Impedances and pickups

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DIPARTIMENTO DI SCIENZE
DI BASE E APPLICATE
PER L'INGEGNERIA

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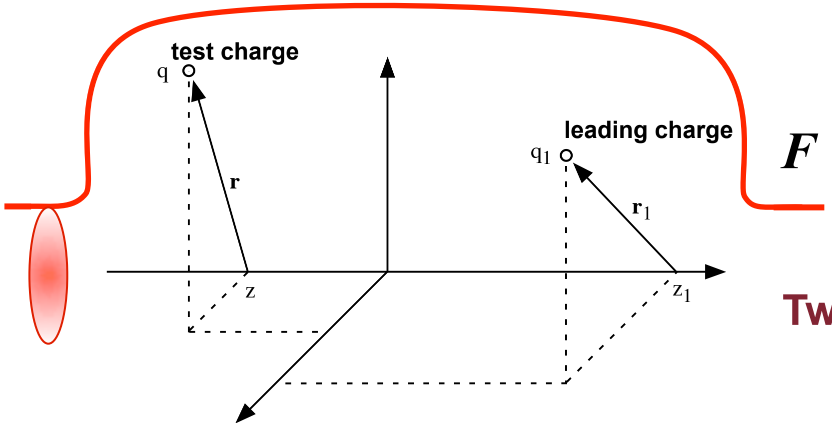
Summary

- Coupling impedance
- Bench impedance measurement methods
- Beam based impedance measurement methods
- Coupling impedance due to pickups

Coupling impedance



$$\boldsymbol{F} = q\left[E_z\hat{z} + \left(E_x - vB_y\right)\hat{x} + \left(E_y + vB_x\right)\hat{y}\right] \equiv \boldsymbol{F}_{//} + \boldsymbol{F}_{\perp}$$

Two approximations:

- rigid beam
- impulse approximation

Longitudinally:
(energy change)

$$U(\Delta z) = \int_0^L F_{//} ds \quad \Rightarrow \quad w_{//}\left(\Delta z\right) = -\frac{U\left(\Delta z\right)}{q^2}$$

Longitudinal wake field

Transversally:
(momentum kick)

$$\boldsymbol{M}\left(r_1, \Delta z\right) = \int_0^L \mathbf{F}_{\perp} ds \quad \Rightarrow \quad \boldsymbol{w}_{\perp}\left(\Delta z\right) = \frac{1}{r_1}\frac{\boldsymbol{M}\left(r_1, \Delta z\right)}{q^2}$$

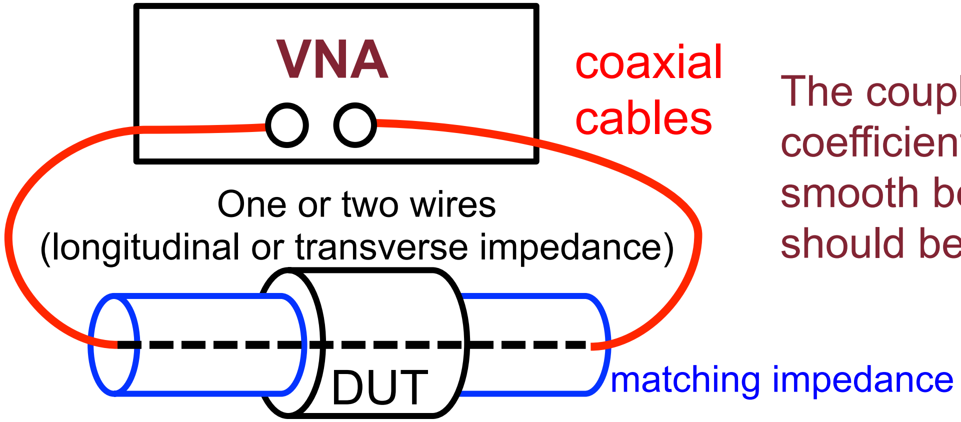
transverse dipole wake field

$$Z_{//}\left(\omega\right) = \frac{1}{v}\int_{-\infty}^{\infty} w_{//}\left(z\right) e^{j\frac{\omega z}{v}} dz$$

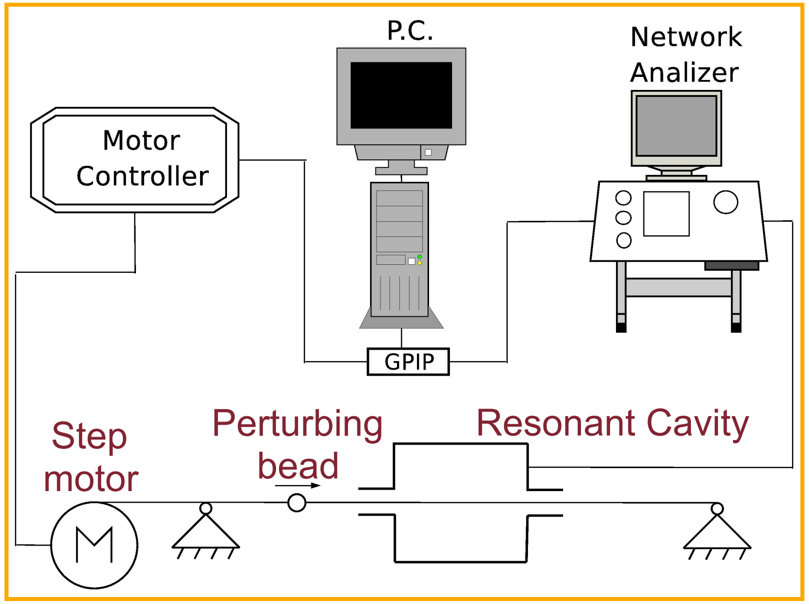
Coupling impedance

$$\boldsymbol{Z}_{\perp}\left(\omega\right) = -\frac{j}{v}\int_{-\infty}^{\infty} \boldsymbol{w}_{\perp}\left(z\right) e^{j\frac{\omega z}{v}} dz$$

Bench measurements: wire method, bead pull, …



The coupling impedance is related to the transmission coefficients. A reference measurement, e. g. with a smooth beam pipe with homogeneous cross-section, should be performed before inserting the DUT.



Used to measure resonant structures. The resonant field is "sampled" by introducing a (small) perturbing object and measuring the change in resonant frequency.

$$\frac{\Delta f(z)}{f_0} \simeq \frac{1}{2Q_L}\tan\left(\angle S_{12}(z)\right)$$

Q_L Loaded quality factor

$$\left(\frac{\Delta f}{f_0}\right)_{diel} \simeq -k_{Ed\perp}\varepsilon_0\frac{\left|\vec{E}_{\perp}\right|^2}{W}$$

$$\left(\frac{\Delta f}{f_0}\right)_{met} \simeq k_{Bm\perp,\parallel}\mu_0\frac{\left|\vec{B}_{\perp,\parallel}\right|^2}{W} - k_{Em\perp,\parallel}\varepsilon_0\frac{\left|\vec{E}_{\perp,\parallel}\right|^2}{W}$$

(see A. Mostacci talk)

Beam based measurements

- Coupling impedances can also be determined by means of beam based measurements. In general one measures the effects the impedance produces on beam dynamics, such as tune or phase shifts with intensities, but also unwanted collective instabilities, as coupled bunch instabilities, can give important information on machine coupling impedances.

- Of course with the use of the beam we can determine the impedance of the whole machine.

- In some particular cases it could be possible to get the impedance of some important elements (e.g. localized impedance method).

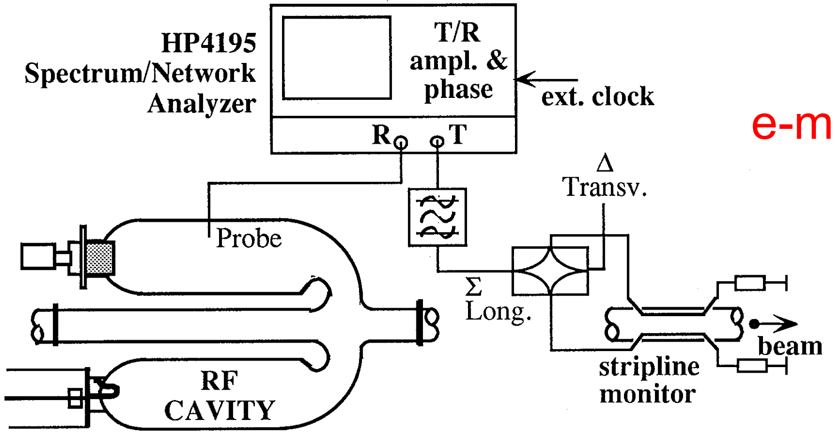
Beam based measurements

Real part of the longitudinal coupling impedance: synchronous phase shift vs beam current

ELSEVIER
Nuclear Instruments and Methods in Physics Research A 418 (1998) 241–248
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

DAΦNE accumulator ring coupling impedance measurements

R. Boni, A. Drago, A. Gallo, A. Ghigo, F. Marcellini, M. Migliorati, F. Sannibale,
M. Serio, A. Stella, G. Vignola, M. Zobov*

