Beam Loading and Signal Detection for a TESLA 1.3 GHz Cavity

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DESY-TEMF Meeting
November 02, 2020

Outline

- Motivation
- Computational Modeling
  - Field Excitation
  - Field Extraction
- Numerical Results
  - Beam-Loading Simulations
  - Signal Mixing and Filtering
  - Magnitude and Phase Measurement
- Summary / Outlook

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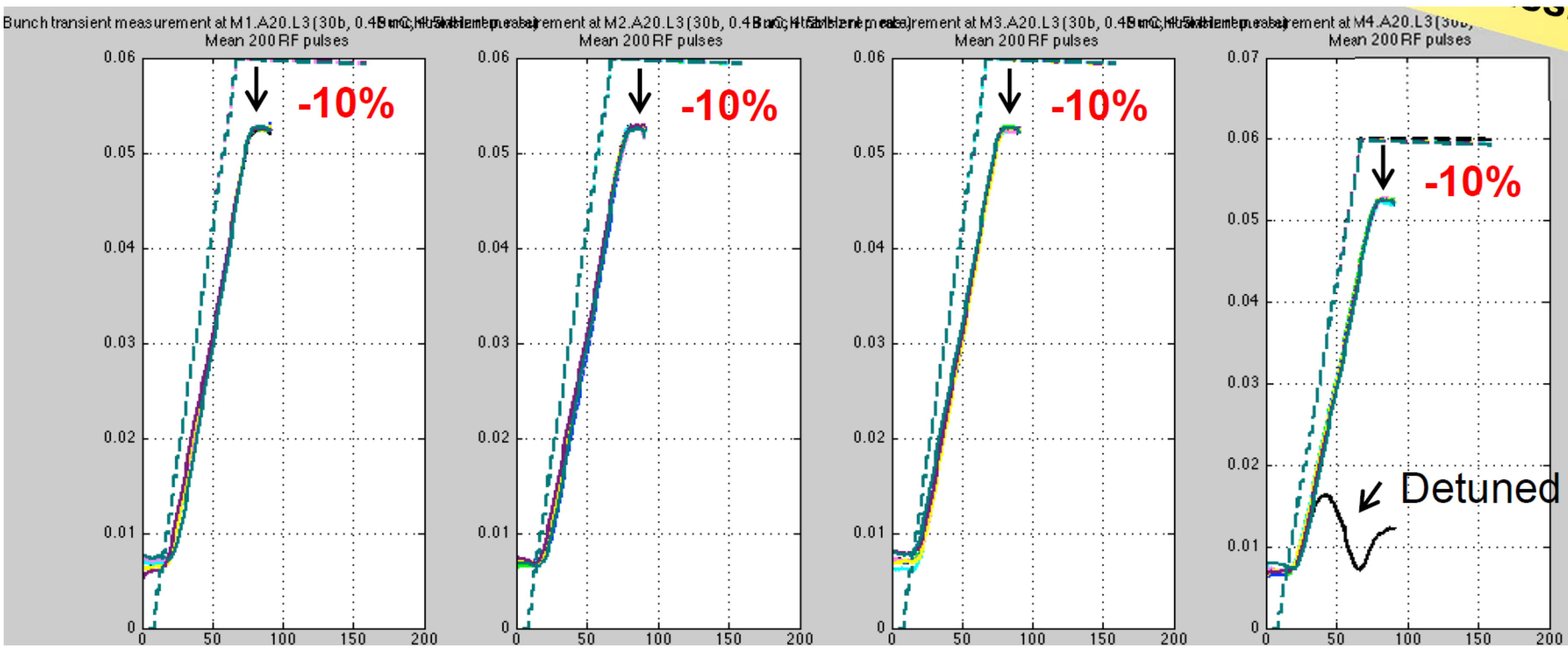
Motivation

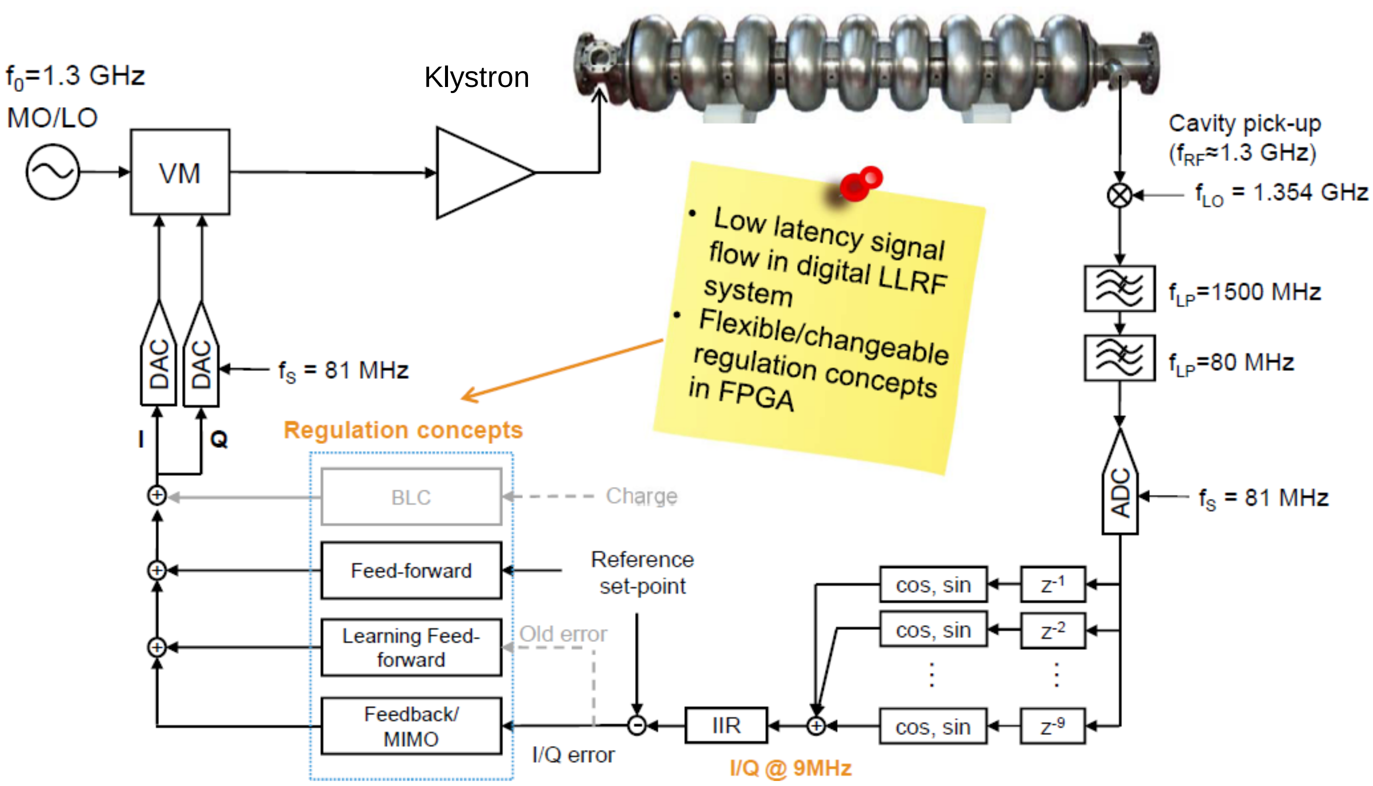
- Beam Loading of a 9 Cell TESLA 1.3 GHz Cavity
  - Comparison of theory with measurement



Source: „Precision Control of SRF Cavities“, Sven Pfeiffer, 15.11.2018

Motivation

- SRF Cavity Regulation



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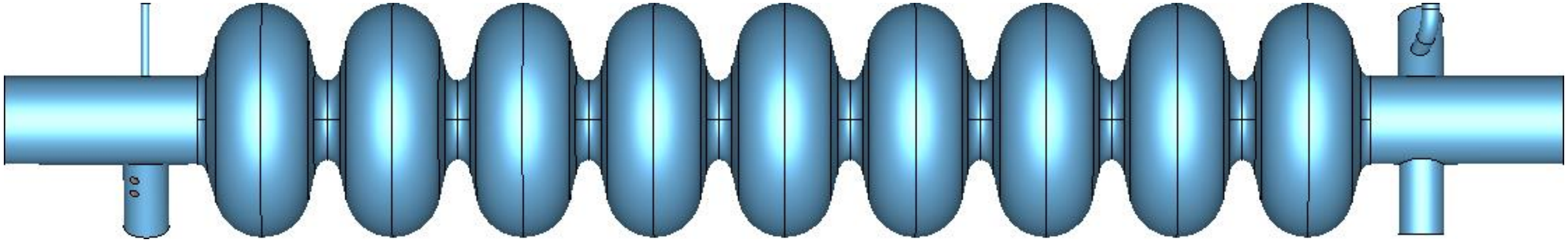
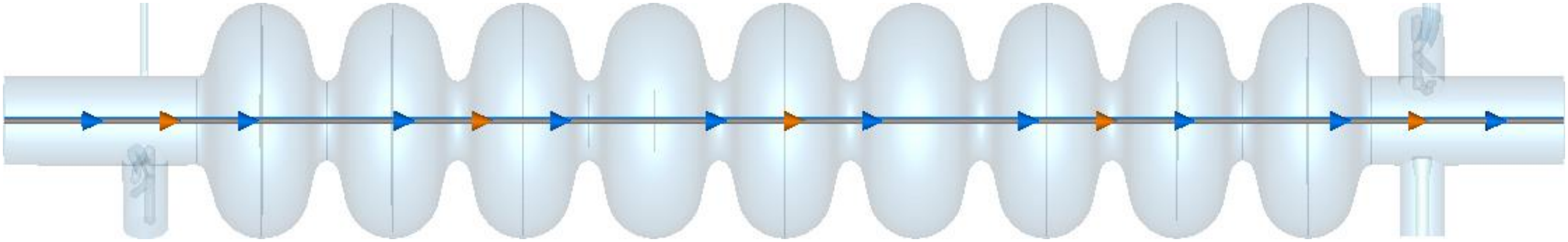
Computational Modeling

- Beam Loading Simulations in Time Domain
  - CST Model



Vacuum Model



Line-Current Excitation

Computational Modeling

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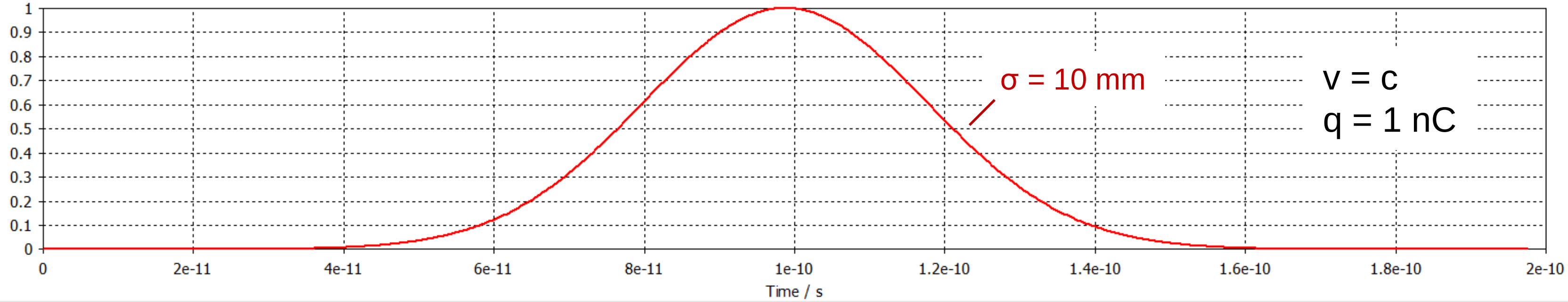
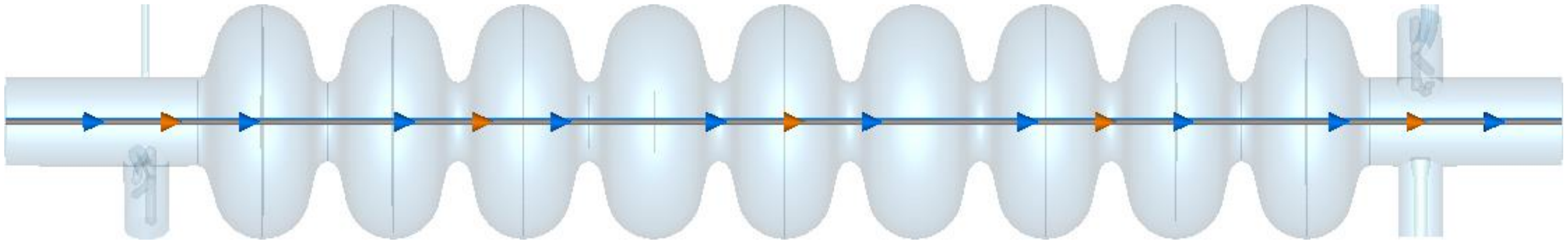
- Beam Loading Simulations in Time Domain
  - CST Model



Excitation Signal



Line-Current Excitation

Computational Modeling

- Beam Loading Simulations in Time Domain
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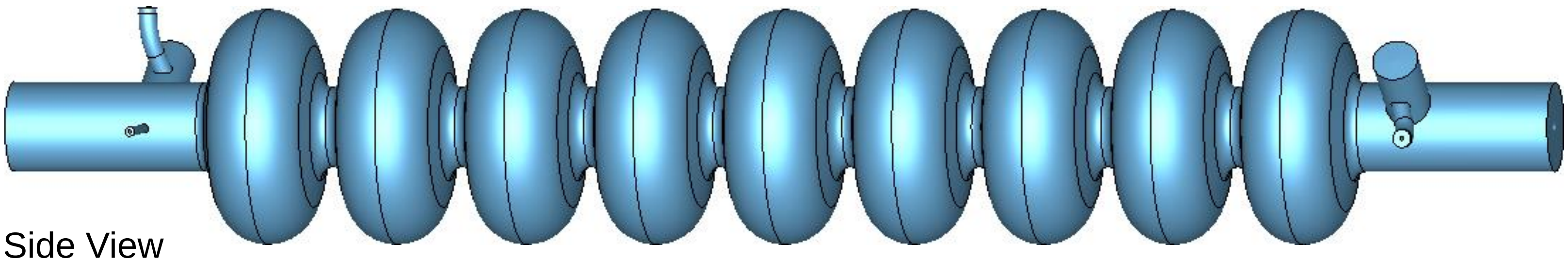
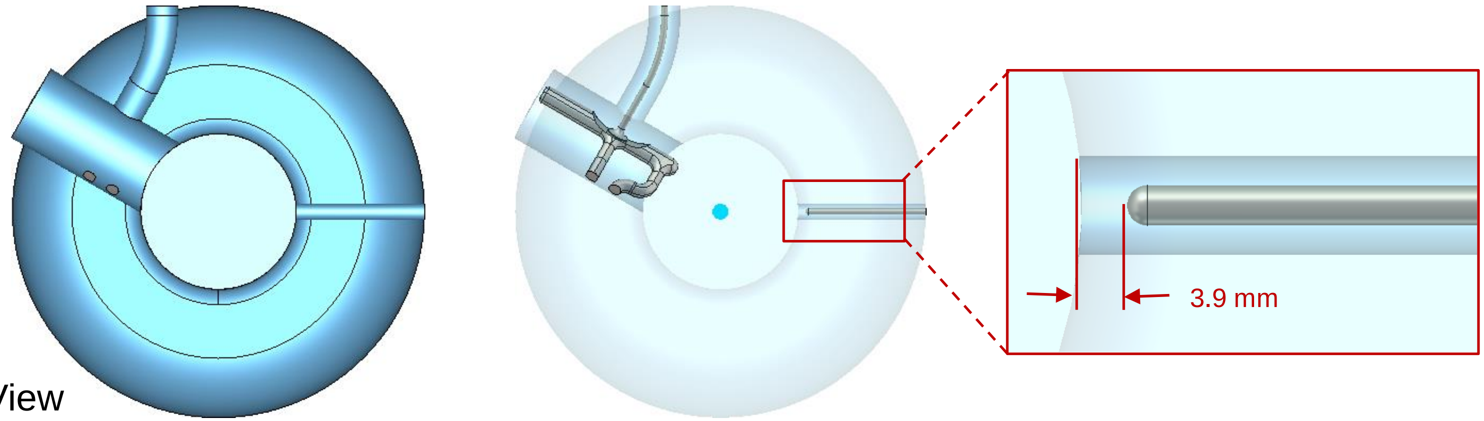


