FY'12 MURI
Transformational Electromagnetics
MTMs design
MTMs design and characterization, antennas
High Power VEDs, MTMs, plasma diagnostics
VEDs, MTMs

Degenerate band edge oscillator (DBEO)

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University of California, Irvine

Collaboration with

Edl Schamiloglu, Christos Christodoulou
S. Yurt, X. Pan, Y. Atmatzakis

UNM Electrical & Computer Engineering

May 6, 2016

Outline and Summary

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- ❑ Degenerate band edge (DBE) in slow-wave structures
- ❑ Progress in cold test study of DBE in metallic waveguide (collaboration with UNM*)
- ❑ Low starting current calculations for DBE oscillators (DBEO)
- ❑ All metallic slow-wave structures (SWSs) with DBE
- ❑ Preliminary PIC calculations for the interaction between an SWS with DBE and electron beam (collaboration with UNM**)
- ❑ Conclusion

**** Collaboration with X. Pan, G. Atmatzakis and Prof. C. Christodoulou,*** **ECE Department, University of New Mexico**

***** Collaboration with S. Yurt, and Prof. E. Schamiloglu,*** **ECE Department, University of New Mexico**

Publications

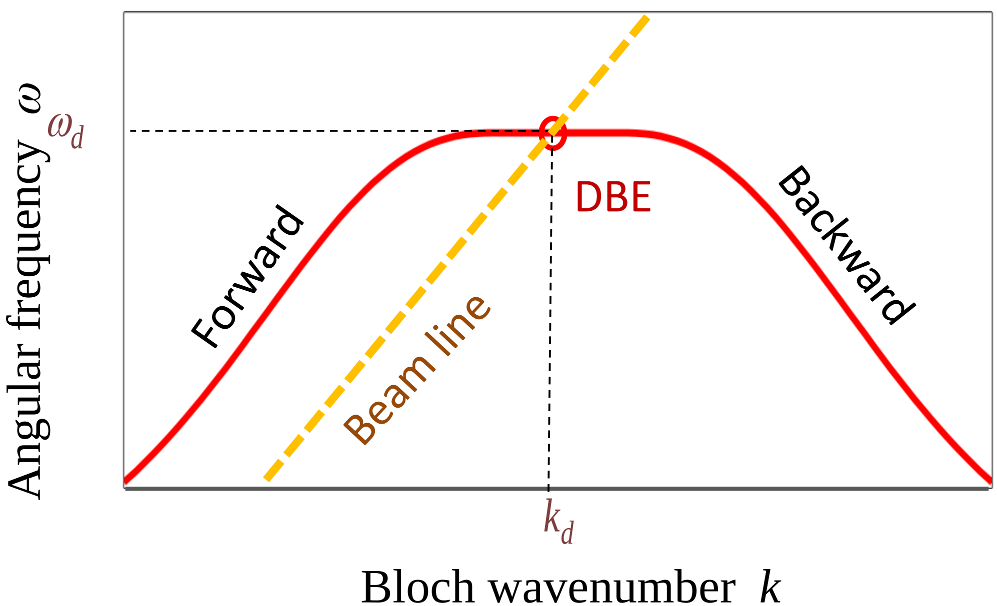
University of California, Irvine

1) A. Figotin and G. Reyes, “Multi-transmission-line-beam interactive system,” *J. Math. Phys.*, vol. 54, no. 11, p. 111901, 2013. [Link]
2) V. A. Tamma and F. Capolino, “Extension of the Pierce Model to Multiple Transmission Lines Interacting With an Electron Beam,” *IEEE Trans. Plasma Sci.*, vol. 42, no. 4, pp. 899–910, Apr. 2014. [Link]
3) M. A. K. Othman and F. Capolino, “Demonstration of a Degenerate Band Edge in Periodically-Loaded Circular Waveguides,” *IEEE Microw. Wirel. Compon. Lett.*, vol. 25, no. 11, 2015. [Link]
4) A. Figotin and G. Reyes, “Lagrangian variational framework for boundary value problems,” *J. Math. Phys.*, vol. 56, no. 9, p. 093506, 2015. [Link]
5) M. A. K. Othman, F. Yazdi, A. Figotin, and F. Capolino, “Giant gain enhancement in photonic crystals with a degenerate band edge,” *Phys. Rev. B*, vol. 93, no. 2, p. 024301, Jan. 2016. [Link]
6) V. A. Tamma, A. Figotin, and F. Capolino, “Concept for Pulse Compression Device Using Structured Spatial Energy Distribution,” *IEEE Trans. Microw. Theory Tech.*, vol. 64, no. 3, pp. 742–755, Mar. 2016. [Link]
7) M. A. K. Othman, M. Veysi, A. Figotin, and F. Capolino, “Giant Amplification in Degenerate Band Edge Slow-Wave Structures Interacting with an Electron Beam,” *Phys. Plasmas 1994-Present*, vol. 23, no. 3, p. 033112, Mar. 2016.[Link]
8) M. A. K. Othman, V. A. Tamma, and F. Capolino, “Theory and New Amplification Regime in Periodic Multi Modal Slow Wave Structures with Degeneracy Interacting with an Electron Beam,” *IEEE Trans Plasma Sci*, vol. 44, no. 4, pp. 594 – 611, April 2016. [Link]
9) M. A. K. Othman, M. Veysi, A. Figotin, and F. Capolino, “Low Starting Electron Beam Current in Degenerate Band Edge Oscillators,” *IEEE Trans Plasma Sci*, in print 2016. [Link]

Degenerate band edge (DBE)

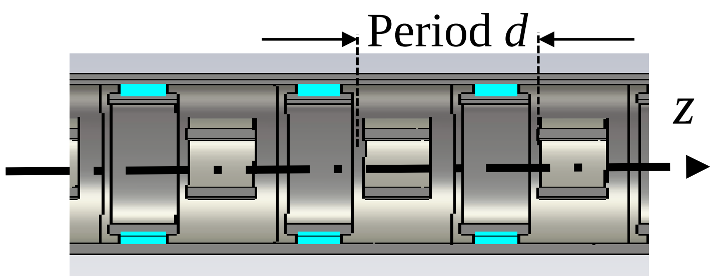
Waveguide structures can support a DBE, instead of only an RBE (regular band edge). At DBE, we have four degenerate modes

DBE dispersion $\left(\omega_d - \omega\right) \propto \left(k - k_d\right)^4$



$$k_d = \pi / d$$

Periodic slow-wave structure



Bloch waves

$$e^{j\omega t} e^{-jkz}$$

Figotin, Vitebskiy, *Phys. Rev. E*, vol. 72, no. 3, p. 036619, Sep. 2005.

Othman, Capolino, *IEEE Microw. Wirel. Compon. Lett.*, vol. 25, no. 11, 2015

Four mode synchronization

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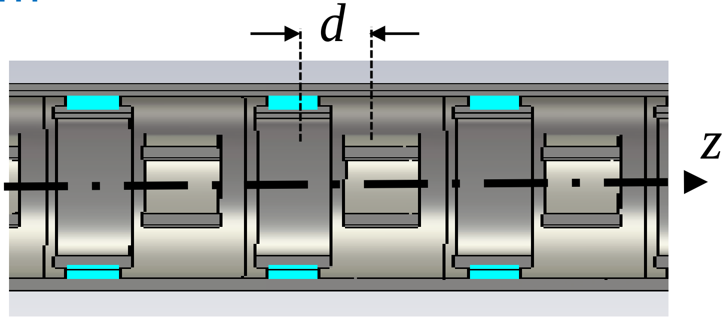
Dispersion relation for SWS with DBE and e-beam

$$\left[(\omega_d-\omega)-h(k-k_d)^4\right]\left[\omega-u_0k\right]^2=C(\omega,k,I_0)$$

Four EM modes — e-beam — coupling

Periodic waveguide with DBE

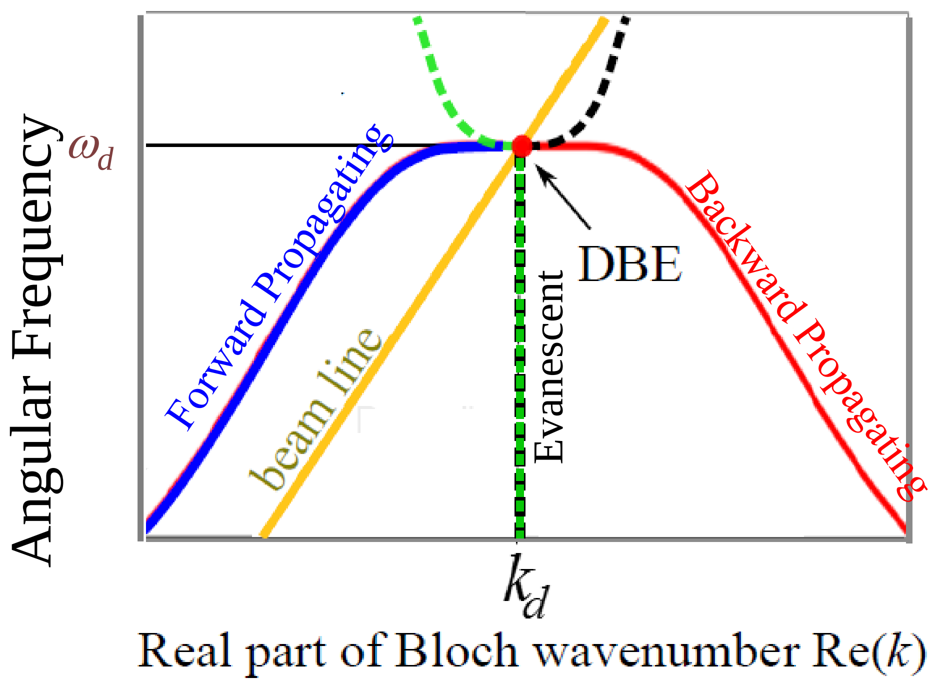


Bloch waves $e^{j\omega t}e^{-jkz}$

Four mode super synchronization

$$u_0 \approx \frac{\omega_d}{k_d}$$

u_0 : electron's average velocity



$k_d=\pi/d$

Othman, Veysi, Figotin, Capolino, "Giant amplification in degenerate band edge slow-wave structures interacting with an electron beam," *Phys. Plasmas*, Vol. 23, No. 3, 033112, 2016.

Othman, Tamma, Capolino, "Theory and New Amplification Regime in Periodic Multi Modal Slow Wave Structures With Degeneracy Interacting With an Electron Beam," *IEEE Trans. on Plasma Science*, Vol. 4, No. 4, 2016.

Slow wave structures with DBE

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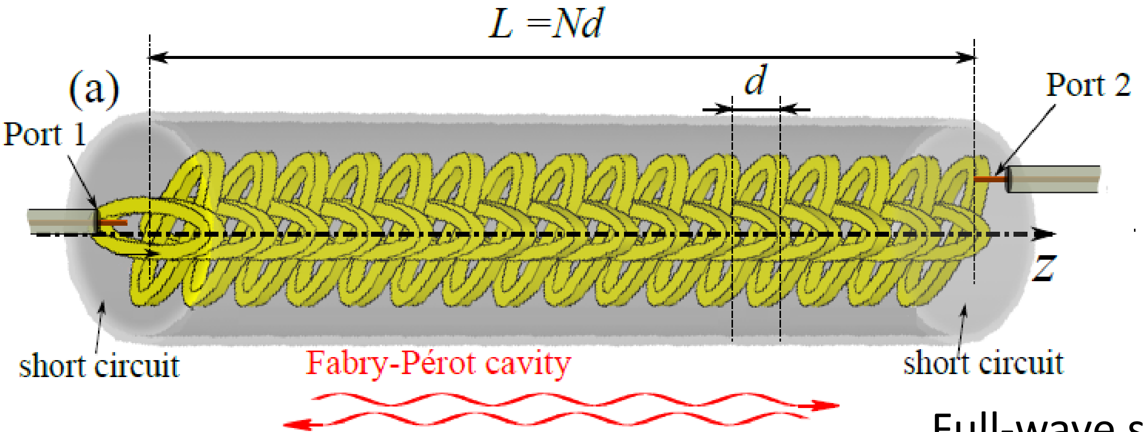
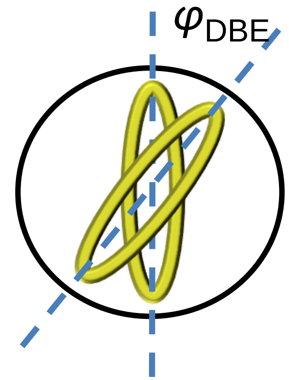




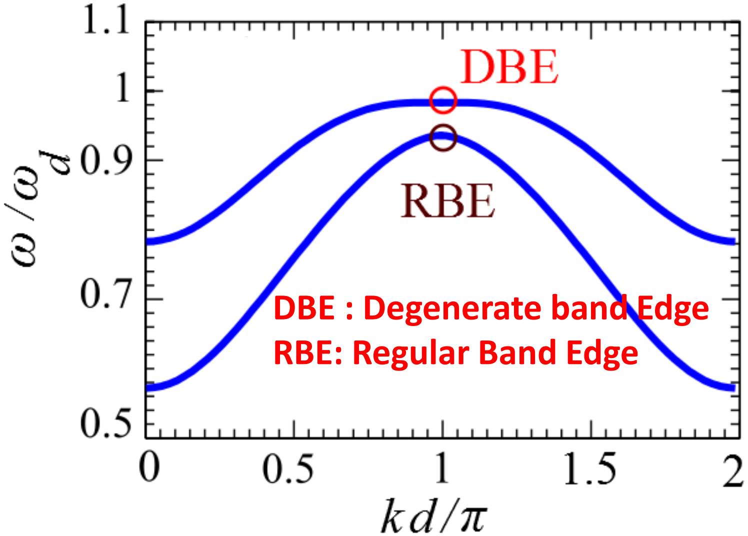
Full-wave simulations (CST Microwave Studio)

DBE Frequency 2.1 GHz

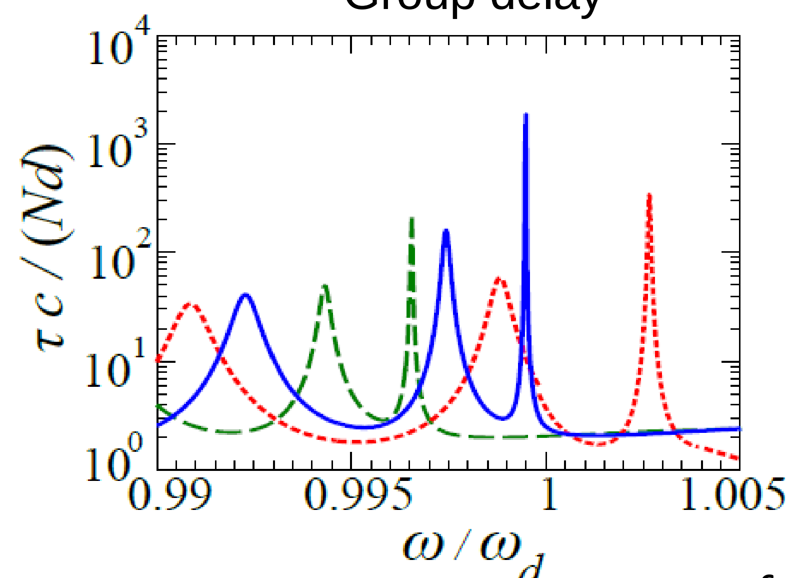
$\varphi_{\mathrm{DBE}} \sim 68^{o}$

φ_{DBE} $0.95\varphi_{\mathrm{DBE}}$ $1.05\varphi_{\mathrm{DBE}}$

Dispersion diagram



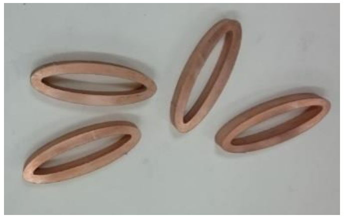
Group delay



M. A. K. Othman, M. Veysi, A. Figotin and F. Capolino, Low starting electron beam current in degenerate band edge oscillators",*IEEE Trans. Plasma Science*, in print 2016.

