Optics-measurement-based
Beam Position Monitor Calibration

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The Large Hadron Collider Complex
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5 Summary of thesis work and Conclusions
The equation of motion of a particle in a synchrotron is defined by the configuration of:

- **Dipolar field**: defines the beam ideal closed orbit.

\[ z = z_{\text{ideal orbit}} \text{ where } z = x, y \]
The equation of motion of a particle in a synchrotron is defined by the configuration of:

- **Dipolar field**: defines the beam ideal closed orbit.
- **Quadrupolar field**: defines the oscillation around the closed orbit *(betatronic oscillations).*

\[ z = z_{\text{ideal orbit}} + z_{\text{betatronic}} \text{ where } z=x,y \]
The equation of motion of a particle in a synchrotron is defined by the configuration of:

- **Dipolar field:** defines the beam ideal closed orbit.
- **Quadrupolar field:** defines the oscillation around the closed orbit (betatronic oscillations).
- **Beam momentum spread:** defines the deviation of the closed orbit with respect to the ideal value.

\[ z = z_{\text{ideal orbit}} + z_{\text{betatronic}} + z_{\text{dispersion}} \text{ where } z = x, y \]
• Equation of motion $z'' + k_z(s)z = 0$, $z' = \frac{dz}{ds}$ where $k_z(s) = \text{focusing strength}$.

• Solution $z = \sqrt{\beta_z(s) \epsilon_z} \cos(\phi_z(s) + \phi_{z,0})$. 
Beam dynamics: Optics

- Equation of motion \( z'' + k_z(s)z = 0, \quad z' = \frac{dz}{ds} \) where \( k_z(s) = \) focusing strength.
- Solution \( z = \sqrt{\beta_z(s)e_z} \cos(\phi_z(s) + \phi_{z,0}). \)
- **Important term:** Tune \( Q_{x,y} = \frac{1}{2\pi} \oint \frac{1}{\beta_{x,y}(s)} \, ds \)
Beam dynamics: Optics

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- Important term: Tune $Q_{x,y} = \frac{1}{2\pi} \oint \frac{1}{\beta_{x,y}(s)} \, ds$
Beam Position Monitors

- Non-invasive measurement of the beam centroid position.
  - Electrodes: different characteristics depending on the BPM location.
    - Button and wide aperture button (1).
Beam Position Monitors

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    1. Button and wide aperture button (1).
    2. Stripline.
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    2. Stripline.
  - Also cabling and readout electronics.
Beam Position Monitors: Calibration factors

• Beam position monitors **do not provide** a direct measurement of the beam position → Electrostatic BPMs measure **voltage** and **current**.

• After filtering and processing measured analogue signals, those signals are converted to position.

\[ z_{i,\text{measured}} = C_{z,i} z_{i,\text{real}} \]
Building a BPM component @ CERN Accelerator School (CAS), RHUL
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4. **Optics-measurement-based BPM calibration factors**

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MOTIVATION

Measured $\beta$ function during LHC commissioning in 2015 revealed a miss-calibration in the Beam Position Monitors.
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GOALS
- To develop and validate a method:
  1. Based on beam optics measurements in order to complement the current calibration procedure.
  2. Method that does not require physical access to the accelerator.
MOTIVATION

New injection system may impact the beam injection efficiency and control.
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GOALS
1. Commissioning the beam instrumentation upgrades.
2. Automatising of the optics measurements procedure
3. Develop and validate a method for measuring calibration factors based on optics measurements.
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5 Summary of thesis work and Conclusions
WHAT? Measure lattice parameters (e.g. $\beta$-function, dispersion...) at BPM locations.
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2. **HOW?** Measuring the beam centre-of-mass position at given locations while applying an external force (**Driven oscillation**).
**Optics measurements**

1. **WHAT?** Measure lattice parameters (e.g. $\beta$-function, dispersion...) at BPM locations.

2. **HOW?** Measuring the beam centre-of-mass position at given locations while applying an external force (**Driven oscillation**).

