Closed orbit feedback (COFB) system at GSI SIS18

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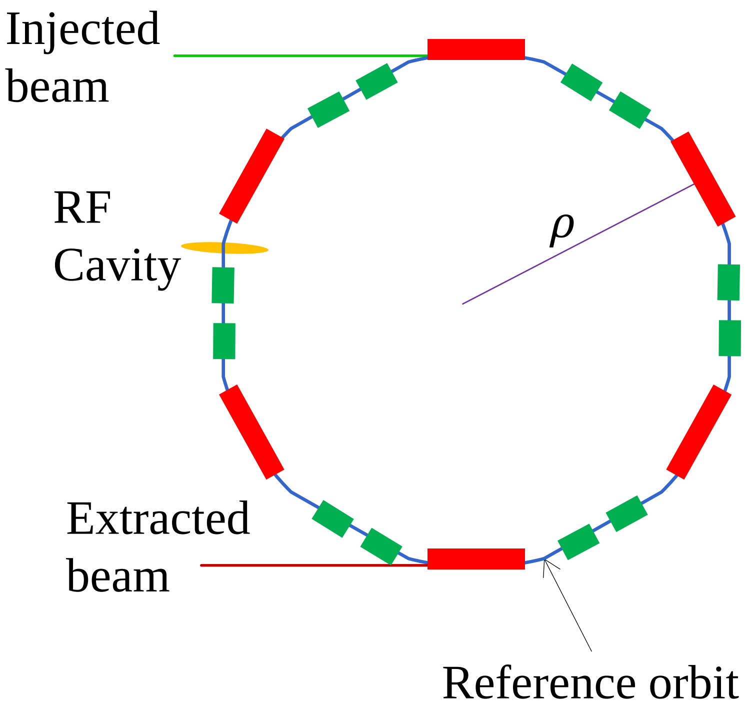
Outline

- **Introduction**
  - Introduction to closed orbit in a synchrotron
  - Closed orbit perturbation
  - Typical examples of closed orbit perturbations in GSI
- **Closed orbit correction methods**
- **Closed control loop**
- **What's new in SIS18 COFB?**
- **Model errors**
- **Dispersion**
- **Project status**
- **Conclusions**
- **Outlook**

Guide fields and equations of motion



Dipole

Bending Guide field

$$\boxed{B\,\rho = \frac{p}{q}}$$

Nominal momentum

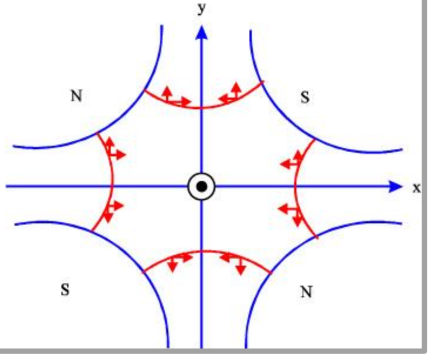
Charge

Bending radius

Quadrupole Focusing Guide field

$$K_x = \frac{dB_y}{dx}/B\rho$$

$$K_y = \frac{dB_x}{dy}/B\rho$$



Hill's equation for on-momentum particle for $K_{x,y}(s) = K_{x,y}(s+L)$

$$x'' = \left(\frac{1}{\rho^2} - K_x(s)\right) x$$

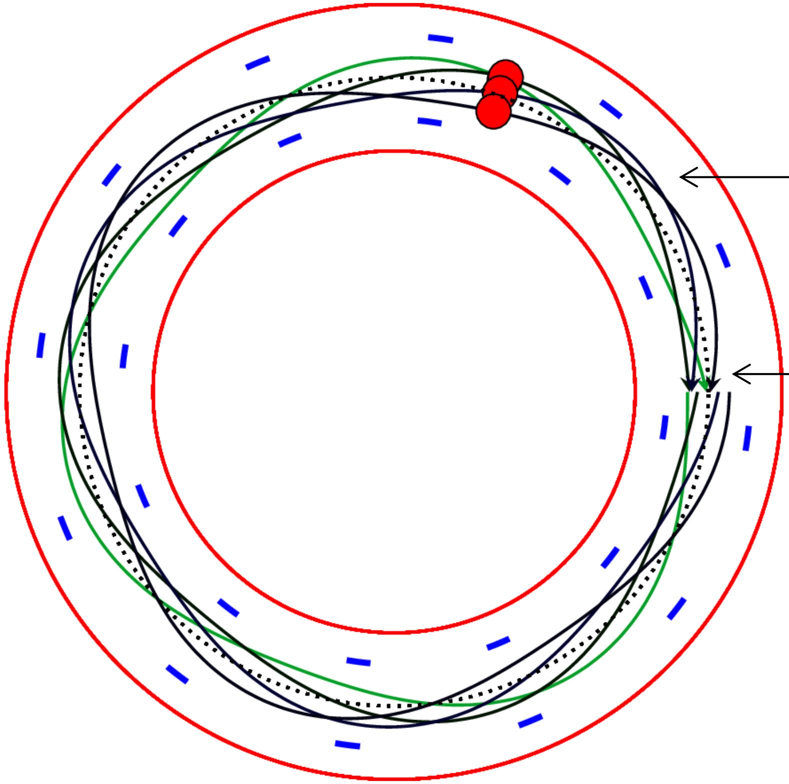
$$y'' = K_y(s) y$$

Solution $y = \sqrt{\epsilon\beta_y(s)}\cos(\mu_y(s) - \delta)$

where $\mu(s) = \int_0^s \frac{1}{\beta(s)} ds$

$\beta(s)$ have the same periodicity in space as $K(s)$

Single particle motion and closed orbit



Betatron motion

non-closed orbits due to non-integer betatron frequency called tune Q

$$y = \sqrt{\epsilon\beta_y(s)}\cos(\mu_y(s) - \delta)$$

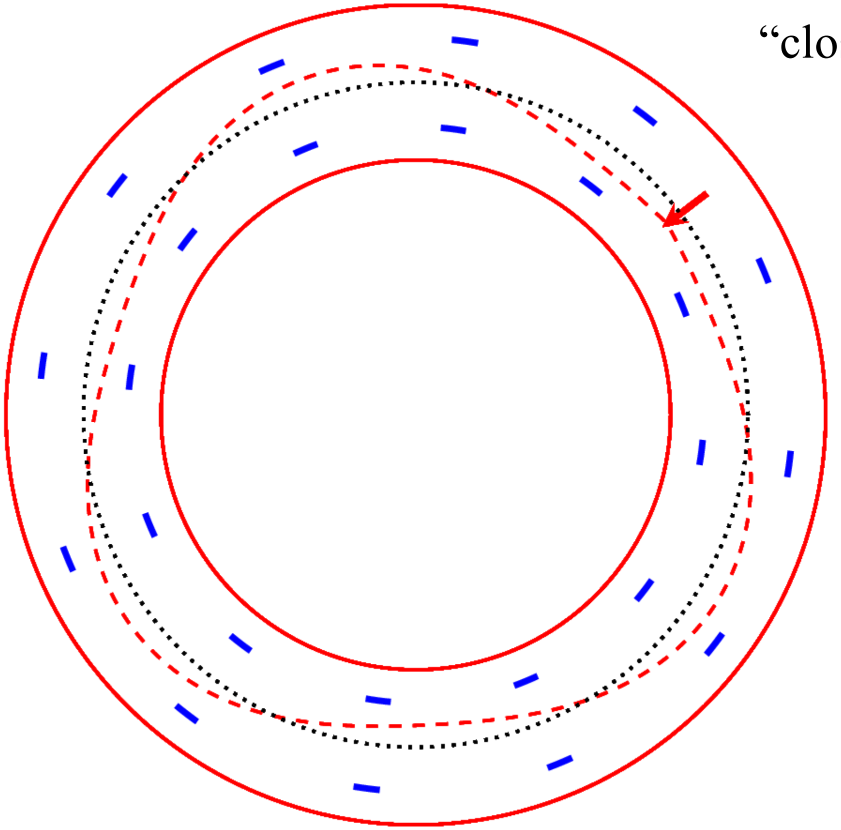
$$\mu(s) = \int_0^s \frac{1}{\beta(s)} ds$$

Closed orbit is measured by averaging the turn by turn orbit over ~ 1000 turns

Why is Closed orbit important?

M.Sands, The Physics of Electron Storage Rings: An Introduction, Conf. Proc. C6906161

Field errors and Closed orbit perturbation



"closed orbit" closes back at the location of field error

$$\{\, y_c(0) = y_c(L) \quad y'_c(0) = y'_c(L) + \theta \}$$

for s ≠0, the perturbed reference orbit has free betatron oscillations and non-integral frequency

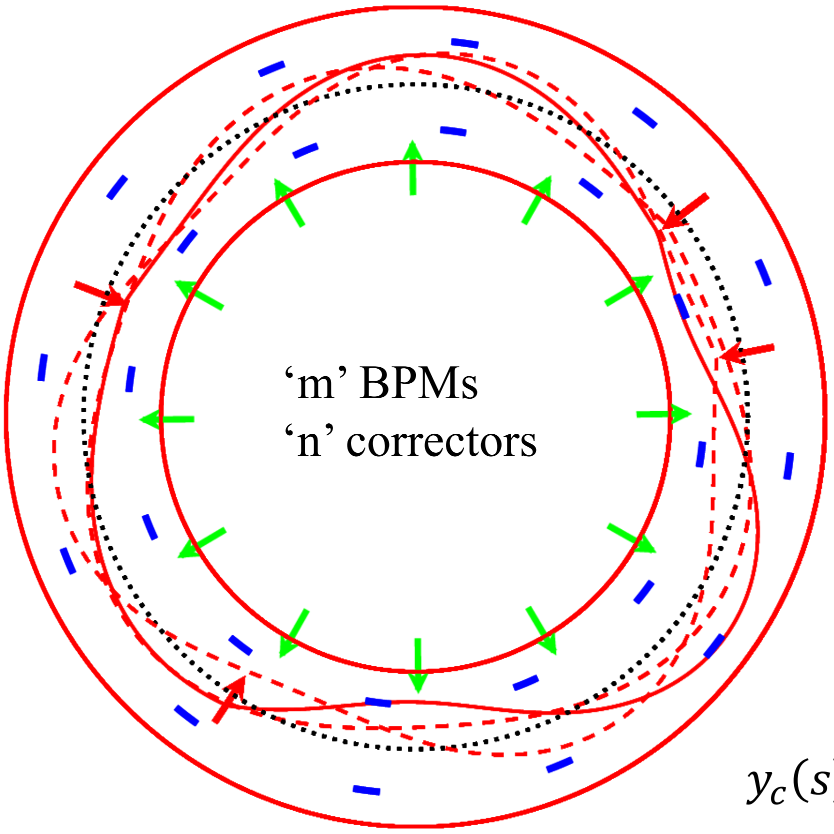
$$y(s \neq) = \sqrt{\epsilon \beta_y(s)} \cos(\mu_y(s) - \delta)$$

Solution of Hill's equation in this case

$$y_c(s) = \theta \frac{\sqrt{\beta(s_0)\beta(s)}}{2\sin(\pi Q_y)} \cos(|\mu(s) - \mu_{s0}| - \pi Q_y)$$

θ is the kick provided by field error
$\beta(s)$ is the beta function at kick location
$\mu(s)$ is the phase advance
Q is the tune of the machine

Closed orbit perturbation (distortion)



Single error perturbed orbit is

$$y_c(s) = \theta \frac{\sqrt{\beta(s_0)\beta(s)}}{2\sin(\pi Q_y)} \cos(|\mu(s) - \mu_{s0}| - \pi Q_y)$$

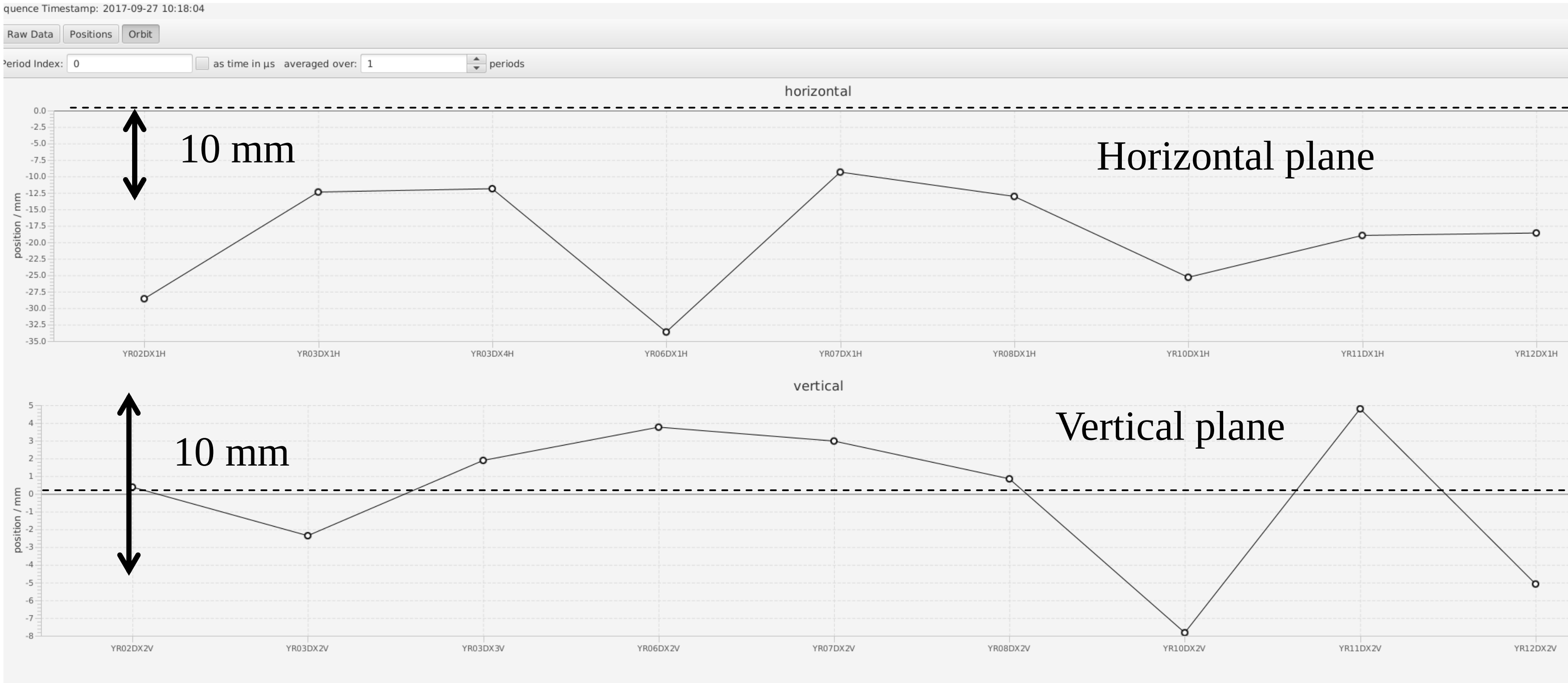
θ is the kick provided by field error
$\beta(s)$ is the beta function at kick location
$\mu(s)$ is the phase advance
Q is the tune of the machine

$$y_c(s) = \sum_{i=1}^{N} \theta_i \frac{\sqrt{\beta(s_i)\beta(s)}}{2\sin(\pi Q_y)} \cos(|\mu(s) - \mu_{si}| - \pi Qy)$$

R is called the orbit response matrix

$$[\mathbf{Y}]_{\boldsymbol{m}\times\mathbf{1}} = [\boldsymbol{R}]_{\boldsymbol{m}\times\boldsymbol{n}}[\Theta]_{\boldsymbol{n}\times\mathbf{1}}$$

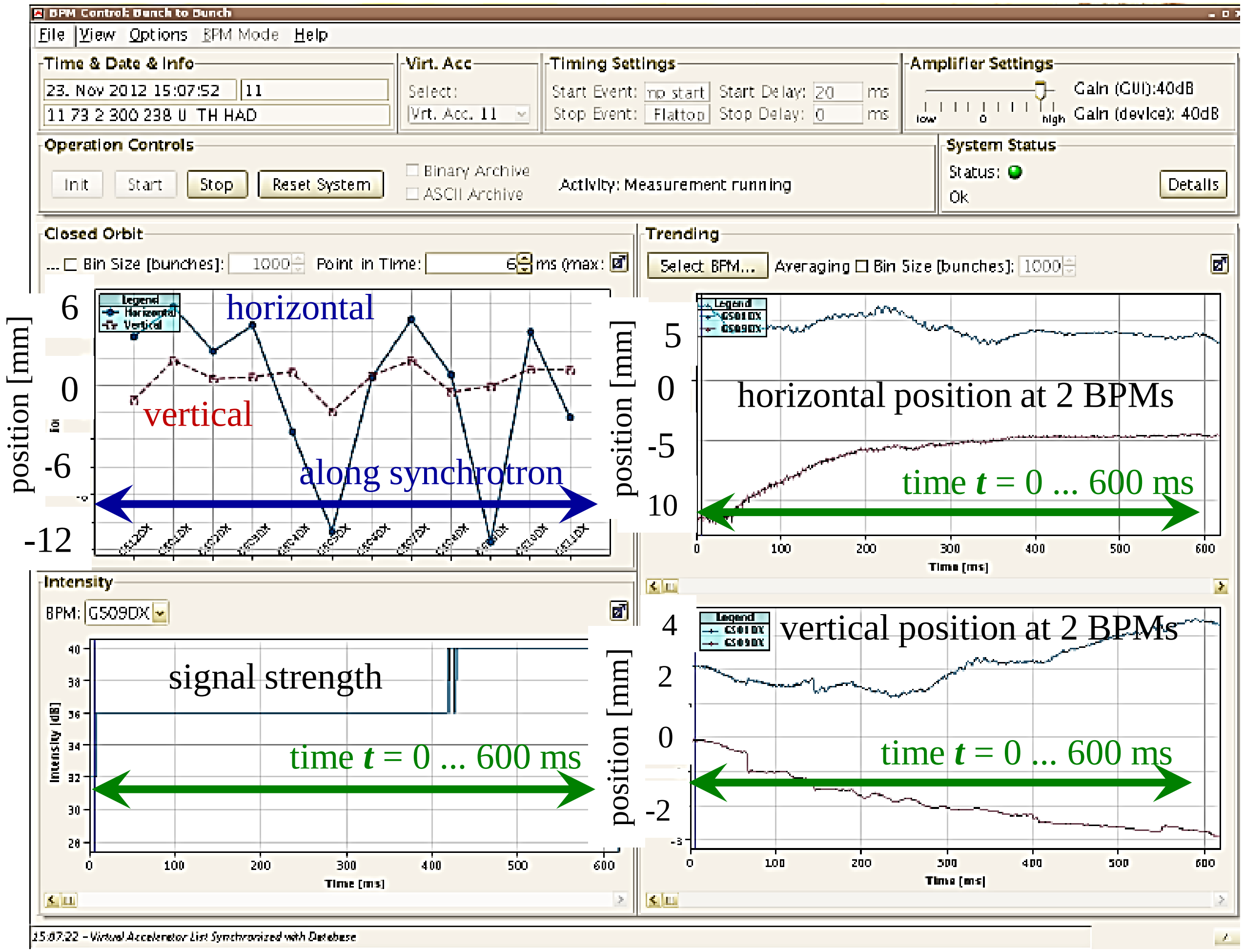
Closed orbit during CRYRING commissioning



- Dotted lines is the “reference or desired orbit”
- Injection is in horizontal plane, mismatched injection and wrong energy settings

