Intra Bunch Train Transverse Dynamics in the Superconducting Accelerators FLASH and European XFEL

Thorsten Hellert, FEL-Seminar, 20.09.2016

HELMHOLTZ ASSOCIATION

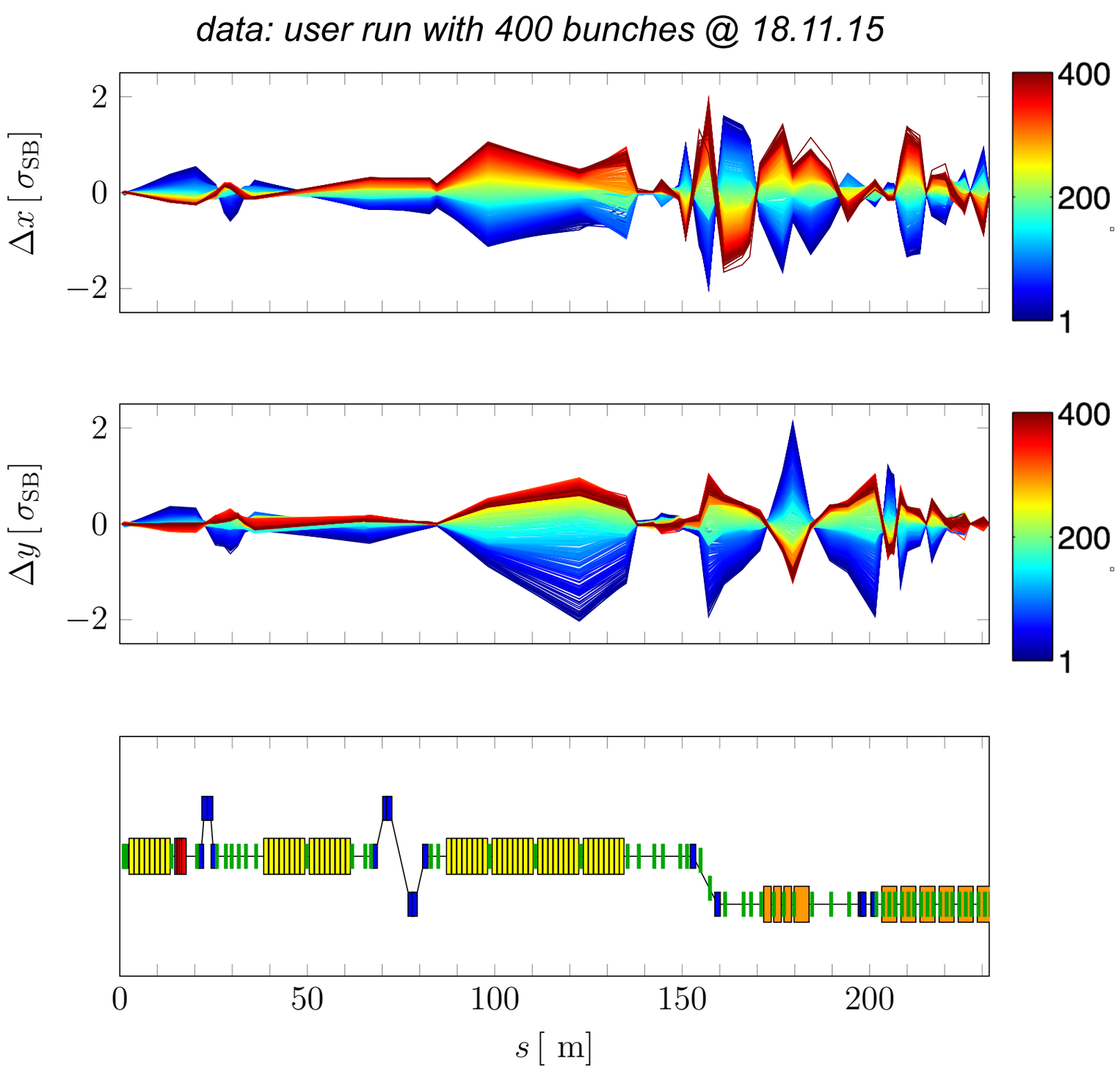
DESY

outline

- motivation
- model development
- simulation results

motivation

multi bunch orbit spread



> **orbit variations > 1kHz**

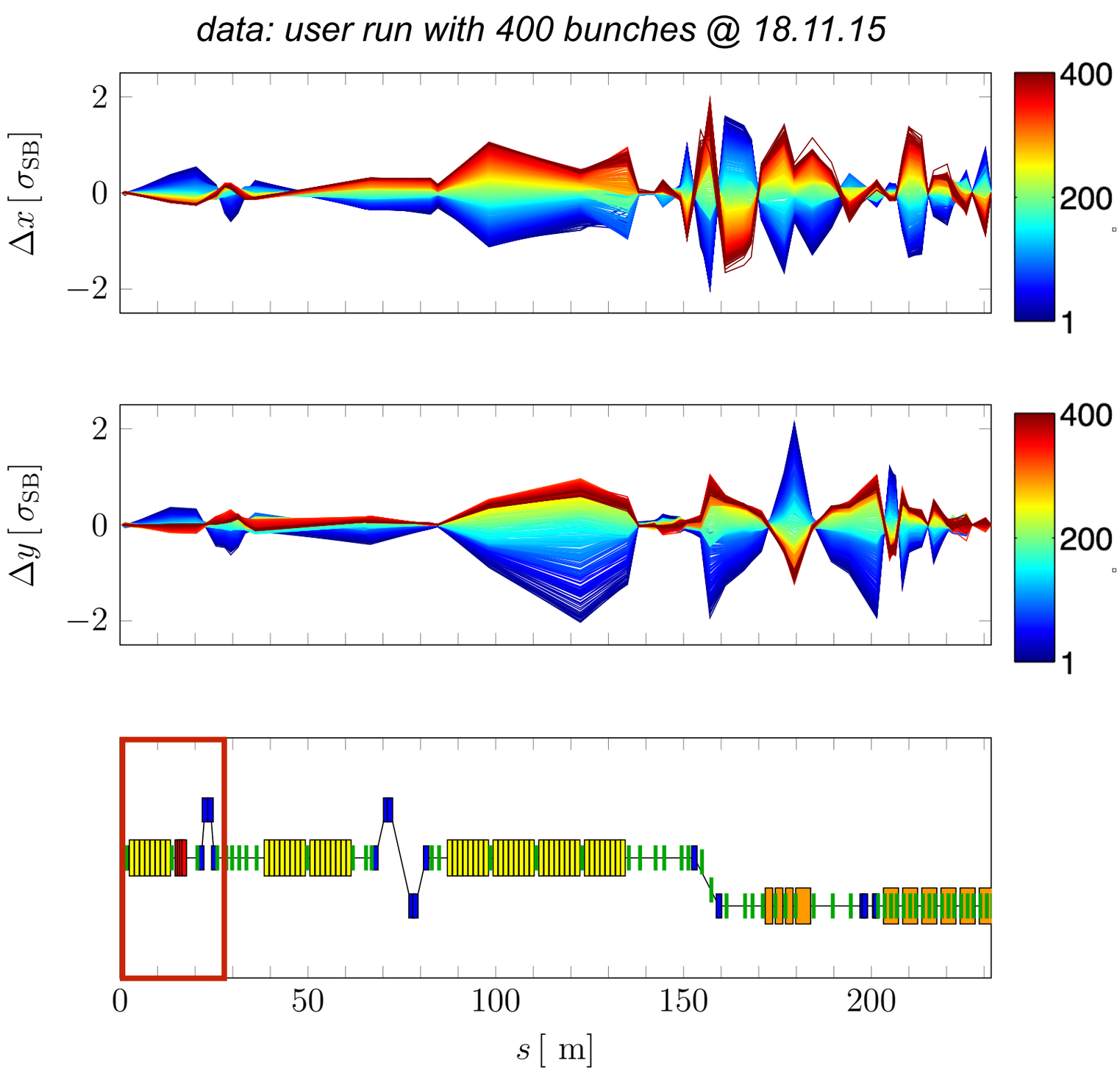
- \- **no iron magnets**
- \- **no vibrations**
- \+ **GUN**
- \+ **RF modules**
- \+ **non closed dispersion**
- \+ **wakefields, resonances …(?)**

> **difficulties**

- **unknown sources**
- **small number of BPMs**
- **insufficient model**

motivation

multi bunch orbit spread



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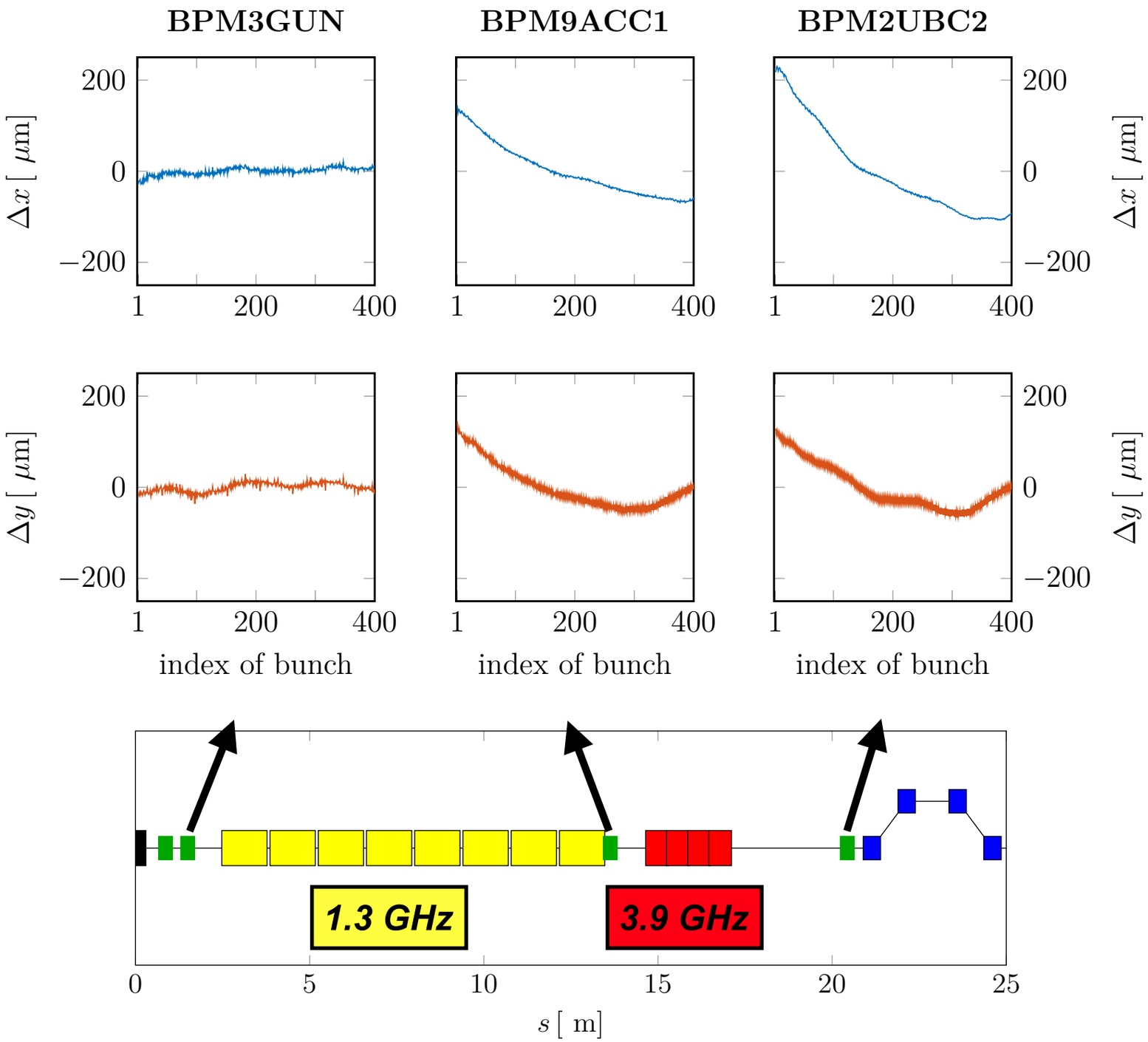
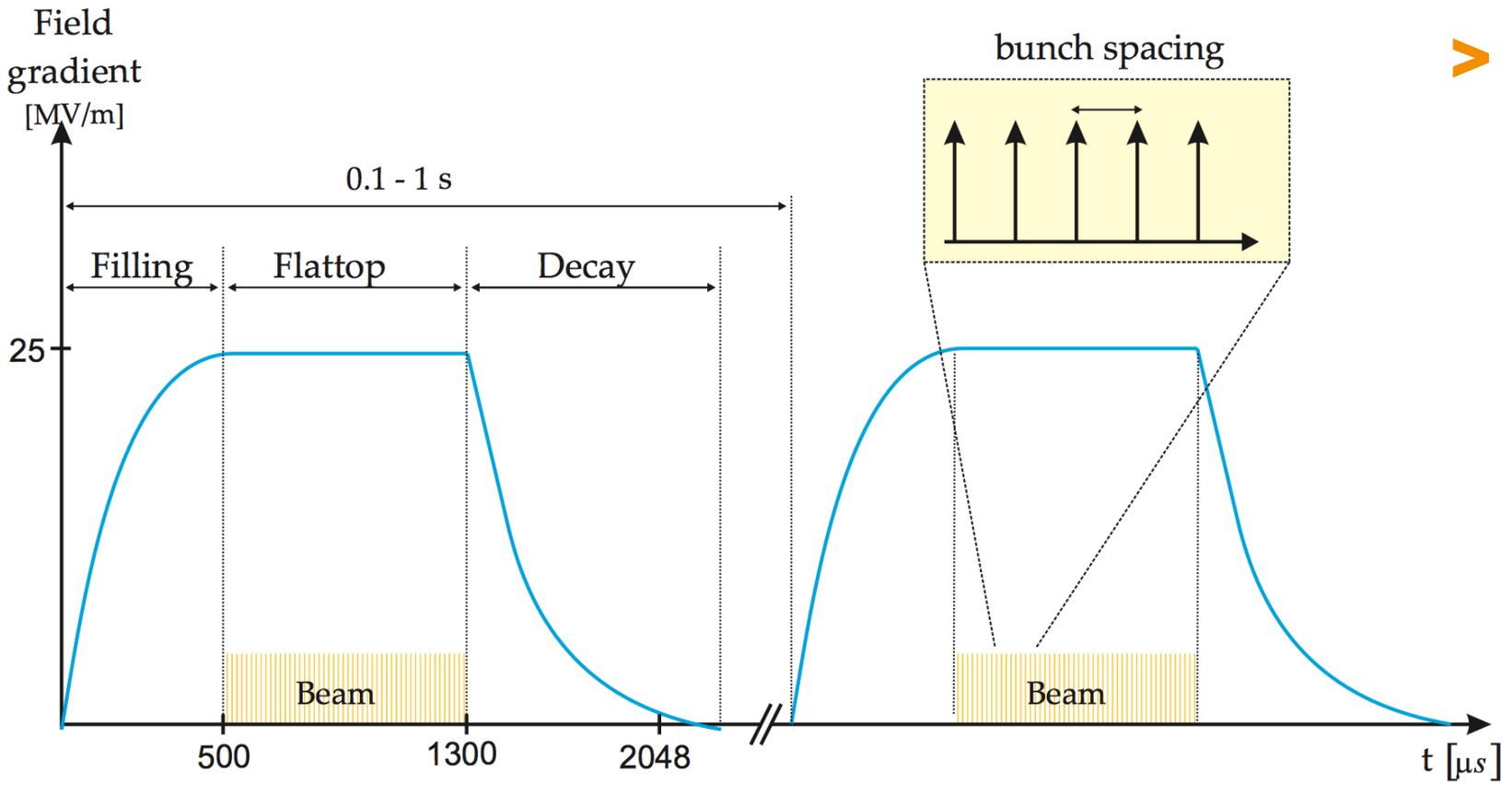


> RF modules

- significant orbit spread after injector module
- higher oscillation frequencies after 3rd harmonic module

motivation

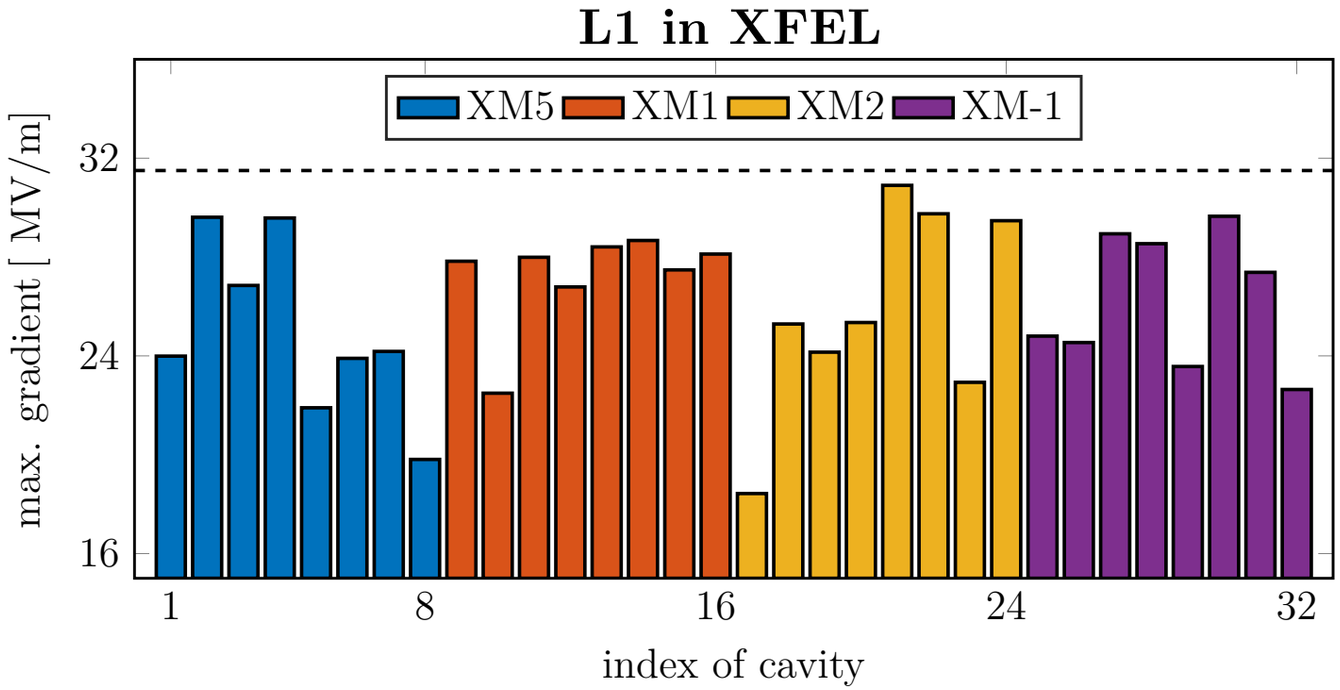
super conducting cavity operation



- **RF modules**
  - **pulsed operation**
    - less heat load
    - high gradients
    - Lorentz force detuning

motivation

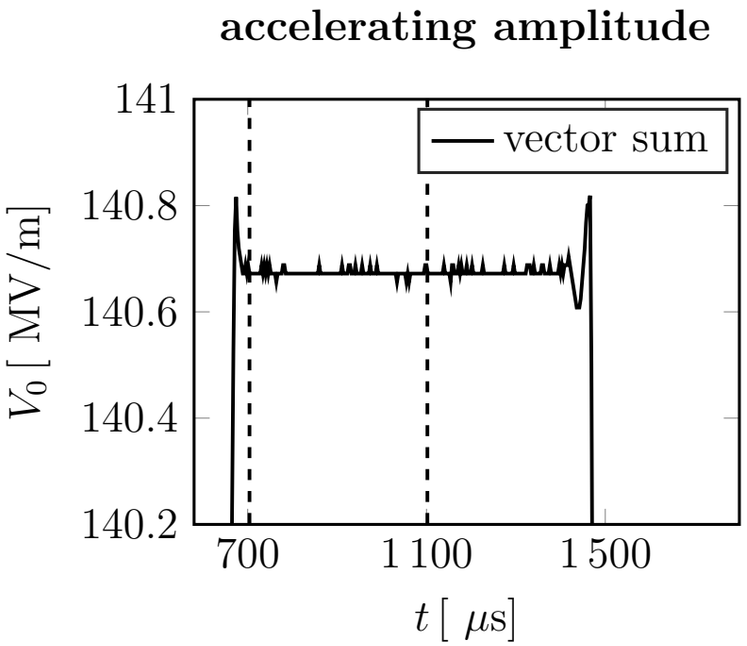
super conducting cavity operation

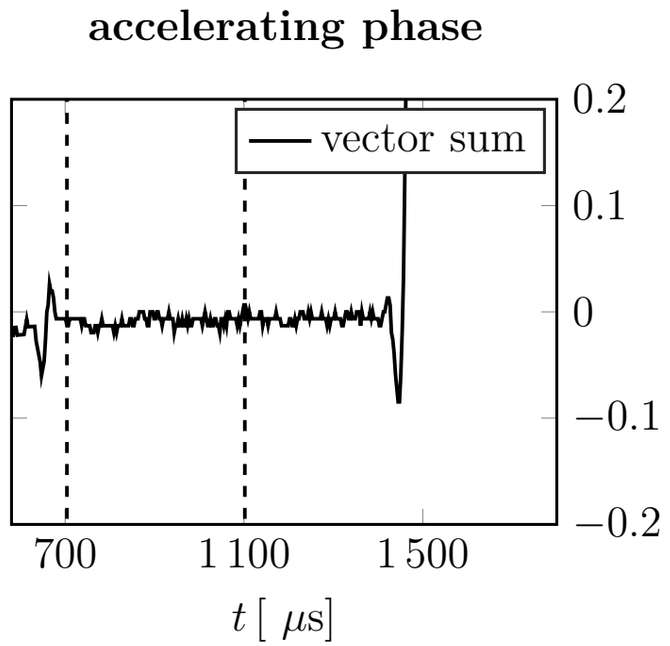


- **RF modules**
  - **pulsed operation**
  - **operational gradients**
    - Q_0
    - quench limits
    - radiation
    - RF power distribution
    - wave guide properties

motivation

super conducting cavity operation



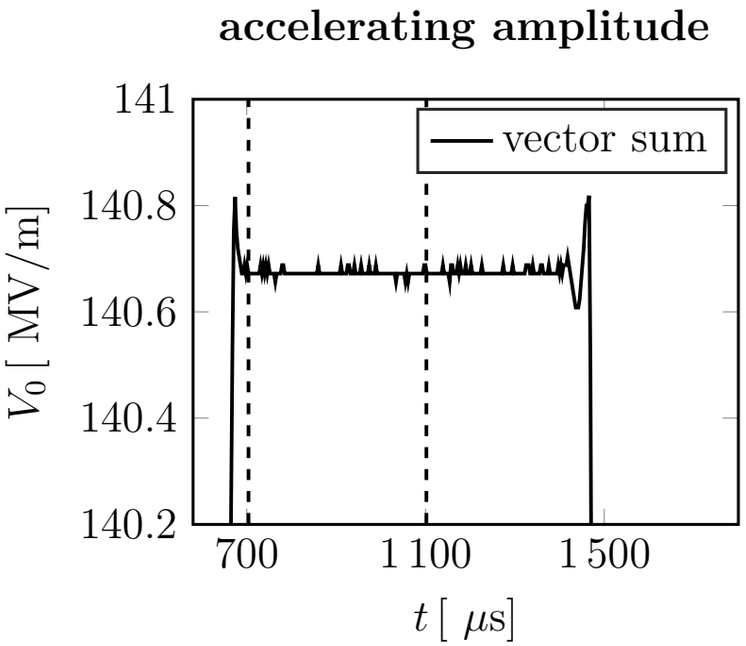


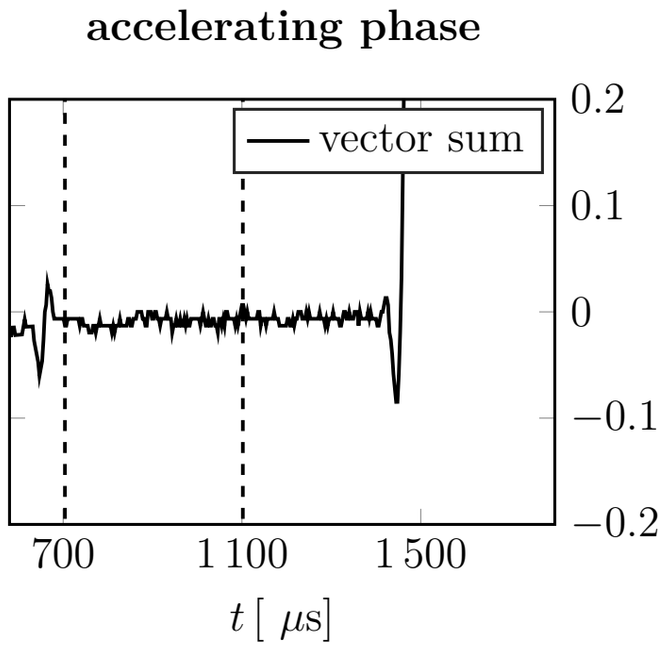
> RF modules

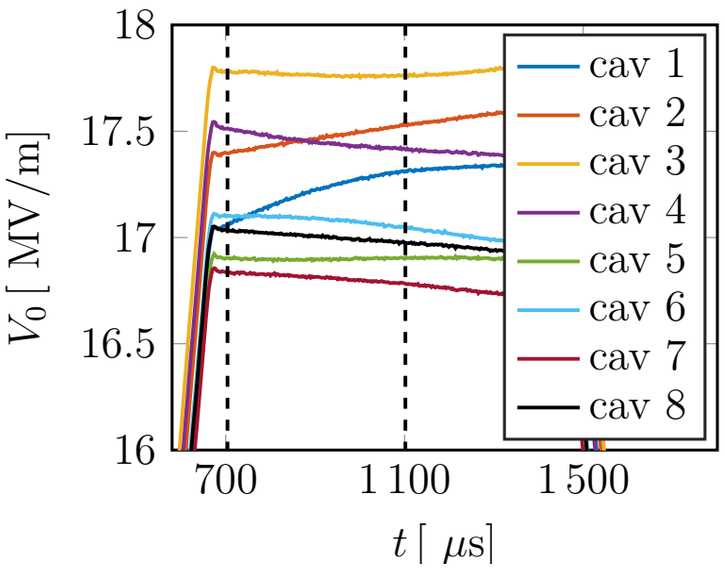
- **pulsed operation**
- **operational gradients**
- **LLRF**
  - vector sum control
  - $\delta V_0 < 3 \cdot 10^{-4}$
  - $\Delta\phi < 0.06\,^\circ$