3. **WHY?** Safety and luminosity balance requirements.

\[
\sigma_{x,y} = \sqrt{\beta_{x,y}^* \epsilon_{x,y}} \rightarrow \mathcal{L} = \frac{1}{4\pi} \frac{N_1 N_2 f N_b}{\sigma_x \sigma_y}
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So imagine ATLAS would get more luminosity...
And discovers a new particle...
Optics measurements

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At the same time there is a physicist in CMS...
Optics measurements

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2. HOW? Measuring the beam centre-of-mass position at given locations while applying an external force (Driven oscillation).

3. WHY? Safety and luminosity balance requirements.

4. WHO? Optics measurements and corrections Team.
Optics measurements approaches

- What observable can we measure?
  - Centroid position.
Optics measurements approaches

• What **function** can we measure?
  • Centroid position → $\beta$-function, dispersion

  **Turn-by-turn measurements**
Optics measurements approaches

- **What function can we measure?**
  - Centroid position $\rightarrow \beta$-function, dispersion

**Turn-by-turn measurements**

- **Where do we want to measure?**
  1. Global measurements.
Optics measurements approaches

• What **function** can we measure?
  • Centroid position $\rightarrow \beta$-function, dispersion

**Turn-by-turn measurements**

• Where do we want to measure?
  1. Global measurements.
  2. Local measurements.
Project Overview

Turn-by-turn measurements

Calibration independent

Calibration dependent

Optics-based BPM Calibration factors calculation

BPM diagnostics

Dedicated Optics
Beam kickers: Configuration

- Driven motion → shifts the beam to a larger phase space amplitude and inducing betatron oscillations which can be observed in the BPM. Allows to excite the beam in phase space, to larger amplitudes.
  - **LHC**: Dipole kicker connected to a FPGA that generates a sinusoidal (modulated) function (**AC-dipole**).
  - **PSB**: Modification of the transverse feedback (**ADT**).
Turn-by-turn measurements: Acquisition

- Time domain:
  1. Record the beam centre-of-mass position vs. time.
  2. Filtering techniques (SVD).
Turn-by-turn measurements: Acquisition

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\[ \text{Fourier Transform} \]
Turn-by-turn measurements: Acquisition

- Time domain:
  1. Record the beam centre-of-mass position vs. time.
  2. Filtering techniques (SVD).

- Frequency domain:
  1. Obtain the $\phi$, $A$ and orbit.
  2. Optics calculation: $\beta^\phi, \beta^A$, dispersion and normalised dispersion.

![Graph showing turn-by-turn measurements](image-url)
Project Overview

- Turn-by-turn measurements
- Calibration independent: $\beta$ from phase
- Calibration dependent: $\beta$ from amplitude
- Optics-based BPM Calibration factors calculation
- BPM diagnostics
- Dedicated Optics
Calibration independent: $\beta$ from phase ($\beta^\phi$)

- **Methodology:**
  - Combination of phase advance between three BPMs.

\[
\beta^\phi_i = \frac{\epsilon_{ijk} \cot \phi_{i,j} + \epsilon_{ikj} \cot \phi_{i,k}}{\epsilon_{ijk} \frac{M11(i,j)}{M12(i,j)} + \epsilon_{ikj} \frac{M11(i,k)}{M12(i,k)}}
\]

$\epsilon_{i,j,k} = \text{Levi-Civita symbol}$

$M11$, $M12$ represent the model lattice parameters.
Calibration independent: $\beta$ from phase ($\beta^\phi$)

- **Methodology:**
  - Combination of phase advance between three BPMs.

- **Method evolution:**
  1. P. Castro: Method introduced considering only neighbouring BPMs (4).
  2. A. Langner: In 2012, method expanded to an arbitrary BPM (5).

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\beta^\phi_i = \frac{\epsilon_{ijk} \cot \phi_{i,j} + \epsilon_{ikj} \cot \phi_{i,k}}{\epsilon_{ijk} M_{11}(i,j) + \epsilon_{ikj} M_{12}(i,k)}
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Calibration independent: $\beta$ from phase ($\beta^\phi$)

- Limitations:
  - Small phase advance between BPMs (LHC, HL-LHC)
  - Values close to $\frac{\pi}{2}$ (PSB)

Courtesy of A. Langner (5).
Calibration dependent: $\beta$ from Amplitude ($\beta^A$)

- Methodology: $\beta$-function based on measurement of betatronic amplitude measurements.
Calibration dependent: $\beta$ from Amplitude ($\beta^A$)

