Beam-based impedance measurements

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JUAS, course I
1-2-2023

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06:00 AM

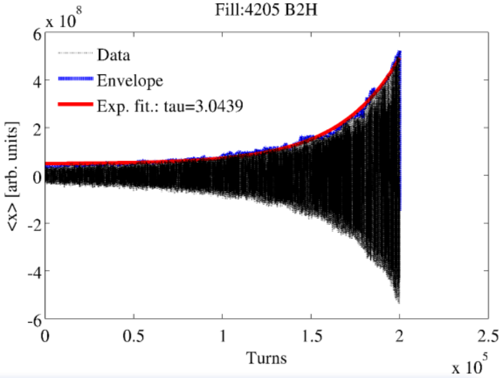
You:

Your boss:

Look, this night there was an instability in the LHC!

Really?! Can you send me a picture please?

Sure, here it is!



Interesting. It is in horizontal plane.

What was the chroma? Coupling? Octupoles?

Uhm… I have to check for the rest...

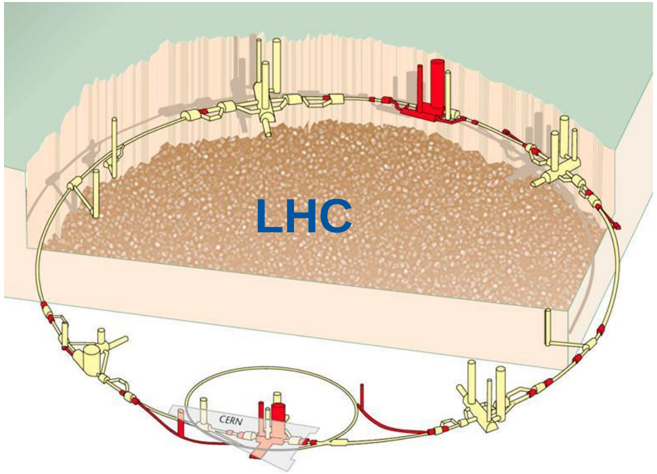
Great. And let’s compare with the impedance model predictions

CERN

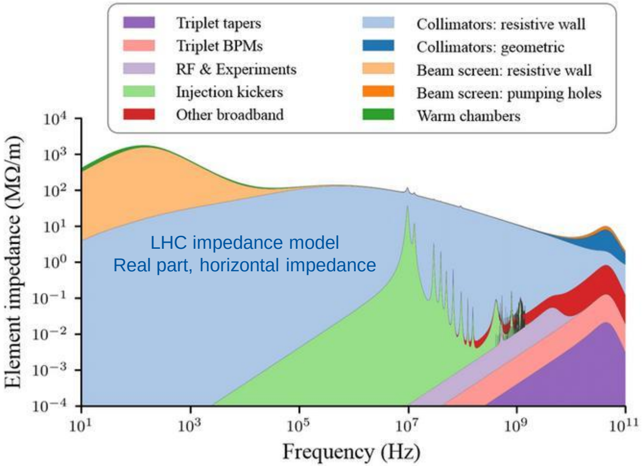
Introduction

- The beam coupling impedance represents the electromagnetic interaction of a particle beam with its surrounding space.
- By definition, it is inherently present in every accelerators.
- It contributes to the intensity limitations of a machine, together with other collective effects (space charge, IBS, electron cloud, beam-beam, etc..).
- It is important to build a machine impedance model to:
  1. predict the impedance-related machine performance limitations.
  2. prepare for machine upgrades (adding/removing impedances).
  3. optimize beam parameters for existing machine operation modes.
  4. be ready to address expected and unexpected instabilities.

Real machine



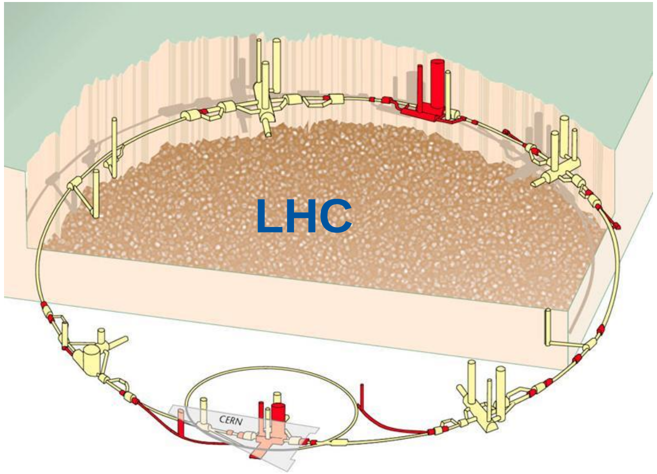
Impedance model



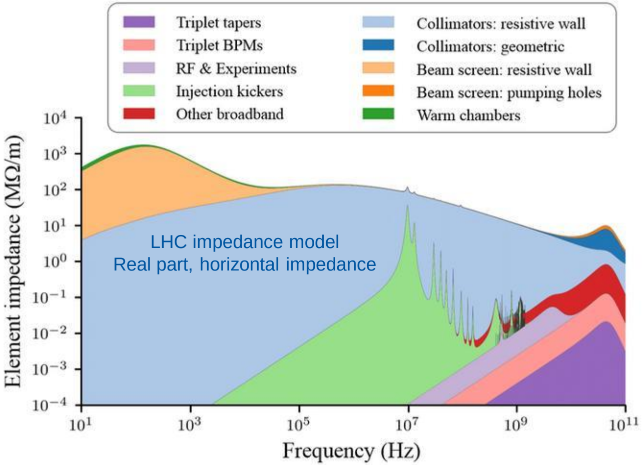
Each machine element is associated to an impedance, i.e. a complex, frequency dependent functions in L,H,V planes

Beam-based impedance measurements

Real machine



Impedance model



Each machine element is associated to an impedance, i.e. a complex, frequency dependent functions in L,H,V planes

Beam-based impedance measurements

Beam-based impedance measurements

Transverse plane

Imaginary part

- Tune shift vs intensity

Tune shift versus intensity

We use the beam as an impedance-measurement tool looking at the perturbation that the impedance induces on its motion.

In the transverse plane (for example on the y-plane) beam motion is given by:

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

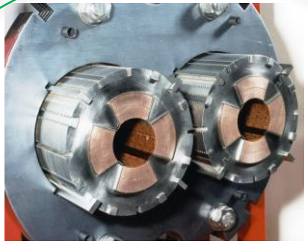
Unperturbed focusing strength

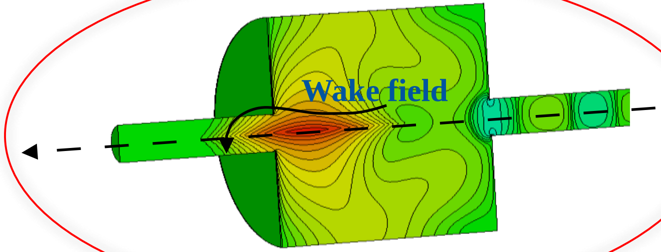
Phase advance

When the impedance perturbation is negligible, the particles oscillate at the machine programmed tune Q_y.

Tune shift versus intensity

When the impedance perturbation is not negligible, the beam motion is affected by the additional driving force the impedance is producing.





