First preliminary results of CTR measurement in AWAKE runs June/September 2017

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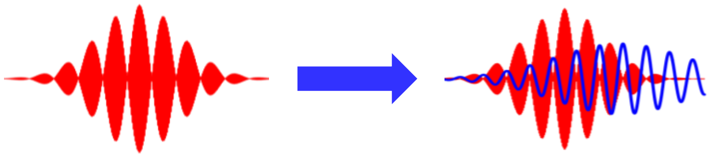
3rd European Advanced Accelerator Concepts Workshop (EAAC),
Isola d'Elba, September 24-30, 2017

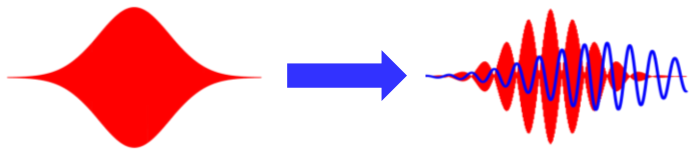
The Zoo of Plasma Wake-field Accelerators

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

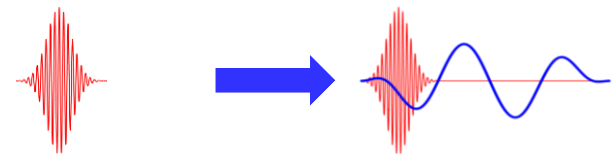
Laser Beat-Wave WFA (~1 ns)
Two frequencies laser pulse (pulse train)



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

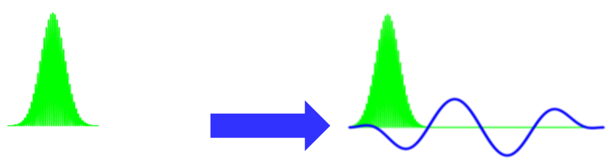


Laser WFA (~0.1 ps)
Short intense laser pulse

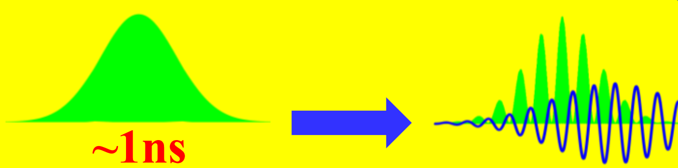


Particle Bunch WFA
Short intense particle bunch

~ 1ps proton bunch does not exist !