- **Methodology:** $\beta$-function based on measurement of betatronic amplitude measurements.
- **Evolution:**
  1. P. Castro: Method described in P. Castro thesis but not used because its BPM calibration dependency (4).
  2. R. Tomás and R. Calaga: Introduce the first calibration-independent dispersion method (7).
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  3. **A. García-Tabarés Valdivieso**: Analytical $\beta^A$ error-bar calculation (8).
Calibration dependent: $\beta$ from Amplitude ($\beta^A$)

- Methodology: $\beta$-function based on measurement of betatronic amplitude measurements.
- Evolution:
  1. P. Castro: Method described in P. Castro thesis but not used because its BPM calibration dependency (4).
  2. R. Tomás and R. Calaga: Introduce the first calibration-independent dispersion method (7).
- Limitations:
  - Model-dependent method.
  - Biased by possible calibration factor errors.
\( \beta \) from Amplitude (\( \beta^A \)): Methodology

- **Ideal** driven amplitude is proportional to \( \sqrt{\beta^D_z} \) and to the exciter configuration (action \( 2J^D_z \))

\[
A^D_{z,i} = \sqrt{2J^D_z \beta^D_{z,i}}.
\]
**β from Amplitude (β³): Methodology**

- **Ideal** driven amplitude is proportional to $\sqrt{\beta_z^D}$ and to the **exciter** configuration (action $2J_z^D$)

  $$A^D_{z,i} = \sqrt{2J^D_z \beta^D_{z,i}}.$$ 

- **Measured** driven amplitude is also biased by BPM calibration errors:

  $$A^D_{z,i,\text{meas}} = C^A_{z,i} A^D_{z,i}.$$
$\beta$ from Amplitude ($\beta^A$): Methodology

- **Ideal** driven amplitude is proportional to $\sqrt{\beta^D_z}$ and to the exciter configuration (action $2J^D_z$)

  $$A^D_{z,i} = \sqrt{2J^D_z \beta^D_{z,i}}.$$ 

- **Measured** driven amplitude is also biased by BPM calibration errors:

  $$A^D_{z,i,\text{meas}} = C^A_{z,i} A^D_{z,i}.$$ 

- Therefore, **measured** $\beta$-function:

  $$\beta^D_{z,i} = \frac{(C^A_{z,i} A^D_{z,i})^2}{2J^D_z}.$$ 

  **One** observable, 3 unknown quantities!

  First calculation
**β from amplitude: Driven motion calculation**

1. Normalisation of the driven amplitude as an average for a set of BPMs.

\[
2J_{z}^{D,C} = \frac{1}{N} \sum_{i=1}^{N} \frac{(C_{z,i}^{A}, A_{i}^{D})^2}{\beta_{z,i}^{D}}
\]

2. \(\beta_{z,i}^{D}\)-function:
   - \(\beta^{\phi}\) only in the BPMs with good phase advance → in case of LHC reduce to the button BPMs placed in the arcs.
   - \(\beta^{\text{model}}\) only if the errors in the machine does not exceed a certain limit → PSB
\( \beta \) from amplitude: Driven motion compensation

• Once the amplitude is normalised \( \beta \) from amplitude can be computed at given location

\[
\beta_{z,i}^{A,D,\text{meas}} = \frac{(A_{i,z}^{D,\text{meas}})^2}{2J_{D,C}^z} = \frac{\left(C_{z,i}^A A_i^D\right)^2}{(C_{x,y}^A)^2 2J_{D}^z}.
\]

• Driven motion has to be compensated in order to extract the natural \( \beta \)-function \( \rightarrow \beta_{z,i}^{A,\text{meas}} \) (9).
Project Overview

Turn-by-turn measurements

Calibration independent: Dispersion

Calibration dependent: Normalised dispersion

Optics-based BPM Calibration factors calculation

BPM diagnostics

Dedicated Optics
Dispersion relates the dependency on the orbit change $\Delta CO_{x,i}$ with energy fluctuations $\frac{\Delta p}{p}$:

$$D_{x,i} = \frac{\Delta CO_{x,i}}{\Delta p}.$$
Dispersions depend on the orbit change $\Delta CO_{x,i}$ with energy fluctuations $\frac{\Delta p}{p}$:

$$D_{x,i} = \Delta CO_{x,i} / \frac{\Delta p}{p}.$$ 

- Measured relative momentum deviation:

$$\left(\frac{\Delta p}{p}\right)_{\text{meas}} = \frac{D_{x,\text{model}} C^A \Delta CO_x}{(D_{x,\text{model}})^2}.$$
Calibration dependent: Dispersion

