep underground, former CNGS facility



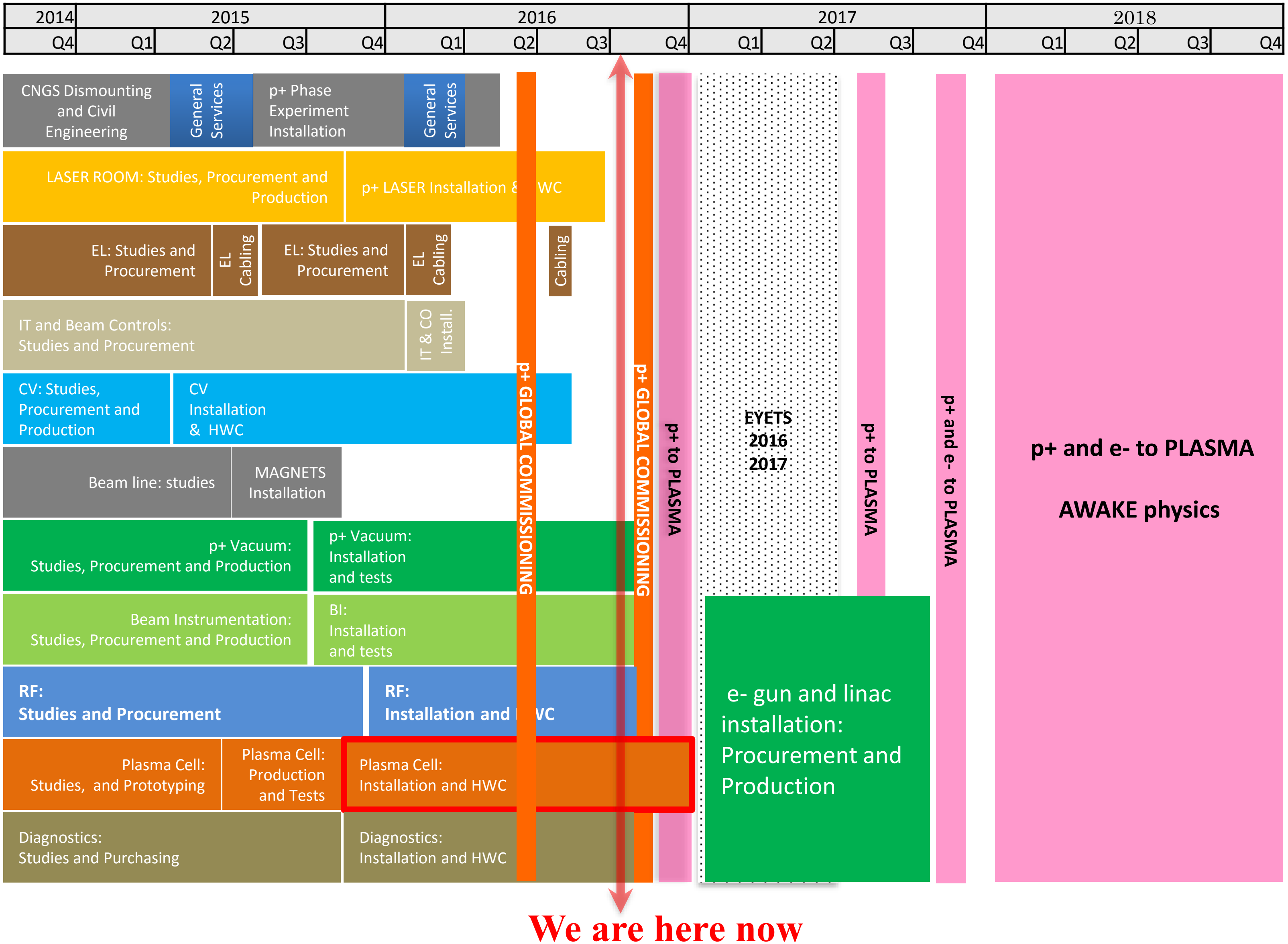
AWAKE "Submarine"

AWAKE Experimental Facility:

Limited space available

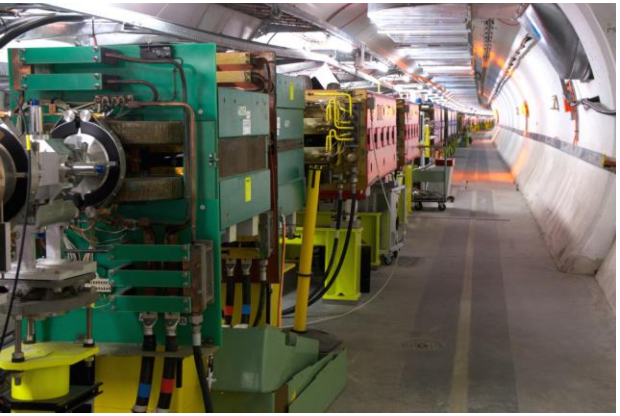


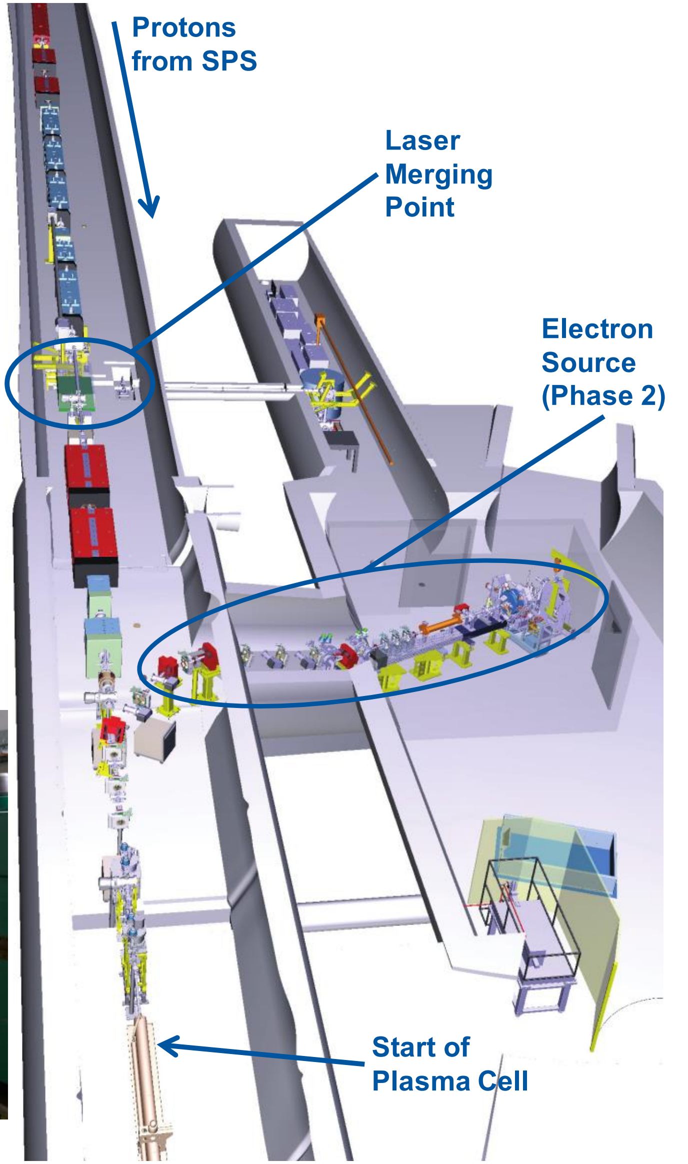
AWAKE Timeline



Proton beam line: commissioned

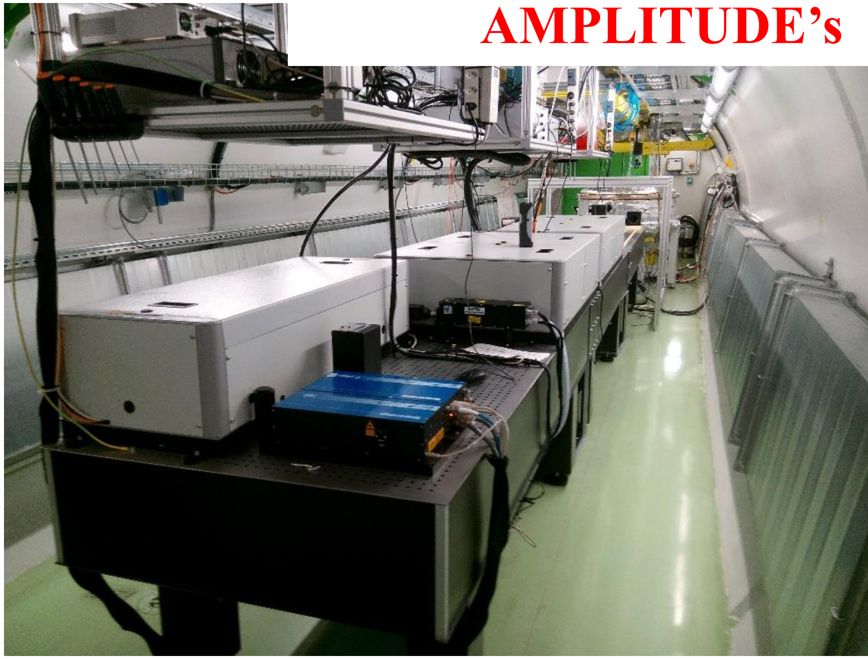
Parameter	Protons	Electrons
Momentum [MeV/c]	400 000	10-20
Momentum spread [%]	±0.35	±0.5
Particles per bunch	$3 \cdot 10^{11}$	$1.25 \cdot 10^{9}$
Bunch length [mm]	120	1.2
Norm. emittance [mm·mrad]	3.5	2
Repetition rate [Hz]	0.033	10
1σ spot size at focal point [μm]	200 ±20	<250
β-function at focal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