Closed orbit distortions in SIS18

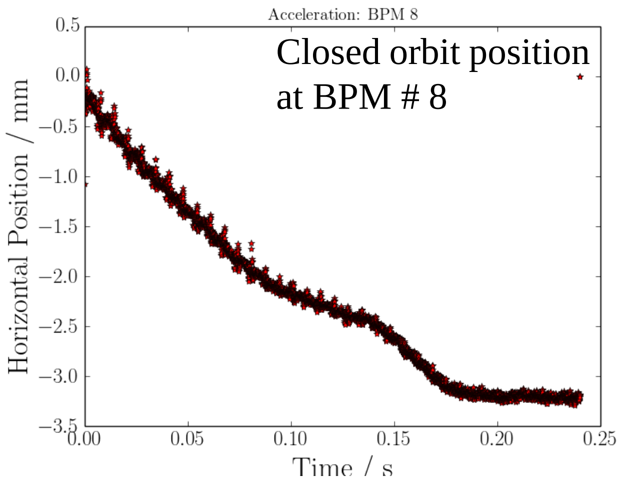
1000 turn average during acceleration



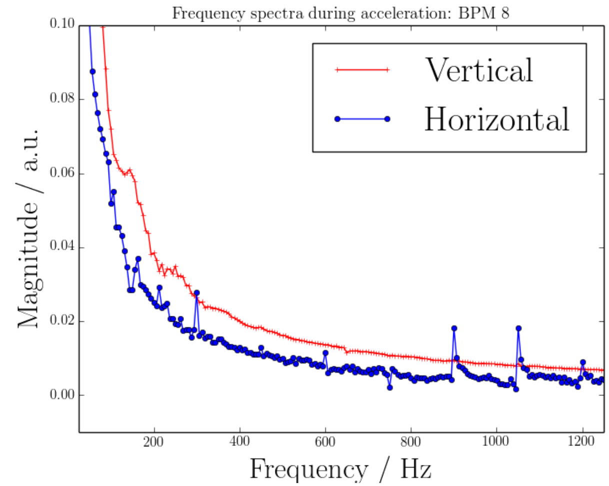
Lectures notes on “Pick-ups for bunched beams” by P. Forck in JUAS

Beam perturbations in SIS18 during ramp and injection

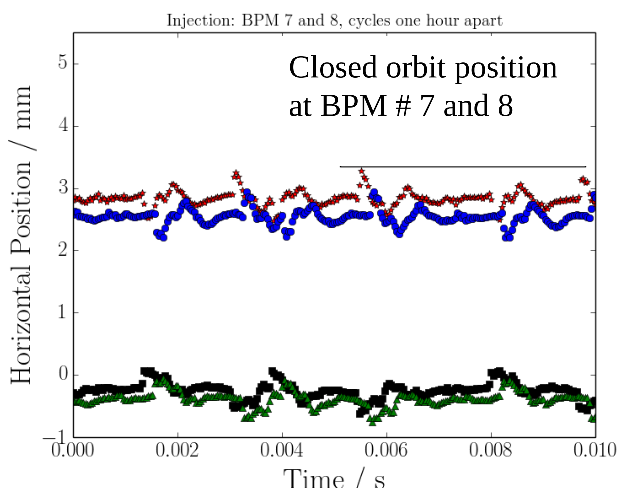
Ramp



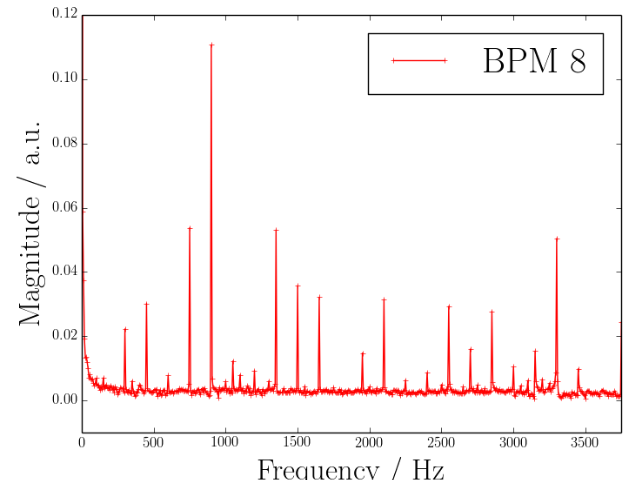
Fourier transform



Injection



Fourier transform



Next topic

- Introduction
- **Closed orbit correction methods**
  - General concept of correction
  - Local bump based correction method
  - Harmonic correction method
  - Singular value decomposition based correction
  - A new DFT based correction method and application
- Closed control loop
- What's new in SIS18 COFB?
- Model errors
- Dispersion
- Project status
- Conclusions
- Outlook

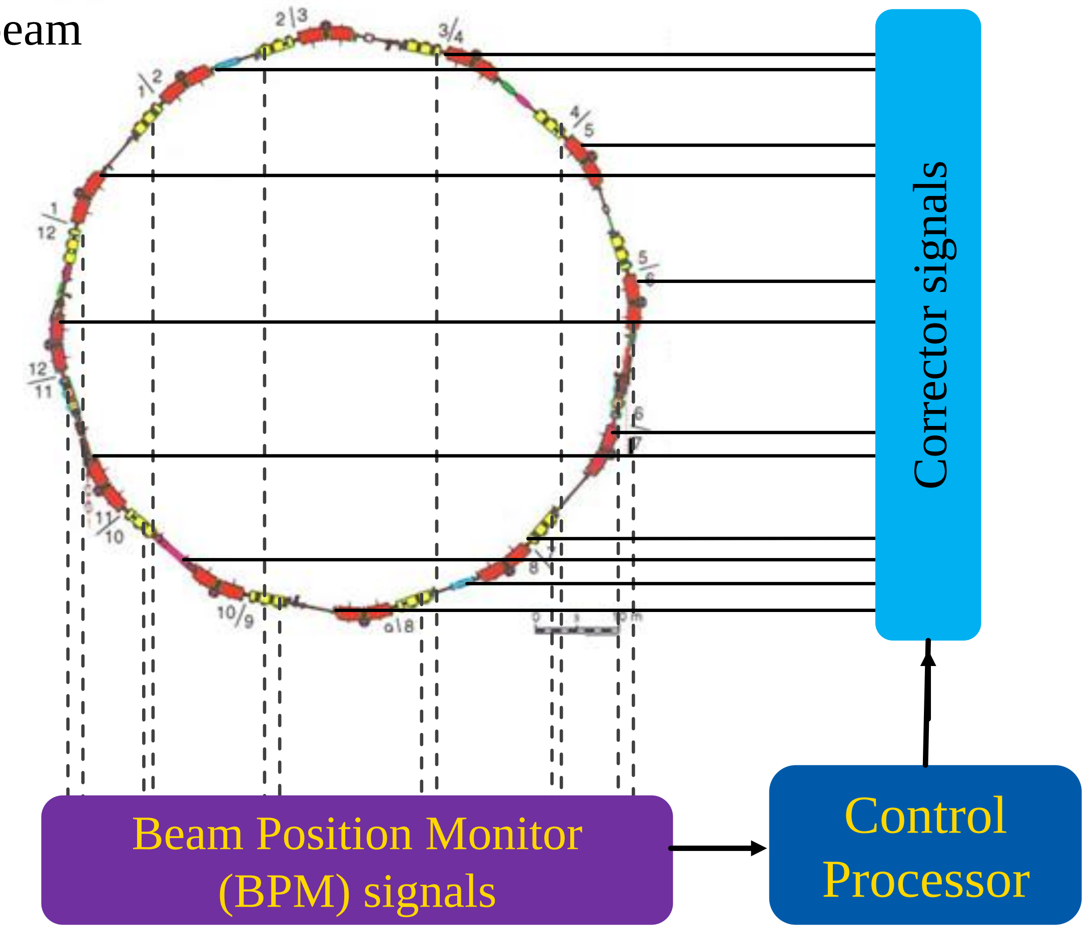
General concept of COFB System in a Synchrotron

BPMs (typically N ∝ 4×tune) read the beam position which is averaged over ~ 1000 turns to estimate the closed orbit.

Controller calculates the required corrector strengths to suppress the oscillations at the required bandwidth

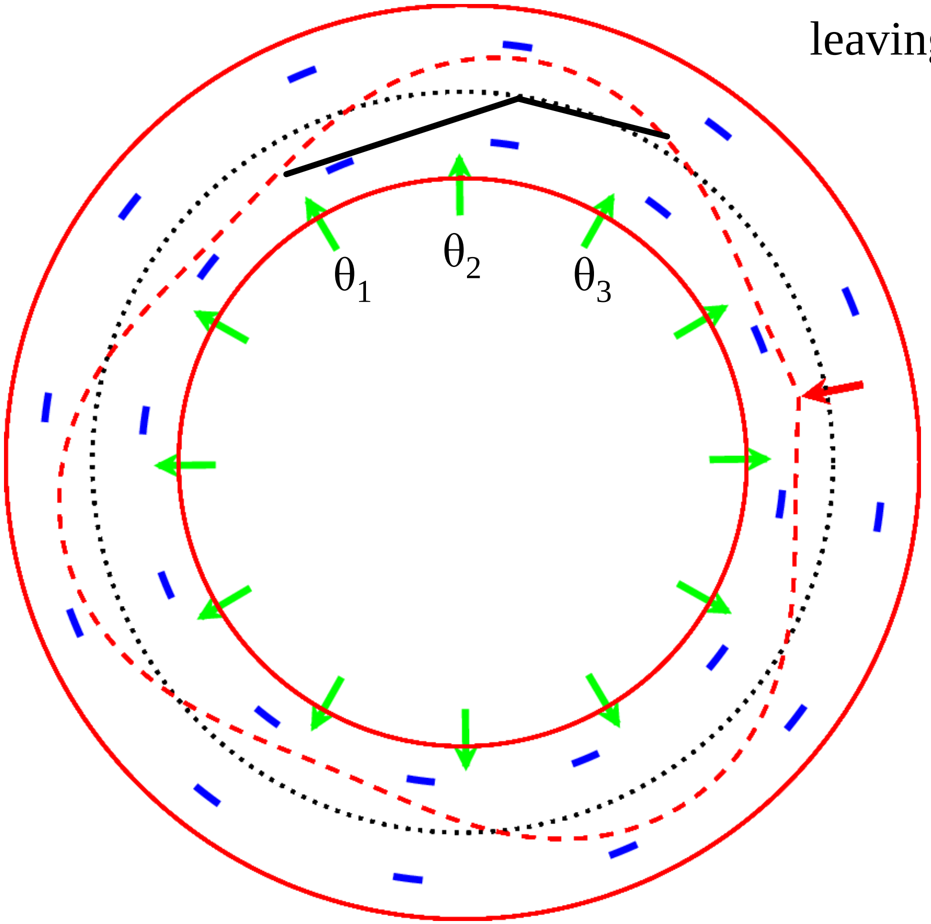
Correctors are dipole magnets whose strength is regarded as angles θ_i given to the beam

$$\theta_i \propto B_{kicker}$$



Note: Diagrams not fit to scale

Local bump orbit correction (Concept of orbit correction)



Correct orbit at one BPM using three steerers while leaving the rest of orbit untouched

$$\theta_2 = -\theta_1 \sqrt{\frac{\beta_1}{\beta_2}} \frac{\sin \mu_{31}}{\sin \mu_{32}}$$

$$\theta_3 = -\theta_1 \sqrt{\frac{\beta_1}{\beta_3}} \frac{\sin \mu_{21}}{\sin \mu_{32}}$$

Repeat the procedure for all BPM positions iteratively until some minimum is reached

So called Sliding bump method!

Was in use at GSI till last beam time!

PhD thesis “Linear and non-linear response matrix and its application to the SIS18 Synchrotron ” by Angelina

Local bump orbit correction in SIS18 (Simulation in MADX)

First bump $\theta'_1 \quad \theta'_2 \quad \theta'_3$

Second bump $\theta''_2 \quad \theta''_3 \quad \theta''_4$

Third bump $\theta'''_3 \quad \theta'''_4 \quad \theta'''_5$

$$\theta'_2 = -2\theta'_1 \cos\Delta\mu$$

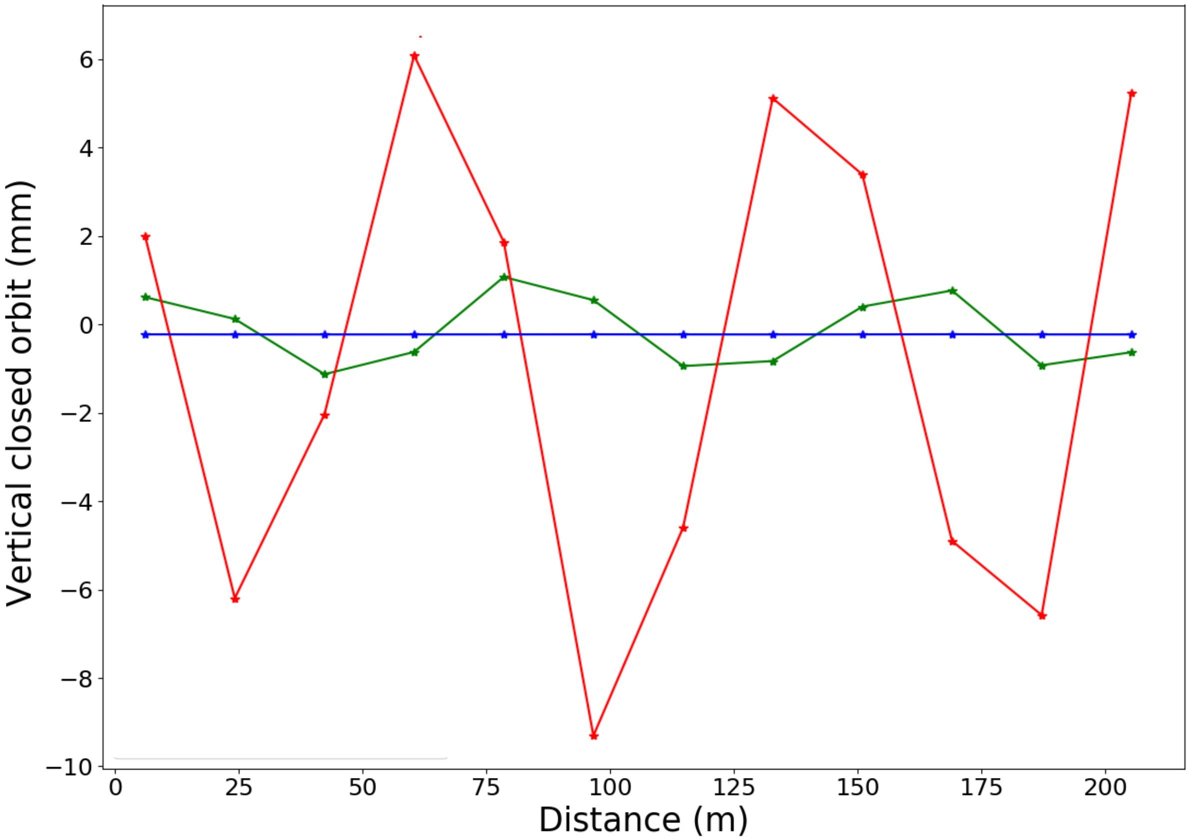
$$\theta'_3 = -\theta'_1$$

$$\theta''_3 = -2\theta''_2 \cos\Delta\mu$$

$$\theta''_4 = -\theta''_2$$

$$\theta'''_4 = -2\theta'''_3 \cos\Delta\mu$$

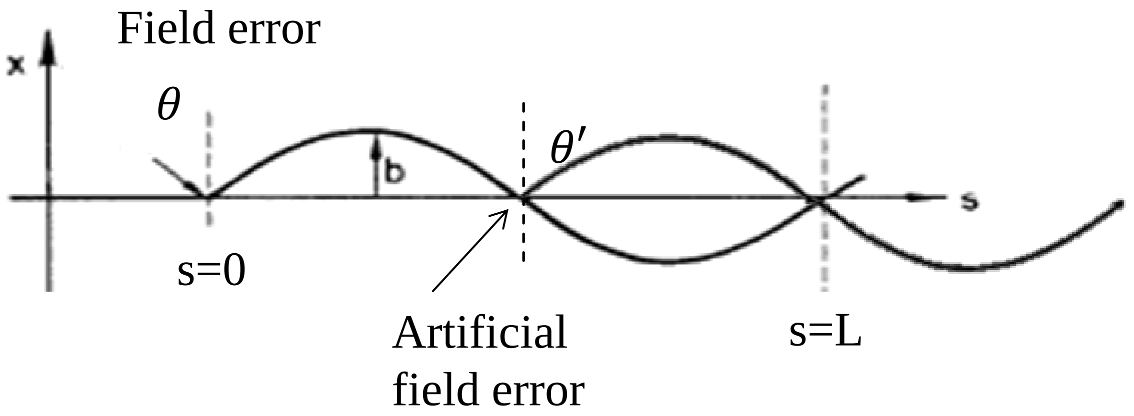
$$\theta'''_5 = -\theta'''_3$$



Cross talk between local bumps
Less degrees of freedom
Out of 12 correctors, only 10 can be independent

Concept of global correction

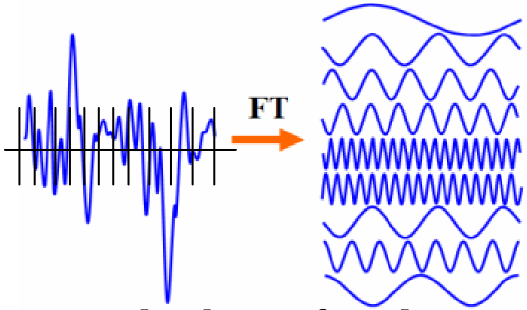
Sinusoidal approximation of disturbance removal



Number and position of BPMs and steerers is important!

Harmonic analysis (global correction)

$$y_c(s) = \theta \frac{\sqrt{\beta(s_0)\beta(s)}}{2\sin(\pi Q_y)} \cos(|\mu(s) - \mu_{s0}| - \pi Q_y)$$



Perturbed orbit can be Fourier expanded

Modes to be removed (corrected) are selected before-hand and measured orbit is fitted over corresponding mode e.g. modes around tune frequency.