Waveguide fabrication and cold test

Copper rings

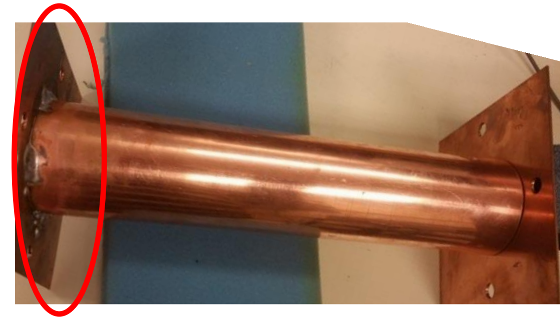


+

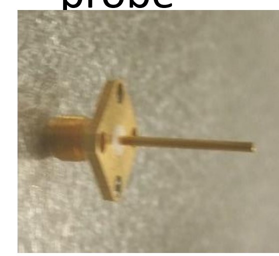
Circular waveguide

Foam support for rings

Waveguide flanges



probe

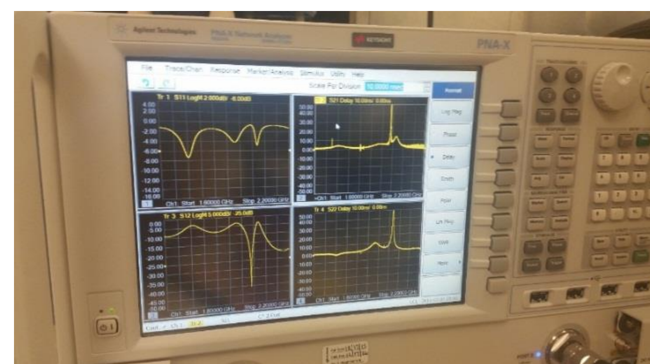


S-parameters measurement done using KEYSIGHT N5247A PNA-X Microwave Network Analyzer

Different lengths of SWS

Measurements:

1- Reflection and transmission parameters
2- Group delay
3- Dispersion relation



Collaboration with UNM, **Christos Christodoulou, X. Pan, Y. Atmatzakis, UNM**

Cold test: 1 port, S-parameters

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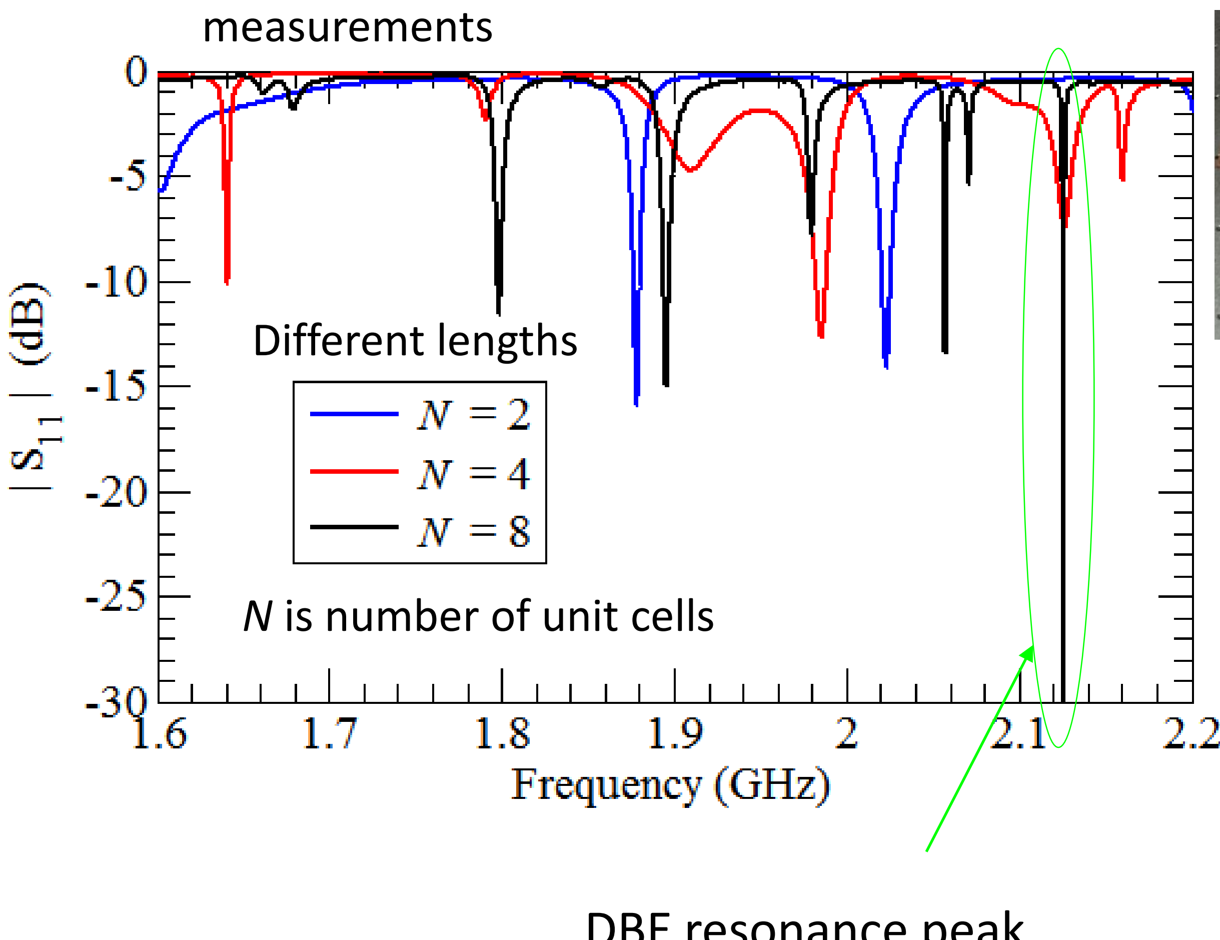
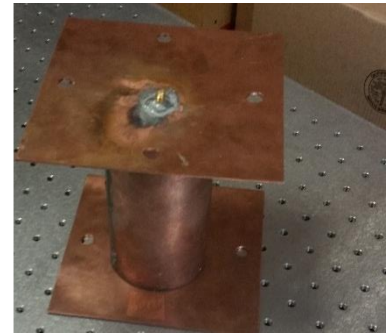
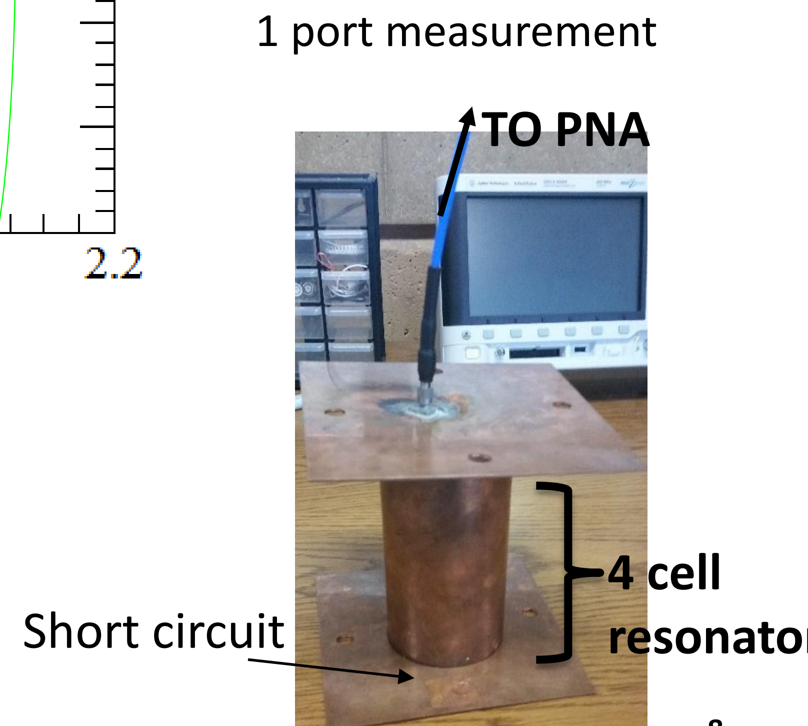


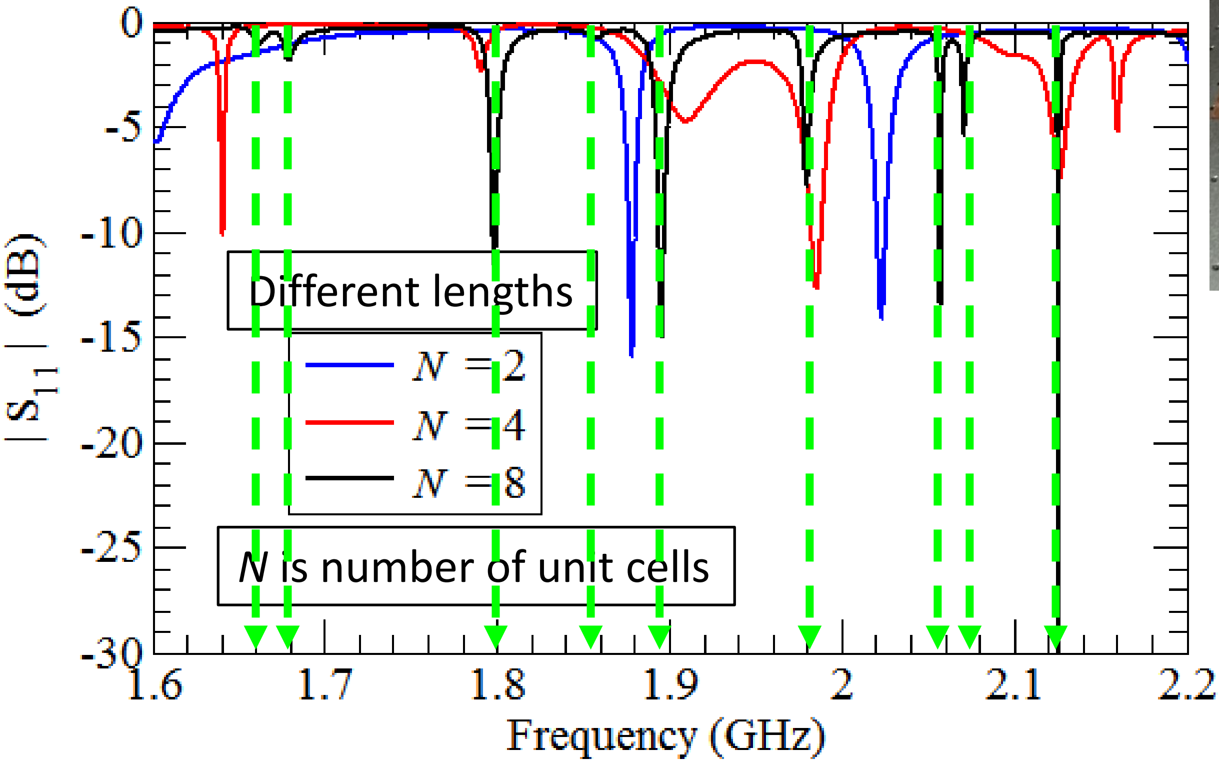


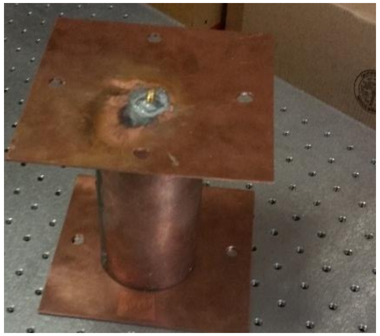


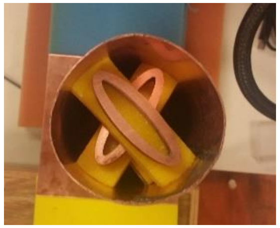
- Only measuring S11 (the end of the waveguide is shorted)
- |S11| < 0 dB means coupling to losses in the waveguide

Cold test: resonances

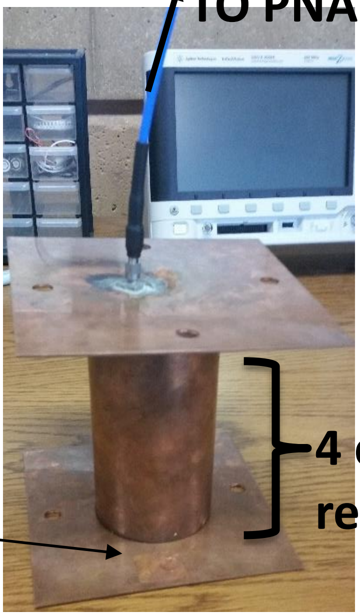
Number of resonances= *N* +1, *N* = number of cells







1 port measurement



9 resonances are extracted from measurements for the 8 cell resonator

- Resonance frequencies are used to synthesize the dispersion relation of the periodic waveguide

Measurement of dispersion relation

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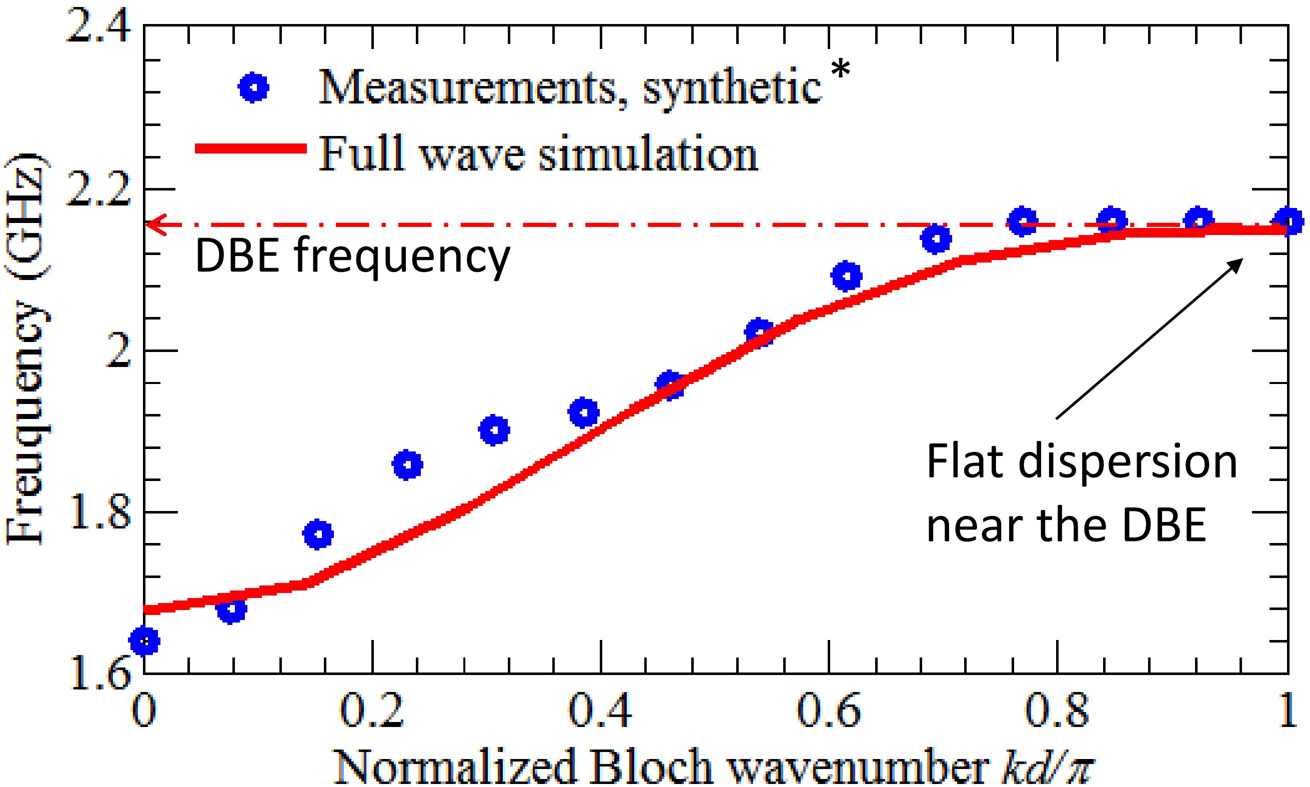

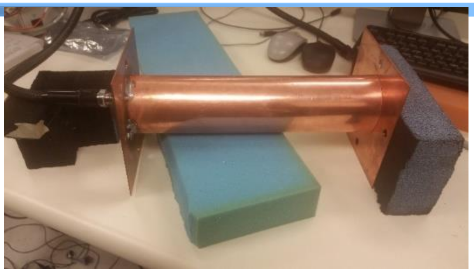

1 port measurement

- Good agreement between full-wave simulations (CST) and measurements
- Other measurements (quality factor, delay, etc) have been also carried out, confirming the existence of DBE

* Guo, et al. "A novel highly accurate synthetic technique for determination of the dispersive characteristics in periodic slow wave circuits." *IEEE Trans. Microwave Theory Techniq.* 40.11 (1992).

