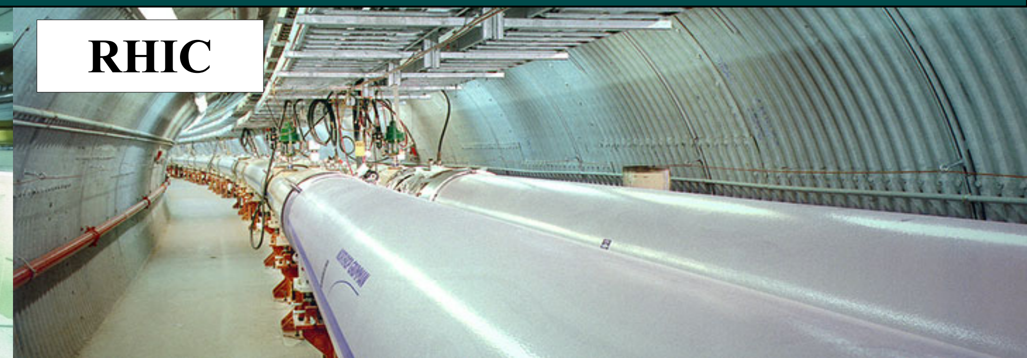
The impedance localization method: theory, simulations, measurements and predictions for accelerator machines

Nicolò Biancacci

TWIICE workshop, Paris, 17-01-2014



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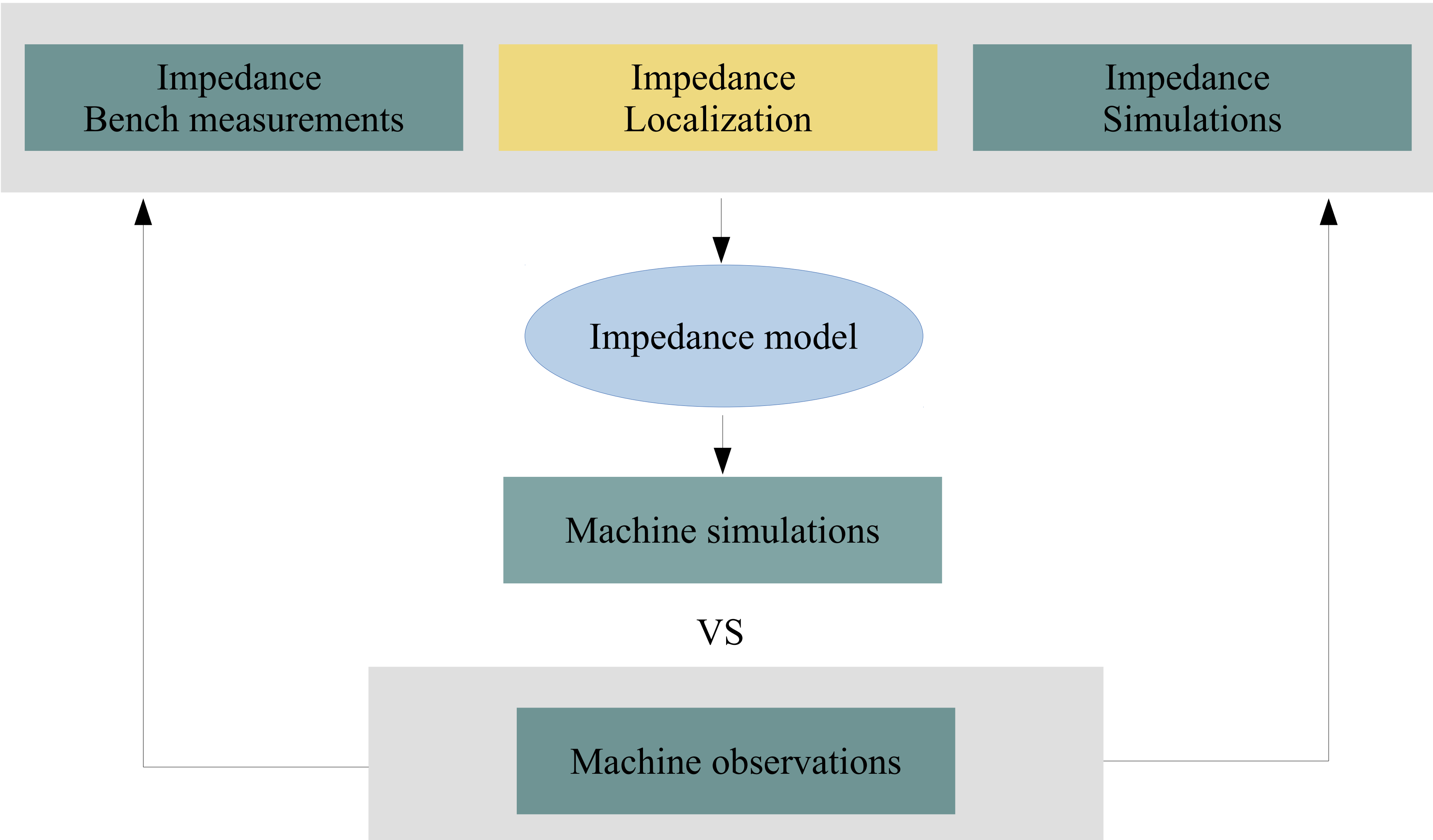
Outline

- ***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



Theory: machine observables

Each particle moving in an accelerator performs betatron oscillations:

$$\frac{d^2}{ds^2}y_i(s) + K_o(s)y_i(s) = 0 \longrightarrow \quad y_i(s) = A_i(s)\cos(2\pi\mu_y(s) + \theta_i)$$

Unperturbed lattice focusing strength (Hill's equation)

Phase advance

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

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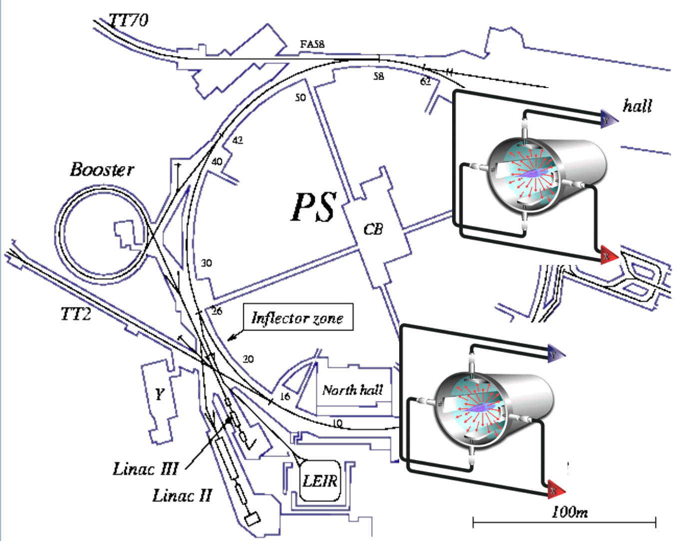
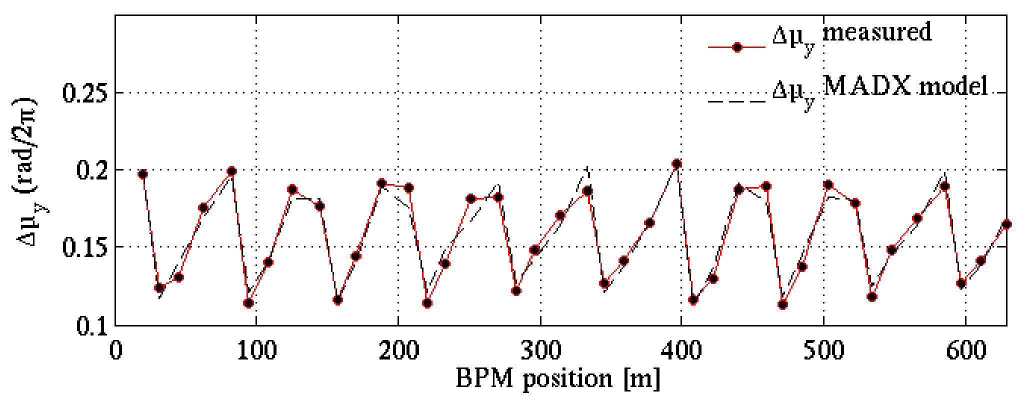


A Beam Position Monitor (BPM) system allows for the measurement of the optics functions (tune, phase advance).



