Overview of Beam Diagnostics for the AWAKE Experiment at CERN

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on behalf of AWAKE Collaboration

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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 (Geneva) with an 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 at a glance

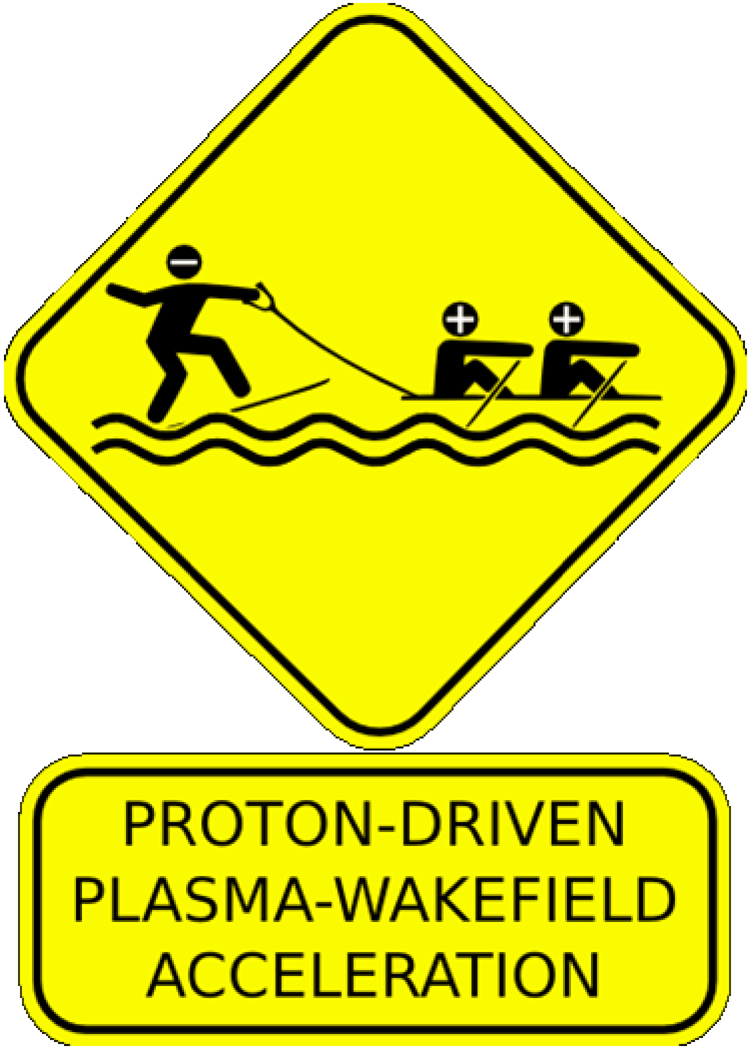
Four Ingredients:

- **Protons (from CERN 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

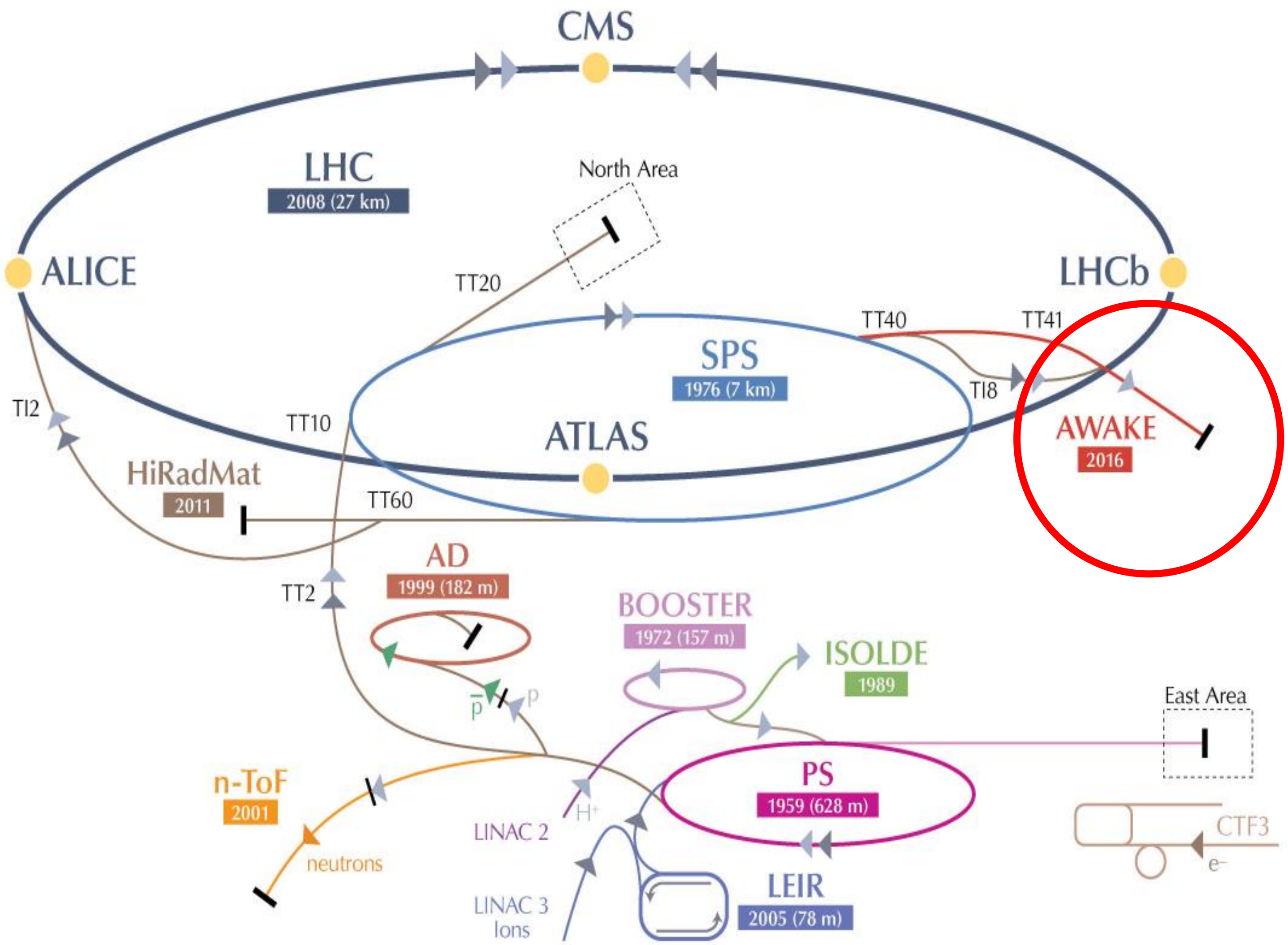
- **Electrons (from photo-gun, 20 MeV)**
  ← to probe a wake fields



AWAKE Baseline Parameters

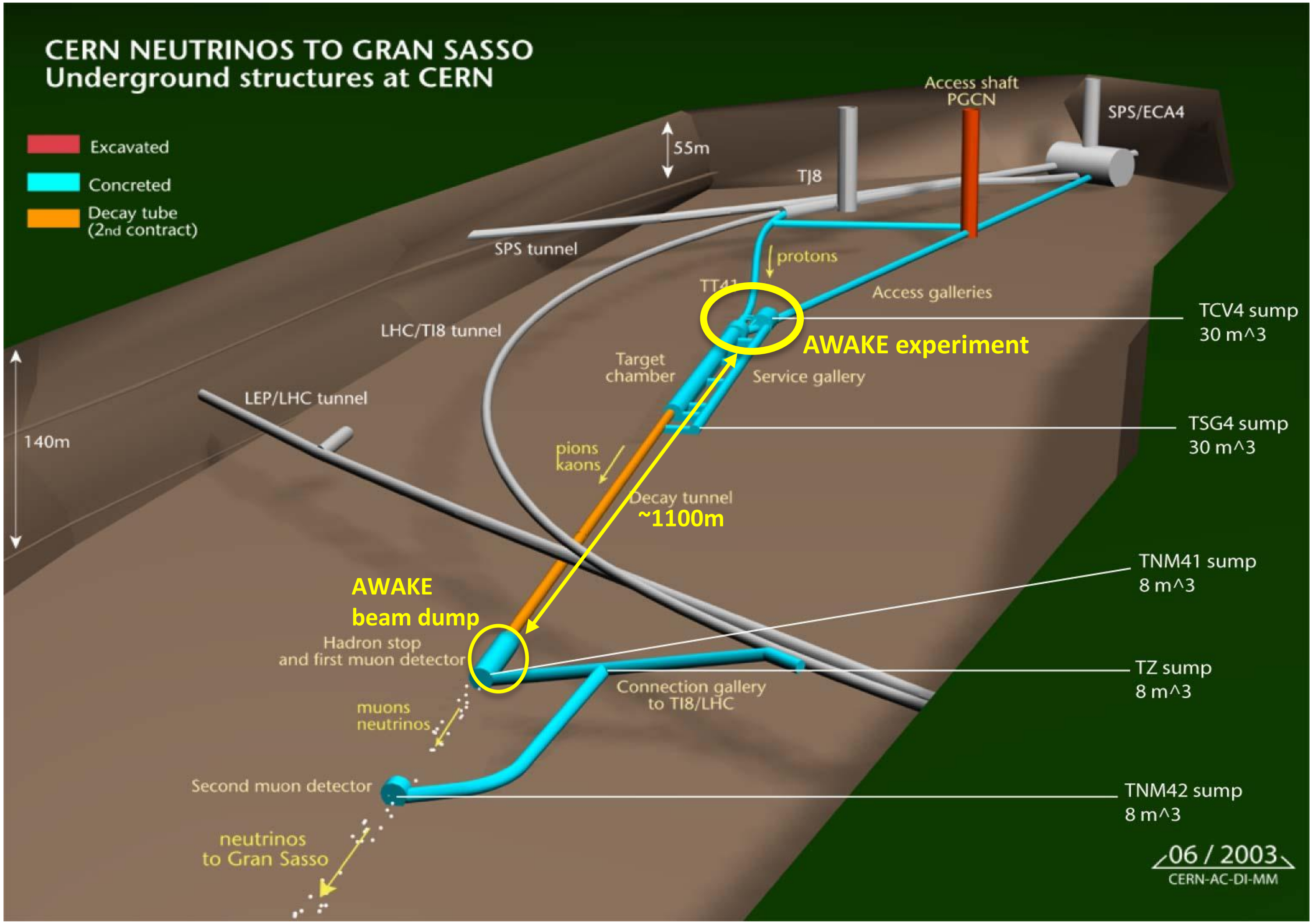
Plasma	Rb plasma density	$10^{14} \div 10^{15}$ cm^{-3} $7\cdot(10^{-3} \div 10^{-2})$ mBar at 500°K
	Uniformity	<0.1%
	Length	10 meters
Proton bunch	Energy	400 GeV → 64 nJ/p$^+$ → $\boxed{\text{19.2 kJ/bunch}}$
	Charge	$3\cdot10^{11}$ particles → 48 nC
	Length, σ_z	12 cm → 400 ps
	Radius, σ_r	200 μm
Electron bunch	Energy	20 MeV → 3.2 pJ/e$^-$ → $\boxed{\text{4 mJ/bunch}}$
	Charge	$1.25\cdot10^{9}$ particles → 200 pC
	Length, σ_z	0.25 cm → 8 ps
	Radius, σ_r	200 μm
Laser	Energy	$\boxed{\text{up to 450 mJ}}$
	Pulse duration	120 fs
	Beam size at Rb vapor (focused from 40m)	a few mm
	Focused intensity	> 50 TW/cm2

AWAKE at CERN



AWAKE at CERN

~100 meters deep underground, former CNGS facility



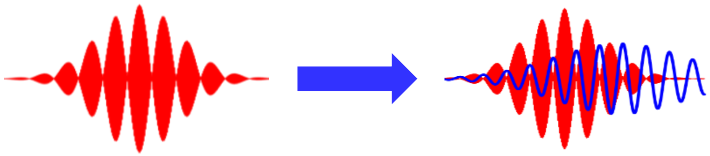
The Zoo of Plasma Wake-field Accelerators

… started from pioneer paper "Laser Electron Accelerator" by T.Tajima and J.Dawson

Phys. Rev. Lett. 43, 267 – Published 23 July 1979

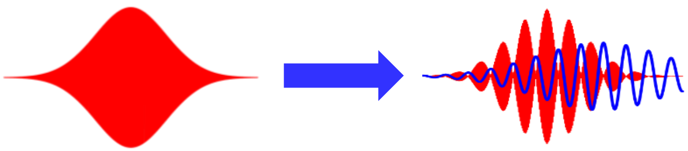
Laser Beat-Wave WFA (~1 ns)

Two frequencies laser pulse (pulse train)



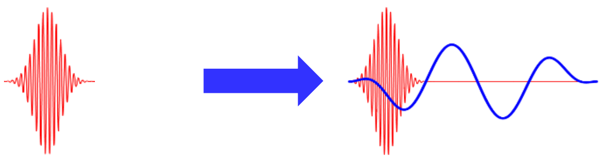
Self-Modulated Laser WFA (~1 ns)

Raman forward scattering instability in a long laser pulse



Laser WFA (~0.1 ps)

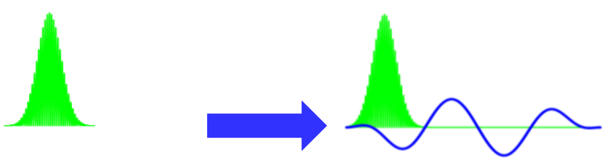
Short intense laser pulse



Particle Bunch WFA

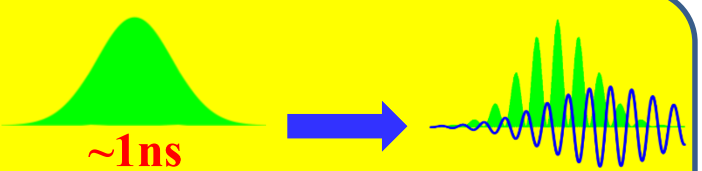
Short intense particle bunch

~ 1ps proton bunch does not exist !



