8th ITG International Vacuum Electronics Workshop

Passive Mode-Locking of Two Helical-Type Gyro-TWTs at sub-THz Frequencies

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Structure

- Motivation
- Passive Mode-Locking
- Helical Gyro-TWTs
- Feedback System
- Passive Mode-Locking of Coupled Helical Gyro-TWTs
- Universal sub-THz Source
- Conclusion

Motivation

- Advanced spectroscopy methods combining Nuclear Magnetic Resonance (NMR) and Electron Spin Resonance (ESR)

→ Microwave radiation at Larmor frequency

- **State of the art**: CW microwave radiation
  - E.g. Dynamic Nuclear Polarization (DNP) NMR
- **Future**: Pulsed methods
  - Pulses shorter than the relaxation time (sub-ns)
  - High power (>100 W)
  - Coherent pulses

→ New source of coherent high-power microwave pulses

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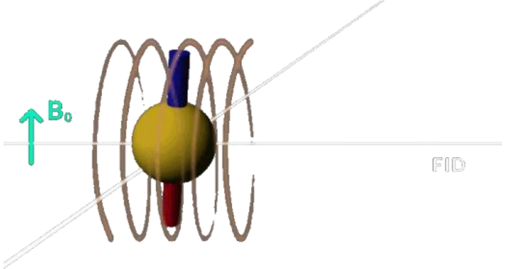
400 MHz NMR in 9.4 T magnet
→ **263 GHz microwave radiation**

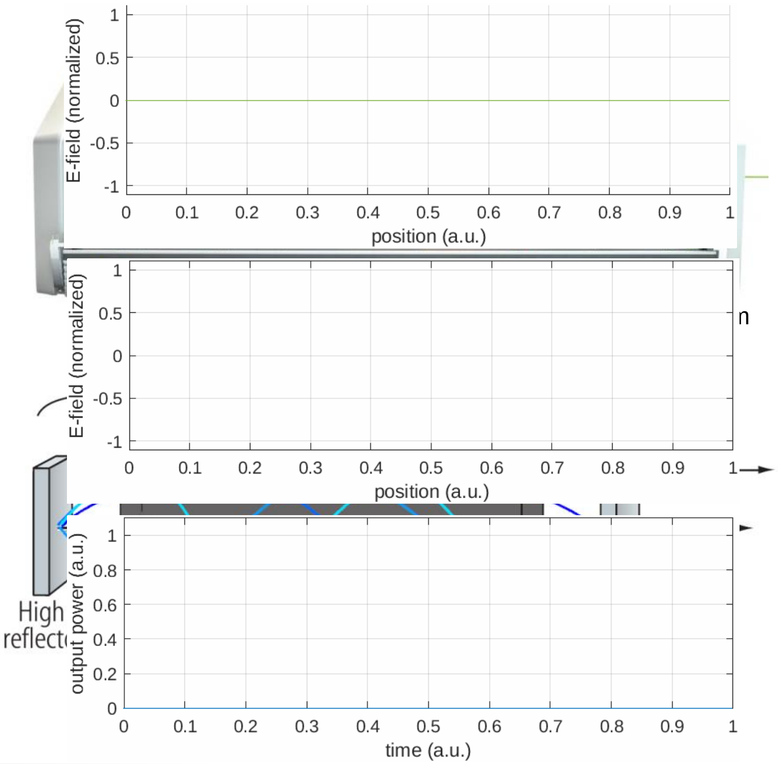


Passive Mode-Locking

- Well known source of ultra-short coherent pulses: **Passive mode-locked lasers**[1]
- E.g.: Ti:sapphire laser:
  <100 fs pulses at $\lambda \approx 1000$ nm (300 THz)
- **Principle**: Synchronization of longitudinal cavity modes
- Electric field is a superposition of all longitudinal modes

$$E(t) = \sum_n a_n \cos(\omega_n t + \phi_n)$$

How to synchronize the longitudinal cavity modes?

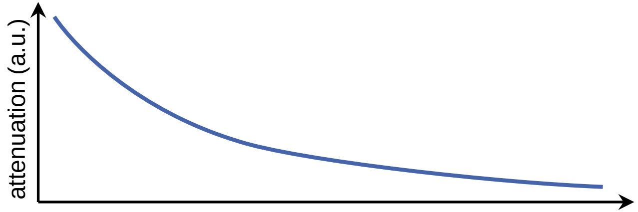


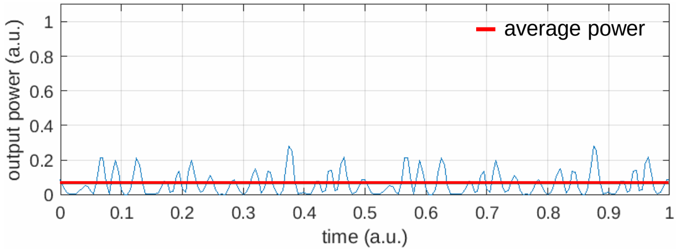
Passive Mode-Locking

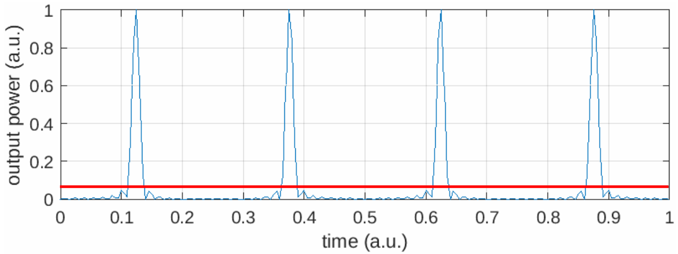
Comparison of free-running and synchronized laser:

- Same average output power
- Higher peak-power for PML laser

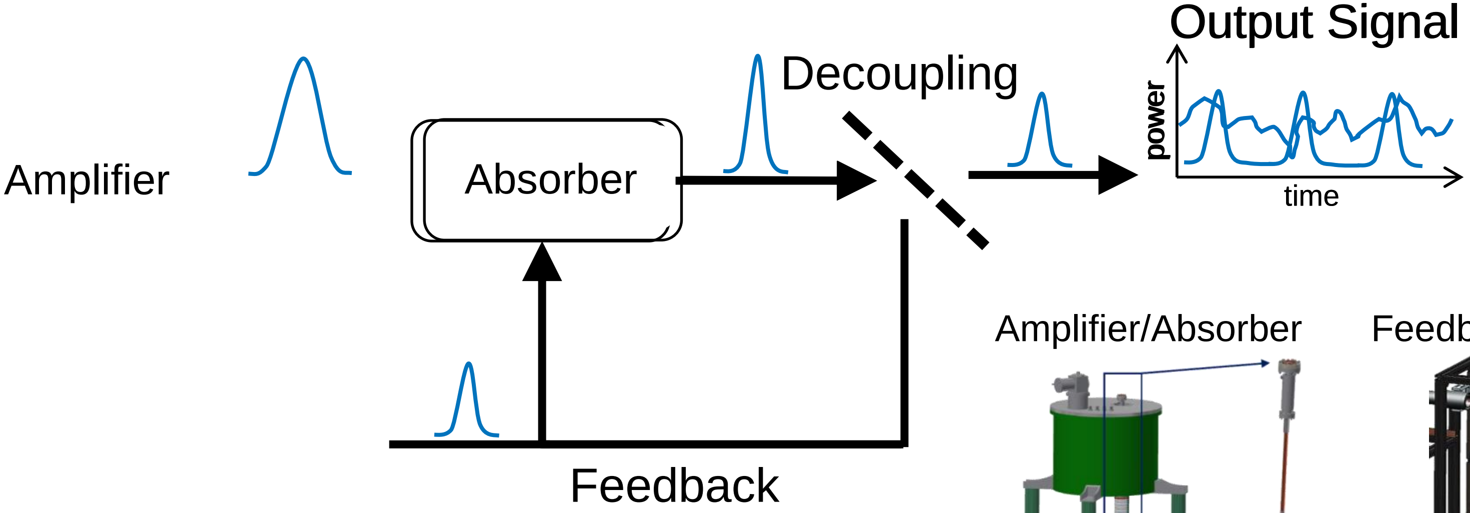
Non-linear losses to favor synchronized modes

