IMPEDANCE LOCALIZATION AND IDENTIFICATION

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Abstract

The beam coupling impedance represents one of the sources of potential beam instabilities in particle accelerators. The localization of large coupling impedance sources is therefore very important in order to focus the efforts for mitigation measures when these are needed. In this work we will focus on the common methods adopted to quantify the transverse impedance of a particle accelerator both from the global and the local point of views. This activity can be performed in both bunched and coasting beams following different strategies.

INTRODUCTION

The beam coupling impedance represents one of the sources of potential beam instabilities in particle accelerators [1, 2]. The localization of large coupling impedance sources is therefore very important in order to focus the efforts for mitigation measures when these are needed. In this work we will describe common measurements performed in particle accelerators to quantify the transverse impedance from global and local point of views. This type of measurements can be done in both bunched and coasting beams following different strategies and methods.

For bunched beams, known techniques as the tune shift versus intensity and phase advance shift versus intensity will be reviewed. The method application to the CERN (Centre Européen pour la Recherche Nucléaire) PS (Proton Synchrotron) and the FNAL (Fermi National Accelerator Laboratory) Booster rings will be presented and advanced techniques based on the AC (Alternating Current) dipole excitation will be reviewed.

For coasting beams, it is not possible to record turn by turn data with standard BPMs (Beam Position Monitors) due to the absence of beam structure. Sources of large transverse impedance can be identified by inspection of the unstable beam spectrum. In this respect, the example of the successful identification and mitigation of the most harmful vertical impedance source of the CERN LEIR (Low Energy Ion Ring) is presented.

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IMPEDANCE LOCALIZATION WITH BUNCHED BEAMS

Tune shift with intensity

The systematic connection between transverse beam coupling impedance and main accelerator observables such as tune, phase advance between BPMs and orbit position was done starting from [3, 4].

The measurement of tune shift with intensity is a well known technique to quantify the total imaginary part of the transverse impedance of a machine.

In the following, a beam of average current $\bar{I} = qN_p/T_0$ is considered, where q is the elementary charge, N_p the number of particles in the beam, T_0 the revolution period of the machine. Given a localized impedance source at the location s_k along the accelerator circumference (e.g. kickers, cavities, etc.), the induced tune shift ΔQ_{y_k} (i.e. in the vertical plane for example) will be given by

$$\Delta Q_{y_k} = -\frac{q\bar{I}T_0}{8\pi^{3/2}\beta E\sigma_\tau}\beta_{y_k}(s_k)\mathrm{Im}\left(Z_k^{eff}\right)L_k, \qquad (1)$$

and, for distributed impedance along the accelerator circumference (e.g. resistive wall, indirect space charge, etc.), by

$$\Delta Q_y = -\frac{q\bar{I}T_0}{8\pi^{3/2}\beta E\sigma_\tau}\oint_C \beta_y(s)\mathrm{Im}\left(Z^{eff}\right)\mathrm{d}s, \qquad (2)$$

where we assumed a beam with longitudinal Gaussian distribution of rms-length σ_τ, E the total energy of the beam, $\beta = v/c$ where v is the beam velocity and c the speed of light, $\beta_y(s)$ the beta function along the ring, L_k the device length, and Z^{eff} the effective beam coupling impedance per unit meter. This last parameter is defined as

$$Z^{eff} = \frac{\int_{-\infty}^{+\infty} Z(\omega)\|S(\omega)\|^2\,\mathrm{d}\omega}{\int_{-\infty}^{+\infty}\|S(\omega)\|^2\,\mathrm{d}\omega}, \qquad (3)$$

where $\|S(\omega)\|^2$ is the beam longitudinal power spectrum over the angular frequency ω. For a Gaussian beam distribution this is given by

$$\|S(\omega)\|^2 = e^{-\omega^2\sigma_\tau^2}. \qquad (4)$$

From Eqs. (1) and (2) we can see how the tune linearly shifts with intensity. The tune shift constitutes the first global parameter used to estimate the total transverse reactive impedance of an accelerator and it often represents the first benchmark measurement for an accelerator transverse impedance model [5].

We present, as an example, the case of the CERN PS, in which the tune shift versus intensity has been measured at different energies in order to disentangle the energy dependent component of the impedance, i.e. the one related to the indirect space charge.

