Heterodyne measurement of Coherent Transition Radiation (CTR) from Seeded Self-Modulation (SSM) in AWAKE

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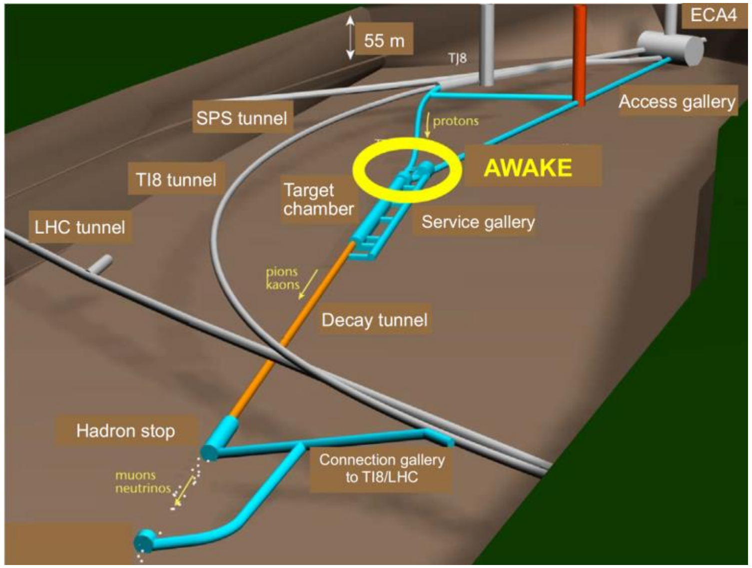

27 September 2017

3rd European Advanced Accelerator Concepts Workshop

Elba, Italy

Outline

- **Setup of heterodyne CTR-measurements**
- **Measurement principle**
- **Measurement processing**
- **Main result: $f_{CTR} = f_{plasma}(n_{Rb})$**
- **Further results: Dependence of SSM on Rb-density gradient**

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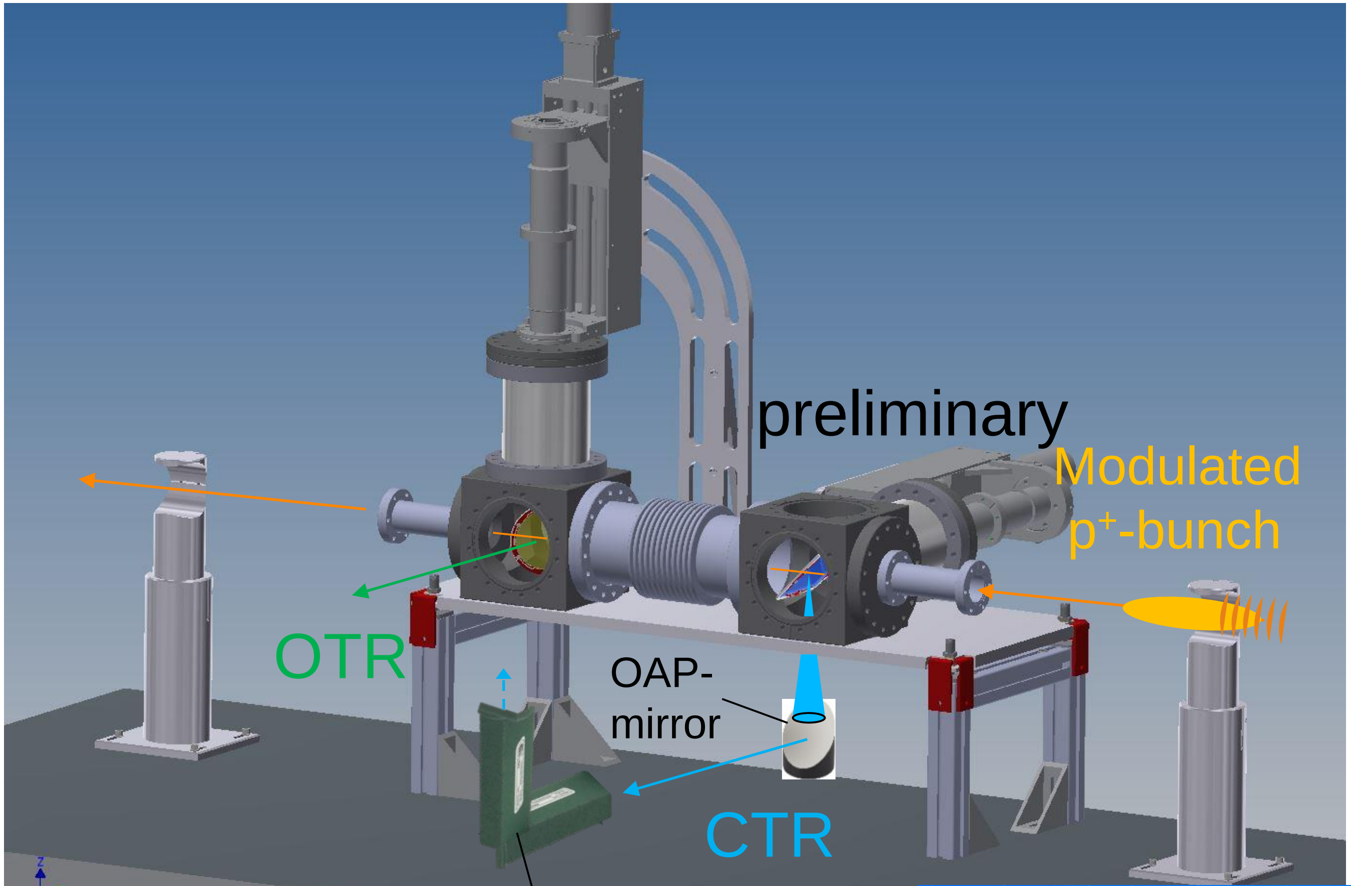
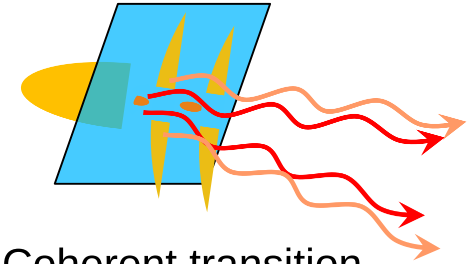
SSM-Diagnostics via CTR