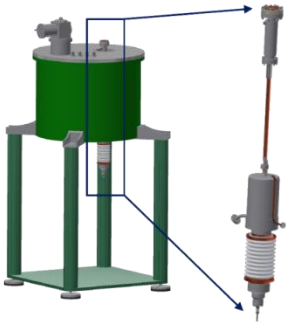




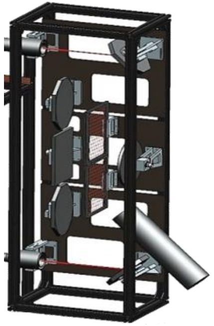


Passive Mode-Locking at Microwave Frequencies





C. R. Donaldson, et. al., *21st International Conference on Vacuum Electronics (IVEC)*, 2020, pp. 103-104,



N. S. Ginzburg, et al. *20st International Conference on Vacuum Electronics (IVEC)*. IEEE, 2019.

PML at 263 GHz:

⇨ Electron tubes for amplifier and saturable absorber

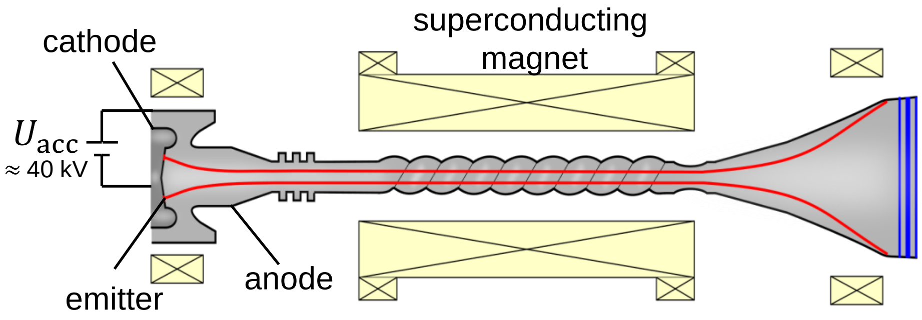
⇨ Quasi-optical feedback system

System Requirements for Amplifier/Absorber

Requirements:

- High-power operation (>100 W)
- Short pulses (<0.1 ns)
  → broad bandwidth
- Sub-THz frequencies (263 GHz)
- Operated as absorber
- High-power feedback

→ Helical Gyro-TWT[1]

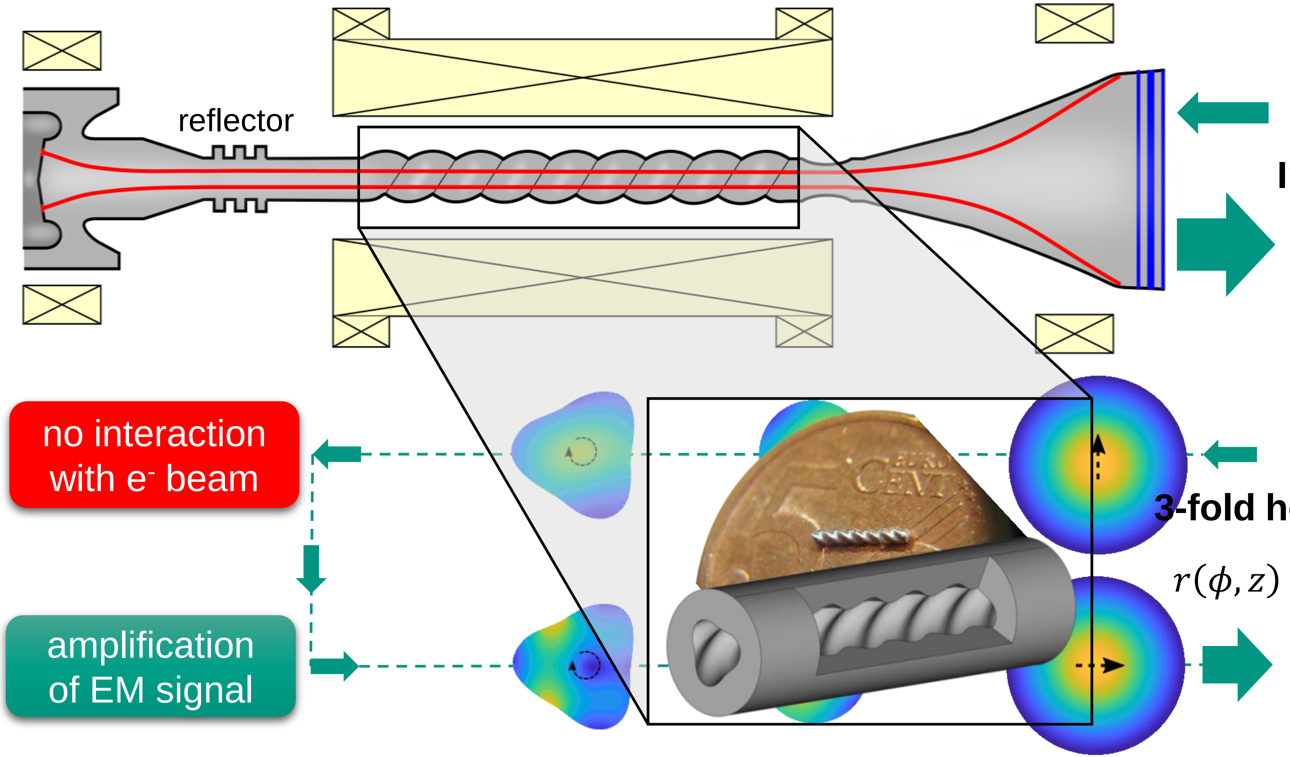


Unique features:

- Beam-wave interaction at the 2nd cyclotron harmonic
- High stability against parasitics
- I/O through a single window

[1] G. Denisov, et al. *IEEE transactions on plasma science* 26.3 (1998): 508-518.