Figure 1 shows the dependence of the imaginary part of the vertical effective impedance versus kinetic energy in the PS. The agreement between the model and the measurements performed in 2015 at zero chromaticity is very good, suggesting a remaining impedance of about 2.5 $M\Omega/m$, not dependent on the energy. The measurement also validates the indirect space charge computed in the impedance model [6].

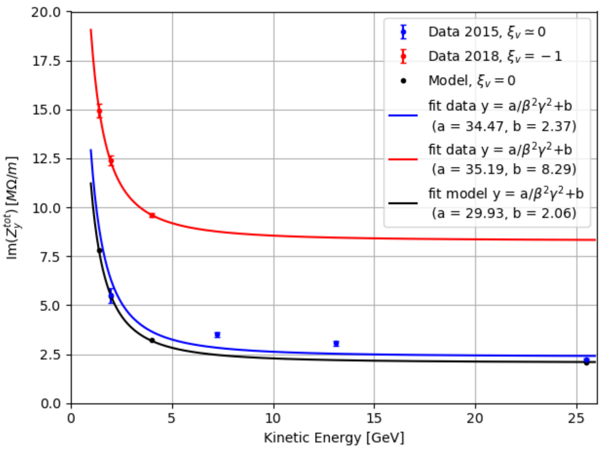

Figure 1: Effective imaginary part of the impedance dependence versus kinetic energy in the PS. Blue and red dots represent measurement data taken in 2015 and 2018 respectively at chromaticity $\xi_v = 0$ and $\xi_v = -1$, black dots are computation based on the impedance model (for zero chromaticity) [6], lines are fit following the energy scaling of the transverse indirect space charge impedance.

The comparison with respect to the 2018 measurements performed at $\xi_v = -1$, is instead in agreement only with the indirect space charge trend versus energy, but presents an offset with respect to the model prediction at zero chromaticity. This behaviour, unexpected from the impedance model, and further confirmed with systematic tune shift measurements as a function of chromaticity [6], has been investigated in 2018 by means of impedance localization measurements.

Phase advance shift with intensity

In order to identify the location of the highest transverse impedance sources in a machine, an extension of the previously described method was proposed for the first time in 1995: measuring the impedance-induced betatron phase advance shift with intensity, the radio-frequency (RF) sections were found to be important impedance contributors in the CERN LEP collider [7].

A linear tune shift with intensity, can be due to the presence in the lattice of lumped or distributed intensity dependent defocusing errors [8]. For each source of impedance, the phase advance shift with intensity $\Delta\mu(s, s_k)$ in the plane of reference can be computed as

$$\Delta\mu(s, s_k) = \Delta Q_k + \frac{\Delta Q_k}{\mathcal{S}(2\pi Q_0)} \mathcal{C}(2\psi_k - \psi)\mathcal{S}(\psi - 2\pi Q_0) \quad (5)$$

for $s \geq s_k$, and

$$\Delta\mu(s, s_k) = \frac{\Delta Q_k}{\mathcal{S}(2\pi Q_0)} \mathcal{S}(\psi)\mathcal{C}(\psi - 2\psi_k + 2\pi Q_0) \quad (6)$$

for $s < s_k$, where ψ and ψ_k are the phase advance respectively at the location s and the impedance location s_k, Q_0 is the bare machine tune (in the plane of reference), ΔQ_k the tune shift computed with Eq. (1) for the k^{th} impedance source. We introduced the short notation $\mathcal{C}(\psi) = \cos(\psi)$ and $\mathcal{S}(\psi) = \sin(\psi)$.

A quadrupole error, therefore, produces a phase beating wave whose amplitude is given by the corresponding tune shift, and presents a step equal to the tune shift at the impedance location. The step will be positive for focusing errors, or negative for defocusing ones. In most of the cases an impedance behaves as a defocusing quadrupole error giving rise to a descending step into the beating wave at the impedance location.

A similar method, based on the impedance-induced orbit shift with intensity, was proposed in 1999 in the Novosibirsk VEPP-4M electron-positron storage ring [9] and in 2001 in the Argonne APS synchrotron accelerator [10]. Later in 2002, the same method was tried in the Grenoble ESRF [11].

The impedance localization method using phase advance shift with intensity, was also applied to the CERN SPS machine [12,13] and in BNL RHIC [14]. In the following years, the method was applied to the PS, SPS and LHC [15] where an innovative methodology using AC dipole excitation was proposed [16]. Recently, the method was also successfully tested at the ALBA accelerator [17].