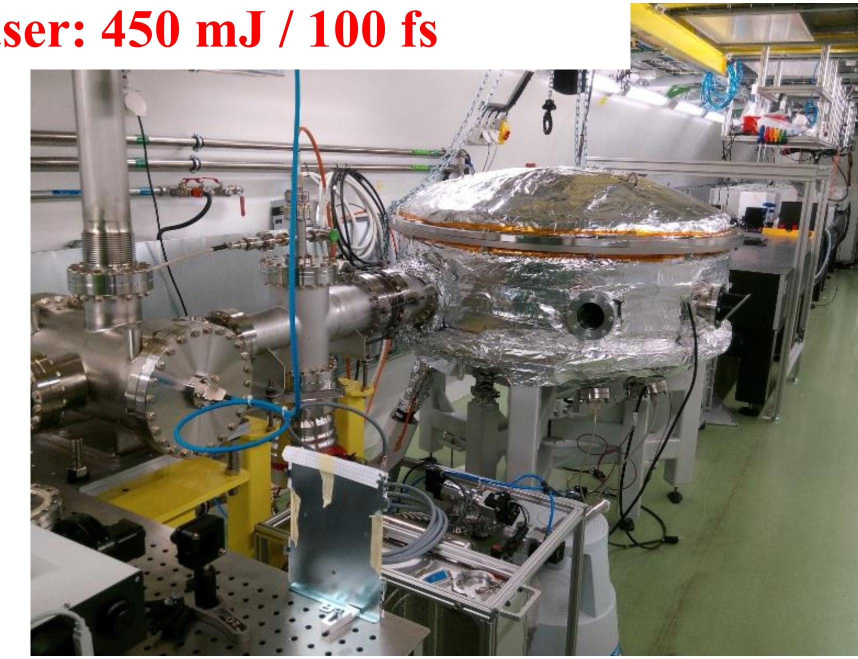


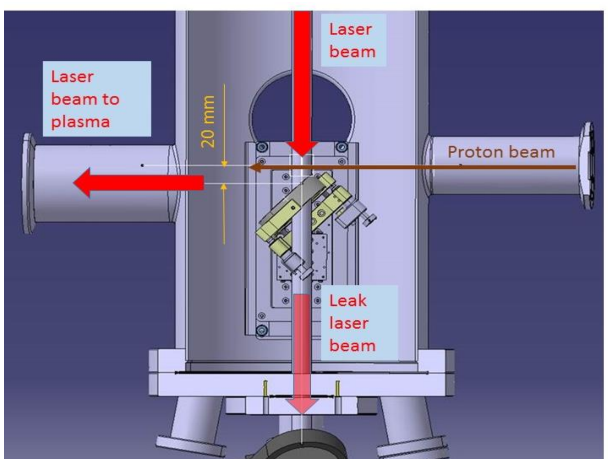


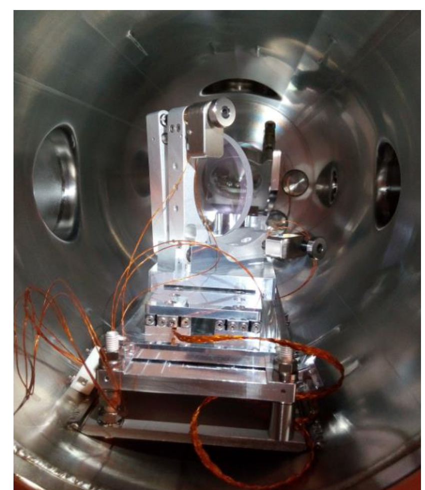
Laser and transfer line: commissioned

AMPLITUDE's laser: 450 mJ / 100 fs









Laser Overview

- **Ti:Sa laser system comprises:**
  - laser with 2 beams (for plasma creation and for the e-gun)
  - delay line is possible in either one of these beams
  - focusing telescope (lenses, in air), long 40m focusing
  - optical compressor (in vacuum)
  - optical in-air compressor and 3rd harmonics generator for e-gun

- **Ti:Sa laser parameters for plasma creation:**
  - max energy 450 mJ
