BEAM COUPLING IMPEDANCE LOCALIZATION TECHNIQUE VALIDATION AND MEASUREMENTS IN THE CERN MACHINES

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Abstract

The beam coupling impedance could lead to limitations in beam brightness and quality, and therefore it needs accurate quantification and continuous monitoring in order to detect and mitigate high impedance sources. In the CERN machines, for example, kickers and collimators are expected to be important contributors to the total imaginary part of the transverse impedance. In order to detect the other sources, a beam based measurement was developed: from the variation of betatron phase beating with intensity, it is possible to detect the locations of main impedance sources. In this work we present the application of the method with beam measurements in the CERN PS, SPS and LHC.

DESCRIPTION OF THE METHOD

The impedance localization method [1, 2, 3] is based on the extension of the well-known method for global impedance measurement [4]: since the transverse tune (i.e. total integrated betatron phase advance over the machine circumference), usually decreases linearly with intensity, analogously, local impedance sources would produce a local phase advance perturbation, i.e. a phase beating along the machine.

The method of measuring localized impedances can be summarized in the following: by varying the intensity of a beam circulating in the machine, a phase advance variation with intensity can be measured from a multi-turn BPM system; the phase beating response matrix from local quadrupole errors representing the impedance source can be constructed to perform a least-square inversion and recover the impedance position.

ACCURACY CONSIDERATIONS

The observable for this measurement is the impedance induced phase advance variation with intensity. In order to assess the feasibility of the measurement, the reachable accuracy for this signal can be estimated a priori. Given two BPMs at a given phase advance $\Delta\phi$, we approximate the betatron signal as two sinusoidal signals s_1 and s_2 at the tune frequency and affected by additive Gaussian noise. In this condition we can estimate with a fit procedure the phase advance accuracy $\sigma_{\Delta\phi}$ as:

$$\sigma_{\Delta\phi} = F\frac{NSR}{\sqrt{N}}, \qquad (1)$$

where N is the number of turns, F is a numerical fit parameter depending on the noise distribution and equal

to 1.12 in the Gaussian case, NSR is the noise to signal ratio from the two signals: if $s_{1,2}$ has amplitude $a_{1,2}$ and the estimated noise standard deviation $\sigma_{n1,2}$, then $NSR = \sqrt{NSR_1^2 + NSR_2^2}/\sqrt{2}$, with $NSR_1 = \sigma_{n1}/a_1$ and $NSR_2 = \sigma_{n2}/a_2$. Considering a number of measurements M along an intensity range X (for example $X = [10^{10} \dots 10^{11}]$), the phase advance slope accuracy can be found as [5]:

$$\sigma_{\frac{\Delta\phi}{\Delta N}} = \frac{\sigma_{\Delta\phi}}{\sigma_X\sqrt{M}}, \qquad (2)$$

where σ_X is the standard deviation of the intensity scan values X. In order to reach a good accuracy it is therefore necessary to have a sufficient number of measurements (usually $M \sim 100$), a high number of turns (N usually varies from 1000 to 5000), a wide beam intensity range (whose lower bound is given by the BPM sensitivity and upper bound by instabilities and non-linear effects), and a small noise (strongly correlated with the BPM system quality).

From Sacherer's theory [4], the tune shift slope with intensity corresponding to the kth generalized (i.e. dipolar + quadrupolar) impedance source in the lattice is:

$$\frac{\Delta Q_k}{\Delta N} = \frac{-e^2 T_0}{4\sqrt{\pi}\gamma m_0 (2\pi)^2 Q_0 \sigma_z}\left(\frac{\beta_k}{\bar{\beta}}Im(Z_{eff}^k)\right). \qquad (3)$$