Helical Gyro-TWT: Input / Output



Interface: Single window for I/O

Input
$HE_{1,1}$ mode vertically polarized

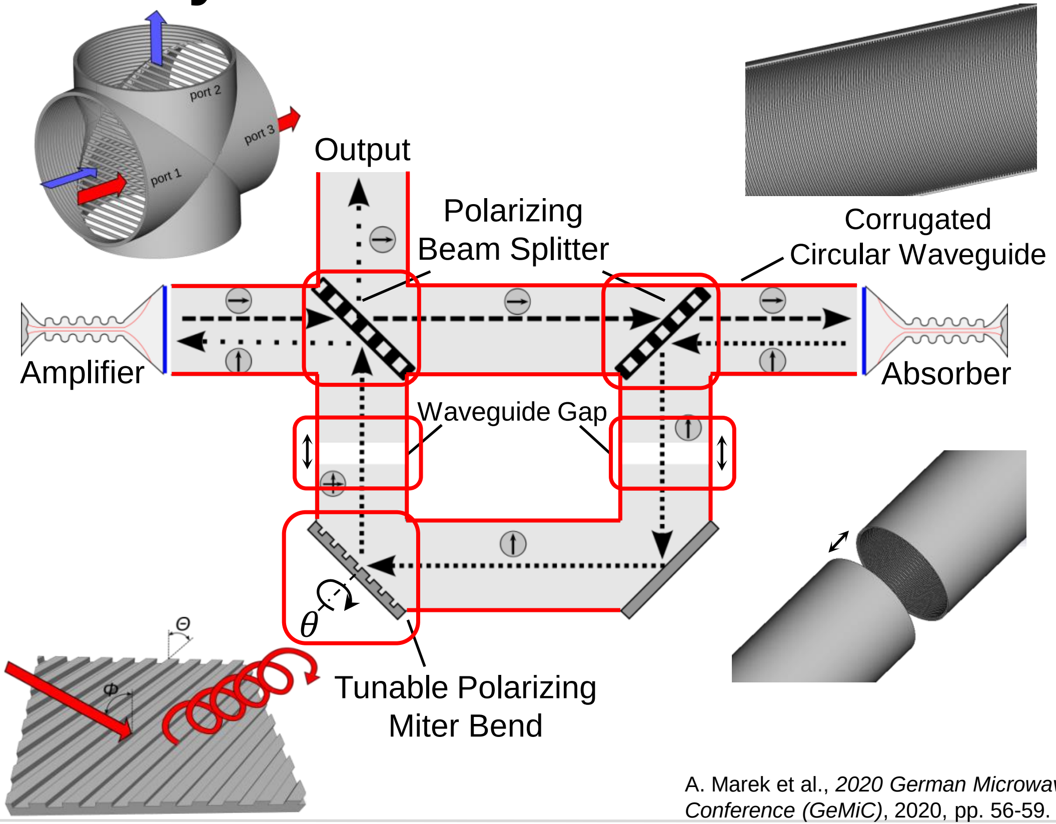
3-fold helical interaction space

$$r(\phi, z) = R + \tilde{r}\cos(3\,\phi - \frac{2\pi}{\tilde{d}})$$

Output
$HE_{1,1}$ mode horizontally polarized

Transmission Line Feedback-System

- High power capability (2000 W)
- Low ohmic losses (<-24 dB/m)
- Tunable delay time (± 0.1 ns)
- Variable power extraction (0 – 70 %)
- Simple alignment of all components



A. Marek et al., *2020 German Microwave Conference (GeMiC)*, 2020, pp. 56-59.

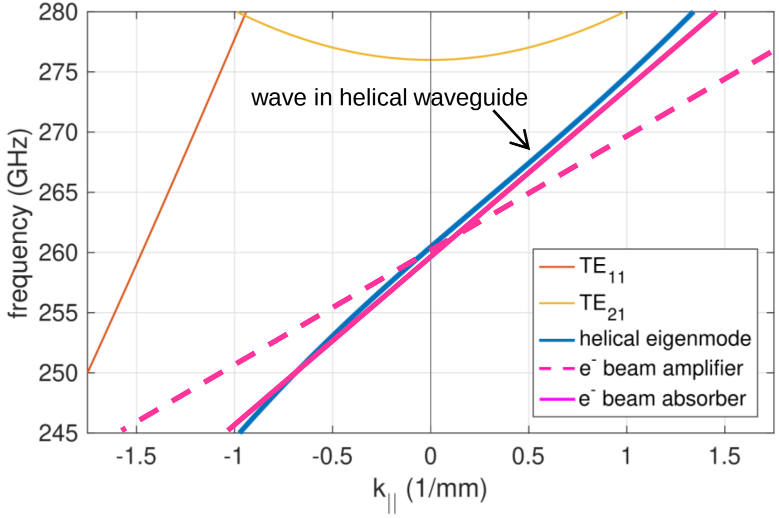
Design Tools and Principles for Amplifier/Absorber

- **Novel simulation tool** *SimpleRick* for the beam-wave interaction simulation[1]
  - Combines coupled modes and 3D PIC
  - **Significantly faster** than e.g. CST MS (speed-up ≈10×)
  - Simulation of **sub-ns phenomena**
- Design principle:
  - Similar interaction space for amplifier and absorber
  - Operation regimes realized by different beam parameters

➡ Alternative regimes of operation

Helical waveguide:

$R = 0.58$ mm; $\tilde{r} = 0.08$ mm; $\tilde{d} = 1.11$ mm



[1]A. Marek *et al*., in *IEEE Transactions on Electron Devices*, 2022, doi: 10.1109/TED.2022.3182292.

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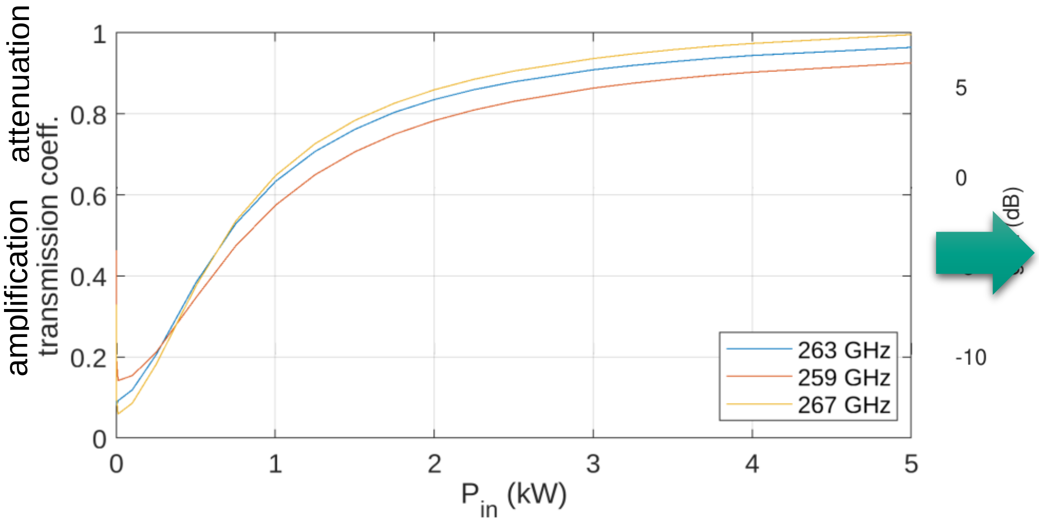
Design Approach: Saturable Absorber