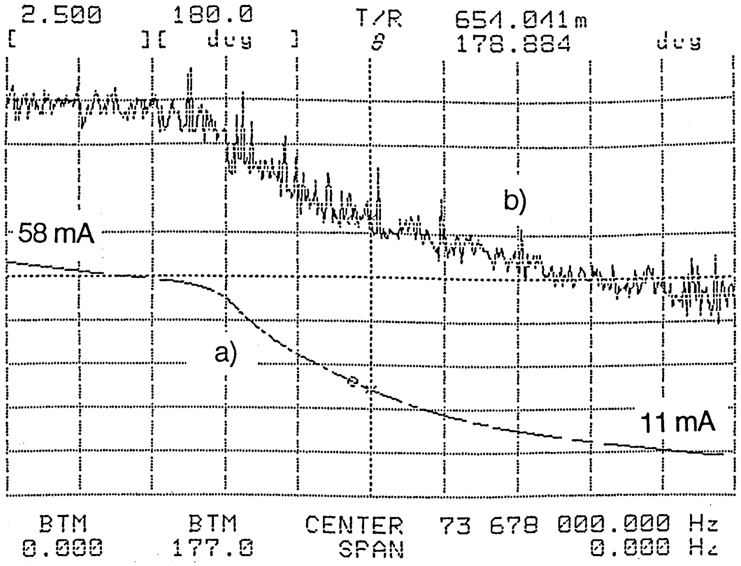


e-machine

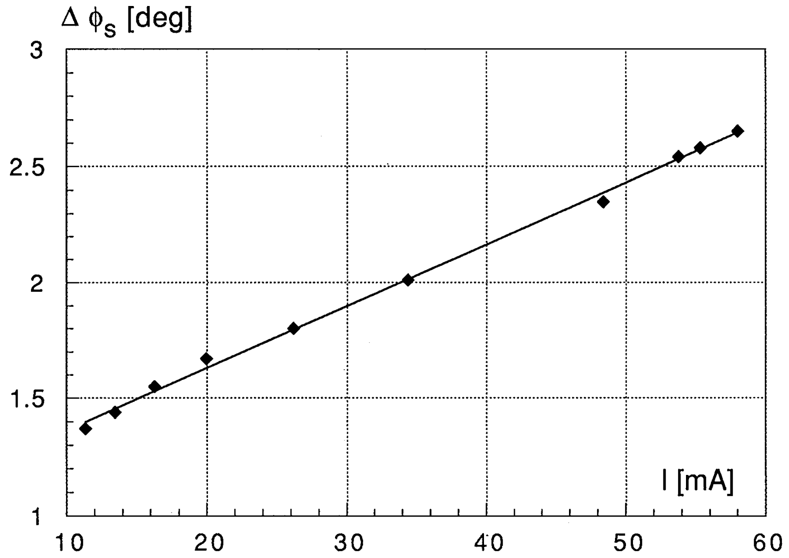
A sample of the cavity voltage is sent to the reference channel of a network analyzer, while the longitudinal beam signal, obtained from a stripline pair in the sum mode, bandpass filtered to get the Fourier term at the RF frequency, was connected to the T channel. Since the measurement was performed at a constant accelerating voltage, the amplitude of T/R versus time is proportional to the beam current decay, while the T/R phase gives a measurement of the synchronous phase shift.

Beam based measurements

Real part of the longitudinal coupling impedance: synchronous phase shift vs beam current



Measured average bunch current (a.u.) (a) and relative synchronous phase shift (0.3°/div) at $\hat{V}_{\mathrm{rf}} = 60\ \mathrm{kV}$ (b).



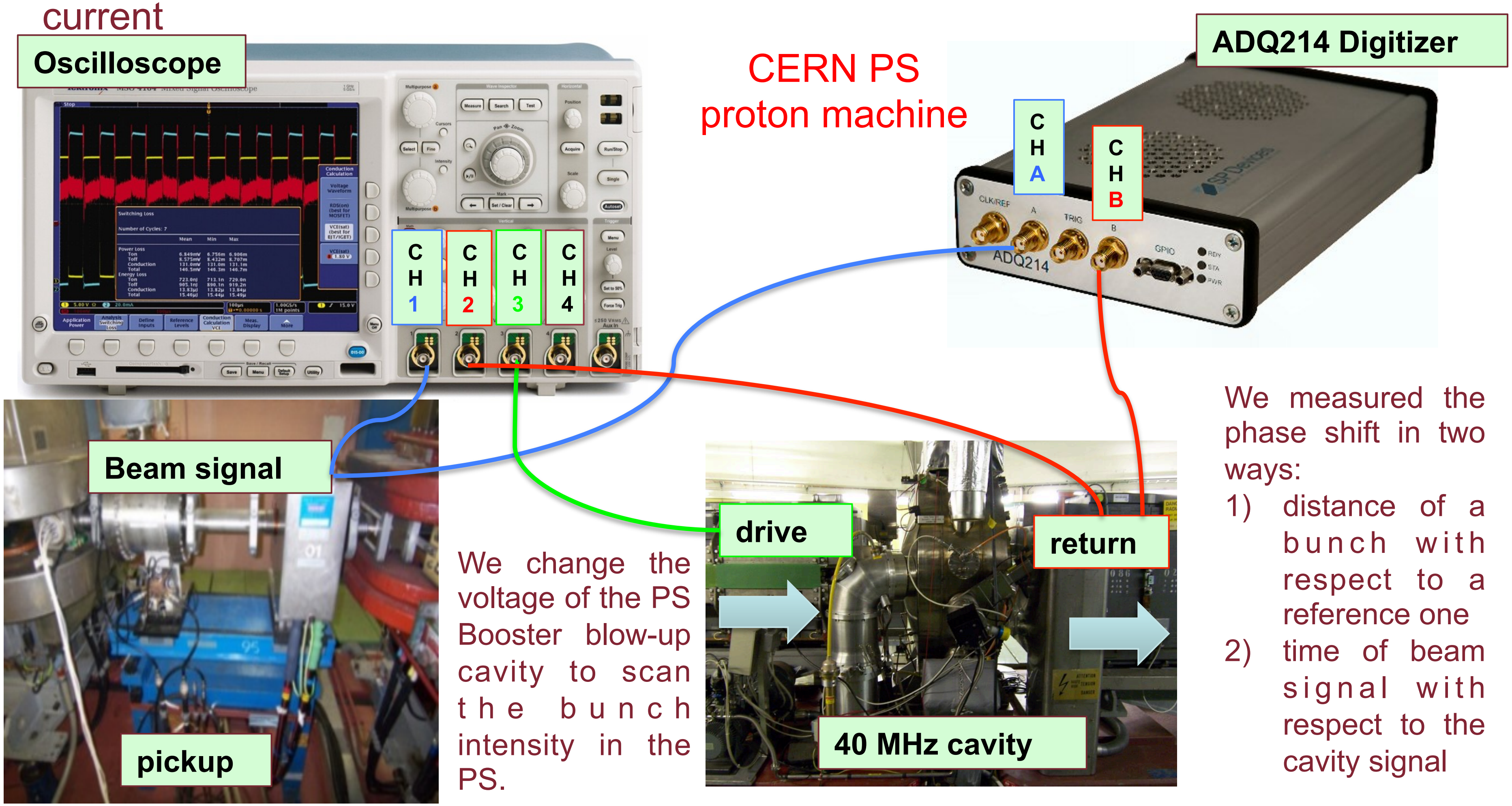
$$\Delta E = e\hat{V}_{RF}\cos\phi_{s0}\Delta\phi =$$

$$eI\sum_{p=-\infty}^{+\infty}\mathrm{Re}\left\{Z\left(p\omega_0\right)\right\}\exp\left\{-\left(p\omega_0\sigma_\tau\right)^2\right\}$$

Due to the imaginary part of the coupling impedance, bunch length can change and, as a consequence, the phase shift may not be linear any more.

Beam based measurements

Real part of the longitudinal coupling impedance: synchronous phase shift vs beam current



