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Delay Line Structures for High-Power and High-Frequency TWTs

IVEW 2026
L3.2-3 / W21T

Philip Birtel, Mathias Pech,
Lucie Sabaut

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DELAY LINE STRUCTURES FOR HIGH-POWER AND HIGH-FREQUENCY TWTS
-OUTLINE-

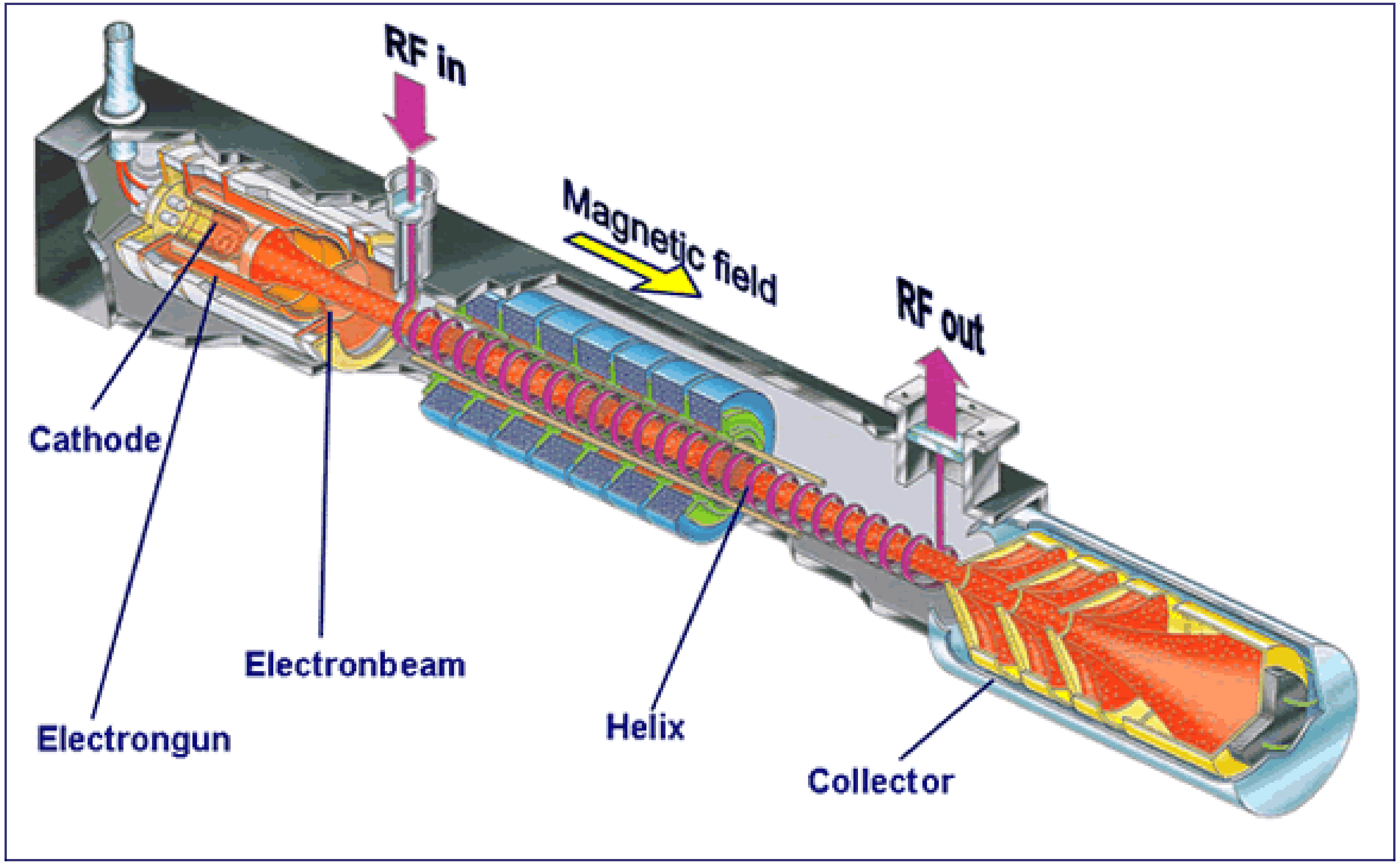
- Helix
- Folded Waveguide
- Double-Comb Folded Waveguide
- Comparison and Options

TWT Delay Line: Purpose

> **TWT: Transfer of kinetic electron energy to RF wave via continuous interaction inside delay line**

> **Requirements:**

1. (Axial) electric field @ beam
2. Synchronism



Delay Line KPIs (I)

> Beam – Wave interaction strength

- Usually described by the coupling impedance relating the electric field to the transmitted power: $Z = E^2/2P\beta^2$
- Helps keeping electron bunch integrity during energy extraction to increase gain and output power
- Direct trade-off between coupling impedance and beam tunnel size

> Dispersion / bandwidth

- TWT vacuum electronic device with high bandwidth (multi-octave in extreme cases)
- Phase velocity should not change too much with frequency

Delay Line KPIs (II)

> Power Handling: Thermal losses need to be conducted to housing

- RF losses near output coupler
- Beam interception

> No Hassle

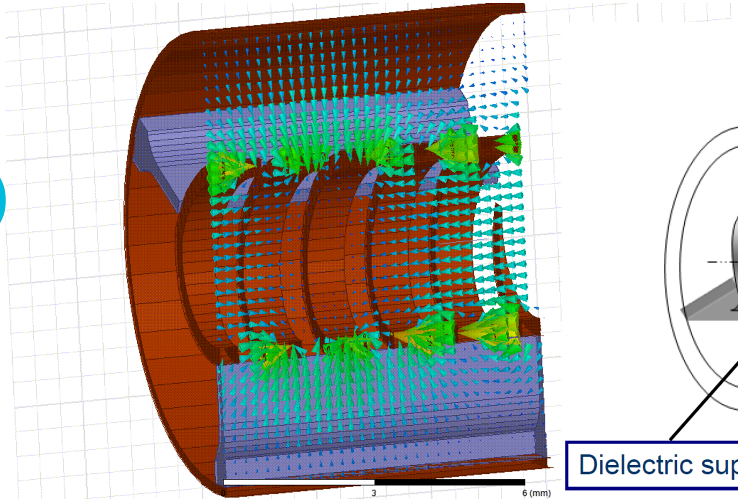
- Manufacturing sensitivity
- Ease of integration (attenuators / couplers / size)
- Oscillation points, parasitic modes

