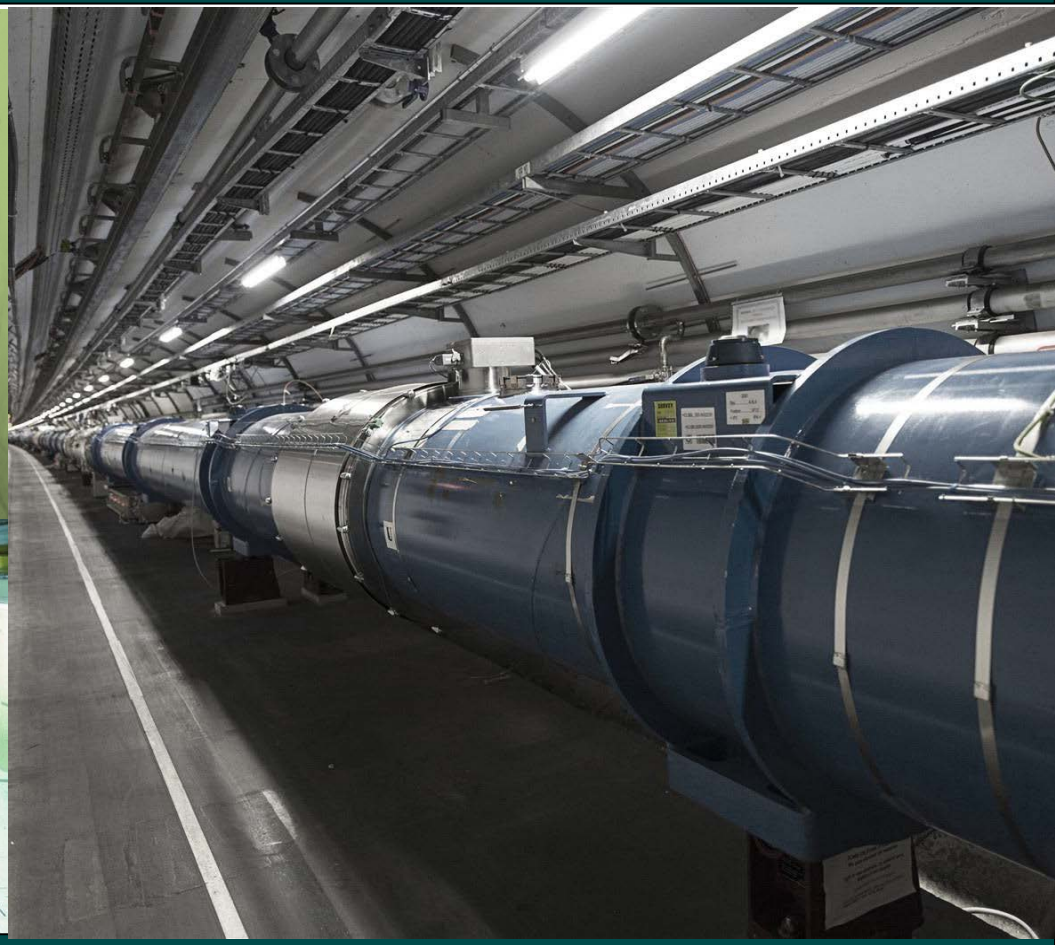
Transverse Impedance Localization Measurements at CERN



N. Biancacci, BNL 2013-04-22

Many people behind this work!

PS, SPS and LHC operators and LHC collimation team.
B.Salvant, E.Métral, M.Migliorati, N.Mounet, R.Tomás,
G.Arduini, H.Bartosik, A.Burov, R.Calaga, K. Cornelis,
S.Gilardoni, M.Giovannozzi, G.Rumolo, G.Sterbini,
F.Zimmermann, C.Boccard, S.Jackson, T.Argyropoulos,
R. De Maria, C.Hernalsteens, J.E.Muller, S.Persichelli,
R.Wasef, S.White, C.Zannini.

Outline

- Transverse impedance localization method.
- Observable: phase advance
  - Accuracy of phase advance detection for noisy signals,
  - Accuracy of slopes for measurements with error bars,
  - Impedance induced phase advance beating,
  - HEADTAIL simulations.
- Application to the PS
  - Measurement of local quadrupolar orbit errors,
  - Measurements at 2 GeV.
- Application to the SPS
  - BPM system,
  - Measurement at injection.
- Application to the LHC
  - Measurements with AC dipole: experience and issues.

- Conclusion and outlook.

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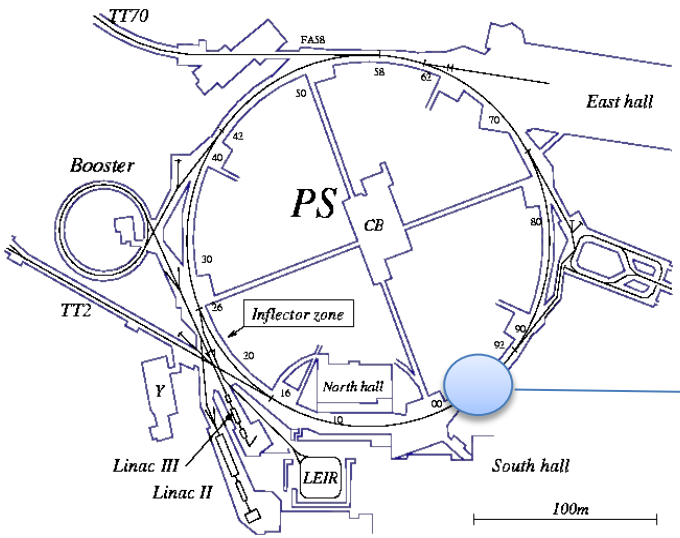
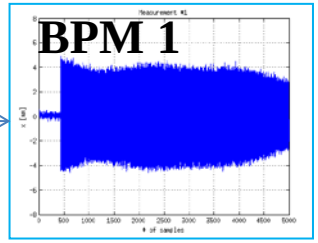
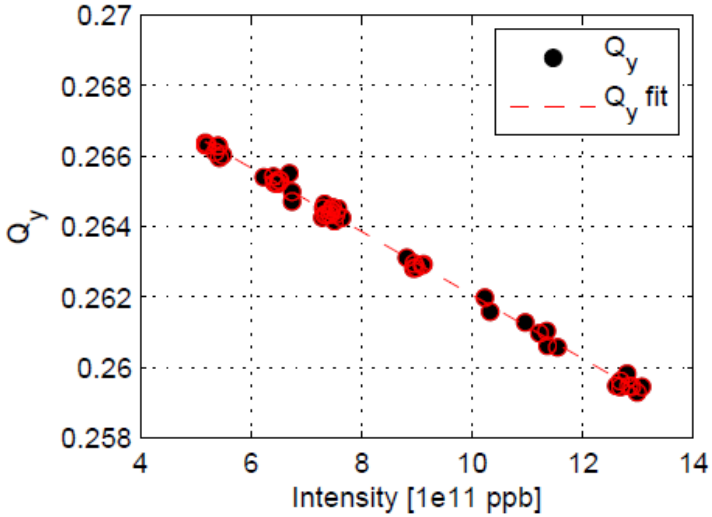
Transverse Impedance Localization Method

The method for local measurements was proposed and applied by G. Arduini et al. in 2004 and 2009 in SPS [1,2], in 2008 in RHIC by R.Calaga [3] and benchmarked with HEADTAIL [4].
The transverse beam coupling impedance can be measured both globally and locally:







In the **global** impedance measurements we measure the variation of tune frequency with intensity.

$$\Delta Q(N_b) \propto Z_{\perp\,(TOT)}$$

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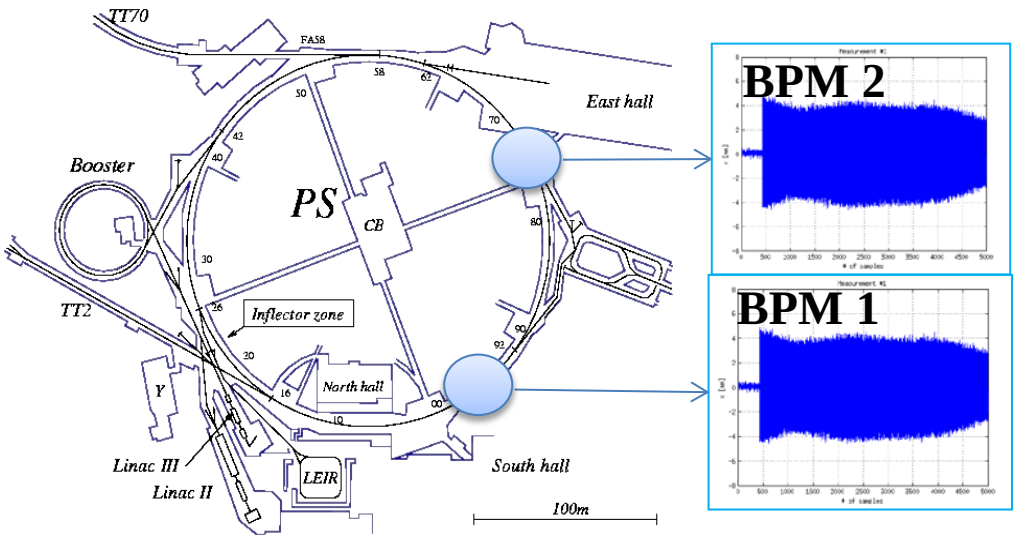


In the **local** impedance measurements we measure the variation of phase advance between BPMs with intensity.

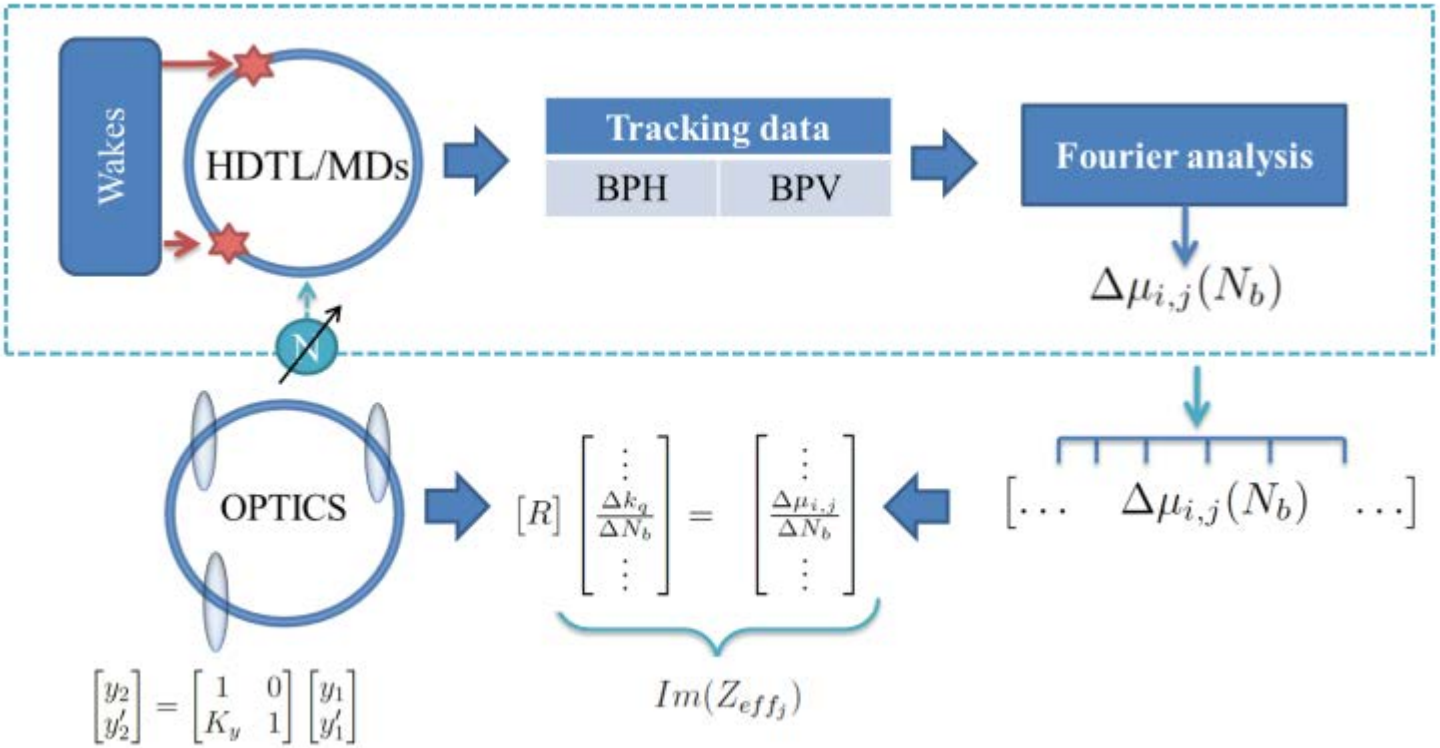
$$\Delta\varphi(N_b)_{1\to2} \propto Z_{1\to2\ (TOT)}$$

In the **global** impedance measurements we measure the variation of tune frequency with intensity.

$$\Delta Q(N_b) \propto Z_{\perp\ (TOT)}$$

Transverse Impedance Localization Method

The aim of the measurement is: correlating the phase advance beating variation with intensity with a local source of impedance.
In “optical” terms, an impedance would behave as a (de)focusing intensity dependent quadrupole.



