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ERRORS CORRECTION AND ORBIT CONTROL IN REAL ACCLERATOR

Esmaeil Ahmadi

Beam Dynamics group

Contents

Introduction

- In designing and constructing an accelerator, physicists and engineers do their best in making a perfect jobs and in predicting any possible operation mode for their device.

- In most of the cases, the ideal machine remains just a concept and one has to deal with more real objects where construction tolerances and unpredicted phenomena generate effects that need to be measured and corrected.

- In this lecture, we will briefly introduce the typical and predictable errors affecting real accelerators and the ways to remedy these effects.

Why we should consider all of possible errors?

- **Get the beam around the machine**

  A perfect machine doesn't need this

  Gross orbit correction (~100's µm scale)

- **Keep the electron orbit through the center of the focusing magnets**

  Results in better quality electron beam, and hence better quality x-ray beam.

- **Steer x-ray beam away from places it shouldn't be**

- **Steer the x-ray beams at the users' samples**

  Long lever arm (typically 40-70m) makes it a challenge to get the beam on target.

  Electron orbit though x-ray source point defines x-ray trajectory.

  Fine orbit correction (<1's µm scale)

Beam Stability Criteria for SR Experiments

Sources of photon beam instability can be divided into 2 categories:

- those associated with beam line optical components and experimental apparatus

the beam line staff's problem!

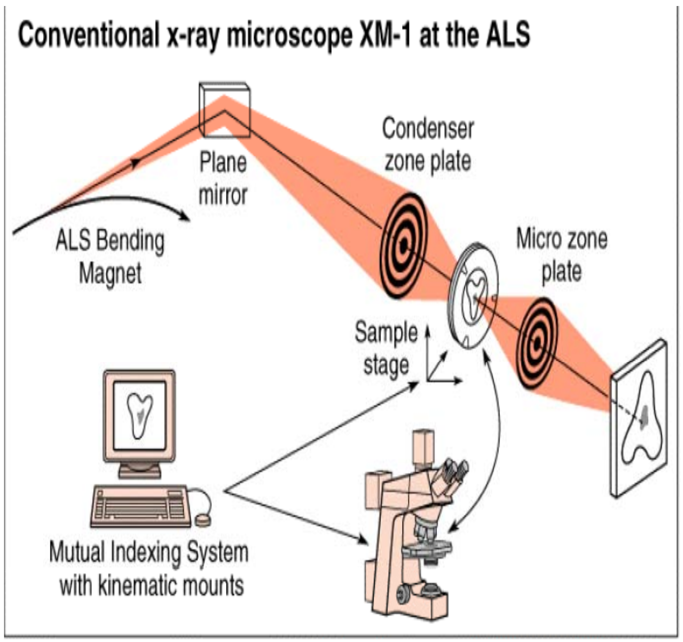
- those associated with the electron beam

✓ **the accelerator staff's problem!**

Beam Stability Criteria for SR Experiments

- **3rd generation stability requirements :**
  - intensity stability < 0.1%
  - pointing accuracy < 5% beam dimensions
  - photon energy resolution < 10-4
  - timing stability < 10% bunch length

⇒ orbit < 1-5 μm, <1-10 μrad   beam size < 0.1 %



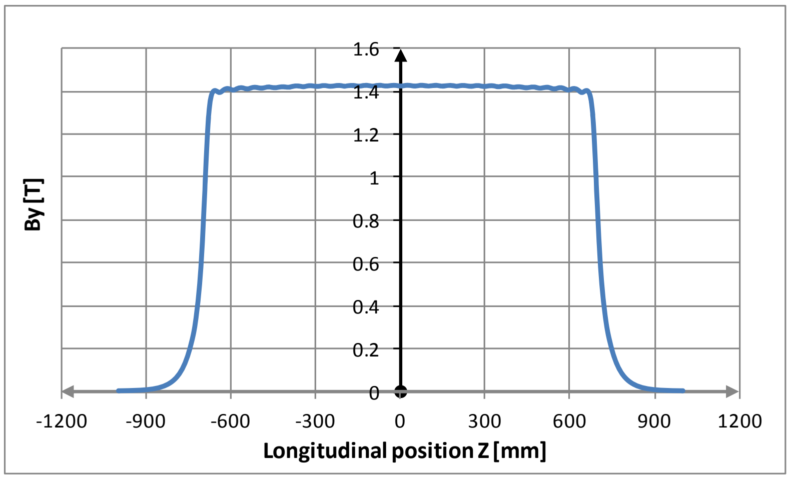
SR requirements:

intensity stability: **10^{-3}**

position stability: **~1 μm**

Type of errors in real accelerators

- Magnet modeliong
  - The real magnets are not the ones used in the simulation codes. Even if the hard-edge model is a good approximation, is not exact. There are the effects of fringe field, changing fields in the body of the magnets, etc:



Central vertical field component versus longitudinal direction in the ILSF storage ring

Type of errors in real accelerators

- Magnet fabrication
  - In fabrication of the magnets, more divergences from our model will be happen:
  - Finite precision in the shaping of the pole faces (in the order of ±20μm
  - Finite precision in the assembly of the magnets.

