The impedance localization method: theory, simulations, measurements and predictions for accelerator machines

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• **Introduction**
  - Developing the impedance model...

• **Transverse impedance localization method**
  - Theory
  - HEADTAIL simulations
  - Measurement accuracy
  - Measurements in the CERN PS
  - Other machines (RHIC, SPS, LHC)

• **Estimations for SOLEIL**

• **Conclusions**
Impedance model

- Impedance Bench measurements
- Impedance Localization
- Impedance Simulations

Impedance model

Machine simulations

VS

Machine observations
Each particle moving in an accelerator performs betatron oscillations:

\[
\frac{d^2}{ds^2} y_i(s) + K_o(s) y_i(s) = 0 \quad \Rightarrow \quad y_i(s) = A_i(s) \cos(2\pi \mu y(s) + \theta_i)
\]

Unperturbed lattice focusing strength (Hill's equation)  
Phase advance

The frequency of particle oscillation is called the Tune: \(Q_y\)
Each particle moving in an accelerator performs betatron oscillations:

\[ \frac{d^2}{ds^2} y_i(s) + K_o(s) y_i(s) = 0 \rightarrow y_i(s) = A_i(s) \cos(2\pi \mu_y(s) + \theta_i) \]

**Unperturbed** lattice focusing strength (Hill's equation)

**Phase advance**

The **frequency** of particle oscillation is called the **Tune**: \( Q_y \)

A Beam Position Monitor (BPM) system allows for the measurement of the optics functions (tune, phase advance).
Theory: machine observables

\[ \frac{d^2}{ds^2} y_i(s) + K(s)y_i(s) = \langle F_i \rangle \quad \text{Perturbing force (wakefields)} \]

The optics functions vary depending on the impedance position and strength.
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\[ \frac{d^2}{ds^2} y_i(s) + K(s) y_i(s) = < F_i > \quad \text{Perturbing force (wakefields)} \]

Theory: machine observables

**Tune** variation

\[ \Delta Q_y \propto \text{Im} \left( Z_{tot}^{eff} \right) \]

Total machine transverse impedance

Tune VS intensity variation

Total machine impedance

Signal at **one** beam position monitor

\[ \Delta Q \approx 9 \, \text{M}\Omega/m \]
\[ \frac{d^2}{ds^2} y_i(s) + K(s) y_i(s) = < F_i > \]  

**Perturbing force (wakefields)**

The optics functions vary depending on the impedance position and strength.

**Phase variation**

**Local machine impedance**

**Impedance at \( k^{th} \) position**

\[ A_k \propto \text{Im} \left( Z_{k}^{\text{eff}} \right) \]

**Signal amplitude**

**Signal at all beam position monitor**

**HEADTAIL simulation**

With impedance at 450m
Theory: Impedance reconstruction

Measure phase variation with intensity

Optic model with quadrupole errors
Theory: Impedance reconstruction

Measure phase variation with intensity

Optic model with quadrupole errors

Least squares inversion

Impedance reconstruction
Localization measurement 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 DIAMOND

D. Brandt et al. proc. of PAC’95
L. Farvacque et al. proc. of EPAC’02
R. Calaga, AB seminar 17-07-2008

V. Kiselev et al. proc. of DIPAC’99
V. Sajaev et al. proc. of PAC’03
G. Arduini et al. proc. of EPAC’04
HEADTAIL simulations

HEADTAIL macro particle simulations

Benchmark for the localization method: the PS at 2 GeV

Example 1: Single Kicker impedance

![Graph showing impedance localization and particle simulations results.](image)
Example 1: Resistive wall + Indirect Space Charge impedance
Example 1: Kickers + Resistive wall + Indirect Space Charge impedance

Benchmark for the localization method: the PS at 2 GeV

HEADTAIL simulation

HEADTAIL macro particle simulations
HEADTAIL simulations

Example 1: Kickers + Resistive wall + Indirect Space Charge impedance

Benchmark for the localization method: the PS at 2 GeV
Example: 1 Kicker impedance + **Additive Gaussian Noise** on BPM data

No noise

**10 um**

rms noise

**30 um**

rms noise
Example: 1 Kicker impedance + **Additive Gaussian Noise** on BPM data

**No noise**

- 10 um rms noise
- 30 um rms noise
Measurement accuracy

We need to quantify analytically and experimentally the measurement accuracy.