Theory: machine observables

$$\frac{d^2}{ds^2}y_i(s) + K(s)y_i(s) = < F_i >$$ ← **Perturbing** force (**wakefields**)

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

Theory: machine observables

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

Tune variation

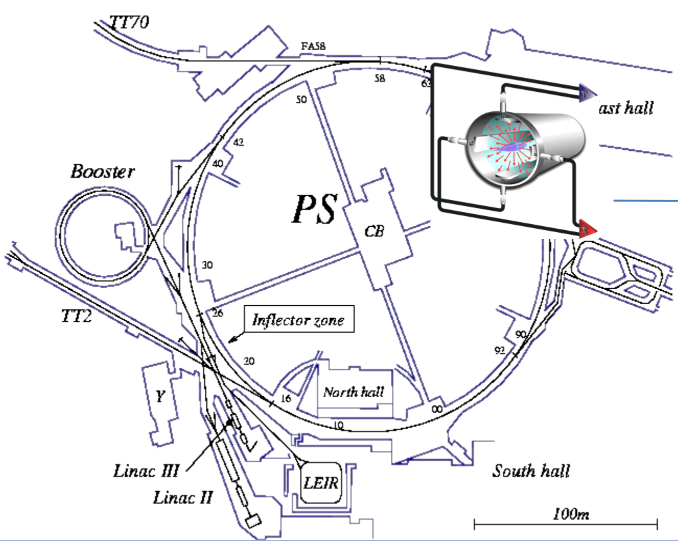
↓

Total machine impedance

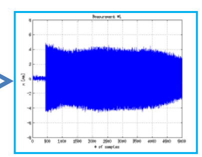
Total machine transverse impedance

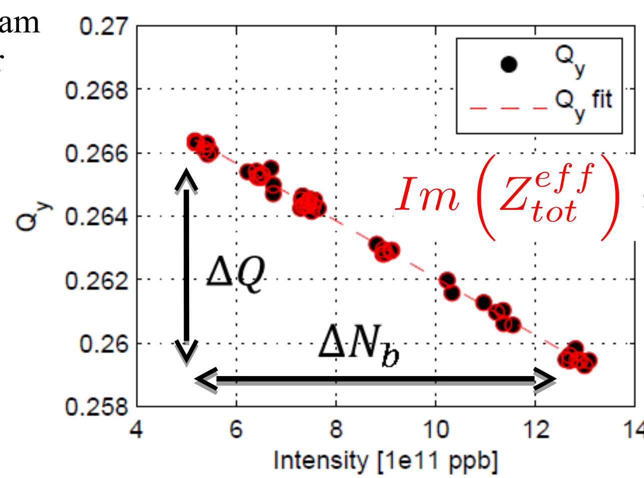
$$\frac{\Delta Q_y}{\Delta N_b} \propto Im\left(Z_{tot}^{eff}\right)$$

Tune VS intensity variation



Signal at **one** beam position monitor





$$Im\left(Z_{tot}^{eff}\right) \simeq 9\ M\Omega/m$$

Theory: machine observables

$$\frac{d^2}{ds^2}y_i(s) + K(s)y_i(s) = < F_i >$$ ← **Perturbing** force (**wakefields**)

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

Phase variation

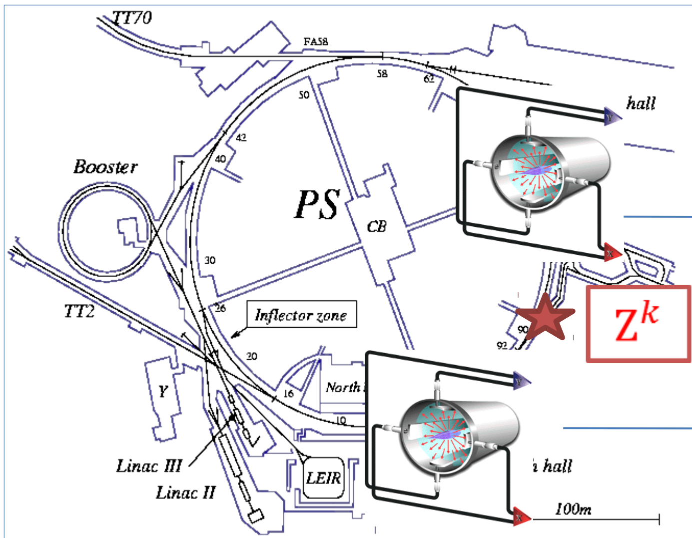
↓

Local machine impedance

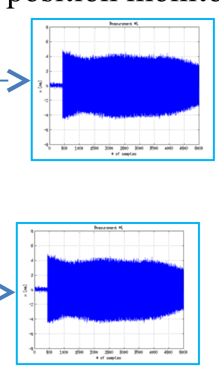
Impedance at **k**th position

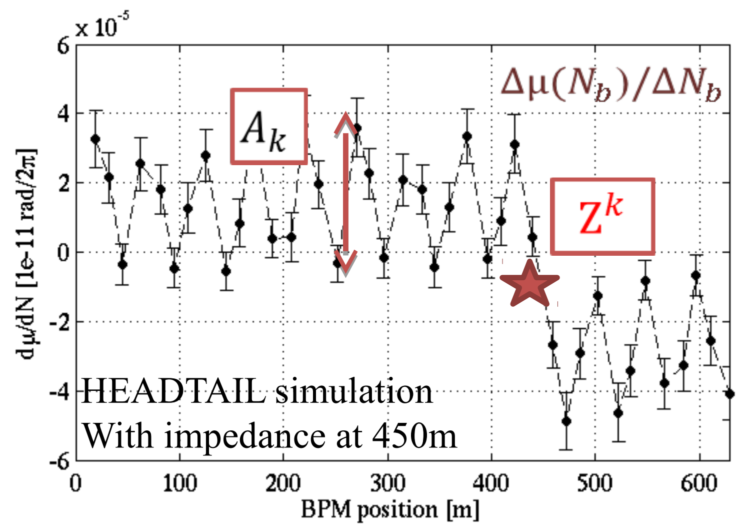
$$A_k \propto Im\left(Z_k^{eff}\right)$$