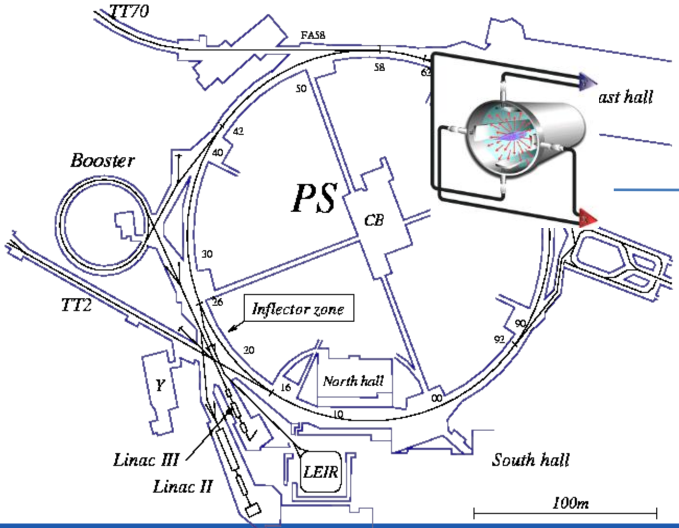
$$\frac{d^2}{ds^2}y_i(s) + K(s)y_i(s) = < F_i > \longleftarrow$$ **Perturbing** force (**wakefields**)

To first approximation (and not in general!) the impedance effect can be modeled as an additional defocusing quadrupole with strength linearly dependent on beam intensity.

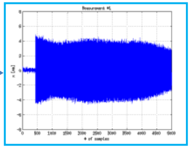
Tune shift versus intensity

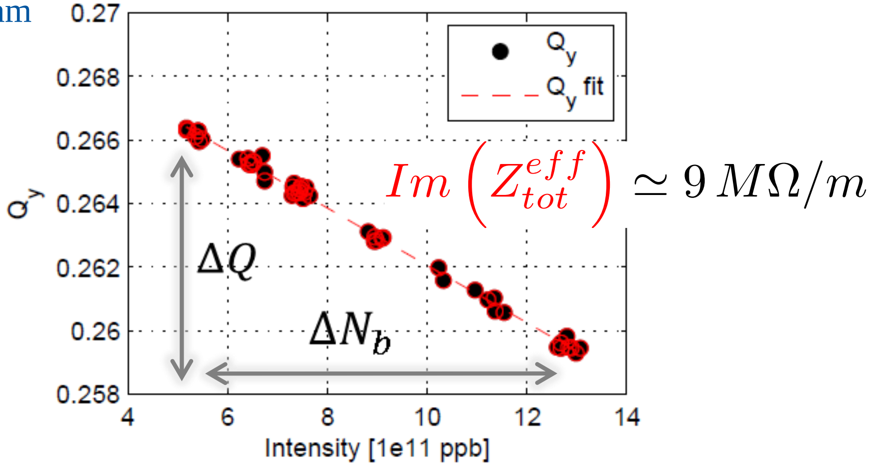
Looking at the tune change versus intensity, we can infer the total machine transverse impedance (imaginary part) as $\frac{\Delta Q_y}{\Delta N_b} \propto Im\left(Z_{tot}^{eff}\right)$

$eff. \rightarrow$ effective, i.e. weighted by the beam spectrum.



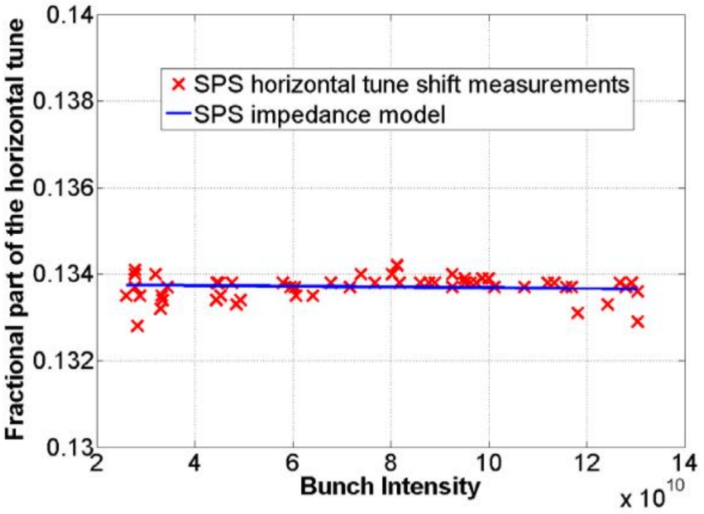
Signal at **one** beam position monitor

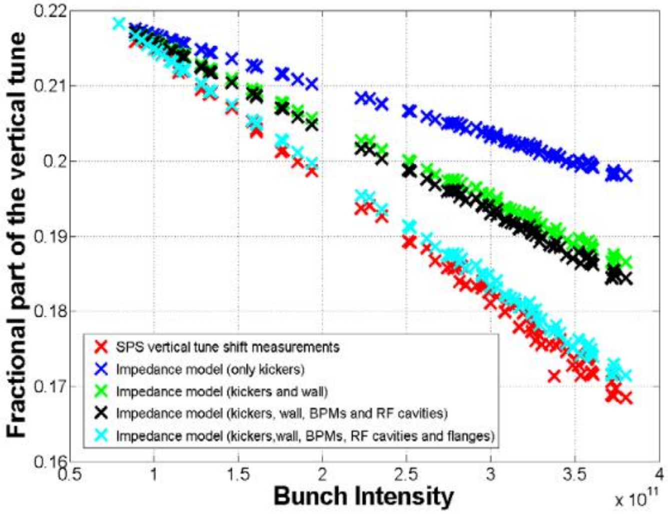




Example from the SPS

A carefully developed impedance model of a machine can reach excellent agreement to beam measurements, as for the SPS:





C. Zannini, " Electromagnetic Simulation of CERN accelerator Components and Experimental Applications", CERN-THESIS-2013-076 (2013)

Impedance localization

So far we have access to the total machine impedance via tune shift measurements.
But, can we measure the impedance of single elements installed the machine?

YES!

1. We can look at the variation of phase advance vs intensity
2. We can perform local orbit bumps around the device
3. If the device is movable (like collimators) we can change its gap
4. ...

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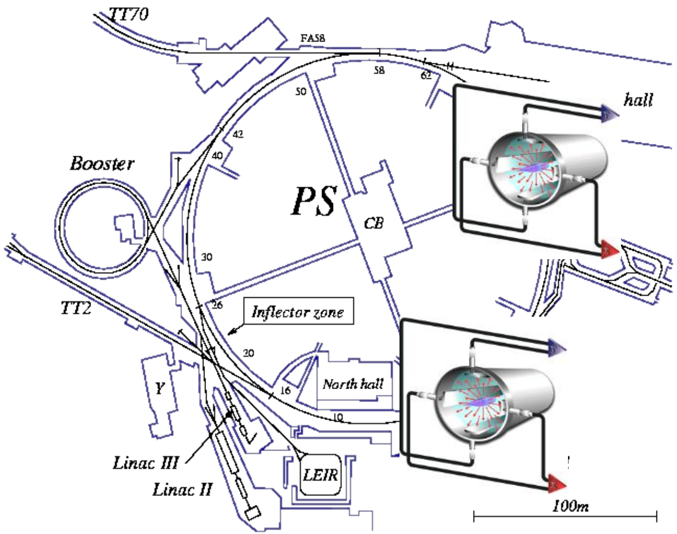
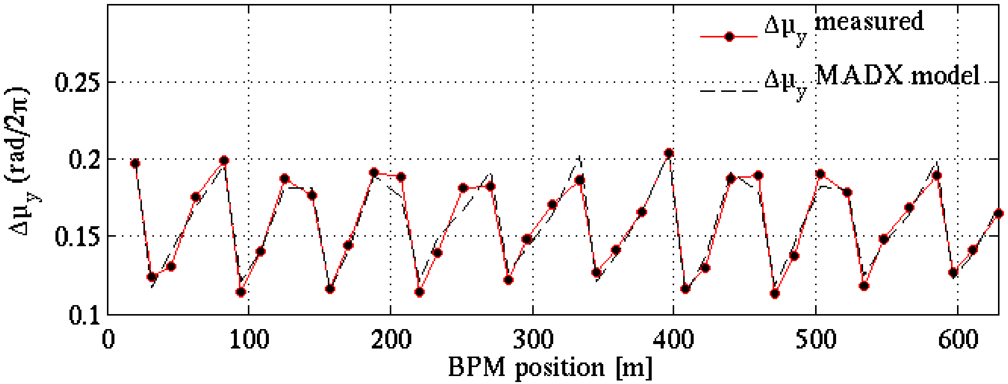
Phase advance w/o impedance effect

