SIMULATIONS TOWARDS THE GENERATION OF ULTRA-SHORT PULSES WITH COUPLED GYRO-DEVICES

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TECHNOLOGY

Structure

- **Generation of ultra-short microwave pulses**
- **Components of the feedback loop and ‘cold’ simulations**
  - Gyro-TWT with helical interaction region
  - Quasi-optical mirror system
- **PIC simulations with PICLas**
  - Overview PICLas
  - Non linear absorber at 30 GHz
- **Conclusion**

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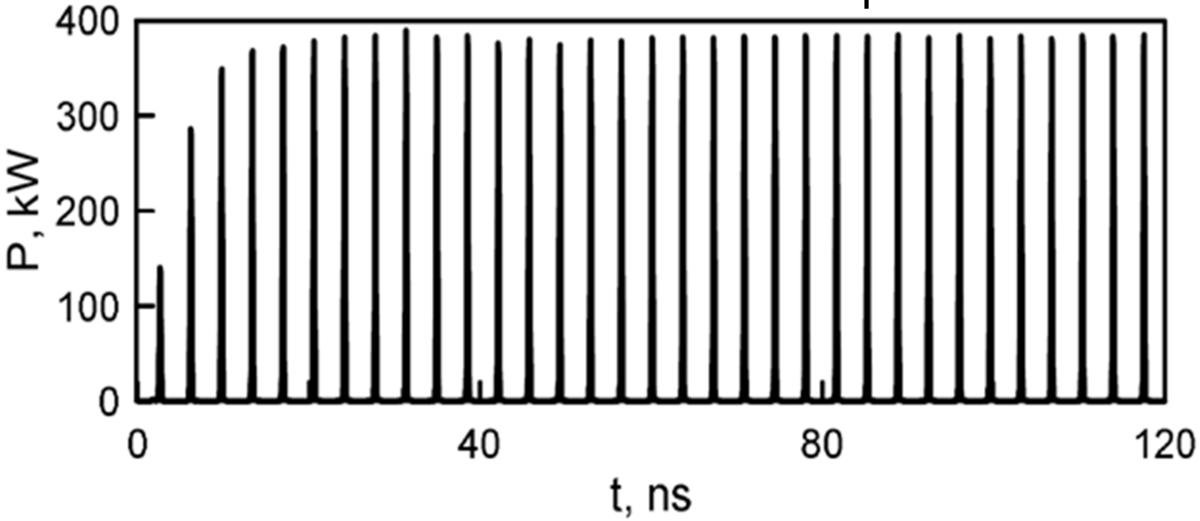
Generation of Ultra-Short Microwave Pulses

- **Joined RSF-DFG Project (IAP-RAS and KIT-IHM)**
- Method of **passive mode locking** (as in laser physics)
  → Feedback loop of amplifier and saturable absorber
- Amplifier: high amplification of ultra short pulses
- Non linear absorber: absorption of low power signals, transmission of high power signals

Train of ultra-short coherent pulses



Ginzburg et. al. *Technical Physics Letters* 2015
Ginzburg et. al. *Phys. Plasmas 24* 2017

Generation of Ultra-Short Microwave Pulses

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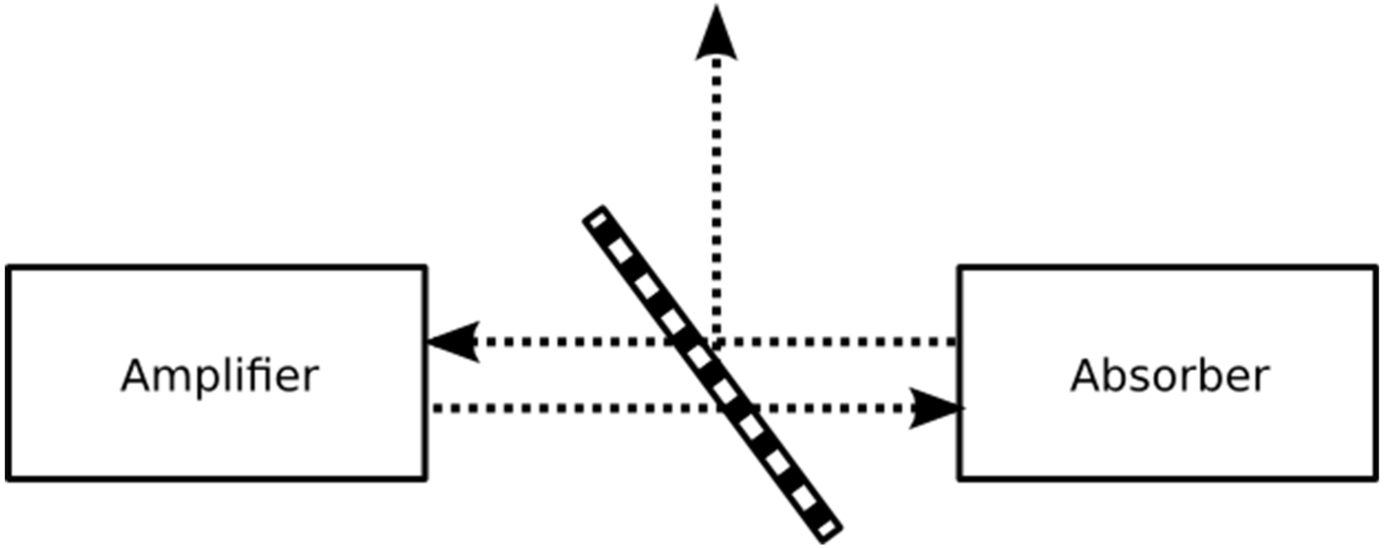


Ginzburg et. al. *Technical Physics Letters* 2015
Ginzburg et. al. *Phys. Plasmas 24* 2017

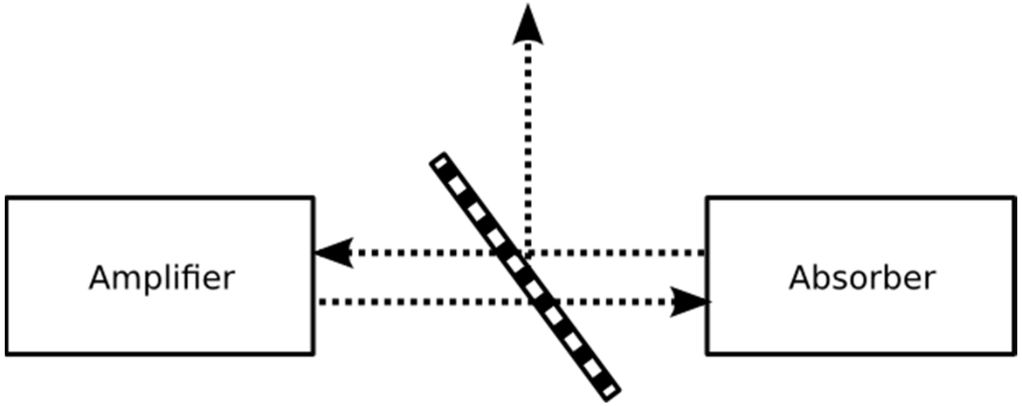
Generation of Ultra-Short Microwave Pulses