- Dispersion relates the dependency on the orbit change $\Delta CO_{x,i}$ with energy fluctuations $\frac{\Delta p}{p}$:

$$D_{x,i} = \frac{\Delta CO_{x,i}}{\frac{\Delta p}{p}}.$$ 

- Measured relative momentum deviation:

$$\left( \frac{\Delta p}{p} \right)_{\text{meas}} = \frac{D_{x,\text{model}} C^A \Delta CO_x}{(D_{x,\text{model}})^2}.$$ 

- Dispersion is then calculated at each BPM

$$D_{x,i,\text{meas}} = C_i^A \Delta CO_{x,i} \left( \frac{\Delta p}{p} \right)_{\text{meas}} \approx \frac{C_i^A \Delta CO_{x,i}}{C_x^A \Delta p/p}.$$
Calibration dependent: Normalised Dispersion

- Normalised dispersion was first introduced in order to use dispersion measurements for correcting lattice imperfections (7).

- Normalised dispersion is defined as:

  \[ ND_{x,i} = \frac{D_{x,i}^{\text{meas}}}{\sqrt{\beta_{x,i}^{\text{meas}}}} \]

- Calibration impact on normalised dispersion:

  \[ ND_{x,i} = \frac{C_{x,i} A D_{x,i}^{\text{ideal}}}{C_x A \sqrt{(C_x A)^2}} = \frac{\sqrt{(C_x A)^2}}{C_x A \sqrt{\beta_{x,i}^{\text{ideal}}}} \]
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- Dedicated Optics
Optics-measurement-based BPM calibration factors

Calibration factors: $\beta$-function

- Based on the calculation of ratio between $\beta^A$ and $\beta^\phi$.

\[
C^A_{\beta,i} = \sqrt{\frac{\beta^A_i}{\beta^\phi_i}} = \frac{C^A_i}{\sqrt{(C^A)^2}}.
\]
Optics-measurement-based BPM calibration factors

Calibration factors: dispersion

• Based on the calculation of ratio between $D_x$ and $ND_x$.

\[ C^A_{D,x,i} = \frac{D_{\text{cal,dependent}}} {D_{\text{cal, independent}}} = \frac{D_{\text{meas},x,i}} {ND_{x,i} \sqrt{\beta_i^\phi}} = \frac{C^A_{x,i}} {C^A_x} \sqrt{\left(\frac{C^A_x}{C_x}\right)^2}. \]
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First observations of calibration errors at LHC

![Diagram of calibration errors]

<table>
<thead>
<tr>
<th>Name</th>
<th>Stripline</th>
<th>Enlarged Aperture</th>
<th>Standard</th>
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<tr>
<td>Geometry</td>
<td>Strip-line</td>
<td>Button</td>
<td>Button</td>
</tr>
<tr>
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<td>BPMS</td>
<td>BPMSX</td>
<td>BPMW</td>
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<tr>
<td>Diameter</td>
<td>61 mm</td>
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<td>61 mm</td>
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Diameter 61 mm 81 mm 61 mm 49 mm
First observations of calibration errors at LHC

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<td></td>
<td>49 mm</td>
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</table>

### Stripline

- **Counts**
  - Horizontal
  - Vertical

### Button

- **Counts**
  - Horizontal
  - Vertical

\[ \sqrt{\beta^A/\beta^\phi} \]
Project Overview

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Optics-measurements-based BPM calibration factors

PROBLEM

1. Optics calibration factors measurements are based on reference values → Accurate $\beta$ and dispersion values needed.

SOLUTION

Calibration factors are calculated in an optics configuration where the lattice systematic errors affect as little as possible the $\beta^\phi$ and dispersion measurements.

