Oscillation Starting Current Approximation by Time-Domain Simulation in Traveling-Wave Tubes

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ITG Workshop, Bad Honnef
Traveling-Wave Tubes - September 7th, 2018

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Outline

Traveling-Wave Tubes

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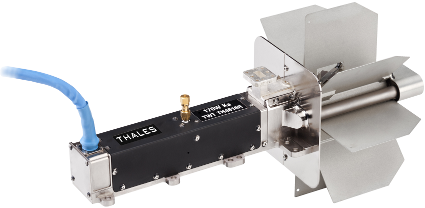
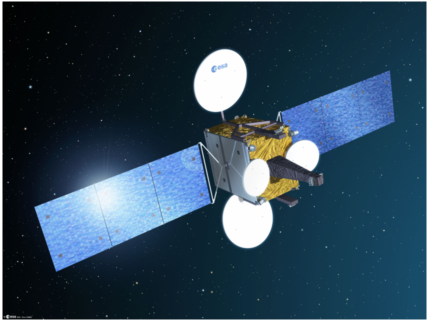
RF power amplifier

- High output power and gain
- Large bandwidth
- Efficiency
- Robustness



Thales, TH 4816RC



DLR Small-Geo, ESA, P. Carril

Traveling-Wave Tubes

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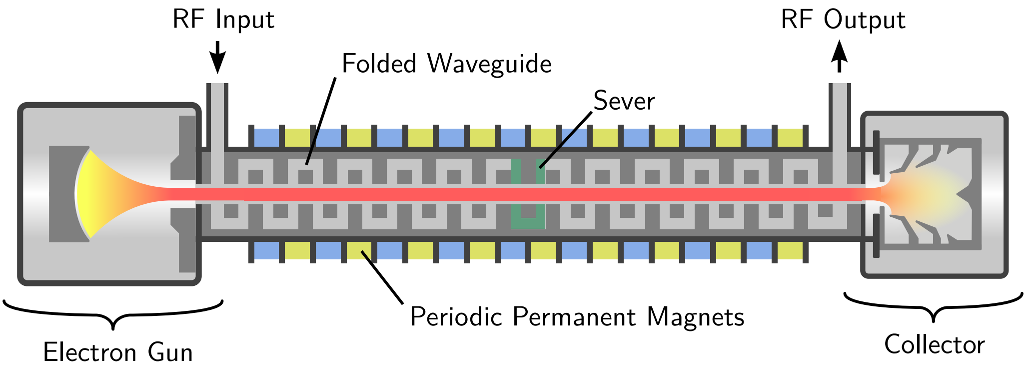

Simulation Tools: General vs. Special Approach

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General approach: 3D PIC Solver

- Direct solution of Maxwell's equations + equation of motion
- Full time domain approach

Advantages

- General purpose tool
- Exploration of new concepts

Disadvantages

- High demand on computer resources
- Long run-time ($\sim$ 1/2 day)

e.g. CST Particle Studio

$\rightarrow$ Not an efficient tool for design process

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Special approach: 2.5D Hybrid Solver

- Uses known analytical expansion
- Employs axial-symmetry inside the beam tunnel

Advantages

- Computationally efficient (run time $\sim$ 1 min)

Disadvantages

- Device specific
- Certain effects are not modeled

MVTRAD = "MouVemenT RADial"

→ Useful for designing and optimizing

Instabilities in Traveling-Wave Tubes

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- Coupled system of RF-fields and electron beam can lead to instabilities
  - Backward-wave oscillations
  - Band-edge oscillations
  - π-Mode oscillations
  - Drive-induced oscillations
- Excitation from noise or RF drive-level
- Occurrence depends on beam current and/or RF power
- Lower boundary for beam current: oscillation starting current