Self-Modulated Particle Bunch WFA

Long bunch experience transverse self-modulation instability

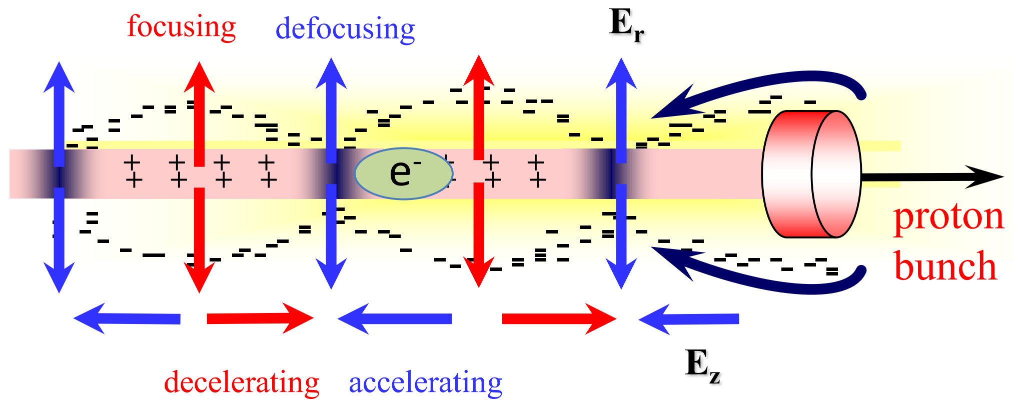


Scope of AWAKE proof-of-principle experiment

Self Modulation Instability

Short proton bunch driver:

No SMI

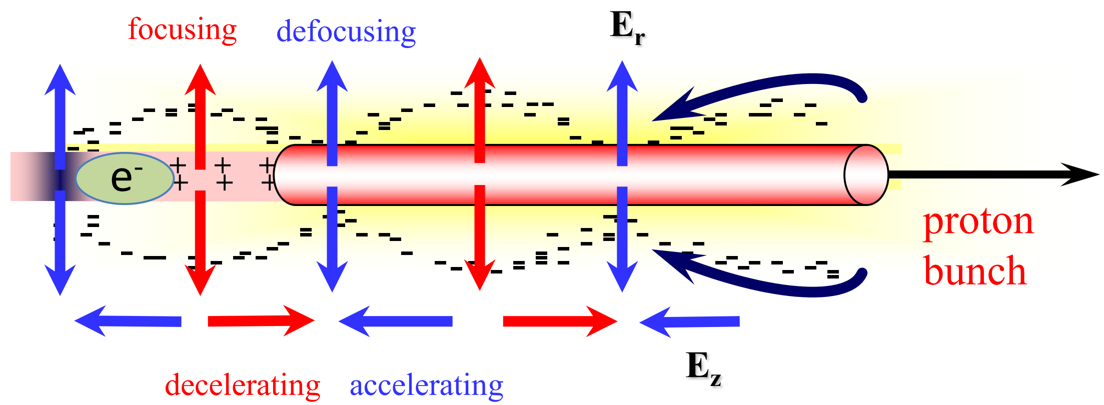


→ Space charge of drive beam expels plasma electrons out.

→ Plasma ions exert restoring force for expelled plasma electrons.

Long proton bunch driver:

SMI develops,
Essentially 3D effect



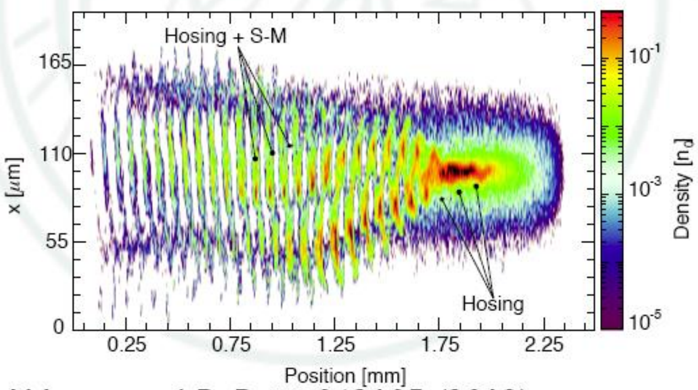
Plasma Wake Field:
Long Particle Bunch Driver

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

Propagation of long bunches in plasmas - instability competition

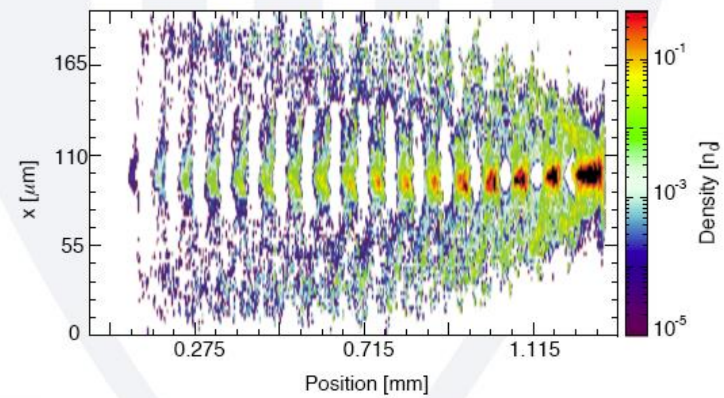
- self-modulation instability: generation of large amplitude wakefields
- hosing instability or beam break up instability: prevent generation of large amplitude wakefields

No seeding



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

With seeding

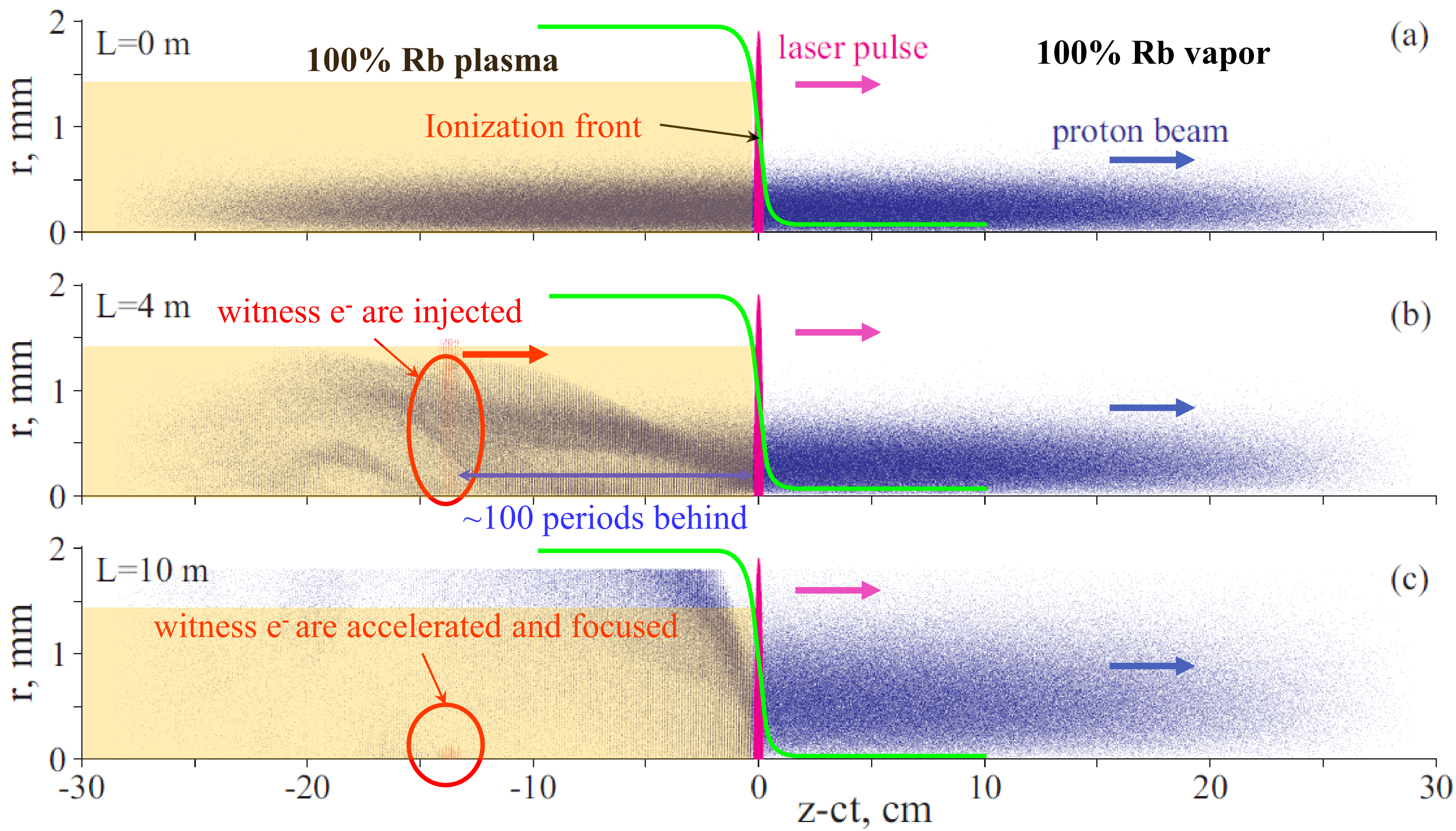


Presented by J. Vieira, 8 March 2013, CERN, Geneva
at AWAKE Collaboration Meeting

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

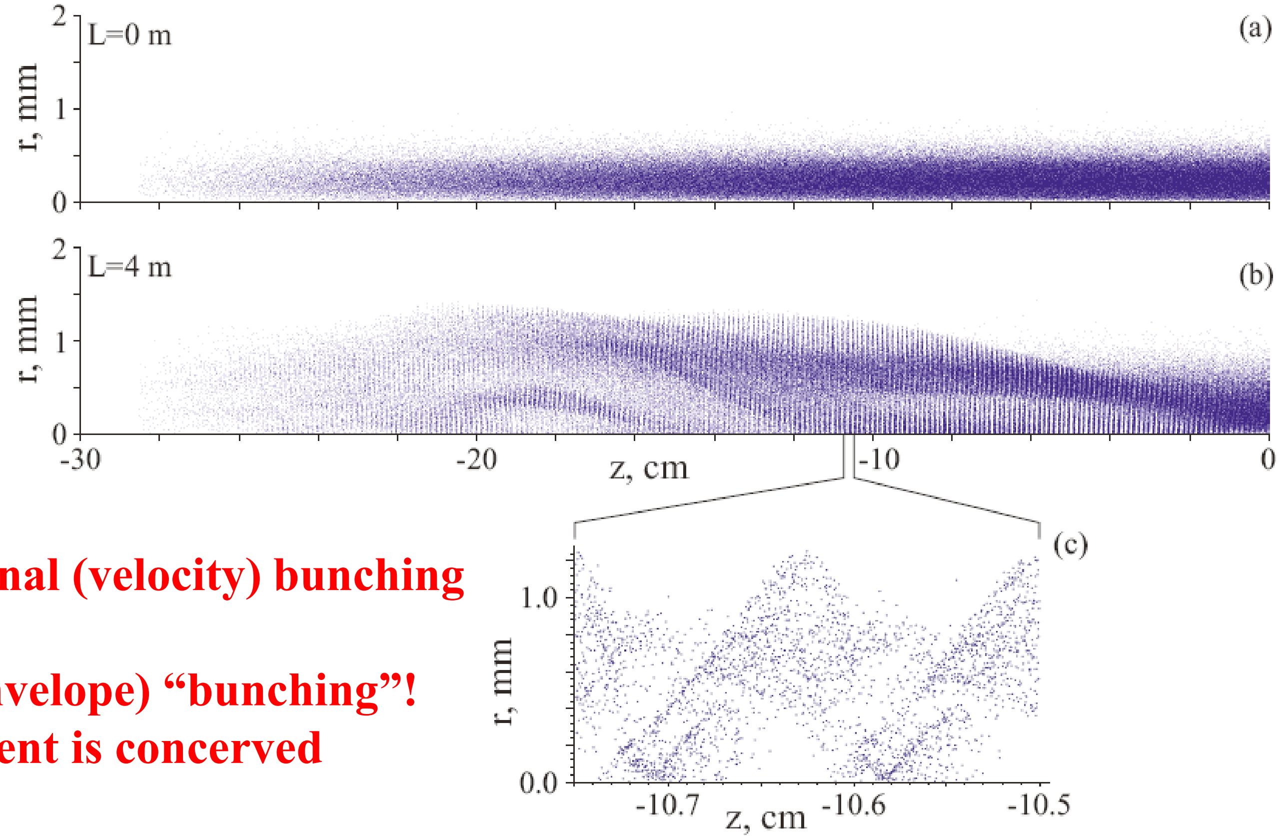


Fig. 11: Simulation result showing (a) the incoming uniform bunch and (b) the self-modulated bunch after 4 m of plasma. (c) Zoomed region of the self-modulated proton bunch, as could be measured using the OTR–streak camera system. The z coordinate is converted to time by the streak camera. The period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