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



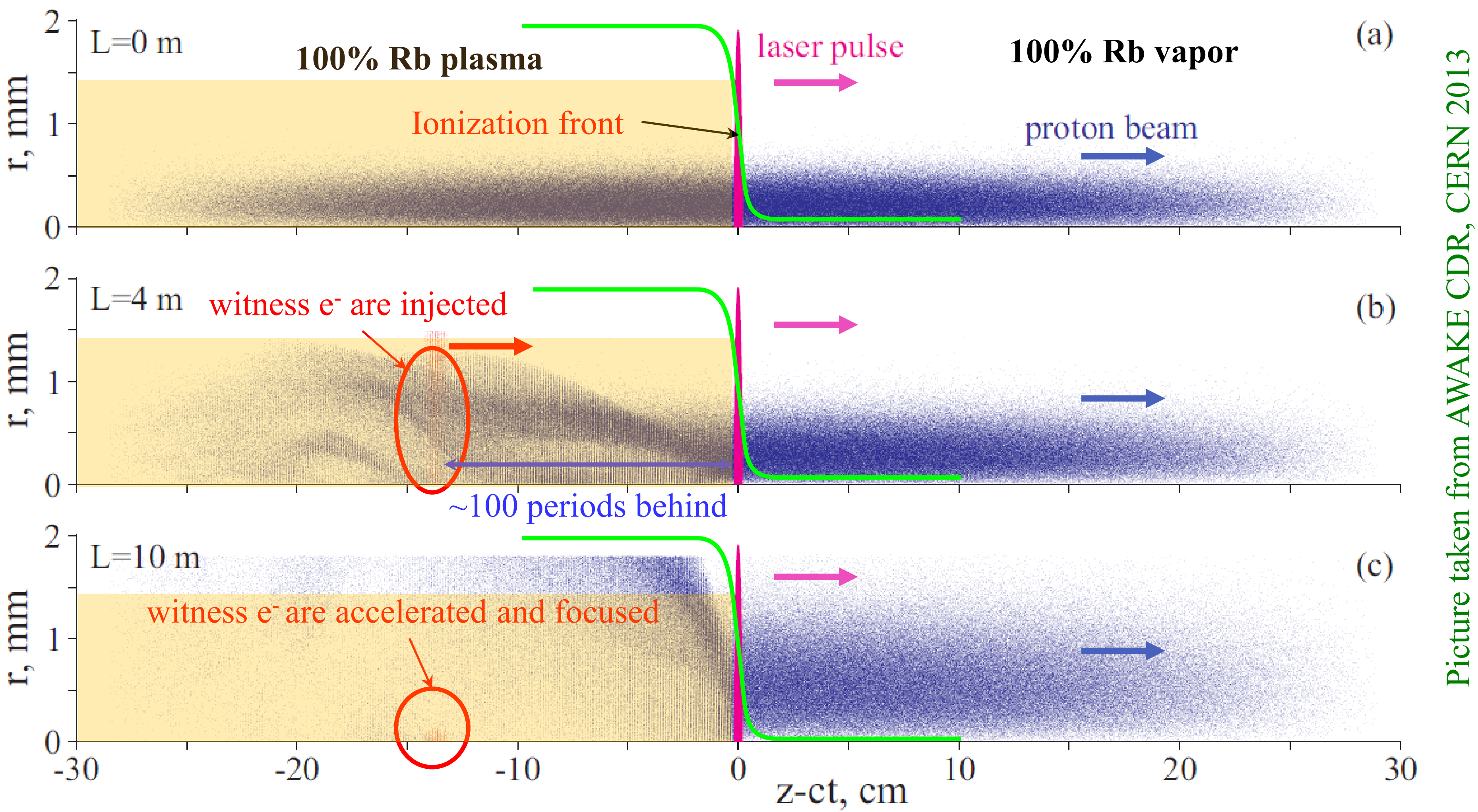
~1ns

Scope of AWAKE proof-of-principle experiment

AWAKE 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



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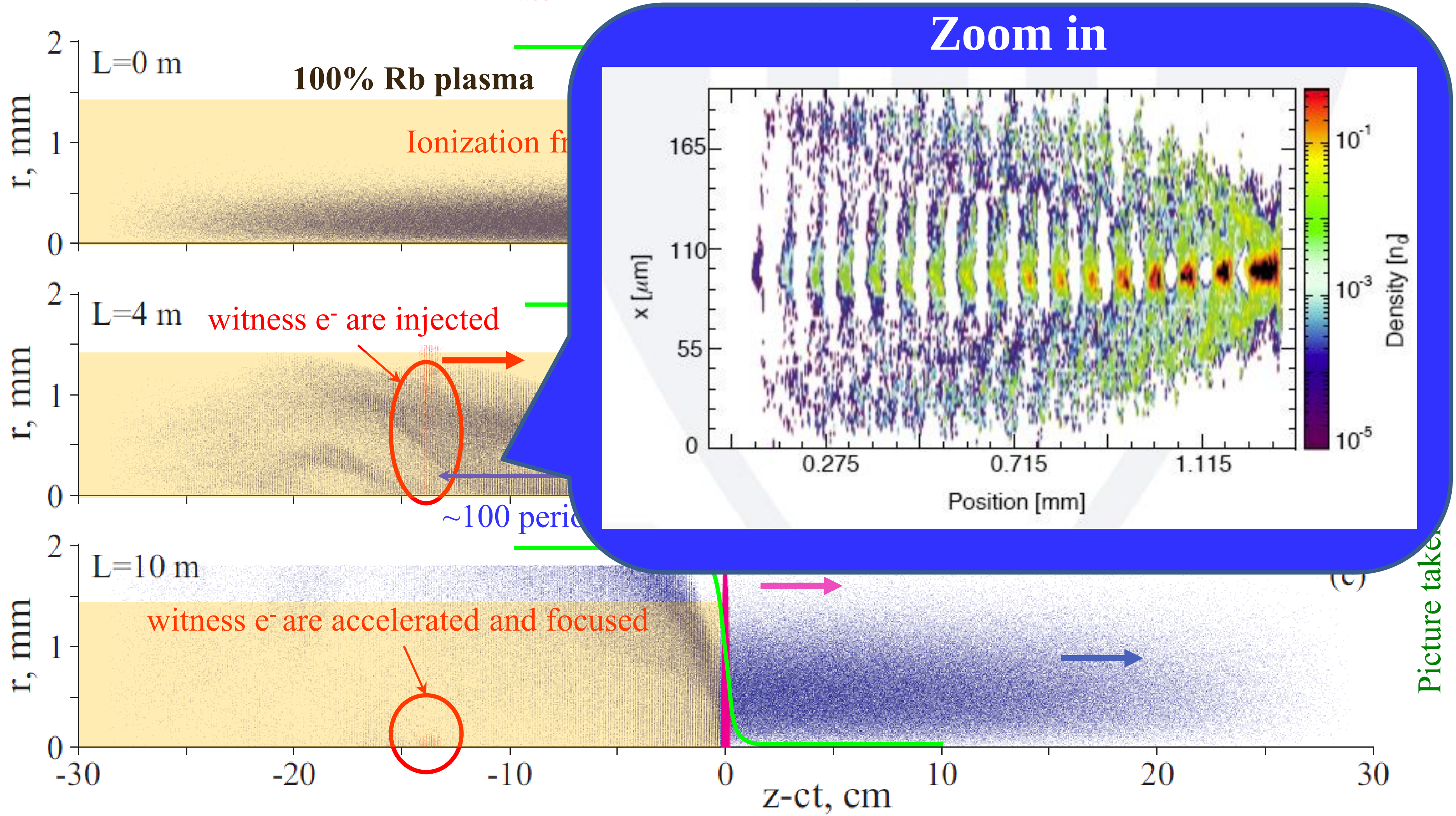
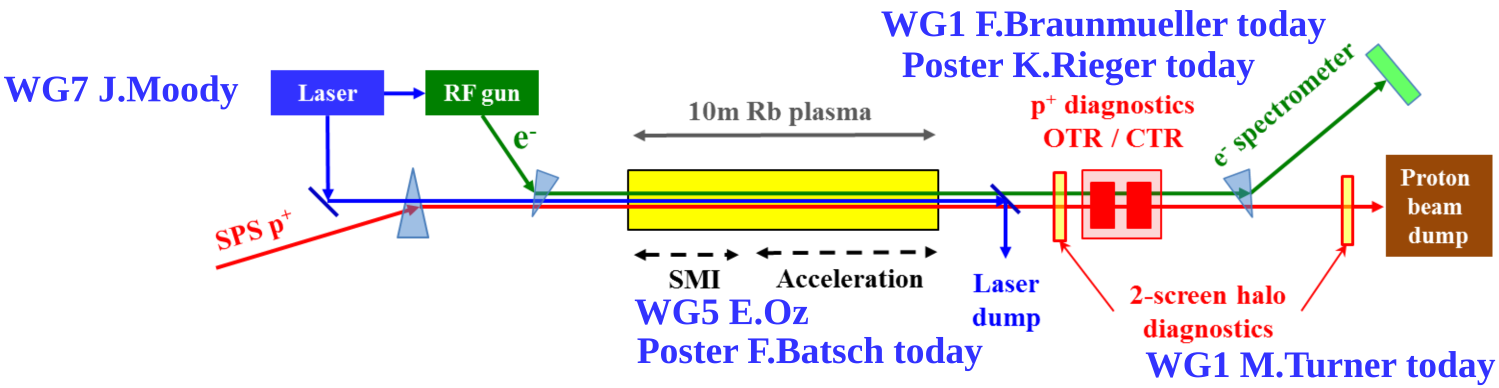
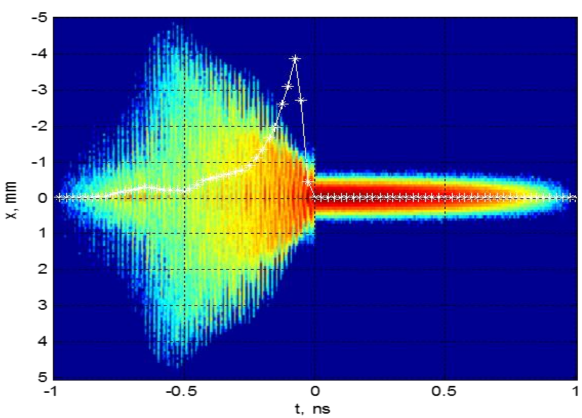


Coherent Transition Radiation (CTR)

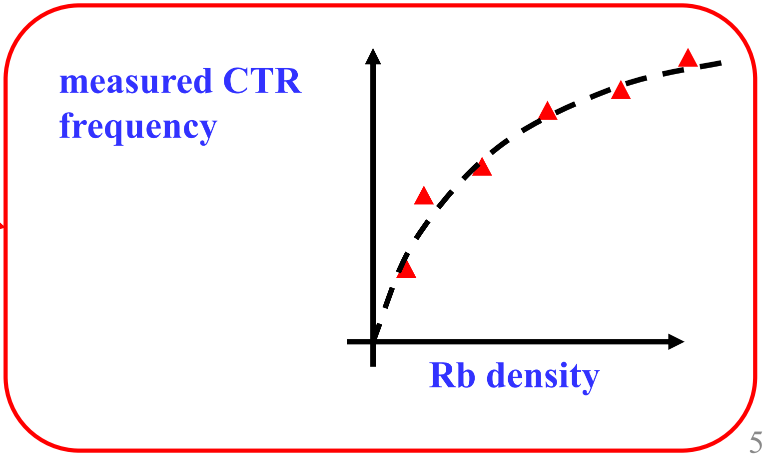


The aims of CTR diagnostics are:

- 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



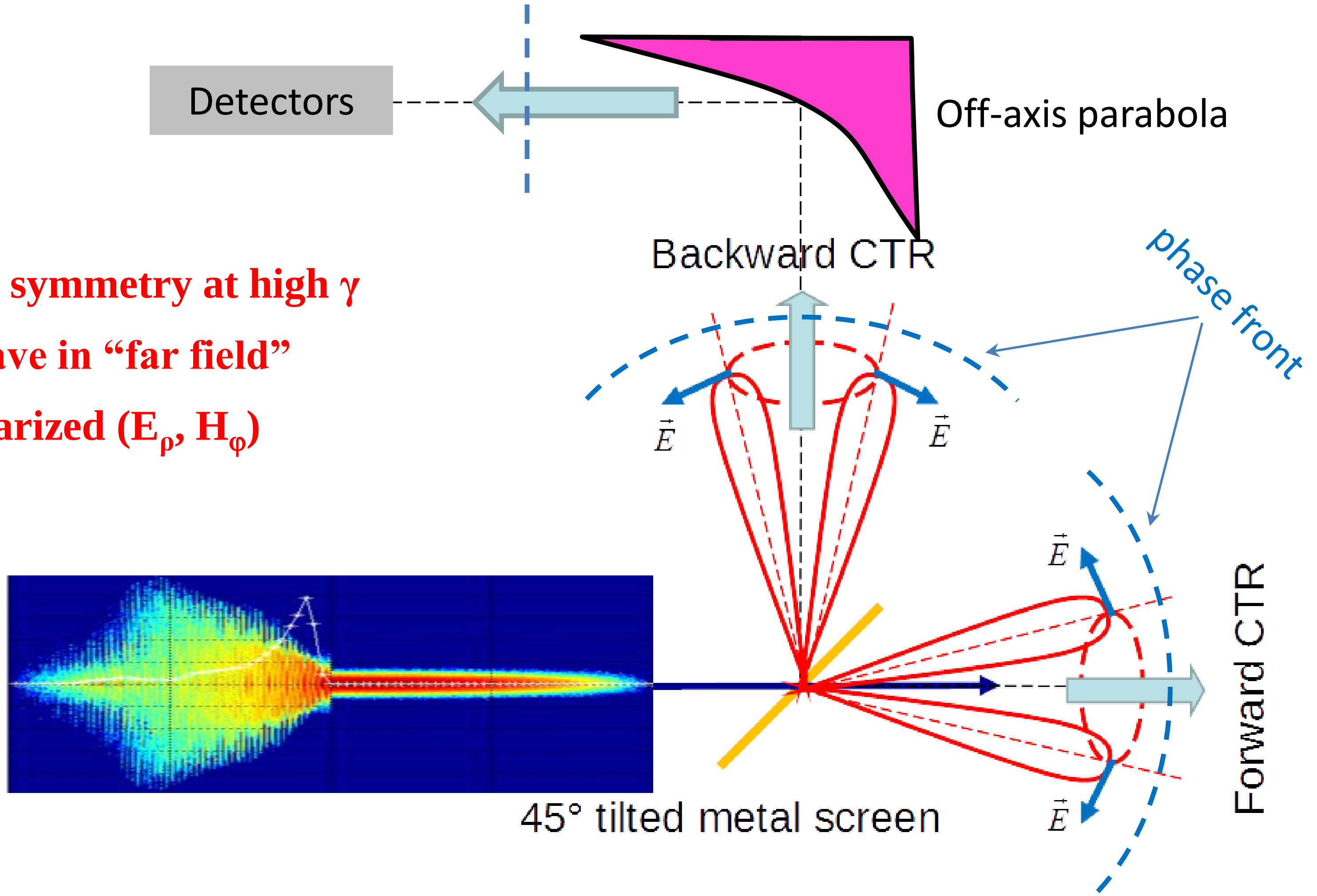
“Golden” figure would look like this



Coherent Transition Radiation (CTR)

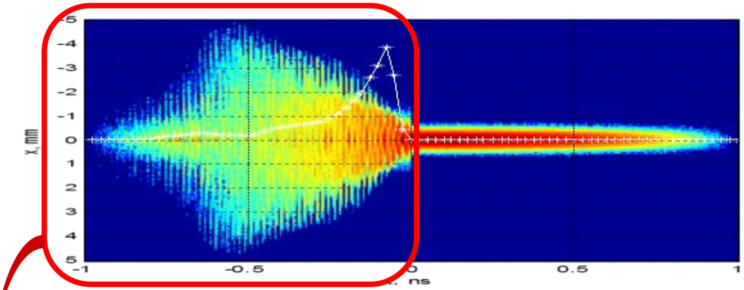
In AWAKE case large-screen and far-field conditions are easily fulfilled for microwave CTR due to a small emitter size – foot print of a bunch Coulomb EM-field at modulation frequency is finite (< 20 mm diameter)

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



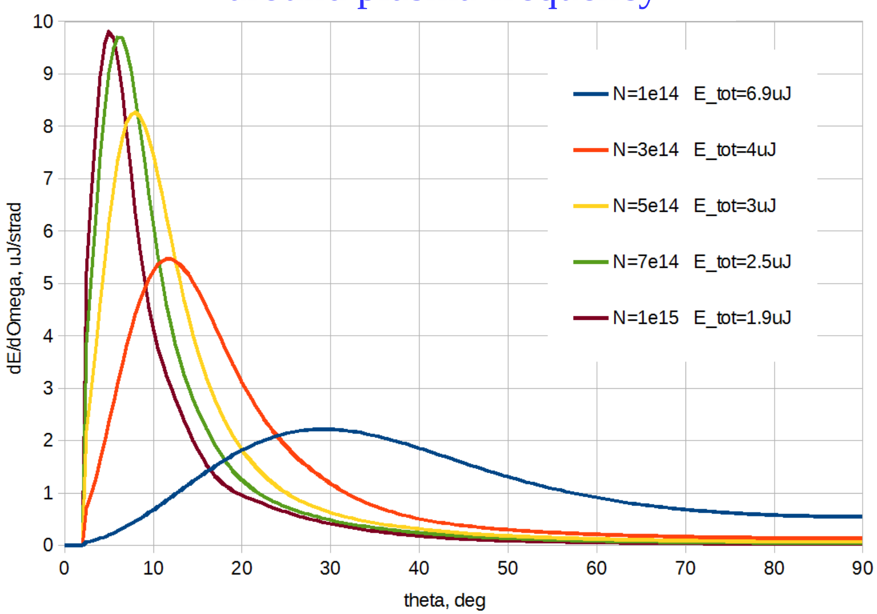
CTR : Simulation

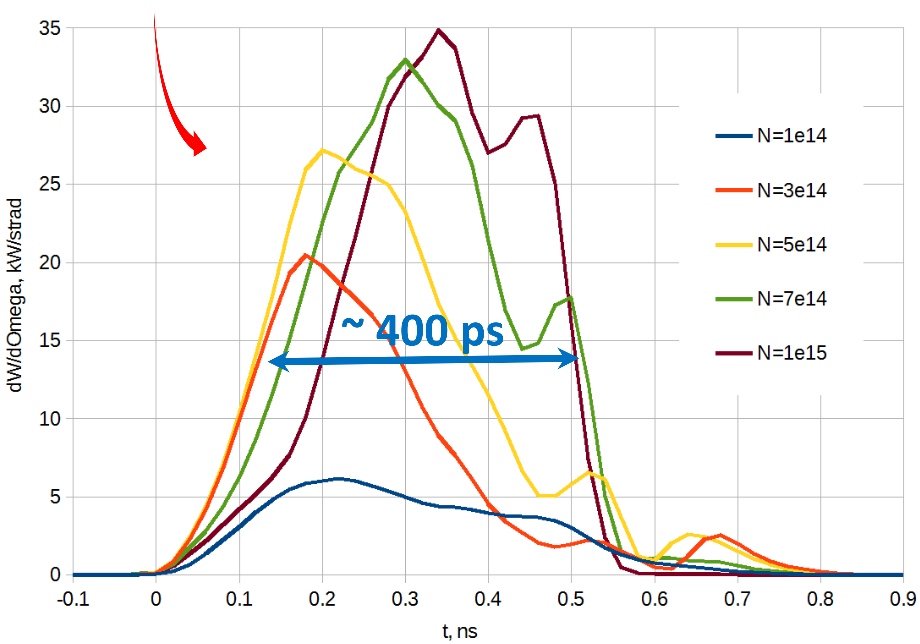
- **Donut-shape spatial pattern of a CTR beam, not 1/γ cone**
- **At peak, pulse fluence is 2-10 μJ/sr => 5-25 nJ/cm^2 at 20 cm**
- **At peak, pulse power is 5-30 kW/sr => 13-75 W/cm^2 at 20 cm**



