Increasing Qext of a TESLA 1.3 GHz Cavity Without Modifying the Coupler

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Hamburg

Outline

- Motivation
- Computational Modeling
  - Increasing Q_{ext} with the help of an additional scatterer
  - Determination of the corresponding scattering matrix
- Numerical Results
  - Excitation and fields in the cavity
  - Single-particle tracking
  - Horizontal and vertical coupler kicks
- Summary / Outlook

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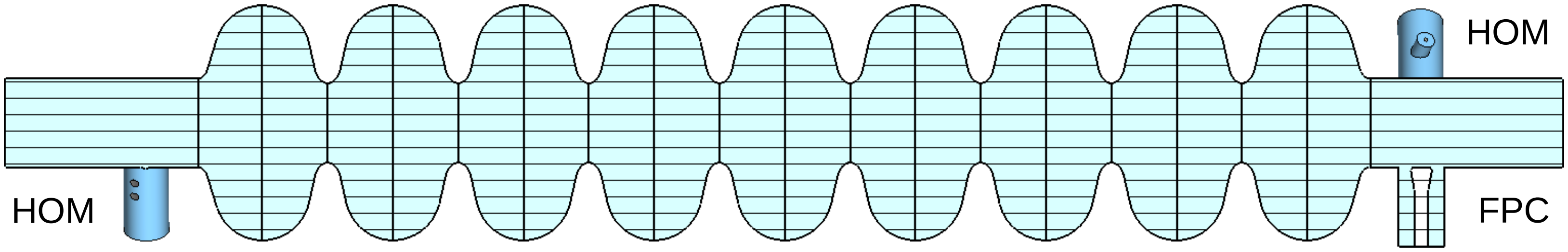
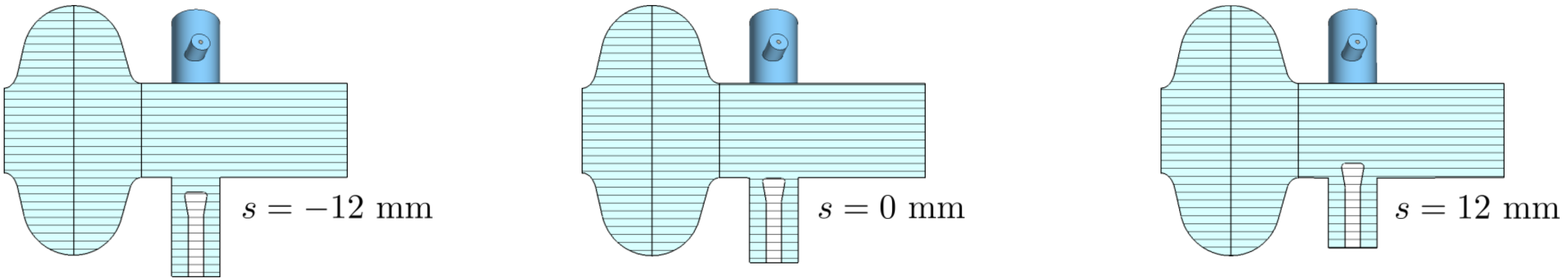
Motivation

- 9-Cell TESLA 1.3 GHz Cavity
  - Fundamental Setup including HOM and FPC

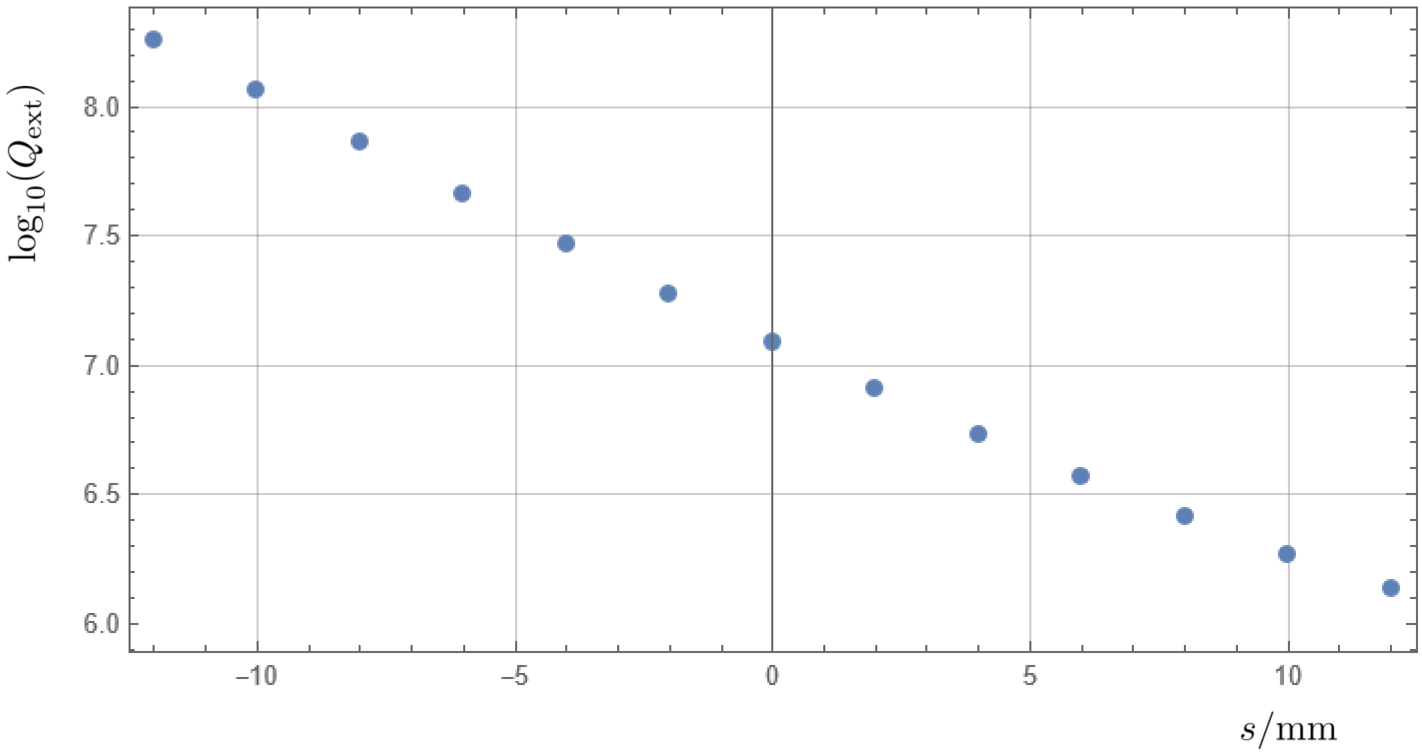


  - Penetration-Depth Variation of the FPC Antenna



Motivation

- 9-Cell TESLA 1.3 GHz Cavity
  - External Quality Factor (numerical solution)



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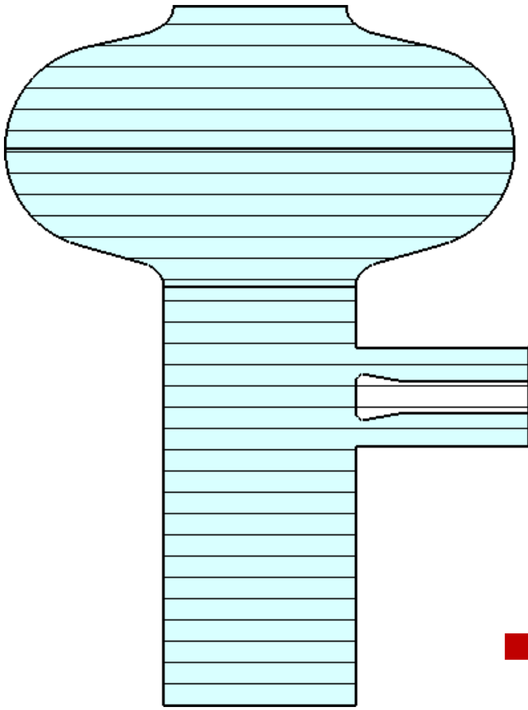
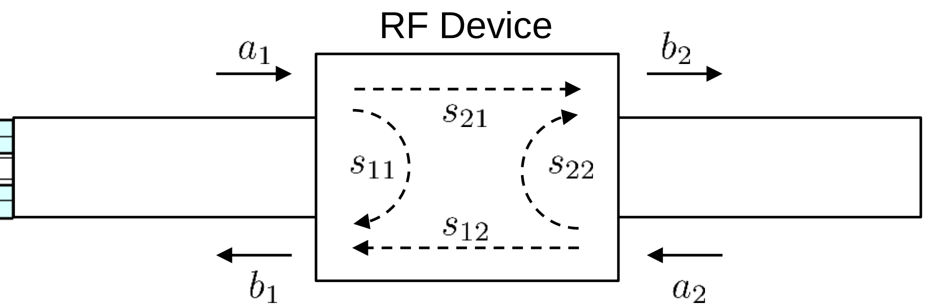
Numerical Modeling

