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

\[ B \rho = \frac{p}{q} \]

Bending radius

Nominal momentum

Charge

**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

\[ y = \sqrt{\varepsilon \beta_y(s) \cos(\mu_y(s) - \delta)} \]

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

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

Why is Closed orbit important?

Betatron motion

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

Field errors and Closed orbit perturbation

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

“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 \( s \neq 0 \), the perturbed reference orbit has free betatron oscillations and non-integral frequency

\[ y(s \neq 0) = \sqrt{\epsilon \beta_y(s)} \cos(\mu_y(s) - \delta) \]

Solution of Hill’s equation in this case

\[ y_c(s) = \theta \frac{\sqrt{\beta(s_0)\beta(s)}}{2\sin(\pi Q_y)} \cos(|\mu(s) - \mu_{s0}| - \pi Q_y) \]
Closed orbit perturbation (distortion)

Single error perturbed orbit is

\[ y_c(s) = \theta \frac{\sqrt{\beta(s_0)\beta(s)}}{2\sin(\pi Q y)} \cos(|\mu(s) - \mu_{s0}| - \pi Q y) \]

- \( \theta \) 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

\[ y_c(s) = \sum_{i=1}^{N} \theta_i \frac{\sqrt{\beta(s_i)\beta(s)}}{2\sin(\pi Q y)} \cos(|\mu(s) - \mu_{si}| - \pi Q y) \]

\( R \) is called the orbit response matrix

\[ [Y]_{m \times 1} = [R]_{m \times n} [\Theta]_{n \times 1} \]
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**

**Closed orbit position at BPM # 8**

**Fourier transform**

**Injection**

**Closed orbit position at BPM # 7 and 8**

**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
BPMs (typically $N \propto 4 \times \text{tune}$) read the beam position which is averaged over $\sim 1000$ 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 $\theta_i$ given to the beam

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

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

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

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

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 $\theta'_1$ $\theta'_2$ $\theta'_3$

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

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

$\theta'_2 = -2\theta'_1 \cos \Delta \mu$
$\theta'_3 = -\theta'_1$
$\theta''_3 = -2\theta''_2 \cos \Delta \mu$
$\theta''_4 = -\theta''_2$
$\theta'''_4 = -2\theta'''_3 \cos \Delta \mu$
$\theta'''_5 = -\theta'''_3$

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

Field error

Artificial field error

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

**Orbit response matrix (ORM) based correction**

Matrix containing proportionality constants can be calculated or measured separately

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

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

\(R\) 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

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

Then apply the negatives of the calculated corrector strengths

\[
\begin{bmatrix}
-\theta_1 \\
-\theta_2 \\
-\theta_3 \\
\vdots \\
-\theta_{n-1} \\
-\theta_n
\end{bmatrix}
\]

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
Singular Value Decomposition (SVD)

\[ R = USV^T \]

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

\( s_i \) are called singular values arranged as \( s_1 > s_2 > s_3 \ldots s_n \)

U and V are orthogonal matrices such that

\[ U^{-1} = U^T \quad \text{and} \quad V^{-1} = V^T \]

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

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

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

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

$$Q_y = 3.28$$
Symmetry exploitation in SIS 18 vertical ORM

\[ \beta_{bpm1} = \beta_{bpm2} = \beta_{bpm3} \ldots \ldots = \beta_{bpm12} \]

\[ \beta_{corr1} = \beta_{corr2} = \beta_{corr3} \ldots \ldots = \beta_{corr12} \]

\[ \Delta \mu_{bpm} = \text{constant} \]

\[ \Delta \mu_{corr} = \text{constant} \]

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

Each row is cyclic shift of previous row.

All diagonal elements are identical.