When the impedance perturbation is negligible, the phase advance can be compared to the MADX model.

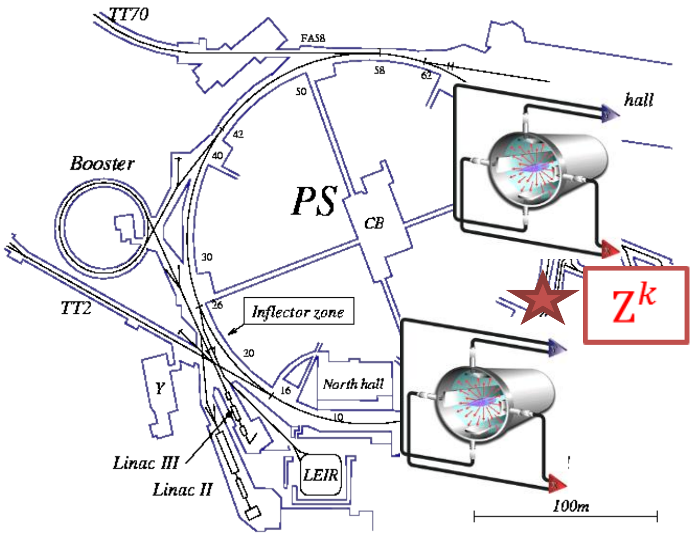


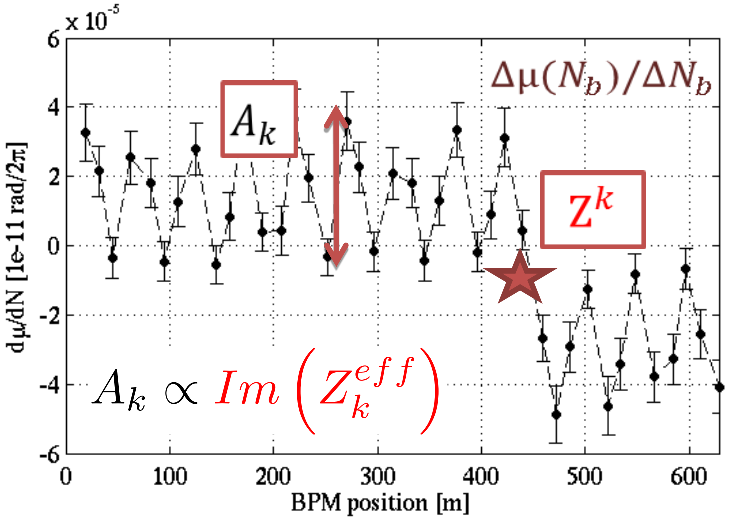
A Beam Position Monitor (BPM) system allows for the measurement of the optics functions (tune, phase advance).



Phase advance w/o impedance effect

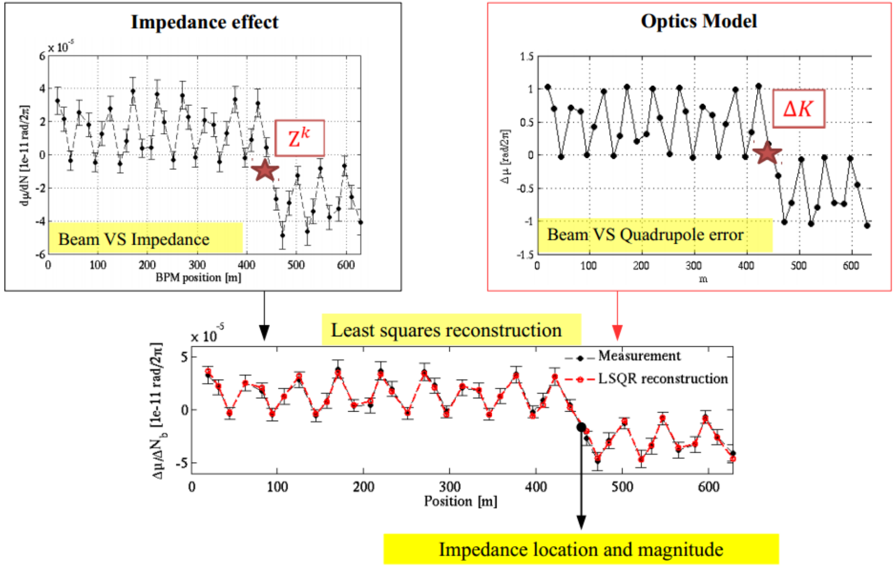
When the impedance perturbation is not negligible, the phase advance exhibits a kink at the impedance location with amplitude proportional to the impedance.



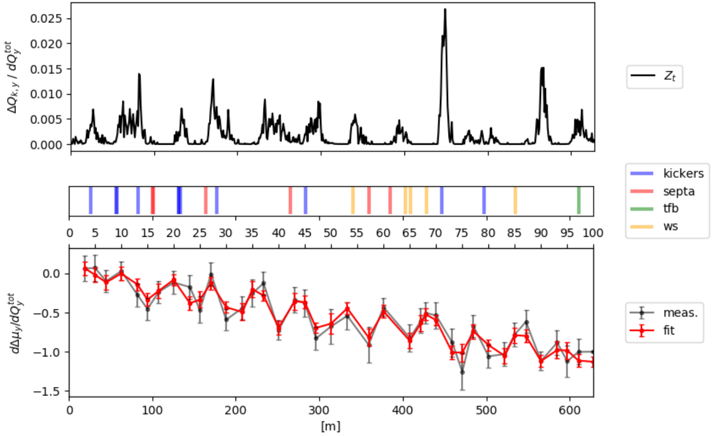


Phase advance w/ impedance effect

Comparing the effect of a (series of) localized thin lens to the measurent, one can reconstruct the impedance location and strength.



Example of impedance localization measurement in the PS at 26 GeV



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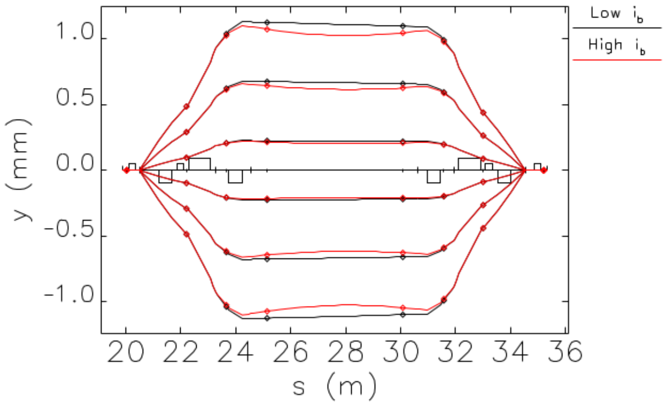
4. ...