Pulse power, kW/sr
at peak, θ=θpeak

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



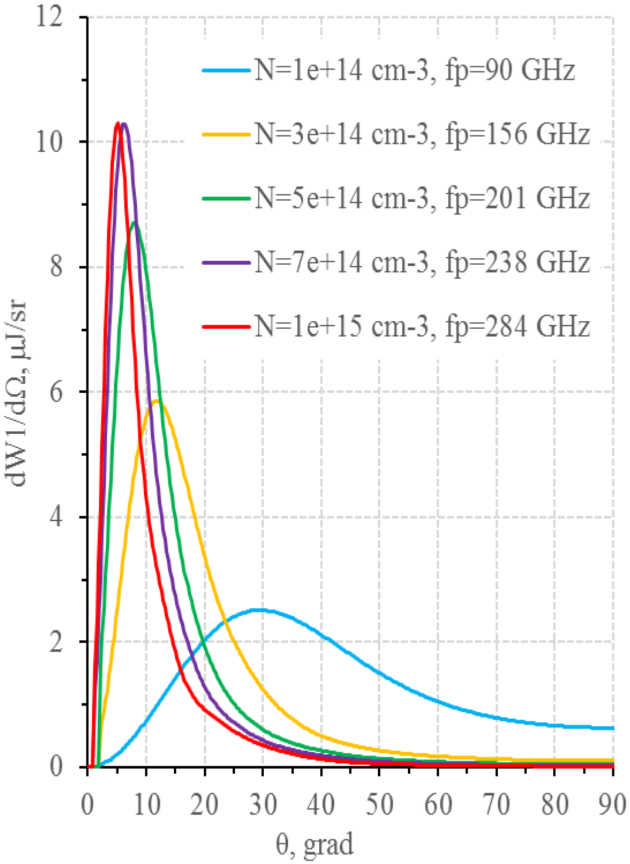


CTR Harmonics : Simulation

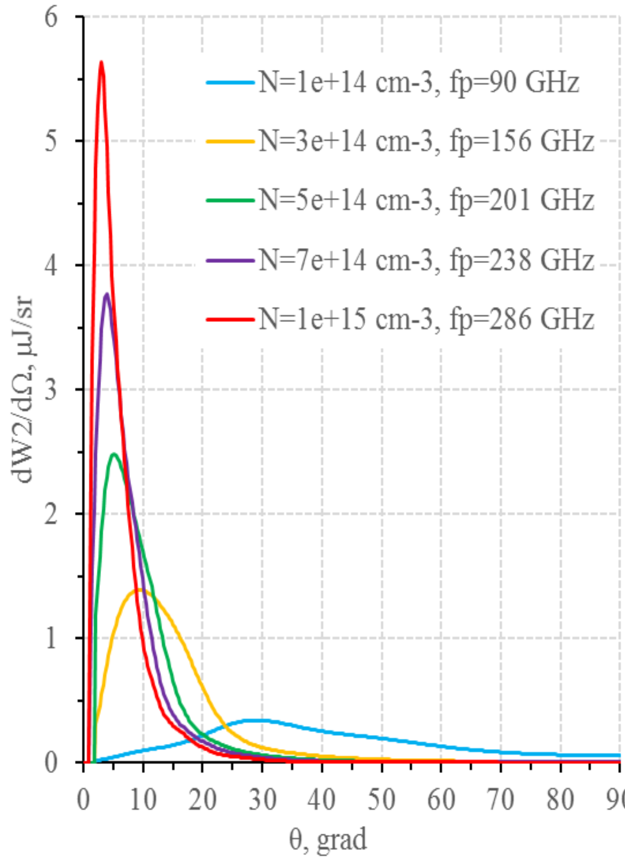
- **Amount of harmonics of plasma frequency is essential and measurable**
- **Note a different scale on vertical axis!**