Application to the CERN PS ring

The phase advance shift versus intensity method was applied during 2018 in the CERN PS in order to gather the relevant reference information before the Long Shutdown 2 (LS2). Measurements were done at the PS extraction energy of 25.4 GeV (kinetic) for minimizing the effect of indirect space charge as shown in Fig. 1. The measurement was performed with vertical chromaticity ξ_y close to zero. Figure 2 shows the localized impedance sources distributed along the 100 sections of the ring together with markers at specific elements in the lattice, such as kickers, septa, wire scanner (shown as *ws*), transverse feedback (shown as *tfb*). The raw data (bottom plot in black) have been fitted by a least squares algorithm accounting for the measurement uncertainty [18]. The localized impedance locations are mostly compatible with the kickers installed in the machine (see for example sections 4, 9, 21, 45 and 71). In other locations, for example between sections 55 and 75, or in section 90, the correlation to the installed equipment is not straightforward.

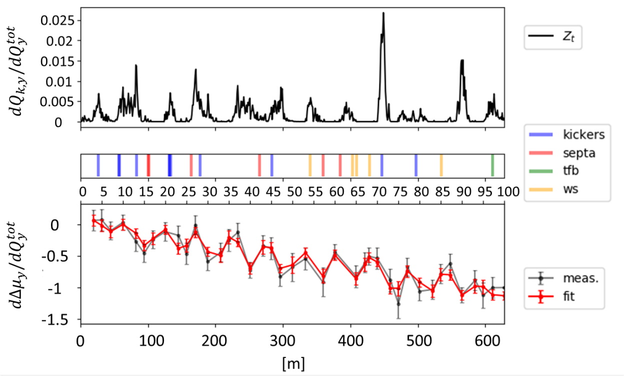

Figure 2: Impedance localization reconstruction in the vertical plane of the PS performed at 25.4 GeV kinetic energy. At the top, impedance strength in units of fraction of the total tune shift, at the middle, the 100 sections of the ring together with markers at specific elements in the lattice such as kickers, septa, wire scanner (*ws*), transverse feedback (*tfb*), at the bottom, the raw phase advance shift with intensity normalized to the total tune shift together with the curve reconstructed by the detected impedances.

The same measurement was performed at the energy of 2 GeV, i.e. below transition energy, with ξ_y of -0.15 and -2.5 in order to probe the source of the impedance chromatic dependence. This measurement was not possible at extraction energy due to the fast signal decoherence.

As from Fig.1 an increment of ~3 MΩ/m is expected moving from 25.4 GeV to 2 GeV kinetic energy due to indirect space charge, comparable with the total impedance measured at extraction. Figure 3, shows the reconstructed impedance and the corresponding raw data with least square fit. While, from one hand, the larger amount of impedance induces a stronger signal, on the other hand this is coming from the indirect space charge, strongly dependent on the accurate aperture model of the machine which is not yet modelled, impedance-wise, at the location by location level. This is a possible cause for the poor correspondence of the impedance sources at low energy with respect to the one at extraction energy shown in Fig. 2.

This measurement can be of interest when compared to the same one performed with larger vertical chromaticity $\xi_y = -2.5$. In this case, as shown in Figure 4, a large beating is visible on the phase advance shift with intensity and a clear lumped source appears in section 97. One of the compatible elements in proximity could be the transverse feedback kicker. Simulations and measurements did not attribute a large impedance source to this element when striplines are correctly matched to load via the RF-transformer [19] and further investigations are required.

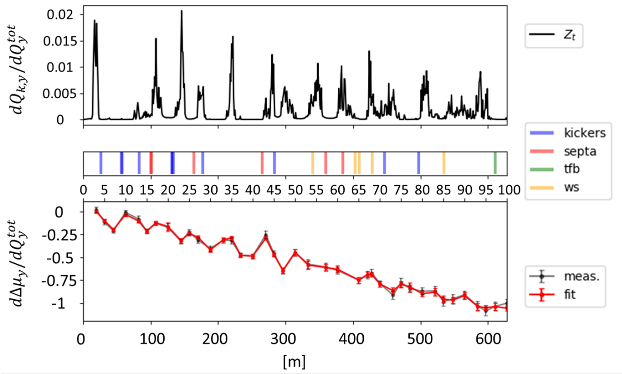

Figure 3: Impedance localization reconstruction in the vertical plane of the PS performed at 2 GeV kinetic energy with corrected chromaticity $\xi_y = -0.15$.