Local bump method

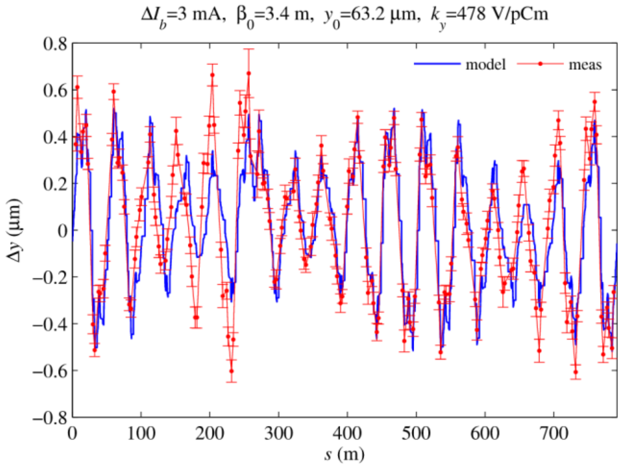
The impedance kick at the a ring location is proportional to the beam orbit displacement. Scanning the local orbit bump we can probe the device transverse impedance.

APS



L. Emery et al. "Local bump method for measurement of transverse impedance of narrow-gap ID chambers in storage rings", PACS2001. Proc. of 2001 Particle Accelerator Conference, 2001

NSLS-II



V.Smaluk et al. “AC orbit bump method of local impedance measurement”, Nuclear Inst. and Methods in Physics Research, A 871 (2017) 59–62

See also “Transverse Linear Imperfections” lectures from H.Bartosik

Impedance localization

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But, can we measure the impedance of single elements installed the machine?

YES!

1. We can look at the variation of phase advance vs intensity
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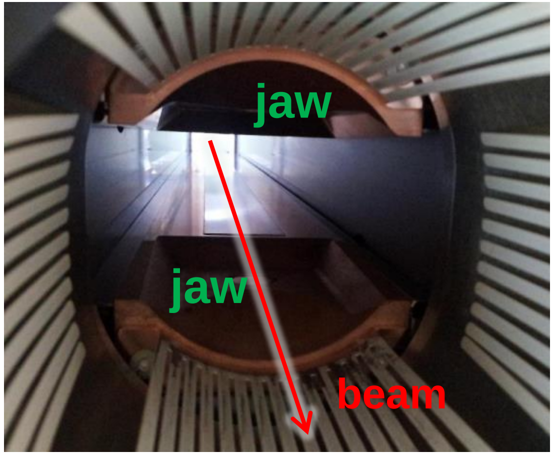
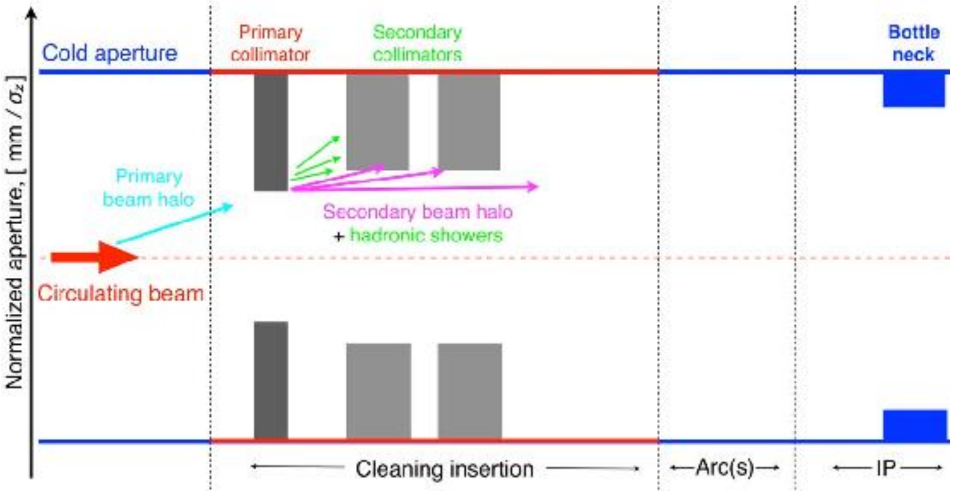
4. ...

Movable devices

Let's consider a collimator as an example of movable device.

This is typically installed to clear the beam halo and protect the machine from uncontrolled beam losses.





Courtesy of S.Redaelli, Beam Cleaning and Collimation Systems, arXiv:1608.03159

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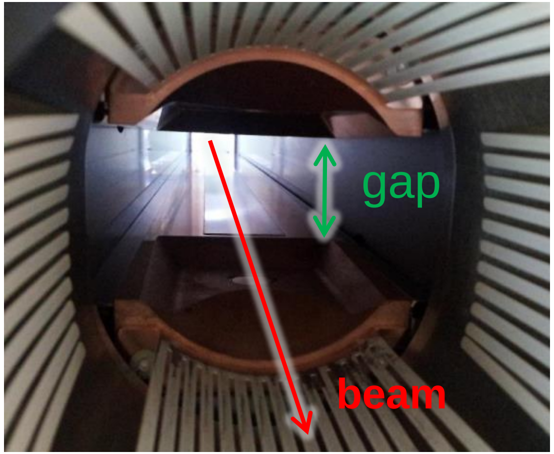

The gap between jaws is set up in order to optimize the collimator system cleaning efficiency.

Changing the gap ↔ changes the impedance

$$Z_y \propto \sqrt{\varrho}/g^3$$

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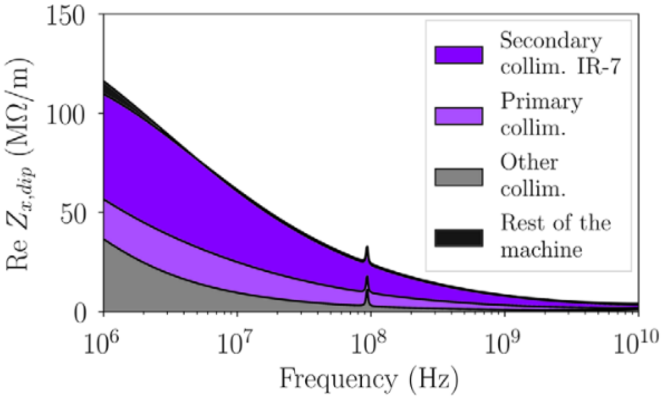


Courtesy of S.Antipov

The gap between jaws is set up in order to optimize the collimator system cleaning efficiency.