Signal amplitude

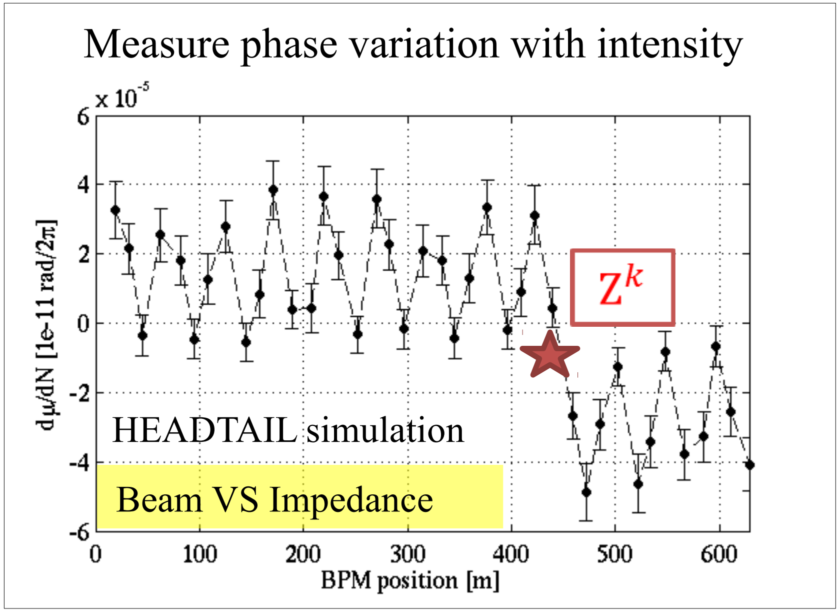


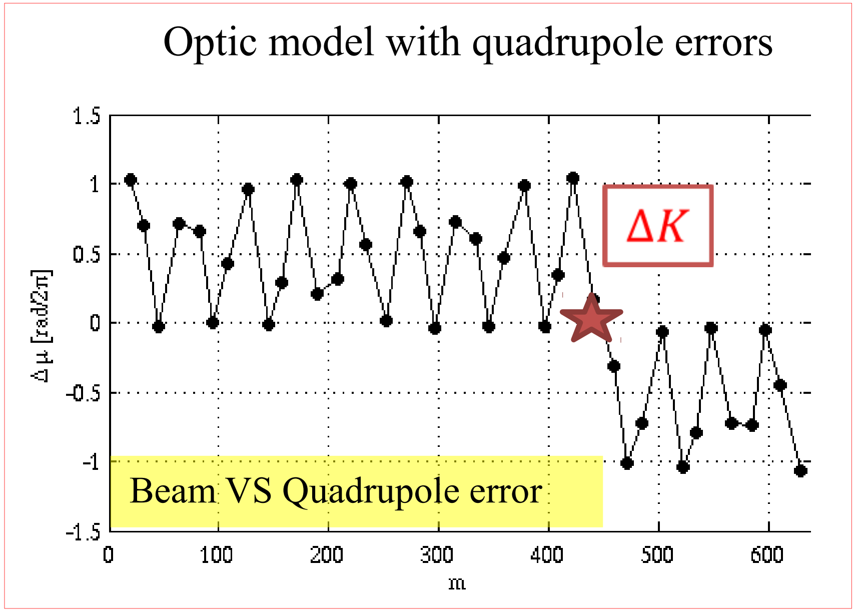
Signal at **all** beam position monitor





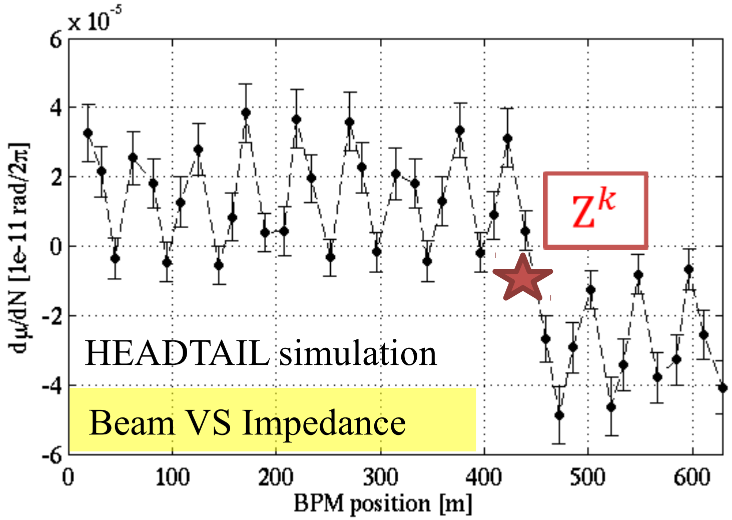
Theory: Impedance reconstruction



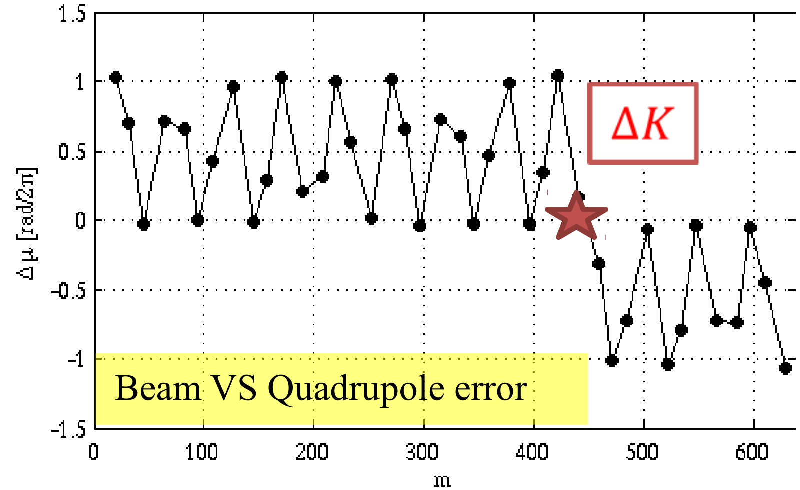


Theory: Impedance reconstruction

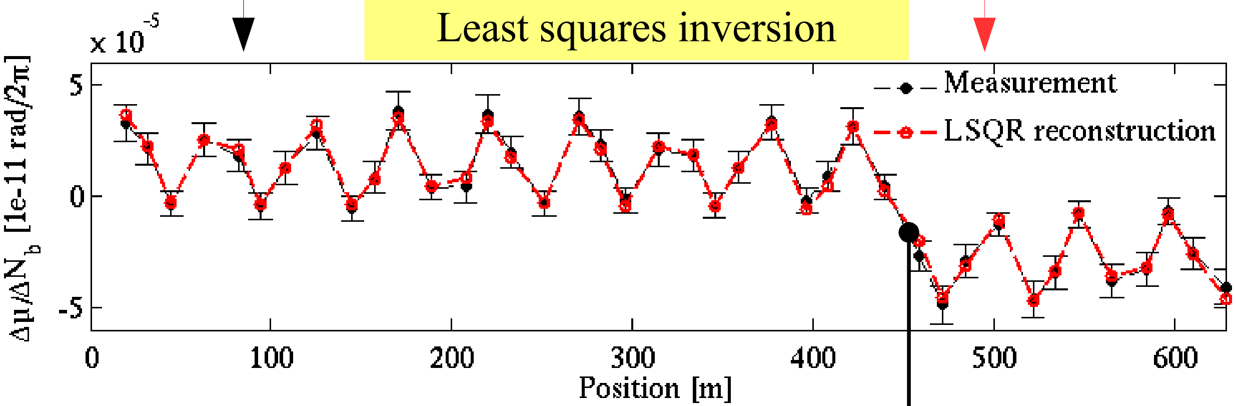
Measure phase variation with intensity



Optic model with quadrupole errors



Least squares inversion



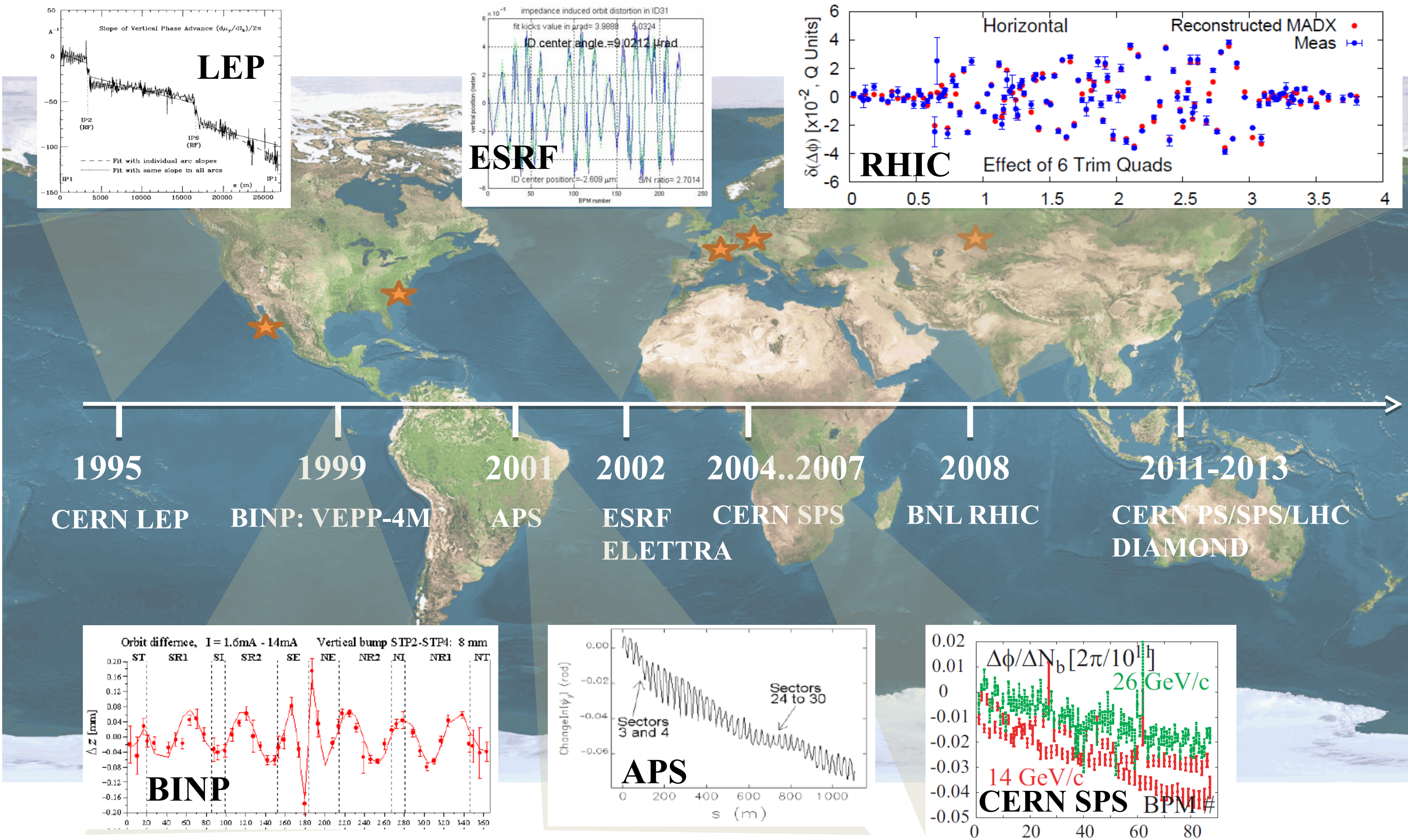
Impedance reconstruction

