Forensic analysis of the TESLA-pickup signal-processing unit

W. Ackermann, H. De Gersem, W.F.O. Müller
Institute for Accelerator Science and Electromagnetic Fields (TEMF), TU Darmstadt

DESY-TEMF Meeting
June 28, 2024
TEMF, Darmstadt

Outline

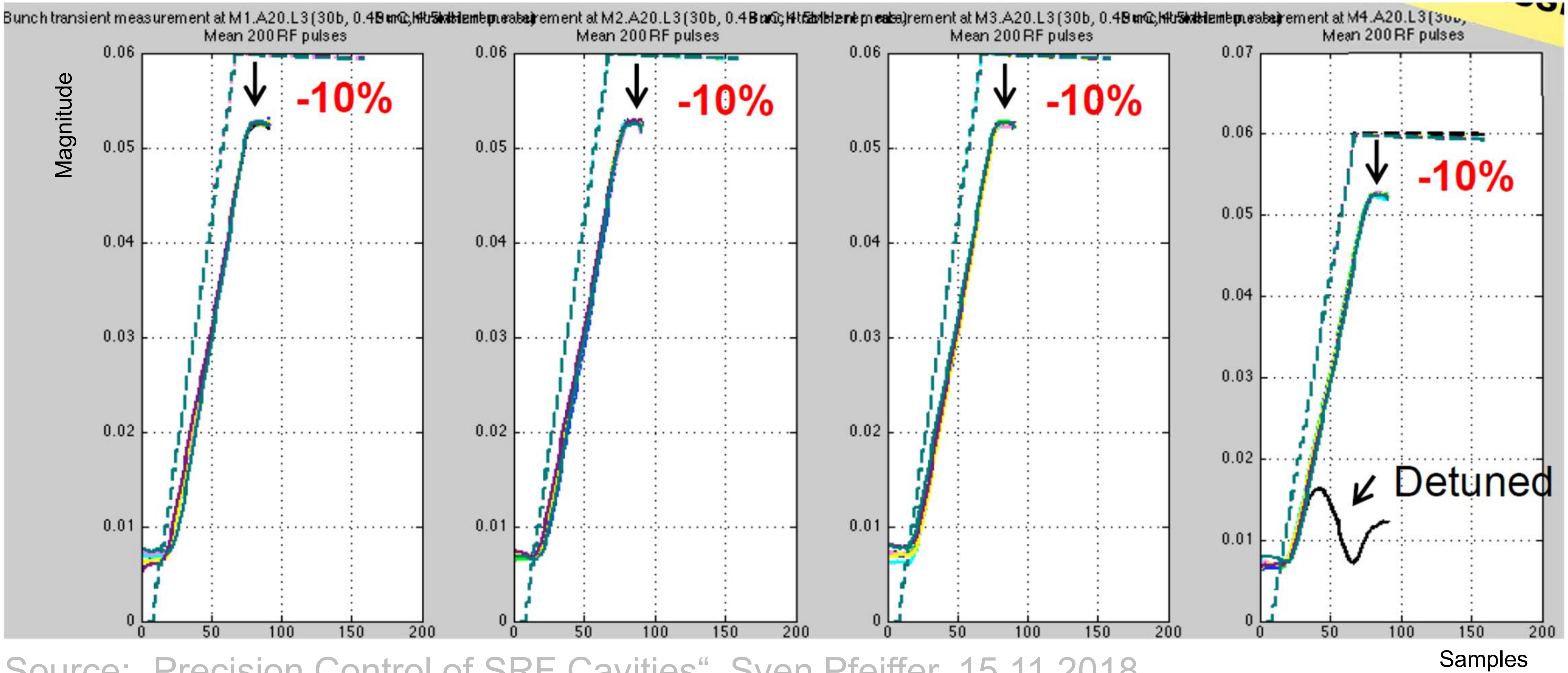
- Motivation
- Computational Modeling
  - Excitation of a 9-Cell TESLA Cavity
    - Klystron (Steady State Case, Single-Mode Operation)
    - Moving Particles (Transient Behavior, Multi-Mode Operation)
  - Measurement of the Field Magnitude in the Cavity
    - Trace the Signal from the Pickup Antenna to the Digital Fourier Analysis
    - Apply the Numerical Model to Representative Signal Patterns
- Summary / Outlook

Outline

- Motivation
- Computational Modeling
  - Excitation of a 9-Cell TESLA Cavity
    - Klystron (Steady State Case, Single-Mode Operation)
    - Moving Particles (Transient Behavior, Multi-Mode Operation)
  - Measurement of the Field Magnitude in the Cavity
    - Trace the Signal from the Pickup Antenna to the Digital Fourier Analysis
    - Apply the Numerical Model to Representative Signal Patterns
- Summary / Outlook

Motivation

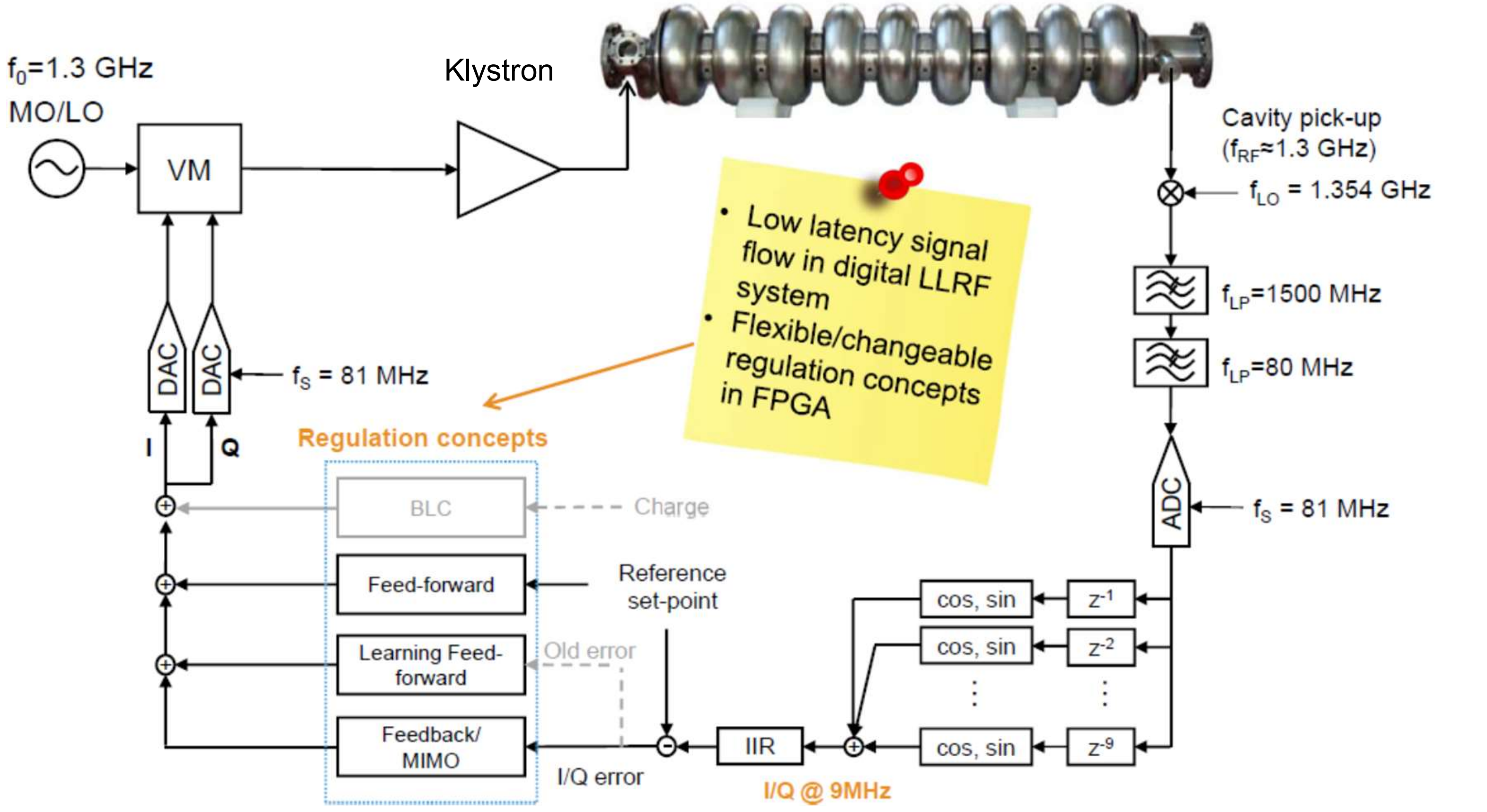
- Beam Loading of a 9 Cell TESLA 1.3 GHz Cavity
  - Comparison of theory with measurement



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

Motivation

- SRF Cavity Regulation



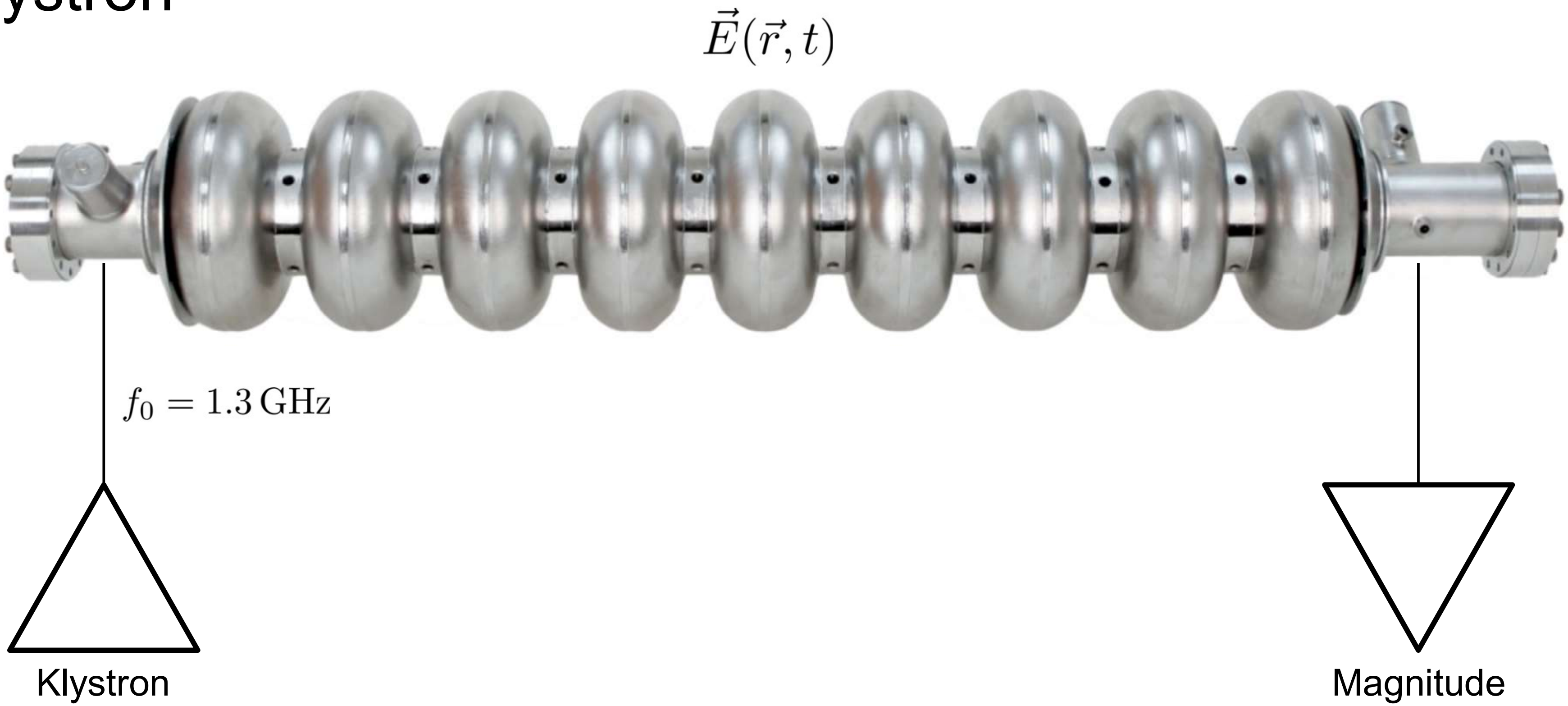
Source: „Precision Control of SRF Cavities", Sven Pfeiffer, 15.11.2018

Outline

- Motivation
- Computational Modeling
  - Excitation of a 9-Cell TESLA Cavity
    - Klystron (Steady State Case, Single-Mode Operation)
    - Moving Particles (Transient Behavior, Multi-Mode Operation)
  - Measurement of the Field Magnitude in the Cavity
    - Trace the Signal from the Pickup Antenna to the Digital Fourier Analysis
    - Apply the Numerical Model to Representative Signal Patterns
- Summary / Outlook

Numerical Modeling

- Cavity Excitation
  - Klystron



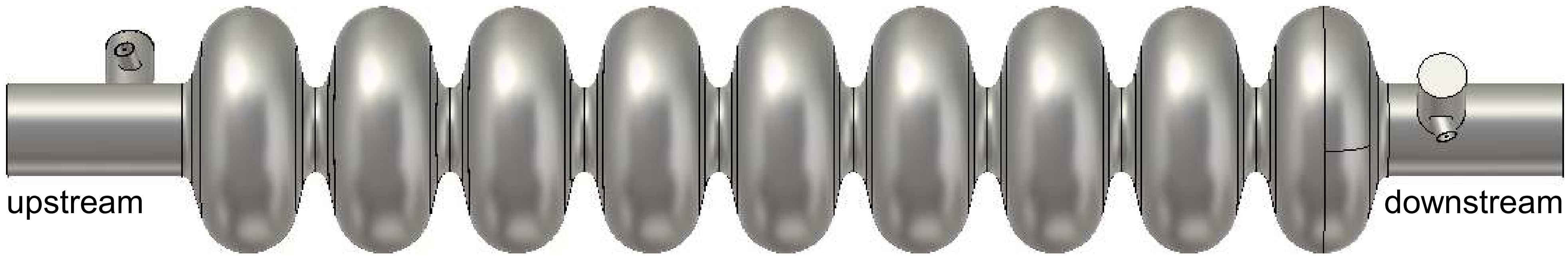
Relation between measured magnitude of the pickup signal and the field strength in the cavity?