Extension of Pierce theory to CTL

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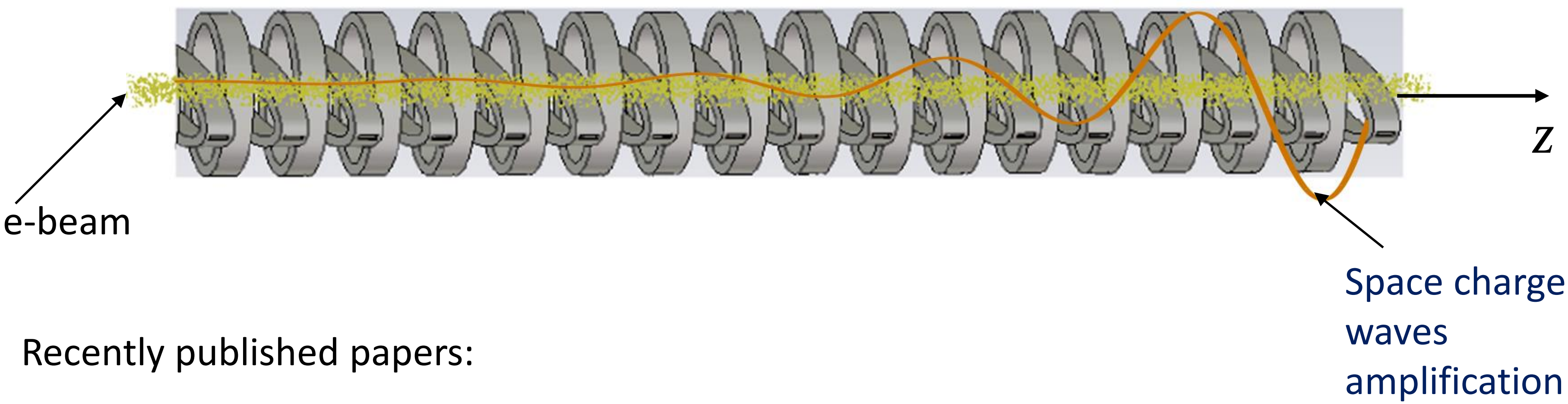
Coupled Transmission Lines (CTL) formalism*

- ❑ At DBE, four degenerate modes interact (synchronized) with the electron beam
- ❑ The interactive system can be modeled using generalized Pierce theory [1–3]. DBE is associated with giant gain and low-start current



Recently published papers:

1. **Othman, Veysi, Figotin, Capolino, "Giant amplification in degenerate band edge slow-wave structures interacting with an electron beam," *Phys. Plasmas*, Vol. 23, No. 3, 033112, Mar. 2016.**
2. **Othman, Tamma, Capolino, "Theory and New Amplification Regime in Periodic Multi Modal Slow Wave Structures With Degeneracy Interacting With an Electron Beam," *IEEE Trans. on Plasma Sci*, Vol. 4, No. 4, April. 2016.**
3. **Othman, Veysi, Figotin, Capolino, "Low Starting Electron Beam Current in Degenerate Band Edge Oscillators," *IEEE Trans. Plasma Sci*, accepted, in print 2016. (in early access on IEEE Xplore)**

Degenerate band edge oscillator (DBEO)

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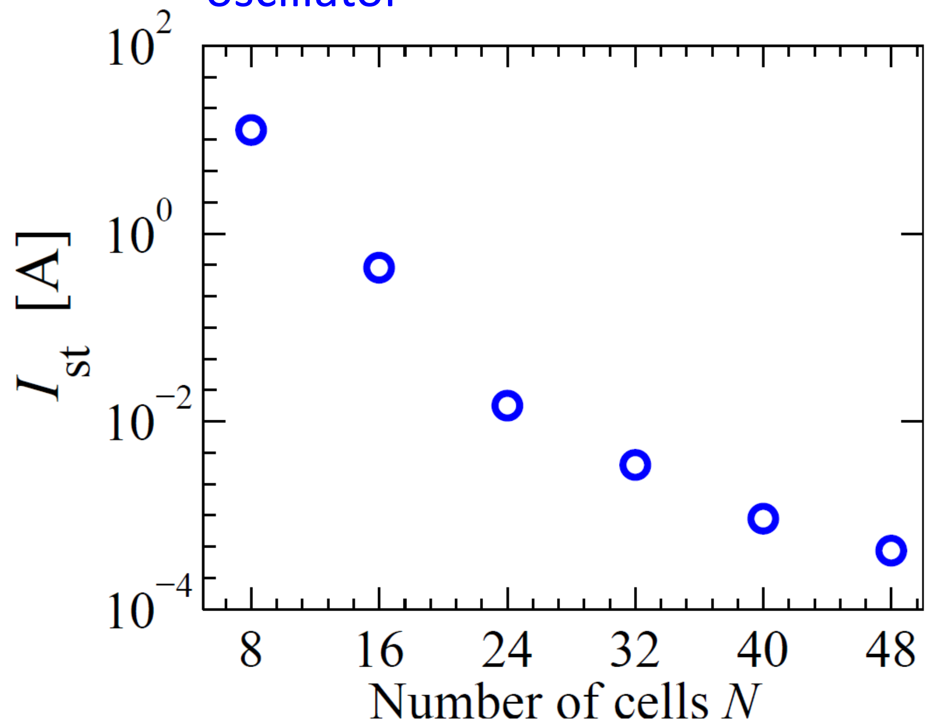
- The starting oscillation current I_{st} decreases with increasing DBEO length

DBEO: Degenerate band edge oscillator



Degenerate band edge oscillator (DBEO)

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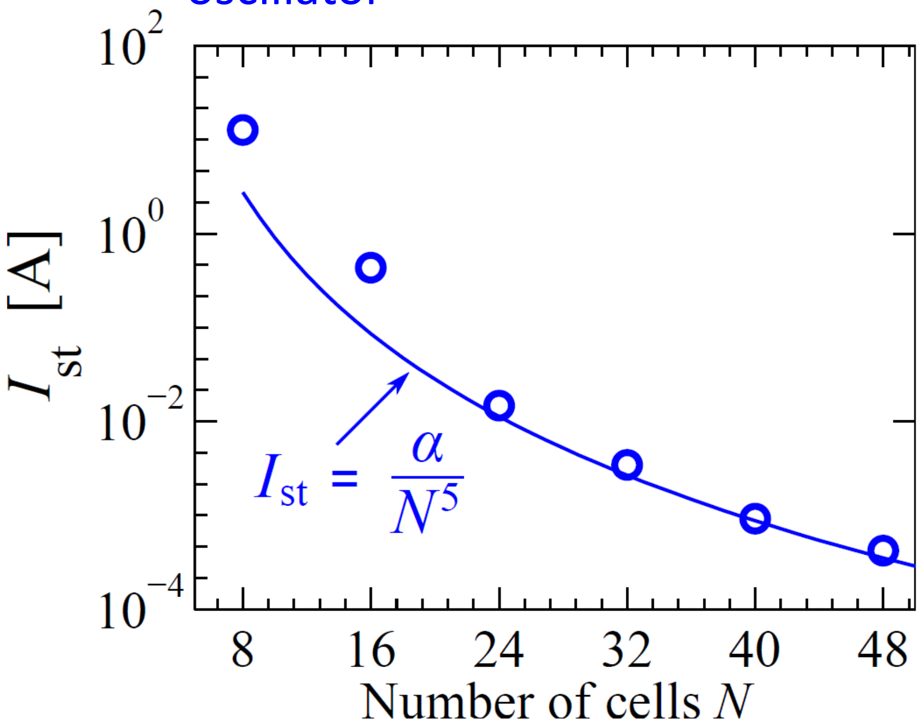
- The starting oscillation current I_{st} decreases with increasing DBEO length

- Scales as

$$I_{st} = \frac{\alpha}{N^5}, \quad N : \text{number of unit cells}$$

DBEO: Degenerate band edge oscillator



Degenerate band edge oscillator (DBEO)

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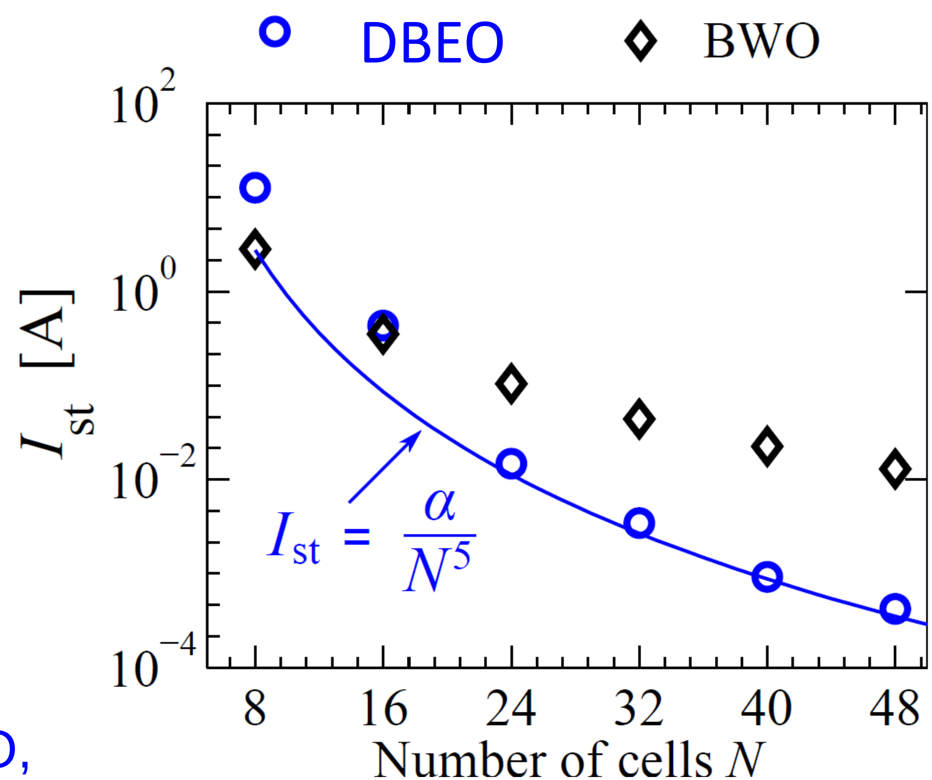


- Scales as

$$I_{st} = \frac{\alpha}{N^5}, \quad N: \text{number of unit cells}$$

- Compared to the conventional BWO, DBEO has lower starting current and better scaling

$$I_{st}(\text{BWO}) \propto \frac{1}{N^3}, \quad N: \text{number of unit cells}$$

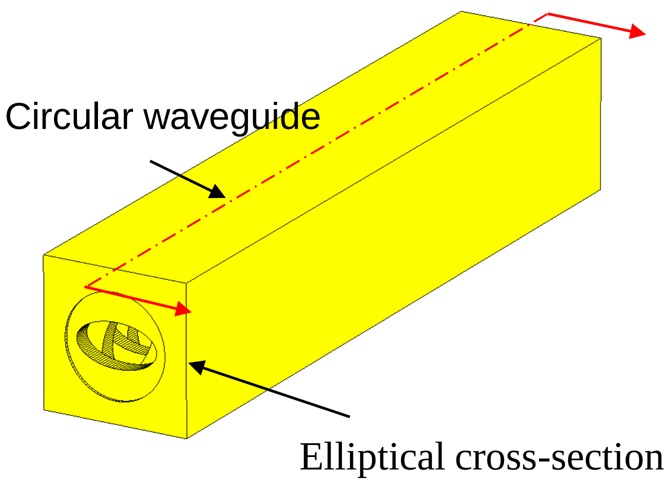
M. A. K. Othman, M. Veysi, A. Figotin and F. Capolino, "Low starting electron beam current in degenerate band edge oscillators", *IEEE Trans. Plasma Science*, in print 2016.

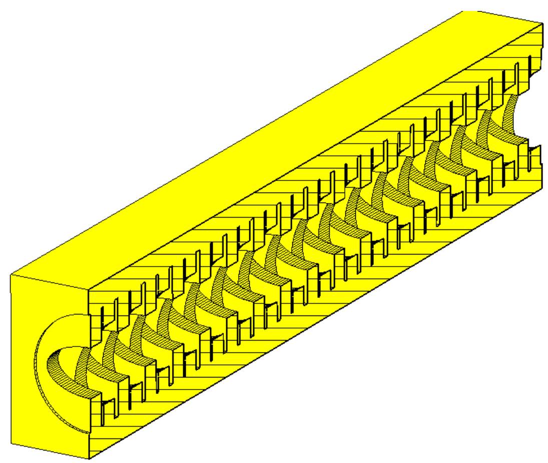
All-metallic SWS with DBE for high power

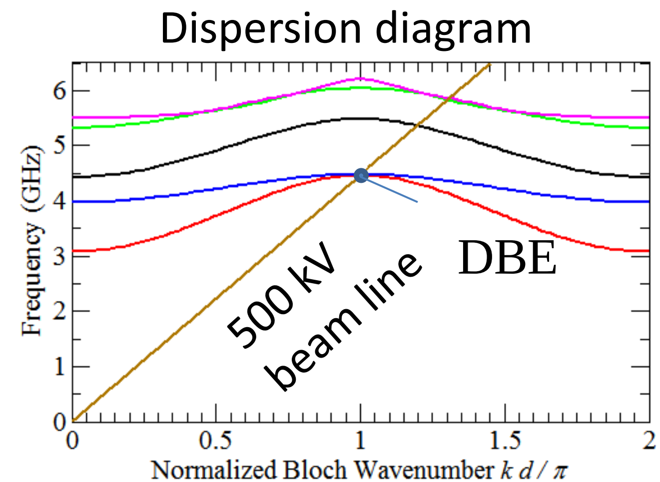
UCI University of California, Irvine

SWS 1 : Periodic "corrugated" waveguide with elliptical cross sections

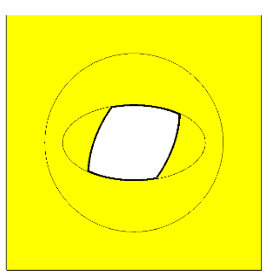
- A unit cell consisting of circular waveguide loaded with two irises of elliptical shape
- Elliptical irises are misaligned with angle φ
- Similar to corrugated waveguides, except the corrugation's cross-sections are elliptic