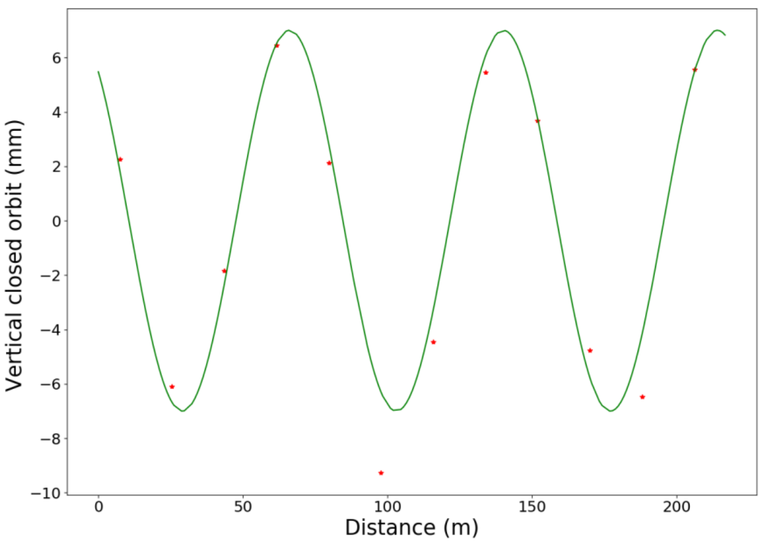
Corresponding Fourier coefficients are measured and made zero

$$y_i = \sum_{k=1}^{n} (a_k \cos k\varphi + b_k \sin k\varphi)$$

Corrector strengths are proportional to the Fourier coefficients

Mode switching is possible because of separate channels for each mode

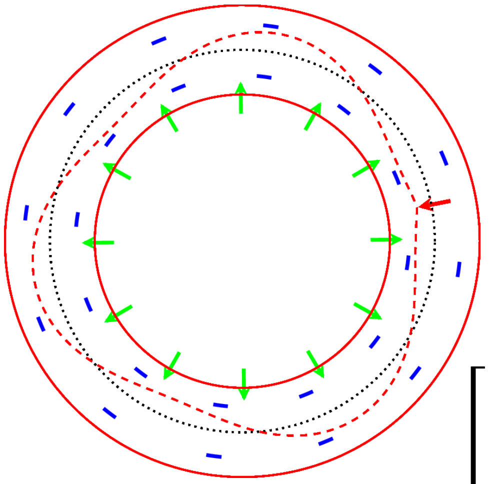
Fitting for each mode is mathematically complicated procedure



L.H.Yu et al.“Real time harmonic closed orbit correction”, Nucl. Instr. Meth. A, vol. 284, pp. 268–285, 1989

Orbit response matrix (ORM) based correction

Matrix containing proportionality constants can be calculated or measured separately



$$[\mathbf{Y}]_{m\times1} = [\boldsymbol{R}]_{m\times n}[\Theta]_{n\times1}$$

$$\begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ \cdot \\ \cdot \\ \cdot \\ Y_{m-1} \\ Y_m \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & R_{13} & \cdots & R_{1n} \\ R_{21} & R_{22} & R_{23} & \cdots & R_{2n} \\ R_{31} & R_{32} & R_{33} & \cdots & R_{3N} \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & \cdot & \ddots & \cdot \\ \cdot & \cdot & \cdot & & \cdot \\ R_{m-1,1} & R_{m-1,2} & R_{m-1,3} & \cdots & R_{m-1,n} \\ R_{m1} & R_{m2} & R_{m3} & \cdots & R_{mn} \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \cdot \\ \cdot \\ \cdot \\ \theta_{n-1} \\ \theta_n \end{bmatrix}$$

R is called orbit response matrix

(ORM)

Y. Chung, "Closed orbit correction using singular value decomposition of the response matrix", (Argonne National Laboratory, IL, 1993)

Orbit response matrix (ORM) based correction

For a given perturbed orbit, we calculate the corrector strengths which could be responsible for the given perturbations

$$\begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ . \\ . \\ . \\ \theta_{n-1} \\ \theta_n \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & R_{13} & \cdots & R_{1n} \\ R_{21} & R_{22} & R_{23} & \cdots & R_{2n} \\ R_{31} & R_{32} & R_{33} & \cdots & R_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ R_{m-1,1} & R_{m-1,2} & R_{m-1,3} & \cdots & R_{m-1,n} \\ R_{m1} & R_{m2} & R_{m3} & \cdots & R_{mn} \end{bmatrix}^{-1} \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ . \\ . \\ . \\ Y_{m-1} \\ Y_m \end{bmatrix}$$

Then apply the negatives of the calculated corrector strengths

$$\begin{bmatrix} -\theta_1 \\ -\theta_2 \\ -\theta_3 \\ . \\ . \\ . \\ -\theta_{n-1} \\ -\theta_n \end{bmatrix}$$

1. ORM is not always invertible (for example rectangular)
2. Calculated corrector values are beyond the corrector magnet range

SVD for ~ ill conditioned ORMs

SVD -> Quite popular in Darmstadt region

SPORTVEREIN
DARMSTADT 1898 e.V.

Singular Value Decomposition (SVD)

$$R = USV^T$$

$$\begin{bmatrix} R_{11} & \cdots & R_{1n} \\ \vdots & \ddots & \vdots \\ R_{m1} & \cdots & R_{mn} \end{bmatrix} = \begin{bmatrix} U_{11} & \cdots & U_{1m} \\ \vdots & \ddots & \vdots \\ U_{m1} & \cdots & U_{mm} \end{bmatrix} \begin{bmatrix} s_1 & \cdots & 0 \\ \vdots & s_2 & \vdots \\ 0 & \cdots & s_n \end{bmatrix} \begin{bmatrix} V_{11} & \cdots & V_{1n} \\ \vdots & \ddots & \vdots \\ V_{n1} & \cdots & V_{nn} \end{bmatrix}^T$$

s_i are called singular values arranged as $s_1 > s_2 > s_3 \ldots . s_n$

U and V are orthogonal matrices such that

$$U^{-1} = U^T \text{ and } V^{-1} = V^T$$

where the columns of U and V are the eigenvectors of RR^T and R^TR

Which helps to find inverse R^{-1} (if R is invertible) as

Pseudo-inverse

$$\begin{bmatrix} R_{11} & \cdots & R_{1n} \\ \vdots & \ddots & \vdots \\ R_{m1} & \cdots & R_{mn} \end{bmatrix}^{-1} = \begin{bmatrix} V_{11} & \cdots & V_{1m} \\ \vdots & \ddots & \vdots \\ V_{m1} & \cdots & V_{mm} \end{bmatrix} \begin{bmatrix} 1/s_1 & \cdots & 0 \\ \vdots & 1/s_2 & \vdots \\ 0 & \cdots & 1/s_n \end{bmatrix} \begin{bmatrix} U_{11} & \cdots & U_{1n} \\ \vdots & \ddots & \vdots \\ U_{n1} & \cdots & U_{nn} \end{bmatrix}^T$$

William H. Press, Numerical recipes; The art of scientific computing (2007) Cambridge university press

Strengths of SVD

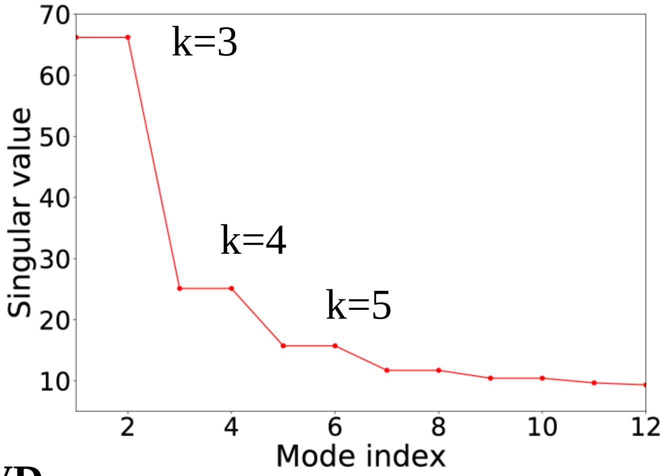
- Columns of U and V are Eigen modes which are orthogonal to each other (linearly independent)
- SVD can decompose and invert (or pseudo-invert) “any” matrix
- A robust algorithm for global orbit correction

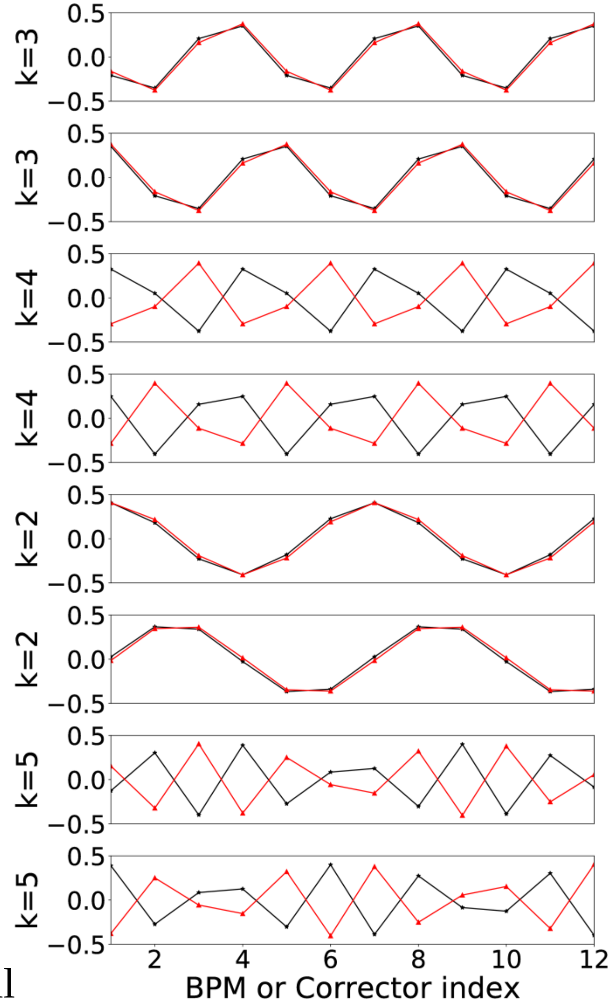
Benefits of SVD over harmonic analysis

- One needs not to select the modes to be corrected before correction: decompose in all possible modes
- “simple” matrix inversion
- Modal correction is still possible through selecting certain eigenvalues

SVD of vertical SIS18 ORM

$Q_y = 3.28$





Columns of U:Black
Columns of V: Red

Weaknesses of SVD

- Time complexity of the order of N^3 , N being dimension of matrix
- Loss of physical meaning of modes
- Phase difference between corresponding U and V columns
- What happens with orbit correction if one or more BPMs fail?
- U, S and V are interconnected so uncertainty modeling required in all three matrices
- Over the ramp, updating of all three matrices required

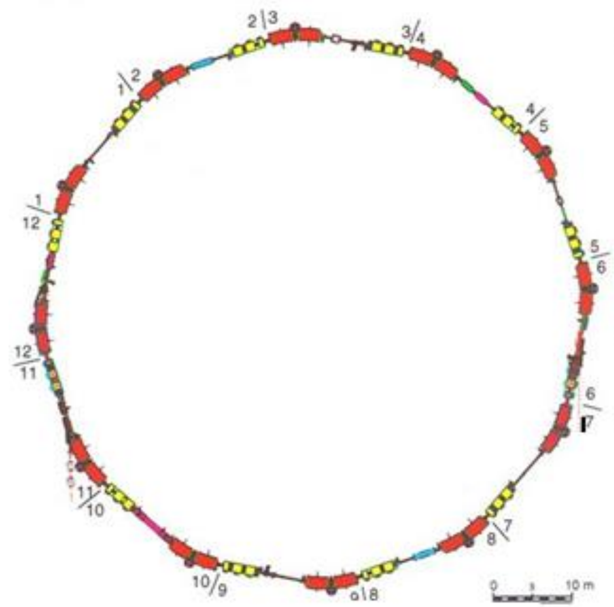
Symmetry exploitation in SIS 18 vertical ORM

$$\beta_{bpm1} = \beta_{bpm2} = \beta_{bpm3} \dots \dots = \beta_{bpm12}$$

$$\beta_{corr1} = \beta_{corr2} = \beta_{corr3} \dots \dots = \beta_{corr12}$$

$$\Delta\mu_{bpm} = constant$$

$$\Delta\mu_{corr} = constant$$



$$R = \begin{bmatrix} R_1 & R_2 & R_3 & R_4 & \cdots & R_n \\ R_n & R_1 & R_2 & R_3 & \cdots & R_{n-1} \\ R_{n-1} & R_n & R_1 & R_2 & \cdots & R_{n-2} \\ R_{n-2} & R_{n-1} & R_n & R_1 & \cdots & R_{n-3} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ R_2 & R_3 & R_4 & R_5 & \cdots & R_1 \end{bmatrix}$$

Each row is cyclic shift of previous row.

All diagonal elements are identical.

Such a square matrix is called **Circulant Matrix**

Reference: Philips J.Davis, Circulant matrices, (1994), Chelsea

Diagonalization Circulant matrix

$$R = \begin{bmatrix} \cancel{R_1} & \cancel{R_2} & \cancel{R_3} & \cancel{R_4} & \cancel{\cdots} & \cancel{R_n} \\ R_n & R_1 & R_2 & R_3 & \cdots & R_{n-1} \\ R_{n-1} & R_n & R_1 & R_2 & \cdots & R_{n-2} \\ R_{n-2} & R_{n-1} & R_n & R_1 & \cdots & R_{n-3} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ R_2 & R_3 & R_4 & R_5 & \cdots & R_1 \end{bmatrix}$$

Inverse is straightforward

$$R^{-1} = F^* H^{-1} F$$

H^{-1} =diag($\frac{1}{\sigma_k}$) ,k=1…n

$$\sigma_k = \sigma_{rk} + j\,\sigma_{ik} = \sum_{n}^{N-1} R_n\, e^{-j2\pi kn/N}$$

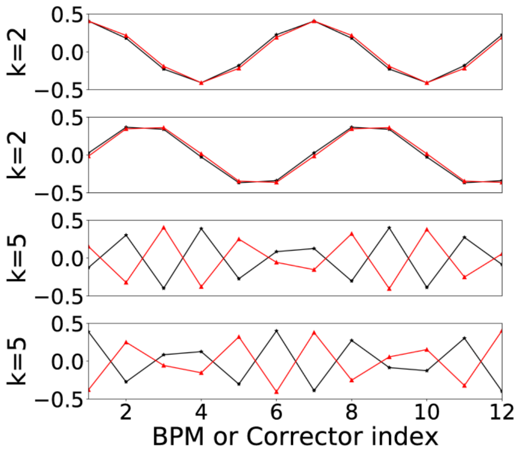
$$\mathrm{R} = \begin{bmatrix} F_{11} & \cdots & F_{1m} \\ \vdots & \ddots & \vdots \\ F_{m1} & \cdots & F_{mm} \end{bmatrix} \begin{bmatrix} \sigma_1 & \cdots & 0 \\ \vdots & \sigma_2 & \vdots \\ 0 & \cdots & \sigma_n \end{bmatrix} \begin{bmatrix} F_{11} & \cdots & F_{1n} \\ \vdots & \ddots & \vdots \\ F_{n1} & \cdots & F_{nn} \end{bmatrix}$$

Standard Fourier matrix containing DFT modes

$$F_k = F_{kc} + jF_{ks} \qquad F_{ks} = \sin\left(\frac{2\pi km}{n} + \varphi_k\right)$$

Equivalence of DFT and SVD

DFT:
$$\begin{bmatrix} R_{11} & \cdots & R_{1n} \\ \vdots & \ddots & \vdots \\ R_{m1} & \cdots & R_{mn} \end{bmatrix} = \begin{bmatrix} F_{11} & \cdots & F_{1m} \\ \vdots & \ddots & \vdots \\ F_{m1} & \cdots & F_{mm} \end{bmatrix} \begin{bmatrix} \sigma_1 & \cdots & 0 \\ \vdots & \sigma_2 & \vdots \\ 0 & \cdots & \sigma_n \end{bmatrix} \begin{bmatrix} F_{11} & \cdots & F_{1n} \\ \vdots & \ddots & \vdots \\ F_{n1} & \cdots & F_{nn} \end{bmatrix}$$



$$\varphi_{dk} = \text{phase}(\sigma_k)$$

$$s_k = |\sigma_k| = \sqrt{{\sigma_{rk}}^2 + {\sigma_{ik}}^2}$$

SVD:
$$\begin{bmatrix} R_{11} & \cdots & R_{1n} \\ \vdots & \ddots & \vdots \\ R_{m1} & \cdots & R_{mn} \end{bmatrix} = \begin{bmatrix} U_{11} & \cdots & U_{1m} \\ \vdots & \ddots & \vdots \\ U_{m1} & \cdots & U_{mm} \end{bmatrix} \begin{bmatrix} s_1 & \cdots & 0 \\ \vdots & s_2 & \vdots \\ 0 & \cdots & s_n \end{bmatrix} \begin{bmatrix} V_{11} & \cdots & V_{1n} \\ \vdots & \ddots & \vdots \\ V_{n1} & \cdots & V_{nn} \end{bmatrix}$$

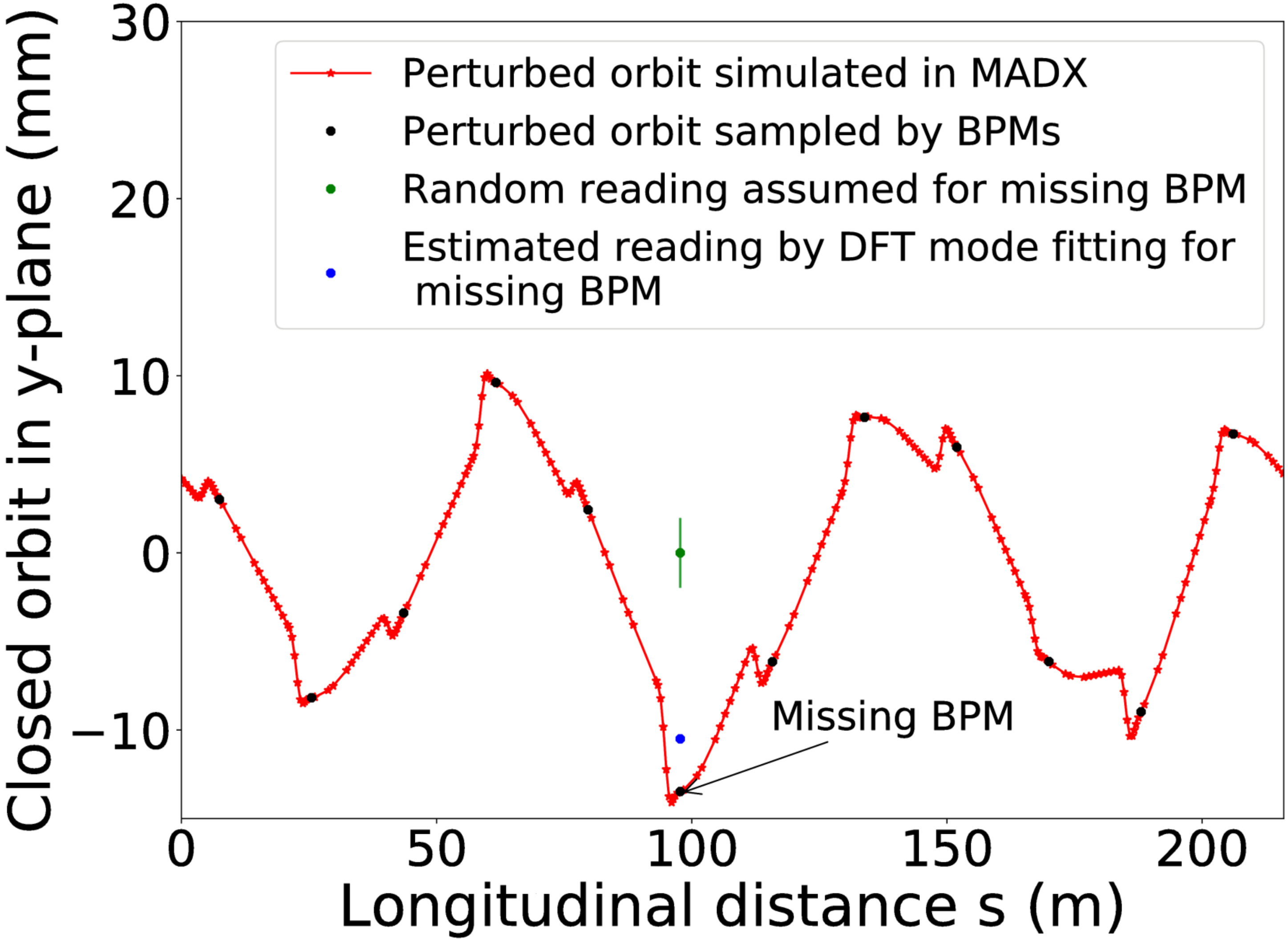
Why to do SVD when Circulant symmetry exits?