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

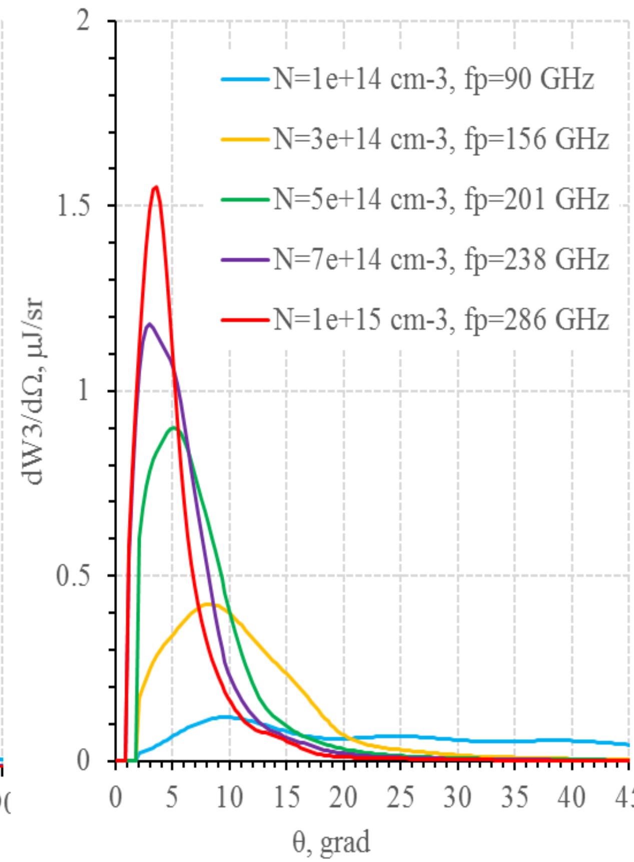
Fundamental plasma frequency



2nd harmonic of plasma frequency



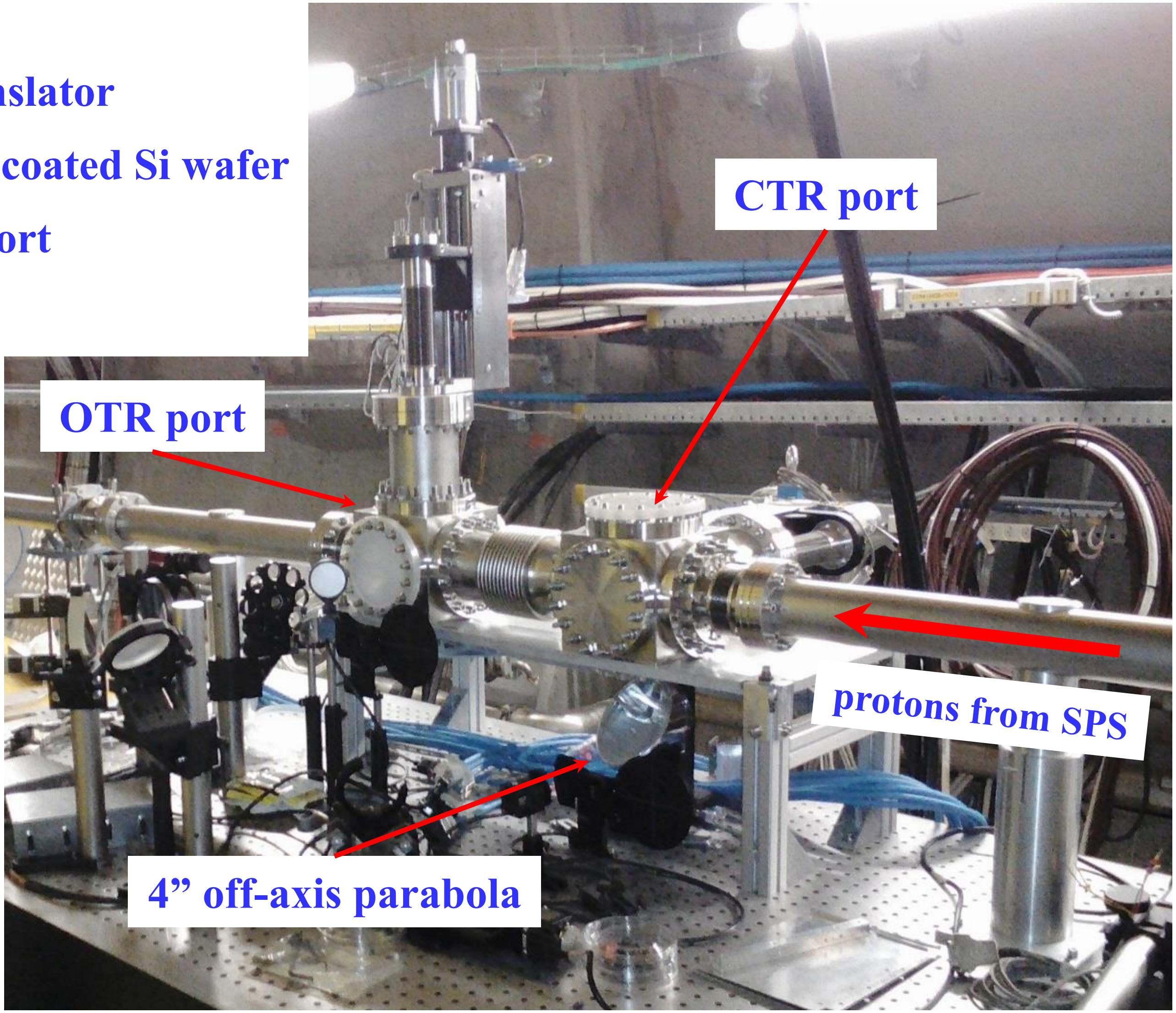
3rd harmonic of plasma frequency



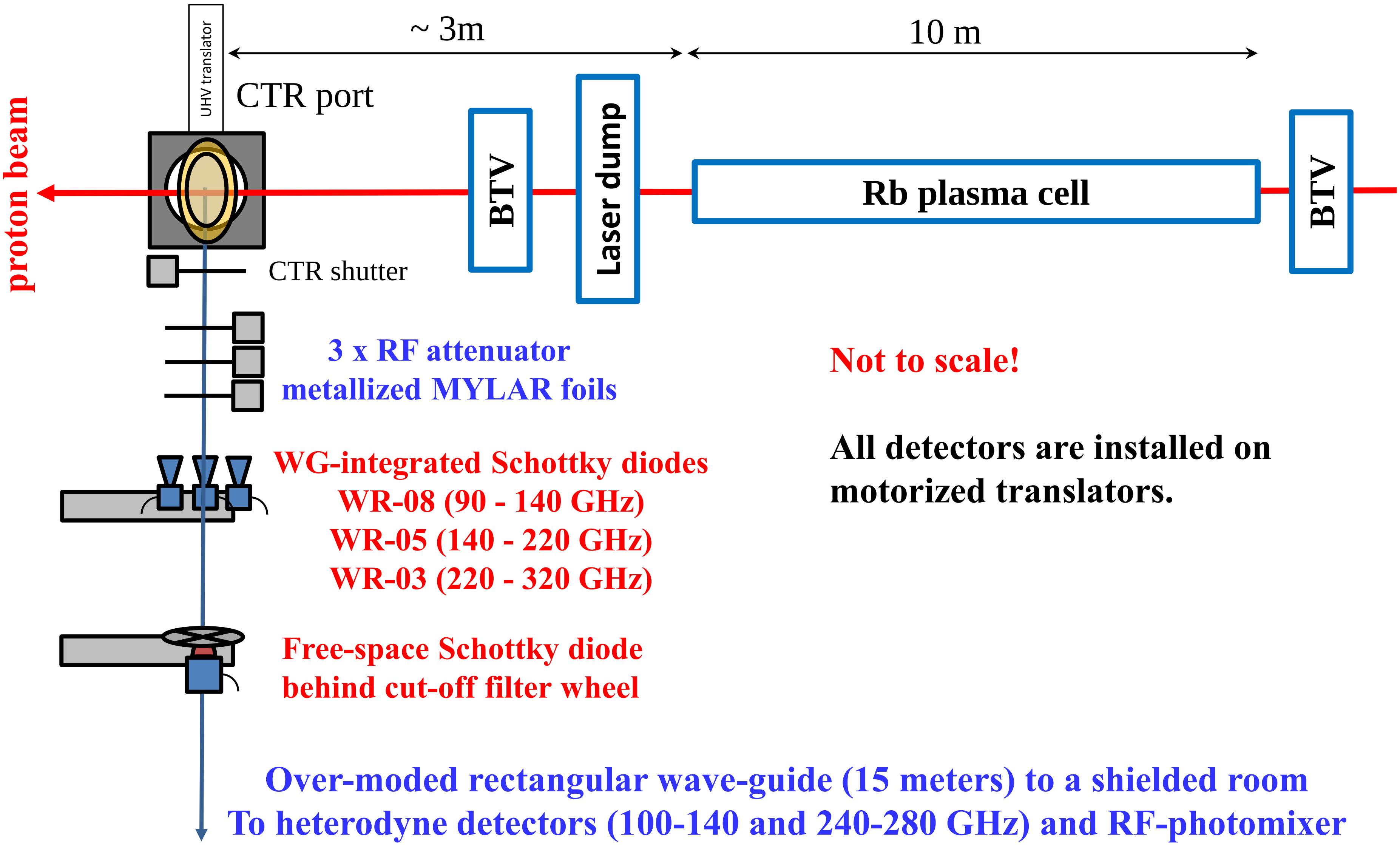
CTR Diagnostics: Setup

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



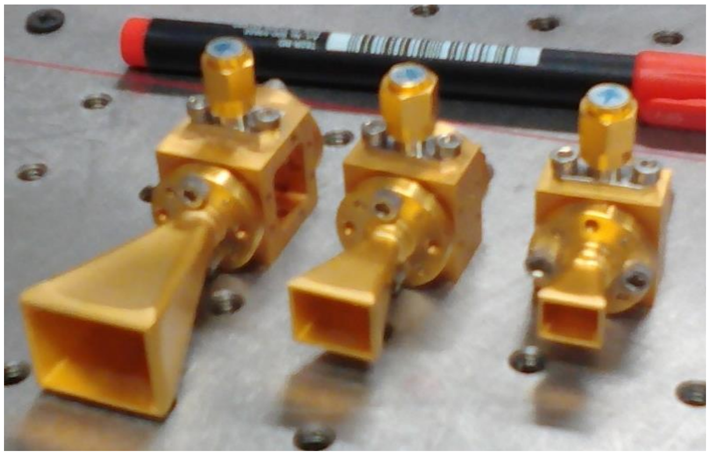
Not to scale!

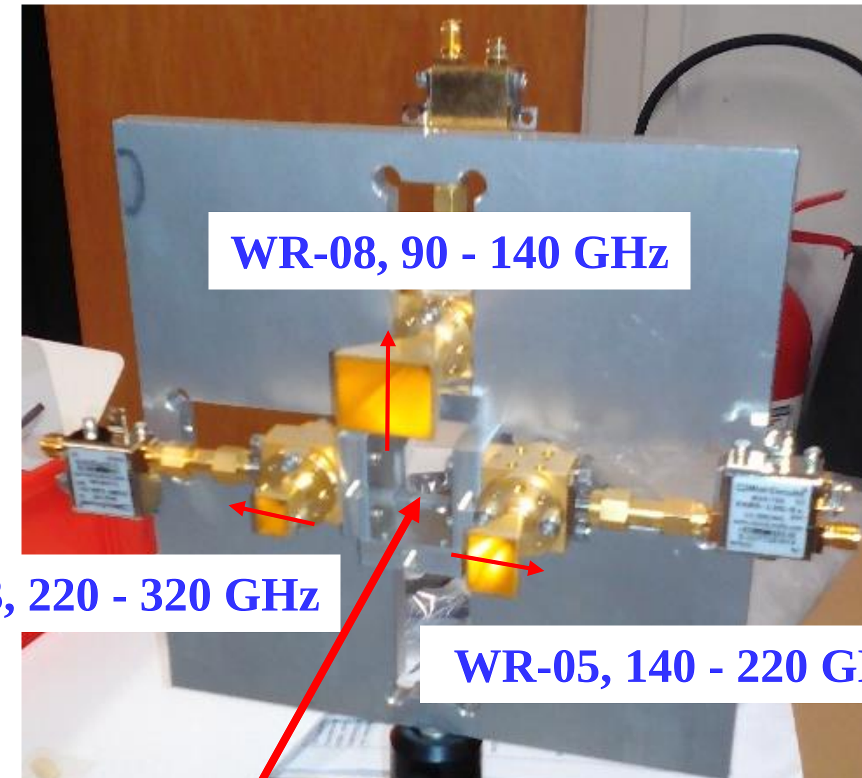
All detectors are installed on motorized translators.