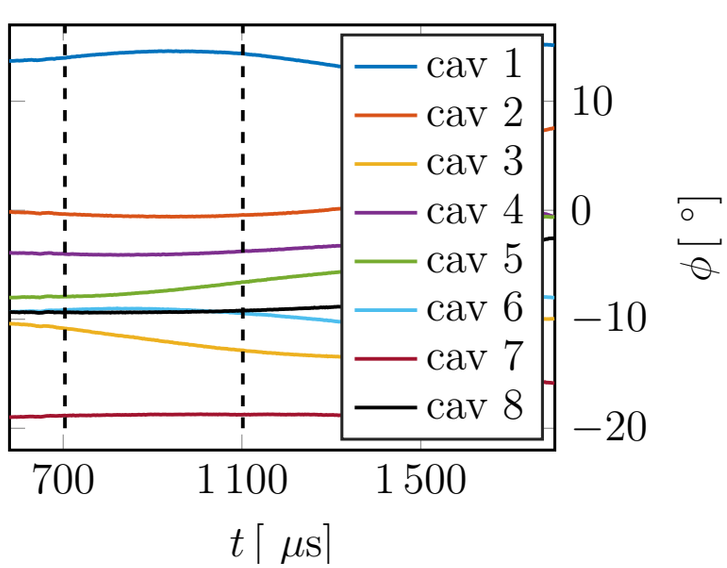
motivation

super conducting cavity operation





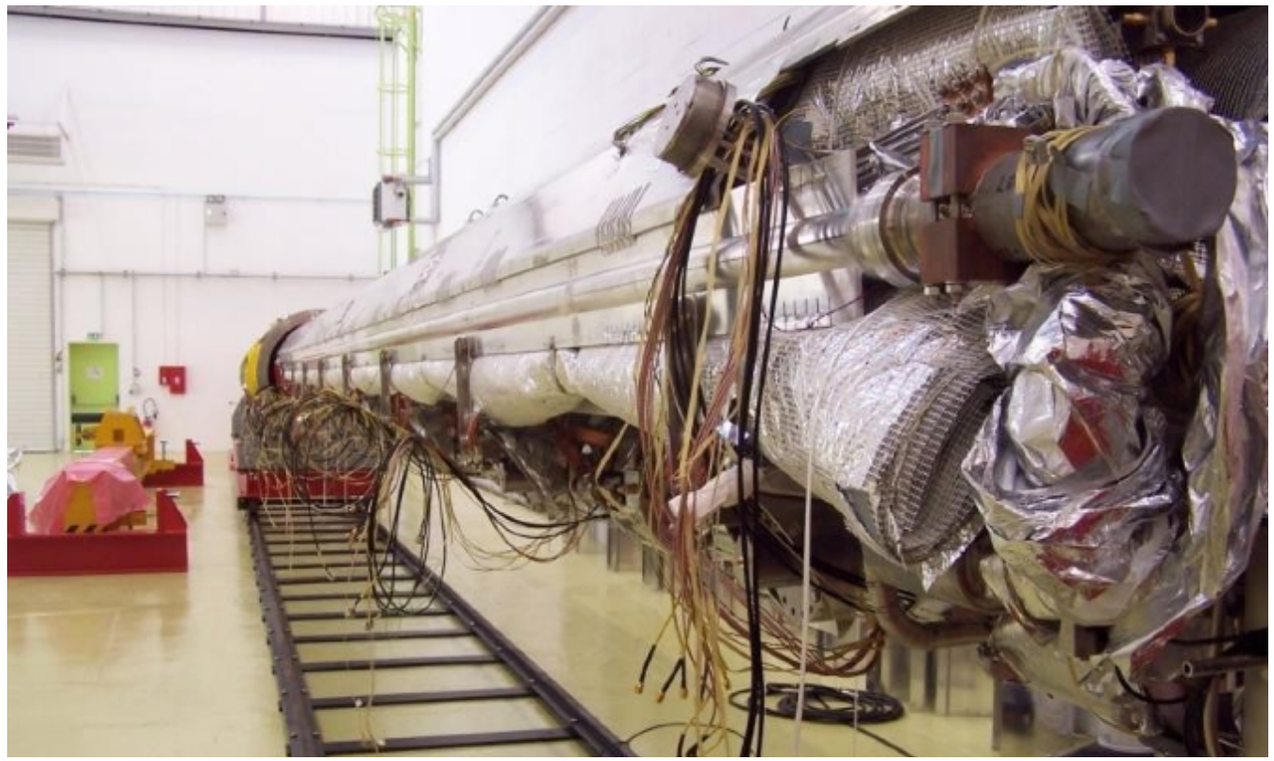




- **RF modules**
  - **pulsed operation**
  - **operational gradients**
  - **LLRF**
  - **gradient spread**
    - no automated Q_L correction

motivation

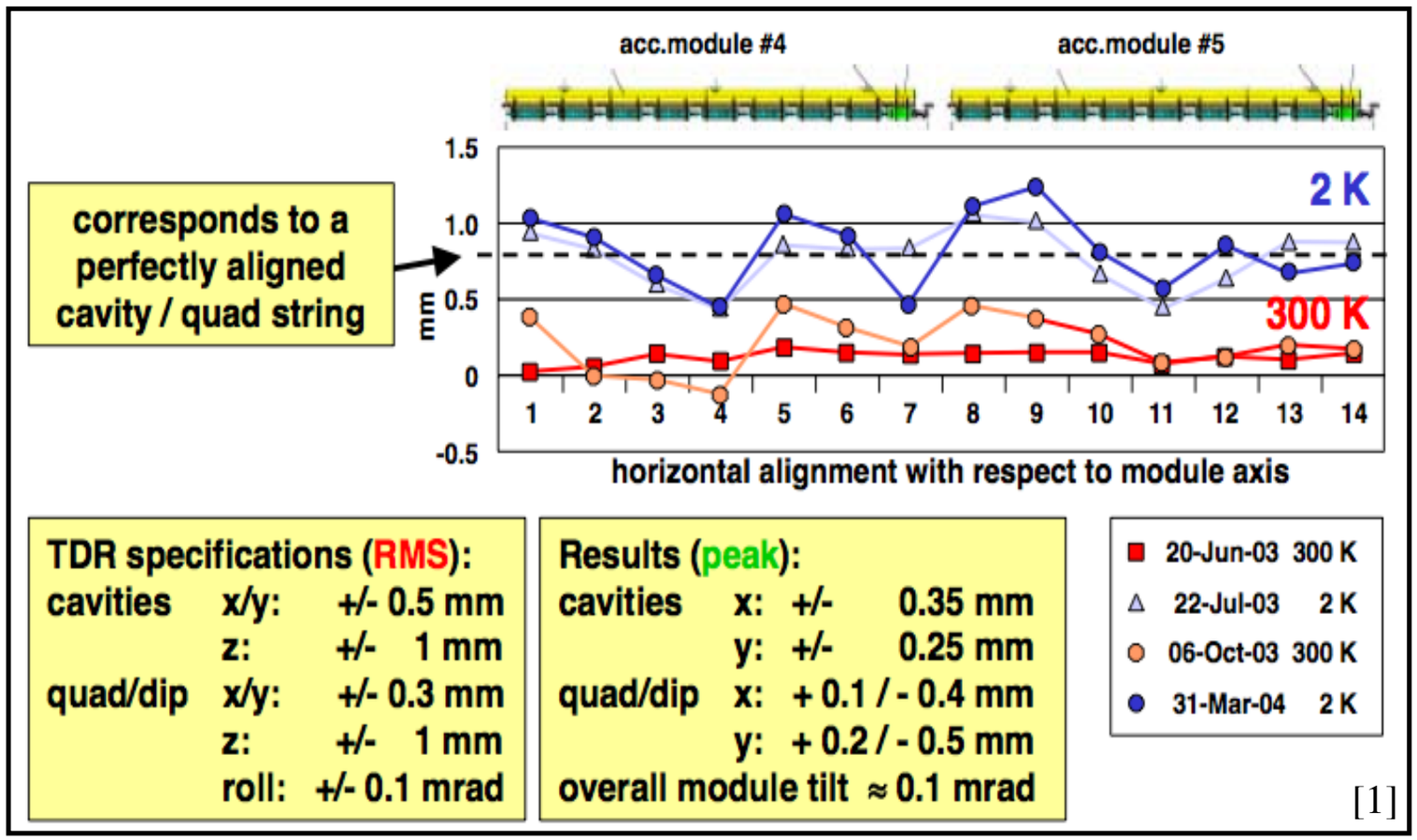
super conducting cavity operation



- **RF modules**
  - **pulsed operation**
  - **operational gradients**
  - **LLRF**
  - **gradient spread**
  - **cryogenic string**
    - 8 cavities within one module
    - thermal contraction

motivation

super conducting cavity operation



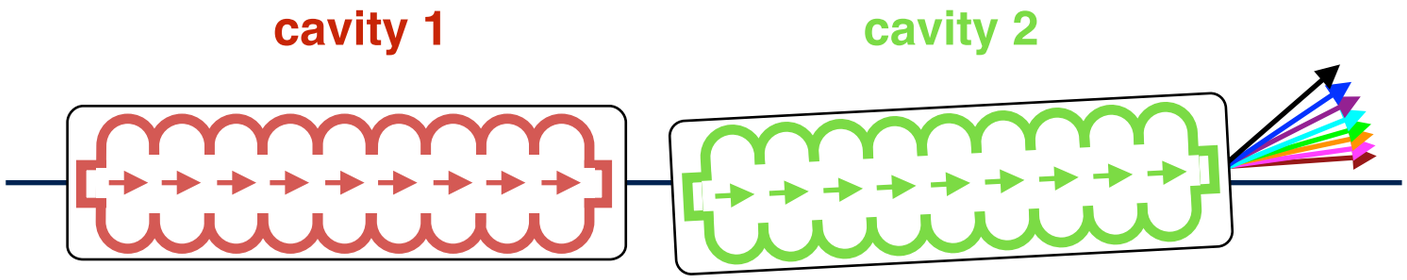
[1]

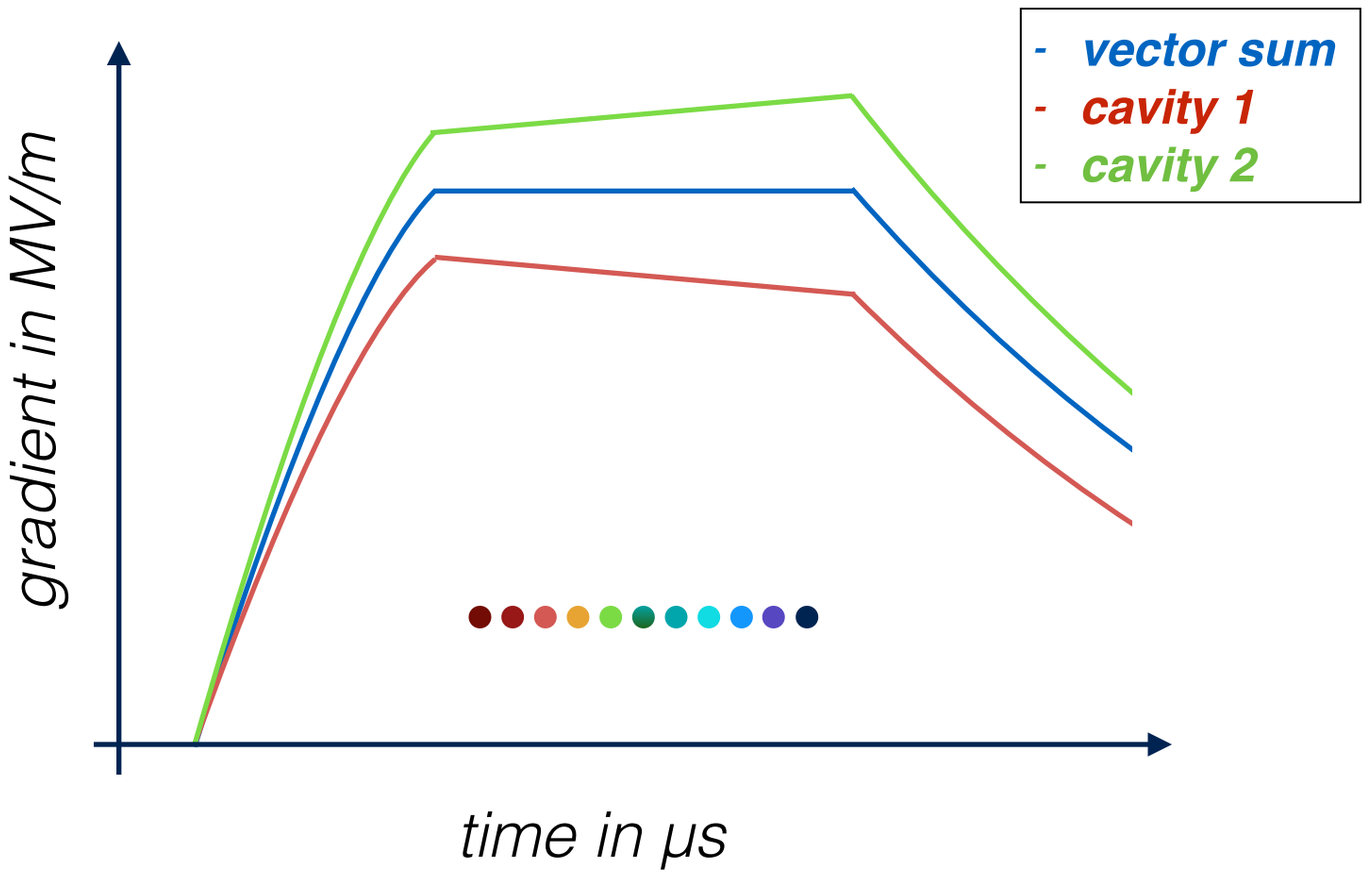
- **RF modules**
  - **pulsed operation**
  - **operational gradients**
  - **LLRF**
  - **gradient spread**
  - **cryogenic string**
  - **misalignments**
    - measurement till 2004
    - results within TDR limits
    - not reproducible

[1] https://labcit.ligo.caltech.edu/~BCBAct/PDF%20files/ITRP_Weise_TTF.pdf

motivation

super conducting cavity operation





- **RF modules**
  - **pulsed operation**
  - **operational gradients**
  - **LLRF**
  - **gradient spread**
  - **cryogenic string**
  - **misalignments**
  - **orbit spread**
    - variable RF parameters within bunch-train
    - off-axis fields

model development

- motivation
- **model development**
- simulation results

model development

set up a theoretical model for injector module:

- ***start-to-end tracking***[2]
  - \+ **accurate at low beam energy**
  - \- **slow** $\mathcal{O}(\mathrm{s})$
- ***analytic models***[3]
  - \+ **fast** $\mathcal{O}(\mathrm{ms})$
  - \- **ultra-relativistic assumptions**
- ***objective***
  - develop fast model
  - study RF-misalignment correlations

[2] K. Flöttmann. A space charge tracking algorithm - astra, 1997

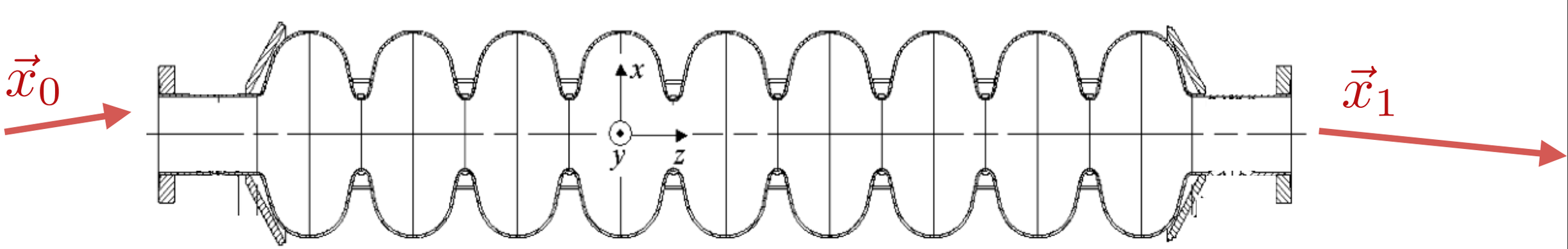
[3] J. Rosenzweig and L. Serafini, *Phys. Rev. E*,vol. 49,p. 1599, 1994

model development

set up a theoretical model for injector module:

- axial-symmetric cavity
- linear beam dynamics

$$\vec{x}_1 = M_{\mathrm{cav}} \cdot \vec{x}_0$$

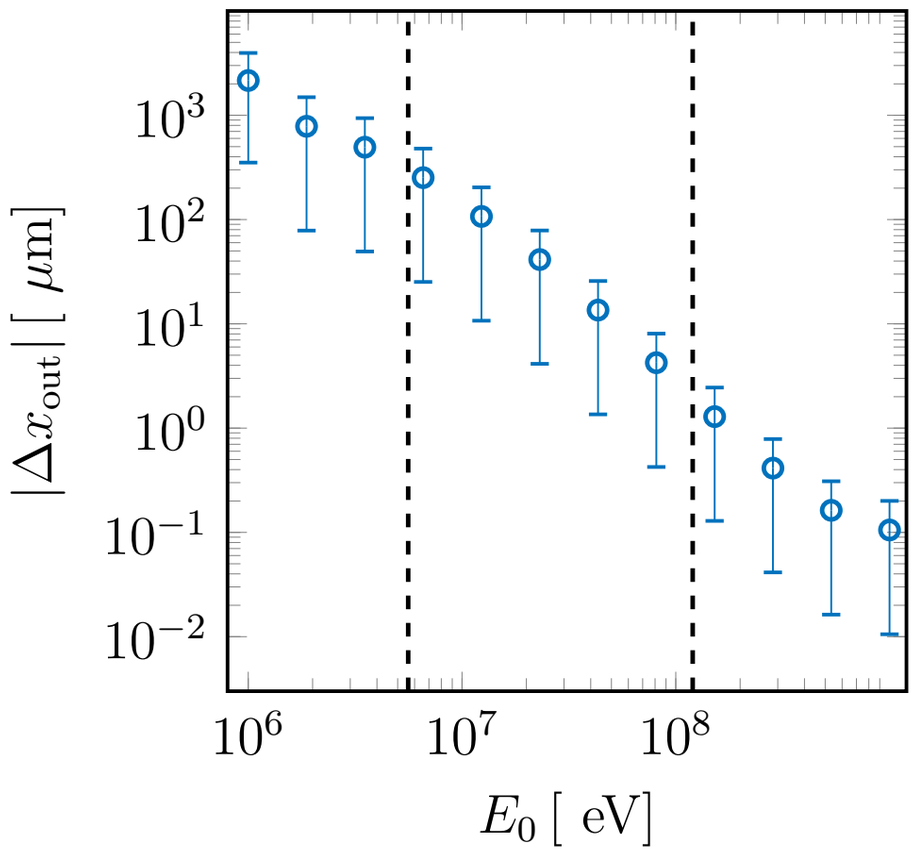


model development

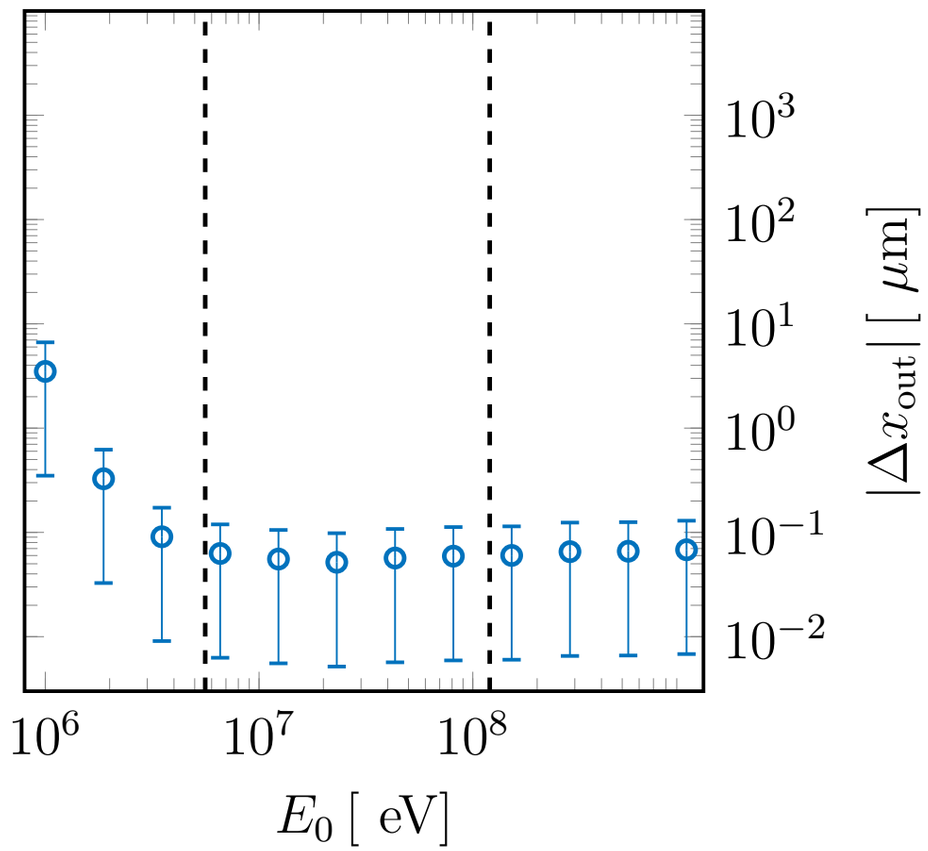
set up a theoretical model for injector module:

- axial-symmetric cavity
- numerical transfer matrix: *‚Runge-Kutta-tracking' & ‚least-squares-fit'*

ASTRA vs. analytic model[3]



ASTRA vs. numerical model



[3] J. Rosenzweig and L. Serafini, *Phys. Rev. E*,vol. 49,p. 1599, 1994

model development

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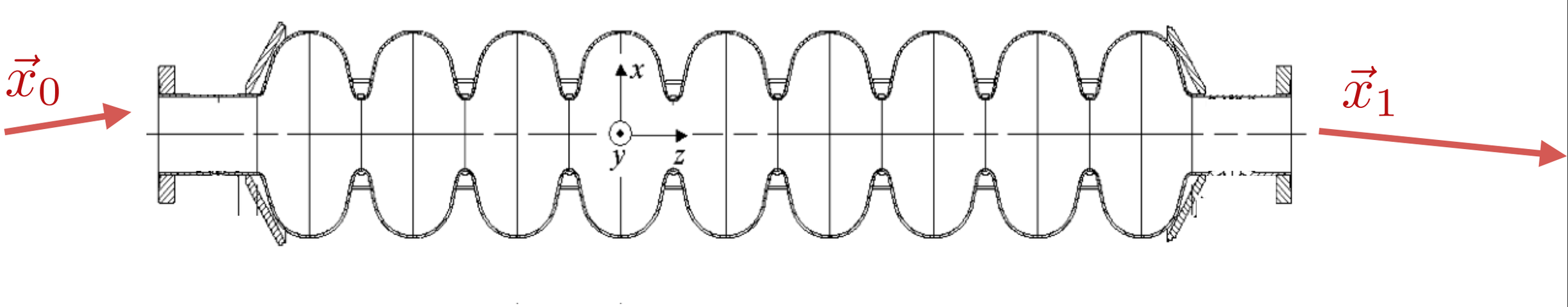
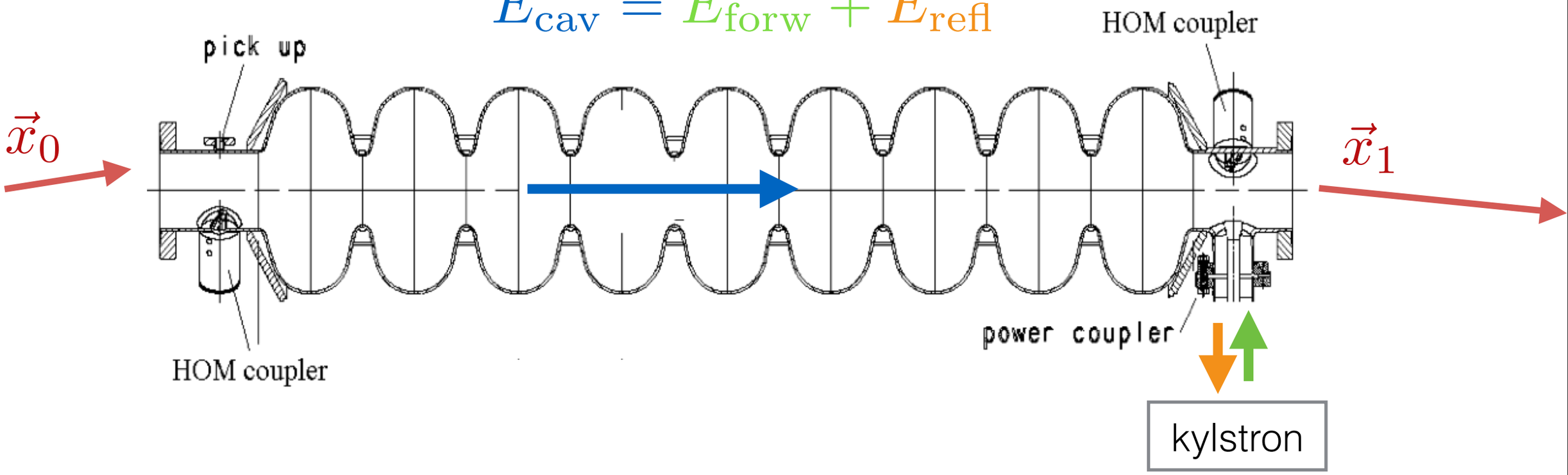


model development

set up a theoretical model for injector module:

- axial-symmetric cavity
- numerical transfer matrix
- coupler fields

$$\vec{E}_{\mathrm{cav}} = \vec{E}_{\mathrm{forw}} + \vec{E}_{\mathrm{refl}}$$



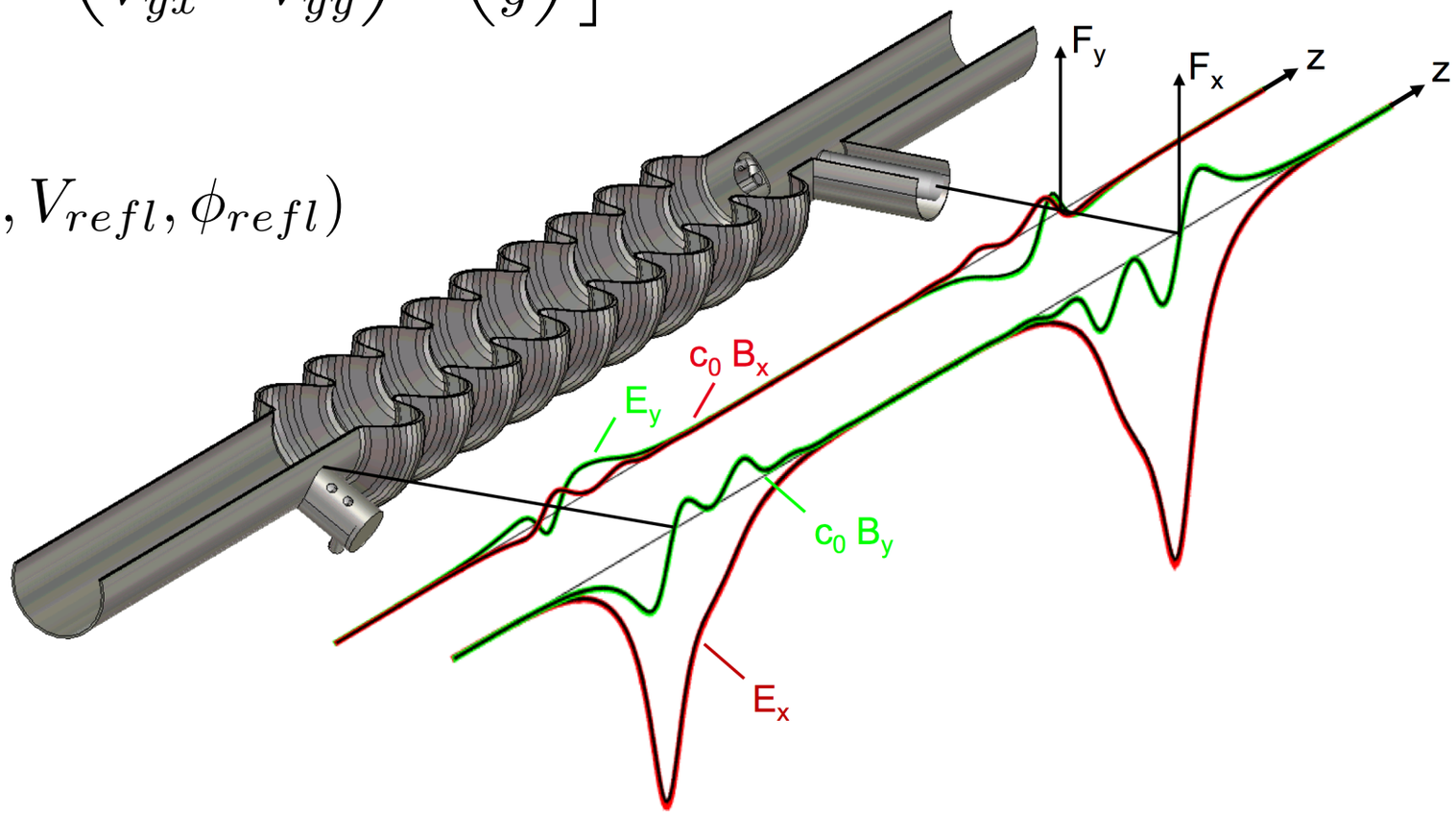
model development

set up a theoretical model for injector module:

- axial-symmetric cavity
- numerical transfer matrix
- discrete coupler kicks[4]

$$\vec{k}(x,y) = \frac{\Delta E}{E_0} \cdot \left[\begin{pmatrix} V_{0x} \\ V_{0y} \end{pmatrix} + \begin{pmatrix} V_{xx} & V_{xy} \\ V_{yx} & V_{yy} \end{pmatrix} \cdot \begin{pmatrix} x \\ y \end{pmatrix} \right]$$

- 3D field map[5]
- $V_{ij} = f(E_0, V_{forw}, \phi_{forw}, V_{refl}, \phi_{refl})$



[4] M. Dohlus et al, “Coupler kick for very short bunches and its compensation,” in *Proc. EPAC’08*

[5] W. Ackermann and T. Weiland, “High precision cavity simulations,” in *Proc. ICAP’02*, Jul. 2004

model development

set up a theoretical model for injector module:

- axial-symmetric cavity
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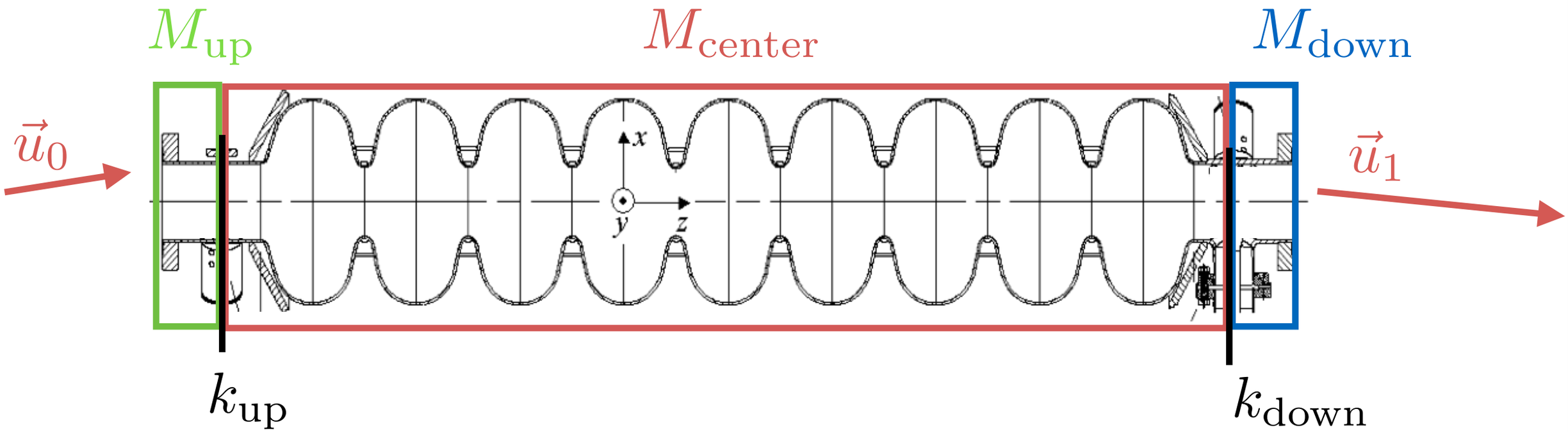
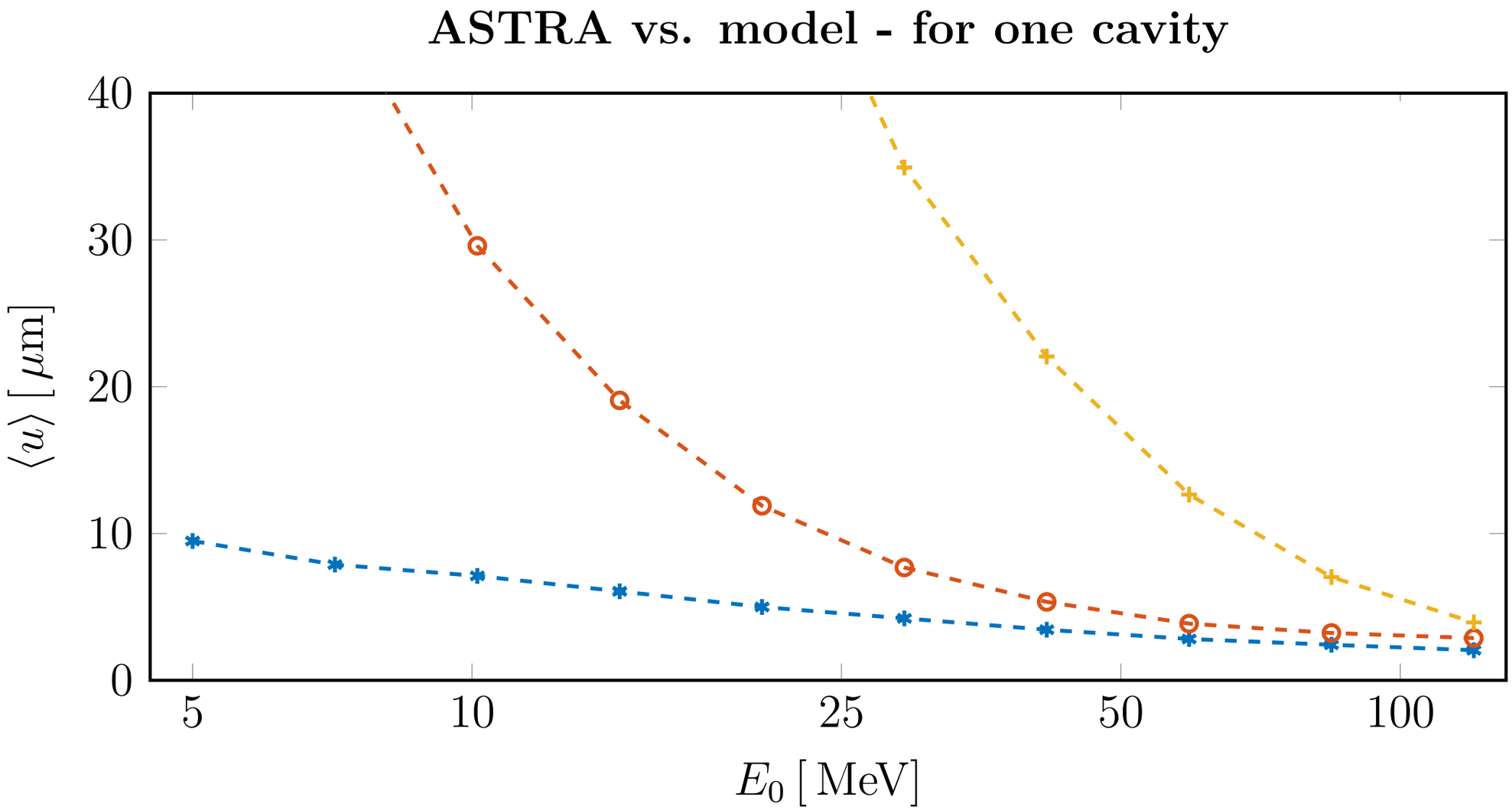


$$M_n = f(E_0, V_0, \phi_0)$$

$$k_n = f(E_0, V_{forw}, \phi_{forw}, V_{refl}, \phi_{refl})$$

error after injector module

- analytical matrix & ultra-relativistic coupler kicks $\approx 3\,\mathrm{mm}$
- numerical matrix & ultra-relativistic coupler kicks $\approx 1.3\,\mathrm{mm}$
- numerical matrix & low energy coupler kicks $\approx 50\,\mu\mathrm{m}$



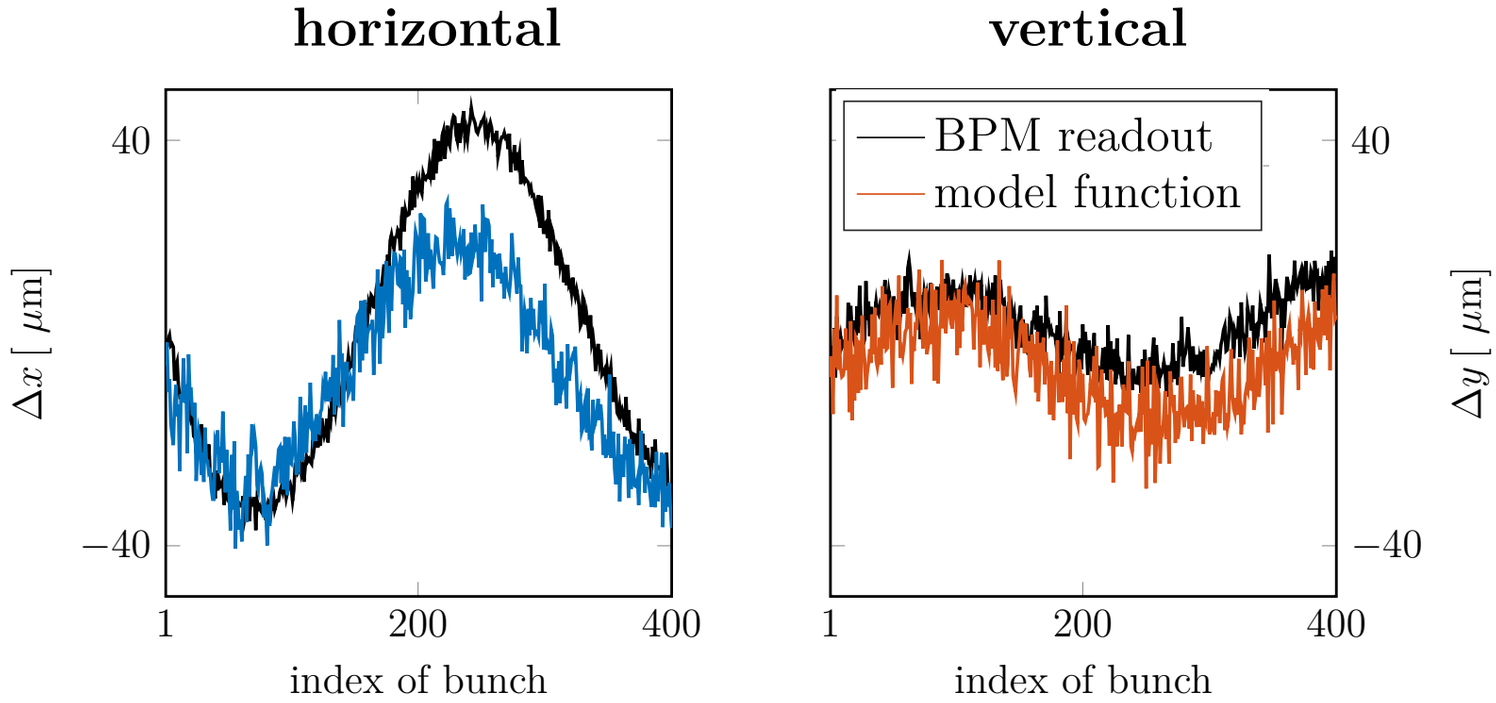
model validation

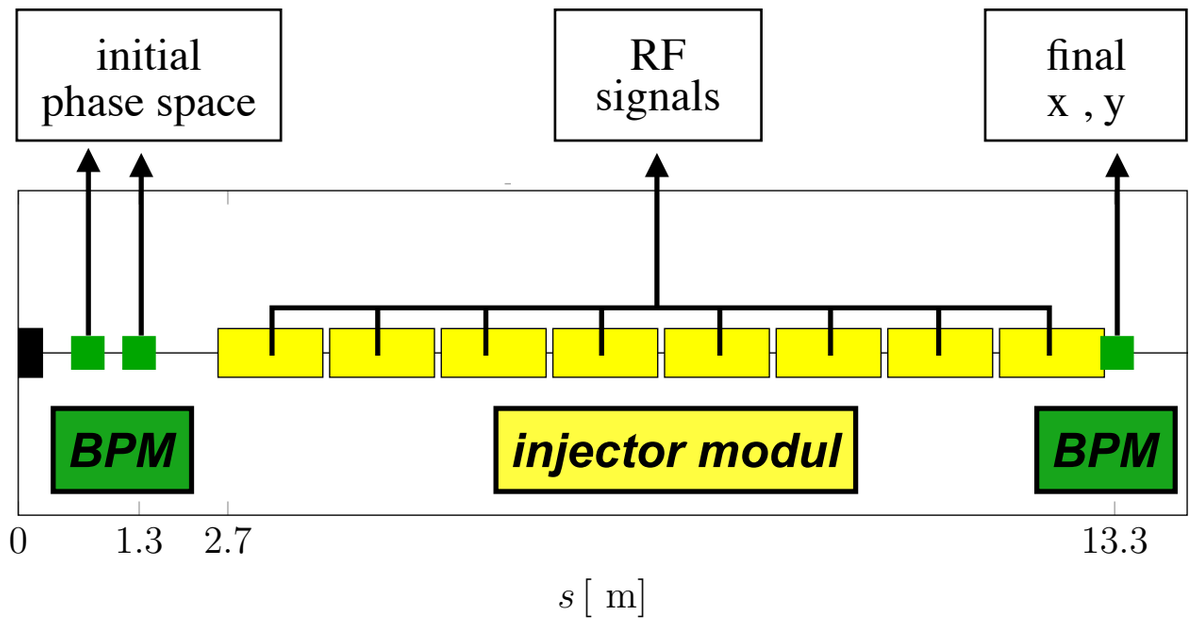
experimental

experimental setup

- 400 bunches
- read RF- and BPM-values
- apply slow modulation on RF
- response to fundamental mode

> ***satisfactory agreement***



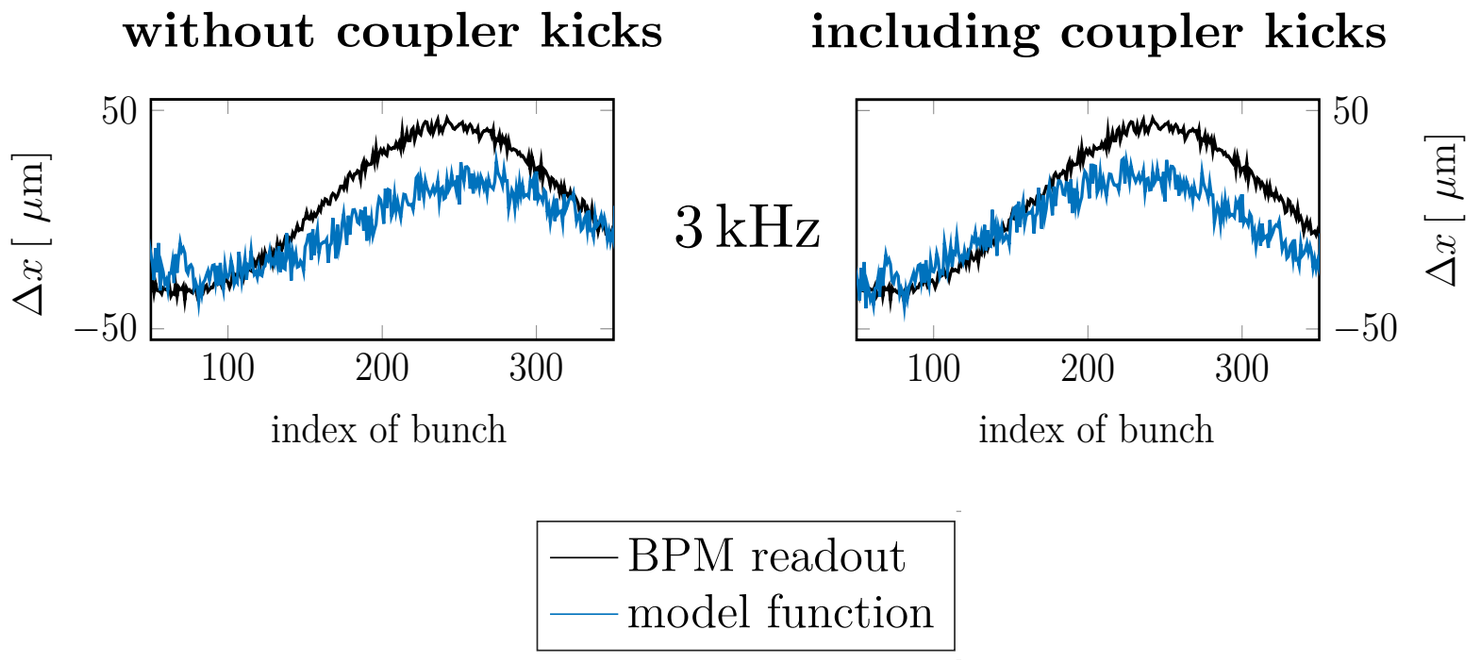


model validation

experimental

experimental setup

- increase RF modulation frequency
- limited cavity bandwidth
- higher reflected power
- response to coupler kicks



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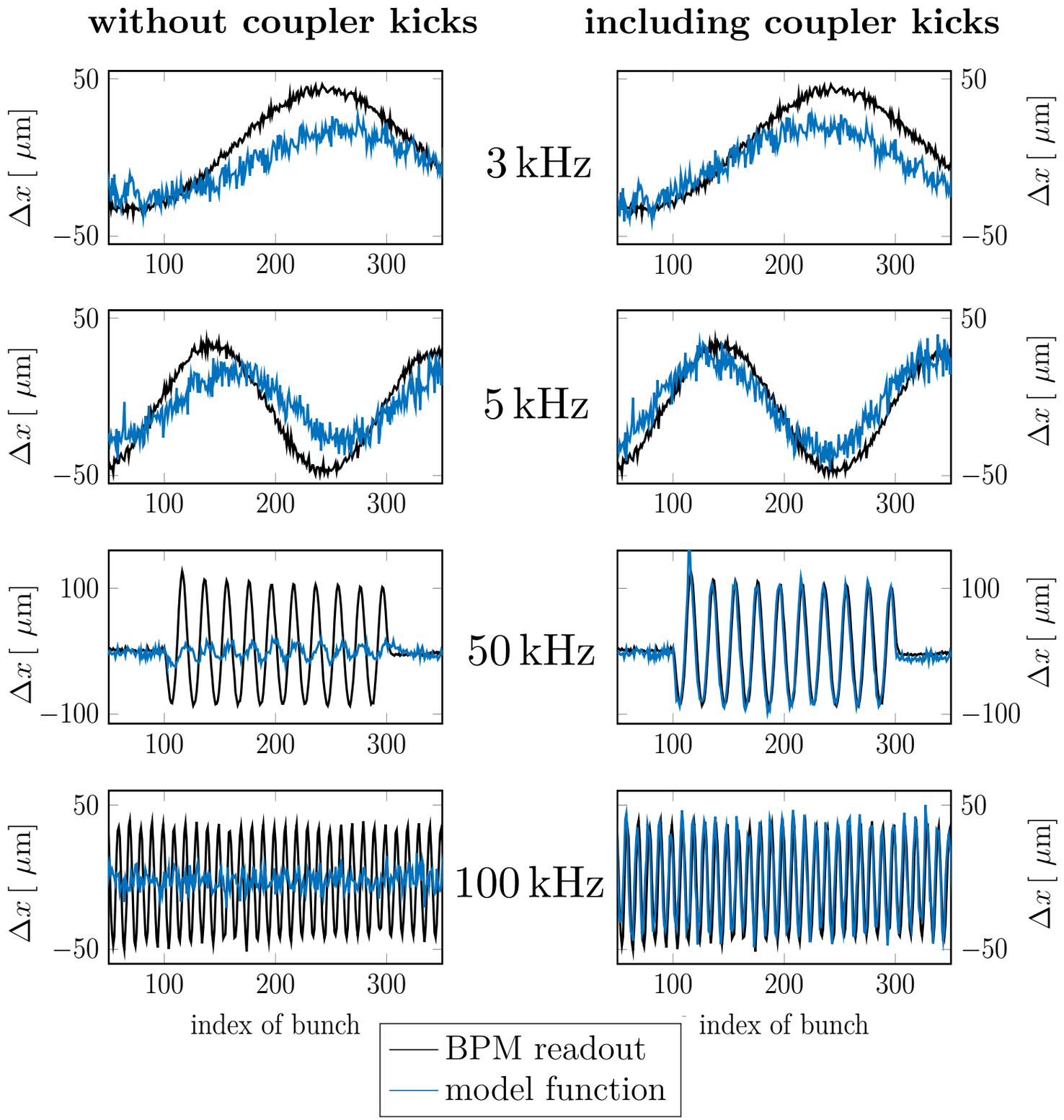


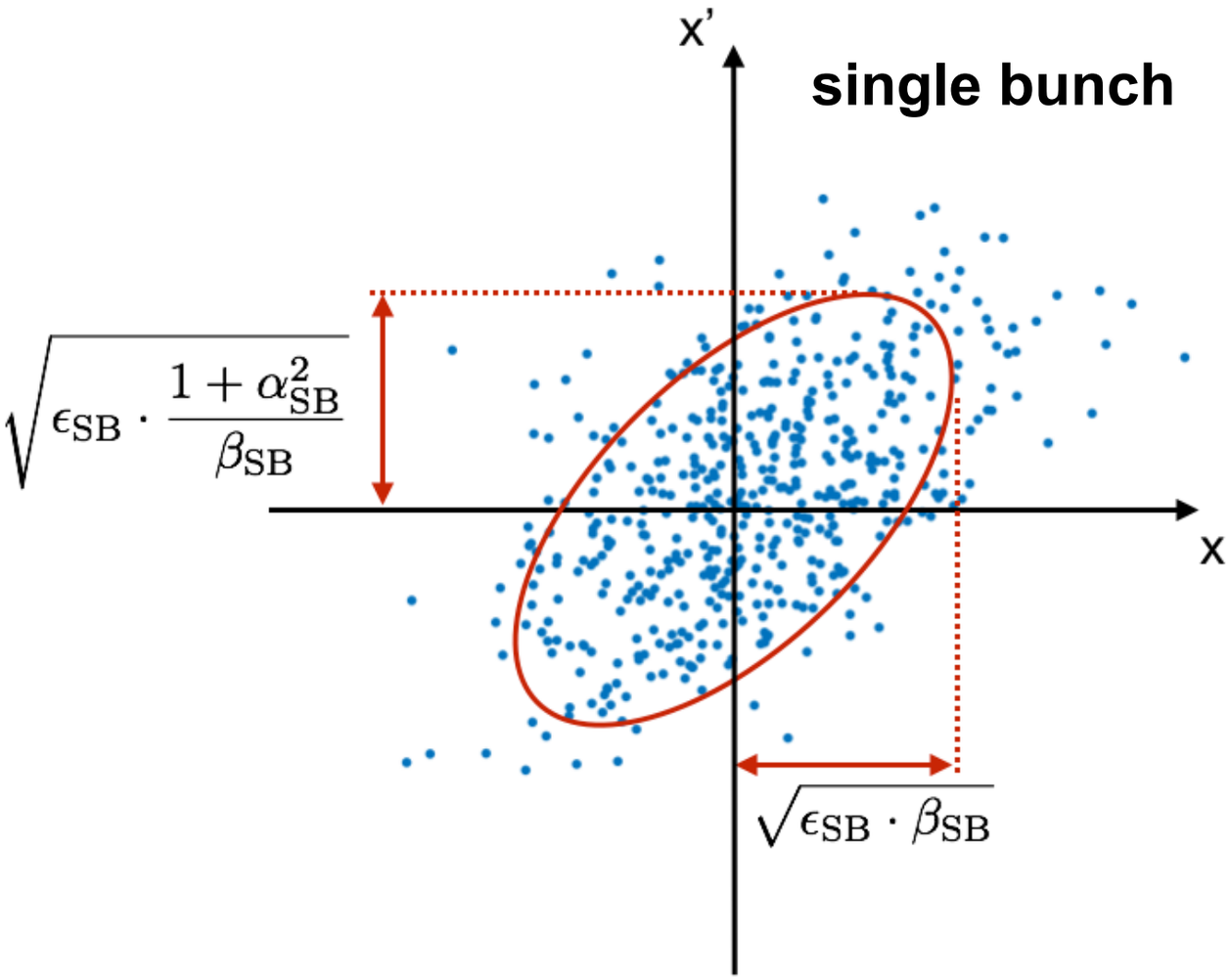
simulation

- motivation
- model development
- **simulation results**

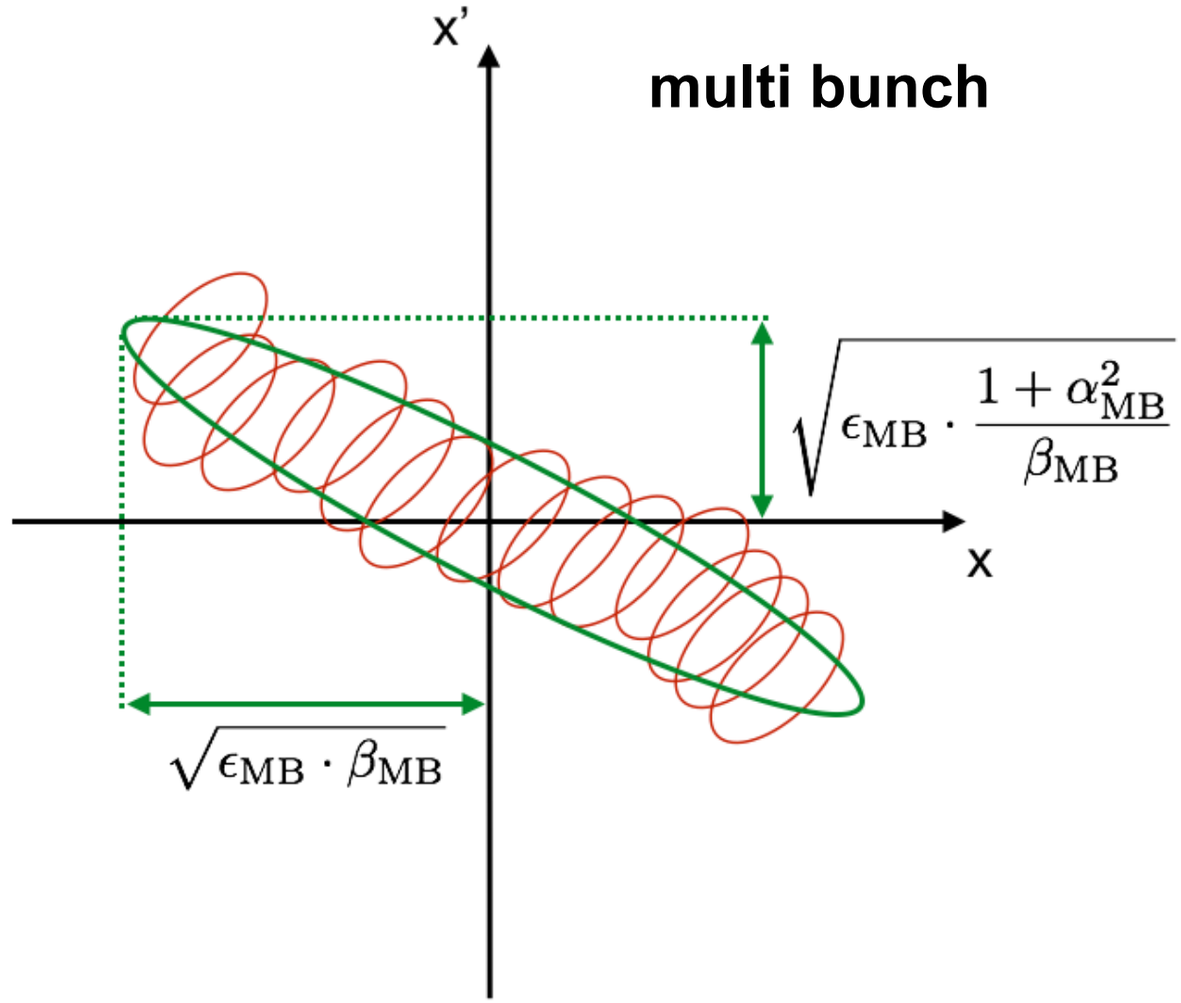
Simulation results

simulation setup

- figure of merit: $\tau = \dfrac{\epsilon_{SB}}{\epsilon_{MB}}$



single bunch

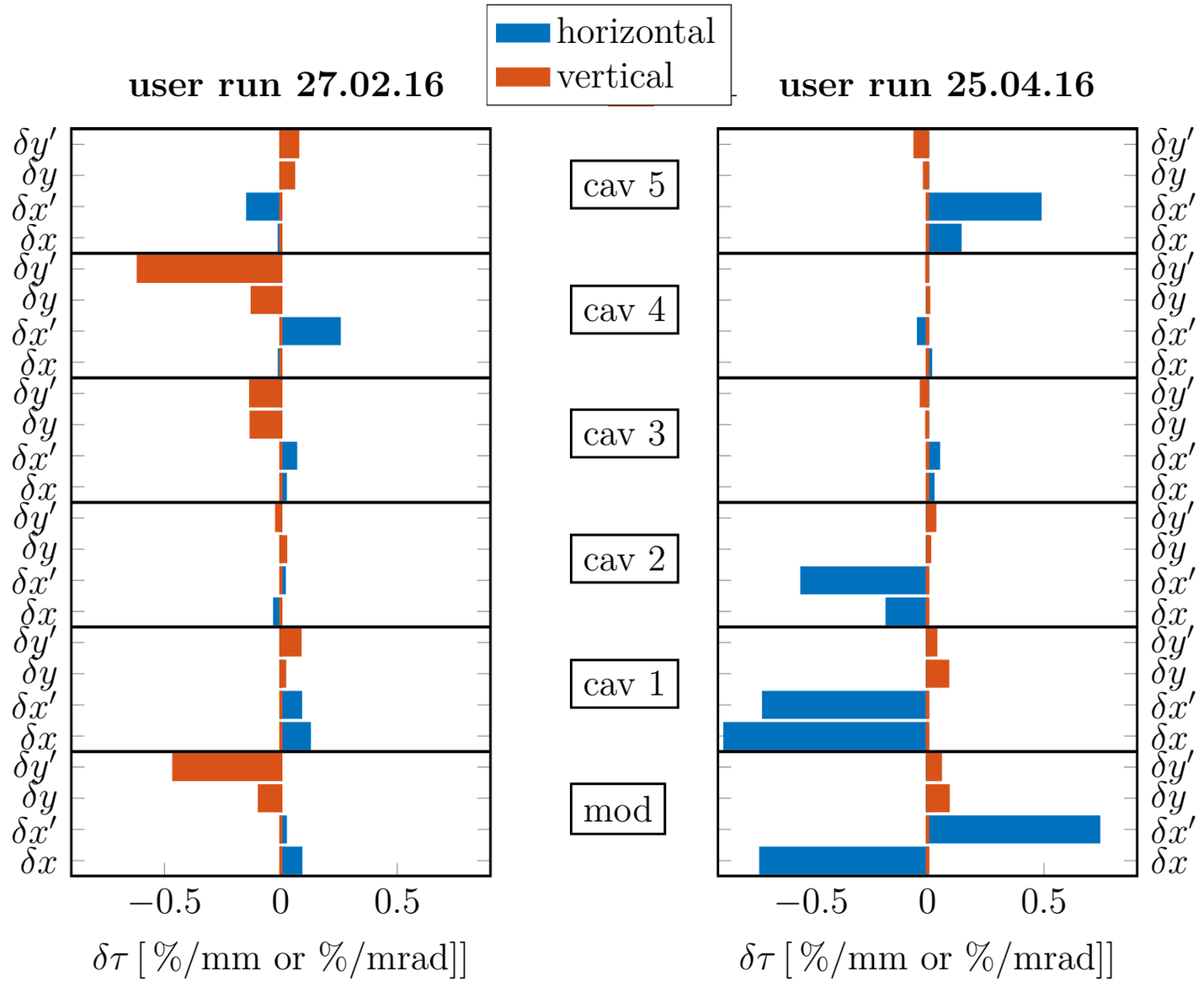


multi bunch

Simulation results

simulation setup

- figure of merit: $\tau = \dfrac{\epsilon_{SB}}{\epsilon_{MB}}$
- ***first order effect of misalignments?***
- RF- and beam parameters from 2 user runs (400 b.)
- model misalignments
- effect depends on complex interactions
- ***statistical approach needed***