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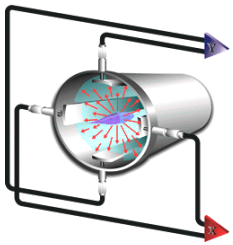
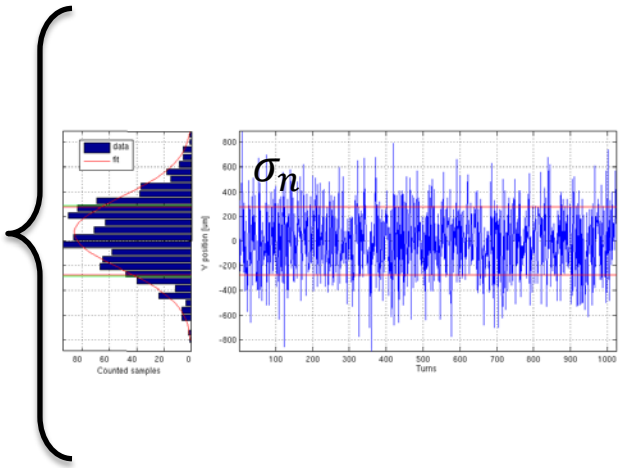
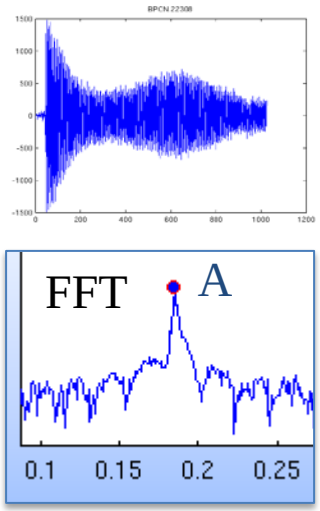
Observable: Phase advance

The uncertainty chain:



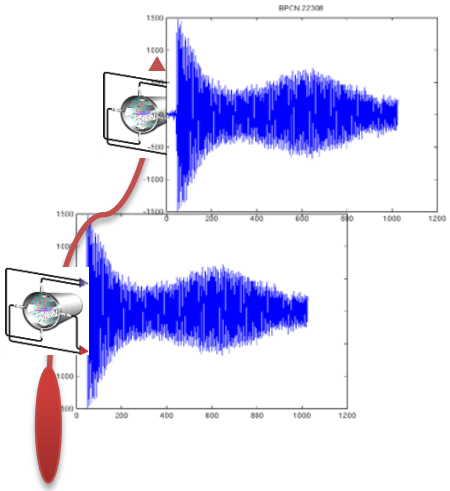
BPM system





$$\boxed{\mathrm{NSR} = \frac{\sigma_n}{A}}$$

Noise Signal Ratio



$$\boxed{\sigma_{\Delta\varphi}}$$

Phase advance accuracy

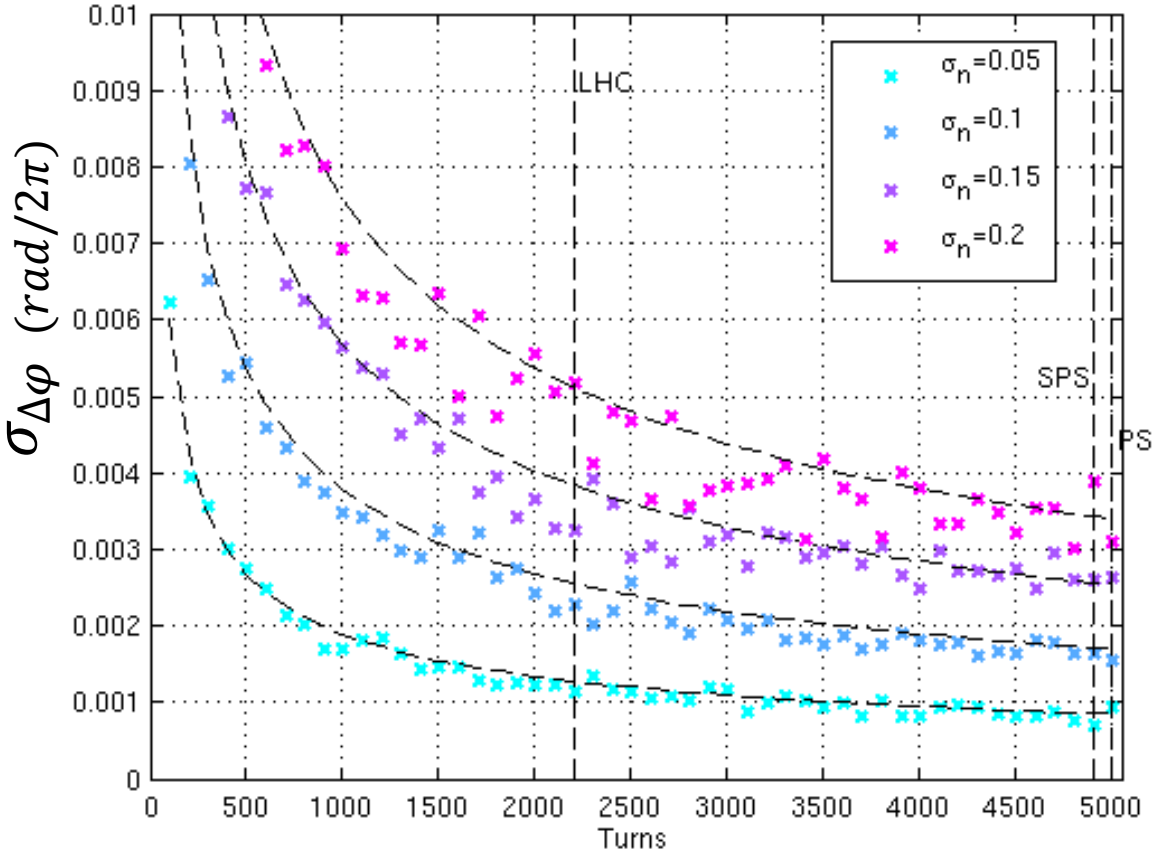
$$\boxed{\sigma_{\frac{\Delta\varphi}{\Delta N}}}$$

Phase advance slope accuracy

Accuracy of phase advance detection for noisy signals

Numerical estimation of phase uncertainty on simulated signal:

1. Take 2 aleatory sinusoidal signals, with additive Gaussian noise of sigma σ_n, same tune and fixed phase advance $\Delta\varphi$, amplitude A=1 (NB: NSR=σ_n/A=σ_n in this case).
2. Run 100 times and measure the phase advance.
3. Measure the standard deviation $\sigma_{\Delta\varphi}$ for the phase advance (accuracy in measurements).
4. Fit it.



$$\sigma_{\Delta\varphi} \approx 1.12 \frac{\sigma_n}{\sqrt{N}}$$

and in general,

$$\sigma_{\Delta\varphi} \approx 1.12 \frac{NSR}{\sqrt{N}}$$

Accuracy of phase advance slope measurements

Given a set of **M** measurements of $\Delta\boldsymbol{\varphi}$ with equal error bars $\boldsymbol{\sigma}_{\Delta\boldsymbol{\varphi}}$, obtained along an intensity scan **X** , we can calculate $\boldsymbol{\sigma}_{\frac{\Delta\boldsymbol{\varphi}}{\Delta\boldsymbol{N}}}$ using a standard straight line least square formula [5]:

$$\sigma_{\frac{\Delta\varphi}{\Delta N}} = \frac{\sigma_{\Delta\varphi}}{\sigma_X\sqrt{M}}$$ with σ_X standard deviation of the intensity scan X.

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with σ_X standard deviation of the intensity scan X.

Comparing with the previous formula one has:

$$\sigma_{\frac{\Delta\varphi}{\Delta N}} = \frac{1.12\ NSR}{\sigma_X\sqrt{N}\sqrt{M}}$$

To be reduced
(noise level, kicker strength, BPMs gain, BPM transfer function)

To be increased: M= number of measurements. Usually a 100 points it's the case.

To be increased: It is the width of the scan of intensity. Upper threshold can be TMCI. Lower is BPM sensitivity.

To be increased: N=Number of turns. Depends on ability on hardware and data trasmission from BPM to storage.

Impedance induced phase advance beating

A phase beating is induced by impedance kicks similarly to what is done by a quadrupolar kick. From standard formulas [6, 7] we can calculate the phase beating amplitude and therefore compare it with the accuracy we can get in measurements.

$$\frac{\Delta Q_k}{\Delta N} = \frac{-e^2 T_0}{4\sqrt{\pi}\gamma m_0 (2\pi)^2 Q_0 \sigma_z}\left(\frac{\beta_k}{\bar{\beta}} Im(Z_{eff}^k)\right)$$

Tune shift with intensity

$$\frac{\Delta \phi_k}{\Delta N} = \frac{\beta_k \Delta K / \Delta N}{4\pi \sin(2\pi Q_0)}$$

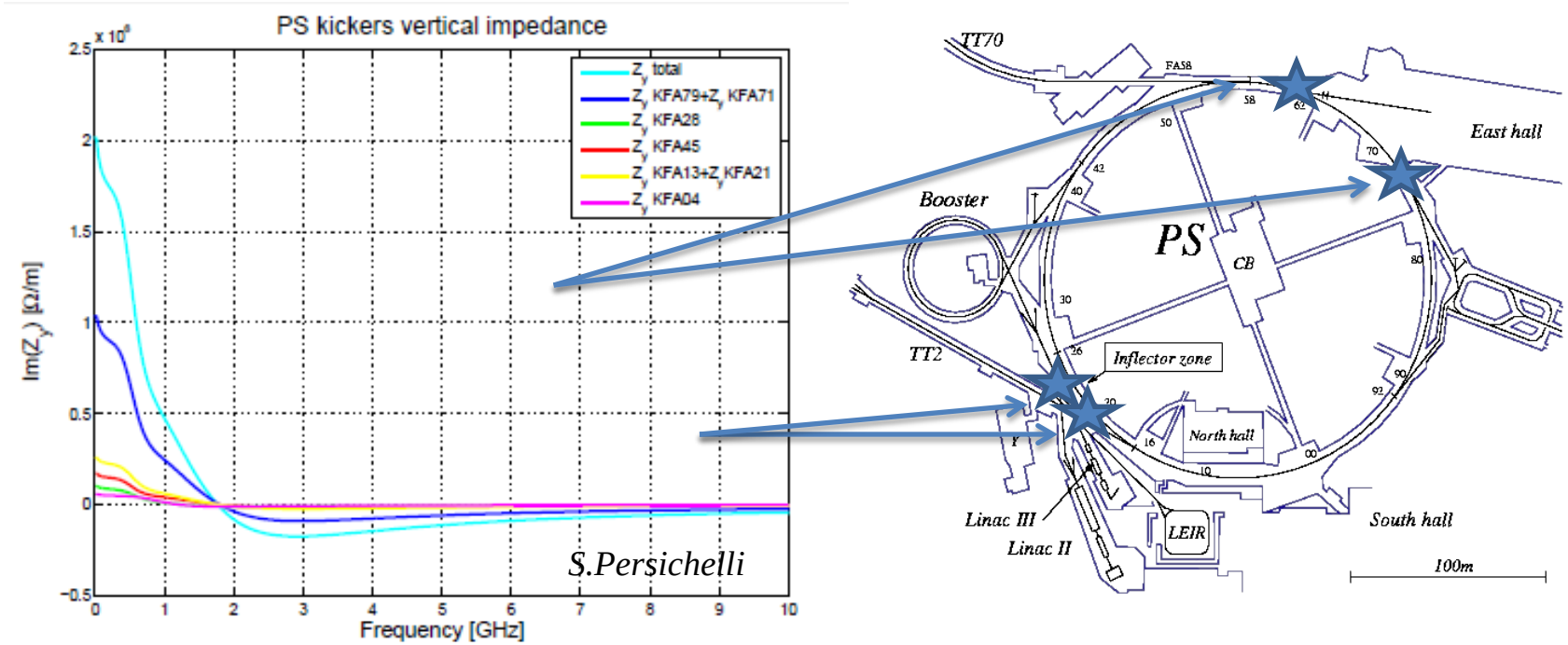
Tune shift with intensity

$$A_{k\frac{\Delta\phi}{\Delta N}} = \frac{\Delta Q_k / \Delta N}{\sin(2\pi Q_0)}$$

Impedance-induced phase beating amplitude

HEADTAIL simulations

To verify our understanding of the measurement we run HEADTAIL [8] simulations with different noise floor.
As an example we choose the PS machines with kicker impedances calculated theoretically with the Tsutsui's model [9].



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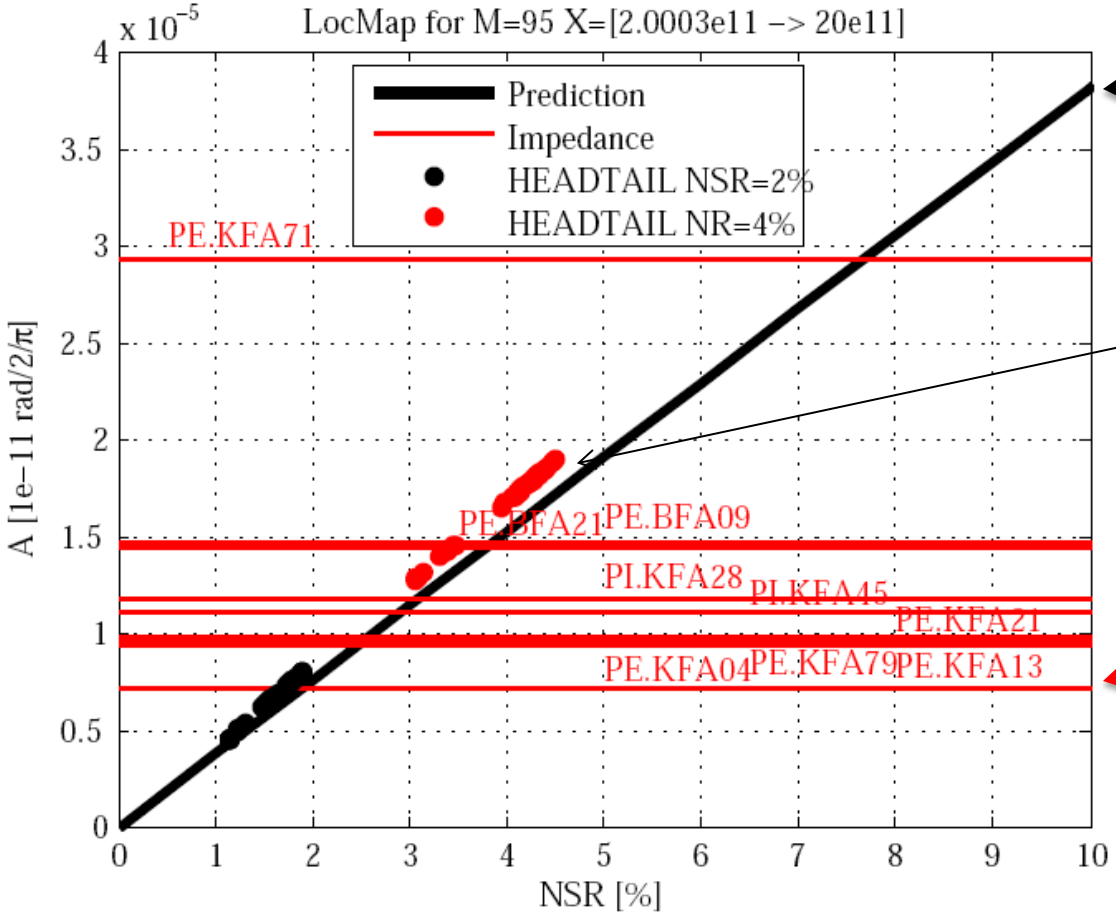