- 9-Cell TESLA 1.3 GHz Cavity
  - Increasing the External Quality Factor



$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$



➡ Classical S-Parameter Description

Numerical Modeling

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- Properties of the Scattering Matrix
  - **Symmetric** if only passive components are involved (no magnetized ferrites or plasmas)

$$S^{\mathrm{T}} = S$$

$$\rightarrow \quad s_{12} = s_{21}$$

$$S = \begin{pmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{pmatrix}$$

$$S^{\mathrm{T}} = \begin{pmatrix} s_{11} & s_{21} \\ s_{12} & s_{22} \end{pmatrix}$$

  - **Unitary** if passive and lossless

$$S^{\mathrm{H}} = S^{-1}$$

$$S^{\mathrm{H}} = \begin{pmatrix} s_{11}^* & s_{21}^* \\ s_{12}^* & s_{22}^* \end{pmatrix}$$

$$\rightarrow \quad \begin{pmatrix} s_{11}^* & s_{21}^* \\ s_{12}^* & s_{22}^* \end{pmatrix} \begin{pmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$s = s_{\mathrm{re}} + i\, s_{\mathrm{im}}$$

$$s^* = s_{\mathrm{re}} - i\, s_{\mathrm{im}}$$

Computational Modeling

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- Properties of the Scattering Matrix
  - Unitary if passive and lossless

$$\begin{pmatrix} s_{11}^* & s_{21}^* \\ s_{12}^* & s_{22}^* \end{pmatrix} \begin{pmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$\rightarrow \quad \begin{aligned} s_{11}^* s_{11} + s_{21}^* s_{21} &= 1 \\ s_{11}^* s_{12} + s_{21}^* s_{22} &= 0 \\ s_{12}^* s_{11} + s_{22}^* s_{21} &= 0 \\ s_{12}^* s_{12} + s_{22}^* s_{22} &= 1 \end{aligned} \qquad \rightarrow \quad \begin{aligned} |s_{11}|^2 + |s_{21}|^2 &= 1 \\ s_{11}^* s_{12} &= -s_{21}^* s_{22} \\ s_{11} s_{12}^* &= -s_{21} s_{22}^* \\ |s_{12}|^2 + |s_{22}|^2 &= 1 \end{aligned}$$

$$\overset{s_{12} = s_{21}}{\rightarrow} \quad |s_{11}||\cancel{s_{12}}| = |\cancel{s_{21}}||s_{22}| \qquad -\arg(s_{11}) + \arg(s_{12}) = \pi - \arg(s_{21}) + \arg(s_{22})$$

$$|s_{11}| = |s_{22}| \qquad \arg(s_{21}) = \frac{\pi}{2} + \frac{1}{2}(\arg(s_{11}) + \arg(s_{22}))$$

Computational Modeling

- Properties of the Scattering Matrix
  - Symmetric if only passive components are involved

$$S^{\mathrm{T}} = S$$

  - Unitary if passive and lossless

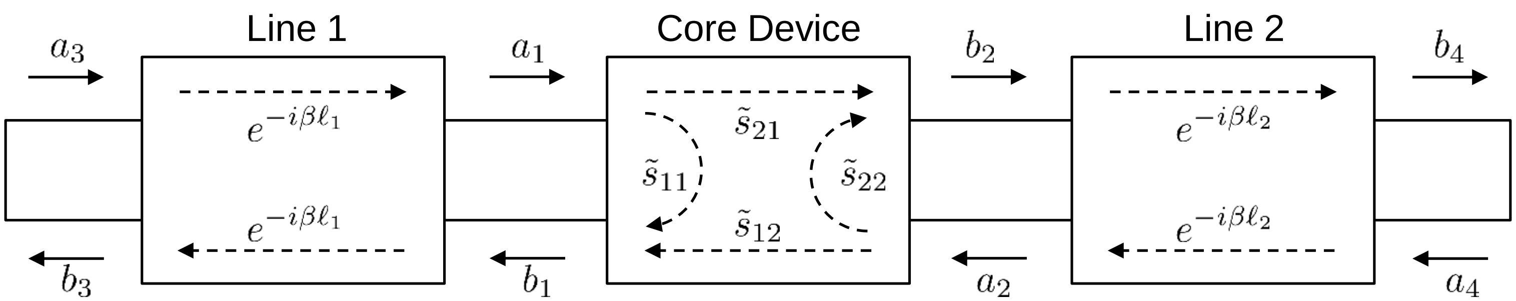
$$S^{\mathrm{H}} = S^{-1}$$

$$\rightarrow \quad S = \begin{pmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{pmatrix} = \begin{pmatrix} \sqrt{1-|s_{21}|^2}\, e^{i\varphi_1} & |s_{21}|\, e^{i\frac{\pi+\varphi_1+\varphi_2}{2}} \\ |s_{21}|\, e^{i\frac{\pi+\varphi_1+\varphi_2}{2}} & \sqrt{1-|s_{21}|^2}\, e^{i\varphi_2} \end{pmatrix}$$

general form of the symmetric and unitary scattering matrix (3 DoF)

Computational Modeling

- Transformation of the Scattering Matrix
  - Concatenation using ideal transmission lines



$$\begin{pmatrix} b_3 \\ b_4 \end{pmatrix} = \begin{pmatrix} \sqrt{1-|s_{21}|^2}\; e^{i\varphi_1} & |s_{21}|\; e^{i\frac{\pi+\varphi_1+\varphi_2}{2}} \\ |s_{21}|\; e^{i\frac{\pi+\varphi_1+\varphi_2}{2}} & \sqrt{1-|s_{21}|^2}\; e^{i\varphi_2} \end{pmatrix} \begin{pmatrix} a_3 \\ a_4 \end{pmatrix}$$

$$= \begin{pmatrix} \tilde{s}_{11}\; e^{-i\beta\ell_1} e^{-i\beta\ell_1} & \tilde{s}_{12}\; e^{-i\beta\ell_1} e^{-i\beta\ell_2} \\ \tilde{s}_{21}\; e^{-i\beta\ell_2} e^{-i\beta\ell_1} & \tilde{s}_{22}\; e^{-i\beta\ell_2} e^{-i\beta\ell_2} \end{pmatrix} \begin{pmatrix} a_3 \\ a_4 \end{pmatrix}$$