Here: π-Mode oscillation analysis with CST Particle Studio

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Homogeneous Tube Section

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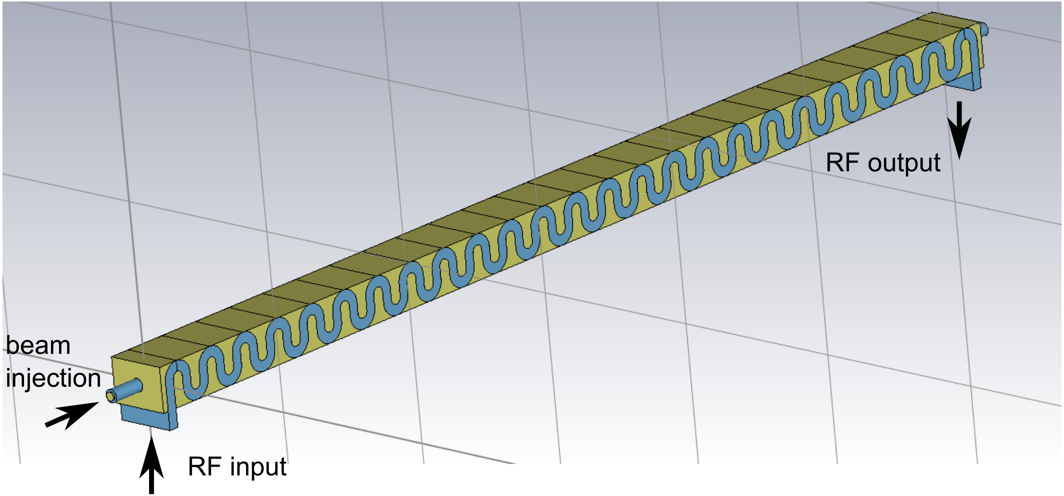

Dispersion

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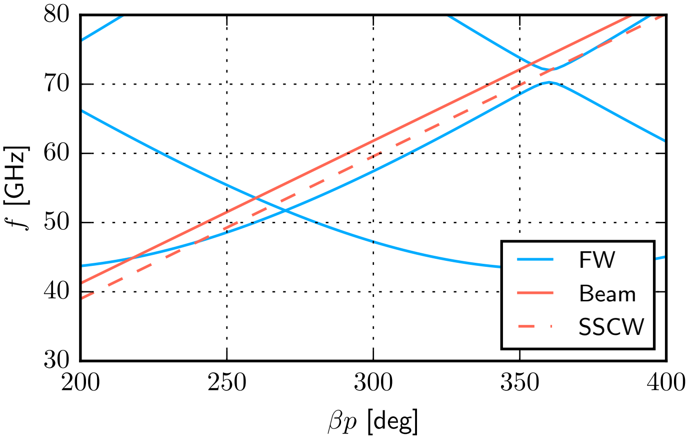
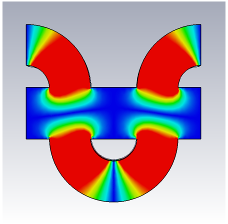
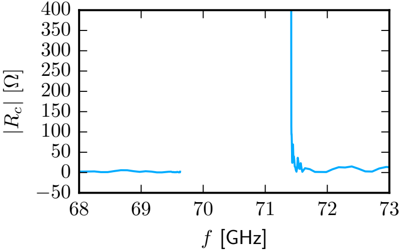