- Pulse **duration** is determined by the **bandwidth** of the absorber
- Pulse **distance** is determined by the **time** for passing through the feedback loop
- Pulse **power** is limited by the output-power of the **amplifier**

- Target frequency: **260 GHz**
- First prove of concept: **30 GHz**

For 30 GHz	
Duration:	0.25 ns (→ absorber bandwidth ≈ 5 GHz)
Distance:	5 ns
Power:	300 kW

Generation of Ultra-Short Microwave Pulses



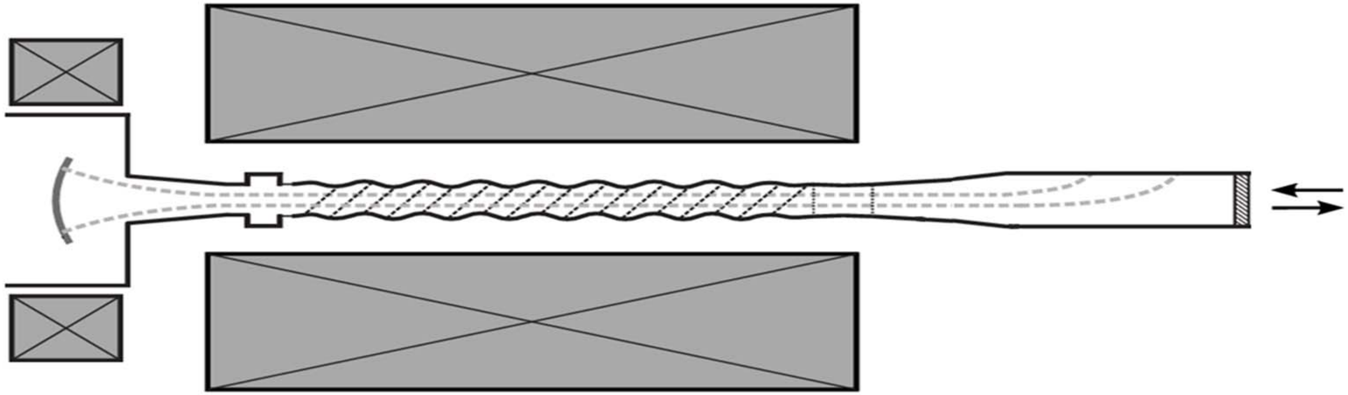
- Amplifier and absorber could be realized as **gyro-TWTs with helical waveguide**
  - Gyro-TWT as amplifier: optimized for amplification of ultra-short pulses
  - Gyro-TWT as saturable absorber: operating in the Kompfner dip regime
  - Both Gyro-TWTs with single window input/output
- Amplifier and absorber coupled with a **quasi-optical mirror system**
  - Polarization splitter as tunable semitransparent reflector

Ginzburg et. al. *Technical Physics Letters* 2015
Ginzburg et. al. *Phys. Plasmas 24* 2017

Karlsruhe Institute of Technology

Components of the feedback loop

Gyro-TWT with helically corrugations



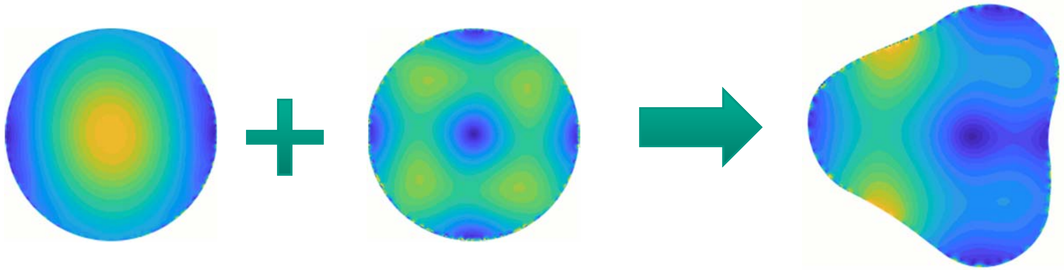
- Gyro-TWT with helical corrugated interaction region

$$r = r_0 + h_0 \cos(m_B\varphi - 2\pi z/d)$$

- Corrugation couples modes which fulfill:

$$m_1 - m_2 = m_B \quad \text{and} \quad h_1 - h_2 = 2\pi/d$$

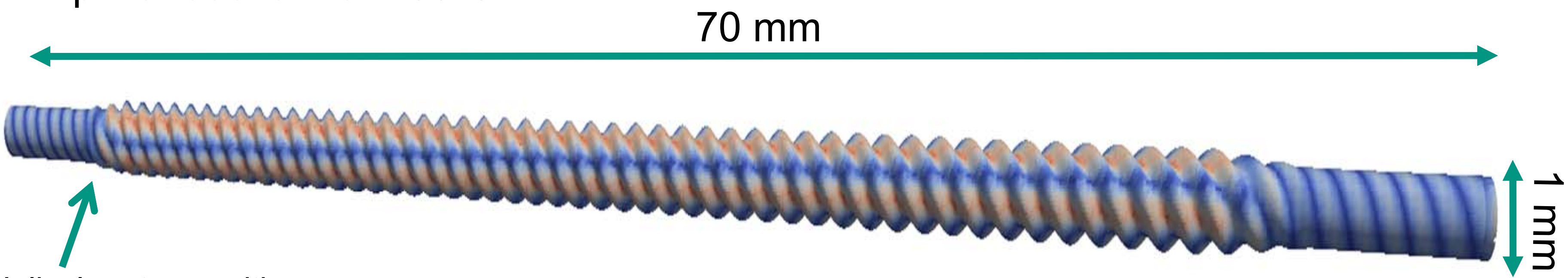
- Single window input/output
- $m_B = 3 \rightarrow$ coupling of $TE_{2,1}$ and counter-rotating $TE_{-1,1}$ mode to $TE_{2,1}$ like eigenmode