Localization measurement chronology

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

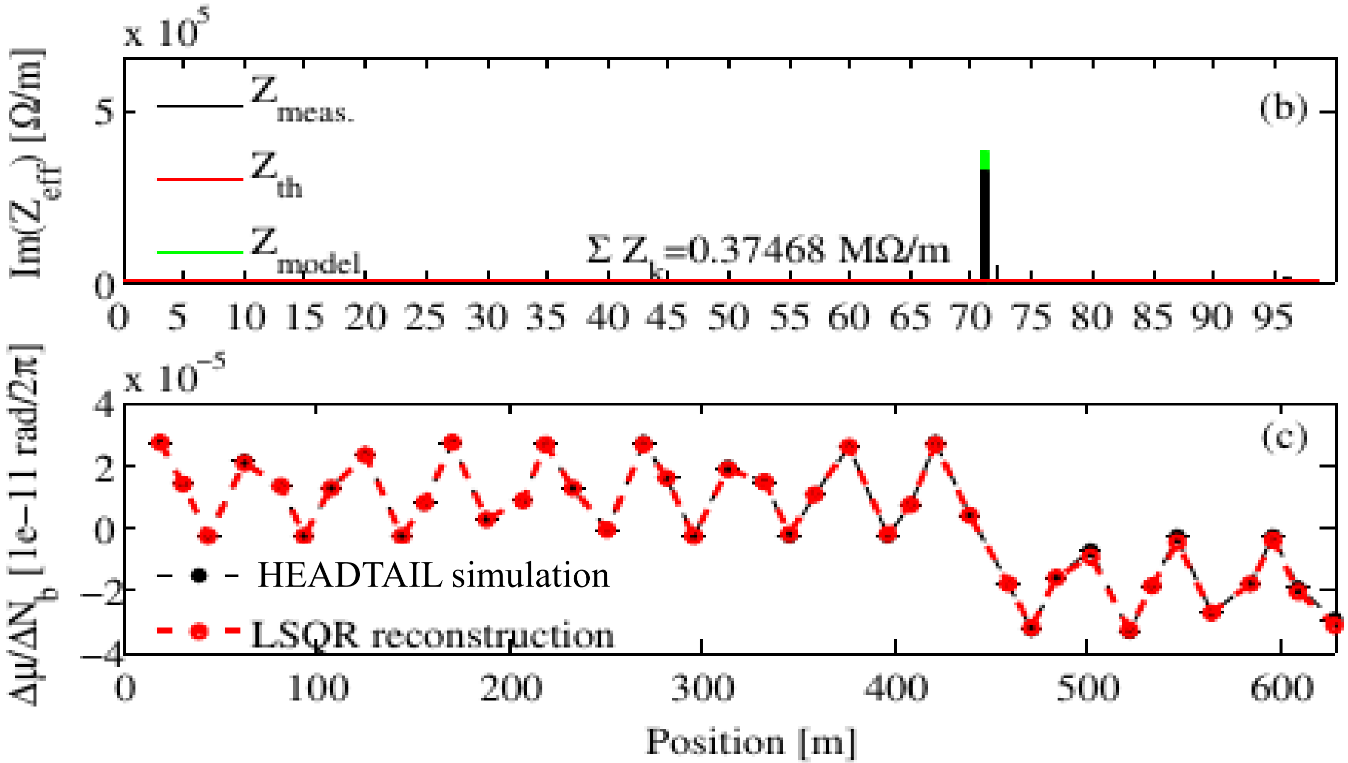
V. Sajaev *et al.* proc. of PAC'03

G. Arduini *et al.* proc. of EPAC'04

HEADTAIL simulations

HEADTAIL macro particle simulations → Benchmark for the localization method: the **PS** at **2 GeV**

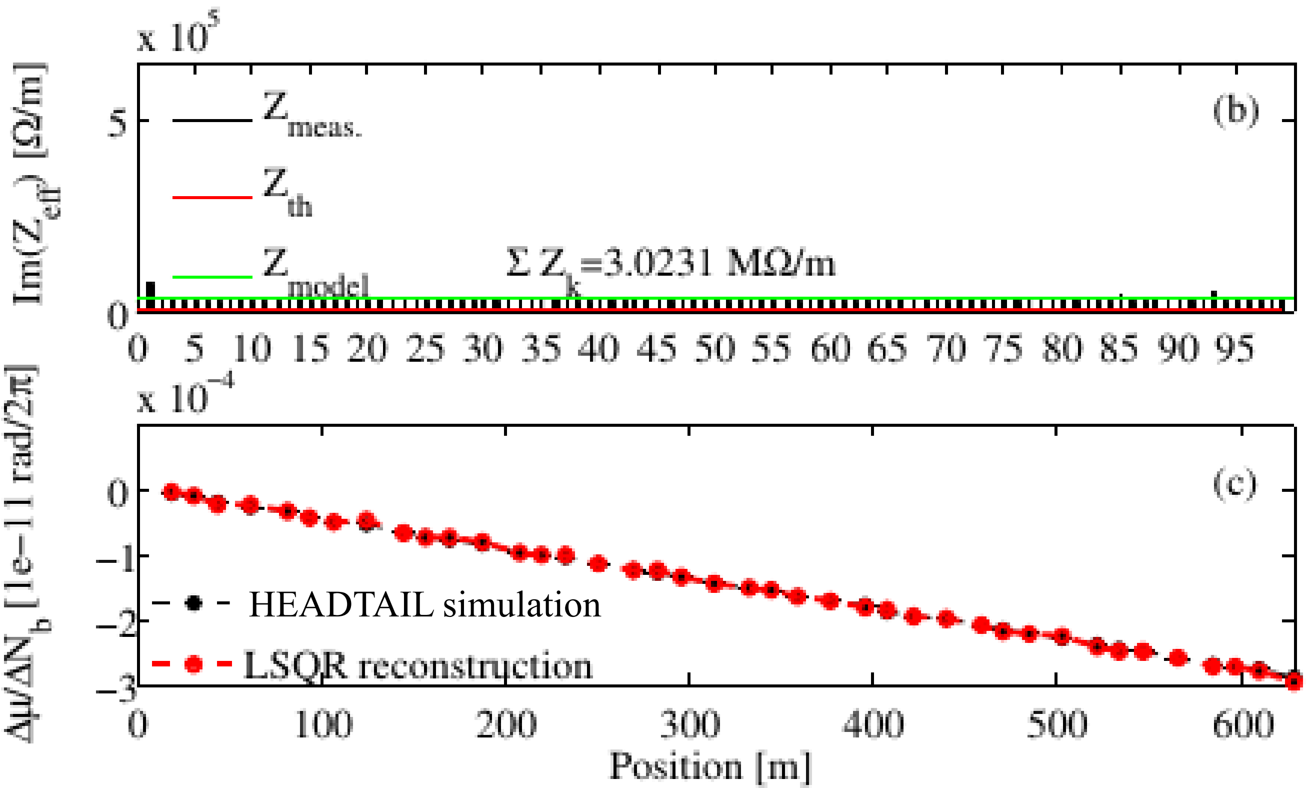
Example 1: Single Kicker impedance



HEADTAIL simulations

HEADTAIL macro particle simulations → Benchmark for the localization method: the **PS** at **2 GeV**