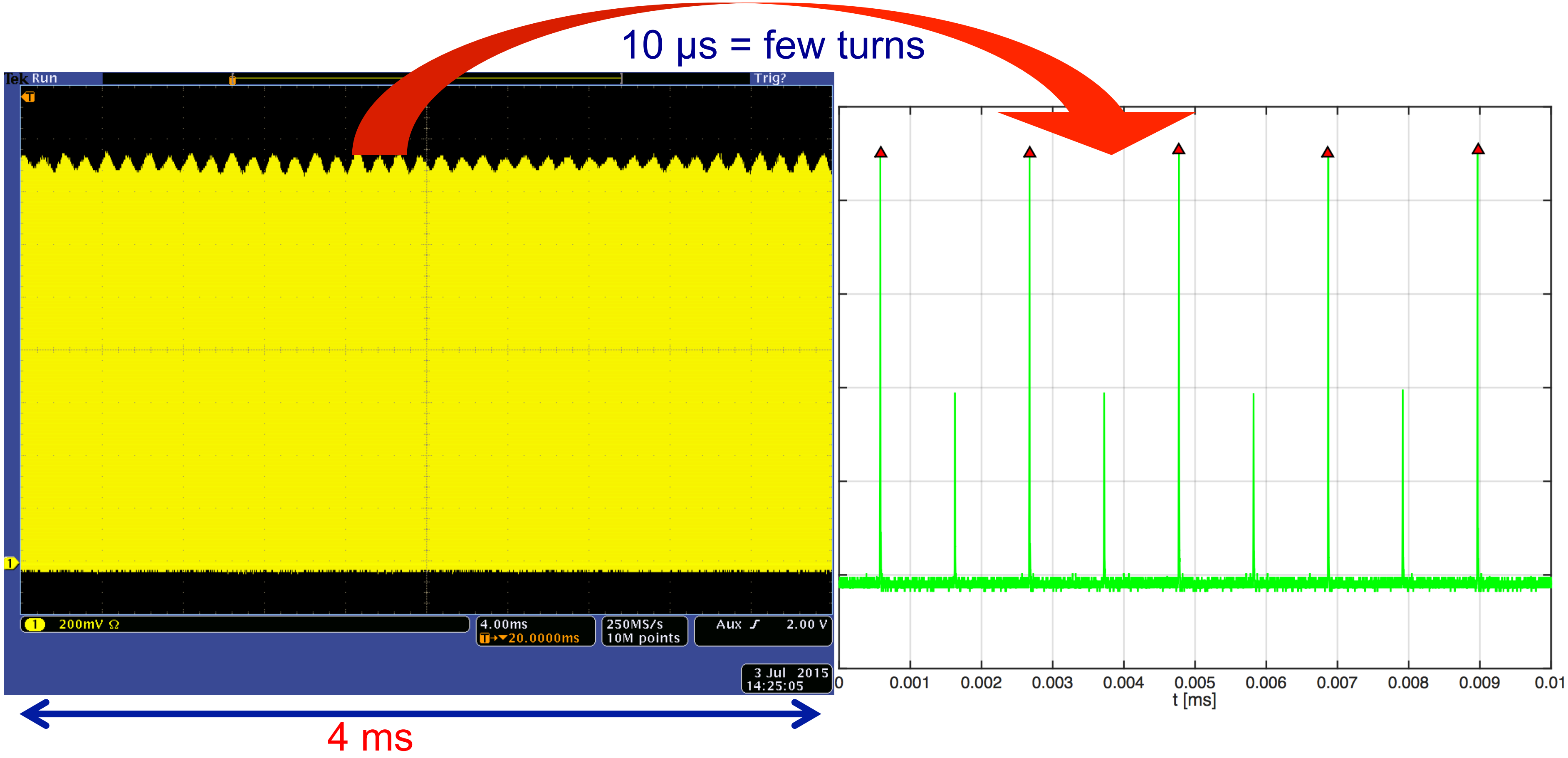
We change the voltage of the PS Booster blow-up cavity to scan the bunch intensity in the PS.

We measured the phase shift in two ways:

1) distance of a bunch with respect to a reference one
2) time of beam signal with respect to the cavity signal

Beam based measurements

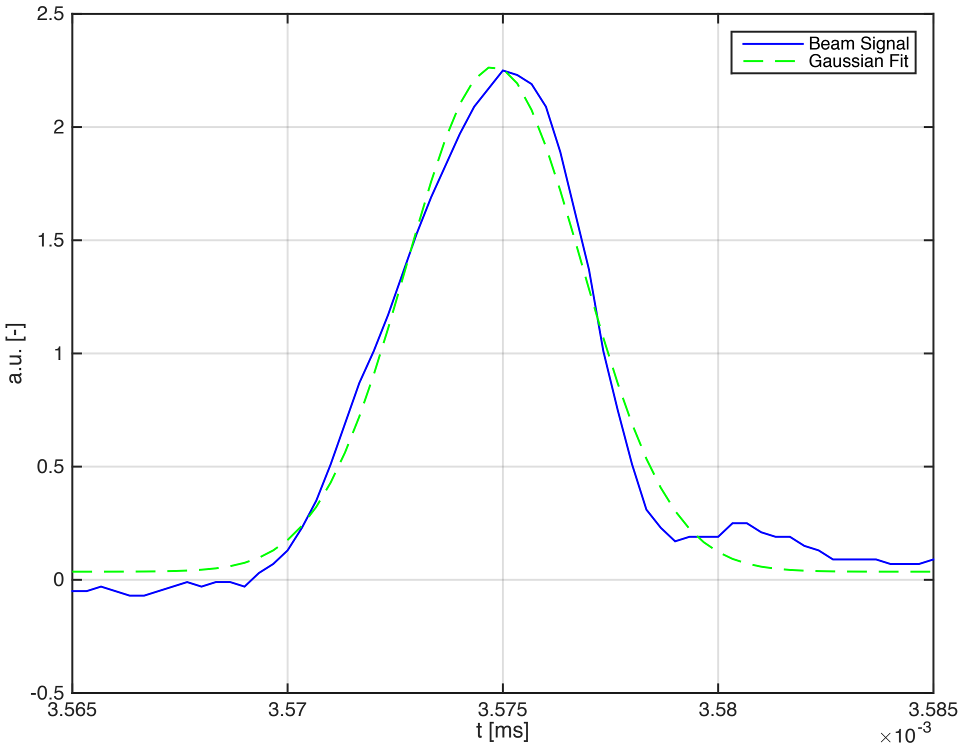
Real part of the longitudinal coupling impedance: synchronous phase shift vs beam current

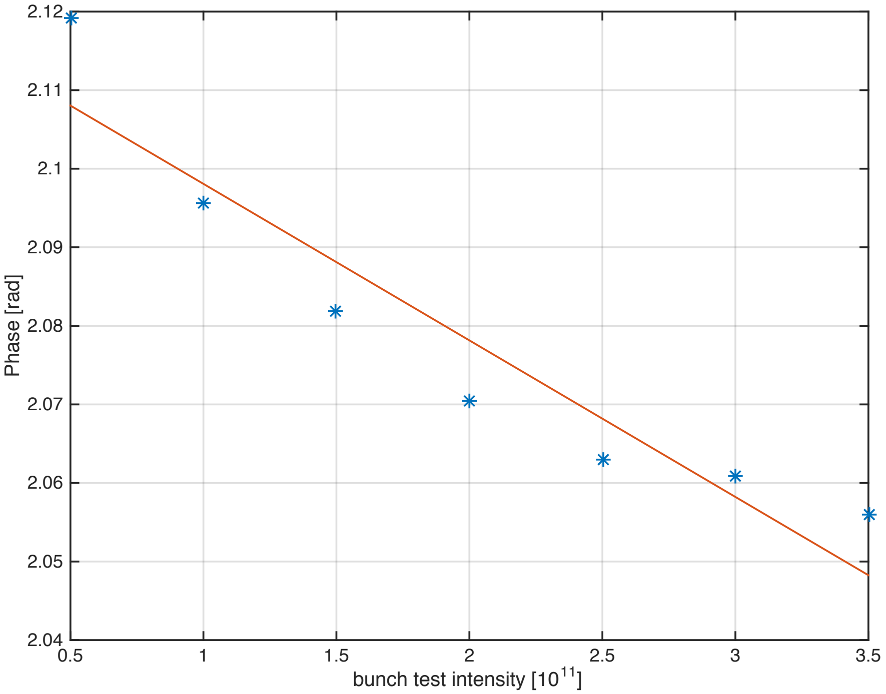


Beam based measurements

Real part of the longitudinal coupling impedance: synchronous phase shift vs beam current

further zoom

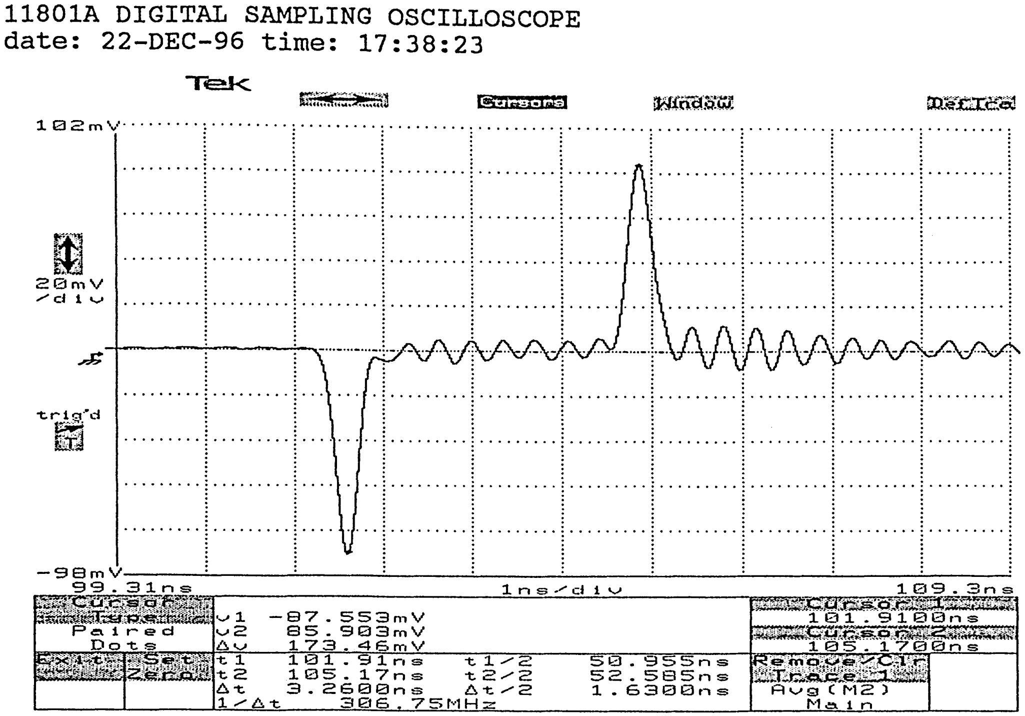




The phase shift equation is the same, the results of the two methods (distance between bunches and time with respect to cavity signal) are the same.