- **LHC**: Ballistic Optics.
- **PSB**: New horizontal and vertical phase advance (working point).
Optics configuration

• Adaptation of an old optics designed for quadrupolar alignment (10).
• Generate a controlled drifted section where $\beta \phi$ can be accurately measured (11).
• ONLY in 2017. Dispersion not matched to 0 in the interaction region.
Ballistic optics: $\beta$-function

- Based on the propagation of a $\beta$-function on a drift.
Ballistic optics: $\beta$-function

- Based on the propagation of a $\beta$-function on a drift.
Ballistic optics: Dispersion

- Linear propagation of dispersion function in a drift area, delimited by separation dipoles.

ATLAS

![Graph showing dispersion function](image-url)
Ballistic optics: Dispersion

- Linear propagation of dispersion function in a drift area, delimited by separation dipoles.
Results

Measured calibration errors:

- **Calibration factor (Beam 1)**
  - 2016 $< C^A_\beta > = 0.97$
  - 2017 $< C^A_\beta > = 0.97$

- **Calibration factor (Beam 2)**
  - 2016 $< C^A_\beta > = 0.96$
  - 2017 $< C^A_\beta > = 0.96$

Associated uncertainty:

- **Calibration factor uncertainty (Beam 1)**
  - 2016 $< \sigma(C^A_\beta, i) > = 4.2 \times 10^{-3}$
  - 2017 $< \sigma(C^A_\beta, i) > = 4.9 \times 10^{-3}$

- **Calibration factor uncertainty (Beam 2)**
  - 2016 $< \sigma(C^A_\beta, i) > = 3.8 \times 10^{-3}$
  - 2017 $< \sigma(C^A_\beta, i) > = 3.9 \times 10^{-3}$
PSB Optics configuration

- Combination of phase advance and BPM location leads to a phase advance between the BPMs close to $\pi/2$
• Combination of phase advance and BPM location leads to a phase advance between the BPMs close to $\pi/2$
• Moving the tune to a different value will modify the phase advance between the BPMs.
PSB Calibration factors

Measured calibration factors and associated errors:

- Ring 2 has been used as example but all the 4 rings show the same behaviour.
Project Overview

- Turn-by-turn measurements
  - Calibration independent
  - Calibration dependent
    - Optics-based BPM Calibration factors calculation
      - BPM diagnostics
      - Dedicated Optics
        - BPM re-calibration
BPM re-calibration

- **Time domain:**
  1. Record the beam centre-of-mass position vs. time.
  2. Filtering techniques (SVD)

- **Frequency domain:**
  1. Obtain the $\phi$, $A$ and orbit.
  2. Multiply the amplitude by $A_{x,y,i} \rightarrow \frac{1}{C_{x,y,i}} A_{x,y,i}$
  3. Optics calculation: $\beta^\phi, \beta^{A,\text{calibrated}}, \text{dispersion and normalised dispersion.}$

![Graph showing position vs. turn number for BPM i and BPM j]
Method validation: LHC

- Does re-calibrating the BPM improve the $\beta^A$ approach?
- Comparison of the distribution $\frac{\beta^A - \beta^\phi}{\beta^\phi}$ vs $\frac{\beta^A,\text{calibrated} - \beta^\phi}{\beta^\phi}$ for the range of BPM calibrated.

**Beam 1**

![Graph for Beam 1]

**Beam 2**

![Graph for Beam 2]
Method validation: PSB

- $\beta$ functions measured in **Ring 2** before and after BPMs re-calibration:

**Horizontal**

<table>
<thead>
<tr>
<th>Position [m]</th>
<th>$\beta_x$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>40</td>
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<td>120</td>
<td>8</td>
</tr>
<tr>
<td>140</td>
<td>9</td>
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**Vertical**

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<tr>
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<td>40</td>
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GOALS

- To develop and validate a method:
  1. Based on beam optics measurements in order to complement the current calibration procedure.
  2. Method that does not require physical access to the accelerator.
**GOALS**

- To develop and validate a method:
  - ✔ Based on $\beta$ *measurements* in order to complement the current calibration procedure.
  - ✗ Relative method not absolute calibration.
  - ✗ Based on *dispersion measurements* in order to complement the current calibration procedure.
  - ✔ Method that does not require access to the accelerator.
1. An Analytical study of the error-bar associated to the $\beta^A$ method has been developed as part of this thesis.