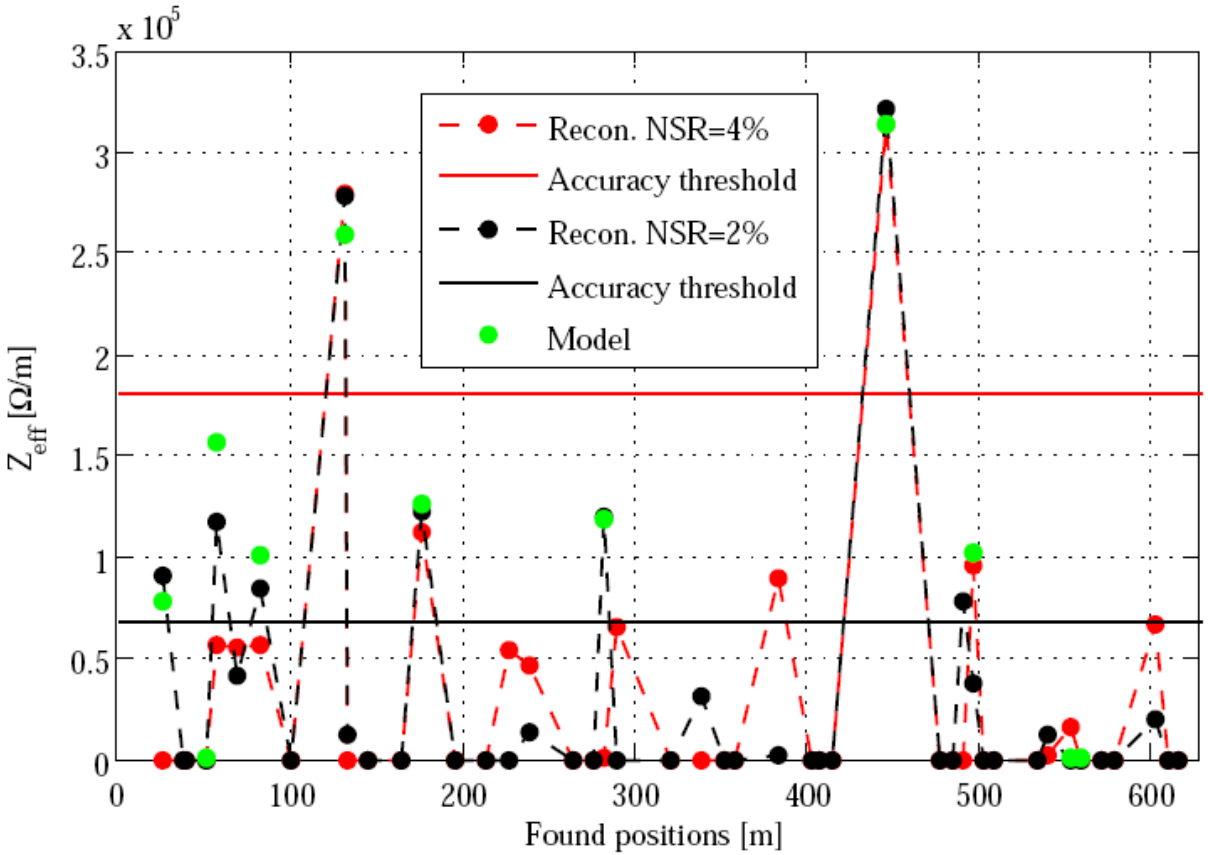
Accuracy estimated <u>before</u> simulation on TbT data.

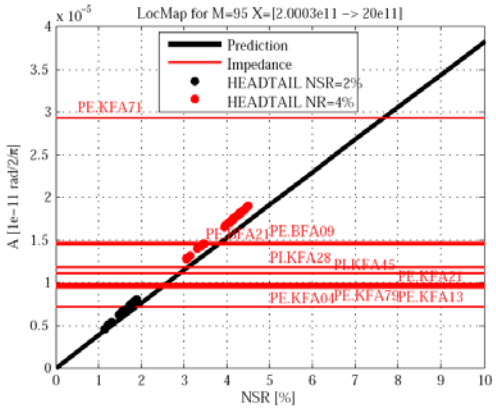
Accuracy calculated <u>after</u> simulation on TbT data for NSR=2% and 4%.

Impedance-induced phase beating amplitude

HEADTAIL simulations

The reconstruction appears to be better in the “black” case, NSR=2%, since the condition $\sigma_{\frac{\Delta\phi}{\Delta N}} < A_{k\frac{\Delta\phi}{\Delta N}}$ is satisfied for all the kickers. In the “red” case, NSR=4%, only sources above the accuracy limit are correctly detected.





PS

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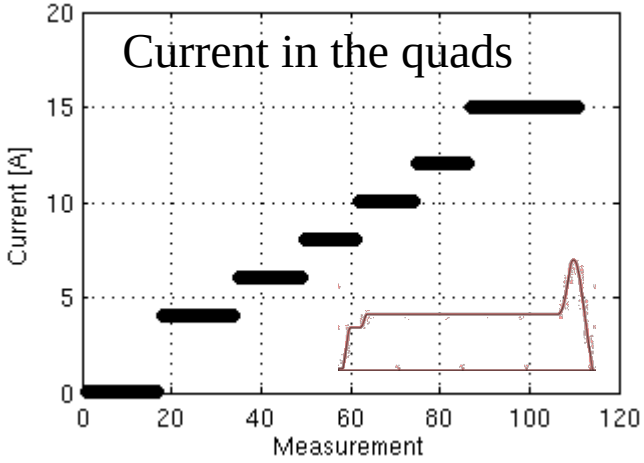
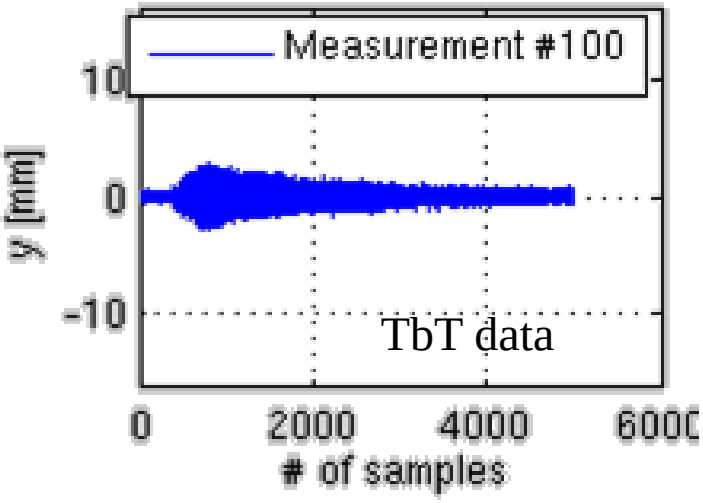
Measurement of local quadrupolar orbit errors

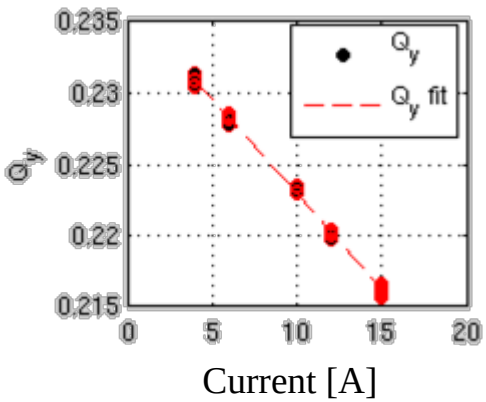
Method validation:

- take a couple of quadrupoles, QLS29 and QSE87.
- vary their current in order to provoke a tune shift of ~0.02.
- Try to localize back the quadrupoles.

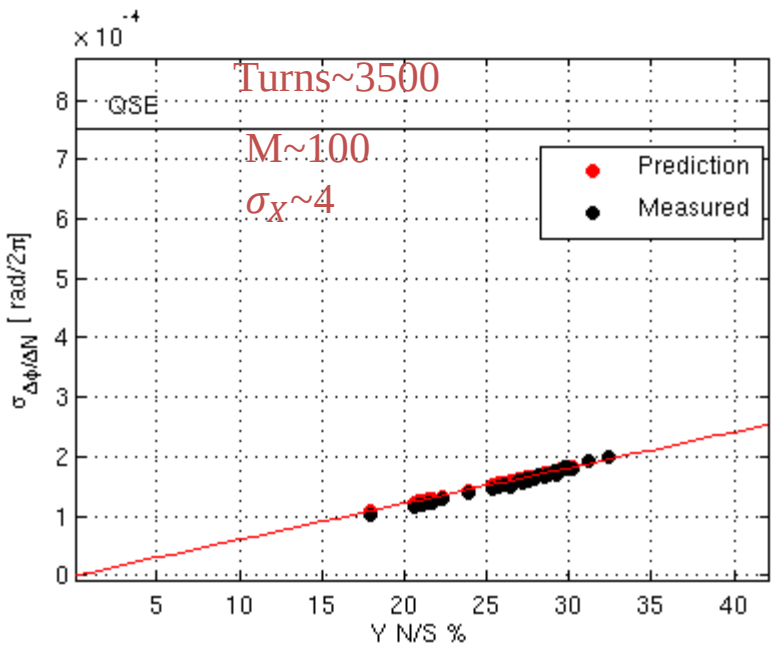




Measurement of local quadrupolar orbit errors

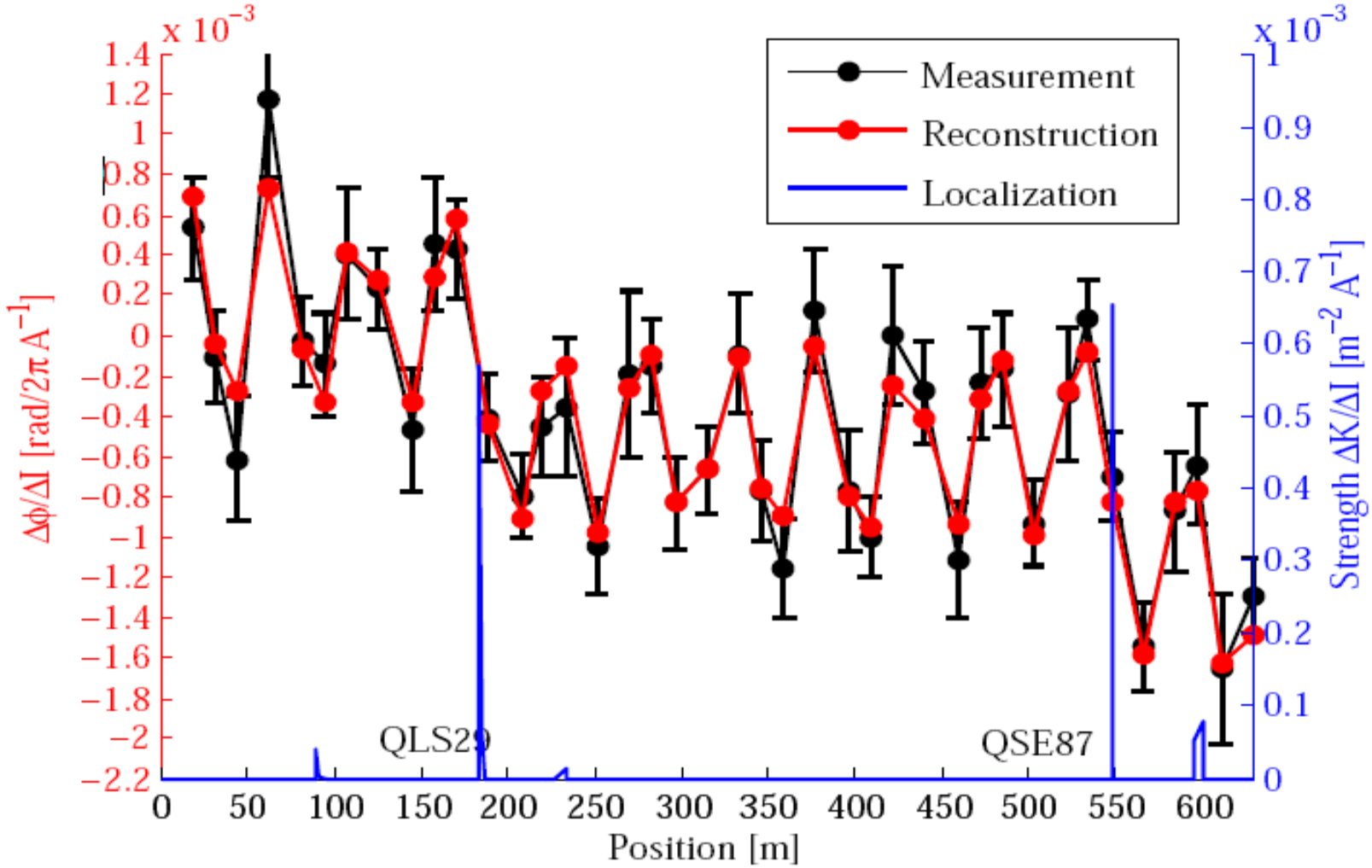


From the tune shift we verified that a considerable scan was achieved.



An error in QLS29 and QSE87 quads provokes a beat of amplitude A~7.5e-4. This is well within the accuracy limit. QSE are 2, so the beating waves can interact constructively or destructively.