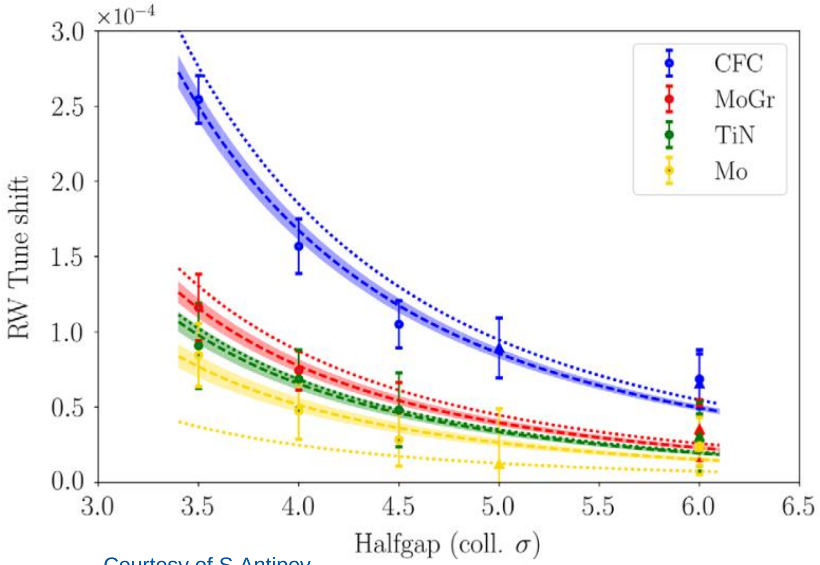
Changing the gap ↔ changes the impedance

$$Z_y \propto \sqrt{\varrho}/g^3$$

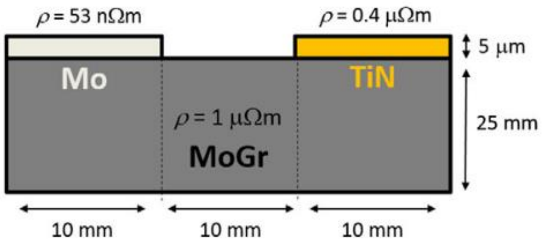
Several of these device can easily dominate the total machine impedance due to the small gap g and low resistivity ϱ typically used for the absorbing jaws.

Example: low impedance collimators

The tune shift of a collimator was measured in the LHC in order to test different coating materials on the jaws (low resistivity → low impedance).



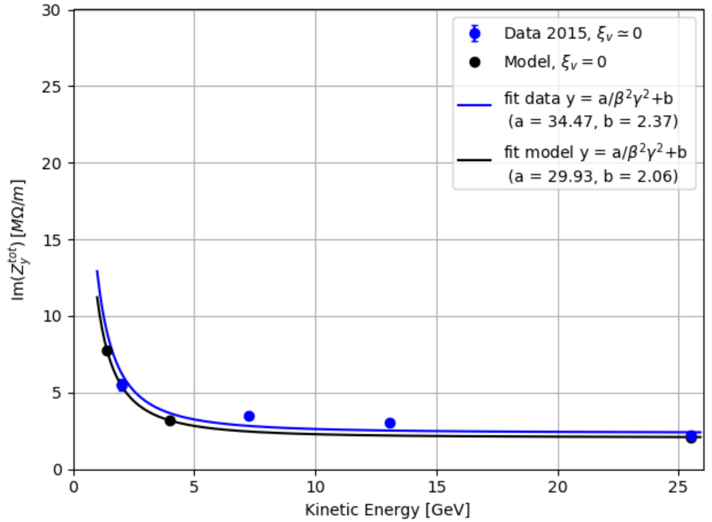
Courtesy of S.Antipov



In this case, Mo confirmed to have the best resistivity and was adopted for the HL-LHC low impedance collimator production.

Bonus: impedance measurement versus energy

- Measuring the transverse impedance (tune shift) versus intensity at various energies allows to disentangle the role of the energy-dependent contribution to the impedance.
- Typically the indirect space charge is dominant w.r.t. to the rest of the machine.



Example from the PS:

Good agreement between model and predictions:

- Energy dependence → indirect space charge impedance.
- High energy value → rest of the machine impedance.

Beam-based impedance measurements

Transverse plane

Imaginary part

- Tune shift vs intensity
- Phase advance shift ”
- Orbit distortion “
- Tune shift vs energy

Beam-based impedance measurements

Transverse plane

Real part

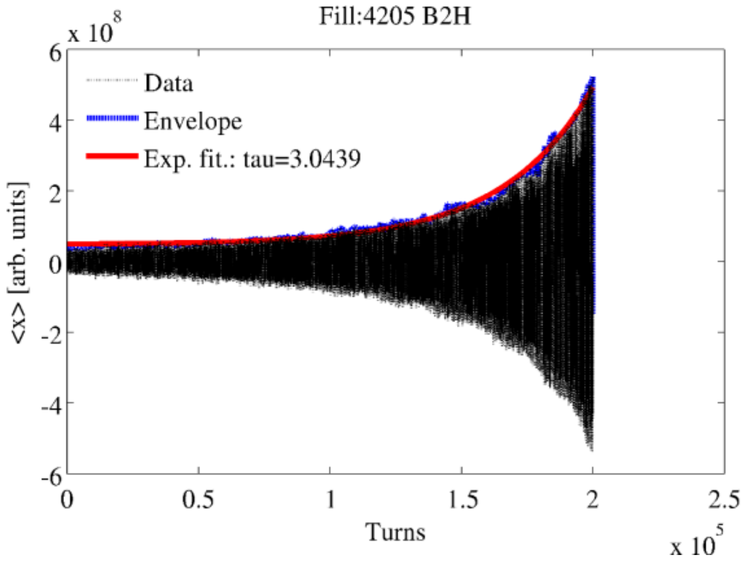
Rise time vs Q’

Imaginary part

- Tune shift vs intensity
- Phase advance shift ”
- Orbit distortion “
- Tune shift vs energy

Rise time measurements

- Looking at the dependence of rise time τ on chromaticity, one can deduce the real part of the machine impedance.



$$Ae^{t/\boldsymbol{\tau}} \longrightarrow \boldsymbol{\tau^{-1}} \propto Re\left(Z_{tot}^{eff}\right)$$

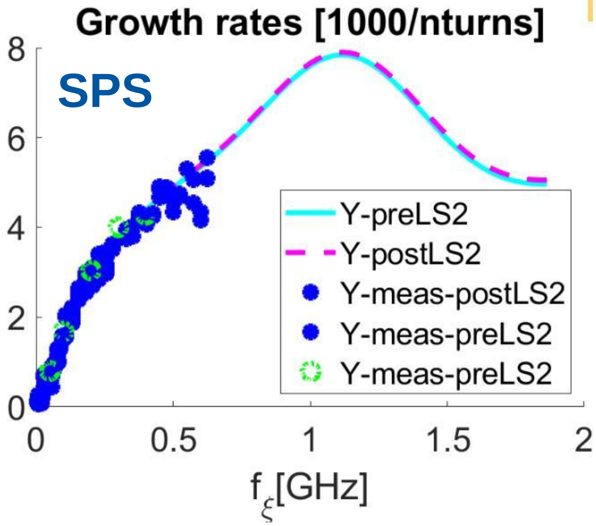
Rise time $\rightarrow \tau \quad \rightarrow s$

Growth rate $\rightarrow \tau^{-1} \quad \rightarrow s^{-1}$

Larger the impedance, shorter the rise time (larger the growth rate)

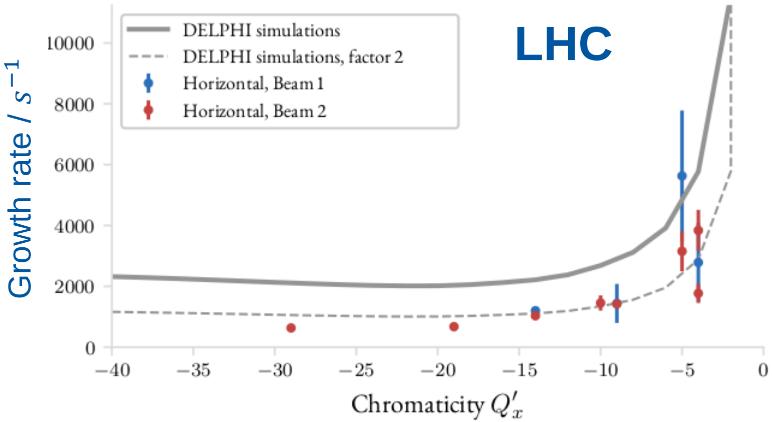
Rise time measurements

- Looking at the dependence of rise time τ on chromaticity, one can deduce the real part of the machine impedance.