Beam based measurements

Imaginary part of the longitudinal coupling impedance: bunch lengh vs beam current



11801A DIGITAL SAMPLING OSCILLOSCOPE
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```
v1    -87.553mV
v2     85.903mV
Δv    173.46mV
t1    101.91ns    t1/2    50.955ns
t2    105.17ns    t2/2    52.585ns
Δt    3.2600ns    Δt/2    1.6300ns
1/Δt     306.75MHz
```

In order to measure the bunch shape, a beam signal can be picked up from a bi-directional stripline normally used as a beam kicker in the tune measurement system. The strip length should be such that the back-reflected pulse, typical of such kind of pick-up, is well separated from the first induced pulse, which is the one zoomed-in and analyzed.

The stripline signal can be split by means of a large bandwidth resistive divider and one part was used as trigger. In this way it is possible to get a stable waveform even in the presence of longitudinal oscillations. The length of the measuring cables should also be kept as short as possible, to give negligible signal distortion, that can be tested and calibrated by comparing the Gaussian shape measured at a very low current with predicted natural bunch length.

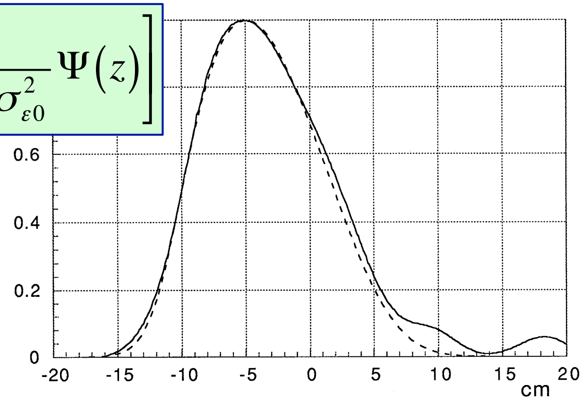
Beam based measurements

Imaginary part of the longitudinal coupling impedance: bunch lengh vs beam current

- Bunch lengthening below the microwave instability threshold is mainly caused by the imaginary part of the machine impedance, above it by both real and imaginary part.

$$\lambda_0(z) = \bar{\lambda}\exp\left[-\frac{1}{E_0\alpha_c\sigma_{\varepsilon 0}^2}\Psi(z)\right]$$

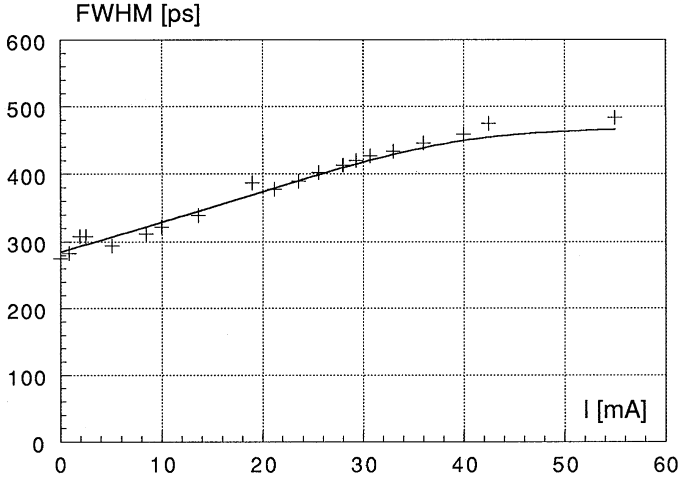
$$\Psi(z) = \frac{1}{L_0}\int_0^z \left[eV_{RF}(z') - U_0\right]dz' - \frac{e^2N_p}{L_0}\int_0^z dz'\int_{-\infty}^{\infty}\lambda_0(z'')w_{\parallel}(z''-z')dz''$$



Bunch shape at $I = 28$ mA: solid line – measurement result; dotted line – fit with $Z(\omega) = (600 + j6.2\text{e-}08\omega)\Omega$.

- The information of bunch length vs current allows to check a machine impedance model, but one cannot infer directly the impedance from this measurement.

- In order to get information on the imaginary part of the longitudinal impedance we can exploit another effect of the wakefield on the bunch: the incoherent synchrotron frequency shift.



Beam based measurements

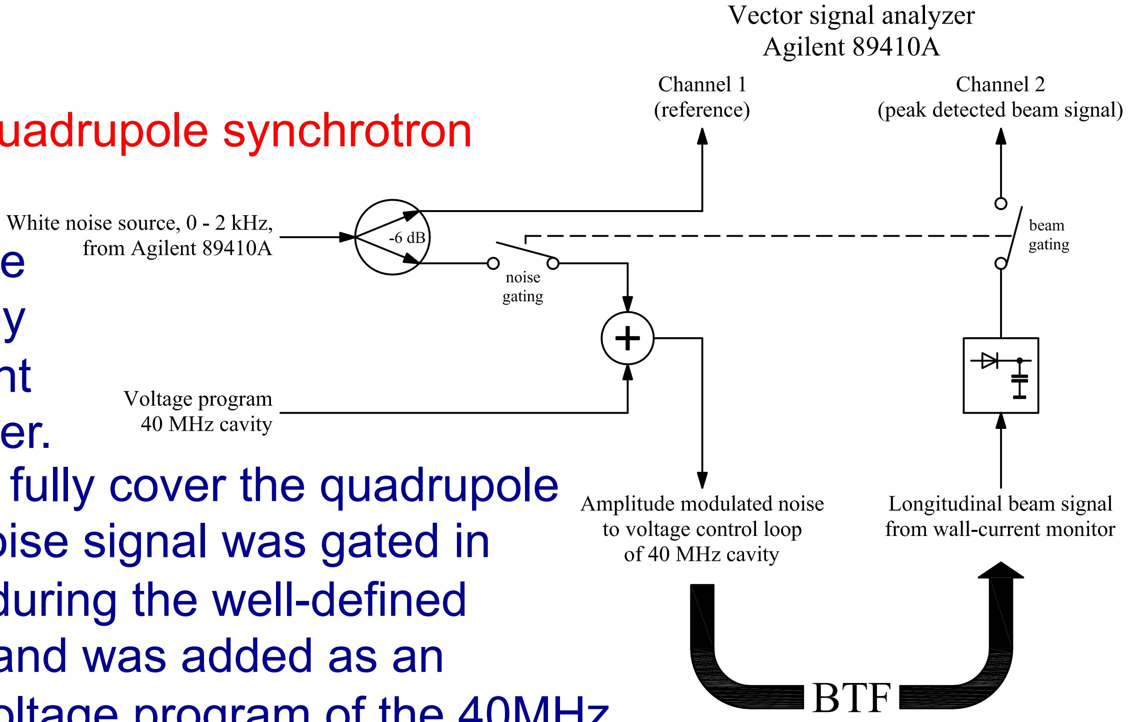
Imaginary part of the longitudinal coupling impedance: incoherent quadrupole synchrotron frequency shift vs beam current

- Set-up used to measure the quadrupole synchrotron frequency in the CERN PS:

A bandwidth limited white noise (up to 2 kHz) was generated by the internal source of an Agilent 89410A vector network analyzer.

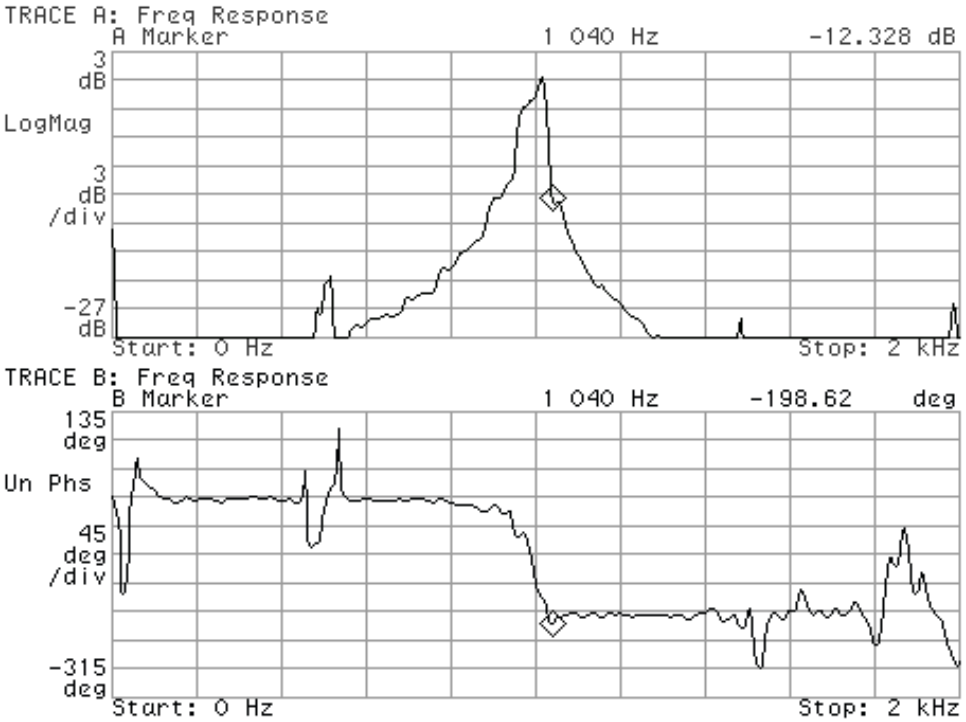
The bandwidth was chosen to fully cover the quadrupole synchrotron frequency. The noise signal was gated in order only to affect the beam during the well-defined duration of the measurement and was added as an amplitude modulation to the voltage program of the 40MHz