CTR Diagnostics: waveguide Schottky diodes

Three waveguide-integrated Schottky diodes with horn antennas

Three different bands, for quick CTR signal check-up





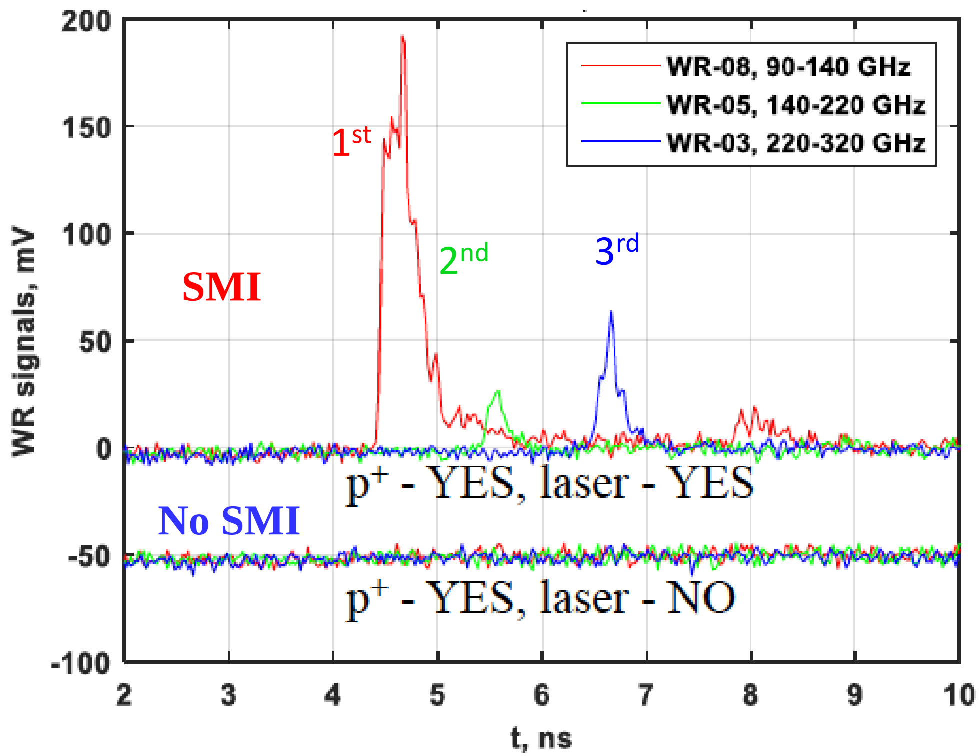
Typical CTR signal from wide-band Schottky diodes

- 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



Typical CTR signal vs. Bunch charge

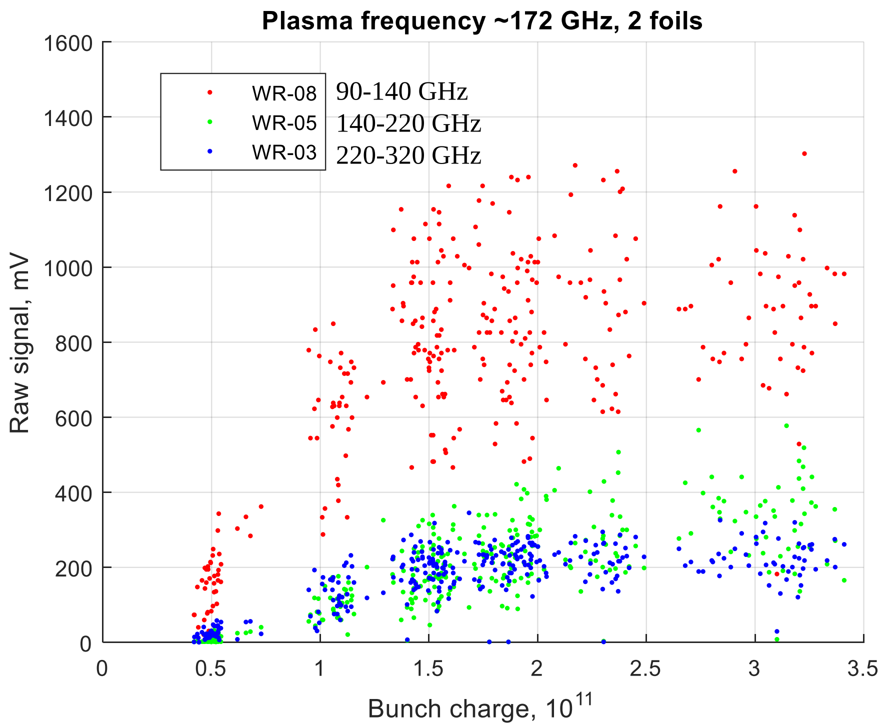
Preliminary !!!

- **Signal has a large scatter – source is not understood, laser/proton overlap jitter?**

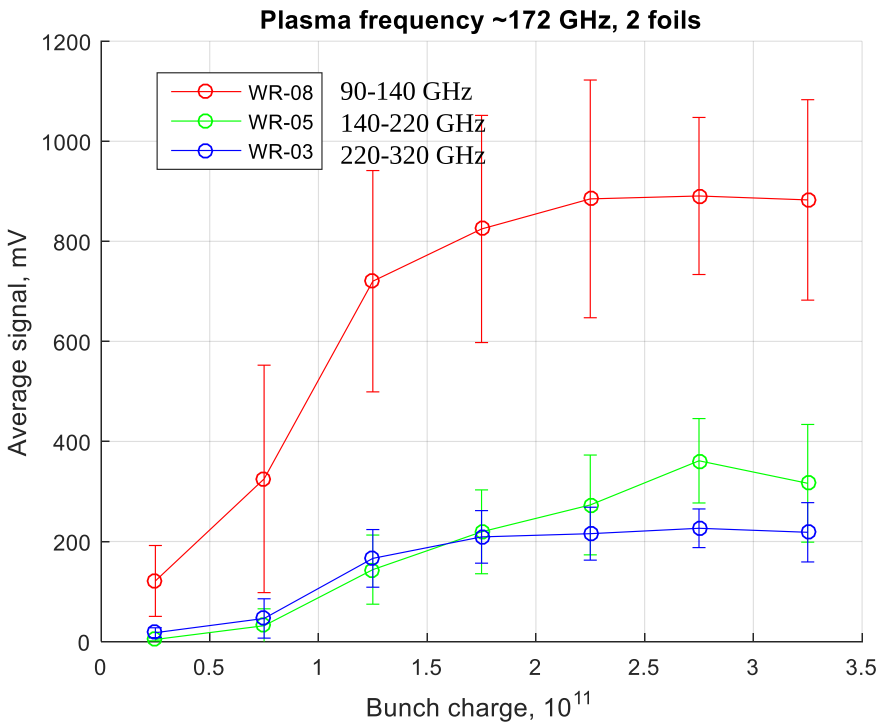
In this particular example:

- **Plasma frequency about ~172 GHz**
- **Laser-proton delay 125ps (TiSa is in the 1st quarter of a proton bunch)**

Raw WR's signal



… and binned with a bunch charge



Typical CTR signal vs. Plasma frequency

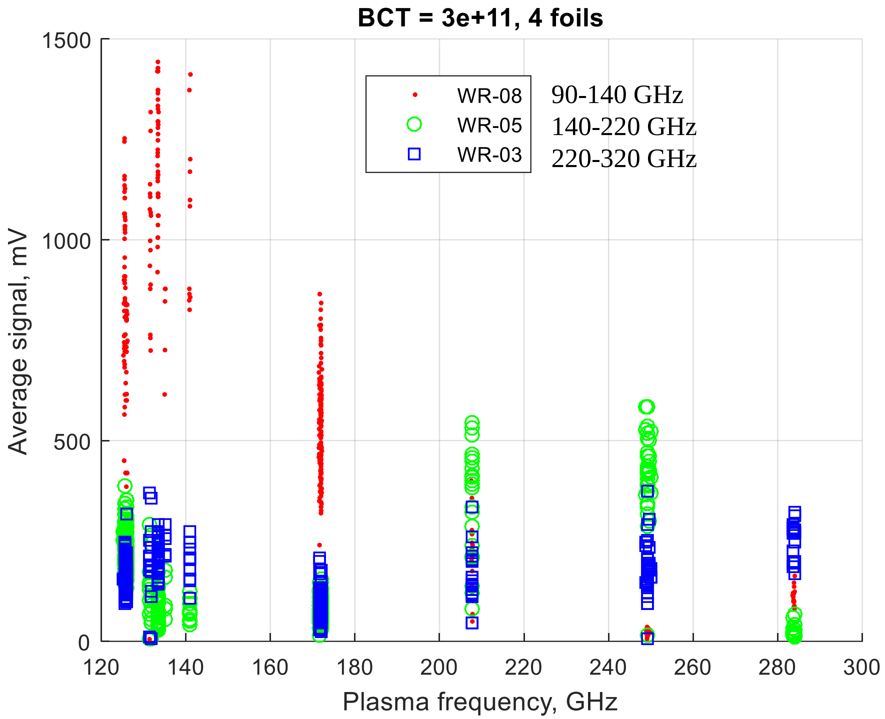
- **Signal has a large scatter – source is not understood, laser/proton overlap jitter?**