One quick application: Missing BPM scenario

$$F_{ks} = \sin\left(\frac{2\pi km}{n} + \varphi_k\right)$$

$$F_{kc} = \cos\left(\frac{2\pi km}{n} + \varphi_k\right)$$

Fit the measured orbit at functioning BPMs and fit over dominant Fourier modes



One quick application: Missing BPM scenario

$$F_{ks} = \sin\left(\frac{2\pi km}{n} + \varphi_k\right)$$

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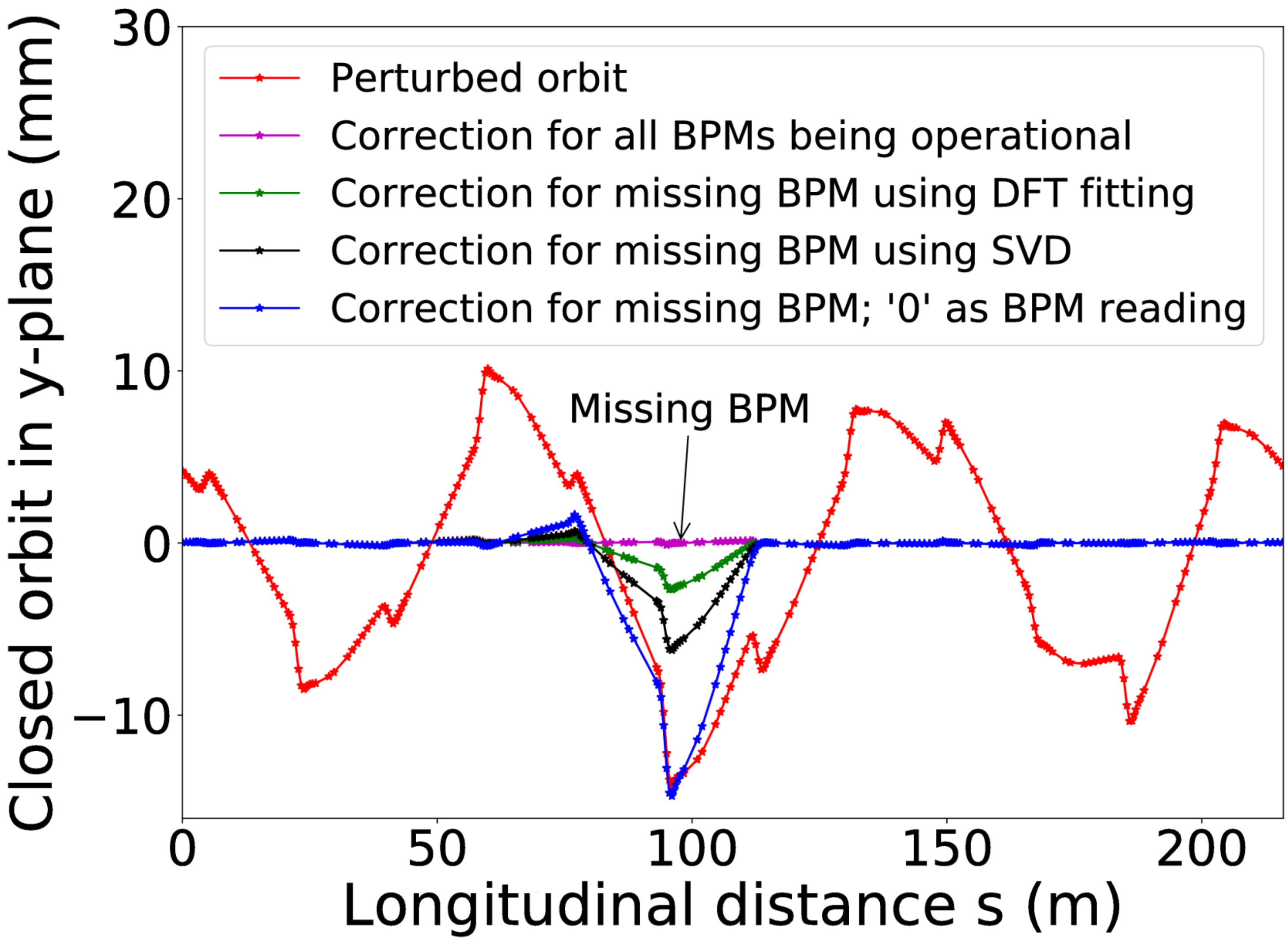
Fit the measured orbit at functioning BPMs and fit over dominant Fourier modes



Next topic

- Introduction
- Closed orbit correction methods
- **Closed control loop**
  - Feedback loop
  - System identification for controller design
  - PID controllers
- What’s new in SIS18 COFB?
- Model errors
- Dispersion
- Project status
- Conclusions
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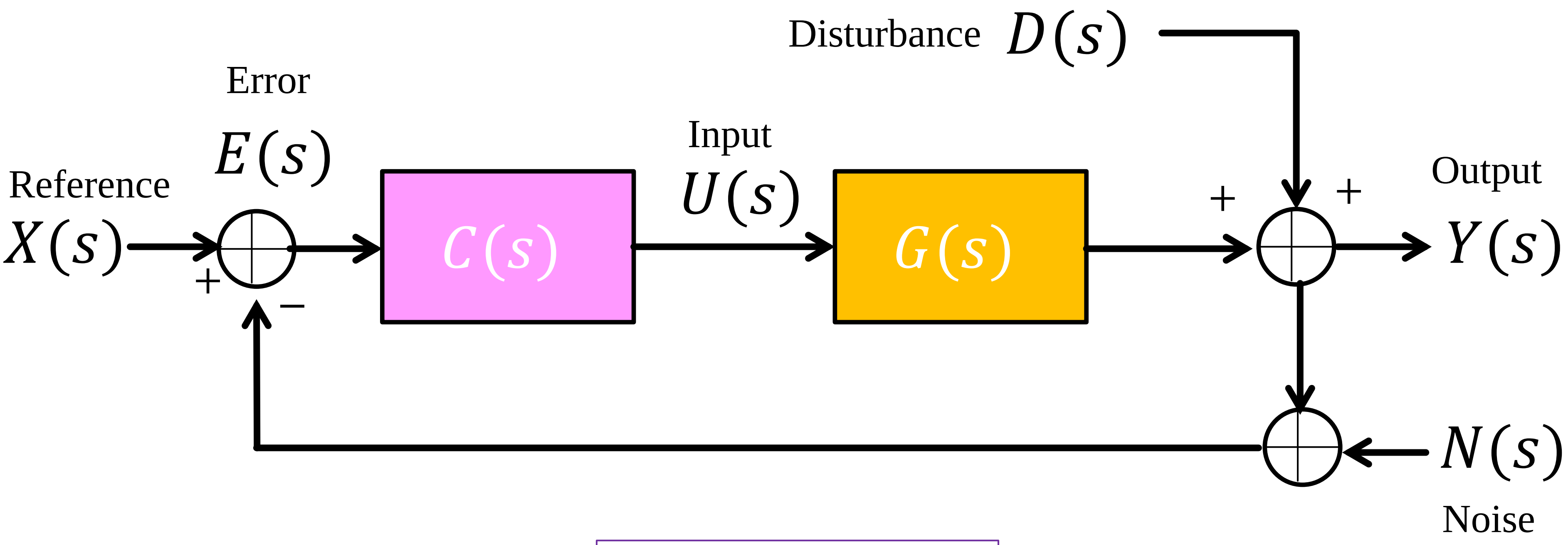
Feedback loop in orbit correction



$$\mathbf{G(s)} = \boldsymbol{g}\mathbf{(s)}\ \boldsymbol{R}$$

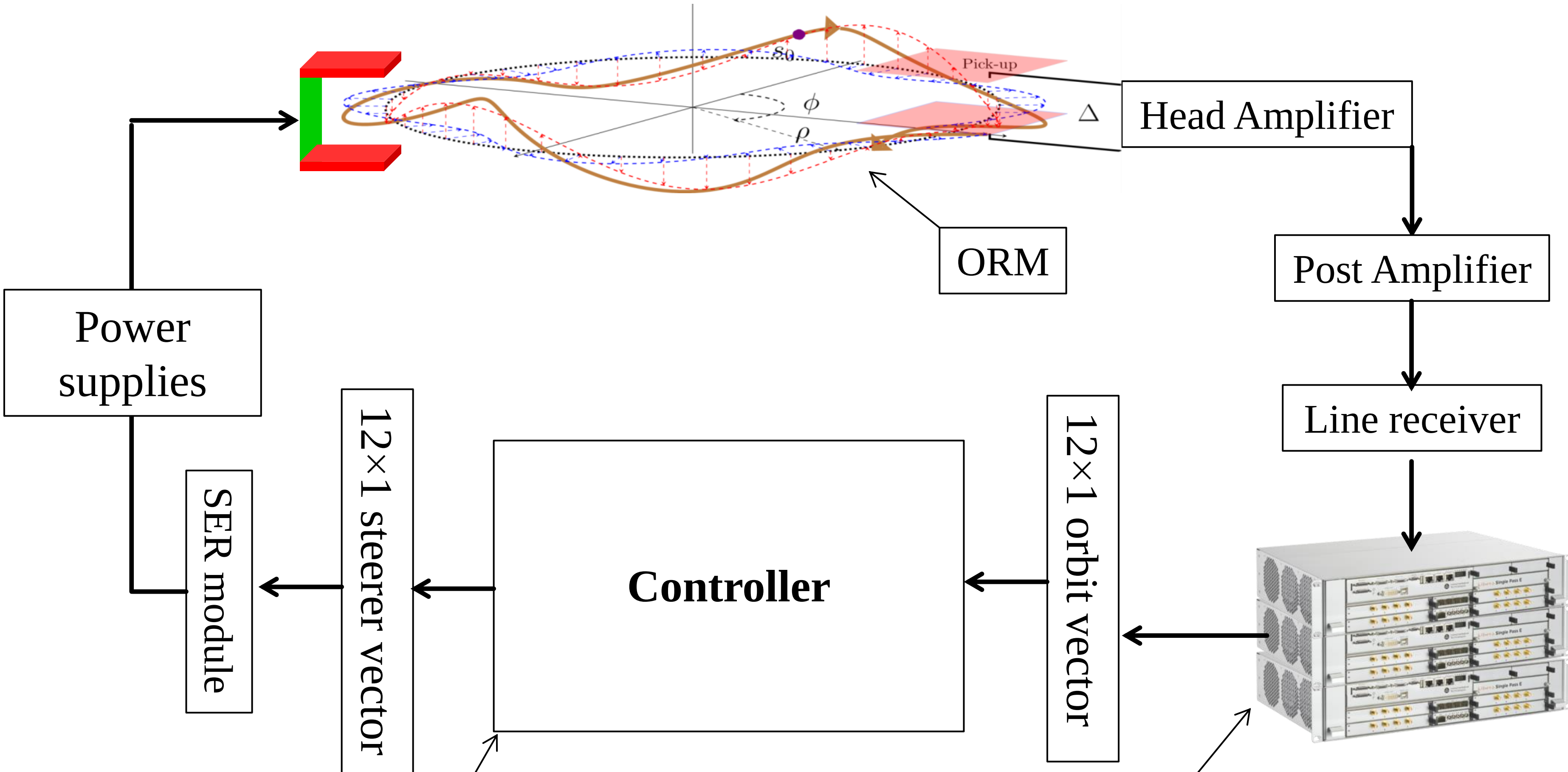
g(s) requires frequency response of all components

$\boldsymbol{g}(s) = \boldsymbol{g_1}(s)_{\text{BPM}} \ldots \boldsymbol{g_m}(s)_{\text{power supplies.}}\ \boldsymbol{g}_{\boldsymbol{n}}(s)_{\text{correctors}}$

Orbit response matrix

Reference: S. Gayadeen, Fast orbit feedback control in mode space: Proceedings of ICALEPCS 2013

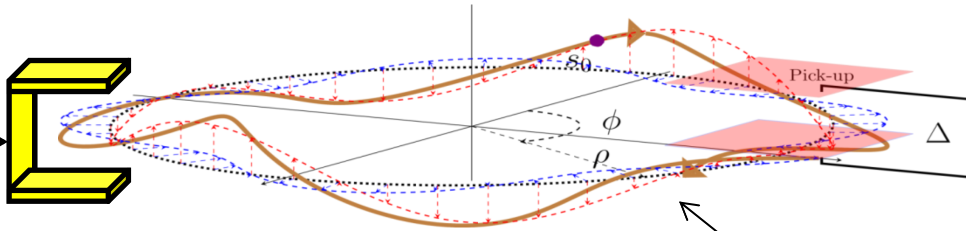
System identification necessary before controller design



Controller action (bandwidth realization)
Matrix multiplication acts as gain of controller

sampling 4 ns ~ 250 MS/sec
stores data for 100 μ s ~ 10 kHz
position calculation

System identification necessary before controller design



Head Amplifier

Post Amplifier

Line receiver

ORM

g(s)= transfer functions and delays

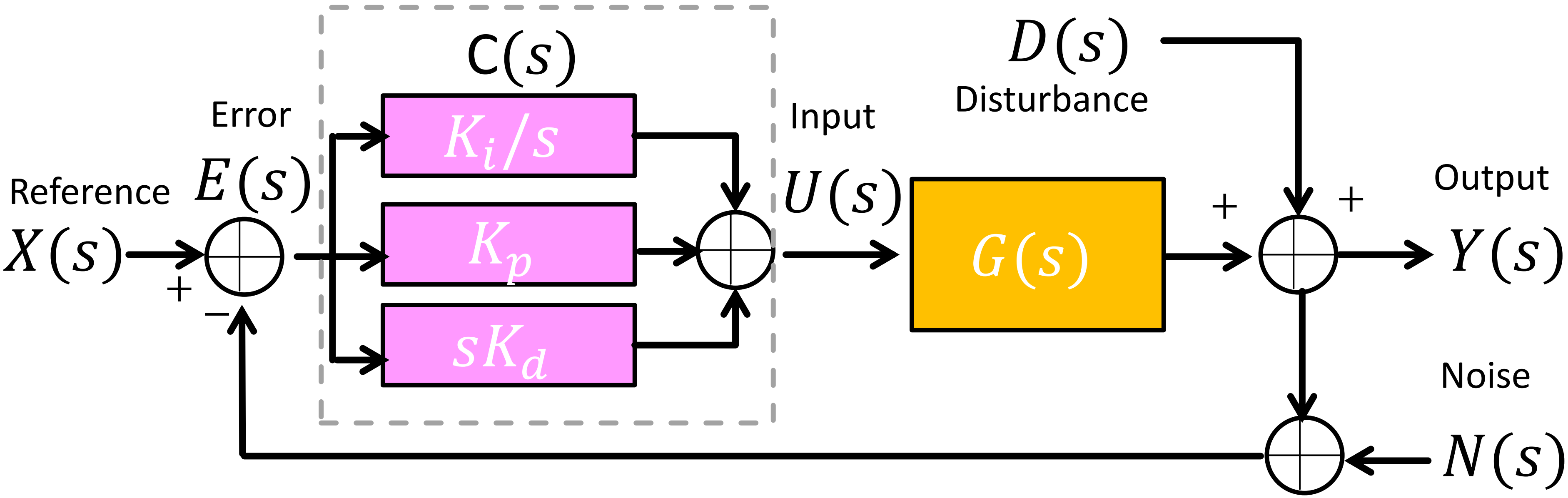
Power supplies

Network Analyzer

To measure the transfer functions of all components in the loop

sampling 4 ns ~ 250 MS/sec
stores data for 100 μ s ~ 10 kHz
position calculation

PID controllers



$$u(t) = K_p e(t) + \int_0^t k_i e(t) + K_d \frac{de(t)}{dt} \qquad U(s) = (K_p + \frac{K_i}{s} + sK_d)\mathrm{E(s)}$$

- Explicit knowledge of model not needed
- Tuning is crucial; several heuristics available
- Can be optimally tuned for first and second order processes
- Perspective: More than 70% industrial controllers based on PID controller
- Model based controller (IMC) is under study for SIS18

Next topic

- Introduction
- Closed orbit correction methods
- Closed control loop
- **What’s new in SIS18 COFB?**
- Model errors
- Dispersion
- Project status
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What are challenges for SIS18 COFB system?

- **Higher Bandwidth of the feedback system** (light sources call 100 Hz as “high”)
  - Power supply ripples are coupled to the orbit due to extra thin vacuum chambers (0.3 mm for Quad-chambers)
  - faster correction (within ramp)
  - Actual realizable bandwidth to be known after system-identification
- **Correction during ramp**
  - Lattice changes during ramp (uncertainties in Lattice parameters)
  - Variable ramp rates(100 ms-1s)
- **Cycle to cycle magnetic hysteresis**
- **Dynamic changes in beam energy and intensity (user dependent)**
- **BPM failures due to radiation shower**

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- Introduction
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- What's new in SIS18 COFB?
- **On ramp correction and Model errors**
  - On ramp systematic lattice change (constant tune)
  - On ramp tune shift
  - Image charge tune shift
  - Beta beating
- Dispersion
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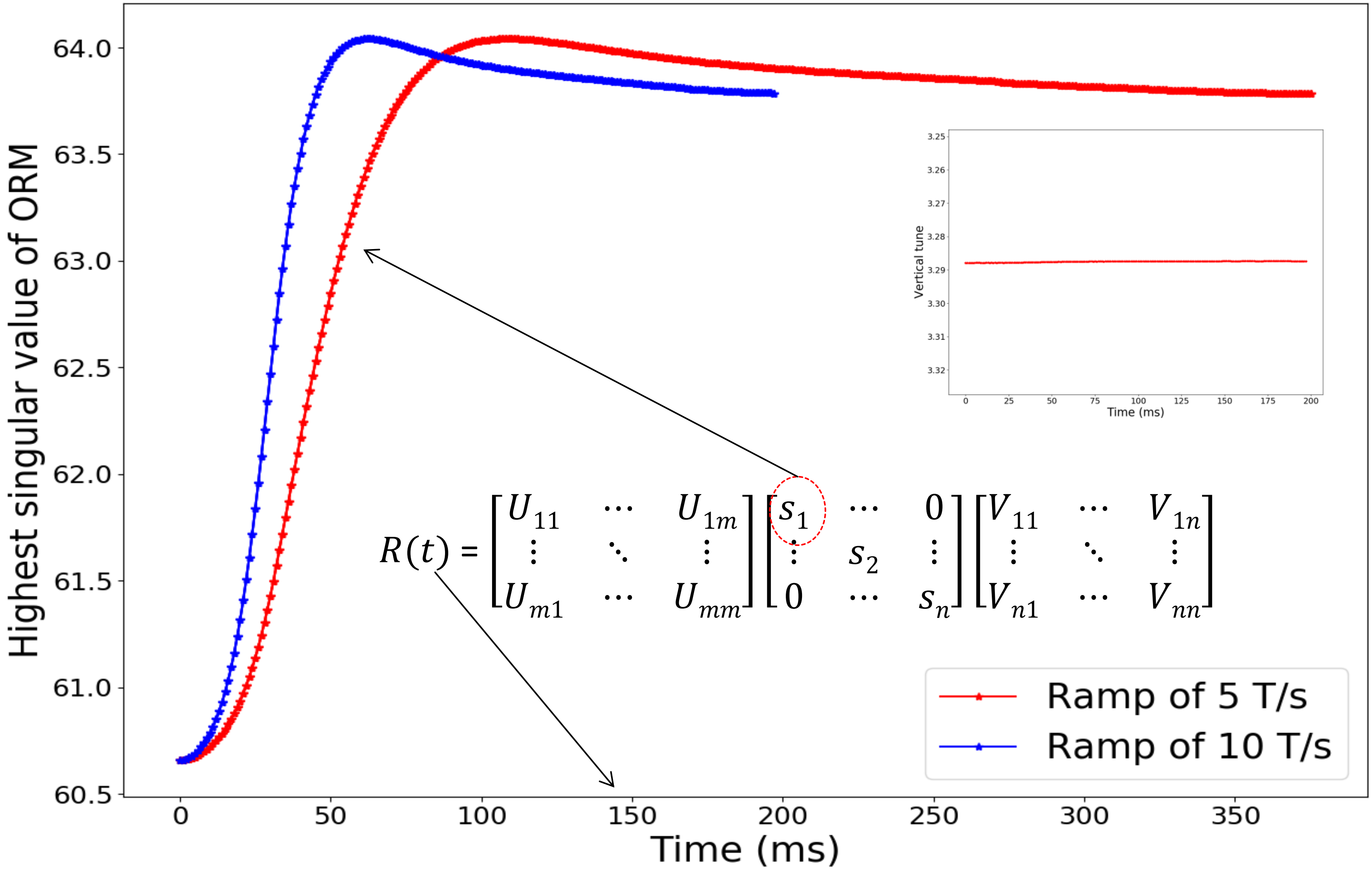
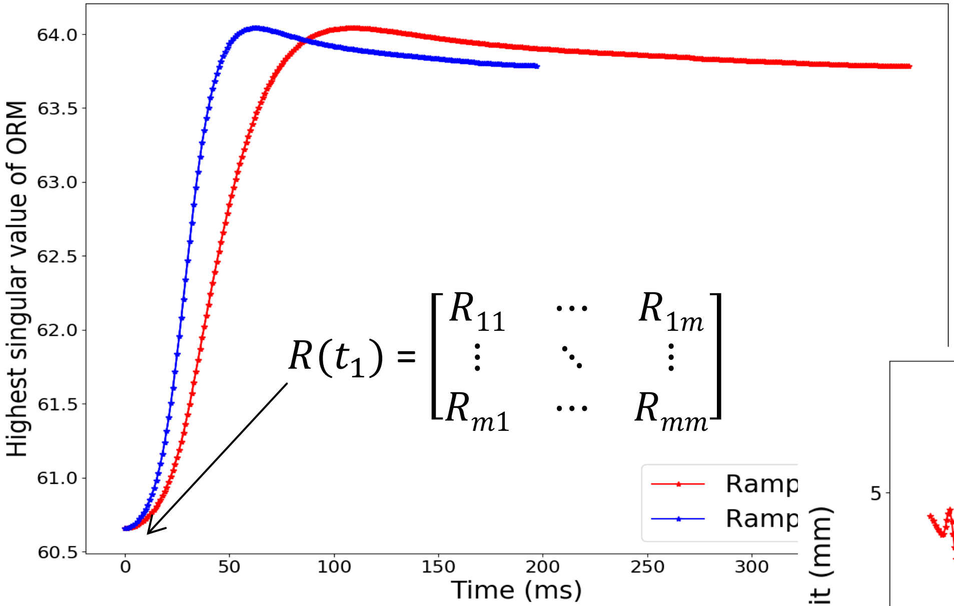
Systematic lattice changes over ramp