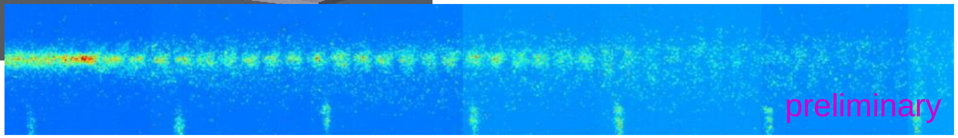


Courtesy: T.Haubold



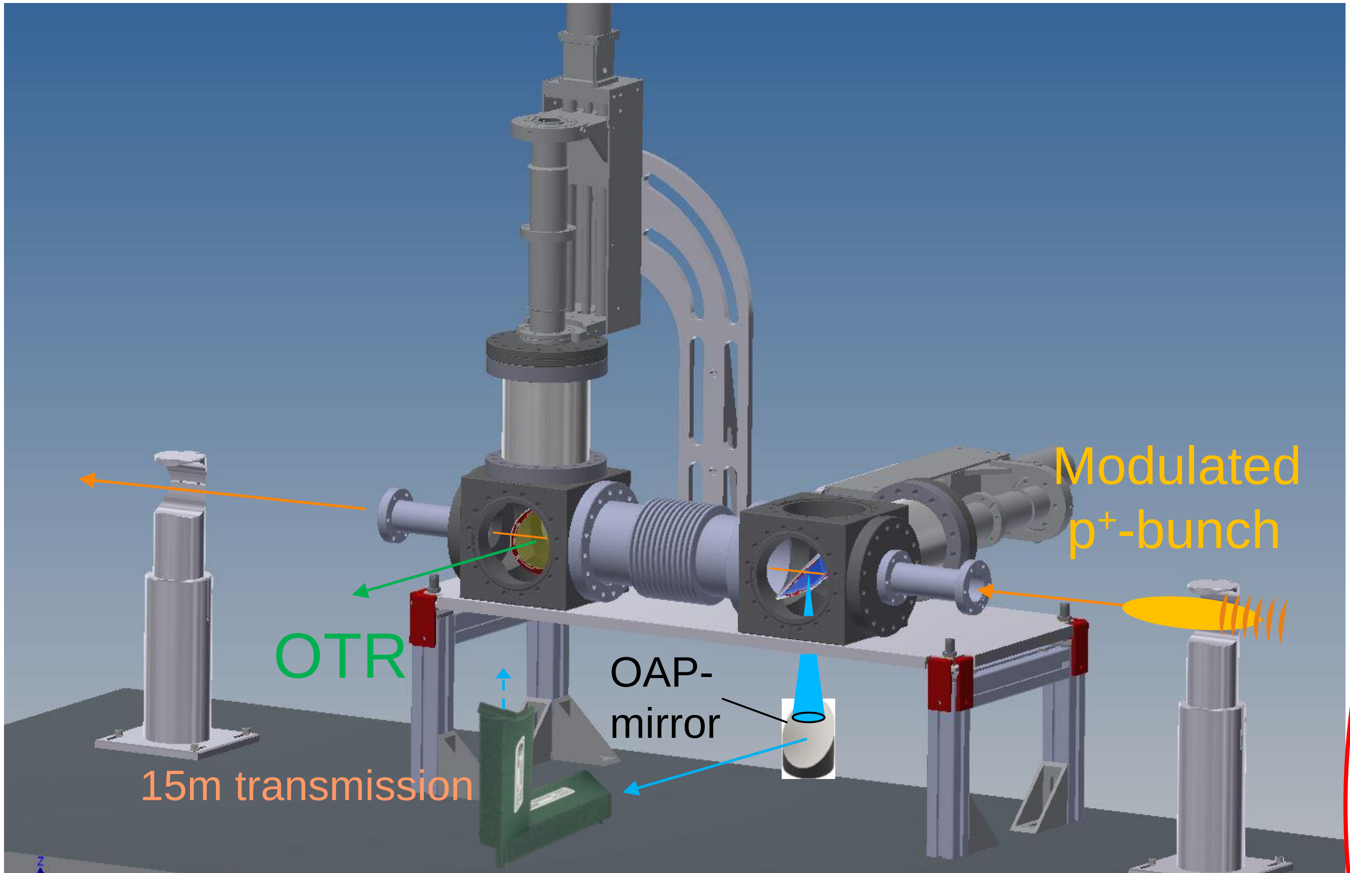
Coherent transition radiation @ $f_{modulation}$ (90-280GHz)

F. Batsch, Poster session 19:30



Coupled into WR90 waveguide →15m transmission

SSM-Diagnostics via CTR



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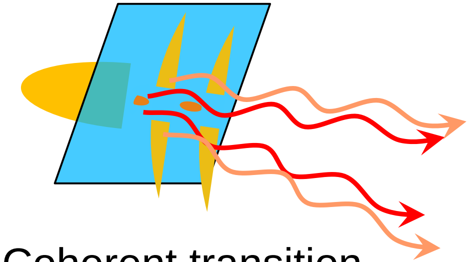
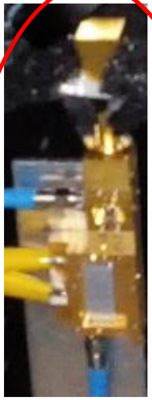
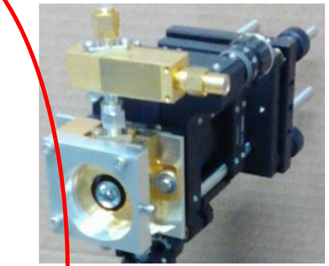


Coherent transition radiation @ $f_{modulation}$ (90-280GHz)