Optimal saturation by over bunching effects

Electron beam amplifier:

$E_{\mathrm{kin}} = 30$ keV; $\alpha = {}^{v_\perp}/_{v_\parallel} = 1.3$; $I = 0.25$ A

$B_0 = 4.91$ T

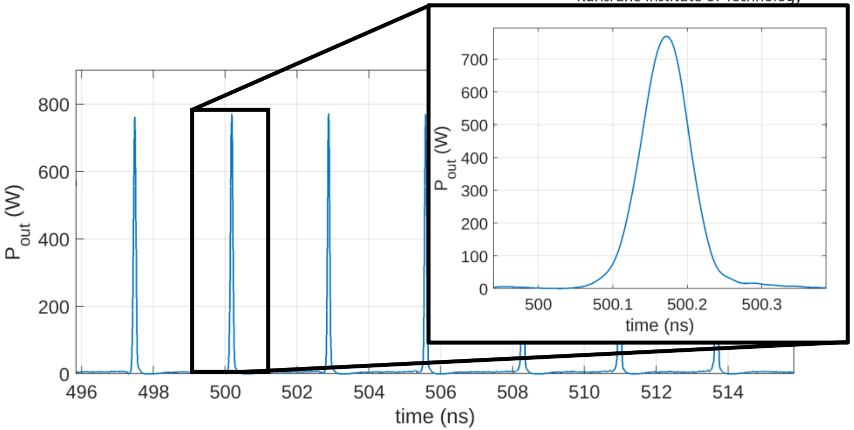
Electron beam absorber:

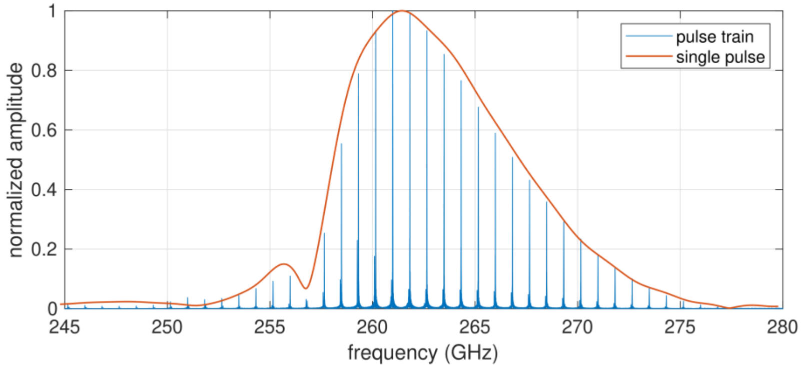
$E_{\mathrm{kin}} = 40$ keV; $\alpha = {}^{v_\perp}/_{v_{||}} = 0.8$; $I = 0.2$ A

$B_0 = 5.045$ T

PML System Design

- Study of PML at 263 GHz
- Results:
  - Peak power $P_{\mathrm{out}} = 750 - 1400$ W
  - Pulse length $\tau_{\mathrm{p}} = 0.075 - 0.110$ ns
  - PRF, max $f_{\mathrm{r}} = 1.12$ GHz
  - Spectral centroid $f_0 = 262.9$ GHz
  - Distance spectral lines $\Delta f = f_{\mathrm{r}}$





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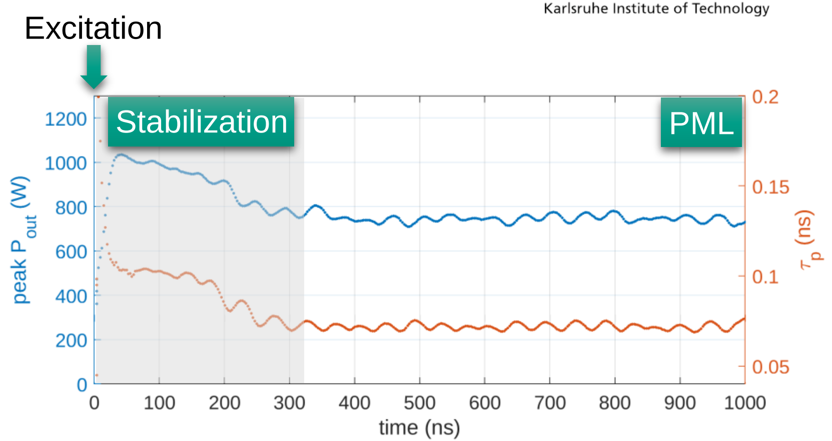
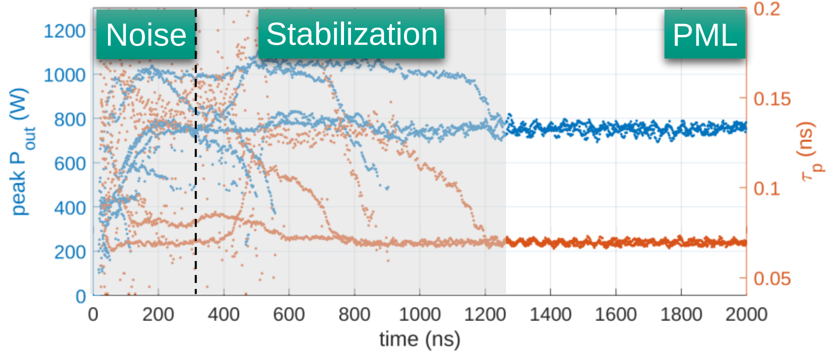
Possibilities for PML Start-up

- Hard excitation:
  - Start-up by external signal
  - High-power signal required (100 W)
  - Single pulse in the feedback system



- Soft excitation:
  - Start-up from noise
  - No external signal required
  - Several pulses in the feedback system



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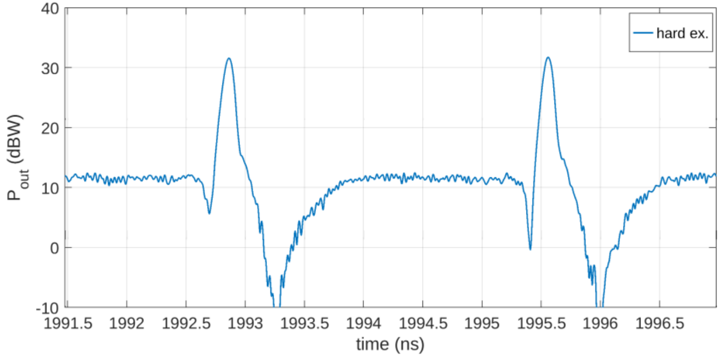