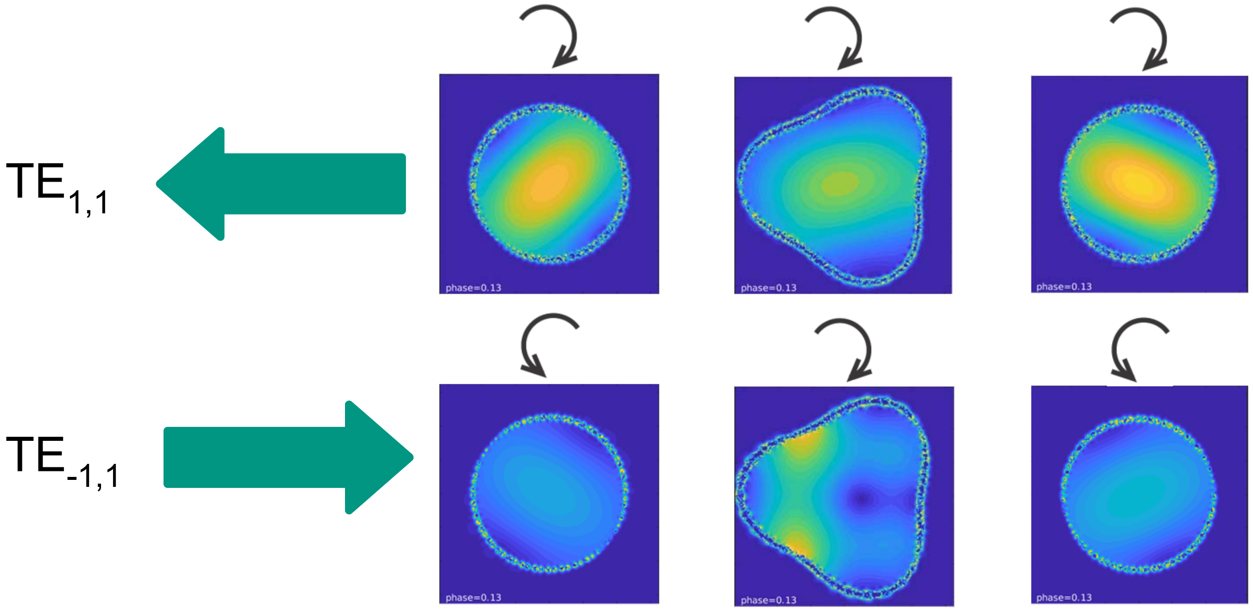
G. DENISOV et al. IEEE ELECTRON DEVICE LETTERS, VOL. 35, NO. 7, JULY 2014

Single window input/output

Amplifier section for 260 GHz:



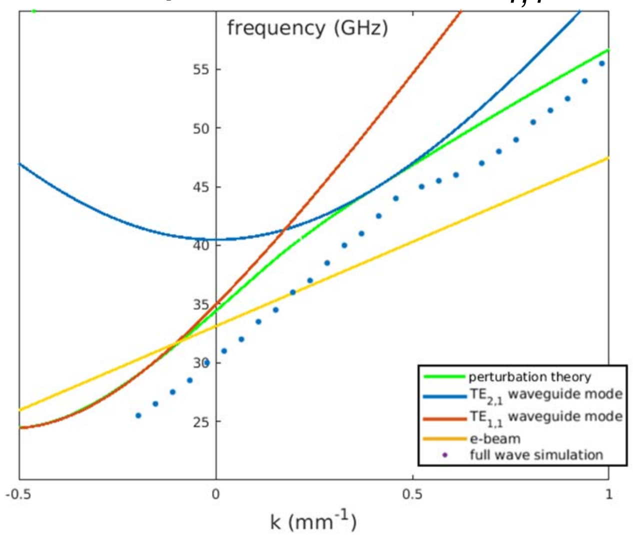
Helical up-taper with linear increase



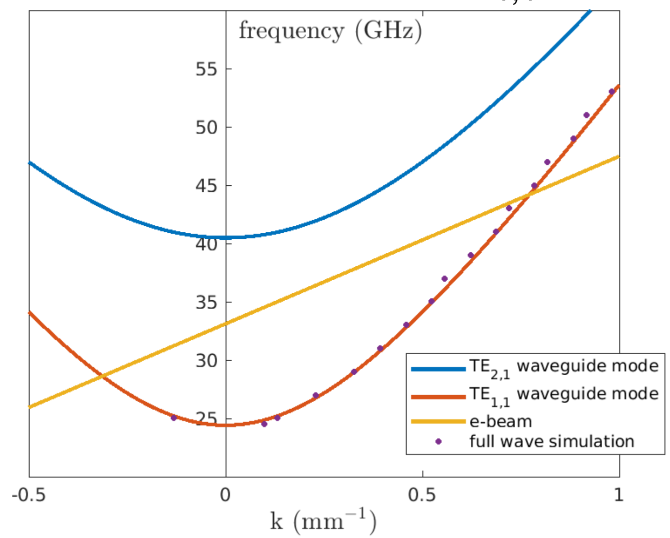
Dispersion of Helically Corrugated Waveguides

- Optimized dispersion relation by coupling of $TE_{2,1}$ and $TE_{-1,1}$ mode
- Perturbation theory not usable for high corrugation amplitudes
- Simulation of the dispersion with own MoM-EFIE-Code:
- Frequency-Domain → Simulations at different frequencies
- Spatial Fourier transformation of the radial electric field E_r along a line parallel to the z-axis

Dispersion of a $TE_{-1,1}$



Dispersion of a $TE_{1,1}$

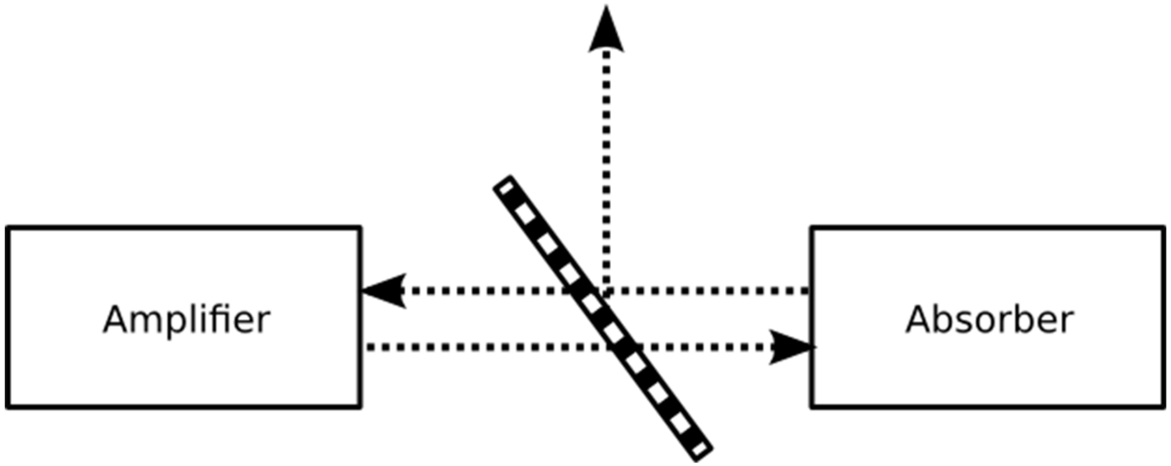


L. Zhang et al. IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 60.1 (2012)

Quasi-Optical Mirror System for the Feedback Loop

Required:

- Semi transparent mirror:
    - Non-transparent in Amplifier-Absorber direction
    - Semi-transparent in Absorber-Amplifier direction
    - Suitable for high energies
    - Available for 30 GHz up to the sub-THz range
    - Tunable reflection coefficient



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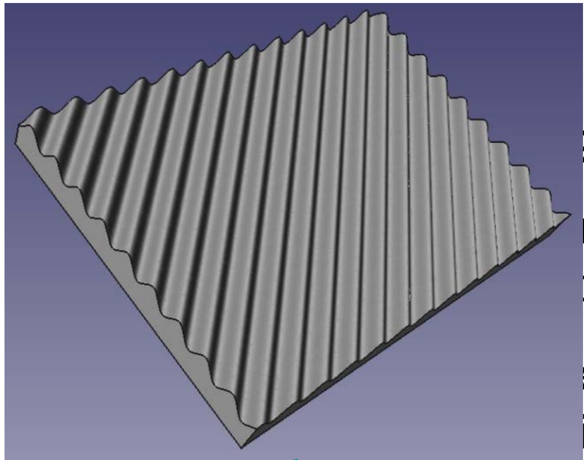
Quasi-Optical Mirror System for the Feedback Loop