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

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

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

Inverse is straightforward

\[ R^{-1} = F^*H^{-1}F \]

\[ H^{-1} = \text{diag}(\frac{1}{\sigma_k}), k=1\ldots n \]

Standard Fourier matrix containing DFT modes

\[ F_k = F_{kc} + jF_{ks} \quad F_{ks} = \sin\left(\frac{2\pi km}{n} + \varphi_k\right) \]
Equivalence of DFT and SVD

DFT: \[
\begin{bmatrix}
R_{11} & \cdots & R_{1n} \\
\vdots & \ddots & \vdots \\
R_{m1} & \cdots & R_{mn}
\end{bmatrix}
= \begin{bmatrix}
F_{11} & \cdots & F_{1n} \\
\vdots & \ddots & \vdots \\
F_{m1} & \cdots & F_{mn}
\end{bmatrix}
\begin{bmatrix}
\sigma_1 & \cdots & 0 \\
\vdots & \ddots & \vdots \\
0 & \cdots & \sigma_n
\end{bmatrix}
\begin{bmatrix}
F_{11} & \cdots & F_{1n} \\
\vdots & \ddots & \vdots \\
F_{m1} & \cdots & F_{mn}
\end{bmatrix}
\]

Why to do SVD when Circulant symmetry exits?

SVD: \[
\begin{bmatrix}
R_{11} & \cdots & R_{1n} \\
\vdots & \ddots & \vdots \\
R_{m1} & \cdots & R_{mn}
\end{bmatrix}
= \begin{bmatrix}
U_{11} & \cdots & U_{1m} \\
\vdots & \ddots & \vdots \\
U_{m1} & \cdots & U_{mn}
\end{bmatrix}
\begin{bmatrix}
s_1 & \cdots & 0 \\
\vdots & \ddots & \vdots \\
0 & \cdots & s_n
\end{bmatrix}
\begin{bmatrix}
V_{11} & \cdots & V_{1n} \\
\vdots & \ddots & \vdots \\
V_{m1} & \cdots & V_{mn}
\end{bmatrix}
\]

\[\varphi_{dk} = \text{phase}(\sigma_k)\]

\[s_k = |\sigma_k| = \sqrt{\sigma_{rk}^2 + \sigma_{ik}^2}\]
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.

- Perturbed orbit simulated in MADX
- Perturbed orbit sampled by BPMs
- Random reading assumed for missing BPM
- Estimated reading by DFT mode fitting for missing BPM

Closed orbit in y-plane (mm)

Longitudinal distance s (m)
One quick application: Missing BPM scenario

\[ F_{ks} = \sin \left( \frac{2\pi km}{n} + \phi_k \right) \]

\[ F_{kc} = \cos \left( \frac{2\pi km}{n} + \phi_k \right) \]

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

- Perturbed orbit
- Correction for all BPMs being operational
- Correction for missing BPM using DFT fitting
- Correction for missing BPM using SVD
- Correction for missing BPM; '0' as BPM reading

Missing BPM
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
- Outlook
Feedback loop in orbit correction

\[ G(s) = C(s) \]

\[ X(s) \]

Error

\[ E(s) \]

Input

\[ U(s) \]

Disturbance \[ D(s) \]

Output

\[ Y(s) \]

Reference

\[ E(s) \]

+ +

\[ N(s) \]

Noise

\[ G(s) = g(s) \]

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

\[ g(s) \text{ requires frequency response of all components} \]

\[ g(s) = g_{1}(s)_{\text{BPM}} \ldots g_{m}(s)_{\text{power supplies}}. g_{n}(s)_{\text{correctors}} \]
System identification necessary before controller design

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

Controller

ORM

Line receiver

Post Amplifier

Head Amplifier

Power supplies

SER module

12×1 steerer vector

12×1 orbit vector

Controller

stores data for 100 μs ~ 10 kHz
position calculation

sampling 4 ns ~ 250 MS/sec
System identification necessary before controller design

\[ g(s) = \text{transfer functions and delays} \]

To measure the transfer functions of all components in the loop

sampling 4 ns ~ 250 MS/sec
stores data for 100 μs ~ 10 kHz
position calculation
PID controllers