Simulation results

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- ***first order effect of misalignments?***
- RF- and beam parameters from 2 user runs (400 b.)
- model misalignments
- effect depends on complex interactions
- ***statistical approach needed***
- define parameter space
- run model $\mathcal{O}(10^6)$
- find tool for multi-dimensional investigation
- ***regional sensitivity analysis***[6]

parameter range for the injector module

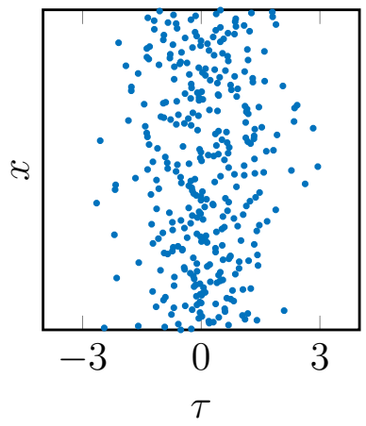
parameter	*value*	*description*
n_{bunch}	400	number of bunches per bunch-train
$\overline{V_0}$	155 MV	vector sum amplitude
$\overline{\phi_0}$	0 °	vector sum phase
ΔV_0	2 MV/m	max. variation of cavity gradients
$\Delta\phi_0$	4 °	max. variation of cavity phases
Δf	100 Hz	max. variation of cavity detuning
σ_{cav}	0.5 mm	max. offset of cavities
σ'_{cav}	0.5 mrad	max. tilt of cavities
σ_{mod}	5 mm	max. offset of module
σ'_{mod}	0.5 mrad	max. tilt of module

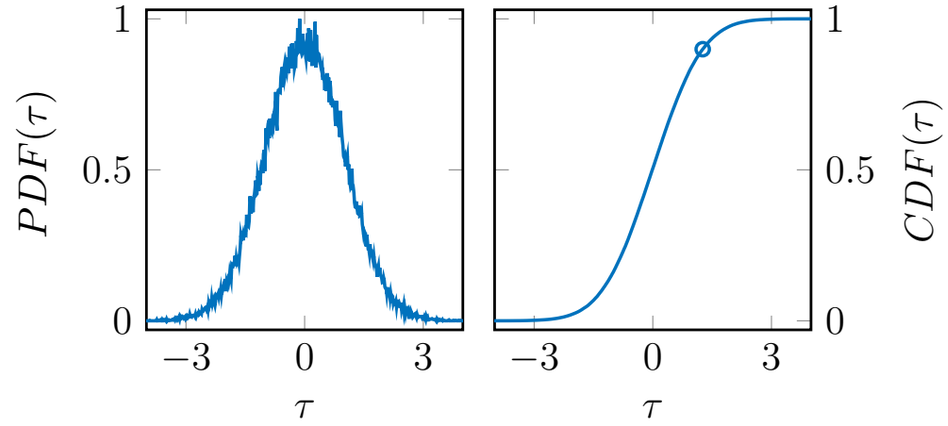
[6] A. Saltelli, *Global sensitivity analysis: the primer*. John Wiley, 2008

Simulation results

data evaluation

- figure of merit: $\tau = \dfrac{\epsilon_{SB}}{\epsilon_{MB}}$
- calculate $\tau(x, y, ...)$
- ***cumulative distribution function (CDF)***
- CDF(τ_c) = 0.9





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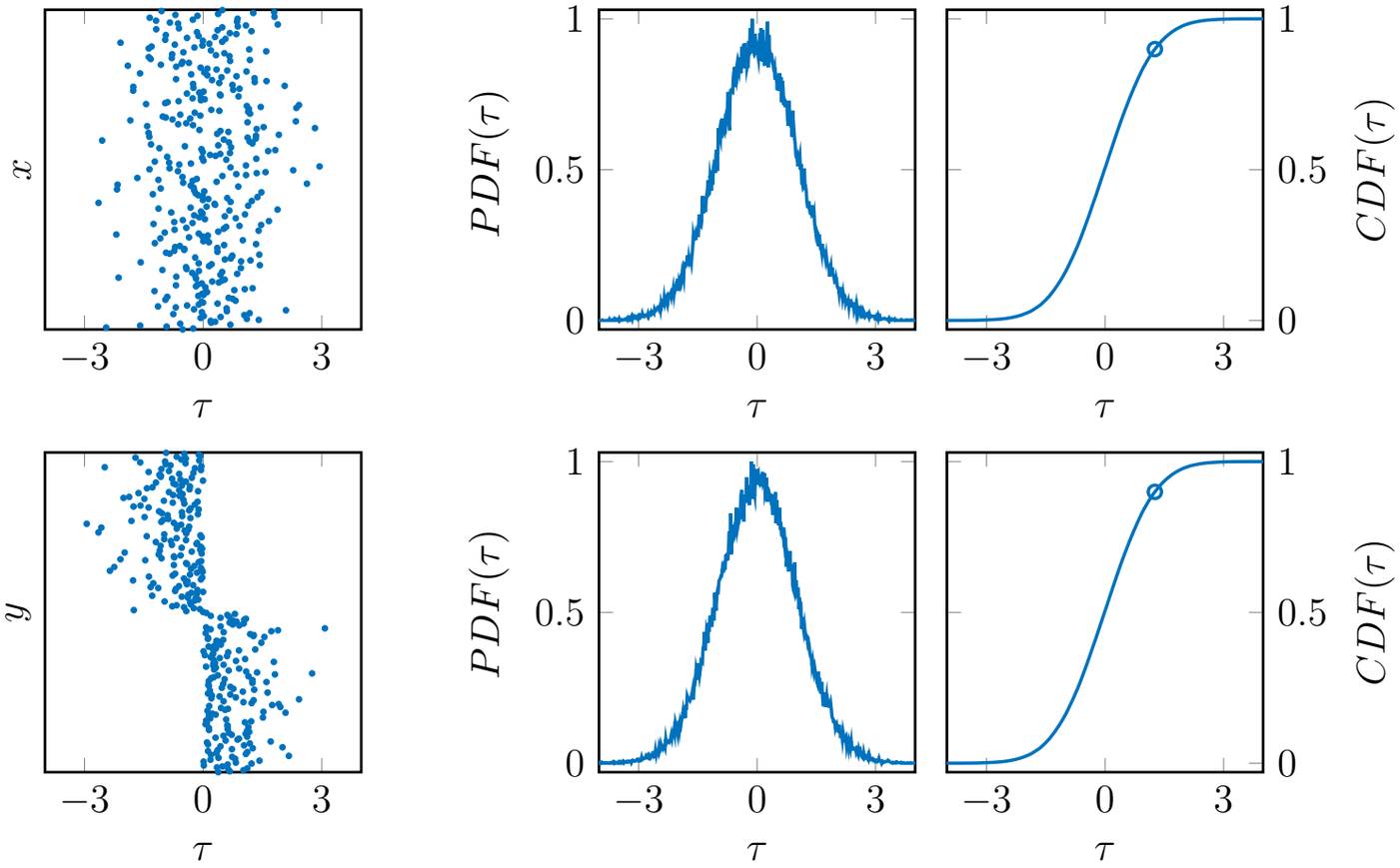

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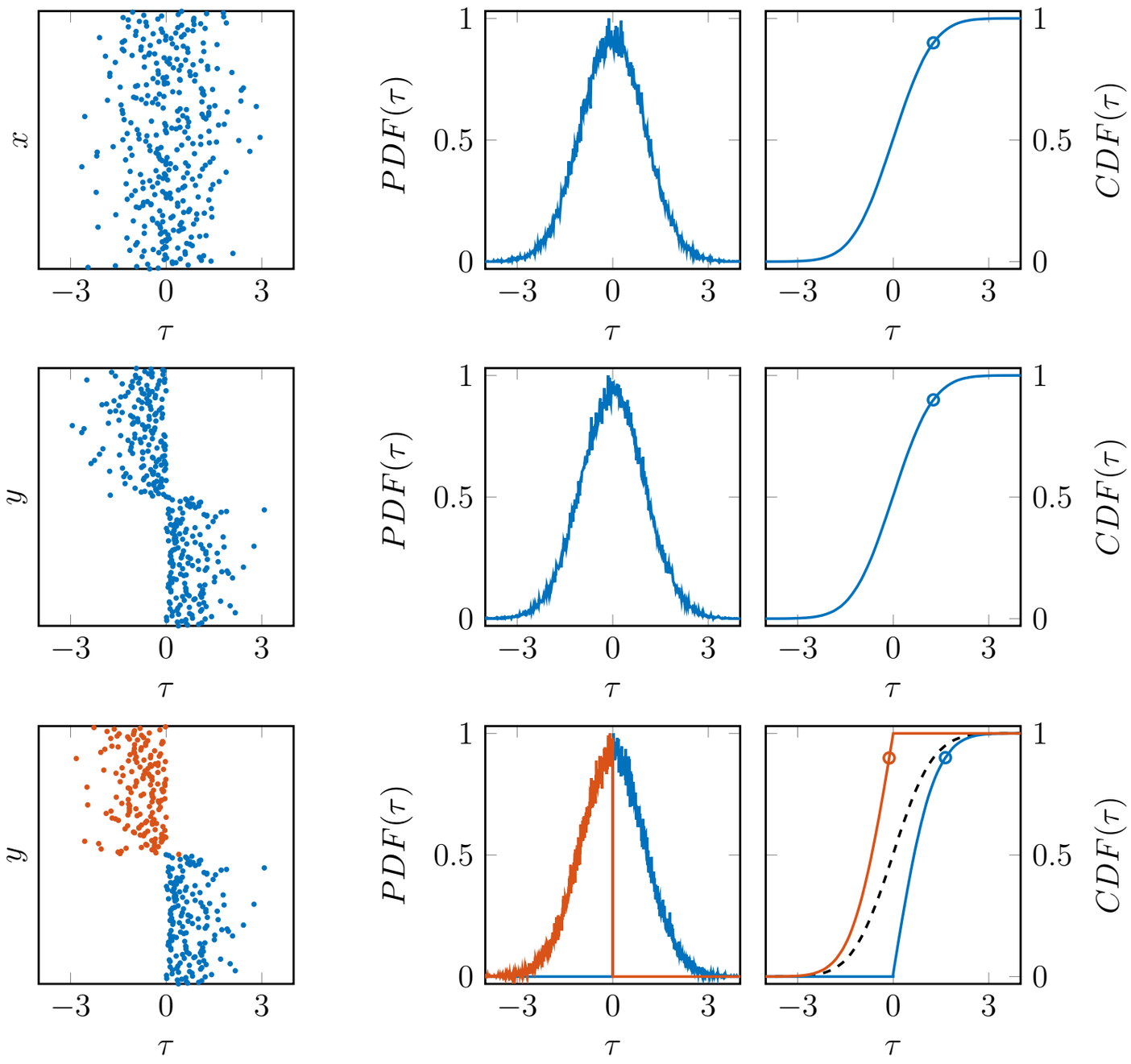
- *sort* τ *by* y
- get conditional CDF
- analyse $\tau_c(y)$
- first order sensitivity analysis
- ***find influential parameters***



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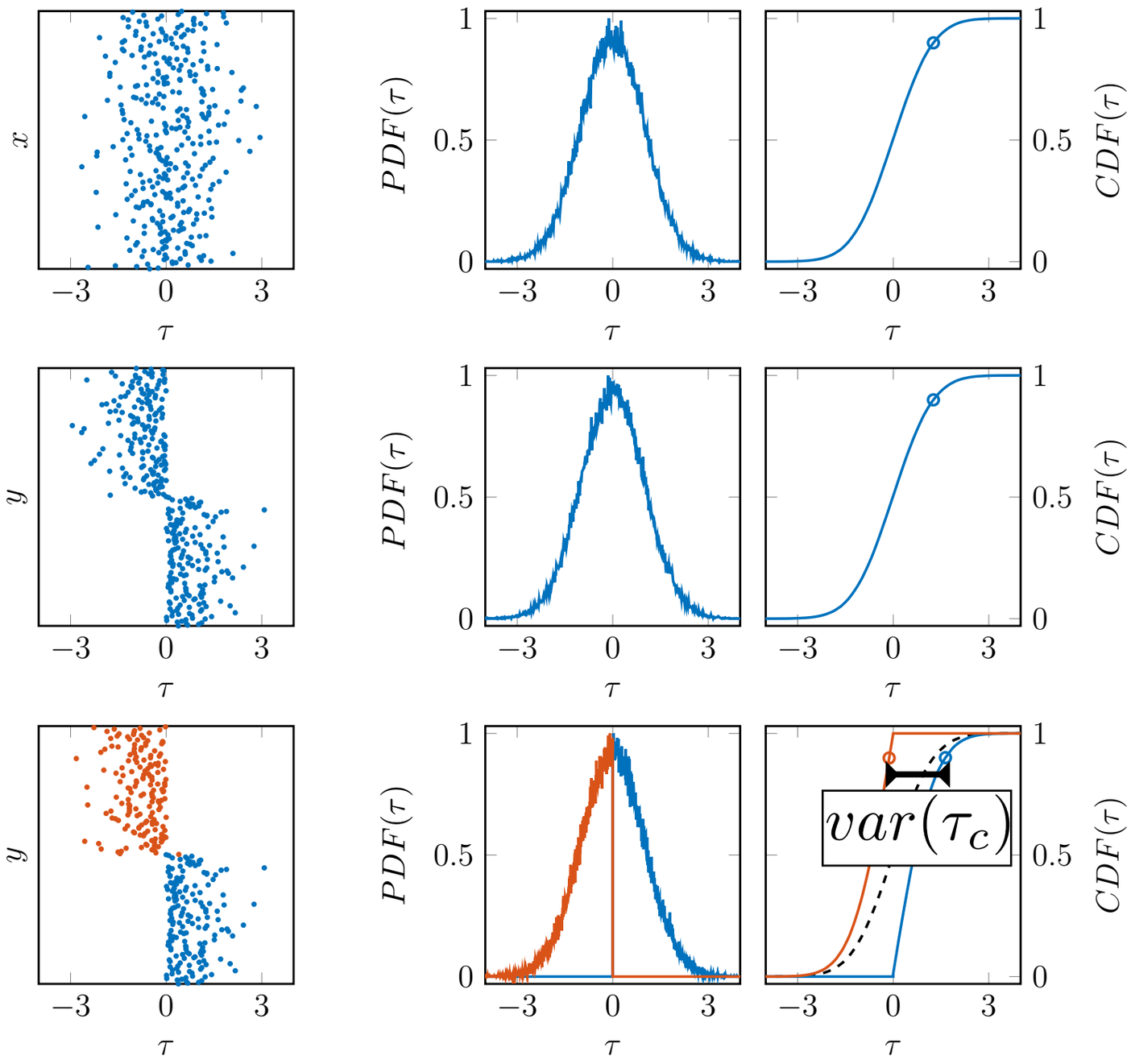
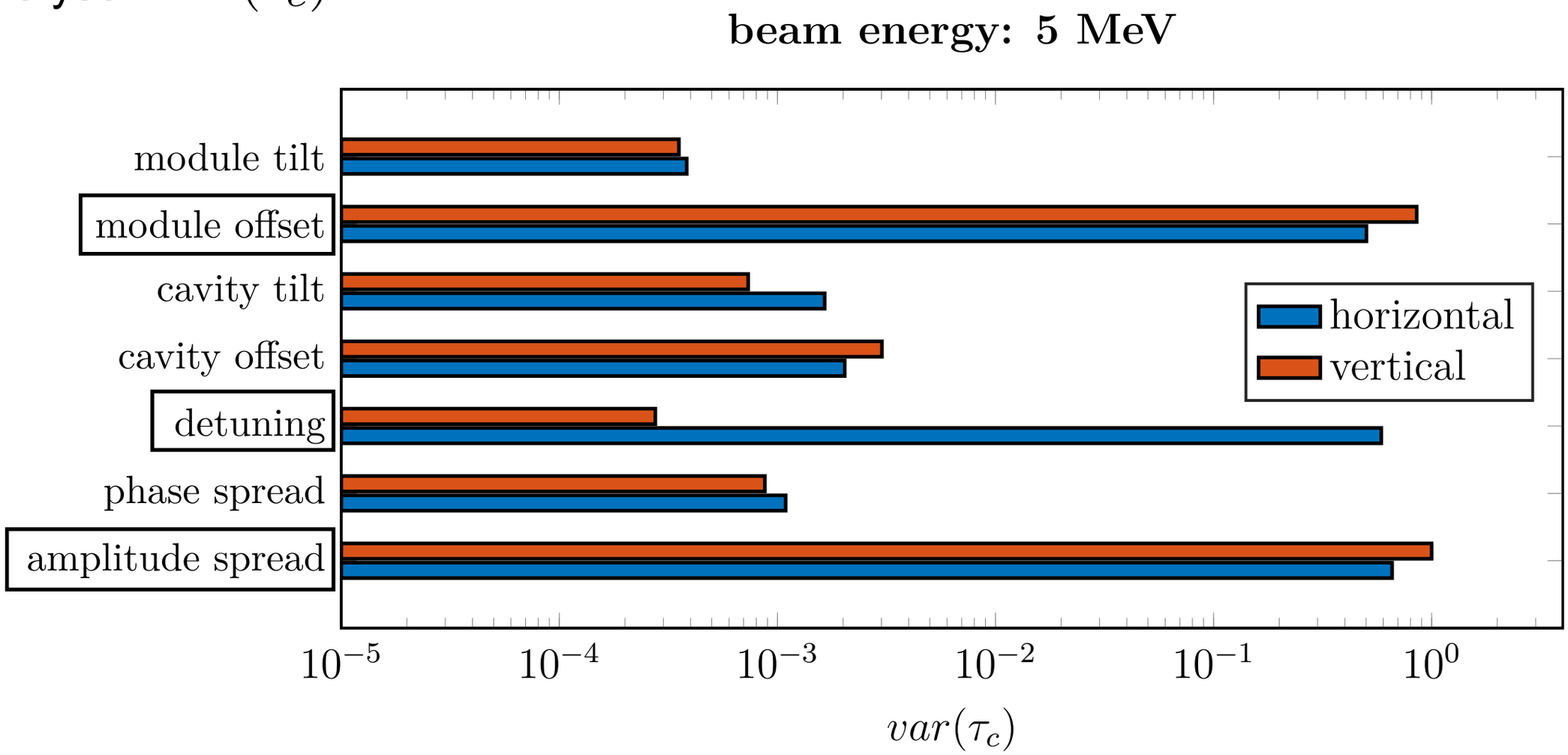


Simulation results

data evaluation

- figure of merit: $\tau = \dfrac{\epsilon_{SB}}{\epsilon_{MB}}$
- analyse $var(\tau_c)$



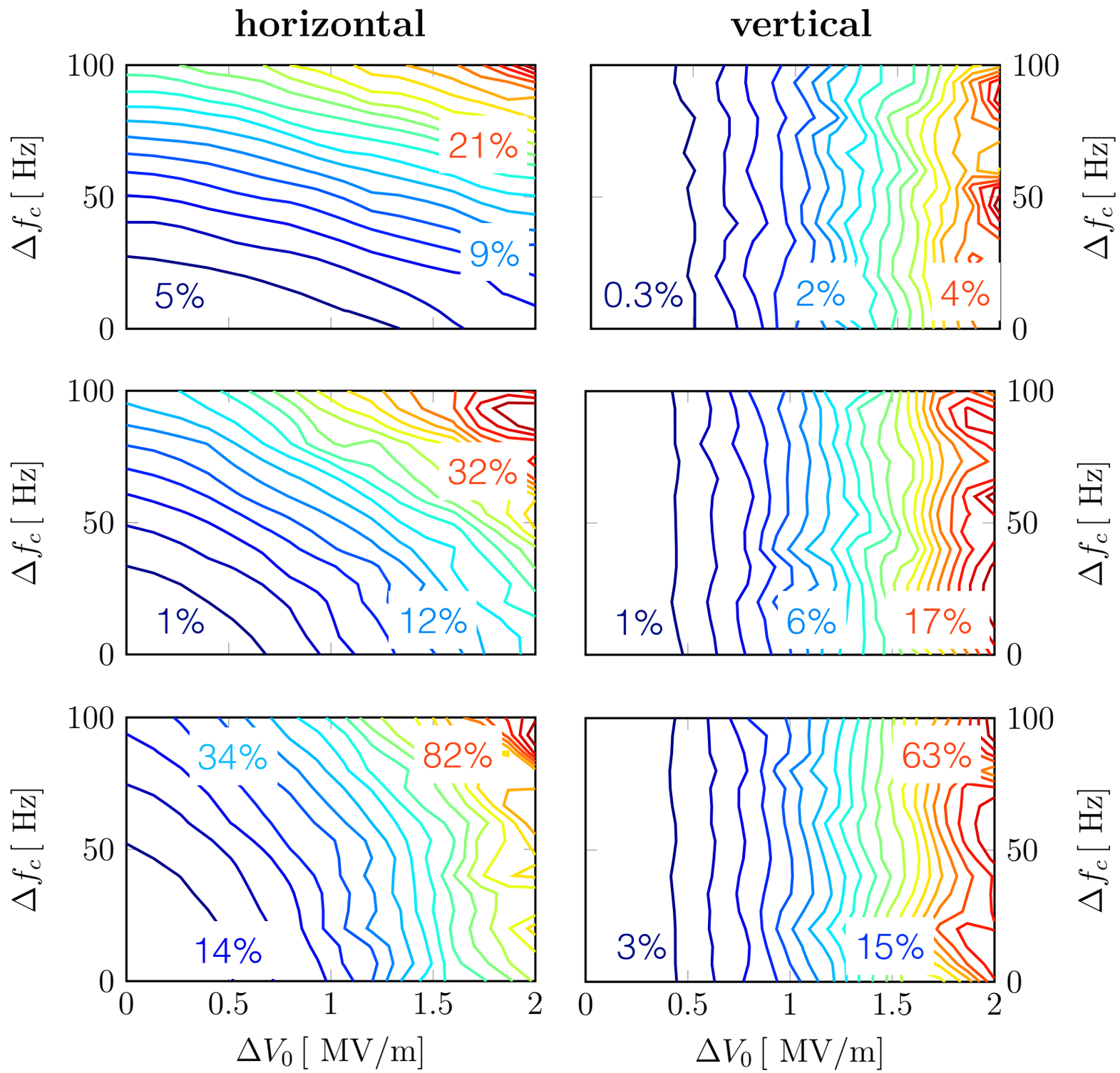
Simulation results

injector module

data evaluation

- figure of merit: $\tau = \dfrac{\epsilon_{SB}}{\epsilon_{MB}}$
- $\tau_c(\Delta V_0, \Delta f, \sigma_{\mathrm{mod}})$
- find relations
- study sensitivity
- ***guidance for engineering***

top:	$\sigma_{\mathrm{mod}} = 0\,\mathrm{mm}$
mid:	$\sigma_{\mathrm{mod}} = 2\,\mathrm{mm}$
bottom:	$\sigma_{\mathrm{mod}} = 4\,\mathrm{mm}$



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- find relations
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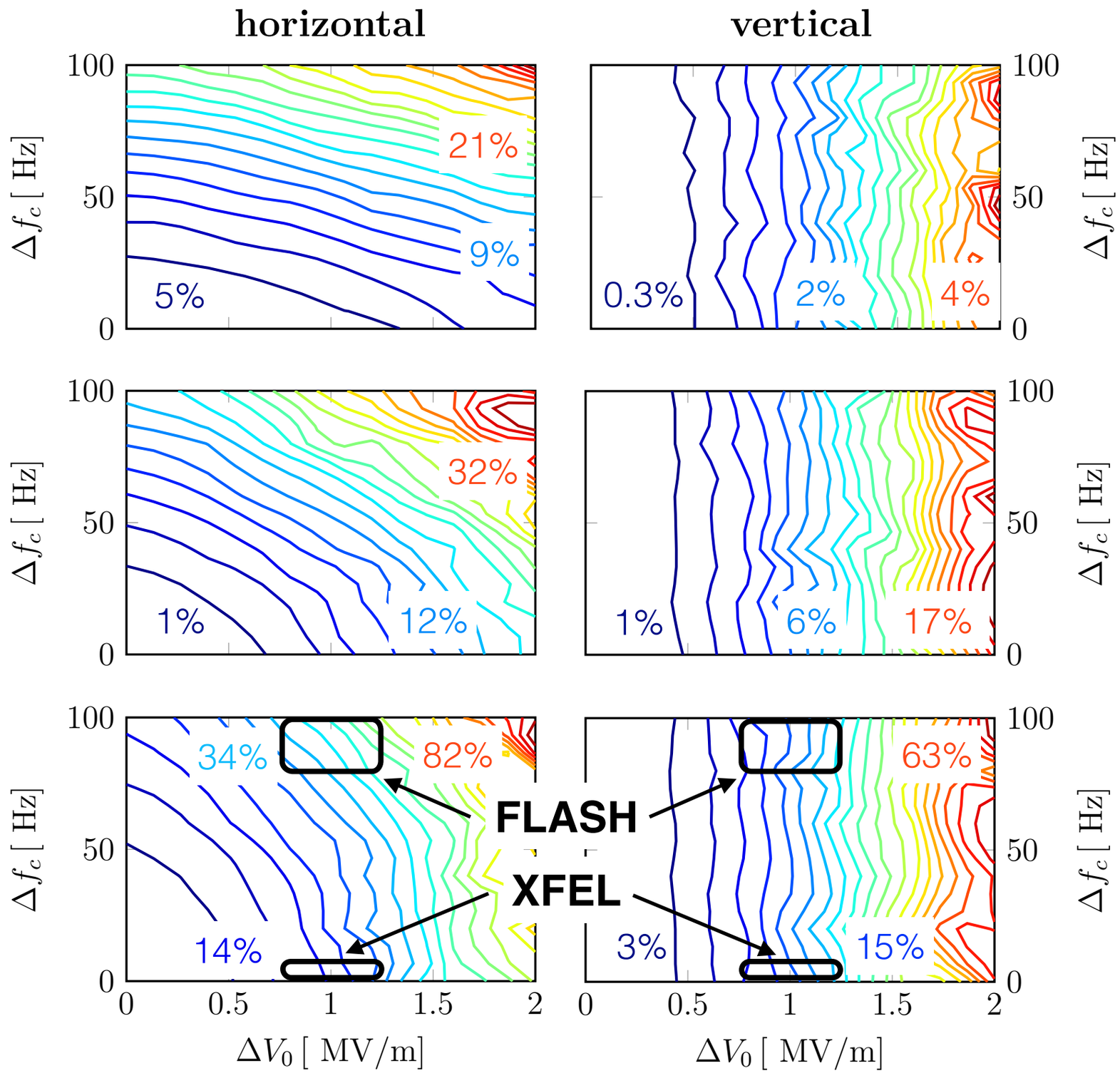
- ***guidance for engineering***
- *piezo tuner?*
- *Q_L correction?*
- *GUN alignment?*

top:	$\sigma_{\mathrm{mod}} = 0\,\mathrm{mm}$
mid:	$\sigma_{\mathrm{mod}} = 2\,\mathrm{mm}$
bottom:	$\sigma_{\mathrm{mod}} = 4\,\mathrm{mm}$