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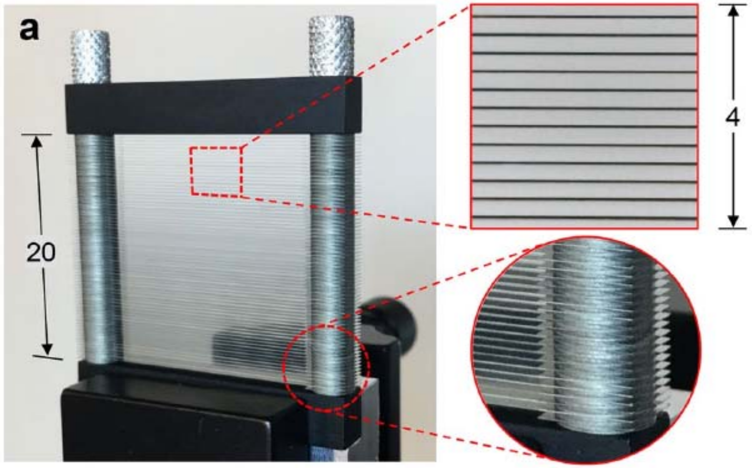
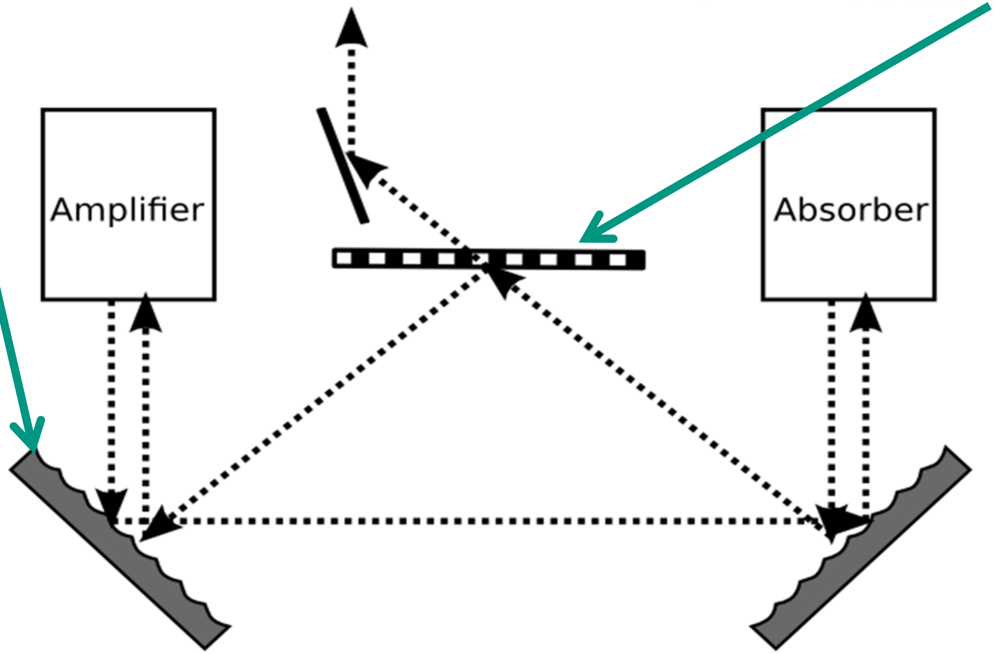
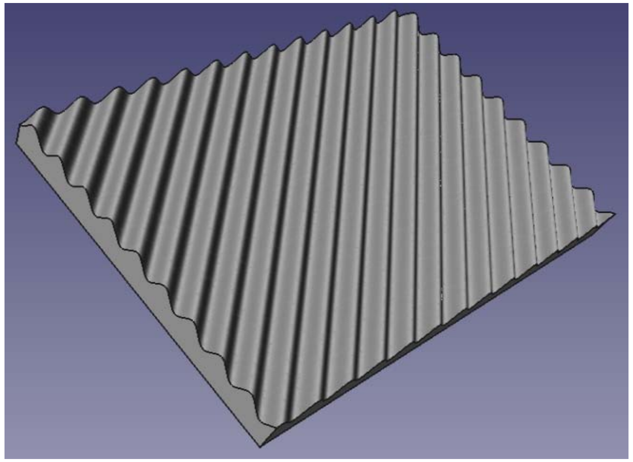




Mendis, Rajind, et al. Scientific Reports 7.1 (2017): 5909.

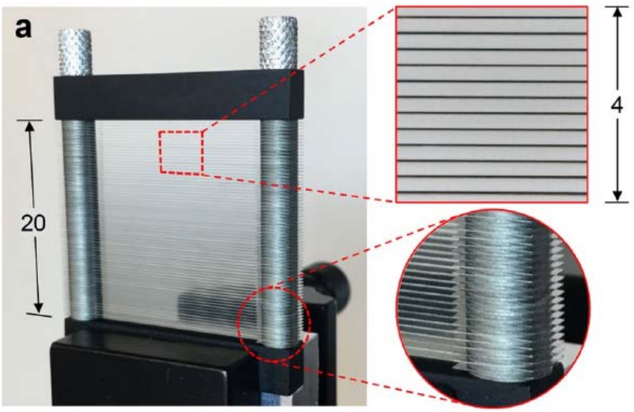
A. Marek, EPJ Web of Conferences 149, 04016 (2017)

Quasi-Optical Mirror System for the Feedback Loop



Simulated results (250 | <u>260</u> | 270 GHz):

- Up-reflection arm:
  - Power efficiency: (97 % | 99 % | 97 %)
  - Extinction ratio: (17 dB | 23 dB | 16 dB)
  - Back-Reflection: (-39 dB | -38 dB | -34 dB)
- In-plane-reflection arm:
  - Power efficiency: (98 % | 99 % | 99 %)
  - Extinction ratio: (17 dB | 22 dB | 21 dB)
  - Back-Reflection: (-42 dB | -40 dB | -37 dB)



From Literature (200 GHz):

- Transmission arm:
  - Power efficiency: 96 %
  - Extinction ratio: 42 dB
- Reflection arm:
  - Power efficiency: 96 %
  - Extinction ratio: 28 dB

Mendis, Rajind, et al. Scientific Reports 7.1 (2017): 5909.