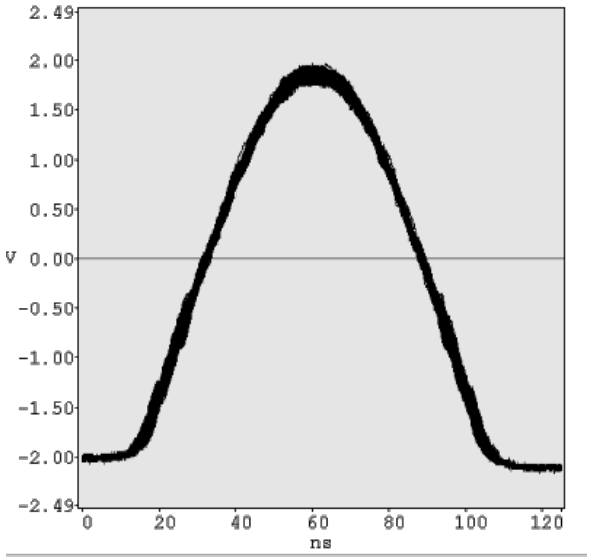
Measurement of local quadrupolar orbit errors



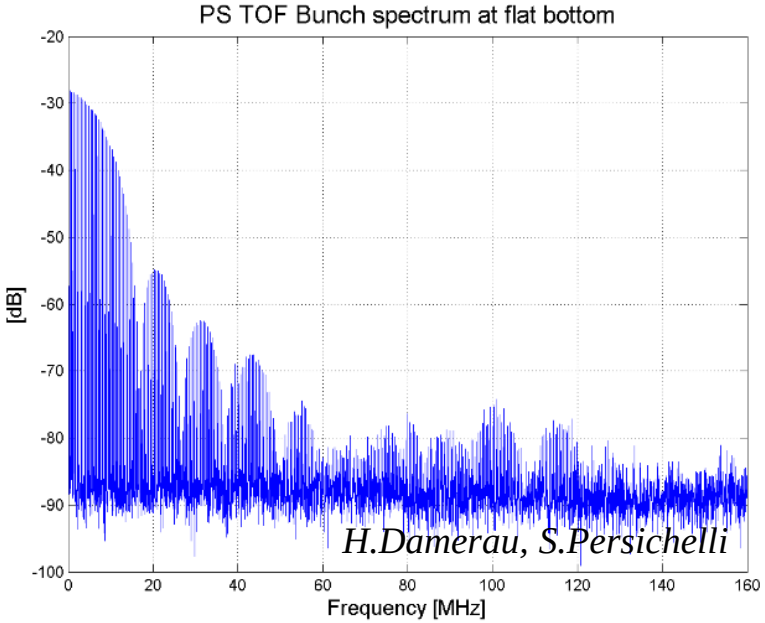
Measurements at 2GeV

- The measurement with single bunch at injection energy 2GeV.
- Intensity scan from 1e12 to 2e12 ppb.
- TFB was used as vertical kicker.
- The smallest bunch length is 90ns (4σ).

Typical bunch in time



Typical bunch in frequency



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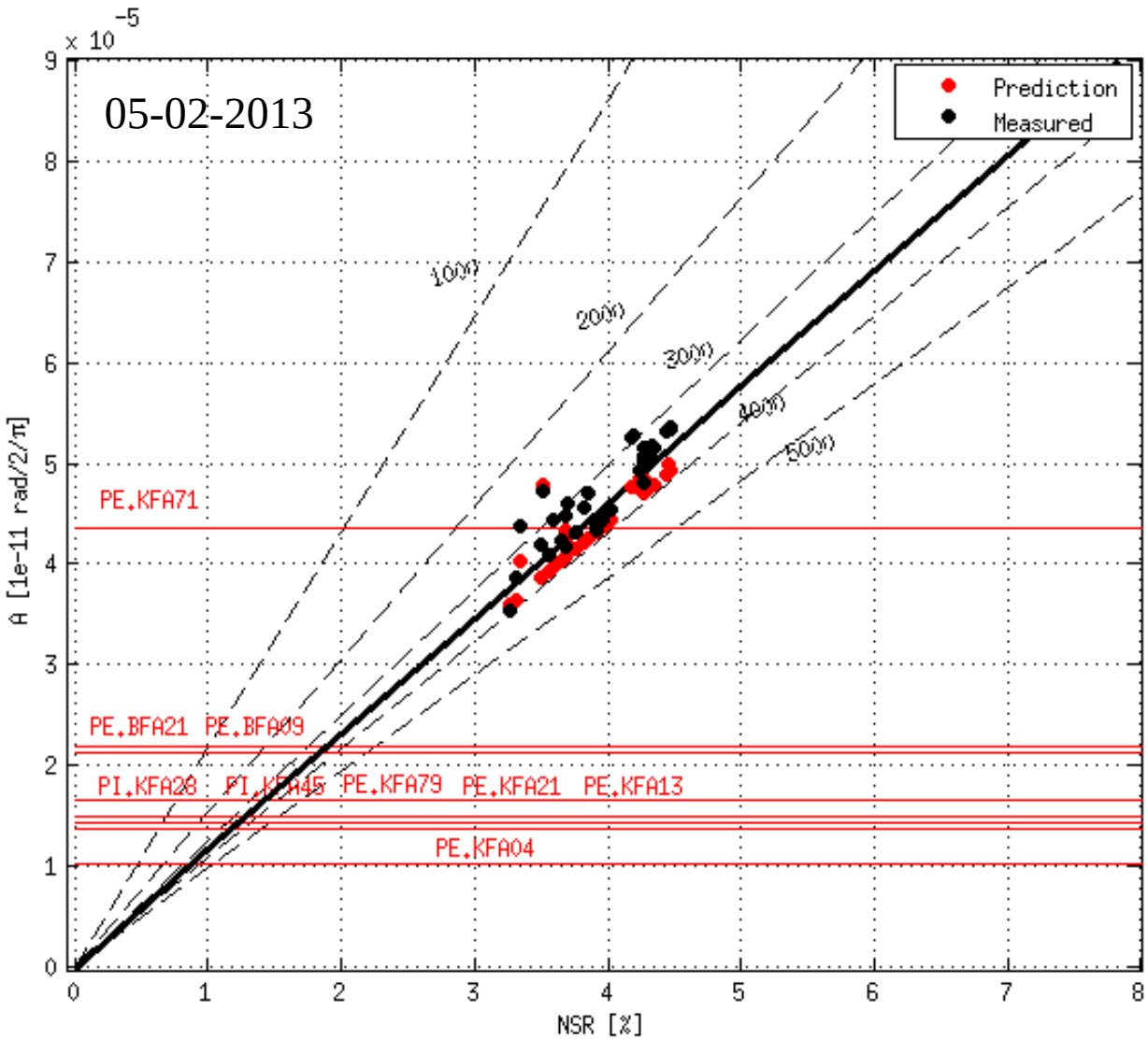
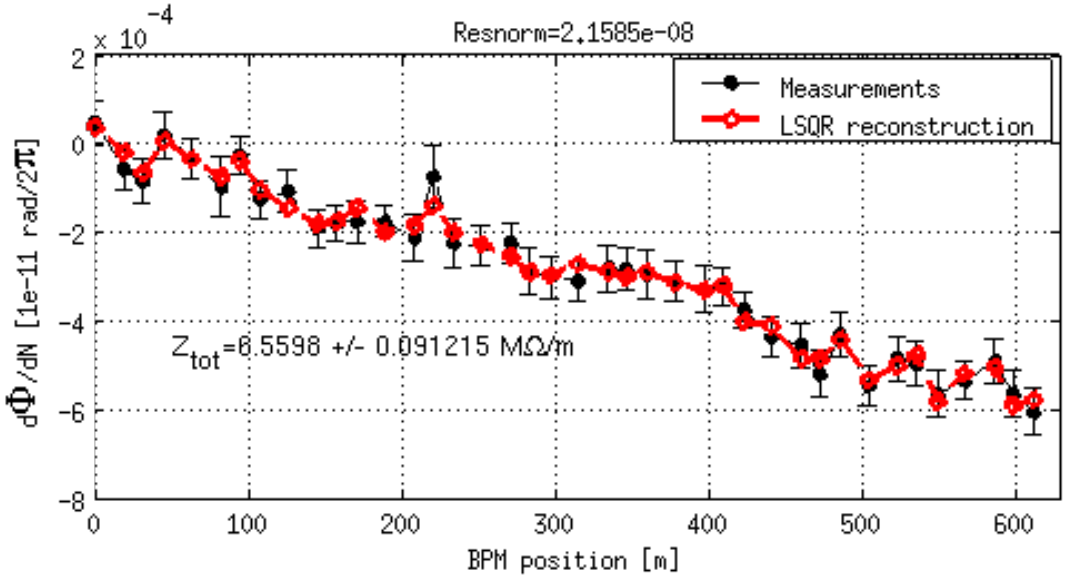


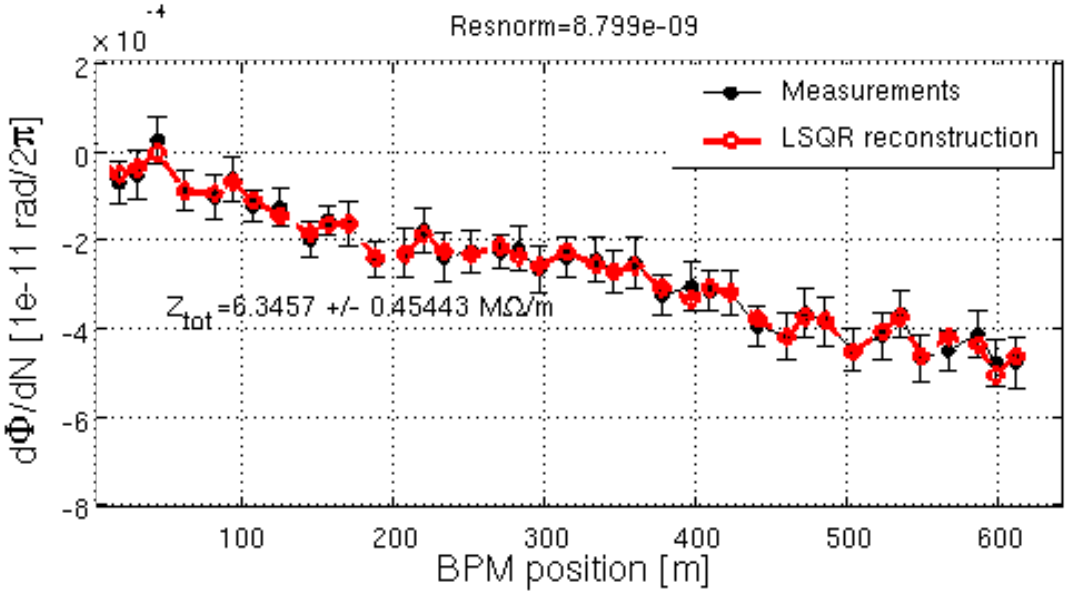
The impedance-induced beating appears to be small with respect to the measurement accuracy usually achieved (NSR~5%) during MDs.

Only big impedance source are expected to be localized.

Measurements at 2GeV



PS-05-02-2013_#2
Bunch length~90ns (rf@200kV)
Ztot~6.5 MOhm/m (from tune shift)



PS-05-02-2013_#3
Bunch length~107ns (rf@100kV)
Ztot~6.3 MOhm/m (from tune shift)

NB: Resistive wall ~ 3MOhm/m has been cut out!

Measurements at 2GeV

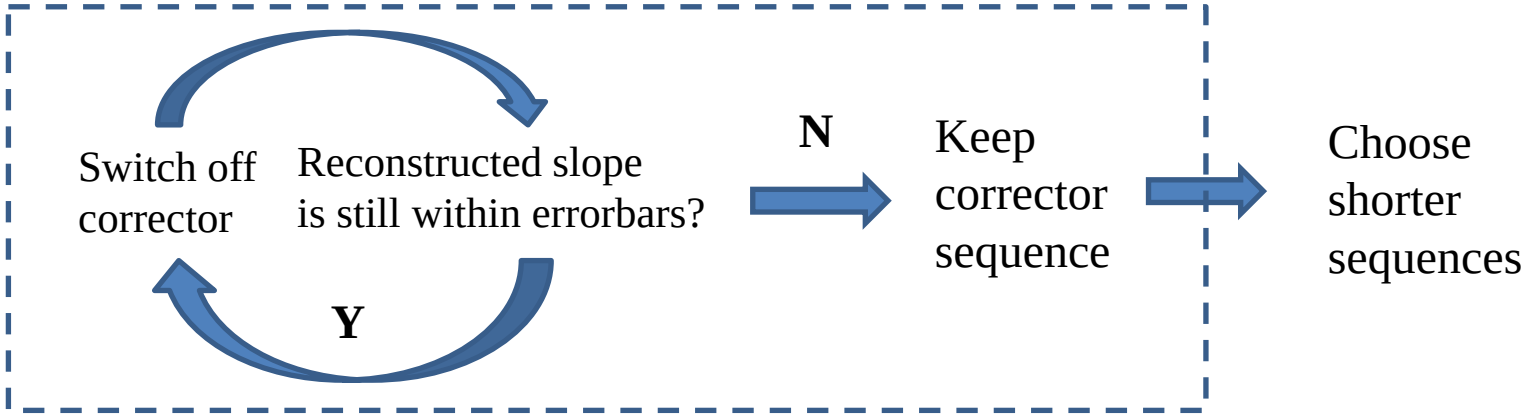
Before reconstruction:

- We chose the reconstruction points as everything in the machine except monitors, vacuum port and magnets. So:
  - ✓ **Cavities;**
  - ✓ **Kickers;**
  - ✓ **Wirescanners;**
  - ✓ **TFB;**
  - ✓ **Septa;**

Response matrix size: **49** reconstructors x **40** BPMs.

