AWAKE Experiment at CERN.

Project Review

Mikhail Martyanov (Max-Planck Institute for Physics)

on behalf of AWAKE Collaboration

Max Plank Institute for Physics, Munich, December 18-19, 2017

What is AWAKE?

AWAKE = Advanced WAKefield Experiment

- **Proton-driven Plasma Wakefield Acceleration Experiment**
- **Aiming to accelerate electrons to high energy (GeV-TeV)**
- **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)

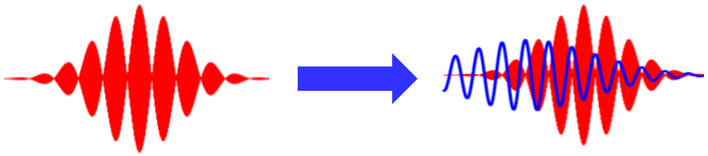
Some useful links:

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

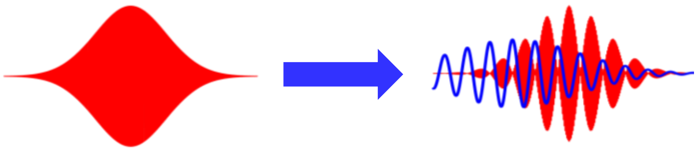
The Zoo of Plasma Wake-field Accelerators

… started from pioneer paper "Laser Electron Accelerator" by T.Tajima and J.Dawson
Phys. Rev. Lett. 43, 267 – Published 23 July 1979

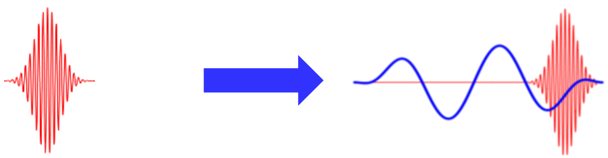
Laser Beat-Wave WFA (~1 ns)
Two frequencies laser pulse (pulse train)



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

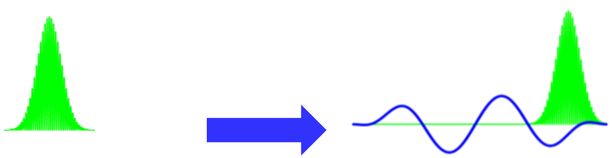


Laser WFA (~0.1 ps)
Short intense laser pulse



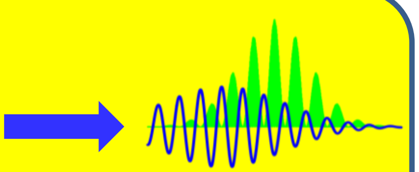
Particle Bunch WFA
Short intense particle bunch

~ 1ps proton bunch does not exist !



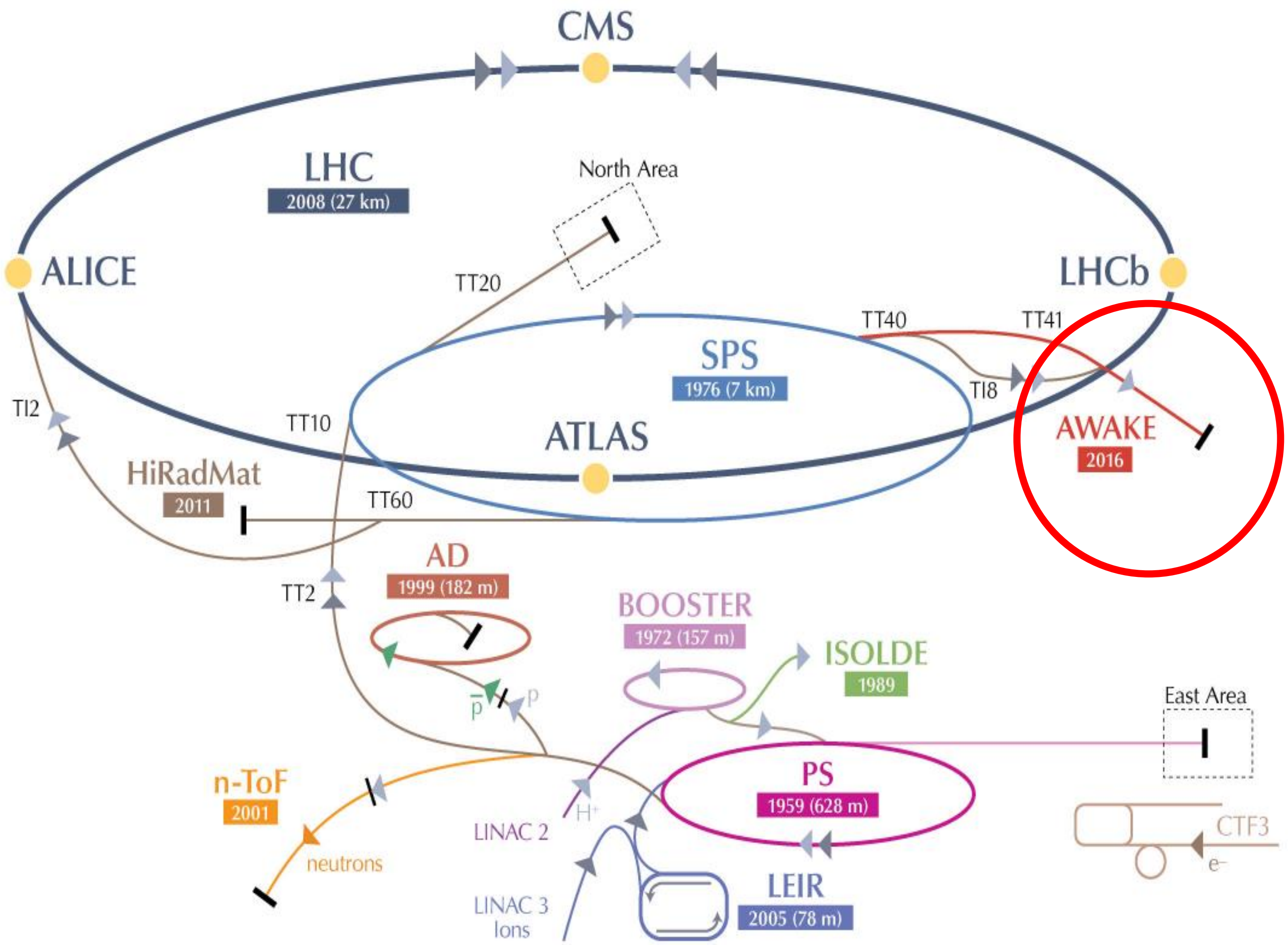
Self-Modulated Particle Bunch WFA
Long bunch experience transverse self-modulation instability