  - pulse duration 120 fs after compression
  - max beam diameter 40 mm

} Only reflective optics on the compressed pulse way

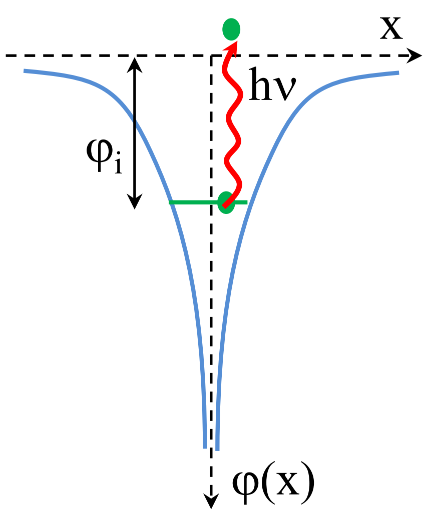
Rule of thumb ($B<1$):
$I[GW/cm^2] \cdot L[cm] < 36$

How to ionize Rubidium? Types of Laser Ionization

Rubidium φ_i = 4.2 eV = 300 nm
Laser hν = 1.6 eV = 785 nm

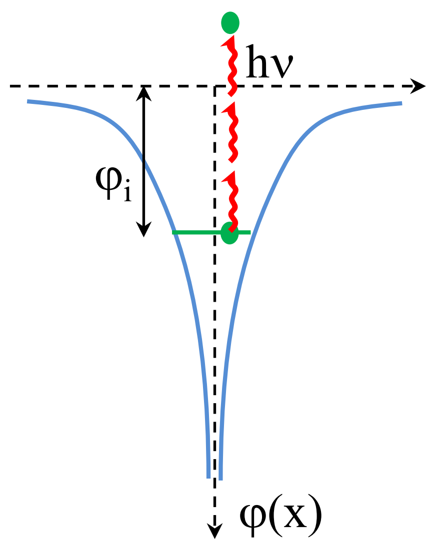
Single photon
(photo-effect)

$h\nu > \varphi_i$
$\nu >> \nu_t$
field E is small,
$\Delta\varphi << \varphi_i$



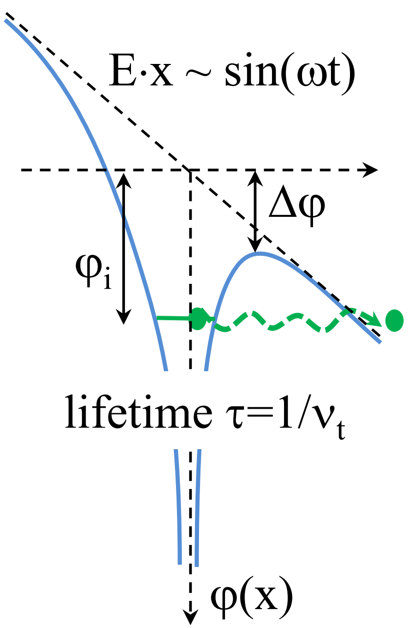
Multi-photon

$n \cdot h\nu > \varphi_i$
$\nu >> \nu_t$
field E is small,
$\Delta\varphi << \varphi_i$