After reconstruction:

- Check how the measured and reconstructed slope overlap;
- Do stress-test to check the stability of the solution:



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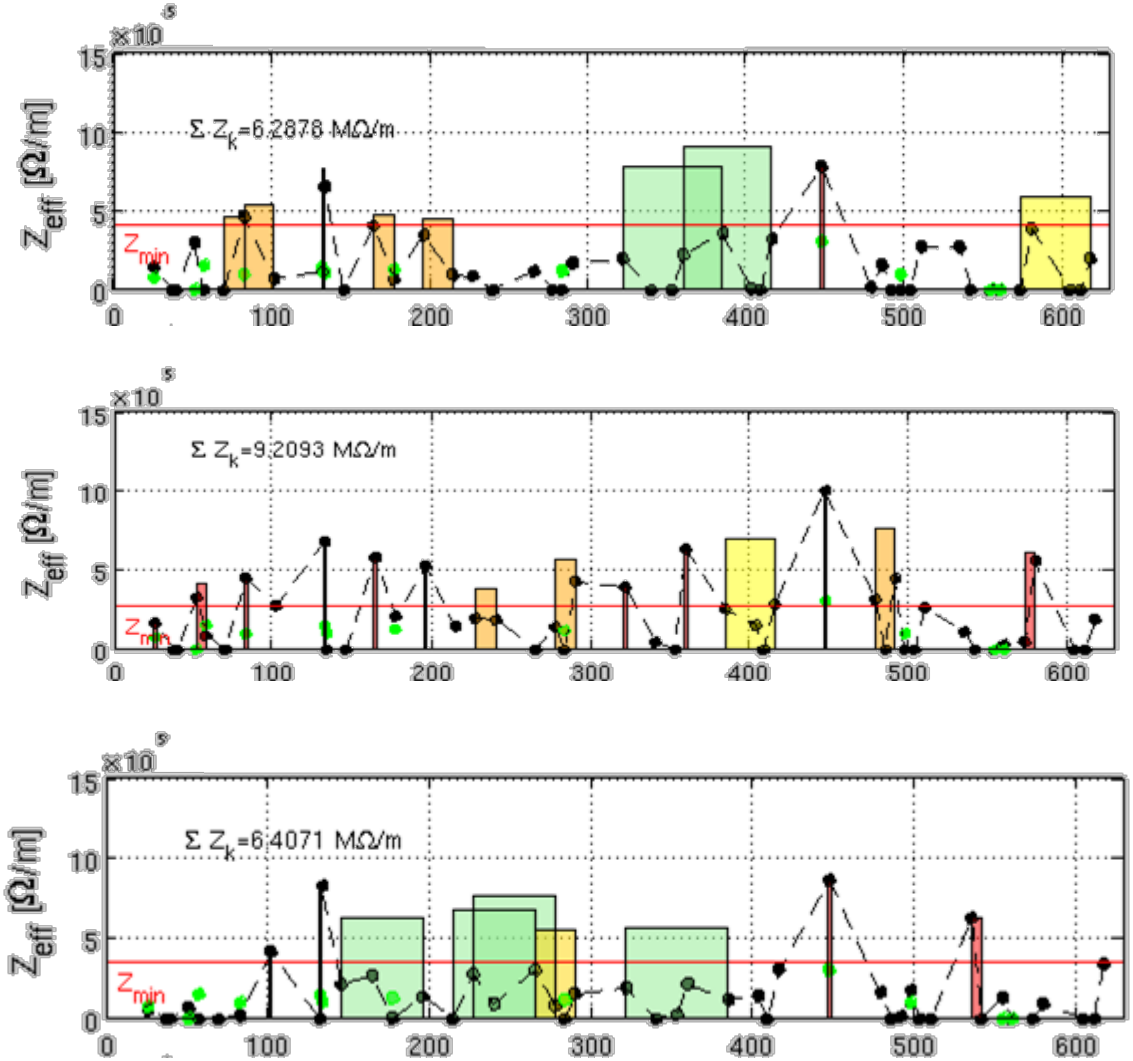
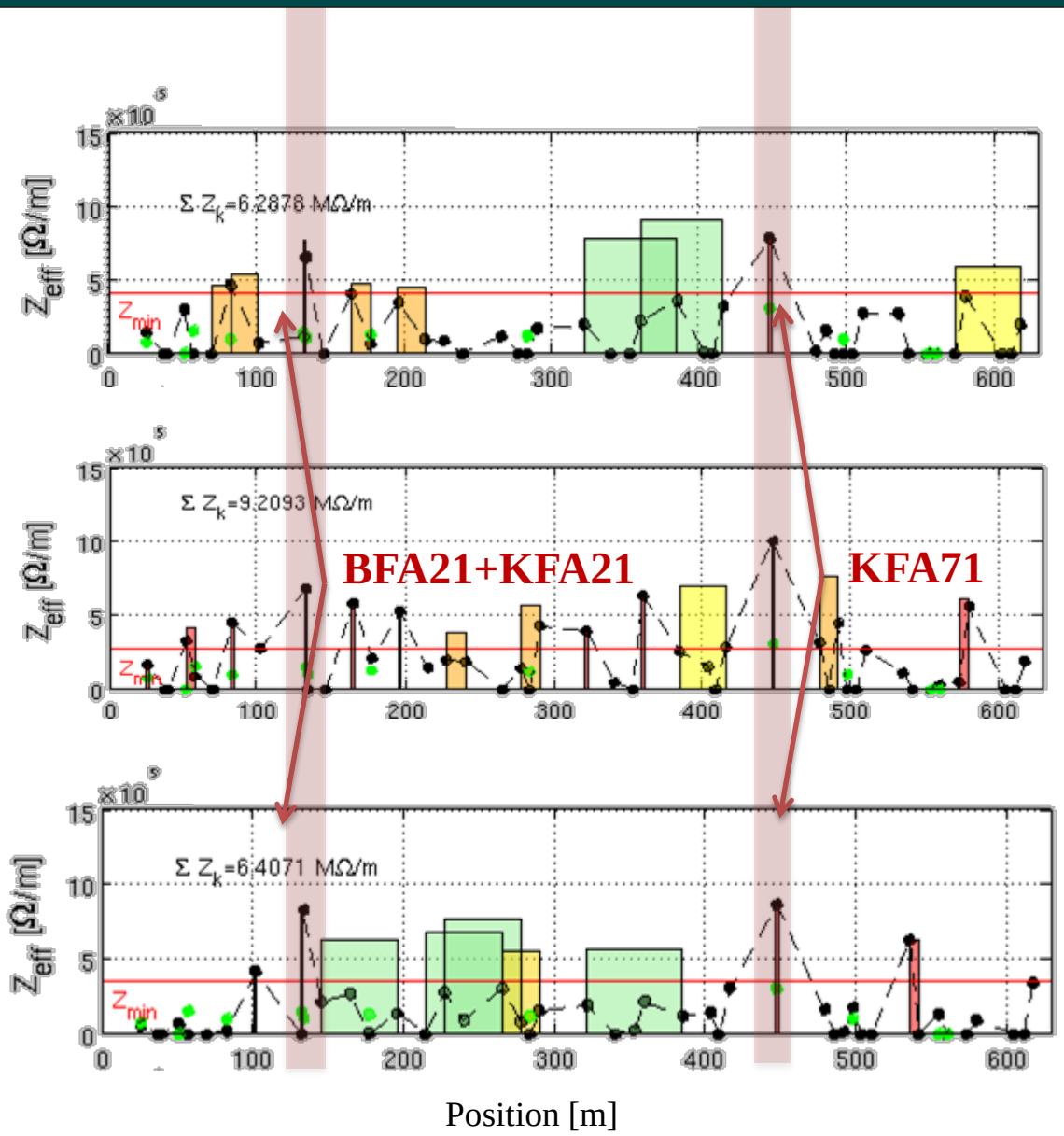


Meas #1

Meas #2

Meas #3

Measurements at 2GeV



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Measurement at injection

The measurements has been tempted also in SPS.

- Used 2 different operational optics “Q20” and “Q26” [10].
- Scan in intensity X from 4e10 to 1.6e11 at injection (26GeV).
- Shortest bunch length ~1/1.2 ns.
- Kick with Q-meter -> NSR ~ 10/20%.
- Number of turns N from 1000 to 5000 depending on BPM status.
- Measurements per fill M~100.
- Estimations for kicker impedance measured and available [11], but still to be included in the model.

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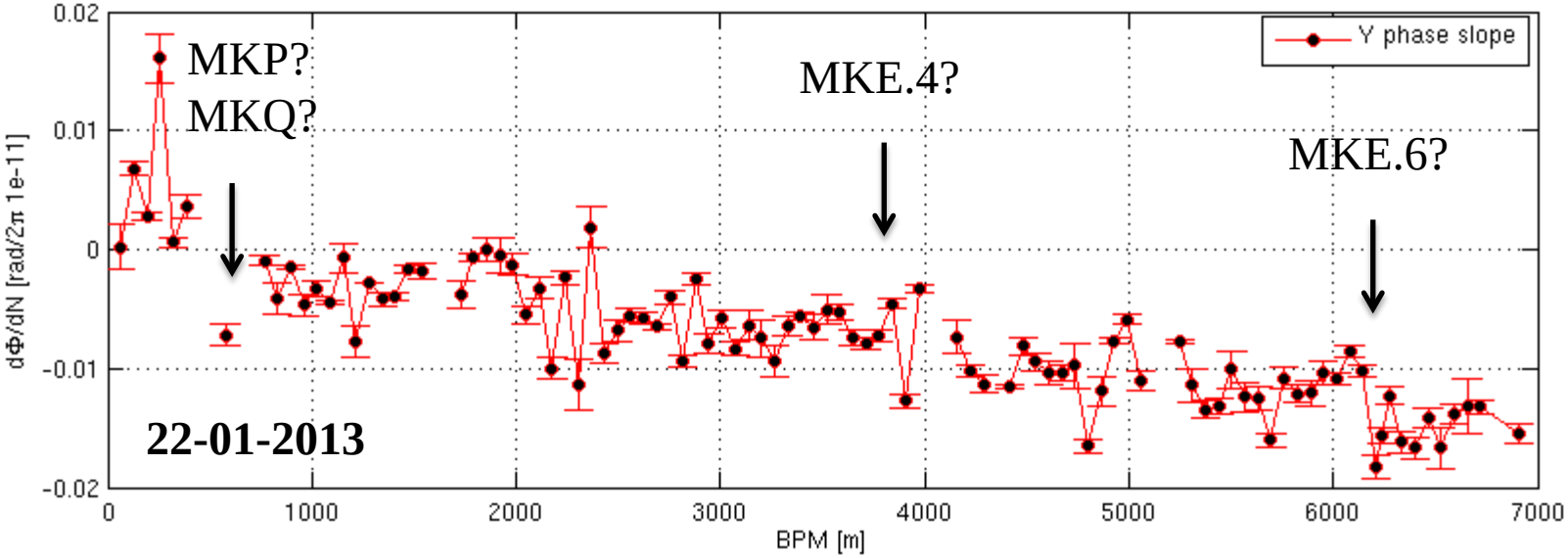

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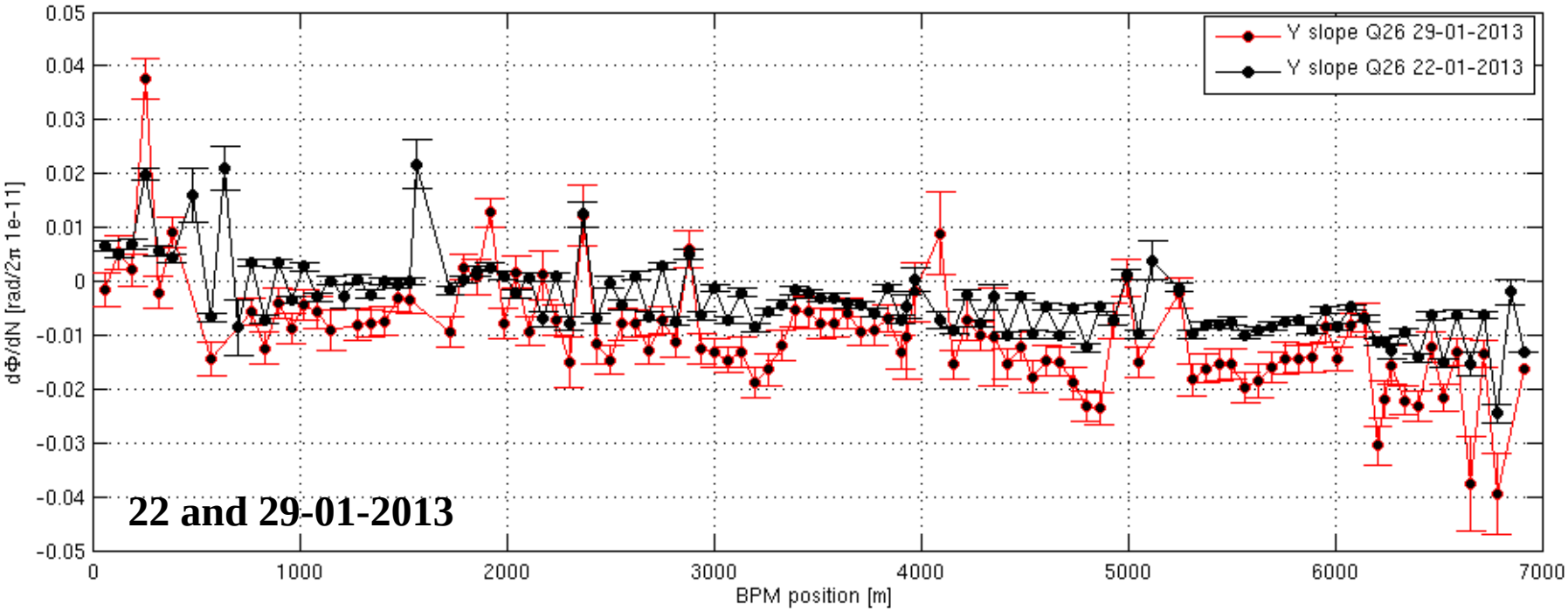