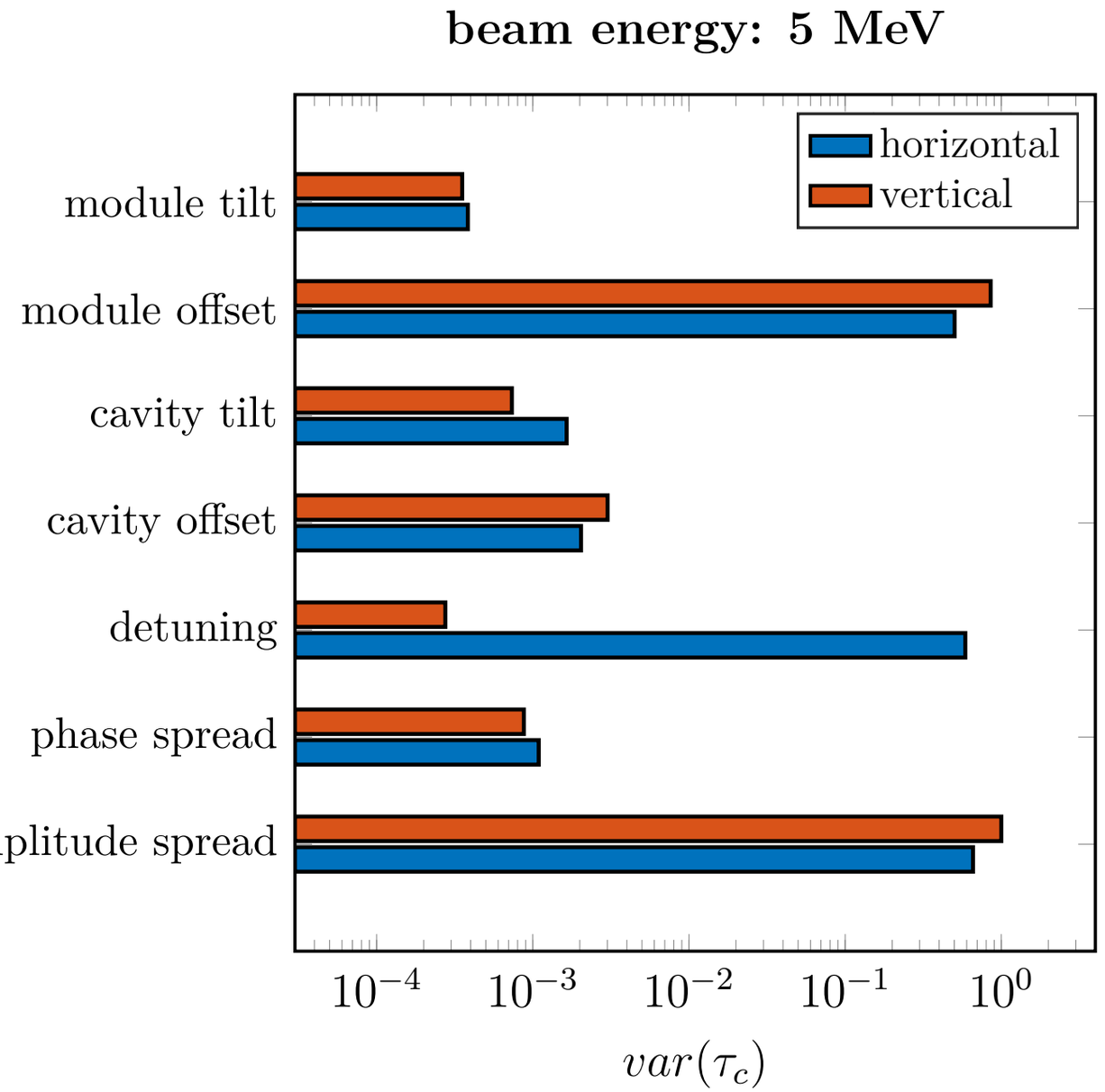


Simulation results

high beam energy

module at high beam energy

- figure of merit: $\tau = \dfrac{\epsilon_{SB}}{\epsilon_{MB}}$
- influential parameter: $var(\tau_c)$

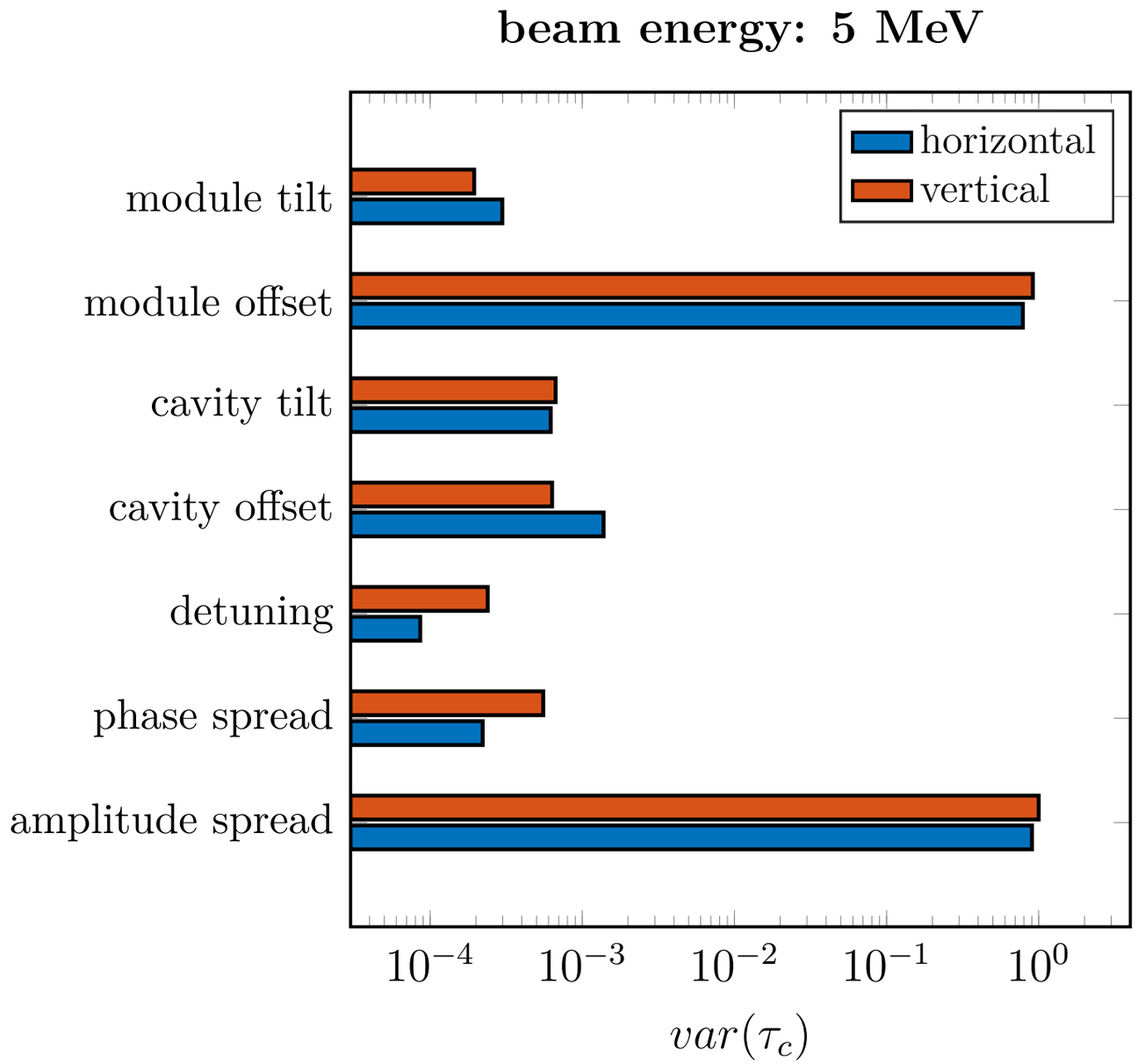


Simulation results

high beam energy

module at high beam energy

- figure of merit: $\tau = \dfrac{\epsilon_{SB}}{\epsilon_{MB}}$
- influential parameter: $var(\tau_c)$
- piezo tuner: $\Delta f = 5\,\mathrm{Hz}$

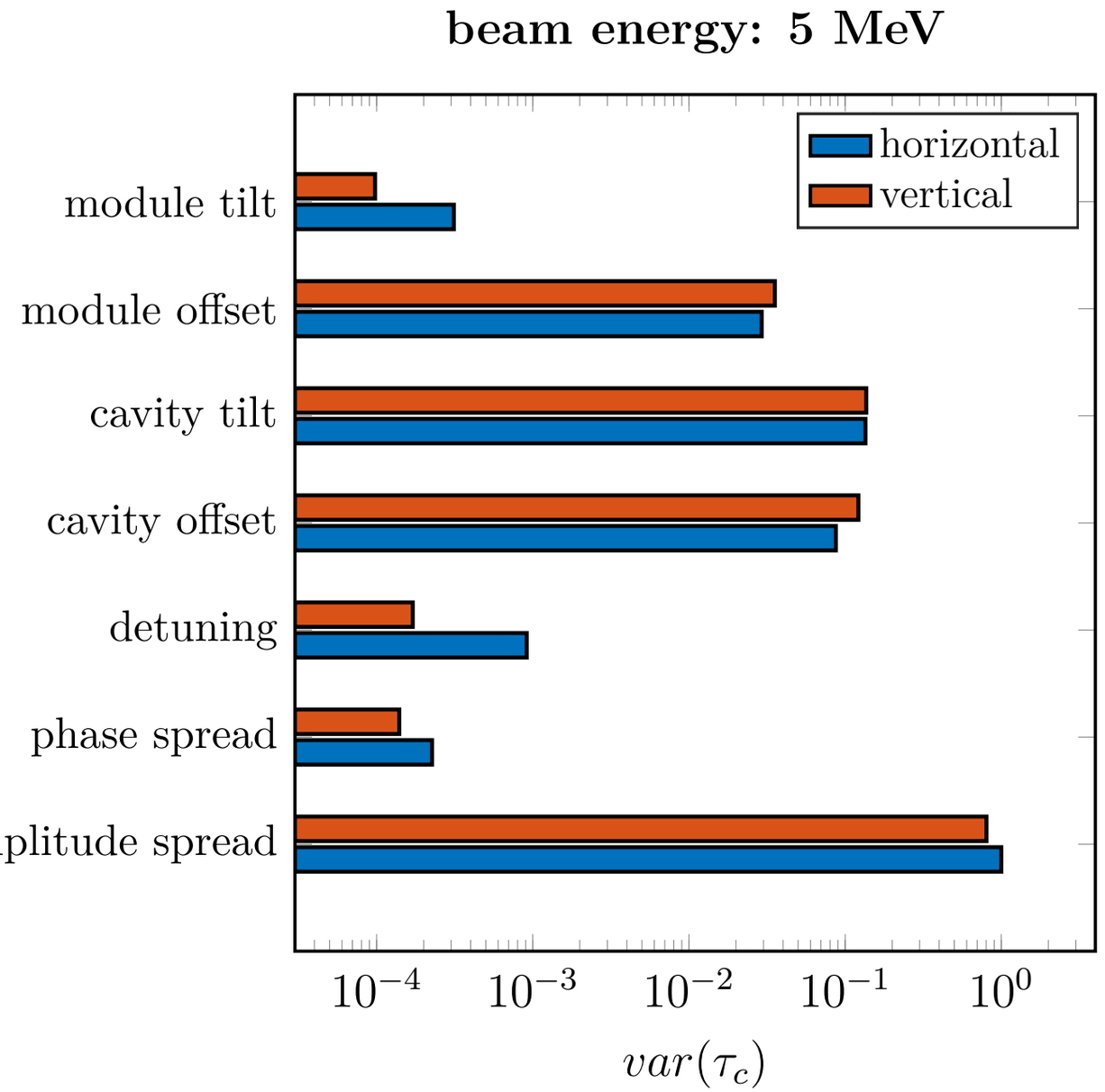


Simulation results

high beam energy

module at high beam energy

- figure of merit: $\tau = \dfrac{\epsilon_{SB}}{\epsilon_{MB}}$
- influential parameter: $var(\tau_c)$
- piezo tuner: $\Delta f = 5\,\mathrm{Hz}$
- module strings: $\sigma_{mod} = 0.5\,\mathrm{mm}$

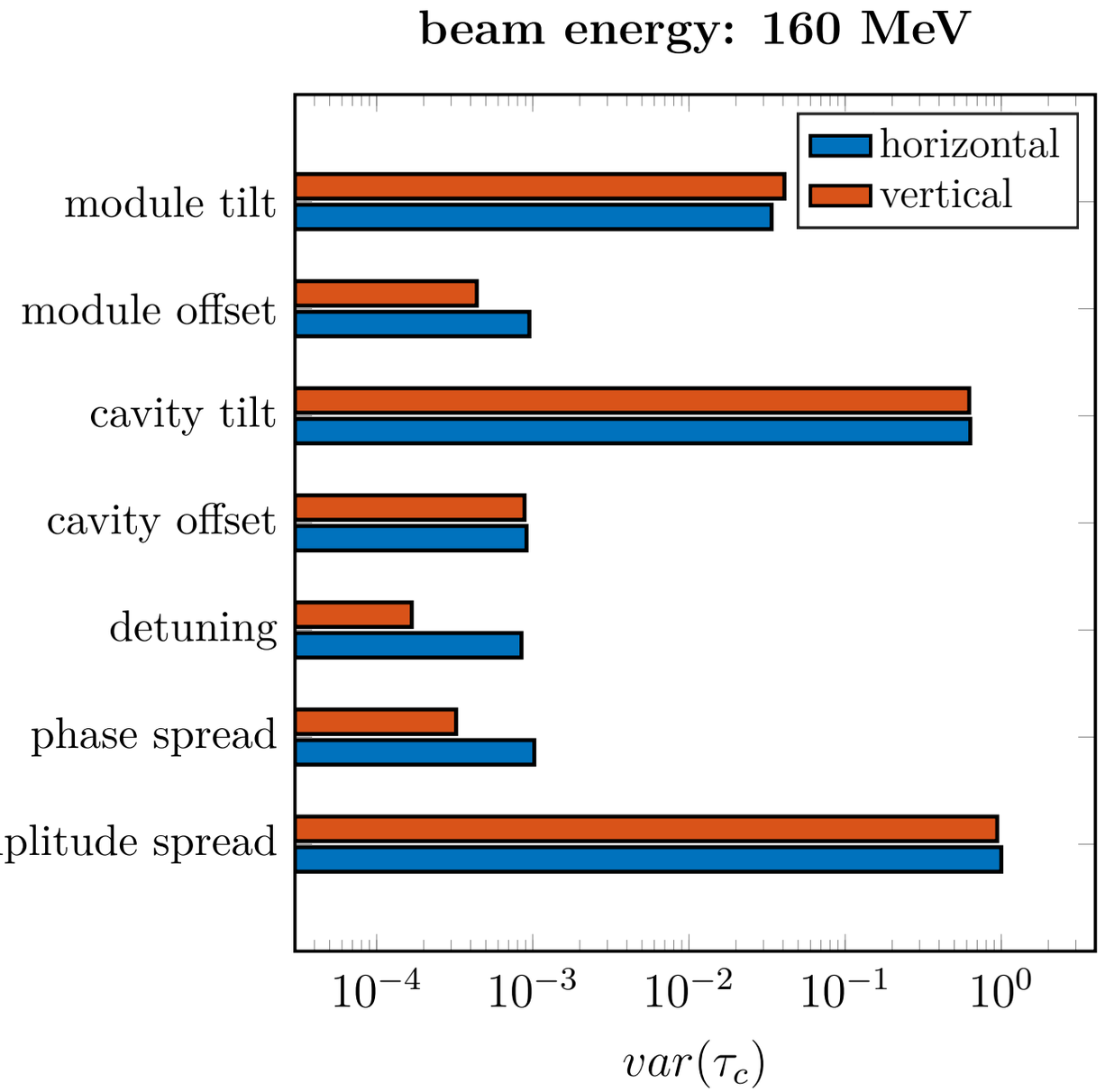


Simulation results

high beam energy

module at high beam energy

- figure of merit: $\tau = \dfrac{\epsilon_{SB}}{\epsilon_{MB}}$
- influential parameter: $var(\tau_c)$
- piezo tuner: $\Delta f = 5\,\mathrm{Hz}$
- module strings: $\sigma_{mod} = 0.5\,\mathrm{mm}$

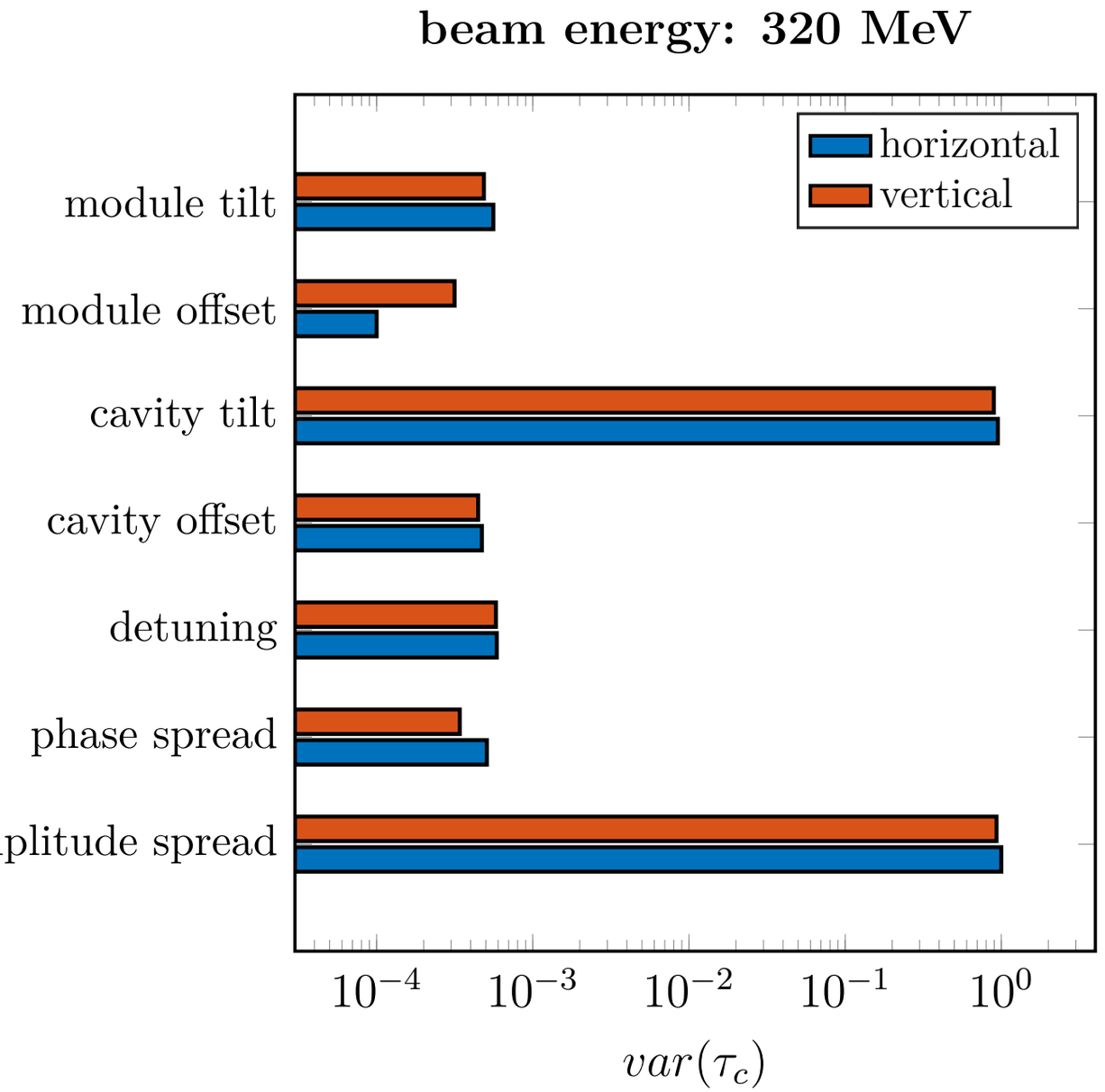


Simulation results

high beam energy

module at high beam energy

- figure of merit: $\tau = \dfrac{\epsilon_{SB}}{\epsilon_{MB}}$
- influential parameter: $var(\tau_c)$
- piezo tuner: $\Delta f = 5\,\mathrm{Hz}$
- module strings: $\sigma_{mod} = 0.5\,\mathrm{mm}$

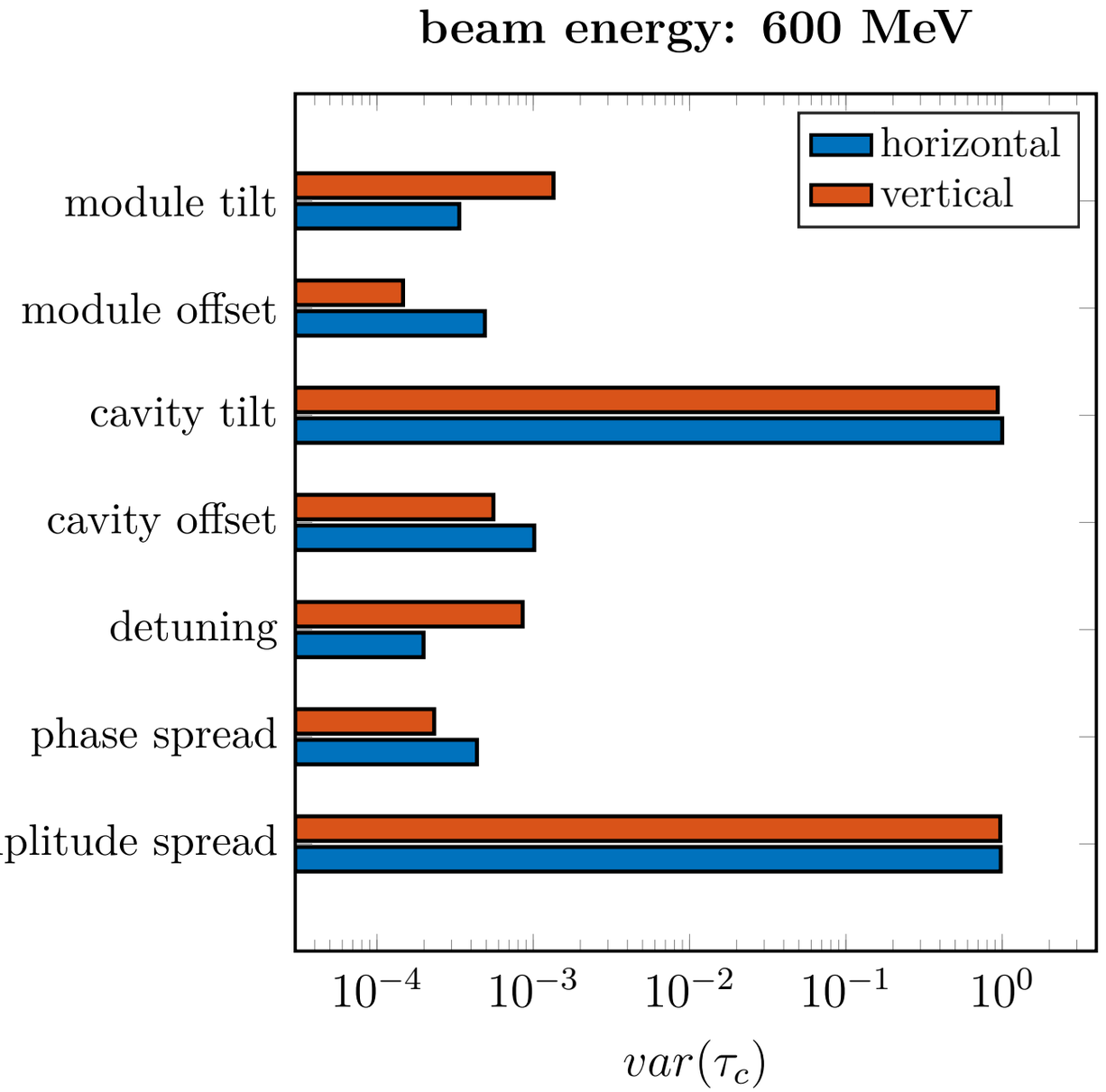


Simulation results

high beam energy

module at high beam energy

- figure of merit: $\tau = \dfrac{\epsilon_{SB}}{\epsilon_{MB}}$
- influential parameter: $var(\tau_c)$
- piezo tuner: $\Delta f = 5\,\mathrm{Hz}$
- module strings: $\sigma_{mod} = 0.5\,\mathrm{mm}$
- $\gamma \gg 1$

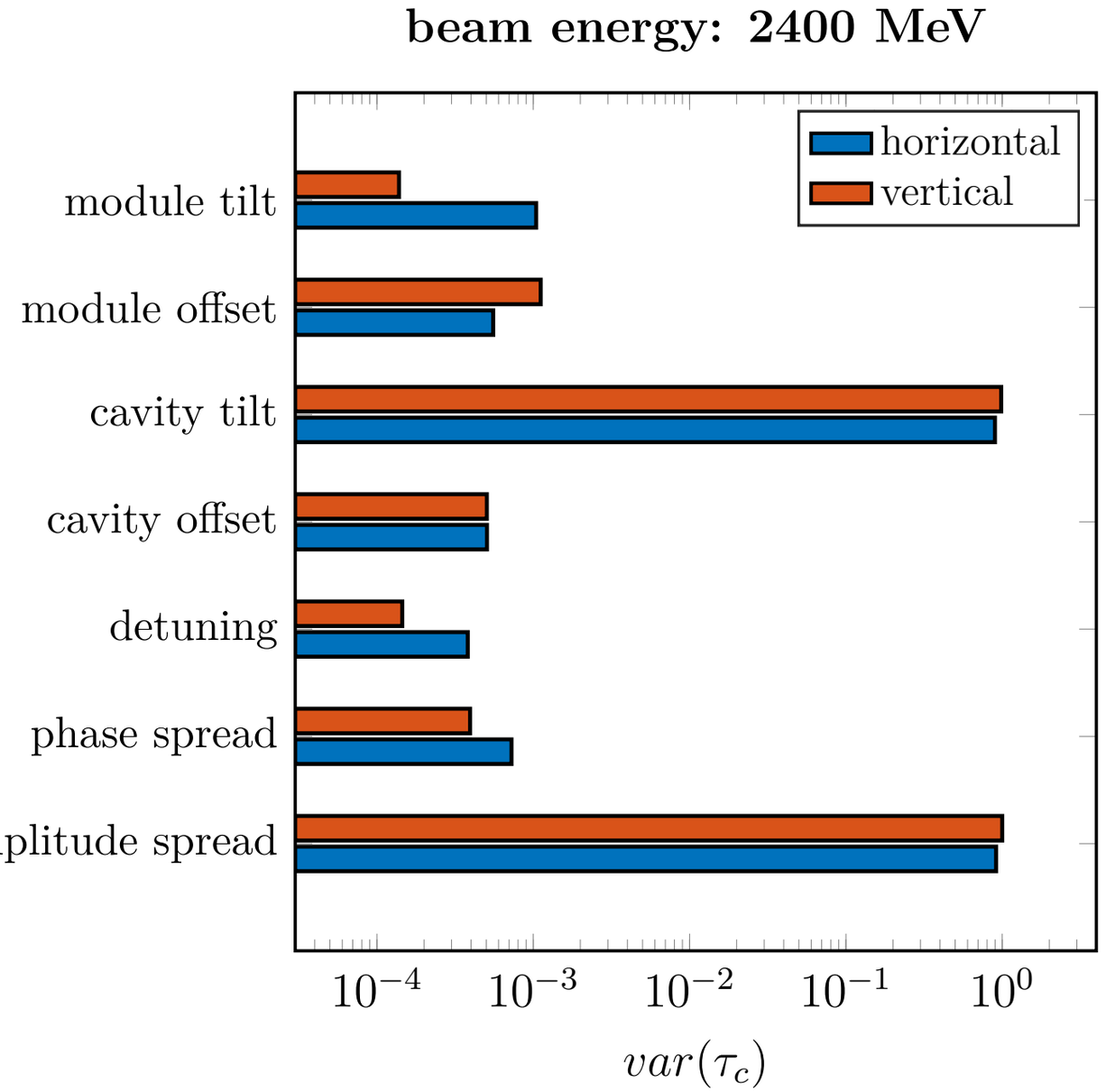


Simulation results — high beam energy

module at high beam energy

- figure of merit: $\tau = \dfrac{\epsilon_{SB}}{\epsilon_{MB}}$
- influential parameter: $var(\tau_c)$
- piezo tuner: $\Delta f = 5\,\mathrm{Hz}$
- module strings: $\sigma_{mod} = 0.5\,\mathrm{mm}$
- $\gamma \gg 1$