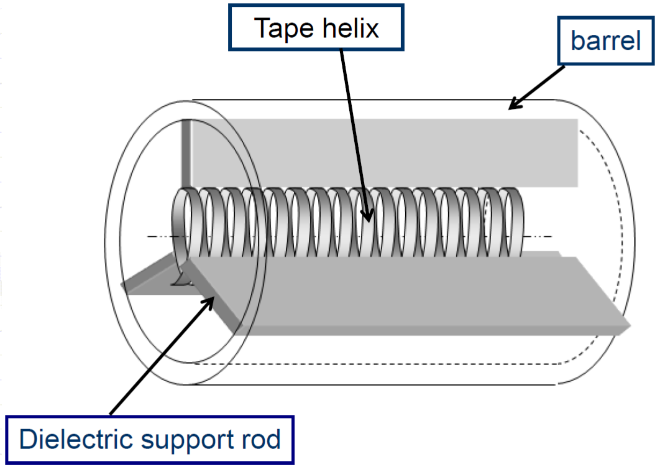
Helix: Concept

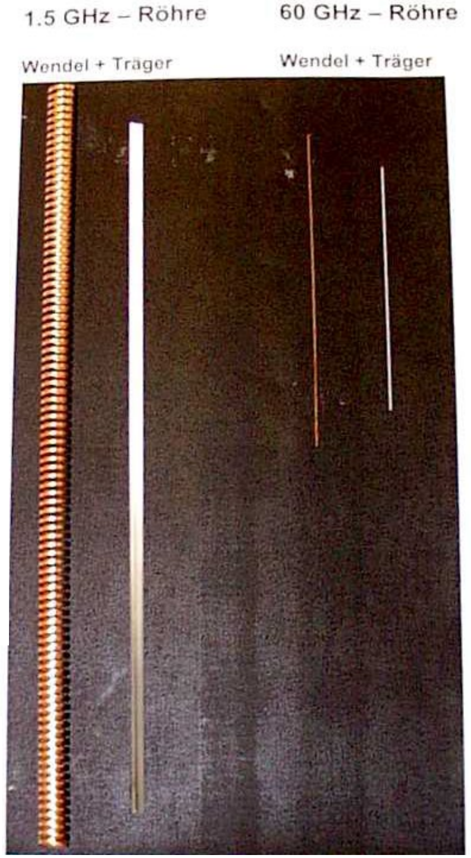
> Wire wound around mandrel to form helix

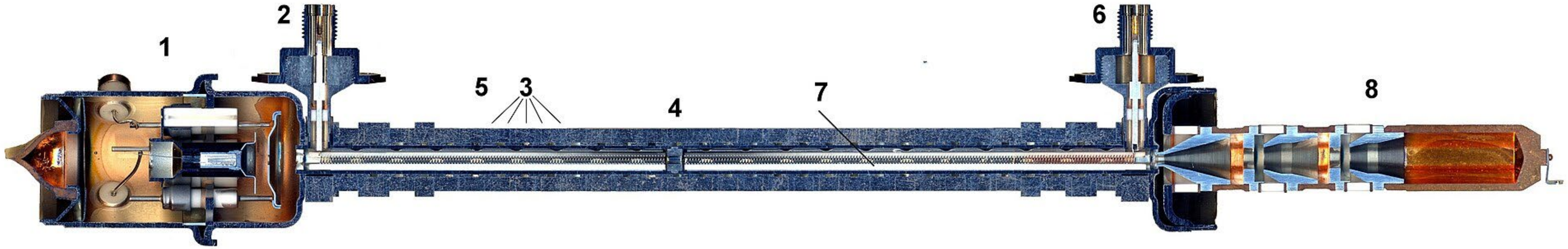
> Helix fixed in barrel by 3 ceramic rods (BN or BeO)