A copy of the noise signal used for amplitude modulation was directly fed to the reference channel of the vector network analyzer.



Beam based measurements

Imaginary part of the longitudinal coupling impedance: incoherent quadrupole synchrotron frequency shift vs beam current



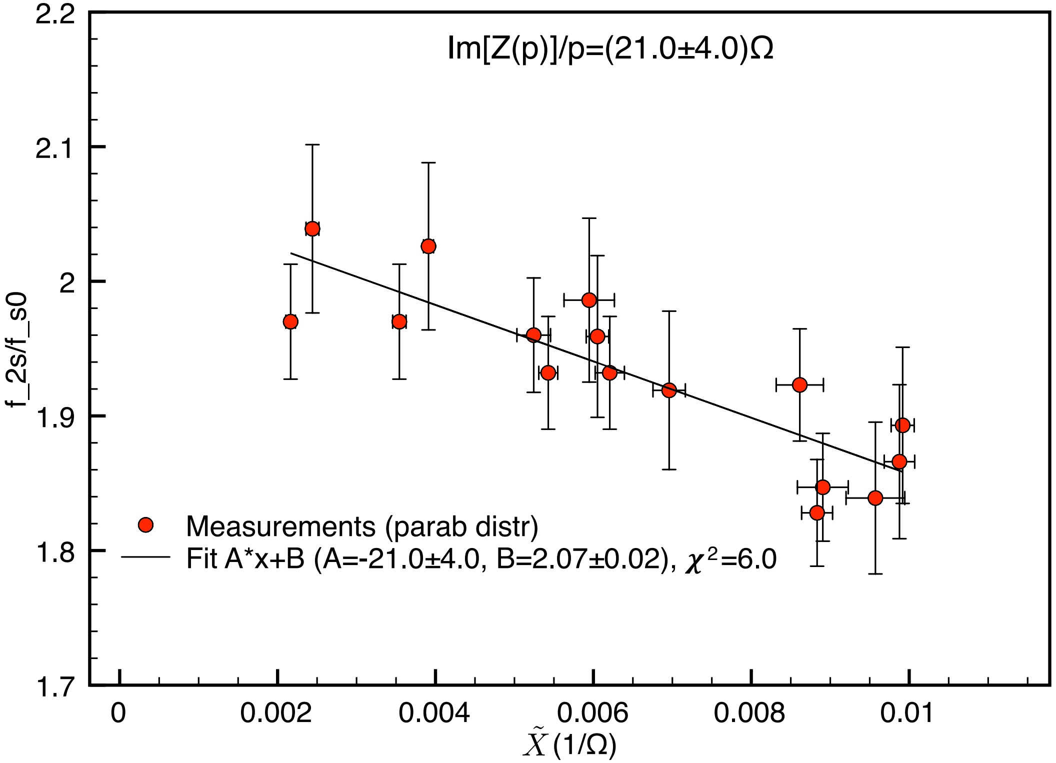
- A wall-current monitor was used to pick-up the longitudinal beam signal, followed by a peak detector with a time constant of several turns, but well below the quadrupole synchrotron tune. The peak-detected beam signal was then fed to the second channel of the vector network analyzer. The gating switch in front of the second input protects the measurement instrument from over-voltage which may occur outside the measurement time window.
- Amplitude and phase of the quadrupole frequency are then determined by the analyzer by calculating the vectorial ratio of peak-detected beam signal and noise excitation and subsequent averaging of measurements on many individual acceleration cycles.

Beam based measurements

Imaginary part of the longitudinal coupling impedance: incoherent quadrupole synchrotron frequency shift vs beam current

$$\frac{f_{2s}}{f_{s0}} = 2 + \frac{12eN_p}{V_{RF}h\cos\phi_s\omega_0^2\tau_b^3}\frac{\mathrm{Im}\left[Z(p)\right]}{p} = 2 - \tilde{X}\frac{\mathrm{Im}\left[Z(p)\right]}{p}$$

$$p = \frac{\omega}{\omega_0}$$

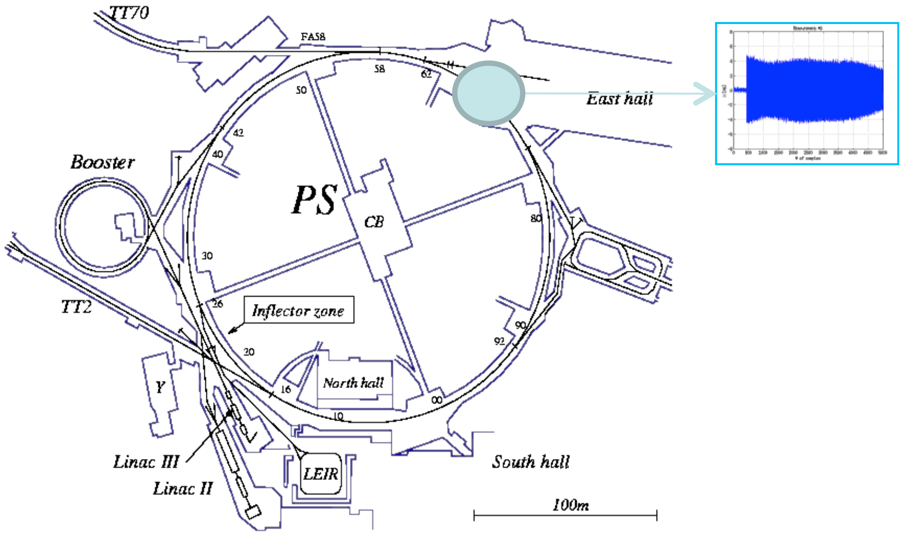


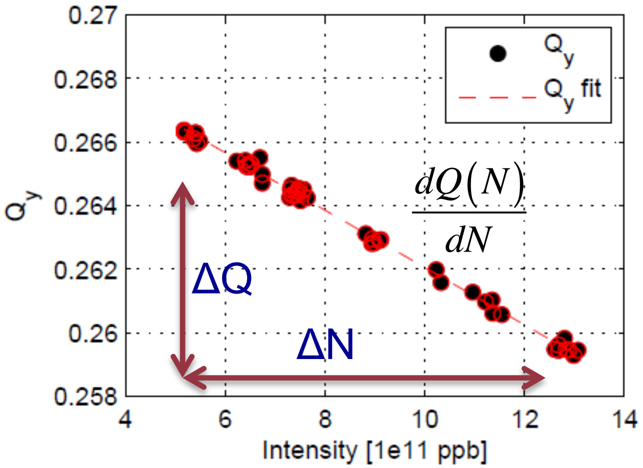
Beam based measurements

Global machine transverse impedance measurements: The imaginary part of the total transverse beam coupling impedance can be estimated from the tune shift with intensity.

$$\frac{dQ(N)}{dN} \propto \mathrm{Im}\left(Z_{\perp,eff}^{tot}\right)$$

BPM 1





Beam based measurements

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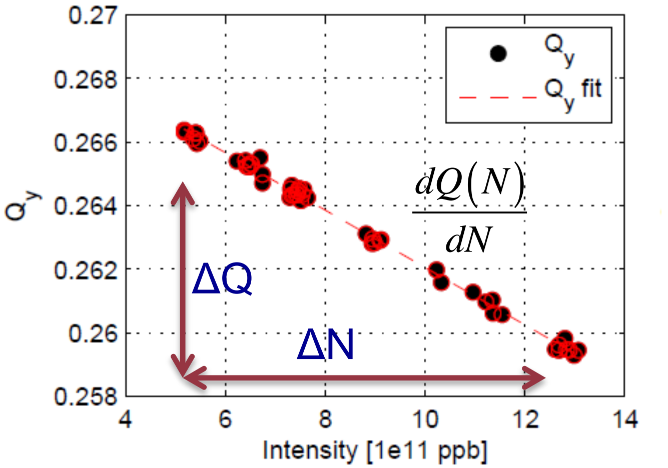
$$\frac{dQ(N)}{dN} \propto \mathrm{Im}\left(Z_{\perp,eff}^{tot}\right)$$

Depending on the machine impedance we need to satisfy:

$$\sigma_{\frac{dQ}{dN}} \propto \frac{1}{\sigma_{\Delta N} N^{\alpha} SNR} << \frac{dQ}{dN}$$



SNR: Signal/Noise Ratio
$\sigma_{dQ/dN}$: Tune accuracy
N^{α}: Number of turns acquired needed dependent on Fourier Transform method.
dQ/dN: Total expected tune shift (from theory).
$\sigma_{\Delta N}$: RMS of total intensity scan.

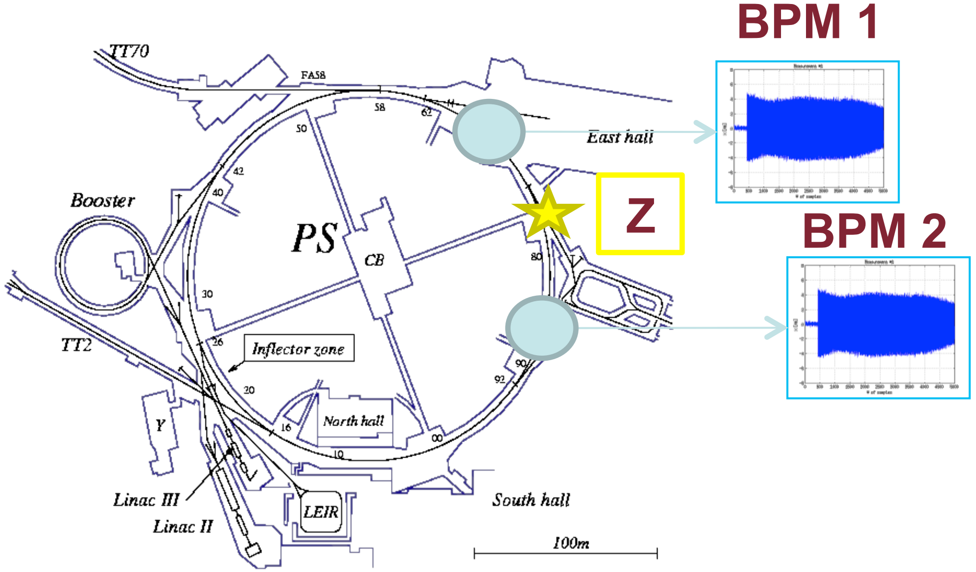
Beam based measurements

Local machine transverse impedance measurements: The local contribution may be estimated with different methods using distributed BPMs:

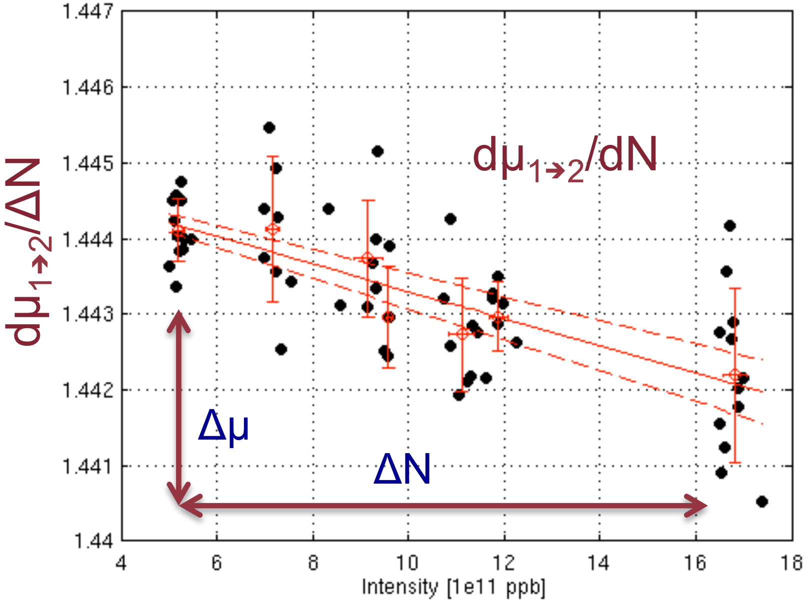
1. Impedance-induced orbit shift with intensity.
2. **Impedance-induced phase beating with intensity by means of kick excitation.**
3. ..

A transverse impedance acts as a defocusing quadrupole with strength