Numerical Modeling

- Cavity Modeling
  - Photograph

http://newsline.linearcollider.org

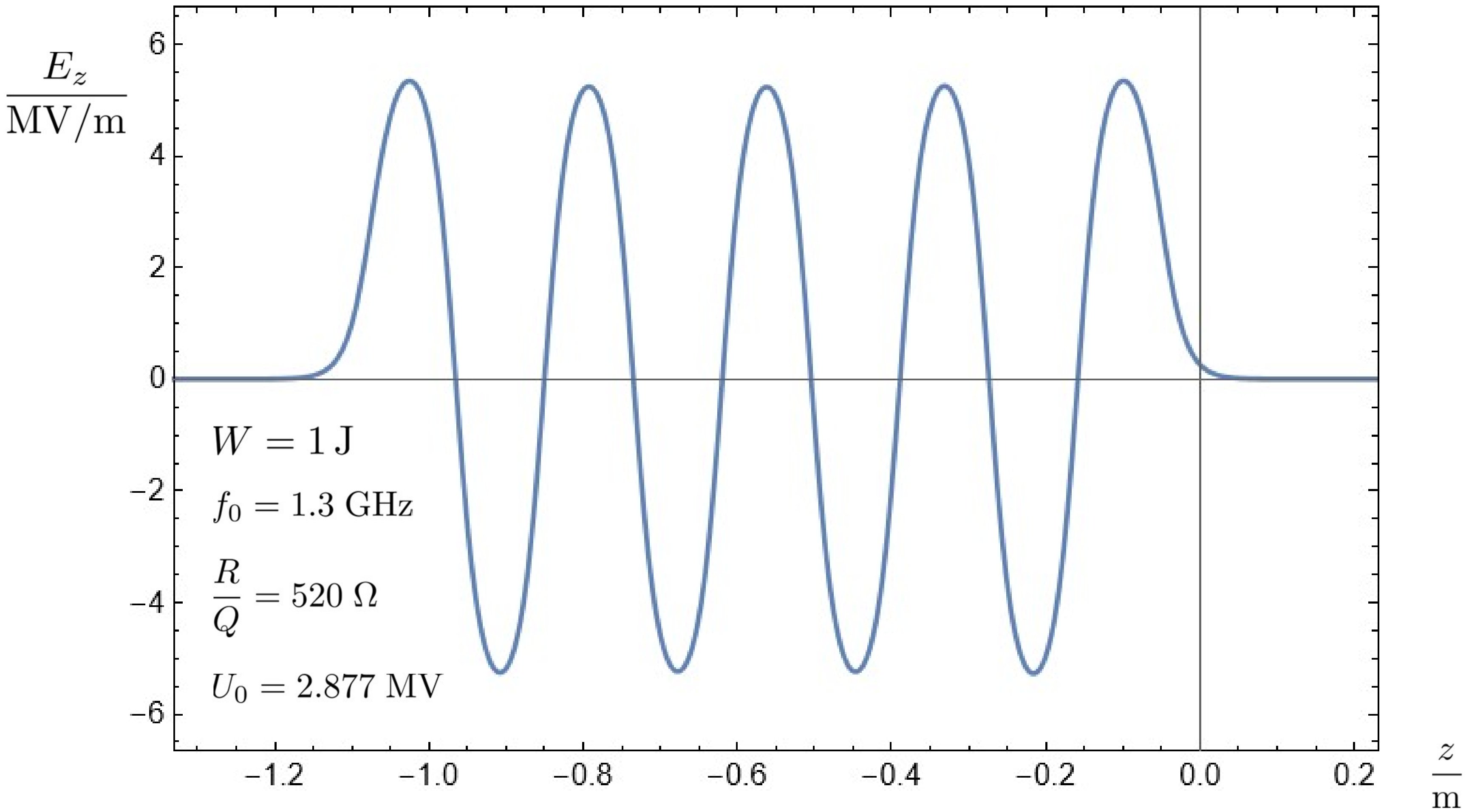
  - Numerical model



CST Studio Suite 2024

Numerical Modeling

- Cavity Field Distribution for the Accelerating Mode



Numerical Modeling

TECHNISCHE UNIVERSITÄT DARMSTADT

- Cavity Excitation
  - Klystron

$$\iiint_V \varepsilon\, \vec{E}_\nu \cdot \vec{E}_\eta \,\mathrm{d}V = \delta_{\nu,\eta}\, 2W \qquad W \stackrel{!}{=} 1\,\mathrm{J}$$

$$\vec{E}(\vec{r},t) = a_0(t)\, \vec{E}_0(\vec{r}) \qquad a_0(t) = \Re(\underline{A}_0\, e^{i\omega_0 t})$$

W_0

$W_0 + \Delta W_0$

$f_0 = 1.3\,\mathrm{GHz}$

Klystron

Point charge acceleration:

$$\underline{A}_0 = \frac{q_0}{2W} \int_{-\infty}^{\infty} (\vec{e}_z \cdot \vec{E}_0)\, e^{-i\omega_0 \frac{z}{v}}\, \mathrm{d}z = \frac{q_0\, \underline{U}_0}{2W}$$

$$|\underline{A}_0| = \frac{q_0\, |\underline{U}_0|}{2W} = \frac{\Delta W_0}{2W}$$

$\underline{A}_0$

Magnitude
(complex number)

➡ Scaling is independent of the charge.

Numerical Modeling

TECHNISCHE UNIVERSITÄT DARMSTADT

- Cavity Excitation
  - Moving Particle

$$\iiint_V \varepsilon\, \vec{E}_\nu \cdot \vec{E}_\eta \,\mathrm{d}V = \delta_{\nu,\eta}\, 2W \qquad W \stackrel{!}{=} 1\,\mathrm{J} \qquad \Delta W = \sum_{\nu=1}^{\infty} \Delta W_\nu$$

$$\vec{E}(\vec{r},t) = \vec{E}_\mathrm{P}(\vec{r},t) + \sum_{\nu=1}^{\infty} a_\nu(t)\, \vec{E}_\nu(\vec{r}) \qquad a_\nu(t) = \Re(\underline{A}_\nu\, e^{i\omega_\nu t})$$

Point charge excitation:

$$\underline{A}_\nu = \frac{q_0}{2W} \int_{-\infty}^{\infty} (\vec{e}_z \cdot \vec{E}_\nu)\, e^{-i\omega_\nu \frac{z}{v}}\,\mathrm{d}z = \frac{q_0\, \underline{U}_\nu}{2W}$$

$$|\underline{A}_\nu| = \frac{q_0\, |\underline{U}_\nu|}{2W} = \frac{\Delta W_\nu|}{2W} = q_0 \sqrt{\left(\frac{R}{Q}\right)_\nu \frac{\omega_\nu}{2\,W}}$$

$$\Delta W = q_0\, |\underline{U}_0|$$

$$Q = \frac{\omega\, W}{P}$$

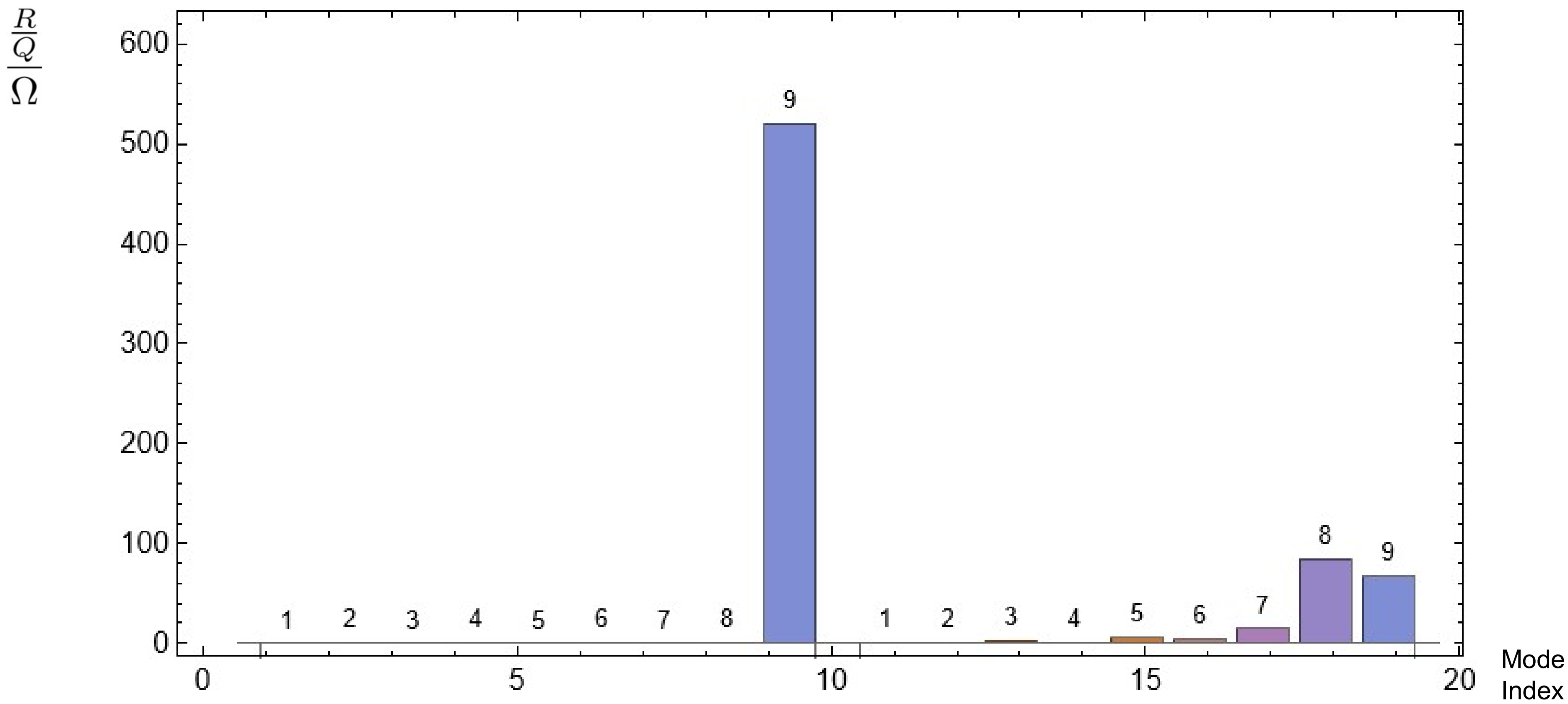
$$R = \frac{|\underline{U}_0|^2}{2\,P}$$

$\underline{A}_0$?

Magnitude
(complex number)