Courtesy of C.Zannini

$f_\xi = Q' f_{rev}$



Courtesy of D.Amorim

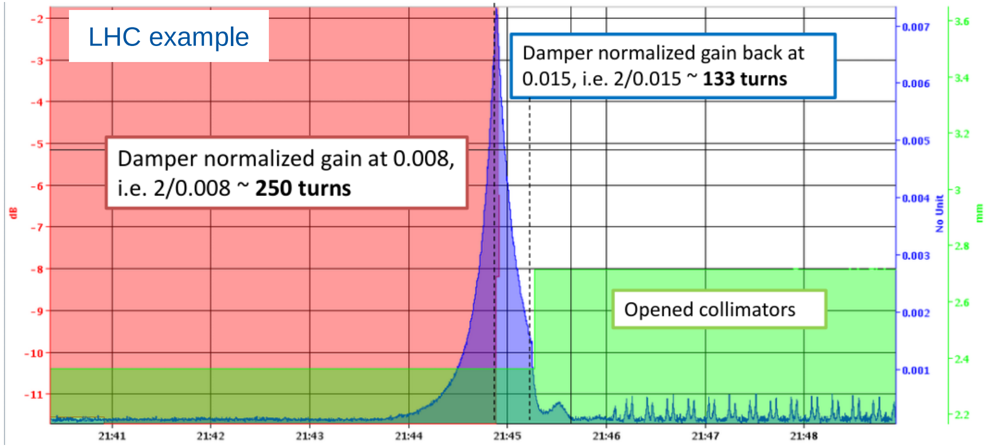
Rise time measurements

- A beam undergoing oscillations with exponentially increasing amplitude will eventually hit the vacuum chamber and be lost.
- Rise time measurements are therefore "easier" in fast cycling machines, as one can inject new bunches each time. In large colliders, like the LHC, a refill can take hours.

A transverse feedback can help!

Feedback off → instability grows

Feedback on → instability damps



If beam properties are not significantly affected, one can repeat the experiment.

Beam-based impedance measurements

Transverse plane

Real part

Rise time vs Q’

Imaginary part

- Tune shift vs intensity
- Phase advance shift ”
- Orbit distortion “
- Tune shift vs energy

Longitudinal plane

Real part

Synchronous phase shift vs intensity

Synchronous phase shift

Under the effect of a longitudinal impedance, the beam looses energy which needs to be supplied back by the RF cavities.

$$\Delta E = \frac{e^2 N_p}{T_0} \sum_p Re[Z(p\omega_0)] \lambda^2(p\omega_0)$$

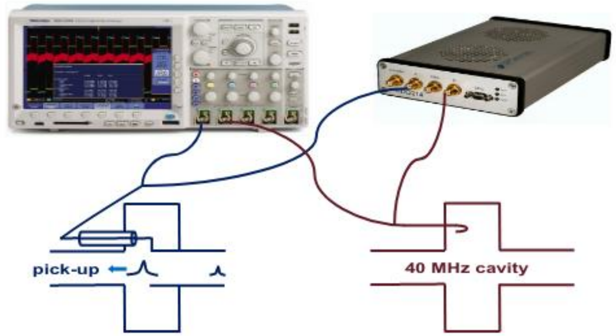
The additional energy is recovered by a (synchronous) phase shift given by

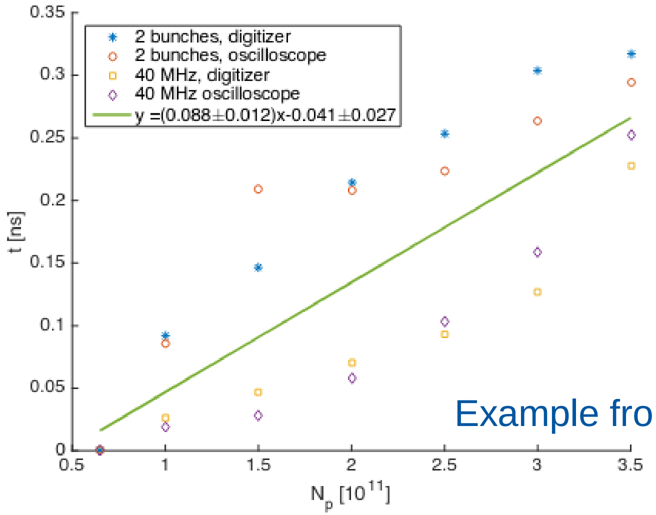
$$\Delta E = \Delta\varphi V_{RF} \cos\varphi_0$$

See A. Chao, Physics of Collective Beam Instabilities in High Energy Accelerators, Wiley Publishers, 1993

Synchronous phase shift

Measuring, for example, the delay between a high intensity bunch and a small intensity one (probe), it is possible to infer the total real part of the longitudinal impedance.





Example from the PS

M.Migliorati et al, "Measurements of the CERN PS Longitudinal Resistive Coupling Impedance" in proceedings of IPAC2016, Busan, Korea

Beam-based impedance measurements

Transverse plane

Real part

Rise time vs Q’

Imaginary part

- Tune shift vs intensity
- Phase advance shift ”
- Orbit distortion “
- Tune shift vs energy

Longitudinal plane

Real part

Synchronous phase shift vs intensity

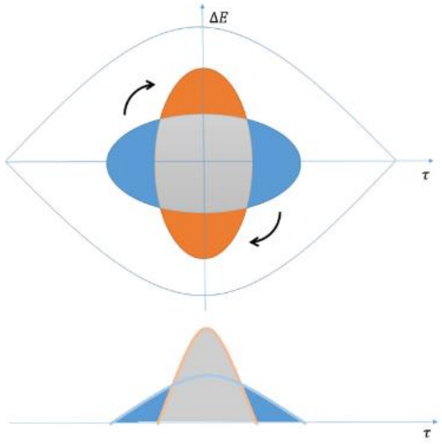
Imaginary part

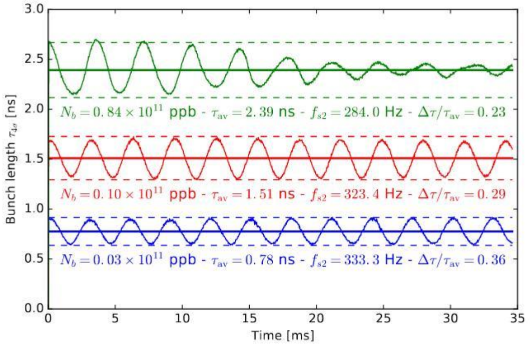
Quadrupole frequency shift vs intensity

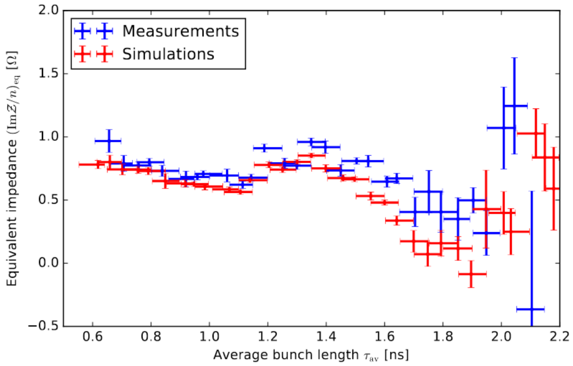
Quadrupolar frequency shift

The quadrupole mode of oscillations can be effectively used to measure the imaginary part of the longitudinal impedance.