Example 1: Resistive wall + Indirect Space Charge impedance



HEADTAIL simulations

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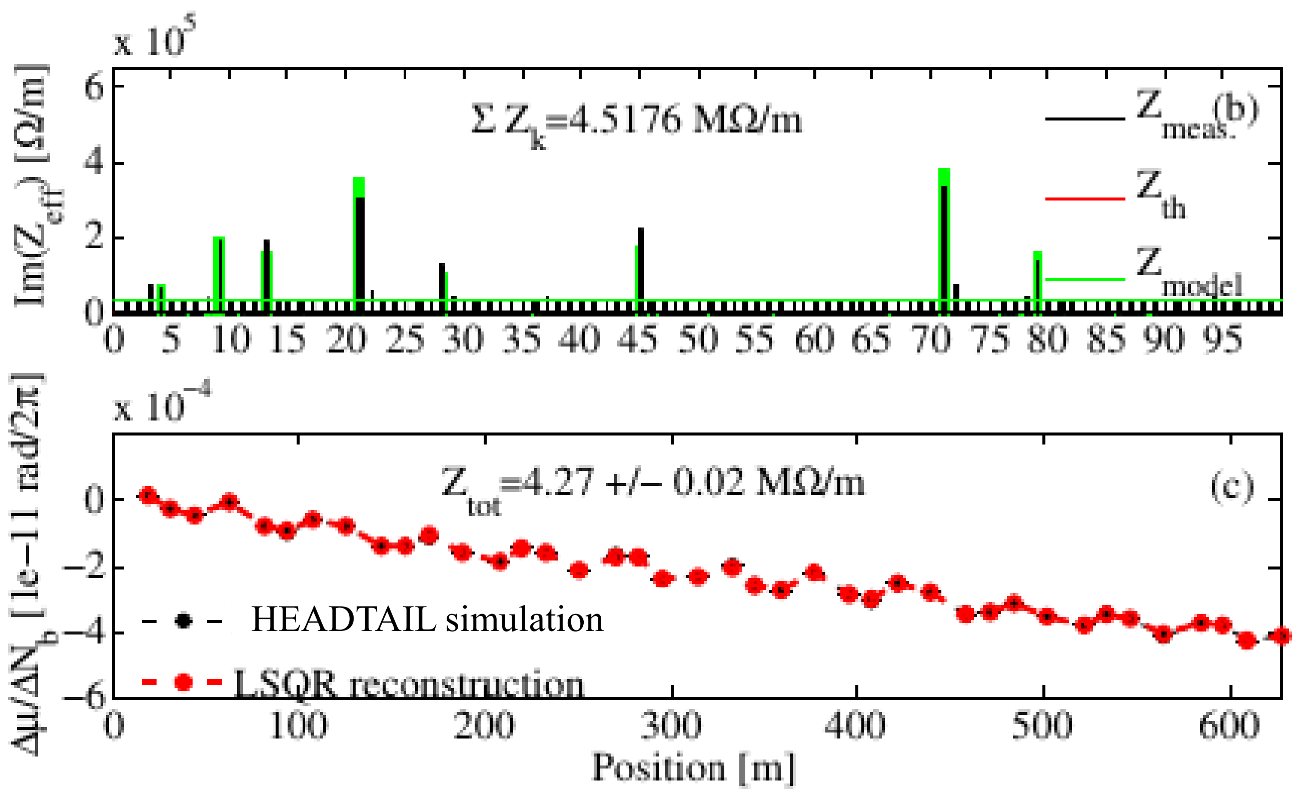

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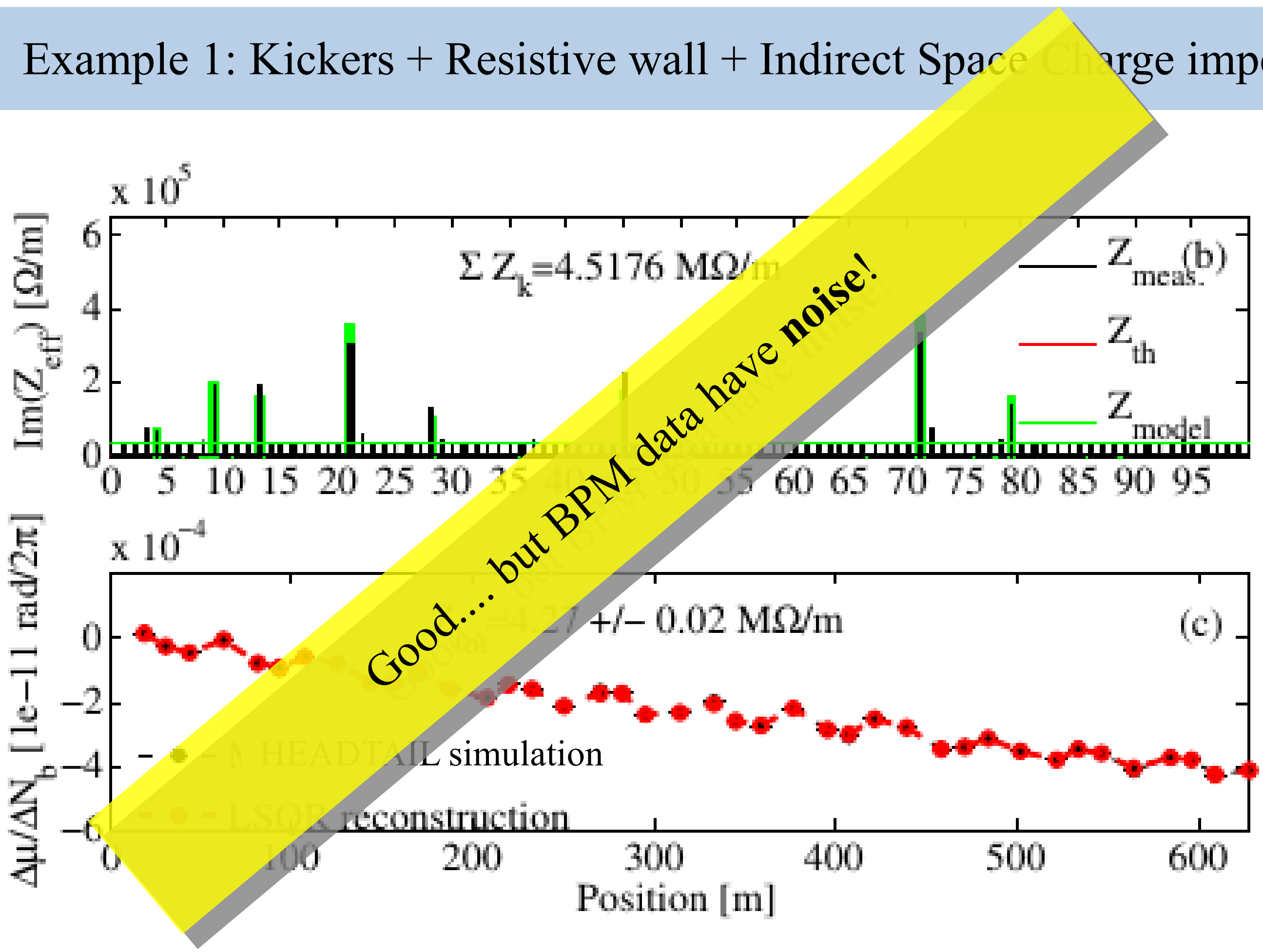