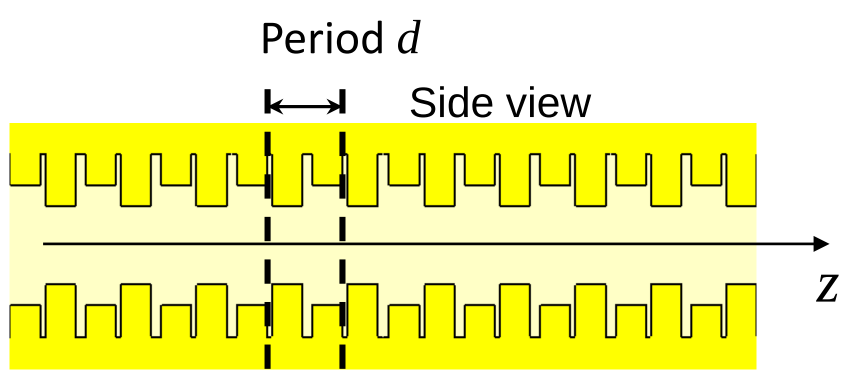






Cross-section





All-metallic SWS with DBE for high power

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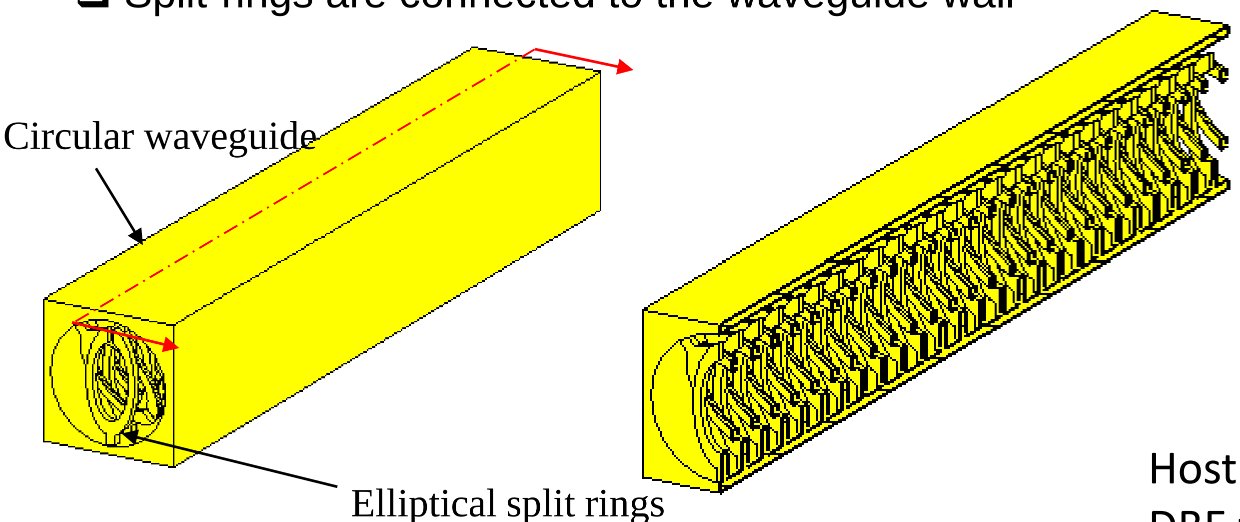
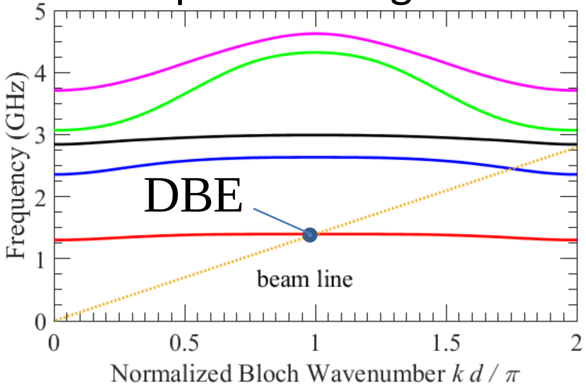
SWS 2 : Periodic waveguide with split-ring loading

- ❑ A unit cell consisting of circular waveguide loaded with two coupled split-rings
- ❑ Circular or elliptical split-rings
- ❑ Split-rings are connected to the waveguide wall



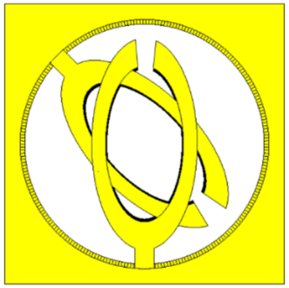
Dispersion diagram



Host waveguide operates below cutoff

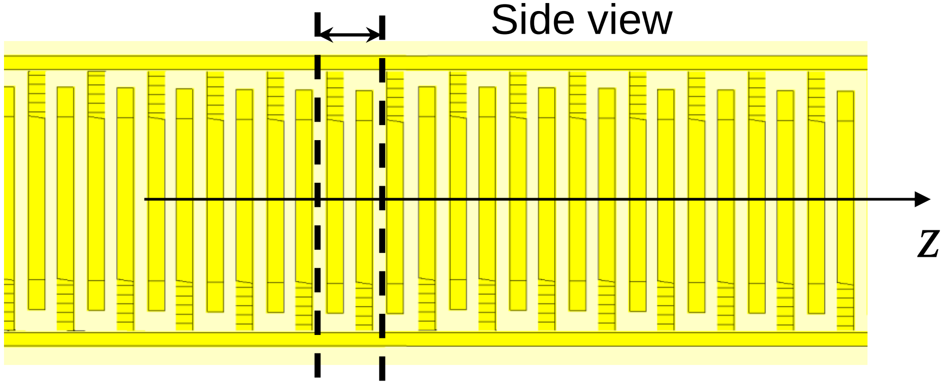
DBE frequency ~ 1.2 GHz

Cross-section



Period d

Side view



All-metallic SWS with SBE for high power

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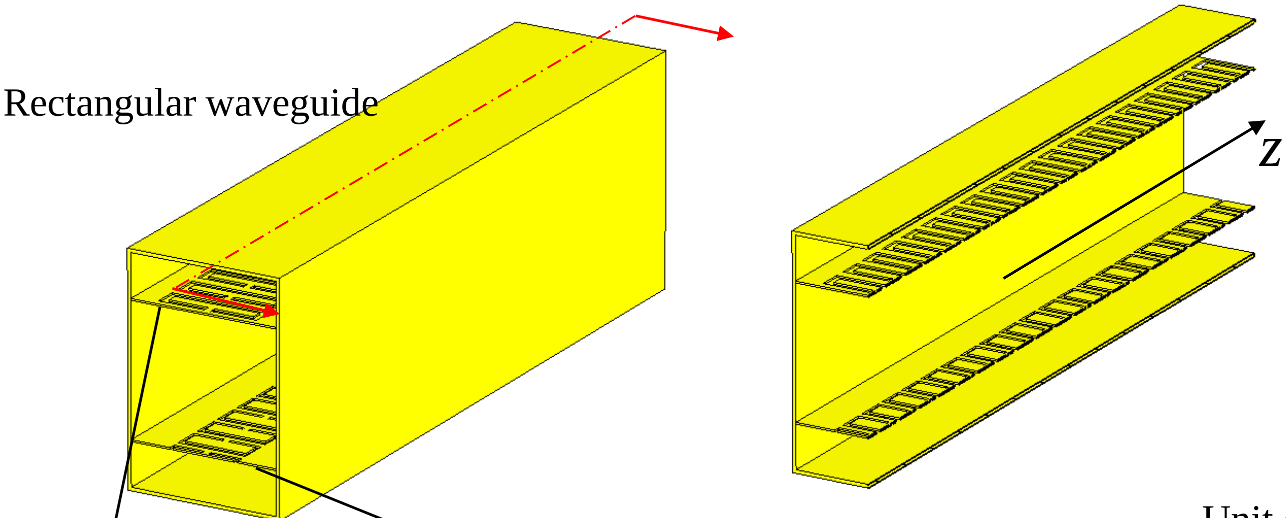
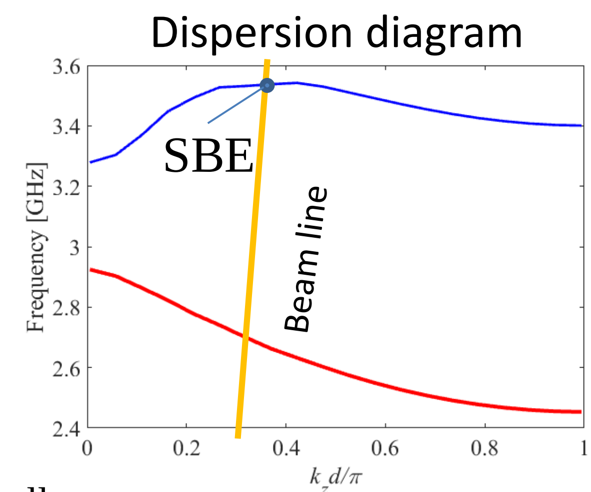
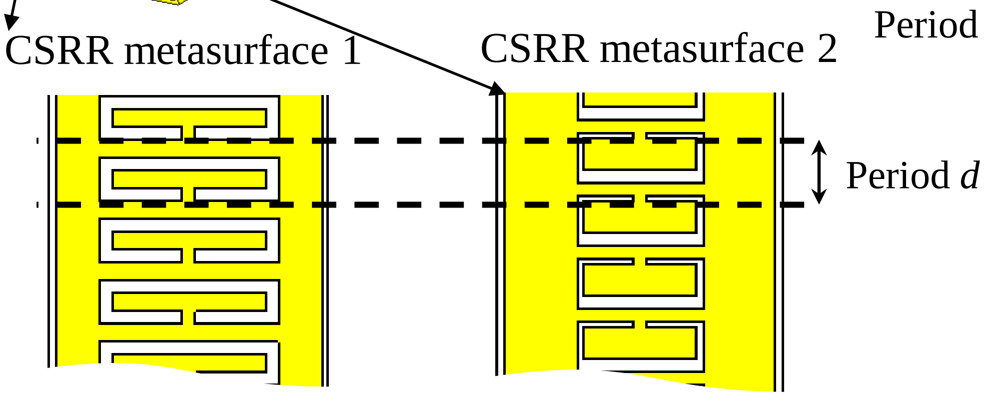
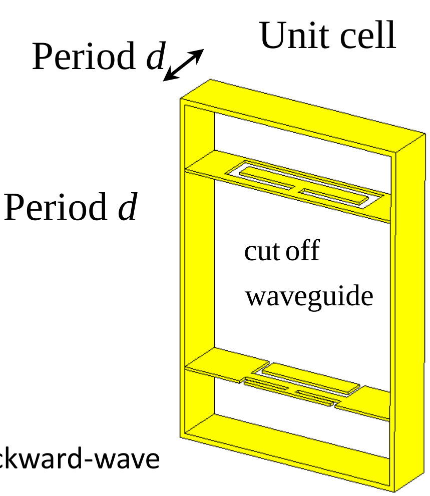
SWS 3 : Rectangular waveguide loaded with coupled CSRR metasurfaces

- A unit cell consisting of rectangular waveguide loaded with two metasurfaces
- Two coupled metasurfaces are implemented with Complimentary Split Ring Resonators (CSRR)
- There is asymmetry between the two metasurfaces (shape+longitudinal offset)









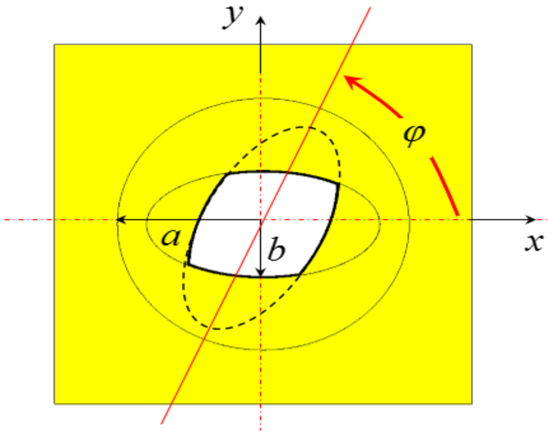
SBE: Split band edge

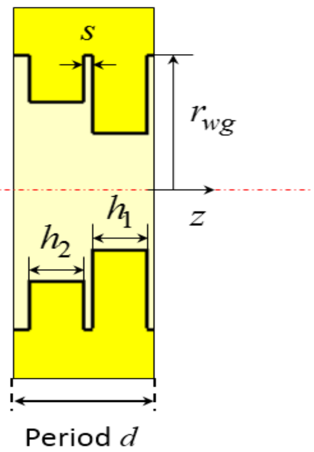
group velocity =0

Can be readily optimized to exhibit a DBE as well

Hummelt, Lewis, Shapiro, Temkin, "Design of a metamaterial-based backward-wave oscillator." *IEEE Trans Plasma Science,* vol. 42, no. 4, 930-936, 2014.

Corrugated SWS, elliptical cross sections





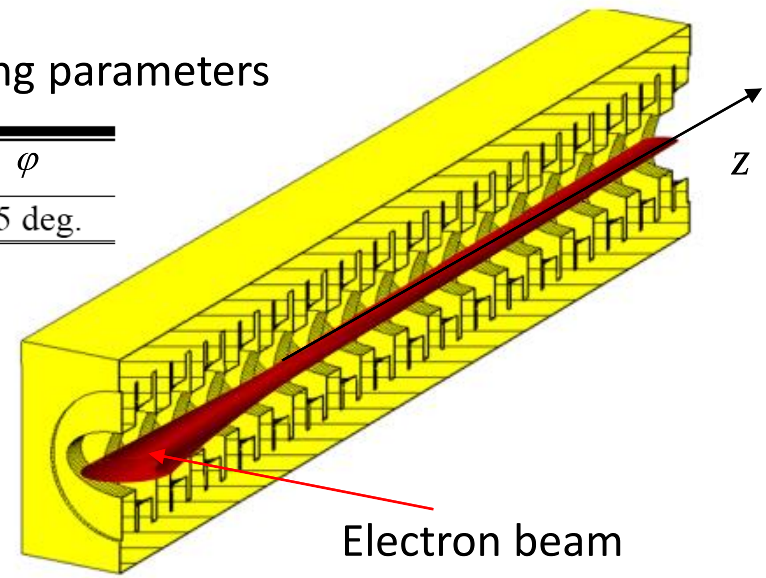
Yellow: metal

r_{wg} : circular waveguide radius, d : period,
a : elliptical iris major radius
b : elliptical iris minor radius
φ : misalignment angle, h : iris thickness
s: sepration between irises

The structure is designed to exhibit a DBE for the following parameters

r_{wg}	d	h_1	h_2	a	b	φ
33 mm	30 mm	15 mm	3 mm	33 mm	18 mm	45 deg.

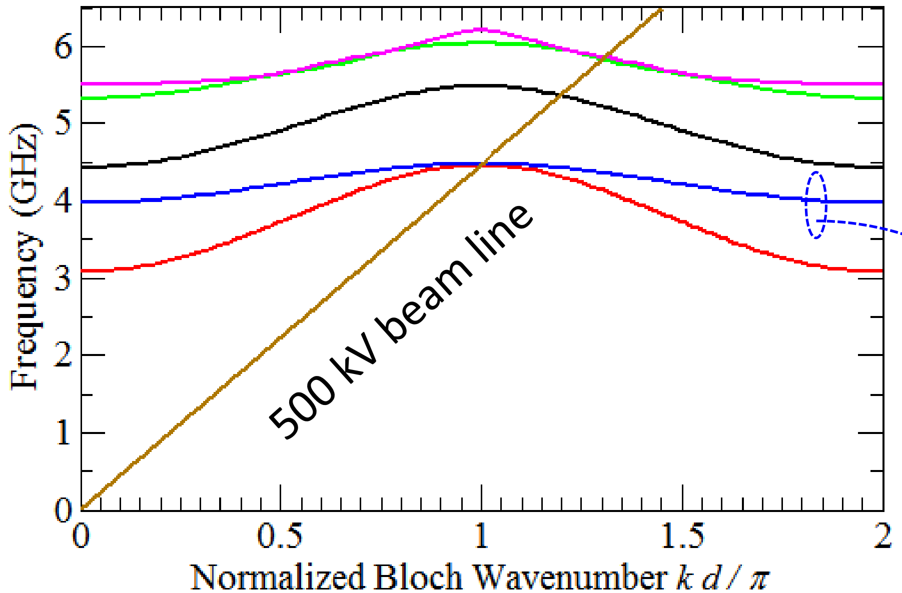
DBE frequency ~ 4.5 GHz



- Elliptical cross sections support two polarizations
- Modes are coupled periodically
- DBE, and other degeneracy conditions can be achieved

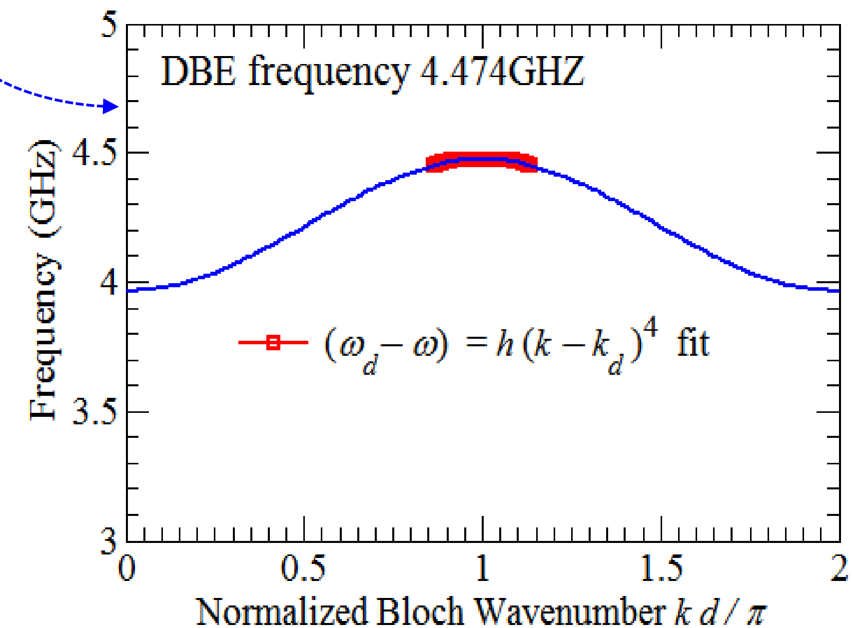
Corrugated SWS, elliptical cross sections

