Beam Based Impedance Measurements

CAS - Intensity Limitations in Particle Beams
4 November 2015

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CERN

Why do we need to measure impedance with beam?

Indeed beam coupling impedance of various machine elements can be estimated using

- advanced EM simulations (various codes)
- bench measurements – see previous talks!

→ To verify how good is the existing impedance model since

- there are elements - difficult for measurements and calculations,
- material properties are not always well known,
- nonconformities also exist…

→ To identify the offending impedance driving instability or posing some other intensity limitations

Outline of the talk:
impedance measurements with

- Stable beam:
  - synchrotron (and betatron) frequency shifts
  - change in debunching time
  - bunch lengthening

  → reactive impedance (ImZ)
  - synchronous phase shift → resistive impedance (ReZ)
- Unstable beam: instability characteristics
  - spectra
    - single bunch (RF off)
    - multi-bunch (RF on)
  - growth rates
  - thresholds

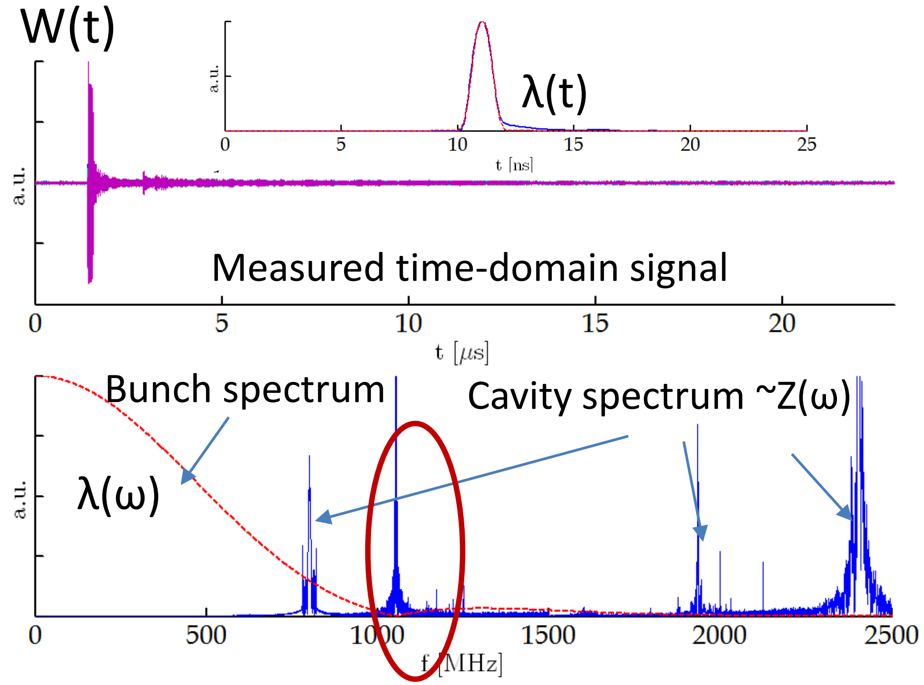
→ Practically all intensity effects can be used for impedance evaluation by comparison of measurements with simulations and/or analytical formulas!

Below: circular, proton, high energy (> GeV) accelerators → relatively long bunches (ns) – very different from ps or even fs bunches for the impedance range of interest

Measurements with stable beam

Beam measurements: intermediate case

Impedance of particular element in the ring (cavity, …) can be evaluated from the signal excited by a single bunch with known (measured) profile.



$Z(\omega) \sim W(\omega)/\lambda(\omega)$

Example [1]: ~2 ns long bunch excites fundamental and HOM modes in the probe of the SPS 800 MHz TW cavity (f_0 = 43.4 kHz, n_r = 4x4620)

Absolute values depend on RF probe characteristics, but can be evaluated for the SW structures

[1] J. Varela et al., CERN ABT-Note-2015, to be published, 2015
[2] See also J. M. Byrd et al., NIM A 455, 2 (2000) and article in Handbook of Accelerator Physics and Engineering, 2nd edition, edited by A. Chao et al.

Potential well distortion

In equilibrium the particle distribution is a function of Hamiltonian H: F = F(H) with potential well defined by the total voltage seen by a particle:

$$V(\varphi) = V_{rf}(\varphi) + V_{ind}(\varphi),$$

where $V_{ind} = - e\,\omega_0\, \Sigma_n\, G_n\, Z_n\, e^{in\theta}$, $\omega_0 = 2\pi f_0$ is revolution frequency, $Z_n = Z(n\omega_0)$

G_n is the n-th Fourier harmonic of the bunch line density λ in equilibrium

→ Modified synchrotron frequency distribution (not only the shift)

→ Bunch lengthening (or shortening – depends on sign of ηImZ)

- Haissinski equation for electron bunches in equilibrium
- Arbitrary distribution function for proton bunches