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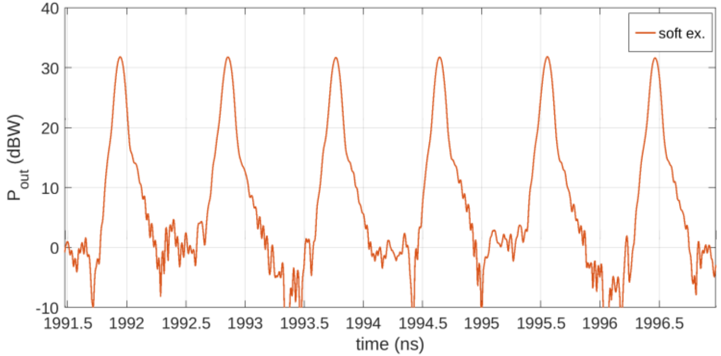
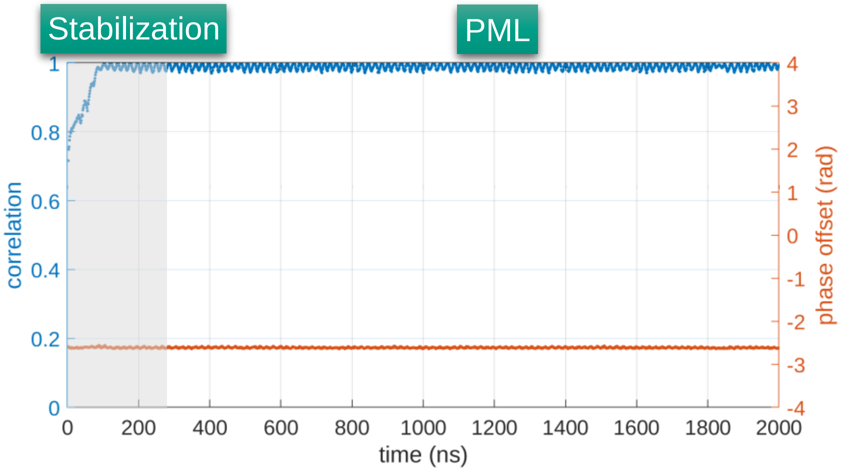


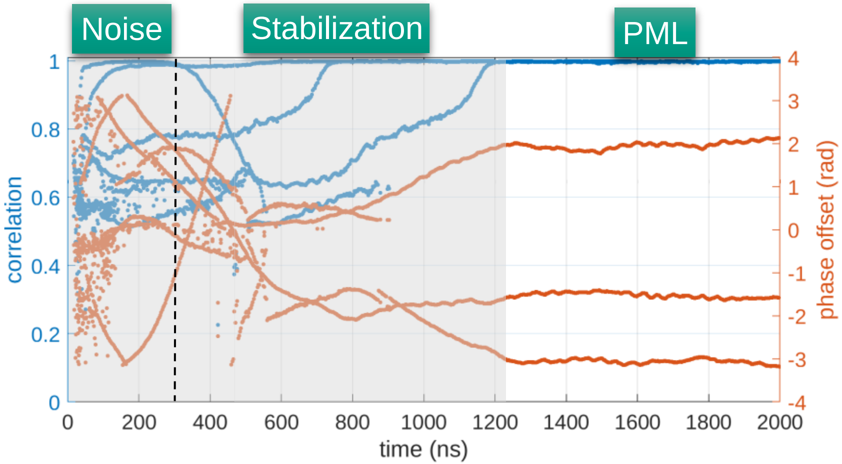
Coherence in Soft and Hard Excitation

Hard Excitation



- Excitation by high-power pulse
- ➡ Single pulse
- ➡ Fixed phase relation

Soft Excitation



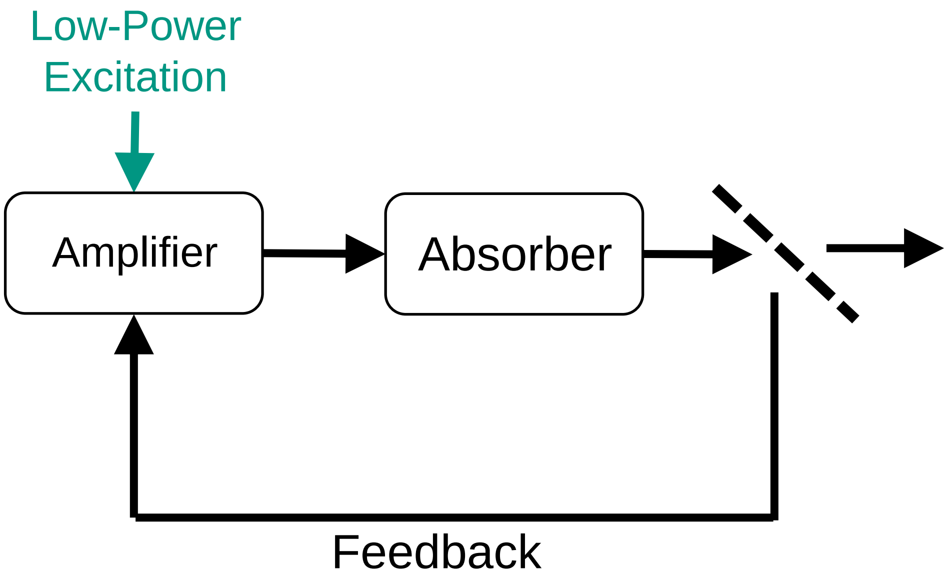
- Pulse formation from noise
- ➡ Multiple pulses
- ➡ Arbitrary phase offset between pulses

New Possibility for Operation in Hard Excitation

Requirements:

- Additional input port
- High gain
- Strong isolation of the input port

➡ Realizing the amplifier as high-gain helical gyro-TWT[1]