Computational Modeling

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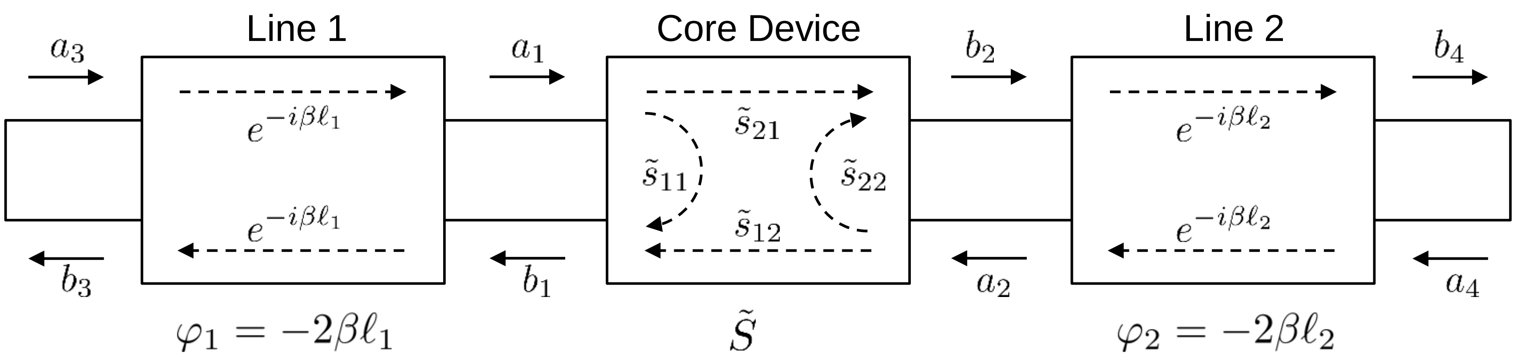
- Transformation of the Scattering Matrix
  - Concatenate using ideal lines



$$\tilde{S} = \begin{pmatrix} \sqrt{1 - |s_{21}|^2} & i\,|s_{21}| \\ i\,|s_{21}| & \sqrt{1 - |s_{21}|^2} \end{pmatrix}$$

reduced form of the symmetric and unitary scattering matrix (1 DoF)

Computational Modeling

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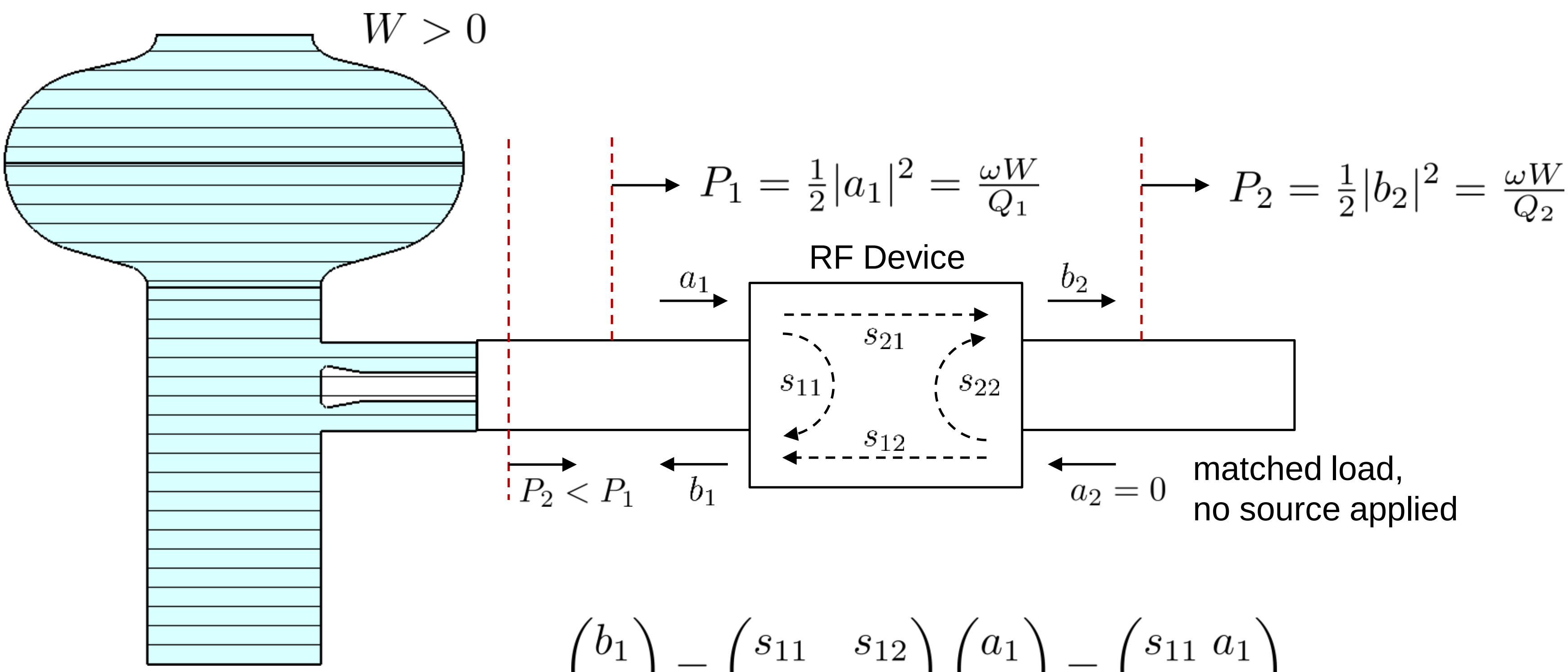
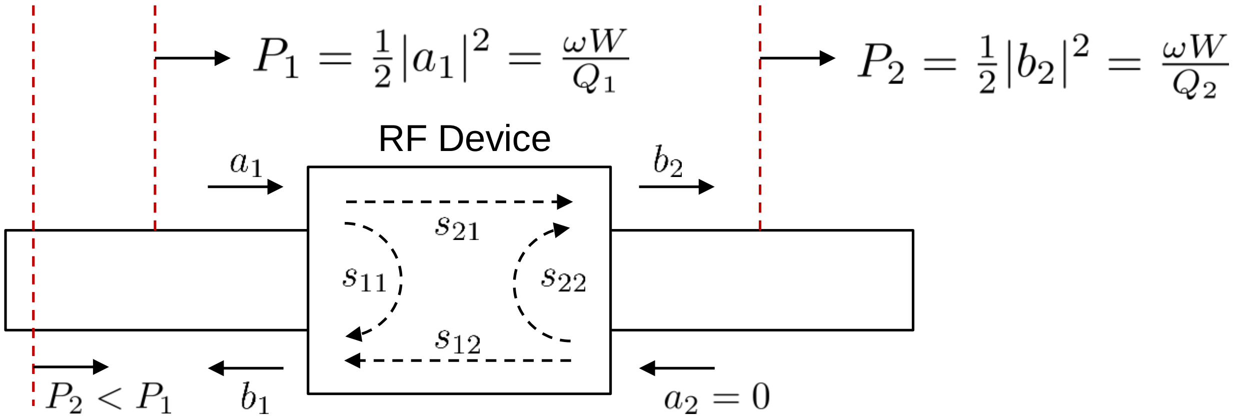
- Determination of the Reduced Scattering Matrix



$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} s_{11}\ a_1 \\ s_{21}\ a_1 \end{pmatrix}$$