Frequency: Heterodyne mixing

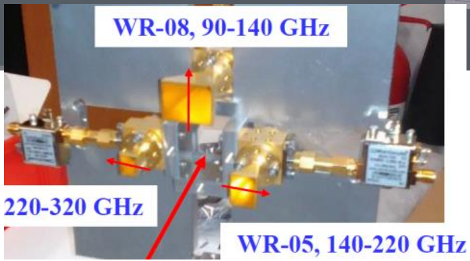




Laser-based

Waveguide-based

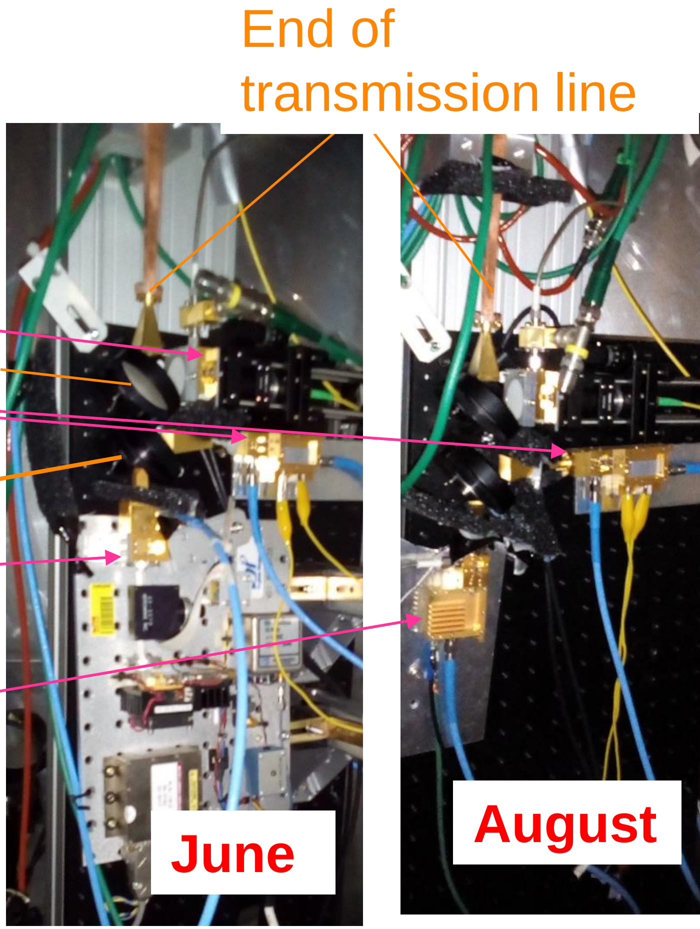
Amplitude: Schottky diodes



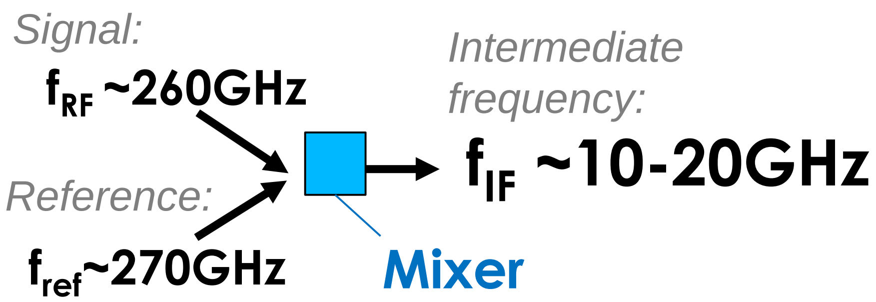
Diagnostic setup

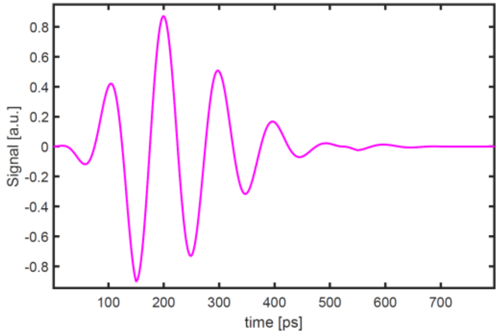
- **3 Heterodyne receivers for CTR:**
  - **Laser-based mixing** (last presentation)
  - **WR8 / 90-140GHz: Radiometer-system**$^{\text{new}}$
  - **WR3.4 / 255-270GHz: VDI-system from EPFL**

  ↳ **replaced by WR4.3/170-260GHz system**
- **Can detect 2nd harmonics of $f_{\text{modulation}}$**



Measurement principle




Expected signal (f_{IF}=10GHz)

- **f_{ref} from frequency-multiplication of tunable local oscillator**
  $f_{ref} = n_{harm} f_{LO}$

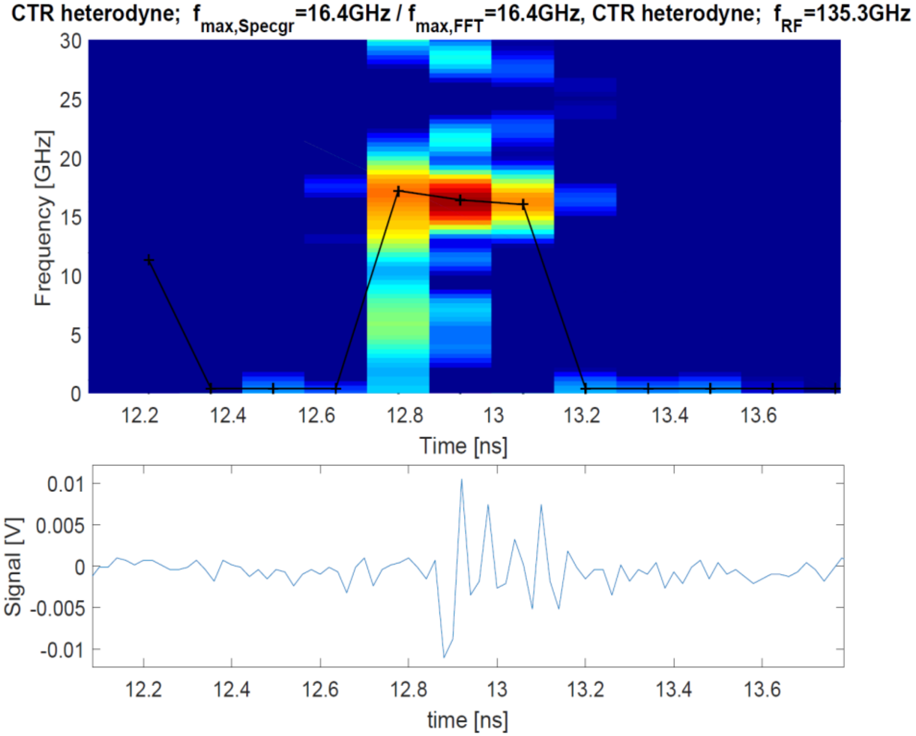
➔ **Also mixing with weaker parasitic reference frequencies**
$f_{ref} = n_{harm,1} f_{LO}$. **($n_{harm,1}= n_{harm}$ +/-1 , …)**

➔ **Confirm that signal on oscilloscope is from mixing with correct reference frequency:**

- $$\underbrace{f_{IF}}_{\text{measured}} = \left| \overset{\text{fix}}{f_{RF}} - \underbrace{n_{harm}}_{\text{to be determined}} \underbrace{f_{LO}}_{\text{setting}} \right|$$ ➔ $$n_{harm} = \Delta f_{IF} / \Delta f_{LO}$$

CTR-signal from mixer

- **Short signal, close to expected length**
- **Very precise**
- **Strong single-frequency-component (find via spectrogram)**
  → f_{IF}



Data-selection

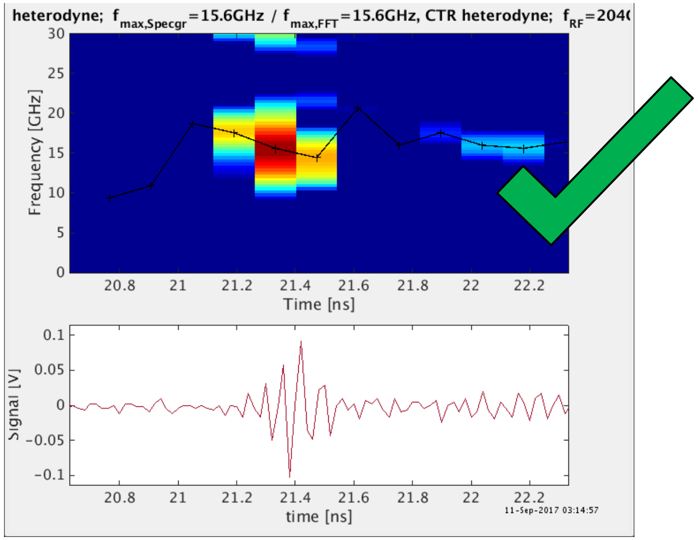
Choice of useful data:

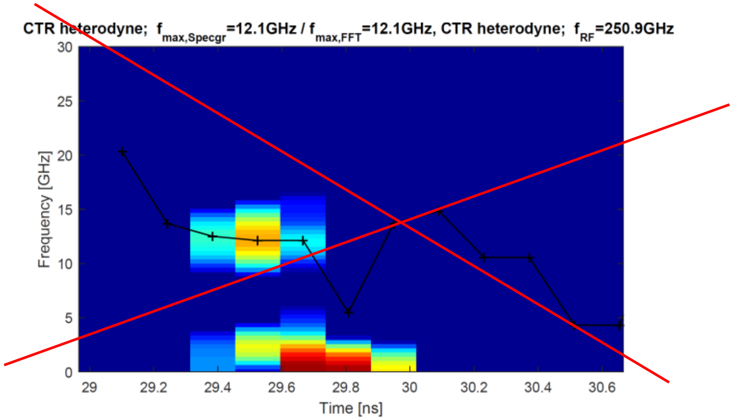
- **Signal level large enough, e.g. > 40mV**
- **Use only ‘prominent peaks’:**

  Significantly higher than other IF-peaks

Previously: selection ‘by eye’

(shot-to-shot variation of parameters)