2. BPM calibration factors have been computed for the first time in LHC using measured $\beta$-function and dispersion.

3. Calibration factors measured with a sub-per cent resolution.

4. This method has been validated for several optics configurations, showing an improvement in the accuracy of a 6% on average. From -7% to 0.2% in Beam 1 and -6% to -1.8% in Beam 2.
GOALS

1 Commissioning the Beam instrumentation upgrades.
2 Automatising of the optics measurements procedure
3 Develop and validate a method for measuring calibration factors based on optics measurements
Protron Synchrotron Booster

GOALS

✓ Commissioning the Beam instrumentation upgrades.
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× Develop and validate a method for measuring calibration factors based on optics measurements.
PSB Conclusions

1. Completely automatised software and hardware developed, that would allow faster and more accurate optics measurements in Run3 of LHC.

2. BPM calibration factors have been computed for the first time in PSB using measured $\beta$-function.

3. Calibration factor accuracy limited by the Q3Q5 stability, so the method has not been fully validated.

4. After BPM calibration, $\beta^A$-measured error bar is within the specification of PSB optics control.
Future work

- Optics-measurement-based calibration factors will be periodically measured in order to understand calibration factors evolution with time.
- Instrumentation (wire scanners, Beam Synchrotron Light Telescopes, Interferometers...) dedicated to emittance measurement required an accurate knowledge of $\beta$-function. Therefore a good control of the BPM calibration factors in the region.
Thank you for your attention!
Back-up slides
• What magnets do we have to correct?

1 Linear corrections: quadrupolar imperfections, linear coupling, dispersion.

2 Non-linear corrections: higher order magnets imperfections.

• Where do we want to correct?

• Global errors

• Local corrections
• What magnets do we have to correct?

1. Linear corrections: quadrupolar imperfections, linear coupling, dispersion.
• What magnets do we have to correct?
  1. Linear corrections: quadrupolar imperfections, linear coupling, dispersion.
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• Where do we want to correct?
  • Global errors
Optics corrections

• What magnets do we have to correct?
  1. Linear corrections: quadrupolar imperfections, linear coupling, dispersion.
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• Where do we want to correct?
  • Global errors
Optics corrections

• What magnets do we have to correct?
  1. Linear corrections: quadrupolar imperfections, linear coupling, dispersion.
  2. Non-linear corrections: higher order magnets imperfections.

• Where do we want to correct?
  • Global errors
  • Local corrections
All together

- On-momentum measurements
  - Coupling corrections
  - Off-momentum measurements
    - K-modulation
    - Tbt Analysis
  - Global and local corrections
    - OK
    - Keep iterating
\[ \beta_i^A = \frac{(C_i^A A_i^D)^2}{2J_C^D} \frac{1 + \lambda^2 + 2\lambda \cos(\phi_i \Rightarrow AC\text{-dipole})}{1 - \lambda^2} \]
For one given Turn-by-turn measurements:

- Amplitude noise
- Action uncertainty

$$\beta_i^A = \frac{(C_i^A A_i^D)^2}{2J_C^D} \frac{1 + \lambda^2 + 2\lambda \cos(\phi_i \Rightarrow AC\text{-dipole})}{1 - \lambda^2}$$
\[ \beta_i^A = \frac{(C_i^A A_i^D)^2}{2J_C^D} \frac{1 + \lambda^2 + 2\lambda \cos(\phi_i \Rightarrow AC\text{-dipole})}{1 - \lambda^2} \]
\( \beta \) from amplitude: Error propagation

- For one given **Turn-by-turn** measurements:
  - Amplitude noise
  - Action uncertainty
  - Tune uncertainty
- For N consecutive **Turn-by-turn** measurements:
$\beta$ from amplitude: Error propagation

- For one given **Turn-by-turn**
  measurements:
  - Amplitude noise
  - Action uncertainty
  - Tune uncertainty
- For N consecutive **Turn-by-turn**
  measurements:
from amplitude: Error propagation

• For one given **Turn-by-turn** measurements:
  • Amplitude noise
  • Action uncertainty
  • Tune uncertainty
• For N consecutive **Turn-by-turn** measurements:
  • Fluctuations of machine over time
Is it Ballistic needed?

- Do we need a dedicated-optics?
- Comparison of several optics not specifically designed for calibration factors calculation: Injection and Flattop

![Graphs showing calibration factors for beams 1 and 2.](image)
References 1


References II