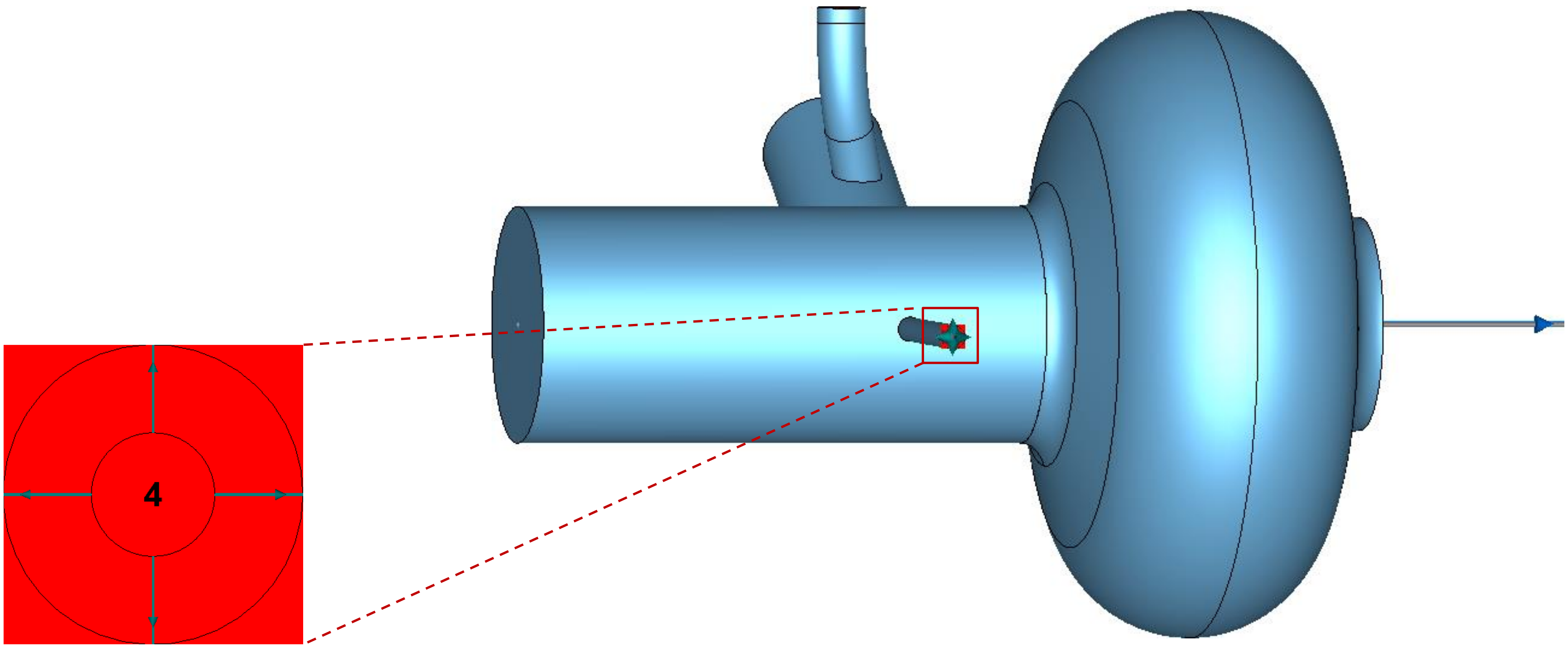
Side View



Front View

Computational Modeling

- Beam Loading Simulations in Time Domain
  - CST Model



Voltage Monitors

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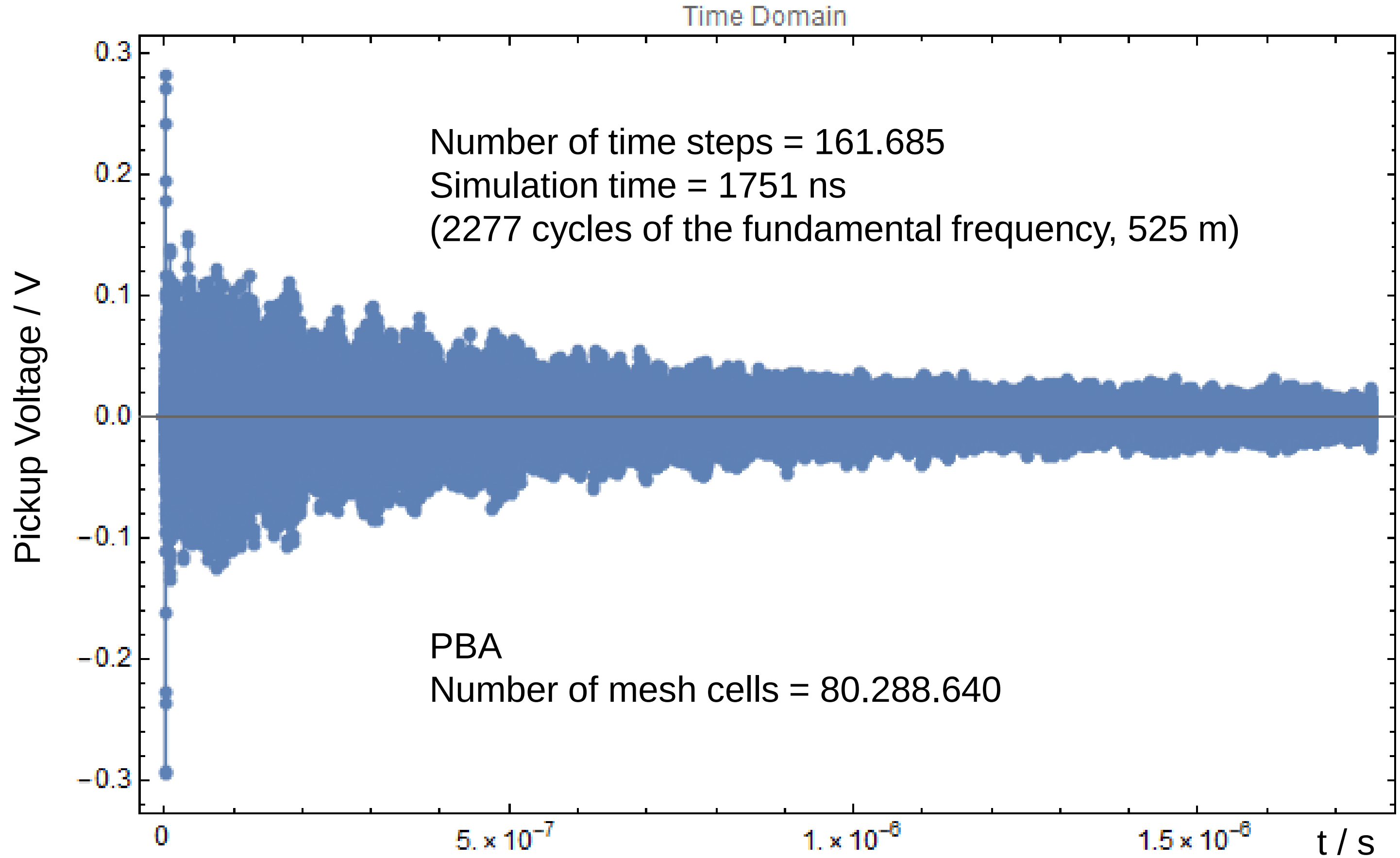
Numerical Results

- Pickup Signal for Single Pulse Excitation



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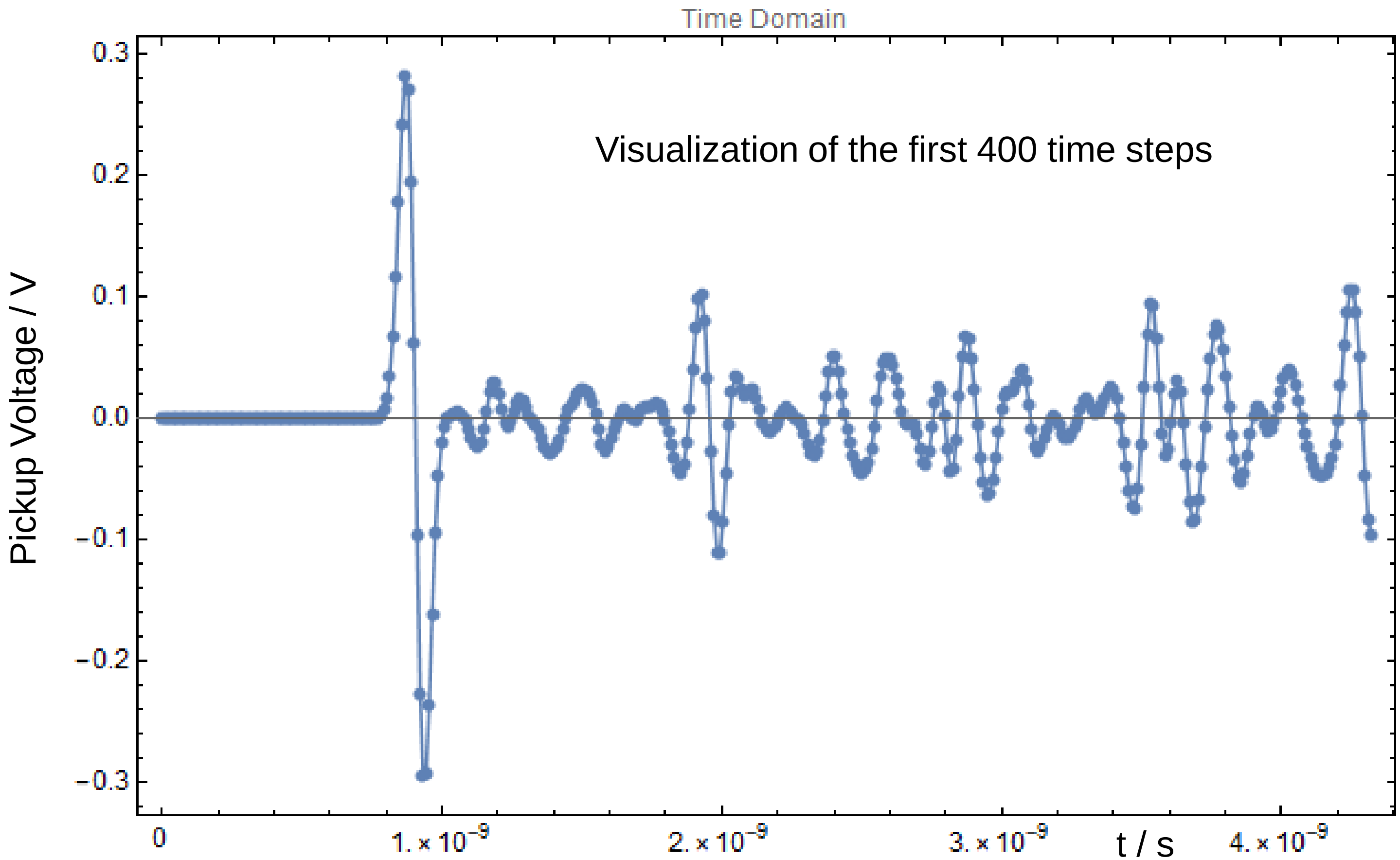

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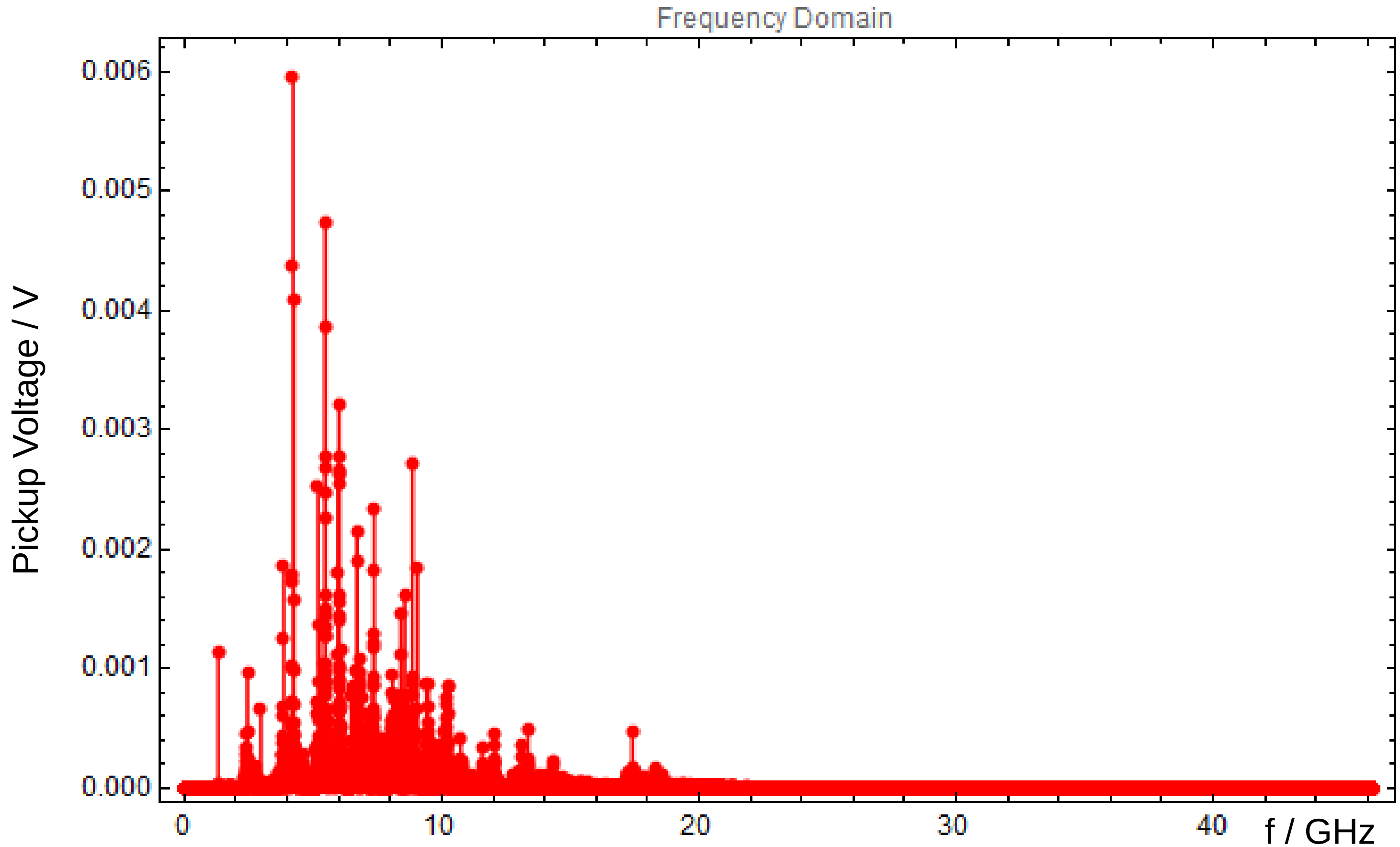

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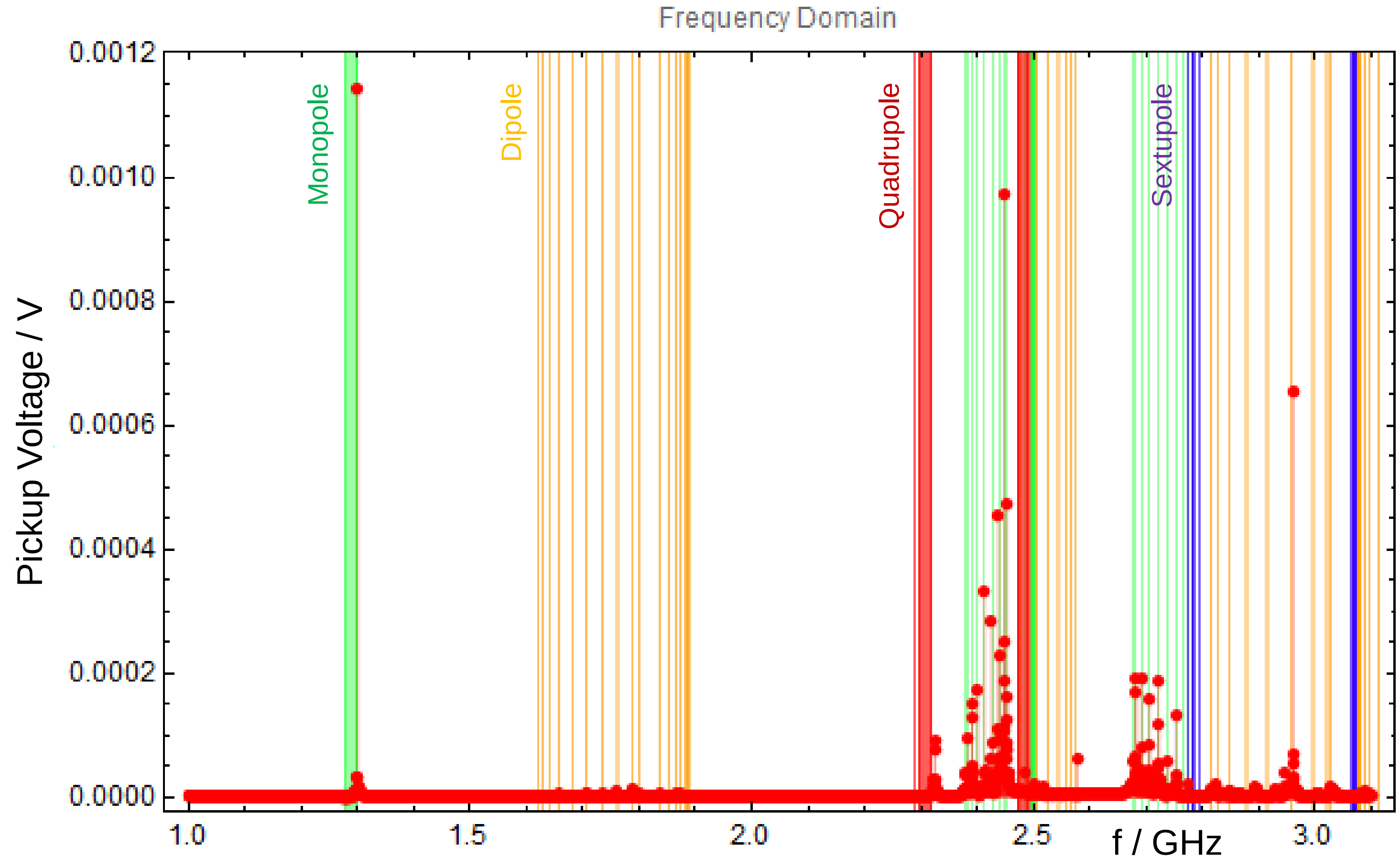