A. Marek, EPJ Web of Conferences 149, 04016 (2017)

PIC simulations of the non-linear absorber with PICLas

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PICLas

- Developed at Institut für Aerodynamik und Gasdynamik (**IAG**) and Institute of Space Systems (**IRS**), Universität Stuttgart
- Full-wave simulations via **Particle-In-Cell**
  - Maxwell’s equations on hexahedral meshes via **high-order** Discontinuous Galerkin Spectral Element Method
  - Vlasov’s equation via 6d macro particle approximation with Lorentz forces
- **Curvilinear mesh** of arbitrary order
- Support for **Super-Computers** → can run on >100000 Cores
- Full access to the source-code → **no ‘black box’**

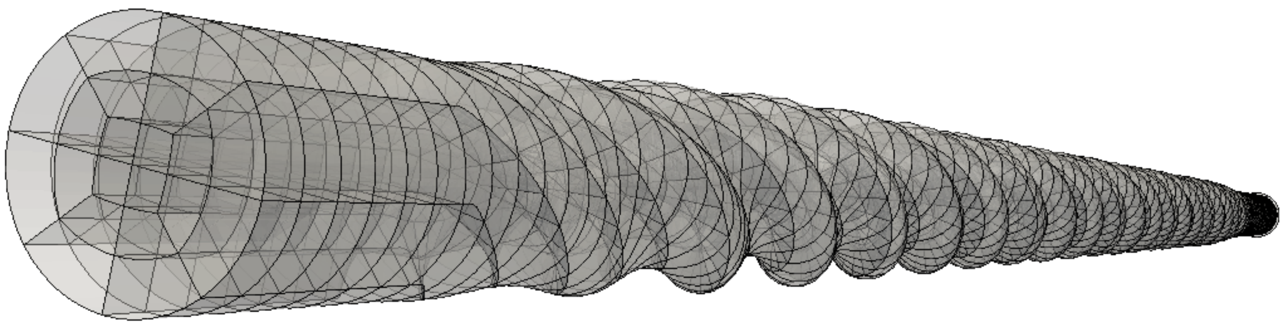
C.-D Munz et al. Comptes Rendus Mécanique 342(10-11), 662–670. (2014)

High Order Mesh Generation

- Mesh creation with **HOPR**
- Open source tool developed from Aerodynamik und Gasdynamik (IAG), Universität Stuttgart
- New algorithm for the creation of an optimal mesh for helical structures

→ **Optimized Curvilinear mesh of arbitrary order**

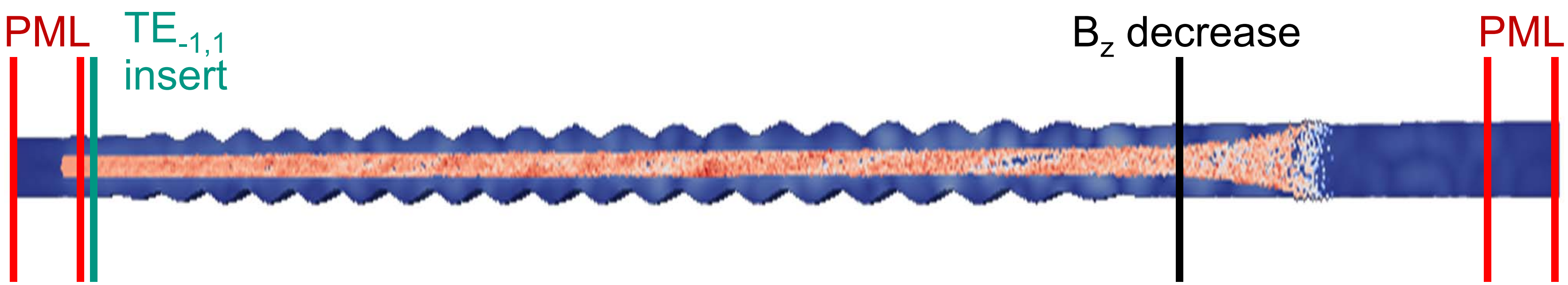
$$r = r_0 + h_0 \cos(m_B \varphi - 2\pi z/d)$$



F. Hindenlang et al. IDIHOM Springer, 1, pp. 133–152 (2015)

Simulation Setup

- Absorbing boundaries (PML) at beginning and end of the geometry
  → avoid reflections
- Particle insert inside the PML
  → avoid radiation from the inserting process
- Insertion of the input signal at the end of the PML
- Separation of e^- beam and RF by a B_z decrease



Simulations for a feedback loop at 30 GHz

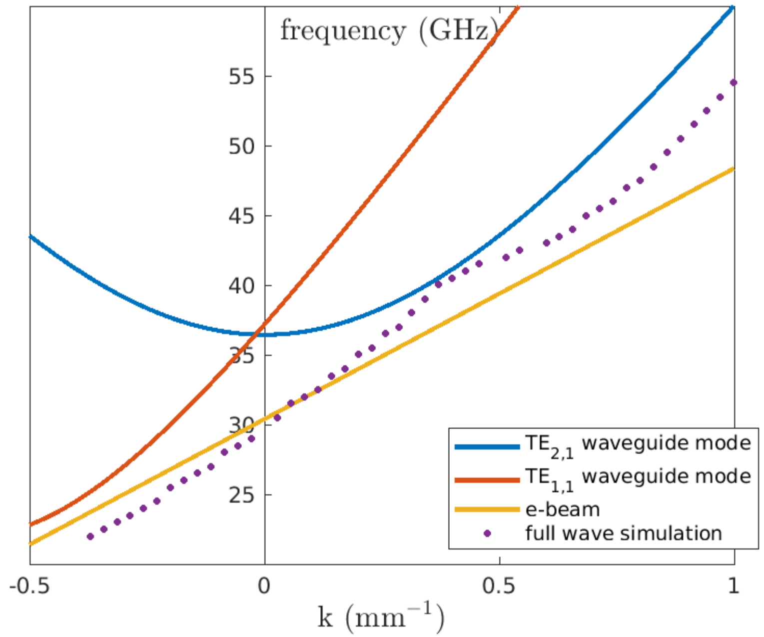
- Feedback loop at 30 GHz
- Simulations in "*N. S. Ginzburg, et al. IEEE Transactions on Electron Devices 65.6 (2018): 2334-2339*" are performed with CST
→Reproduction of the same simulations with PICLas

- Absorber
  - Current: I = 2.4 A — Waveguide radius: r_0 = 0.4 cm
  - Beam voltage: U = 54 kV — Corrugation amp.: h = 0.1 cm
  - Pitch factor: α = 0.53 — Corrugation per.: d = 1.0 cm
- Amplifier
  - Current: I = 10 A — Waveguide radius: r_0 = 0.4 cm
  - Beam voltage: U = 68 kV — Corrugation amp.: h = 0.06 cm
  - Pitch factor: α = 1.2 — Corrugation per.: d = 1.2 cm

