Beam Coupling Impedance Localization Technique Validation and Measurements in the CERN machines


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Outline

• Transverse impedance localization: method description.

• Observable: phase advance between BPMs
  - Accuracy of phase advance variation with intensity.

• Application to the PS
  - Measure validation with local quadrupolar errors,
  - Measurements at 2 GeV.

• Application to the SPS and LHC
  - Measurements at injection: experience and issues.

• Conclusion and outlook.
**Motivation:** Increasing the beam intensity, detrimental effects like beam instabilities and beam losses may arise due to the beam coupling impedance. Need impedance quantification!
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1. Impedance-induced orbit shift with intensity.
2. Impedance-induced phase advance beating with intensity.
3. Others?

![Diagram showing beam path with BPMs labeled BPM 1 and BPM 2.](image)
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Chronology

1995
CERN LEP

1999
BINP: VEPP-4M

2001
APS

2002
ESRF

2004..2007
CERN SPS

2008
BNL RHIC

2011..2013
CERN PS/SPS/LHC

D. Brandt et al. proc. of PAC’95

L. Farvacque et al. proc. of EPAC’02

R. Calaga, AB seminar 17-07-2008

LEP

ESRF

RHIC

V. Kiselev et al. proc. of DIPAC’99

V. Sajaev et al. proc. of PAC’03

G. Arduini et al. proc. of EPAC’04
Accuracy in measurement

BPM system

Background noise

Turn by turn signal

Noise over Signal Ratio

\( \text{NSR} = \frac{\sigma_n}{A} \)

\( \sigma_n \)

\( A \)
Accuracy in measurement

Model:
- 2 sinusoidal waves.
- $\Delta \mu$: phase advance.
- Same frequency.
- Additive Gaussian noise of rms $\sigma_n$.
- $N$: number of turns.
- NSR: signal to noise ratio.
- NAFF: algorithm for accurate FFT.

$$\text{NSR} = \frac{\sigma_n}{A}$$

$$\sigma_{\Delta \mu} \approx 1.12 \frac{\text{NSR}}{\sqrt{N}}$$
Width of the intensity scan. To be increased (upper threshold can be instability or non-linearities, lower is BPM sensitivity).

\[
\sigma_{\Delta \mu} = \frac{1.12 \ \text{NSR}}{\sigma_{\Delta N_b} \sqrt{N} \sqrt{M}}
\]

N = Number of turns. To be increased (depends on length of coherent oscillation and data transmission from BPM to storage).

M = Number of measurements. To be increased (usually ~100. Limited by machine parameter drift with time).

Noise level: To be reduced (kicker strength, BPMs gain, SVD noise reduction, etc…).
Reconstruction principle

Theory of lattice imperfection:

\[ \Delta Q_k = \frac{1}{4\pi} \beta_k \Delta K \]

Tune shift from a \( k \)th quadrupole error.

\[ A_k = \frac{\Delta Q_k}{\sin(2\pi Q_0)} \]

Phase advance beating amplitude from a \( k \)th quadrupole error.

Theory of beam instability:

\[ \frac{\Delta Q_k}{\Delta N_b} = \frac{-e^2 T_0}{4\sqrt{\pi} \gamma m_0 (2\pi)^2 Q_0 \sigma_z} \left( \frac{\beta_k}{\bar{\beta}} \right) \text{Im}(Z_{\perp, eff}^k) \]

tune shift slope from a \( k \)th impedance source \( Z^k \).

\[ A_k = \frac{\Delta Q_k / \Delta N_b}{\sin(2\pi Q_0)} \]

Phase advance beating amplitude from a \( k \)th impedance source \( Z^k \).

Given the similar behaviour we can reconstruct the measured/simulated phase beating using the MAD-X response matrix to quadrupole errors!
Method validation in the PS:

- We chose two quadrupoles with independent power supply: QLS29 and QSE87.
- We increased their current to provoke a vertical tune shift $\Delta Q_y \sim -0.02$.
- We tried to localize back the quadrupoles.

- Beat of amplitude $A_k \sim 7.5e^{-4}$ expected from the quadrupole strength variation.
- Accuracy limit $\sigma_{\Delta \mu/\Delta N_b} \sim 2e^{-4}$

Enough margin, should be able to localize.
Measurement of local quadrupolar orbit errors

- MAD-X reconstructors: all available quadrupoles in the lattice.
- Good agreement with the real quadrupole positions and strength!
Measurements at 2GeV

- Measurement with single bunch at the energy of 2GeV.
- Intensity scan from 1e12 to 2e12 ppb.
- Transverse feedback (TFB) excitation at tune frequency.