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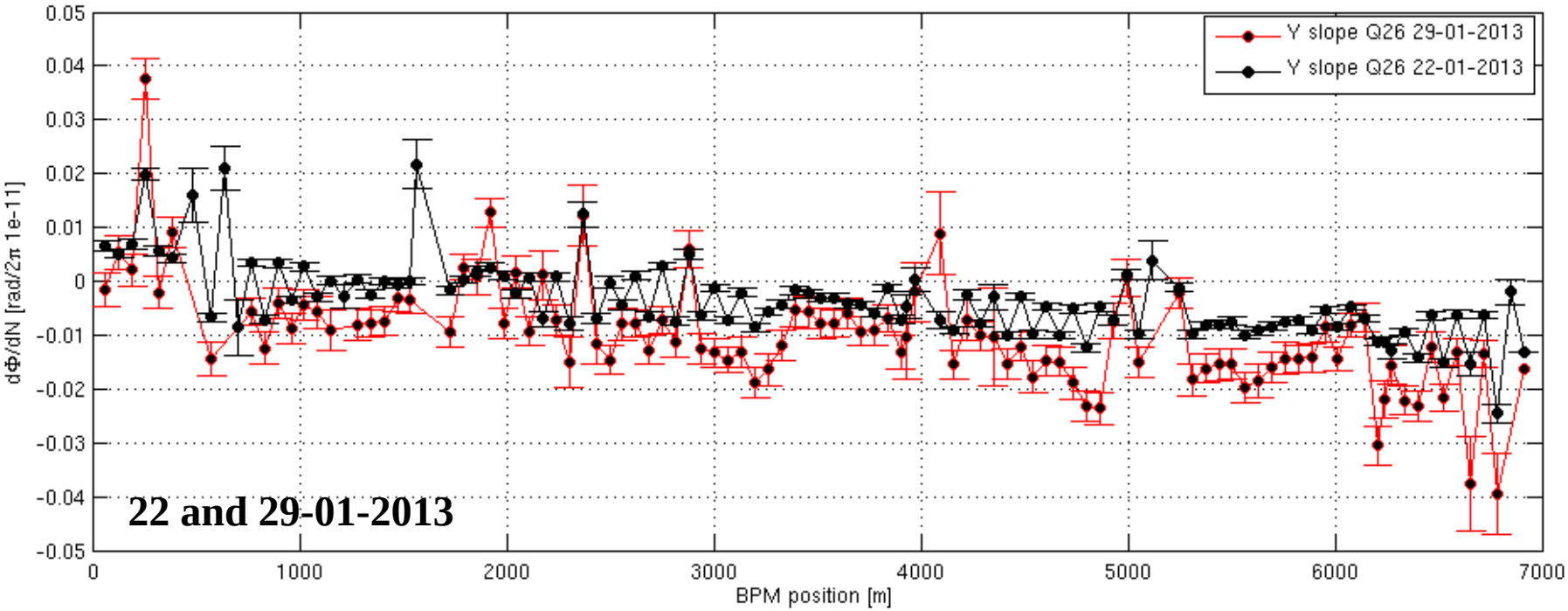
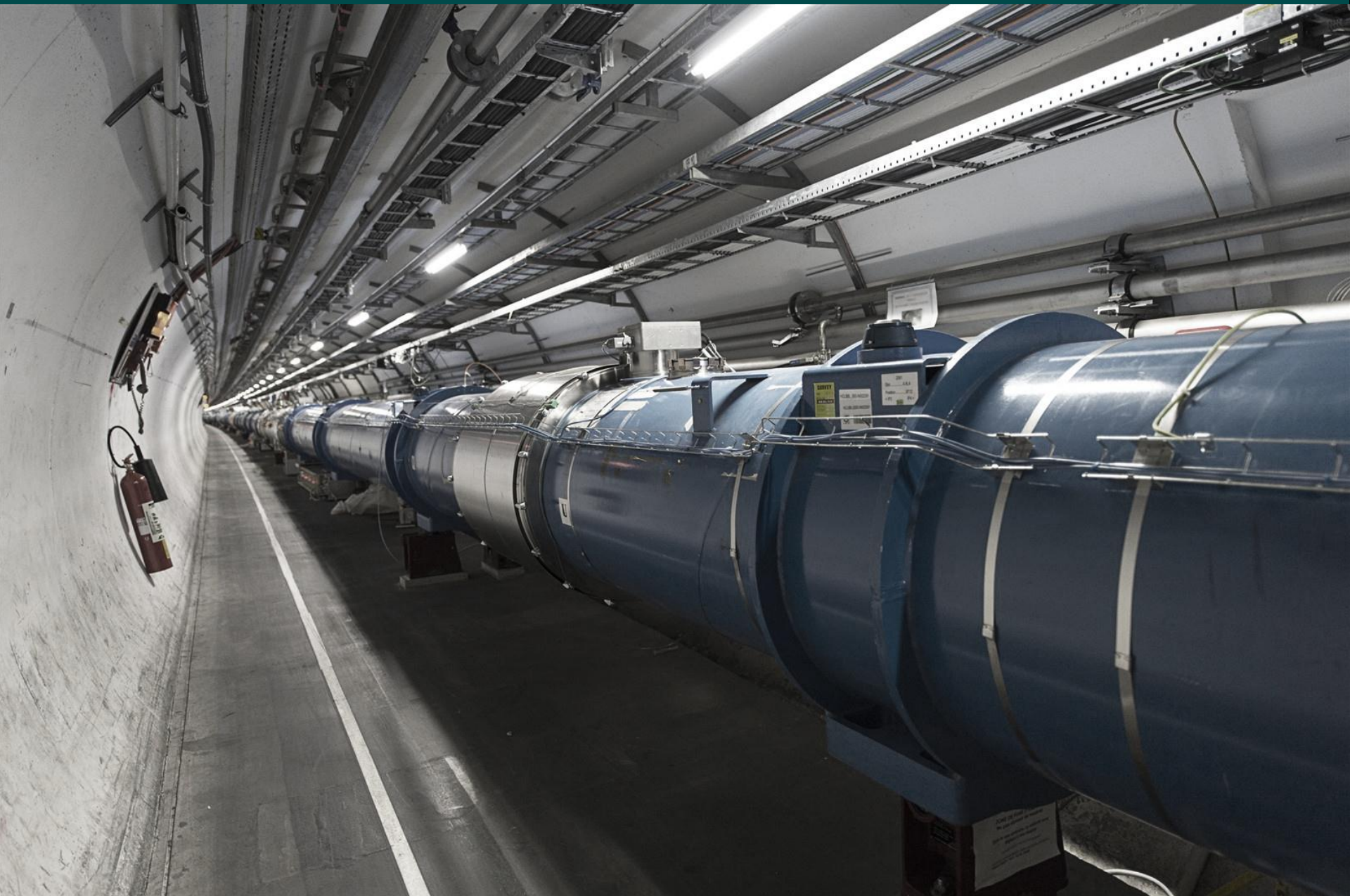


Measurements seem to be acceptable from a NSR point of view.
But….

- Difficulties in getting all BPM working,
- Measurements are scarcely reproducible: not all parameters under control.

LHC



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Measurements with AC dipole

The measurements has been quickly tried in LHC.

- 3 LHC fills (3338-3339-33340), 2h in total.
- Measurements only in B1 (problems in B2).
- Single bunch with high intensity scraped with AC dipole kicks.
- Intensity X from 3e11 down-to 5e10.
- Number of turns N=2220.
- Measurements per fill M~15
- Bunch length ~ 1.2 ns

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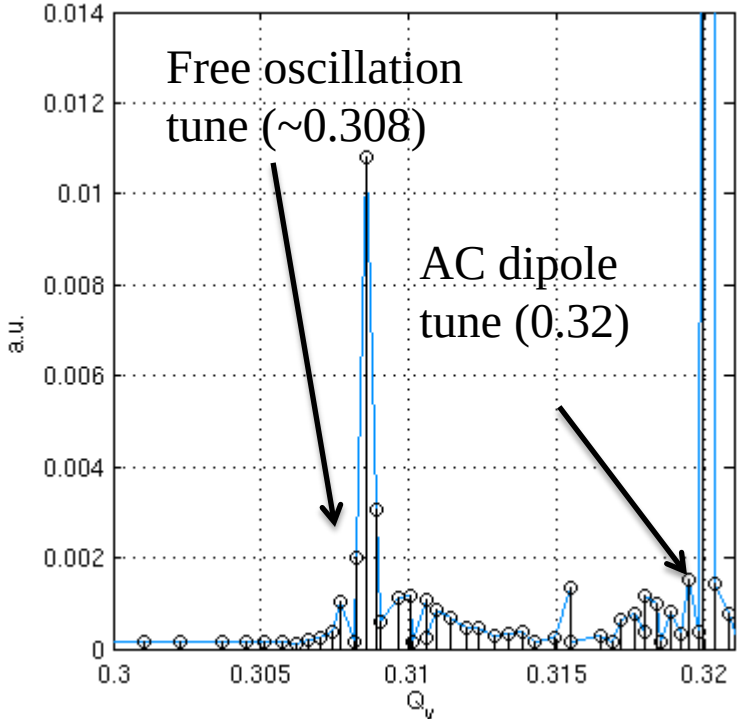

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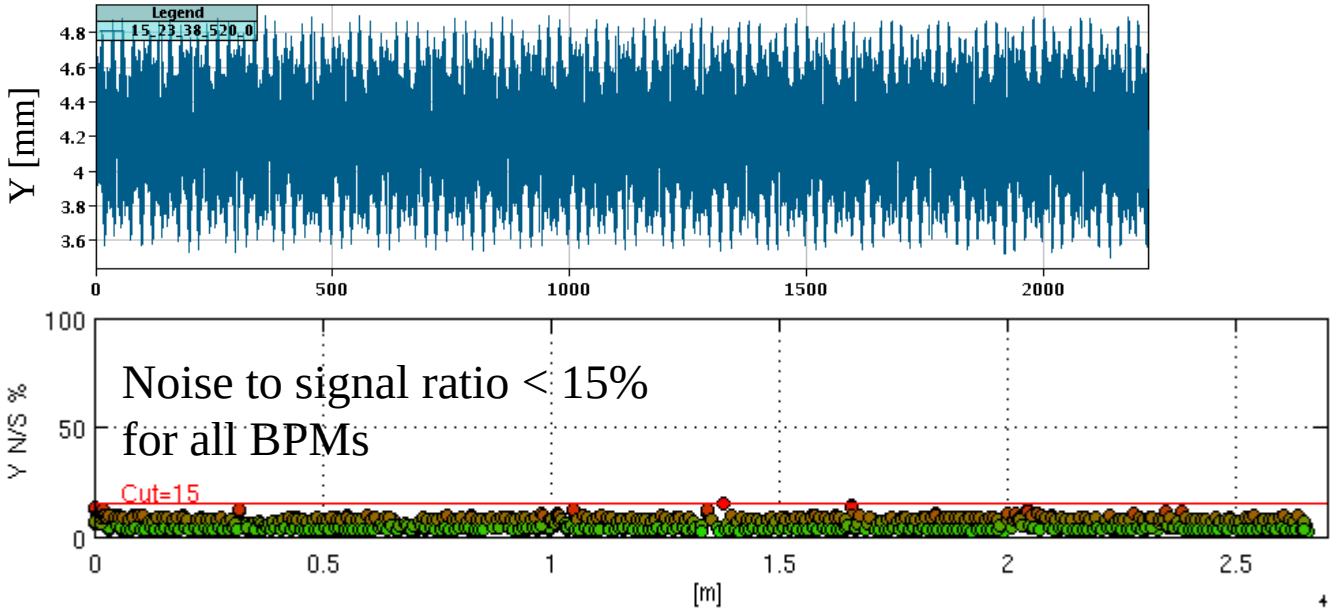
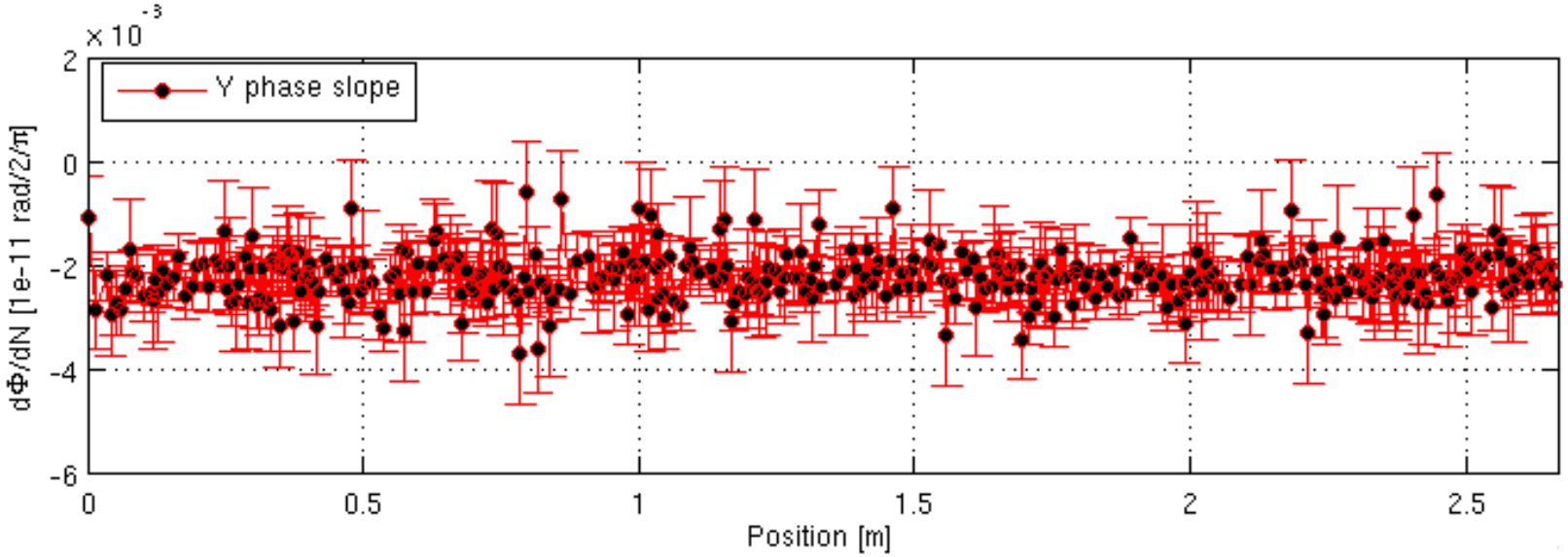
- Measurements per fill M~15
- Bunch length ~ 1.2 ns



Measurements with AC dipole



The AC dipole phase advance look rather noisy,
But….