Dispersion relation

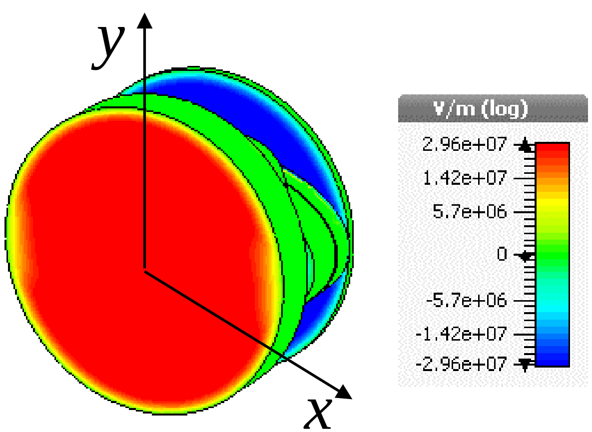


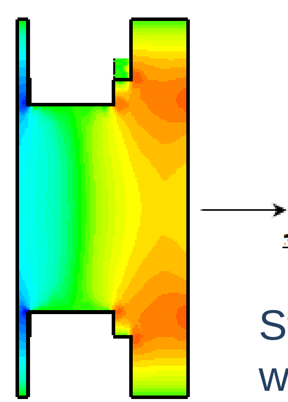
The DBE mode is designed to have a higher interaction impedance than the lower order mode

DBE mode (blue curve)



Electric field E_z component distribution of DBE mode





Strong E_z component on the waveguide axis

Preliminary PIC simulations: MAGIC 3D

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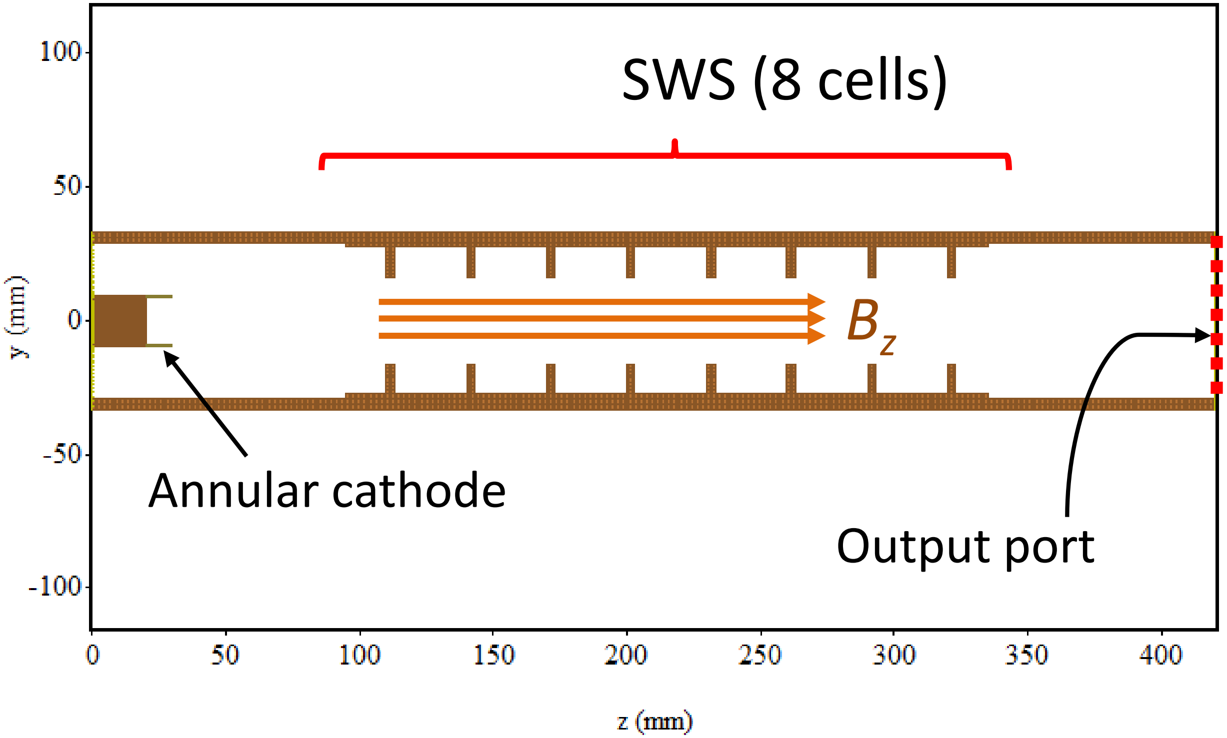

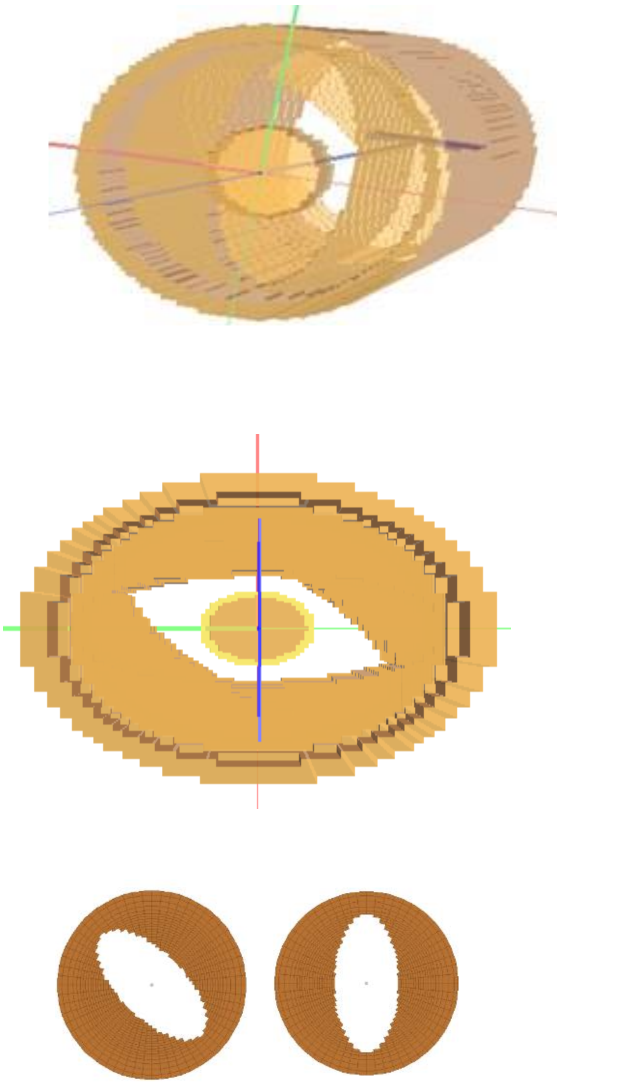

Simulation Parameters	
Cathode Radius	1 cm
Anode Radius	3 cm
Applied Voltage	500 kV
Voltage Rise-Time	2 ns
Magnetic Field	3 T

Collaboration with UNM, **Edl Schamiloglu, S. Yurt**

Case 1: Constant beam voltage

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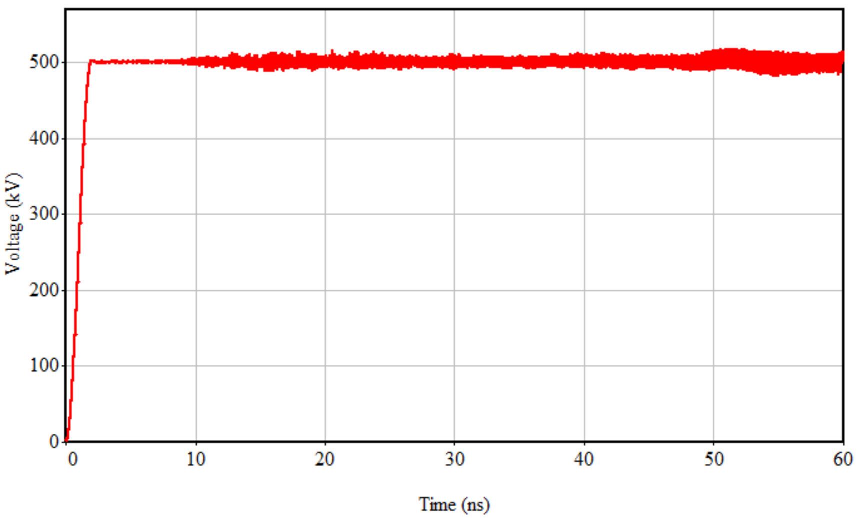
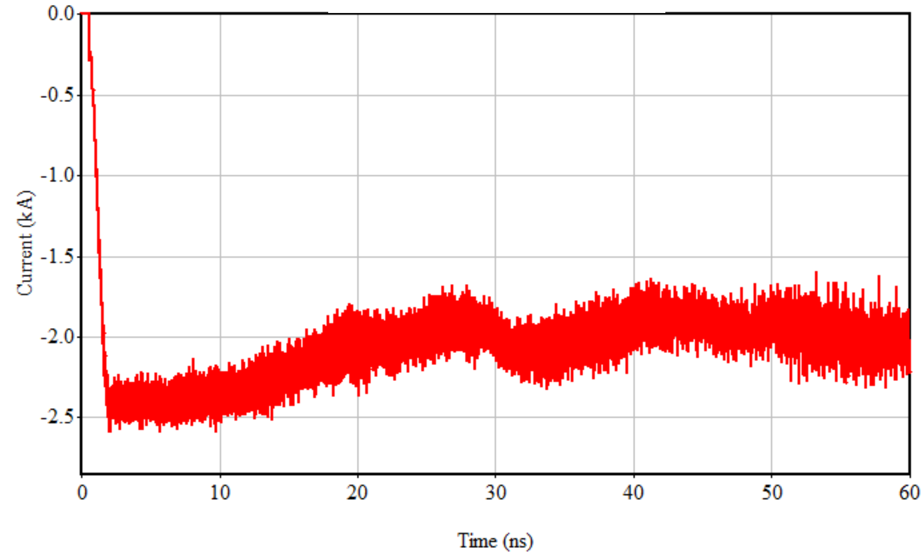
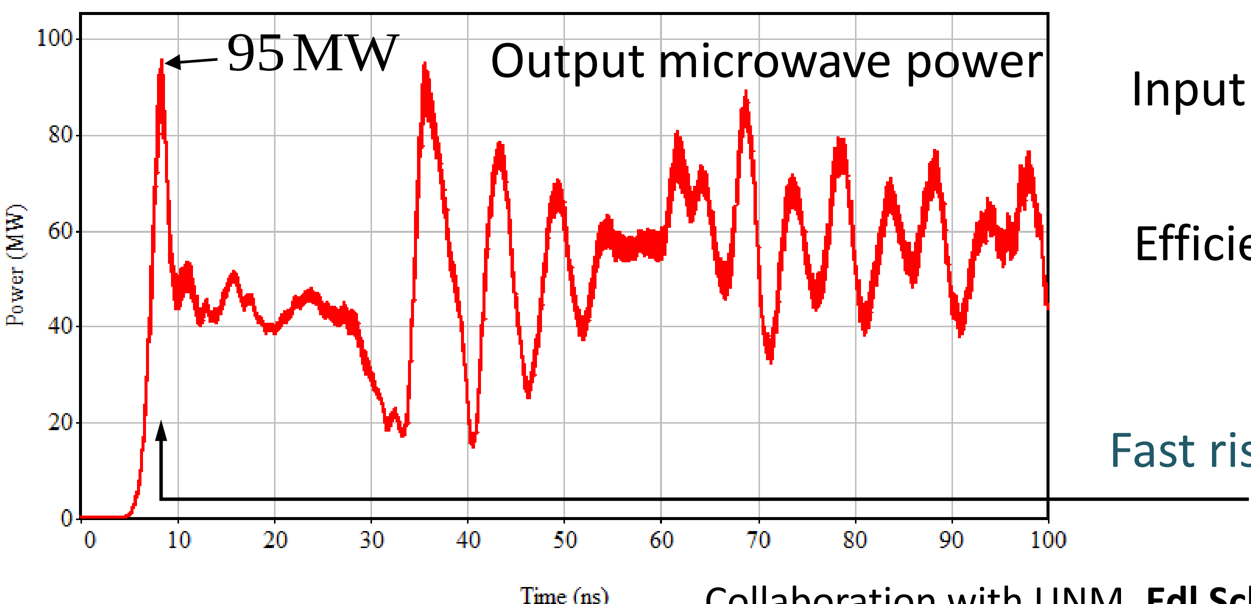
Beam voltage



Beam current





Input beam power ~1 GW

Efficiency ~ 9.5 %

Fast rise time ~ 8 ns

Collaboration with UNM, **Edl Schamiloglu, S. Yurt**

Case 2: 12 ns beam pulse (UNM's SINUS-6)

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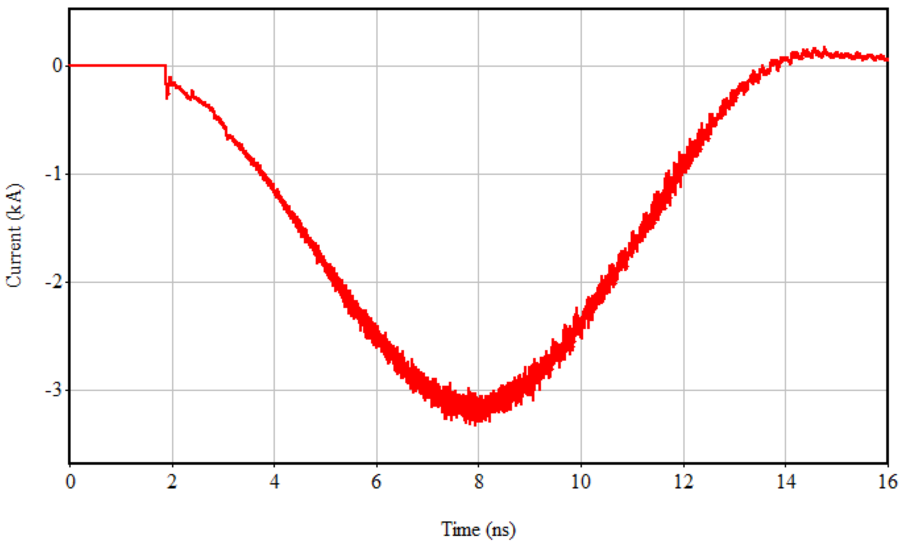
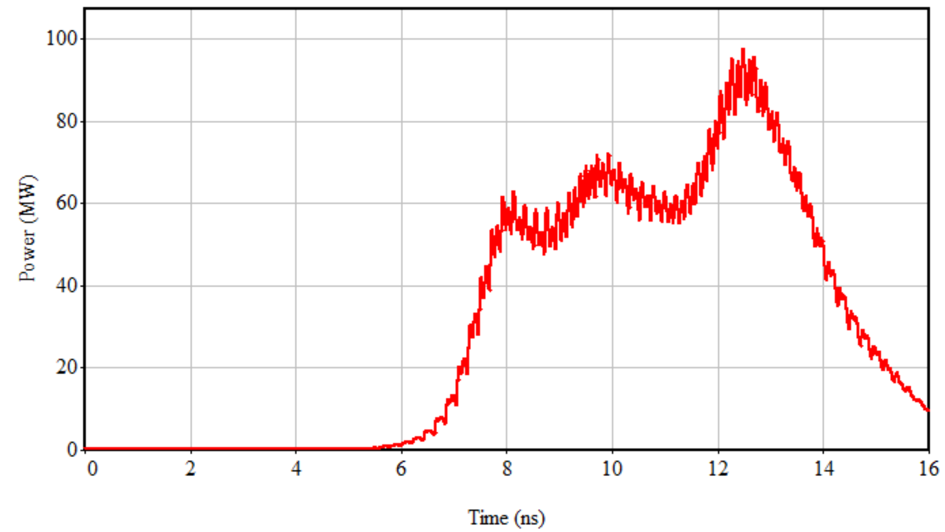
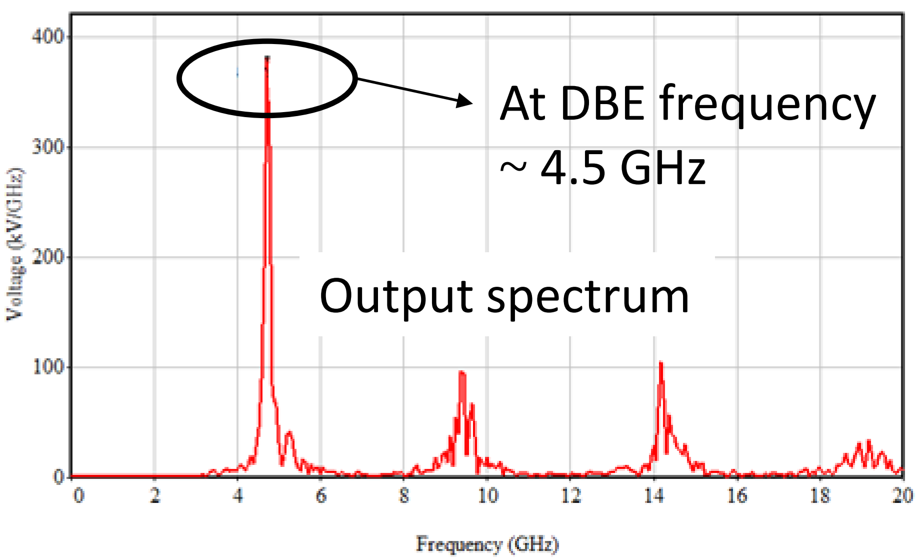
Beam current pulse



Output power





- ✓ Fast starting of oscillation
- ✓ Will be optimized for power extraction and suppression of higher order modes (this is a first demonstration, it has not been optimized for high power. We have a scheme to do it.)

