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

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Outline

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

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

F. Batsch, Poster session 19:30

Coupled into WR90 waveguide \( \rightarrow \) 15m transmission

Courtesy: T. Haubold
SSM-Diagnostics via CTR

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

Frequency: Heterodyne mixing

Amplitude: Schottky diodes

Laser-based

Waveguide-based
Diagnostic setup

- 3 Heterodyne receivers for CTR:
  - Laser-based mixing (last presentation)
  - WR8 / 90-140GHz: Radiometer-system\textsuperscript{new}
  - WR3.4 / 255-270GHz: VDI-system from EPFL
    \(\Rightarrow\) replaced by WR4.3/170-260GHz system
- Can detect 2\textsuperscript{nd} harmonics of \(f_{\text{modulation}}\)
Measurement principle

Signal:
\[ f_{RF} \sim 260\text{GHz} \]
Reference:
\[ f_{ref} \sim 270\text{GHz} \]
Intermediate frequency:
\[ f_{IF} \sim 10\text{-}20\text{GHz} \]

- \( f_{ref} \) from frequency-multiplication of tunable local oscillator
  \[ f_{ref} = n_{\text{harm}} f_{LO} \]
- Also mixing with weaker parasitic reference frequencies
  \[ f_{ref} = n_{\text{harm},1} f_{LO} \cdot (n_{\text{harm},1} = n_{\text{harm}} +/\!/- 1, \ldots) \]
- Confirm that signal on oscilloscope is from mixing with correct reference frequency:

\[ \text{measured \ } \left| f_{IF} - n_{\text{harm}} f_{LO} \right| \]

\[ \Rightarrow \quad n_{\text{harm}} = \frac{\Delta f_{IF}}{\Delta f_{LO}} \]
CTR-signal from mixer

- Short signal, close to expected length
- Very precise
- Strong single-frequency-component (find via spectrogram) \( \rightarrow f_{IF} \)
Data-selection

Choice of useful data:

- Signal level large enough, e.g. > 40mV

- Use only ‘prominent peaks’:
  Significantly higher than other IF-peaks

(shot-to-shot variation of parameters)

Previously: selection ‘by eye’
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: \( f_{\text{CTR}} \) vs. \( n_{\text{RB}} \)

\[ f_{\text{CTR}} = f_{\text{plasma}}(n_{\text{RB}}) \]

\( \rightarrow \) SSM with \( f_{\text{CTR}} = f_{\text{plasma}} \) as predicted

\( \rightarrow \) Rb fully ionized

- Good match between fundamental & 2nd harmonics

\( \rightarrow \) proof that correct \( n_{\text{harm}}(f_{\text{LO}}) \) was chosen

- Excellent fit result: parameters within 0.3%

- Error analysis incomplete

Preliminary result

\[ \text{fit result: } f_{\text{CTR}} = A n_{\text{RB}}^B, \quad A = 90.1 \quad / \quad B = 0.499 \]

(Theory: \( f_{\text{plasma}} = 89.8 \sqrt{n_{\text{RB}}} \) GHz, with \( n_{\text{RB}} \) in \([10^{14} \text{ cm}^{-3}]) \)
CTR-amplitude

Amplitude increasing with beam-charge

\( E_{\text{CTR}} \sim q \), but:
- SSM-amplitude affected in nontrivial way
- Emission angle & coupling may be affected

\( \Rightarrow \) Promising for future analysis
$f_{\text{CTR}}$-dependence on $n_{\text{Rb}}$-gradient

- Frequency increasing with positive gradient, but basically constant with negative gradient
  → Explanation from SSM?
SSM-Dependence on $n_{\text{Rb}}$-gradient

No/Small gradient $\Rightarrow$ microbunches reach less far

Gradient >5%:
- Microbunches longer visible after seeding
- $f_{\text{RF}}$ corresponds more to $f_{\text{plasma}}(\text{end})$
$\Rightarrow$ longer interaction in plasma?

Negative Gradient:
$f_{\text{CTR}} = 129\text{GHz} \approx \text{const.}$

Check with simulations ?!

Preliminary result & possibly varying parameters
Summary

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

Preliminary results
Thanks for your attention!

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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 \( V(2^{\text{nd}} \text{harmonics})/V(\text{fundamental}) \) vs. p⁺ charge 
  • idea: more non-linear \( \rightarrow \) stronger 2\(^{\text{nd}}\) harmonics?
Measurement principle

- \( f_{RF} = n_{harm} f_{LO} +/− f_{IF} \)
  - known
  - measured

To be determined

Find \( n_{harm} \) by scanning \( f_{LO} \):

\[
n_{harm} = \frac{\Delta f_{IF}}{\Delta f_{LO}}
\]
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

- \( f_{RF} = n_{harm} f_{LO} \pm f_{IF} \)

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

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