Numerical Results

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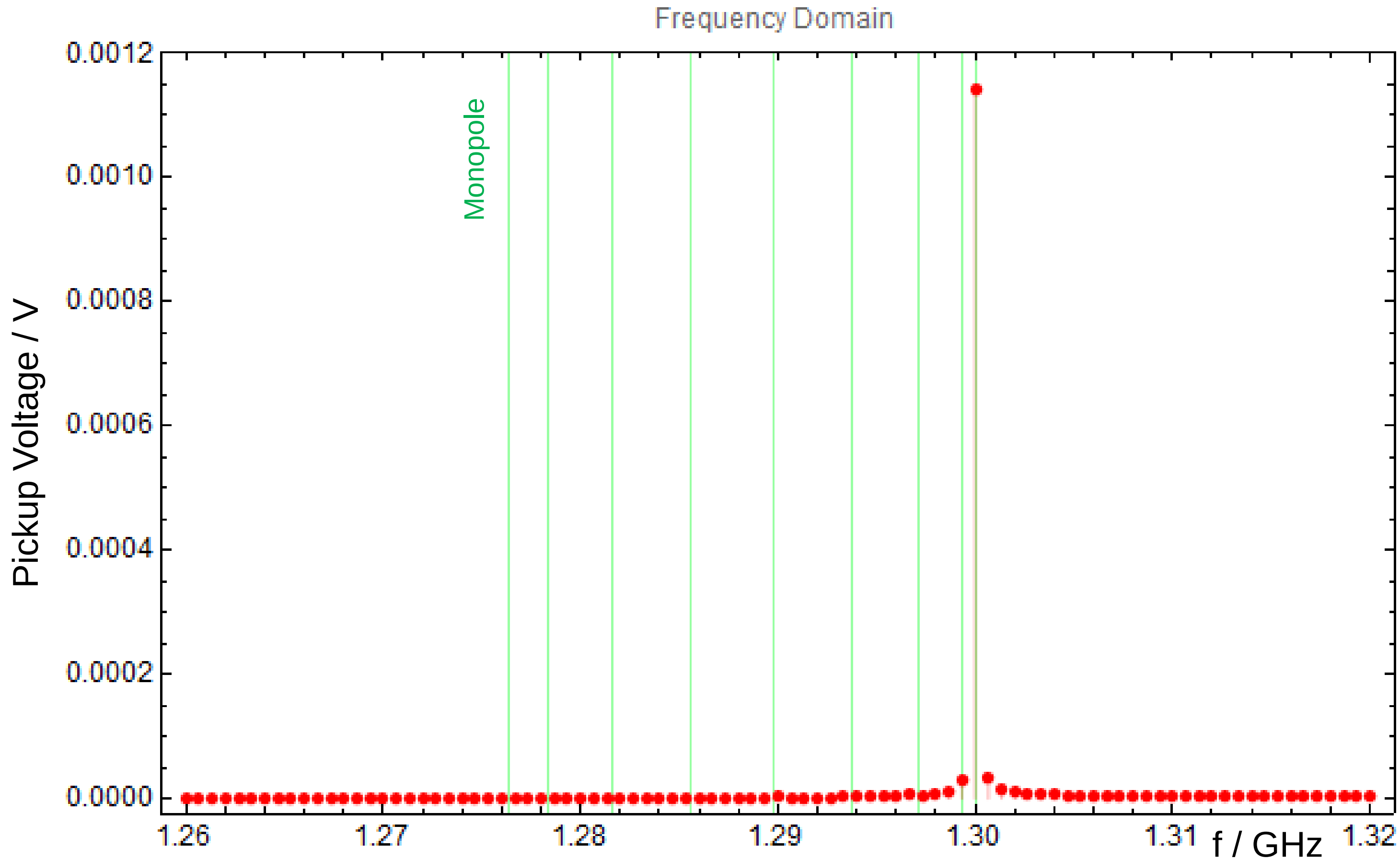

Numerical Results

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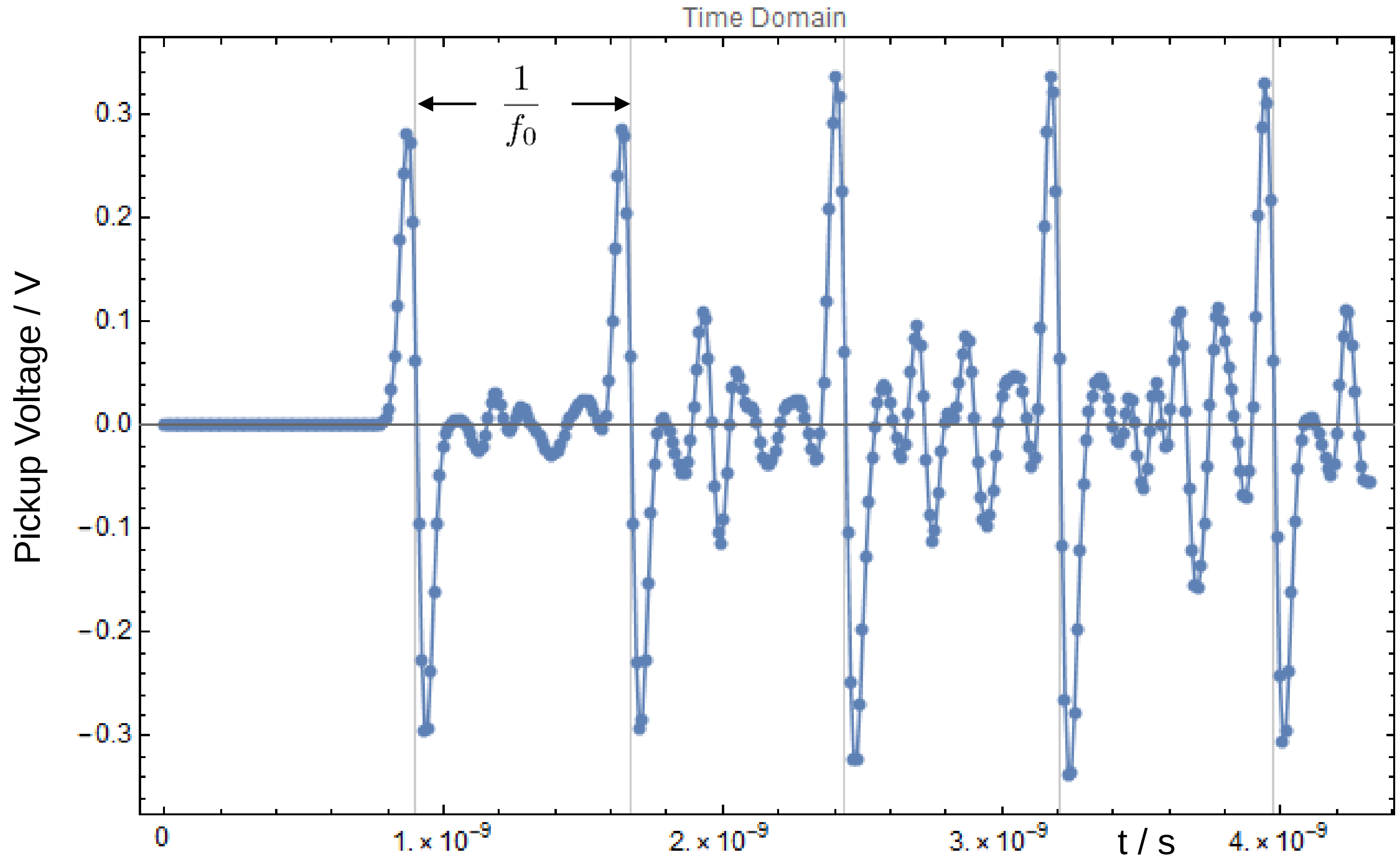

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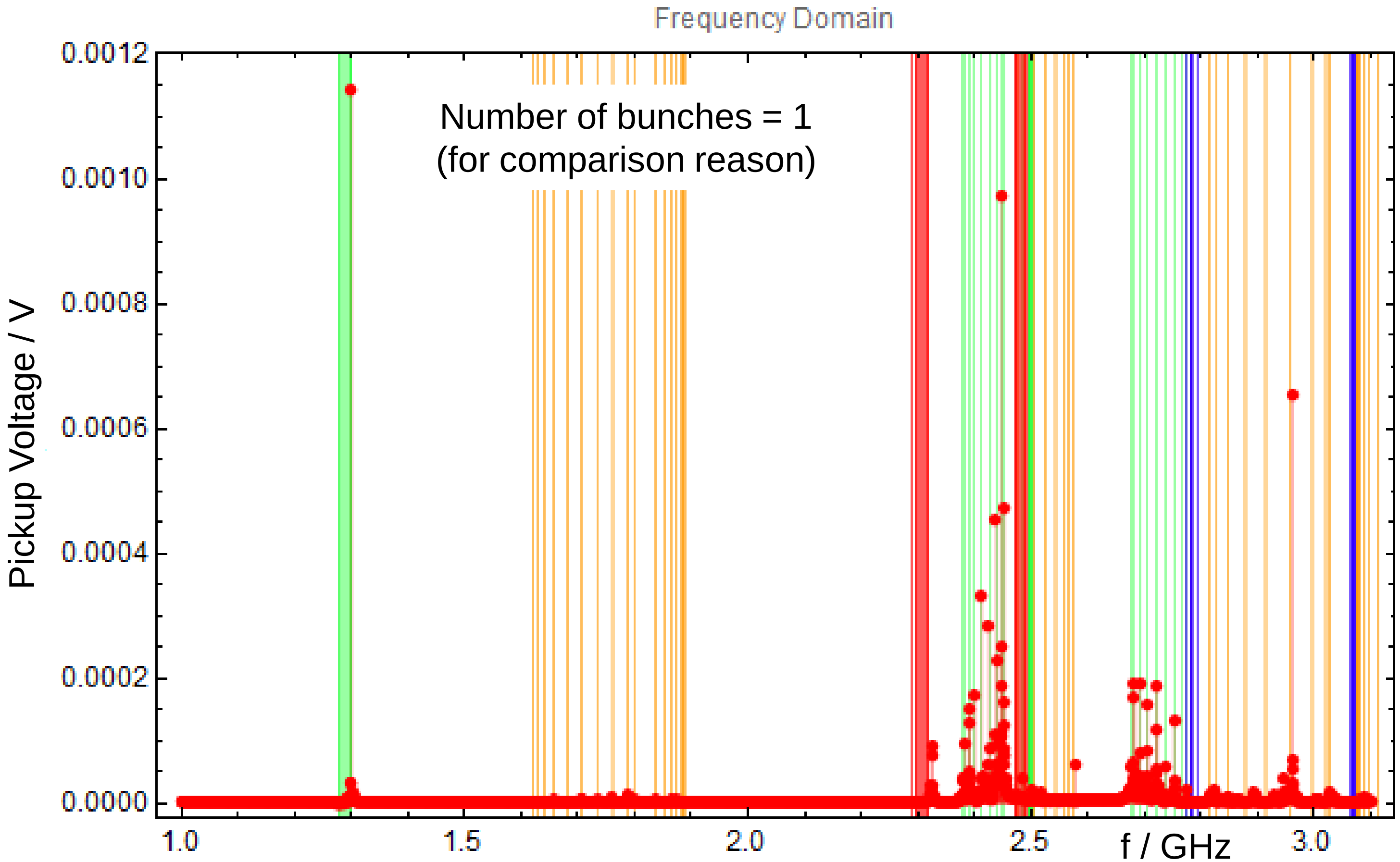

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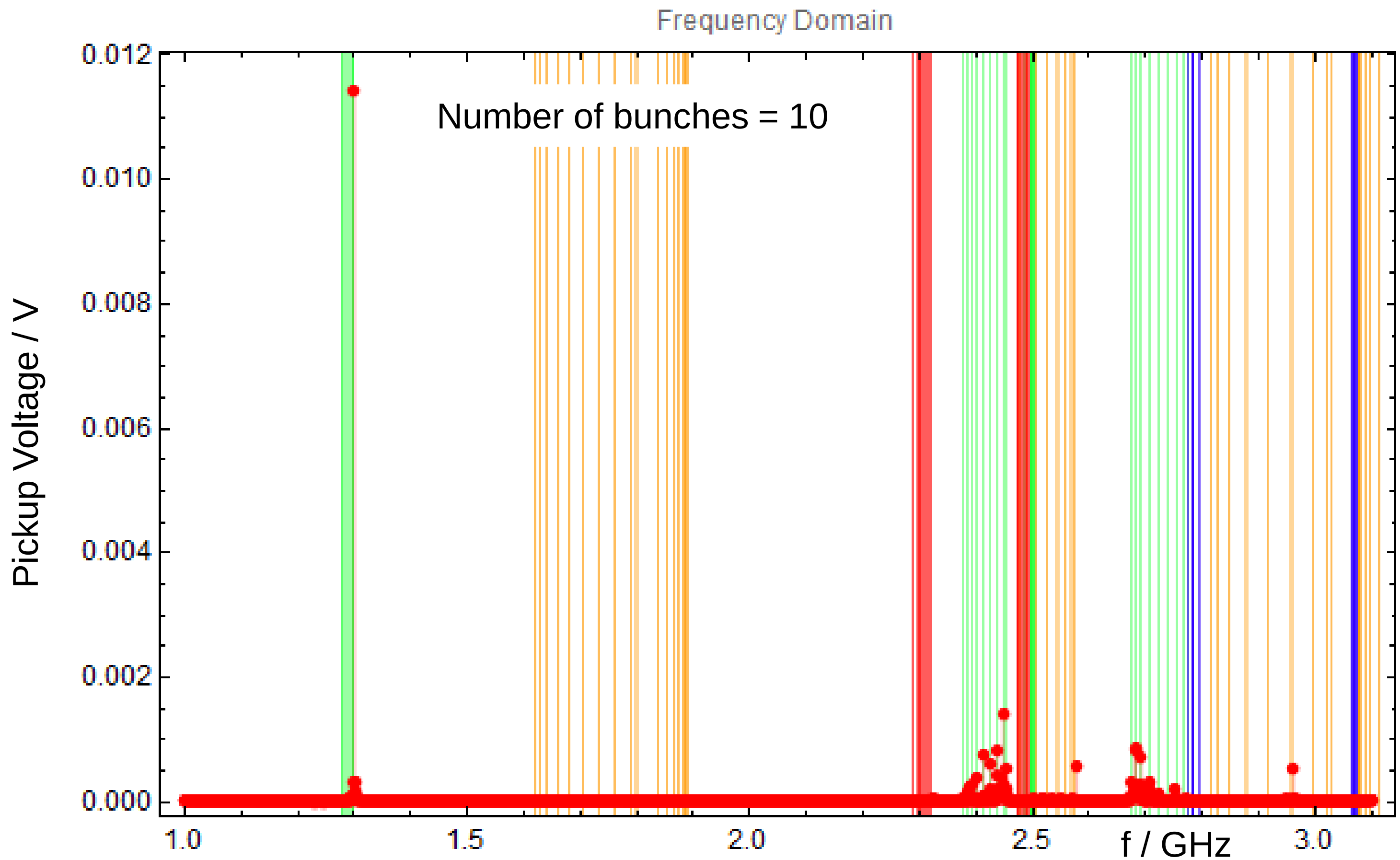

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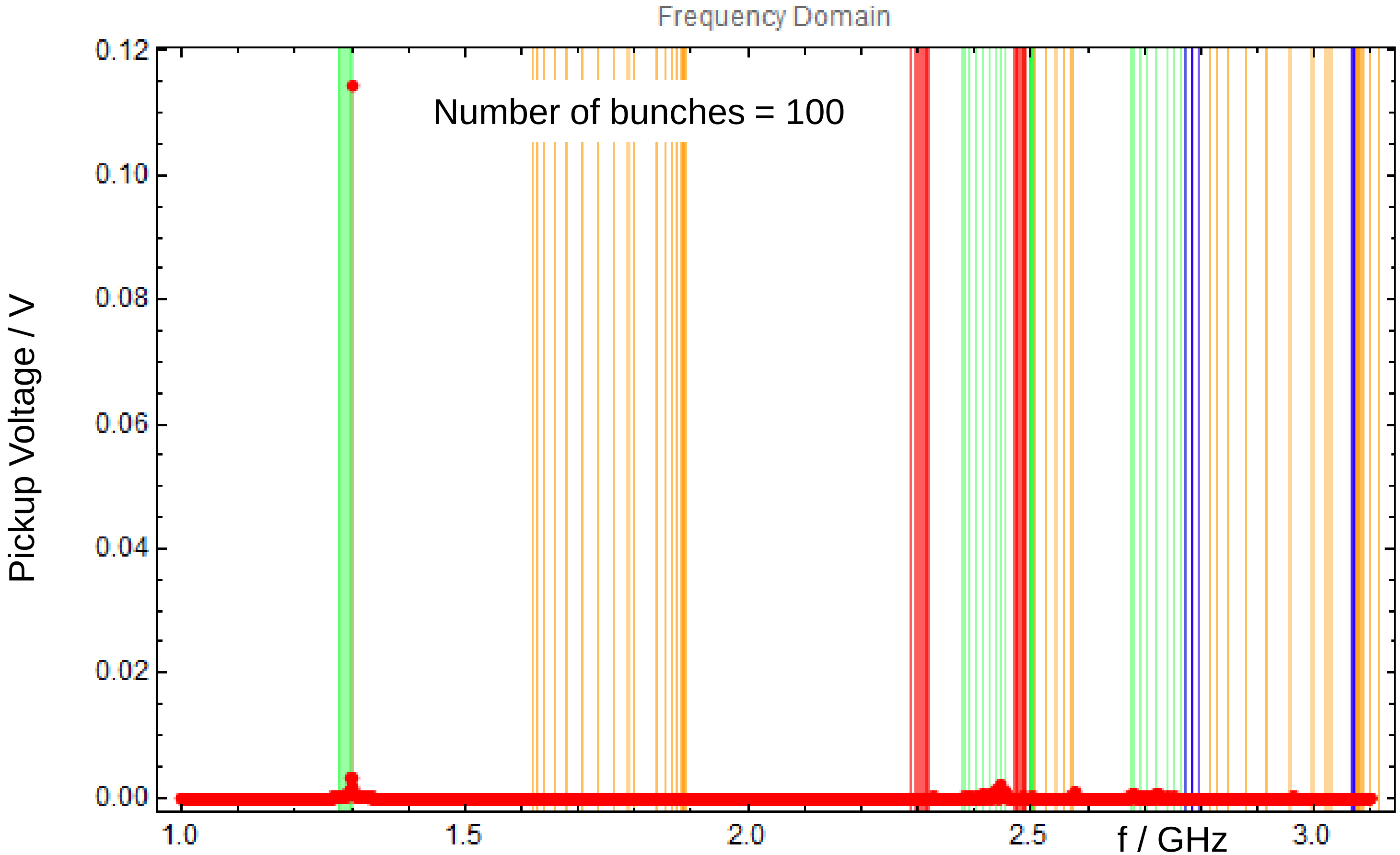