Collaboration with UNM, **Edl Schamiloglu, S. Yurt**

Conclusions

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❑ Cold experimental test was performed to demonstrate for the first time DBE in all metallic slow-wave structures

❑ Degenerate band edge oscillator was shown to have a lower starting current with better scaling than conventional backward wave oscillator

❑ We have shown that DBE can be obtained in various metallic loaded waveguides including metamaterial-based SWSs (based on MIT design)

❑ Preliminary PIC simulations demonstrated fast rise time for the DBEO

Future work

❑ Optimize potential DBE structures using PIC codes (MAGIC + CST Particle Studio) for high power applications

❑ Optimize power extraction to improve efficiency (for low beam current)

❑ Investigate gain/loss balance scheme to maintain the DBE with high power beam in a pulse-compression-based operation (with beam as switch)

Thank you

Auxiliary slides

Corrugated SWS, elliptical cross sections

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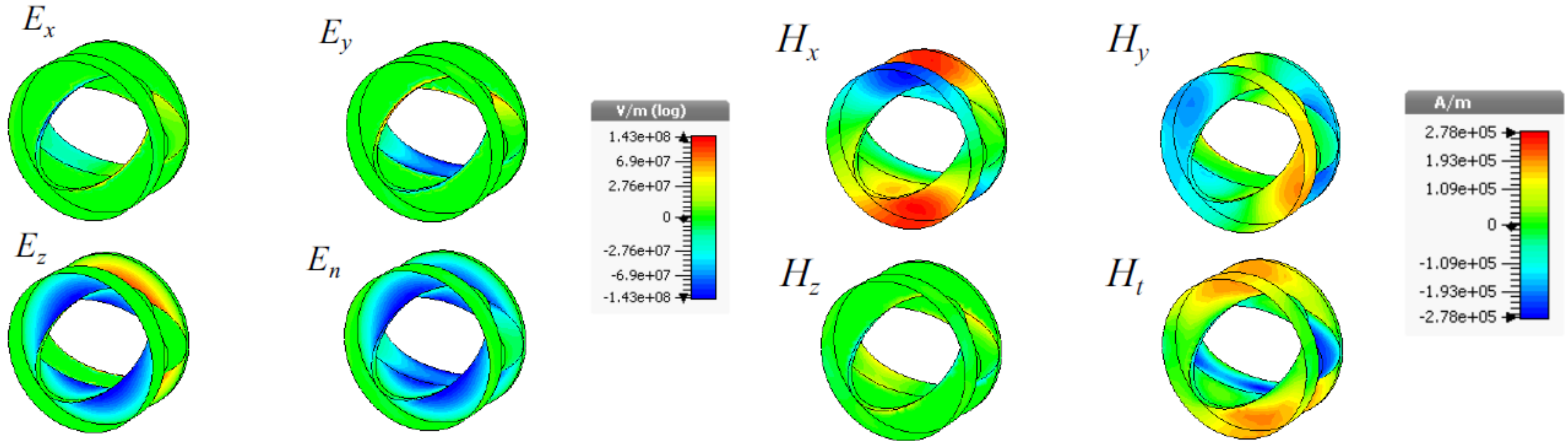
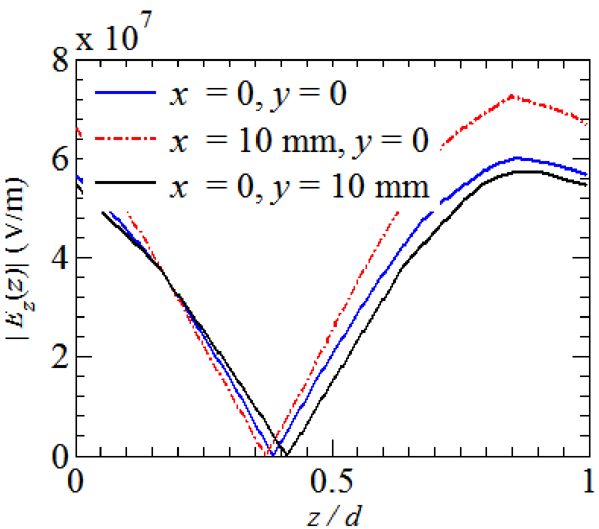
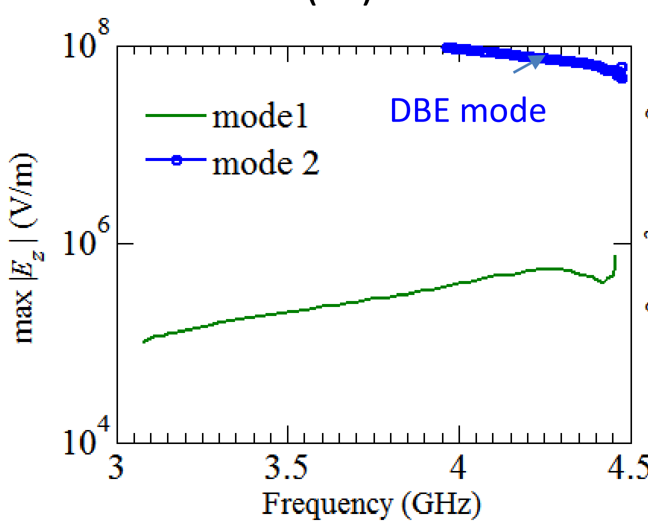
Field maps of the DBE mode



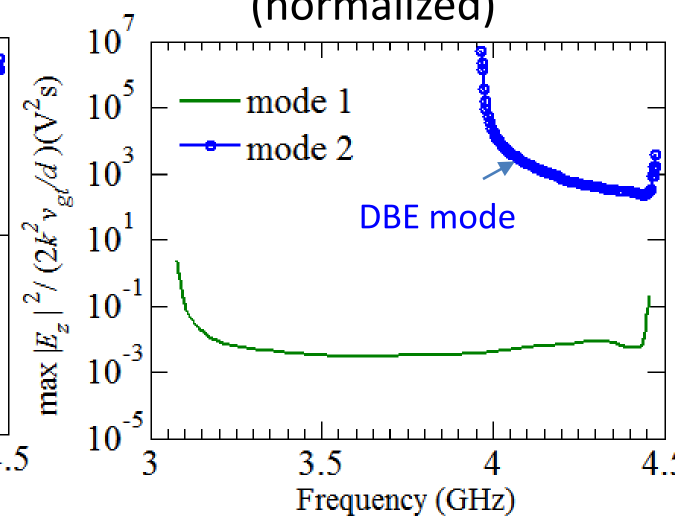
Distribution of Ez



max(Ez) on axis



interaction impedance (normalized)



MAGIC PIC simulation: output voltage

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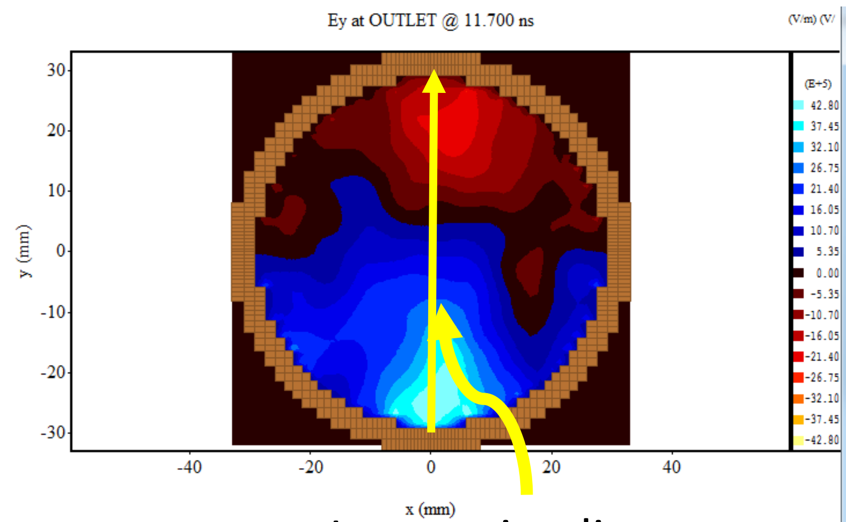
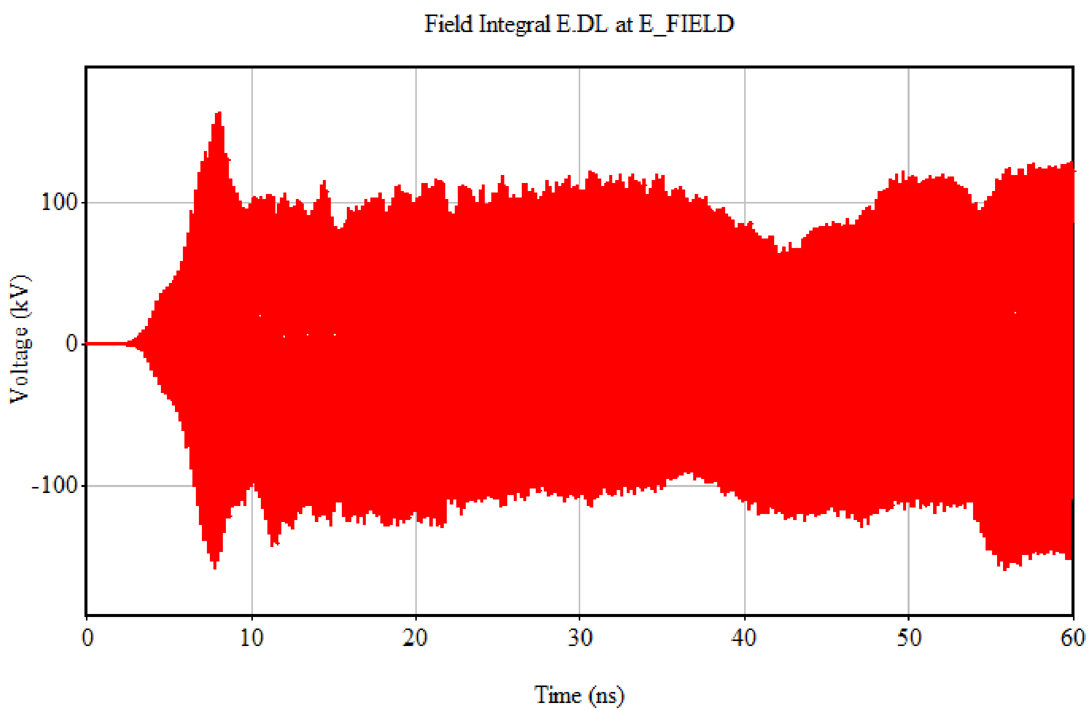
$$V_{out} = -\int_{line} \mathbf{E} \cdot d\mathbf{l}$$



Integration line over the output port



Simulation Parameters	
Cathode Radius	1 cm
Anode Radius	3 cm
Applied Voltage	500 kV
Voltage Rise-time	2 ns
Magnetic Field	3 T