Field

In general is the precission magnetic fields will be of the order of $\Delta B/B = 10^{-3}$

  - This effect will include additional magnetic fields, that can introduce orbit distortions, coupling between the planes, change of the optical functions, tune shifts, and non linear terms in the equation of motion.

Type of errors in real accelerators

- Magnet Installation
  - When positioning the magnets in their position at the accelerator complex, the precision of the positioning is limited, either by the accuracy in the installation and the accuracy in the measuring.

Position

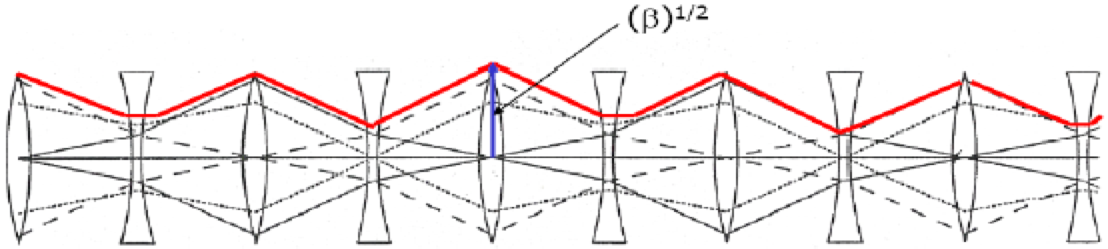
In general is the precission of the position of the magnetic center will be of the order of $\Delta x, y = 150\ \mu m$ and $\Delta s \sim 1mm$, Angular$\sim 100\ \mu rad$.

Other type of errors in real accelerators

- Noise and surroundings
  - The magnets will be placed in noise environments.
  - Long term Causes (Years - months)
    - ❑ Ground settling, season changes, diffusion
  - Medium - Days/Hours
    - ❑ Sun and moon, day-night variations (thermal), rivers, rain, wind, refills and start-up, sensor motion, drift of electronics, local machinery, filling patterns
  - Short (Minutes/Seconds)
    - ❑ Ground vibrations, power supplies, injectors, experimental magnets, air conditioning, refrigerators/compressors, water cooling

Betatron oscillation

- Beta function $\beta_x(s)$
  - Describes the envelope of the betatron oscillation in an accelerator



- Phase advane
  - The fraction of the oscillation performed in a periodic cell is called the phase advance per cell(x or y)

$$\psi(s) = \int_0^s \frac{1}{\beta_x(s)} ds$$

- Betatron tune: number of betatron oscillations in one orbital turn

$$Q_x = \frac{\psi(0\,|\,C)}{2\pi} = \oint \frac{ds}{\beta_x(s)} / 2\pi = \frac{R}{\langle \beta_x \rangle}$$

Dipolar errors

- Source of errors
  - Dipole field errors
  - Dipole misalignments
  - Quadrupole misalignments
    - Consider the displacement of a particle δx. from the ideal orbit.
      The vertical field is:

$$B_y = G\bar{x} = G\left(x + \delta x\right) = Gx + G\,\delta x$$

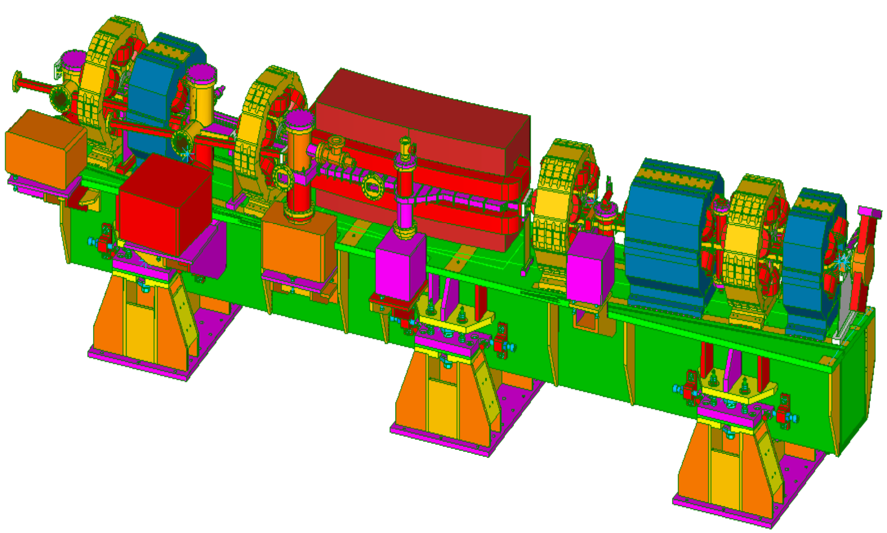
- Effect of orbit errors in any multi-pole magnet

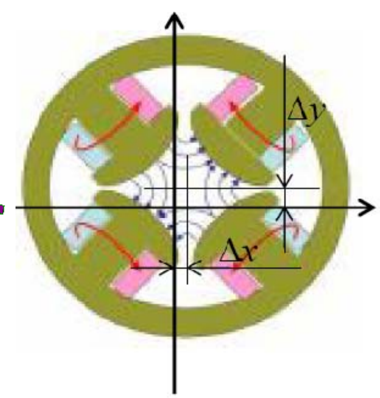
$$B_y = b_n \bar{x}^n = b_n\left(x + \delta x\right)^n = b_n\left(\underbrace{x^n}_{2(n+1)\text{pole}} + \underbrace{n\delta x x^{n-1}}_{2n\text{pole}} + \underbrace{\frac{n(n-1)}{n!}(\delta x)^2 x^{n-2}}_{2(n-1)\text{pole}} + \cdots + \underbrace{(\delta x)^n}_{\text{dipole}}\right)$$