$$\Delta K \propto \int_{-\infty}^{\infty} \mathrm{Im}\left(Z_k\right)\left|S(\omega)\right|^2 d\omega$$



Pair of BPMs



Beam based measurements

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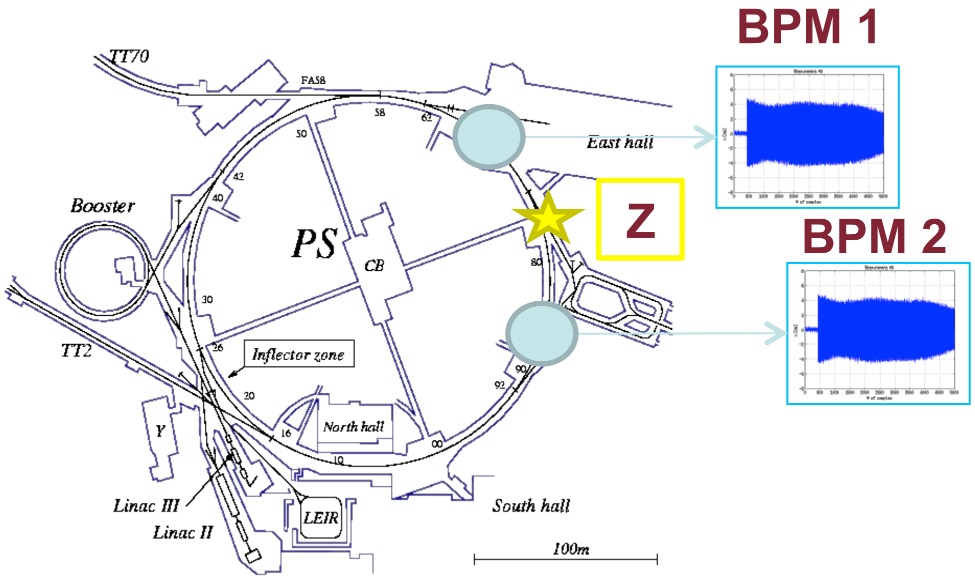
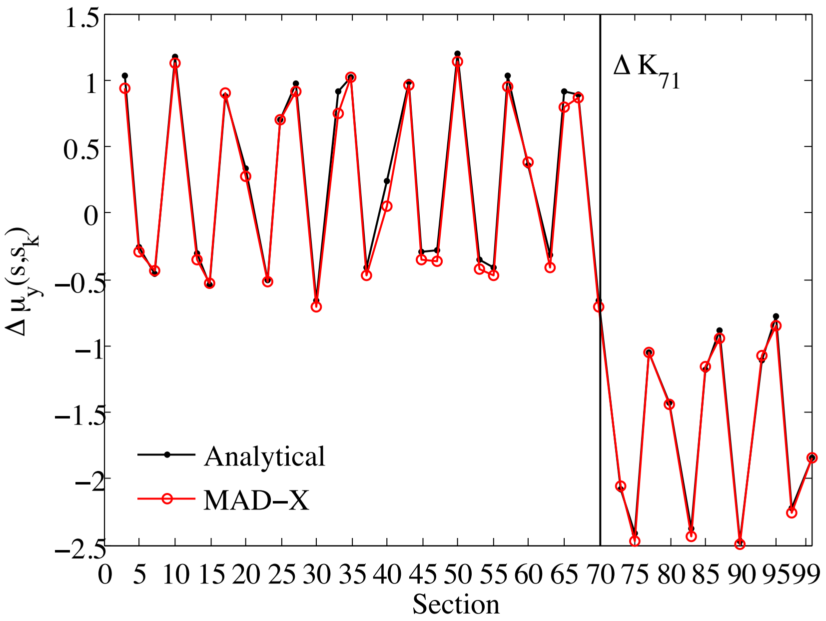




Beam based measurements

Local machine transverse impedance measurements: The local contribution may be estimated with different methods using distributed BPMs:

1. Impedance-induced orbit shift with intensity.
2. **Impedance-induced phase beating with intensity by means of kick excitation.**
3. ..

Depending on the machine impedance we need to satisfy:

$$\sigma_{\frac{d\mu_k}{dN}} \propto \frac{1}{\sigma_{\Delta N} SNR \sqrt{N}} << \frac{d\mu_k}{dN}$$

- Small phase shifts to be measured.
- Slow dependence on turns

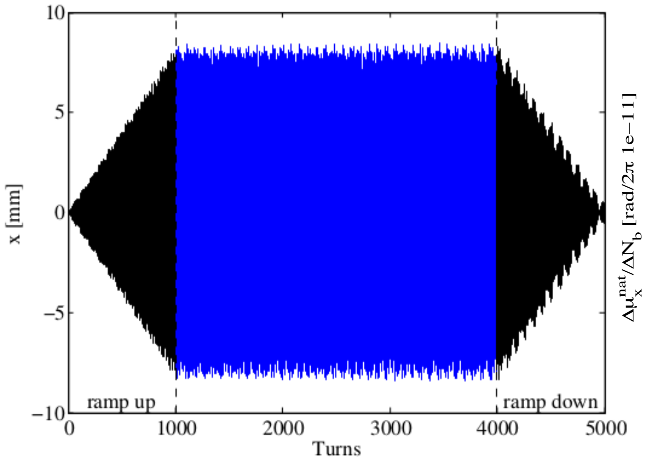
Not applicable in machines like the LHC!

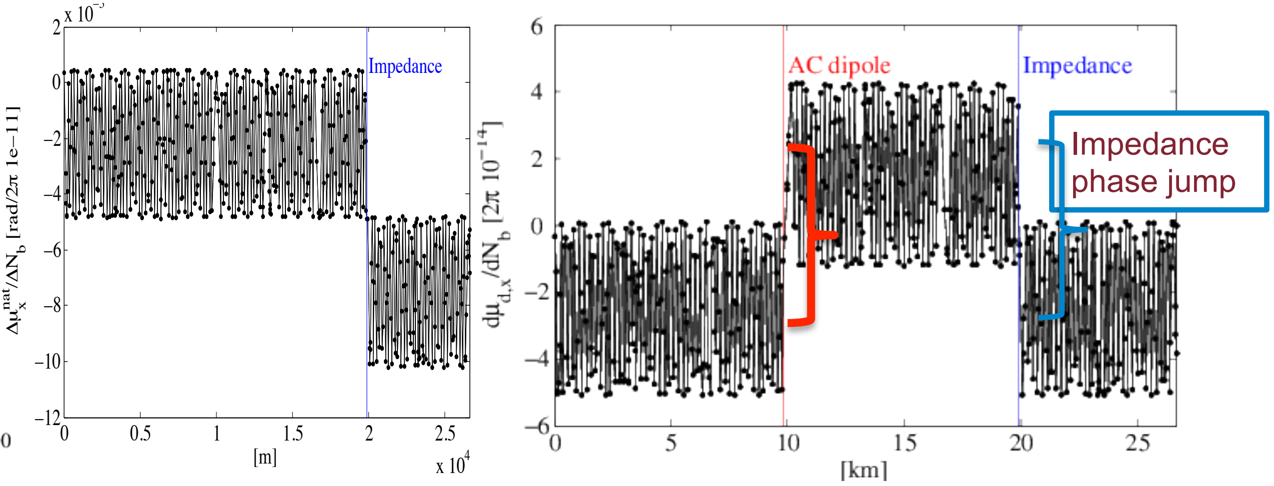
SNR: Signal/Noise Ratio
$\sigma_{d\mu/dN}$: Uncertainty in phase advance shift with intensity
N: Number of turns acquired needed dependent on Fourier Transform method.
$d\mu_k/dN$: Total expected tune shift from the k-th impedance source (from theory).
$\sigma_{\Delta N}$: RMS of total intensity scan.

Beam based measurements

Local machine transverse impedance measurements: The local contribution may be estimated with different methods using distributed BPMs:

1. Impedance-induced orbit shift with intensity.
2. Impedance-induced phase beating with intensity by means of kick excitation.
3. **Impedance-induced phase beating with intensity by means of AC-dipole excitation.**


Excitation at the driven frequency close to the tune


Simulated driven phase advance beating with a localized impedance

Advantages:

- **> 5k turns** in the LHC.
- Limited emittance blow up
- Limited particle losses

Beam based measurements

Local machine transverse impedance measurements: The local contribution may be estimated with different methods using distributed BPMs:

1. Impedance-induced orbit shift with intensity.
2. Impedance-induced phase beating with intensity by means of kick excitation.
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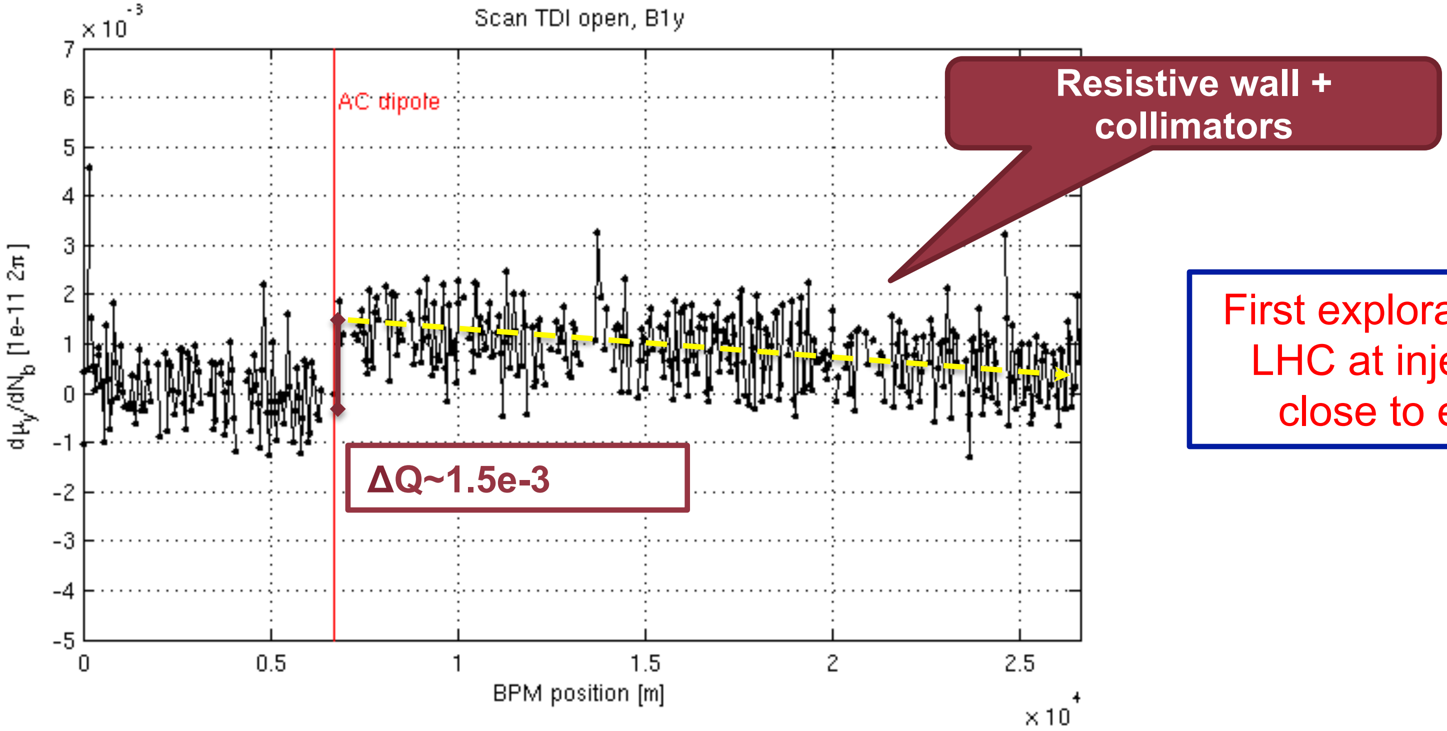


Resistive wall + collimators

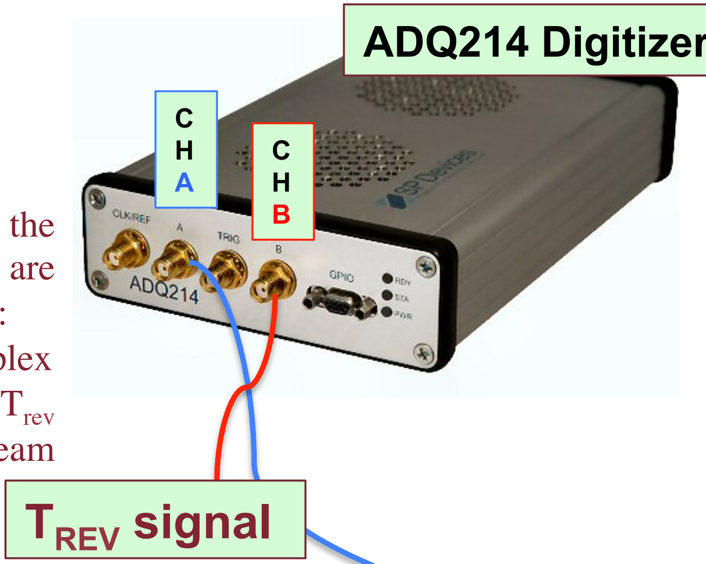
ΔQ~1.5e-3

First exploratory MD in the LHC at injection energy close to expectation!

Beam based measurements and HOMs

The effects of HOMs in the accelerator can be put in evidence if they produce coupled bunch instabilities. By measuring beam oscillations it is possible to get information on the unstable coherent oscillation modes and on possible frequencies and intensities of resonant modes

Acquisition

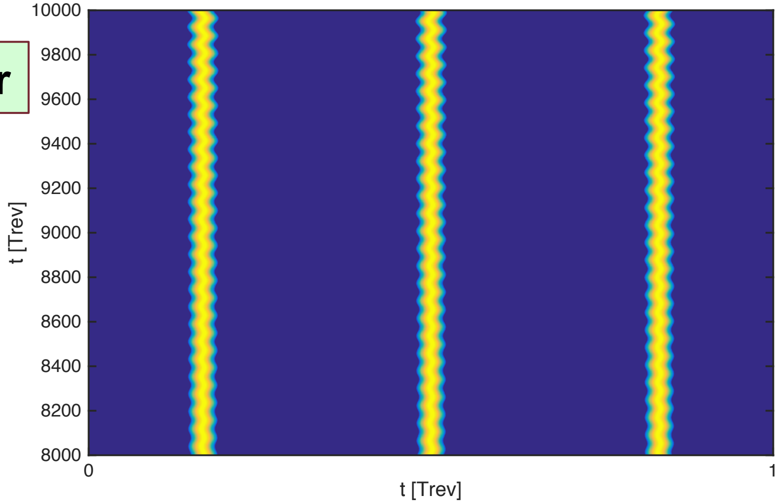


ADQ214 Digitizer

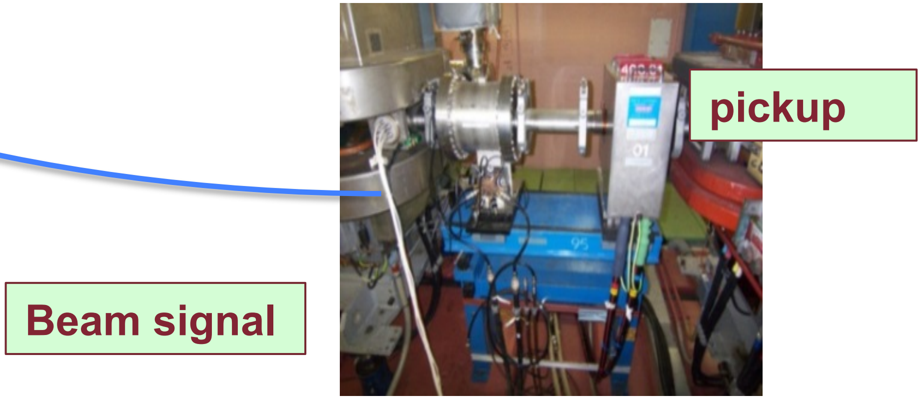
CH A

CH B

T_{REV} signal



T_{rev} changes during the acquisition since we are accelerating the beam:
→ the gating is complex