N. S. Ginzburg, et al. IEEE Transactions on Electron Devices 65.6 (2018): 2334-2339.

Simulations of a Gyro-TWT Operating as Saturable Absorber

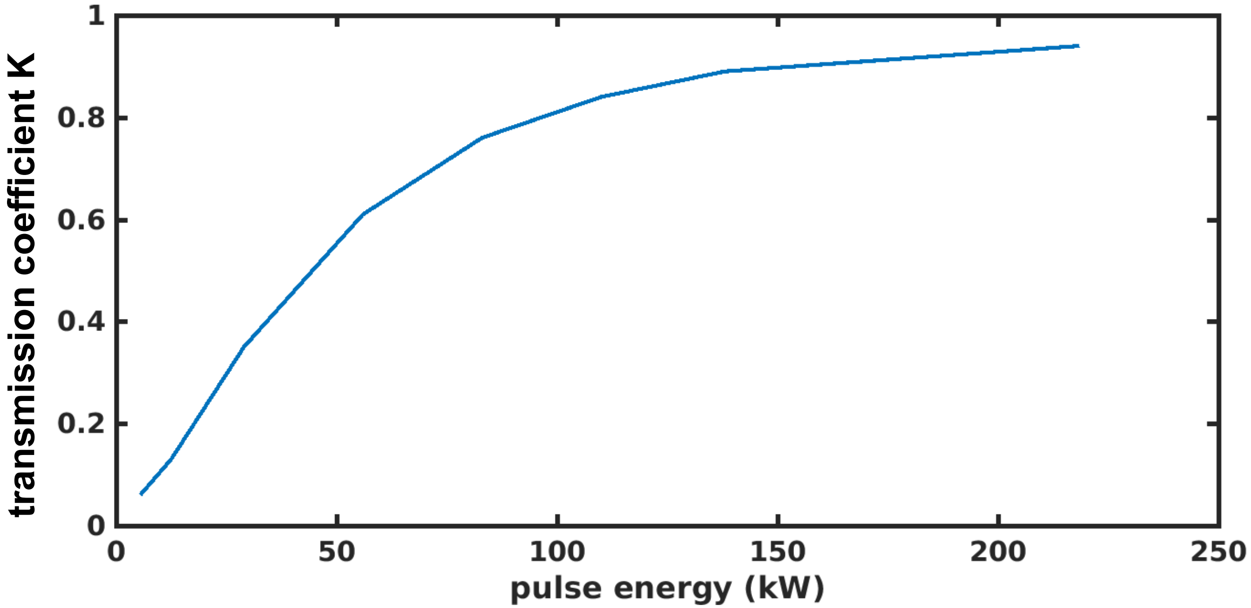
- Operates in the so-called Kompfner-Dip regime
  →electromagnetic wave is absorbed by the e^- beam
- Realized by a small detuning of the resonant guiding magnetic field (0.59 T → 0.6 T)
- Group velocity should be close to the axial velocity of the e^- beam
  →electromagnetic pulse interacts with a specific fraction of the e^- beam



N. S. Ginzburg, et al. IEEE Transactions on Electron Devices 65.6 (2018): 2334-2339.

Simulations of a Gyro-TWT Operating as Saturable Absorber

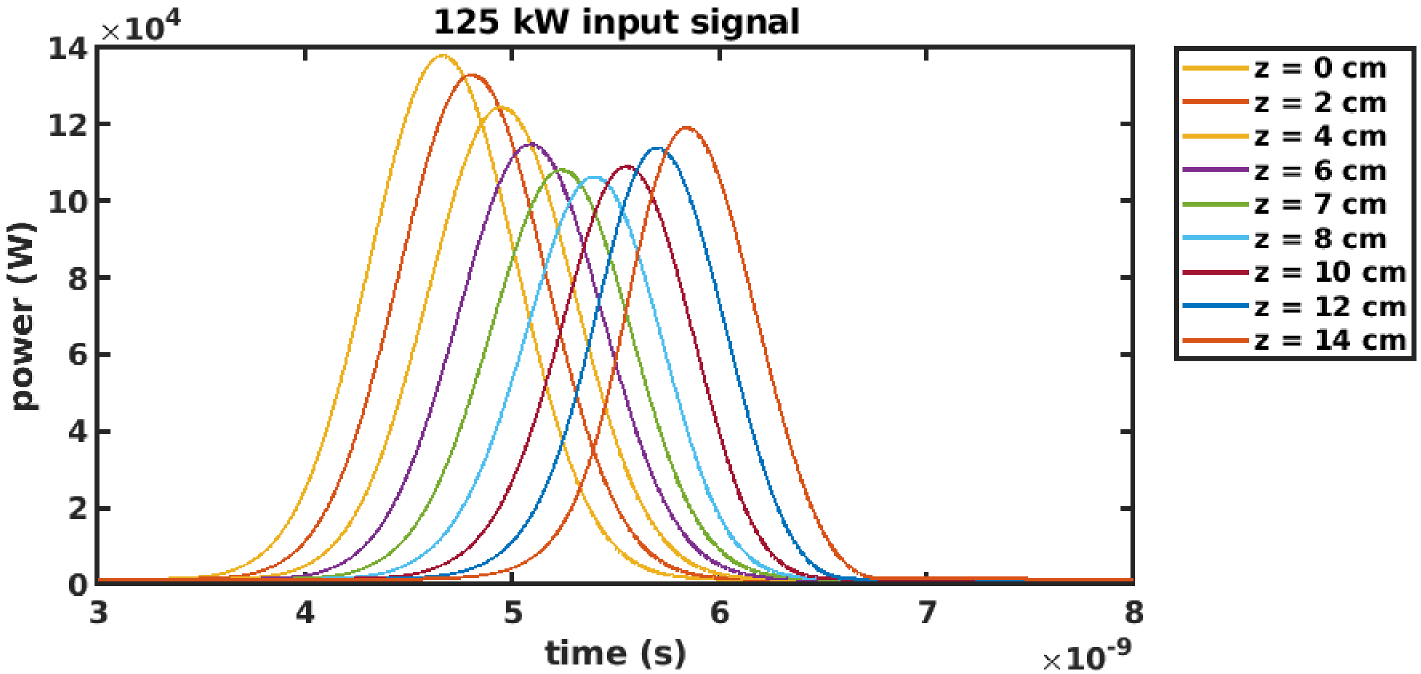
- Saturable Absorber: Signal with low amplitude → high attenuation
  Signal with high amplitude → low attenuation
- Transmission coefficient: $K = P_{out} / P_{in}$
- Gaussian pulse with f = 30 GHz and σ = 0.5 ns



Mechanism of Saturable Absorber

- Group velocity ≈ axial velocity
- RF transfers energy to a specific fraction of the e^- beam
- High energy transfer > 30 kW
  → e^- beam comes into the amplification regime