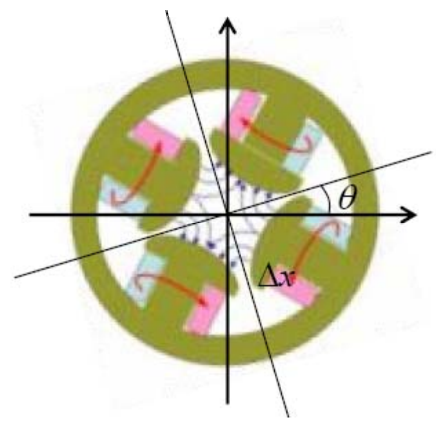
Dipolar errors

Typical number for imperfections in the storage rings

- Girder transverse displacement: 0.1 mm (rms).
- Girder roll: 0.1 mrad (rms).
- Quadurpole and sextupole transverse displacement with respect to girder: 0.03 mm (rms).
- Dipole transverse displacement with respect to girder: 0.05 mm (rms).
- Dipoles roll with respect to girder: 0.1 mrad (rms).
- Dipole filed error : $\frac{\Delta B}{B} = 10^{-4}$

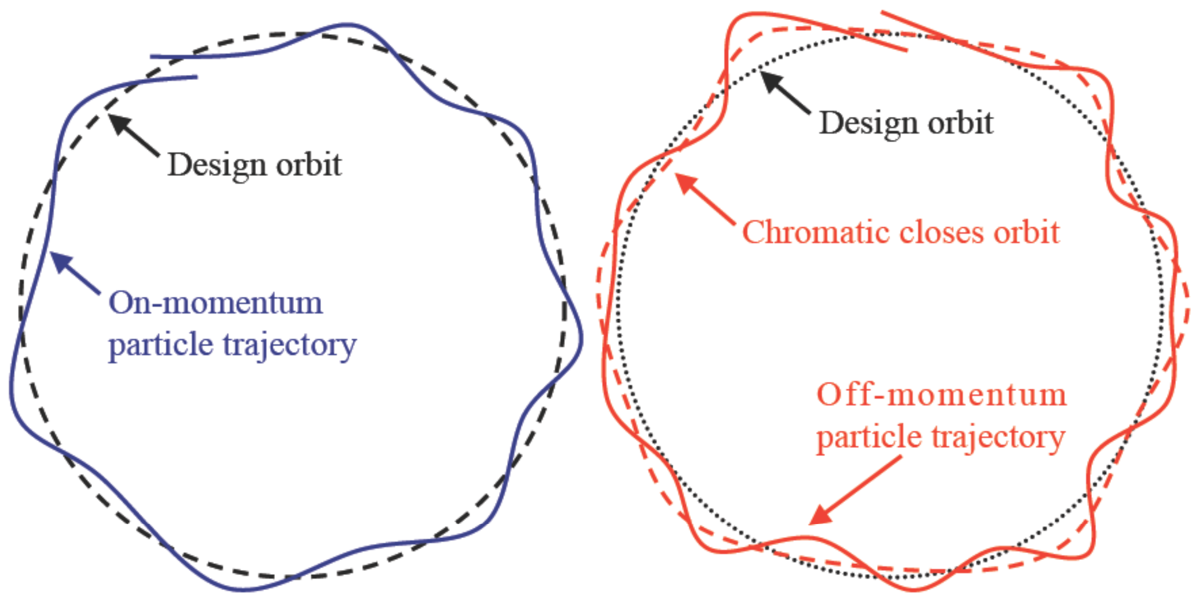






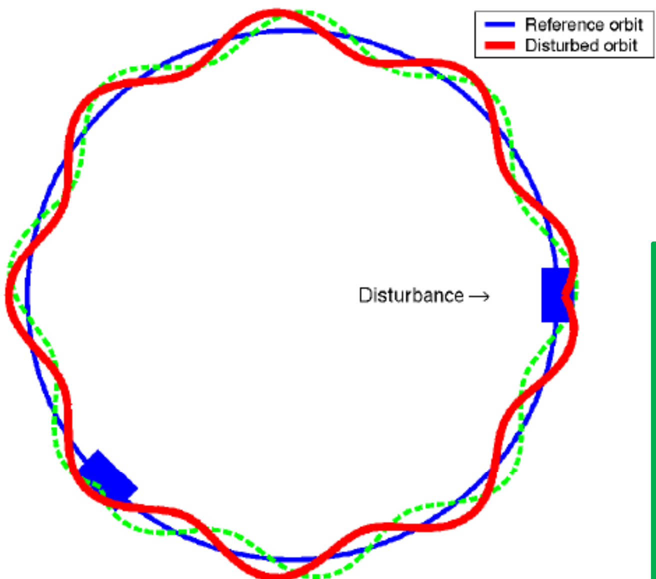
Closed orbit

- Design orbit defined by main dipole field
- On-momentum particles oscillate around design orbit
- Off-momentum particles are not oscillating around design orbit, but around chromatic closed orbit
- Distance from the design orbit depends linearly with momentum spread and dispersion



closed orbit distortion

- A single kick (a point-like change in the momentum of the particle) has been placed in the lattice we can see the effect of the kick, and that the trajectory does not close over itself. .
- Regardless of the location of the disturbance, the entire orbit is affected.