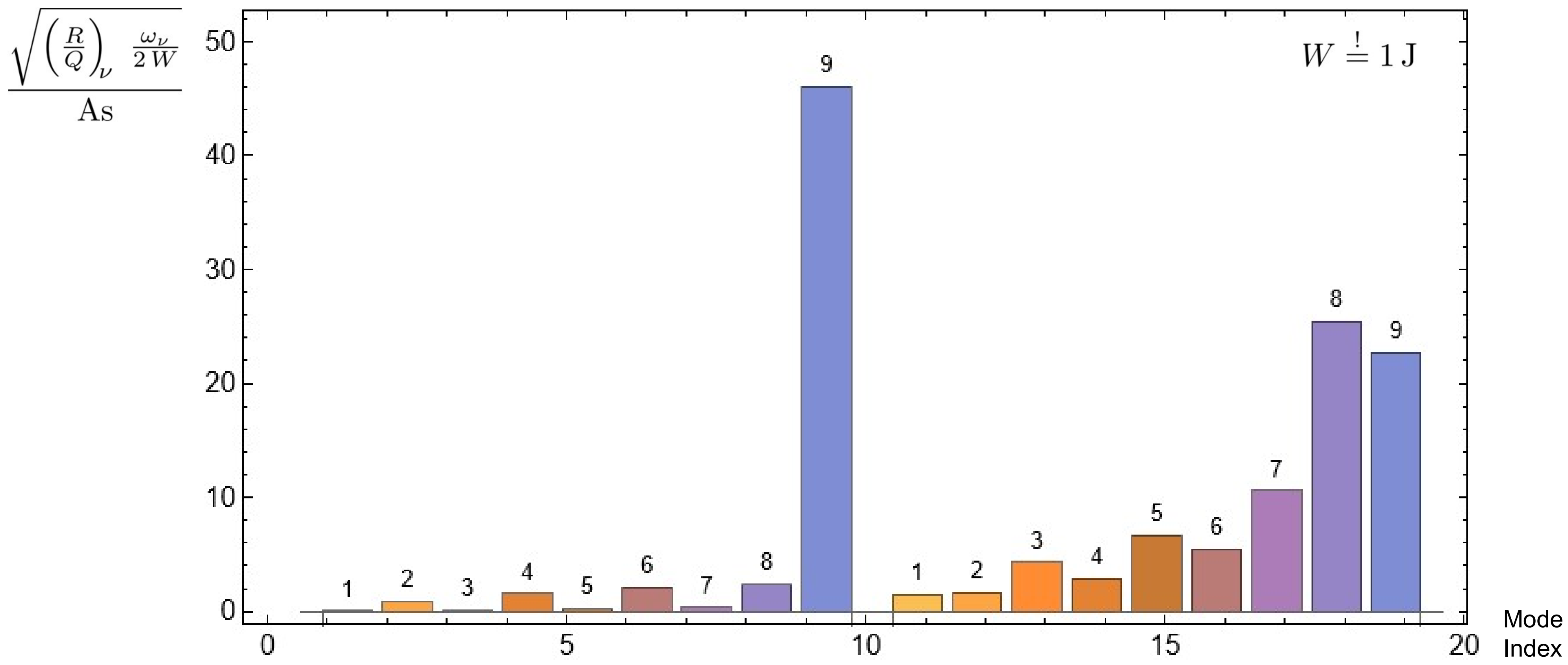
Numerical Results

- Data from Mode Atlas
  - First and Second Monopole Passband



Numerical Results

- Mode Atlas
  - First and Second Monopole Passband

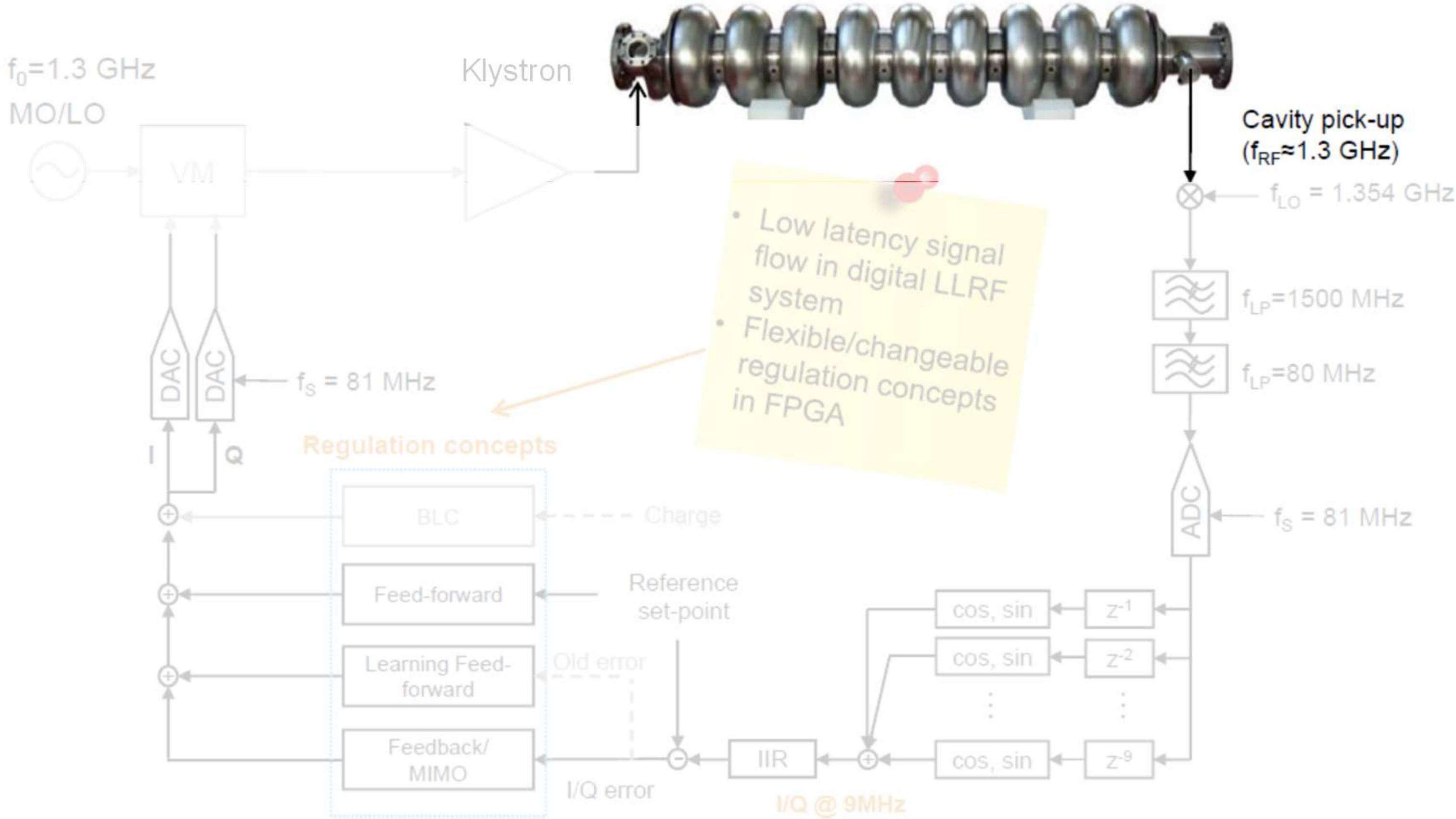


Outline

- Motivation
- Computational Modeling
  - Excitation of a 9-Cell TESLA Cavity
    - Klystron (Steady State Case, Single-Mode Operation)
    - Moving Particles (Transient Behavior, Multi-Mode Operation)
  - Measurement of the Field Magnitude in the Cavity
    - Trace the Signal from the Pickup Antenna to the Digital Fourier Analysis
    - Apply the Numerical Model to Representative Signal Patterns
- Summary / Outlook

Numerical Results

- SRF Cavity Regulation

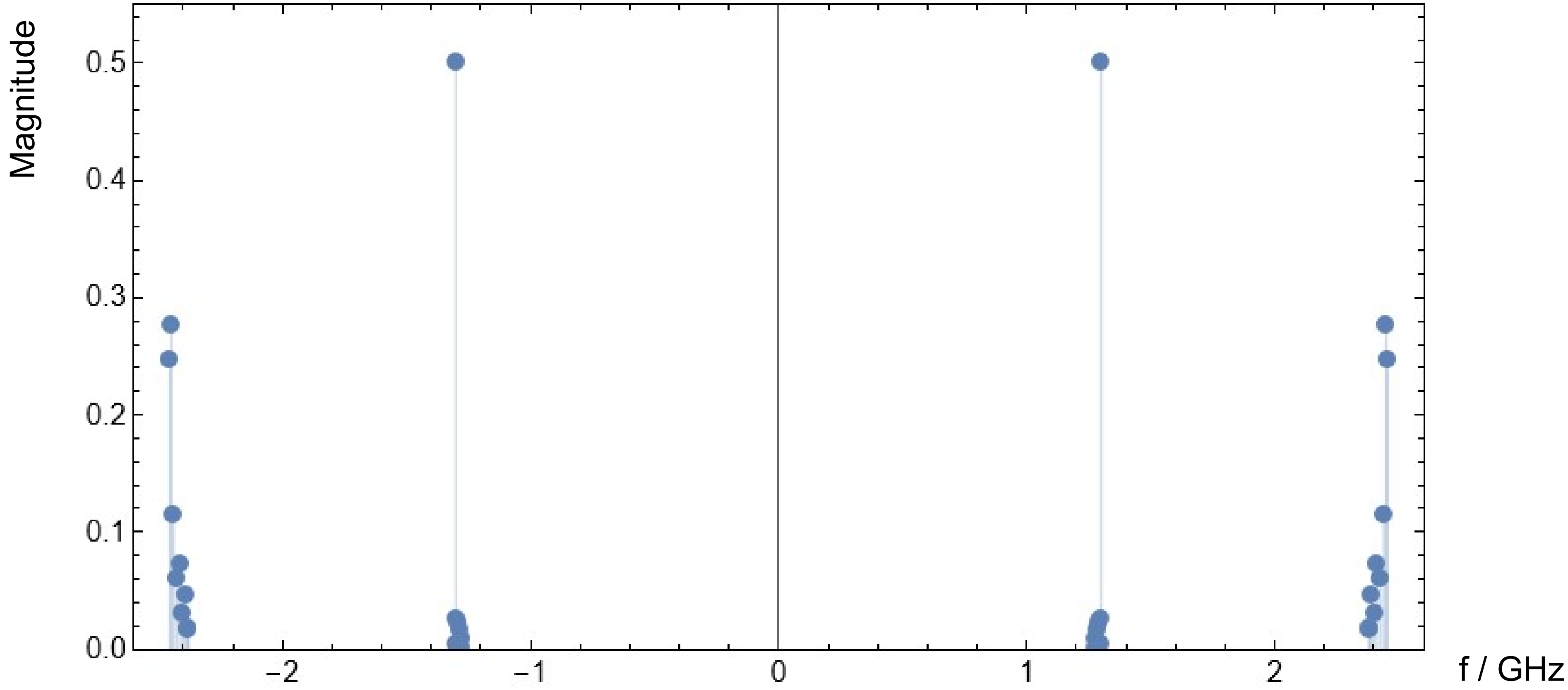


Source: „Precision Control of SRF Cavities“, Sven Pfeiffer, 15.11.2018

Numerical Results

TECHNISCHE UNIVERSITÄT DARMSTADT

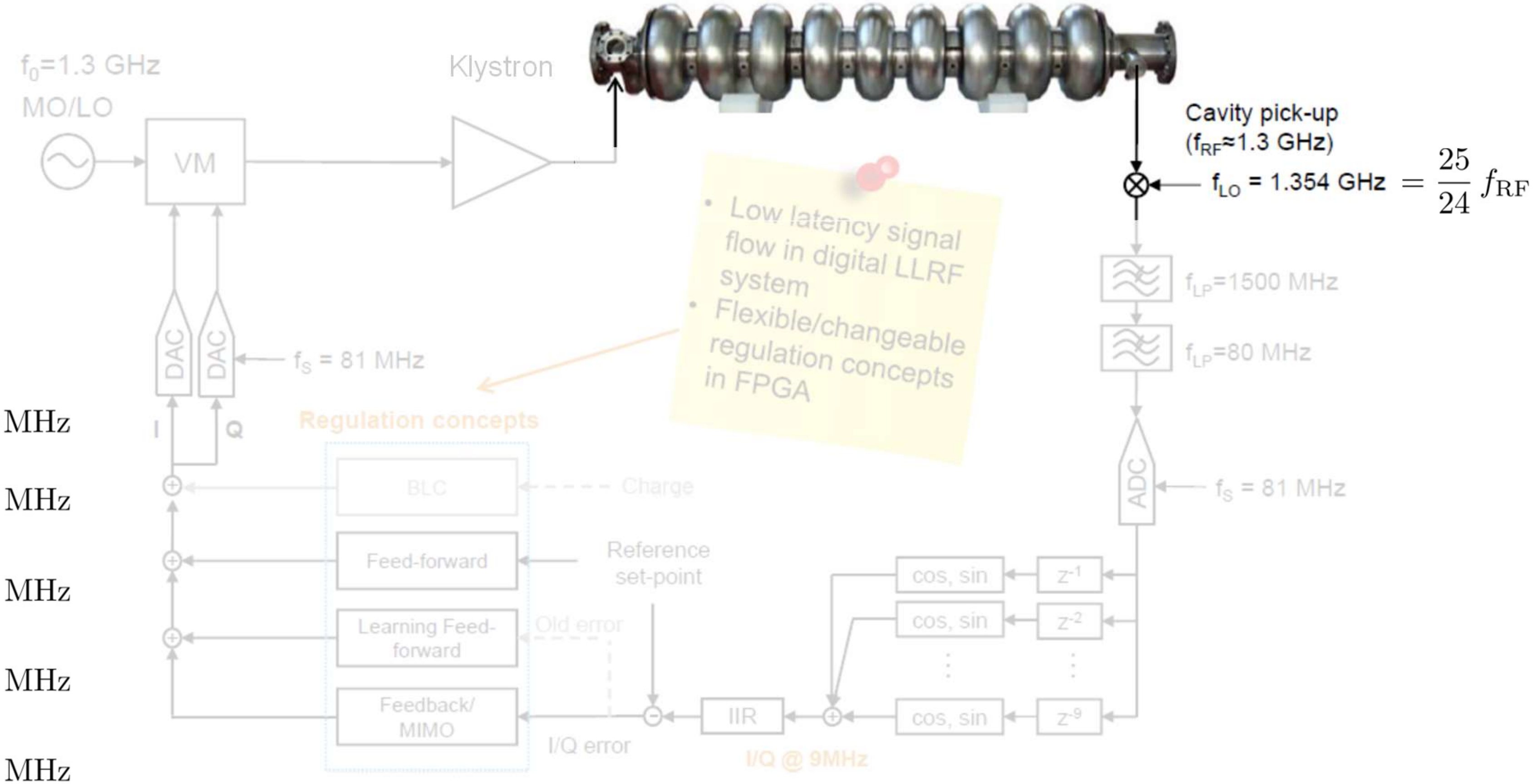
- Spectrum after Point-Charge Excitation
  - First and Second Monopole Passband