Example from the SPS







A.Lasheen, E.Shaposhnikova, PRAB 20, 064401 (2017)

Many more methods, e.g.:

- *Loss Landau damping*
- *BTF*
- *AC-dipole*
- *Schottky*
- *Debunched beams*
- *....*

Beam-based impedance measurements

Transverse plane

Real part

Rise time vs Q'

Imaginary part

- Tune shift vs intensity
- Phase advance shift "
- Orbit distortion "
- Tune shift vs energy

Longitudinal plane

Real part

Synchronous phase shift vs intensity

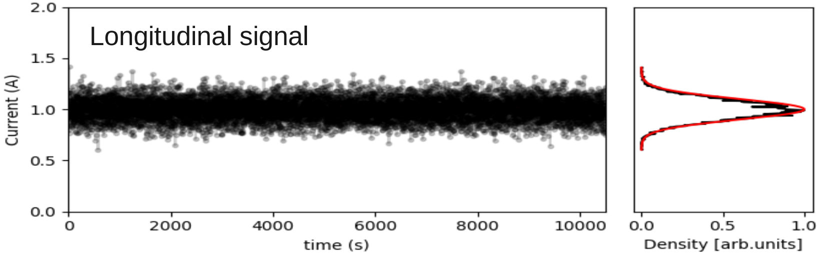
Imaginary part

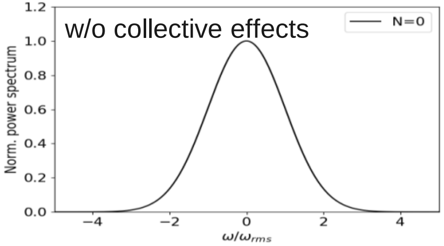
Quadrupole frequency shift vs intensity

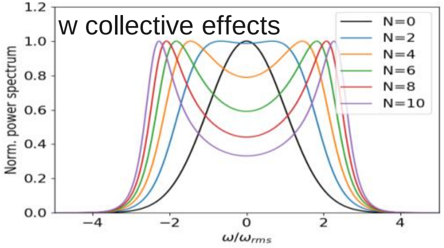
Debunched beams

Schottky spectrum: powerful measurement tool

A coasting (or debunched) beam is constituted by a DC current with random fluctuation







W/o collective effects, the power spectrum ("Schottky" spectrum) directly relates to:

- ✓ Intensity
- ✓ Momentum spread
- ✓ …

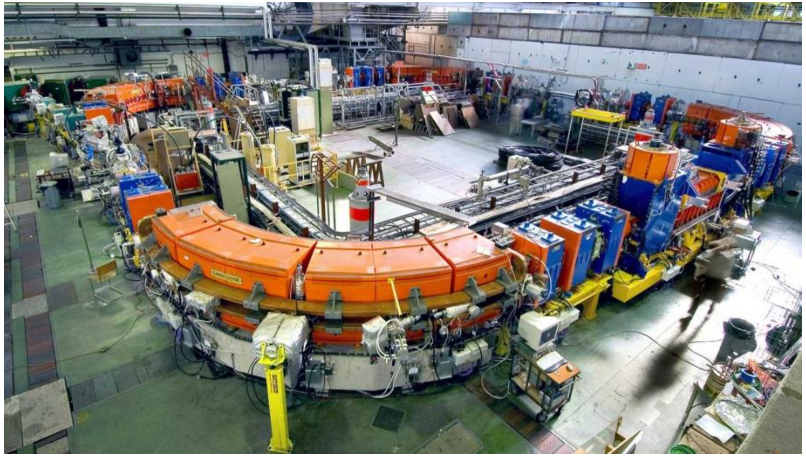
→ Powerful tool to retrieve the beam parameters!

W/ collective effects (e.g. impedance), the Schottky spectrum is deformed with intensity.

The deformation can be "used" to retrieve the impedance of a machine.

Example from LEIR

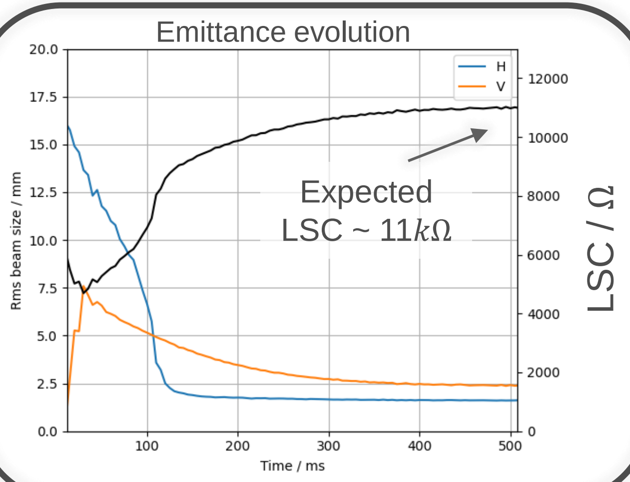
No, not another intro ☺

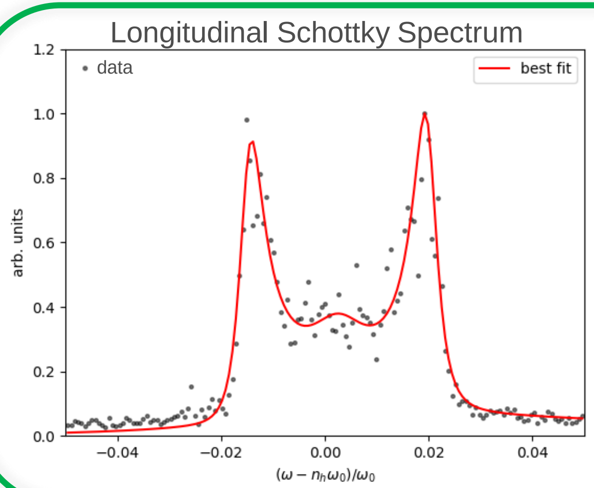


JUAS @ LEIR, 23-1-2023

Reconstructing the longitudinal impedance

In LEIR we can experimentally measure the Longitudinal SC (LSC).





Reconstructed LSC and momentum spread

$LSC = (10746 \pm 144)\ \Omega$

$\delta_p^{rms} = 1.8 \cdot 10^{-4} \pm 1\%$

Similar approaches can be used for the transverse space charge …

Many more methods, e.g.:

- *Loss Landau damping*
- *BTF*
- *AC-dipole*
- *Schottky*
- *Debunched beams*
- *....*

Beam-based impedance measurements

Better the synergy between methods better the machine impedance model is!