transverse kicks caused by dipole errors:

$$\varphi_j = \frac{\int \Delta B_y ds}{B\rho}$$

- $\varphi_j = \dfrac{\Delta B_j L_j}{B\rho} \rightarrow$ dipole field error
- $\varphi_j = \dfrac{B_j L_j \sin\theta_j}{B\rho} \rightarrow$ dipole roll error
- $\varphi_j = \dfrac{G_j L_j \Delta_{x,y_j}}{B\rho} \rightarrow$ quadrupole displacement

Iranian Light Source Facility

IPM

closed orbit distortion

Approximate errors as detla functions in n locations

$$\delta_{x,y;i} = -\frac{\sqrt{\beta_{x,y;i}}}{2\sin(\pi Q_{x,y})} \sum_{j=i+1}^{i+n} \phi_{x,y;j} \sqrt{\beta_{x,y;j}} \cos(|\pi Q_{x,y} + \psi_{x,y;i} - \psi_{x,y;j}|)$$

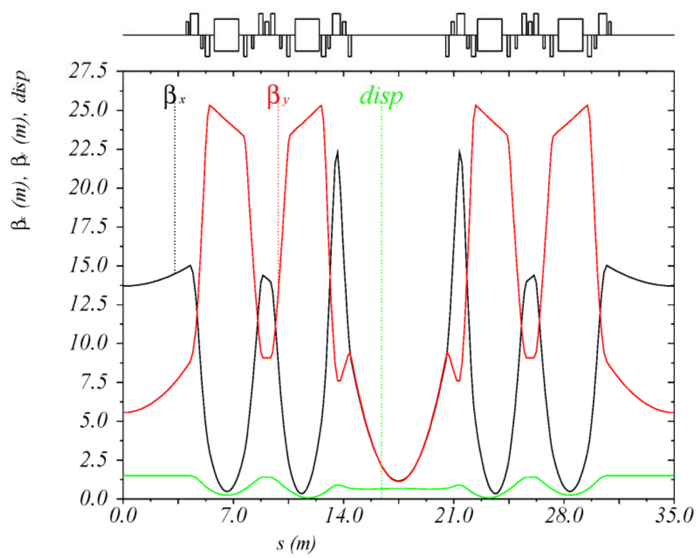
$\beta_{x,y;j}$: beta function in the place of error source

$\beta_{x,y;i}$: beta function in the place of each element

$Q_{x,y}$: tune number

$\psi_{x,y}$: betatronic phase advance

$\varphi_{x,y:j}$: kick produced by jth element



One super-period of ILSf low field storage ring

closed orbit distortion

- In the ILSF storage ring, the vertical beta function is 23m in the dipoles and 25.32m in the quadrupoles and vertical tune number is 11.27 :
- Consider dipole field error is $\frac{\Delta B}{B} = 10^{-4}$

$$\text{kick produced by dipole field error} \rightarrow \varphi_j = \frac{\Delta B_j L_j}{B\rho} = (10^{-4})(\frac{1.55}{13.81}) = 1.1\times 10^{-4} rad$$

- The maximum orbit distortion in the dipoles position is

$$\delta_y = \frac{\beta_y}{2\sin(\pi Q_y)} \times \varphi_j = \frac{23}{2\sin(11.27\pi)} \times 1.1\times 10^{-4} = 2.18 mm$$

- For a quadrupole with 0.15 mm displacement

$$\textit{kick produced} \text{ by quadrupole displacement} \rightarrow \varphi_j = \frac{G_j L_j \Delta_{x,y_j}}{B\rho} = \frac{(23.49T/m)(0.27m)(1.5\times 10^{-4} m)}{(0.723T)(13.81m)} = 9.5\times 10^{-5} rad$$

- The maximum orbit distortion in the dipoles position is

$$\delta_y = \frac{\beta_y}{2\sin(\pi Q_y)} \times \varphi_j = \frac{25.32}{2\sin(11.27\pi)} \times 9.5\times 10^{-4} = 2.05 mm$$

Statistical distribution of errors

- Consider random distribution of errors in N magnets
- The expectation value is given by

$$< u(s) >= \frac{\sqrt{\beta(s)}}{2\sqrt{(2)}\sin(\pi\nu)}\sum_i \beta_i \delta u_i' = \frac{\sqrt{\beta(s)\langle\beta\rangle}\sqrt{N}}{2\sqrt{(2)}\sin(\pi\nu)}\frac{(\delta Bl)_{\text{rms}}}{B\rho}$$

- Examples
  - In the ILSF low field storage ring there are 56 dipole and 252 quadrupole magnets
  - The expectation value of the orbit distortion in the dipoles

$$y_0 = \frac{\sqrt{23\times 23}\times\sqrt{56}}{2\sqrt{2}\sin(11.27\pi)}\times 1.1\times 10^{-4} = 8.789mm$$