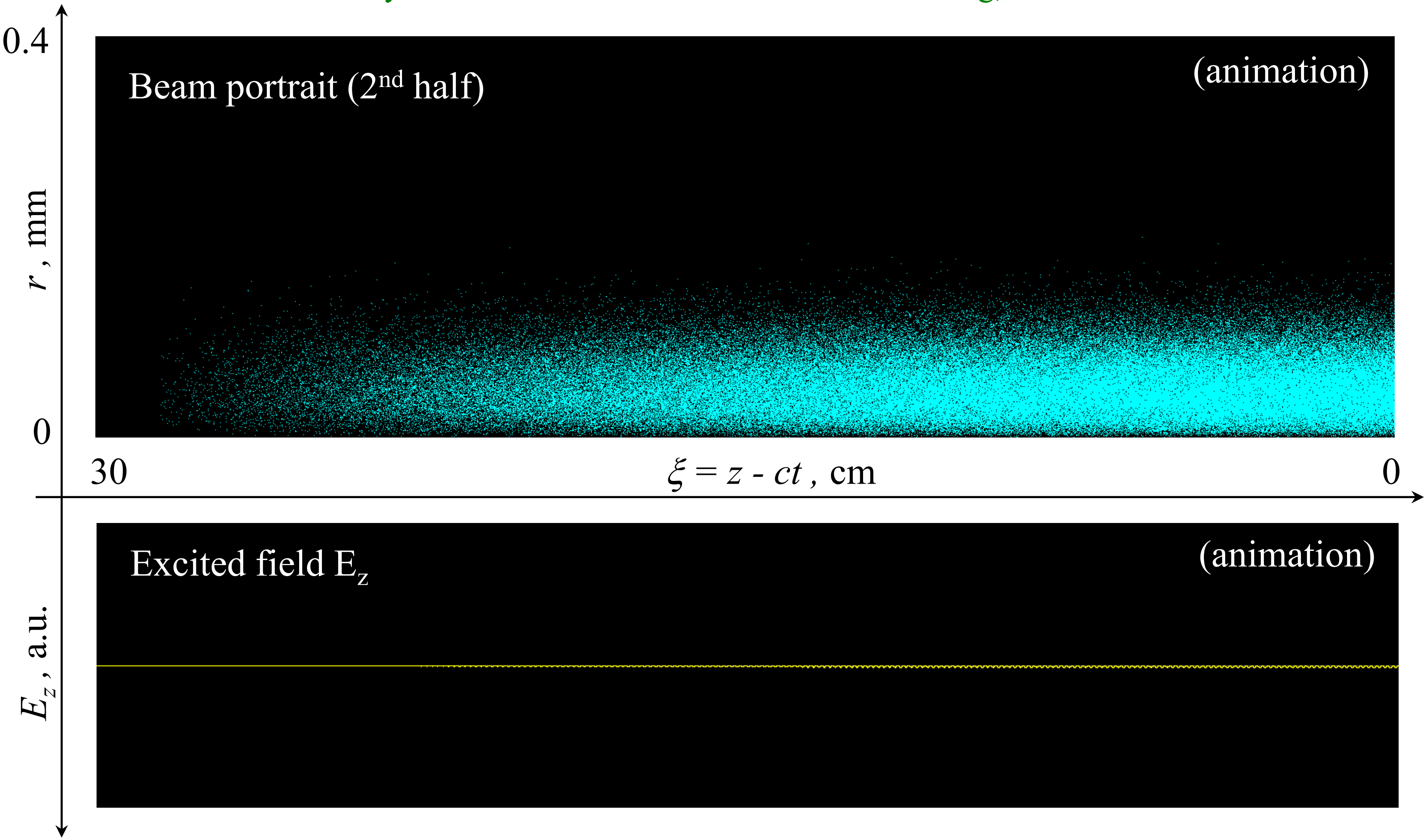
NB! No longitudinal (velocity) bunching

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

Picture taken from AWAKE CDR, CERN 2013

Proton bunch evolution

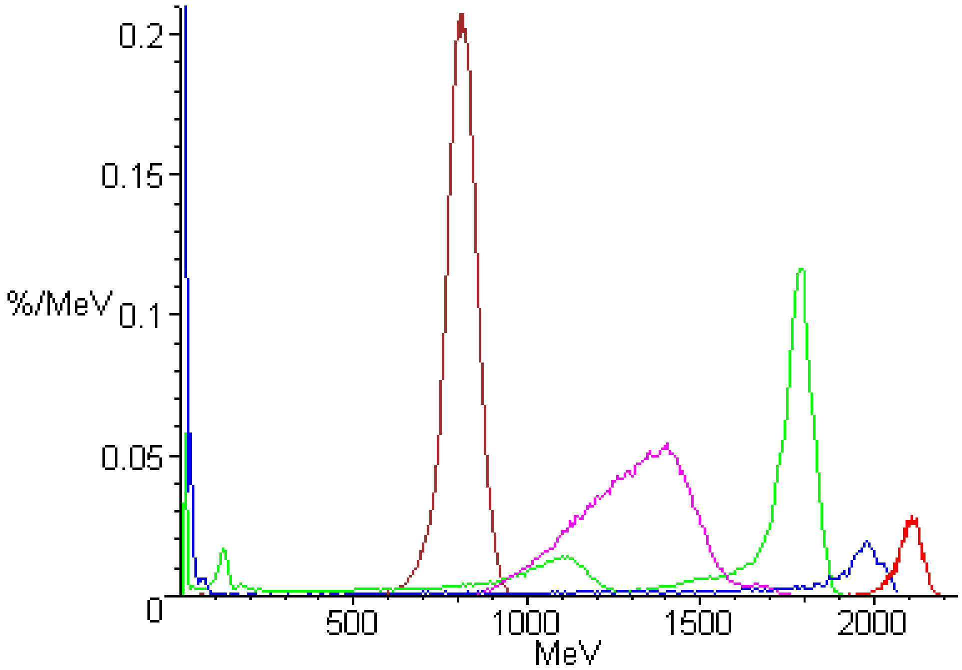
Presented by K.Lotov at AWAKE Collaboration Meeting, CERN 08.03.2013



Simulation results: e⁻ energy and spread

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

Comparison of best simulation results for witness e⁻ energy and spread



- 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

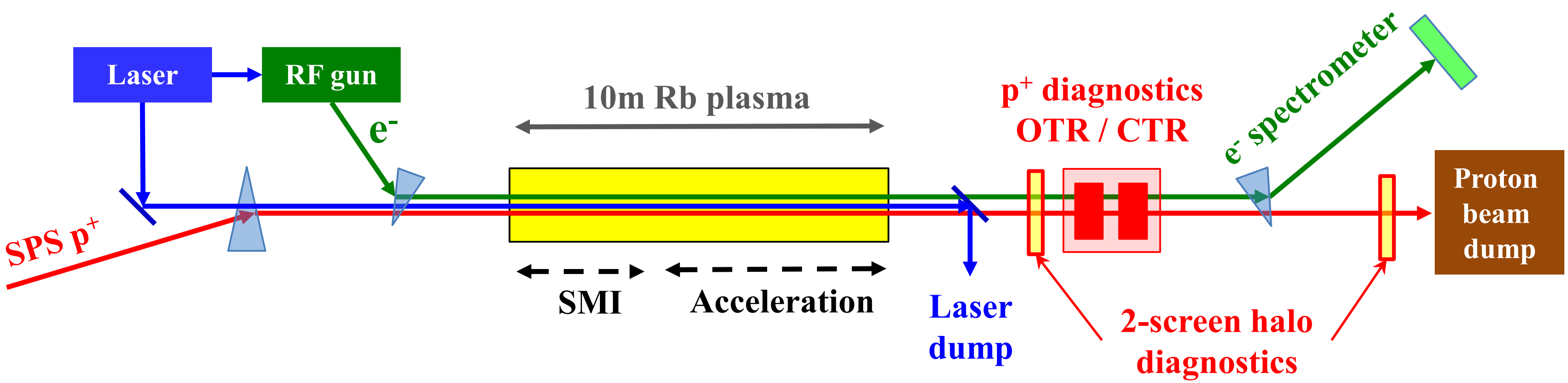
AWAKE Experiment at CERN

- **Phase 1:**

  Understand **the physics of self-modulation instability** processes in plasma ➔ started Q4 2016

- **Phase 2:**

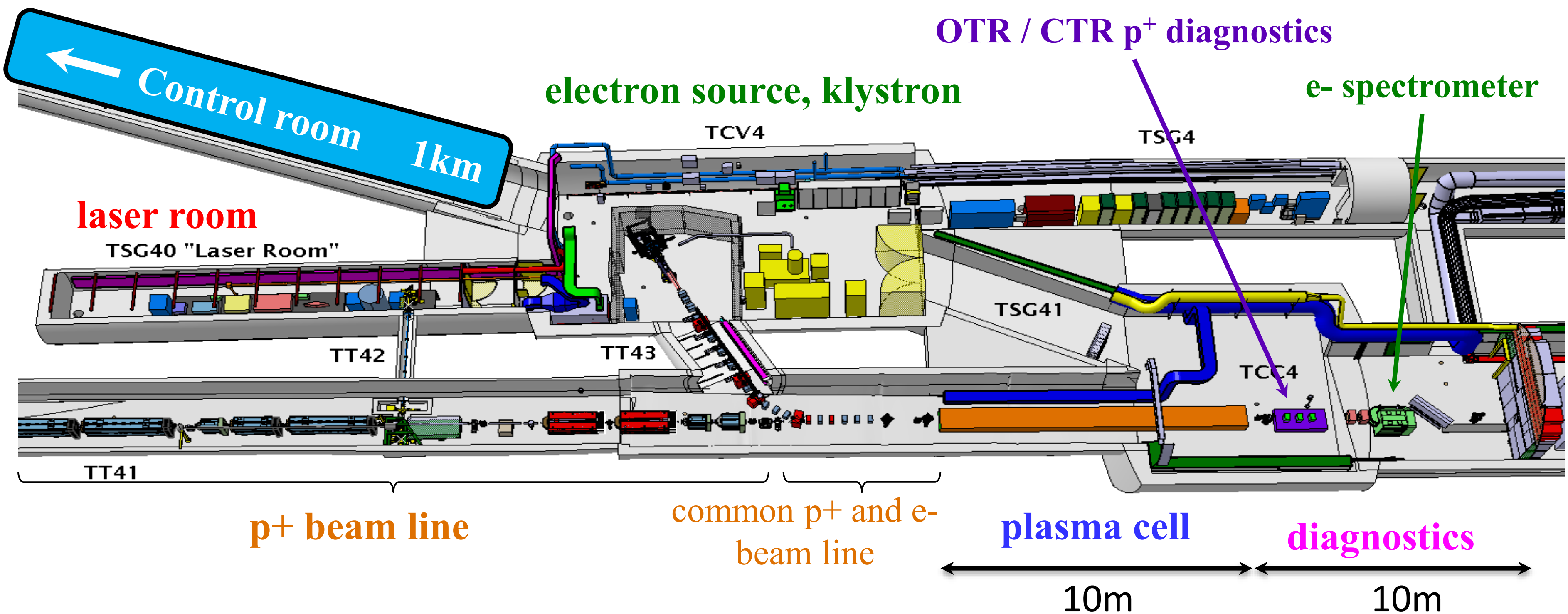
  Probe the accelerating wakefields with externally injected electrons ➔ starts Q4 2017



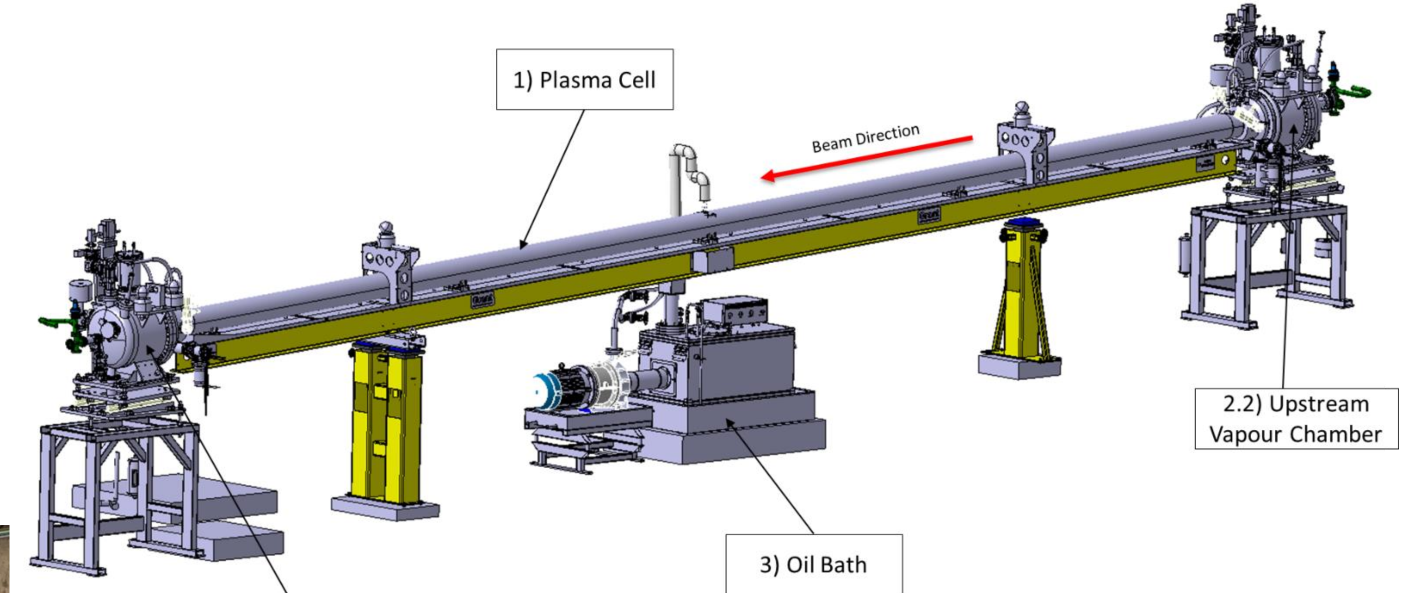
AWAKE "Submarine"

AWAKE Experimental Facility:

Limited space available in the underground cavern



Key Component : Rb vapour cell



10 meter long heated oil bath to provide $\Delta n/n \sim 0.1\%$ uniformity

Beam Diagnostics overview

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

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

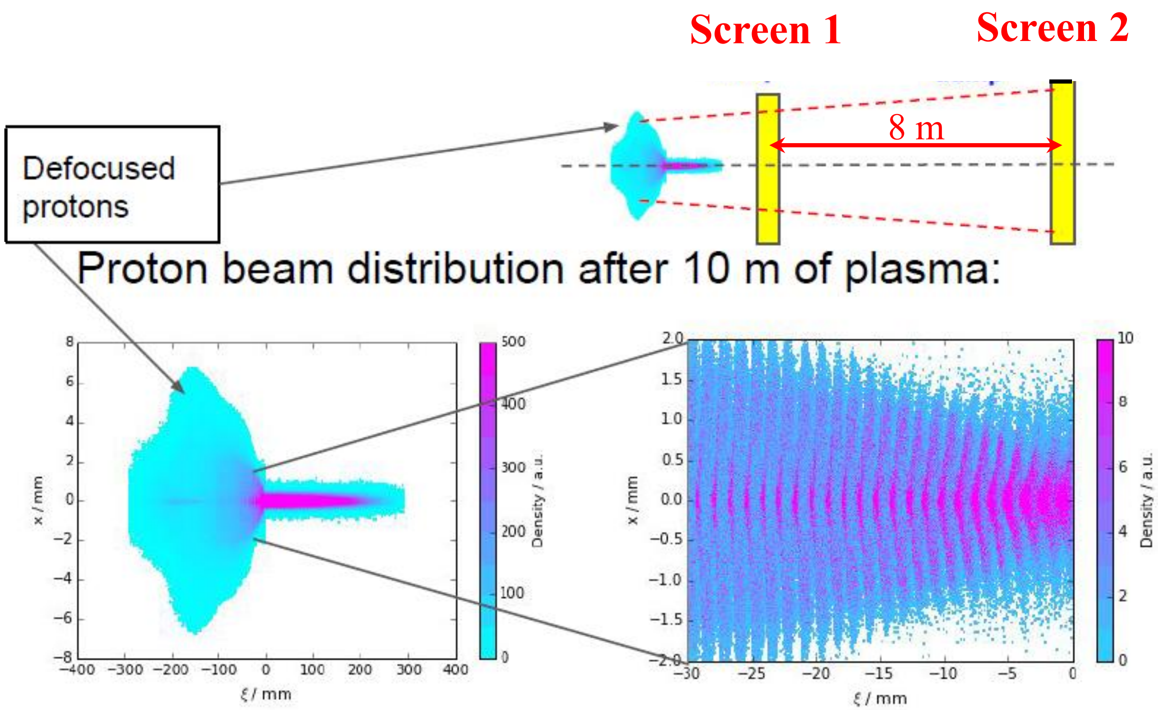
p^+ diagnostics:
- Standard (BCT, BPM's, luminescent / OTR screens)
- Two-screen halo diagnostics
- Visible OTR, 2 streak cameras – SMI visualization
- Microwave CTR – SMI frequency measurement

Scope of my further talk

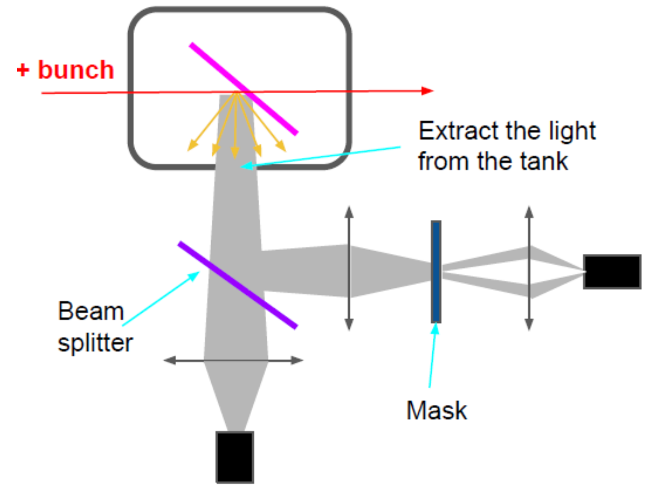
e^- diagnostics :
- Standard (BCT, BPM's, screens)
- Large wide-band spectrometer (20 MeV to 3 GeV)