RF-Power along the interaction-region



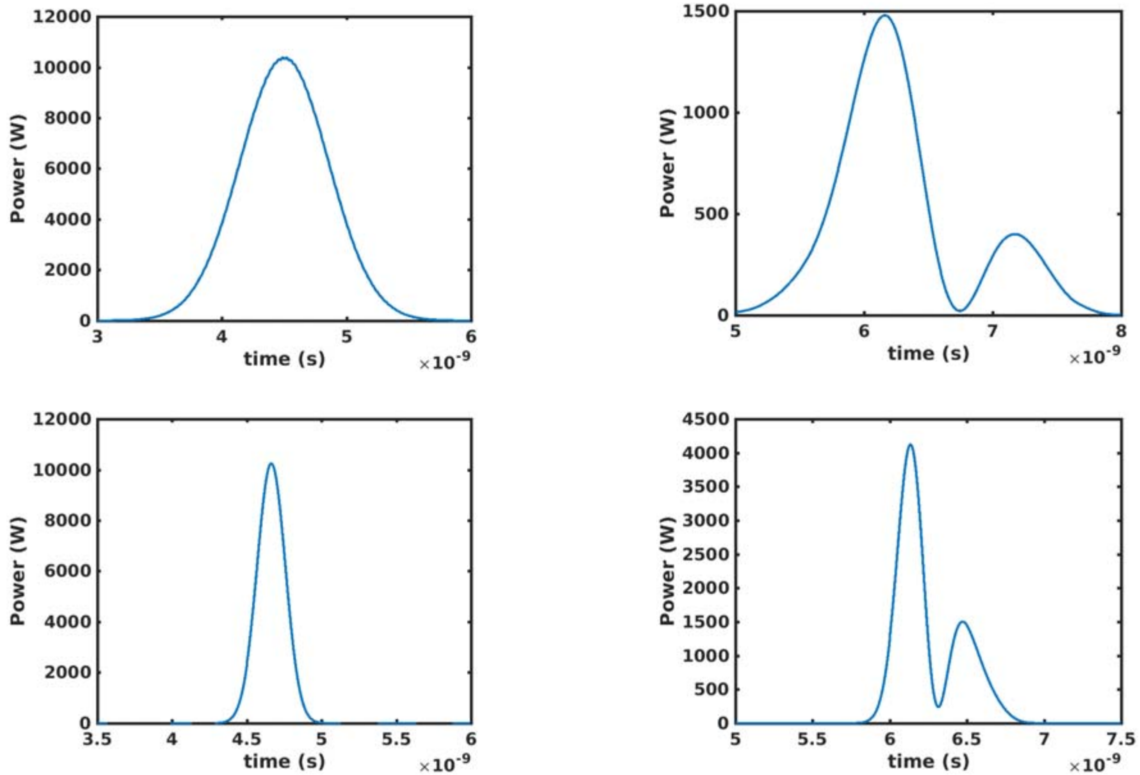
Absorption of Short Pulses

- The length of the generated pulses in the feedback loop depends on the bandwidth of the gyro-devices
- Target pulse-length: 0.25 ns → required bandwidth > 5 GHz

Input Signal | Output Signal

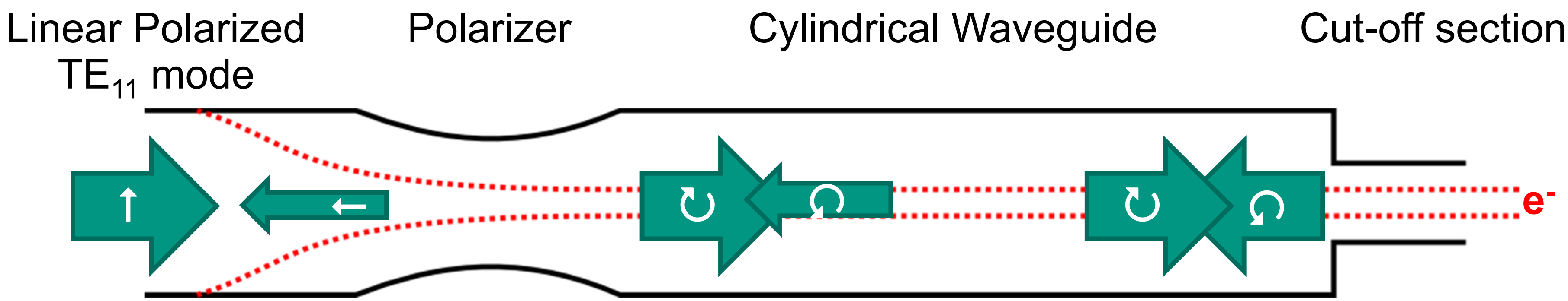
Pulse-length: 1 ns

Pulse-length: 0.25 ns



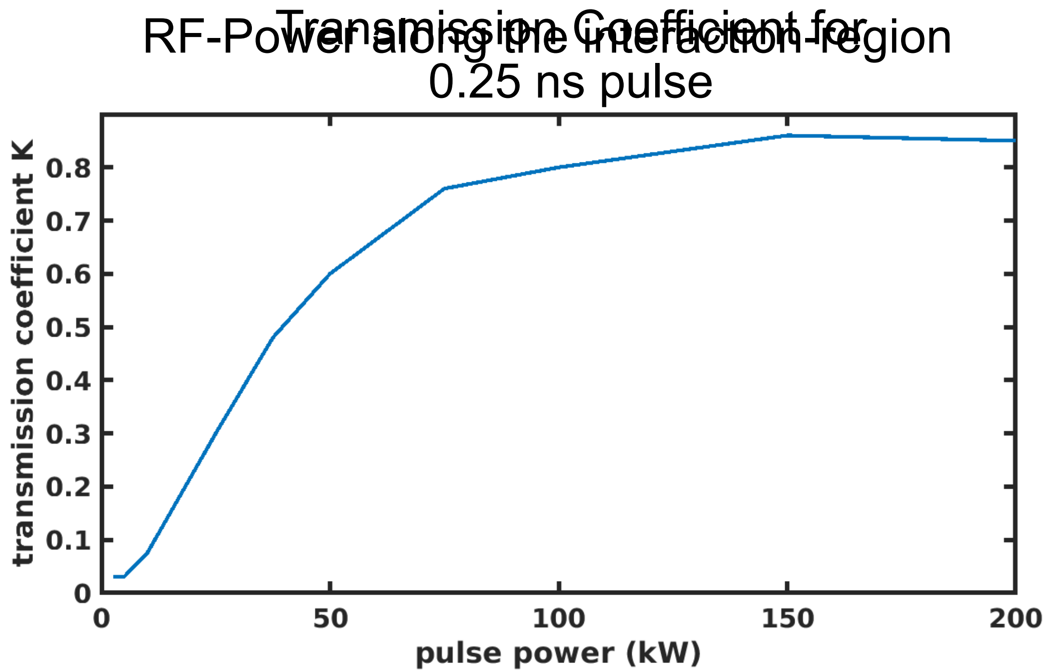
Cyclotron Absorber with Rectilinear e⁻ Beam

- Absorber with rectilinear e^- beam
- Cyclotron absorption
- Operates at the fundamental cyclotron harmonic → $B \approx 1$ T
- Beam parameter: $I \approx 1.2$ A
  $E \approx 55$ keV