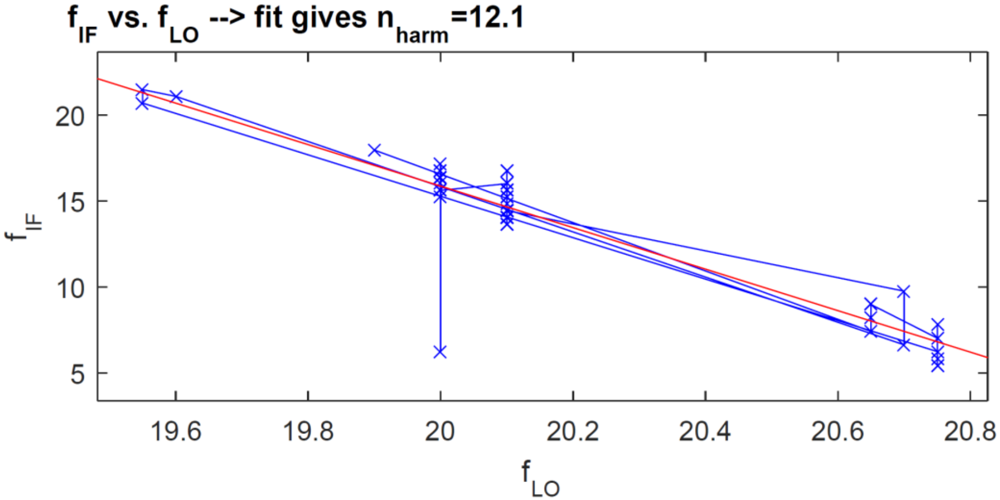
CTR-analysis

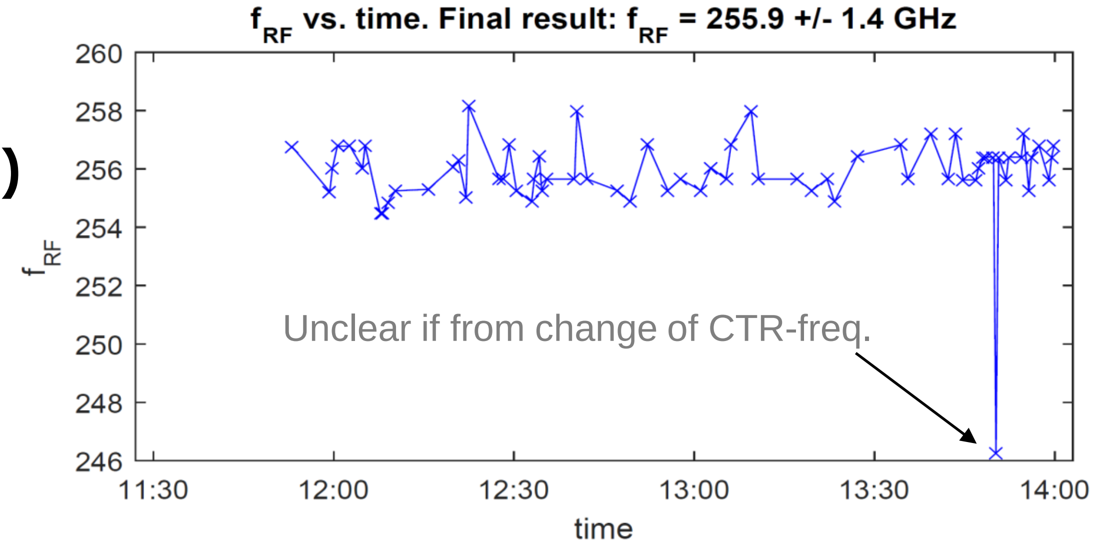
Fit f_{IF} vs. f_{LO} to check n_{harm}

→ In general, expected n_{harm} =8 / 12 / 24 is confirmed (sometimes ambiguous)

→ f_{RF} = n_{harm} f_{LO} +/– f_{IF}

→ Average & standard deviation of f_{RF} (here: 255.9GHz +/- 1.4GHz)





Unclear if from change of CTR-freq.

Results of CTR-analysis

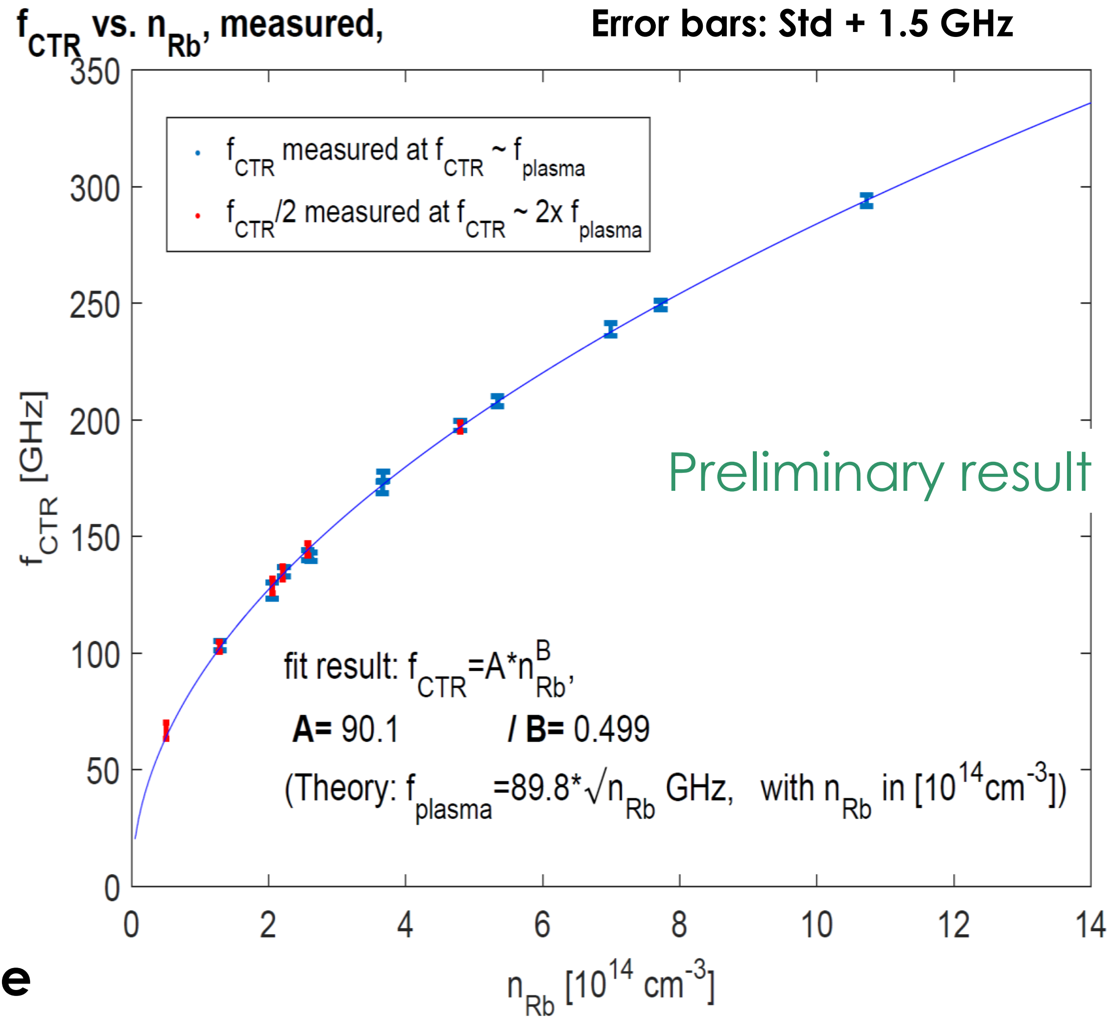
Result: f_{CTR} vs. n_{RB} ← vapour

$f_{CTR} = f_{plasma}(n_{Rb})$

- → **SSM with f_{CTR}=f_{plasma} as predicted**
- → **Rb fully ionized**
- **Good match between fundamental & 2nd harmonics**