E-Field and Coupling at Band Gap

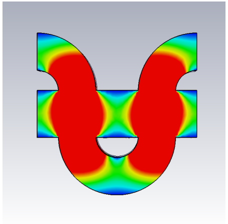
Lower band edge:
70.3 GHz



coupling ≈ 0



Upper band edge:
72.1 GHz



coupling $\to \infty$

Simulation Parameters

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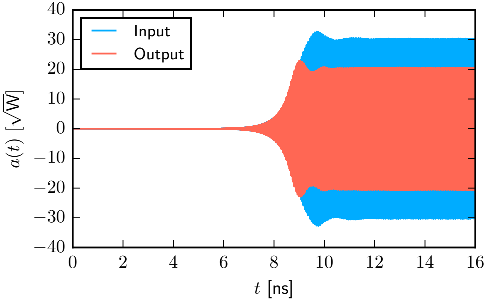
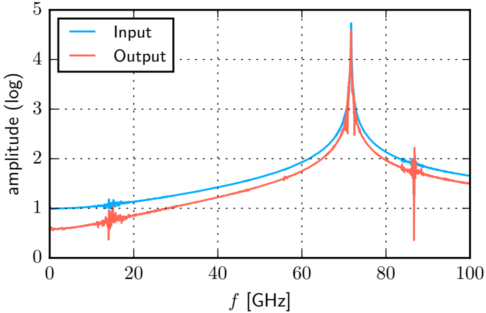
- Serpentine folded-waveguide delay-line
- Homogeneous tube section $\sim$60 mm
- Material: lossy metal $\sigma = 3.9 \cdot 10^7$ S/m
- Electron beam: $\sim$28 kV beam voltage
  $\rightarrow$ Beam voltage chosen to force an oscillation
- PPM focusing field
- Waveguide ports without excitation
- Oscillation excites from noise of the beam start up

CST Time Signals





Stable and saturated oscillation at 71.7 GHz with ∼650 W (340 mA beam current)

Outline

Oscillation Start Up

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Problem in time-domain simulation tools:
$t_{\mathrm{sim}} \rightarrow \infty$ at/below oscillation starting current

Oscillation startup:

$$a(t) = B \cdot e^{\alpha t} \cdot \cos(\omega_{\mathrm{osc}} t)$$

- Assumption: $\alpha = \alpha(I)$ and $B = B(I)$
- At oscillation starting current I_{SC}: $\alpha(I_{\mathrm{SC}}) = 0$ or $B(I_{\mathrm{SC}}) = 0$
- Simulation at I_1, $I_2 > I_{\mathrm{SC}}$, where
  - $\alpha(I_1), \alpha(I_2) > 0$
  - $B(I_1)$, $B(I_2) > 0$

$\rightarrow$ Interpolate α or B to calculate I_{SC}

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Port Signals

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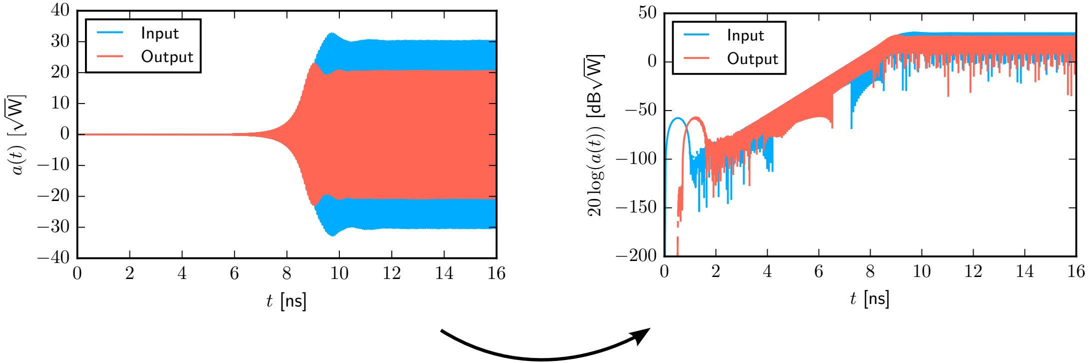

logarithmic scale

Port Signal Analysis

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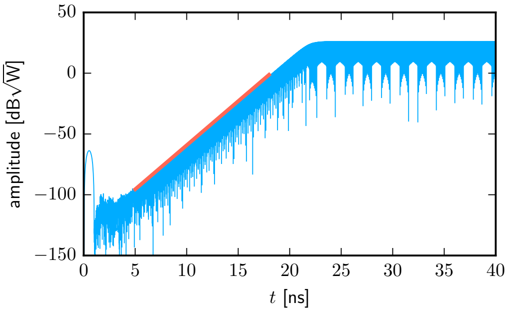