Computational Modeling

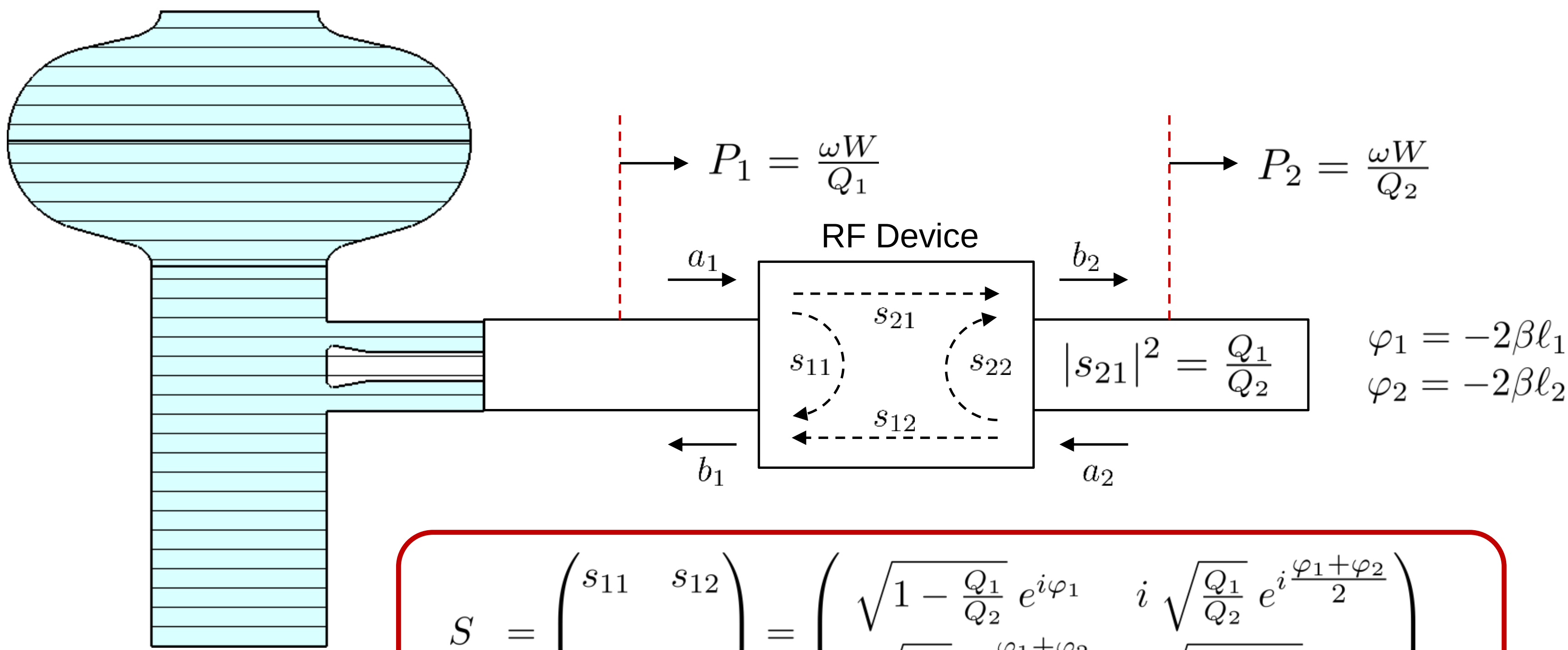
- Determination of the Reduced Scattering Matrix



$$P_2 = \frac{\omega W}{Q_2} = \frac{1}{2}|b_2|^2 = \frac{1}{2}|s_{21}a_1|^2 = \frac{1}{2}|s_{21}|^2|a_1|^2 = P_1|s_{21}|^2 = \frac{\omega W}{Q_1}|s_{21}|^2$$

$$\frac{\cancel{\omega W}}{Q_2} = \frac{\cancel{\omega W}}{Q_1}|s_{21}|^2 \qquad \rightarrow \qquad |s_{21}|^2 = \frac{Q_1}{Q_2} \qquad\qquad Q_2 > Q_1$$

Determination of the Scattering Matrix



$$S = \begin{pmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{pmatrix} = \begin{pmatrix} \sqrt{1-\frac{Q_1}{Q_2}}\; e^{i\varphi_1} & i\,\sqrt{\frac{Q_1}{Q_2}}\; e^{i\frac{\varphi_1+\varphi_2}{2}} \\ i\,\sqrt{\frac{Q_1}{Q_2}}\; e^{i\frac{\varphi_1+\varphi_2}{2}} & \sqrt{1-\frac{Q_1}{Q_2}}\; e^{i\varphi_2} \end{pmatrix}$$

symmetric and unitary scattering matrix

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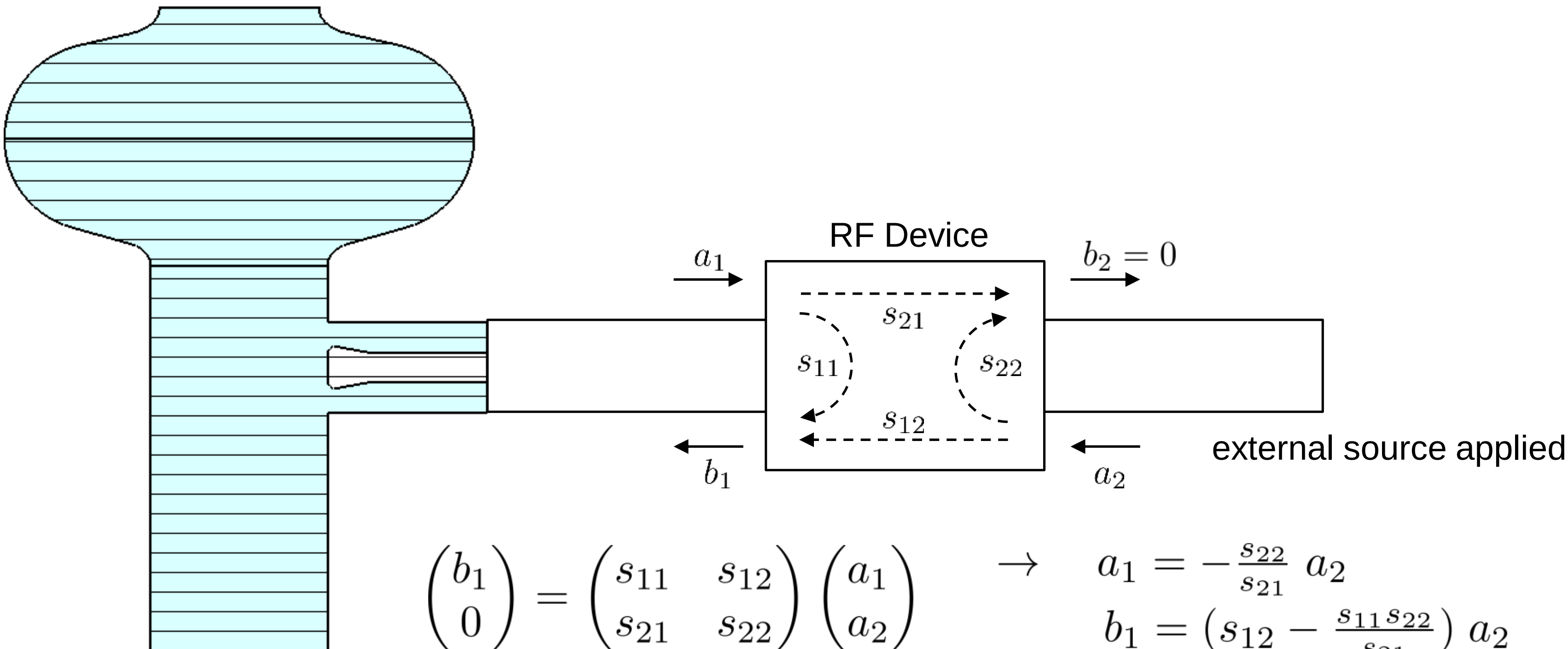
Numerical Results