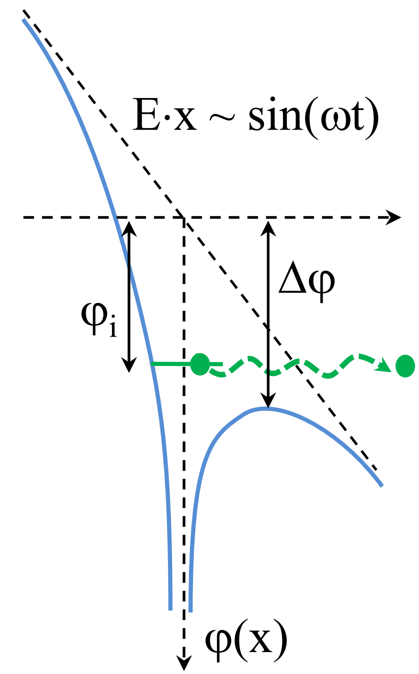
Tunneling

$\nu < \sim > \nu_t$
field E is high,
$\Delta\varphi < \varphi_i$



Strong field

$\nu << \nu_t$
field E is high,
$\Delta\varphi > \varphi_i$



AWAKE: Strong Field Ionization

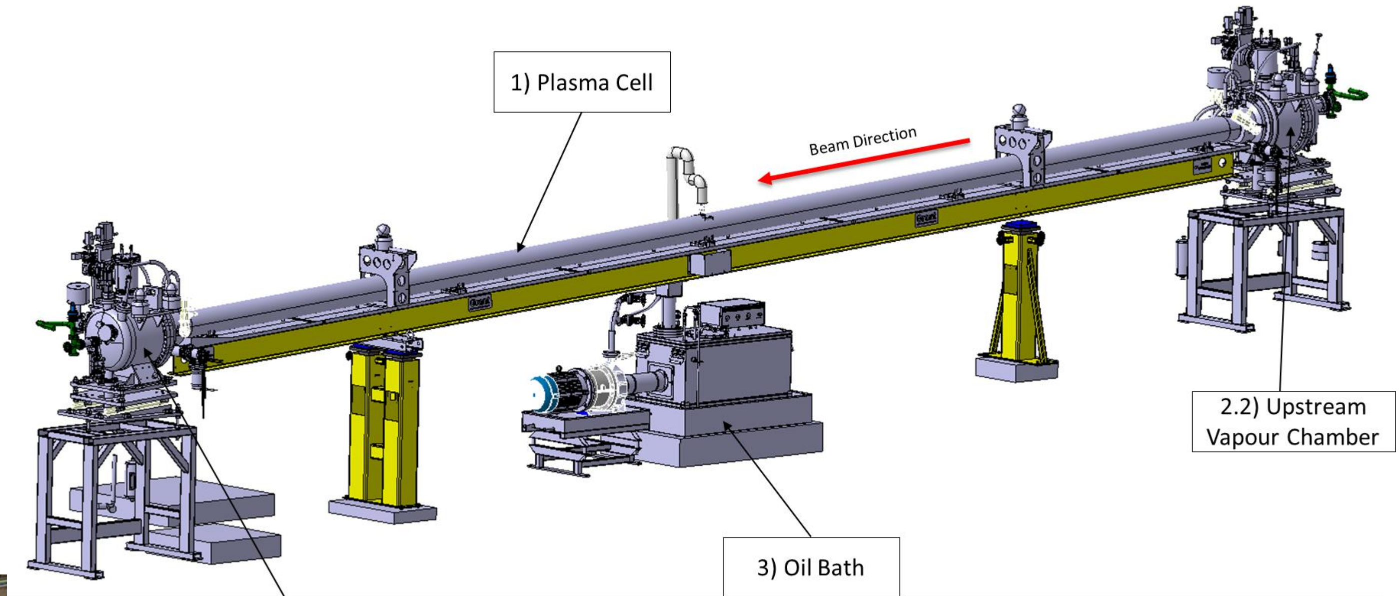
AWAKE Ti:Sa laser parameters for plasma creation:

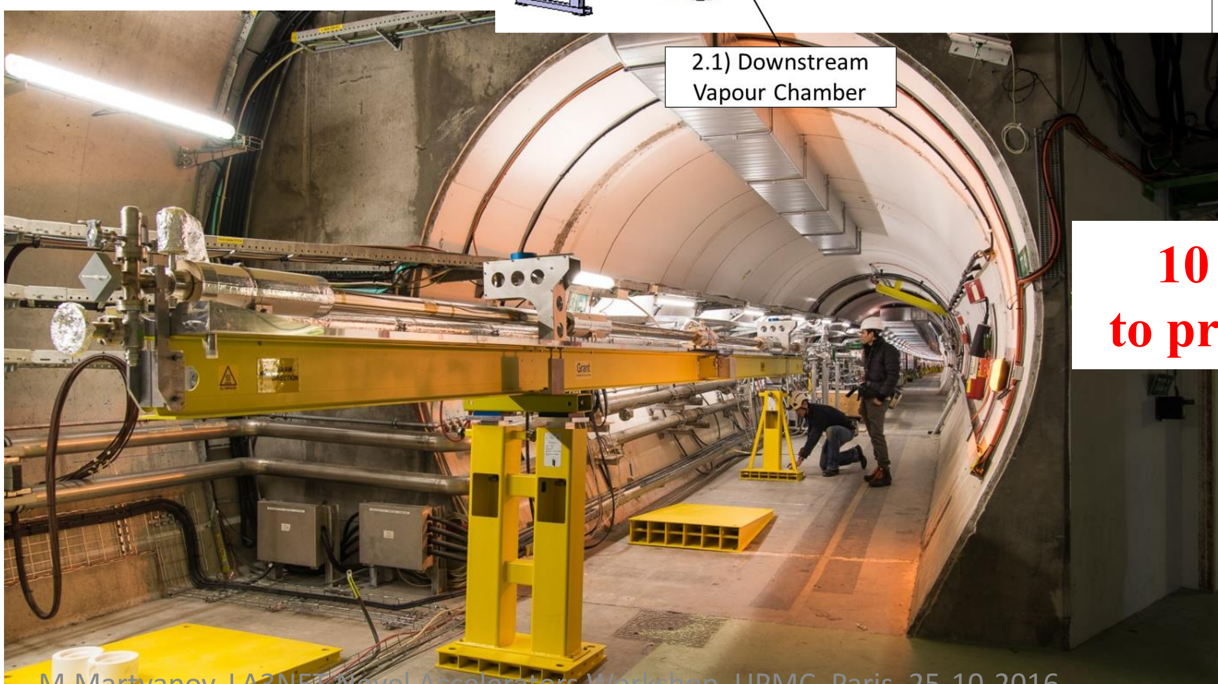
- Wavelength 790 nm
- Max energy 450 mJ
- Pulse duration 100 fs after compression

- Ionization threshold for Rubidium ~ 2 TW/cm2
- Focused laser intensity > 50TW/cm2
- Well above threshold, really strong field ionization

Rb vapour cell: under installation

WDL





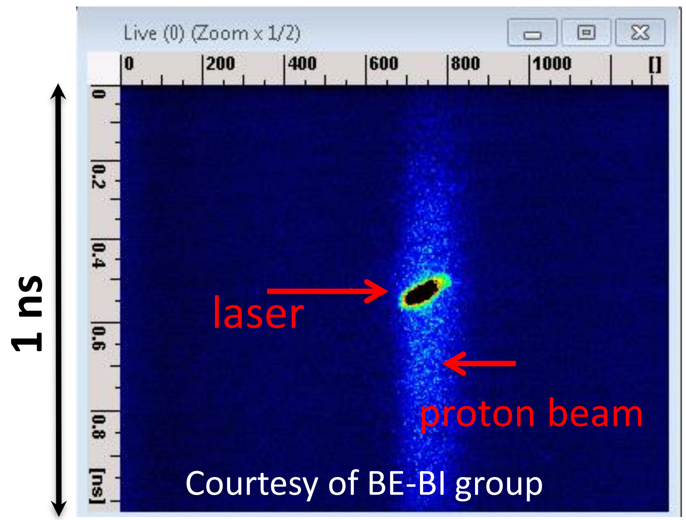
10 meter long heated oil bath to provide Δn/n~0.1% uniformity