Numerical Results

- SRF Cavity Regulation

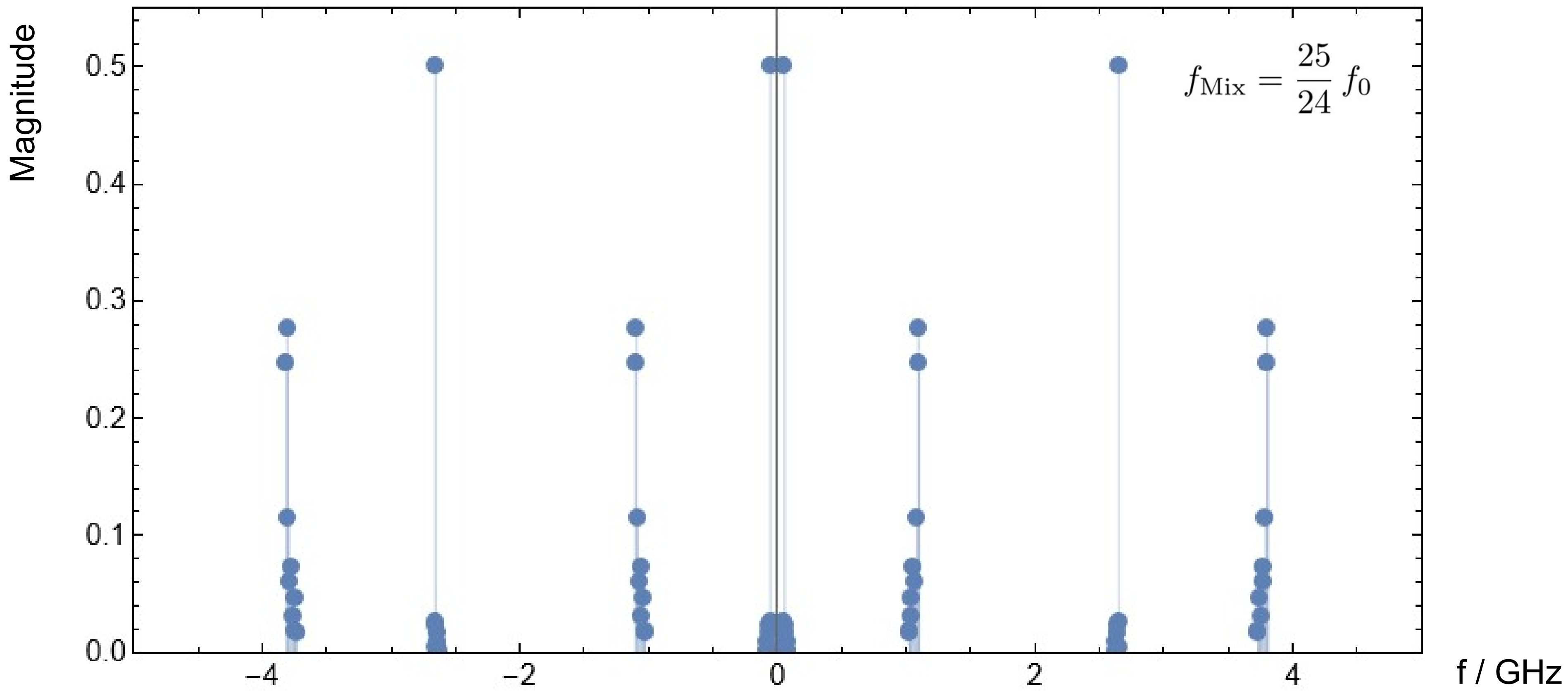
$$f_0 = 1300.000\,\text{MHz}$$
$$\frac{1}{16}\,f_0 = 81.250\,\text{MHz}$$
$$\frac{1}{24}\,f_0 = 54.166\,\text{MHz}$$
$$\frac{1}{144}\,f_0 = 9.027\,\text{MHz}$$
$$\frac{1}{288}\,f_0 = 4.513\,\text{MHz}$$



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

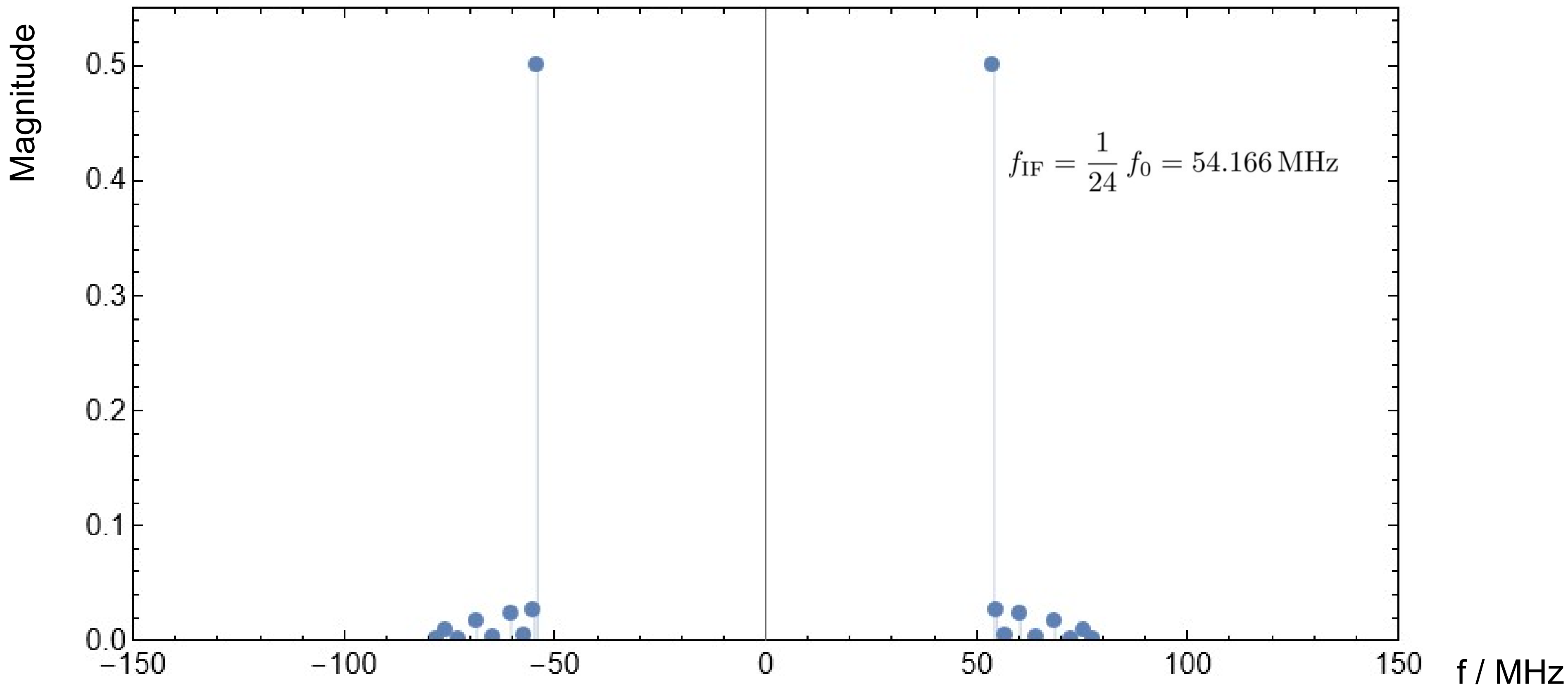
Numerical Results

- Spectrum after Point-Charge Excitation
  - First and Second Monopole Passband (after Mixer)



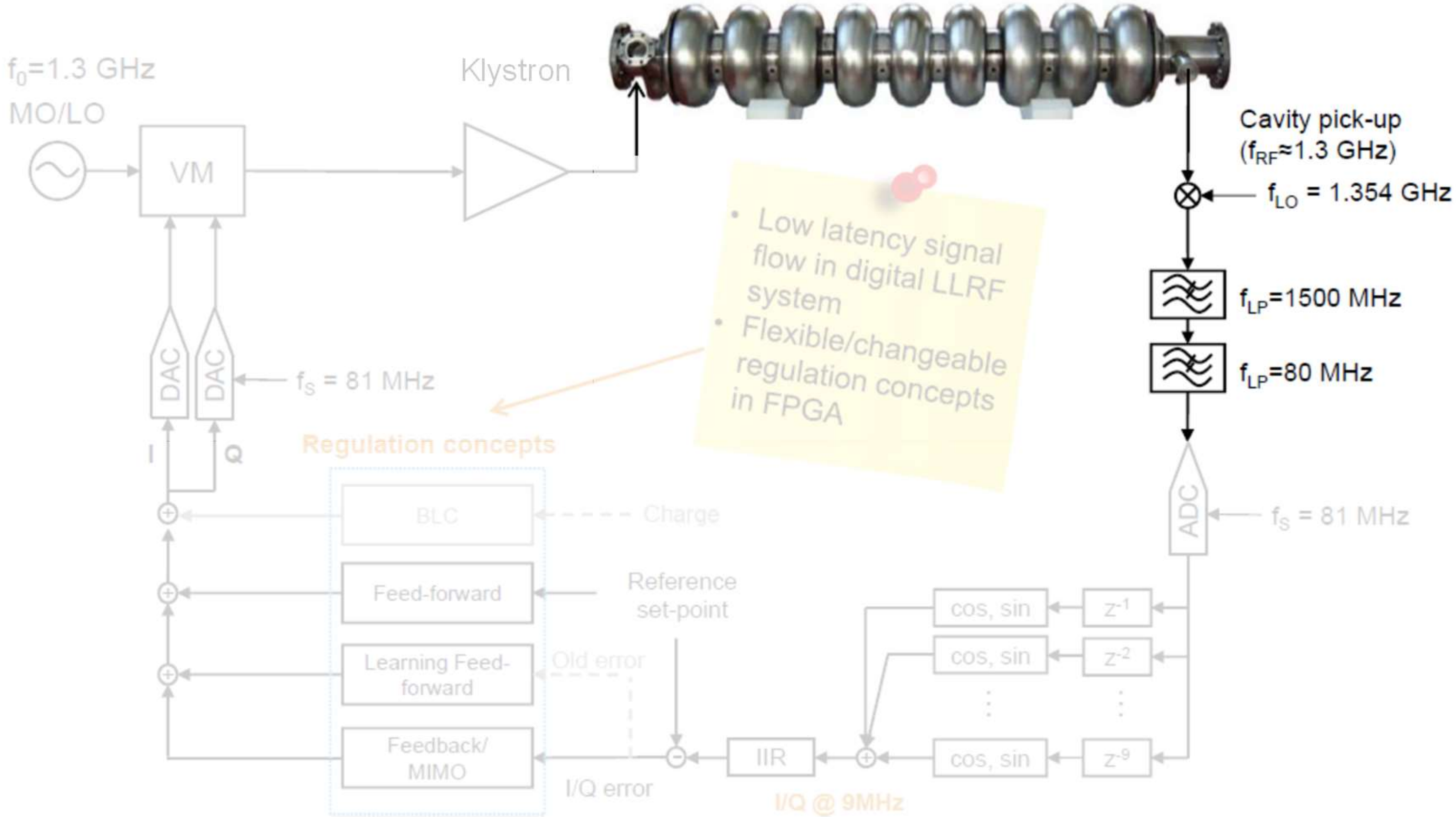
Numerical Results

- Spectrum after Point-Charge Excitation
  - First and Second Monopole Passband (Mixed, Zoom)