- Excitation of the Cavity through the RF Device



$$\begin{pmatrix} b_1 \\ 0 \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \quad \rightarrow \quad \begin{aligned} a_1 &= -\frac{s_{22}}{s_{21}}\, a_2 \\ b_1 &= \left(s_{12} - \frac{s_{11}s_{22}}{s_{21}}\right) a_2 \end{aligned}$$

$$\rightarrow \quad \frac{a_1}{b_1} = s_{11}^*$$

Numerical Results

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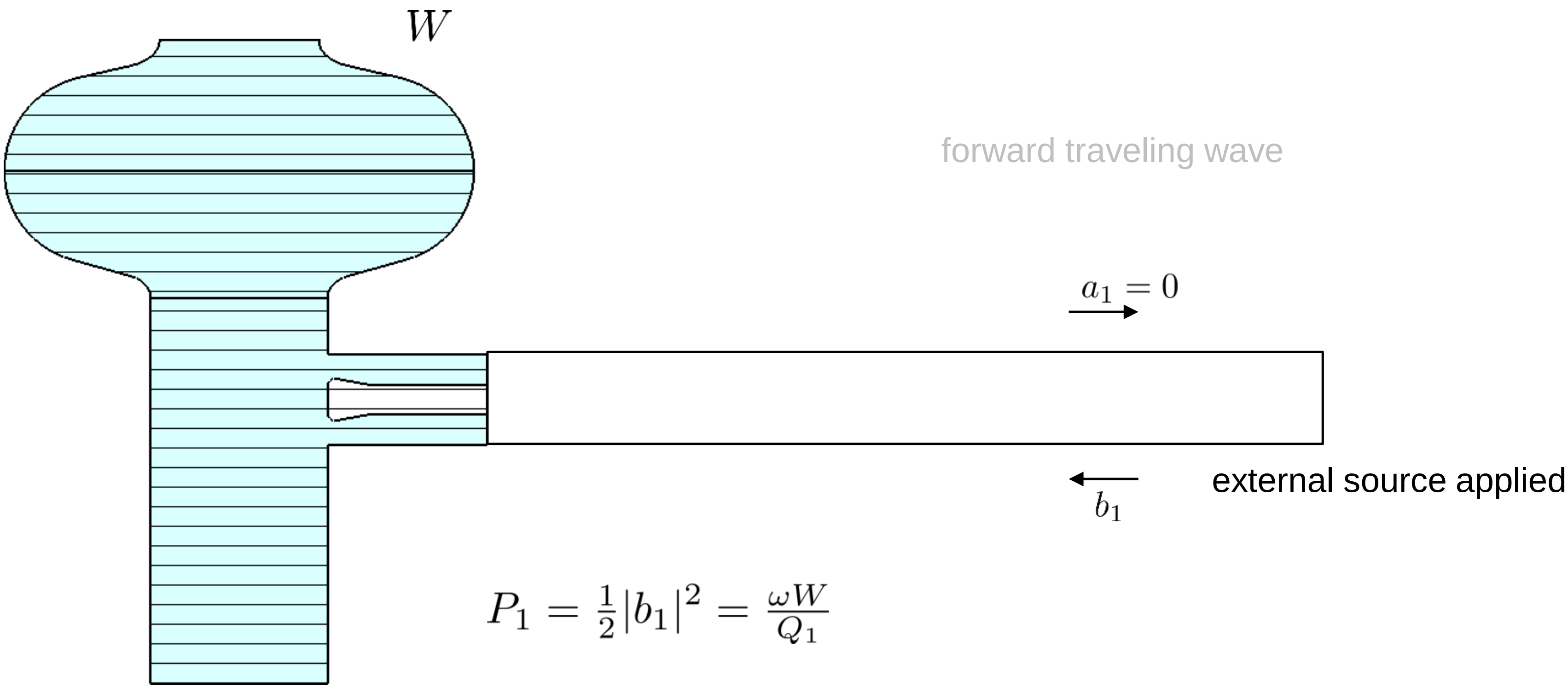
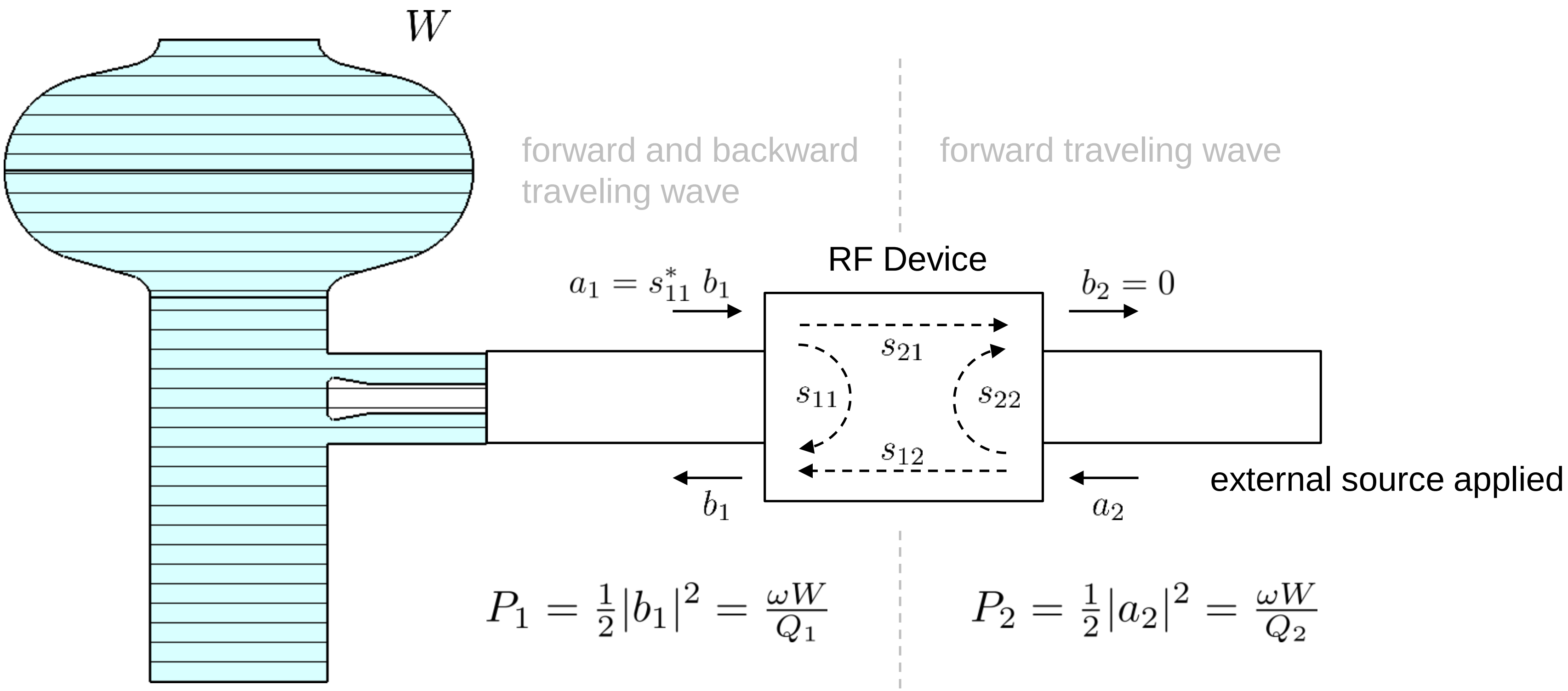
- Comparison of the Different Coupling Schemes
  - Direct insertion of the applied power into the cavity



$$P_1 = \frac{1}{2}|b_1|^2 = \frac{\omega W}{Q_1}$$

Numerical Results

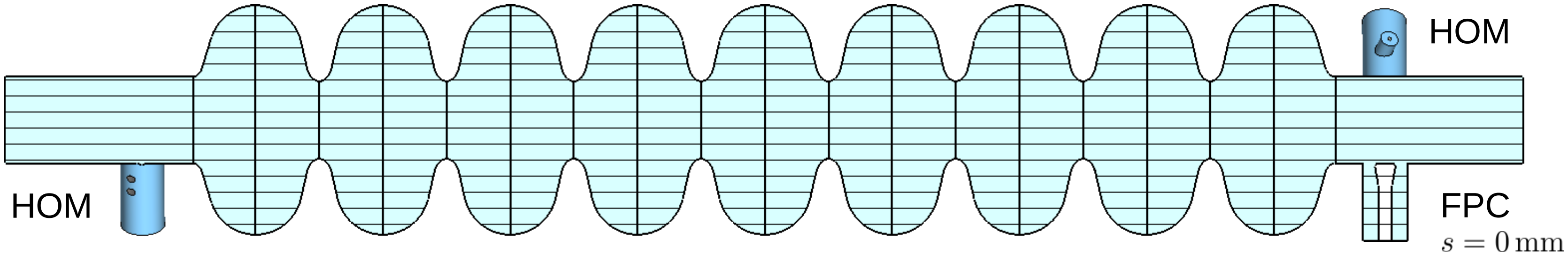
- Comparison of the Different Coupling Schemes
  - Insertion of the applied power through the RF device



$$P_1 = \frac{1}{2}|b_1|^2 = \frac{\omega W}{Q_1} \qquad P_2 = \frac{1}{2}|a_2|^2 = \frac{\omega W}{Q_2}$$

