Review of Linear Optics Measurements and Corrections in Accelerators

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Theory of the Alternating-Gradient Synchrotron:

\[
\left(\frac{\Delta \beta}{\beta}\right)_{\text{max}} = 4.0 \left(\frac{\Delta k}{k}\right)_{\text{rms}}
\]

“Thus if the variation in k from magnet to magnet were 1% (...) we would have a $\beta$-beating of 4%. Any particular machine (...) would be unlikely to be worse by more than factor of 2.”

→ Expected $\beta$-beating below 8% for any machine
LHCB2 6.5TeV, $\beta^*=40\text{cm}$ (2016)
Even $\Delta \beta/\beta \approx 700\%$ was reached when LER tune was pushed closer to the half integer.
Techniques for optics measurement & correction

- K-modulation
- Turn-by-turn
- Closed orbit (ORM)
- Passive corrections
A. Hofmann and B. Zotter

\[ \bar{\beta} \approx \frac{1}{3} \left( \beta_1 + \beta_2 + \sqrt{\beta_1 \beta_2 - L^2} \right) \approx \pm \frac{4\pi}{L} \frac{\Delta Q}{\Delta k} \]
Techniques for optics measurement & correction

- K-modulation
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AGS 1975: Coupling correction

E.C. Raka, PAC 1975: turn-by-turn at a single location

Closest tune approach:
\[ x(N) = \sqrt{\beta \epsilon} \cos(2\pi QN + \phi) \]

**ISR 1983: \( \beta \) and \( \phi \) from turn-by-turn data**

\( \beta \) computed from oscillation amplitude

J. Borer, A. Hofmann, J-P. Koutchouck et al

CERN/LEP/ISR/83-12
LEAR 1988: $\phi$ from turn-by-turn data

J. Bengtsson, CERN 88-05

Pick-ups

<table>
<thead>
<tr>
<th>Pick-ups</th>
<th>Measured phase advance (degrees)</th>
<th>Calculated by COMFORT (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UEH13 – UEH14</td>
<td>15.4</td>
<td>16.0</td>
</tr>
<tr>
<td>UEH14 – UEH23</td>
<td>192.1</td>
<td>191.2</td>
</tr>
<tr>
<td>UEH21 – UEH22</td>
<td>120.7</td>
<td>118.3</td>
</tr>
<tr>
<td>UEH22 – UEH23</td>
<td>34.1</td>
<td>36.3</td>
</tr>
</tbody>
</table>
LEP, $\beta$ from $\phi$, 1993

$\beta_1(\text{exp}) = \beta_1(\text{theo}) \frac{\cot \Psi_{12(\text{exp})} - \cot \Psi_{18(\text{exp})}}{\cot \Psi_{12(\text{theo})} - \cot \Psi_{18(\text{theo})}}$ (10)

$\beta$ from $\phi$, 3-BPM method, model dep.

$\frac{\Delta \beta}{\beta} = 10\%$

P. Castro et al, PAC 1993
D. Sagan et al, PRSTAB 3 092801.
Using LEP method for $\beta$ functions.
Best optics correction in lepton colliders

FIG. 6. Measurement after correcting the phase and coupling
TABLE III. Systematic error of the measured $\beta$-function at arc BPMs for using different BPM combinations. The phase advance between consecutive BPMs is approximately $\pi/4$.

<table>
<thead>
<tr>
<th>BPM combination</th>
<th>Systematic error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\blacktriangle$: probed, $\blacktriangledown$: used, $\blacktriangleleft$: unused</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>7.9</td>
</tr>
<tr>
<td></td>
<td>22.3</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
</tr>
</tbody>
</table>

Extension of the LEP 3-BPM method to any number of BPMs. Great improvement on $\beta$ measurement (from $\phi$). Good knowledge of lattice errors fundamental.
Further developments (2016)

A. Franchi, arXiv:1603.00281v2:

★ β from φ, extended 3-BPM equation:

\[
\beta_{1\text{ (meas)}} = \beta_{1\text{ (mod)}} \frac{\cot \Delta \phi_{12\text{ (meas)}} - \cot \Delta \phi_{13\text{ (meas)}}}{\cot \Delta \phi_{12\text{ (mod)}} - \cot \Delta \phi_{13\text{ (mod)}} + (\bar{h}_{12} - \bar{h}_{13})}
\]

★ Effects of non-linearities on the β, φ and coupling measurements
Ghost data: Turn-by-turn data not used

80%!
BPM issues required bad BPM detection techniques. The **RMS** in a FFT window is a good indicator.
Singular vectors ordered by singular value

\[ B_{t-b-t} = USV^T \]

BPM matrix

Bad BPMs easily identified as uncorrelated signals.

Noise removed by cutting low singular values

J. Irwin et al., Phys. Rev. Letters 82, 8
PEP-II, from $\phi$ to virtual model to $\beta$

Using SVD modes

Y. Yan et al, SLAC-PUB-11925
2006
AC dipoles were proposed to avoid spin resonances and do optics meas: M. Bai et al, Phys. Rev. Lett. 80, 4673 (1998).