To be **reduced**:
- FFT post-processing: interpolated FFT methods.
- Clean uncorrelated BPM noise,
- Increase kicker strength,
- Increase BPM gain

To be **increased**:
- Width of the scan of intensity.
- Upper threshold: instabilities or non-linearities.
- Lower threshold: BPM sensitivity.

\[
\sigma \frac{\Delta \mu}{\Delta N_b} = \frac{F \Delta \mu N SR}{\sigma \Delta N_b \sqrt{N} \sqrt{M}}
\]

To be **reduced**:
- M=Number of measurements.
  - Usually ~100.
  - Limited by machine parameter drift with time.

To be **increased**:
- N=Number of turns
  - Increase length of coherent oscillation
  - Increase data storage capability.
Measurement accuracy

Experimental comparison: An example from BNL-RHIC.

Total machine tune shift

\[ Im \left( Z_{tot}^{eff} \right) \]

Measured and predicted accuracy

\[ Im \left( Z_{th}^{eff} \right) \]

Localization margin
I improved the least squares reconstruction method:

- Conditions on distributed impedances: Beam pipe impedance along the accelerator.
- Conditions on lumped impedances: only locations with kickers, cavities, septa, etc.
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- Conditions on *distributed* impedances: Beam pipe impedance along the accelerator.
- Conditions on *lumped* impedances: only locations with kickers, cavities, septa, etc..

- Found Kickers in **Sec.21** and **71** with higher impedance than expected.
- Hints for other impedance locations are also being analysed.
Found Kickers in Sec. 21 and 71 with higher impedance than expected. 
Hints for other impedance locations are also being analysed.
CERN-SPS

- Machine model ✔
- Measurement accuracy ✔
- BPM system ✗ (on upgrade)

CERN-LHC

- Machine model ✔
- Measurement accuracy ✗ (highest impedance within the accuracy)
- BPM system ✔

BNL-RHIC

- Machine model ✗ (optics model being improved)
- Measurement accuracy ✔
- BPM system ✔
Prediction for SOLEIL

Measurement accuracy

\[ \sigma \frac{\Delta \mu}{\Delta N_b} = \frac{F \Delta \mu NSR}{\sigma \Delta N_b \sqrt{N} \sqrt{M}} \]

<table>
<thead>
<tr>
<th>$NSR$</th>
<th>$1 %$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>$100$</td>
</tr>
<tr>
<td>$N$</td>
<td>$&gt;100$</td>
</tr>
<tr>
<td>$\Delta N_b$</td>
<td>Up to $1.5 \times 10^{10}$ ppb</td>
</tr>
<tr>
<td>$F_{\Delta \mu}$</td>
<td>$1.12$</td>
</tr>
</tbody>
</table>

\[ \sigma \frac{\Delta \mu}{\Delta N_b} = 2.6 \times 10^{-4} \text{[rad}/10^{10} \text{ ppb}] \]

Tune shift measurements

\[ \frac{\Delta Q_y}{\Delta N_b} = 2 \cdot 10^{-3} \text{[rad}/10^{10} \text{ ppb}] \]

\[ \frac{\Delta Q_{y,miss}}{\Delta N_b} \approx 1 \cdot 10^{-3} \text{[rad}/10^{10} \text{ ppb}] \]

~ Half due to resistive wall and taper

Factor 4 margin! Worth to be tried!

Courtesy of R. Nagaoka

TMCI threshold
Conclusions

Impedance localization method:

☑ Proved the method with HEADTAIL simulations.
☑ Quantified and proved the method's accuracy.
☑ Learnt important measurement constraints:
  1. High performance BPM system (SPS),
  2. Sufficient margin from measurement accuracy and high machine impedance (LHC),
  3. High quality optic model (RHIC).
☑ Successful application to the PS machine.

Outlook:

☑ New measurement in the PS at different energies are planned.
☑ Good prediction for the method applicability to SOLEIL: worth to try!
☑ Studies on MAD-X model accuracy and impact on measurement.
Thanks to the people behind this work...and wall!

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