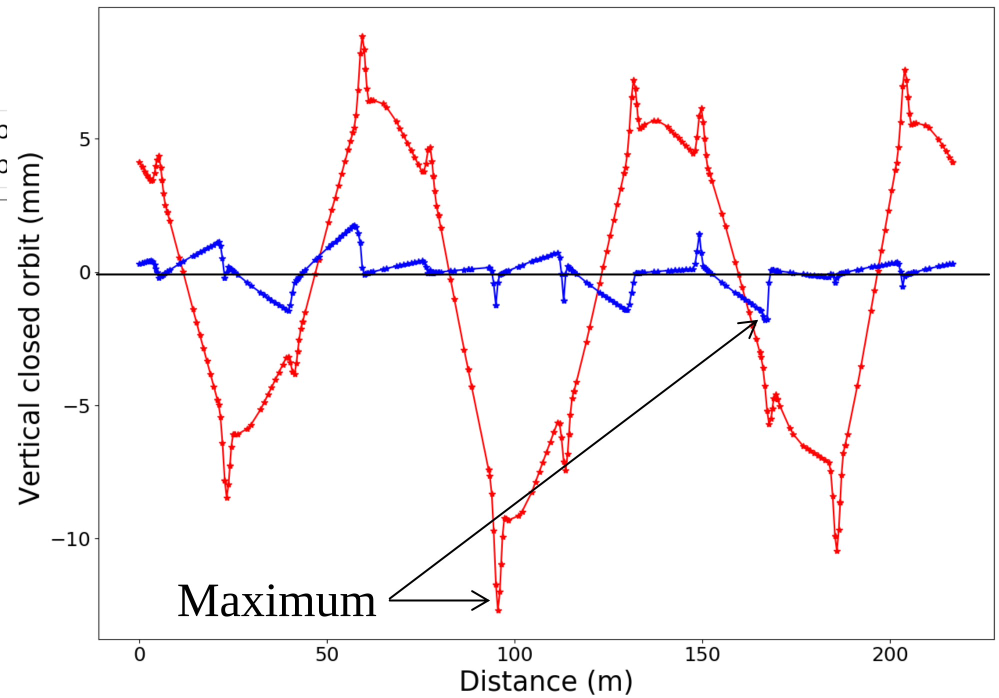
$$R(t) = \begin{bmatrix} U_{11} & \cdots & U_{1m} \\ \vdots & \ddots & \vdots \\ U_{m1} & \cdots & U_{mm} \end{bmatrix} \begin{bmatrix} s_1 & \cdots & 0 \\ \vdots & s_2 & \vdots \\ 0 & \cdots & s_n \end{bmatrix} \begin{bmatrix} V_{11} & \cdots & V_{1n} \\ \vdots & \ddots & \vdots \\ V_{n1} & \cdots & V_{nn} \end{bmatrix}$$

Systematic lattice changes over ramp



$$R(t_1) = \begin{bmatrix} R_{11} & \cdots & R_{1m} \\ \vdots & \ddots & \vdots \\ R_{m1} & \cdots & R_{mm} \end{bmatrix}$$

Typical example of orbit correction



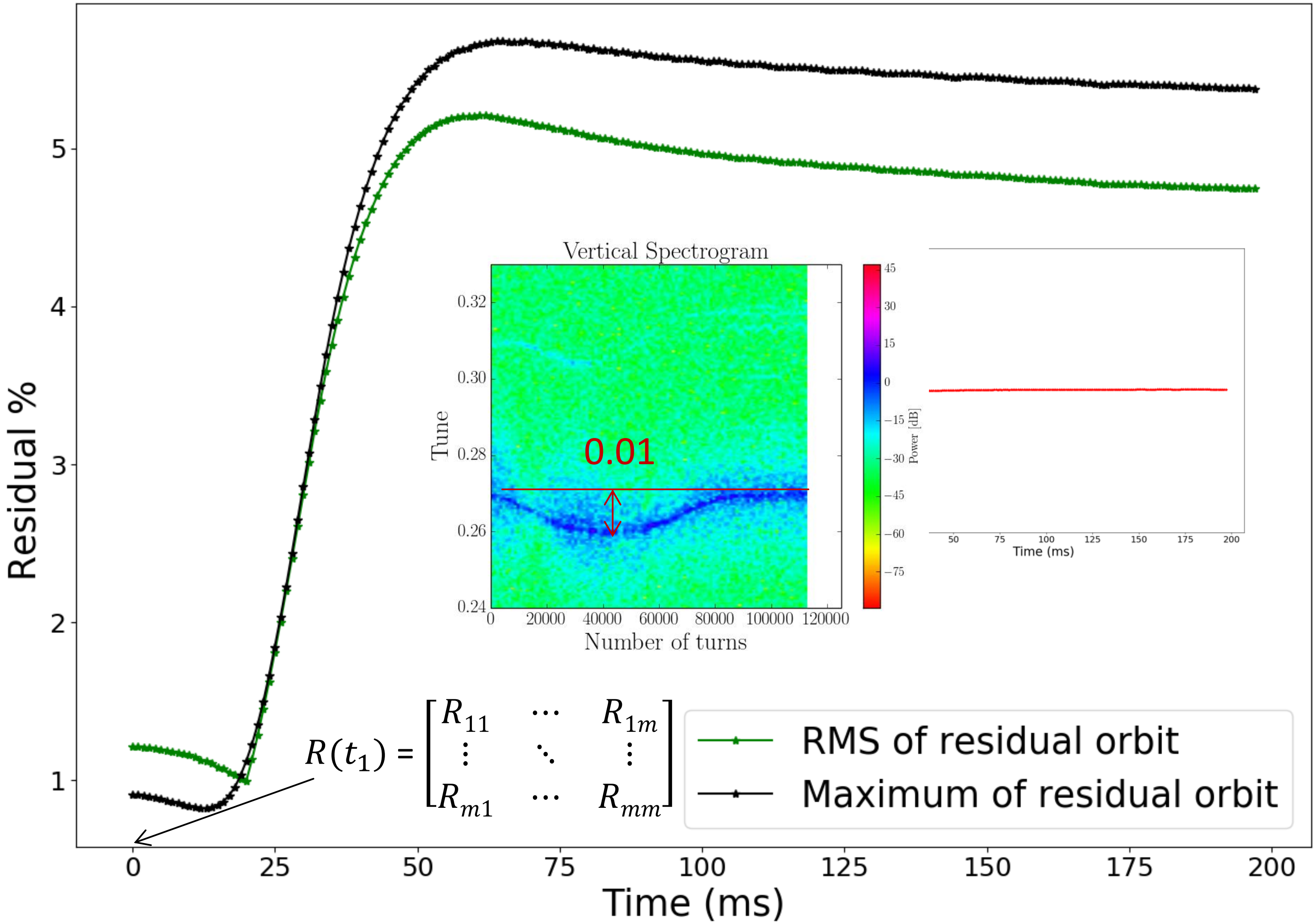
Residual (%) =

$$\frac{Max. of\ corrected\ orbit}{Maximum\ of\ uncorrected\ orbit} \times 100$$

Similarly RMS residual %

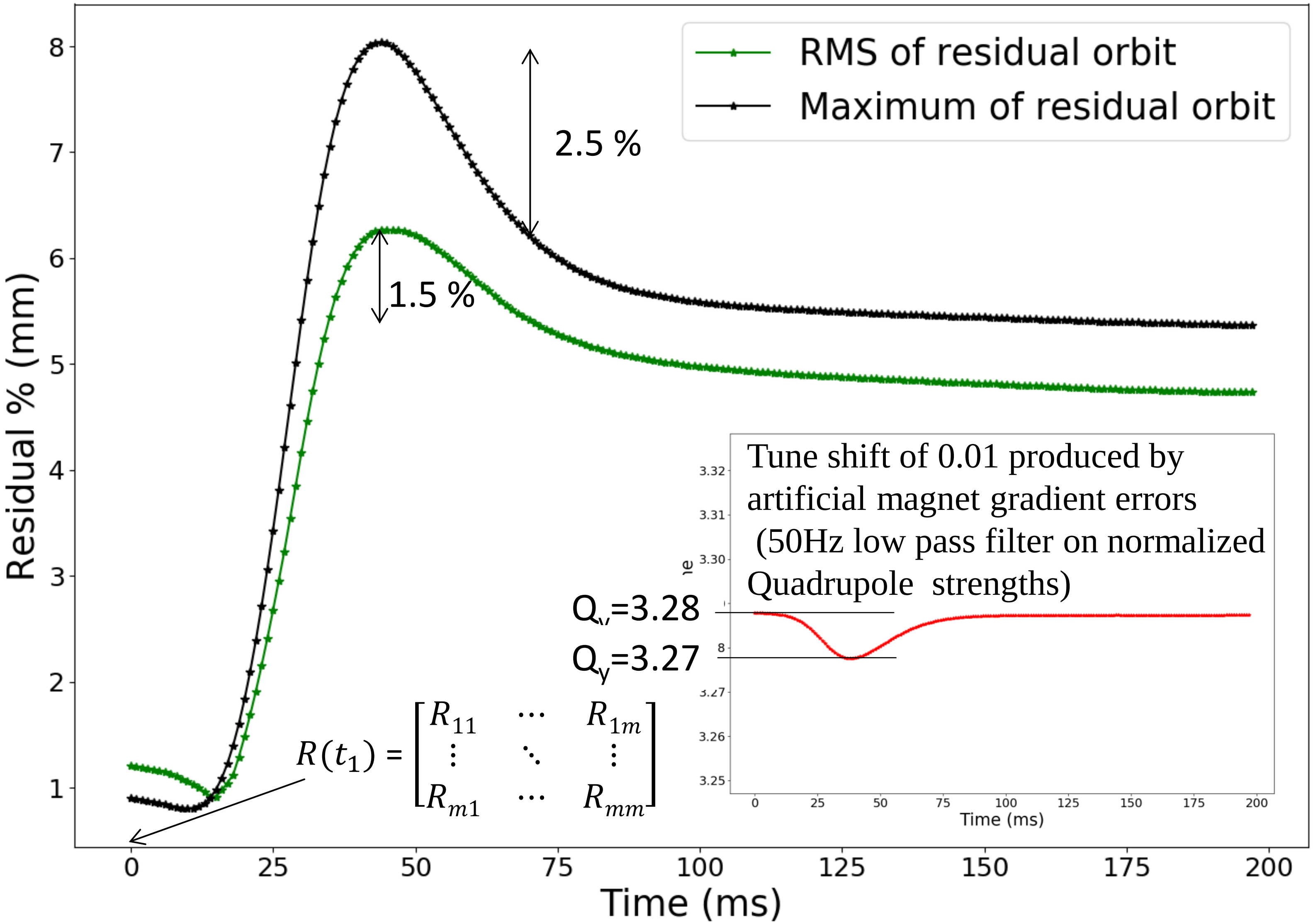
High residual means bad correction

Orbit correction over ramp of 5 T/s (constant tune)



PhD thesis “Tune measurement at GSI SIS18: Methods and Applications” by R. Singh

Orbit correction over ramp of 5 T/s (tune variation of 0.01)



Other sources of model errors

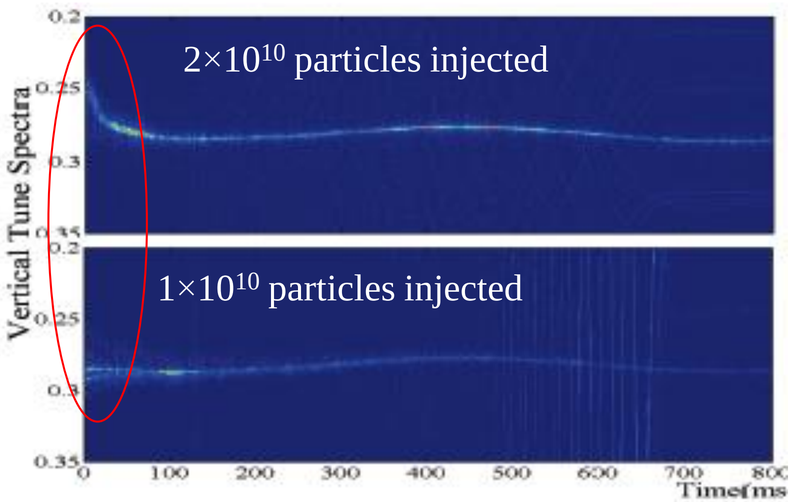
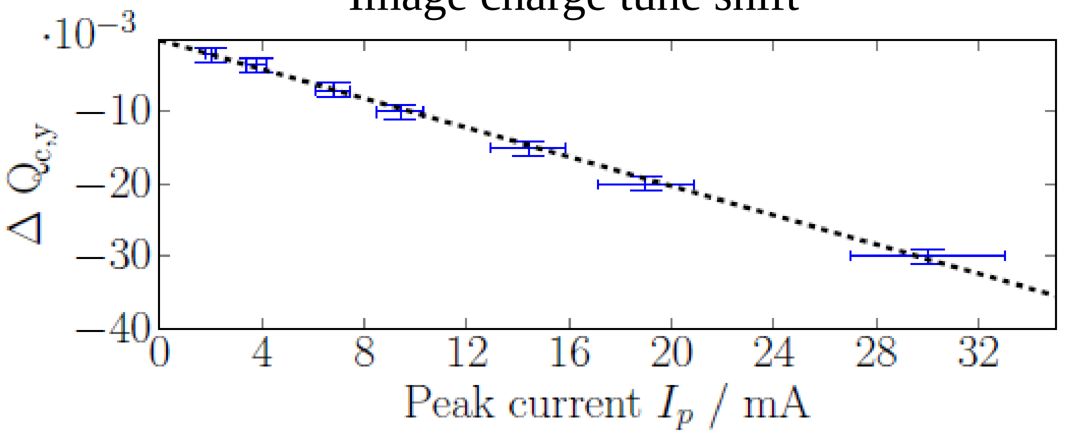
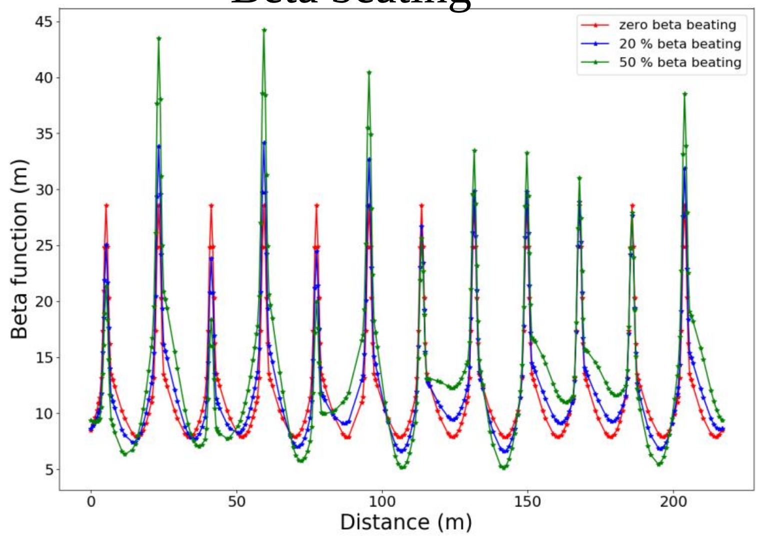