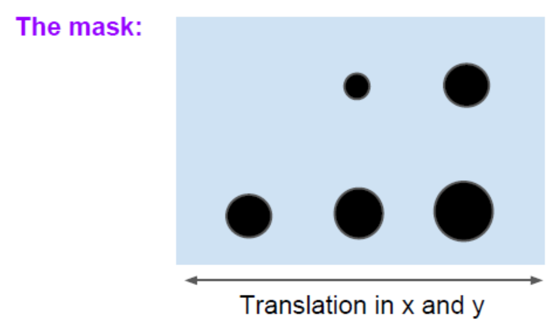
Two-Screen p^+ Halo Diagnostics

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



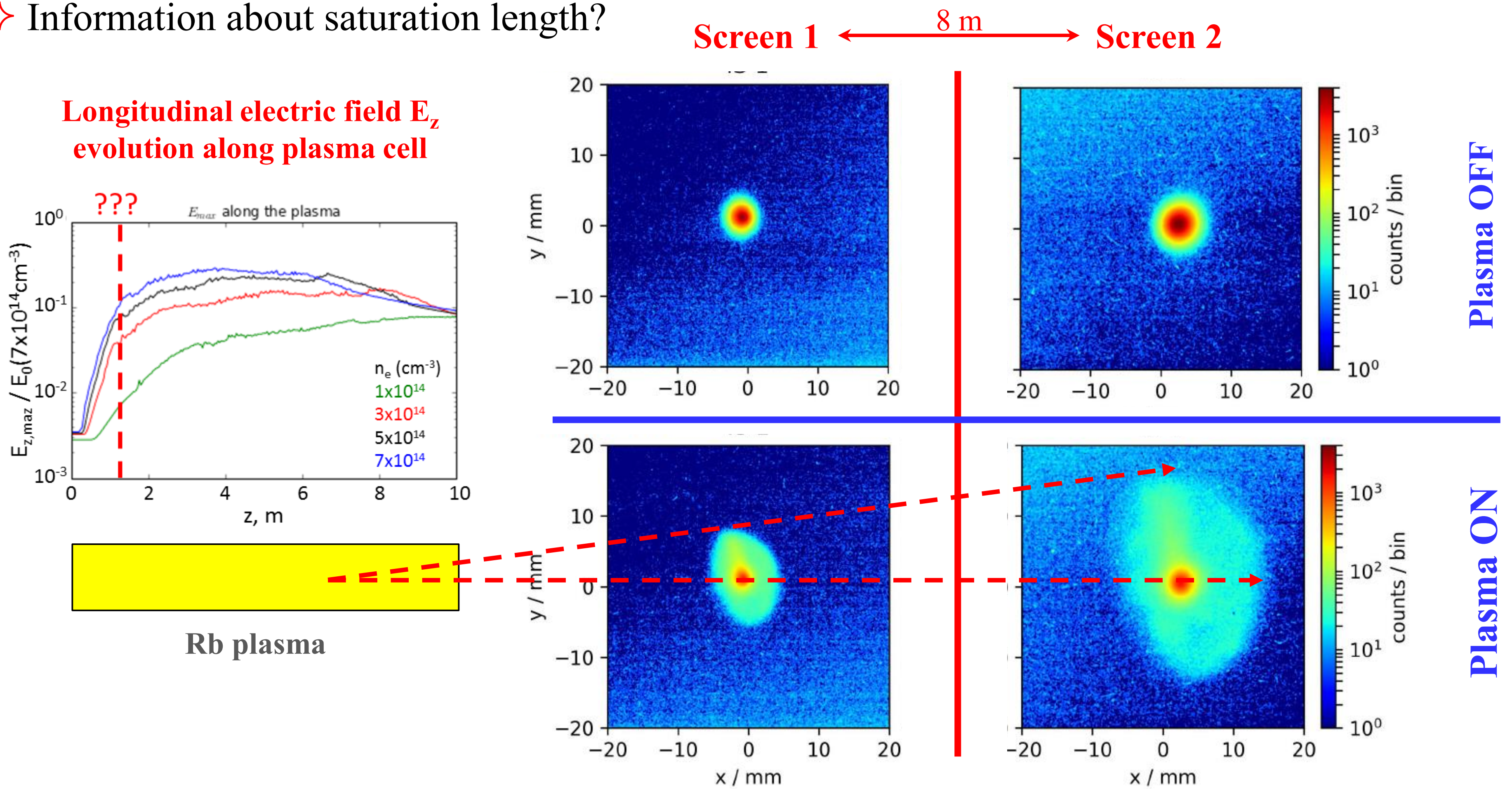


Courtesy of M.Turner (CERN)

Two-Screen p^+ Halo Diagnostics

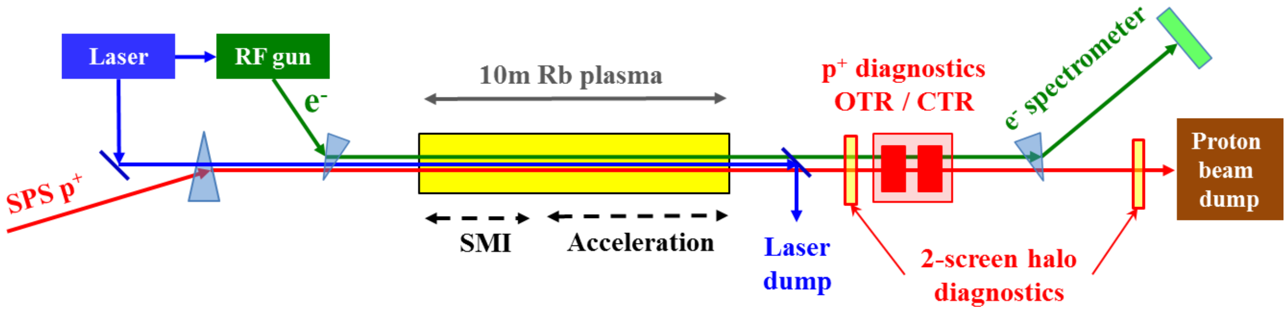
- p^+ defocused by the transverse wakefield (SMI) form a halo
- focused p^+ form a tighter core
- Estimate of the transverse wake-field amplitude (integral)
- Information about saturation length?

Preliminary !!!



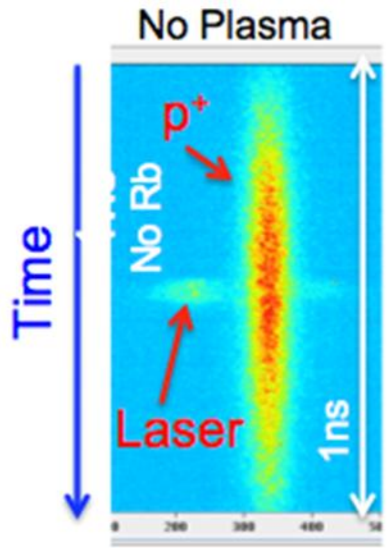
Courtesy of M.Turner (CERN)

OTR Diagnostics: Streak Camera

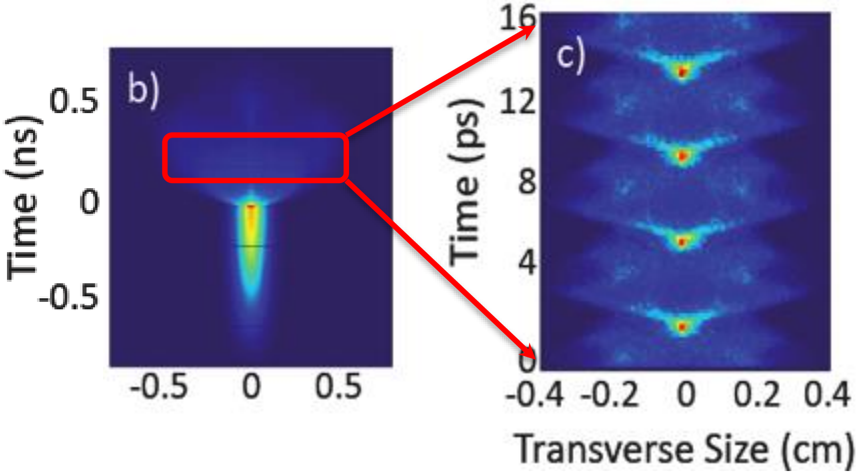


SPS proton beam **synchronized** with AWAKE laser within ~20ps accuracy

We want to see something like this (simulation) :



Streak image downstream plasma (measurement)



Proton Beam Self-Modulation Instability (simulation)

Courtesy of K. Rieger (MPP)

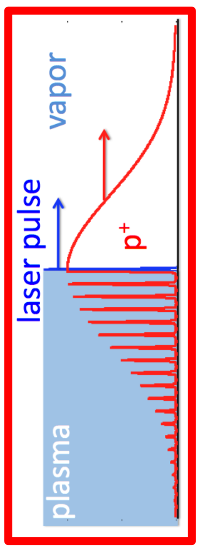
OTR Diagnostics: Seeded SMI

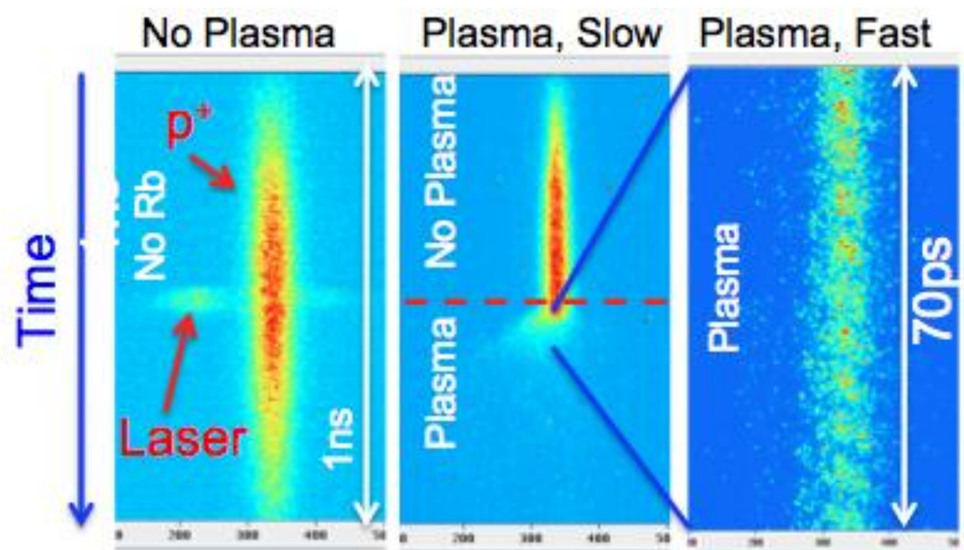
Preliminary !!!

- Timing at the ps scale
- Effect starts at laser timing => **SMI seeding**
- Density modulation at the 10ps-scale visible

OTR light in visible band

Streak camera Images





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

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

$f_{mod} \sim 164 GHz$

Courtesy of K. Rieger (MPP)

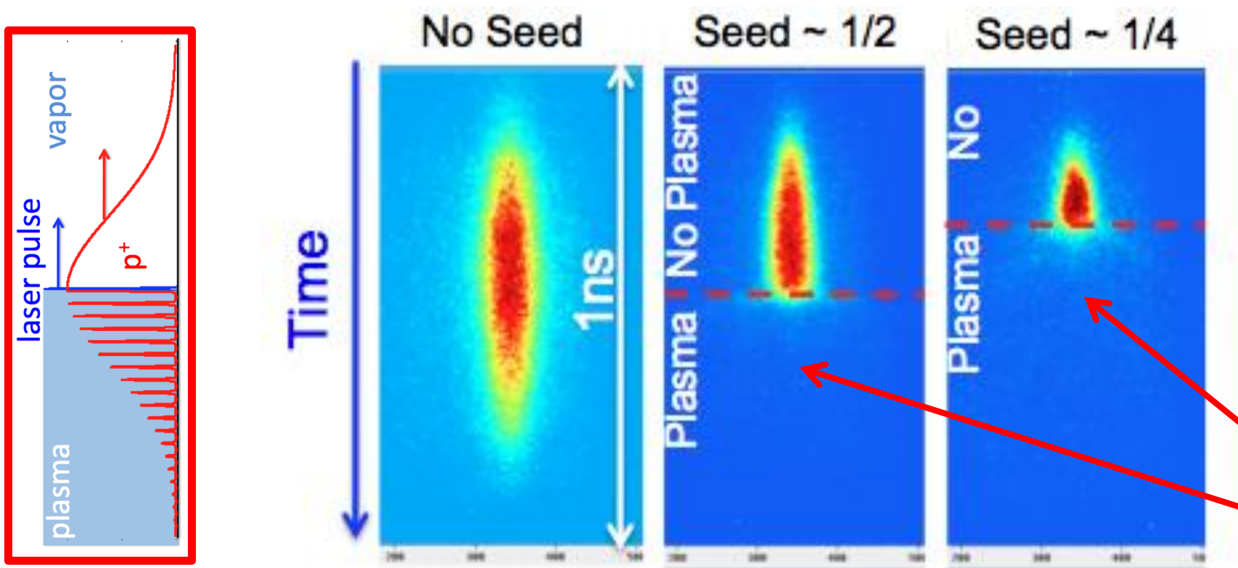
OTR Diagnostics: Seeded SMI

- Various seeding position / times
- Effect starts at laser timing => SMI seeding
- Stronger effects with seed at ¼ than ½

Preliminary !!!

OTR light in visible band

Streak camera Images



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

$n_{Rb} = 2.2{\cdot}10^{14}$ cm^{-3}

p^+ symmetrically defocused by SMI

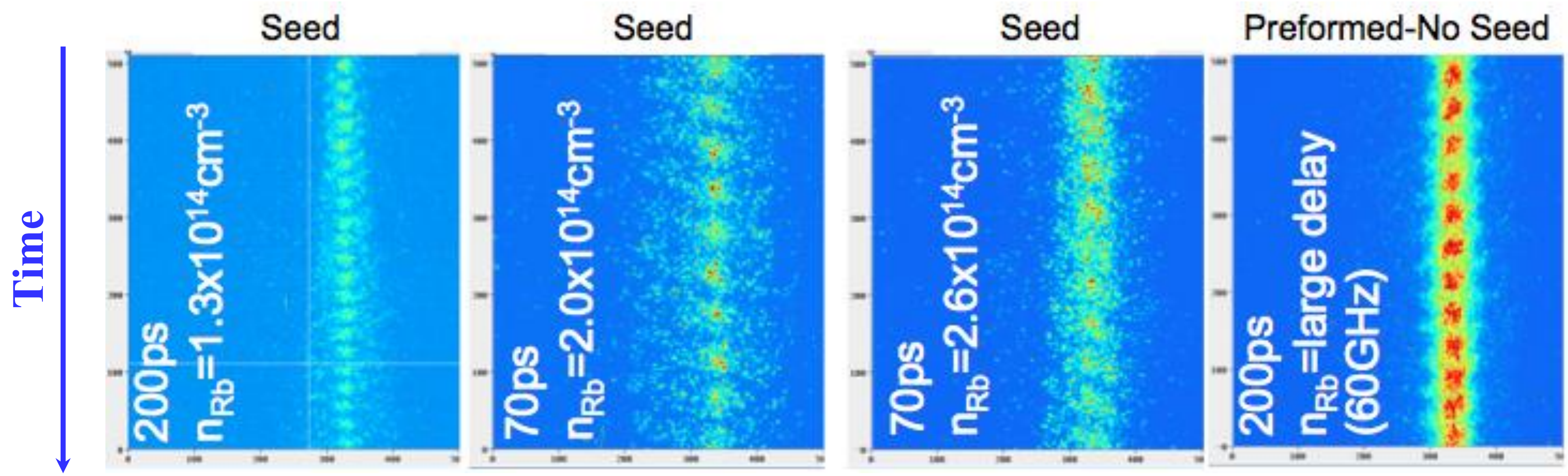
Courtesy of K. Rieger (MPP)

OTR Diagnostics: μ-Bunches

- ✧ Modulation visible at low densities (< $3{\cdot}10^{14}$ cm^{-3})
- ✧ FFT => modulation frequency at higher densities

Preliminary !!!