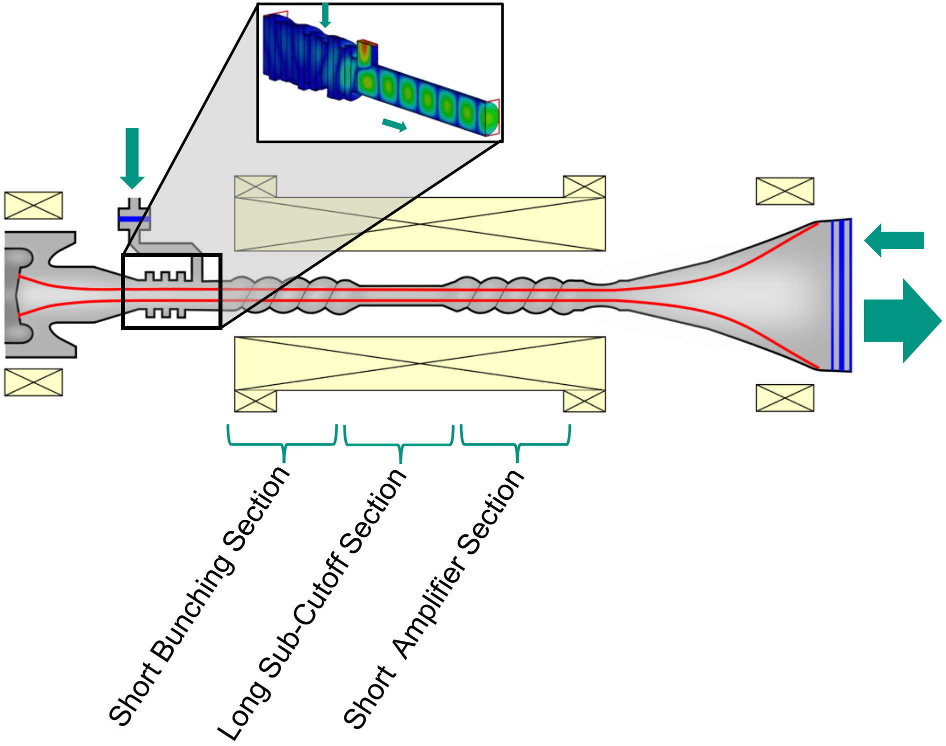


[1]S. V. Samsonov, et al., *IEEE Electron Device Letters* 41.5 (2020): 773-776.

High-Gain Helical Gyro-TWT

- Additional input port for low-power signals
- Sectioned interaction space
  → High gain (30 – 40 dB)
- Single window operation still possible
- Realization as frequency-doubling amplifier possible[1]

→ 10-100 mW sufficient for hard excitation



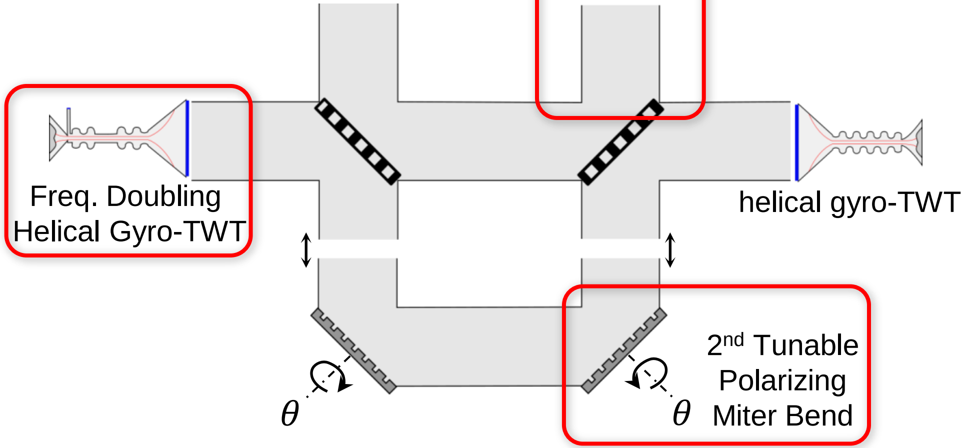
[1]A. Marek, et al. *IEEE Electron Device Letters* 43.8 (2022): 1347-1350.

Additional Operation Regimes

- Extensions:
  - Freq. doubling helical gyro-TWT
  - Extended feedback system
- Additional operation regimes:
  - Pulser (coherent pulses)
  - Oscillator (CW source)
  - 2-stage amplifier (arbitrary signal)
  - Frequency doubling amplifier

→ Universal sub-THz Source

Extended feedback system[1]



[1]A. Marek et. al, *IEEE Transactions on Electron Devices* 67.12 (2020): 5729-5735.

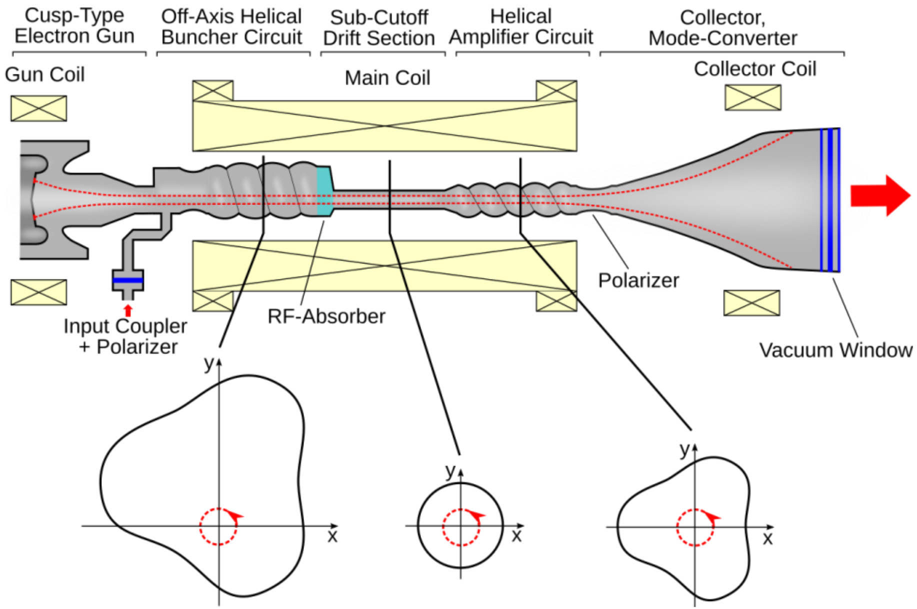
Conclusion

- **First investigation of passive mode-locking at 263 GHz**
  - Design of a 263 GHz passive mode-locked oscillator
  - Observation of phase offsets in the soft excitation regime
- **Innovative new multi-propose high-power sub-THz source**
  - Pulser
  - Oscillator
  - Two-stage amplifier
  - Frequency doubling amplifier

Thank You!