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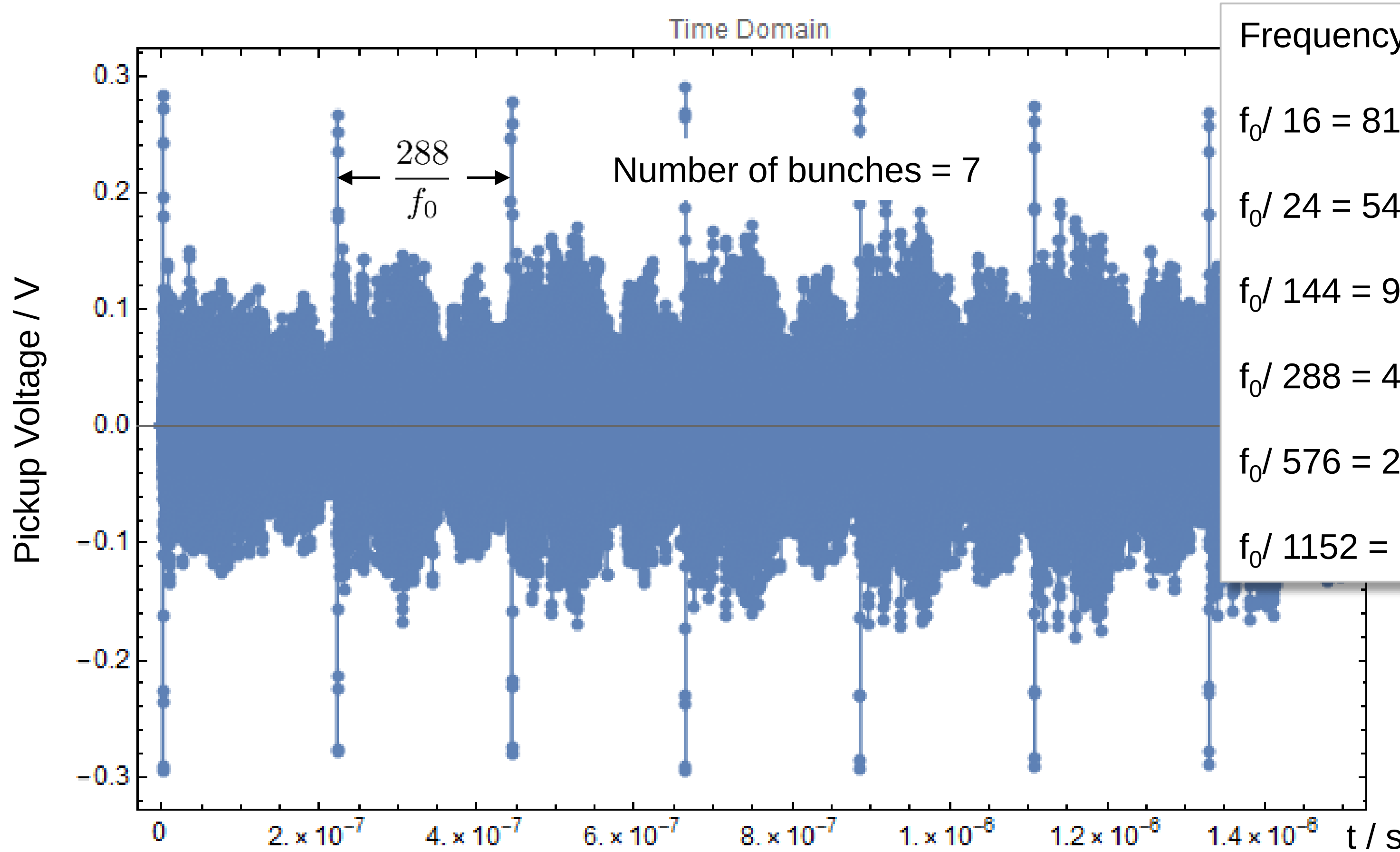

Frequency divider

f_0/ 16 = 81.250 MHz

f_0/ 24 = 54.166 MHz

f_0/ 144 = 9.028 MHz

f_0/ 288 = 4.514 MHz

f_0/ 576 = 2.257 MHz

f_0/ 1152 = 1.128 MHz

Numerical Results

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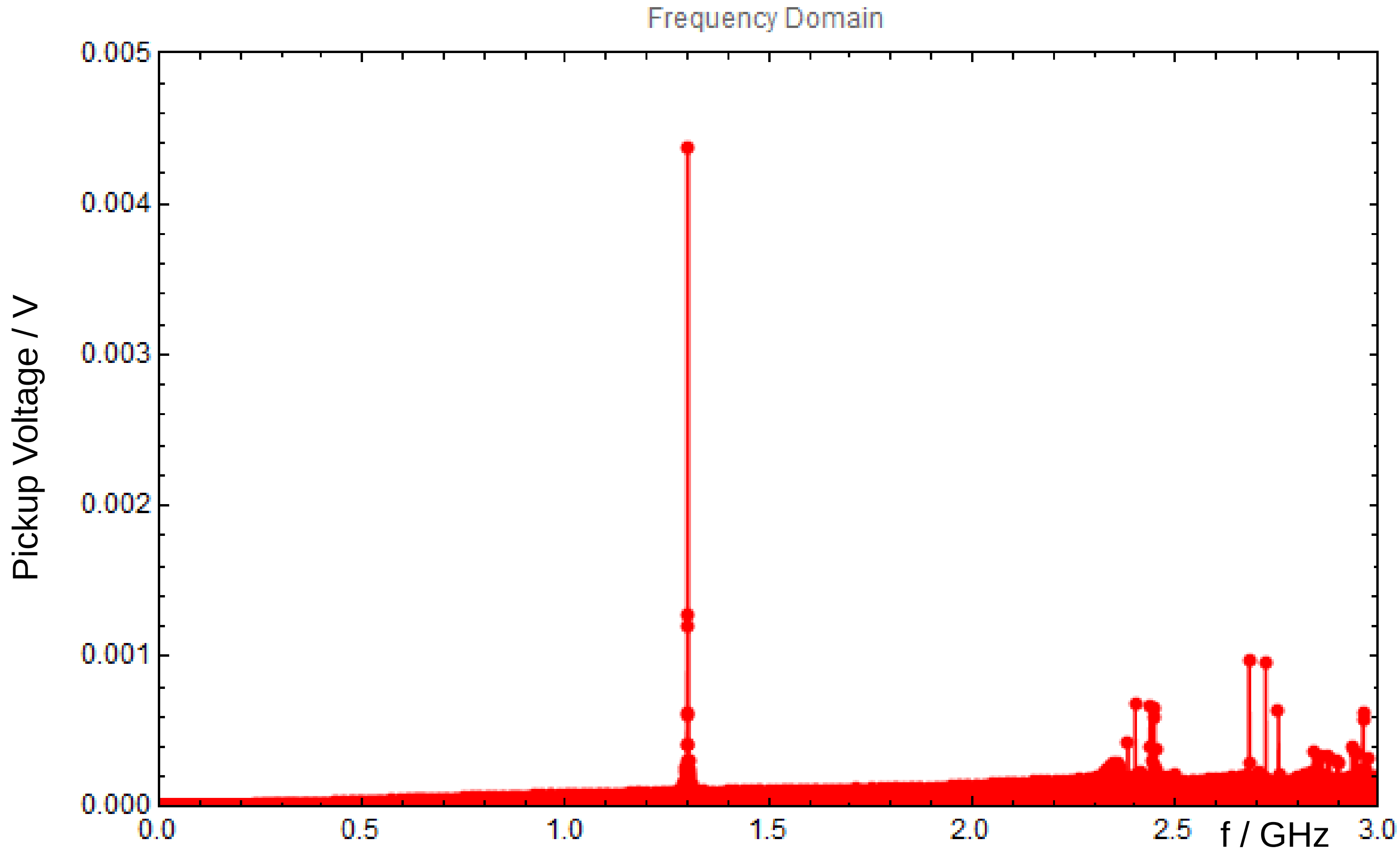
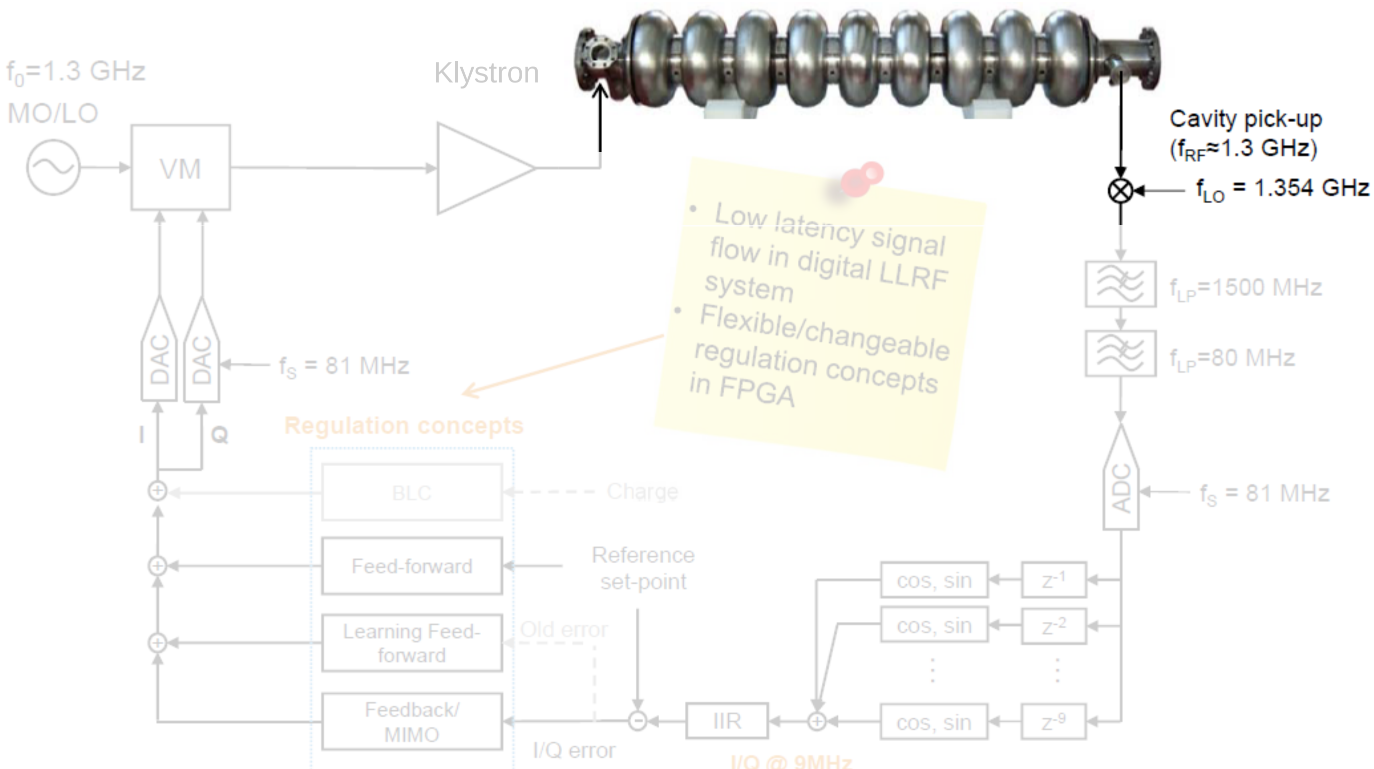