~1ns



Scope of AWAKE proof-of-principle experiment

AWAKE at CERN

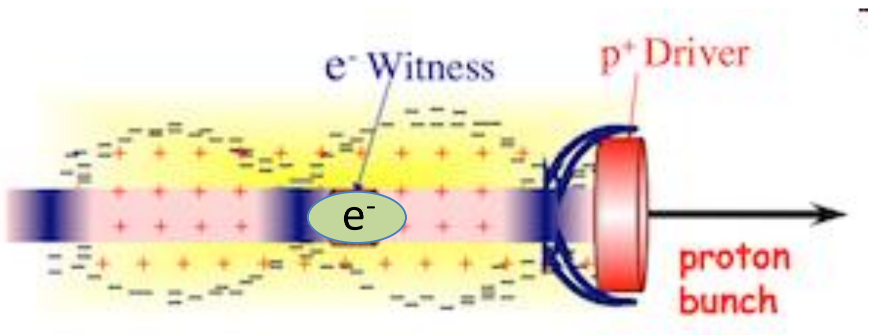


AWAKE Baseline Parameters

Plasma	Rb plasma density	$10^{14} \div 10^{15}$ cm^{-3} $7\cdot(10^{-3} \div 10^{-2})$ mBar at 500°K
	Expected gradient	1 ÷ 3 GV/m
	Uniformity	<0.1%
	Length	10 meters
Proton bunch	Energy	400 GeV → 64 nJ/p^+ → 19.2 kJ/bunch
	Charge	$3\cdot10^{11}$ 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	$1.25\cdot10^9$ 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

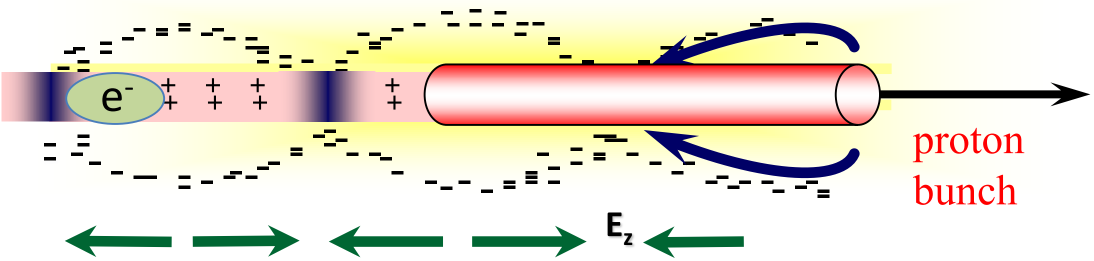
Seeded Self Modulation (SSM)

Short proton bunch driver
No SSM



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

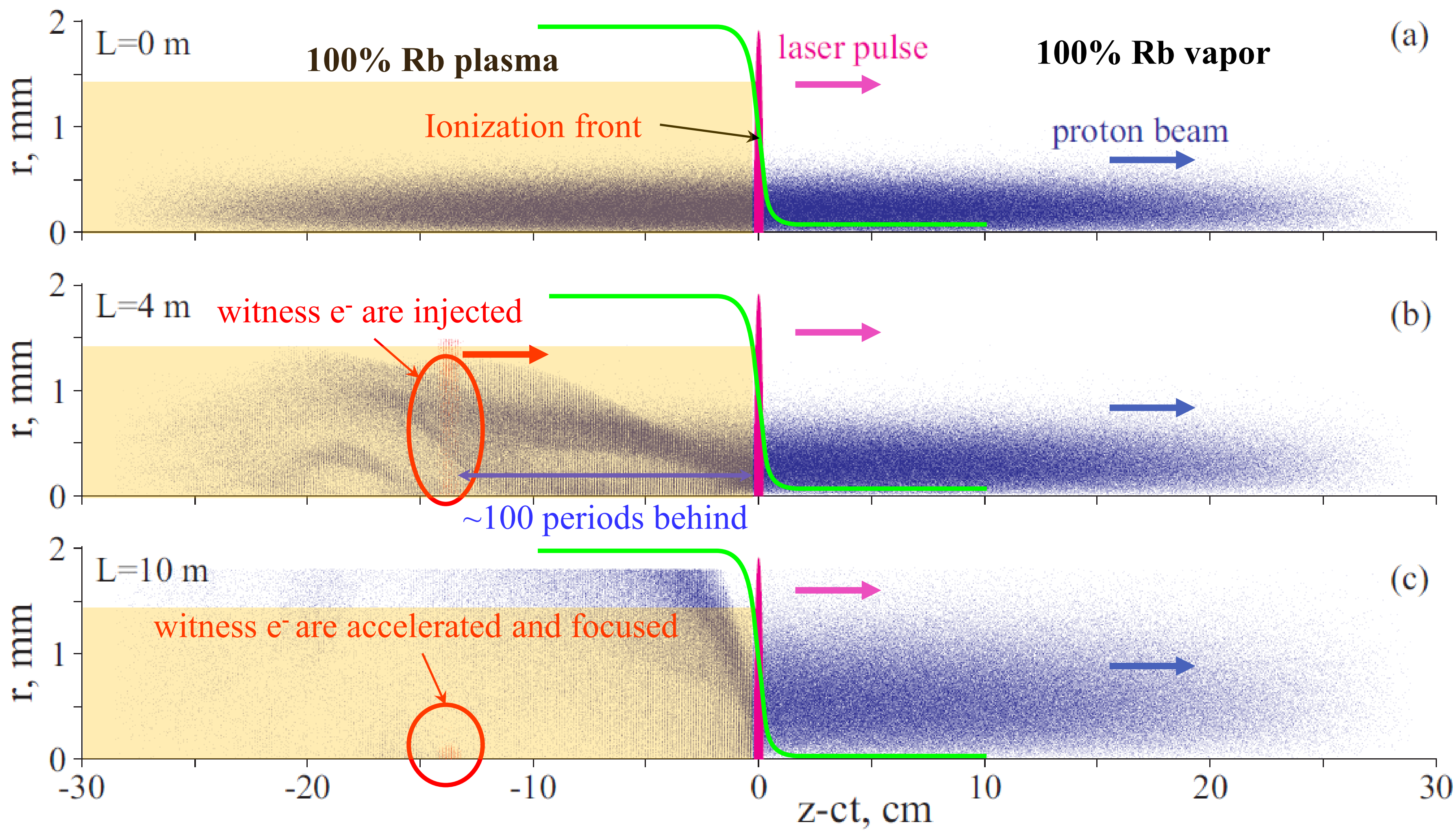
Long proton bunch driver
SSM develops



AWAKE Physics: Principle

Ionization front is co-propagating with a short laser pulse and creates Seeded Self Modulation (SSM)