OTR diagnostics: commissioned

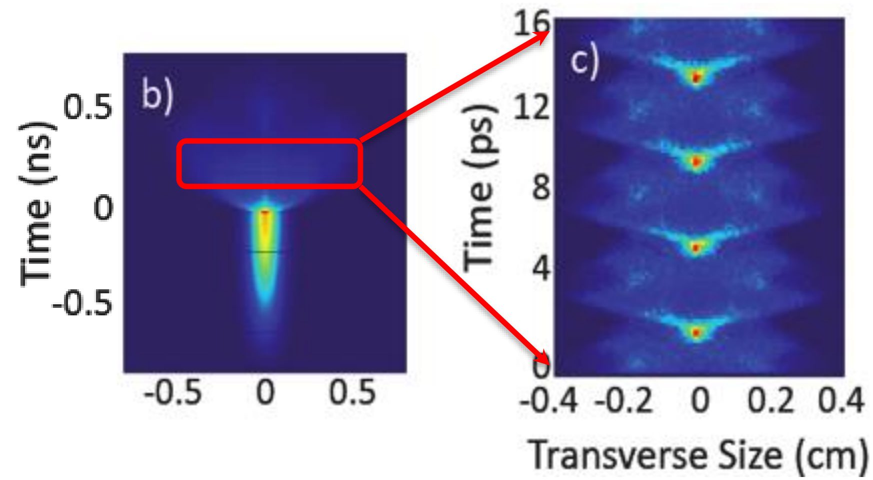
More details in Karl Rieger’s talk today later in this section

SPS proton beam **synchronized** with AWAKE laser within ~20ps accuracy

What we want to see during **the physics run,** starting **Dec 2016**



Streak measurement upstream plasma (measurement)

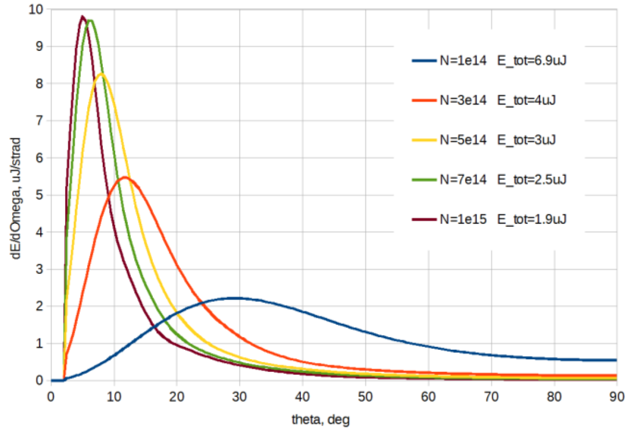


Proton Beam Self-Modulation Instability (simulation)