Streak camera Images

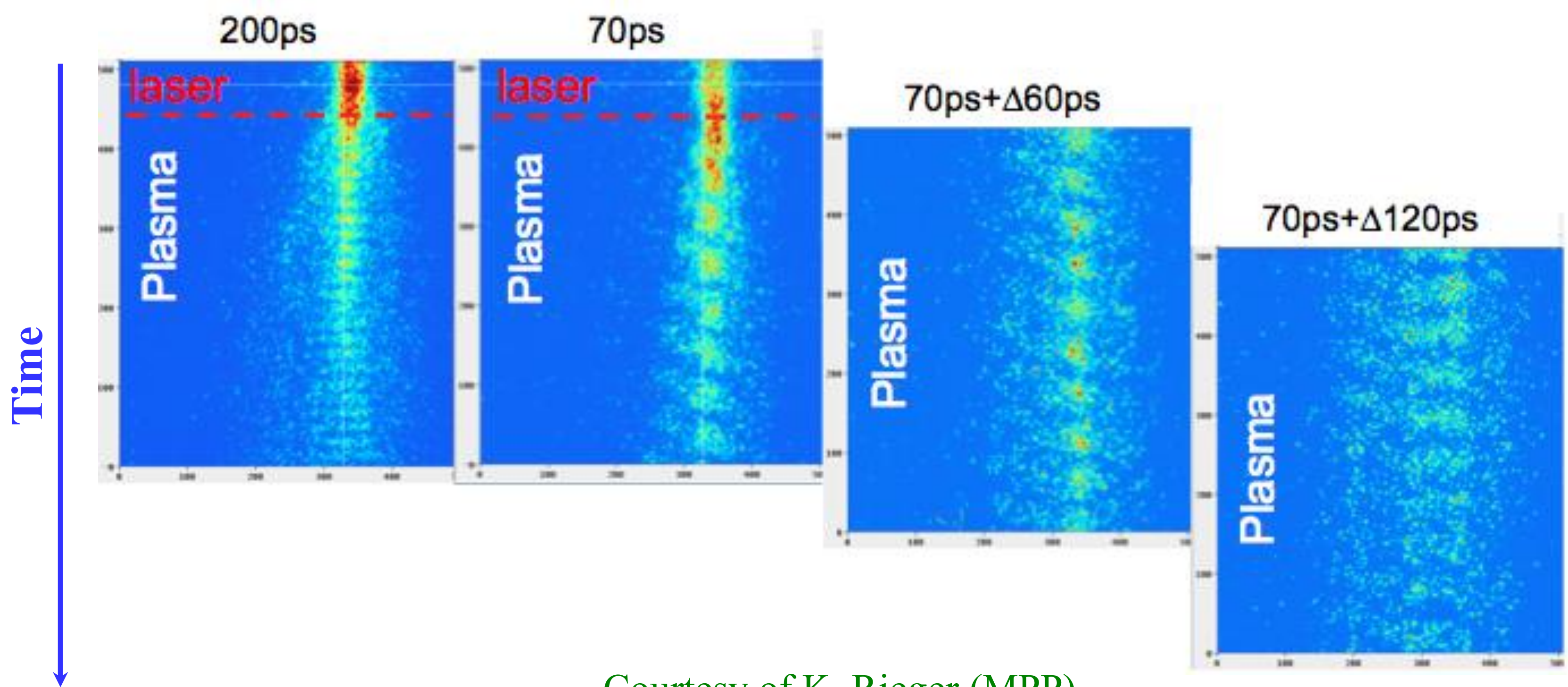


Courtesy of K. Rieger (MPP)

✧ Changes in the μ-bunches along the bunch, at the screen (image)

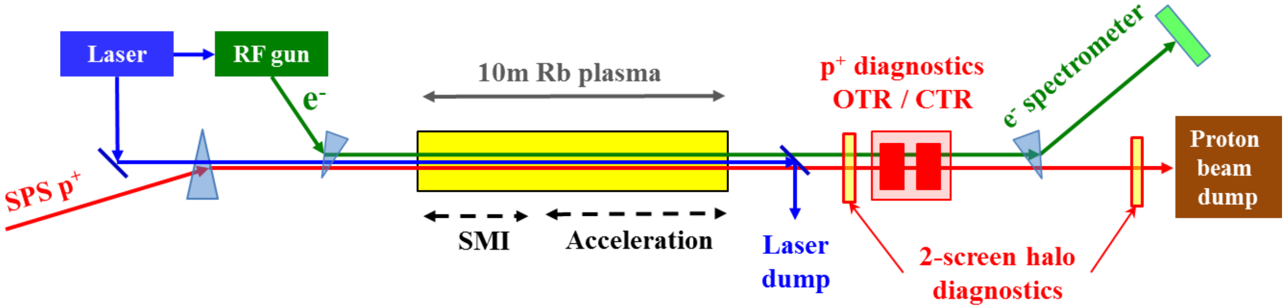
Preliminary !!!

Streak camera Images



Courtesy of K. Rieger (MPP)

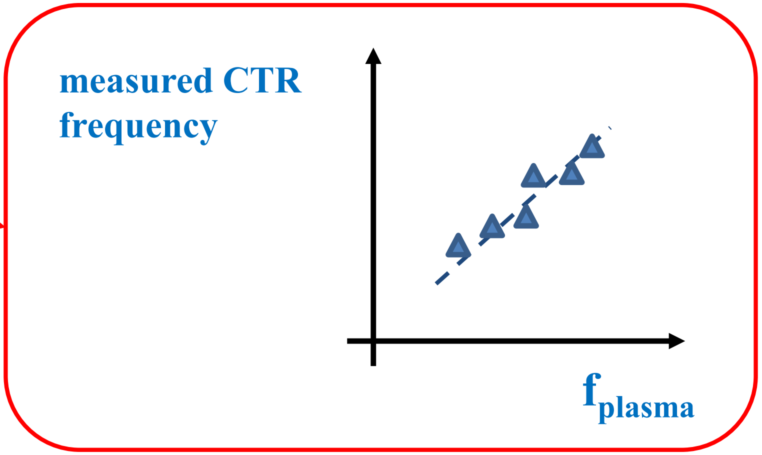
Coherent Transition Radiation (CTR)



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 a plasma frequency**
- **With our AWAKE parameters we expect $f_{CTR} = 90 \div 290$ GHz**

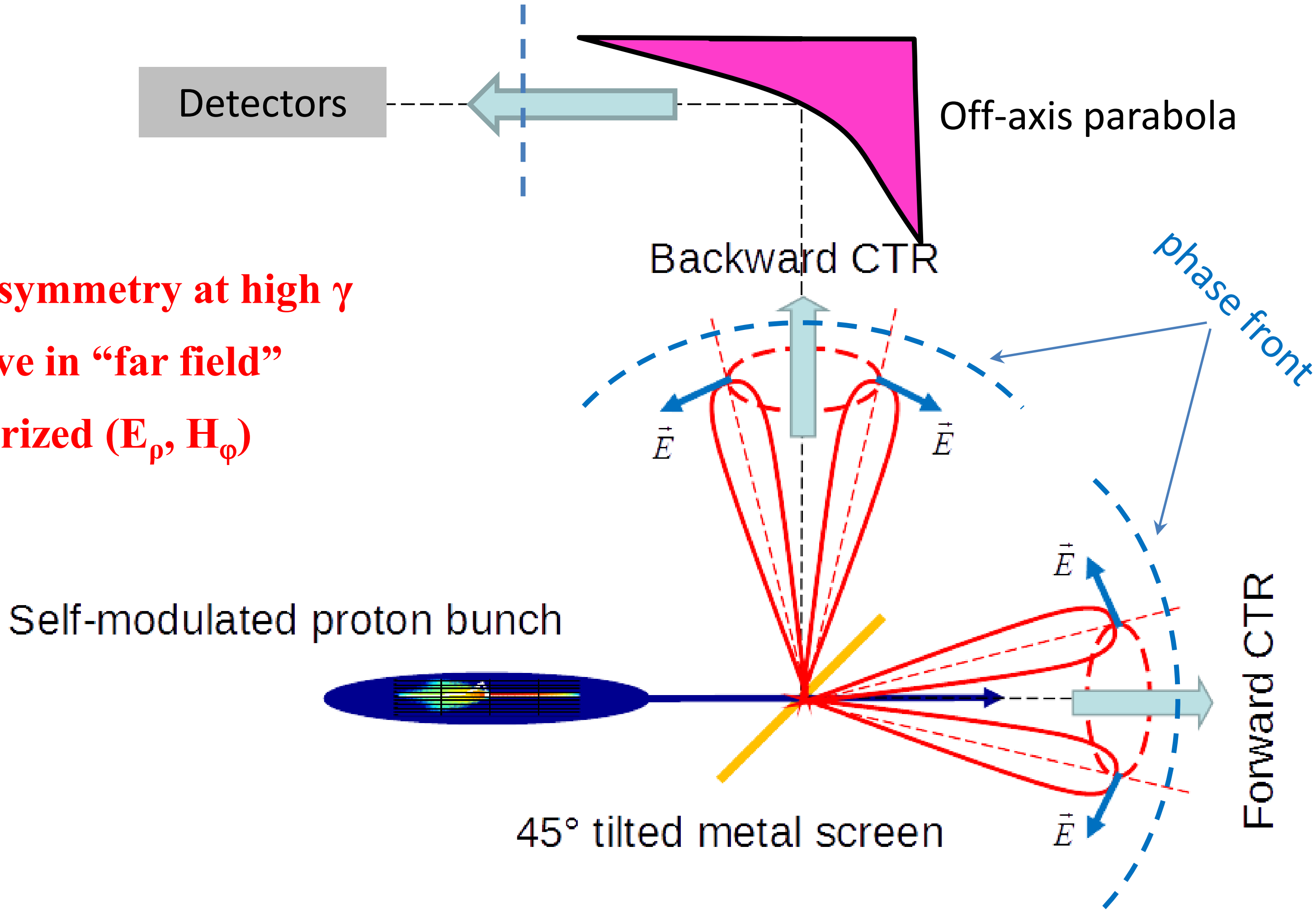
"Golden" figure would look like this



Coherent Transition Radiation (CTR)

In AWAKE case large-screen and far-field conditions are easily fulfilled for microwave CTR due to a small emitter size – foot print of a bunch Coulomb EM-field at modulation frequency is finite (< 20 mm diameter)

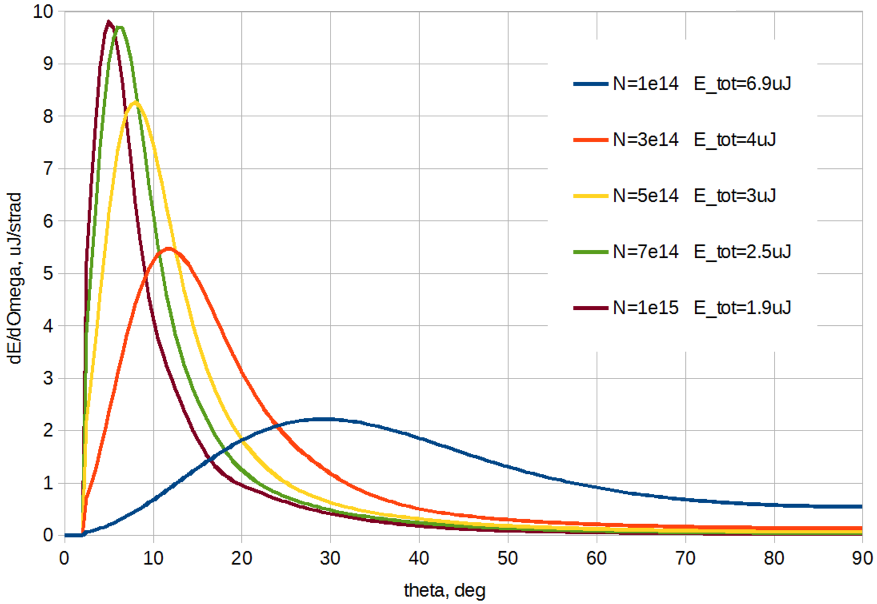
- **Almost axial symmetry at high γ**
- **Spherical wave in "far field"**
- **Radially polarized (E_ρ, H_φ)**



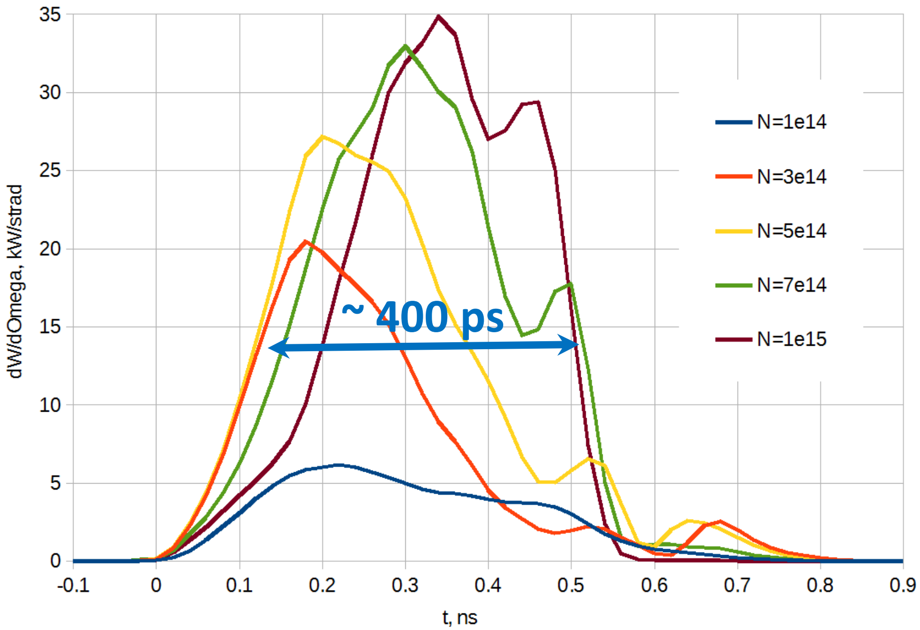
CTR : Simulation

- Donut-shape spatial pattern of a CTR beam
- At peak, pulse fluence is 2-10 µJ/sr => 5-25 nJ/cm² at 20 cm
- At peak, pulse power is 5-30 kW/sr => 13-75 W/cm² at 20 cm

Spectral energy density, µJ/sr
Integrated over 20 GHz band
around plasma frequency