Numerical Results

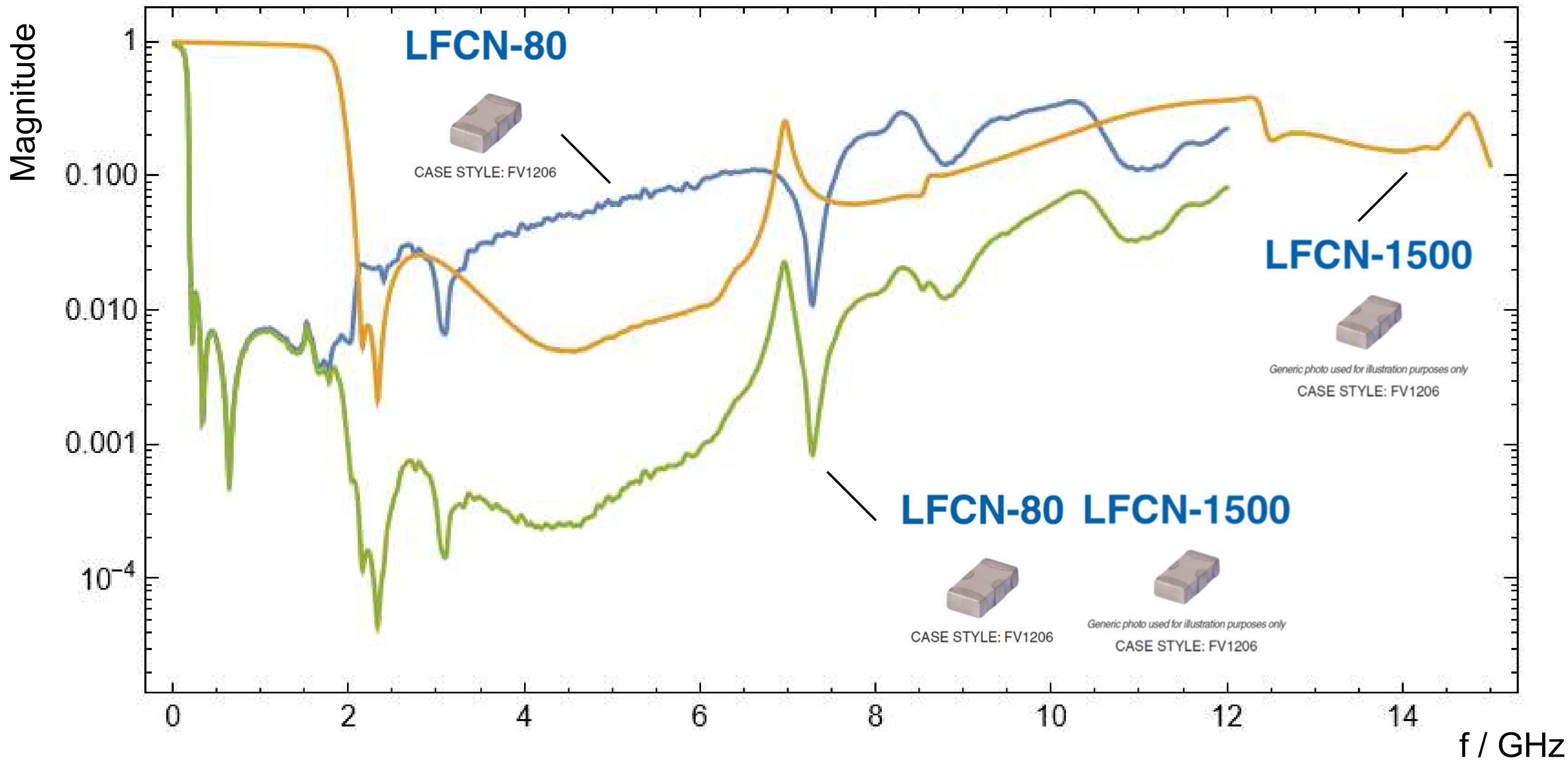
- SRF Cavity Regulation



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

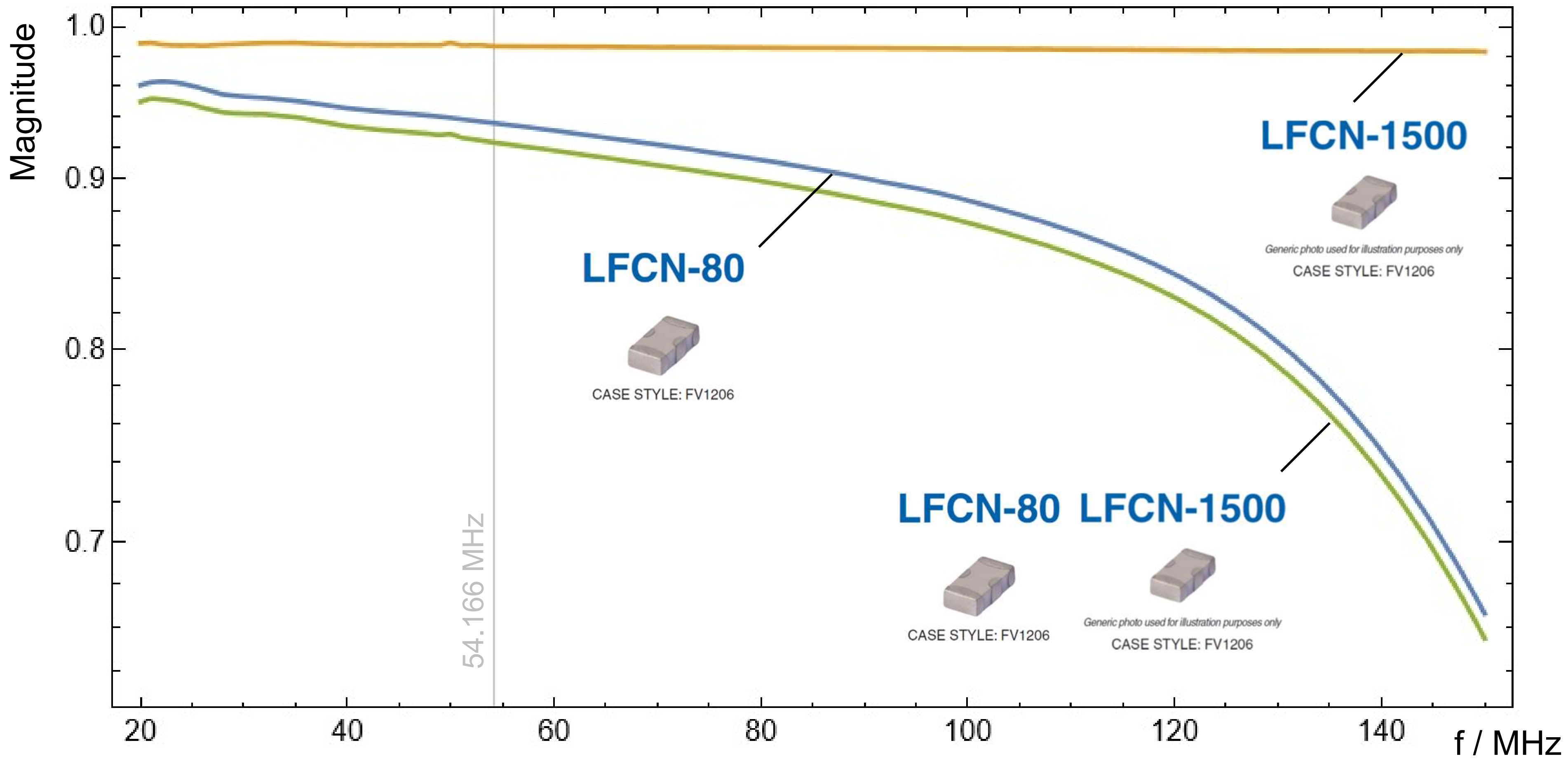
Numerical Results

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



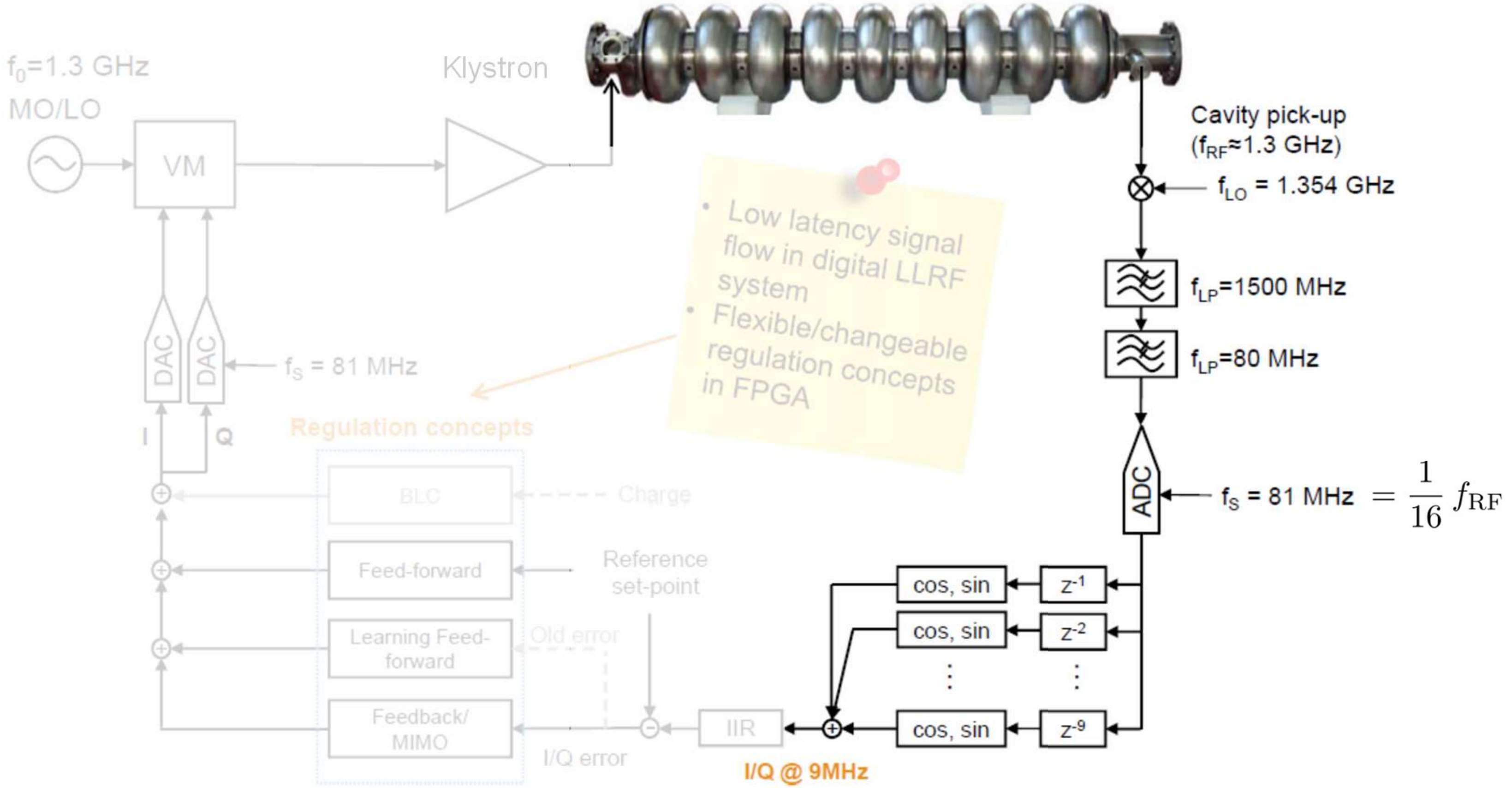
Numerical Results

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



Numerical Results

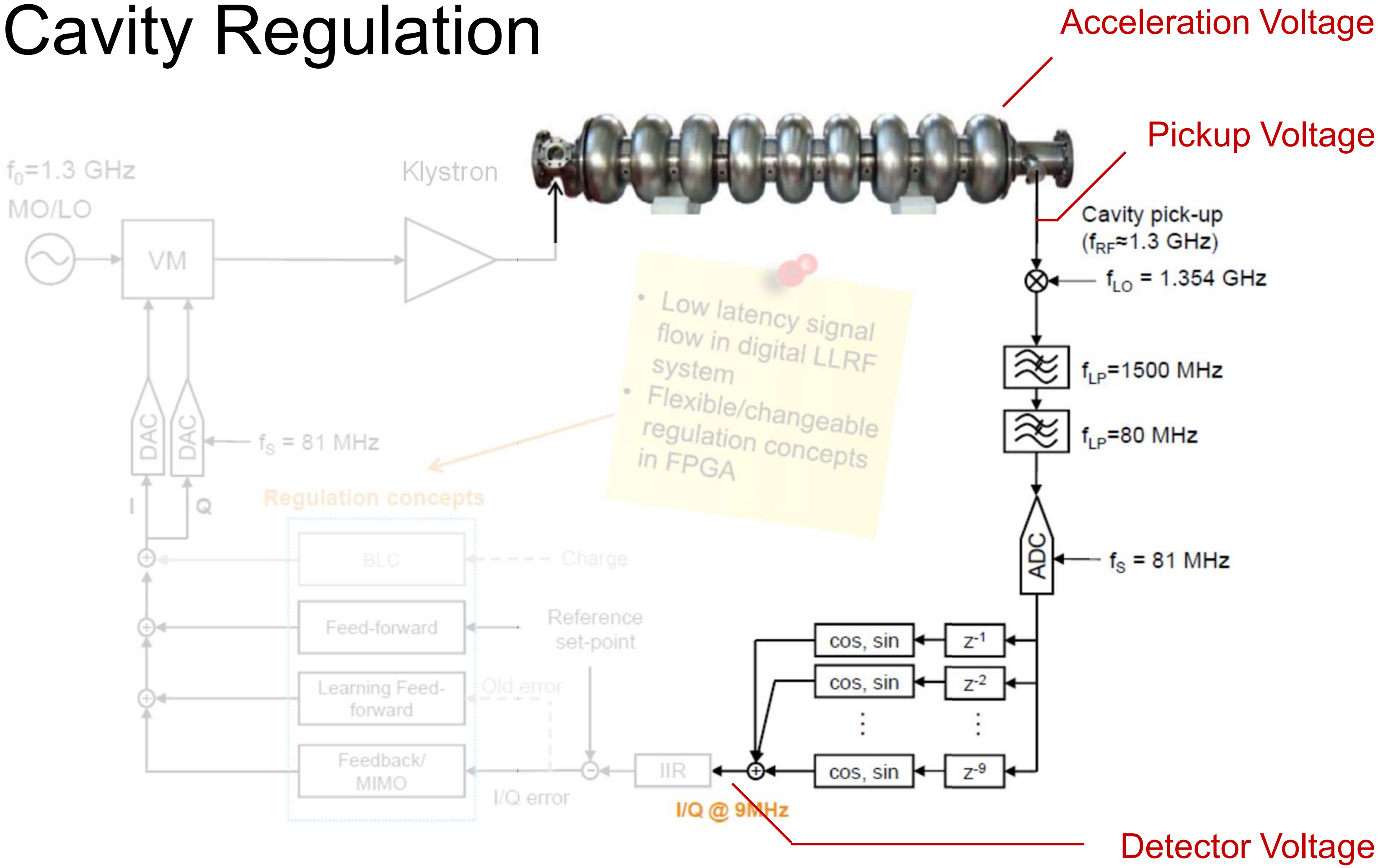
- SRF Cavity Regulation



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

Numerical Results

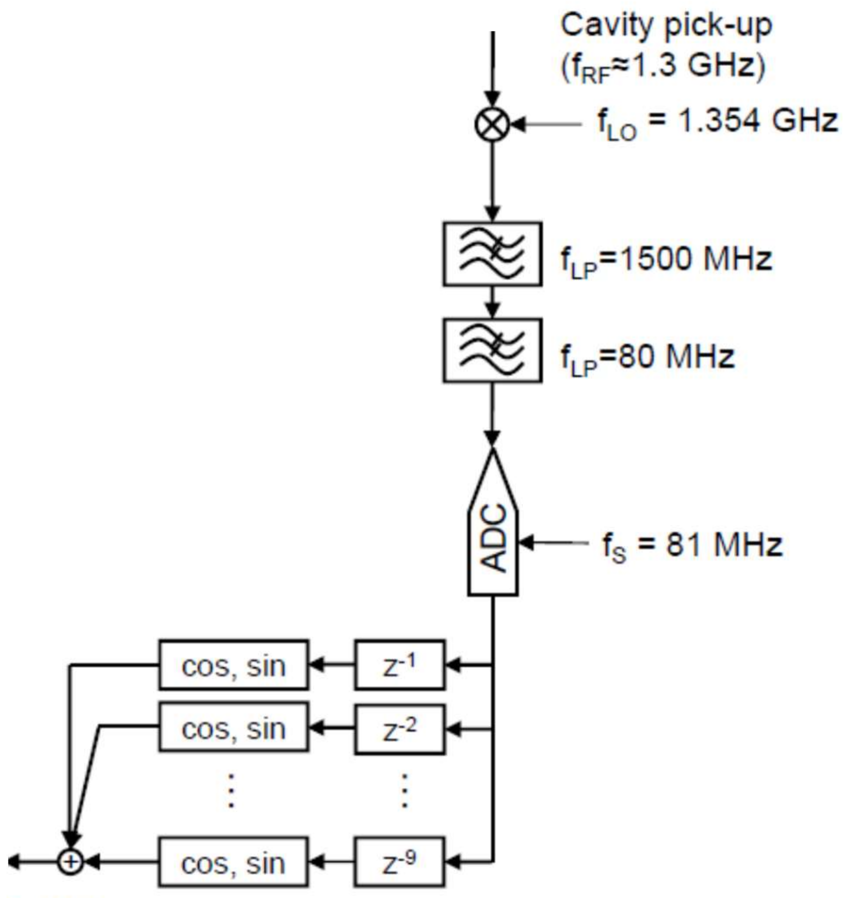
- SRF Cavity Regulation



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

Numerical Results

- Signal-Processing Unit (Digital Fourier Transform)