Transverse plane

Real part

Rise time vs Q'

Imaginary part

- Tune shift vs intensity
- Phase advance shift "
- Orbit distortion "
- Tune shift vs energy

Longitudinal plane

Real part

Synchronous phase shift vs intensity

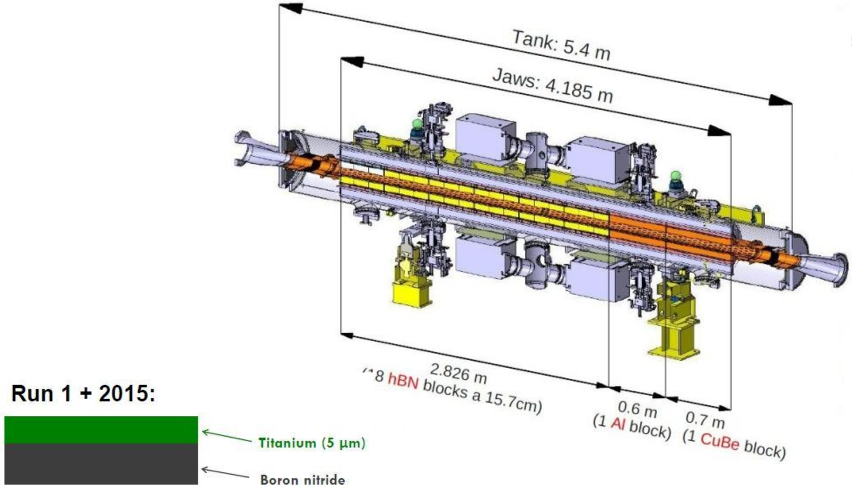
Imaginary part

Quadrupole frequency shift vs intensity

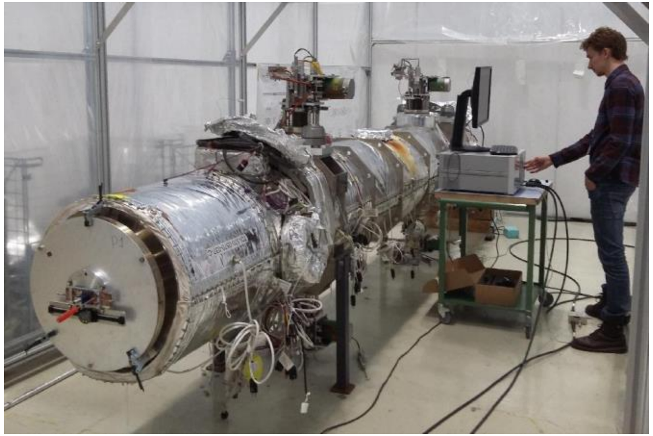
Synergy of methods can help identifying issues

Example: The TDI (Target Dump Injection) is a special device installed in the LHC aiming at protecting the machine from injection failures.

- There is one device per beam: TDI8 (for beam 2) and TDI2 (for beam1)
- The absorbing blocks should sustain the impact of a full LHC beam!
- The jaw was made of a series of Ti-coated hBN blocks, NEG coated Al and CuBe



Courtesy I.Llamas Garcia

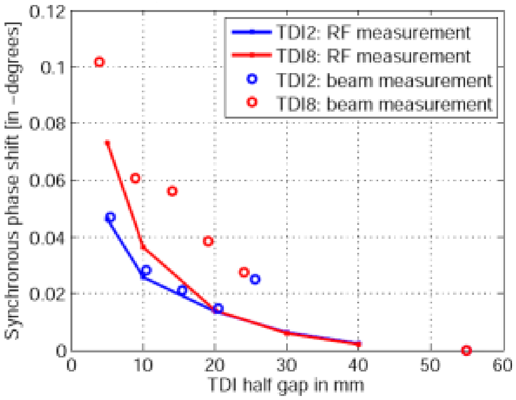


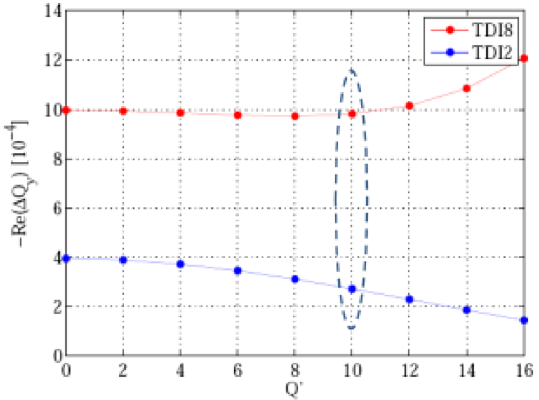
A TDI under “impedance” test

Synergy of methods can help identifying issues

In 2015 an anomalous behaviour was oberved on TDI8 (excessive vacuum spikes)
Correlated with:

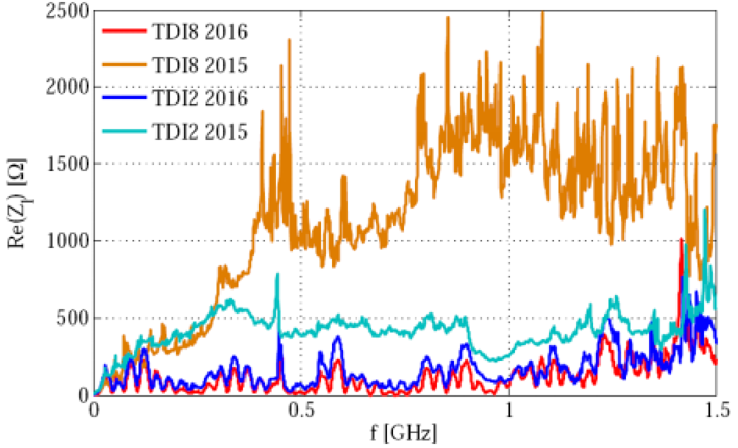
- x2 higher synch. phase shift -> longitudinal impedance
- x4 higher tune shift -> transverse impedance

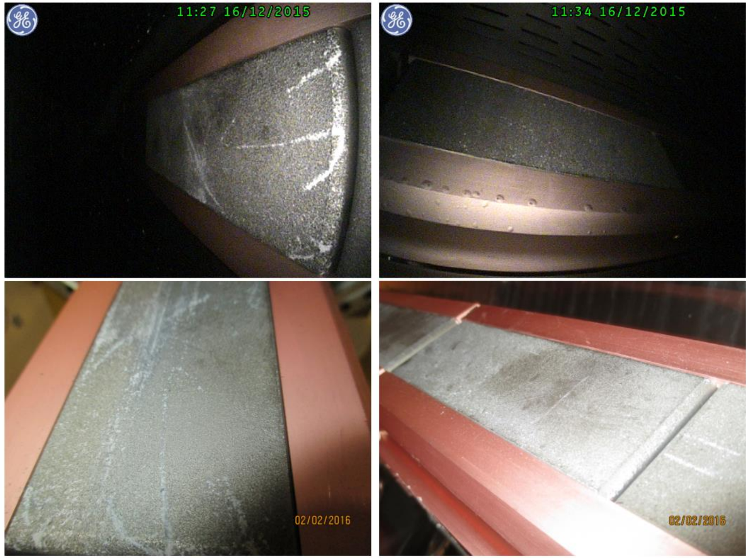




Synergy of methods can help identifying issues

Further confirmed by impedance bench measurements (see JUAS course II) and visual inspection (Ti coating on hBN partly removed).





The issue triggered the device upgrade and installation of alternative absorbers.

Thanks for your attention!

Questions?