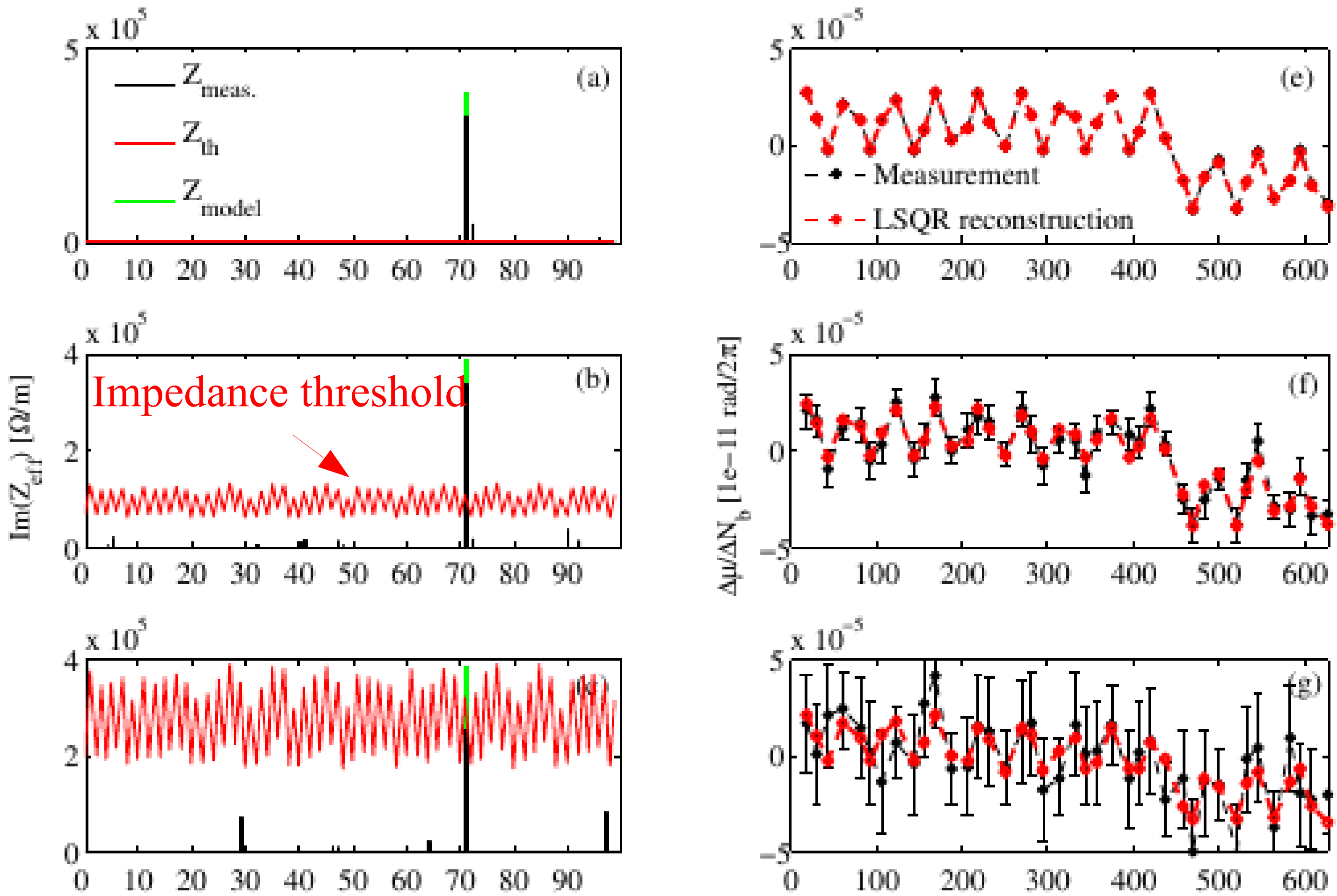
HEADTAIL simulations

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

No noise

10 um
rms noise

30 um
rms noise



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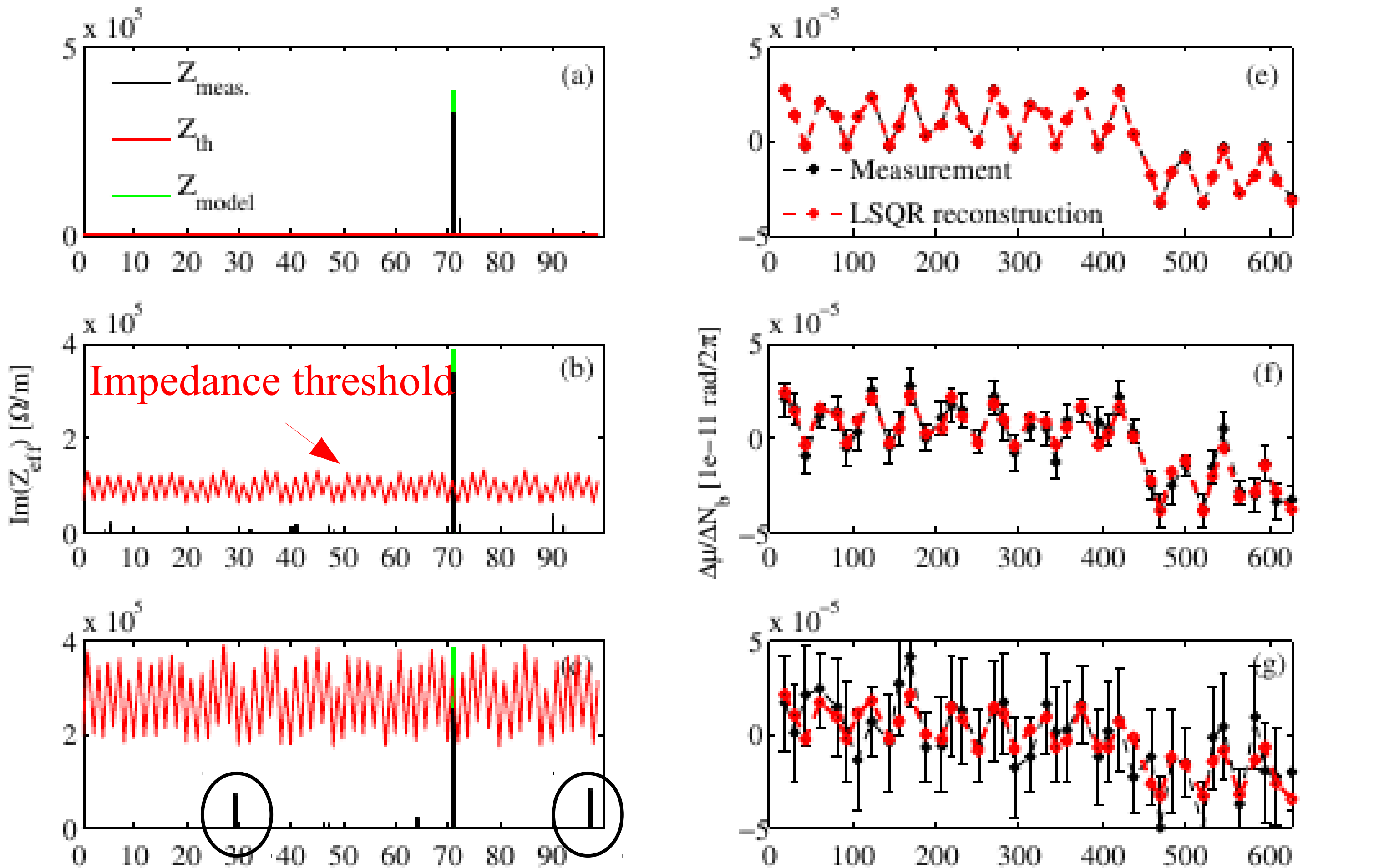


Measurement accuracy

We need to quantify analytically and experimentally the measurement accuracy.

To be **reduced**:

- FFT post-processing: interpolated FFT methods.

To be **reduced**:

- Clean uncorrelated BPM noise,
- Increase kicker strength,
- Increase BPM gain

$$\sigma_{\frac{\Delta\mu}{\Delta N_b}} = \frac{F_{\Delta\mu} NSR}{\sigma_{\Delta N_b}\sqrt{N}\sqrt{M}}$$

To be **increased**:
Width of the scan of intensity.

- Upper threshold: instabilities or non-linearities.
- Lower threshold: BPM sensitivity.

To be **increased**:
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

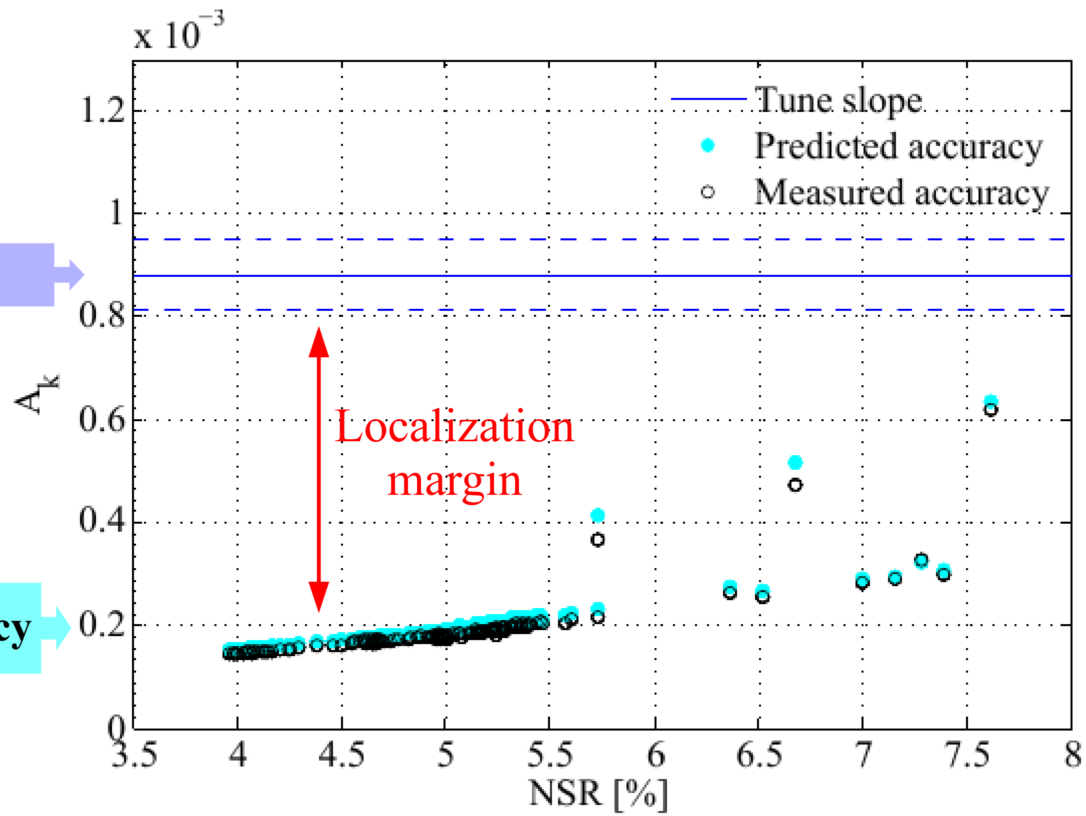
Experimental comparison: An example from BNL-RHIC.