In this particular example:

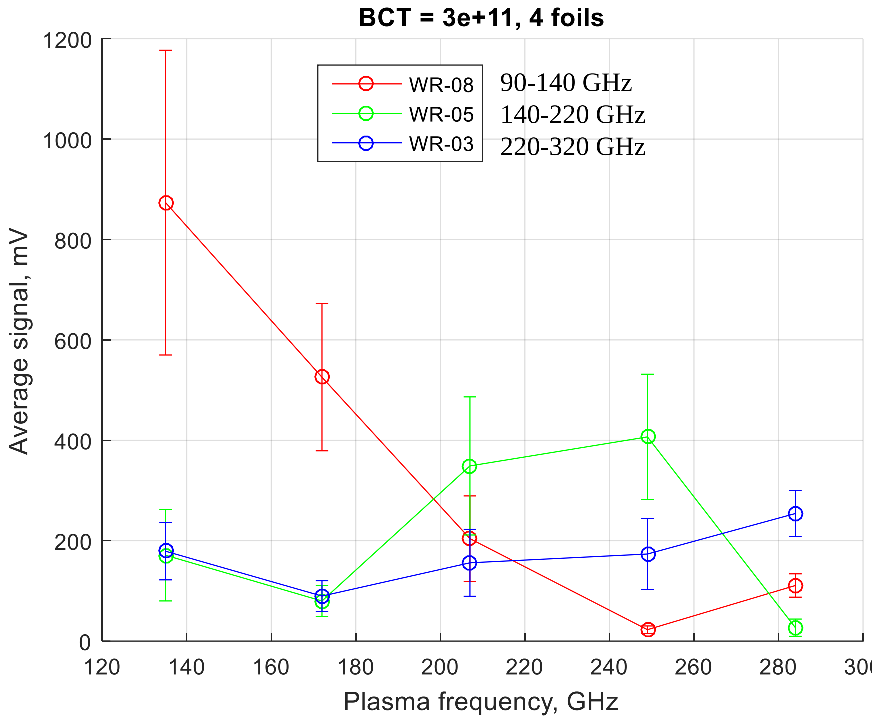
- **Bunch charge 2.5~3.5e+11**
- **Laser-proton delay 125ps (TiSa is in the 1st quarter of a proton bunch)**

Preliminary !!!

Raw WR's signal



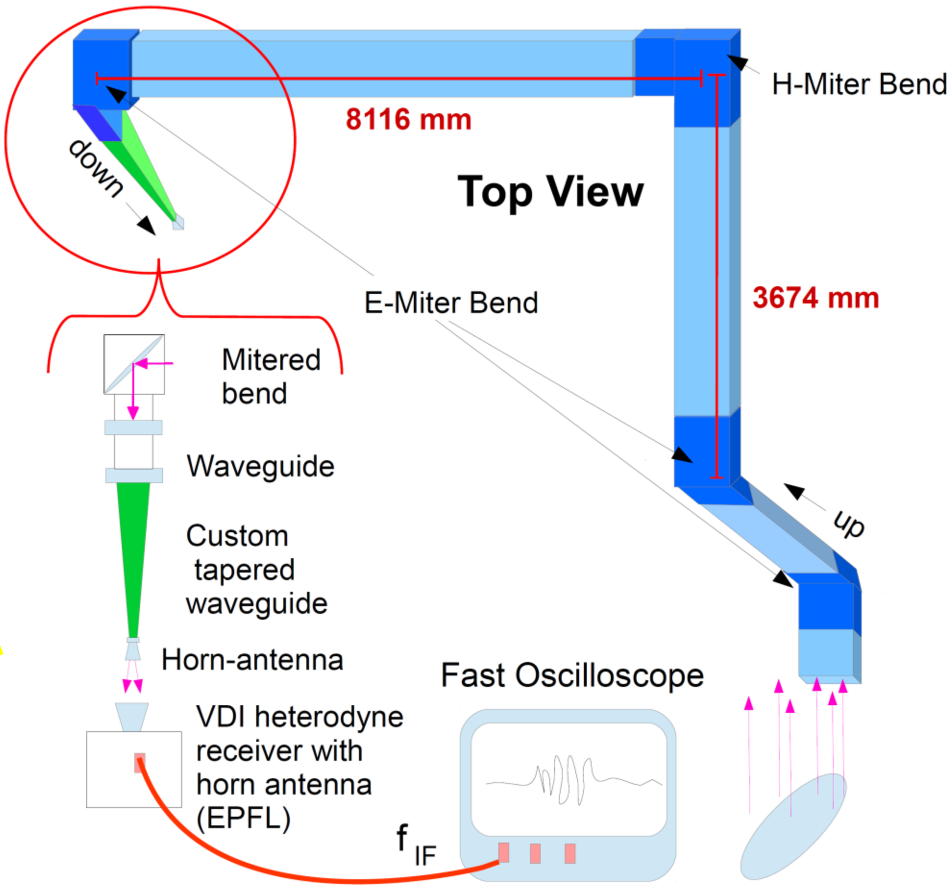
… and binned with a plasma frequency



CTR Diagnostics: waveguide transfer line

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

See Falk's talk today, next

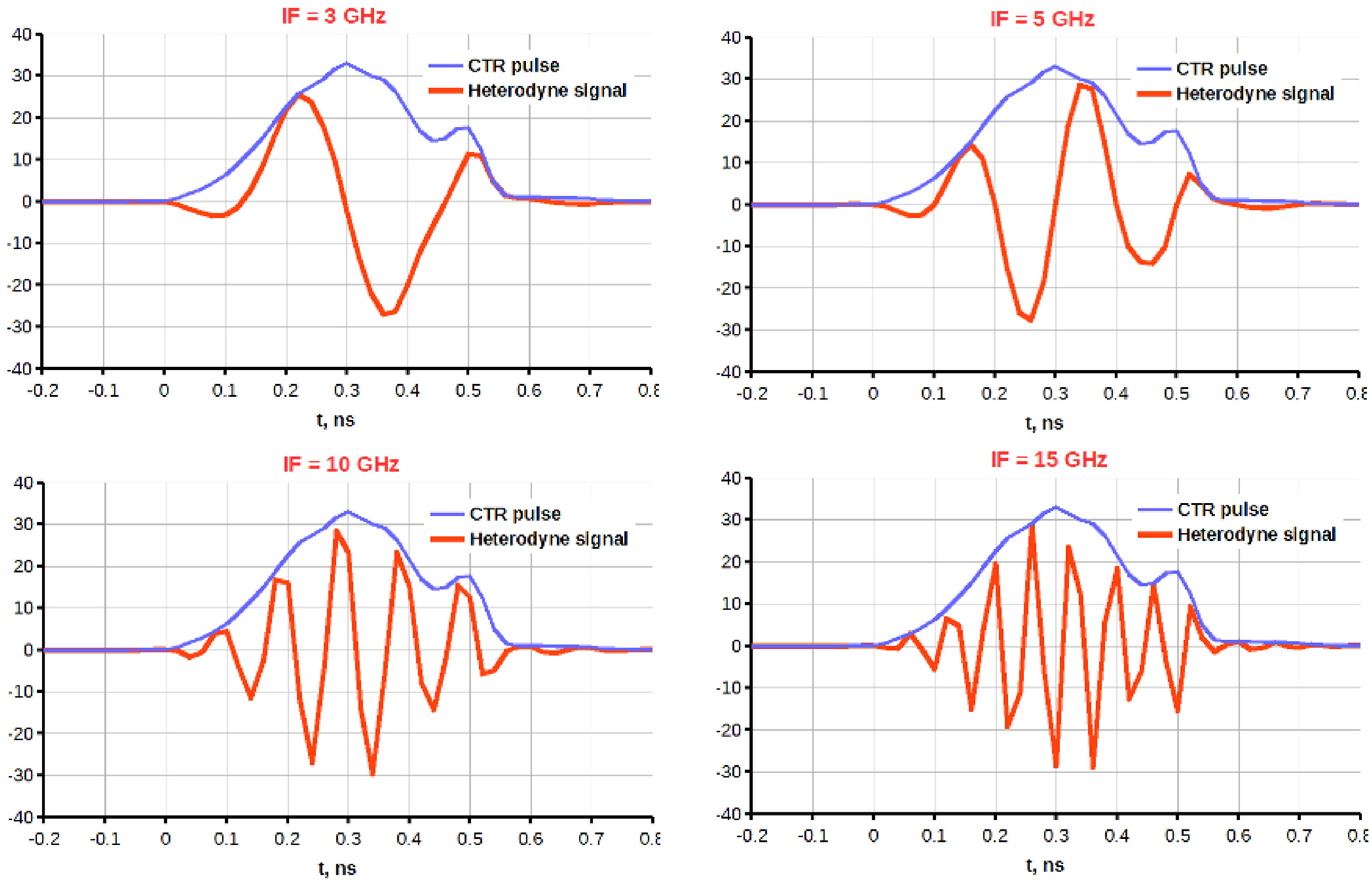


Courtesy of F. Braunmueller (MPP)