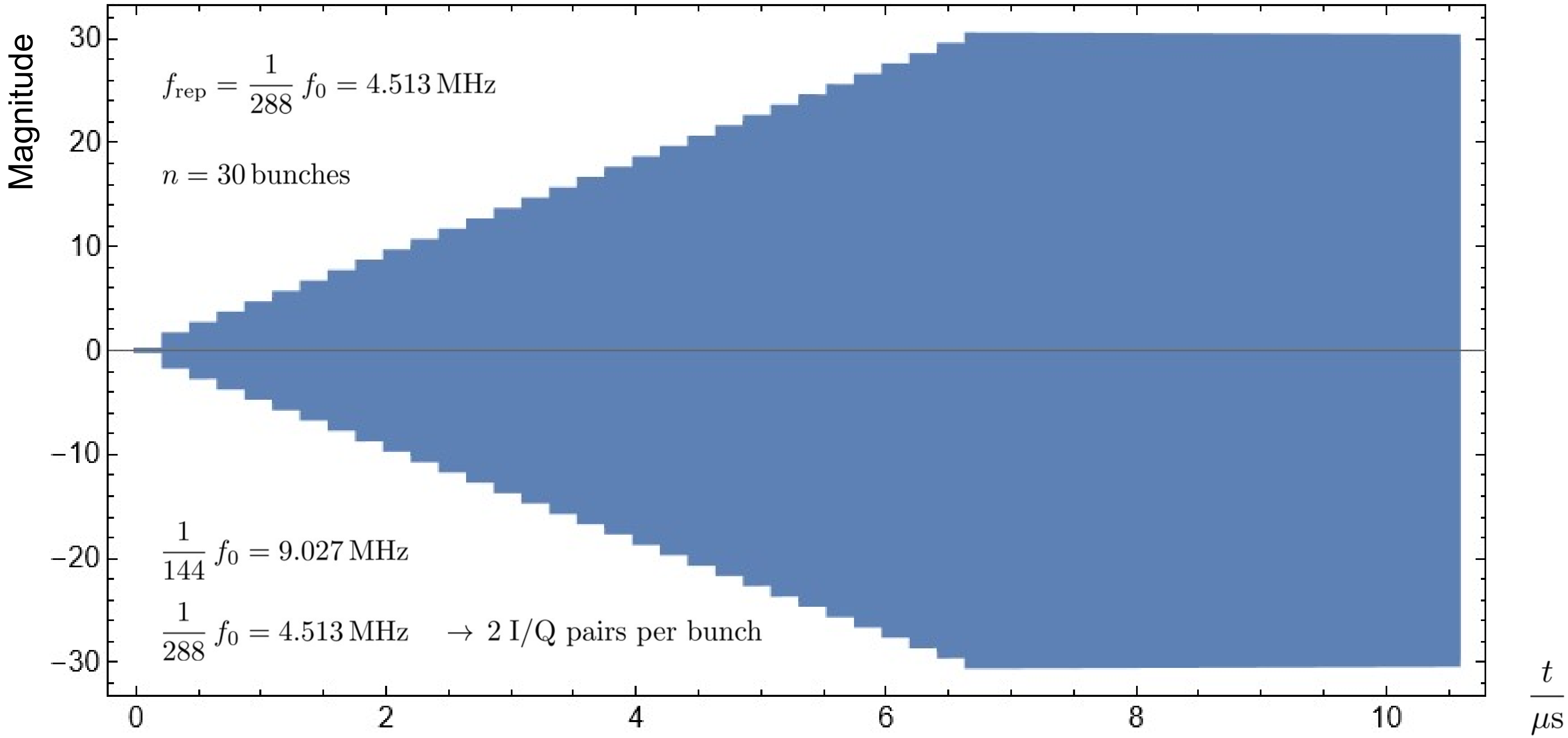


Mode	Frequency (GHz)	Gain	Excitation
1	1.2764	0.238	0.000
2	1.2784	0.248	0.004
3	1.2816	0.185	0.000
4	1.2856	0.309	0.010
5	1.2898	0.117	0.000
6	1.2938	0.483	0.022
7	1.2971	0.944	0.007
8	1.2993	1.022	0.052
9	**1.3000**	**1.000**	**1.000**
10	2.3786	0.005	0.000
11	2.3835	0.007	0.000
12	2.3913	0.002	0.000
13	2.4016	0.002	0.000
14	2.4137	0.002	0.000
15	2.4265	0.002	0.000
16	2.4386	0.007	0.003
17	2.4482	0.004	0.001
18	2.4539	0.002	0.001