Total machine tune shift

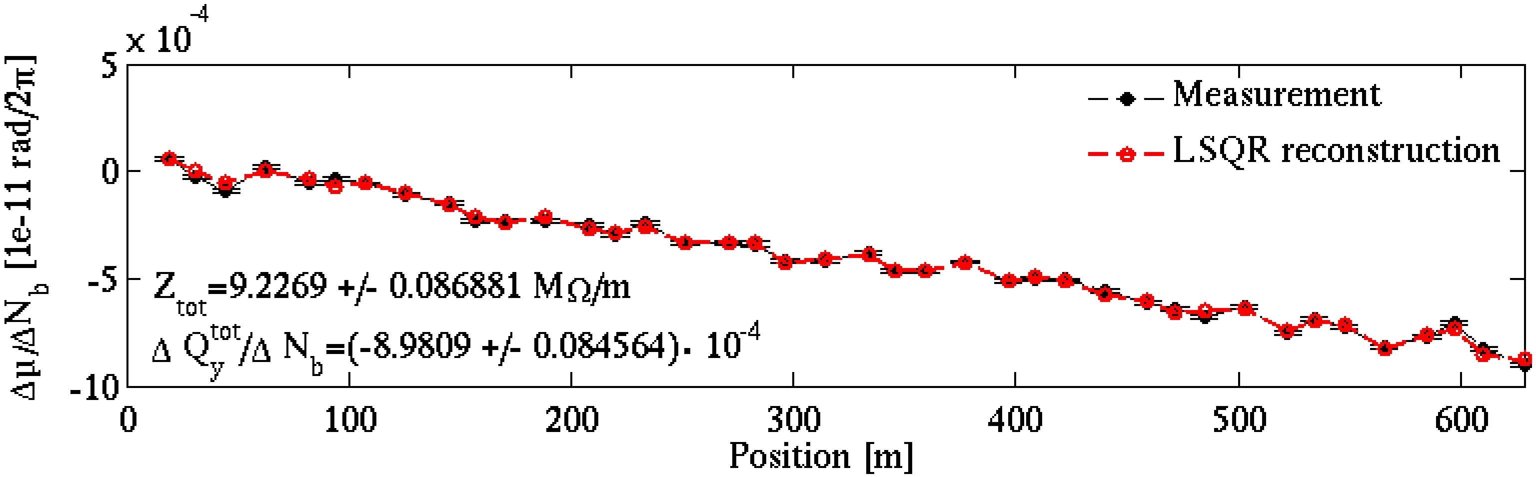
$Im\left(Z_{tot}^{eff}\right)$

Measured and predicted accuracy

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



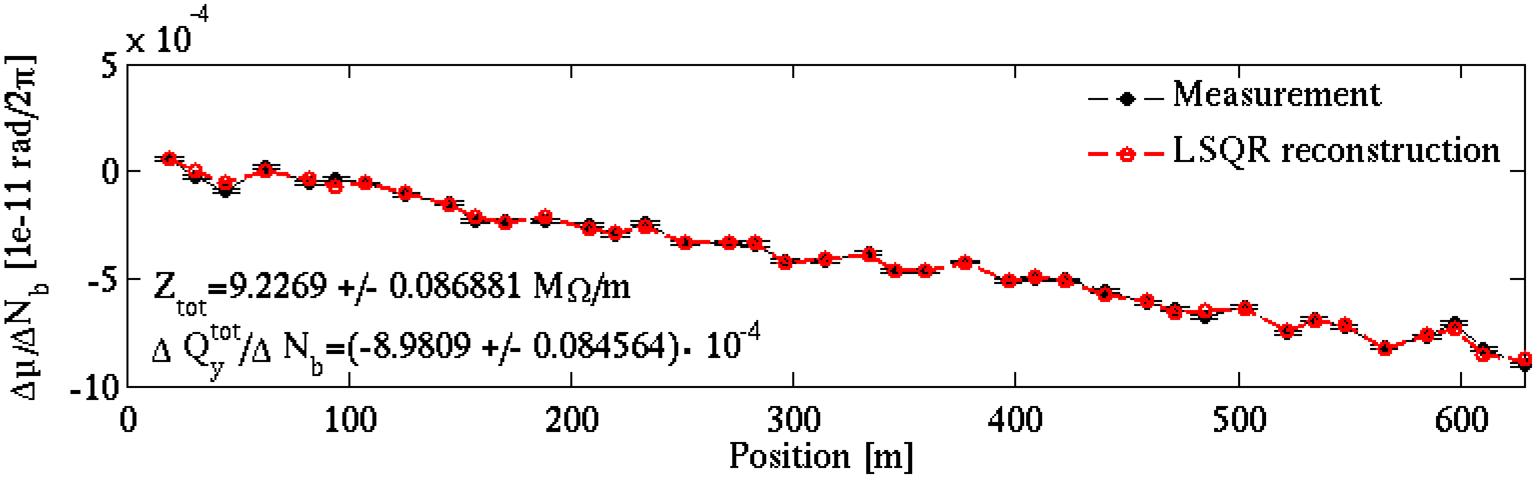
PS measurements at 2GeV



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..

PS measurements at 2GeV



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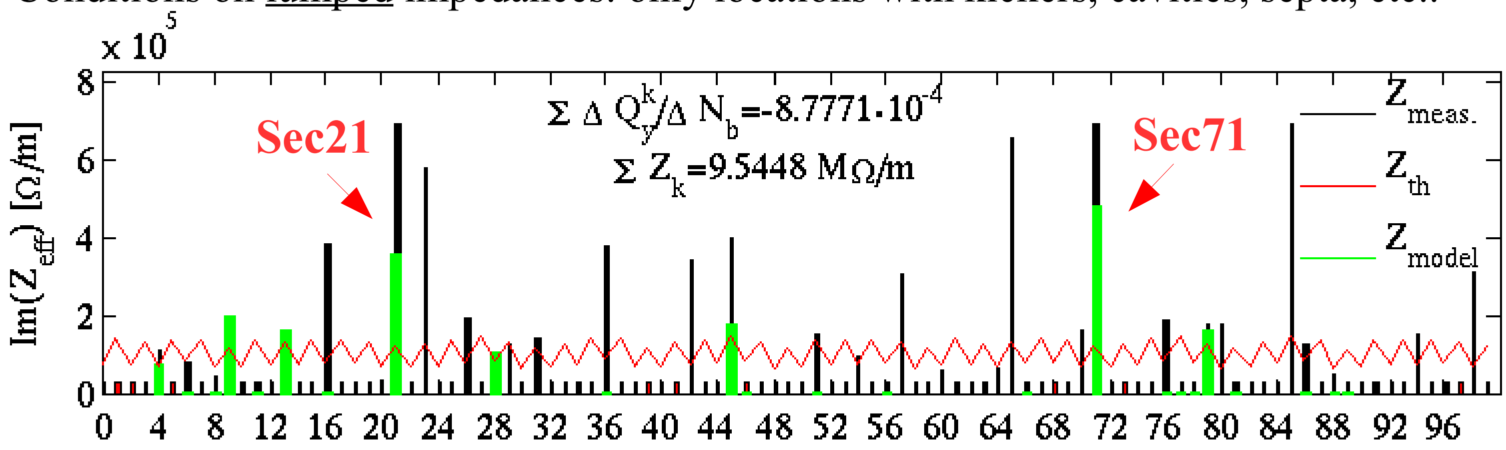
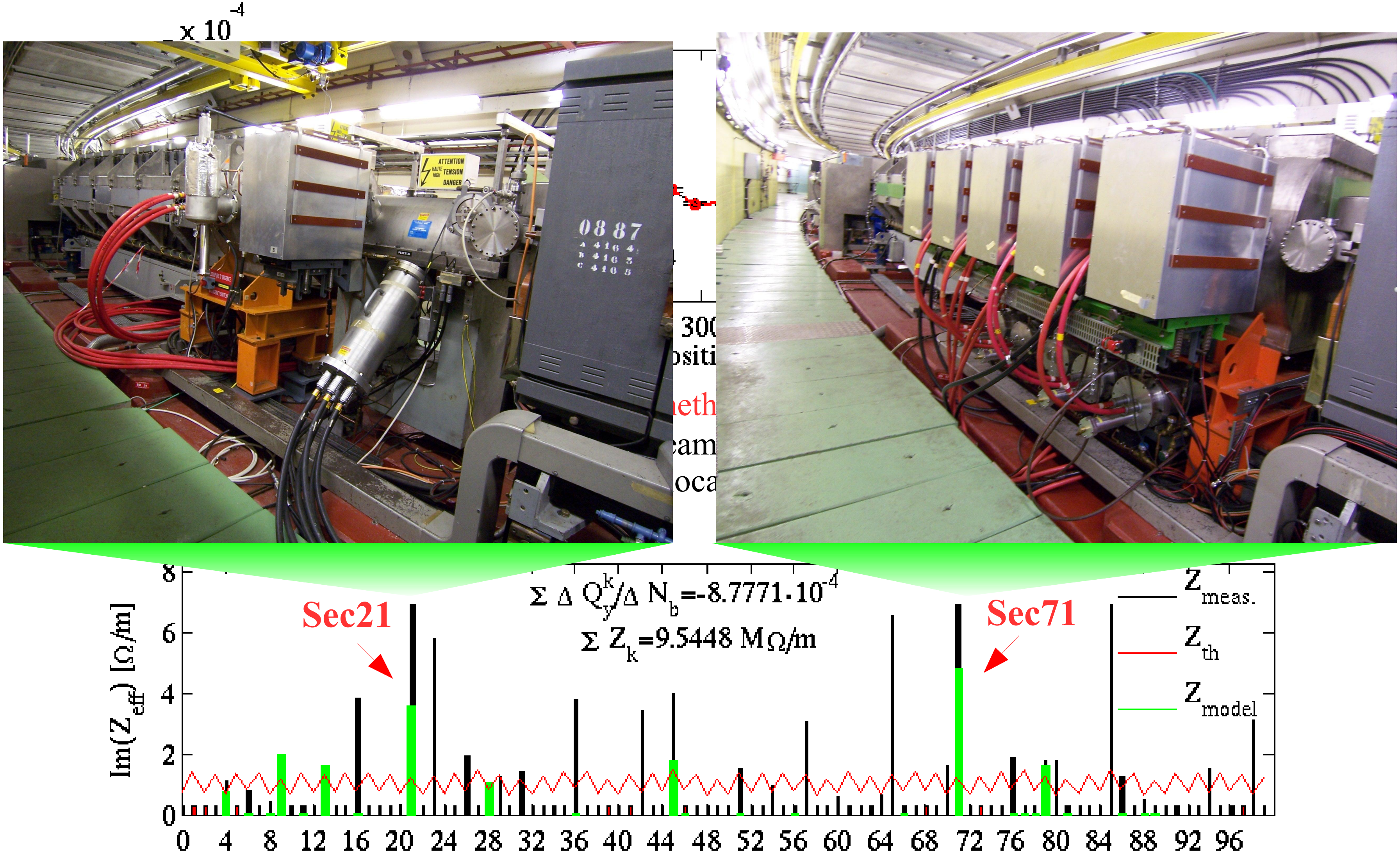