> RF wave slow-down by „detour“ along helix wire







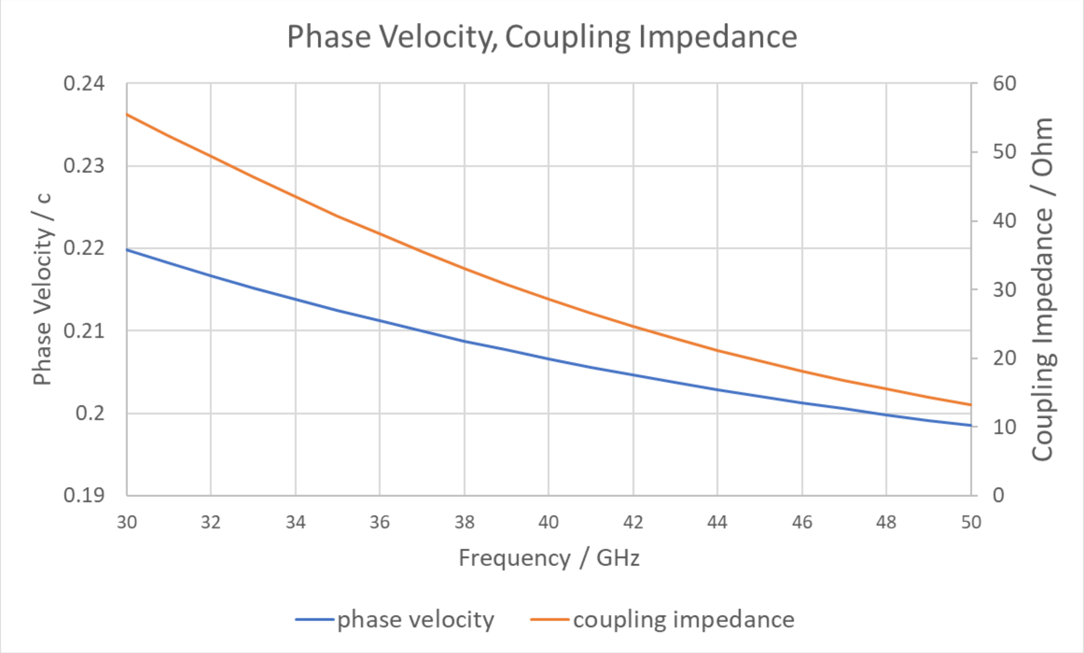


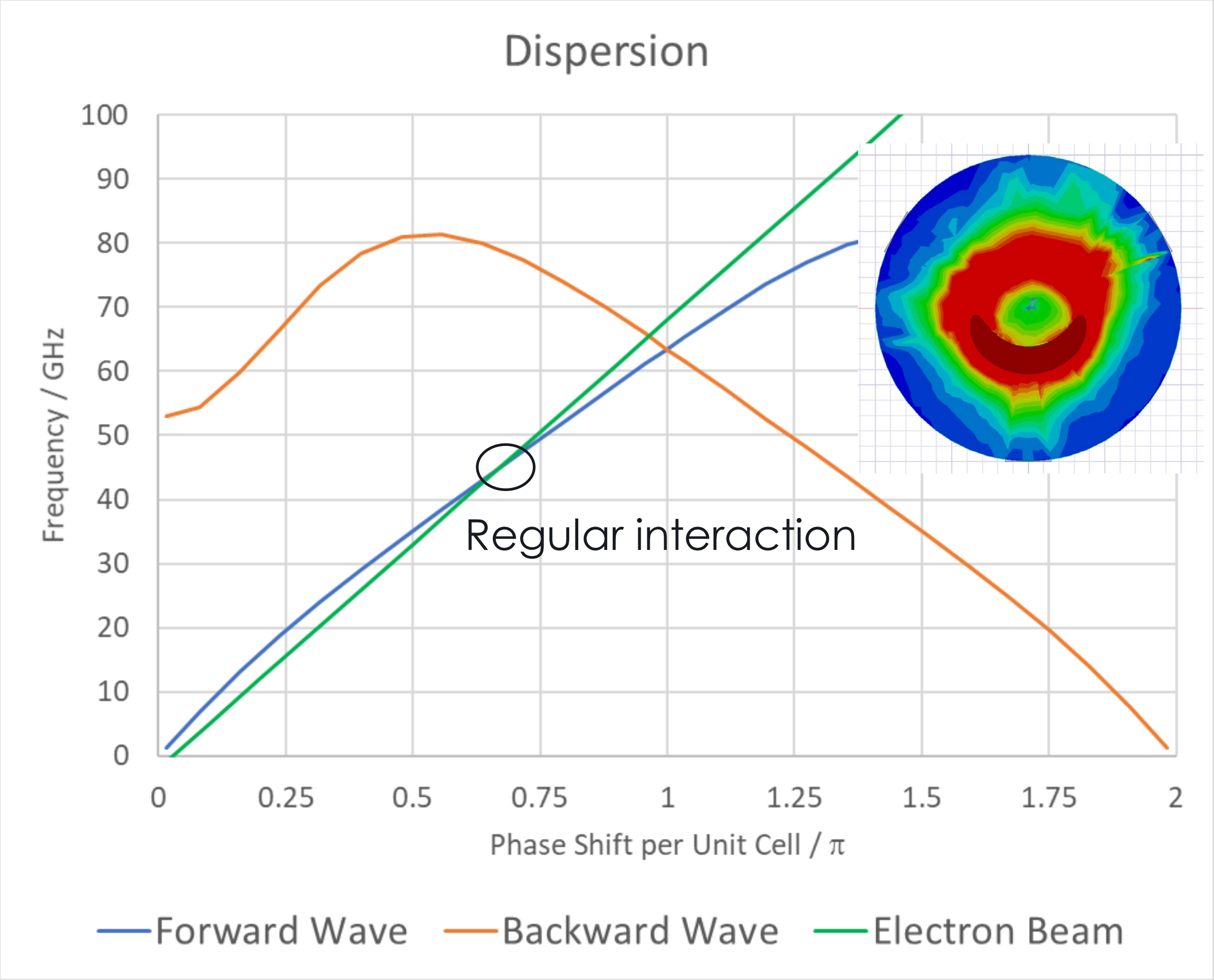
Helix: Electric Properties (Ex.: Q-Band)

> Low dispersion, high bandwidth

- Coupling impedance change ~25% over 10% BW

> Scales well to „low“ voltages (e.g. 9kV in Q-Band)





Helix: Hassle

> Fast mode: Second propagating mode between helix and barrel

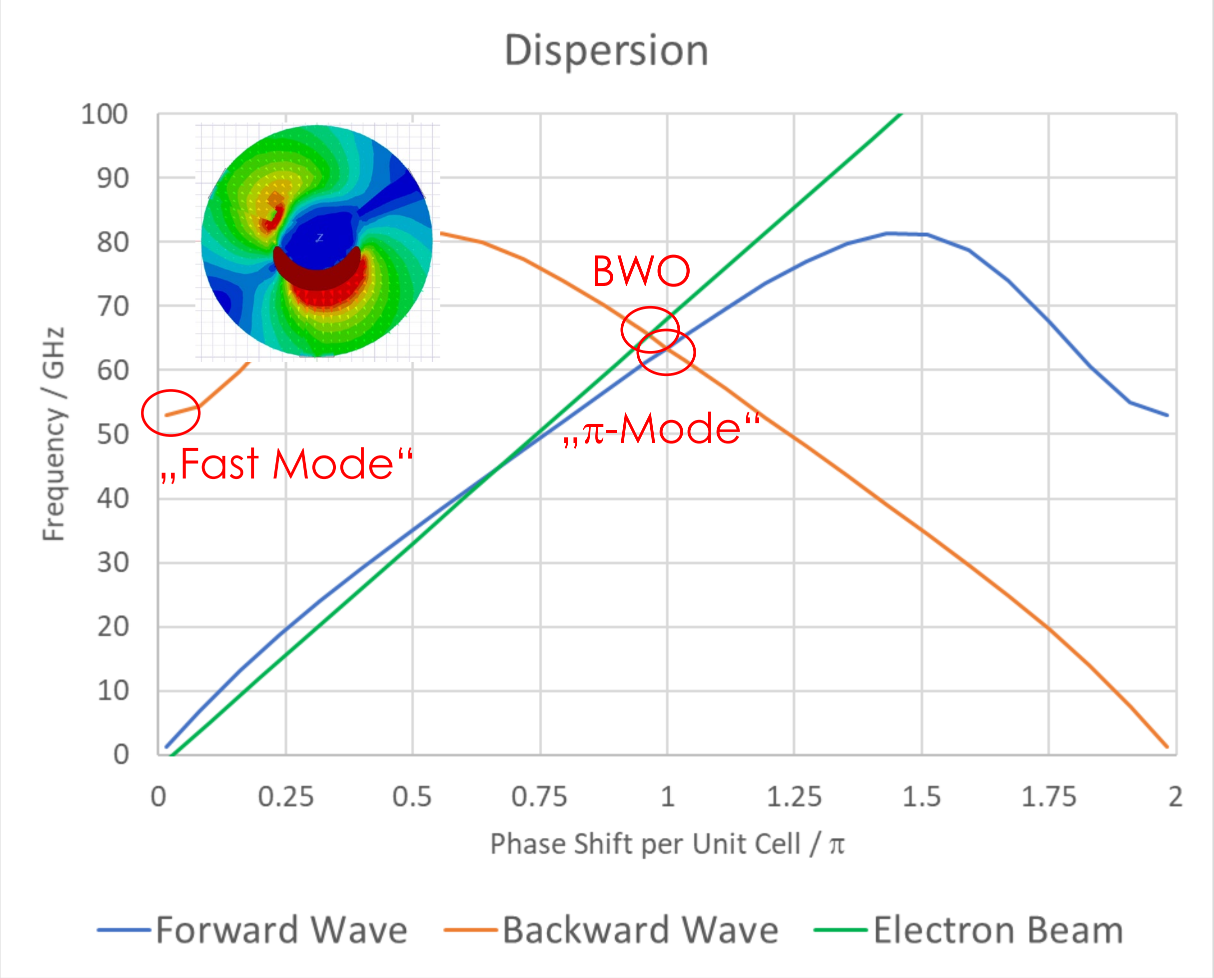
- Matching issues, limits barrel size

> BWO: Backward wave oscillations

- Interaction between backward travelling wave and forward travelling electron beam