![Graph showing measurements for different kickers.]

- Kicker S71
- Kicker(s) S21
- Kicker S28
- Kicker S04

Not much margin.
Some chance to localize kicker S71.

* Estimated with Tsutsui’s model
Before reconstruction:

- We chose as reconstruction points elements that could reasonably be high impedance sources (i.e. not BPMs, vacuum ports, magnets,…).
  - Cavities;
  - Kickers;
  - Wirescanners;
  - TFB;
  - Septa;

MAD-X response matrix: 49 reconstructors x 40 BPMs.
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- Refinement on how the measured and reconstructed slope overlap;

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Reconstruction

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  ✓ Cavities;
  ✓ Kickers;
  ✓ Wirescanners;
  ✓ TFB;
  ✓ Septa;

After reconstruction:

• Refinement on how the measured and reconstructed slope overlap;
• Mismatch if a single or a sequence of reconstructor is switched off.
• It reduces the family of selected impedance candidates.
• It gives a spatial uncertainty $\Delta s$

MAD-X response matrix: 49 reconstructors x 40 BPMs.
Some reconstruction results:

Accuracy threshold from NSR

Impedance values ($\Omega/m$)

$\Delta s < 10m$  $\Delta s < 20m$  $\Delta s > 30m$
Reconstruction

Some reconstruction results:

Impedance values (Ω/m)

Accuracy threshold from NSR

![Graph showing reconstruction results with impedance values and accuracy threshold from NSR.](image)
Reconstruction

Some reconstruction results:

![Diagram showing reconstruction results for 05-Feb-2013 #1 and 05-Feb-2013 #2, with markers for different distances and cavity labels.](image)

Kickers in S21 - S71

Septa

10MHz Cavity
- Measurements NSR acceptable.
- Scarce reproducibility on investigation.
- Analysis with response matrix on-going.

Measurements of 22-Jan-2013 and 29-Jan-2013
LHC

- Good agreement for accuracy expectation and measurements.
- Signal from known impedances expected at the level of noise.
- Difficult to reconstruct... new measurements planned at the machine restart.

Set-up Phase measurement Reconstruction

Injection collimators (see N. Mounet et al. TUPWA047)
Conclusion

Method:
✓ A better understanding of the major constraints and parameter interplay in the impedance localization measurement has been achieved.
✓ The accuracy in the measurements has been studied and benchmarked with measurements (and simulations).
✓ A reconstruction algorithm has been studied in order to include reasonable impedance positions, resistive wall + indirect space charge contribution and spatial accuracy.

Measurements in PS:
✓ The measurements with current dependent quadrupole errors proved the feasibility in the simplest case.
✓ The measurements with beam showed good reproducibility and reconstruction.
✓ Found high impedance sources for kickers in section 21 and 71 with occurrence of septa and 10 MHz cavities.

Measurements in SPS & LHC:
✓ SPS: Measured impedance-induced phase advance beating. Work is on-going to reconstruct the impedance position.
✓ LHC: First localisation measurement was attempted. Accuracy limits may be overcome decreasing NSR with a careful measurement set-up within new measurements planned at the machine restart.

In the meantime: RHIC…. but that’s an other story!
Many people behind this work!

PS, SPS, LHC operators, LHC collimation team,
J. Albertone, C. Boccard, S. Jackson, R. Jones,
D. Brandt, A. Hofmann, A. Burov,
H. Damerau, M. Giovannozzi, C. Hernalsteens,
J. E. Muller, G. Rumolo, G. Papotti, S. White,
C. Zannini, F. Zimmermann.
Thank you!

謝謝!!
REFERENCES

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[3] V. Sajaev et al. proc. of PAC’03
[4] L. Farvacque et al. proc. of EPAC’02

On statistical methods:

On accelerator imperfection theory and collective effects:

On MAD-X and HEDTAIL

On impedance modeling, measurements and cures:
[17] H.Bartosik et al., proc. of IPAC’11
[18] Y. Papaphilippou et al. these proc.
[19] N.Mounet et al., TUPW A047, these proc.