→ it is necessary the T_{rev} signal to gate the beam signal



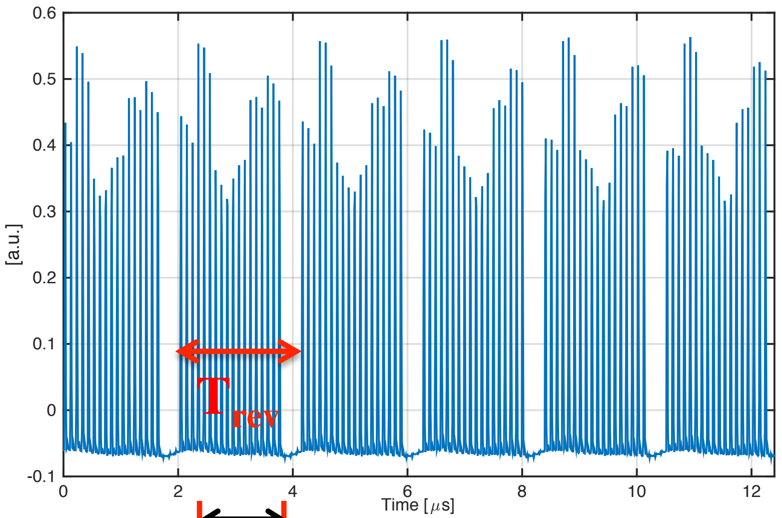
pickup

Beam signal

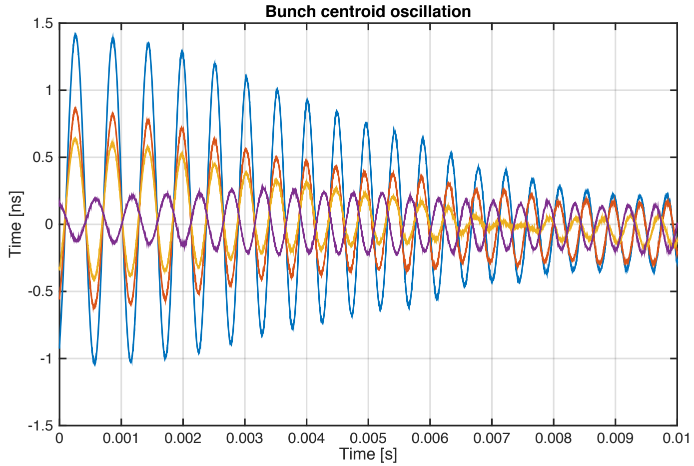
Beam based measurements and HOMs

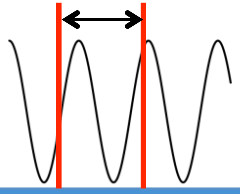
Analysis

Acquisition of the beam signal, turn after turn in the case of a not fully machine.



We find the center of mass using a fast algorithm which identifies the centroid of each bunch with a weighted average for each turn in the measurements acquisition window.





$$\phi_b = A_b \sin\left(\omega_s t + \theta_b\right) = \sum_{\mu=0}^{N_b-1} a_\mu \sin\left(\omega_s t + \frac{2\pi}{N_b}\mu b + \theta_\mu\right)$$

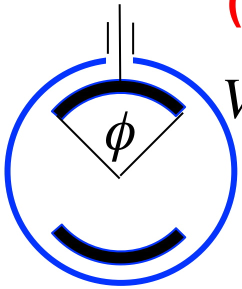
RF phase of each bunch in a given time window → Reconstruction of amplitude and phase oscillation for each bunch → Mode analysis

Coupling impedance of striplines and button electrodes: example

- In general a pickup should have a reasonably high transfer impedance keeping the beam coupling impedance and parasitic losses within acceptably low values.
- As a general rule, a design with higher transfer impedance has also higher coupling impedance because they are related, therefore, a compromise has to be found in order to satisfy the two contradicting requirements.
- To determine analytically the coupling impedance at low frequency we:
  - simplify the 3D geometry with an equivalent circuit consisting of concentrated radio technical elements and transmission lines;
  - use methods of electric circuits and theory of transmission lines to find currents and voltages in the circuit elements;
  - obtain the power dissipated in the loads;
  - since this power is provided by the beam, we can determine the real part of the longitudinal coupling impedance;
  - use the Hilbert transform to get the imaginary part of the transverse impedance.

Coupling impedance of striplines and button electrodes: example

Cylindrical stripline monitor (one plate)

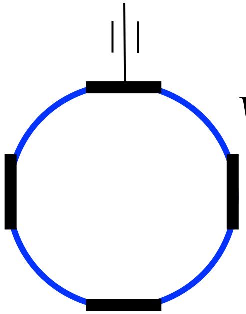


$$V_t = \frac{Z_s}{2}\left(\frac{\phi}{2\pi}\right) I_0\left(1 - e^{-j2\omega l/c}\right)$$

Z_s is the characteristic impedance of the coaxial cable and of both the terminations, l the stripline length

V_t=voltage across the termination

Broadband button electrode (one button)



$$V_t = Z_s\left(\frac{r}{2b}\right)\left(\frac{\omega_1}{\omega_2}\right) I_0 \frac{j\omega/\omega_1}{1 + j\omega/\omega_1}$$

Z_s is the characteristic impedance of the coaxial cable and of the termination, r the button radius, ω_1 and ω_2 constants depending on the button characteristics

$$\langle P(\omega)\rangle = \frac{1}{2}|V_t|^2\frac{1}{Z_s} = \frac{1}{2}|I_0|^2\,\mathrm{Re}\left[Z(\omega)\right]$$

$$\mathrm{Re}\left[Z(\omega)\right] = Z_s\left(\frac{\phi}{2\pi}\right)^2 \sin^2\left(\frac{\omega l}{c}\right)$$

K. Y. Ng, Part. Acc. 1988, Vol. 23, pp. 93-102