Numerical Results

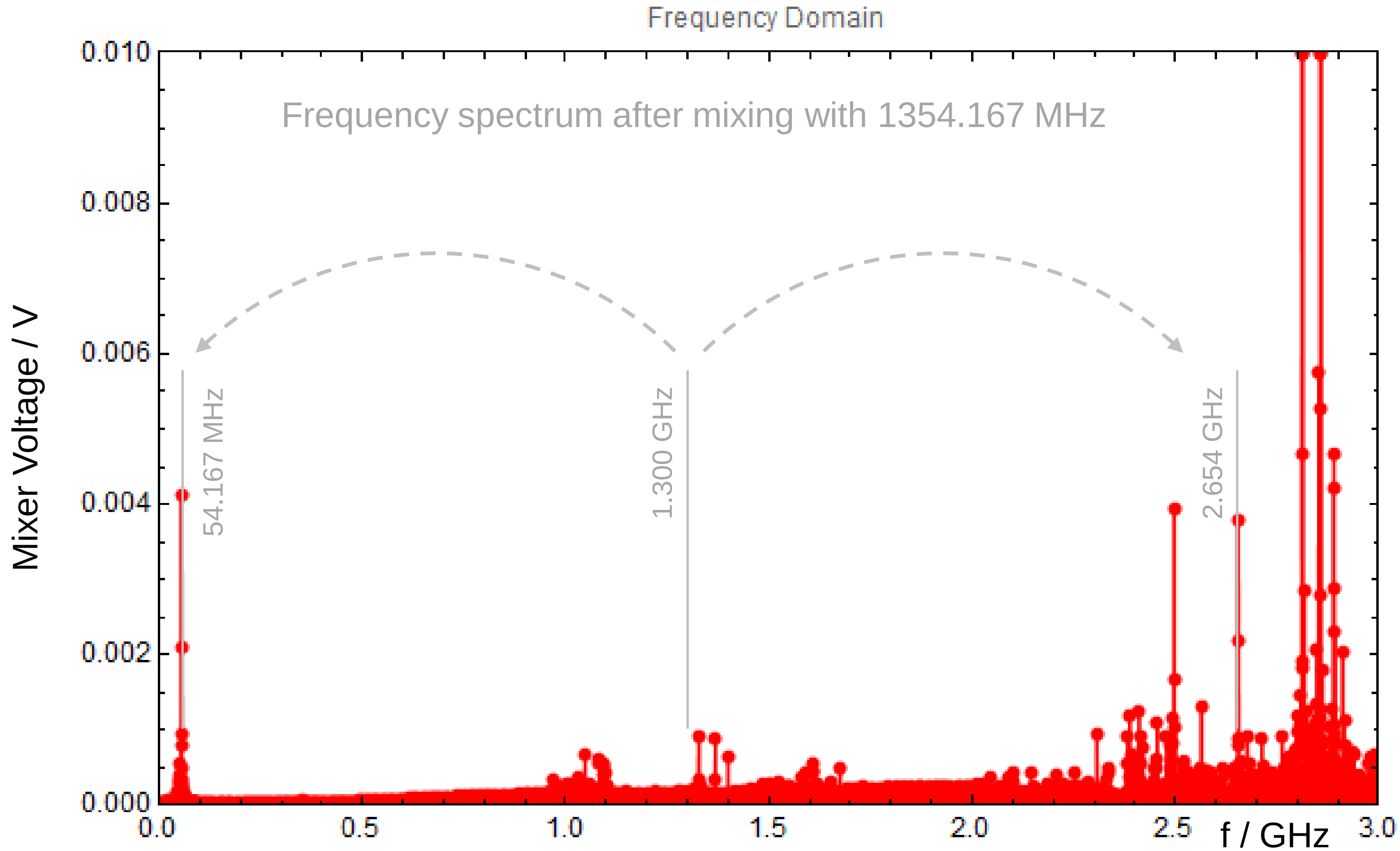
- SRF Cavity Regulation



Source: „Precision Control of SRF Cavities“, Sven Pfeiffer, 15.11.2018

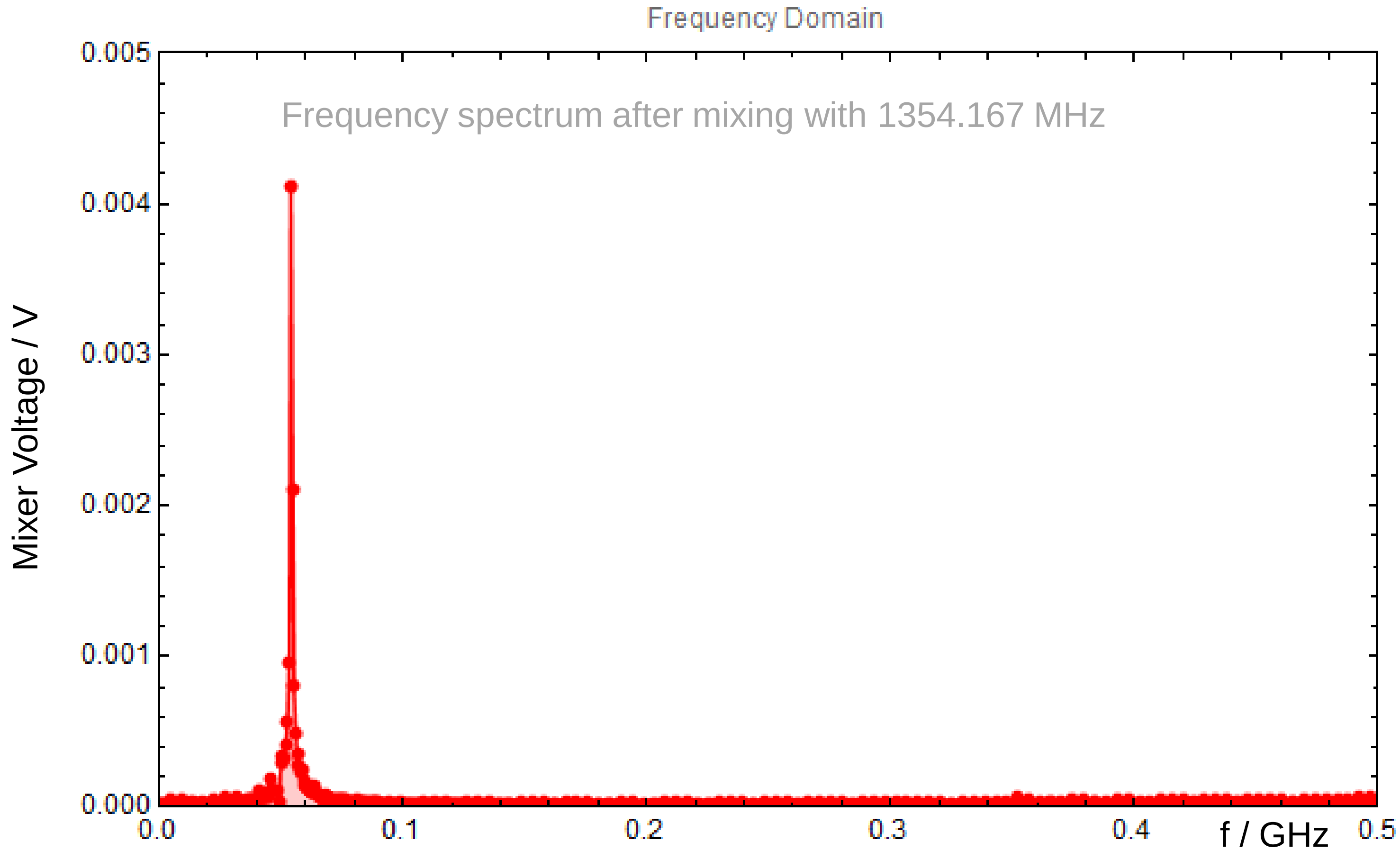
Numerical Results

- Signal after Mixer for Multiple Pulse Excitation



Numerical Results

- Signal after Mixer for Multiple Pulse Excitation



Numerical Results

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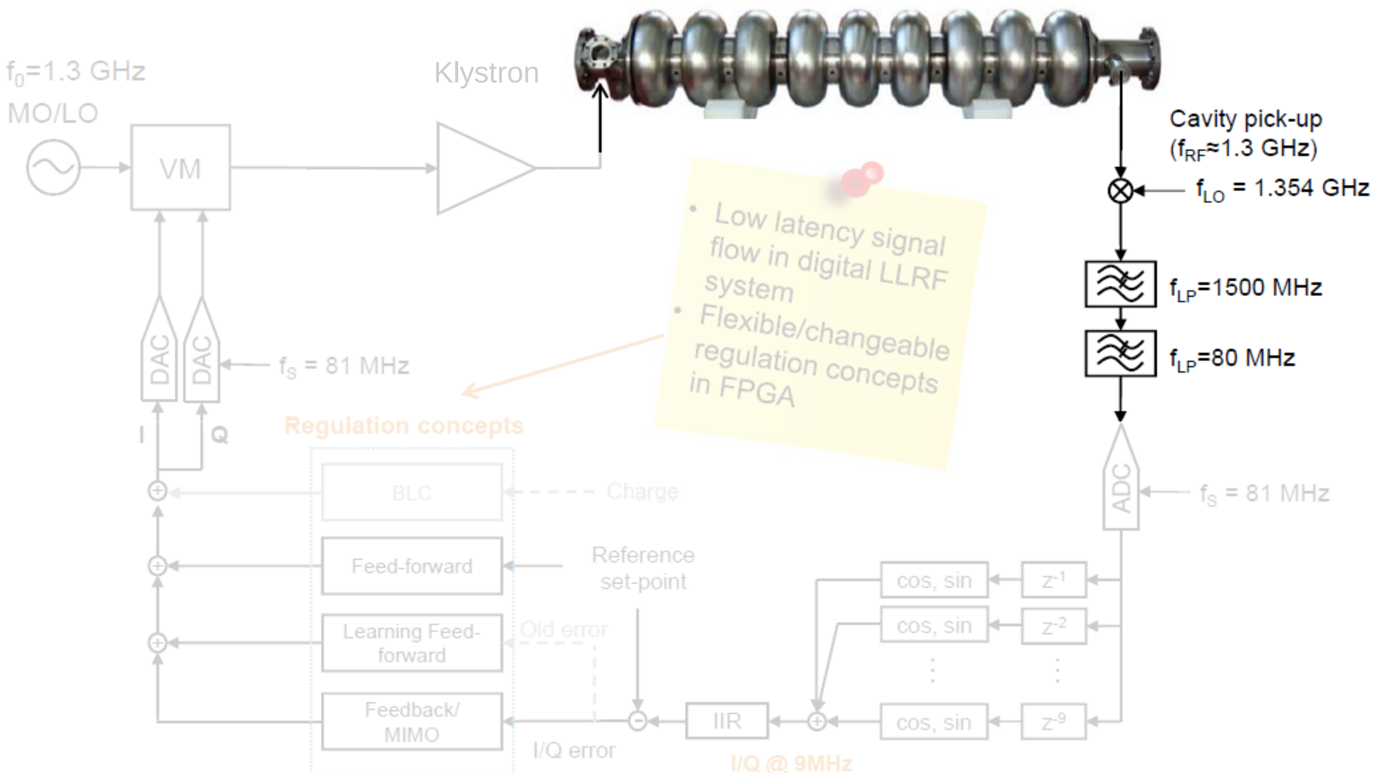
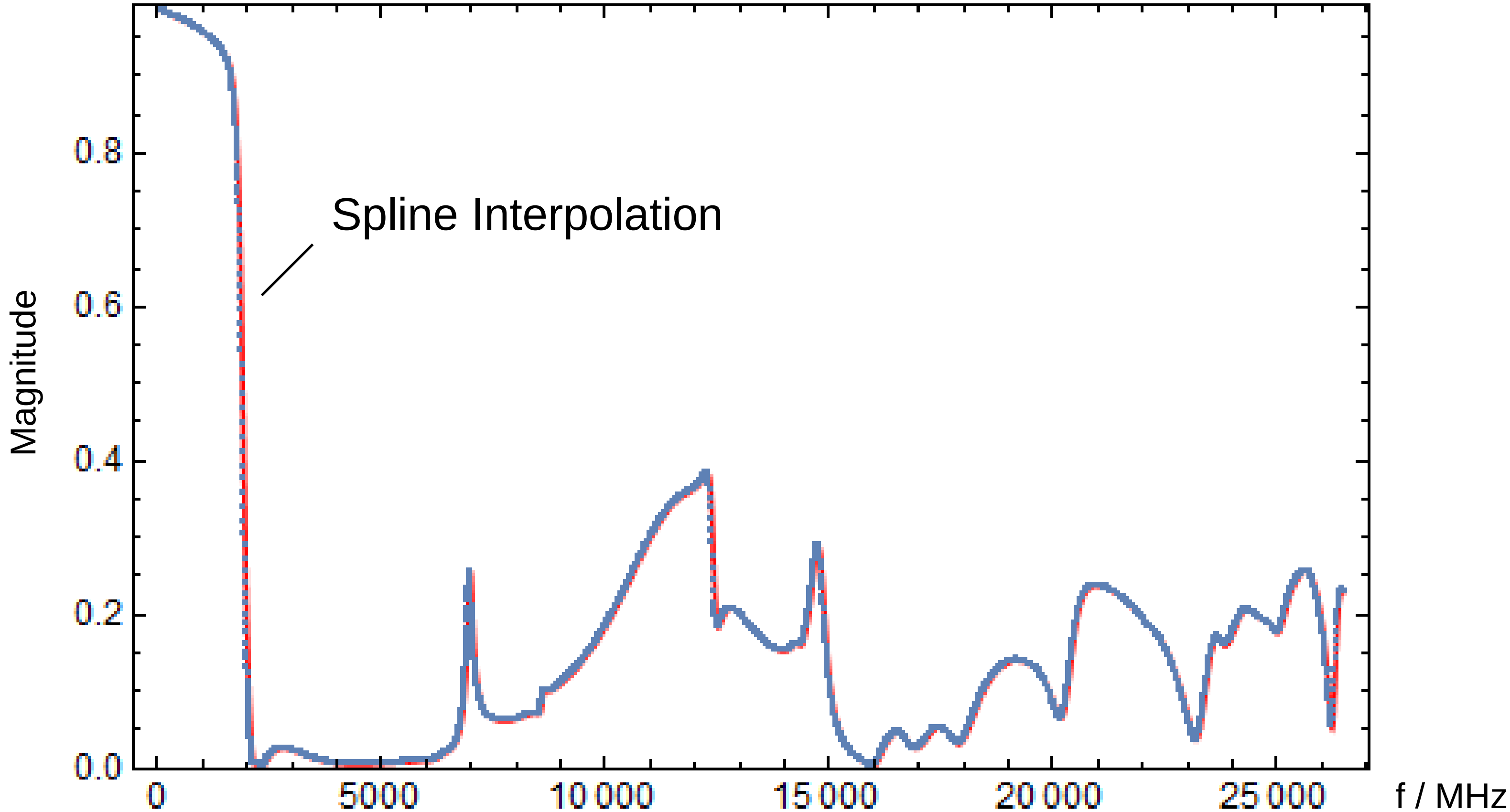


Source: „Precision Control of SRF Cavities“, Sven Pfeiffer, 15.11.2018

Numerical Results

- Low Pass Filter (Mini-Circuits LFCN-1500)



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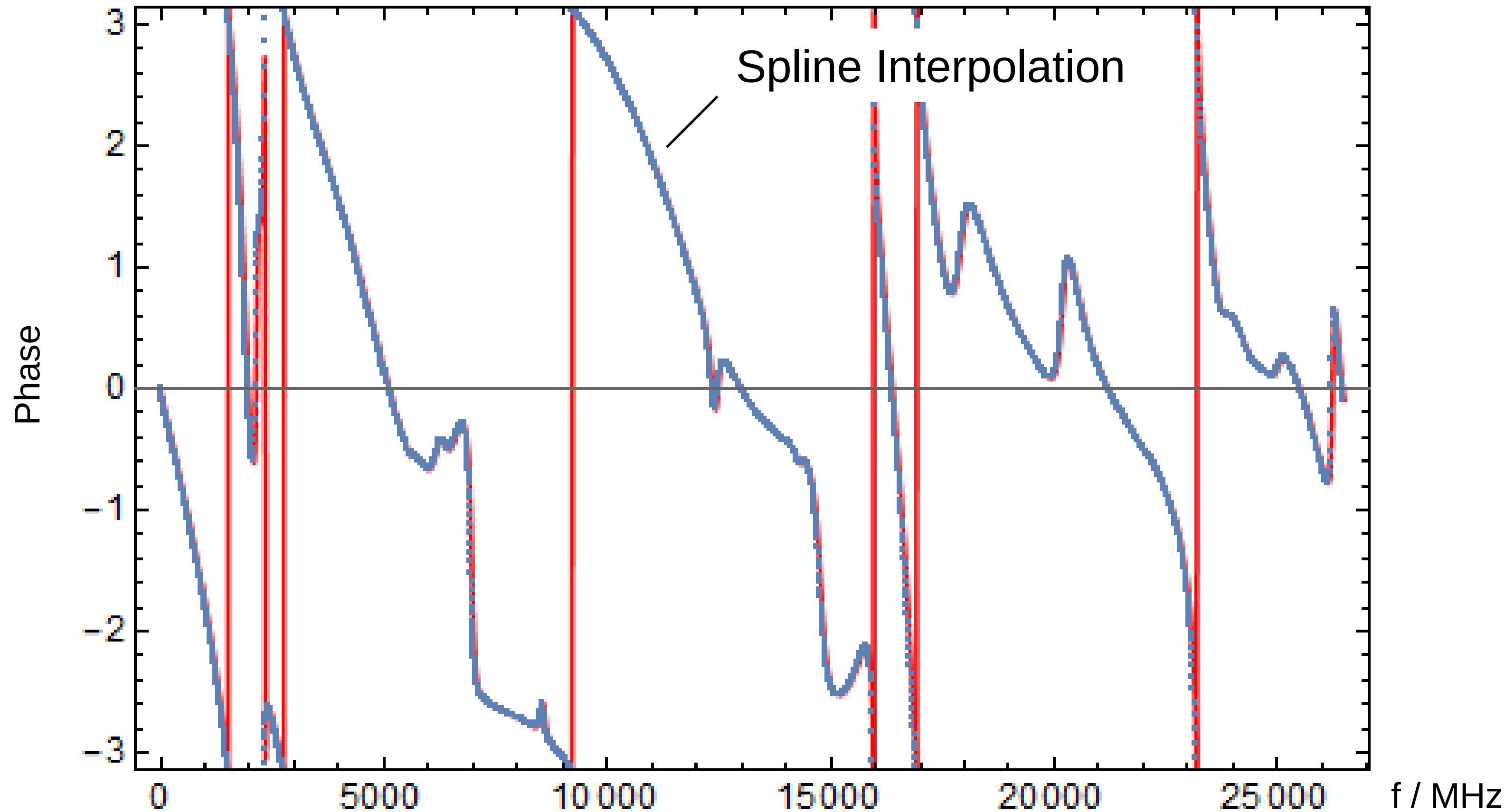
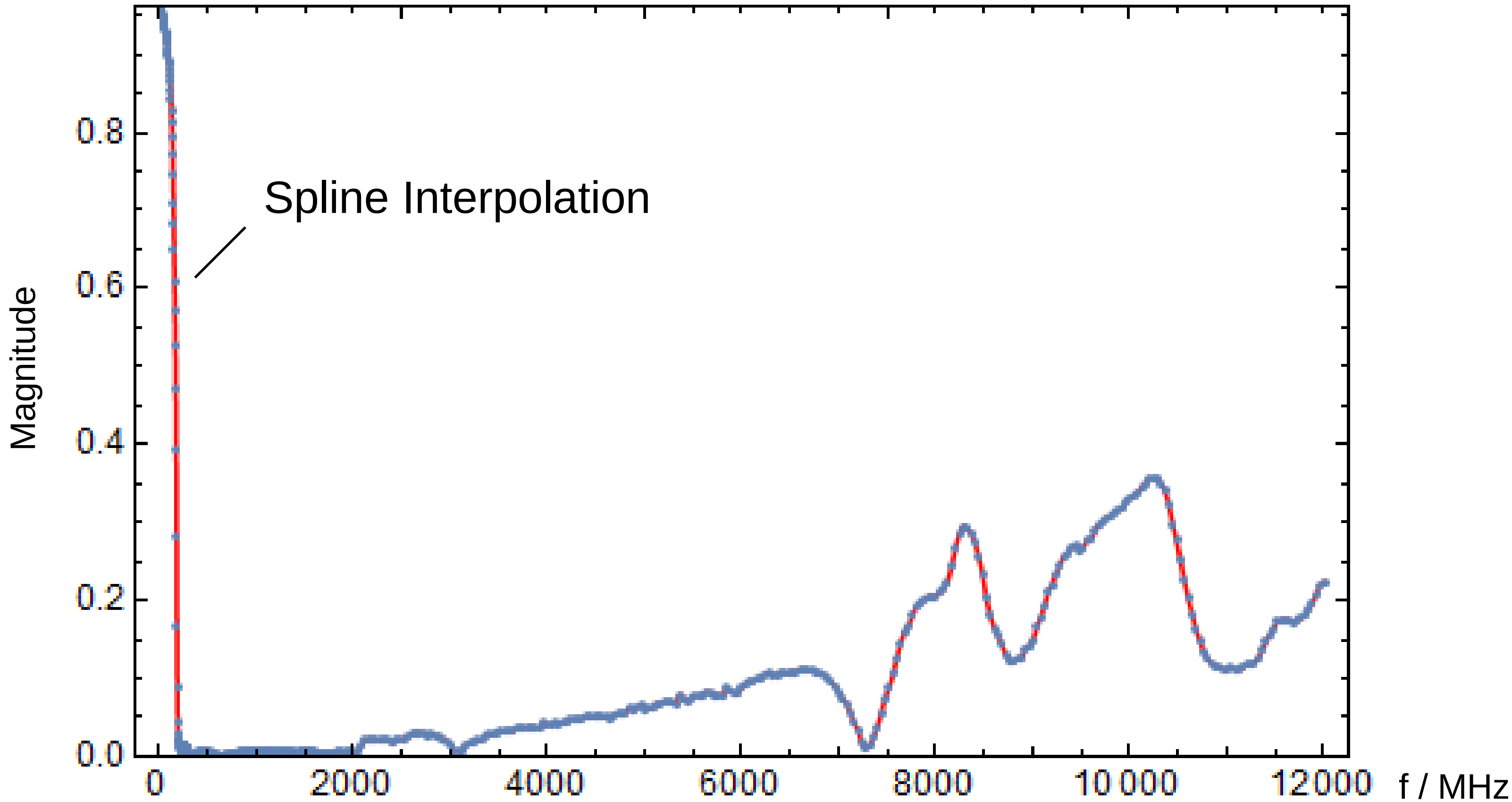


Numerical Results

- Low Pass Filter (Mini-Circuits LFCN-80)