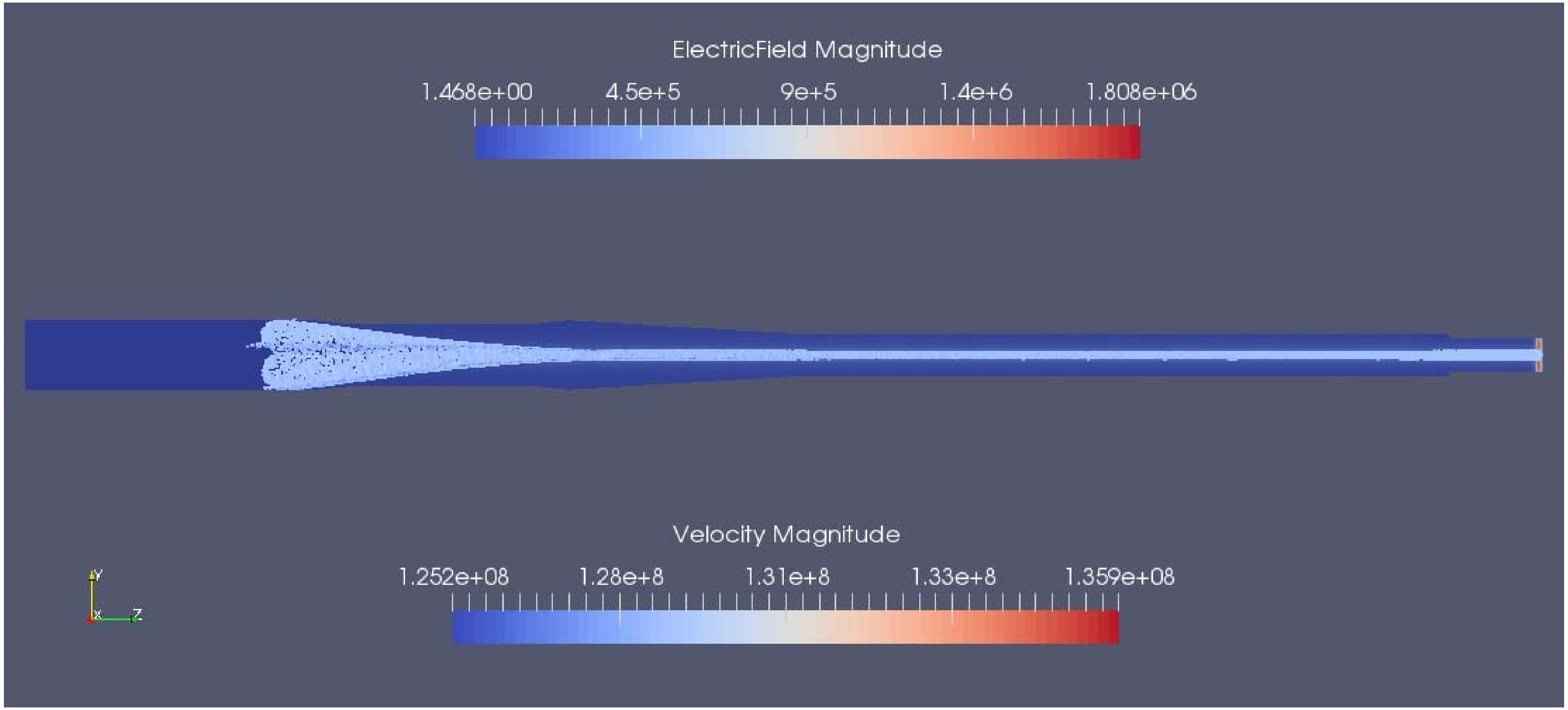
Cyclotron Absorber with Rectangular e⁻ Beam

- Group velocity ≈ axial velocity
- RF transfers energy to a specific fraction of the e⁻ beam
- Bandwidth > 5 GHz
- High energy transfer > 30 kW
  → e⁻ beam comes into the amplification regime



Cyclotron Absorber with Rectangular e^- Beam

- Absorption of a 0.25 ns Gaussian pulse with 10 kW power



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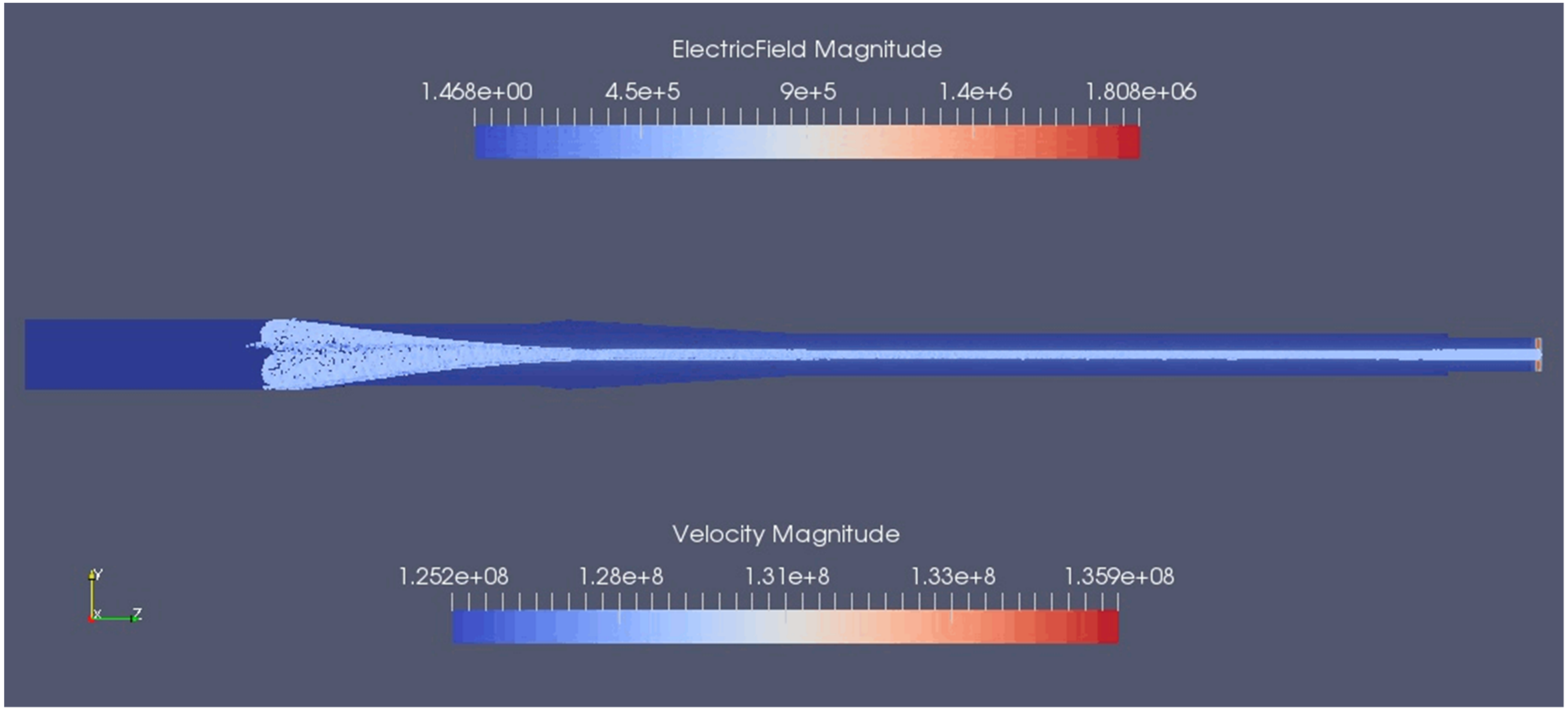

Conclusion & Outlook

Conclusion

- Design of a simple quasi-optical feedback-system
- Qualified setup for accuracy full-wave PIC simulations with PICLas
- Two concepts of sturable absorbers

Outlook

- Full simulation of the complete system of amplifier and absorber
- Simulation with more realistic beam parameters (α-spread, …)
- First experiments end of the year (at the IAP)