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



Picture taken from AWAKE CDR, CERN 2013

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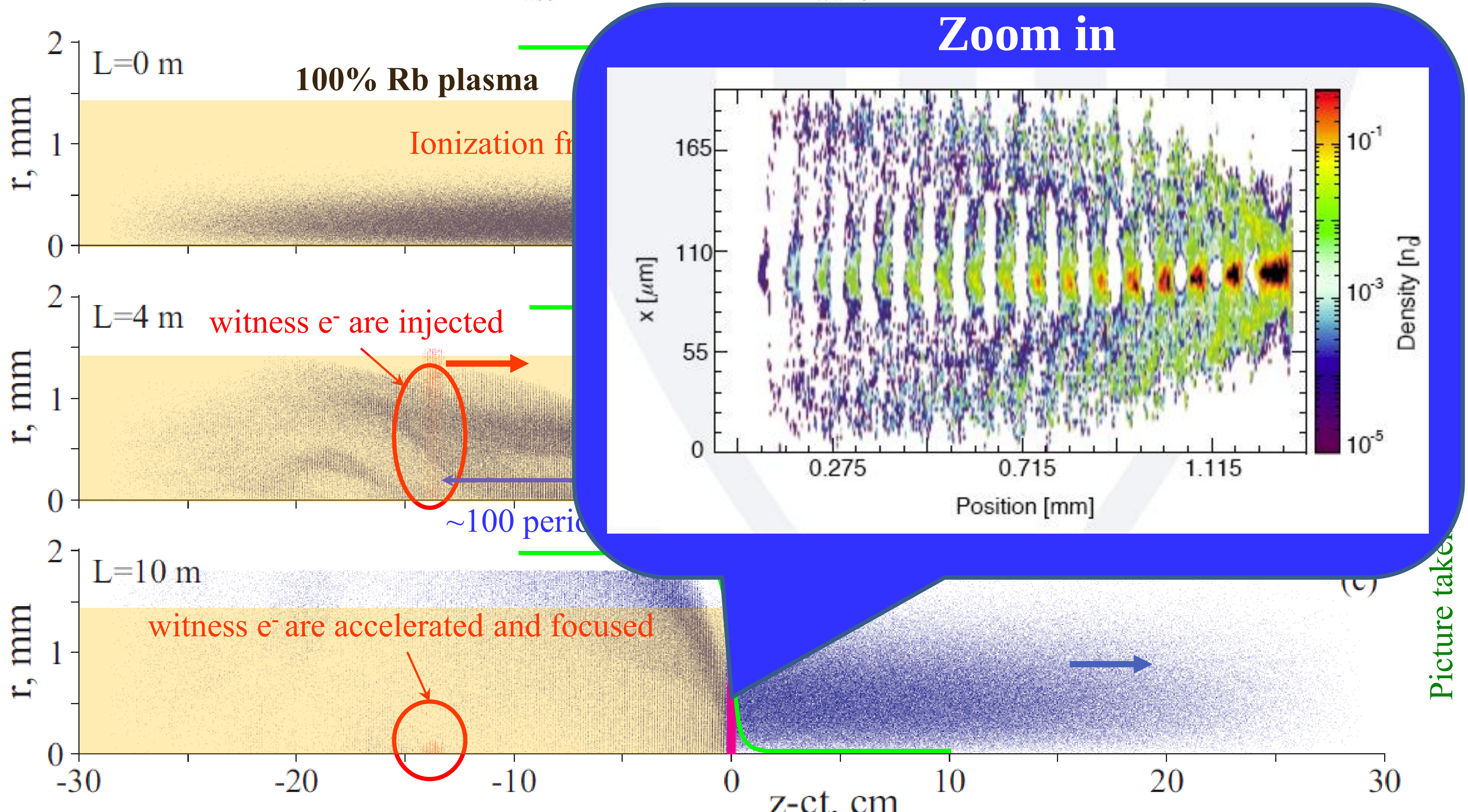
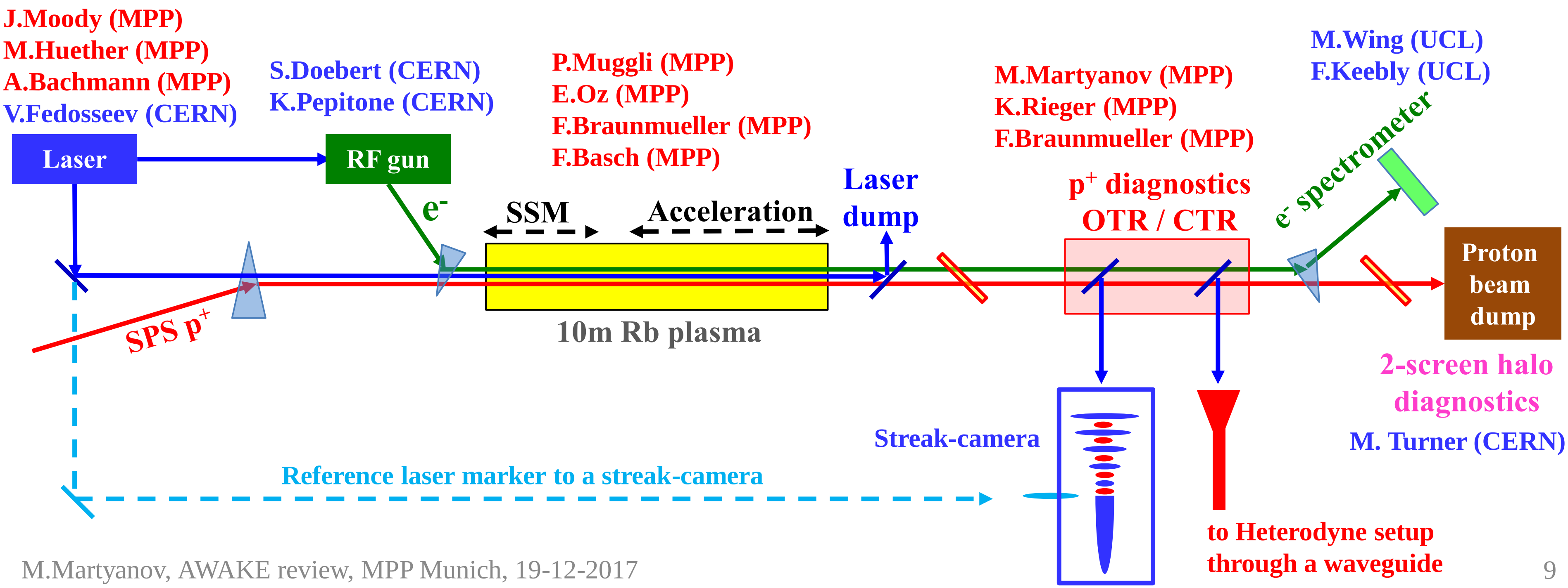


AWAKE Experiment at CERN

- **Phase 1:**
  Understand **the physics of seeded self-modulation** processes in plasma ➔ started Q4 2016
- **Phase 2:**
  Probe the accelerating wakefields with externally injected electrons ➔ started Q4 2017
- **We had a very sucessful AWAKE programm during 2015 - 2017!**
  - **Building an experiment from 2015.**
  - **First SSM at the second day of run in 2016!**
  - **Proven SSM phase stability in 2017.**



Beam Diagnostics overview

- Rb-cell diagnostics (white light interferometry, T-sensors etc.)