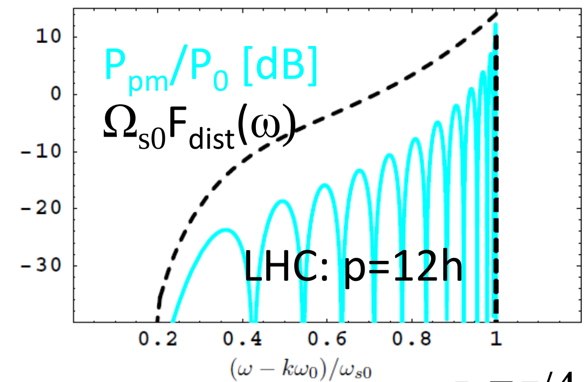
→ Synchronous phase shift

Measurements of incoherent synchrotron frequency

- Longitudinal Schottky: spectral density of current fluctuations [1]:

$$P(\omega) = \frac{e^2 N \omega_0^2}{2\pi} \sum_{k=-\infty}^{\infty} \sum_{\substack{m=-\infty \\ m\neq 0}}^{\infty} \frac{1}{|m|} F\left(\frac{\omega - k\omega_0}{m}\right) |I_{mk}(J)|^2,$$

for short bunches $I_{mk} \simeq i^m J_m(k\phi_a/h)$



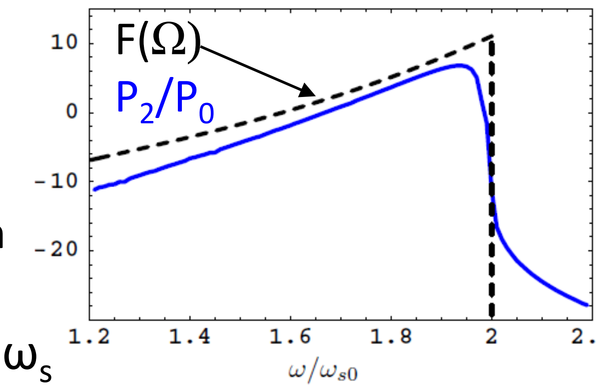
$\sigma_\varphi=\pi/4$

- Peak detected Schottky: power spectral density (quadrupole line) [2]

Frequency distribution

$$P_U(\omega) = \frac{P_0}{\omega_{s0}^2} \sum_{m=1}^{\infty} \int \Omega^2 F(\Omega) |A_m(\Omega)|^2 \, |S(\omega - m\Omega)|^2 d\Omega,$$

The PD Schottky spectrum deviates from distribution function $F(\Omega)$ mainly due to form-factor $A_m(\Omega)$



- Bunch excitation by phase modulation at $\omega_{mod} \sim \omega_s$

[1] S. Chattopadhyay, CERN-84-11, 1984

[2] E. S., T. Bohl, T. Linnecar, Proc. HB2010

Incoherent synchrotron frequency shift and bunch lengthening

The total voltage seen by the bunch is

$$V(\varphi) = V_{rf}(\varphi) + V_{ind}(\varphi),$$

For inductive impedance $V_{ind} = - L\, dI/dt = - e/\omega_0 \; \mathrm{Im}Z/n \;\; d\lambda(t)/dt$

For small amplitude synchrotron motion

$$V \approx [V_0 \cos\varphi_s - e \; \mathrm{Im}Z/n \; d^2\lambda/dt^2/(h\omega_0)\,] \; \varphi$$

For a parabolic bunch $\lambda = \lambda_0 (1 - 4t^2/\tau^2)$ with $\lambda_0 = 3N/(2\tau)$, N - number of particles

Synchrotron frequency:

$$\omega_s^2 = \omega_{s0}^2 \left[1 + \frac{3 \; \mathrm{Ib} \; \mathrm{Im}Z/n}{\pi^2 V_0 \cos\varphi_s \, (f_0\tau)^3}\right],$$ where bunch current $I_b = Nef_0$

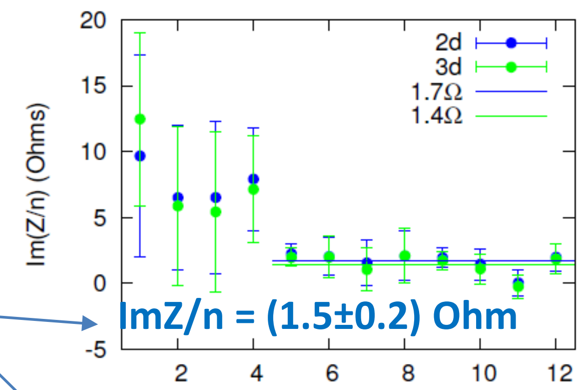
→ Strong dependence on bunch length

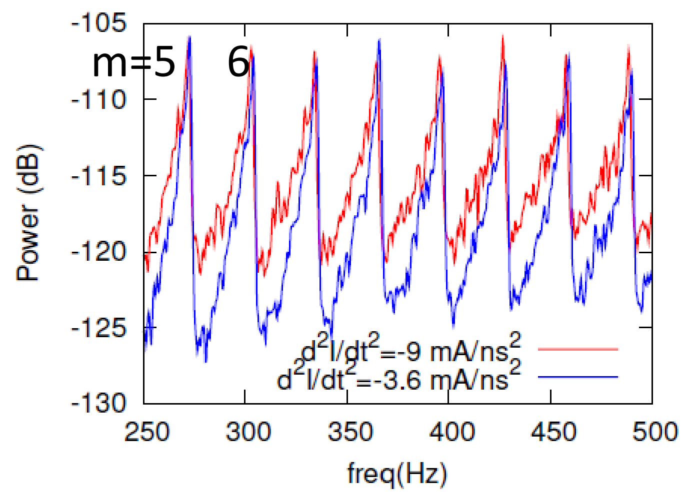
→ Defocusing effect above transition ($\cos \varphi_s < 0$) for $\mathrm{Im}Z/n > 0$