→ **proof that correct $n_{harm}(f_{LO})$ was chosen**

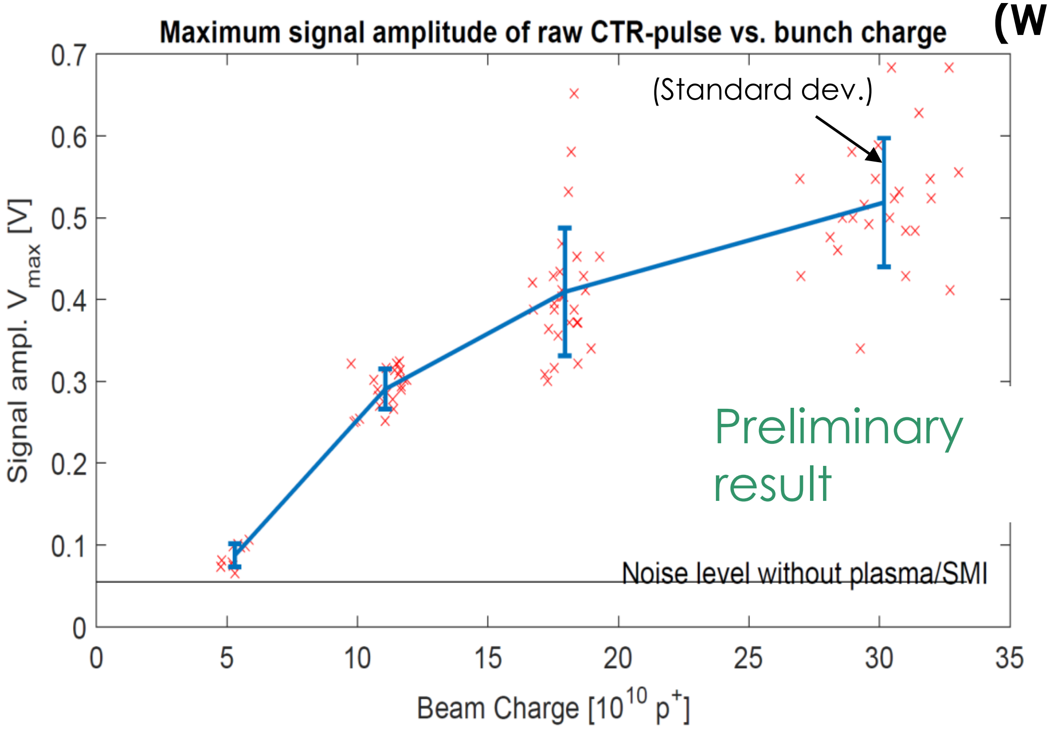
- **Excellent fit result: parameters within 0.3%**
- **Error analysis incomplete**


f_{CTR} vs. n_{Rb}, measured, Error bars: Std + 1.5 GHz

Preliminary result

fit result: $f_{CTR}=A*n_{Rb}^{B}$,
A= 90.1 / B= 0.499
(Theory: $f_{plasma}=89.8*\sqrt{n_{Rb}}$ GHz, with n_{Rb} in $[10^{14}cm^{-3}]$)

CTR-amplitude



(WR4-system)

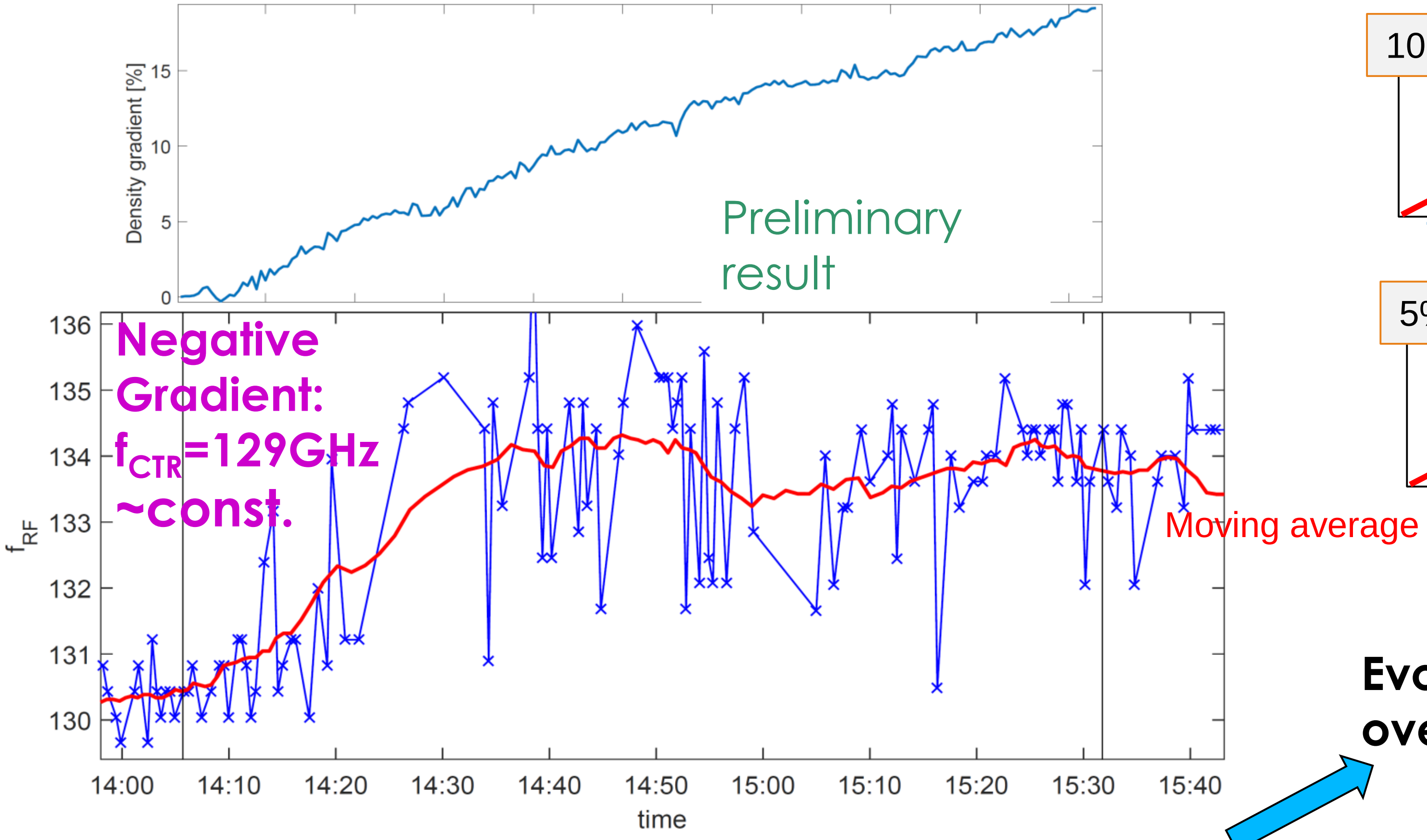
- **Amplitude increasing with beam-charge**

E_{CTR}~q, but:

  - **SSM-amplitude affected in nontrivial way**
  - **Emission angle & coupling may be affected**

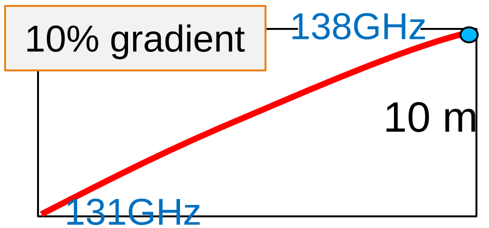
➔ Promising for future analysis

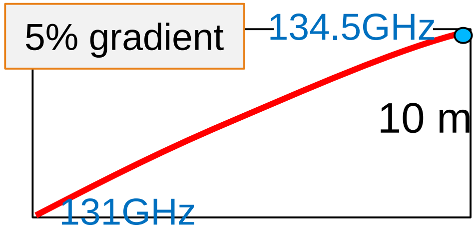
f_{CTR}-dependence on n_{Rb}-gradient



Preliminary result

Negative Gradient: f_{CTR}=129GHz ~const.