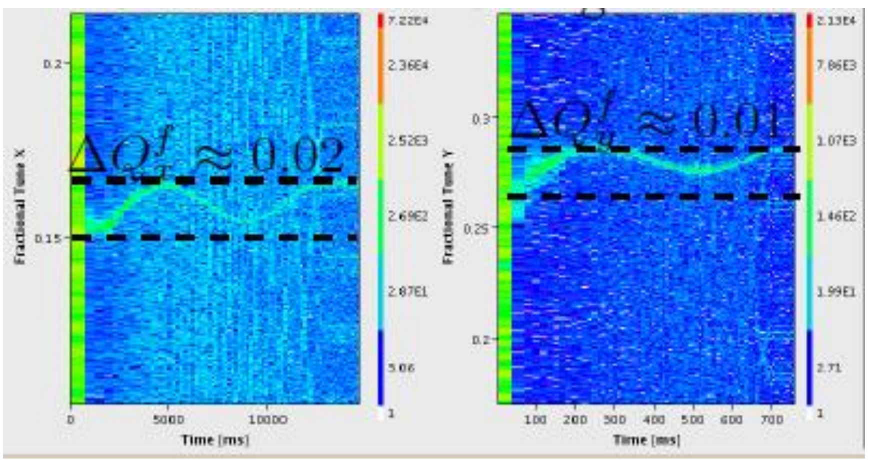
Image charge tune shift



Beta beating



Tune shift during ramp



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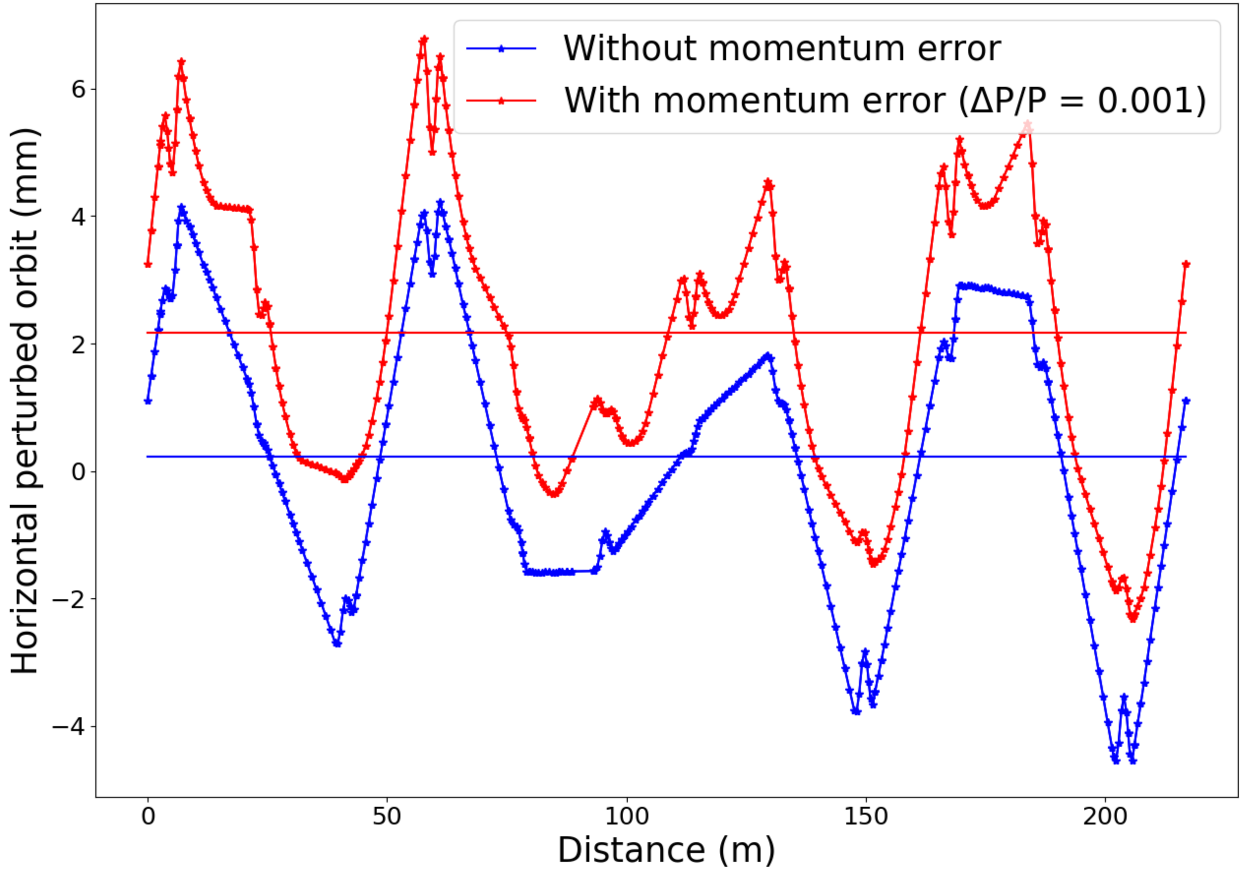
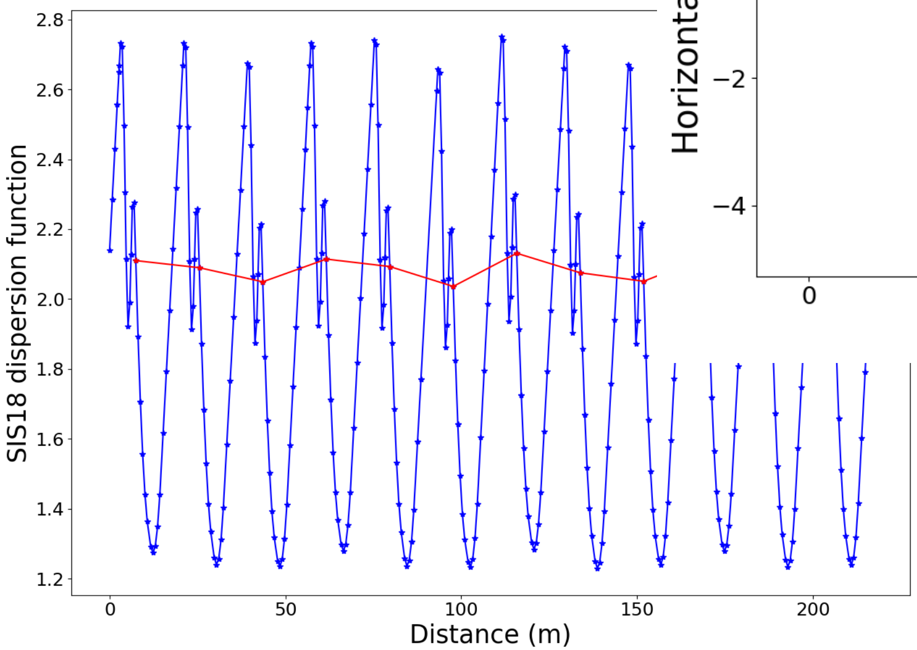
Dispersion(x-plane)

$$\Delta x_{disp} = D(s)\frac{\Delta P}{P}$$

$$\Delta x_{disp} = 2.1\ m\ \times 0.001$$
$$= 2.1\ mm$$





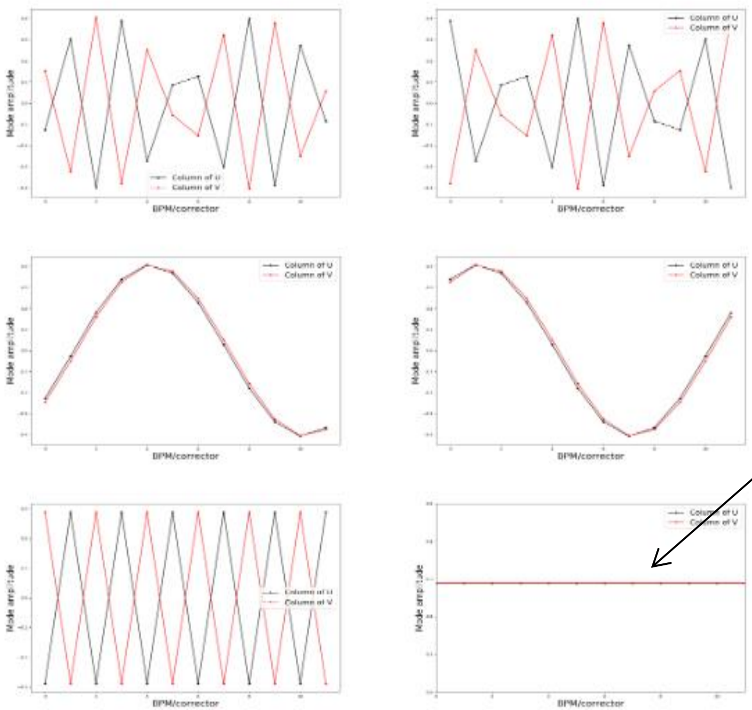
Δp/p= 0.001

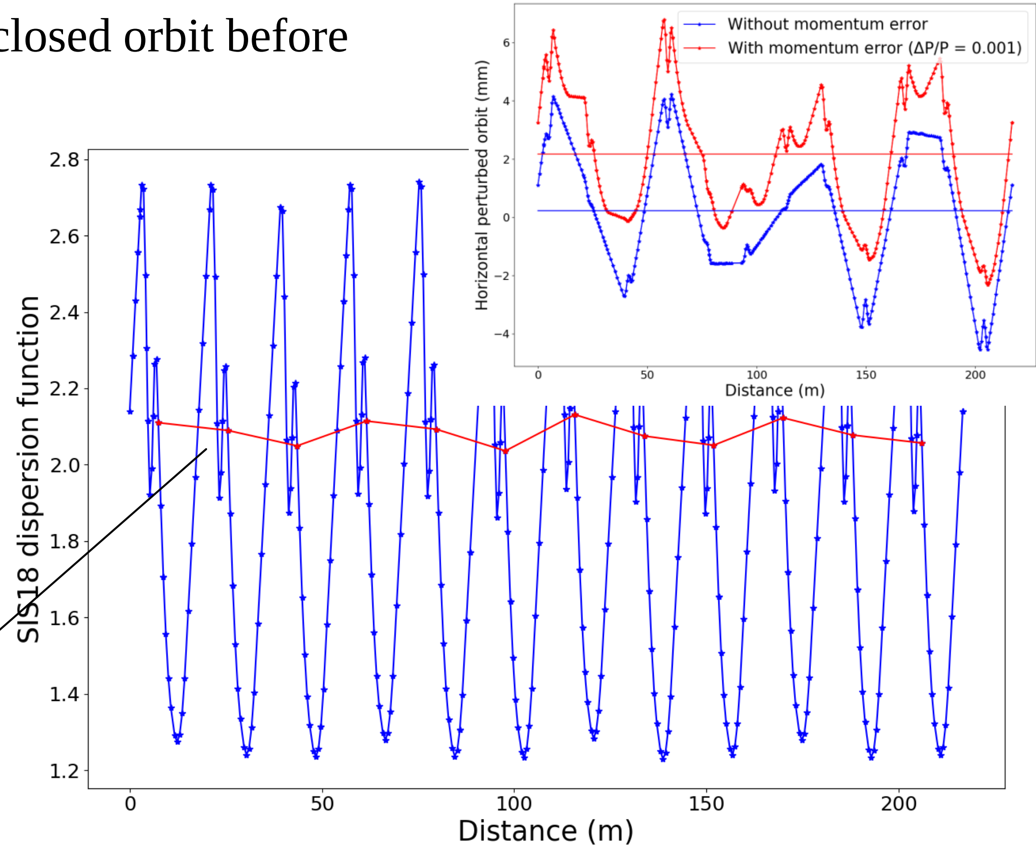
An order of magnitude higher corrector strengths required to correct dispersion effect

Subtracting dispersion effect from closed orbit

Dispersion effect is usually subtracted from closed orbit before correction

SVD modes of SIS18 ORM





Because of symmetry in SIS18, the major coupling of dispersion effect is with DC mode

DC mode truncation can ignore the dispersion effect without measurement?

Next topic

- Introduction
- Closed orbit correction methods
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- What’s new in SIS18 COFB?
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  - Mid-term goals
  - Final goals
- Conclusions
- Outlook

Medium term goals

Model errors might have significant importance
But we shall start from simpler system realization

Mid-term goals

Commissioning of the simpler system for the time resolution:

- for operation on flat up energy instead of ramp
- at low currents ignoring image charge tune shift
- Using simple PI controller

Final goal:

- Model predictive fast robust controller

Hardware Status

- Hardware (BPM+ Magnet correction calculation) delivered
- PID controller implemented for mode-base correction
- FESA class programming (design specifications)
- Digital magnet interface (ACU system) is under installation for remaining two horizontal steerers, 10 are already installed
- (Thanks to Power Supply Group)
- Data available at 10 kHz rate
- Latency of loop ~ 30 μs

Conclusions

- DFT based decomposition blends the benefits of both SVD and Harmonic correction
- DFT modes are shown to provide robustness against missing BPMs (simulations)
- Systematic lattice changes during ramp does not seem to be crucial (based on simulations): A finite number of orbit response matrices can be used
- The non-systematic tune shift during ramp have extra contribution in residual orbit
- Image charge tune shift and effect of beta beating are also being modelled.
- Dispersion effect in horizontal closed orbit can saturate the correctors
- **Outlook:**
- Installation of "I-tech" hardware
- Measurement of parameter uncertainties in next beam time
- Measurement of transfer functions of powers supplies and corrector magnets
- Simulations of advanced model predictive controllers

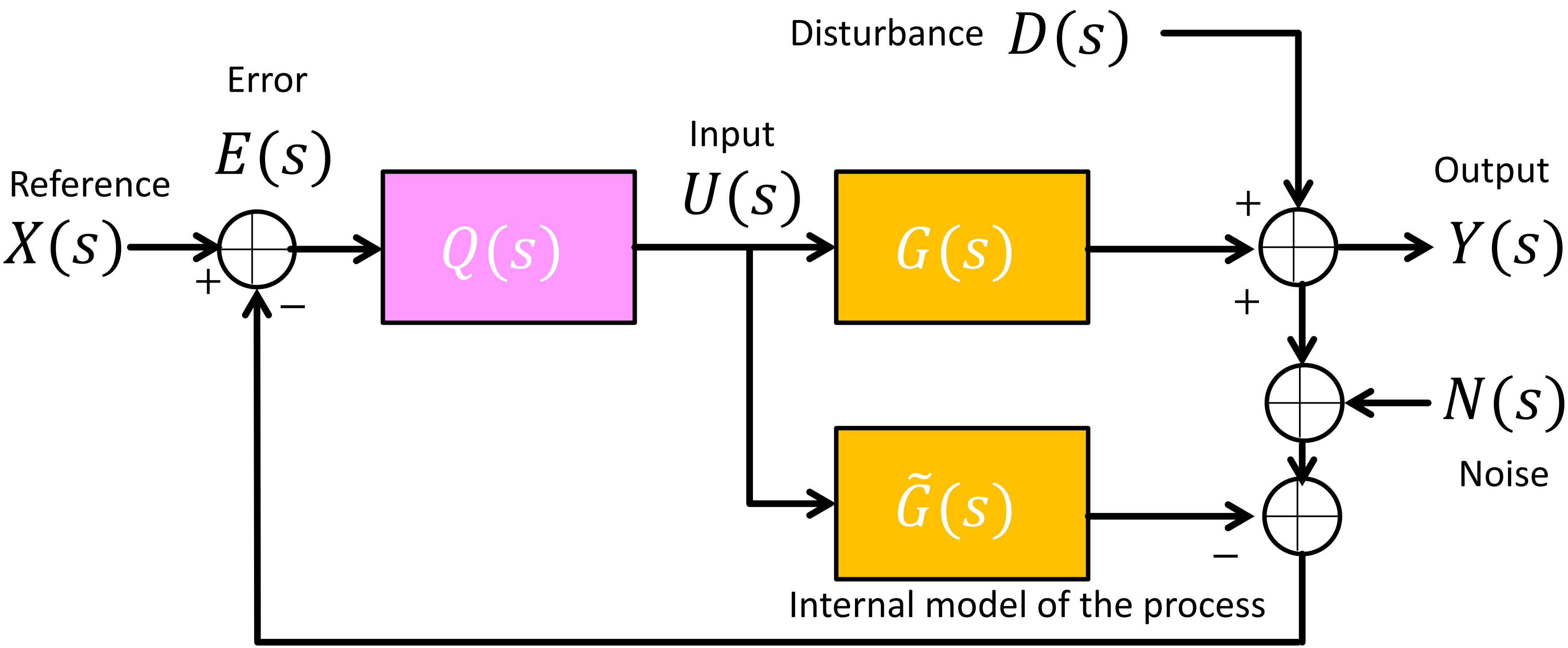
Acknowledgements

David Ondreka (Control)
Stefan Sorge (MADX)
Horst Welker (Power supply)

Carsten Muehle (Magnets),
Franz Klos (Magnets)
Andreas Kraemer (Vacuum chambers)

Extra slides

Internal model control (IMC)



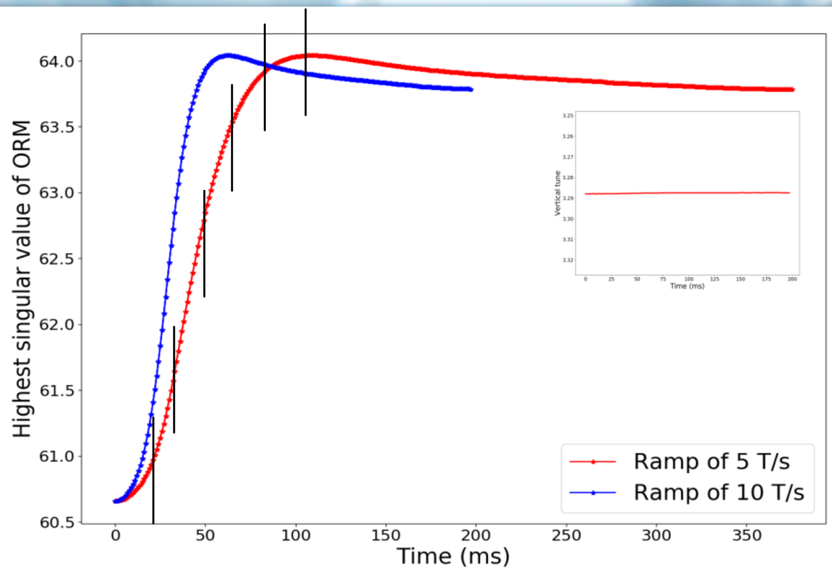
$$T(s) = \left(\frac{Y(s)}{X(s)}\right)_{D(s),N(s)=0} = Q(s)G(s)$$

Reactive yet stable!

Find the process model!

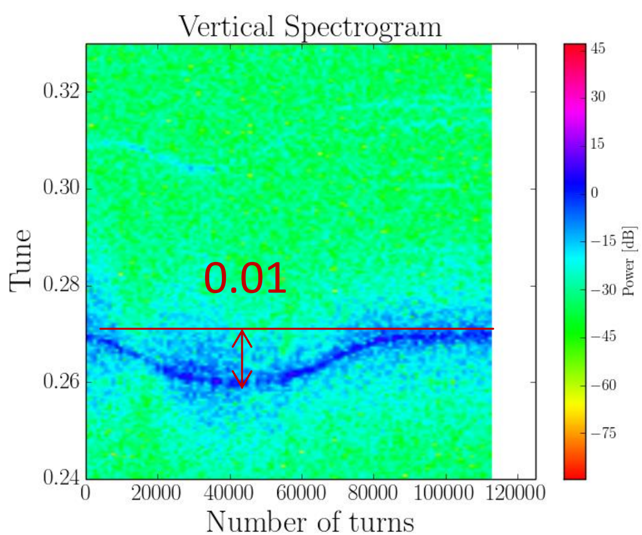
- Stability condition reduced to only finding a stable Q(s)
- Can be written in an PID equivalent form
- Model knowledge can lead to stable and analytically tractable PID tuning

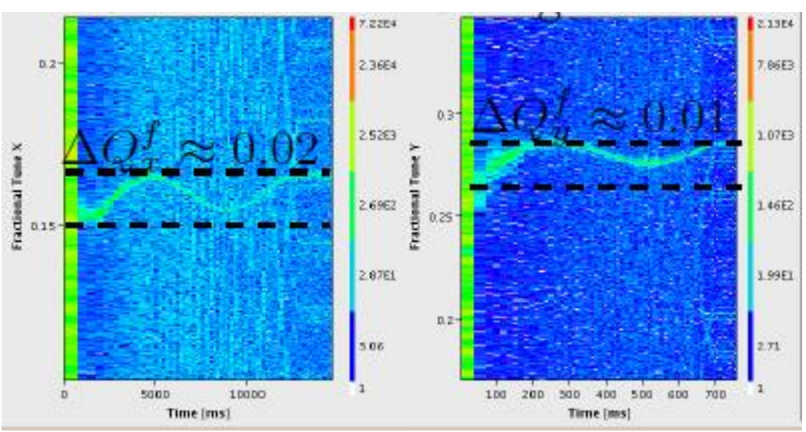
Non-systematic lattice changes over ramp



Uncertainty modeling in ORM is required

First hint on need of robust controller





Orbit correction over ramp of 5 T/s (tune variation of 0.01)