> π-mode: Combined forward- and backward wave oscillations

- Coupling between forward and backward waves due to stop-band
- Both wave synchronous with electron beam
- Usually drive-induced



Helix: Limited by size

> Helix size scales with wavelength

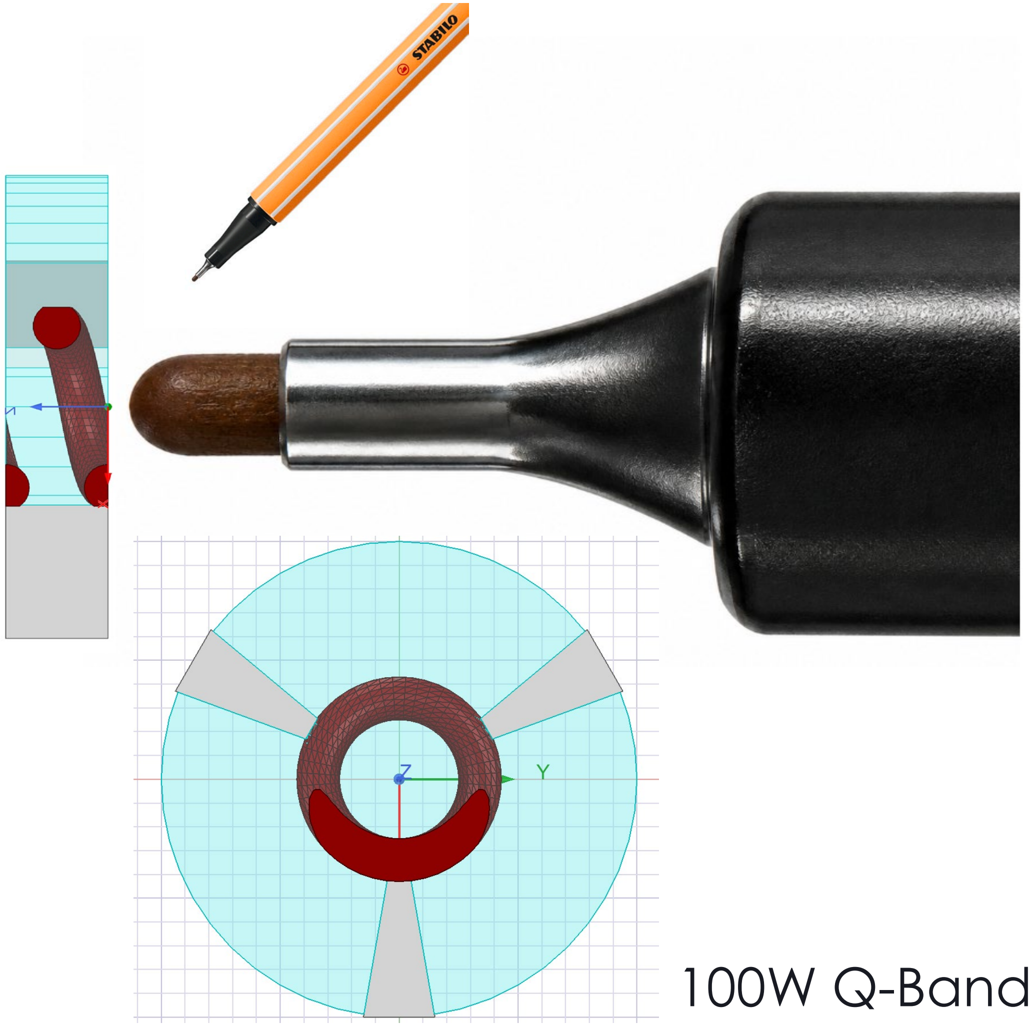
- High frequencies: Coupling impedance quickly decreases with distance from wire

> Small helix size limits thermal capability

> Barrel size limited by fast mode

> Current helix limits:

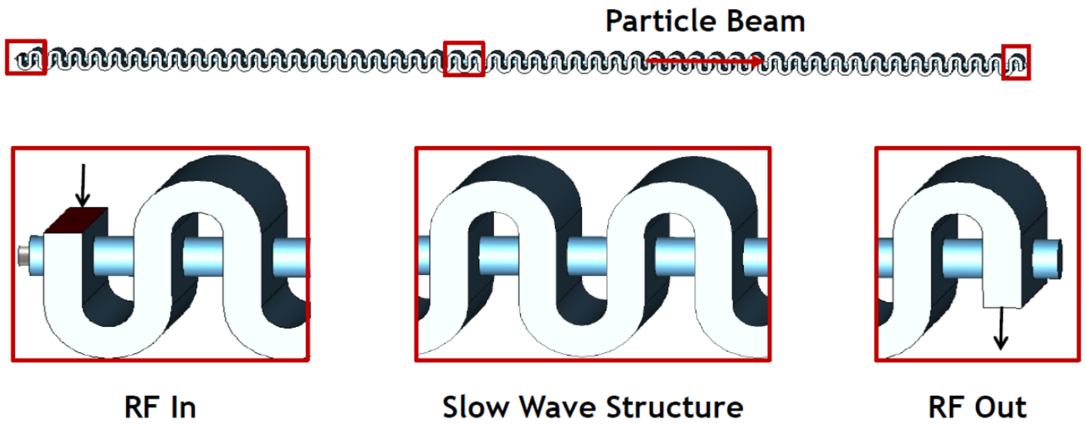
- 500 W in S-Band
- 5 kW in X-Band (pulsed)
- 300 W in Ku-Band
- 250 W space / 500 W ground in Ka-Band
- 80 W at Q-Band (42.5 GHz) for space TWTs (Thales)
- 250 W at V-Band (52 GHz) for ground TWTs (NEC)