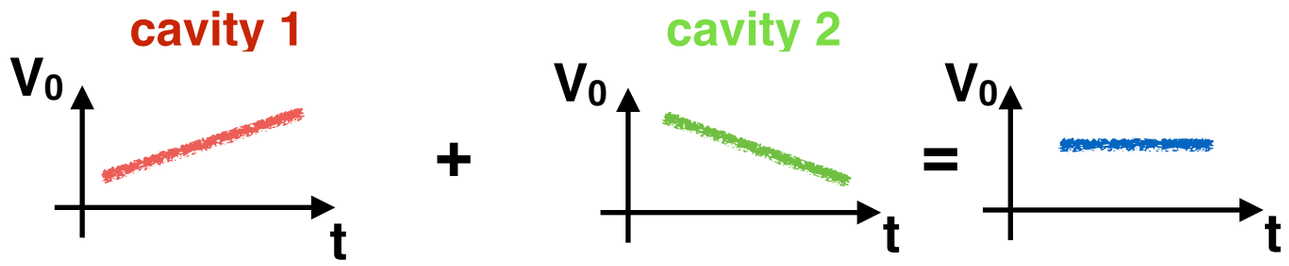
- ***cavity tilts***
- ***gradient spread***



Simulation results — high beam energy

module at high beam energy

- $\gamma \gg 1$
- straight particle trajectories
- no edge fields
- random voltage spread
- vector sum = *const*.
- random misalignments
- ***correlated misalignments cancel***

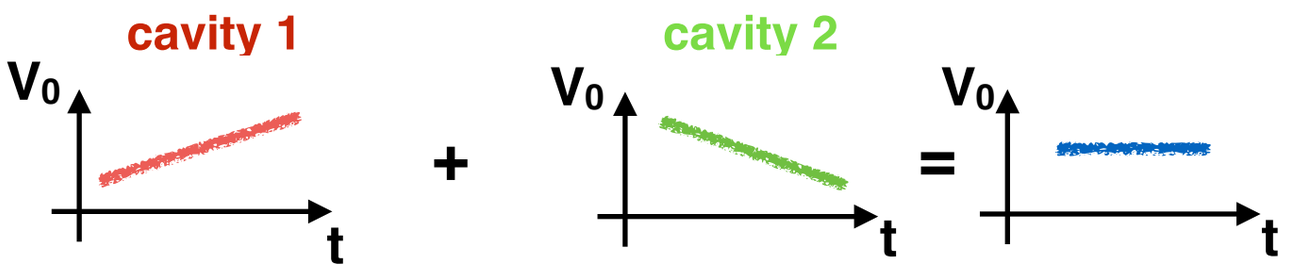


Simulation results

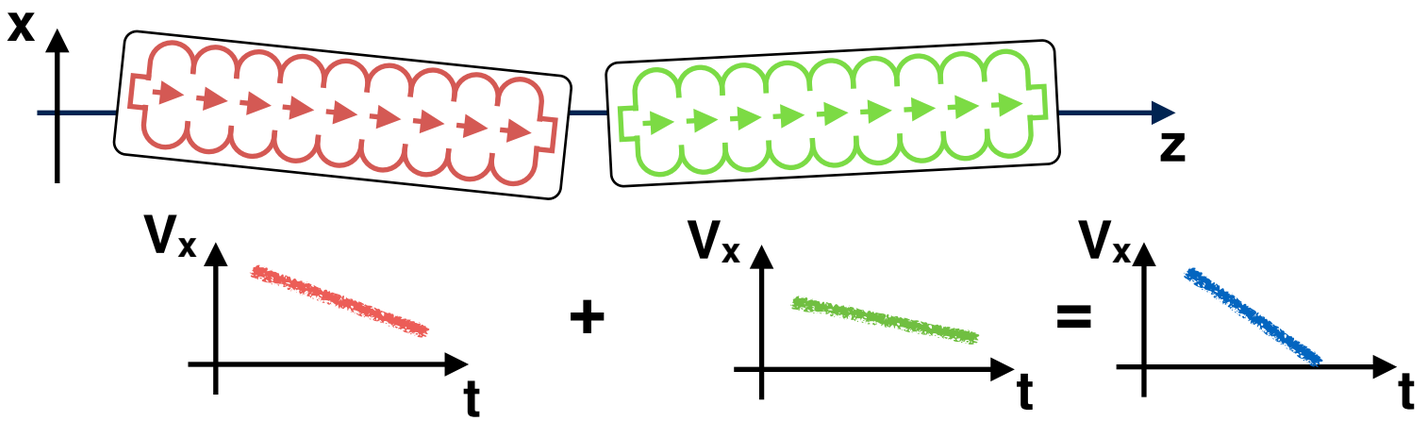
high beam energy

module at high beam energy

- $\gamma \gg 1$
- straight particle trajectories
- no edge fields
- random voltage spread
- vector sum = *const*.
- random misalignments
- ***correlated misalignments cancel***



misaligned cavities

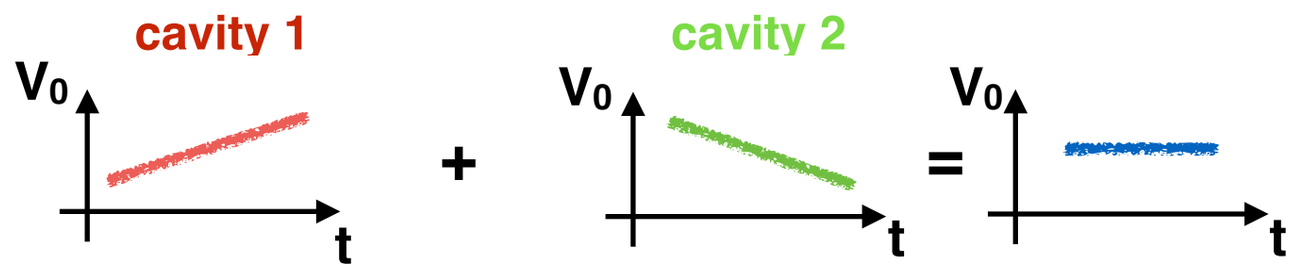


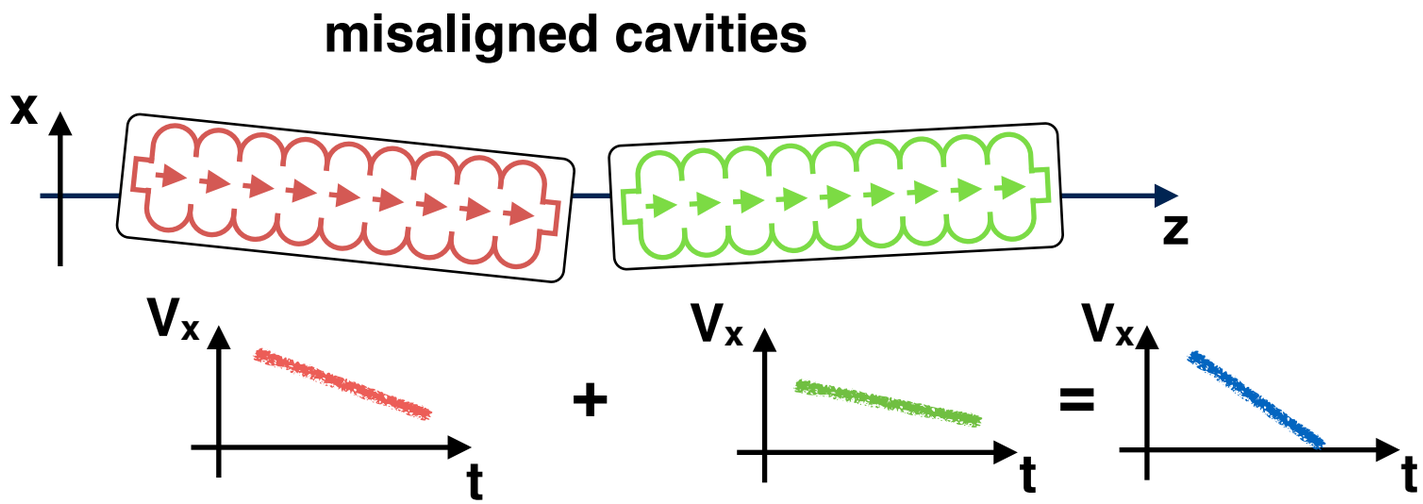
Simulation results

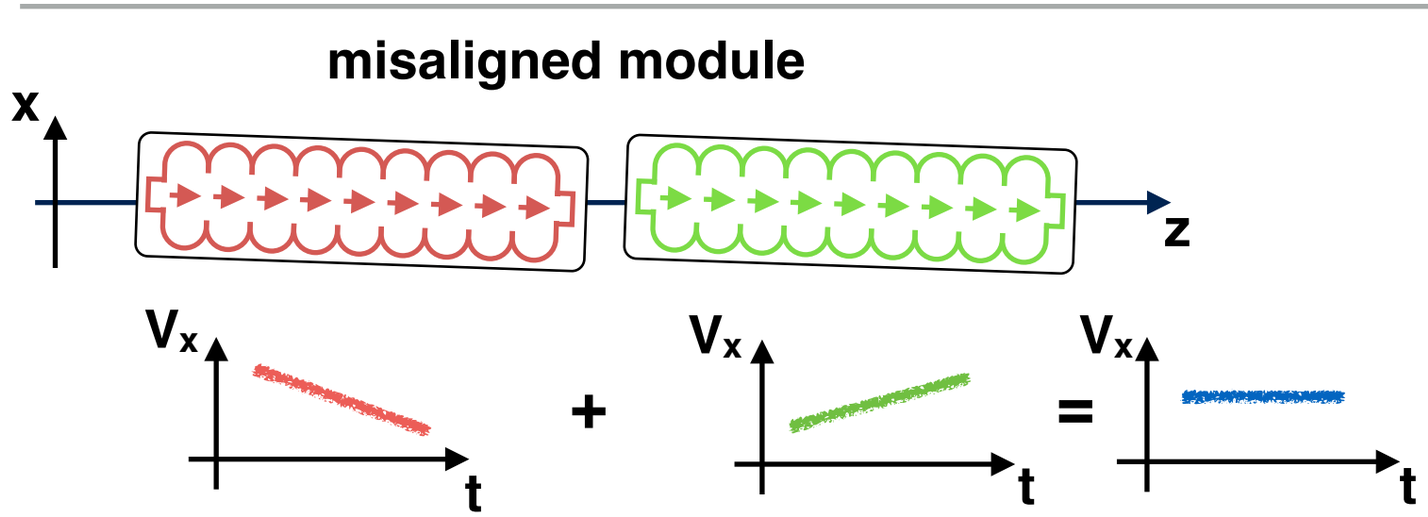
high beam energy

module at high beam energy

- $\gamma \gg 1$
- straight particle trajectories
- no edge fields
- random voltage spread
- vector sum = *const*.
- random misalignments
- ***correlated misalignments cancel***







Simulation results

simulations on *L3*

- 84 modules
- $E_0 = 2.4\,\mathrm{GeV}$
- $E_f = 20\,\mathrm{GeV}$

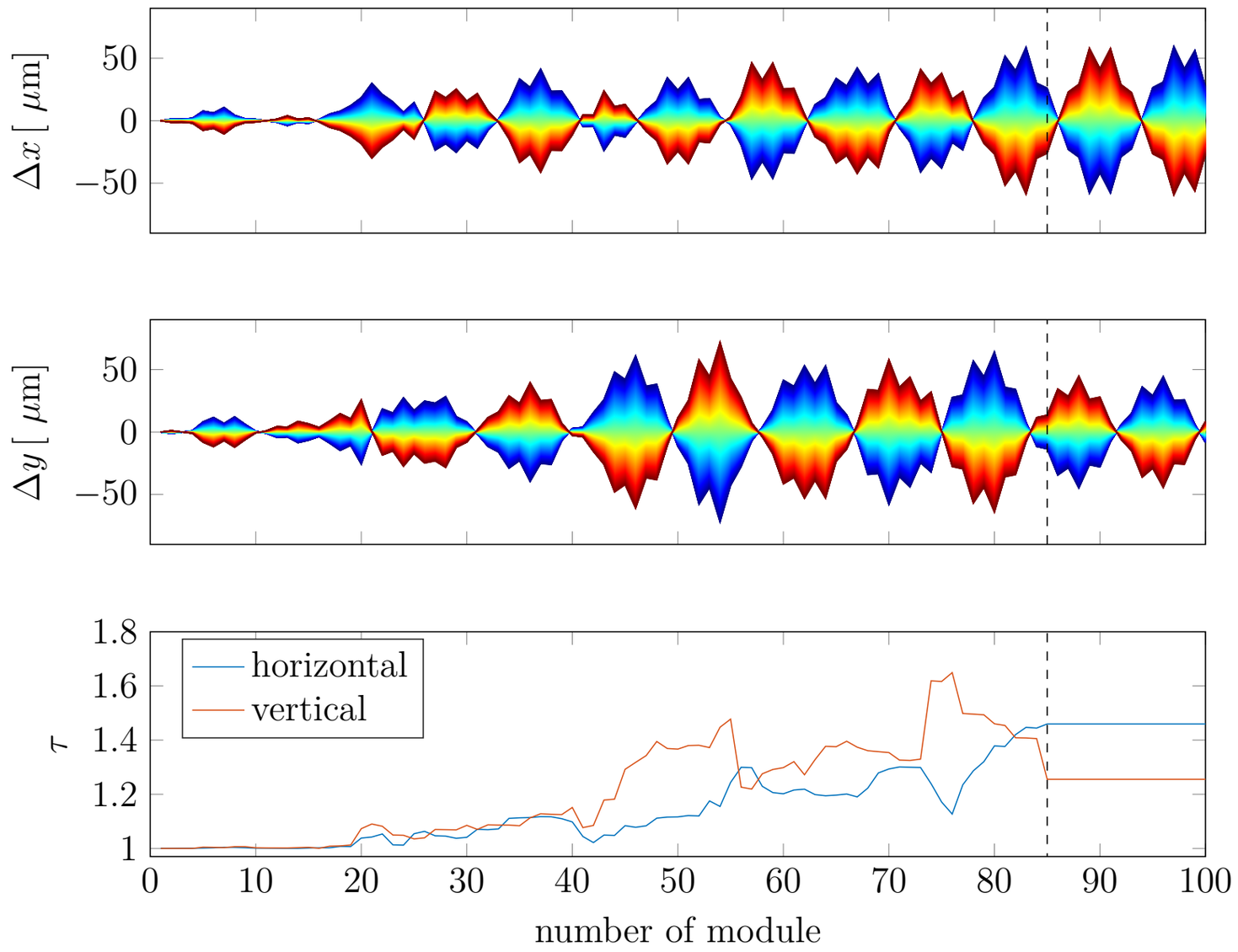
parameter range for the XFEL accelerator

parameter	*value*	*description*
n_{bunch}	2700	number of bunches per bunch-train
$\overline{\mathbf{V}_0}$	200 MV	vector sum amplitude
$\overline{\phi_0}$	0 °	vector sum phase
ΔV_0	1 MV/m	max. variation of cavity gradients
$\Delta\phi_0$	0.1 °	max. variation of cavity phases
Δf	5 Hz	max. variation of cavity detuning
σ_{cav}	0.5 mm	max. offset of cavities
σ'_{cav}	0.25 mrad	max. tilt of cavities
σ_{mod}	0.5 mm	max. offset of module
σ'_{mod}	0.2 mrad	max. tilt of module

Simulation results

simulations on *L3*

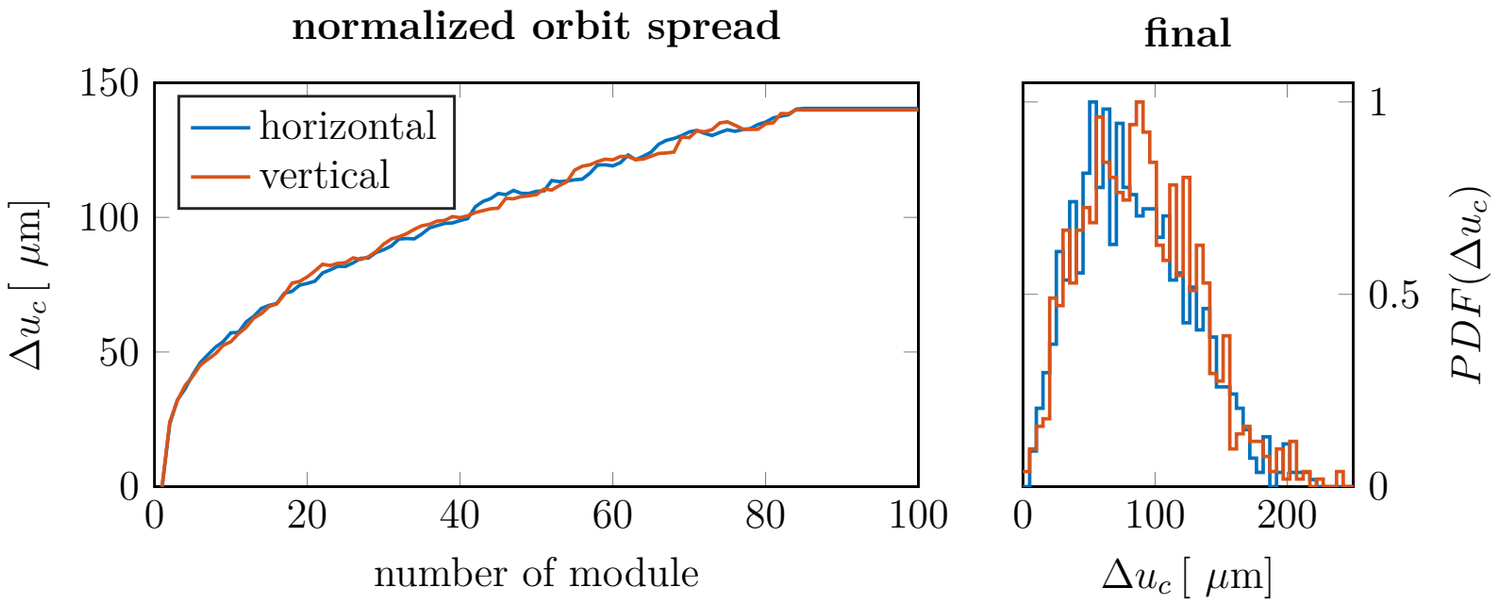
- 84 modules
- $E_0 = 2.4\,\mathrm{GeV}$
- $E_f = 20\,\mathrm{GeV}$

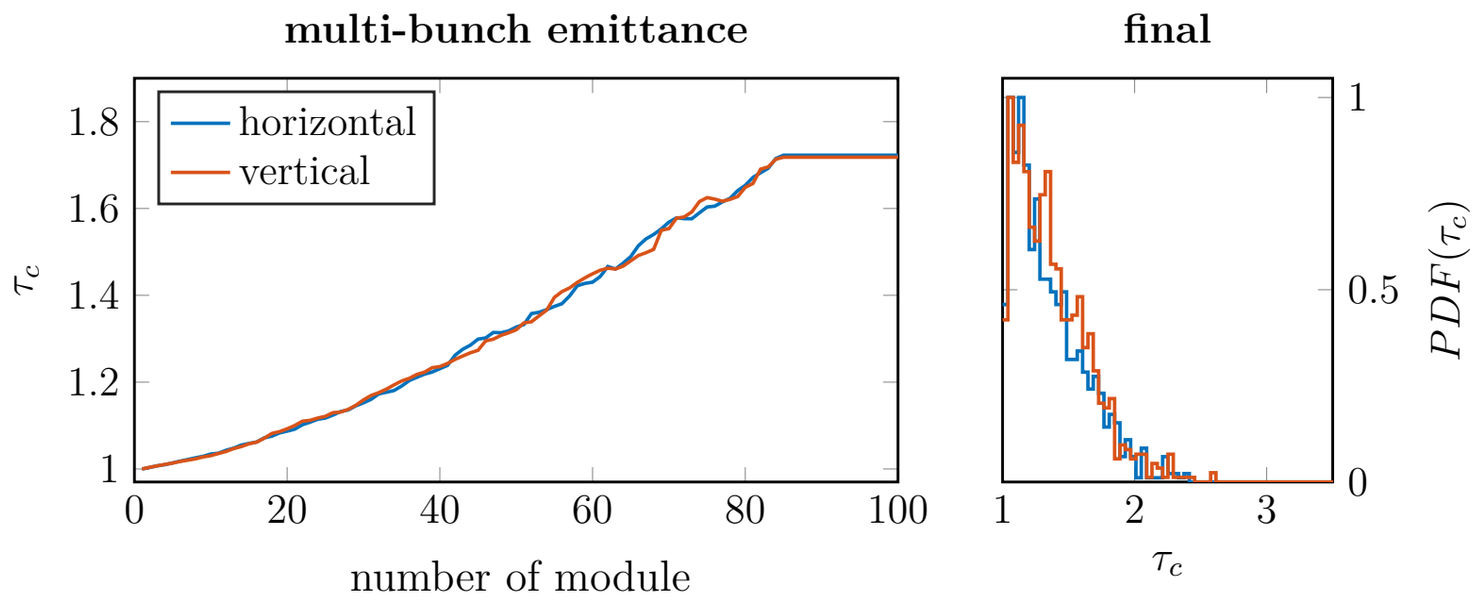


Simulation results

simulations on *L3*

- 84 modules
- $E_0 = 2.4\,\mathrm{GeV}$
- $E_f = 20\,\mathrm{GeV}$
- evaluate 10^5 machines
- ***significant orbit spread possible***



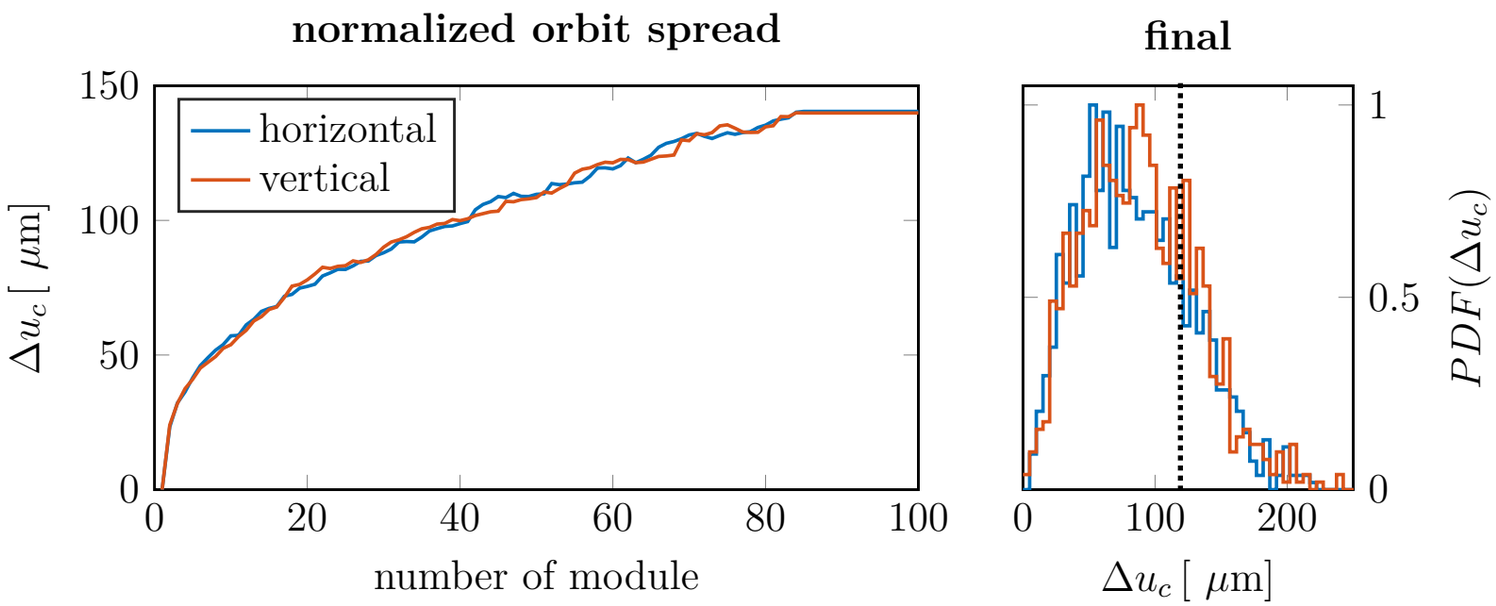


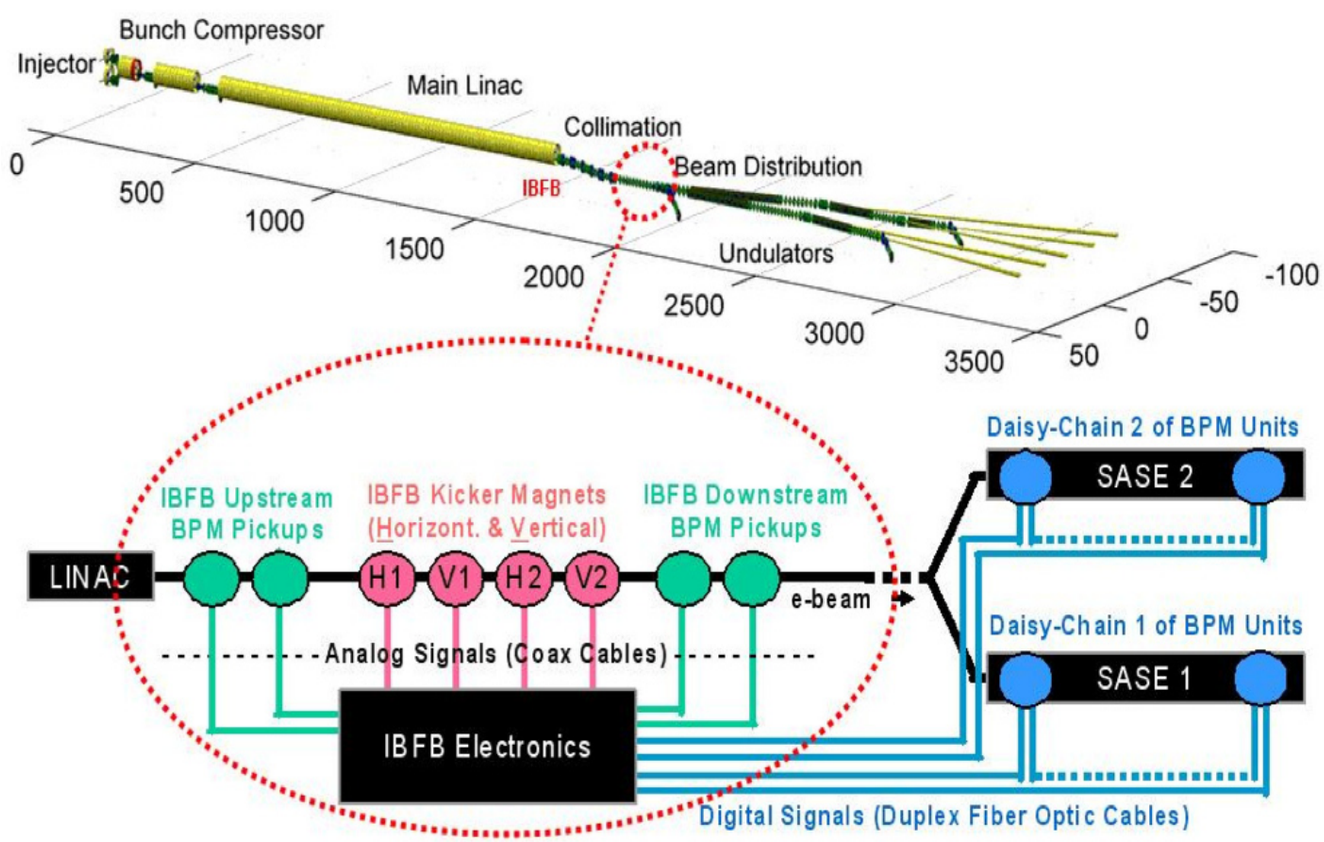
Simulation results

simulations on *L3*

- for SASE: $\Delta u_{\max} = 3\,\mu\mathrm{m}$
- intra-bunch-train feedback[7]
- max. $k_{\mathrm{IBFB}} = 4\,\mu\mathrm{rad}$

$$\Delta u_{\mathrm{IBFB}} \leq 115\,\mu\mathrm{m}$$



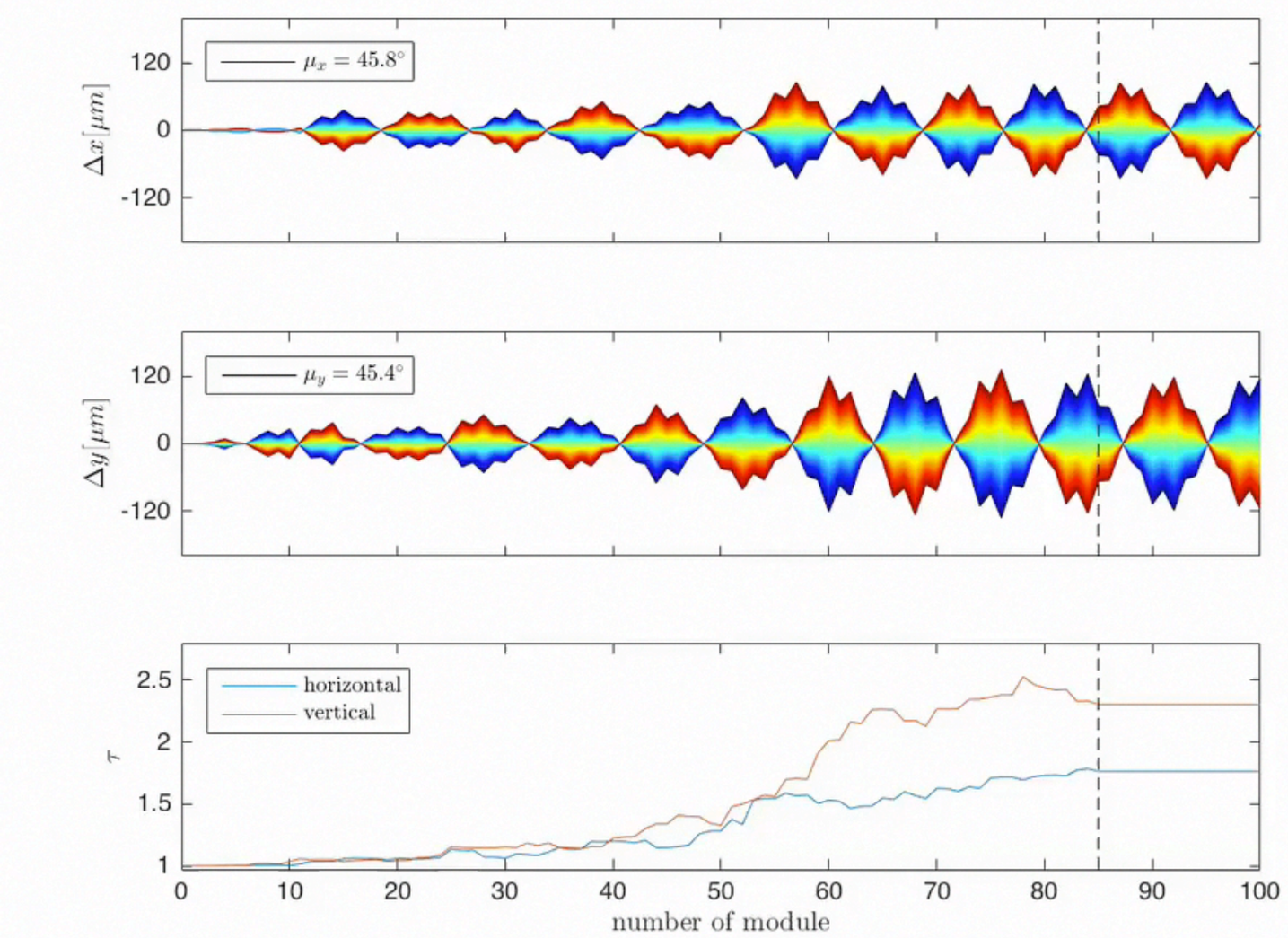


[7] B. Keil et al. “Design of an intra-bunch-train feedback system for the european x-ray fel“, in *Proc. IBIC’02*, Oct. 2002