0.095

Numerical Results

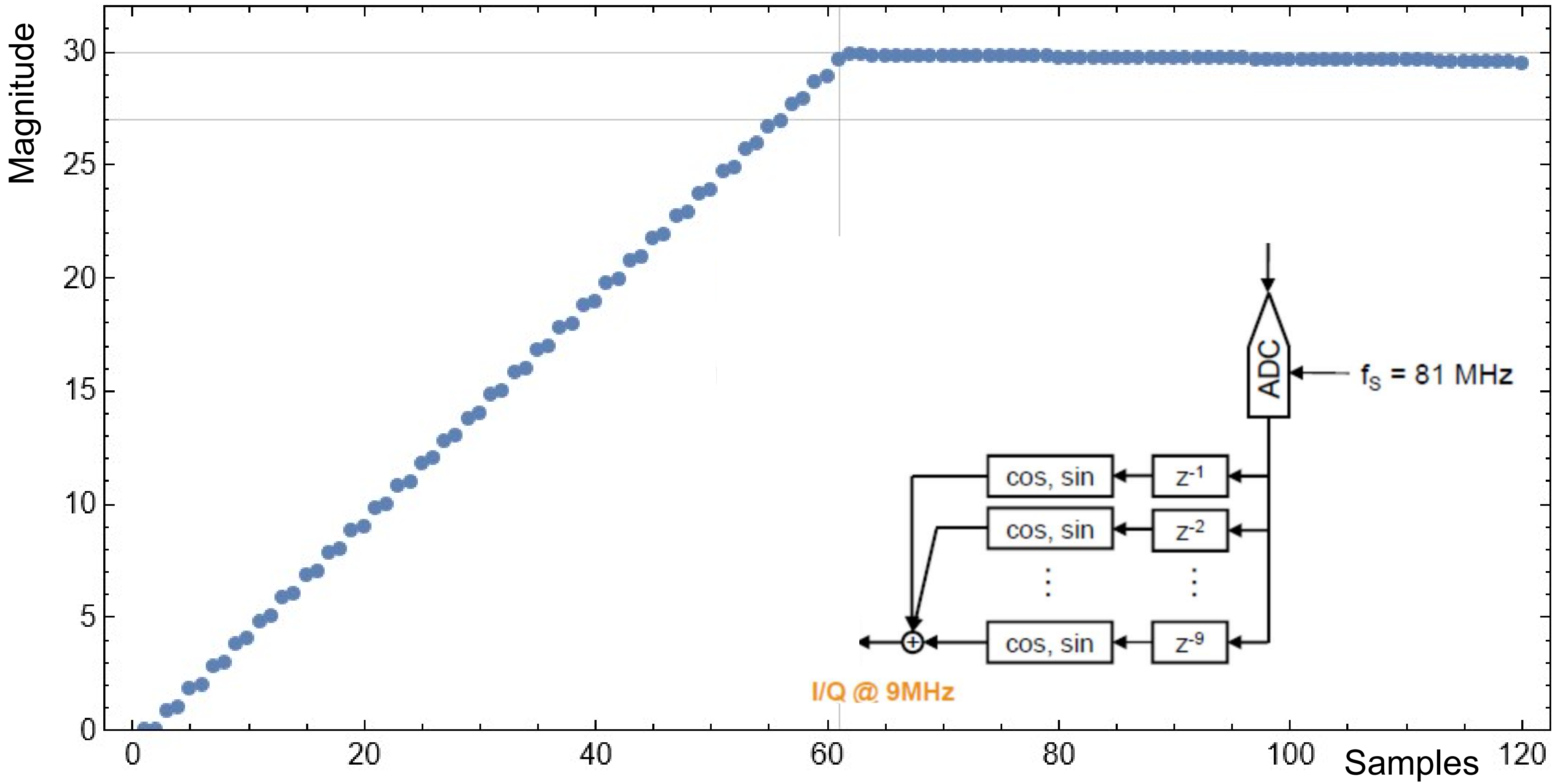
- Pulse-Train Excitation



Numerical Results

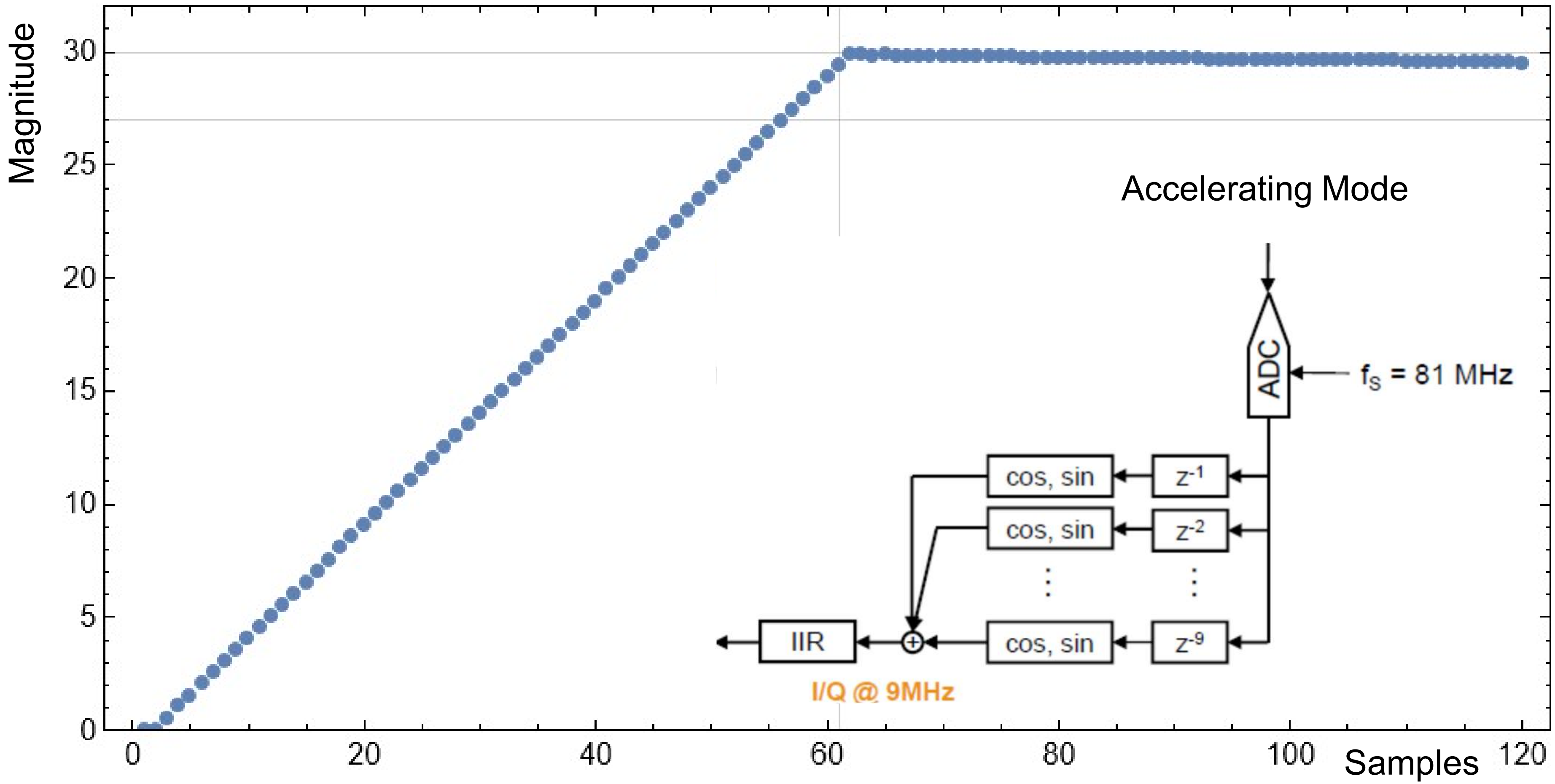
TECHNISCHE UNIVERSITÄT DARMSTADT

- Pulse-Train Excitation



Numerical Results

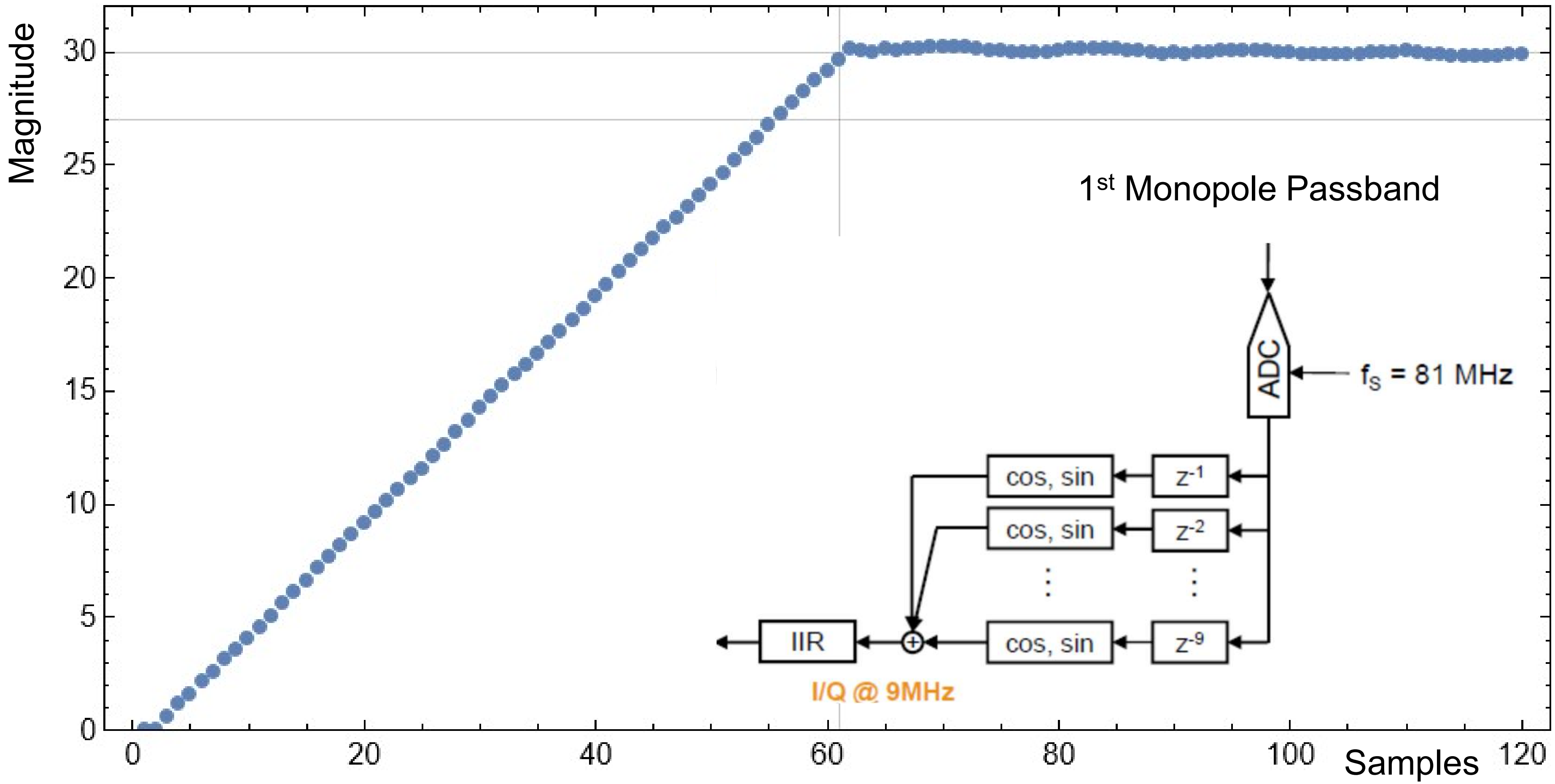
- Pulse-Train Excitation



Numerical Results

TECHNISCHE UNIVERSITÄT DARMSTADT

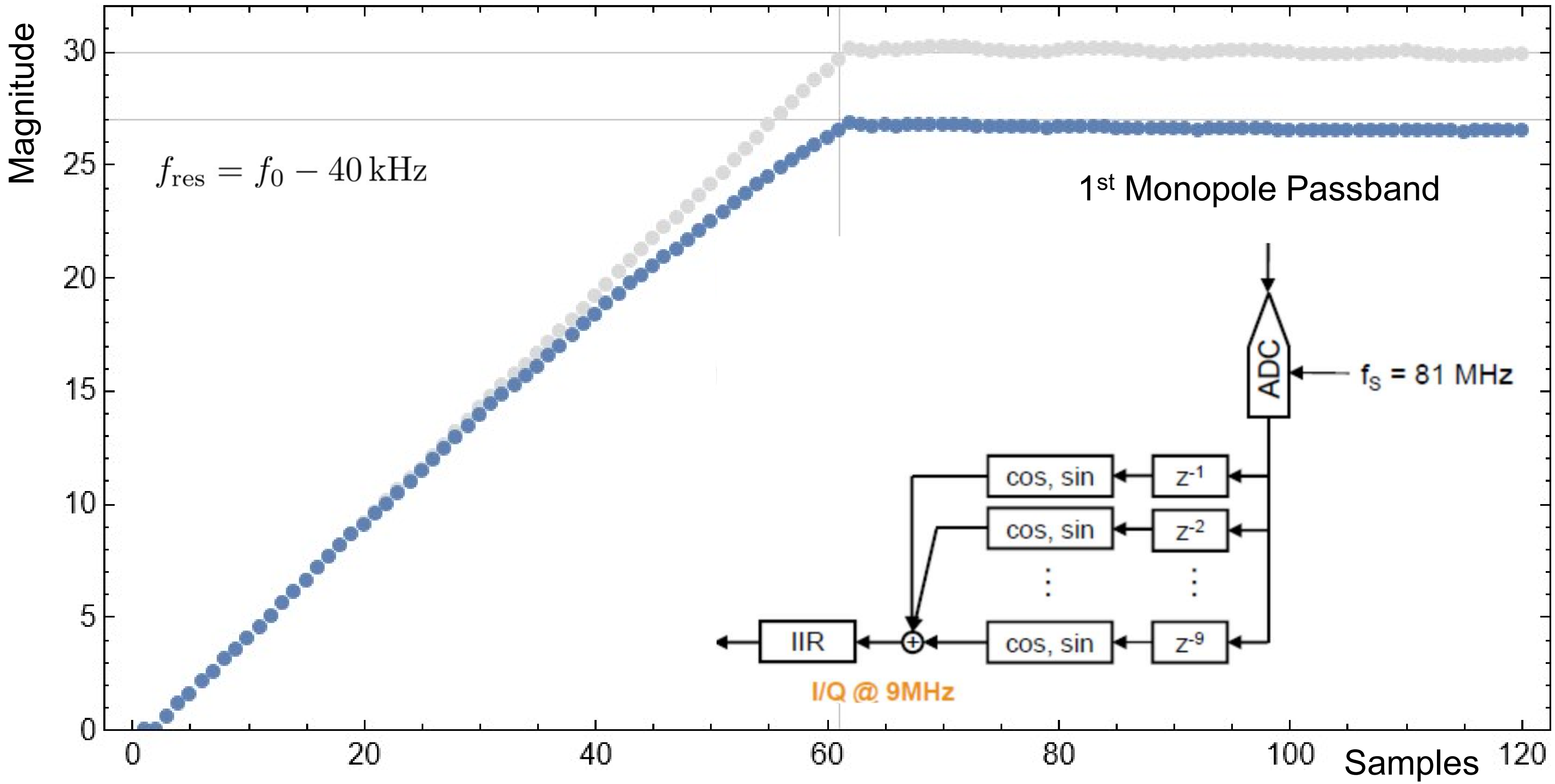
- Pulse-Train Excitation



Numerical Results

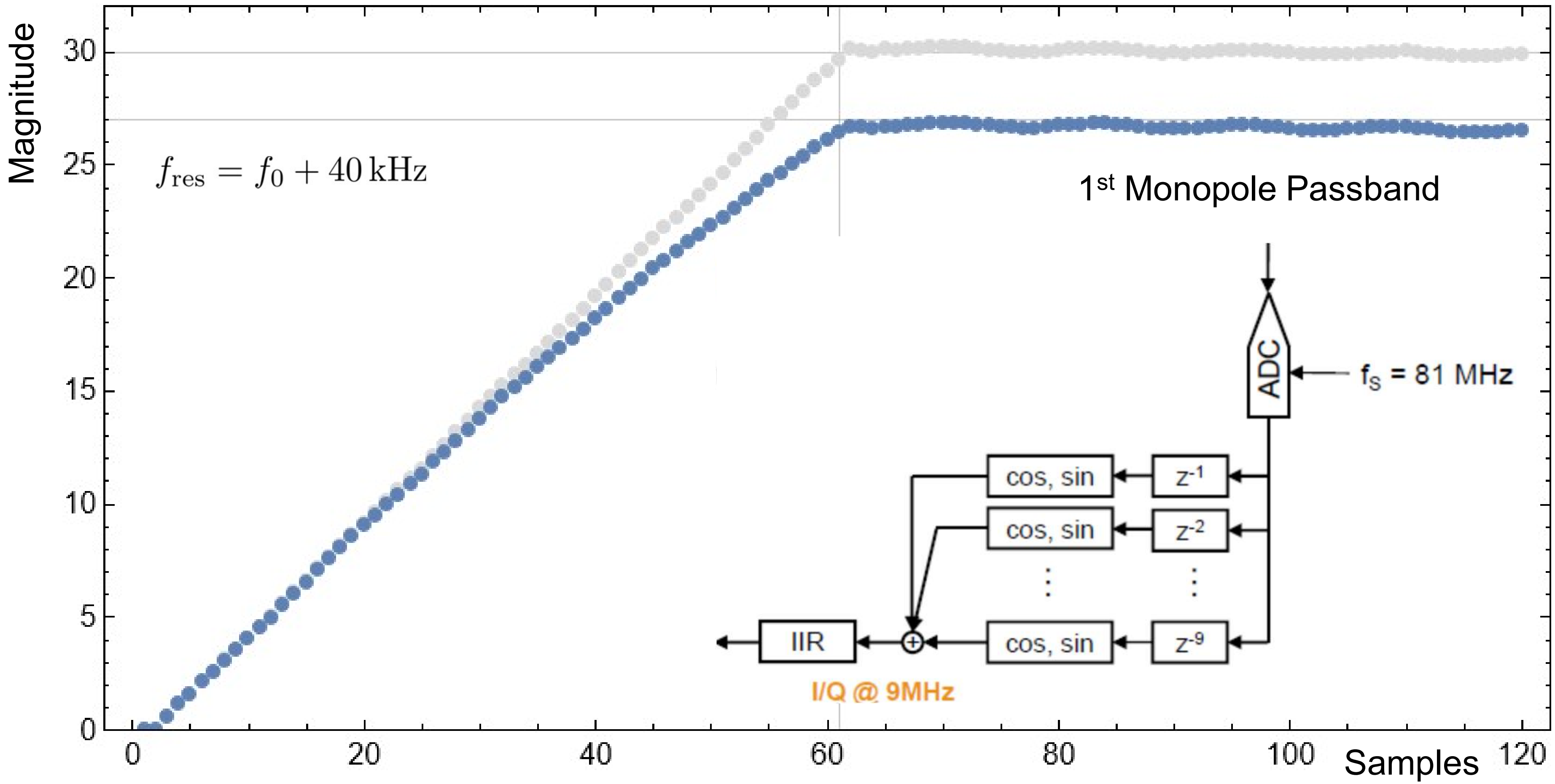
TECHNISCHE UNIVERSITÄT DARMSTADT

- Pulse-Train Excitation



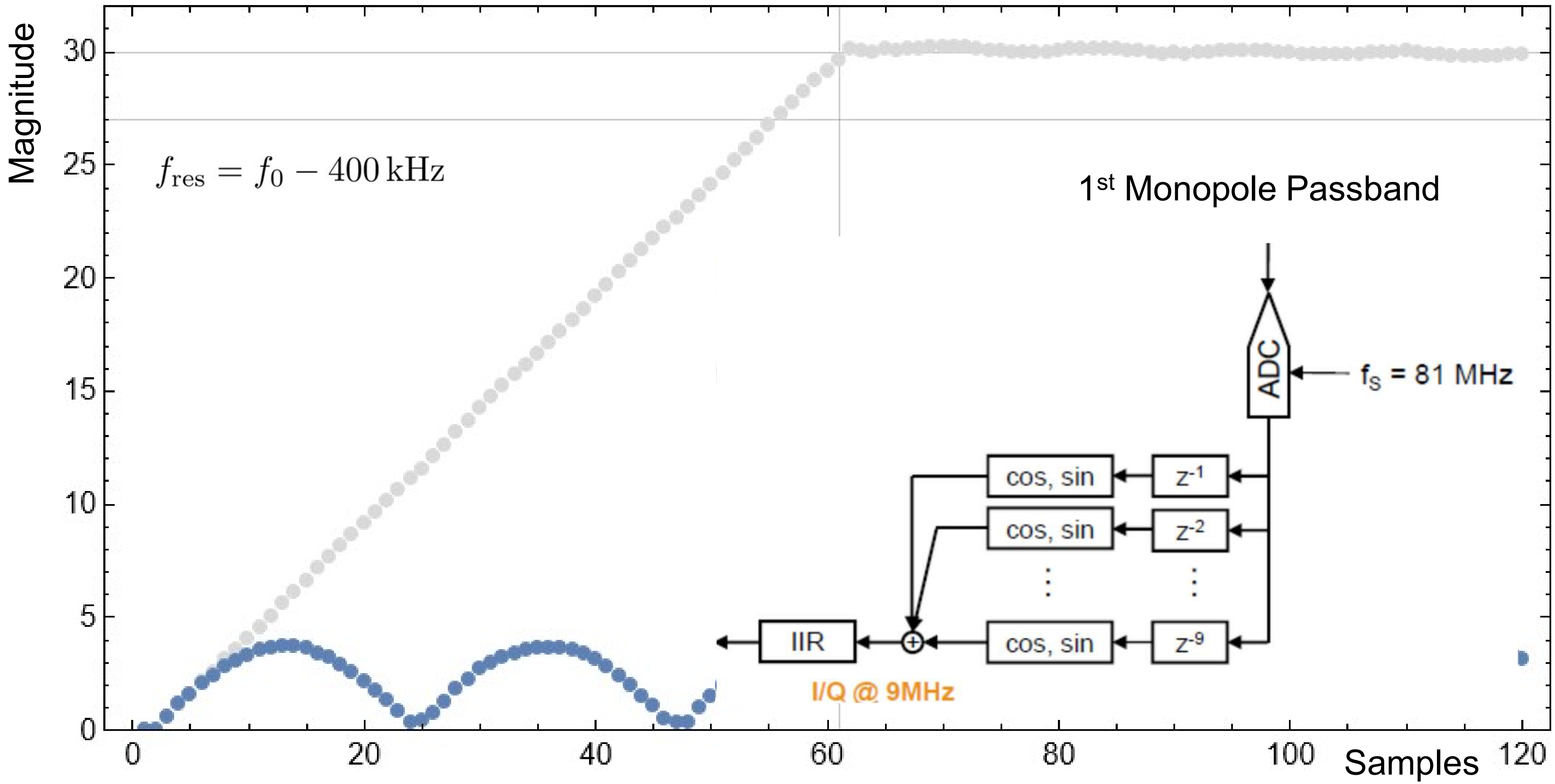
Numerical Results

- Pulse-Train Excitation



Numerical Results

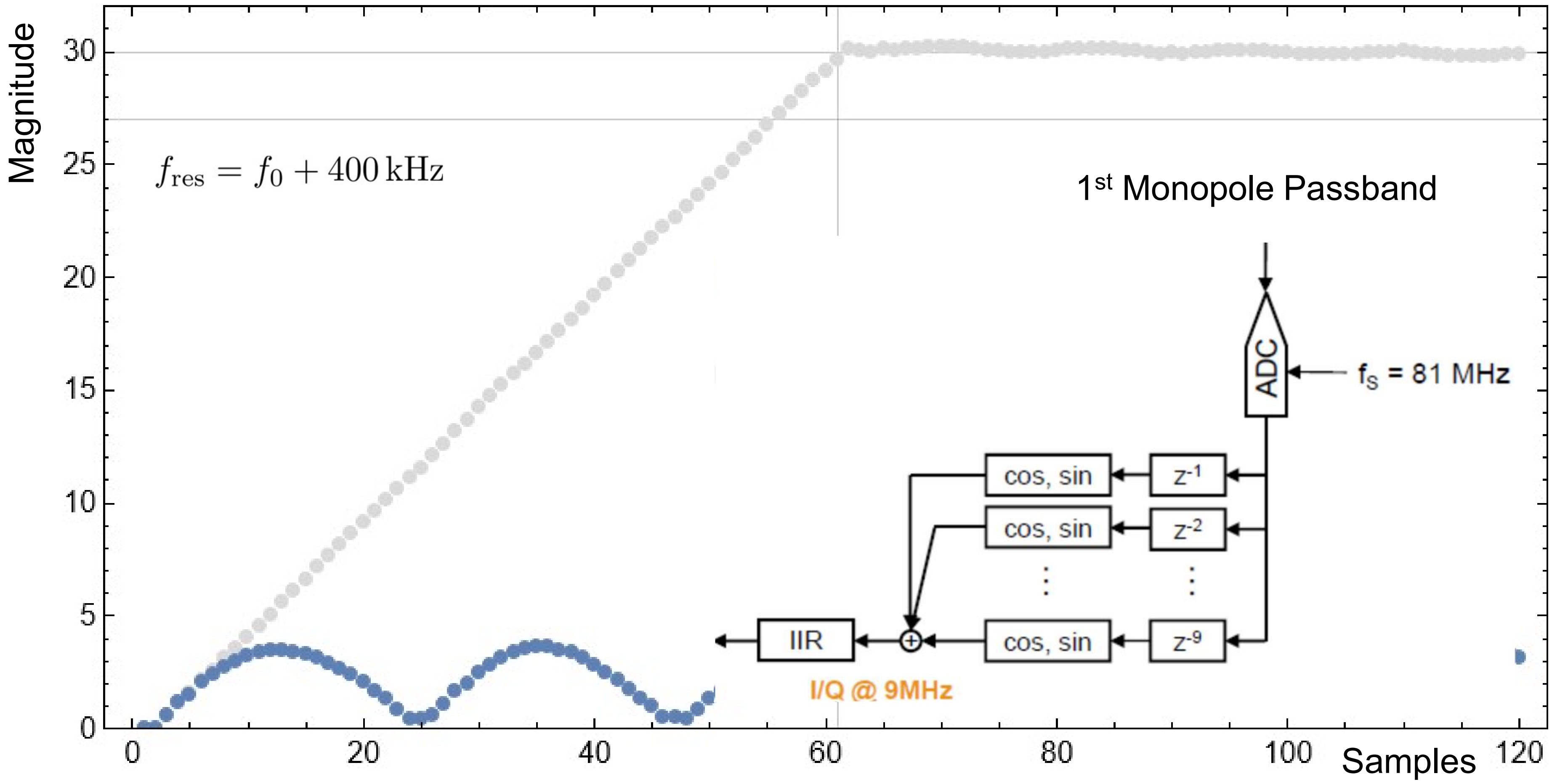
- Pulse-Train Excitation



Numerical Results

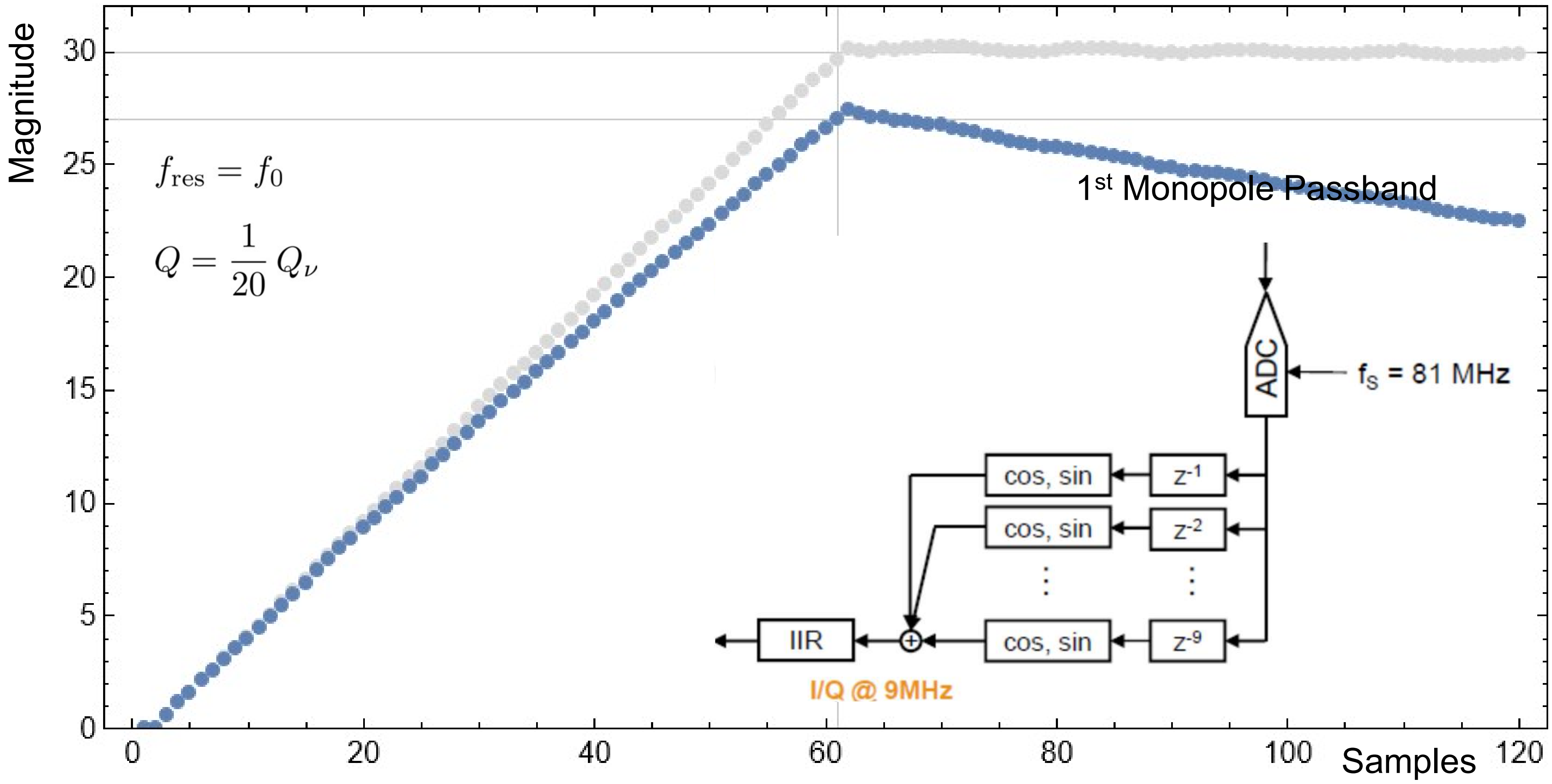
TECHNISCHE UNIVERSITÄT DARMSTADT

- Pulse-Train Excitation



Numerical Results

- Pulse-Train Excitation



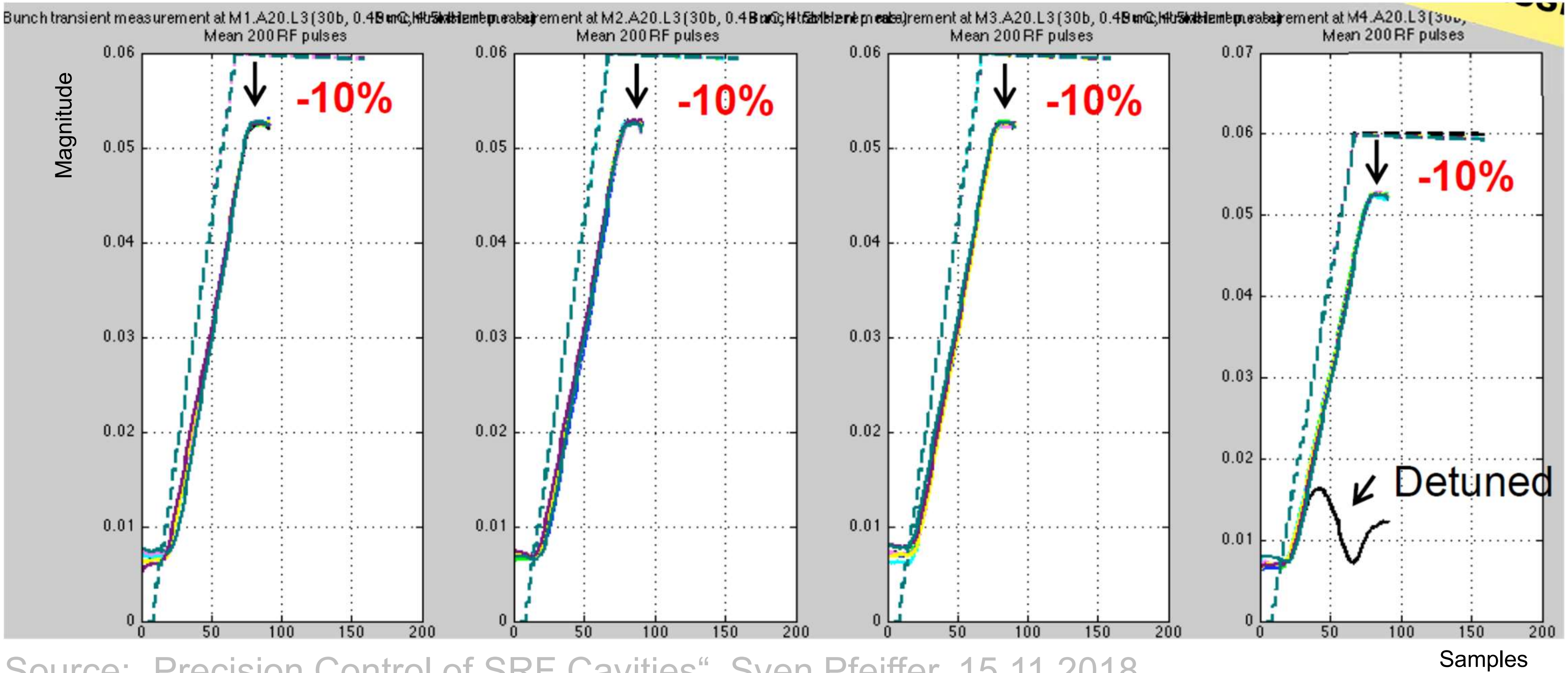
Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

- Motivation
- Computational Modeling
  - Excitation of a 9-Cell TESLA Cavity
    - Klystron (Steady State Case, Single-Mode Operation)
    - Moving Particles (Transient Behavior, Multi-Mode Operation)
  - Measurement of the Field Magnitude in the Cavity
    - Trace the Signal from the Pickup Antenna to the Digital Fourier Analysis
    - Apply the Numerical Model to Representative Signal Patterns
- Summary / Outlook

Summary

- 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

Summary / Outlook

- Summary
  - Modeling of the entire signal-processing line
    - Predefined Input Signal
      - Amplitude, Frequency, Phase
      - Single Mode, Multi-Mode
      - Steady State, Single Particle, Multi-Particle
    - Mixing
    - Analog Filtering
    - Analog to Digital Conversion, Sampling
    - Digital Fourier Transform
    - Digital IIR Filter to obtain smooth Amplitude and Phase

Summary / Outlook

TECHNISCHE UNIVERSITÄT DARMSTADT

- Summary
  - Modeling of the entire signal-processing line

    ➡ No general design problem recognizable

- Outlook
  - Measurement of the original pickup signal possible?
  - Measurement feasible for single-bunch excitation?
  - Characterization of the entire signal-processing line by laboratory-based high-frequency signal generator?