  - And in the quadrupoles

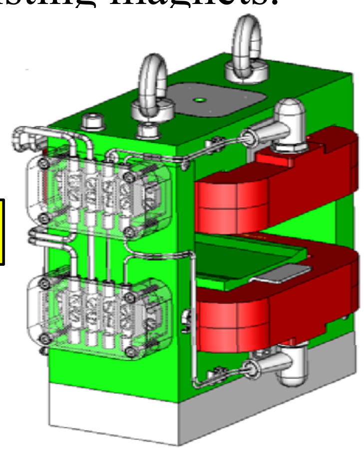
$$y_0 = \frac{\sqrt{25.32\times 25.32}\times\sqrt{252}}{2\sqrt{2}\sin(11.27\pi)}\times 1.1\times 10^{-4} = 27.07mm$$

Closed orbit correction

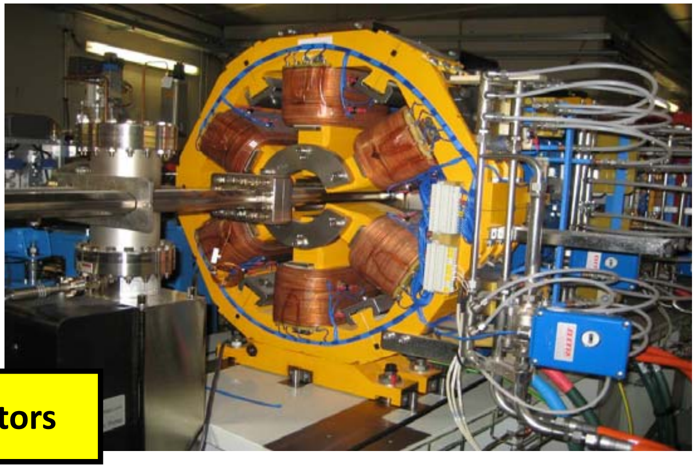
- The control and correction of the closed orbit is one of the most fundamental aspects of the operation of one storage ring, both for synchrotron light sources or colliders. In a synchrotron light source, we want to provide the beam to the users accurately down the beam lines to the users, and in a collider we have to make sure that the beams collide. In modern machines, this requires an stability of the closed orbit down to the sub-μm. Additionally, orbit control is also the first step in the correction of focusing error and coupling; and is required for a good beam lifetime

Closed orbit correction

- To correct the orbit, two components are needed:
  1. Monitors to detect the position of the particles. Usually are the *beam position monitors or BPMs, but is also possible to use* the synchrotron light to measure the position of the particles. Modern BPM system offer sub-μm resolutions in the measurement of the closed orbit, offering sampling rates from the 10 kHz (or more) to the Hz; or offer the possibility to measure the orbit turn by turn.
  2. Actuators to compensate for the orbit deviation. These *steering or corrector magnets allow the operator to apply* dipolar field to compensate for dipolar error along the machine. Can be extra dipolar magnets, or extra coils in some of the existing magnets.



Corrector magnet

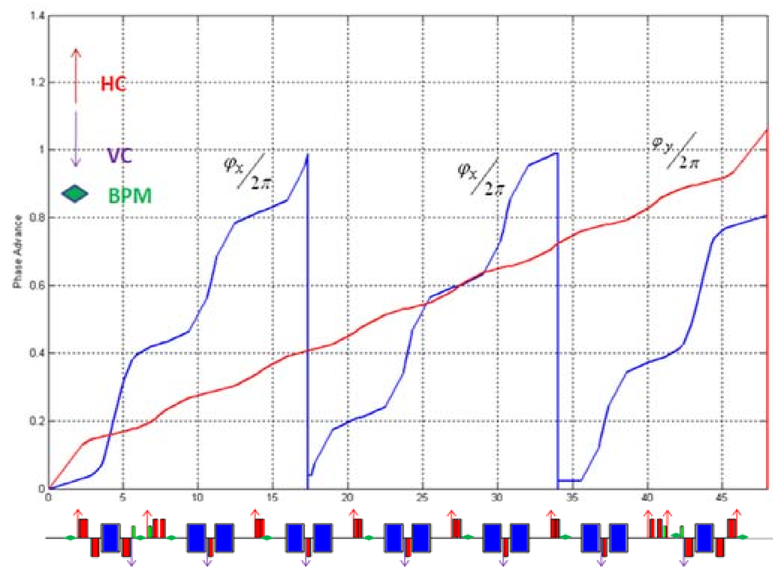


Sextupole and correctors

Closed orbit correction

- Distribution of corrector magnets and BPM
  - place orbit corrector and BPM next to the main quadrupoles
  - horizontal BPM and corrector next to QF
  - vertical BPM and corrector next to QD

- Distribution of correctors and BPMs in ILSF booster Synchrotron



Closed orbit correction

- If $\Delta\vec{c}$ is a vector containing the change in the setting of one corrector magnet, and $\Delta\vec{u}$ is the change in the reading of the BPMs, then the response matrix M is defined from:

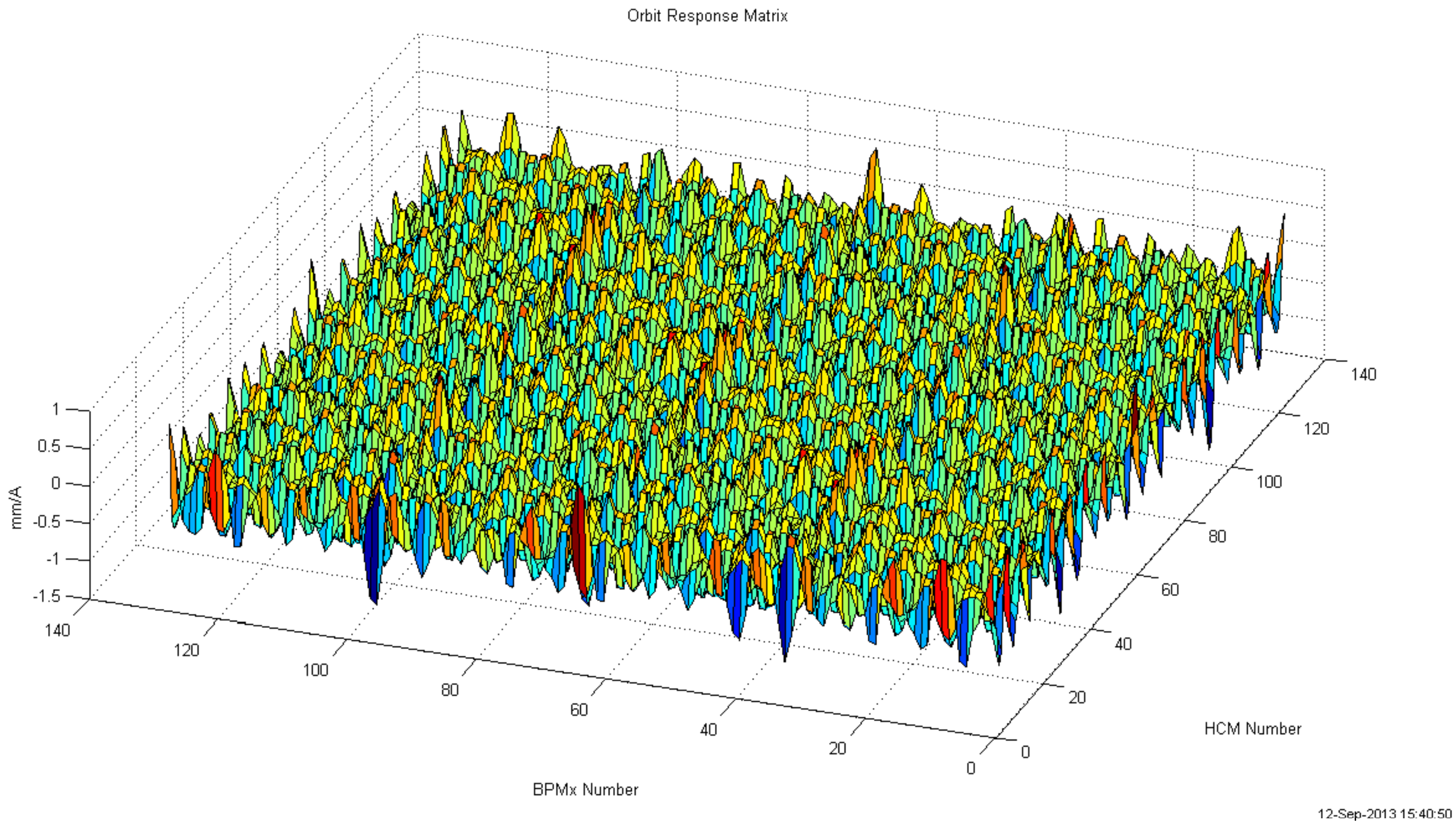
$$\begin{aligned} \Delta\vec{u} &= \mathcal{M} \times \vec{c} \\ \mathcal{M}_{i,j} &= \frac{\Delta BPM(u_i)}{\Delta CM(c_j)} \\ &= \frac{\sqrt{\beta_i \beta_j}}{2\sin\pi Q} \cos\left(\pi Q - |\phi_i - \phi_j|\right) \end{aligned}$$

- M can be calculated from the model of the machine, using one of our accelerator physics code, or may be measured in the real machine, changing the setting of the correctors and recording the change in BPM readings.

Closed orbit correction

- The most direct method of correction the orbit consist in inverting M to predict the change in corrector magnets to compensate an measured closed orbit.
- This is not in general possible: M is not square in general, or can be degenerated.
- Clever algorithms such as Singular Value Decomposition can be used to perform a pseudo-inversion of the response matrix
- Methods not based in the inversion of M, such as local orbit bumps will help in those cases, or when for some reason we do not know the response matrix.

- Response matrix for ILSF storage ring(in hardware unit)



Closed orbit correction

SVD is algorithm to invert non-square matrices. A matrix R of dimensions M× N can be written as:

SVD decomposition: $\boxed{R = U \times W \times V^T}$

where:

- U is an unitary matrix ($U \times U^T = U^T \times U = I$) of dimensions M×M.
- V is an unitary matrix ($V \times V^T = V^T \times V = I$) of dimensions N × N.
- W is a diagonal matrix of dimensions M× N where all the elements are positives or null, and are called the SVD eigenvalues.