Q_0 is the natural tune in the plane of reference (horizontal or vertical), σ_z is the rms bunch length in m, m_0 and e are the proton rest mass and charge, T_0 is the machine revolution time, β_k is the betatron amplitude at the impedance location, $\bar{\beta}$ is the average betatron amplitude, Z_{eff}^k is the effective (i.e. weighted by the beam spectrum) impedance value. The phase advance beating amplitude $\frac{\Delta\phi_k}{\Delta N}$ (in rad/2π units) can be found as well from theory of lattice imperfections [6]. Considering intensity dependent strength of quadrupoles $\Delta K/\Delta N$, we have

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

We therefore get the impedance-induced phase beating amplitude expected A_k as:

$$A_k = \frac{\Delta Q_k/\Delta N}{\sin(2\pi Q_0)}. \qquad (5)$$

We can set a threshold for the detectability of impedances imposing $\sigma_{\Delta\phi/\Delta N} < A_k$. In terms of effective impedance, inverting Eqs. (3) and (5), we can associate the accuracy threshold $\sigma_{\Delta\phi/\Delta N}$ to an impedance threshold Z_{th} and the amplitude A_k to Z_k.

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HEADTAIL SIMULATIONS

We verified the previous analysis with the help of the Headtail (HT) code [7, 8]. The code has been extended to be able to output multi-turn data within a MAD-X [9] lattice tracking.
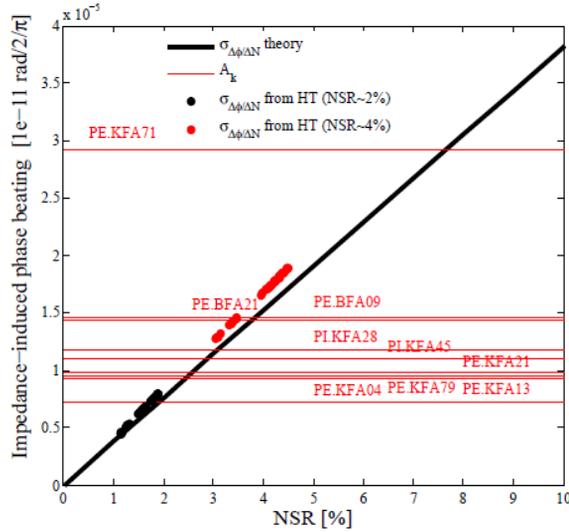

Figure 1: Accuracy map: dots represent the accuracy $\sigma_{\Delta\phi/\Delta N}$ from HT, black line is the theoretical prediction, red lines the impedance induced phase amplitude A_k from kicker families BFAs and KFAs. Numbers after kicker name refers to their lattice section position.

A benchmark has been done including the PS kicker impedance Tsutsui's models [10]. Tracking data were collected in case of an average noise of NSR~2% and NSR~4% as shown in Fig.1.
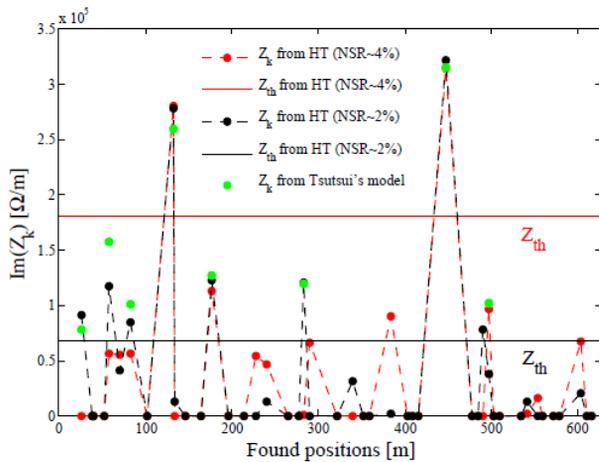

Figure 2: Impedance reconstruction Z_k from HT simulations with NSR~2% and NSR~4%, with impedance detection thresholds Z_{th} and Tsutsui's impedance model.

Reconstructions are shown in Fig. 2: for NSR~2% the impedances Z_k are close to the theoretical values from Tsutsui's model being all above Z_{th}; for NSR~4%, the threshold Z_{th} is higher and the reconstruction is not as efficient for impedances below Z_{th}.