Numerical Results

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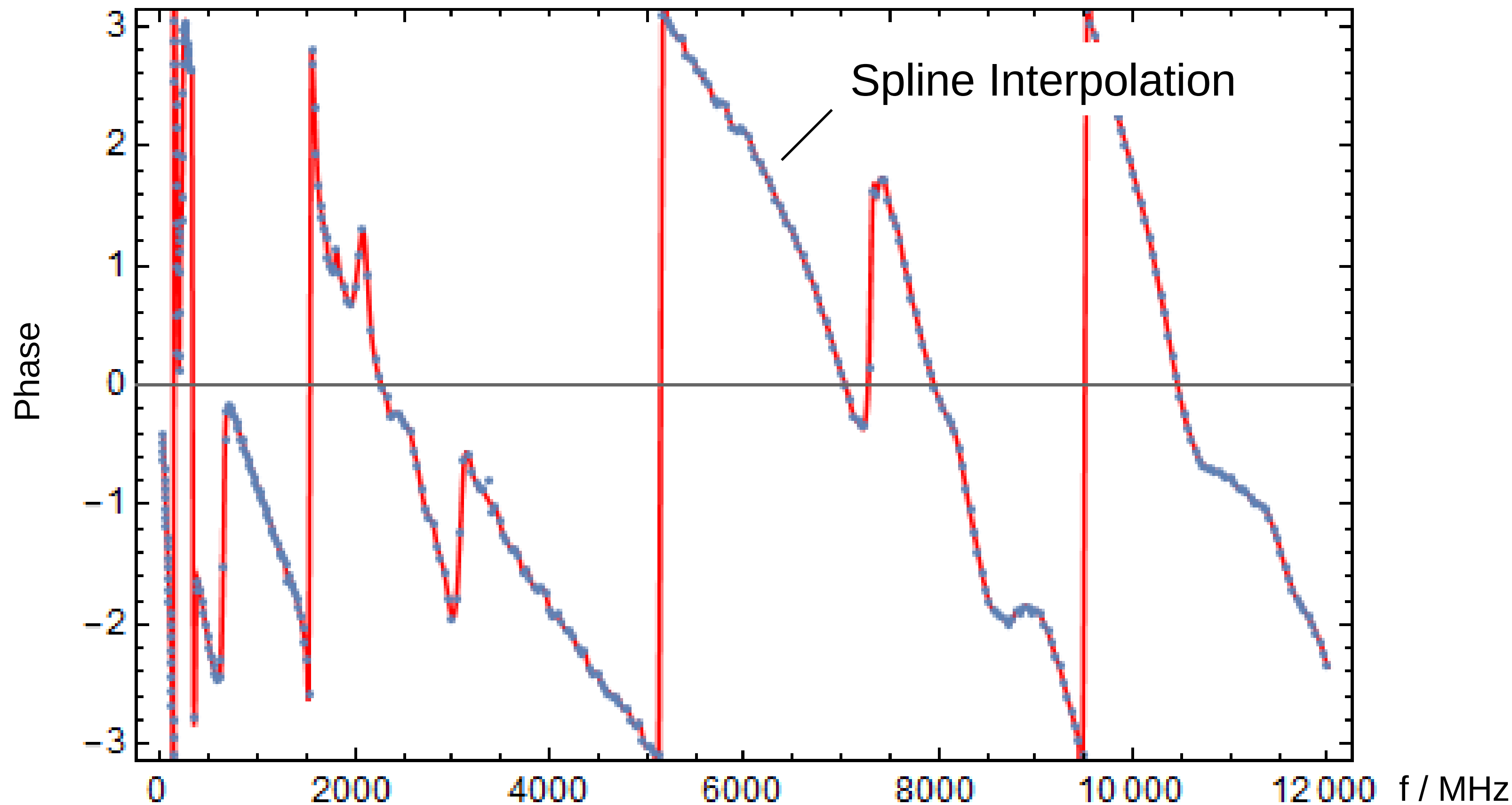
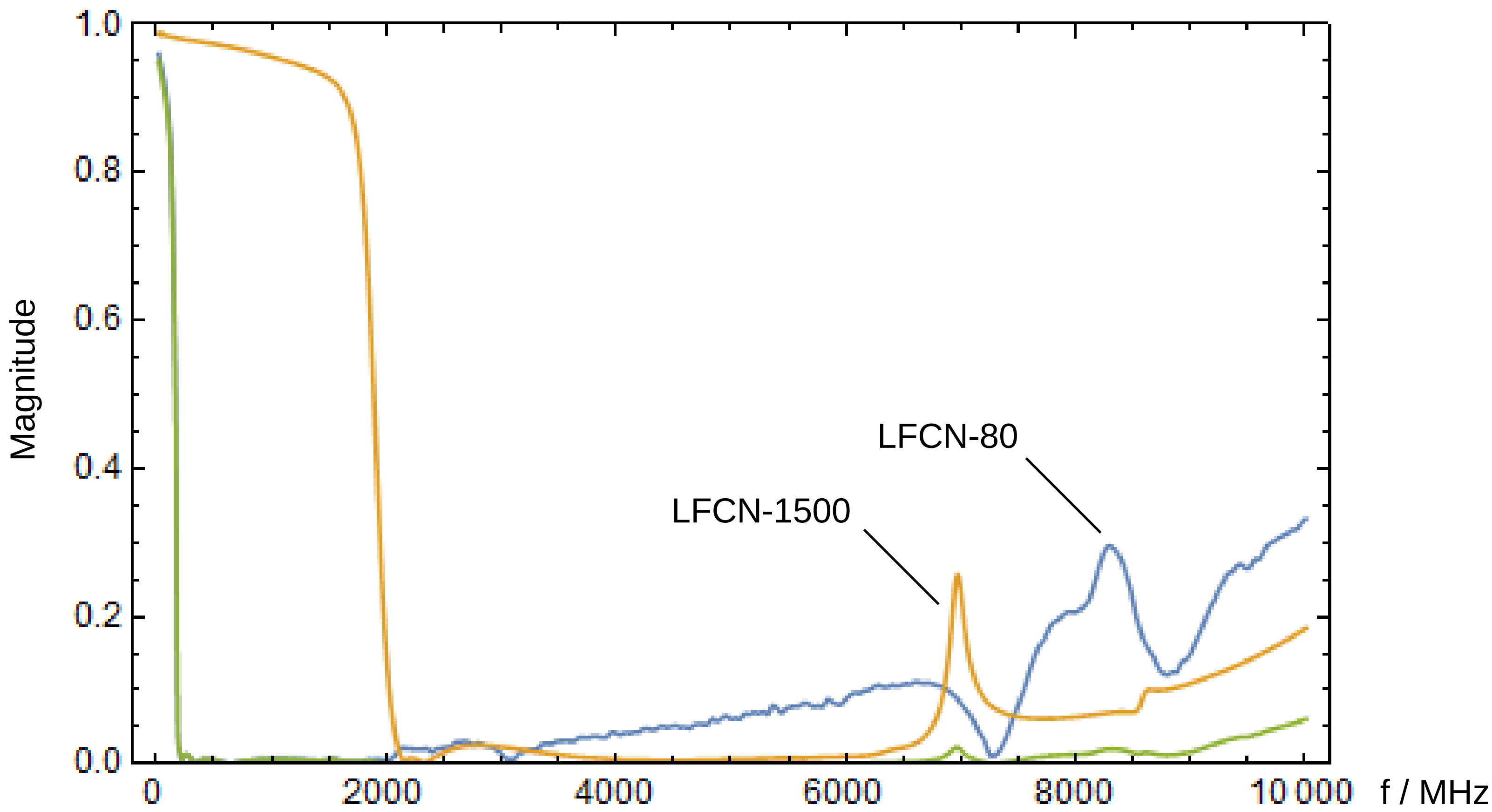
- Low Pass Filter (Mini-Circuits LFCN-80)



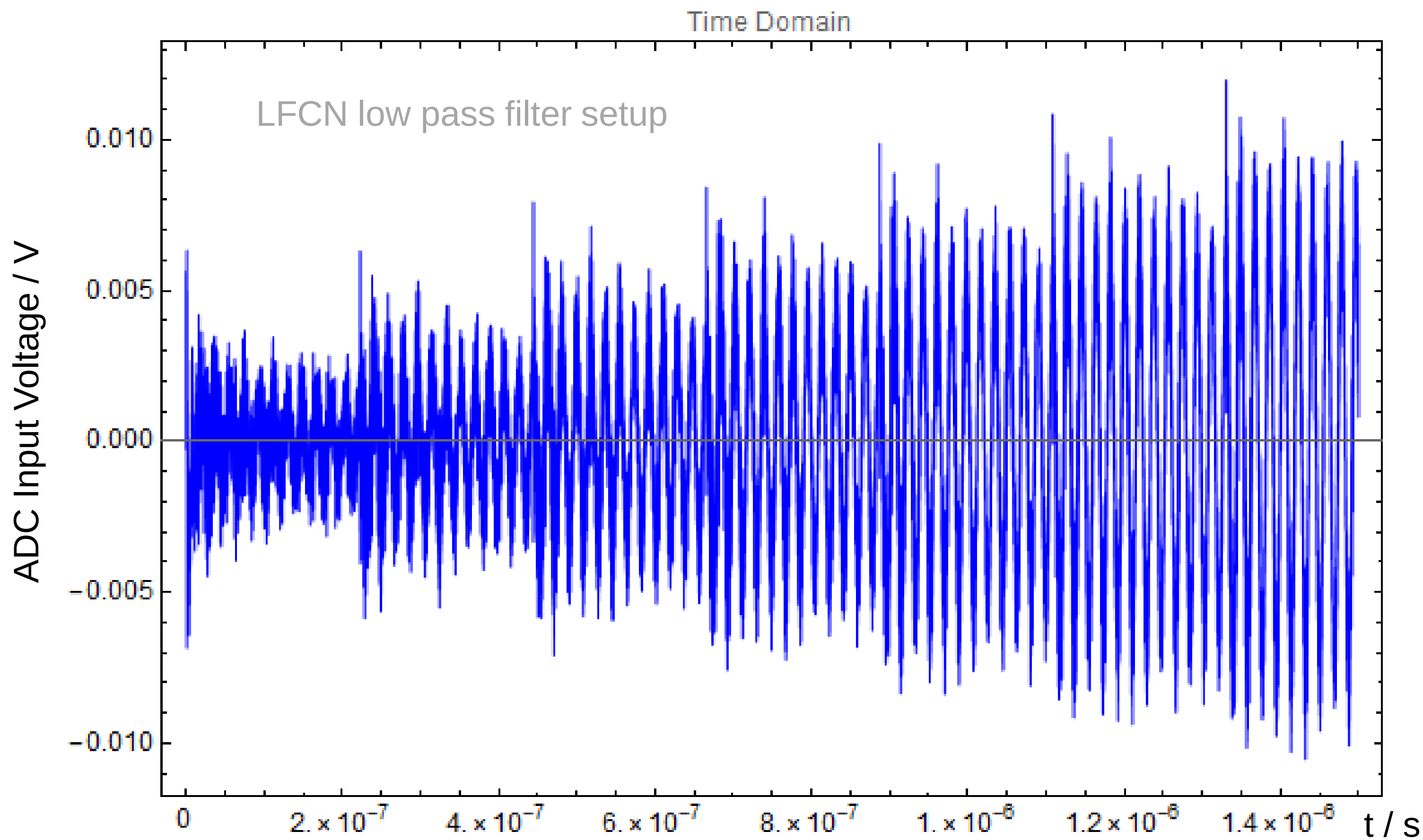
Numerical Results

- Low Pass Filter (Mini-Circuits LFCN-1500 & LFCN-80)



Numerical Results

- Signal after Filters for Multiple Pulse Excitation



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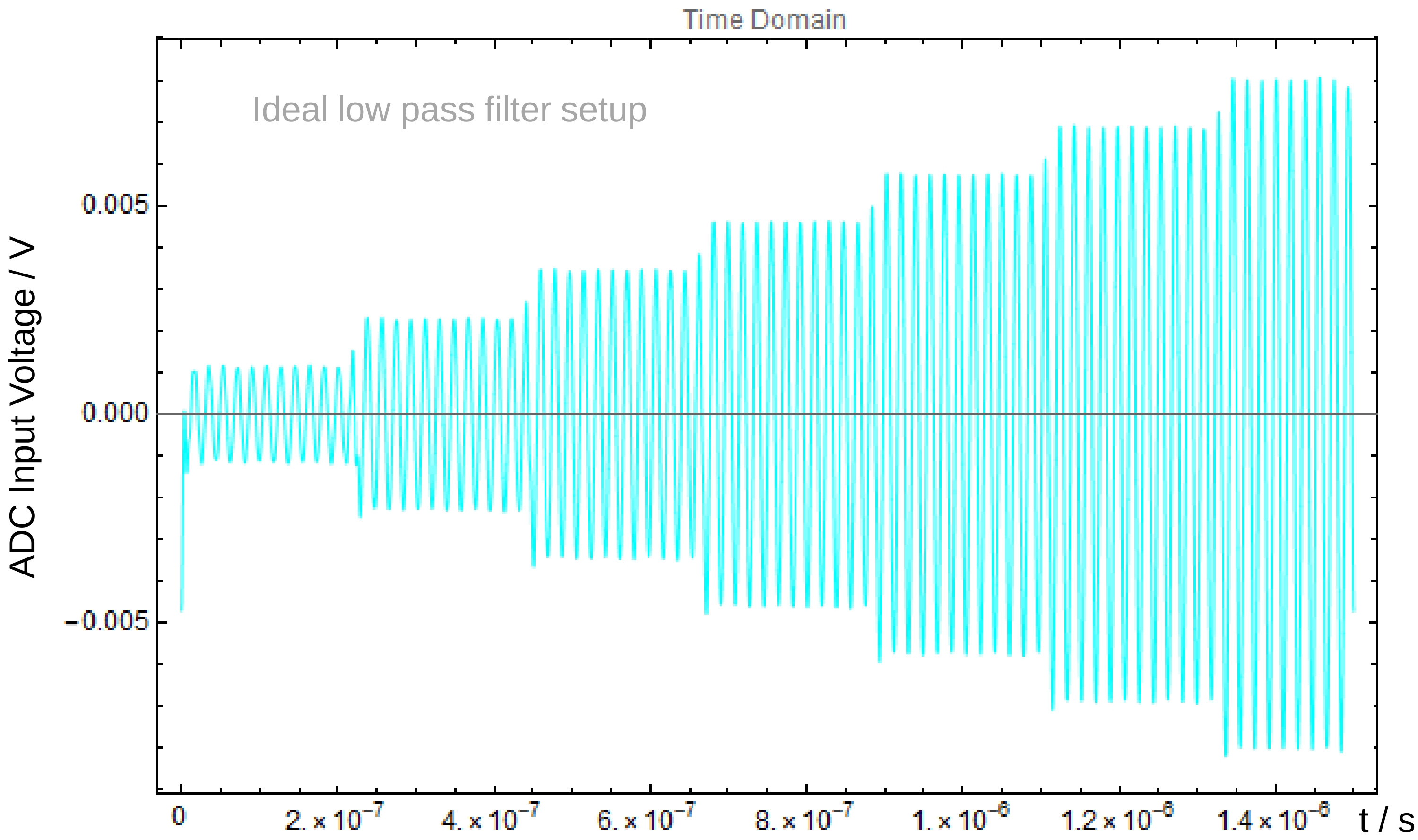

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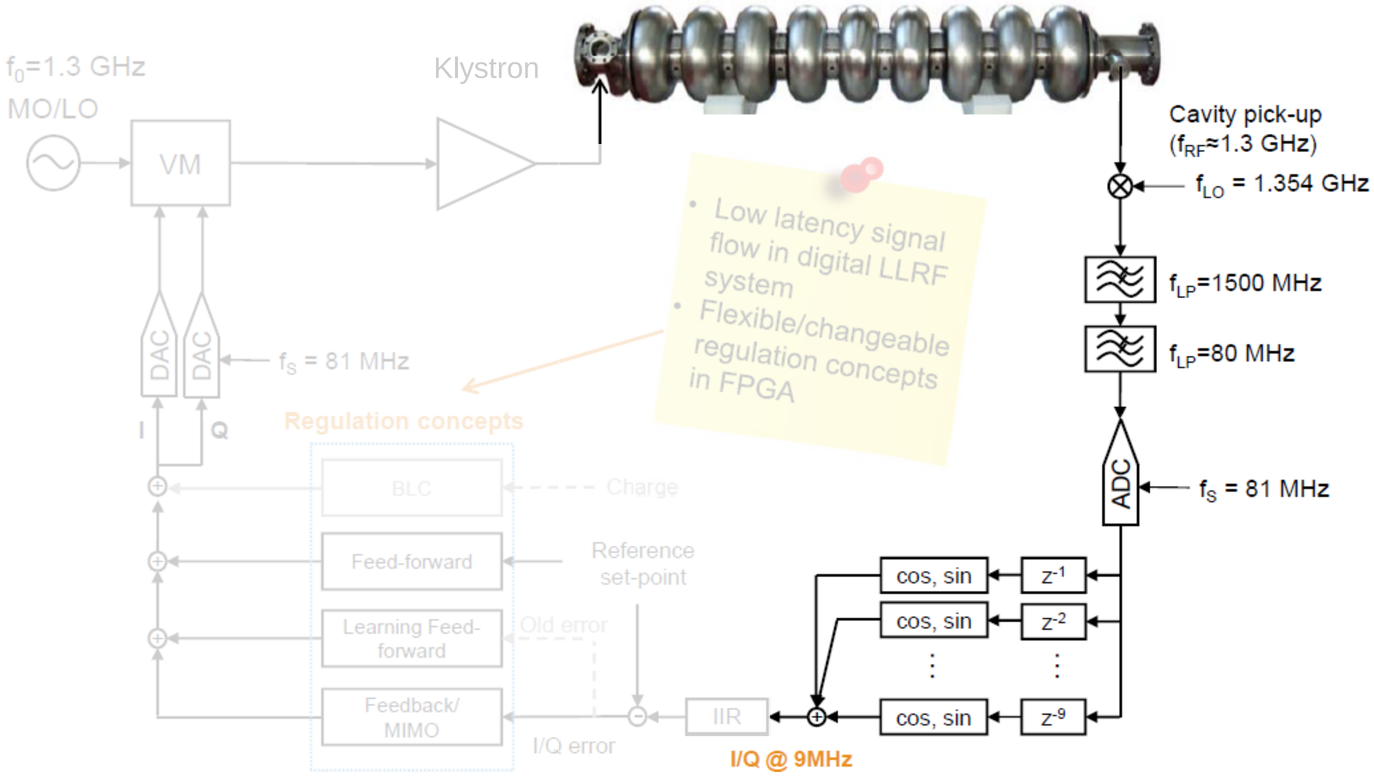