SVD inversion:

$$\Delta c = M^{-1} \Delta x$$

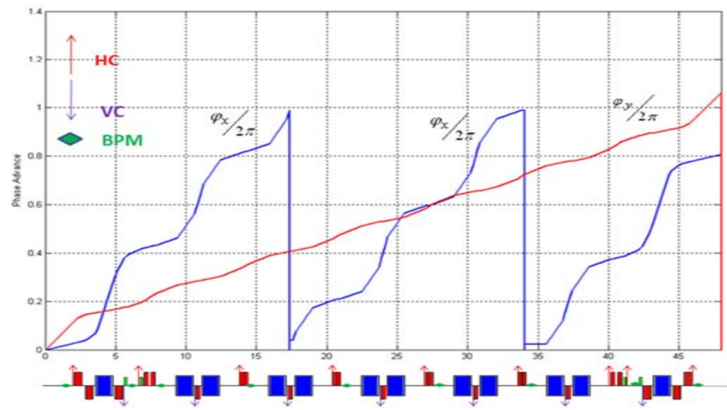
$$= V_M \times W_M^{-1} \times U^T_M \times \Delta x$$

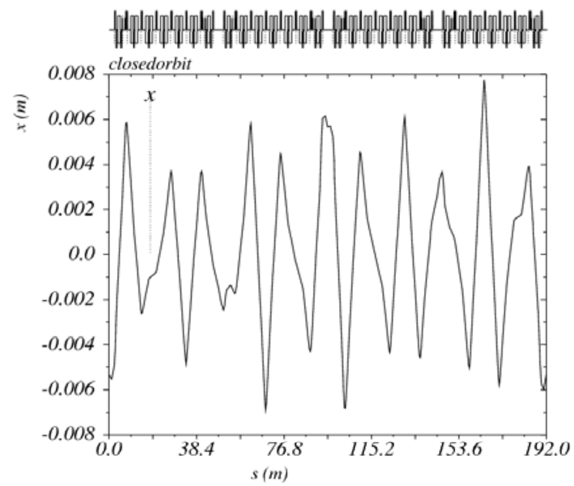
where W^{-1}_M is a diagonal matrix of dimensions N ×M

Closed orbit correction

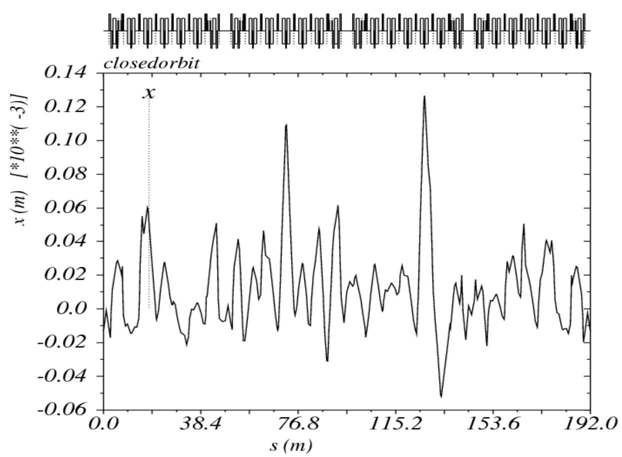
Closed orbit correction for ilsf booster synchrotron