- Laser line diagnostics and alignment (CCD's, energy, ACF etc.)

p^+ diagnostics:

- Standard (BCT, BPM's, luminescent / OTR screens)
- Two-screen halo diagnostics
- Visible OTR, 2 streak cameras – SSM visualization
- Microwave CTR – SSM frequency measurement

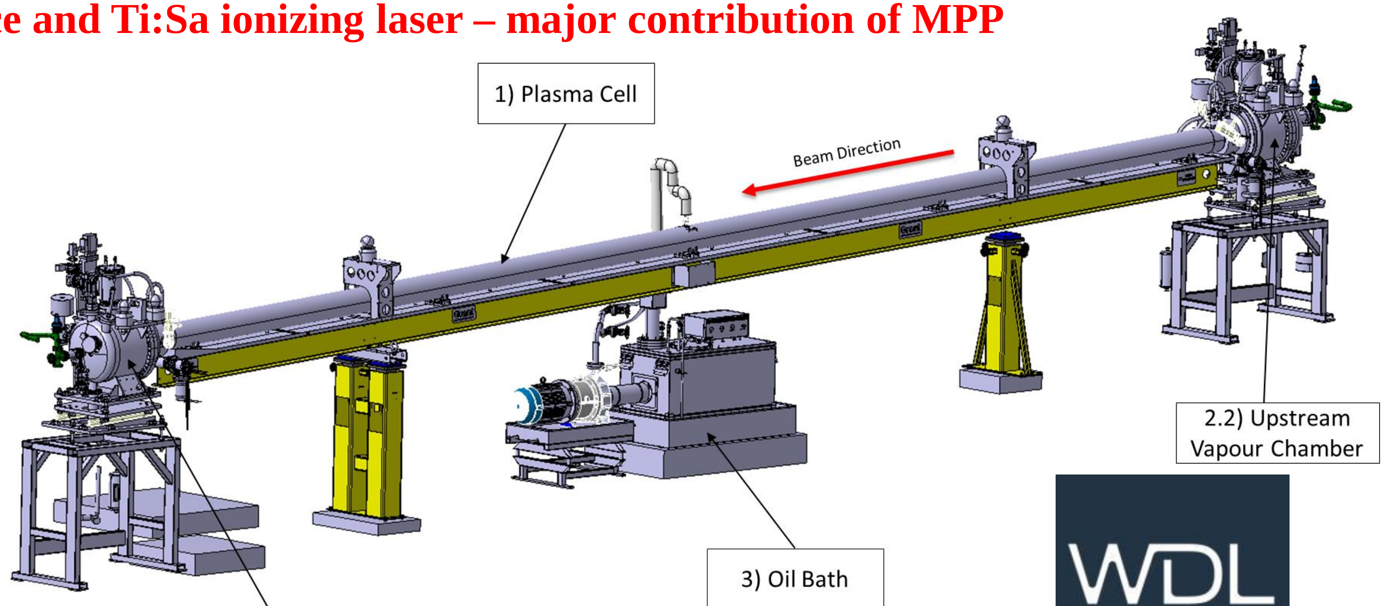
e^- diagnostics :

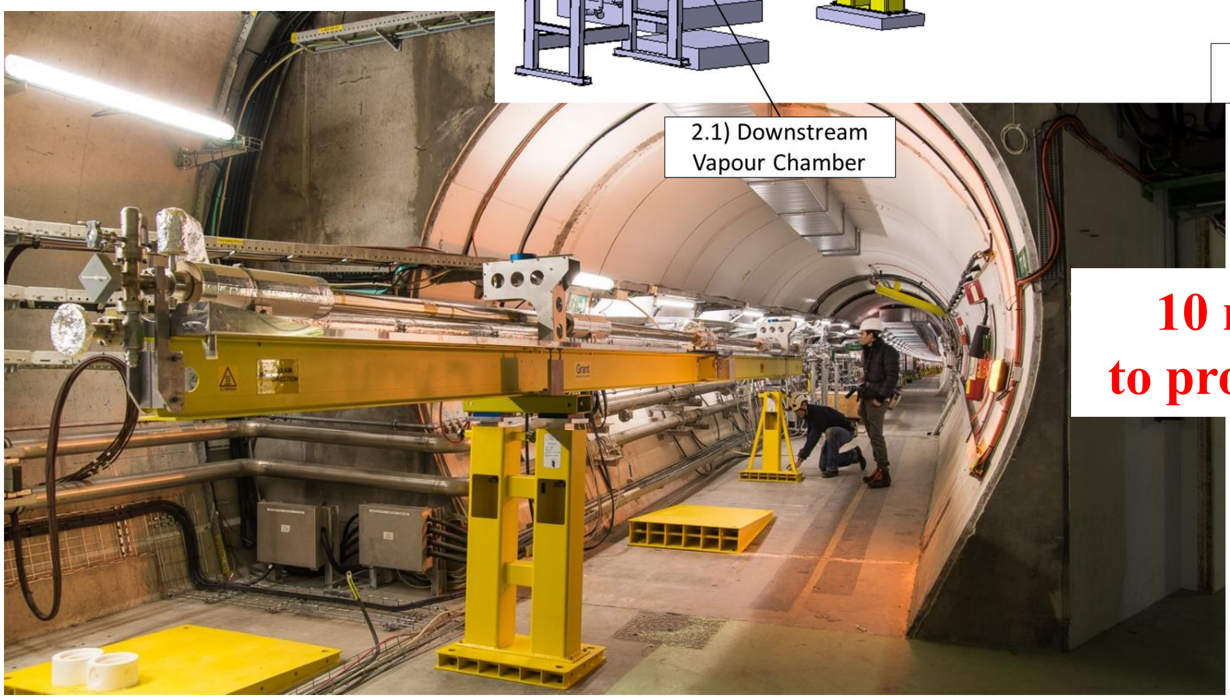
- Standard (BCT, BPM's, screens)
- Large wide-band spectrometer (20 MeV to 3 GeV)

Key Component : Rb vapour cell

Rb vapour / plasma source and Ti:Sa ionizing laser – major contribution of MPP

P.Muggli (MPP)
E.Oz (MPP)
F.Braunmueller (MPP)