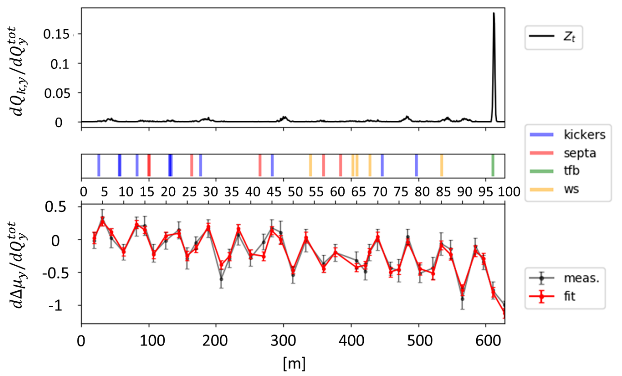

Figure 4: Impedance localization reconstruction in the vertical plane of the PS performed at 2 GeV kinetic energy with larger chromaticity $\xi_y = -2.5$.

Application to FNAL Booster ring

Impedance localization measurements were performed in 2019 in the FNAL Booster ring in order to detect possible unexpected impedance sources in view of the machine upgrade [20, 21]. Measurements were performed both in so called DC (Direct Current) mode, i.e. on the injection plateau, and in *ramped* mode, i.e. throughout the ramp to flat top. The kicker was powered every 500 turns exciting coherent oscillations and the total injected intensity was varied from $\sim 1 \cdot 10^{12}$ to $5 \cdot 10^{12}$ protons. Turn by turn data were collected and their frequency spectra were calculated by Sussix [22] and Harpy [23] to extract the phase advance versus intensity. Figure 5 shows the localization sources obtained in DC mode: the accumulated phase advance steadily drifts along the machine not showing particular step-like or beating behaviour, which is translated also on the normalized impedance strength along the machine.

The result is not surprising as it is already known that the almost totality of the Booster transverse impedance is related to the main bends resistive wall impedance [24].

Measurements in DC mode for the horizontal plane were not accurate enough due to the intrinsically weaker

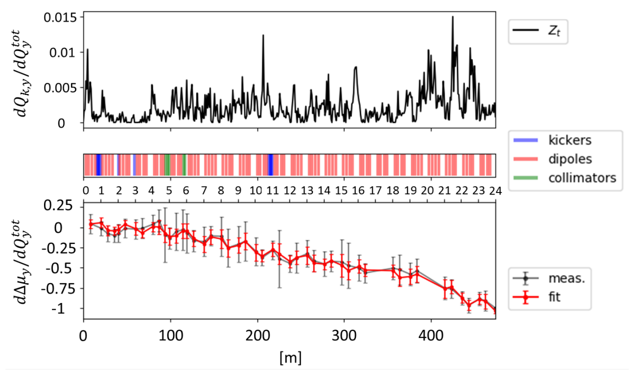

Figure 5: Localized vertical impedance sources at the kinetic energy of 400 MeV along the 25 sections of the FNAL Booster ring together with markers at specific elements in the lattice such as kickers, dipoles and collimators.

impedance [24]. Similarly, measurements in *ramped* mode suffered from reduced kicker strength which affected the quality of the turn by turn signals.

Advanced techniques: AC dipole

An AC dipole is a radio frequency dipole that produces an oscillating field that excites driven oscillations in the beam. While a normal kick would naturally excite the coherent tune oscillation and sidebands, with an AC dipole it is possible to drive the beam oscillation at different frequencies and maintain coherent oscillations for many turns improving the quality and reproducibility of the optics measurement. Tracking simulations recently showed that an AC dipole can be efficiently used to localize impedance sources thanks to the improved quality of turn by turn coherent betatron oscillation data [16]. The first exploratory measurement in the LHC has been so far the only attempt to use the method and new measurement campaigns are planned in the LHC and its injectors.

IMPEDANCE LOCALIZATION WITH COASTING BEAMS

Conventional impedance localization methods based on BPMs acquisitions cannot be easily used to get accurate turn by turn data for coasting beams, i.e. in the absence of longitudinal beam structure. On the other hand, the Schottky signals are very commonly used to inspect the longitudinal and transverse frequency content of the beam [25]. For this reason, the impedance localization methods cannot be intended in the classical way described in the previous section, but require an alternative approach. In the following we will describe the identification and suppression of a fast vertical instability in LEIR based on the inspection of the Schottky spectrum.