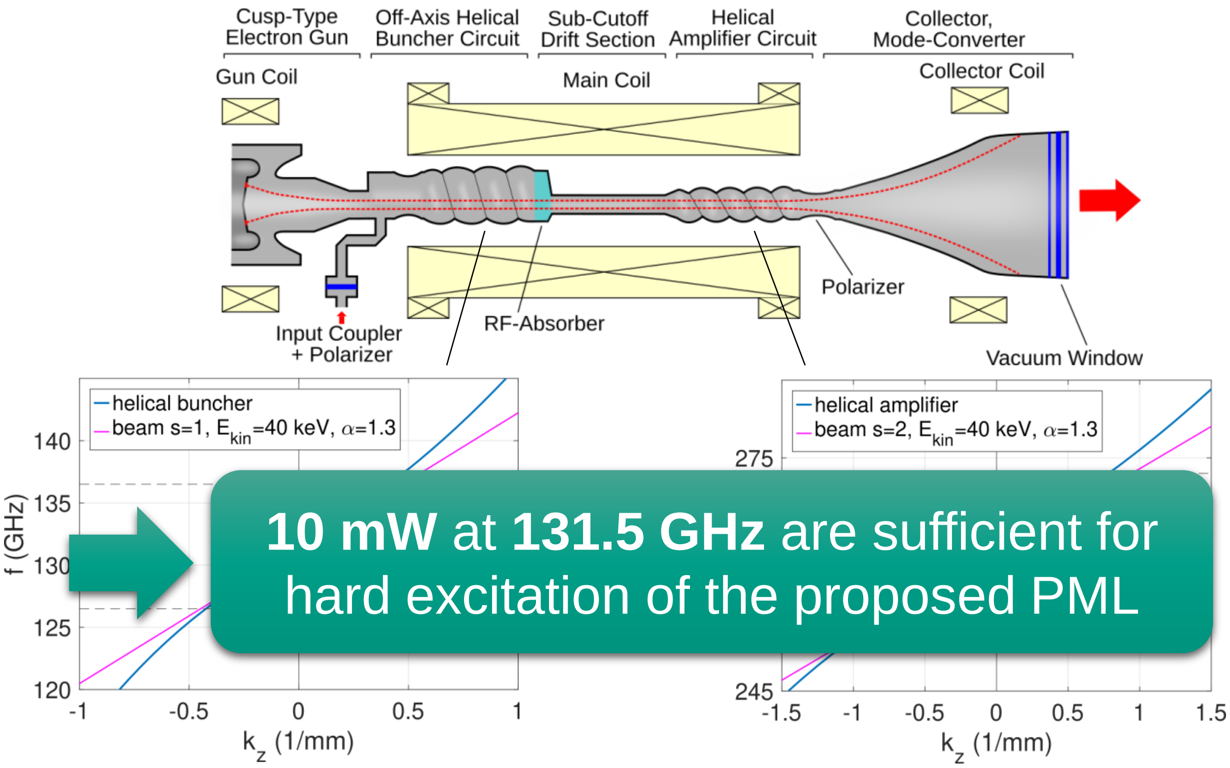
Frequency-Doubling Helical Gyro-TWT

- Amplification and frequency doubling of a low-power input signal
  - $f_{\text{out}} = 2\, f_{\text{in}}$
  - High gain ≈ 40 dB
- Idea:
  - Bunching of e^- beam at fundamental cyclotron harmonic
  - Induction of amplified signal at 2nd cyclotron harmonic
  - Off-axis helical waveguide allows bunching of LOB at fundamental harmonic



A. Marek, et al. *IEEE Electron Device Letters* 43.8 (2022): 1347-1350.

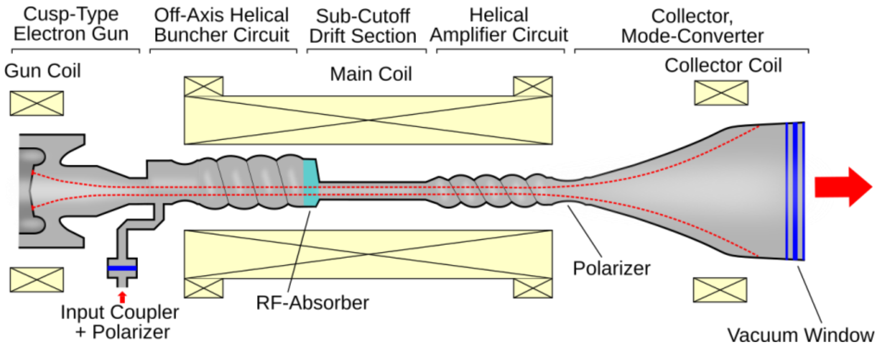
Frequency-Doubling Helical Gyro-TWT



10 mW at **131.5 GHz** are sufficient for hard excitation of the proposed PML

A. Marek, et al. *IEEE Electron Device Letters* 43.8 (2022): 1347-1350.

Frequency-Doubling Helical Gyro-TWT



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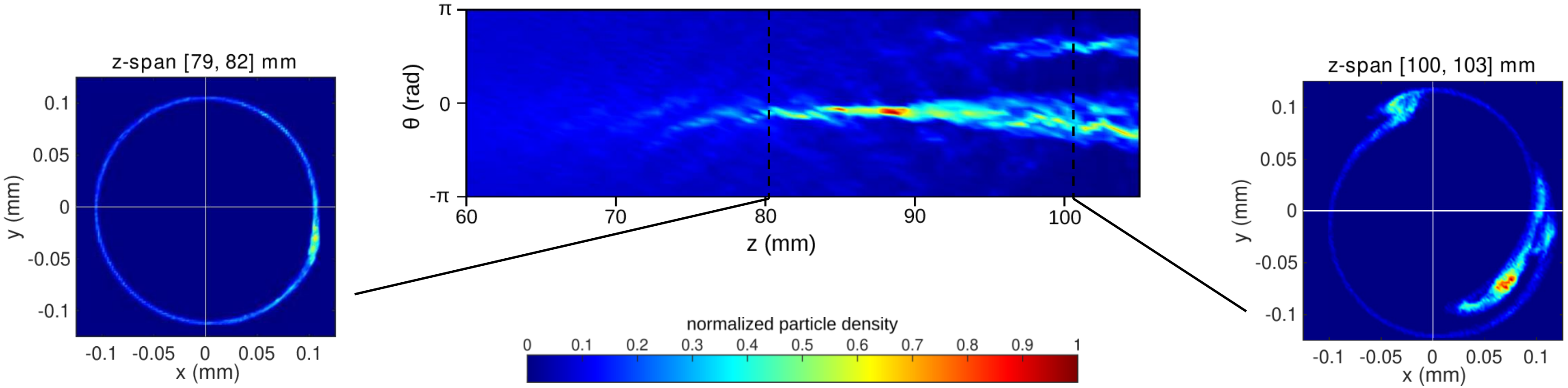
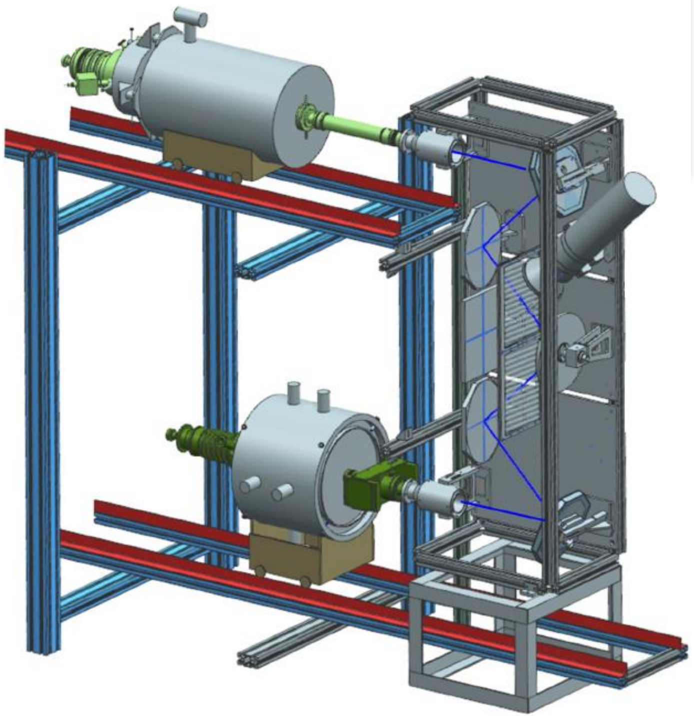