Major breakthrough for protons: *Excite betatron oscillations (forced) without emittance blow-up*

Used in AGS, RHIC, SPS, Tevatron & LHC

LHC has $\approx 20$ optics within the magnetic cycle

The magnetic cycle takes about 2.5h

LHC optics commissioned thanks to AC dipole
Successful corrections of $\beta$ from amplitude using ICA (SVD).
X. Shen et al, PRSTAB 16, 111001 (2013)
Calibrating BPMs by switching off quads

LHC IR5

$\beta$ from phase (x)
$\beta$ from amplitude (x)
$\beta$ fit (x)

BPM gain to be fixed

A. Garcia-Tabares
THPMB041
Techniques for optics measurement & correction

★ K-modulation
★ Turn-by-turn
★ Closed orbit (ORM)
★ Passive corrections
\[ x(s) = \sqrt{\beta(s)} \beta_0 \frac{\theta}{2 \sin(\pi Q)} \cos\left( |\phi(s) - \phi_0| - \pi Q \right) \]

GLOBAL BETA MEASUREMENT FROM TWO PERTURBED CLOSED ORBITS

PAC 1987
M. Harrison, Fermilab*, Batavia, Illinois
S. Peggs, SSC-CDG*, Berkeley, California

The conventional 'cusp' beta measurement technique assumes that the BPM is close enough to the corrector to declare that their \( \beta, \phi \) values are identical, leaving only one unknown, \( \beta \), on the right hand side. Disadvantages of this method are that one closed orbit observation is needed to measure \( \beta \) at only one BPM, and that the BPM may be distant from the corrector. (In the realistic model of the Tevatron used below, each corrector is 2.5 metres away...
\[ C_{ij} = \frac{\Delta x \text{ at BPM } i}{\theta \text{ at corrector } j} \]

\[ \frac{\Delta \beta}{\beta} \approx 20\% \]

Y. Chung, G. Decker and K. Evans extract \( \beta \) and \( \phi \) from NSLS X-Ray ring \( C_{ij} \) data.

W.J. Corbett, M.J. Lee and V. Ziemann fit a model to reproduce the measured \( C_{ij} \) in SPEAR, obtaining: <1\% quad errors and <10\% orbit corrector errors.
K-modulation measurements in agreement with the model fitted to reproduce $C^{ij}$ using the code LOCO.
rms $\Delta \beta / \beta_{loco} = 0.3\%$ after 3 iterations
LOCO fitting was successful ($\Delta C_{ij, \text{rms}} \sim \text{Measurement noise}$)
Lack of convergence ($\Delta C_{ij} >> \Delta C_{ij}$), however, indicated existence of systematics

M. Aiba, PRST-AB 2013
LORM is an ORM but keeping orbit unchanged out of selected region → Revealed systematic errors
ESRF optics stability in time (ORM)

\[ \Delta \beta_y / \beta_y \] after 3.5h

1% peak \( \beta \)-beating develops in 3.5h
ALBA: LOCO Vs N-BPM (turn-by-turn)

A. Langner et al, IPAC 2015

<table>
<thead>
<tr>
<th>Method vs. nominal model</th>
<th>RMS $\beta$-beating (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>horizontal</td>
</tr>
<tr>
<td>N-BPM (phase)</td>
<td>1.5</td>
</tr>
<tr>
<td>From amplitude</td>
<td>2.0</td>
</tr>
<tr>
<td>LOCO</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Techniques are consistent at 1% level, but:

is LOCO underestimating $\Delta \beta / \beta$?

is $\beta$ from amp overestimating it? (due to BPM gain?)

Similar studies in ESRF and NSLS-II:

L. Malina et al., THPMB045

X. Huang et al., IPAC 2015
Techniques for optics measurement & correction

- K-modulation
- Turn-by-turn
- Closed orbit (ORM)
- Passive corrections
F. Bulos et al., SLAC-Pub-5488 (1991): “For future linear colliders (...) with demanding tolerances (...) it becomes increasingly important to use the beam as a diagnostic tool.”

Few optimization algorithms in operation:

- **Simplex**: KEKB injector linac, KEKB and RHIC luminosities
- **Scan of orthogonal knobs**: SLC, FFTB and ATF2 beam sizes, SPEAR3 and BEPCII lumi
- **Random walk**: SLS emittance
Three world records

\[ \epsilon_y = 0.9 \pm 0.4 \text{ pm} \]

via random walk optimization

\[ \sigma_y = 44 \pm 3 \text{ nm} \]

via scanning orthogonal knobs

\[ L = 2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]

Luminosity optimized via downhill Simplex
The LHC High Luminosity upgrade

Peak $\beta$ of 20 km! (today 6 km)
\(\beta\)-beating in HL-LHC before correction

Almost 200% \(\beta\)-beating...

Before corrections

- HL-LHC \(\beta^* = 15\text{cm}\)
- LHC \(\beta^* = 60\text{cm}\)

Max \(\Delta\beta/\beta\)
The HL-LHC challenge lies ahead!
LHC few weeks ago

All planes below $2\%$ rms $\Delta \beta / \beta$. 

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Review of linear optics measurements and corrections
Space charge simulations with measured optics in J-PARC, K. Ohmi et al., IPAC 2013

Beam loss due to introducing measured $\Delta \beta = 5\%$ in simulations

K. Ohmi et al.: “Estimation of errors of accelerator elements is inevitable to study beam loss.”
The 1-2% $\beta$-beating level has been conquered in light sources and large colliders.

Can we measure $\beta$ functions with an accuracy better than 1%?

Could optics correction be as fast as orbit correction?

The challenge lies ahead for HL-LHC, SuperKEKB, MAX IV, ESRF upgrade, etc.

Should light sources use long and weak AC dipole excitations to avoid decoherence and errors from non-linearities?