Windowed Fourier transform of output voltage

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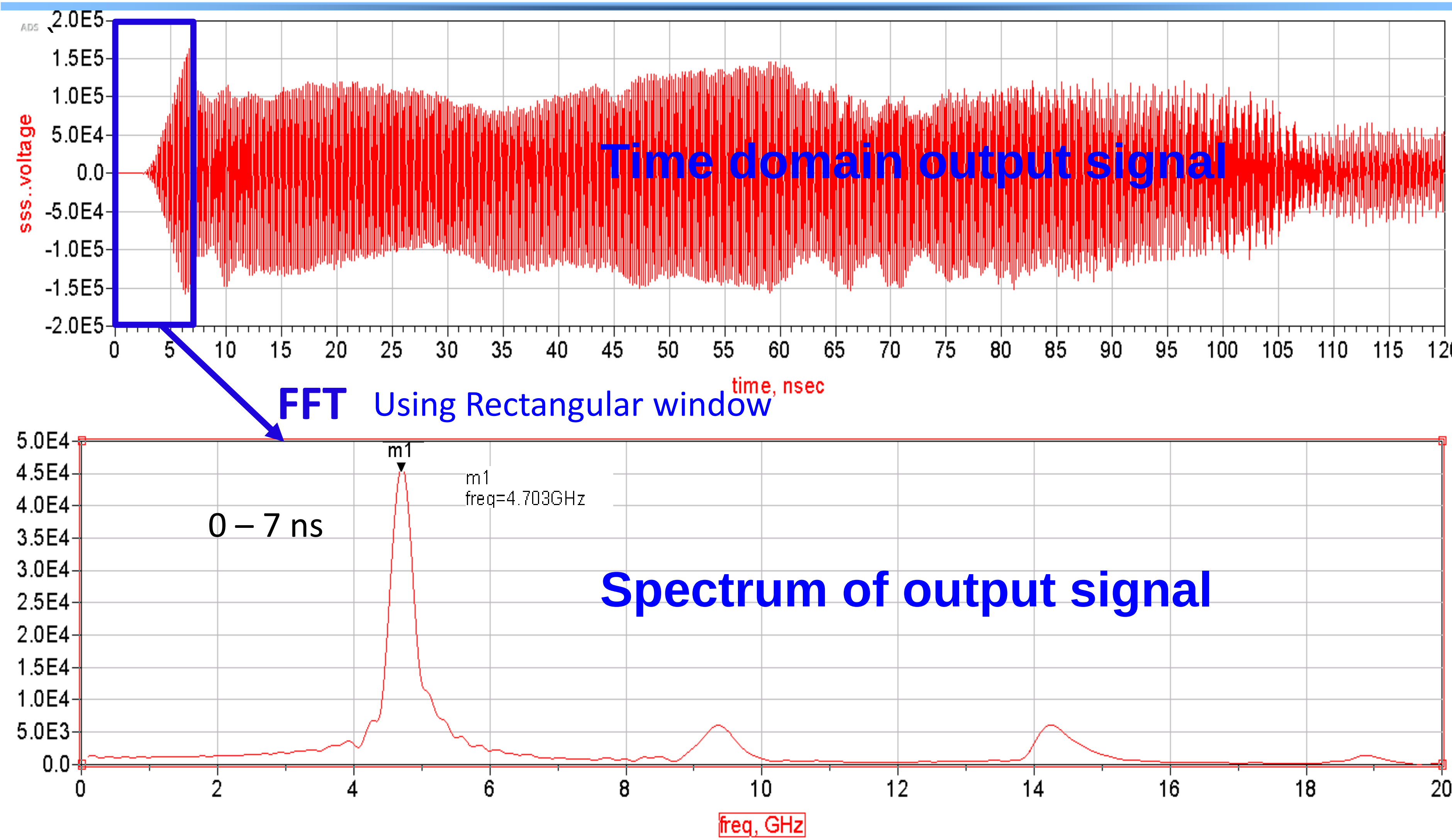
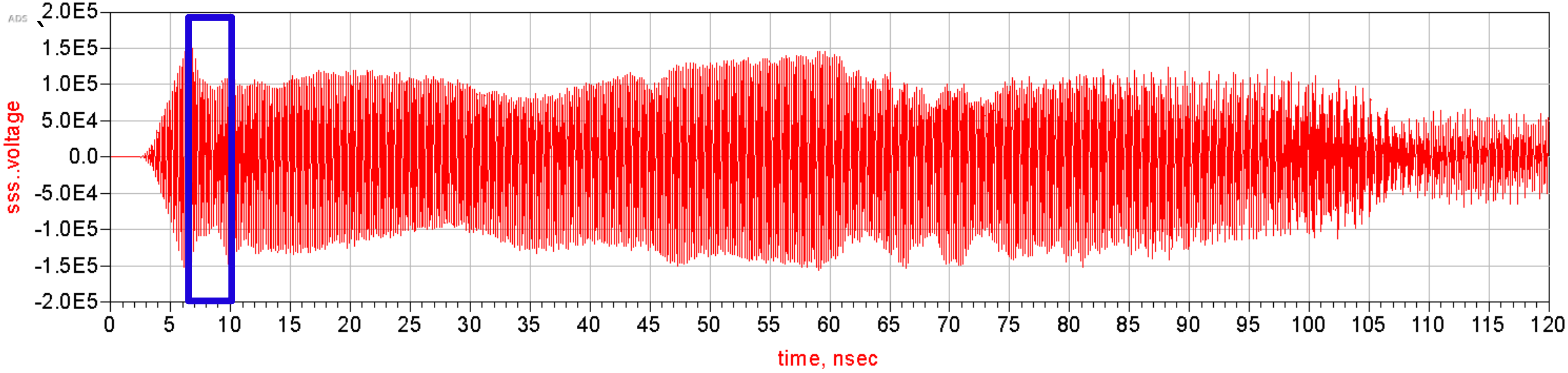
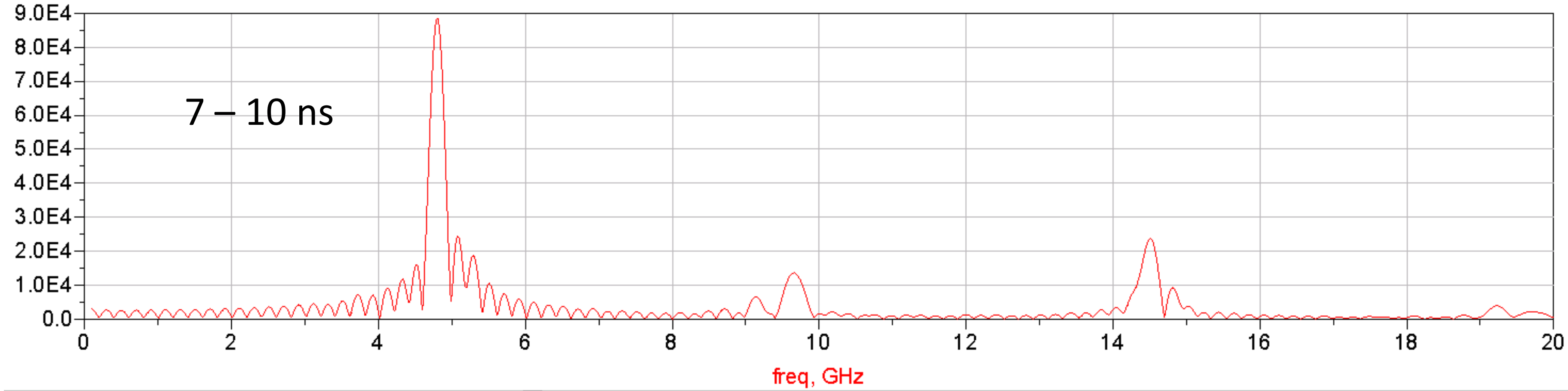


Voltage Spectrum [KV/GHz]

Windowed Fourier transform





Voltage Spectrum [KV/GHz]

Windowed Fourier transform

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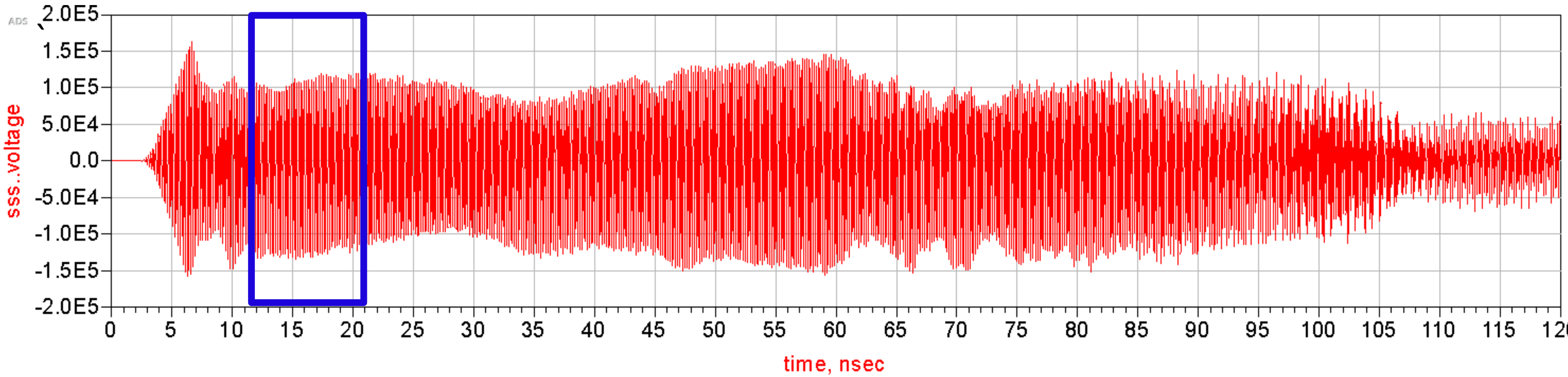

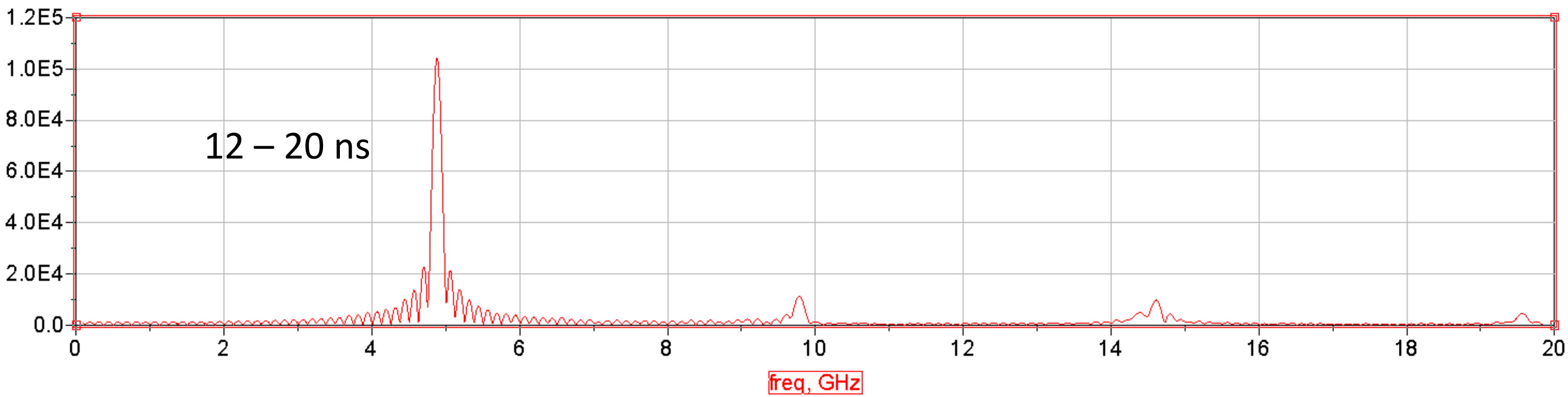

Voltage Spectrum [KV/GHz]

Windowed Fourier transform

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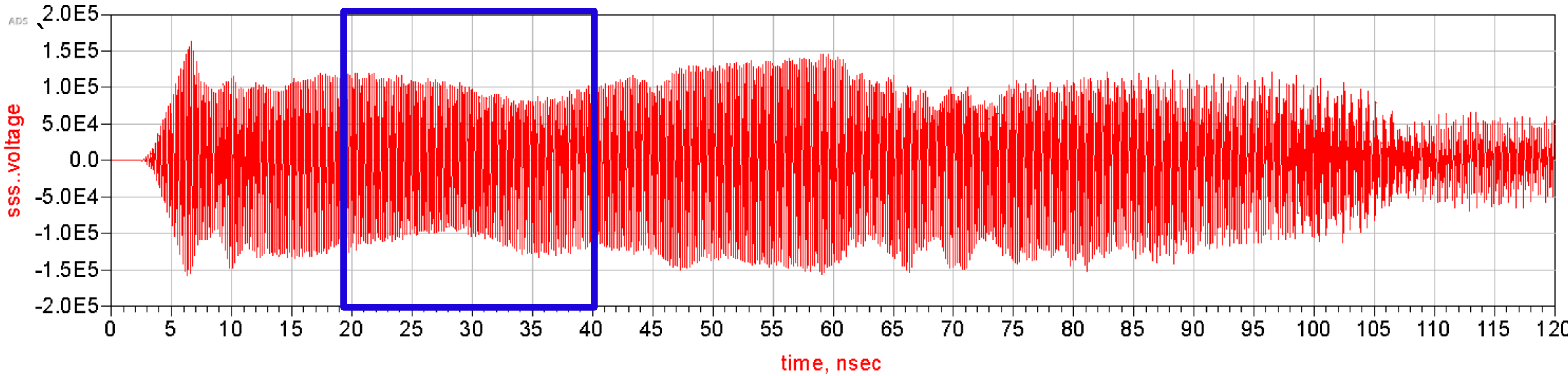
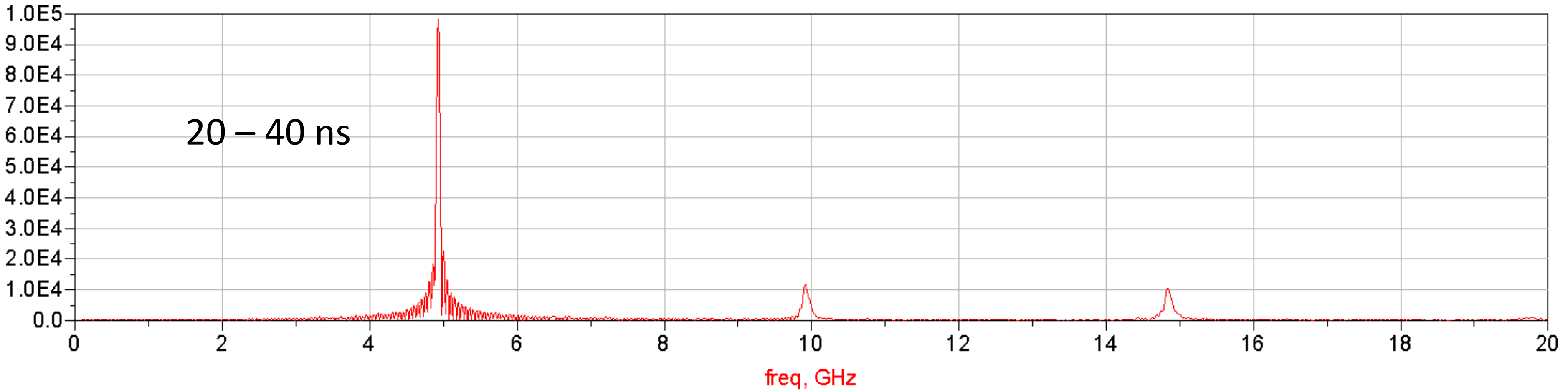
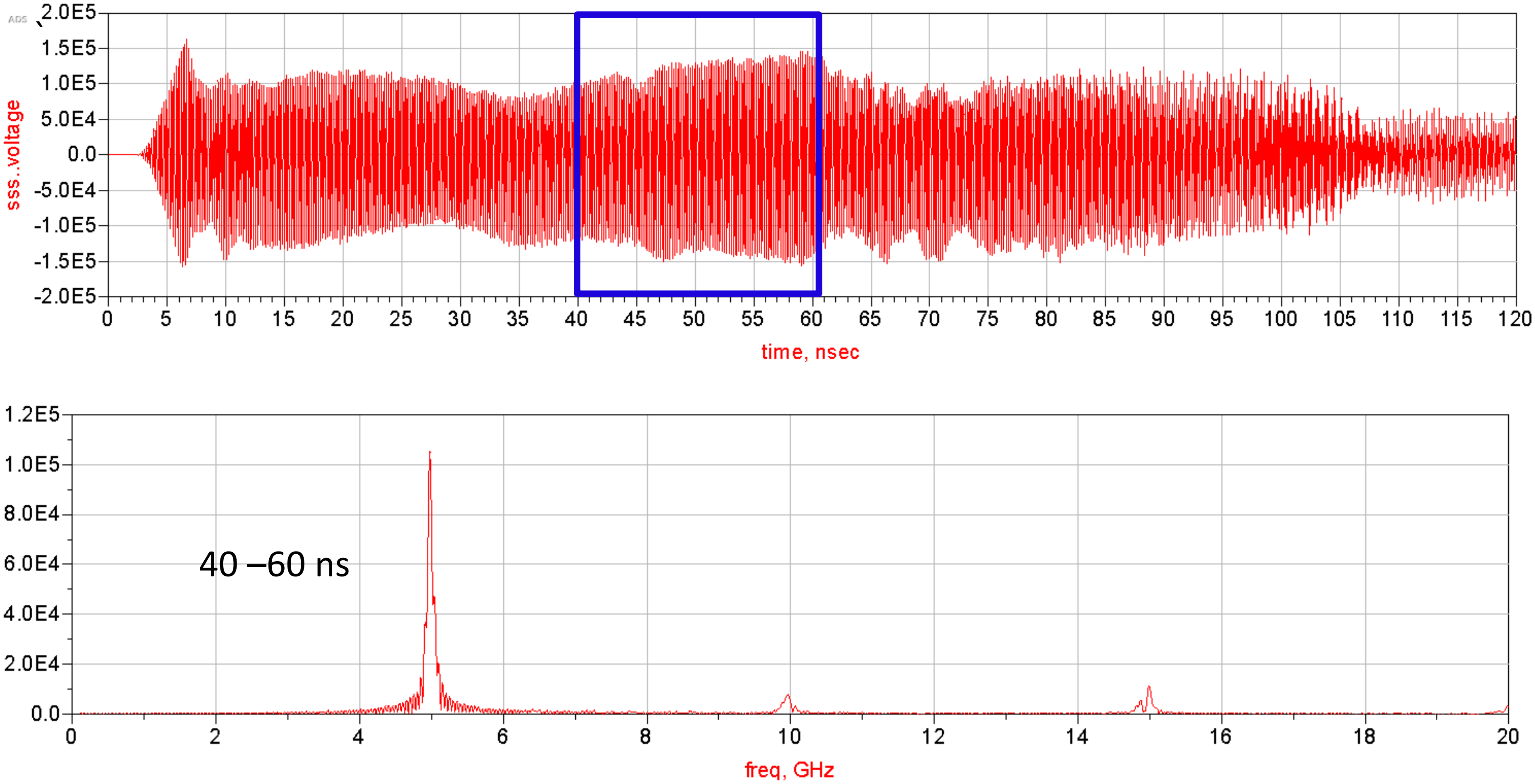