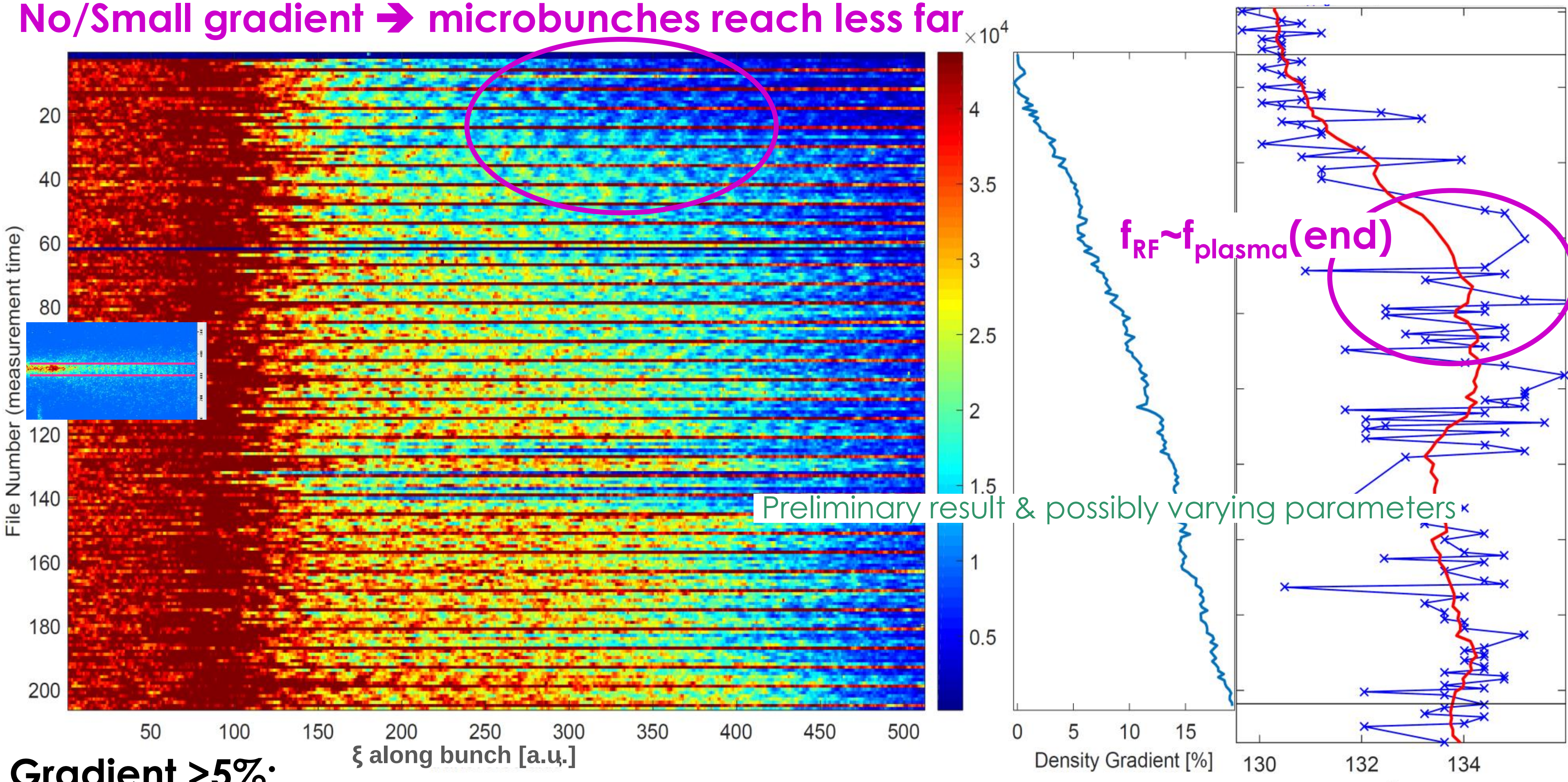


Evolving interaction over several meters!

- **Frequency increasing with positive gradient, but basically constant with negative gradient → Explanation from SSM?**

SSM-Dependence on n_{Rb}-gradient

No/Small gradient ➔ microbunches reach less far



f_{RF}~f_{plasma}(end)

Preliminary result & possibly varying parameters

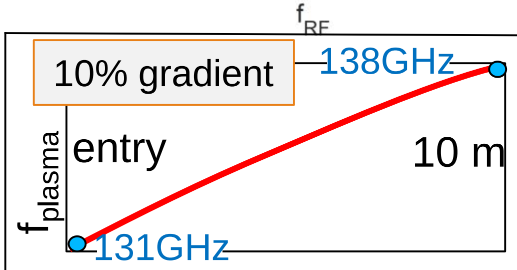
Gradient >5%:

- **Microbunches longer visible after seeding**
- **f_{RF} corresponds more to f_{plasma}(end)**

➔ longer interaction in plasma?

Negative Gradient:
f_{CTR}=129GHz≈const.

Check with simulations ?!



Summary

- **Several successful upgrades of heterodyne CTR setup**
- **Consistent results after data down-selection**
- **Very successful measurement of $f_{CTR}=f_{plasma}(n_{Rb})$, confirming full ionization + character of SSM**
- **Clear correlation between beam charge & signal amplitude**
- **Investigation of self-modulation physics:**
  - **$f_{CTR}=f_{plasma}(n_{Rb}, \text{downstream})$ for positive n_{Rb}-gradient**
  - **Longer persisting microbunches**

➔ longer interaction?

- **Analysis to be continued**

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Preliminary results

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Thanks for your attention!

Acknowledgement (255-275 GHz-system):
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Additional slides

Analysis/Measurement To-Do-List

- **Apply criterion of prominent peak to all points**

- **Analysis of signal amplitude: need to correlate with 'good shots' from streak camera & two-screen halo-BTV**

    - **Frequency-variations correlated with alignment/ angle of p^+-defocusing/… ?**

- **Ratio of signal amplitudes V(2^{nd} harmonics)/V(fundamental) vs. p^+ charge**