- Found Kickers in **Sec.21** and **71** with higher impedance than expected.
- Hints for other impedance locations are also being analysed.

PS measurements at 2GeV



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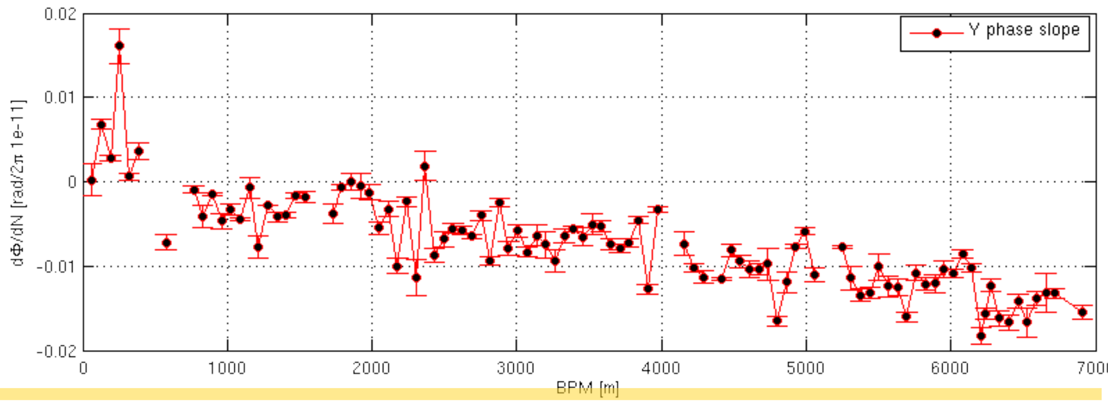
SPS – LHC - RHIC

CERN-SPS

Machine model ✔

Measurement accuracy ✔

BPM system ✗ (on upgrade)

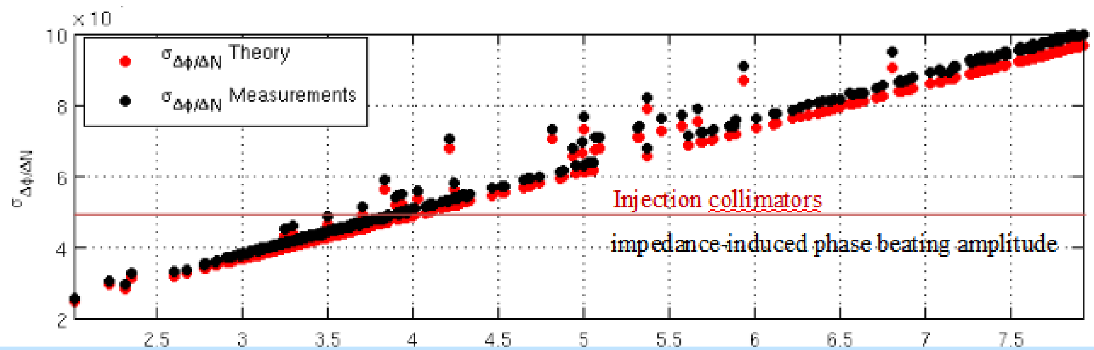


CERN-LHC

Machine model ✔

Measurement accuracy ✗ (highest impedance within the accuracy)

BPM system ✔

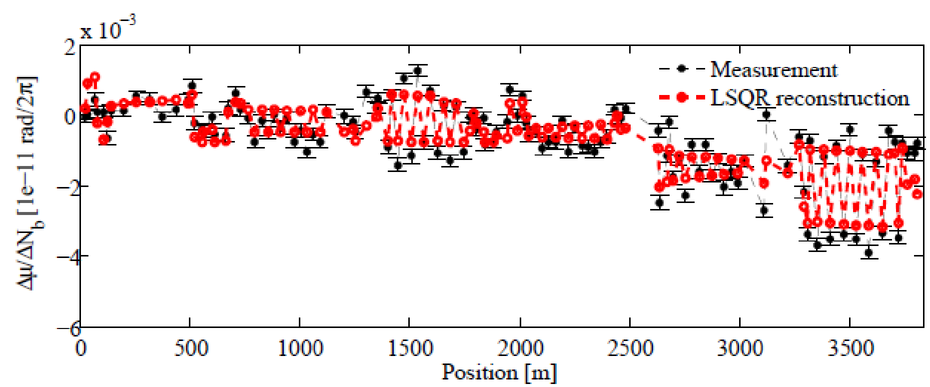


BNL-RHIC

Machine model ✗ (optics model being improved)

Measurement accuracy ✔

BPM system ✔



Prediction for SOLEIL

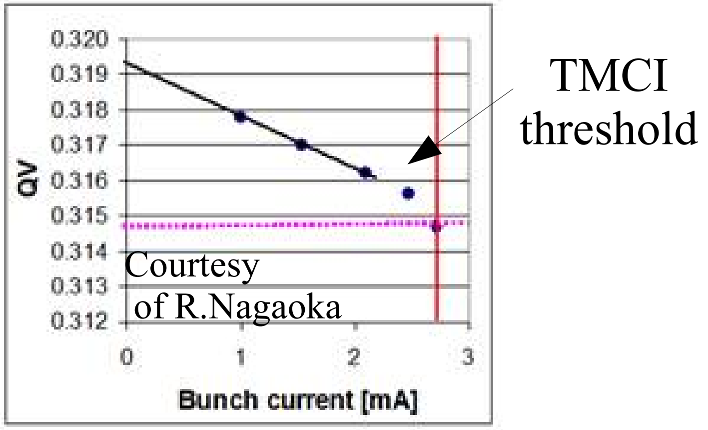
Measurement accuracy

$$\sigma_{\frac{\Delta\mu}{\Delta N_b}} = \frac{F_{\Delta\mu} NSR}{\sigma_{\Delta N_b}\sqrt{N}\sqrt{M}}$$

NSR	1 %
M	100
N	>100
ΔN_b	Up to 1.5 e10 ppb
$F_{\Delta\mu}$	1.12

$$\sigma_{\frac{\Delta\mu}{\Delta N_b}} = 2.6 \cdot 10^{-4} [\mathrm{rad}/10^{10}\ \mathrm{ppb}]$$

Tune shift measurements



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

~ Half due to resistive wall and taper

$$\frac{\Delta Q_y^{miss}}{\Delta N_b} \simeq 1 \cdot 10^{-3} [\mathrm{rad}/10^{10}\ \mathrm{ppb}]$$

Factor 4 margin! Worth to be tried!

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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J.E.Muller,
G.Rumolo,
G.Papotti,
S.White,
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K. Mernick,
C. Liu,
W. Fischer

(SOLEIL)
R. Nagaoka,
L. Nadolski

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