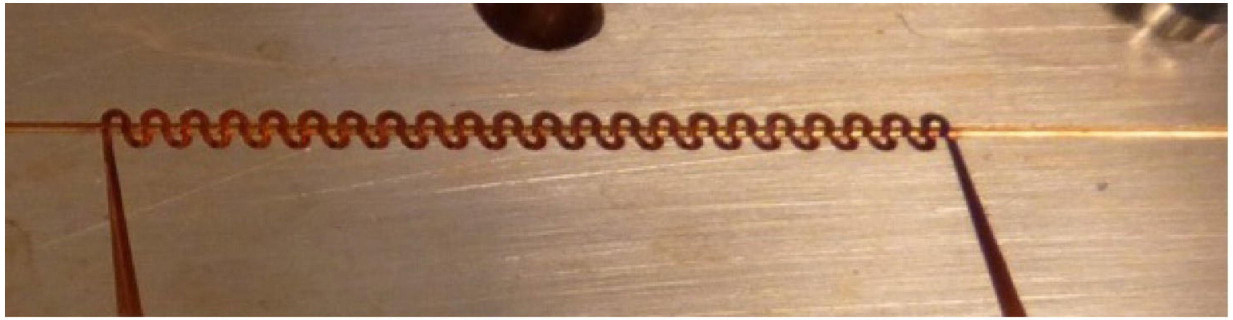


100W Q-Band Helix

Folded-Waveguide Delay Line

- > Rectangular waveguide folded into a serpentine pattern with central beam tunnel
- > Much better thermal capacity than helix (larger size, no support rods necessary)
- > Easier manufacturing at higher frequencies (Thales: 94 GHz 100W prototype)
- > Limited bandwidth, high dispersion, varied and interesting oscillation modes





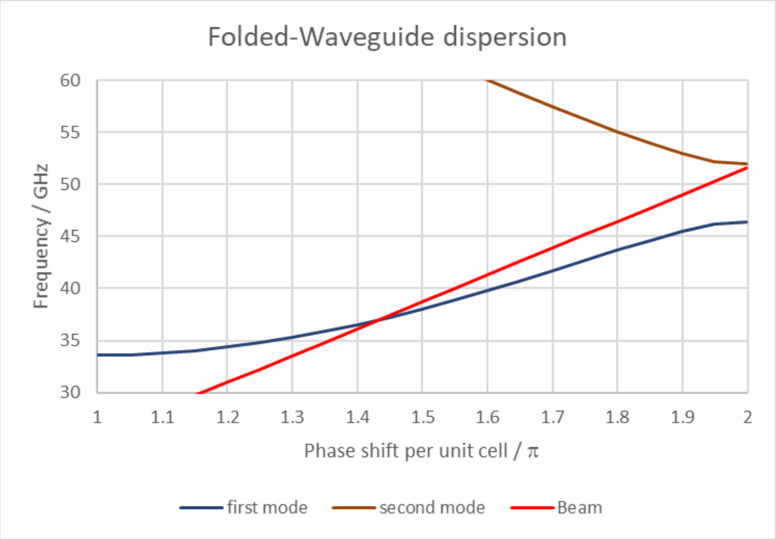
Paoloni, C., Gamzina, D., Letizia, R., Zheng, Y., & Luhmann, N. C. (2021). Millimeter wave traveling wave tubes for the 21st Century. *Journal of Electromagnetic Waves and Applications*, *35*(5), 567–603. https://doi.org/10.1080/09205071.2020.1848643

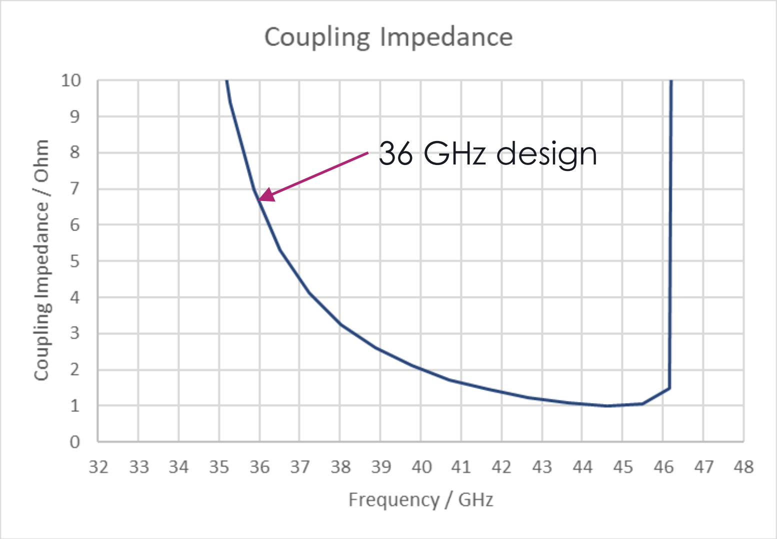
Folded-Waveguide Delay Line: Dispersion

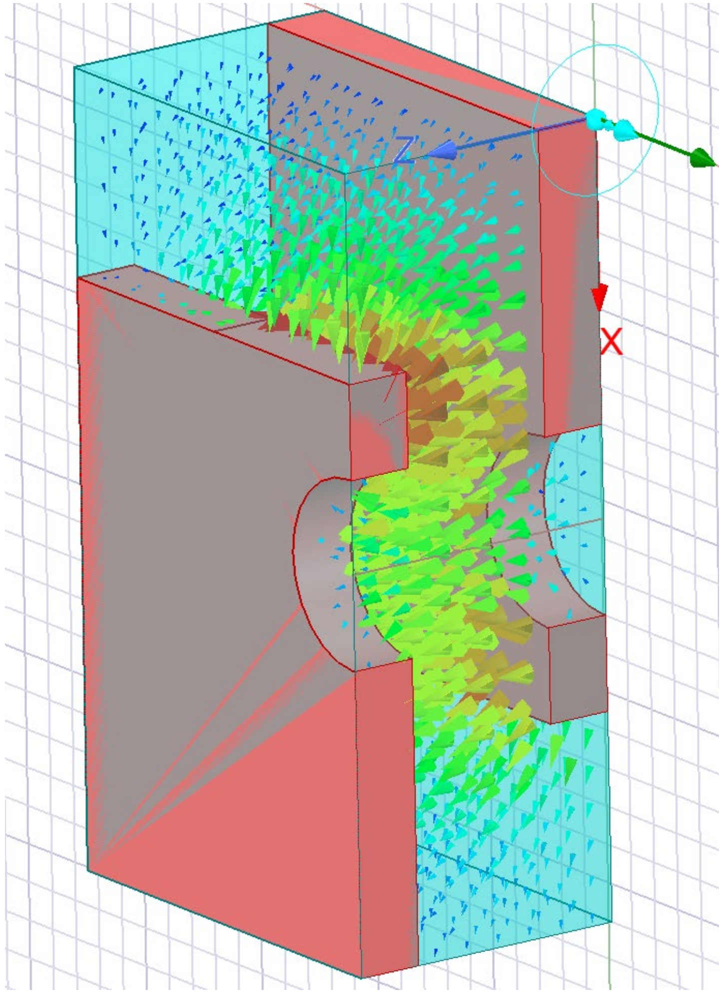
> **TE01 mode with cut-off determined by half-wavelength (e.g. 4.6mm for 36 GHz design)**