Voltage Spectrum [KV/GHz]

Windowed Fourier transform



Windowed Fourier transform

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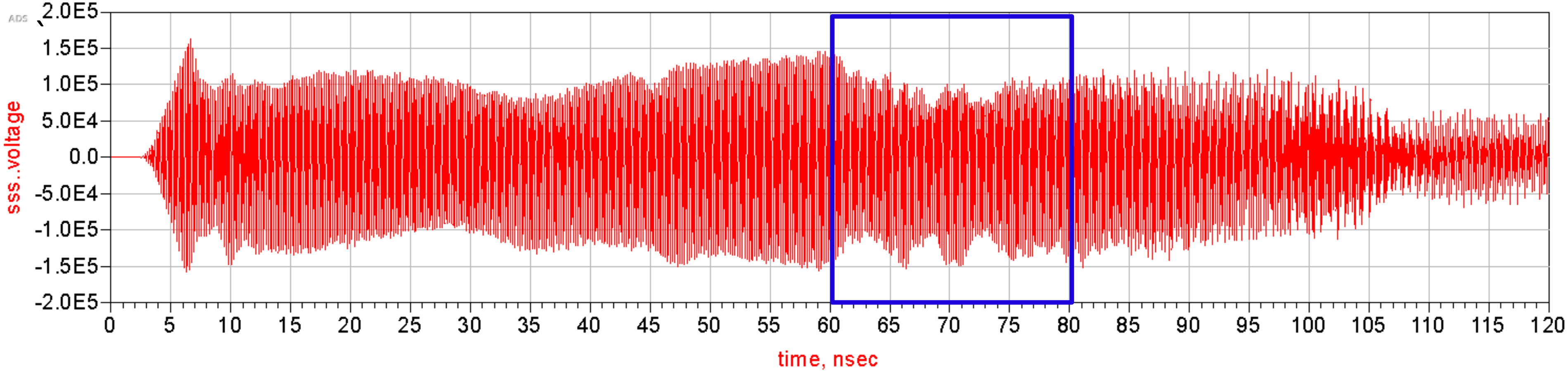
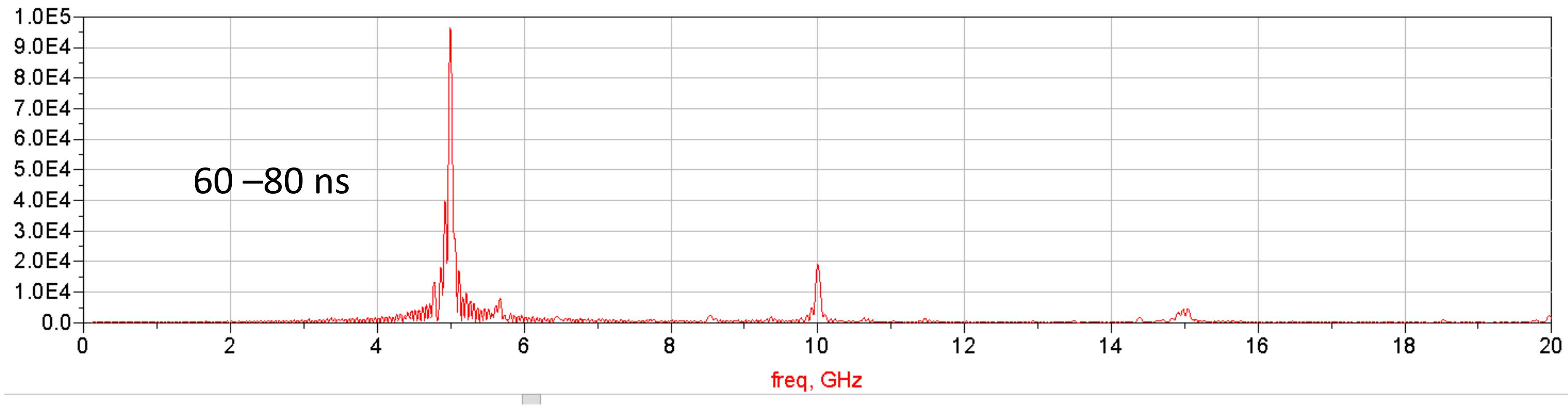
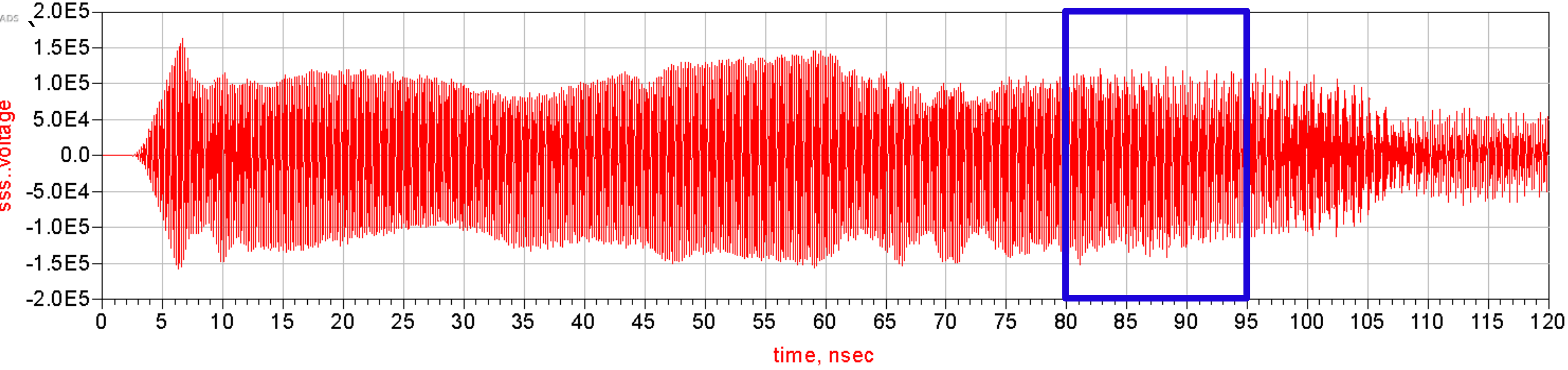
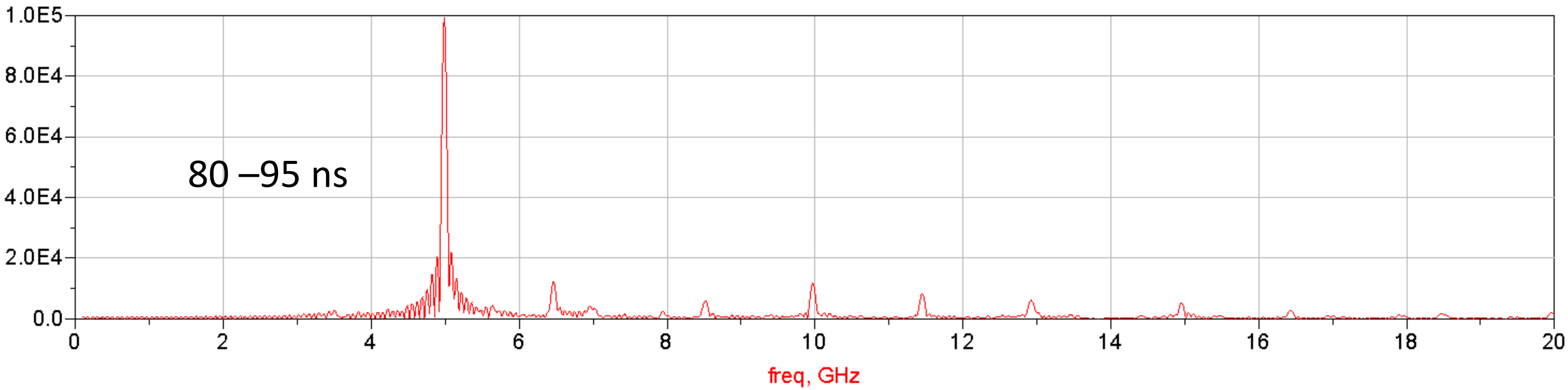




Voltage Spectrum [KV/GHz]

Windowed Fourier transform





Voltage Spectrum [KV/GHz]

Windowed Fourier transform

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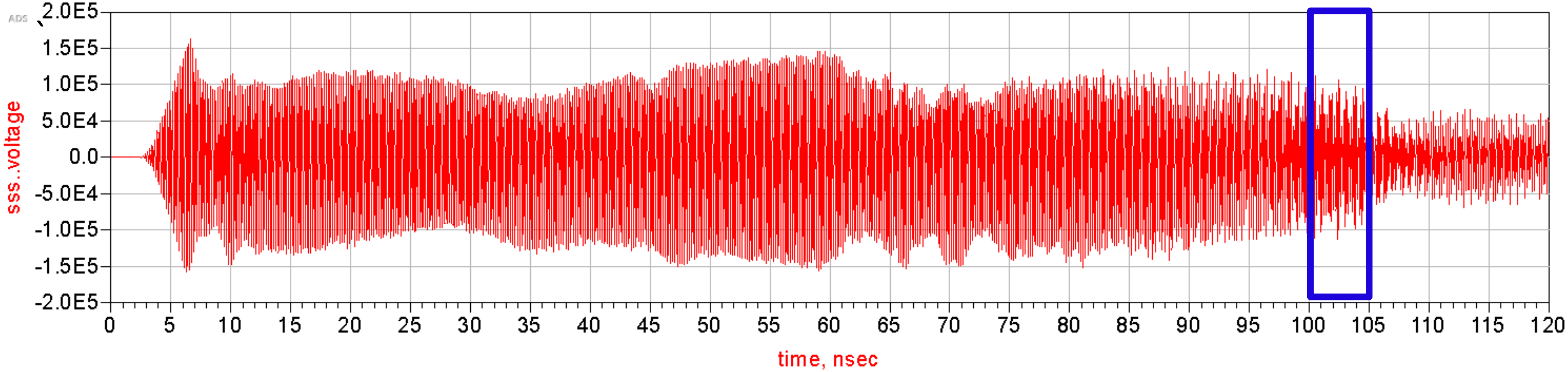
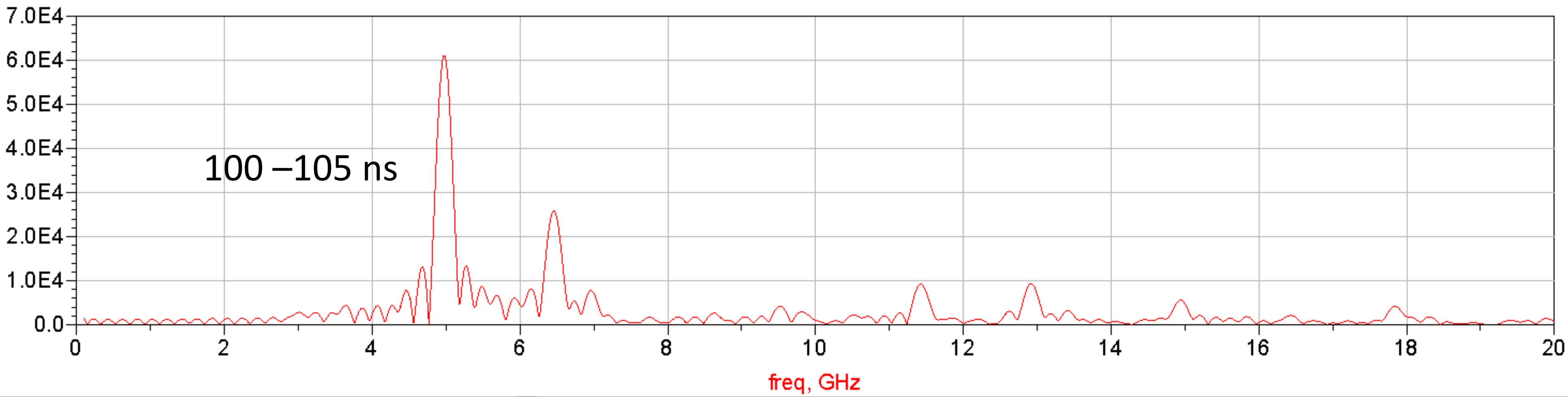
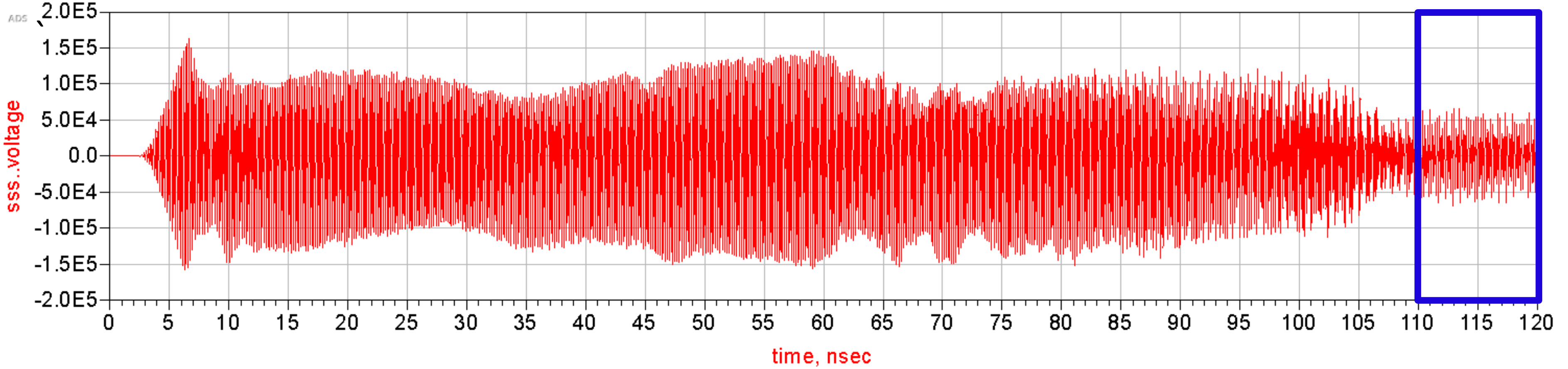
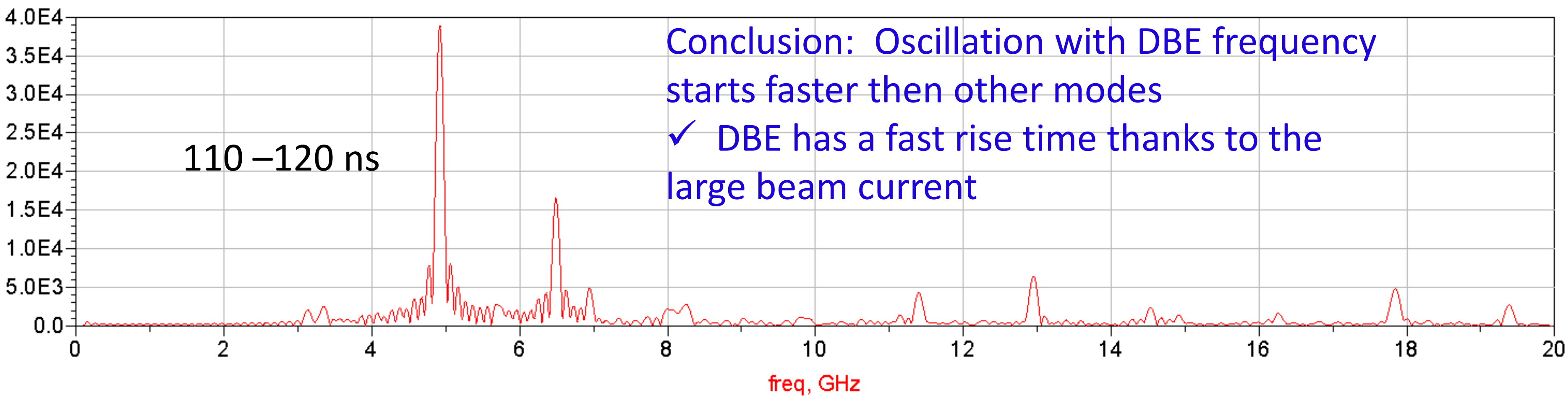




Voltage Spectrum [KV/GHz]

Windowed Fourier transform





Conclusion: Oscillation with DBE frequency starts faster then other modes

✓ DBE has a fast rise time thanks to the large beam current

Voltage Spectrum [KV/GHz]