PS MEASUREMENTS

A first benchmark of the method was done in the PS. The current of two quadrupoles, the QLS29 and QSE87, was varied from 2 A to 15 A in order to provoke a tune shift of ~0.02 to mimic the effect of an impedance source. The accuracy in this case is $\sigma_{\Delta\phi/\Delta N} \sim 2 \cdot 10^{-4}$, lower than the expected beat amplitude $A_k \sim 7.5 \cdot 10^{-4}$. Indeed, the phase advance slope could be reconstructed and the quadrupole location correctly detected, as shown in Fig.3.
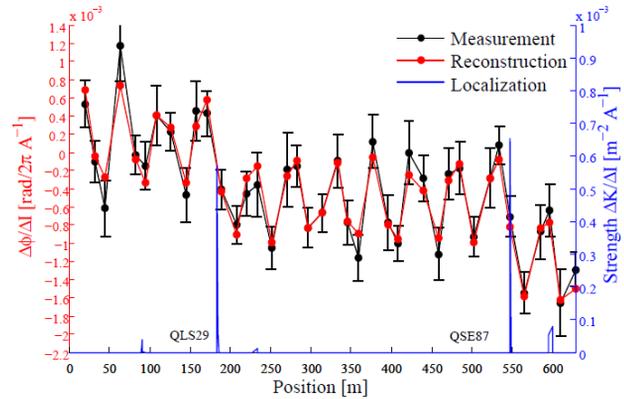

Figure 3: Comparison between measured (black) and reconstructed (red) integrated phase advance slope, with intensity obtained from varying the current of 2 PS quadrupoles. The impedance locations are shown in blue and the 2 quadrupoles QLS29 and QSE87 were clearly identified.

The beam based measurements should show a similar behaviour with an additional decreasing slope due to the distributed resistive wall defocusing effect. A series of measurements was done at 2 GeV with 90 ns long bunch, varying the intensity from $1e12$ to $2e12$ ppb. We choose, as reconstruction elements, only those reasonably believed to be impedance sources: kickers, cavities, septa, dampers, etc. The total number of selected elements is 49 over 40 BPM monitors. Figure 4 shows the reconstructed impedance beating amplitude with the accuracy threshold (top), the main detected impedance locations with theoretical expectations (centre), the slope least square reconstruction (bottom). The total impedance calculated with Eq. (3) summing the contribution from each reconstruction element is 9.2 MΩ/m and agrees with the 9.66 MΩ/m deduced from the classical tune shift with intensity [4]. To estimate the position accuracy Δs in the detection we adopted the following method: switching off a corrector the reconstructed slope is mismatched by the measured slope. If the mismatch exceeds in some location the 2σ uncertainty in the measurement, the corrector appears to be narrow localized impedance. Otherwise, we keep switching-off adjacent correctors until the same effect is reached. The different colours in the impedance locations give therefore the position uncertainty in the measurement (narrow impedance locations in red, large ones in blue). It is worth mentioning that the resistive wall contribution, estimated to be ~3 MΩ/m, was subtracted