- The NSR level should be just enough for localizing injection collimator impedance [12].
- The beam resulted to be unstable, probably due to the scraping with AC dipole.

Conclusion

Resuming:

- A better understanding of the major constraints and parameter interplay in the impedance localization measurement has been achieved.
- Experiments in PS with current dependent quadrupolar errors proved the feasibility of the measurements in the simplest case.
- Measurements for PS showed good reproducibility and reconstruction. Two kicker impedance sources were localized in section 21 and 71.
- Measurements for SPS exhibited scarce reproducibility, still under investigation…
- Measurements for LHC with single bunch and AC dipole scraping were for the first time attempted. The bunch resulted unstable and the measurement is planed to be retried at the restart after LS1.

And now….. RHIC!!

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[7] "Physics of Collective Beam Instabilities in high energy Accelerators", A.W.Chao, John Wiley & Sons, 1993.

[8] "HEADTAIL + MADX", N.Biancacci, HTWG,2012

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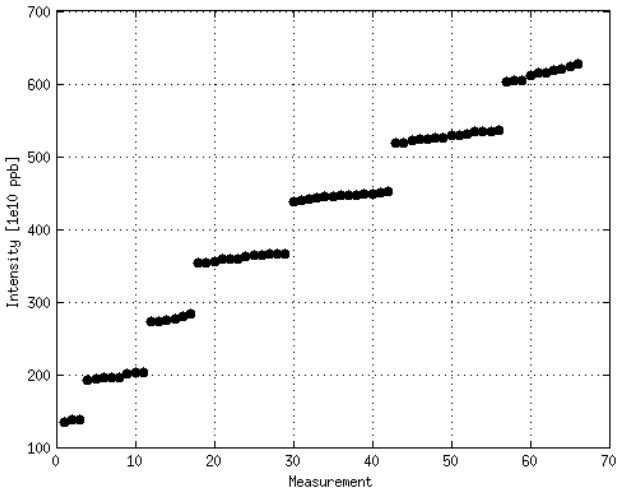
[10] "Experimental studies with low transition energy optics in the SPS" H.Bartosik et al. IPAC'11

[11] Detailed informations on the SPS impedance webpage.

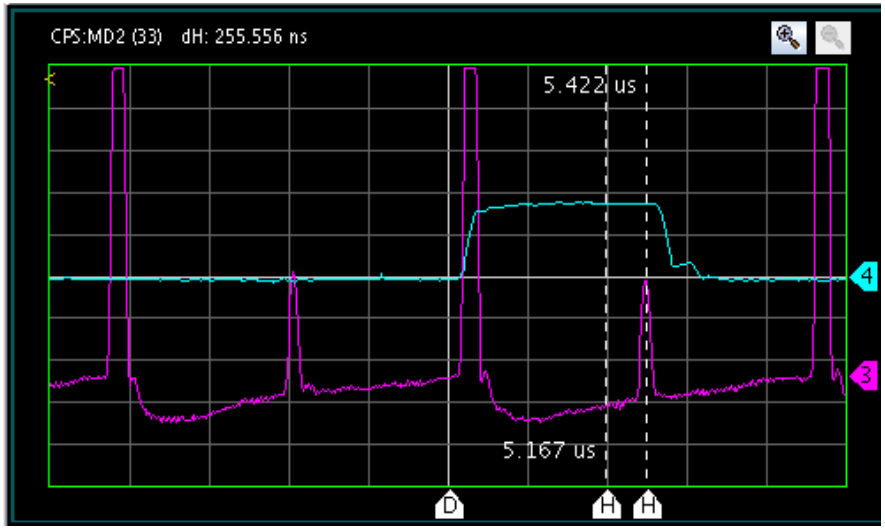
[12] "Impedance effects on beam stability", N.Mounet et al., LHC Beam Operation Workshop, Evian 2011.

BACKUP

Exotic measurements : 2 bunches

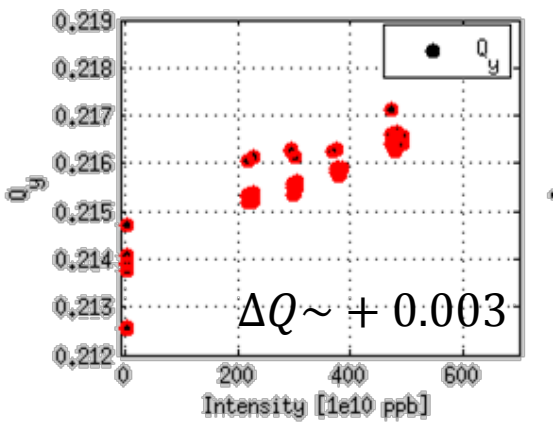


Using two bunches whose the leading one is bringing all the charge, and the trailing one is used as probe, we could measure the effects seen by the probe.

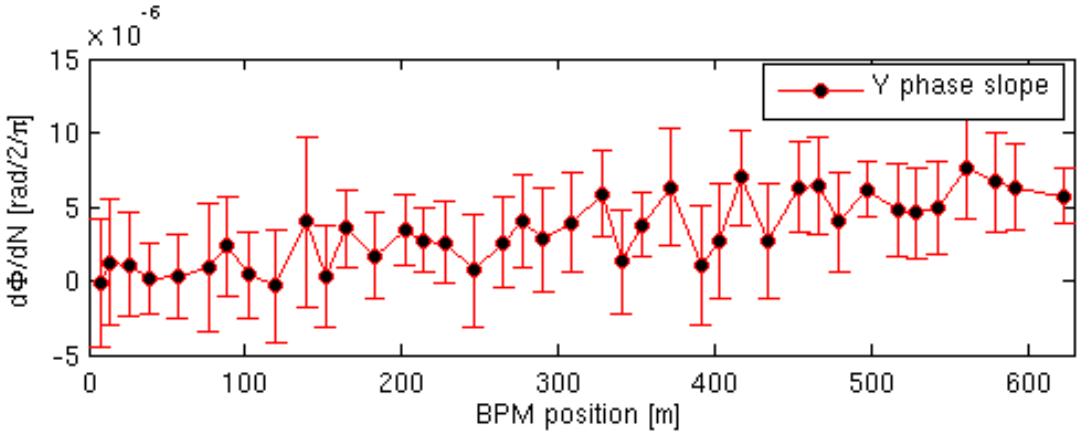


- Bunches are separated of half the machine (1us).
- Kicker is acting horizontally only on the trailing.
- By coupling we measure the trailing in vertical plane.
- Scan in intensity from 1e12 to 6e12.

Exotic measurements : 2 bunches



- Tune shift is due to coupled bunch effects.
- Is going up as corresponds to the horizontal tune.
- Is considerably reduced respect to the single bunch case.
- Imposed NSR~10% led to $\sigma_{\Delta\varphi}$ ~ 0.002 as expected.



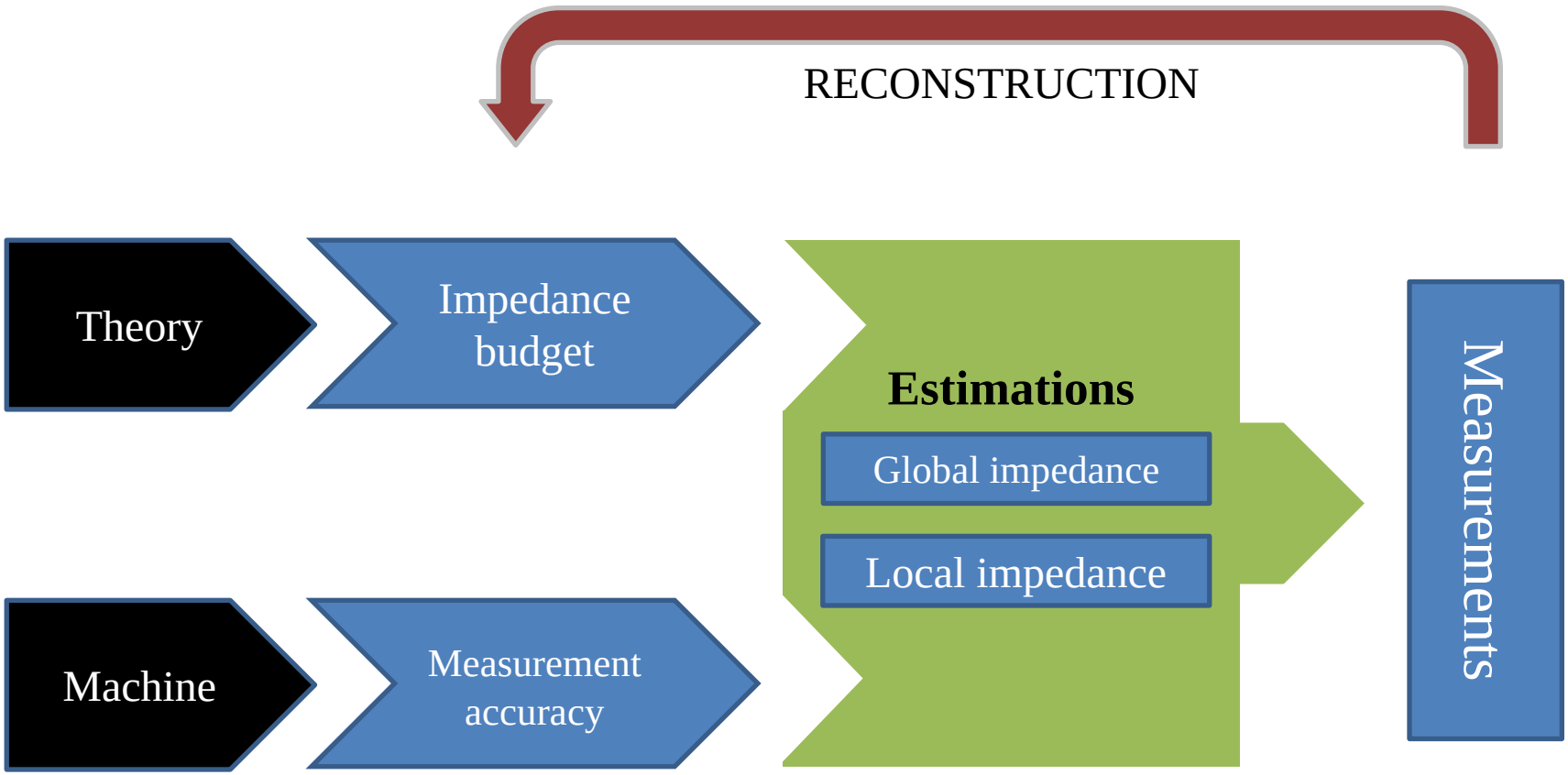
Unfortunately, being the tune shift lower, the error bars become considerably big…

Reconstruction points

1	'"PE.KFA04"'	kicker
2	'"PR.C02106"'	cavity
3	'"PR.C02206"'	cavity
4	'"PR.C02306"'	cavity
5	'"PR.C02406"'	cavity
6	'"PR.C02506"'	cavity
7	'"PR.C02606"'	cavity
8	'"PR.C8008"'	cavity
9	'"PE.BFA09"'	kicker
10	'"PR.C1011"'	cavity
11	'"PE.KFA13"'	kicker
12	'"PE.SMH16"'	septum
13	'"PE.BFA21"'	kicker
14	'"PE.KFA21"'	kicker
15	'"PE.SES23"'	septum
16	'"PI.SMH26"'	septum
17	'"PI.KFA28"'	kicker
18	'"PE.SES31"'	septum
19	'"PR.BCT34"'	wall current
20	'"PR.C1036"'	cavity
21	'"PR.BCT38"'	wall current
22	'"PI.SMH42"'	septum
23	'"PR.BCT44"'	wall current
24	'"PI.KFA45"'	kicker

25	'"PR.C1046"'	cavity
26	'"PR.C1051"'	cavity
27	'"PR.MBP54"'	wirescanner
28	'"PR.C1056"'	cavity
29	'"PE.SMH57"'	septum
30	'"PE.SMH61"'	septum
31	'"PR.MBP64"'	wirescanner
32	'"PR.MBP65"'	wirescanner
33	'"PR.C1066"'	cavity
34	'"PE.KFA71"'	kicker
35	'"PR.C1076"'	cavity
36	'"PR.C4077"'	cavity
37	'"PR.C4078"'	cavity
38	'"PE.KFA79"'	kicker
39	'"PR.C2080"'	cavity
40	'"PR.C1081"'	cavity
41	'"PR.MBP85"'	wirescanner
42	'"PR.C1086"'	cavity
43	'"PR.C8088"'	cavity
44	'"PR.C8089"'	cavity
45	'"PR.C1091"'	cavity
46	'"PR.C2092"'	cavity
47	'"PR.C1096"'	cavity
48	'"PR.KFB97"'	damper
49	'"PR.KFB98"'	damper

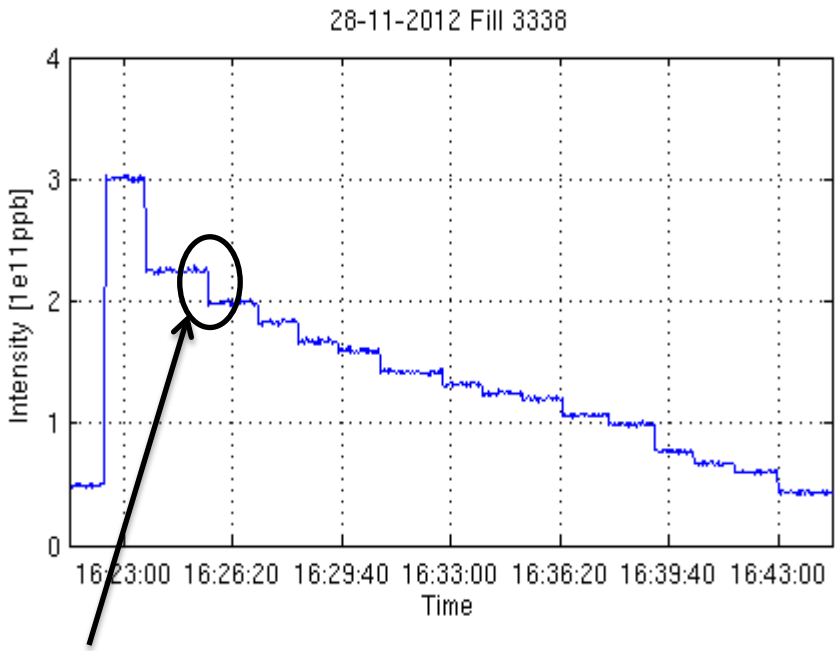
Localization chart



Fill 3338

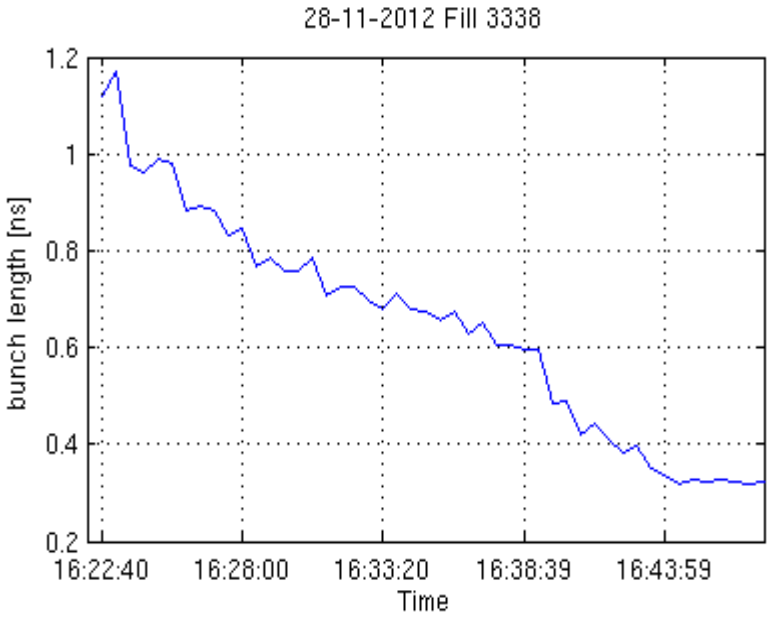
Fill 3338 as an example:

Intensity



Steps obtained by kicking the beam with AC dipole.