Heterodyne Measurement : bandwidth constraint

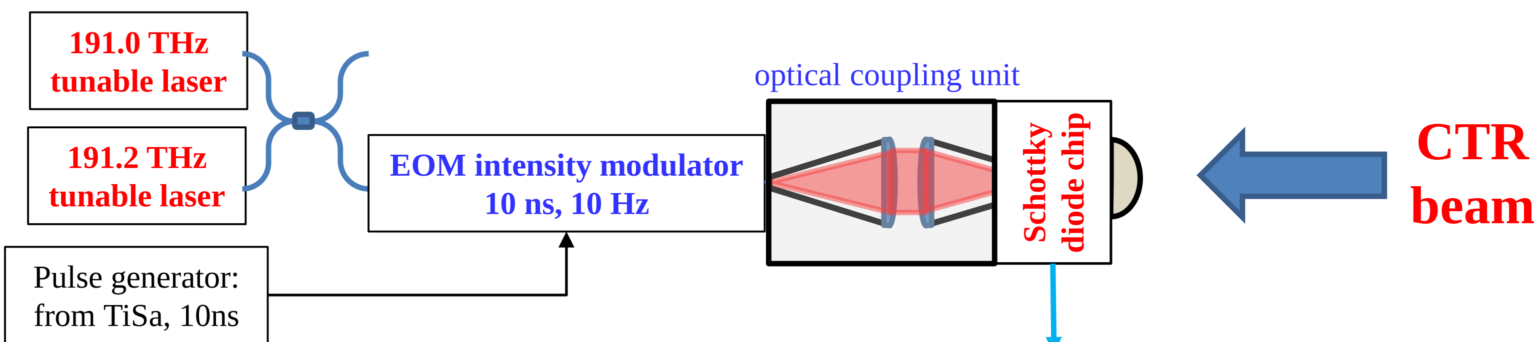
- **Intermediate frequency (IF) above ~10 GHz is amust for correct measurement**
- **Larger bandwidth of a detector facilitates search for apriori unknown CTR frequency**

Numerical example of heterodyne mixing with different IF



CTR Diagnostics: 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) - advantage**
- **Less sensitive (factor ~100) than conventional heterodyne receivers - disadvantage**



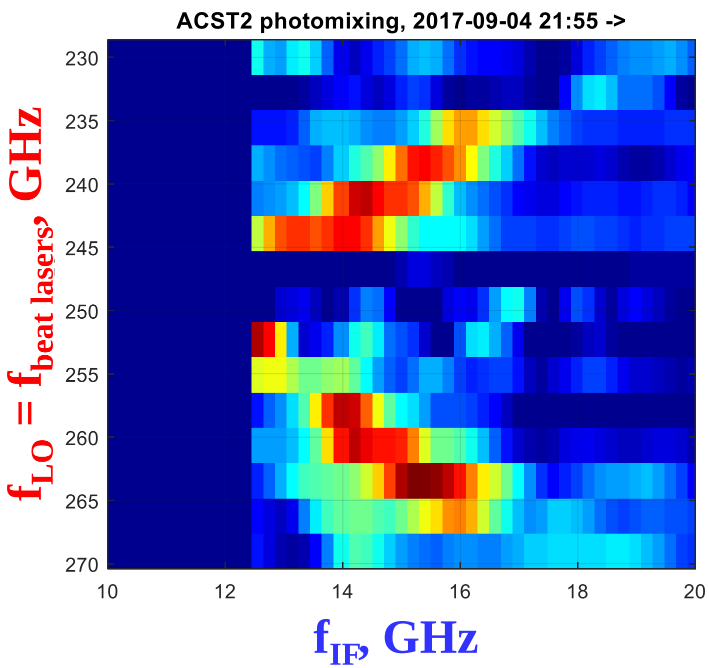
ACST Technology Solutions for Terahertz Electronics

CTR Diagnostics: Schottky photo-mixer

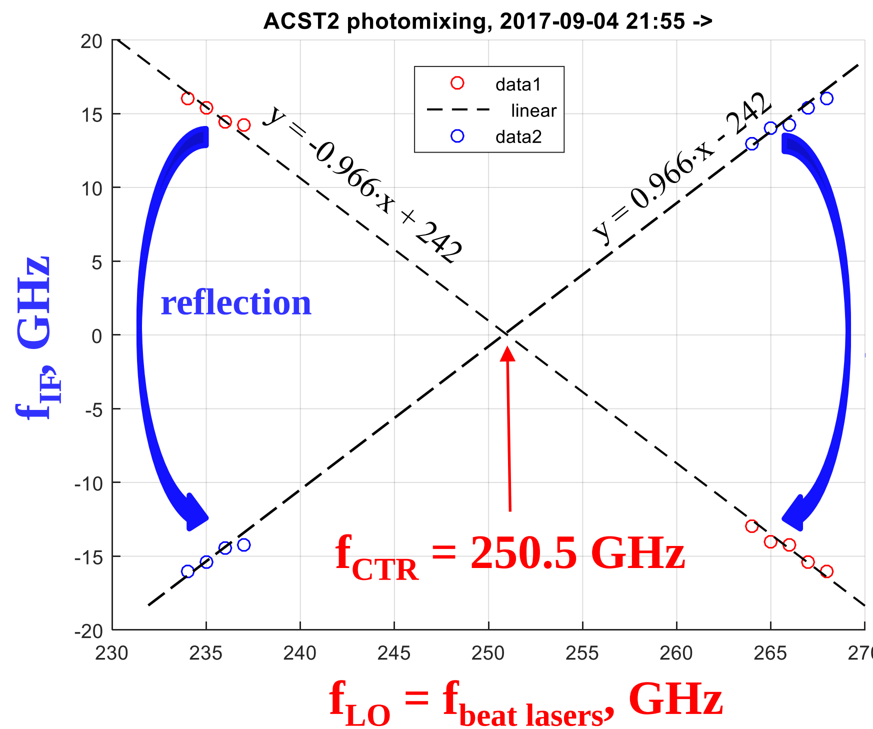
- **Given a low sensitivity of the photo-mixer, multiple events had to be accumulated for every LO frequency point**
- **Rb density 7.7·10^{14} cm^{-3}, plasma frequency f_p = 249.2 GHz**
- **Measured CTR carrier frequency is f_{CTR} = 250.5 GHz**

Preliminary !!!

ACST2 raw FFT signal



… and after processing



Summary (preliminary)

- We observed a strong CTR signal on all detectors on a plasma frequency as well as on its harmonics
- Signal scatter is large, no clear correlation revealed for now
- WR's detectors are not power-calibrated, difficult to interpret the data, further understanding is required
- ACST photo-mixer demonstrated a promising performance, however IF signal is pretty low. New hardware is on the way.
- Measured a CTR carrier frequency is in agreement with a frequency of OTR streak camera FFT and with a plasma frequency calculated from Rb density.
- Overall, CTR diagnostics might be in particular useful at higher Rb density, when streak-camera resolution drops down

Thank you!