Simulation results

simulations on *L3*

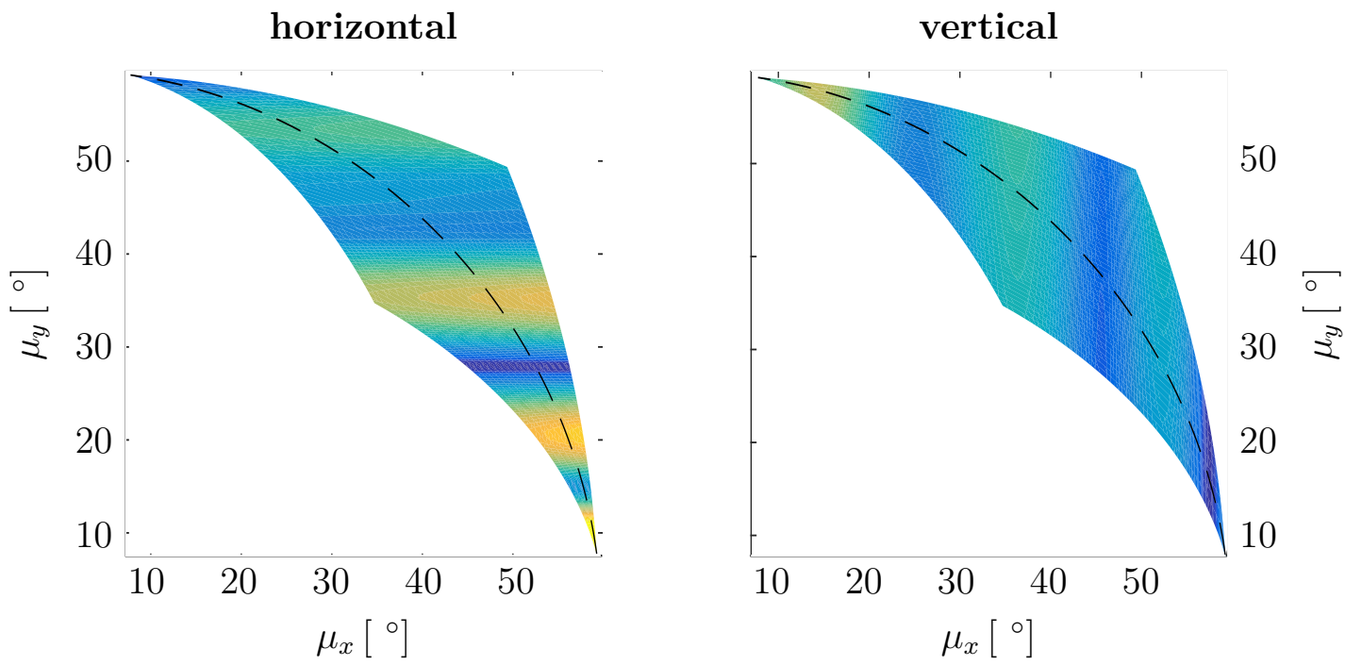
- for SASE: $\Delta u_{\max} = 3\,\mu\mathrm{m}$
- intra-bunch-train feedback[X]
- max. $k_{\mathrm{IBFB}} = 4\,\mu\mathrm{rad}$
- $\Delta u_{\mathrm{IBFB}} \leq 115\,\mu\mathrm{m}$
- scan phase advance

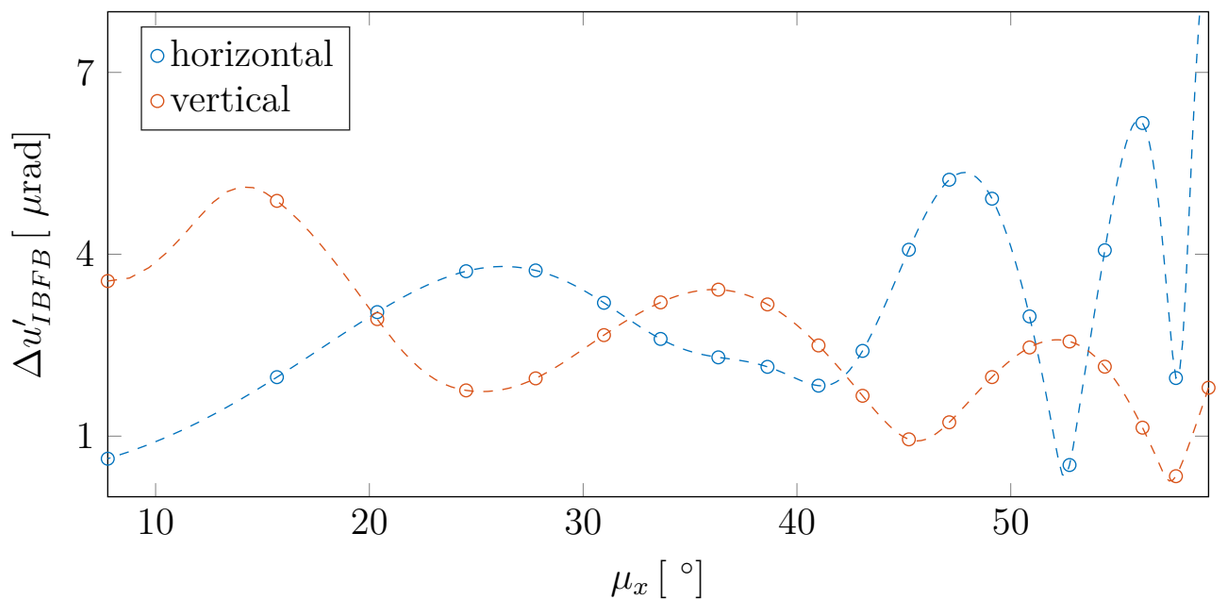


Simulation results

simulations on *L3*

- for SASE: $\Delta u_{\max} = 3\,\mu\mathrm{m}$
- intra-bunch-train feedback[X]
- max. $k_{\mathrm{IBFB}} = 4\,\mu\mathrm{rad}$
- $\Delta u_{\mathrm{IBFB}} \leq 115\,\mu\mathrm{m}$
- scan phase advance
- motion decoupled
- minimize $(\Delta x', \Delta y')_{IBFB}$

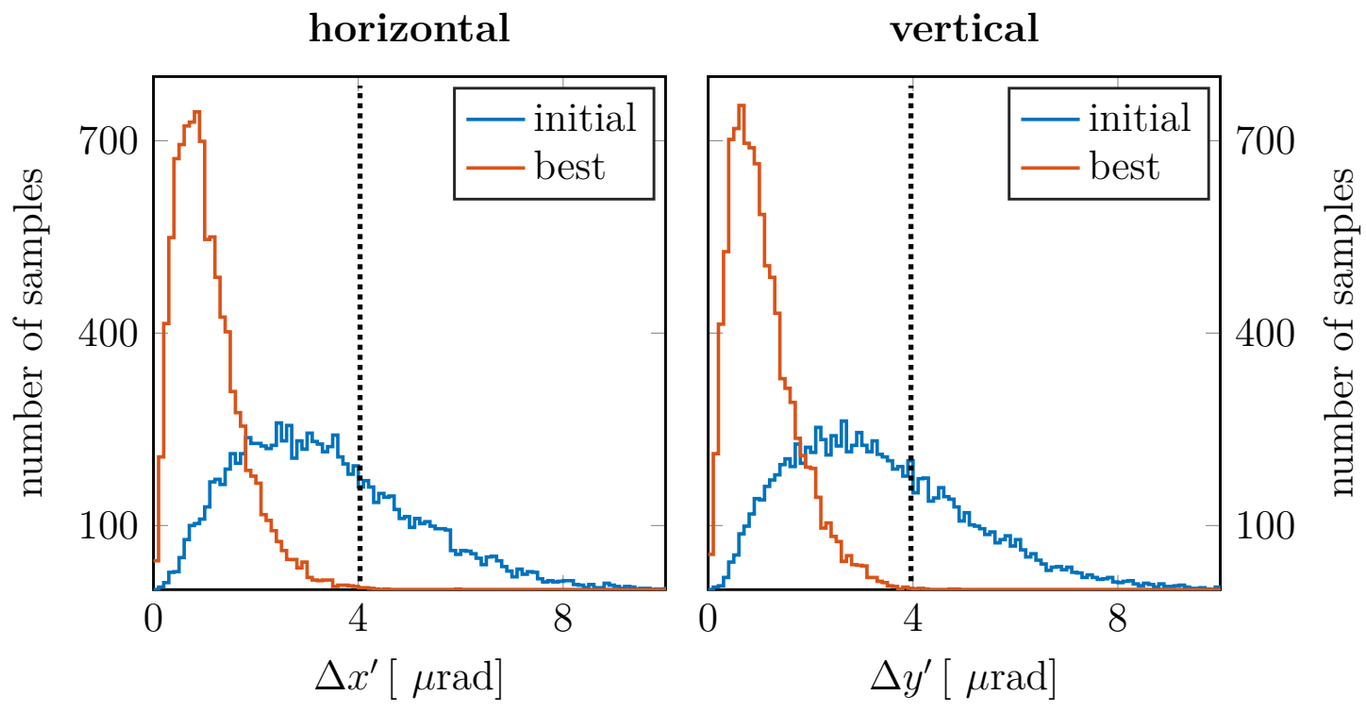




Simulation results

simulations on *L3*

- for SASE: $\Delta u_{\max} = 3\,\mu\mathrm{m}$
- intra-bunch-train feedback[X]
- max. $k_{\mathrm{IBFB}} = 4\,\mu\mathrm{rad}$
- $\Delta u_{\mathrm{IBFB}} \leq 115\,\mu\mathrm{m}$
- scan phase advance
- motion decoupled
- minimize $(\Delta x', \Delta y')_{IBFB}$
- ***orbit spread reduction***



- motivation
- model development
- simulation results
- **summary & outlook**

Summary

- **model development**
  - cross-check against ASTRA and experimental data
  - fast and accurate for low beam energy

- **simulation results**
  - tools for statistical analysis developed
  - parameter correlations investigated
  - methods for orbit spread reduction presented

Outlook

- **experimental data**
  - HOM-based cavity misalignment measurements
  - multi-bunch-based fit of GUN-module-alignment
  - Model independent analysis on beam line

- **finish thesis**

Outlook

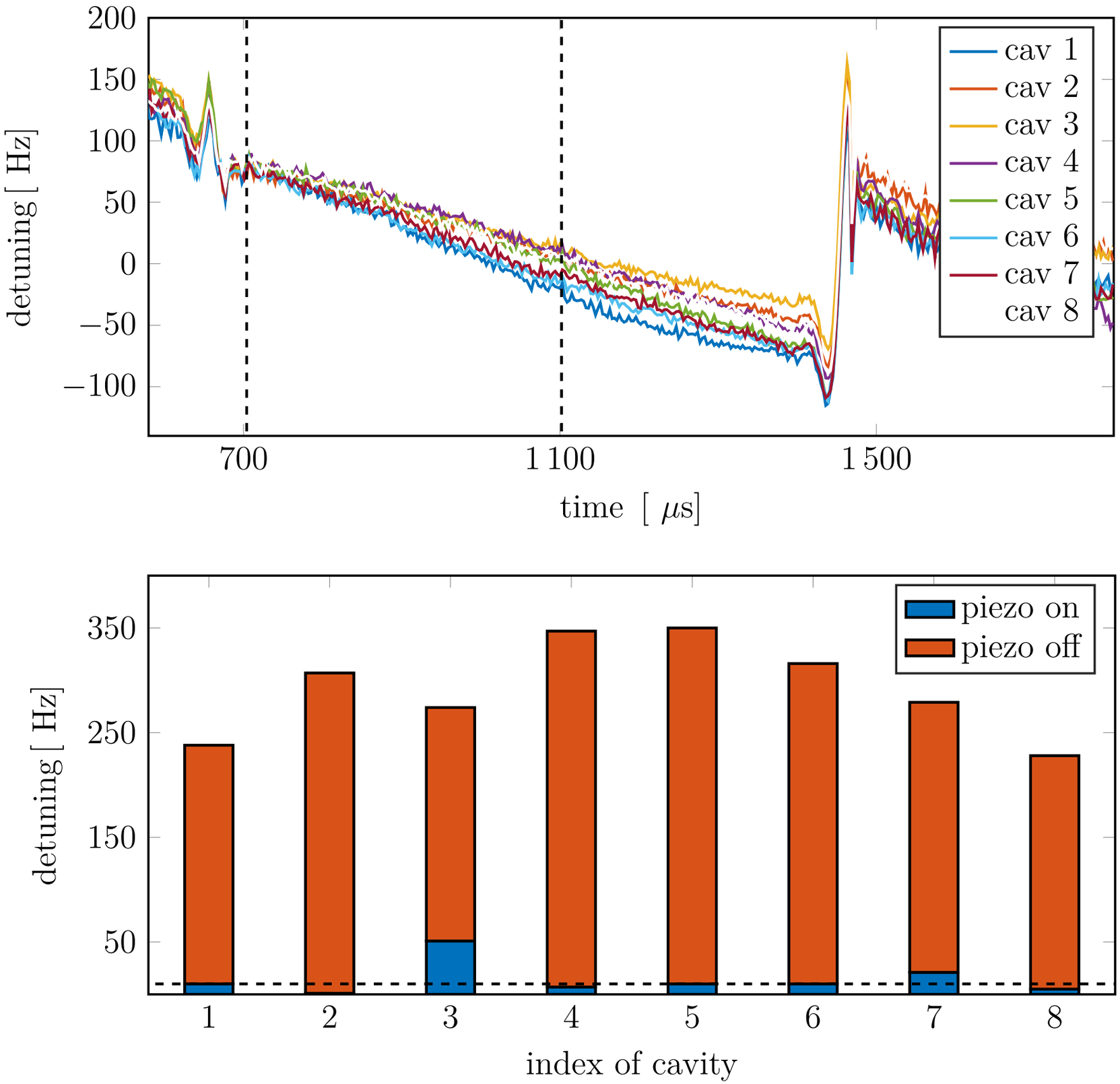
> *thanks for your attention!*

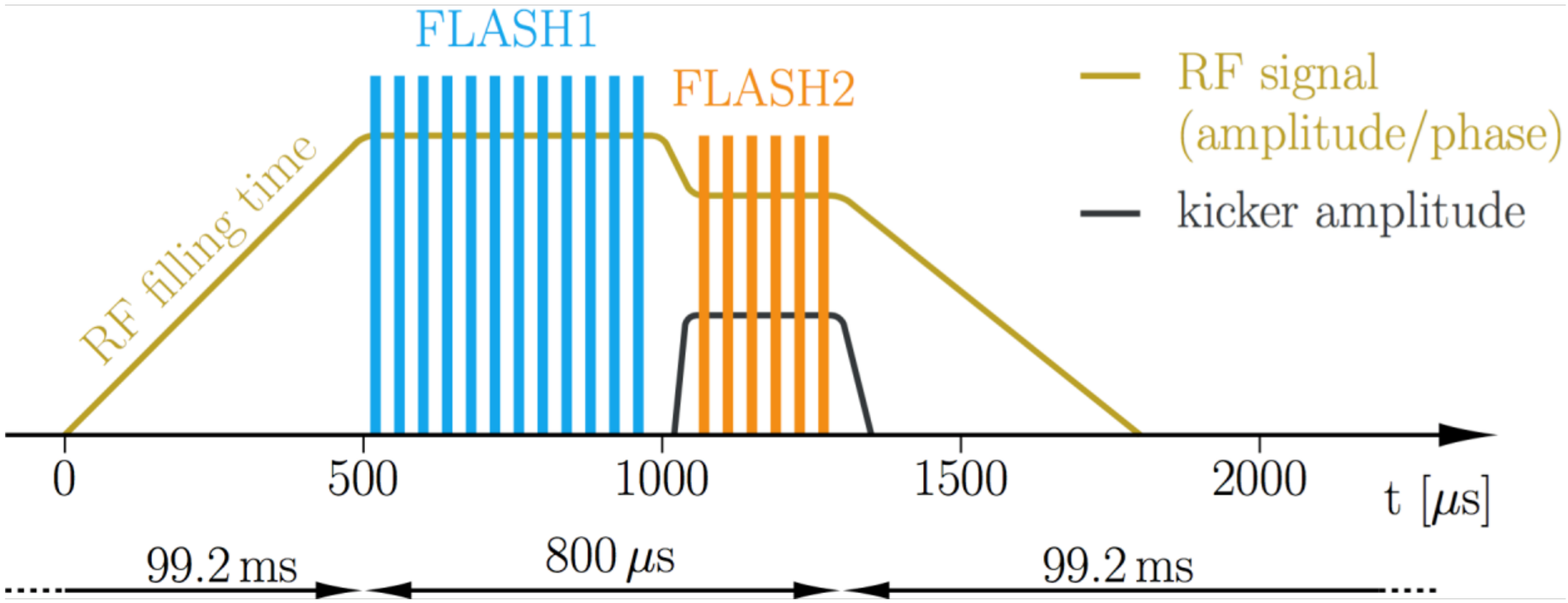
simulation

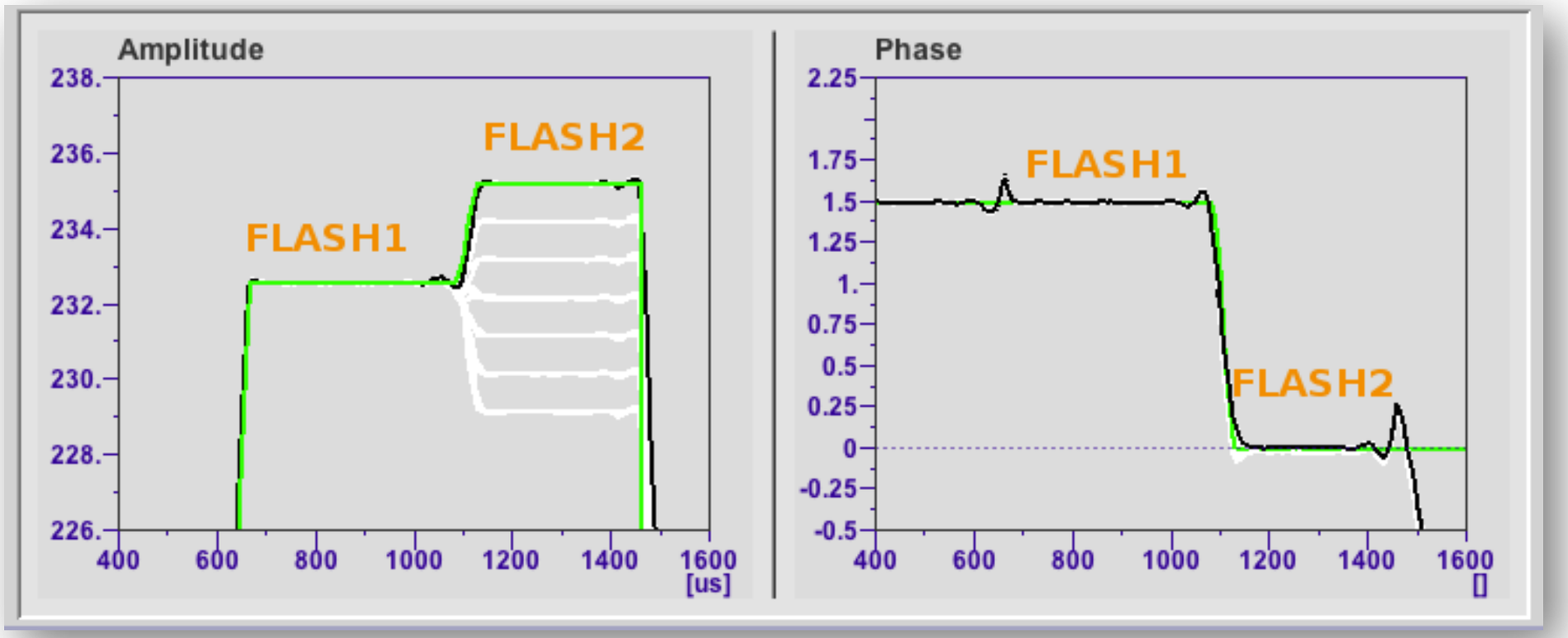
appendix

Appendix

Lorentz force detuning

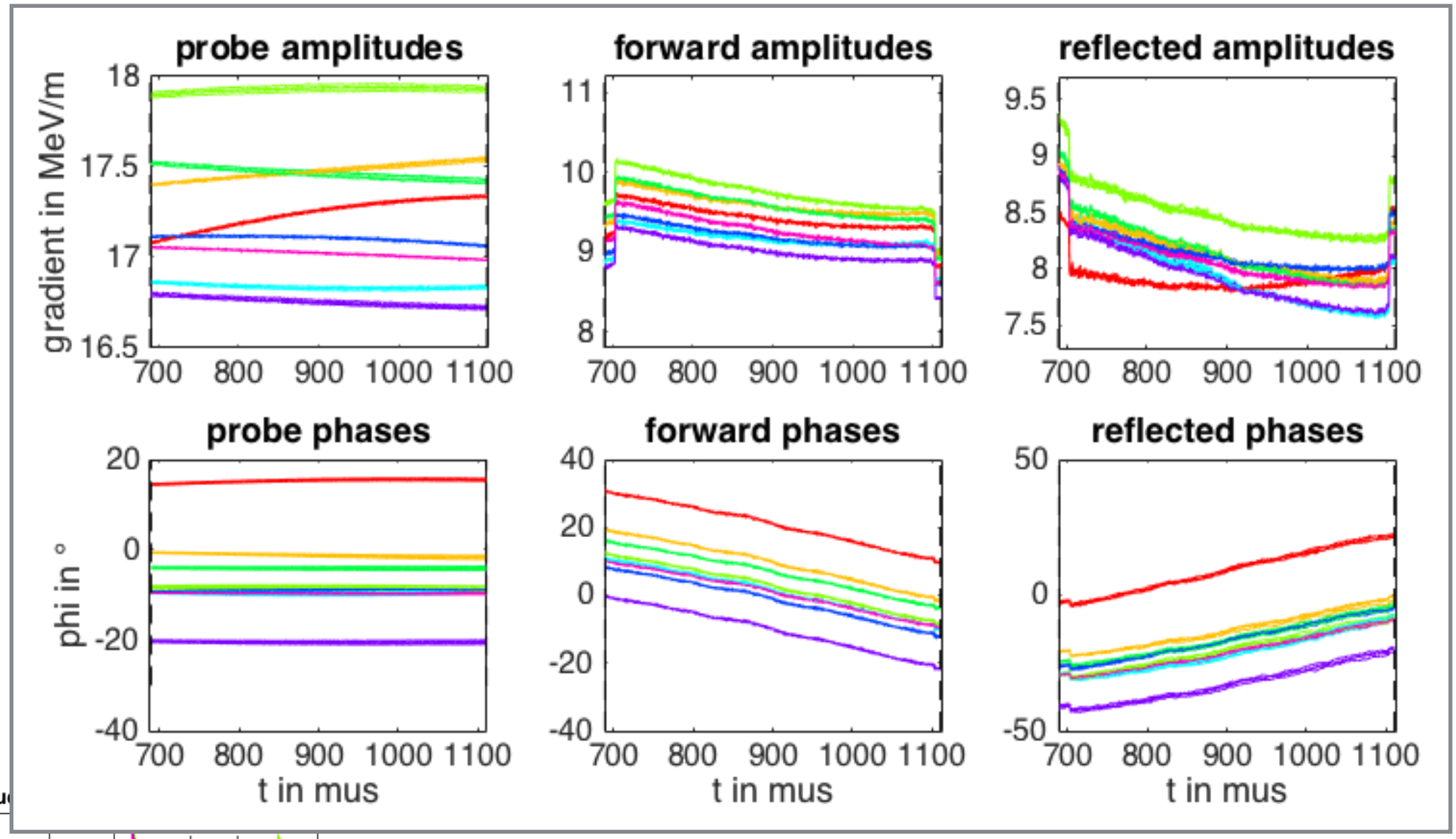


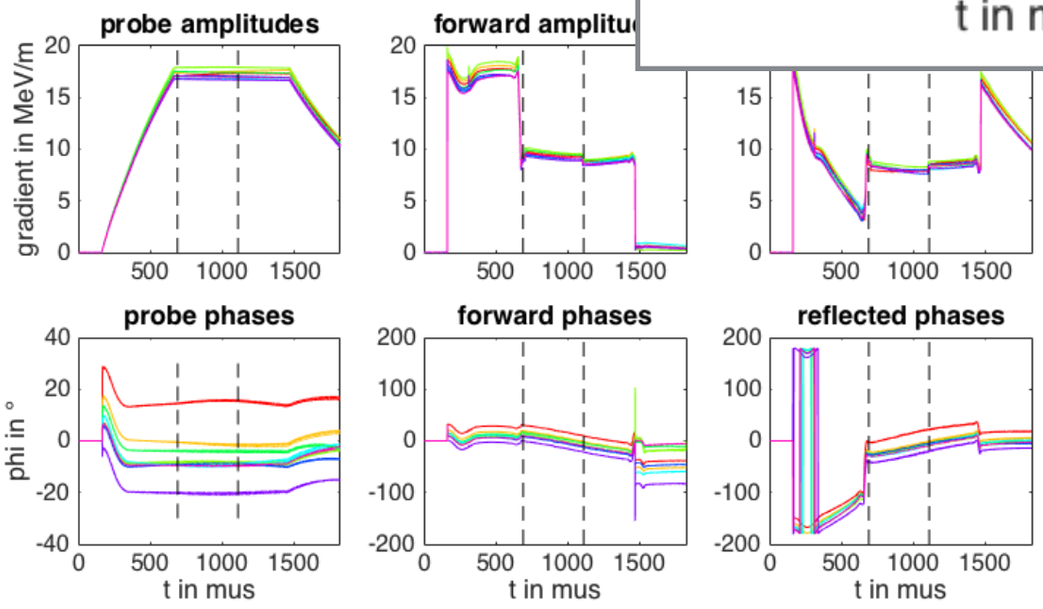

FLASH1
FLASH2
RF filling time
RF signal
(amplitude/phase)
kicker amplitude
0
500
1000
1500
2000
t [μs]
99.2 ms
800 μs
99.2 ms