$$\mathrm{Re}\left[Z(\omega)\right] = Z_s\left(\frac{r}{2b}\right)^2\left(\frac{\omega_1}{\omega_2}\right)^2 \frac{(\omega/\omega_1)^2}{1 + (\omega/\omega_1)^2}$$

F. Marcellini, et al., NIM A 402 (1998) pp. 27-35

Coupling impedance of striplines and button electrodes: example

Hilbert transform:

$$\mathrm{Im}\left[Z(\omega)\right] = \frac{1}{\pi} P.V. \int_{-\infty}^{\infty} \frac{\mathrm{Re}\left[Z(\omega')\right]}{\omega' - \omega} d\omega'$$

Cylindrical stripline monitor (one plate)

$$Z(\omega) = Z_s \left(\frac{\phi}{2\pi}\right)^2 \left[\sin^2\left(\frac{\omega l}{c}\right) + j \sin\left(\frac{\omega l}{c}\right)\cos\left(\frac{\omega l}{c}\right)\right]$$

Broadband button electrode (one button)

$$Z(\omega) = Z_s \left(\frac{r}{4b}\right)^2 \left(\frac{\omega_1}{\omega_2}\right)^2 \frac{j(\omega/\omega_1)}{1 + j(\omega/\omega_1)}$$

Transverse impedance

Pair of cylindrical stripline (vertical impedance)

$$Z_\perp(\omega) = \frac{c}{b^2}\left(\frac{4}{\phi}\right)^2 \sin^2\left(\frac{\phi}{2}\right)\left[\frac{Z_{||}}{\omega}\right]$$

$Z_{||}$ is the longitudinal impedance of a pair of striplines

Coupling impedance of striplines and button electrodes: example

- At low frequency $\frac{\omega l}{c} << 1 \Rightarrow kl << 1 \quad Z(\omega) \cong jZ_s \left(\frac{\phi}{2\pi}\right)^2 \frac{\omega l}{c}$
- We should also remark here that the above expressions underestimate the coupling impedance, since they take into account only that part of fields contributing to the output signal formation.
- High frequency resonances can be excited in the structures formed by a diagnostics element and beam pipe walls. Some of such resonances can be associated with standing waves, which do not dissipate their power in the external terminations.
- Trapped modes could also produce coupled bunch instabilities.
- Generally the coupling impedance of a single device is small compared to the total impedance budget, but since in an accelerator there are many pickups, their contribution could be not negligible.

Conclusions

- Pickups are important diagnostics elements used to detect beam signals.
- The measurements of machine coupling impedance are based on the perturbations the impedance produces on the beam dynamics, which are detected by pickups.
- It’s the way these signals are elaborated which gives information on the machine coupling impedance.
- In addition to that, pickups, as all machine devices, contribute to the coupling impedance, and their evaluation is very important, in particular due to the high number of elements installed in an accelerator.
- A very sensitive pickup has a high transfer impedance, and, as a consequence, also a high coupling impedance. A compromise between the two requirements has to be found.
- Particular care in the design of a pickup has to be taken also to avoid dangerous trapped modes at high frequencies, which could increase energy losses and produce coupled bunch instabilities.