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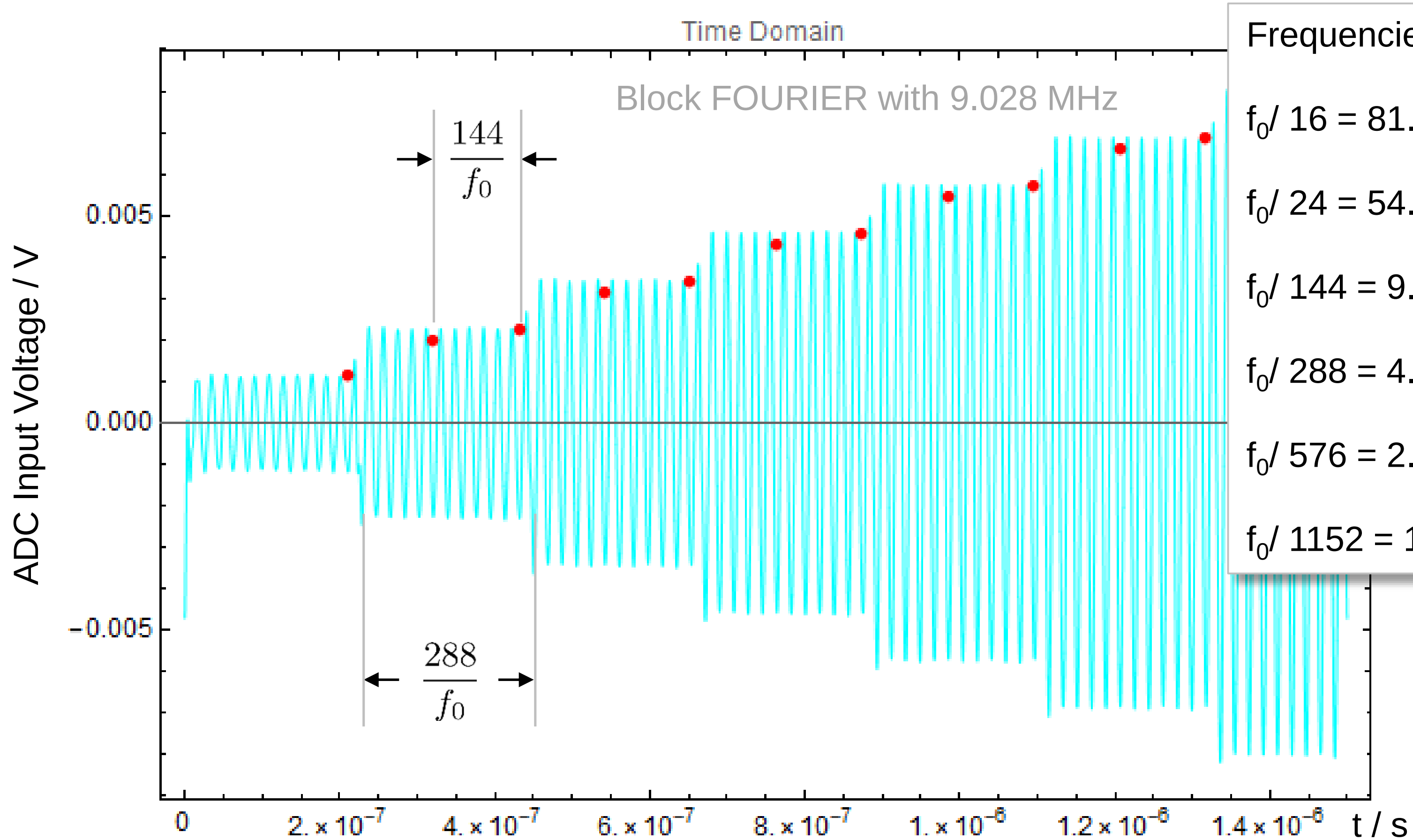

Frequencies

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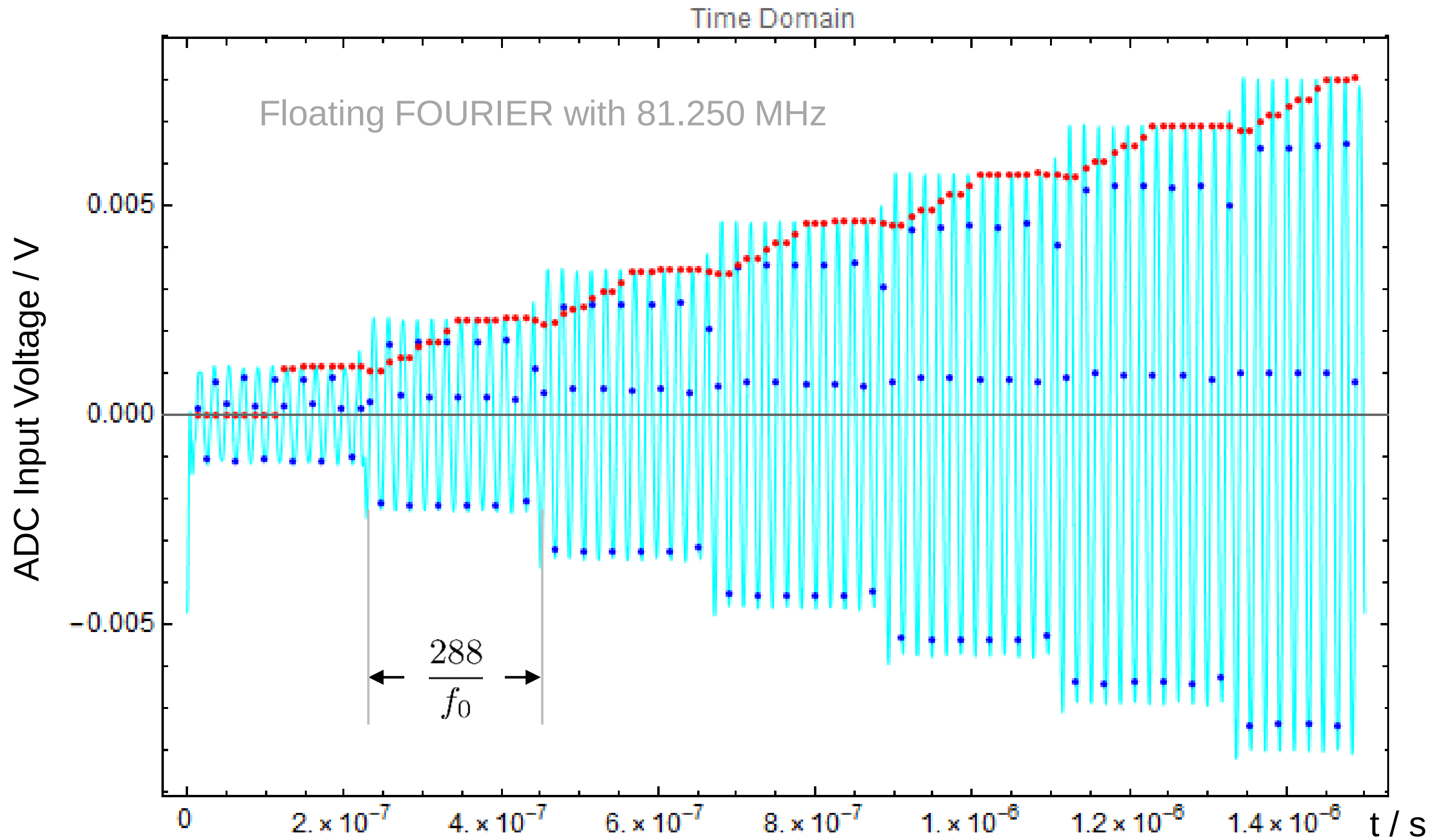

Numerical Results

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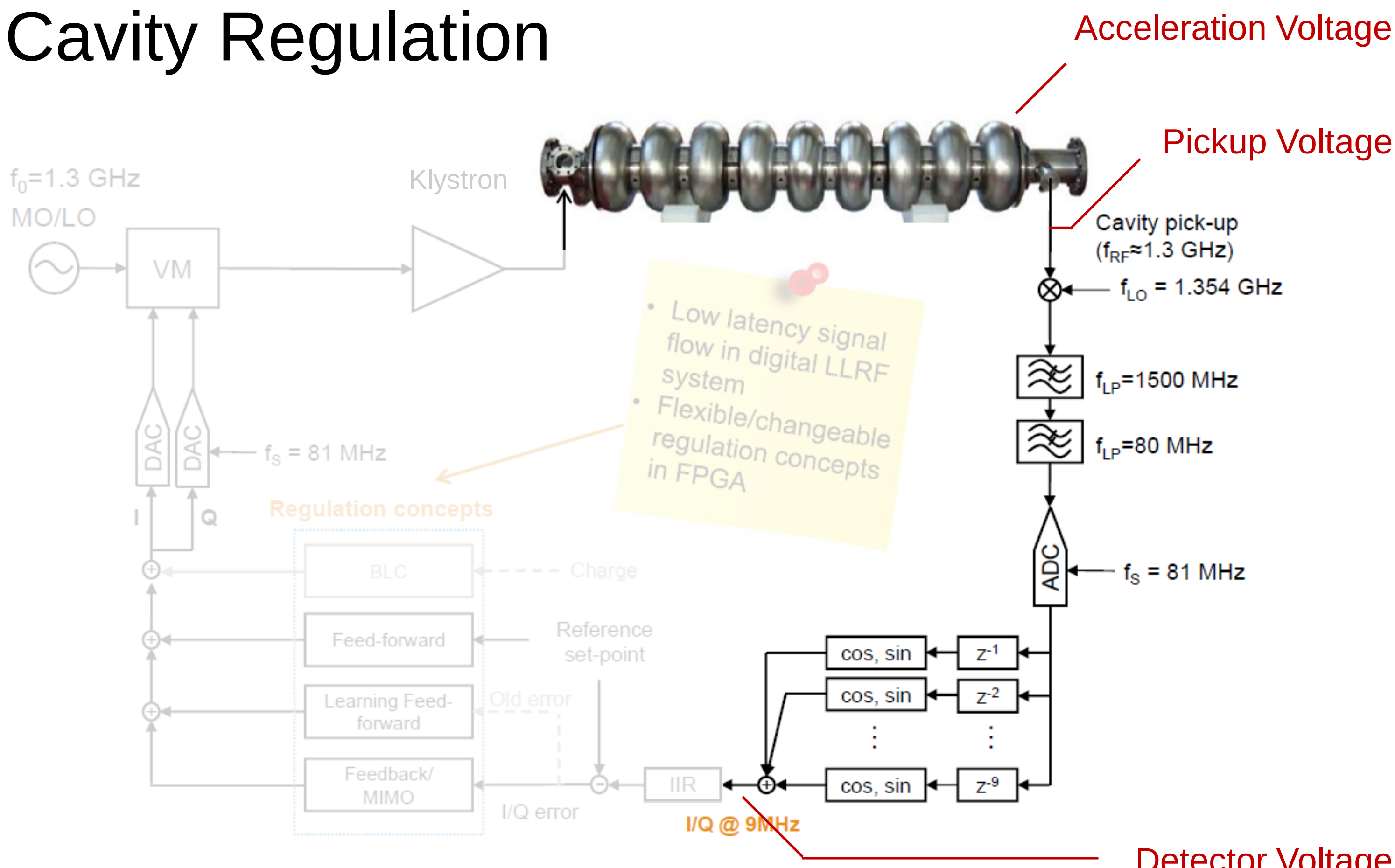