> **Bandwidth limitation by sharp drop in coupling impedance**

- Phase velocity dispersion can be controlled







Folded-Waveguide Delay Line: Hassle

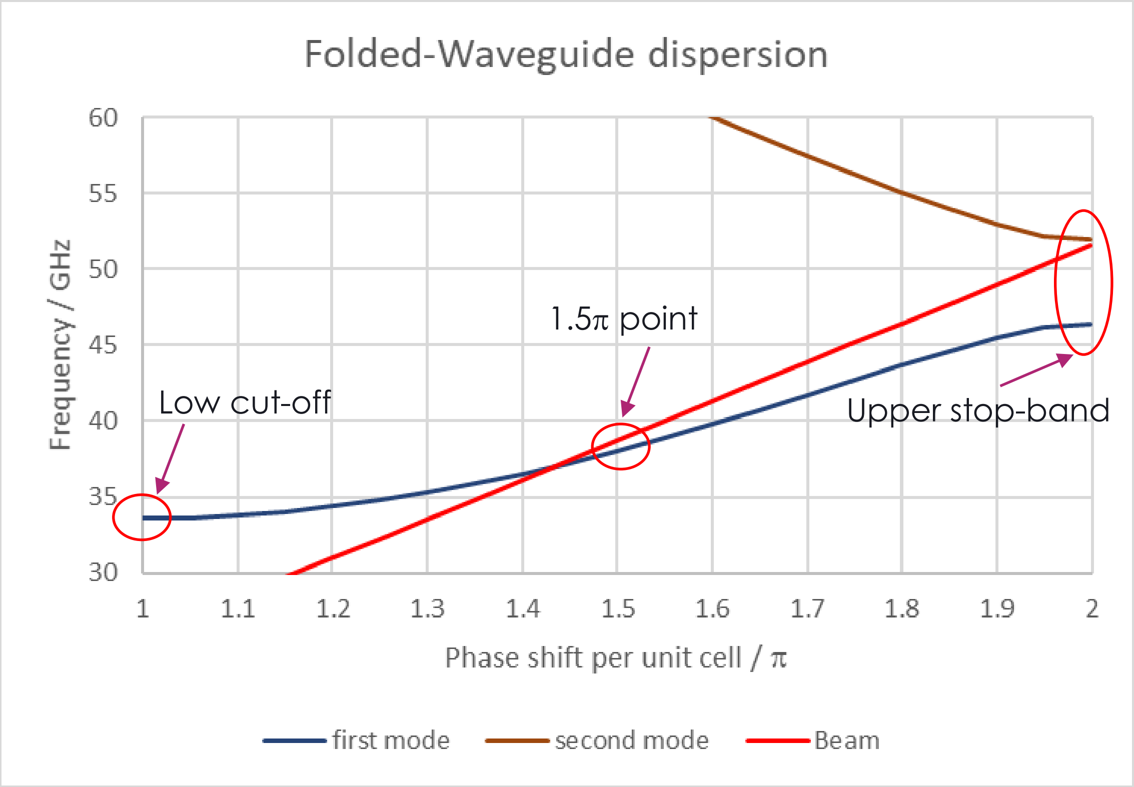
> **Lower Cut-Off: Oscillation risk due to low group velocity**

> **1.5π-point: Oscillation risk due to possible stop-band**

> **Upper cut-off / stop-band: Oscillation risk due to low group velocity**

- Possibly drive-induced

> **Relatively large footprint limits magnetic focusing field**



Double-Comb FWG Delay Line

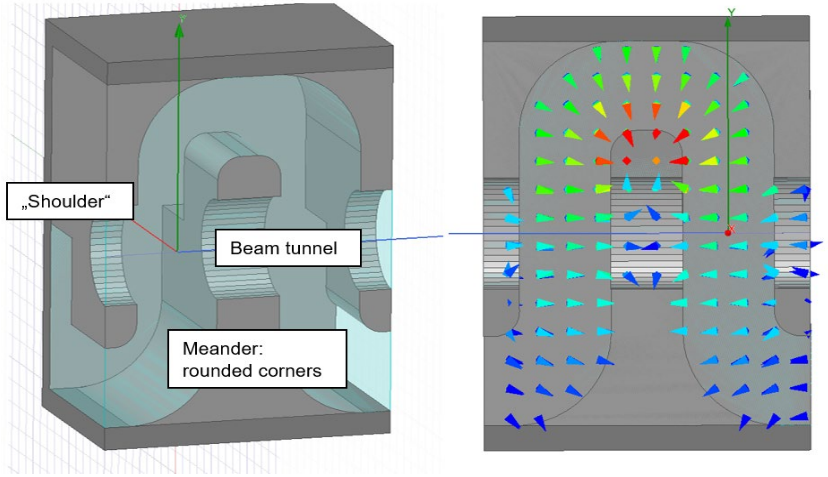
> **Similar-looking to FWG, but including „shoulder“ cut-outs**