Identification and mitigation of LEIR vertical instability

The LEIR machine is the first synchrotron accelerator of the CERN ion chain [26]. It accumulates up to 7 pulses of Pb^{54+}_{208} from the Linac 3 at the kinetic energy of 4.2 MeV per nucleon and accelerates the beam up to 72.2 MeV to the PS[1]. The injection and accumulation phases occur in coasting beam and, until end of 2018, LEIR could not be operated without transverse damper due to a fast vertical instability occurring after 3-4 injections [27].

Figure 6 shows, at the top, a standard cycle of LEIR and, at the bottom, the horizontal (yellow) and vertical (green) Δ signals recorded by the damper wide band pick-ups. The reader can notice 7 spikes corresponding to the 7 injections and a signal increase during capture and acceleration, i.e. from 1840 ms when the coasting beam is captured by the RF cavities into 2 bunches.

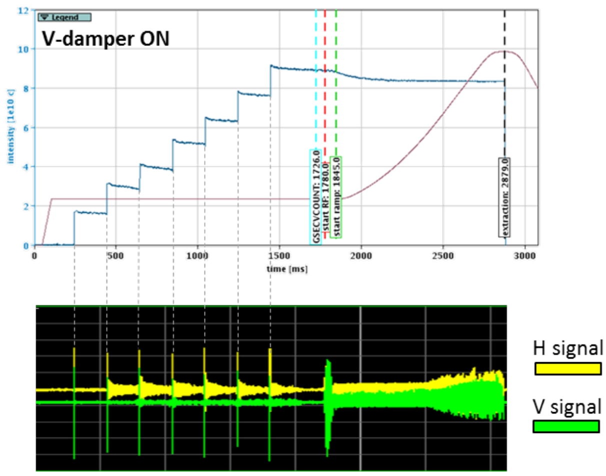

Figure 6: At the top: intensity accumulated in LEIR (blue) and magnetic program (red); in dashed lines, the end of the cooling process, start of capture and acceleration are respectively shown in cyan, red and green. At the bottom: horizontal (yellow) and vertical (green) Δ signals recorded by the damper wide band pick-ups in the ring. Spikes in the signals are correlated to the injections and capture processes. The damper is active all along the cycle.

Figure 7 shows, in a similar way, the effect of removing the vertical damper along the cycle: the vertical signal shows an exponential growth starting from the 4th injection preventing further accumulation.

At the onset of the instability, the vertical Schottky system recorded a repetitive mode pattern, occurring at multiples of 1.9 MHz as shown in Fig. 8. At the top, the Schottky frequency spectrum is showed from 0 to 10 MHz for 350 ms from the start of the instability. At the bottom, selected spectrum projections, corresponding to the dashed lines of the top plot, are taken every 50 ms and show the frequency evolution of the instability in incremental way. The rapid

[1] Other species have been accelerated as well, such as Oxygen, Argon and Xenon.

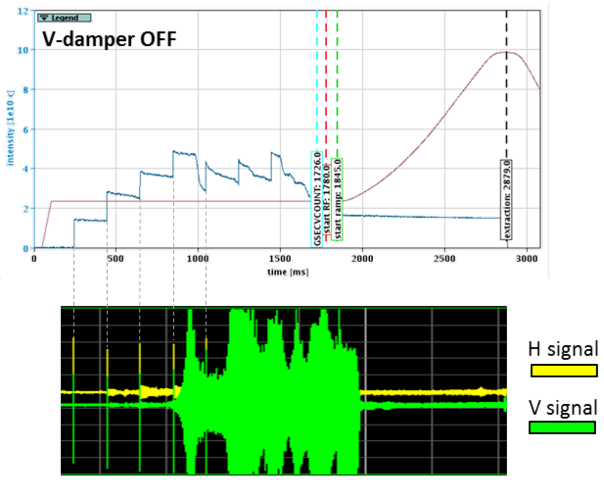

Figure 7: Intensity accumulated in LEIR when the vertical damper is switched-off along the cycle. See Fig. 6 for the details on the plotted lines.

change in the spectrum after 200 ms is associated to beam losses.