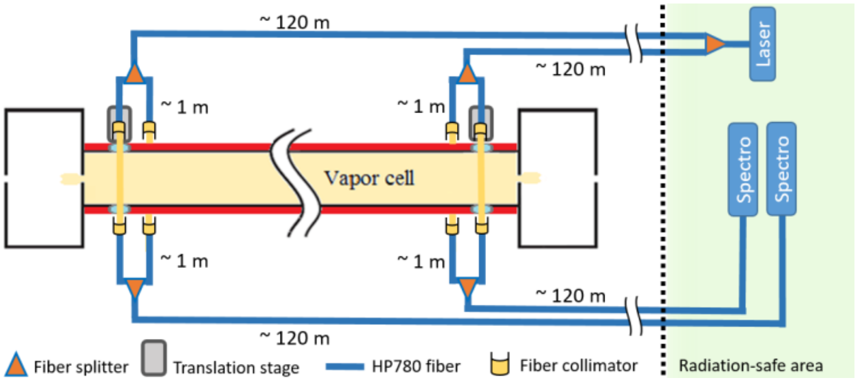




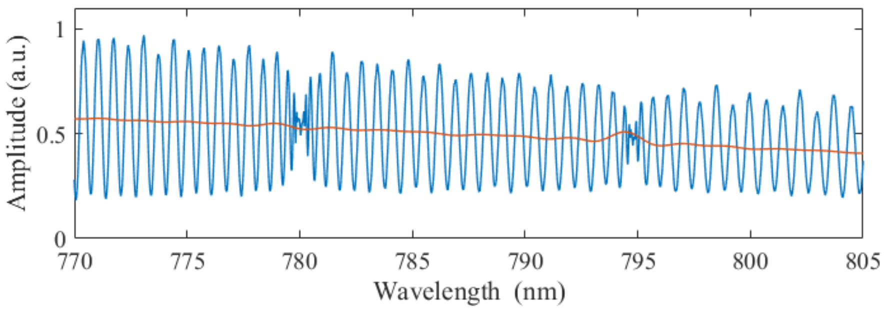
10 meter long heated oil bath to provide Δn/n~0.1% uniformity

Rb vapour cell : density diagnostics

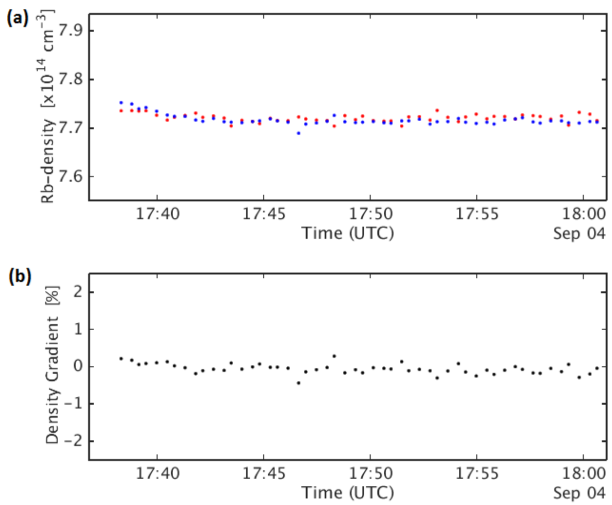
- **Measure at both vapor cell ends with 0.1 to 0.4 % precision for gradient determination**
- Use Mach-Zehnder interferometer and white light interferometer



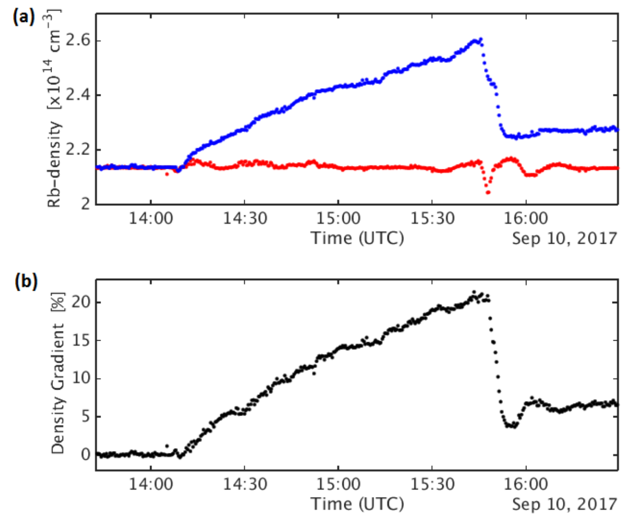
F.Batsch (MPP)



Stable density and gradient:



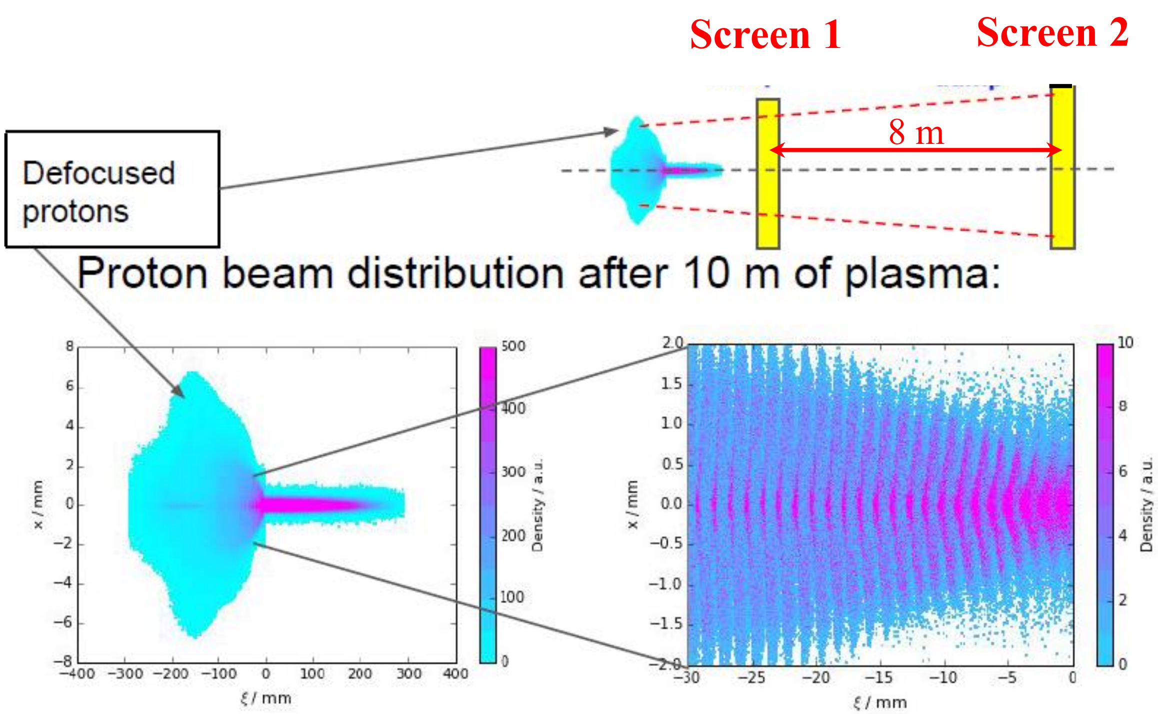
Gradient scan:



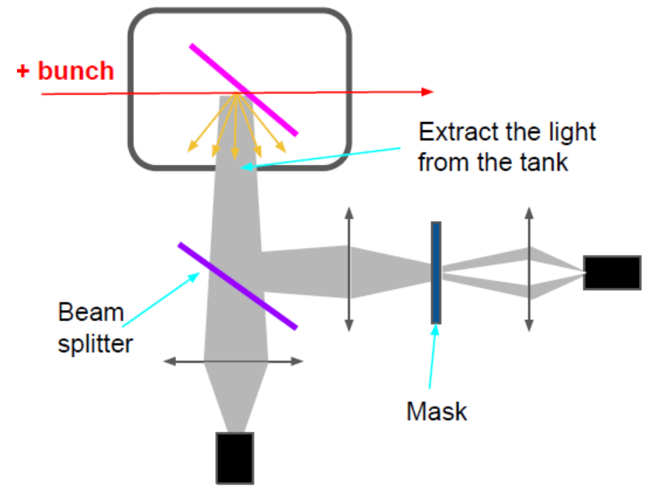
Two-Screen p$^+$ Halo Diagnostics

The aim of the diagnostic – to measure the defocused part of a proton bunch (halo)

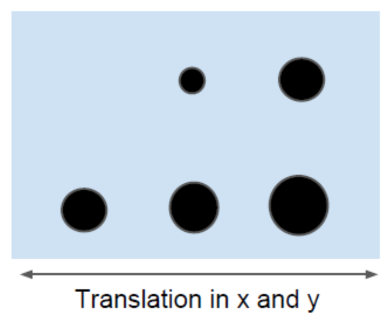
Each screen port has 2-CCD optical system and a mask to hide a core of the beam



*Based on a LCODE simulation with a plasma density of 7e14/cm3



The mask:



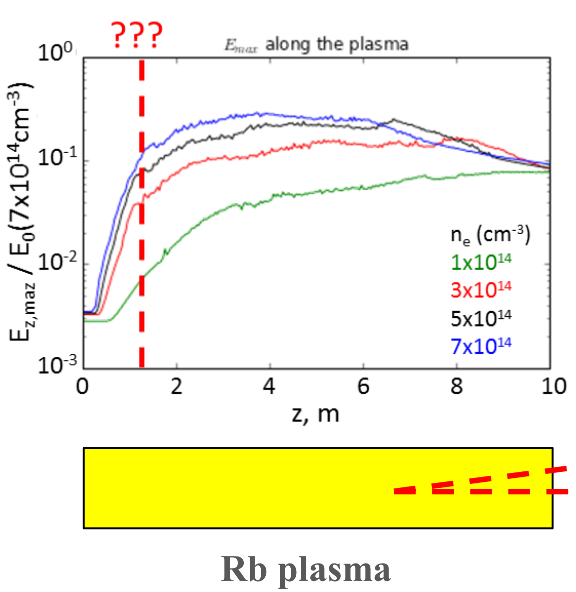
M.Turner (CERN)

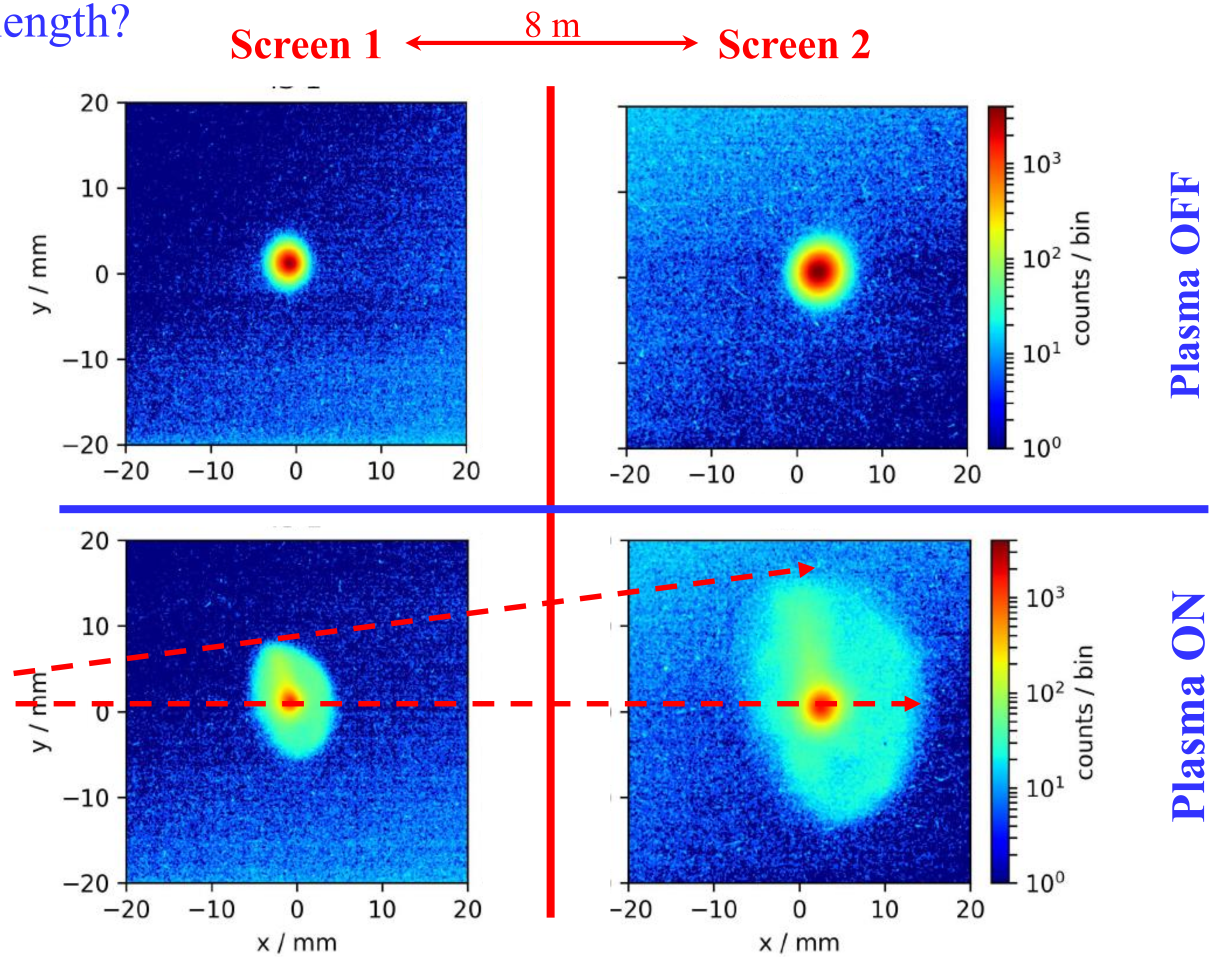
Two-Screen p^+ Halo Diagnostics

- **p^+ are defocused by the transverse wakefield (SSM) form a halo**
- Focused p^+ form a tighter core
- Estimate of the transverse wake-field amplitude (integral)
- Information about saturation length?

Preliminary !!!