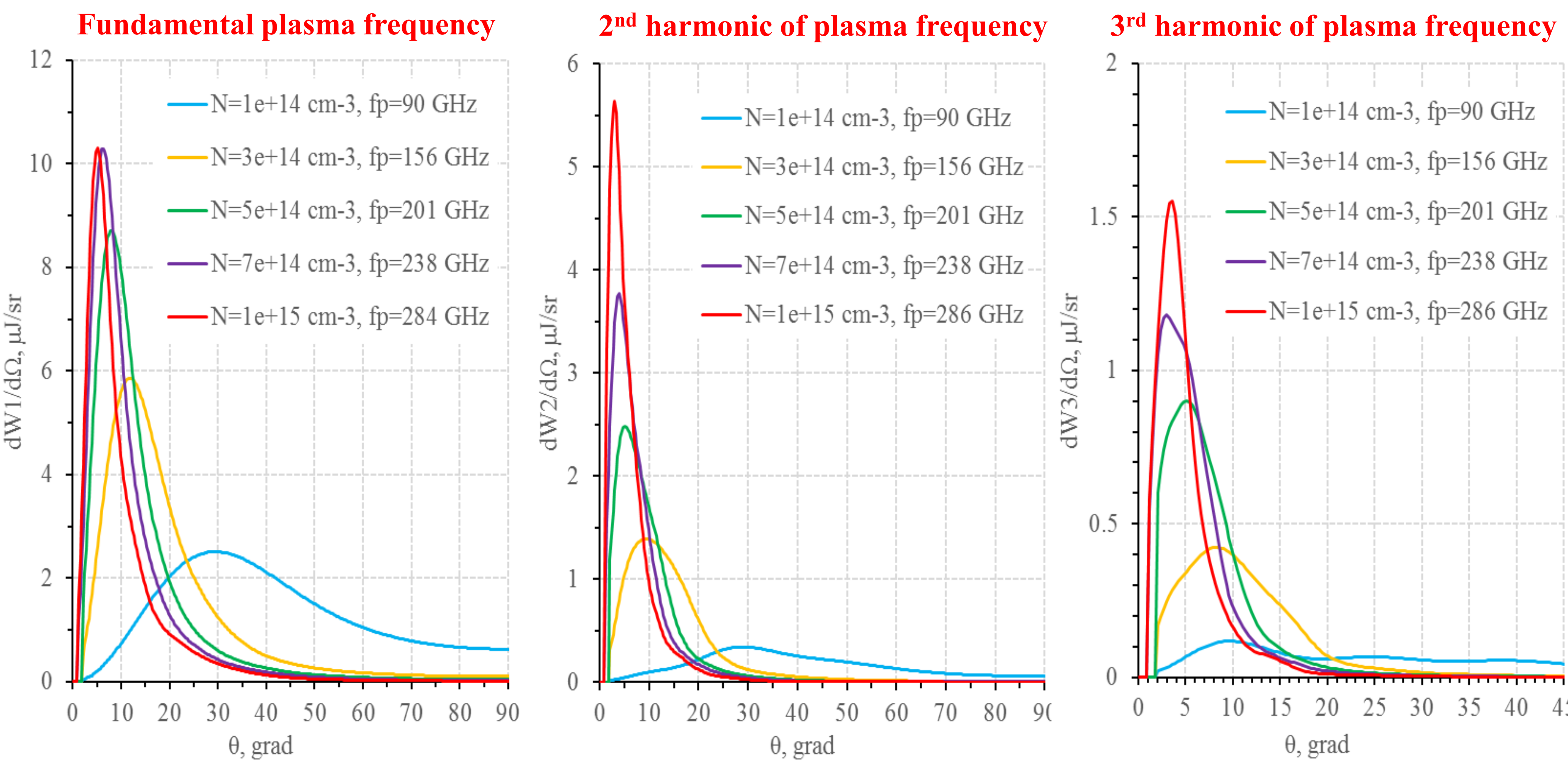
Pulse power, kW/sr
at peak, θ=θpeak



CTR Harmonics : Simulation

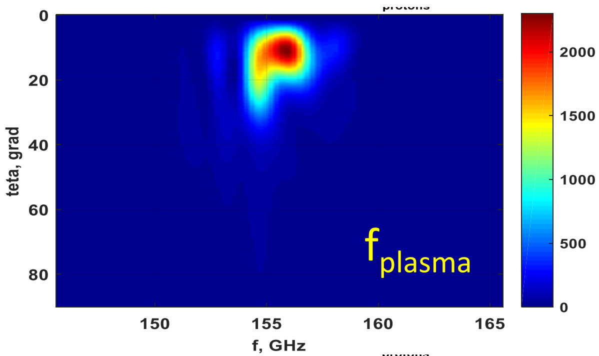
Mind a different scale on vertical axis!

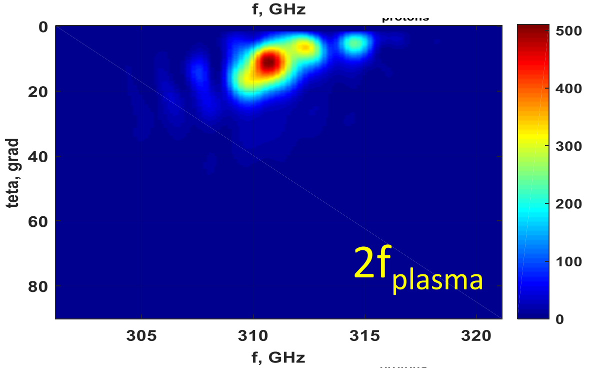
Spectral energy angular distribution, μJ/sr, integrated over 20 GHz band

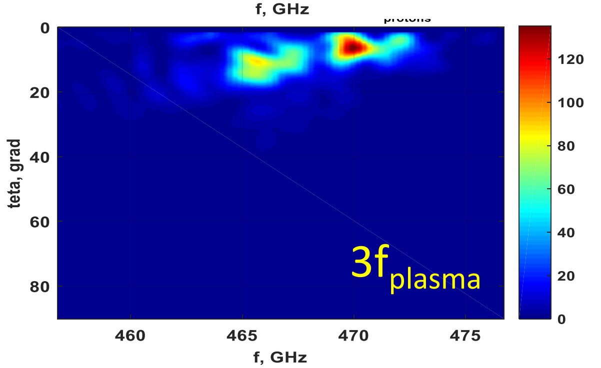


CTR Harmonics : Simulation

Spectral energy distribution nJ/GHz/sr

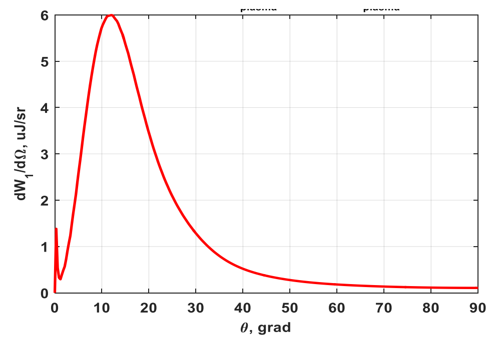


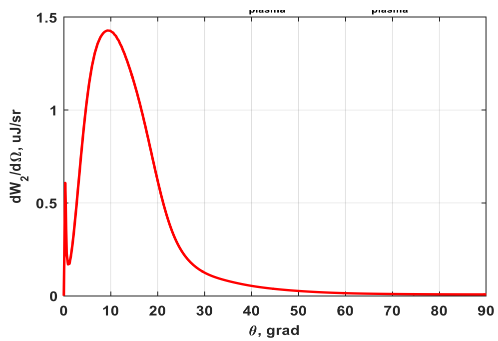


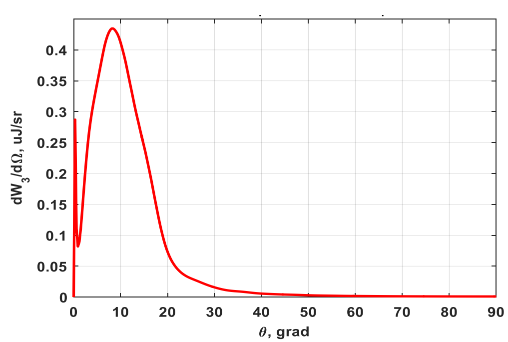


Spectral energy distribution, μJ/sr

Integrated over 20 GHz band







Plasma $N_e = 3 \cdot 10^{14}$ cm^{-3}
f_{plasma} = 156 GHz
λ_{plasma} = 1.9 mm

Ratio between harmonics:

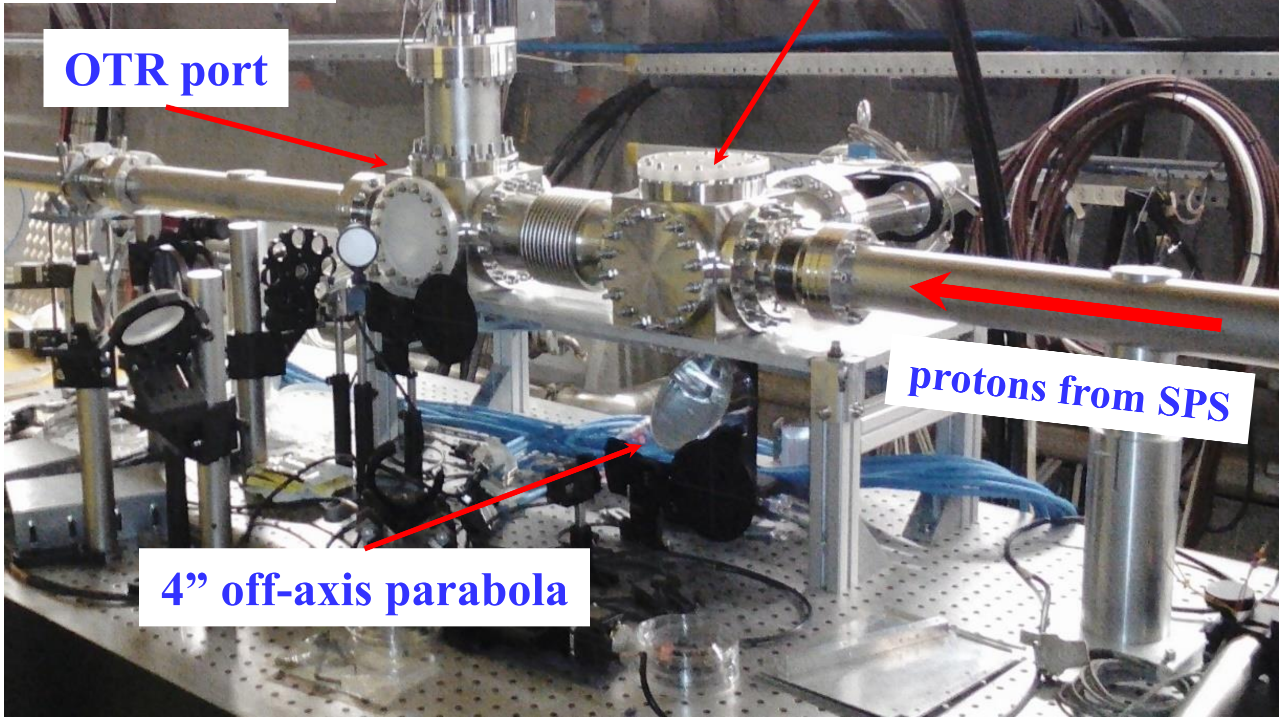
Fundamental to 2nd harmonic: factor 4.2

2nd to 3rd harmonic: factor 3.3

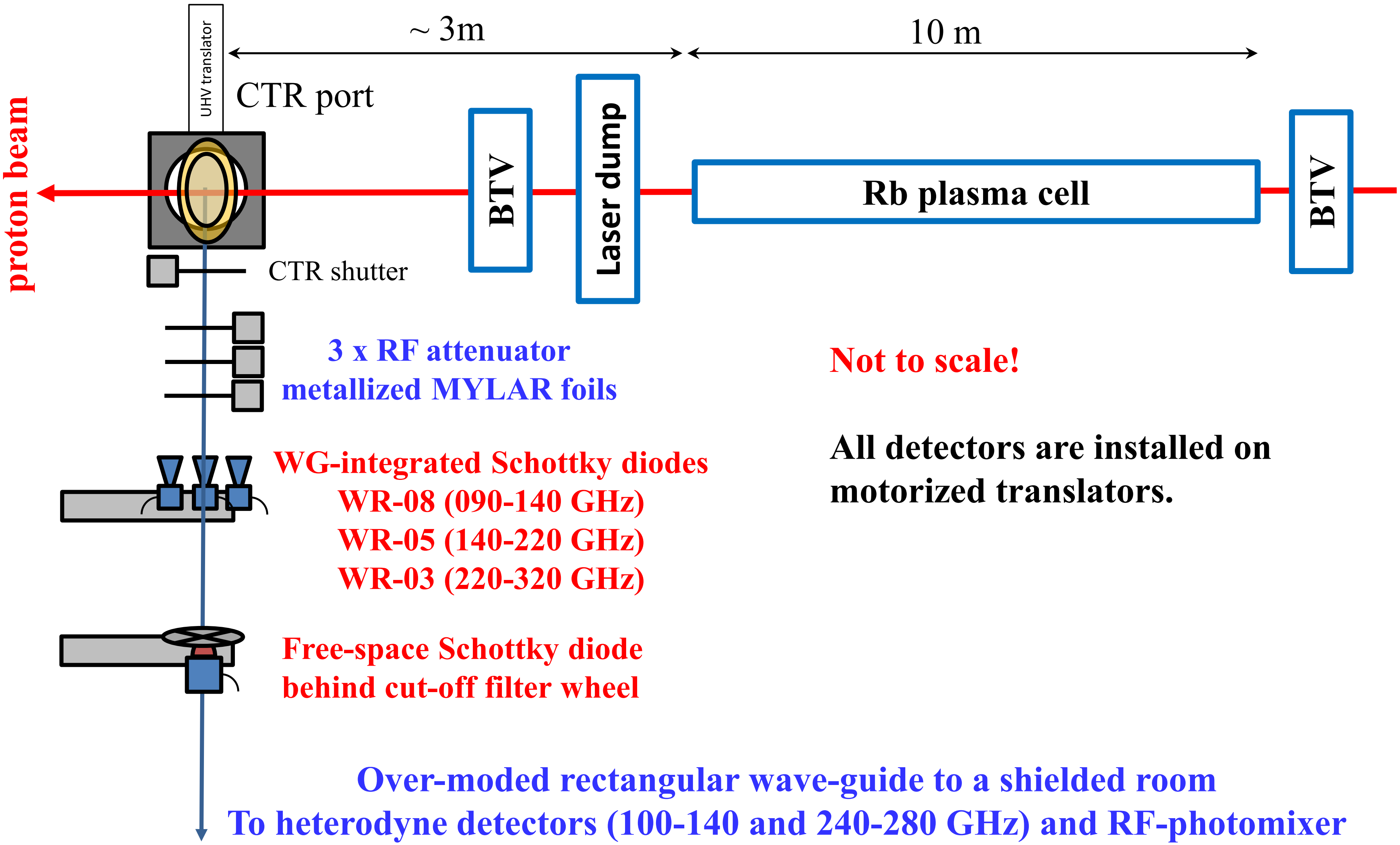
CTR Diagnostics: Setup

Key components:

- **150mm travel UHV translator**
- **Screen is a ∅100mm Al-coated Si wafer**
- **∅100mm quartz view-port**
- **4” off-axis parabola**



CTR Diagnostics: **Layout**



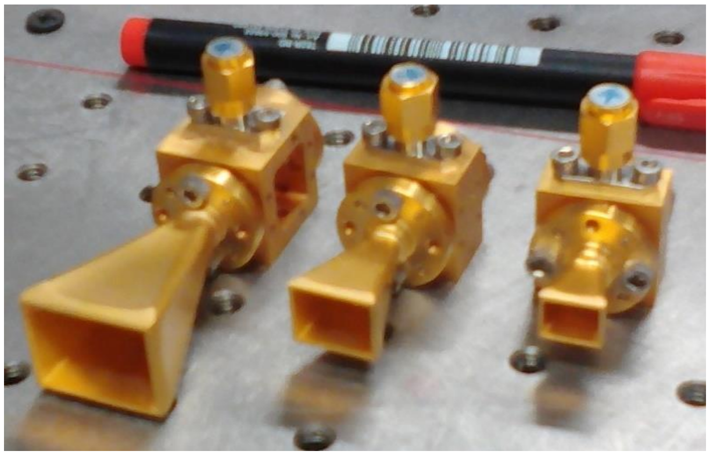
Not to scale!