First Experimental Results

- First prove-of-principle experiment[1] at the IAP
- Passive mode-locking at the Ka-band
- Helical Gyro-TWT + Cyclotron Absorber
- Quasi-optical feedback system

- Soft excitation regime
- 100 kW pulses with a duration of 0.4 ns
- Repetition rate of 400 MHz (2.5 ns)

Passive mode-locking at microwave frequencies is possible



Frequency (GHz)

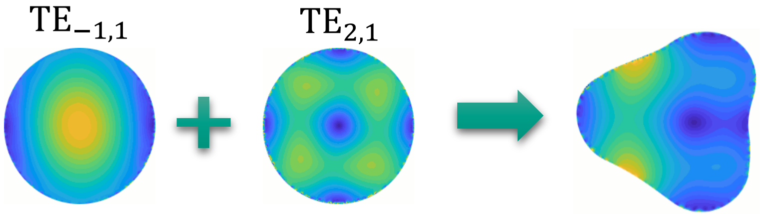
[1]Ginzburg, N. S., et al. *Physical Review Applied* 16.5 (2021): 054045.
RSF-DFG project (Je 711/1-1, 16-42-01078)

Helically Corrugated Waveguide (HCW)

- Corrugation introduces a coupling of specific modes $\mathrm{TE}_{m_\mathrm{A},1}$ and $\mathrm{TE}_{m_\mathrm{B},1}$ with

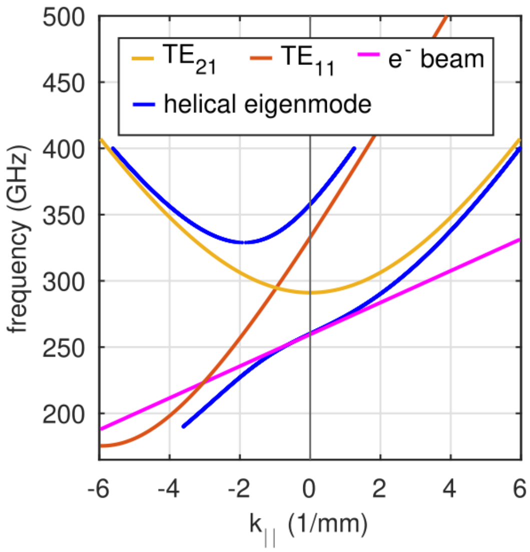
$$3 = m_\mathrm{A} - m_\mathrm{B}$$

$$2\pi/\tilde{d} = k_{||\mathrm{A}} - k_{||\mathrm{B}}$$



⇨ Fundamental mode in HCW has a $\mathrm{TE}_{2,1}$ periodicity
→ suitable for interaction at 2nd cyclotron harmonic with LOB

⇨ Controllable dispersion
  - Optimal for broadband operation
  - Reduced sensitivity to spreads of e⁻ beam parameter

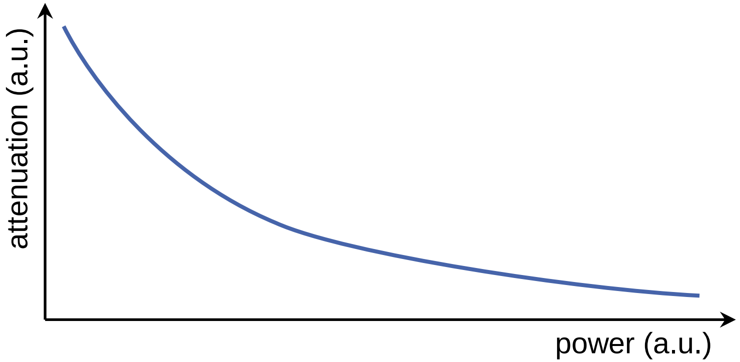


Cyclotron resonance condition:

$$\omega - k_{\|} v_{\|} \approx 2\,\omega_\mathrm{H}$$

Effect of Saturable Attenuation on Pulses

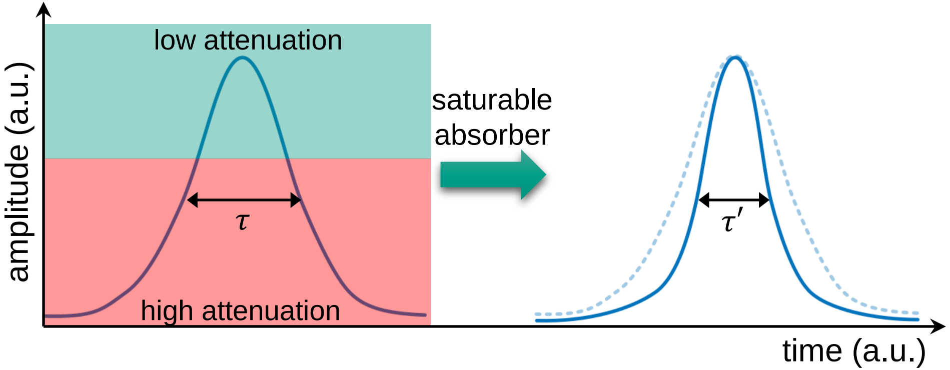
- Saturable attenuation



- Strong attenuation of low power signals
- Low attenuation of high power signals

⇨ Favors high-power signals

- Effect of saturable attenuation on a pulse



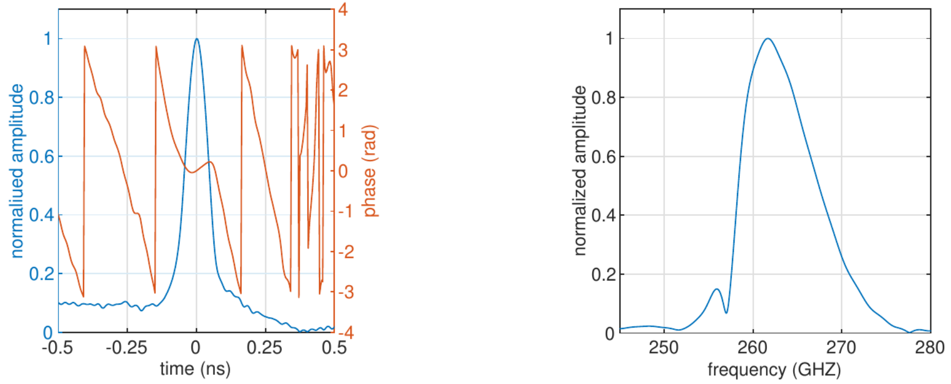
- Higher attenuation of pulse flanges

⇨ Shortening of pulses ($\tau' < \tau$)

Passive mode-locked oscillator:
Gain and saturable attenuation

Pulse Chirp

Simulated amplitude and phase distribution



Analytical chirp and resulting amplitude/phase distribution