Longitudinal electric field E_z evolution along plasma cell





Courtesy of M.Turner (CERN)

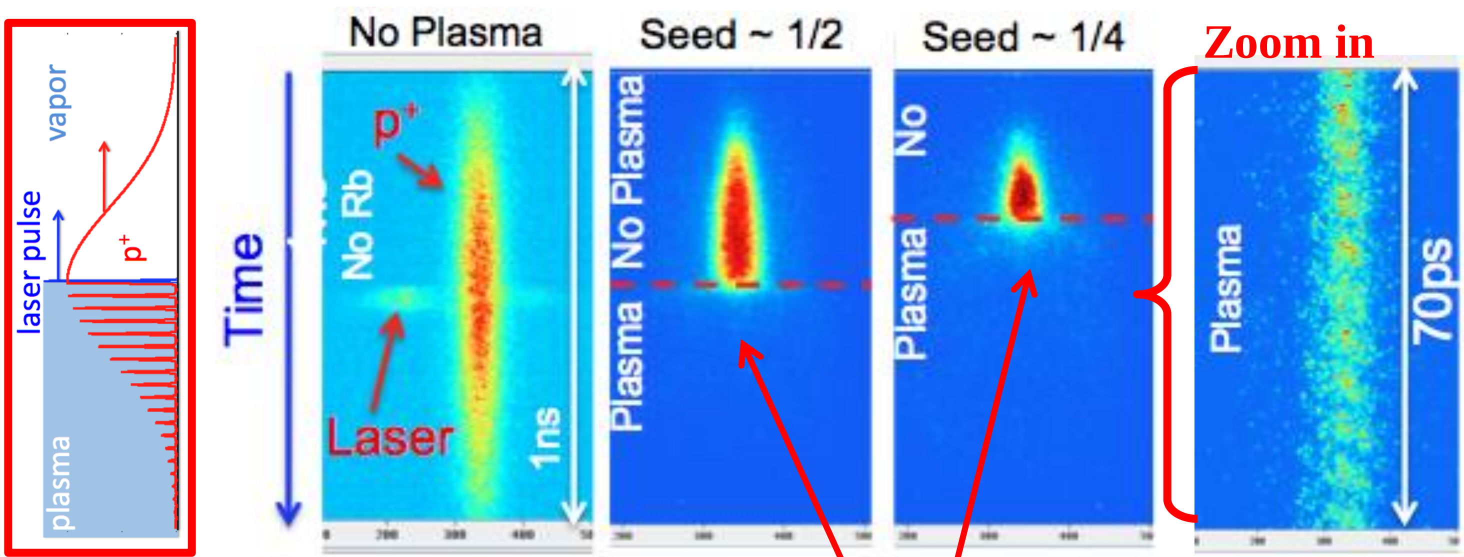
OTR Diagnostics: SSM

Preliminary !!!

- **The aim is to get time resolved picture of SSM**
- Timing at the ps scale
- Effect starts at laser timing => **seeding of SSM**
- Density modulation at the 10ps-scale visible

OTR light in visible band

Streak camera Images



$N_{p+} = 3 \cdot 10^{11}$ (long)

$n_{Rb} = 3.7 \cdot 10^{14} cm^{-3}$

$f_{mod} \sim 164 GHz$

K. Rieger (MPP)

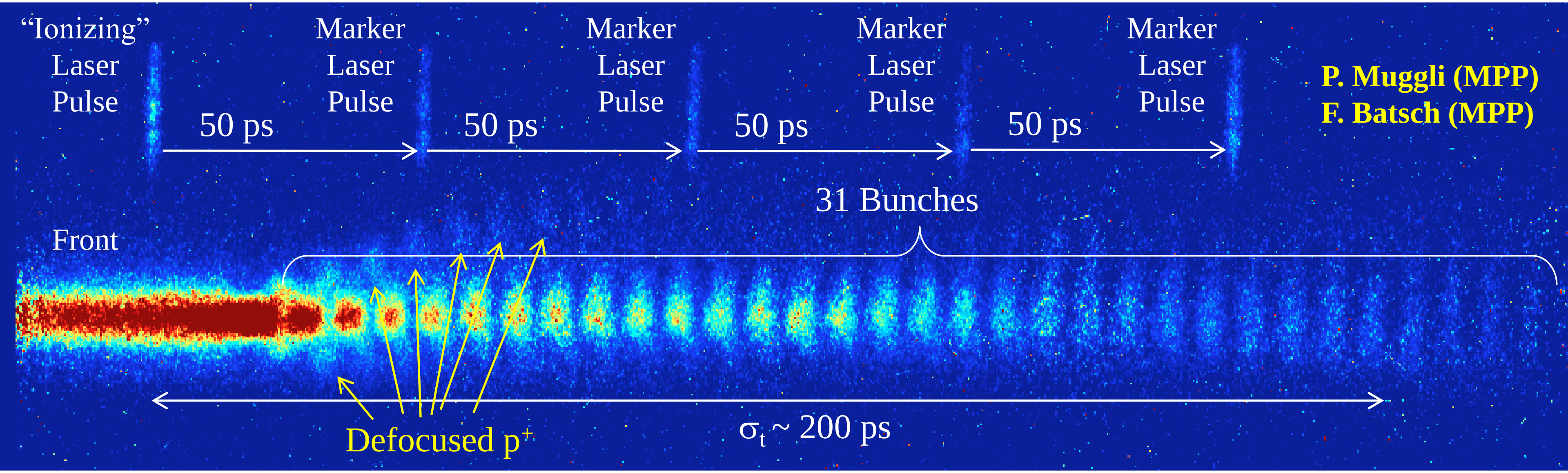
p^+ are symmetrically defocused by SSM

OTR Diagnostics: SSM

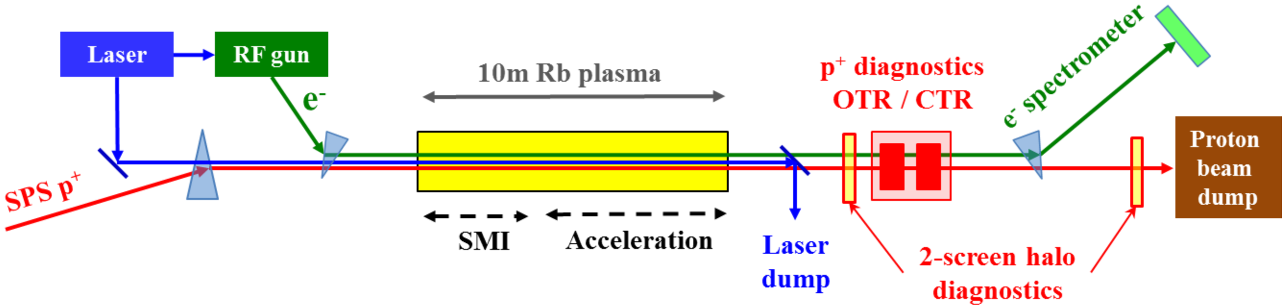
Preliminary !!!