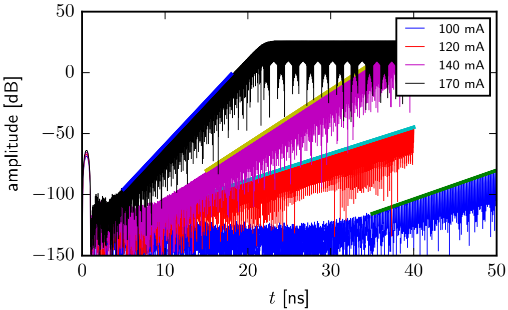

$$\log(a(t)) = \log(B) + \alpha t$$

→ $\alpha = \alpha(I)$

→ $B \neq \mathrm{fct}(I)$, only time shift

Slope vs. Beam Current

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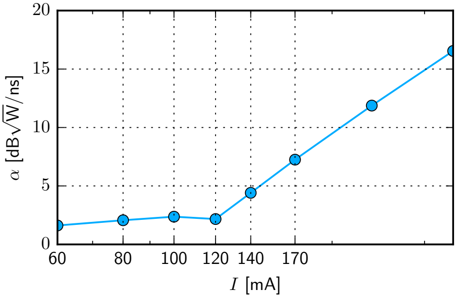
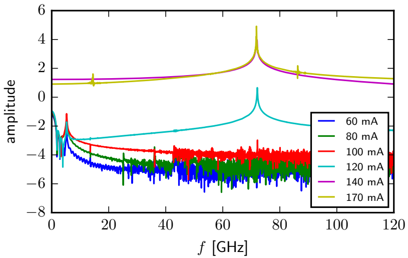
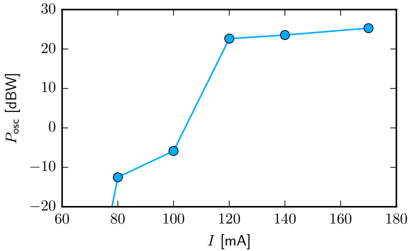




$$\alpha = m \cdot \log(I) + b \ , \ I > I_{SC}$$

- $\alpha \neq 0$ in simulation
- Problem: amplified noise

$\Rightarrow$ Additional information from spectral analysis and oscillation power



Estimated Oscillation Starting Current

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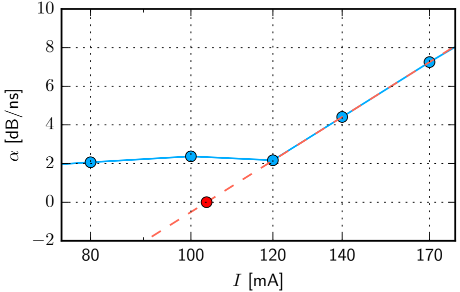

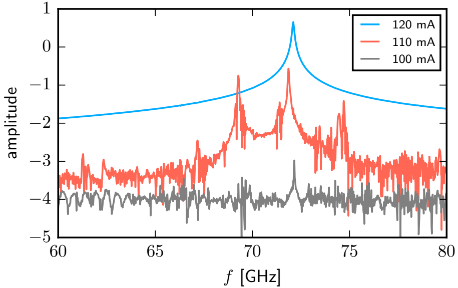

⇒ Estimated starting current I_{SC} = 103.5 mA

- Spectral components at f_{Osc} vanish between 100 mA and 120 mA

⇒ Starting current from simulation [100 mA, 120 mA]

⇒ Error [0.0 %, 13.8 %]

Outline TUHH

Summary

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- Various oscillations can occur in traveling-wave tubes
- Time-domain simulation offers geometry driven approach
- Simulation at or below starting current takes time
- Analysis of oscillation startup provides an approximation of the starting current

Outlook

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- Explicit definition of starting current in CST necessary
  - e.g. extended model including oscillation power or spectral information
- Influence of beam current rise during switch-on on oscillation startup
- Verification by other geometries (e.g. helix TWTs)
- Simulation and verification by other instabilities (e.g. BWO)

Thank you for your attention!

Acknowledgments

Funded by the German Space Agency (DLR) on behalf of the Federal Ministry of Economics and Technology (BMWi).

DLR

Bundesministerium für Wirtschaft und Technologie