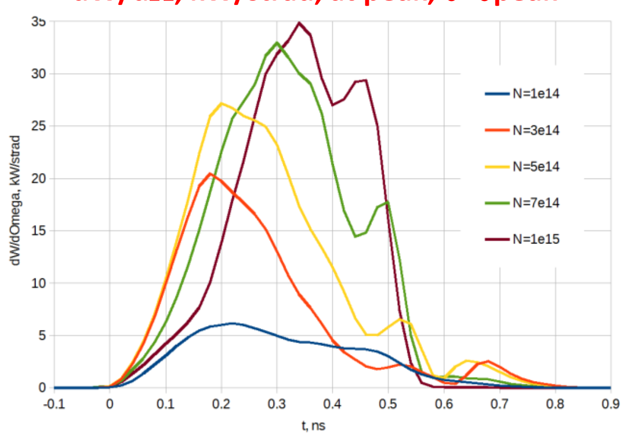
CTR diagnostics: under installation

More details in Falk Braunmueller's talk today later in this section

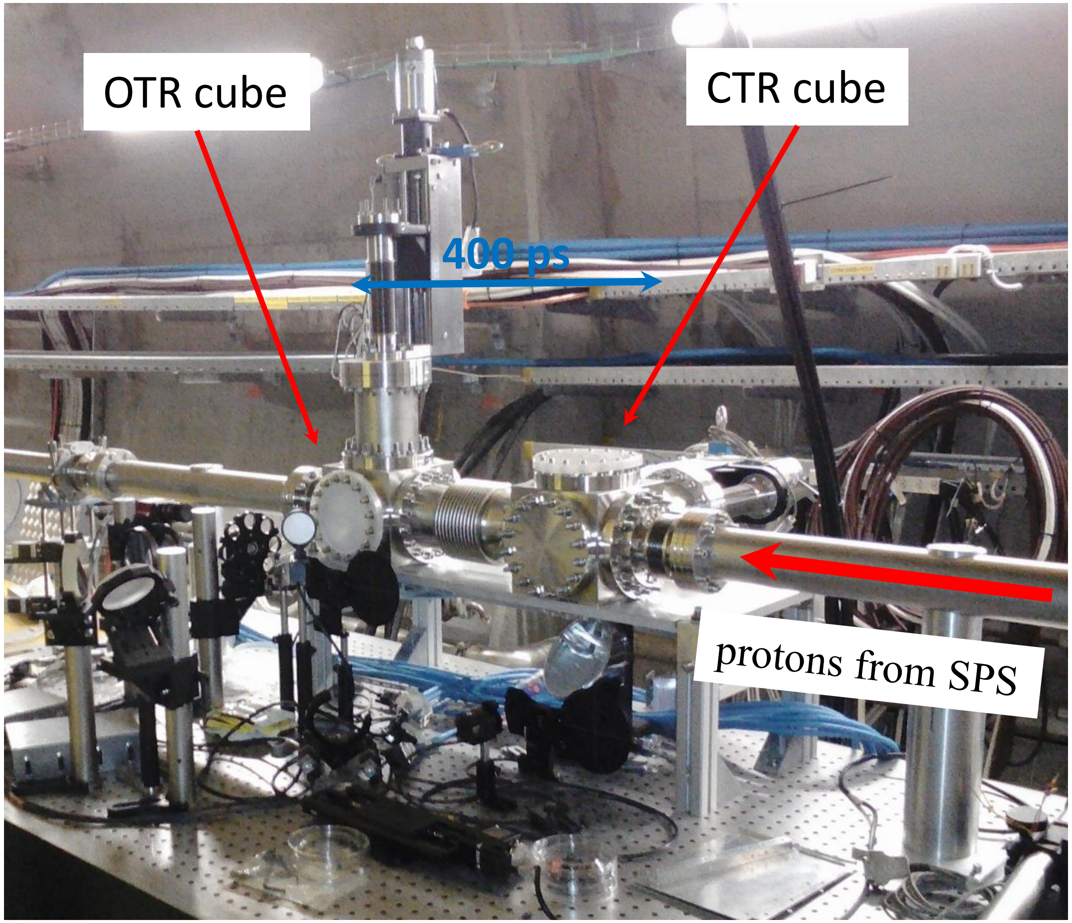
dE/dΩ, µJ/strad, Integrated over 20 GHz



dW/dΩ, kW/strad, at peak, θ=θpeak



- Donut-shape spatial pattern of a CTR beam
- At peak, fluence is 2-10 µJ/str => 5-25 nJ/cm^2 at 20 cm
- At peak, power is 5-30 kW/str => 13-75 W/cm^2 at 20 cm



Many more things not covered

- Vacuum installation
- Proton beam instrumentation
- Electron gun, linac and instrumentation
- Laser transfer line and merging point

- **Rubidium vapour controls to fulfil $\Delta n/n \sim 0.1\%$ uniformity**
- Proton beam halo diagnostics
- Rubidium vapour laser pulse propagation
- Plasma diagnostics
- …and many more…

Summary

- **AWAKE is scientifically and technically challenging experiment with a tight schedule**
- **Main challenges are:**
  - 10 meters long extremely uniform (<0.1%) Rb plasma channel ← oil bath
  - Hot (500K) Rb vapor vessel v.s. ultra high vacuum outside
  - Synchronization in time and space of 3 beams (p^+, e^-, laser)
  - **Seeding of Self Modulation Instability (SMI)**
  - Diagnostics of SMI and others
  - Long focal waste Rb vapor strong field ionization by Ti:Sa laser
  - And many more ...

First physics – end 2016

Thank you!

Plasma Wake Field: Glossary

Plasma oscillations (Langmuir oscillations) frequency

for $n_e=10^{15}$ cm^{-3}

$$\nu_{pe}[GHz] = 89.8\sqrt{n_e\,[10^{14}\,cm^{-3}]}$$

$$\lambda_{pe}[mm] = c/\nu_{pe} = 3.34\,/\,\sqrt{n_e\,[10^{14}\,cm^{-3}]}$$

ν_{pe} = 284 GHz
λ_{pe} = 1.06 mm

Charge density oscillations in a cold plasma

- Response to any local break of quasi-neutrality
- Collective motion of plasma electrons with Langmuir frequency

Wake oscillations

- Caused by a “driver” moving fast in plasma
- Wake fields are intrinsic property of wake oscillations

Simple theory: maximum electric field in plasma

$$E_{0\,max}[GV/m] = 0.962\sqrt{n_e\,[10^{14}\,cm^{-3}]}$$

for $n_e=10^{15}$ cm^{-3}
$E_{0\,max}$ = 3 GV/m