Source: „Precision Control of SRF Cavities“, Sven Pfeiffer, 15.11.2018

Numerical Results

- Lossy Eigenvalue Simulations (Waveguide Ports)
  - Cem3D

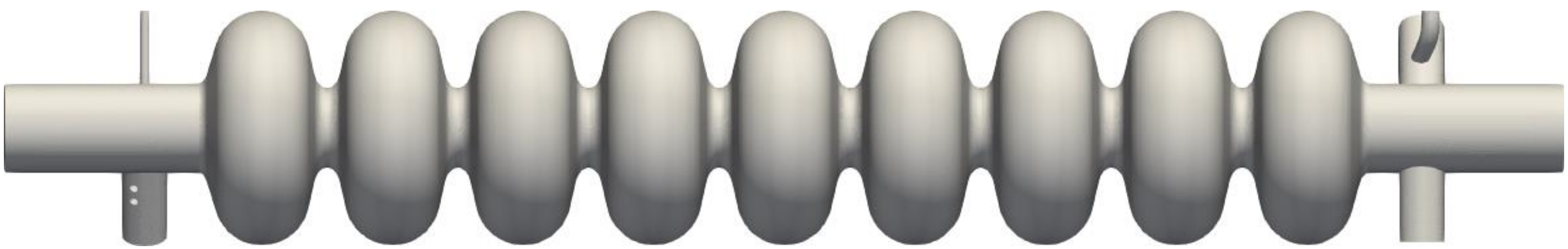
P_4 = 6.402 mW

Energy = 1 J
f_0 = 1.299998 GHz
Q= 2.596e+06

P_2 = 0.222 W

Port 4

Port 2



Port 3

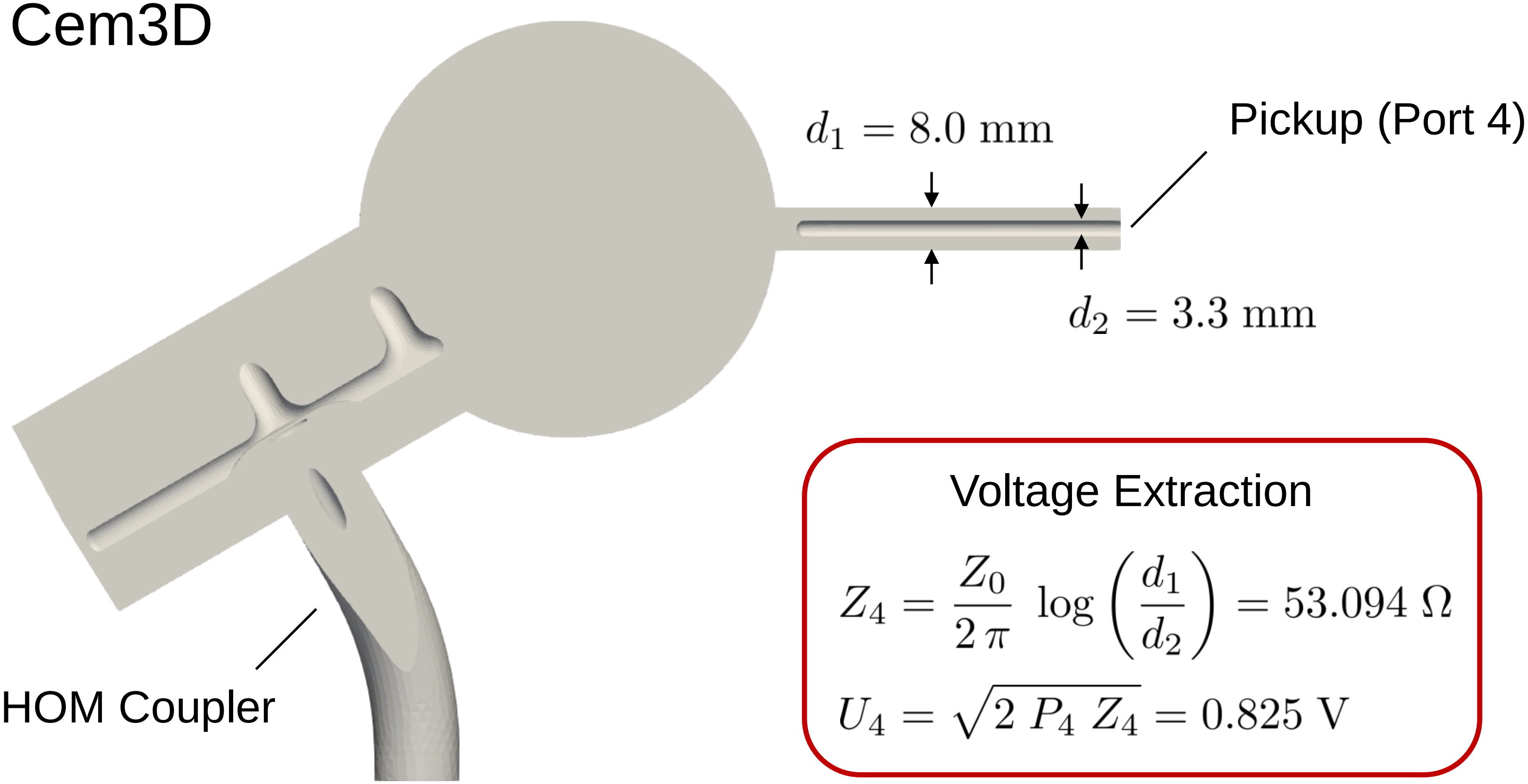
Port 1

P_3 = 0.189 W

P_1 = 3.146 kW

Numerical Results

- Lossy Eigenvalue Simulations (Waveguide Ports)
  - Cem3D



Voltage Extraction

$$Z_4 = \frac{Z_0}{2\,\pi}\,\log\left(\frac{d_1}{d_2}\right) = 53.094\ \Omega$$

$$U_4 = \sqrt{2\ P_4\ Z_4} = 0.825\ \text{V}$$

Numerical Results

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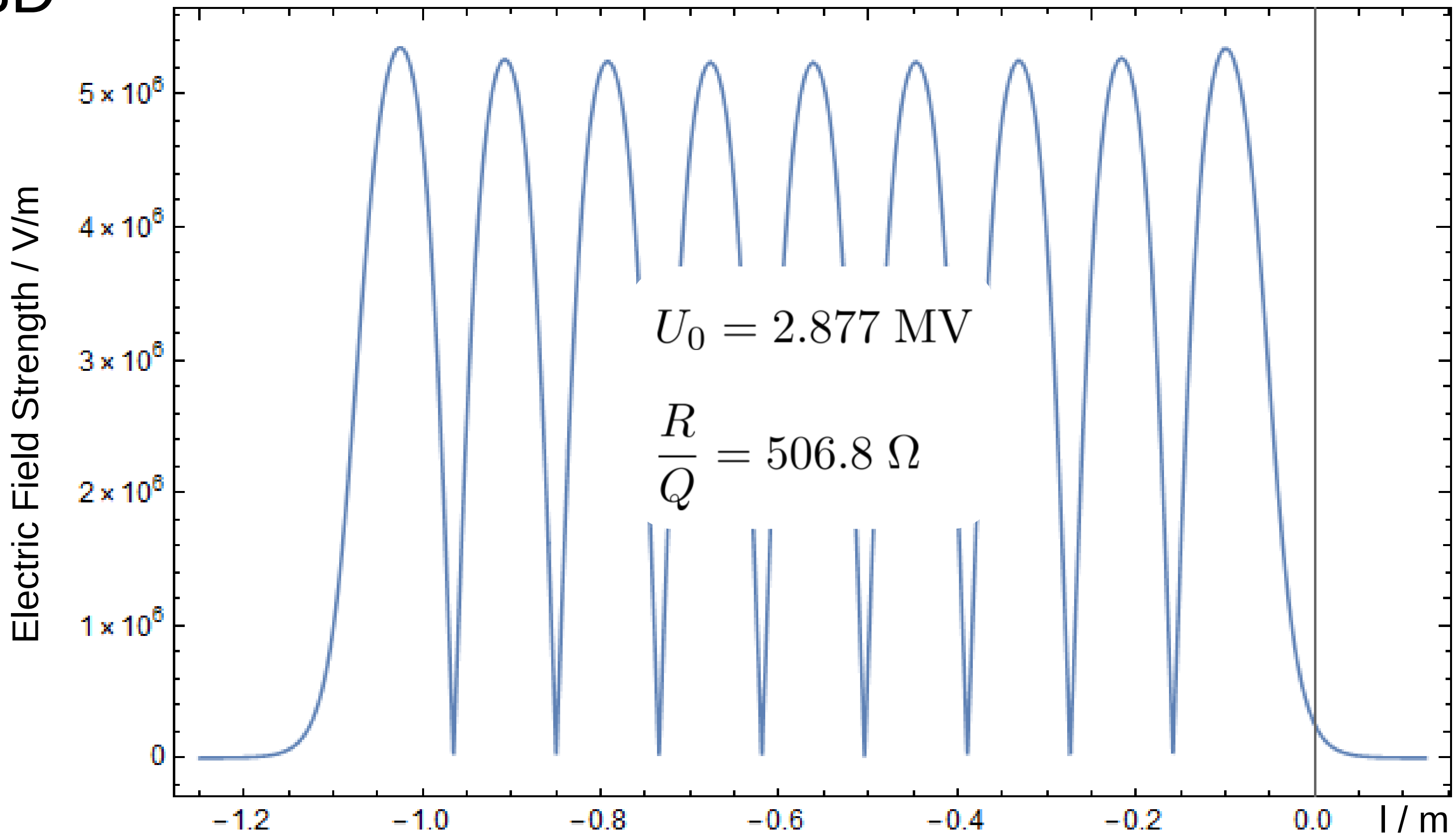
- Lossy Eigenvalue Simulations (Field Distribution)
  - Cem3D



Numerical Results

- Lossy Eigenvalue Simulations
  - Cem3D

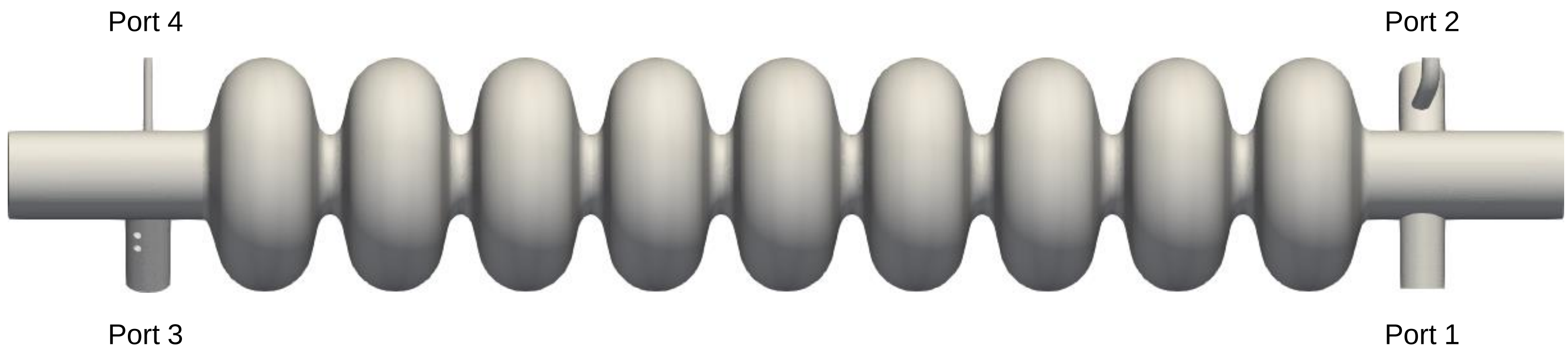
$$U_0 = 2.877\ \mathrm{MV}$$

$$U_4 = \sqrt{2\ P_4\ Z_4} = 0.825\ \mathrm{V}$$

$$P_4 = 6.402\ \mathrm{mW}$$

Scaling

$$\frac{\Delta W}{U_4} = \frac{2.877\,\mathrm{MeV}}{0.825\ \mathrm{V}} = 3.489\ \frac{\mathrm{MeV}}{\mathrm{V}}$$



Numerical Results

- Beam Loading for Multiple Pulse Excitation
  - Beam loading based on a point charge

$$\Delta W_0 = \frac{e_0\, q_0 |\underline{U}_\nu|^2}{2W} = e_0\, q_0\, \omega\, \frac{R}{Q}$$

$$= 0.0041 \text{ MeV} \quad \text{for } q_0 = 1\,\text{nC}, f = 1.3\,\text{GHz}, \ \frac{R}{Q} = 506.8\,\Omega$$

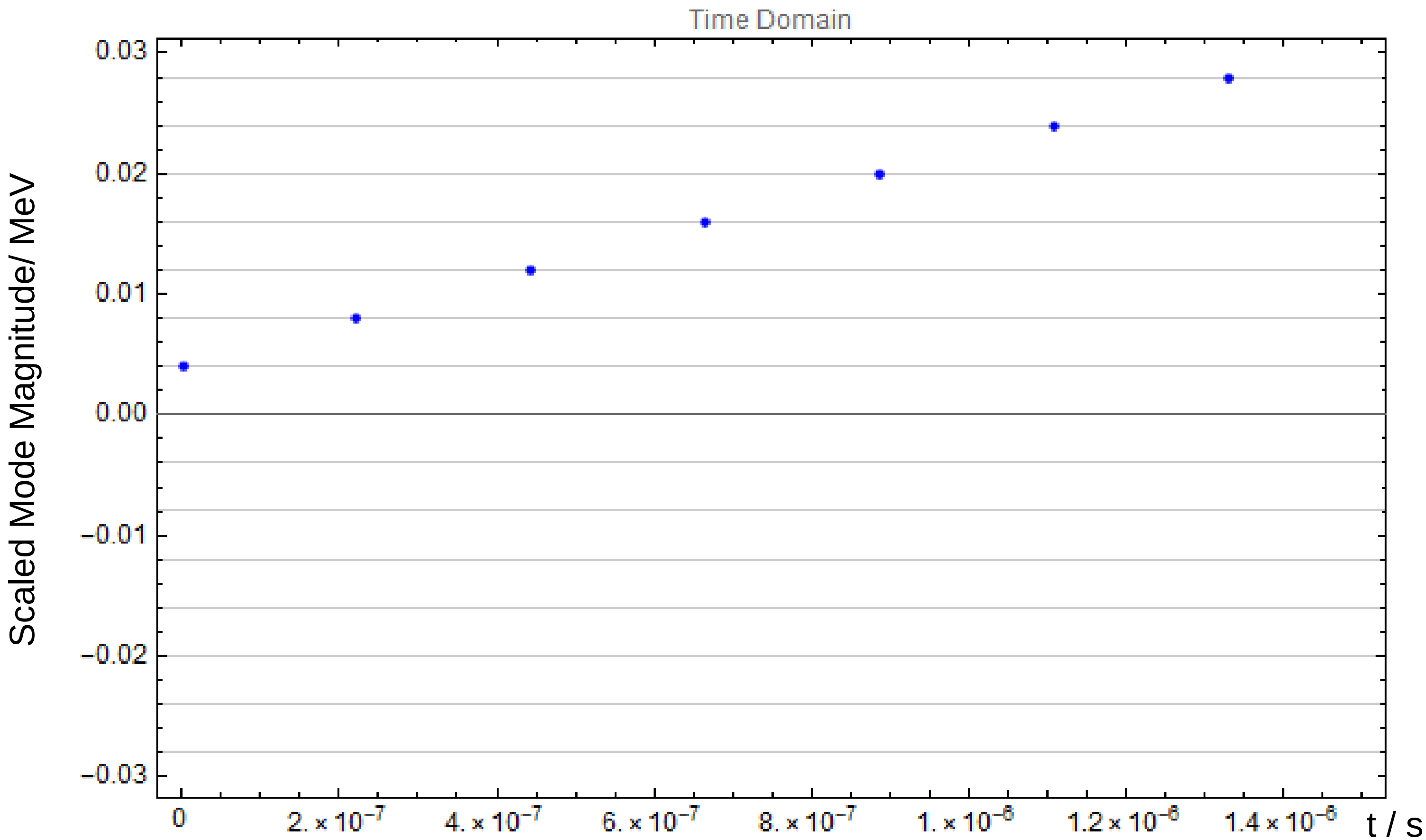
  - Gaussian current distribution

$$\Delta W = \int\limits_{-\infty}^{\infty} \vec{F} \cdot \vec{e}_z \,\mathrm{d}z = \int\limits_{-\infty}^{\infty} \int\limits_{-\infty}^{\infty} \lambda\, E_z \,\mathrm{d}z\,\mathrm{d}z' = U_0 \int\limits_{-\infty}^{\infty} \lambda\, e^{i\frac{\omega}{c}z} \,\mathrm{d}z = \Delta W_0\, e^{-\frac{1}{2}\left(\frac{\omega\sigma}{c}\right)^2}$$

$$= \Delta W_0\, 0.963563 \quad \text{for } \sigma = 10 \text{ mm}$$

Numerical Results

- Beam Loading for Multiple Pulse Excitation



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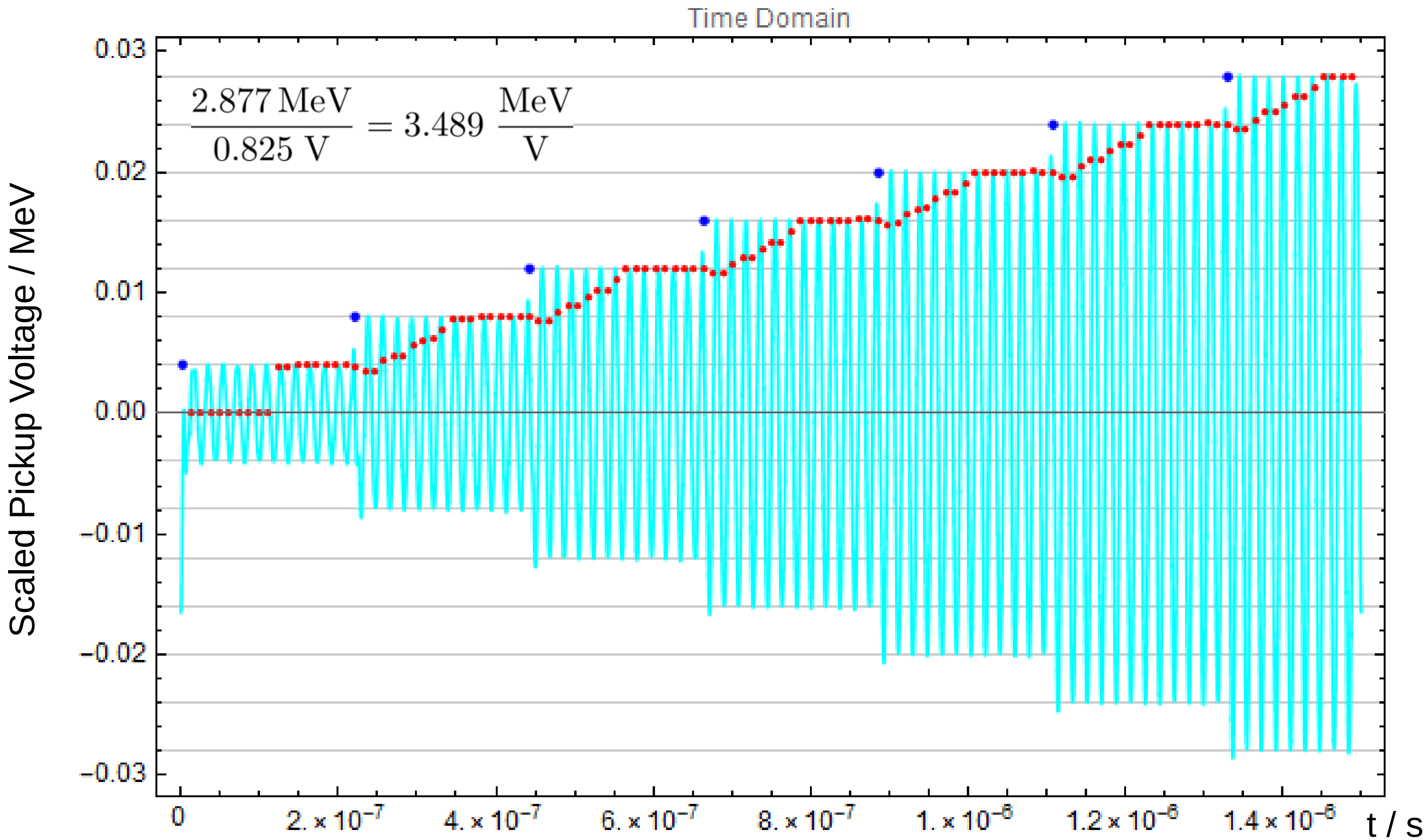

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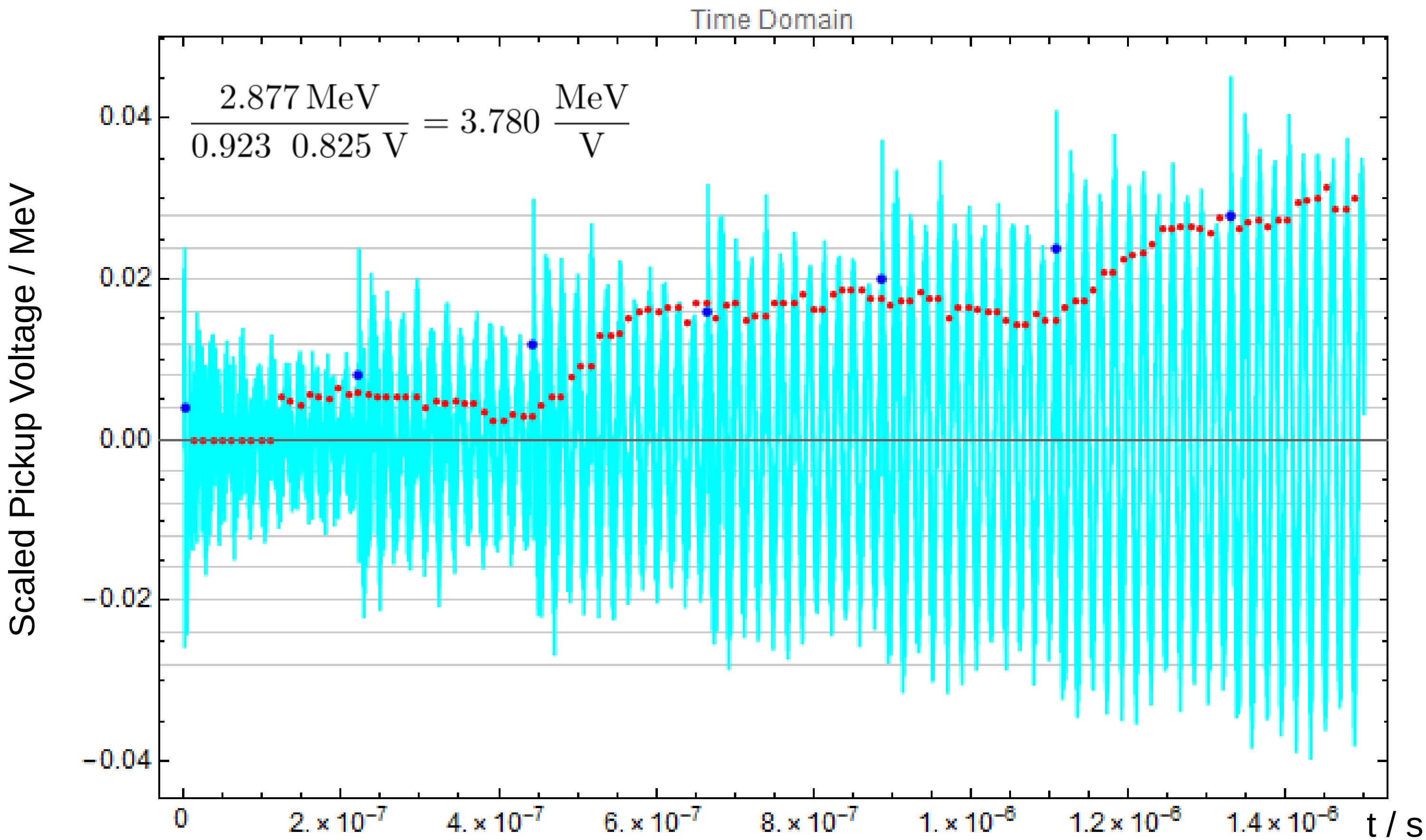

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Summary / Outlook

- Summary
  - Beam loading simulations in time domain (TD)
  - Signal mixing and filtering
  - Magnitude and phase determination
  - Beam loading simulations in frequency domain (FD)
  - Consistency between TD and FD approach:
    10% error not reproducible in the simulations
- Outlook
  - Step by step comparisons to measurements