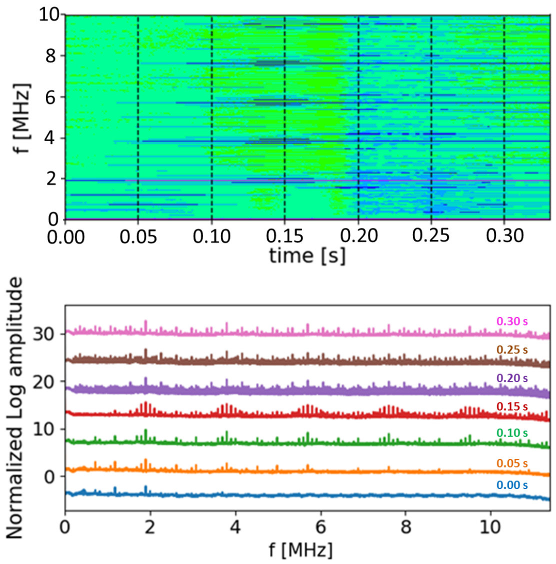

Figure 8: At the top: the Schottky frequency spectrum is showed from 0 to 10 MHz as a function of time, for 350 ms from the start of the instability. At the bottom, selected Schottky spectrum projections corresponding to the dashed lines of the top plot (an offset has been applied for clarity). A clear mode pattern resonating at multiples of 1.9 MHz is visible.

Due to the very low frequency and the resonating behavior the source of the impedance was associated to possible mismatched terminations of devices that can sustain a quasi-TEM (Transverse Electro-Magnetic) mode. These devices are usually kickers or stripline pick-ups (their transverse cross-section is not simply connected). Since the instability was observed only in the vertical plane, stripline pick-ups were considered as possible source (in LEIR kickers are only acting in the horizontal plane).

A selected list of unused devices was selectively disconnected and terminated on a matched load. After the intervention on the UQFHV41 pick-up[2], the repetitive mode pattern was not observed any longer and the instability was effectively suppressed as shown in Fig. 9. After a re-connection test, the instability reappeared confirming the source of the instability.

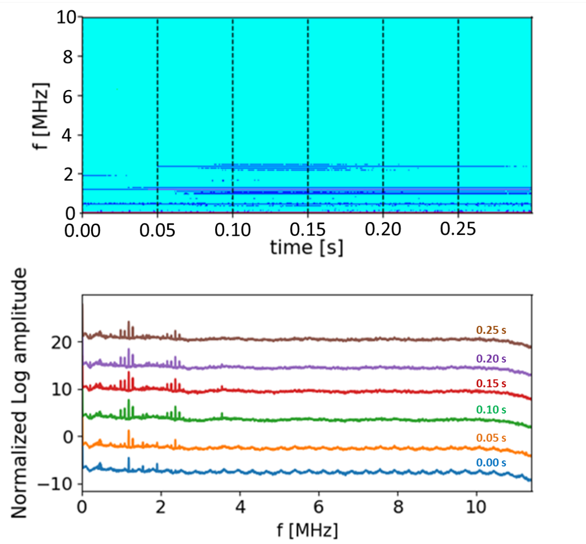

Figure 9: Schottky spectrum after termination of the UQFHV41 pick-up: resonances at multiple of 1.9 MHz have disappeared.

CONCLUSIONS

In this paper we summarized the measurements techniques used to localize impedance sources with bunched and coasting beams.

With bunched beams, we presented the impedance localization method based on the phase advance shift with intensity and the recent application to the CERN PS and FNAL Booster rings.

In the PS, a large source of impedance was detected at injection energy and at large negative chromaticity, which is absent for corrected chromaticity. The effect has also been measured by standard tune shift versus intensity measurements. A possible source has been identified but not confirmed by bench impedance measurements. Further investigations are planned after the machine restart.

In the FNAL Booster ring, the measurement was applied both in DC (injection) and *ramped* operational modes. The achieved data quality allowed accurate measurements only in the vertical plane in DC mode, where no relevant isolated impedance sources were identified.

With coasting beams, we have presented the successful impedance identification and suppression performed in

[2] This pick-up was used for beam transfer function measurements at the time of the Low Energy Antiproton Ring (LEAR).

LEIR. The inspection of the Schottky spectrum measured during the vertical instability onset, allowed to reduce the possible sources of the instability to the machine stripline pick-ups. The instability was suppressed matching the termination of the UQFHV41 pick-up cables.

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