- Micro-bunches present over long time scale ~σ_t from the seed
- "Stitching" demonstrates reproducibility of the µ-bunch process against bunch parameters variations (N = $2 \cdot 10^{11} \pm 5\%$, $\sigma_t = 220 \pm 10$ ps)
- Phase stability was proved, it is essential for e^- external injection !

Streak camera images stitched together with the help of the reference marker laser line

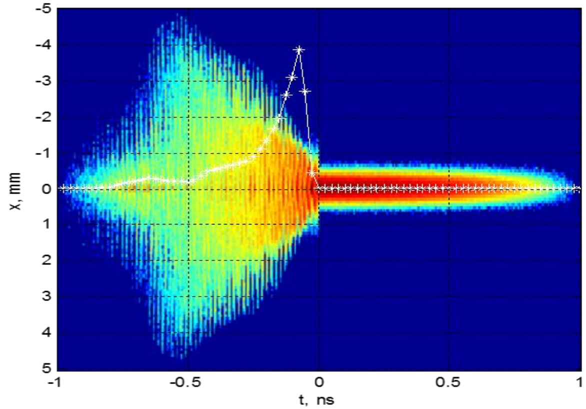


Coherent Transition Radiation (CTR)

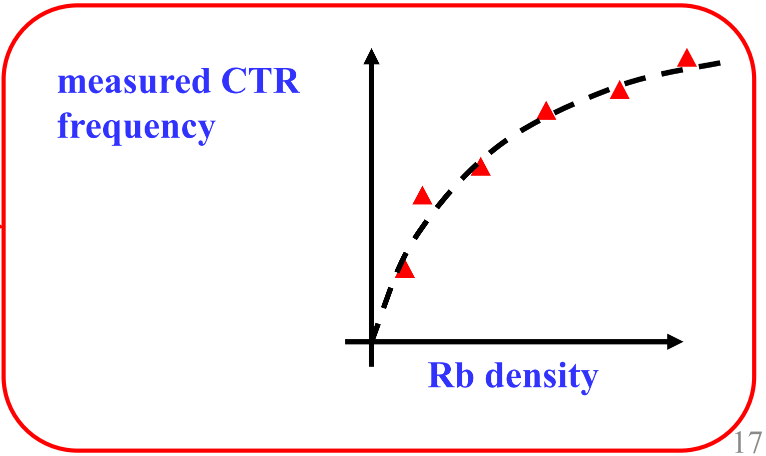


The aims of CTR diagnostics are:

- To measure a relative or absolute CTR signal strength
- To measure a carrier frequency of CTR signal or its harmonics
- To show that it is close to an expected plasma frequency
- With our AWAKE parameters we expect f_{CTR} = 90 - 290 GHz



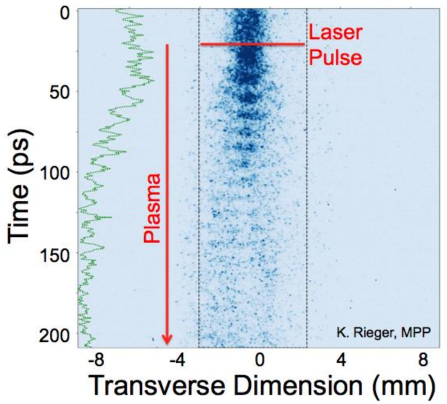
"Golden" figure would look like this



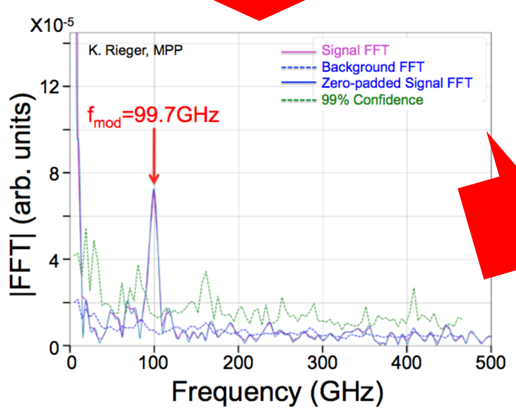
CTR Diagnostics: SSM frequency

Preliminary !!!

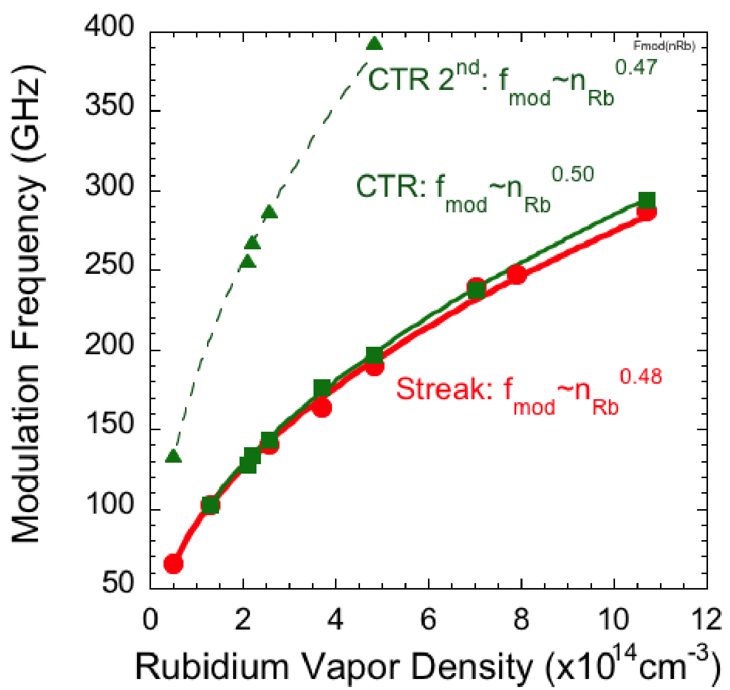
- **At full Rb ionization we expect $f_{mod} = f_{pe} \sim (n_{Rb})^{-0.5}$**
- CTR signal detected also at harmonics (power not calibrated)
- Modulation of p^+ is nonlinear, proven by presence of CTR harmonics



FFT



Heterodyne CTR and streak camera FFT



K.Rieger (MPP), F.Braunmueller (MPP)

Summary

- **Year 2017 was very successful for AWAKE experimental program!**
- **We observed a stable Seeded Self Modulation of a proton bunch**
- **Proven stability of a modulation phase w.r.t. an ionizing laser**
- **We observed defocused protons with the halo measurement**
- **FFT of an OTR streak camera image gives a frequency peak in agreement with an expected plasma frequency assuming full Rb ionization**
- **Measured CTR carrier frequency is in agreement with a frequency of OTR streak camera FFT and with a plasma frequency calculated from Rb density.**
- **Electron line has been recently commissioned**

- **We anticipate year 2018 to be exciting with an electron acceleration!**

Thank you!