from the measured slope as it is, as first approximation, a homogeneously distributed contribution along the ring. At this stage, kickers in section 21 and 71, at around 150 m and 450 m, have been detected as probable source of high impedance, being the only narrow source of impedance present in all the measurement done.
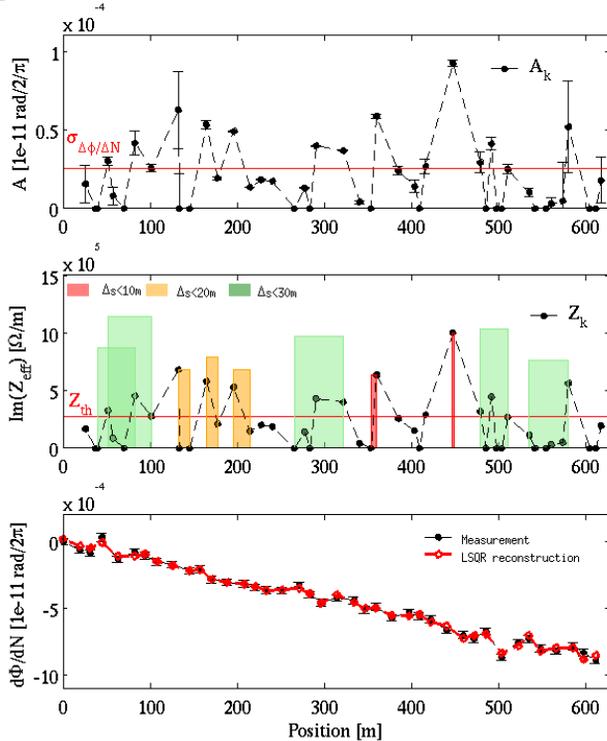

Figure 4: Top: signal reconstructed amplitude from the reconstruction location in the lattice, with accuracy limit given by the noise level (red line); Centre: Reconstructed impedances with spatial confidence bounds. Bottom: Integrated phase advance slope and least square reconstruction (LSQR).
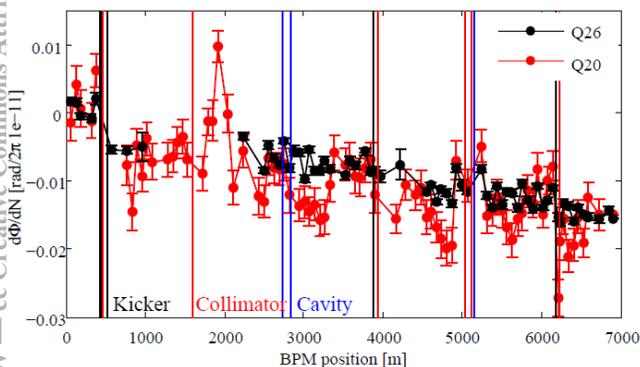
SPS MEASUREMENTS

Figure 5: Integrated phase advance slope in SPS for "Q26" and the "Q20" optics with kickers, collimators and cavities.

Measurements in the CERN SPS have been collected for both the so-called Q20 and Q26 operational optics [11]. Figure 5 shows the phase advance slope for both optics, and the vertical lines show kickers, collimators

and cavities placed at the straight sections. Despite of a good NSR in measurements, the difficulties in BPM setup and the not yet understood scarce reproducibility make the localization difficult to finalize.

LHC MEASUREMENTS

Measurements in LHC have been done at injection energy 450 GeV. A single high intensity bunch was kicked transversely using an AC dipole kick in order to measure the phase advance: 2200 turns were recorded in Beam 1. The intensity has been varied in 16 steps using the AC dipole kick itself, from $5 \cdot 10^{10}$ to $3 \cdot 10^{11}$ ppb . The expected total tune shift is $\sim 3.7 \cdot 10^{-3}$, and for the injection collimators contribution $\sim 5 \cdot 10^{-4}$ [12, 13]. The BPM signal showed $NSR \sim 10\%$, that gives an expected accuracy of $5.3 \cdot 10^{-4}$. Unfortunately the scraping had detrimental effect on the beam distribution and spectrum shape making difficult extracting useful phase information. The AC dipole accuracy seemed anyway to be promising and new trials are planned for the future.

CONCLUSIONS

A quantitative assessment of the accuracy required to apply the transverse impedance localization method has been discussed.

Measurements were performed in the PS, SPS, LHC and confirmed that the accuracy is a crucial parameter: in the PS, the accuracy was sufficient and two probable high impedance locations could be identified in section 21 and 71; in the SPS the phase advance slope could be measured, but signal quality and reproducibility complicated the analysis; in the LHC the adopted procedure made unfortunately the beam unstable and a series of measurements will be prepared for the restart.

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