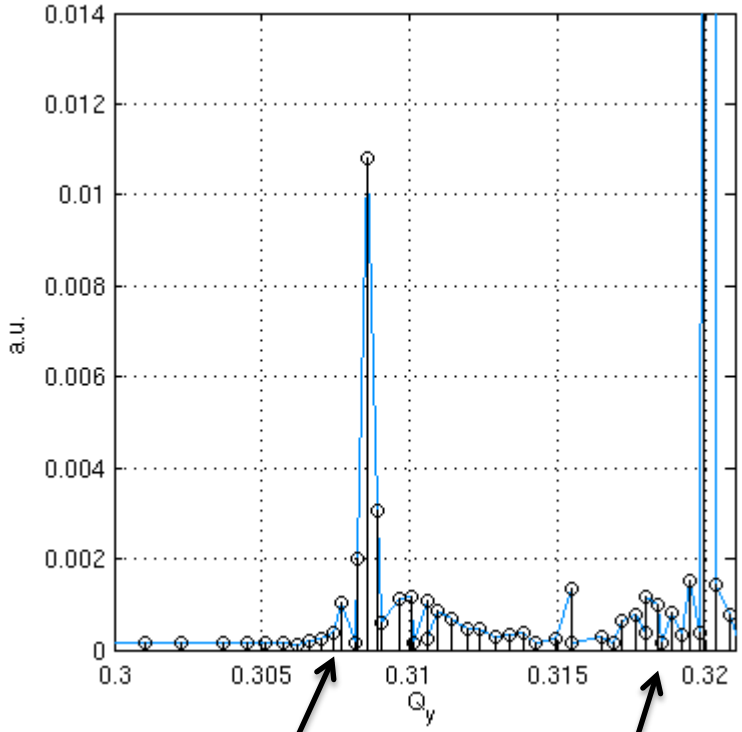
Bunch length



Bunch length decreases after the scraping.

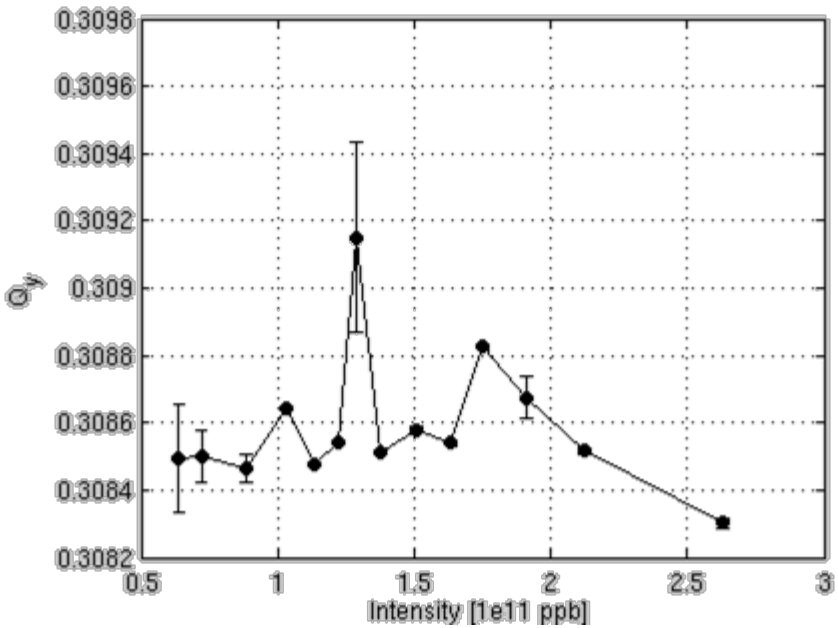
Status of Analysis

The tune frequency is needed to correct the optics from the TBT data measured at the AC dipole frequency.



Free oscillation tune (~0.308)

AC dipole tune (0.32)



The vertical tune shift with intensity looks puzzling…
More checks are to be done.

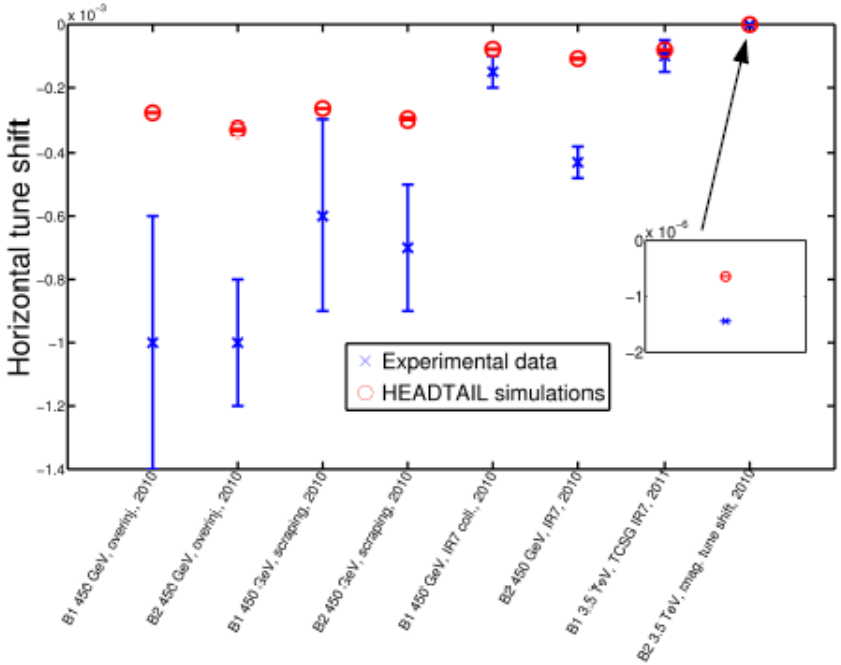


Figure 1: Horizontal tune shifts measured and simulated, in various cases.

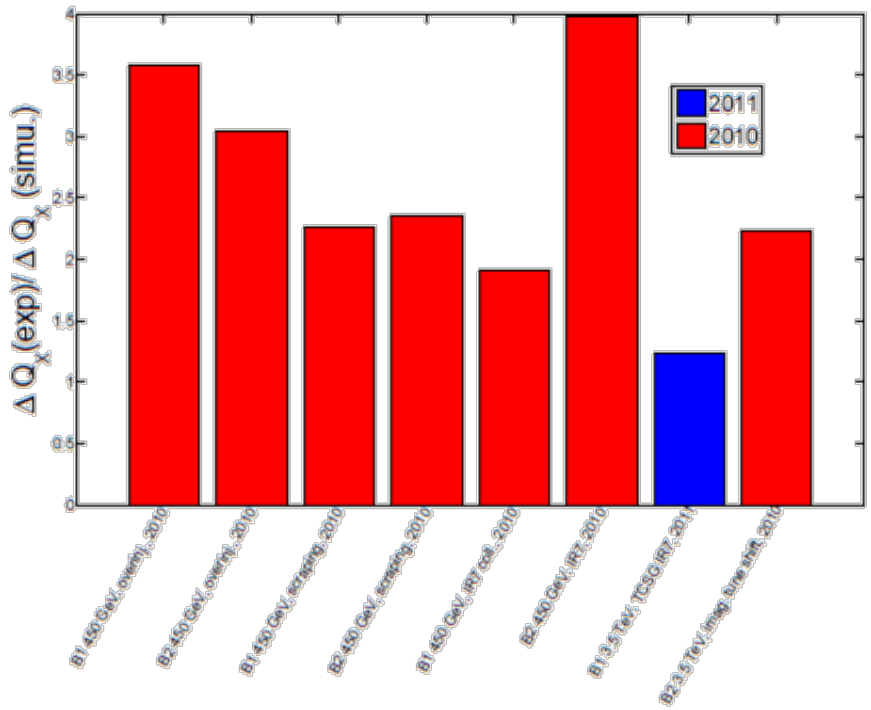


Figure 5: Discrepancy factor between the horizontal tune shifts measured and simulated, in various cases.

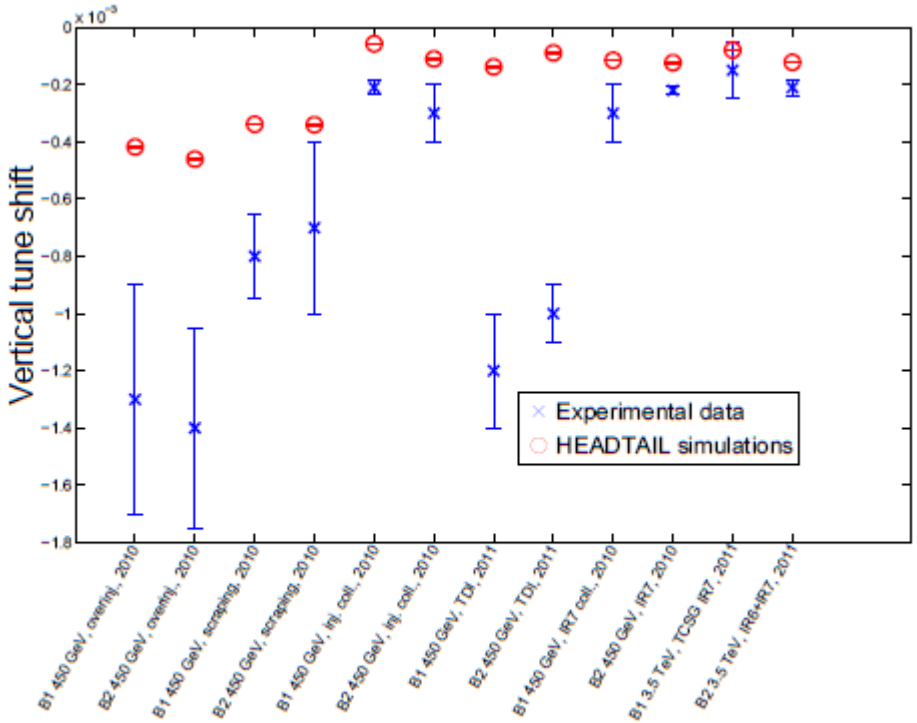


Figure 2: Vertical tune shifts measured and simulated, in various cases.

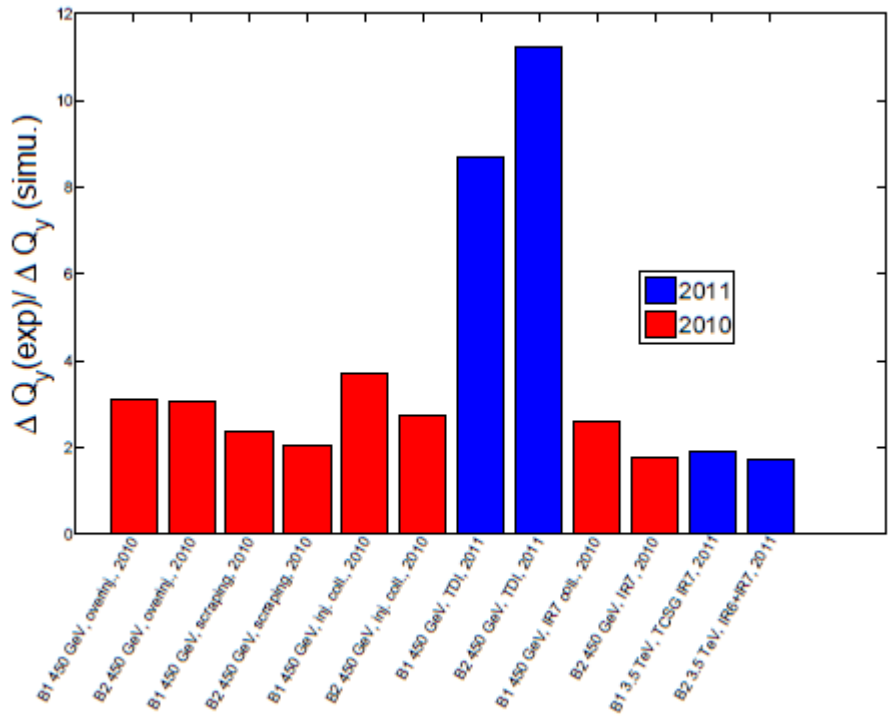


Figure 6: Discrepancy factor between the vertical tune shifts measured and simulated, in various cases.