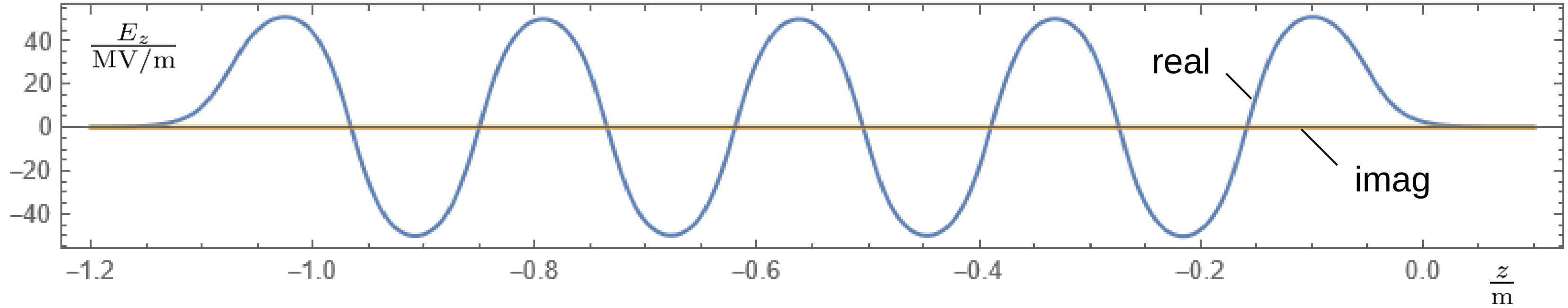
Numerical Results

- 9-Cell TESLA 1.3 GHz Cavity
  - Fundamental Setup including HOM and FPC



  - Calculate Fields on Axis (Ex, Ey, Ez, Bx, By, Bz)

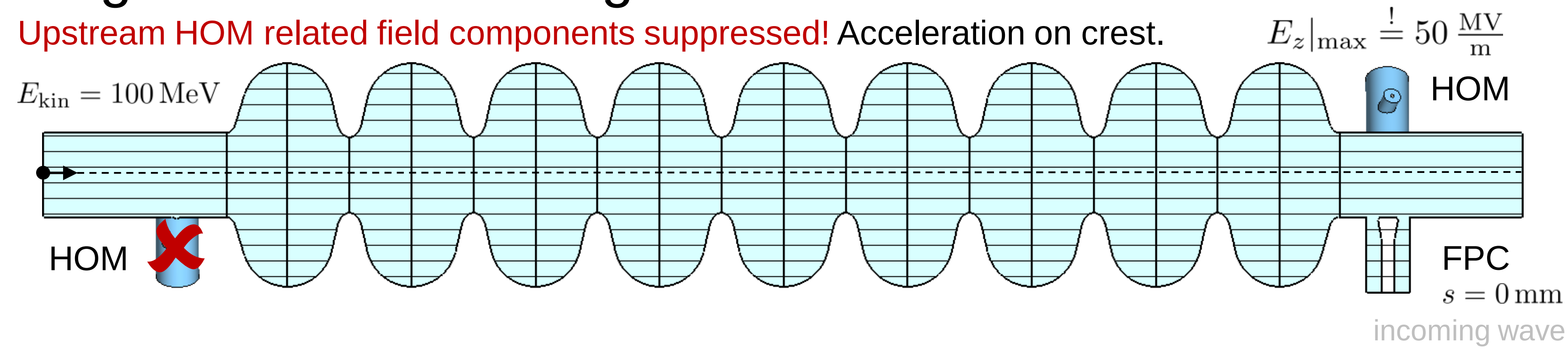
$E_z|_{\max} \overset{!}{=} 50\,\frac{\mathrm{MV}}{\mathrm{m}}$



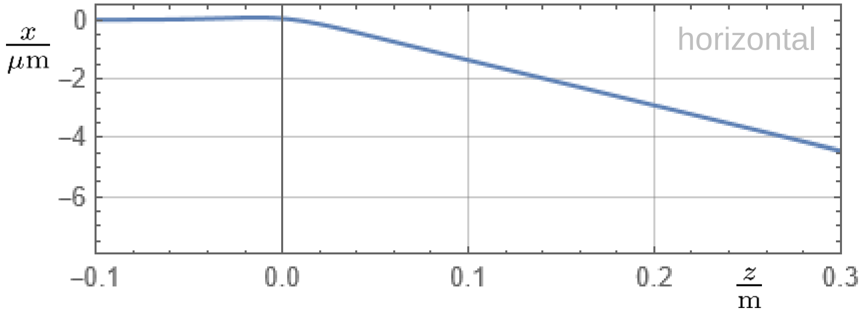
Numerical Results

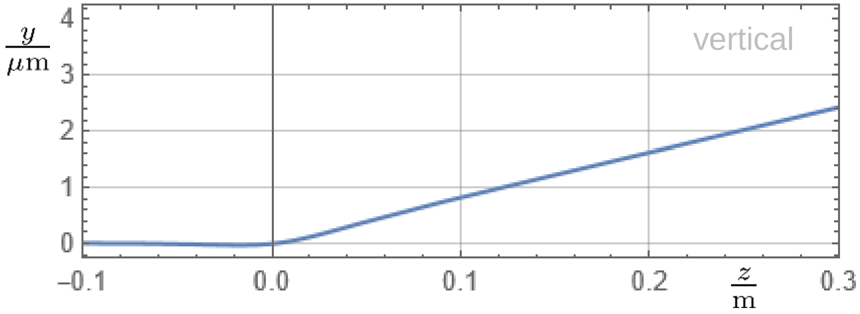
- 9-Cell TESLA 1.3 GHz Cavity
  - Single-Particle Tracking

Upstream HOM related field components suppressed! Acceleration on crest.



  - Trajectory in the Horizontal and Vertical Planes





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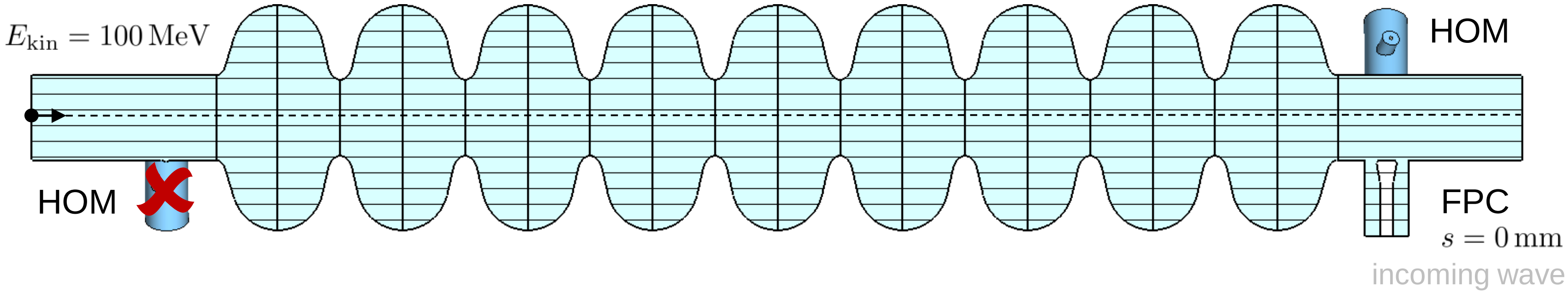