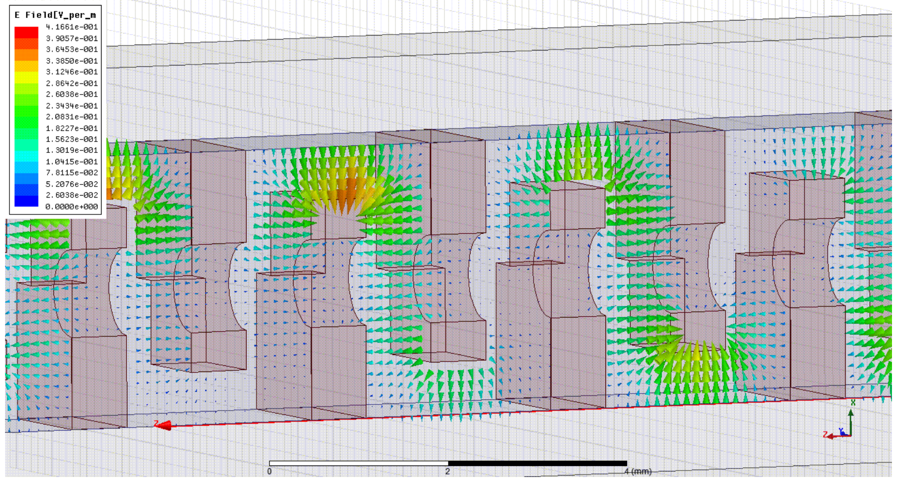
- Actually a coupled-resonator line

> **Similar performance to FWG, but much more compact**

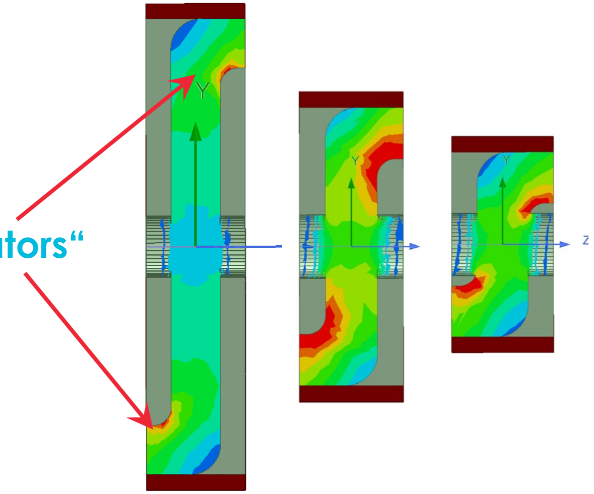
- ~ 66% of FWG cross-section, stronger focusing fields possible

> **More flexible: Selectable attenuation, less sensitive to oscillation**





„resonators“



Coupled resonators
-> Passband

Double-Comb FWG Delay Line: Dispersion and Hassle

> Elevated 1.5π–point (larger bandwidth)

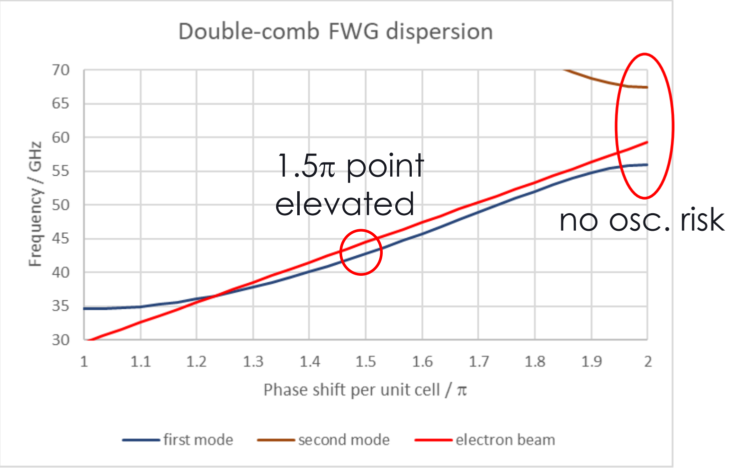
> No oscillation risk @ upper stop-band

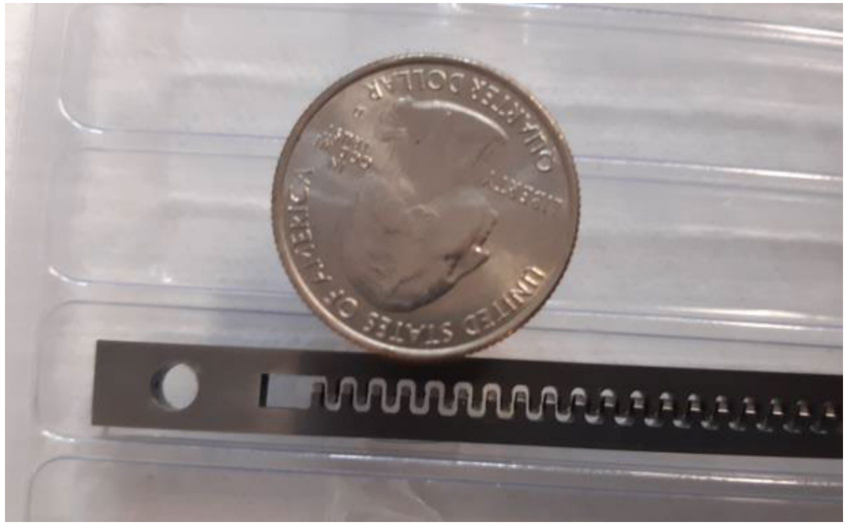
> Manufacturing:

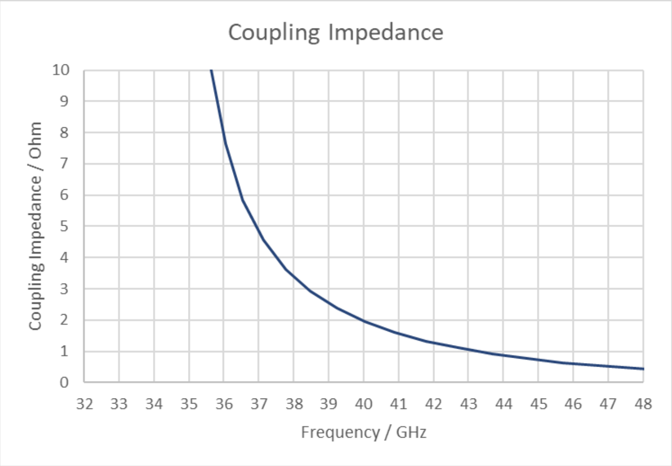
- Electro-Erosion for FWG profile
- Milling for shoulder cut-outs (very sensitive)

> DC FWG variations:

- 1 kW @ 36 GHz (series)
- 2 kW @ 36 GHz (prototype)
- 400 W @ 36 GHz (space)
- 500 W @ 50 GHz (CW)