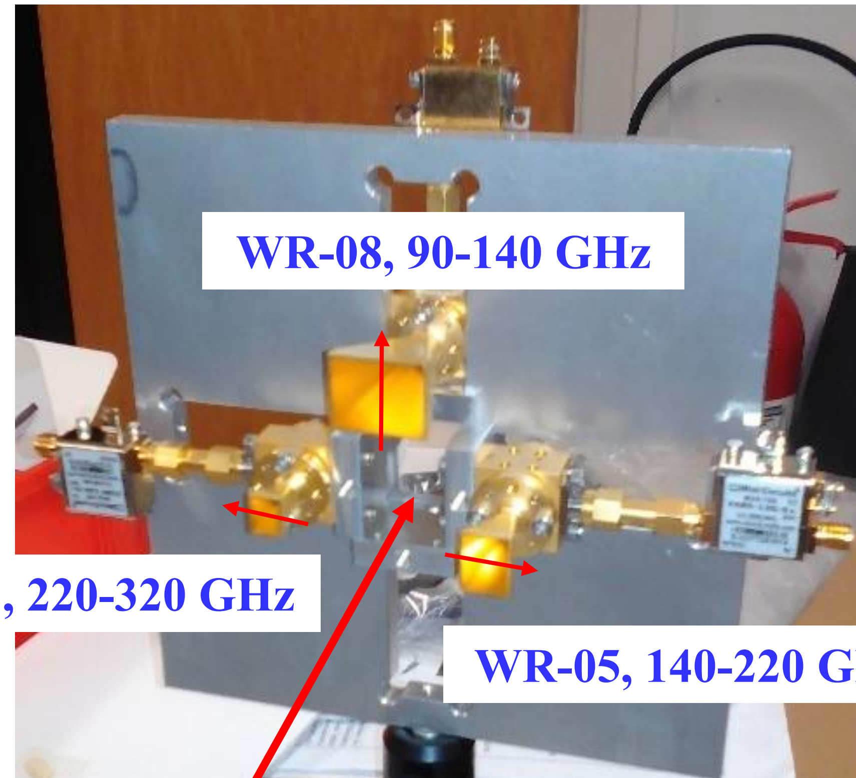
All detectors are installed on motorized translators.

CTR Diagnostics: waveguide Schottky diodes

Three waveguide-integrated Schottky diodes with horn antennas

Three different bands, for quick CTR signal check-up





optical axis

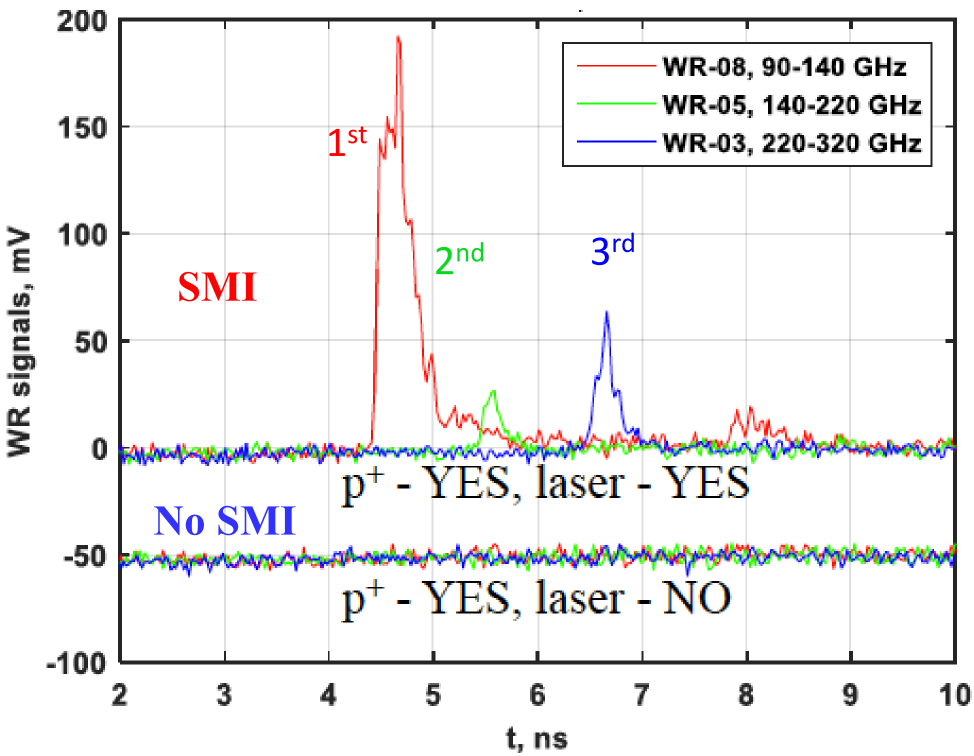
CTR signal from wide-band Schottky diodes

- Single shot diagnostics for quick CTR signal check
- CTR signal detected at harmonics (power not calibrated)
- Modulation of p^+ is nonlinear, hinted by presence of CTR harmonics

Preliminary !!!

Harmonics (?) are visible in the wide-band diodes

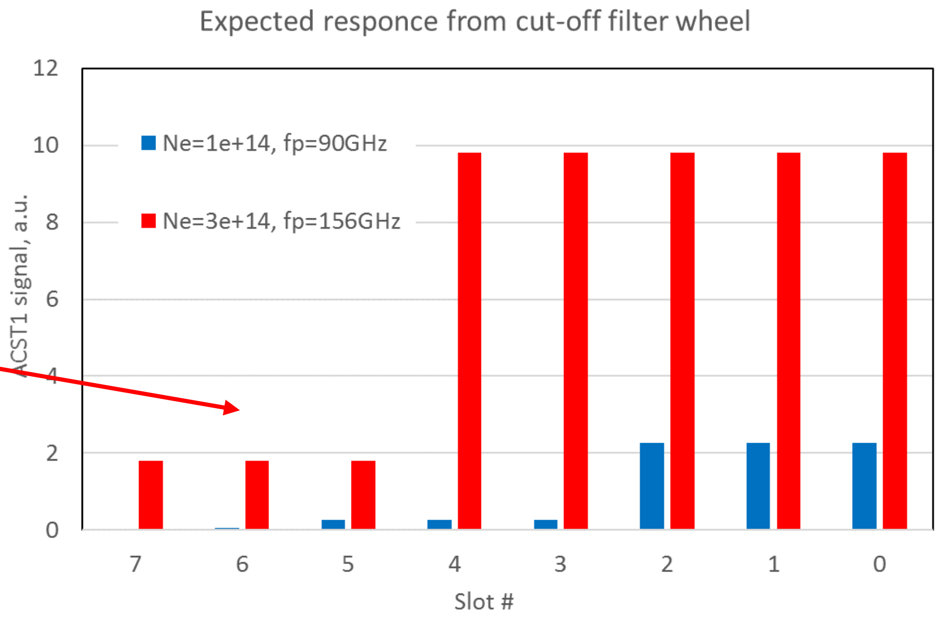
Example for $N_{Rb} = 1.3 \cdot 10^{14}$ cm^{-3}, $f_p = 103$ GHz



CTR Diagnostics: free-space Schottky diode

Free-space Schottky diode (ACST), installed behind 8-slot revolver wheel with 7 round bottle neck horns with a different frequency cut-off

- **Some signal is expected here due to CTR harmonics**
- **Data acquisition is quite lengthy since many events are required for each slot**
- **No reliable data yet to present**



Slot 0, empty

Slot 1, ∅2.4 mm, cut-off 73 GHz

Slot 2, ∅1.8 mm, cut-off 98 GHz

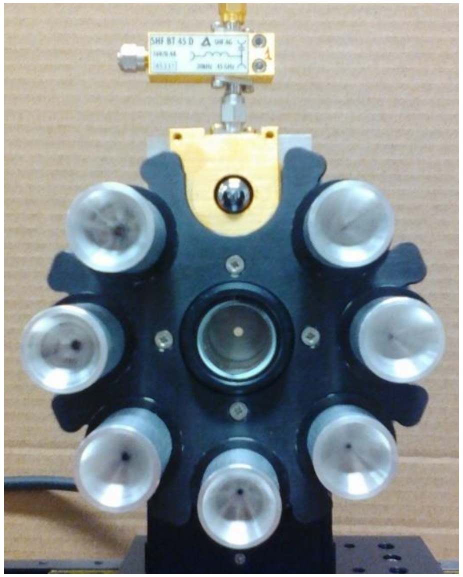
Slot 3, ∅1.5 mm, cut-off 117 GHz

Slot 4, ∅1.2 mm, cut-off 147 GHz

Slot 5, ∅1.0 mm, cut-off 176 GHz

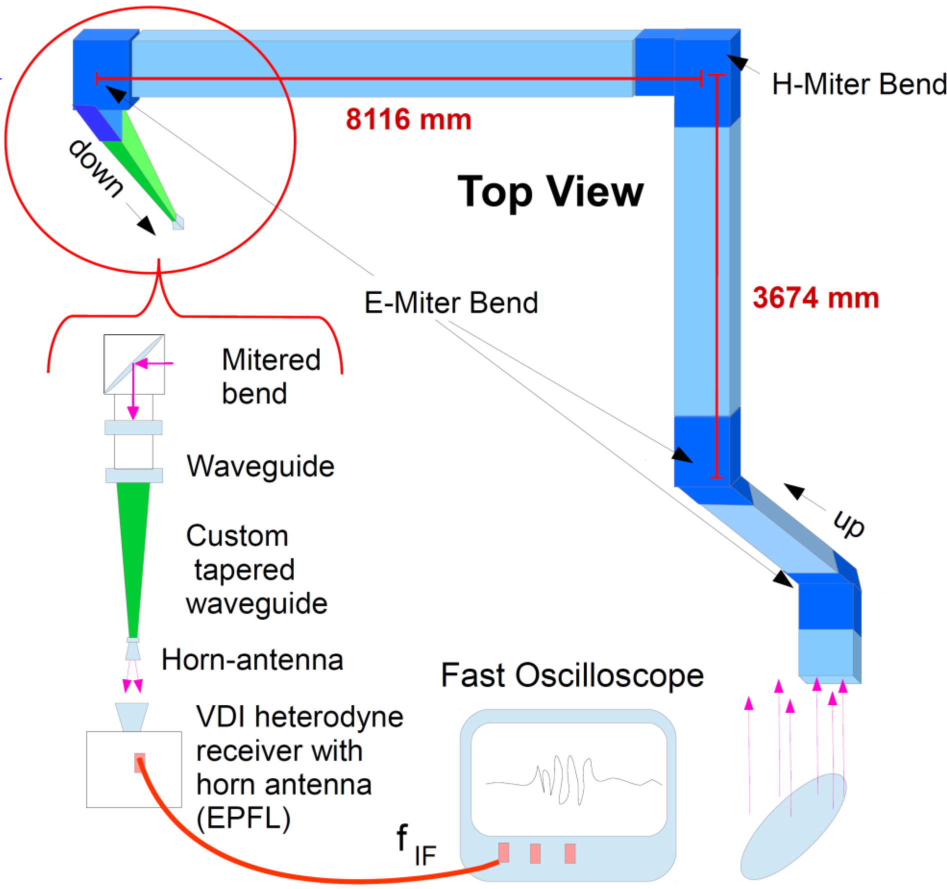
Slot 6, ∅0.8 mm, cut-off 220 GHz

Slot 7, ∅0.6 mm, cut-off 293 GHz



CTR Diagnostics: waveguide transfer line

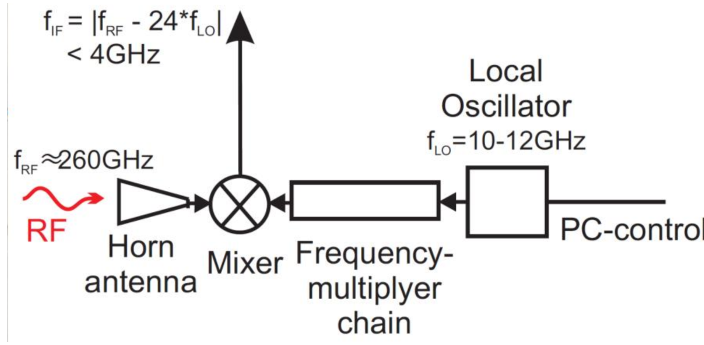
- Microwave transfer line length ~ 15 m
- Brings CTR microwave signal to a shielded room
- Rectangular overmoded waveguide WR-90 (cut-off at 6.5 / 13 GHz)
- Output custom horn antenna
- 3 RF beam splitters to share a signal between different detectors in a shielded room



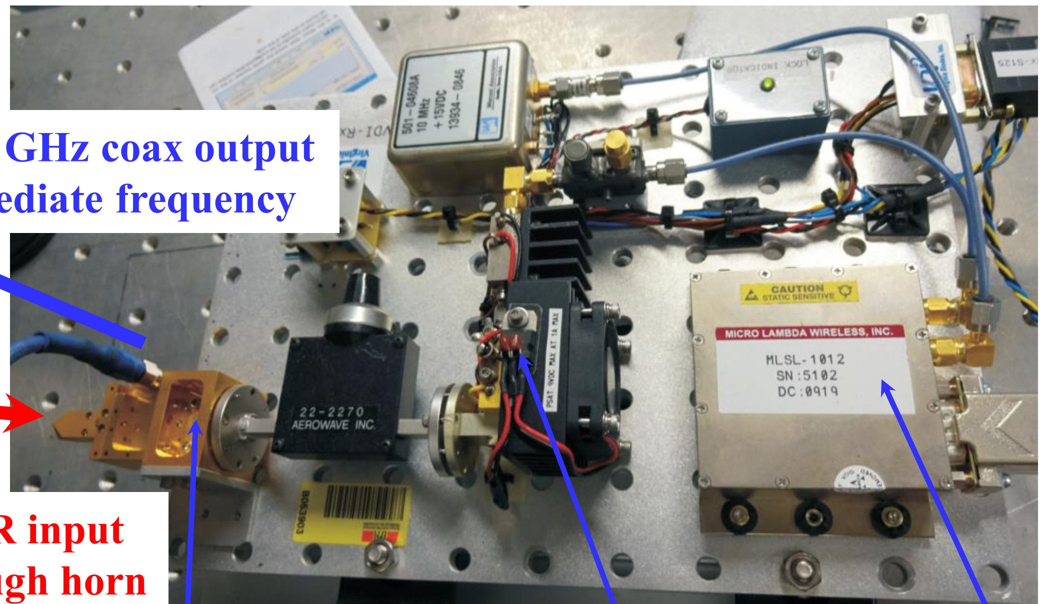
Courtesy of F. Braunmueller (MPP)