- 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

\[
G(s) = \frac{C(s)}{D(s)}
\]

\[
\begin{align*}
U(s) &= (K_p + \frac{K_i}{s} + sK_d)E(s) \\
U(t) &= K_p e(t) + \int_0^t k_i e(t) + K_d \frac{de(t)}{dt}
\end{align*}
\]
Next topic

- Introduction
- Closed orbit correction methods
- Closed control loop
- **What’s new in SIS18 COFB?**
  - Model errors
  - Dispersion
  - Project status
  - Conclusions
  - Outlook
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**
Next topic

- Introduction
- Closed orbit correction methods
- Closed control loop
- 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
- Project status
- Conclusions
- Outlook
Systematic lattice changes over ramp

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

- Red: Ramp of 5 T/s
- Blue: Ramp of 10 T/s

Higher singular value of ORM

Time (ms)
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 (\%) =

\[ \frac{\text{Max. of corrected orbit}}{\text{Maximum of uncorrected orbit}} \times 100 \]

Similarly RMS residual %

High residual means bad correction
Orbit correction over ramp of 5 T/s (constant tune)

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

PhD thesis “Tune measurement at GSI SIS18: Methods and Applications” by R. Singh
Tune shift of 0.01 produced by artificial magnet gradient errors (50Hz low pass filter on normalized Quadrupole strengths)

\[ Q_x = 3.28 \]
\[ Q_y = 3.27 \]

Orbit correction over ramp of 5 T/s (tune variation of 0.01)
Other sources of model errors

2\times10^{10} \text{ particles injected}

1\times10^{10} \text{ particles injected}

Image charge tune shift

\Delta Q_{c,y} \approx 0.02

Tune shift during ramp

\Delta Q_{\phi} \approx 0.01

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

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Dispersion (x-plane)

\[ \Delta x_{\text{disp}} = D(s) \frac{\Delta P}{P} \]

\[ \Delta x_{\text{disp}} = 2.1 \, m \times 0.001 = 2.1 \, mm \]

\[ \Delta p/p = 0.001 \]

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.

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
- Closed control loop
- What’s new in SIS18 COFB?
- Model errors
- Dispersion

- **Project status**
  - 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

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Extra slides
Internal model control (IMC)

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

- 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

Reactive yet stable!
Find the process model!
Non-systematic lattice changes over ramp

Uncertainty modeling in ORM is required

First hint on need of robust controller
Tune shift of 0.01 produced by artificial magnet gradient errors (50Hz low pass filter on normalized Quadrupole strengths)

\[ Q_x = 3.28 \]
\[ Q_y = 3.27 \]

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.

![Graph showing the relationship between vertical tune shift and image charge defocusing effect.](image-url)
Effect of image charge tune shift on closed orbit correction

- **RMS of residual orbit**
- **Maximum of residual orbit**

![Graph showing the effect of tune shift on residual orbit](image)
Effect of beta beating

![Diagram showing the effect of beta beating at different distances. The graph plots the beta function (in m) against distance (in m) for zero beta beating, 20% beta beating, and 50% beta beating. The peaks and troughs are more pronounced as the beta beating increases.](image-url)
Effect of beta beating

- RMS of residual orbit
- Maximum of residual orbit

\[ \text{Percentage of Beta beating (\%)} ]

\[ \text{Residual \% (mm)} \]
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

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

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 \( K(s) \)

**Tune** = Number of Betatron oscillations over one turn

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3/15/2018

S.H. Mirza
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

\[ x'' = 1 - \rho^2 - K x \frac{d}{ds} \]

\[ y'' = K y \frac{d}{ds} \]

\[ y(s) = \mu_y(s) - \delta \]

\[ \beta(s) \]

\[ \alpha \sqrt{\beta} \]

\[ \mu s = 1 - \frac{d}{ds} \]

\[ x_0 ds \]


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S.H. Mirza
Subtracting dispersion effect from closed orbit

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?