Distribution of correctors and BPMs in ILSF booster Synchrotron



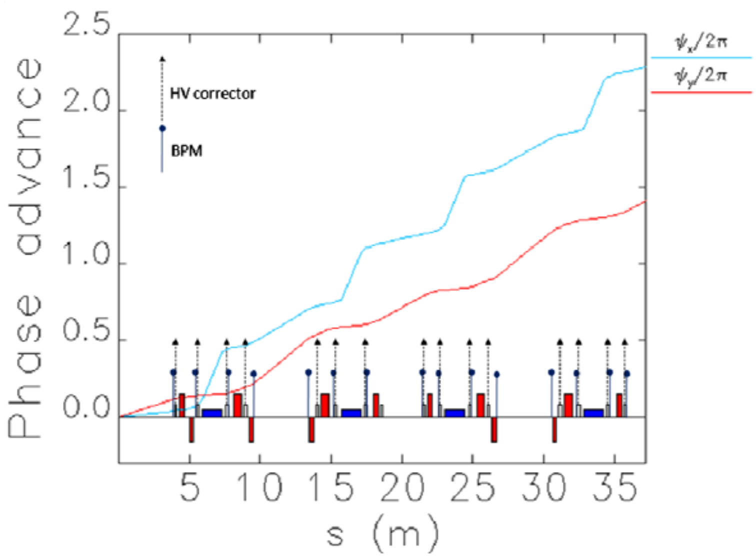


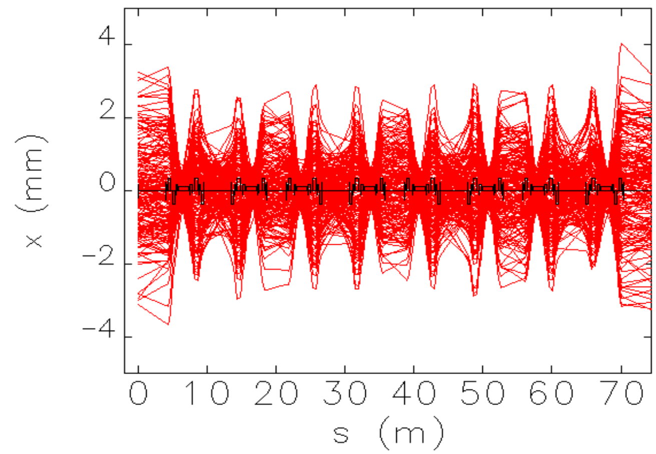
Closed orbit before correction



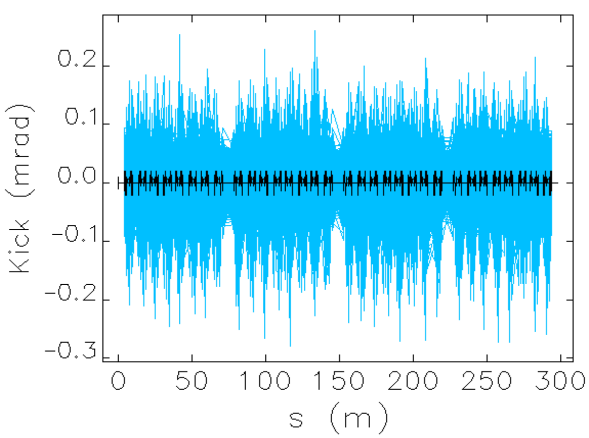
Closed orbit before correction

Closed orbit correction for ILSF high field storage ring

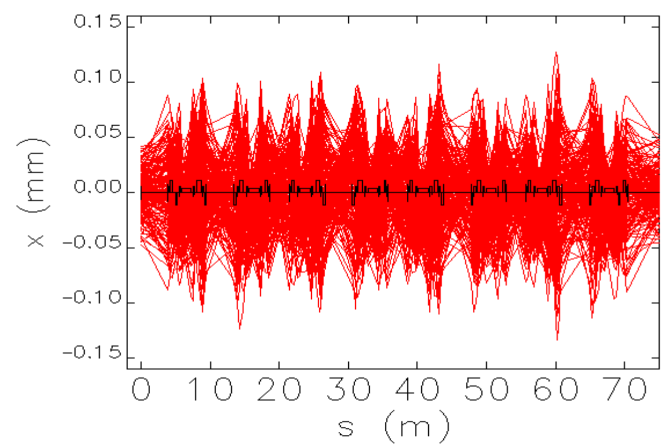




Closed orbit before correction



Strength of quadrupoles

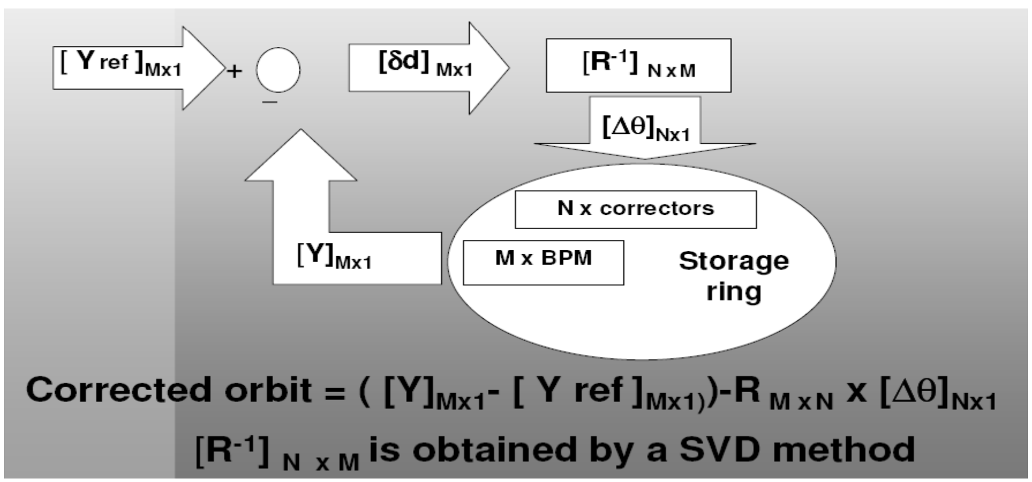


Closed orbit before correction

Orbit feedback

- The static correction compensate the expected errors due to misalignment of the magnets and error in the dipolar field component of the bending magnets (150 µm error in the girders, 50µm of the elements in the girders). The required strength is in the range 100 to 400 µrad.
- Closed orbit stabilization performed using slow and fast orbit feedback system.

- The target in the orbit feedback is to stabilize the orbit down to submicron stability, at the position of the insertion devices.



Local orbit correction principle

Thank you !

Orbit feedback

- Closed orbit stabilization performed using slow and fast orbit feedback system.
- Slow feedback operates every few seconds (~30s for ESRF storage ring) and uses complete set of BPMs (~200 at ESRF) for both planes
- Efficient in correcting distortion due to current decay in magnets or other slow processes
- Fast orbit correction system operates in a wide frequency range (0.1Hz to 150Hz for the ESRF) correcting distortions induced by quadrupole and girder vibrations.
- Local feedback systems used to damp oscillations in areas where beam stabilization is critical (interaction points, insertion devices)