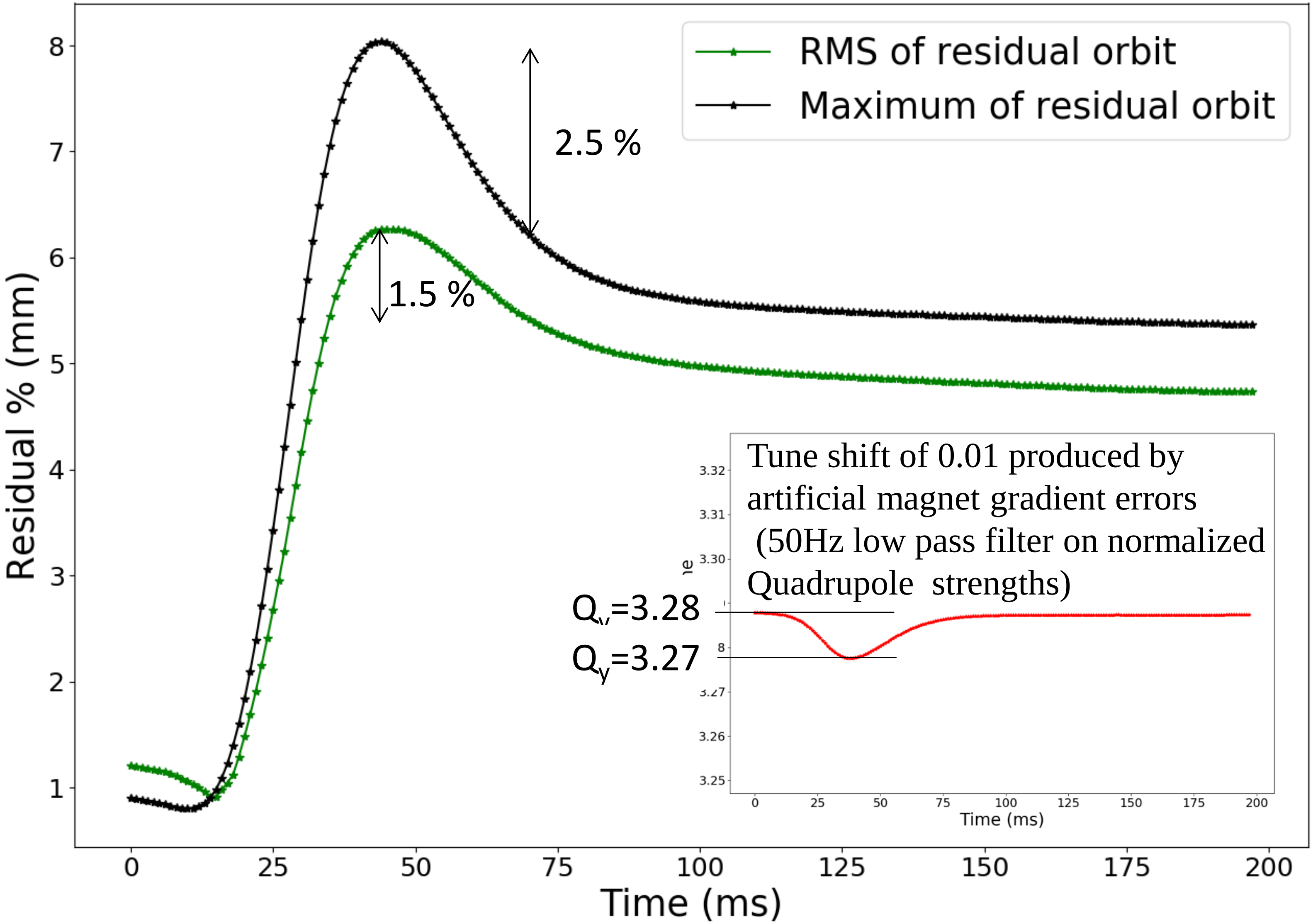
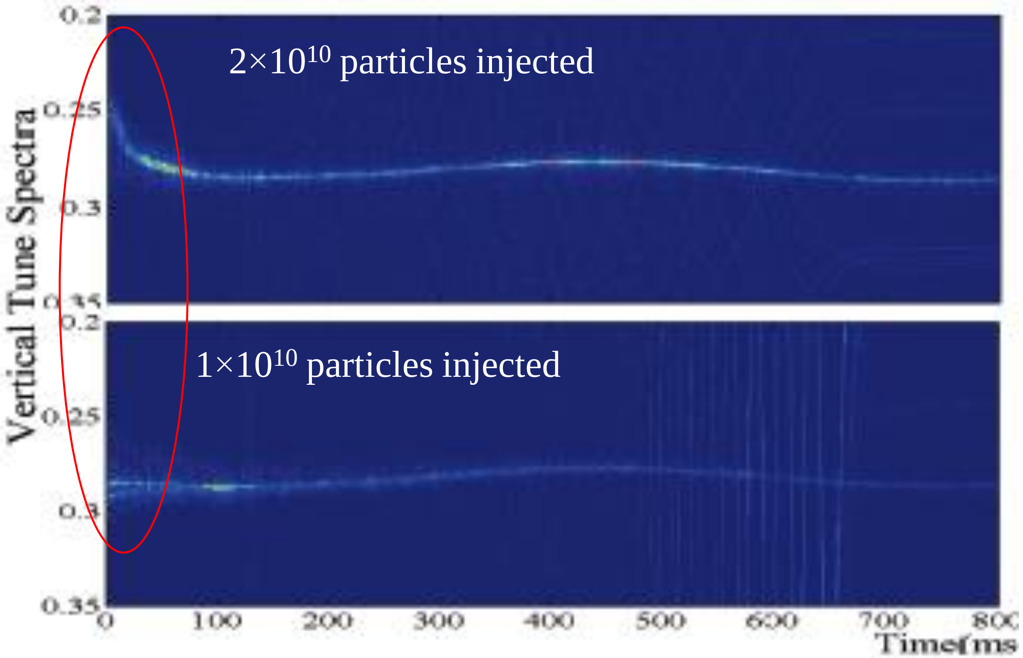
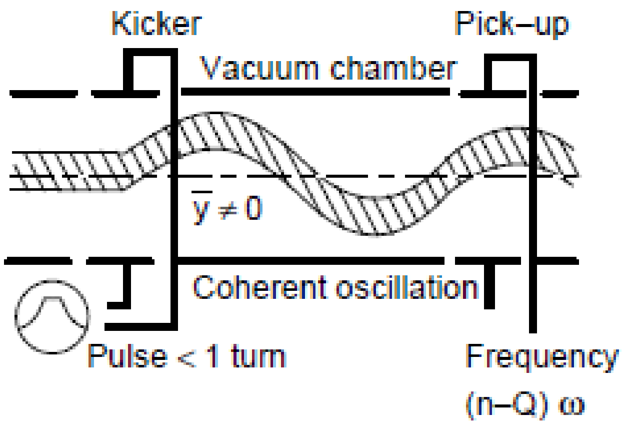


Image charge tune shift





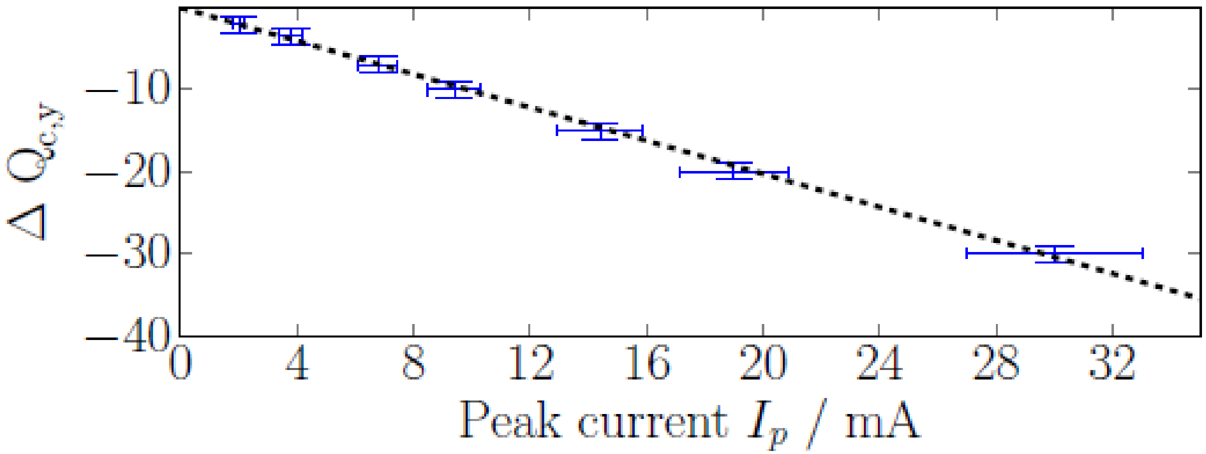
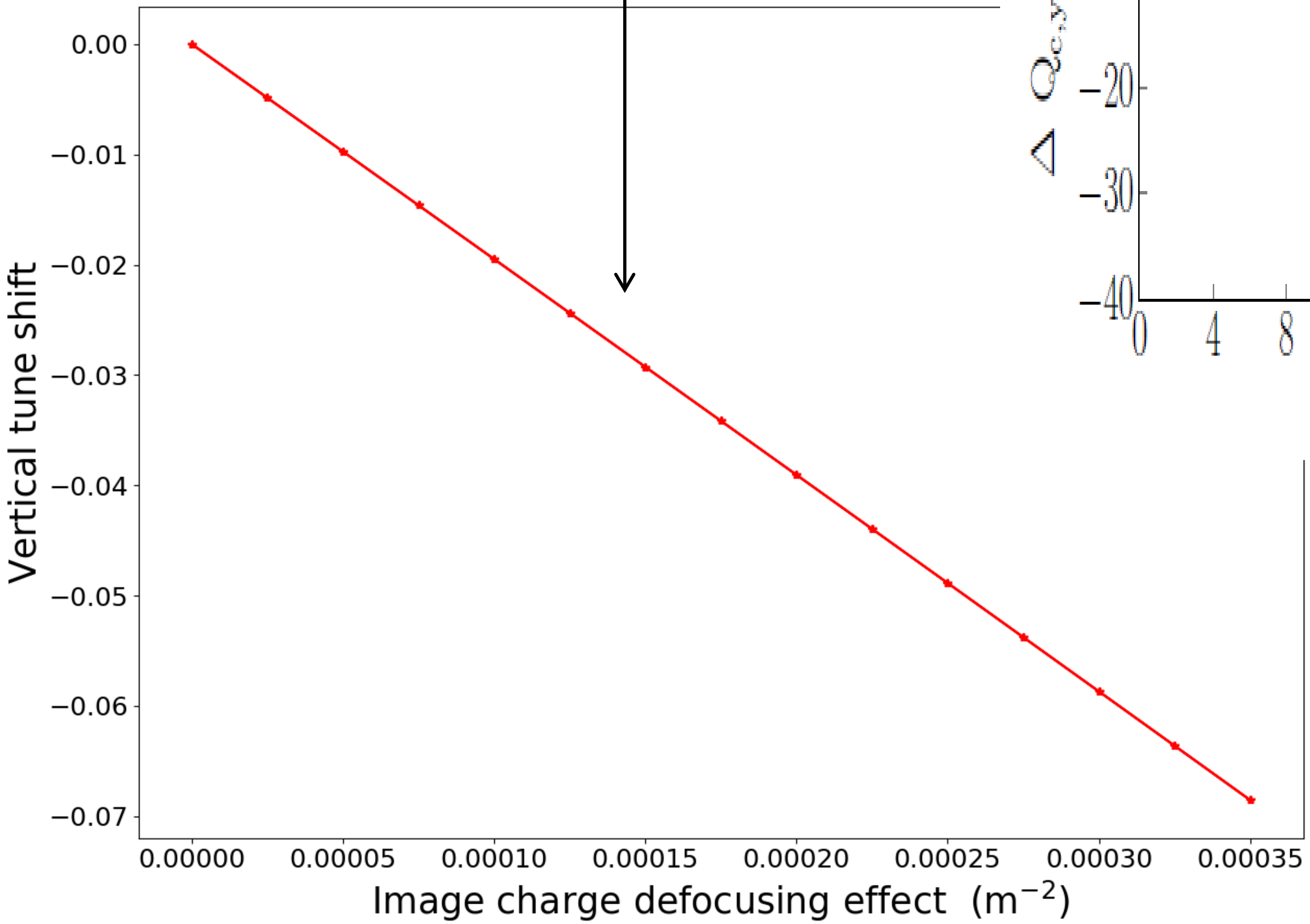
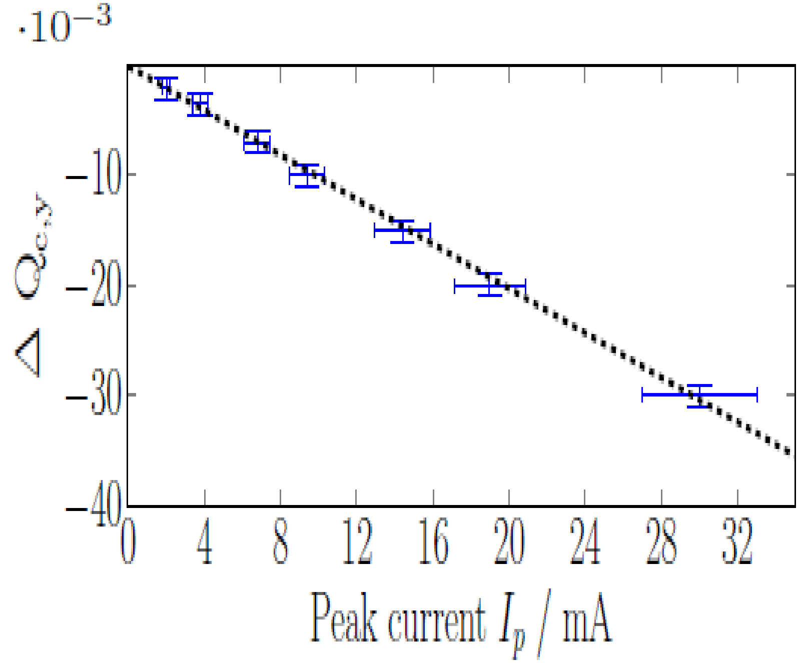


Image charge in the Vacuum chamber act like a defocusing field causing a negative coherent tune shift

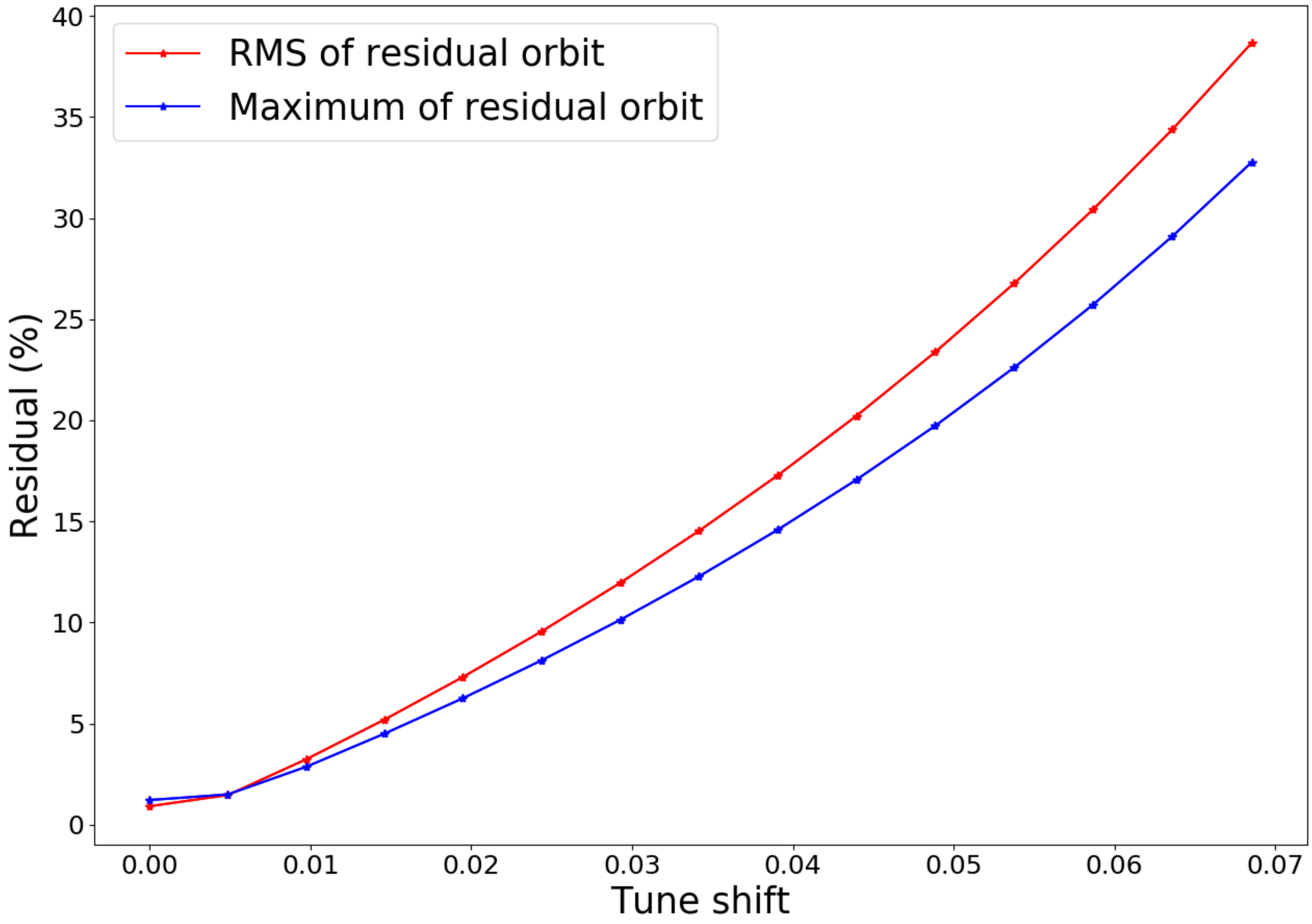
Image charge tune shift simulation

Image charge effect is simulated in MADX by adding a weak defocusing effect throughout the ring