Amplitude
238.
236.
234.
232.
230.
228.
226.
FLASH2
FLASH1
400
600
800
1000
1200
1400
1600
[us]
Phase
2.25
1.75
1.5
1.25
1.
0.75
0.5
0.25
0
-0.25
-0.5
FLASH1
FLASH2
400
600
800
1000
1200
1400
1600
[]

Appendix

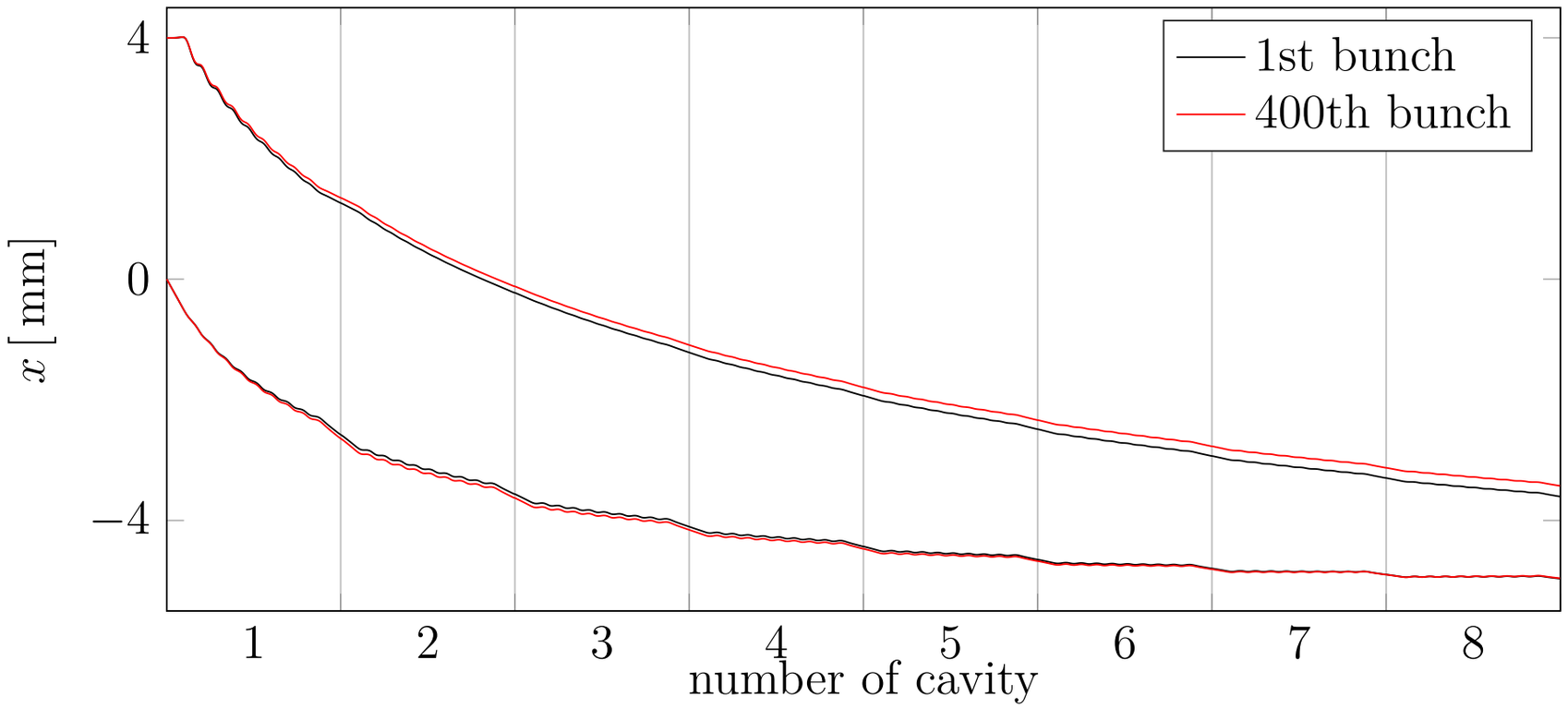
RF signals





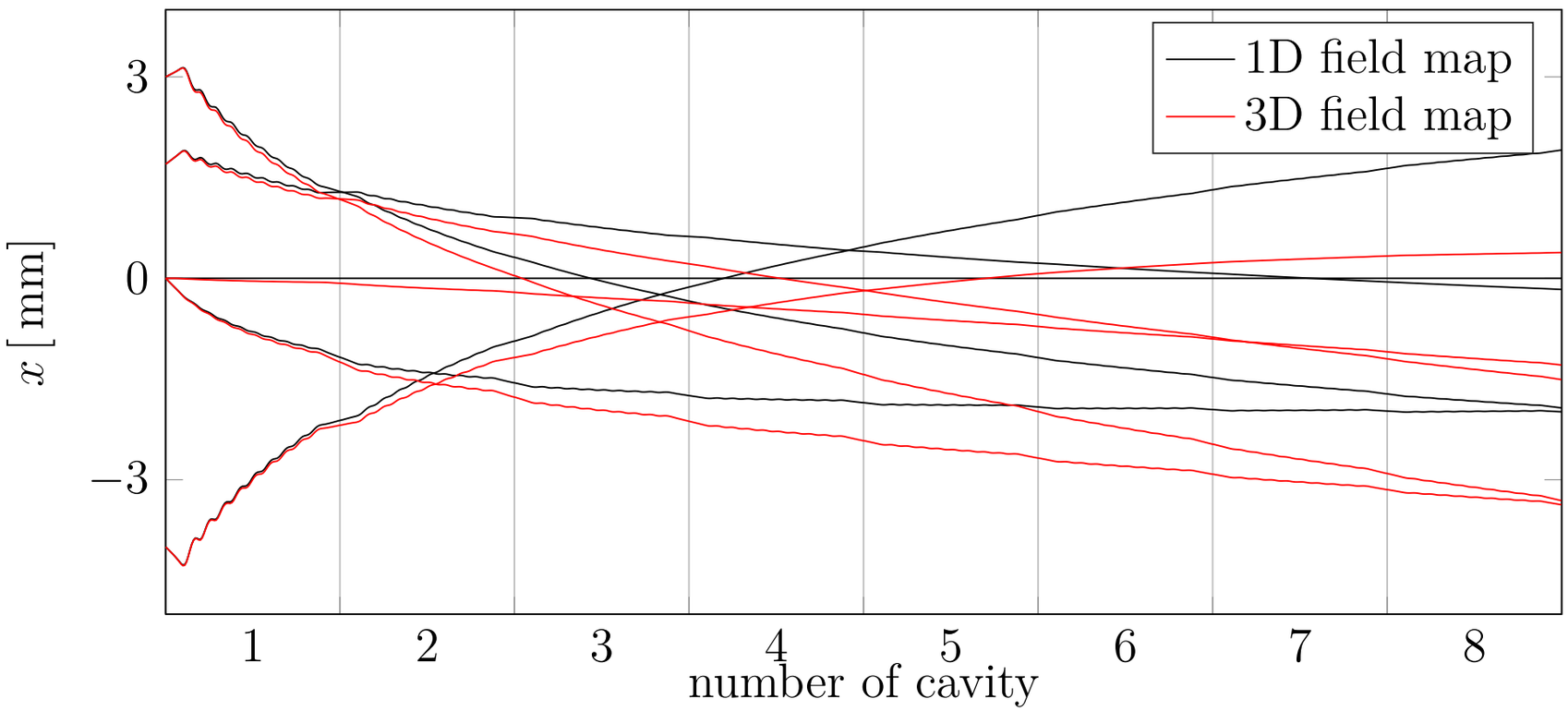
Appendix

trajectories in injector modul



modul tilt
vs.
modul offset

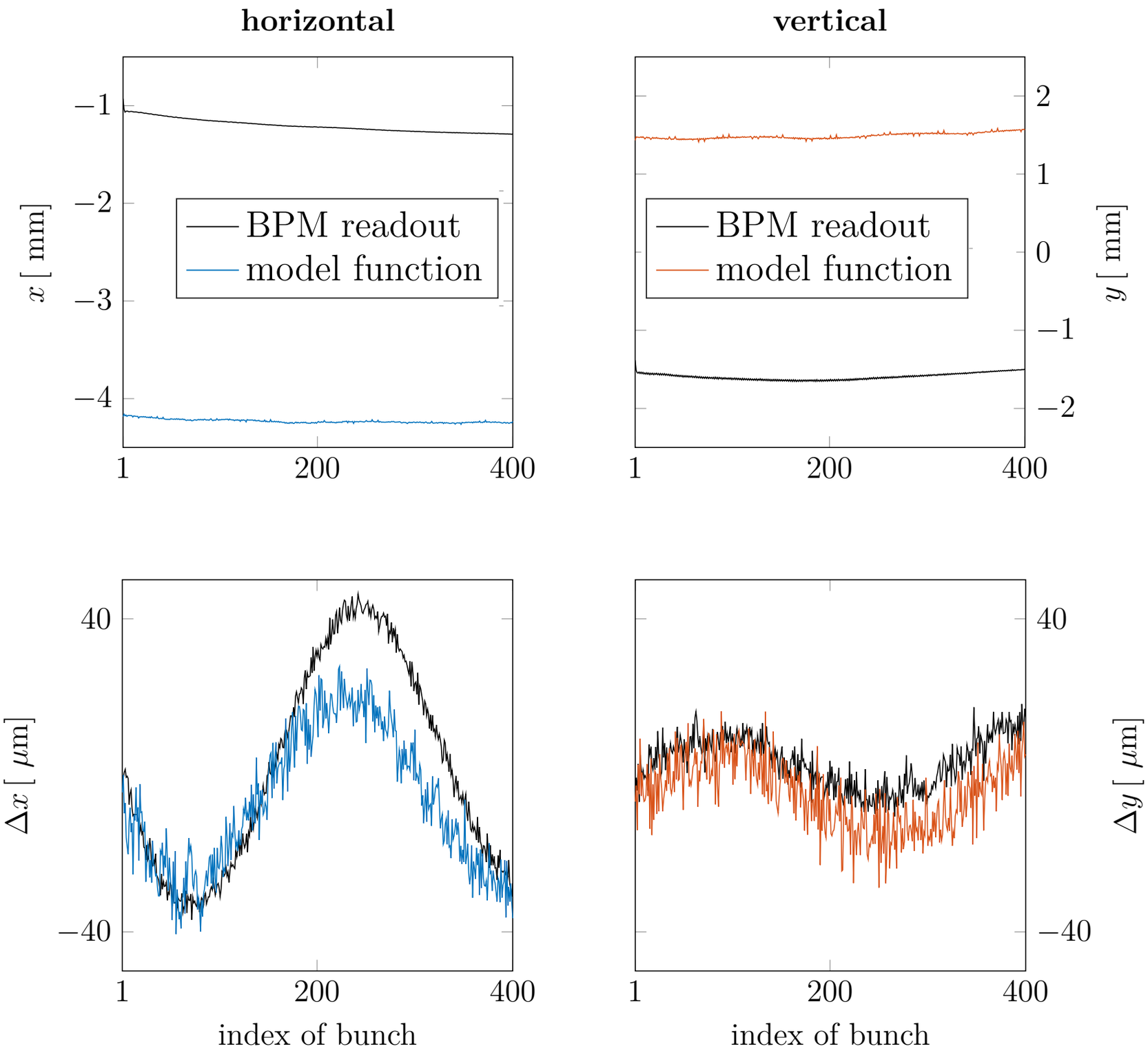
$$\Delta V_0 = 1\,\mathrm{MV/m}$$



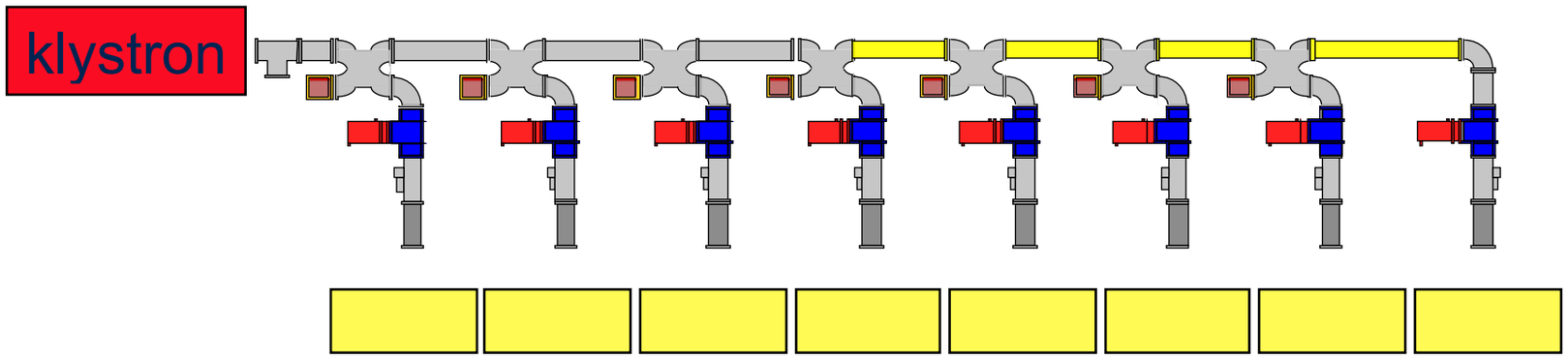
coupler kicks

Appendix

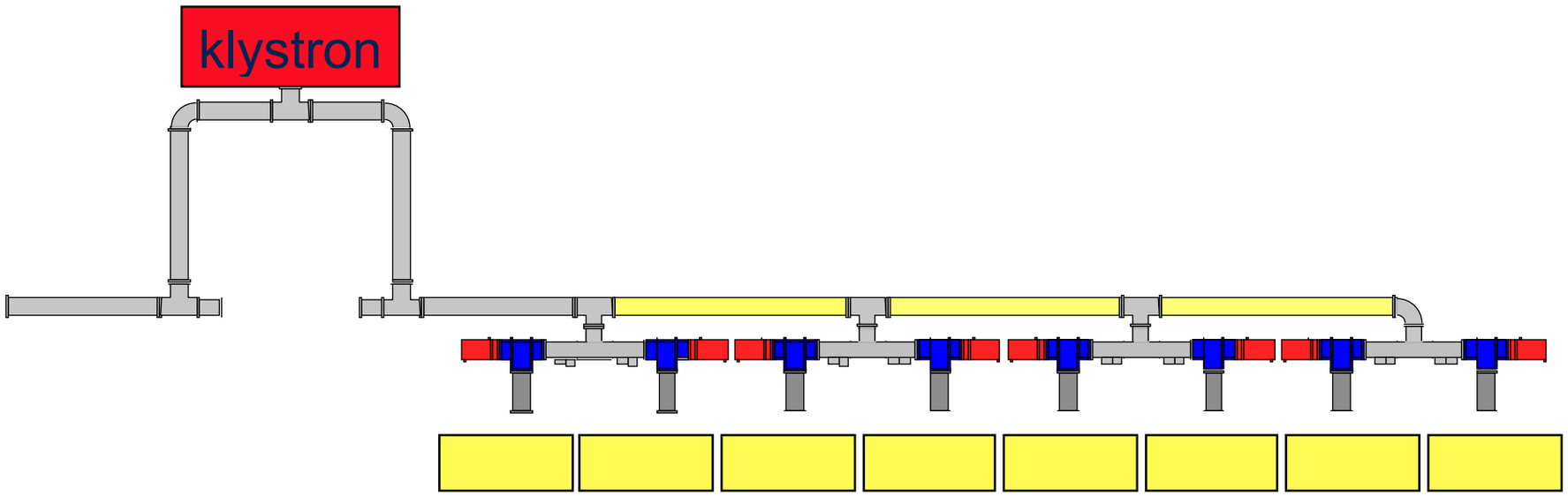
experimental



FLASH

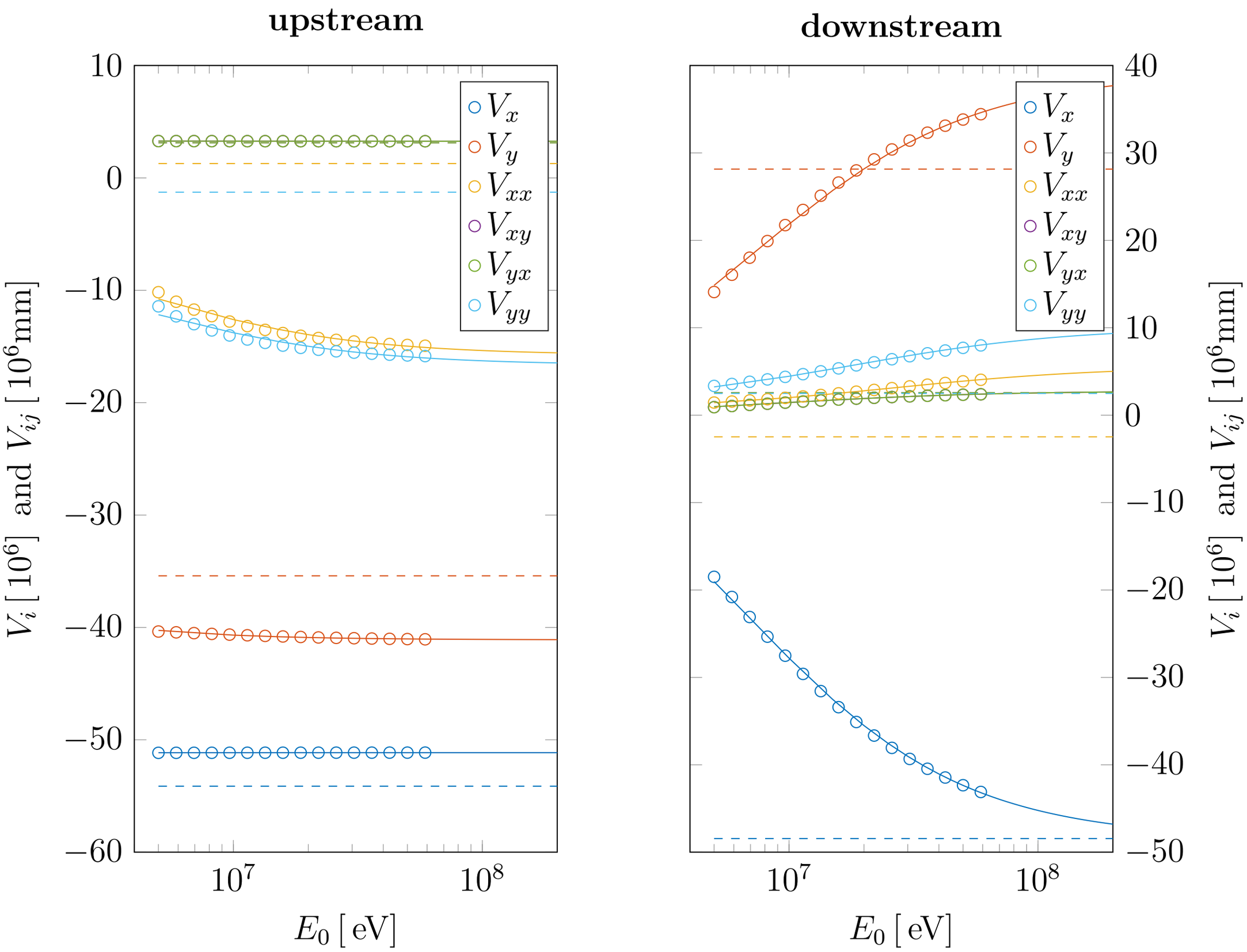


XFEL



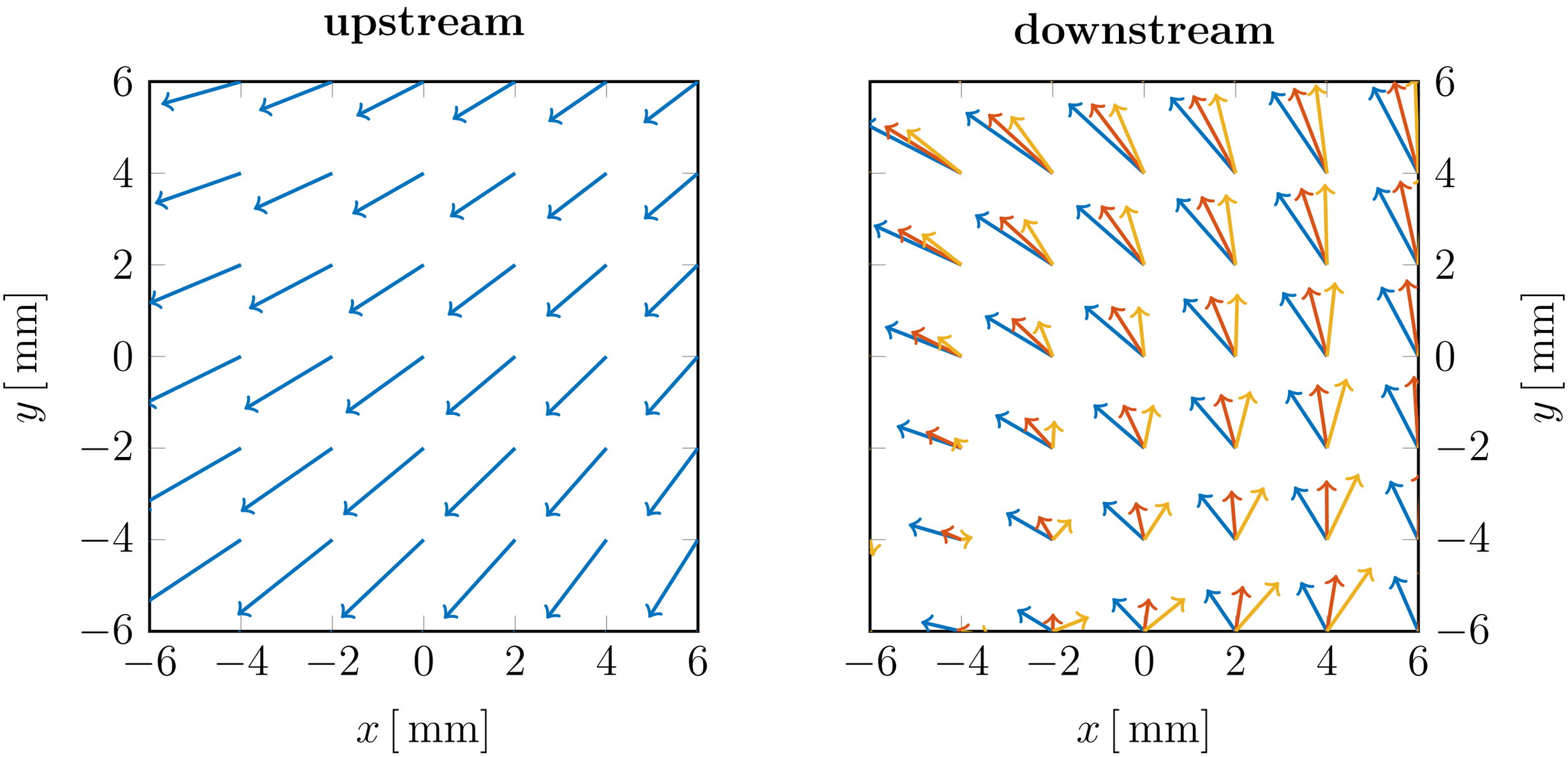
Appendix

coupler kick coefficients

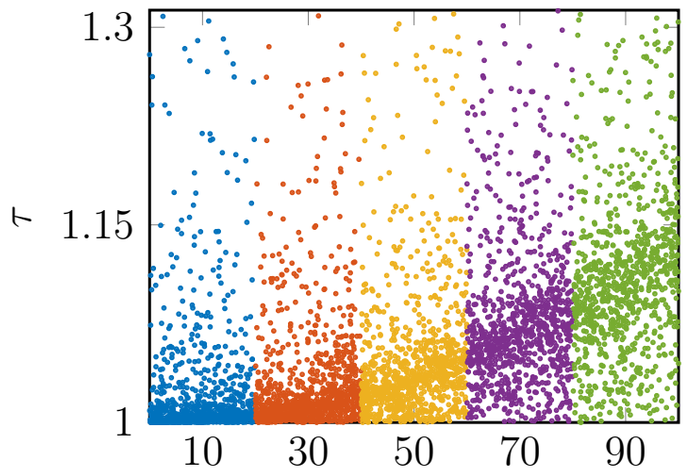
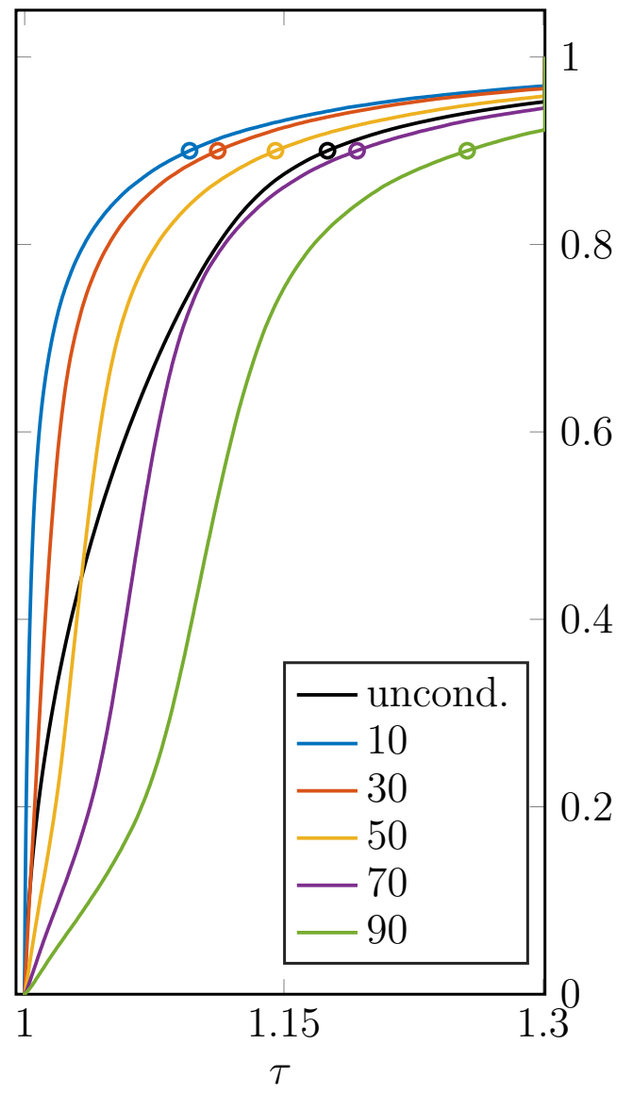
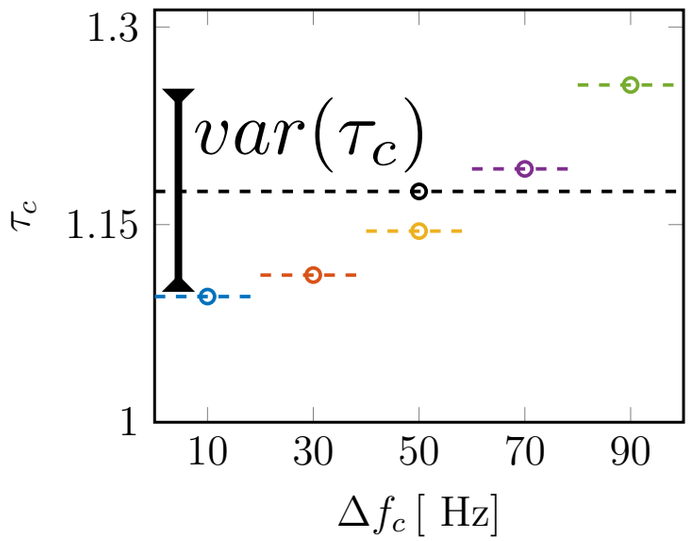


Appendix

coupler kicks



CDF

data evaluation

- figure of merit: $\tau = \dfrac{\epsilon_{SB}}{\epsilon_{MB}}$
- calculate $\tau(\Delta V_0, \Delta f, ...)$
- ***cumulative distribution function (CDF)***
- CDF(τ_c) = 0.9
- *sort* τ *by* Δf
- get conditional CDF
- analyse $\tau_c(\Delta f)$
- first order sensitivity analysis
- ***find influential parameters***