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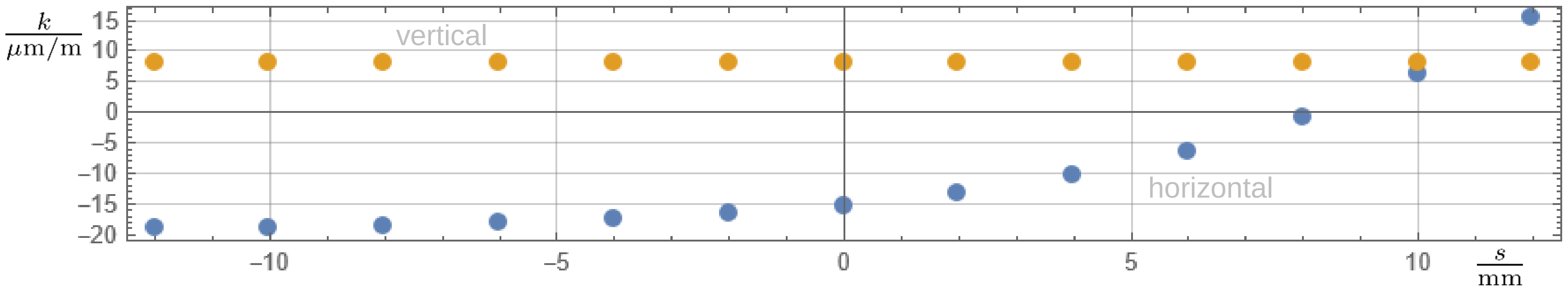

Numerical Results

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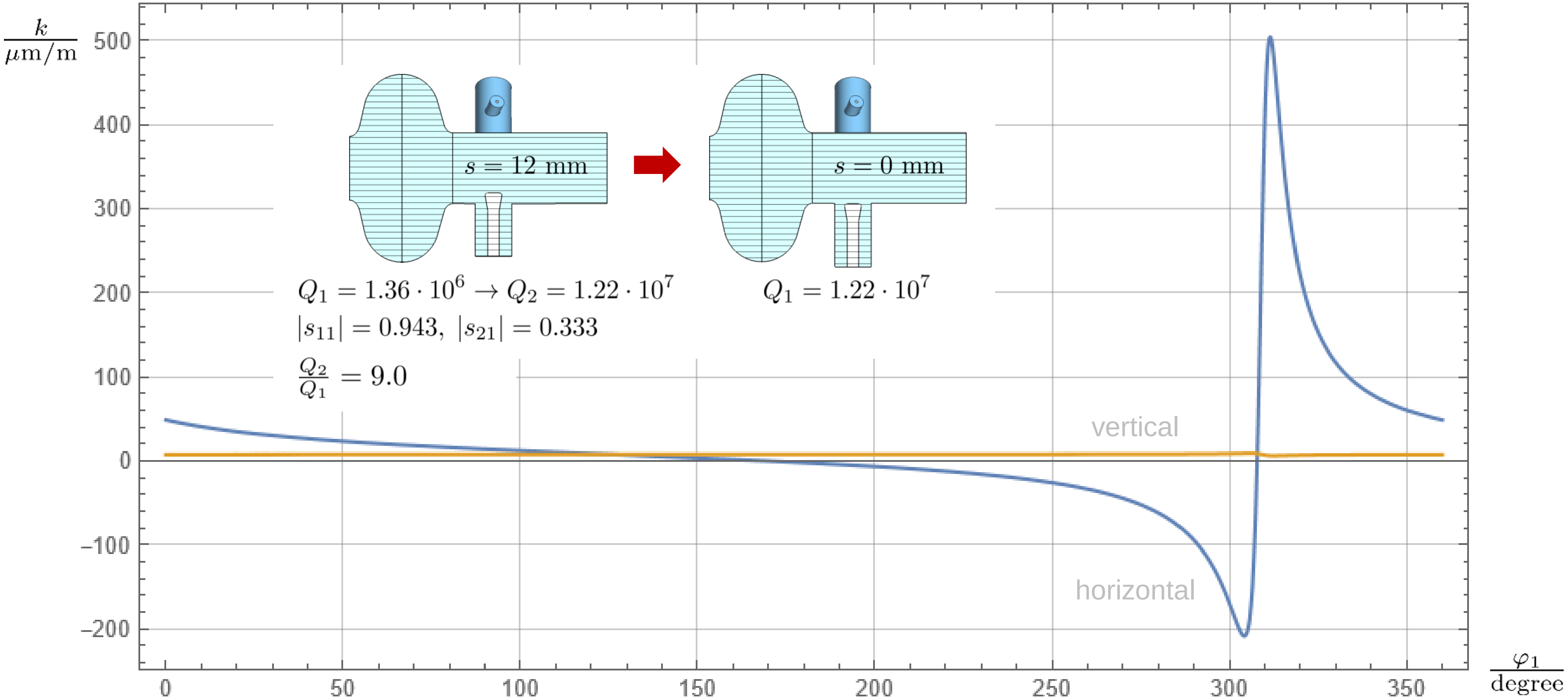
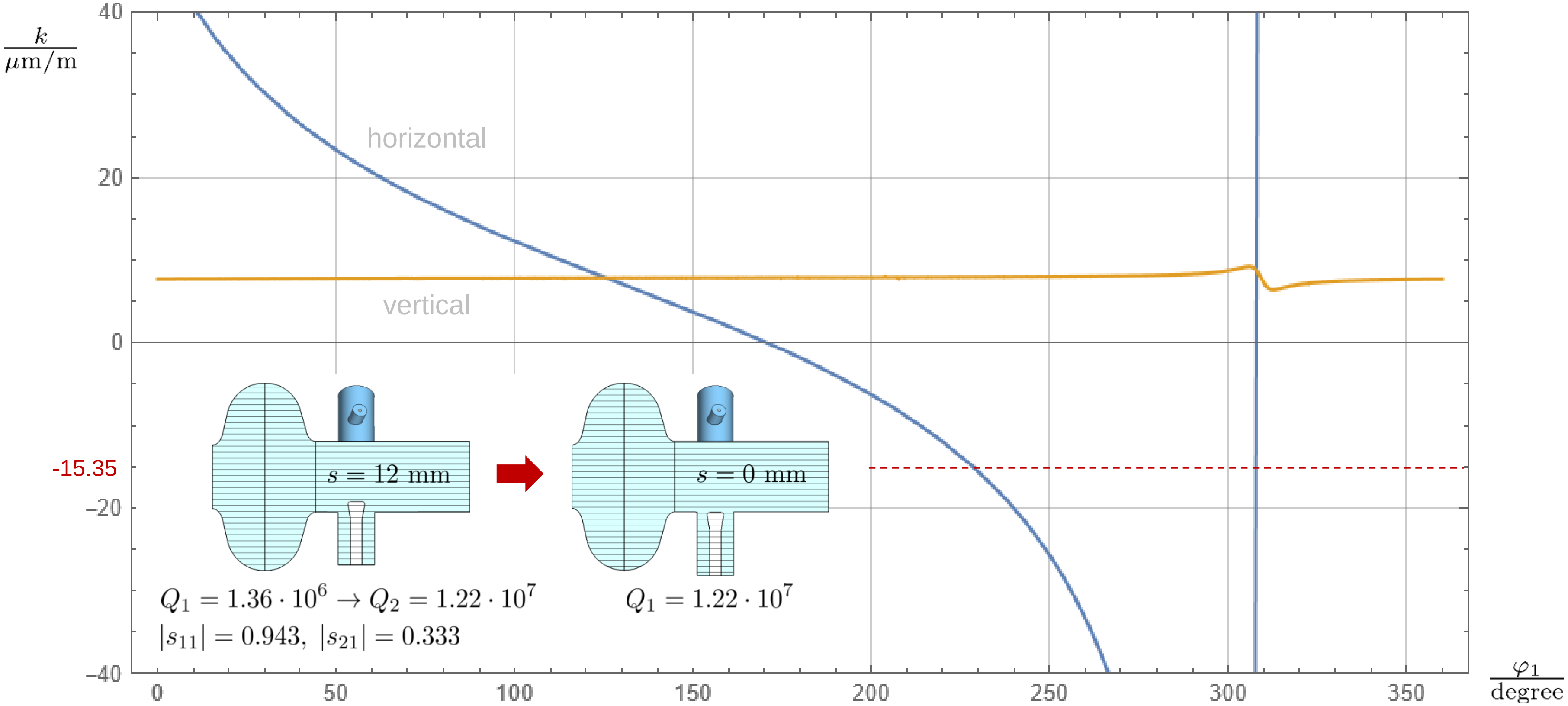
- 9-Cell TESLA 1.3 GHz Cavity
  - Horizontal and Vertical Coupler Kicks