CTR Diagnostics: Heterodyne Detectors

- **Two independent heterodyne systems**
- **RPG WR-8, for 90-140 GHz**
- **VDI WR-3, for 250-270 GHz**
- **Limited band coverage : we need 90-290 GHz**



VDI Virginia Diodes detector



~10-15 GHz coax output intermediate frequency

CTR input through horn

sub-harmonic mixer

12 x harmonics

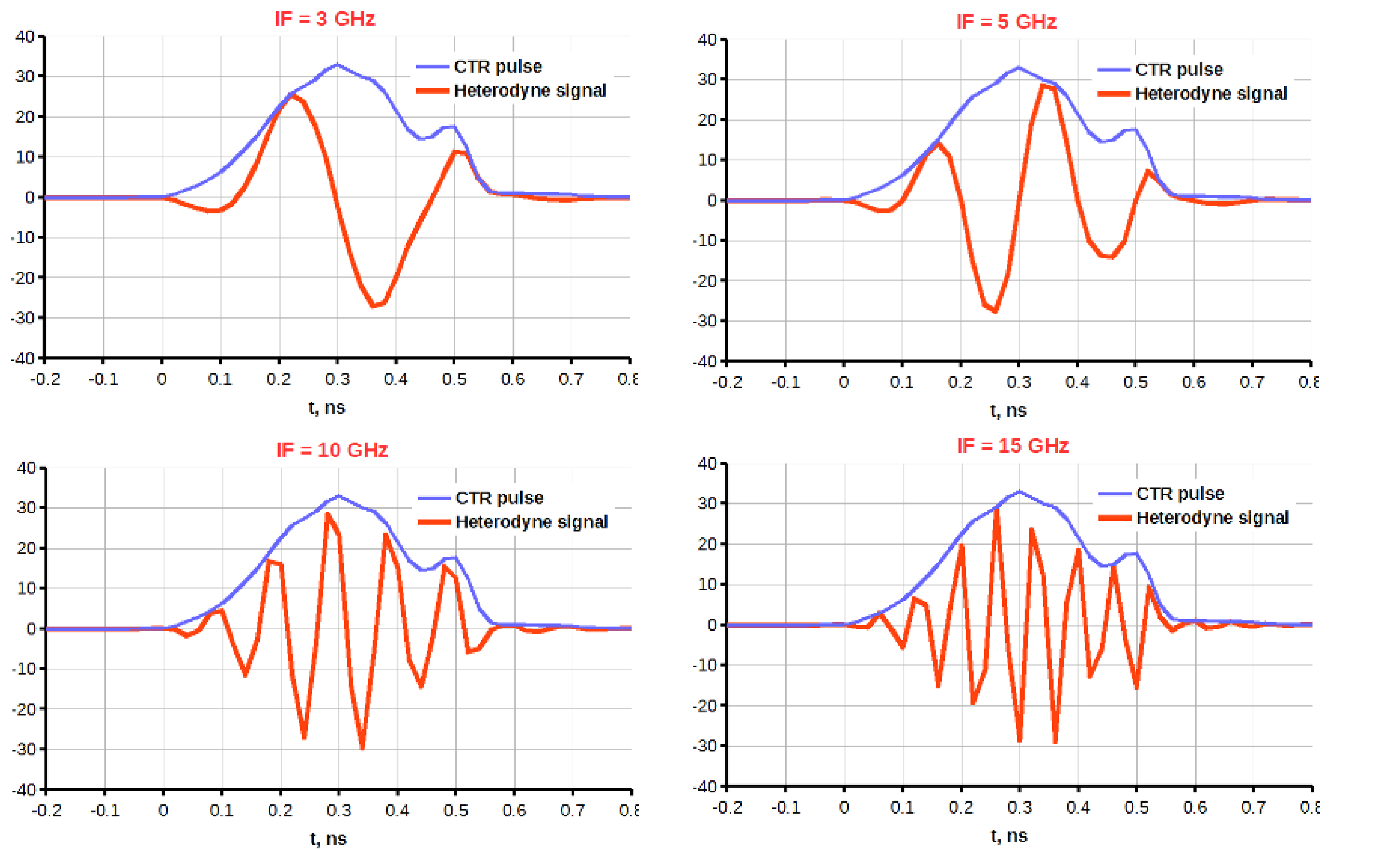
local oscillator

Courtesy of F. Braunmueller (MPP)

Heterodyne Measurement : bandwidth constraint

- **Intermediate frequency (IF) above 5 GHz is amust for correct measurement**
- **Larger bandwidth of a detector facilitates search for apriori unknown CTR frequency**

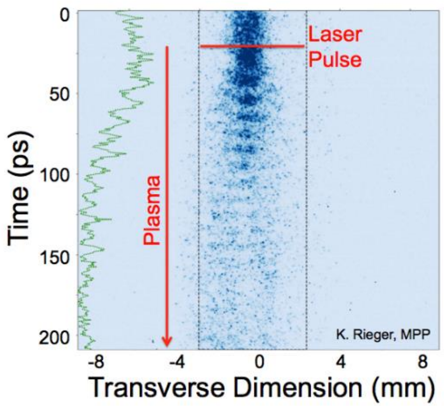
Numerical example of heterodyne mixing with different IF



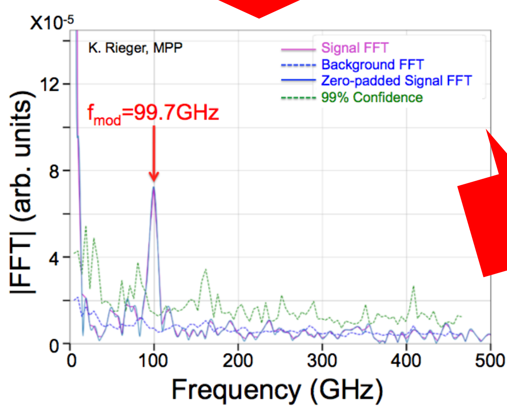
CTR Diagnostics: SMI frequency

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

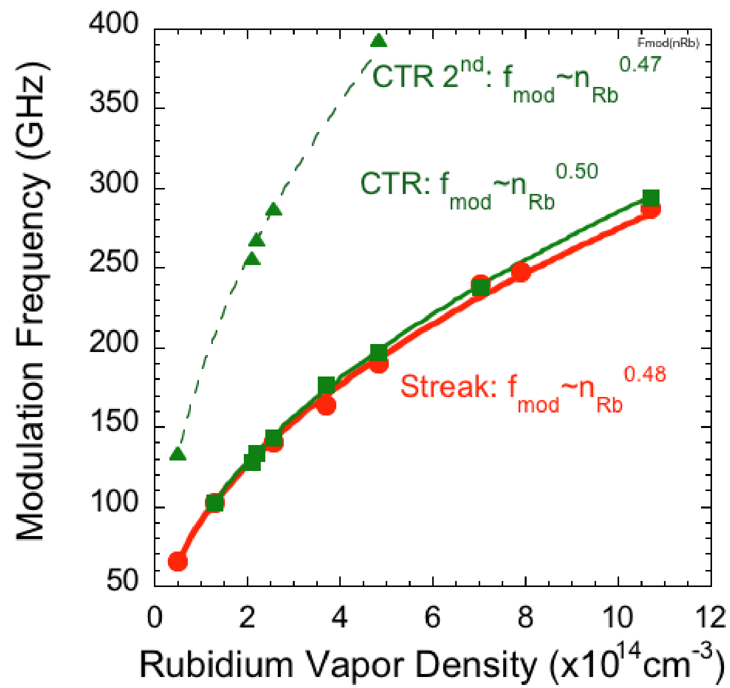
Preliminary !!!



FFT



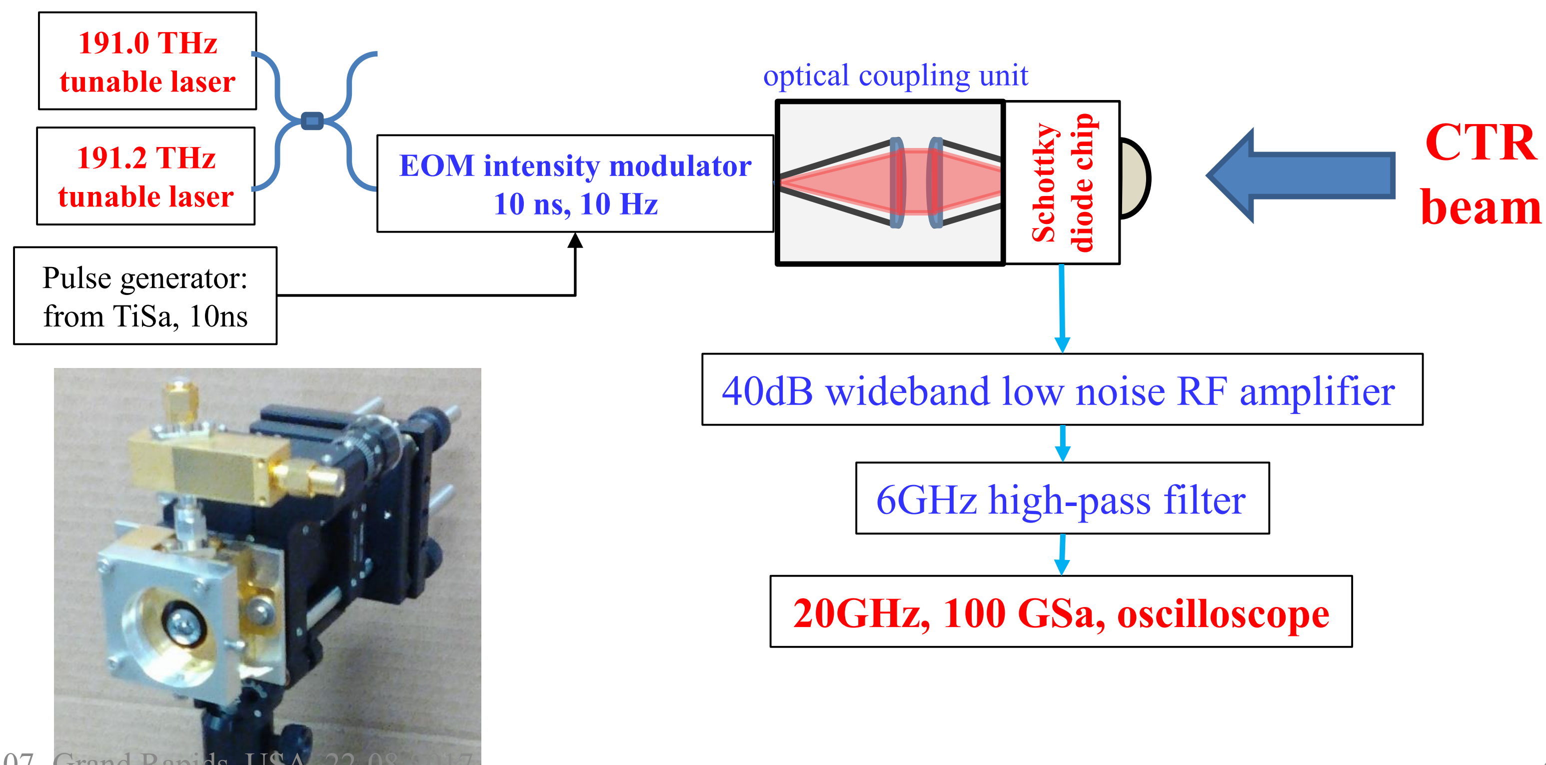
Heterodyne CTR and streak camera FFT



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

CTR Diagnostics: Schottky photo-mixer

- **Also a heterodyne system, based on free space ACST Schottky diode**
- **RF local oscillator is replaced by a photocurrent beat of two tunable CW lasers directly in the Schottky diode chip (custom development)**
- **Almost no band limitation : covers 50÷1000 GHz (we need 90÷290 GHz)**
- **Less sensitive (factor ~100) than conventional heterodyne receivers**



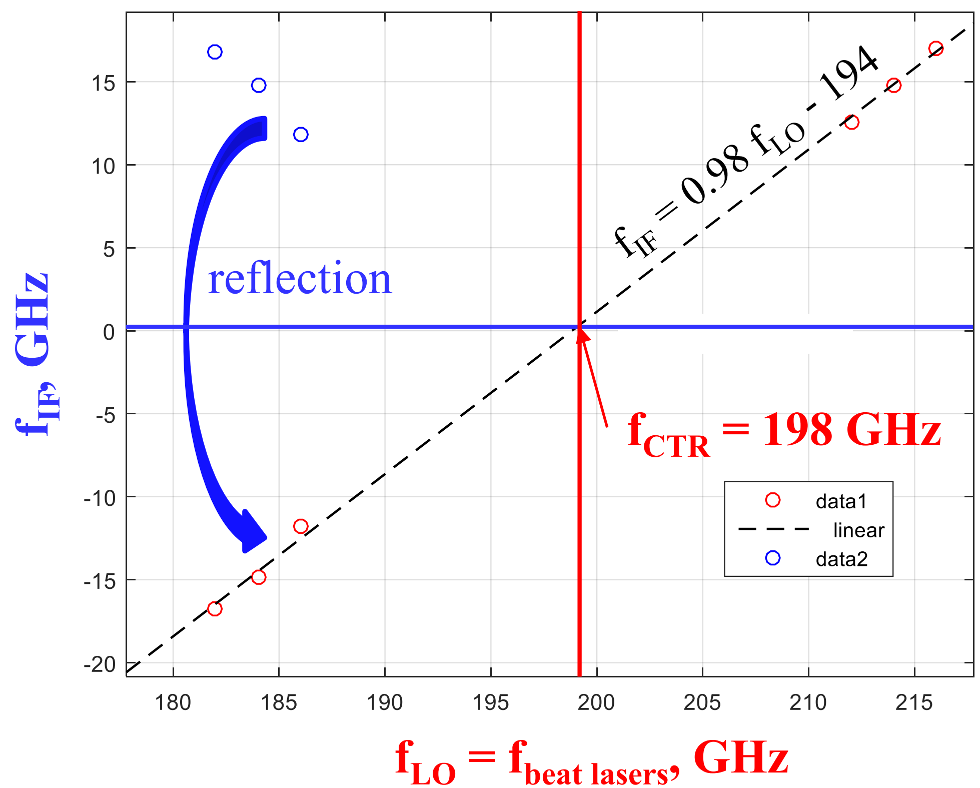
CTR Diagnostics: Schottky photo-mixer

Preliminary !!!

- Given a low sensitivity of the photo-mixer, multiple events had to be accumulated for every LO frequency point

Successful measurement example:

- Rb density $4.8 \cdot 10^{14}$ cm^{-3}, and plasma frequency $f_p = 197$ GHz
- Measured CTR carrier frequency is $f_{CTR} = 198$ GHz



Summary

- **AWAKE is scientifically and technically challenging experiment with a tight schedule**
- **Main achievements so far:**
  - 10 meter long hot Rb vapour source works fine, UHV outside
  - Laser strong field Rb vapour ionization works fine over 10 meters
  - Synchronization and special alignment of p^+ and laser works fine
  - **We observed a Self Modulation Instability (SMI) of p^+ bunch**
  - **We measured a p+ bunch modulation frequency with a streak camera (OTR) and heterodyne receivers (CTR) and showed it is equal to a plasma frequency**

First physics already started end of 2016!

Thank you!

Plasma Wake Field: Glossary

Plasma oscillations (Langmuir oscillations) frequency

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

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

for n_e=10^{15} 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