    - **idea: more non-linear → stronger 2^{nd} harmonics?**

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Measurement principle

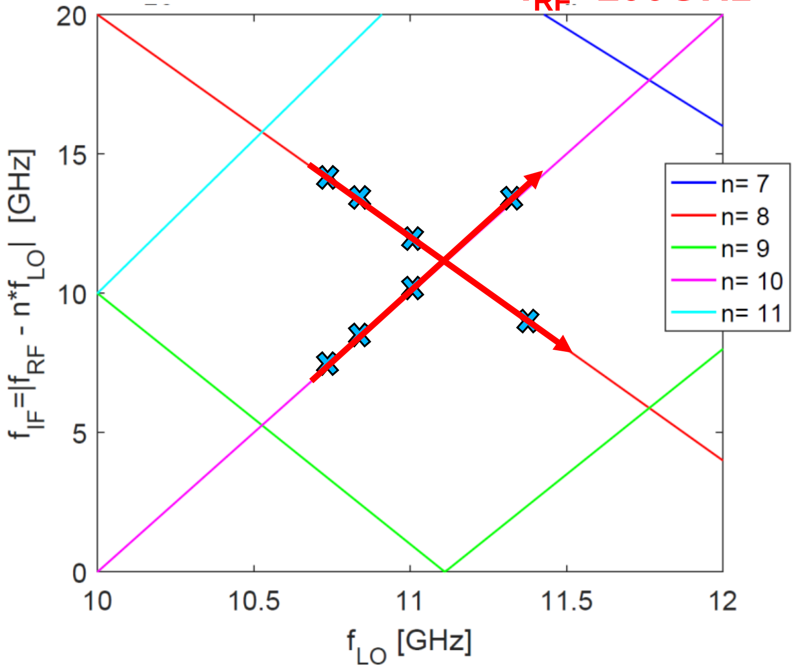
- $f_{RF} = n_{harm}\, f_{LO} \; +/- \; f_{IF}$

to be determined

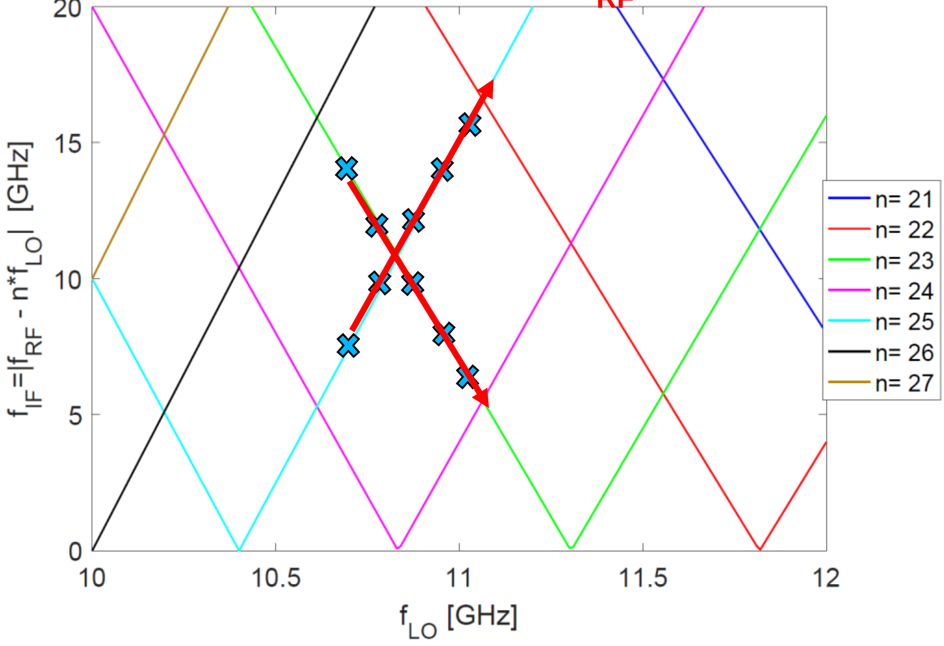
known

measured

f_{RF}=100GHz



f_{RF}=260GHz



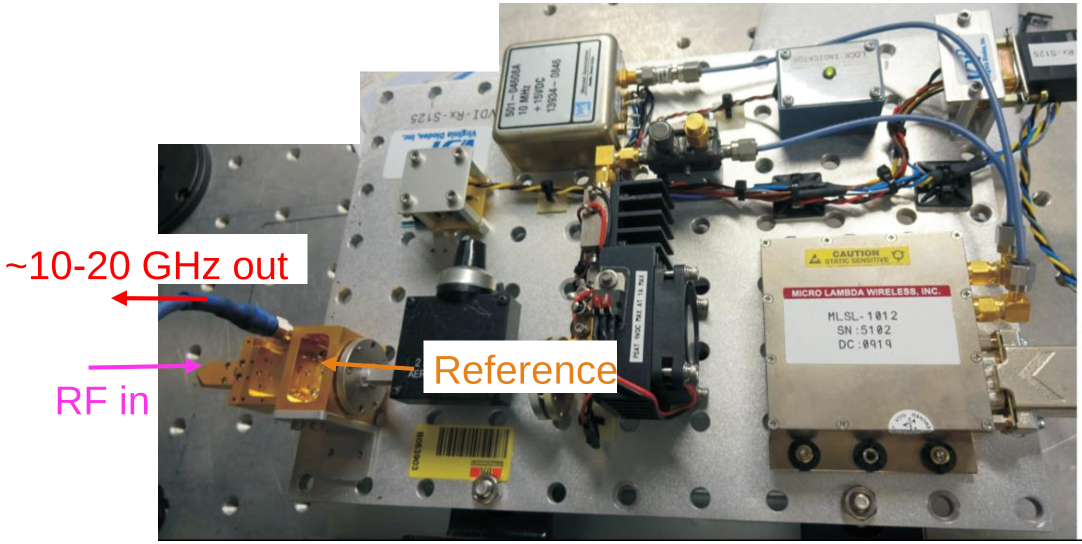
Find n_{harm} by scanning f_{LO}:

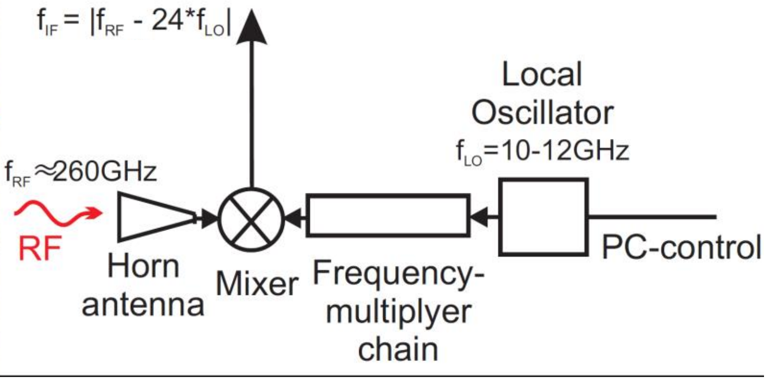
$$n_{harm} = \Delta f_{IF} \,/\, \Delta f_{LO}$$

Heterodyne Measurement

- **Measure intermediate frequency (IF) between CTR-signal (RF) and known reference**
- **Reference signal from frequency-multiplied tunable local oscillator (LO)**
- **Waveguide Transmission of RF over 15m**
- **Small measurement bandwidth**
- **Good signal efficiency**