Numerical Results

- 9-Cell TESLA 1.3 GHz Cavity
  - Horizontal and Vertical Coupler Kicks (zoom)



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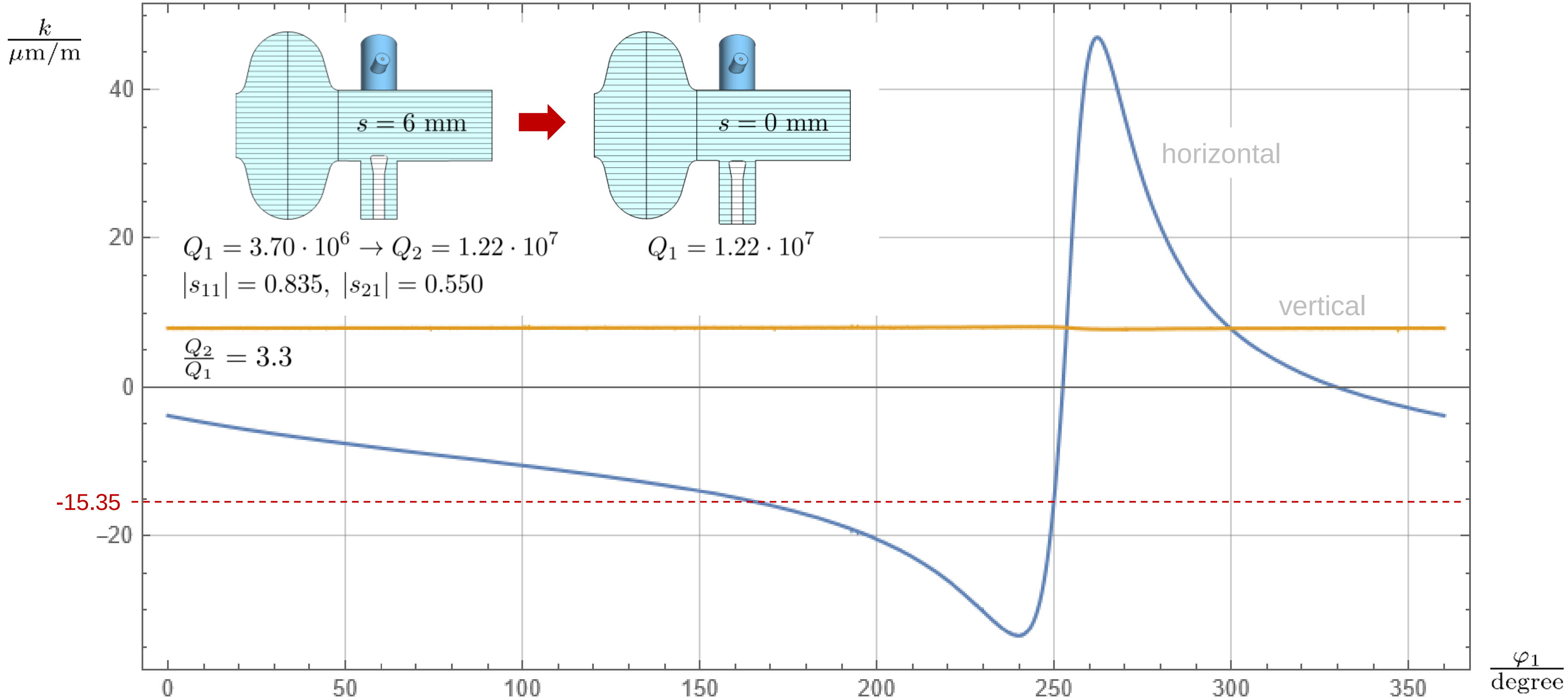

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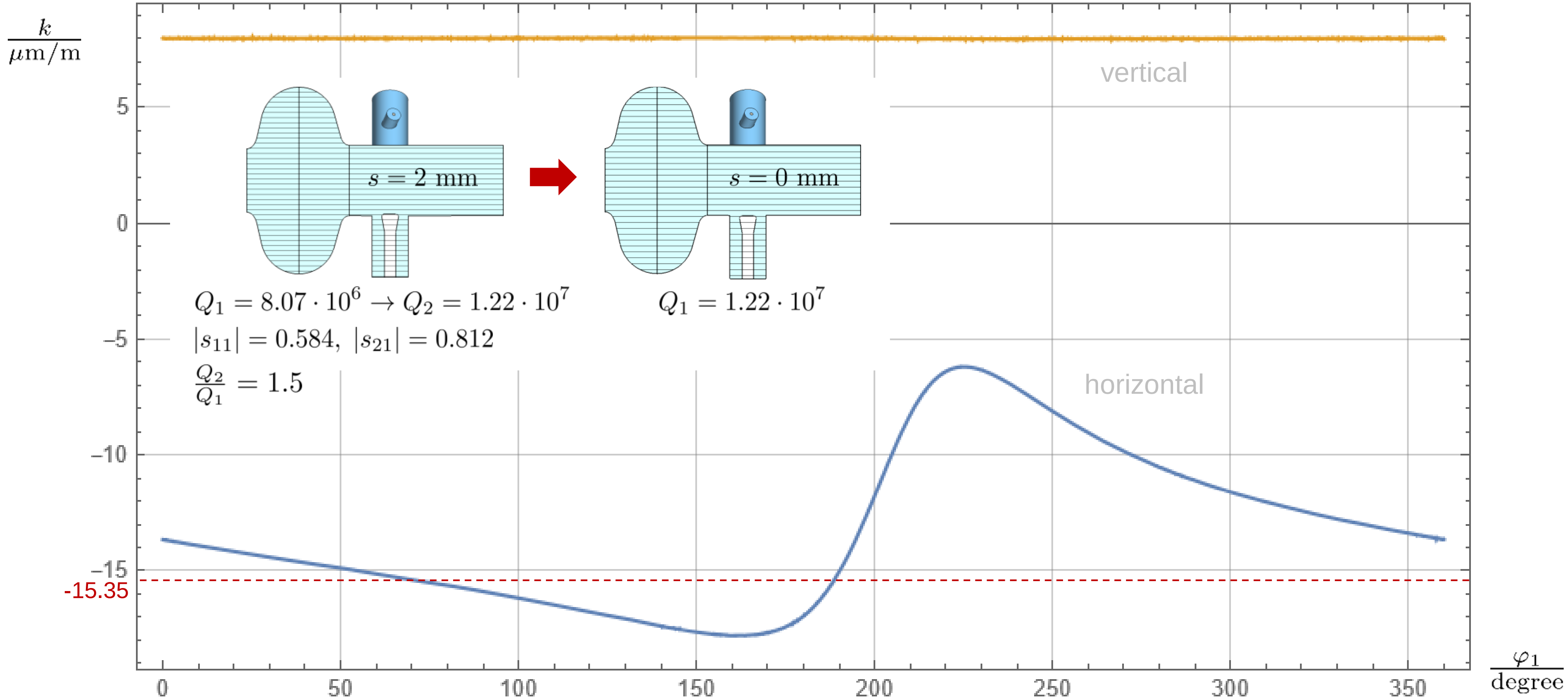

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Summary / Outlook

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- Summary
  - Adding a scatterer in the feeding line of the cavity
  - Determination of the corresponding scattering matrix
  - Feeding the cavity and calculation of the EM fields
  - Single-particle dynamics
  - Kick-factor calculations

  ➡ Even with highly reflecting scatterers moderate kick factors achievable

- Outlook
  - Modeling a scatterer with the desired properties