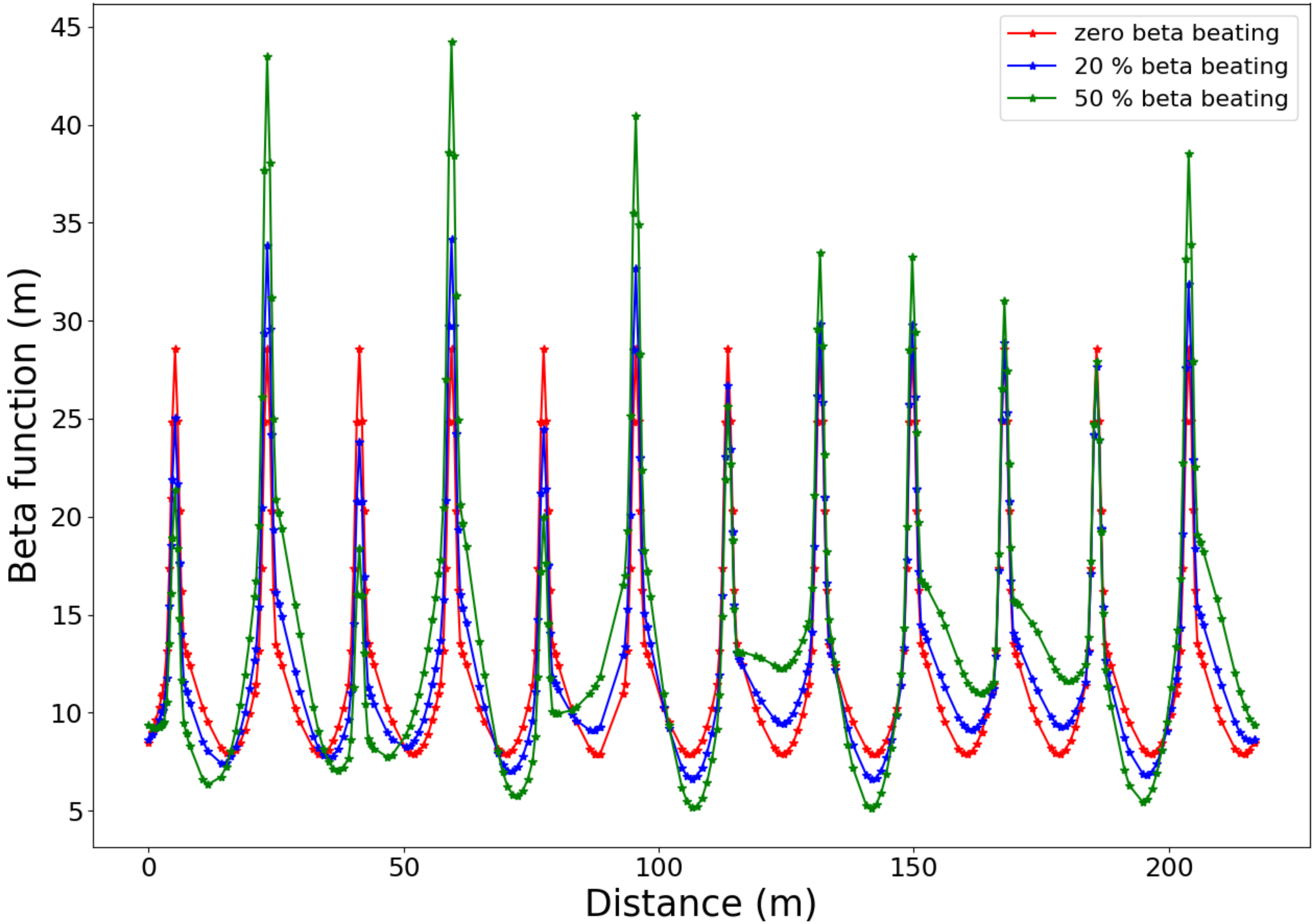




Effect of image charge tune shift on closed orbit correction



Effect of beta beating



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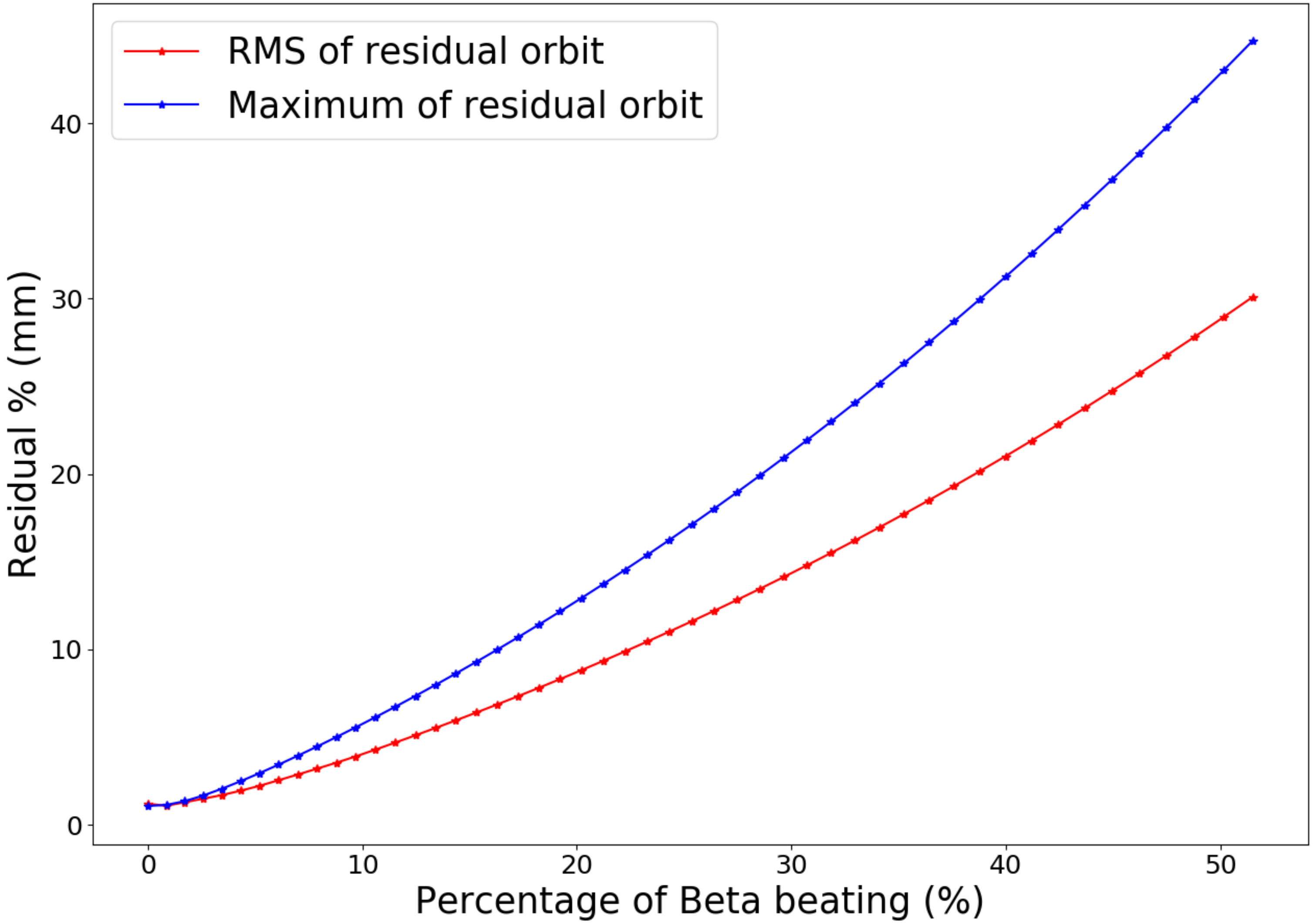
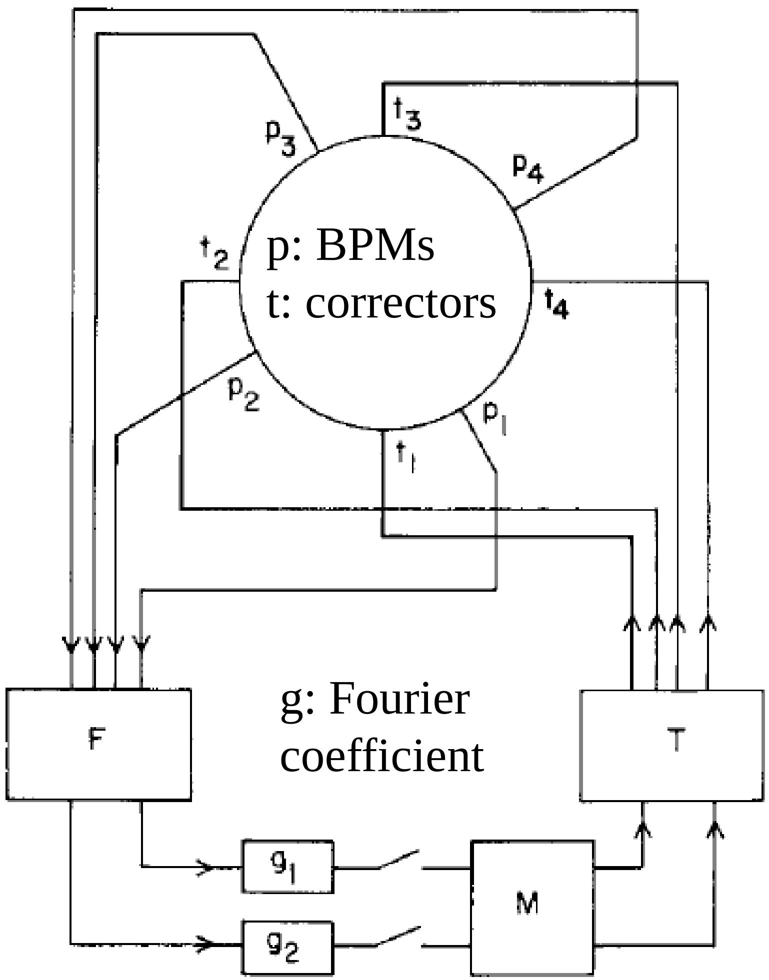


Harmonic analysis (global correction)

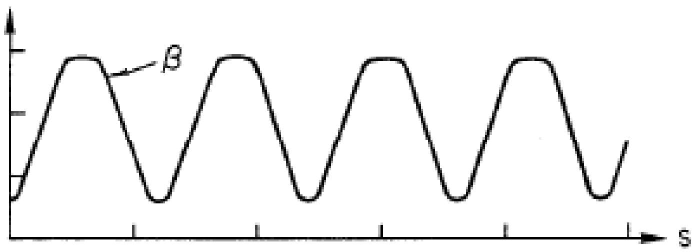
Corrector strengths are proportional to the Fourier coefficients

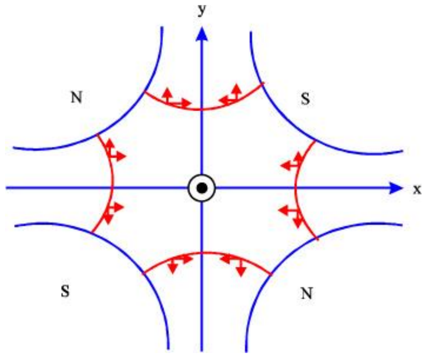
Mode switching is possible because of separate channels for each mode

Complexity:



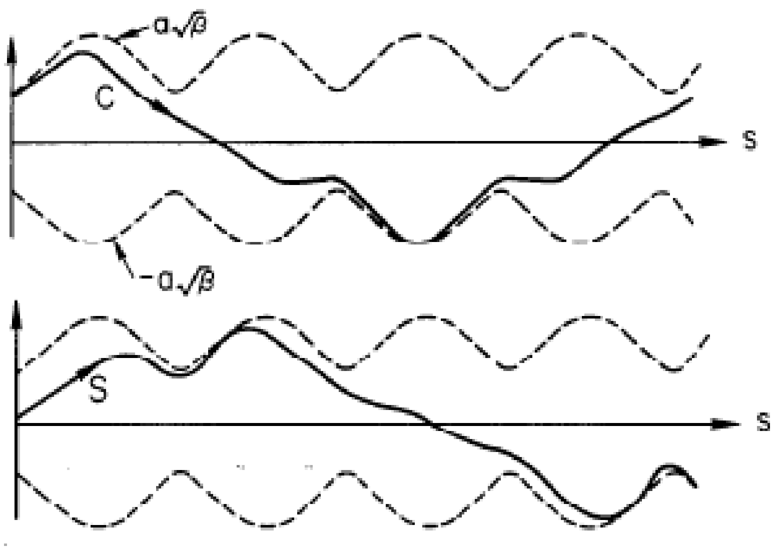
Single particle motion and closed orbit





Hill's equation for off axis particles

$$x'' = \left(\frac{1}{\rho^2} - K_x(s)\right) x \qquad\qquad y'' = K_y(s) y$$



Solution $\quad y = \sqrt{\epsilon \beta_y\,(s)} \cos(\mu_y(s) - \delta)$

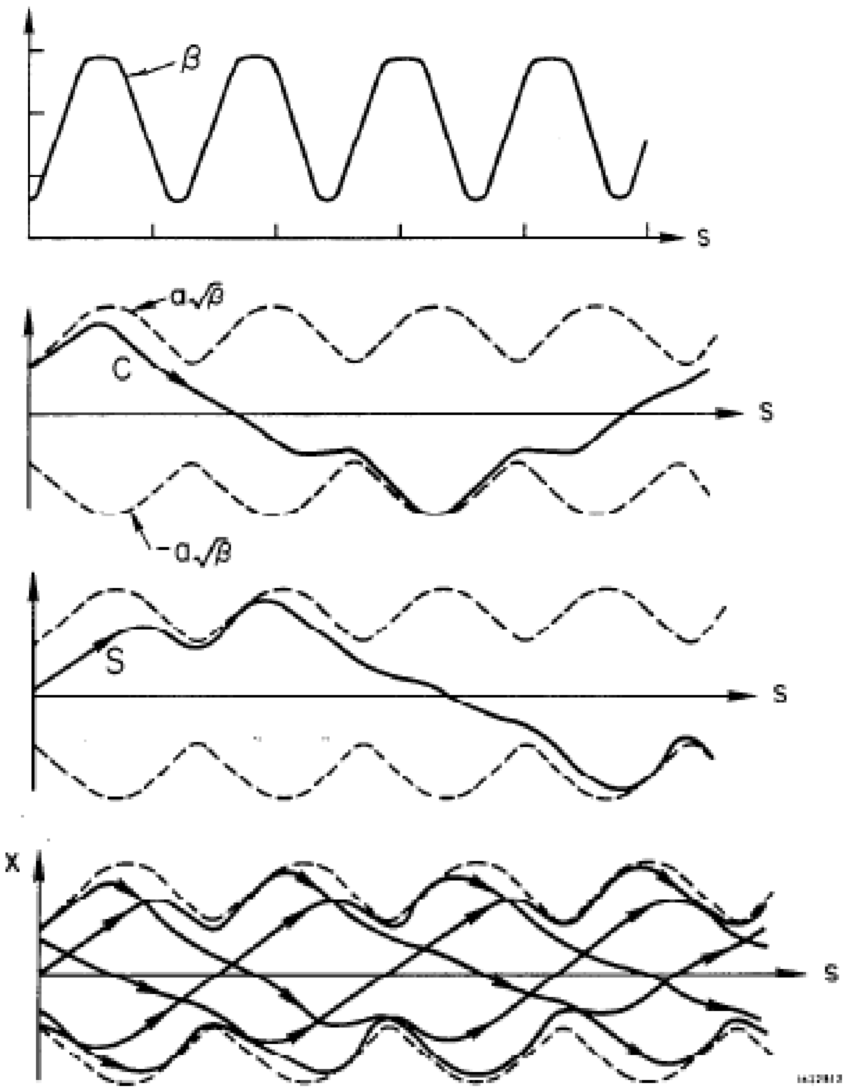
where $\quad \mu(s) = \int_0^s \frac{1}{\beta(s)} ds$

$\beta(s)$ have the same periodicity in space as $K(s)$

Tune=:Number of Betatron oscillations over one turn

M.Sands, The Physics of Electron Storage Rings: An Introduction, Conf. Proc. C6906161

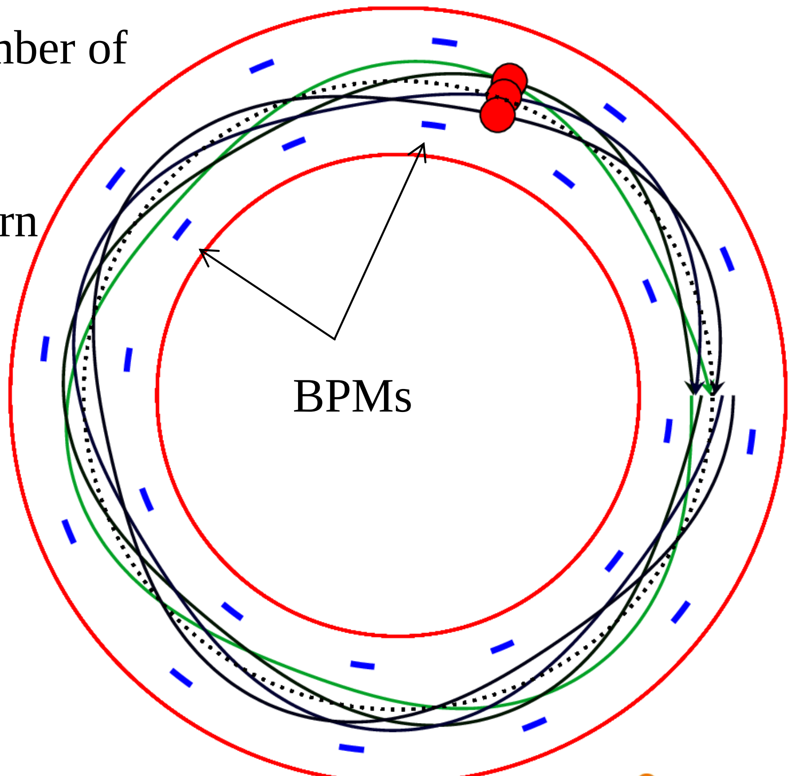
Single particle motion and closed orbit



$$y = \sqrt{\epsilon\beta_y(s)}\cos(\mu_y(s) - \delta)$$

Pseudo-harmonic oscillations modulated by sqrt. of beta function

Tune= Number of betatron oscillations over one turn



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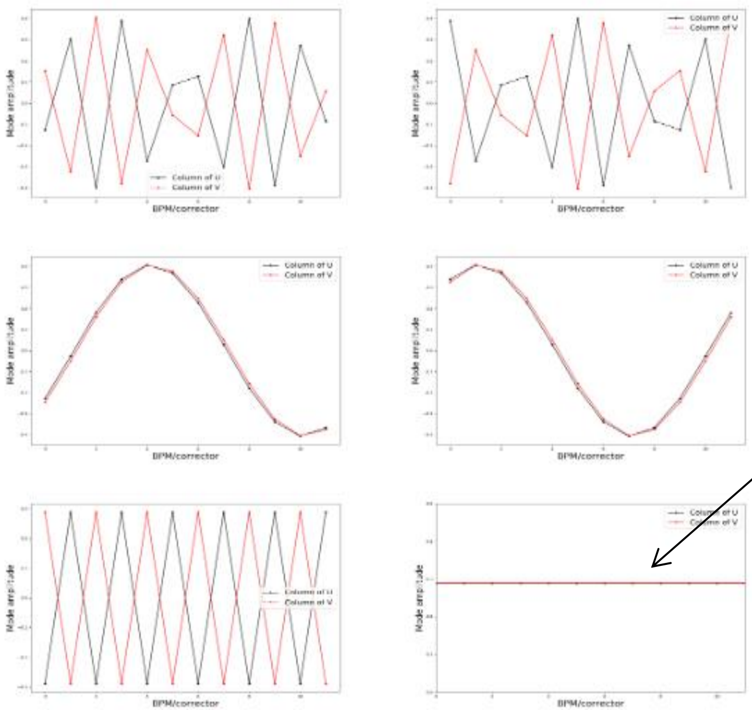
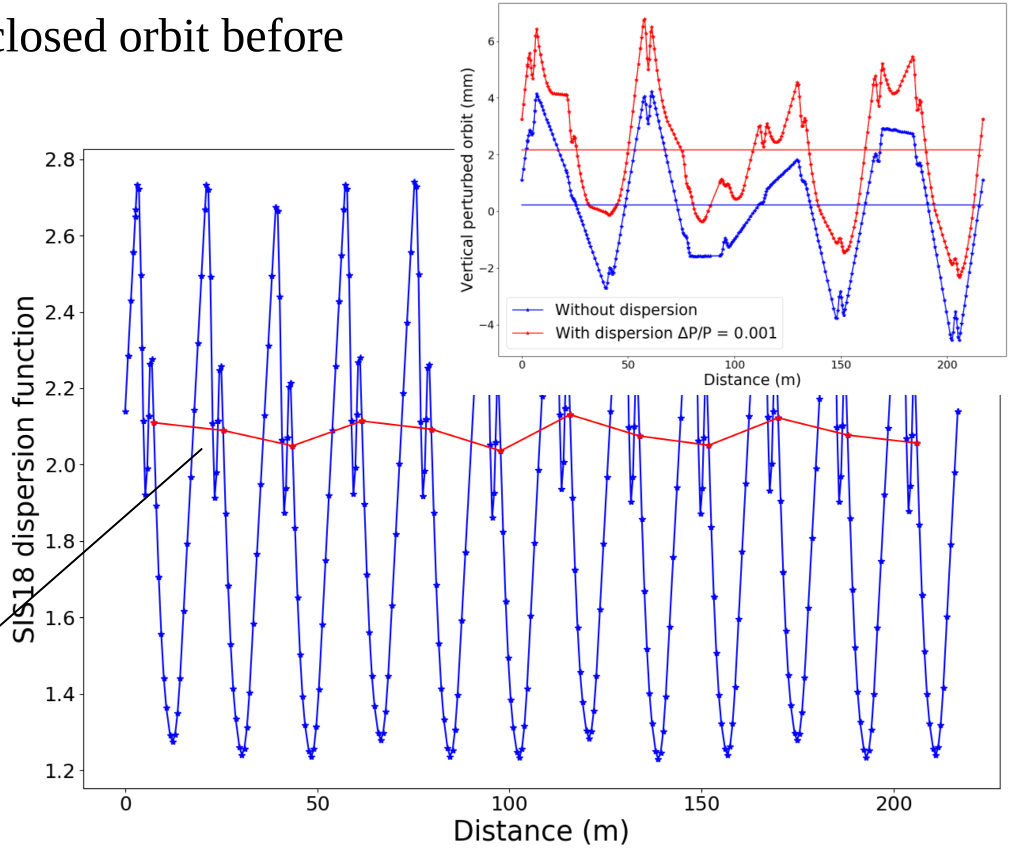
SVD modes of SIS18 ORM





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