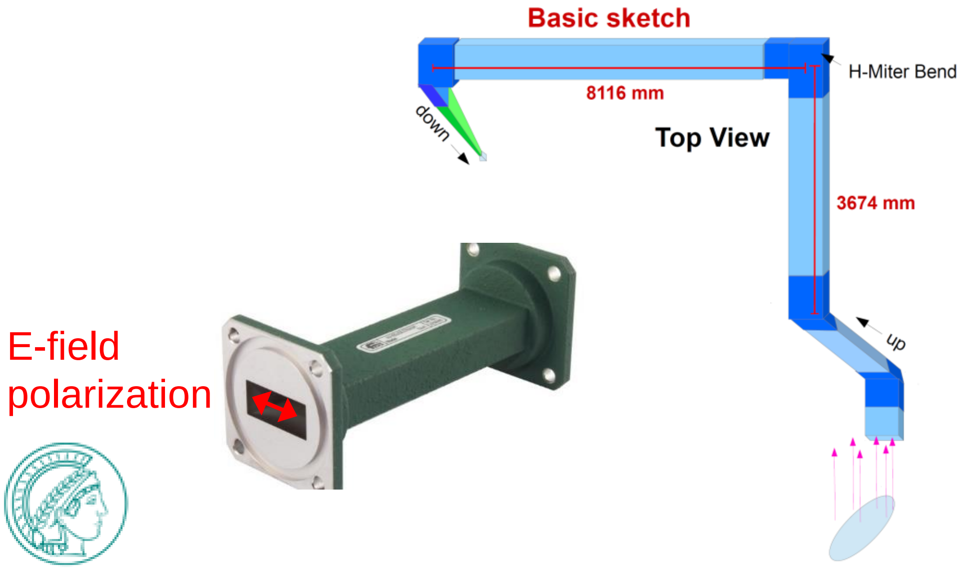
VDI heterodyne receiver from Swiss Plasma Center (SPC) at EPFL (Lausanne)

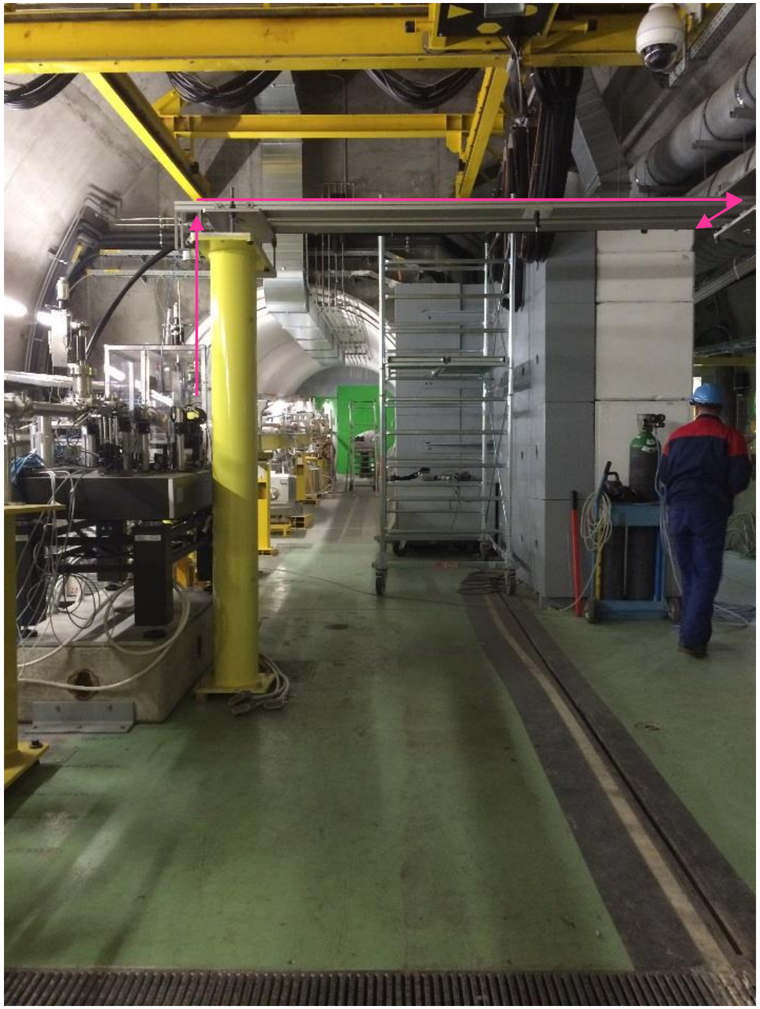




Waveguide Transmission Line

- **Detector behind shielding wall**
- **15m of overmoded waveguide WR90 (fundamental mode 8-12GHz)**



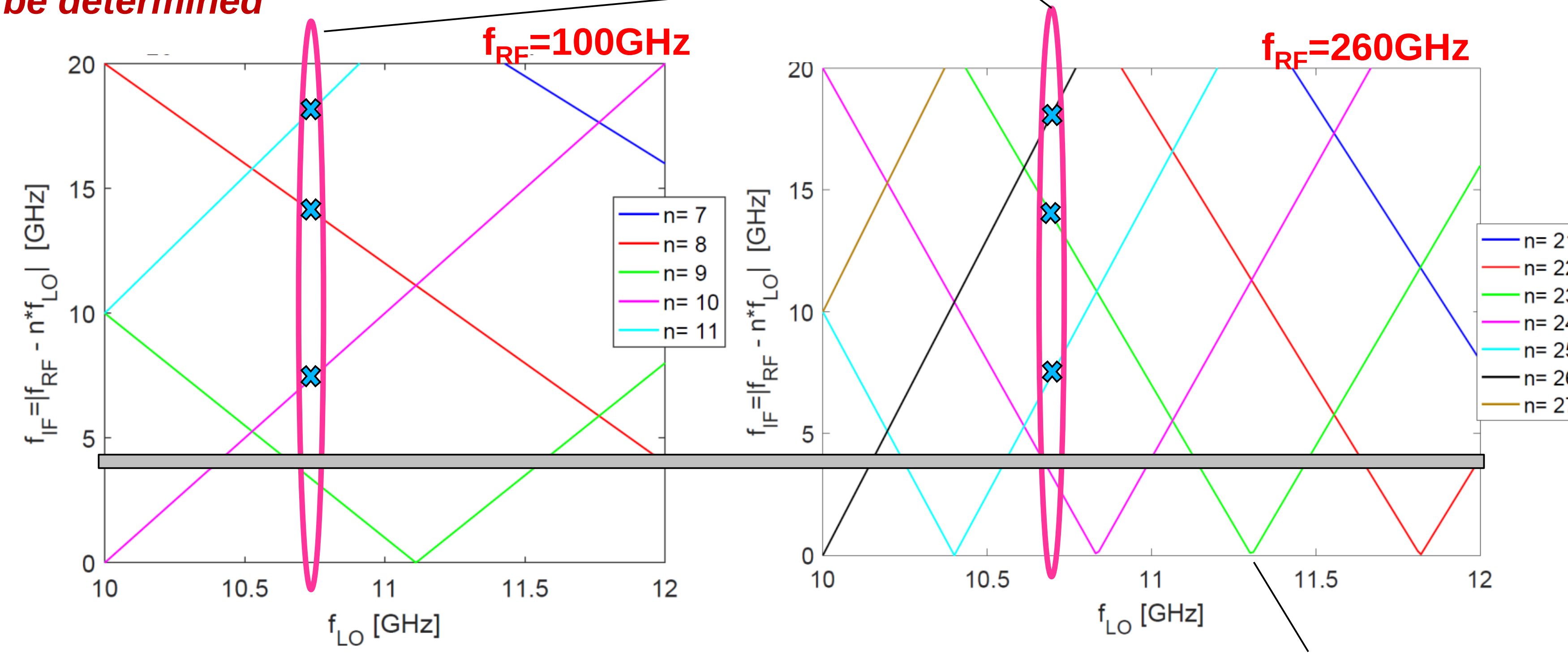


Measurement principle

- $f_{RF} = n_{harm} f_{LO}$ +/– f_{IF}

to be determined *known* *measured*

fixed f_{LO}



$n_{harm} f_{LO} = f_{RF}$

Single f_{RF} with fixed f_{LO} can give several f_{IF}-signals

➔ Signal frequency must be constant to within 1-2GHz!