Comparison Helix – FWG – Double Comb FWG

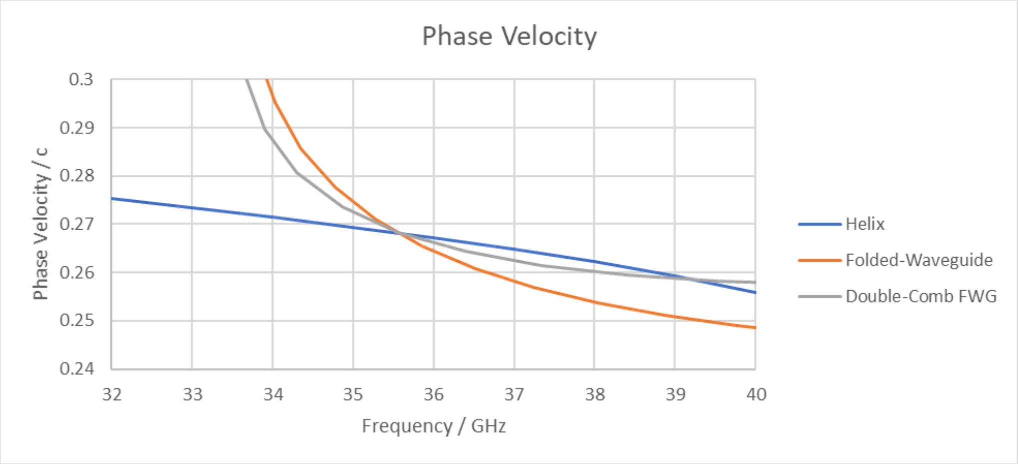
> Example: 36 GHz TWT with 1mm beam tunnel and ~19kV beam voltage

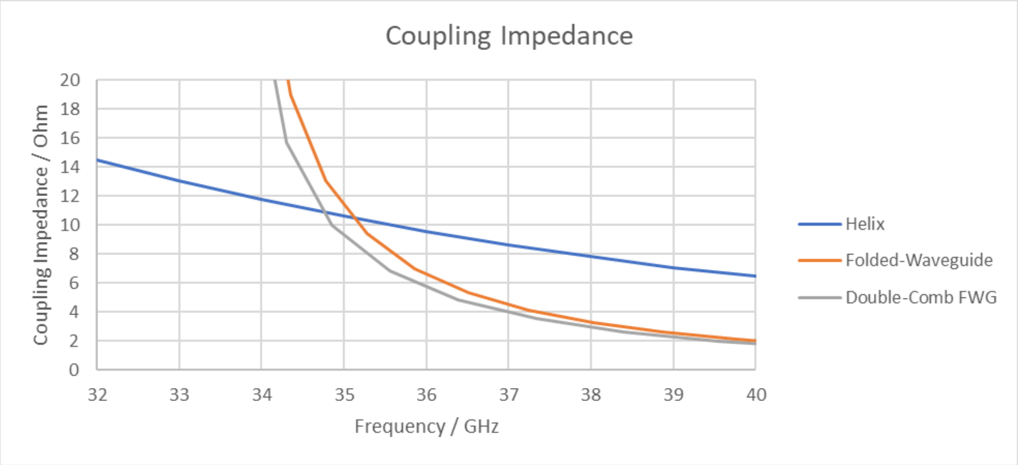
- Helix: 0.2mm by 0.4mm wire, pitch 1.13mm, BN support rods, 4mm barrel

> Helix: Coupling impedance ~ 50% higher, much more broad-band

> FWG / Double-Comb FWG: Coupling impedance very similar

> Double-Comb FWG less dispersive than pure FWG





Comparison Helix – FWG – Double Comb FWG

Parameter	Delay Line		
	Helix	FWG	Double-Comb FWG
Bandwidth	Easily 20%	Up to 10%	Up to 10%
Coupling impedance	High	Medium	Medium
Frequency range	Max. 45 GHz (80 W space) Max. 52 GHz (250 ground) Limited by manufacturing and/or power handling	30 GHz to THz	30 GHz to 55 GHz Limited by manufacturing
Scaling to high power (> 500 W)	Difficult	Good	Good
Scaling to low power (< 100 W)	Good	Medium	Difficult

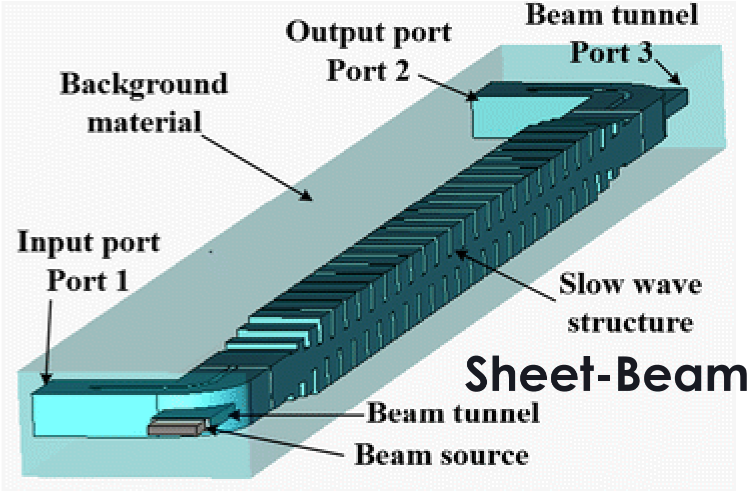
Outlook

> **Sheet beam delay lines: flat rectangular electron beams**
- Higher power, higher efficiency, but focusing difficult

> **Electrically large delay lines (e.g. Gyro TWTs)**

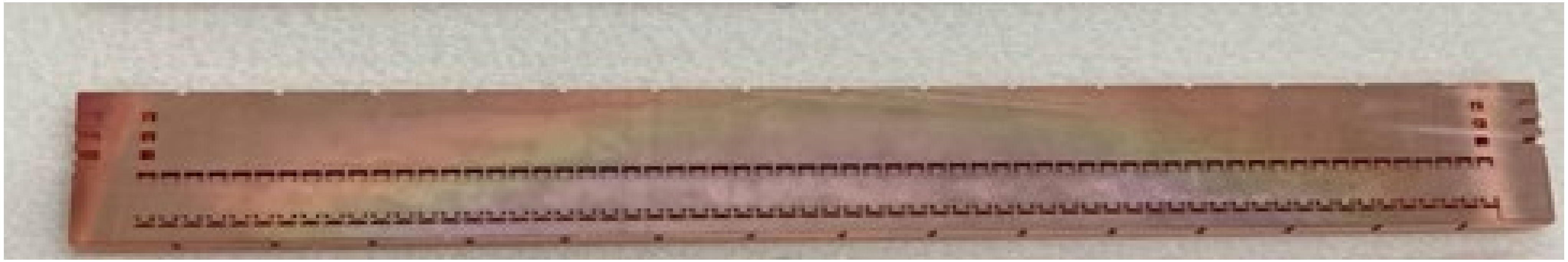
> **New fabrication methods (LIGA, printing…)**

> **Multiple FWG-type structures being investigated**



Sheet-Beam FWG

Wang, Zhan-Liang et.al.(2016). Study on Ka-Band Sheet Beam Traveling Wave Tube Focused by Closed PCM. Journal of Infrared, Millimeter, and Terahertz Waves. 37. 10.1007/s10762-016-0247-z.



LIGA- Manufactured FWG

Thank you

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