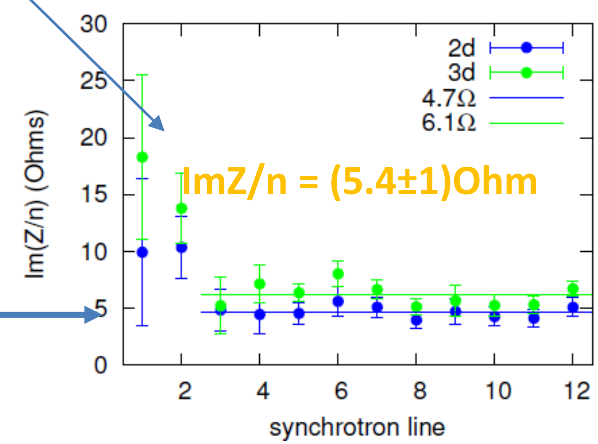
Bunch lengthening is described by equation: $1 = (\tau/\tau_0)^4 + (\tau/\tau_0)\,[\omega_s^2(\tau_0) - \omega_{s0}^2]/\omega_{s0}^2$

Incoherent synchrotron frequency shift from longitudinal Schottky spectrum

- Measure the distance between positive and negative sidebands $2m\Delta f_s$ for different m with time (intensity decay)
- Fit parabolas to top 30% of averaged bunch profiles to find λ″(t) and use it in the fit
- Blue and yellow RHIC rings are very similar, the source of the difference is not known yet







M. Blaskiewicz et al., IPAC'15

Incoherent synchrotron frequency shift: LHC at 450 GeV

LHC Design Report: $ImZ/n = 0.1$ Ohm

Measurements of the LHC impedance:

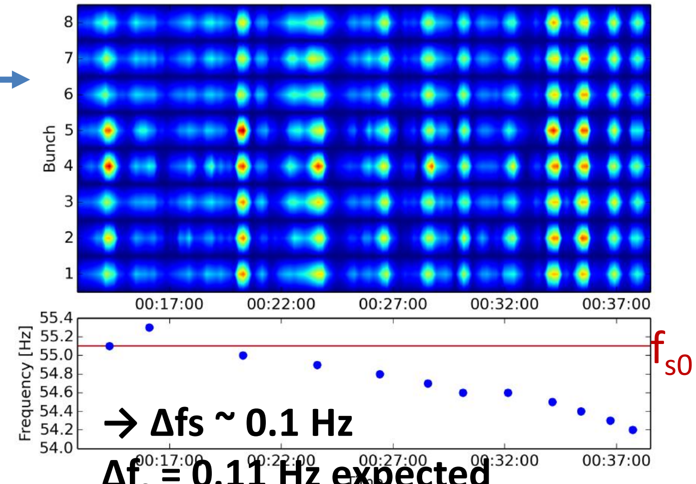
(1) Phase modulation (via cavity set point):

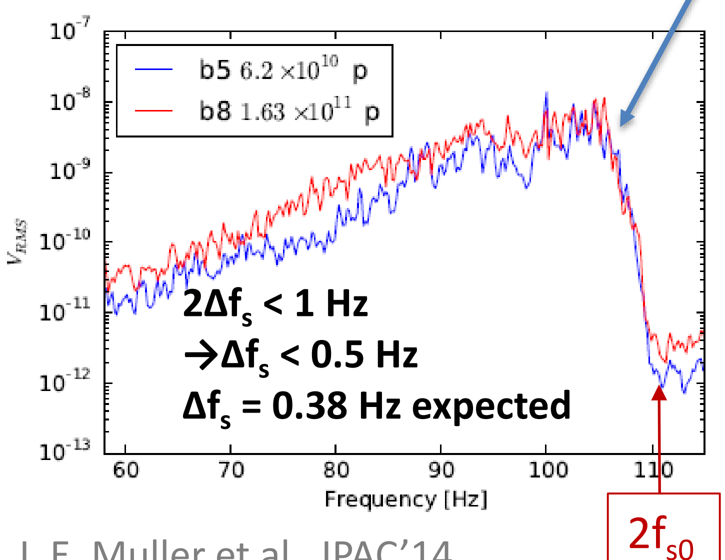
$\varphi = \varphi_0 \sin(\omega_{mod}\, t) \rightarrow$ scan ω_{mod} from above to see bunch excitation as a function of intensity

(2) Peak detected Schottky spectrum

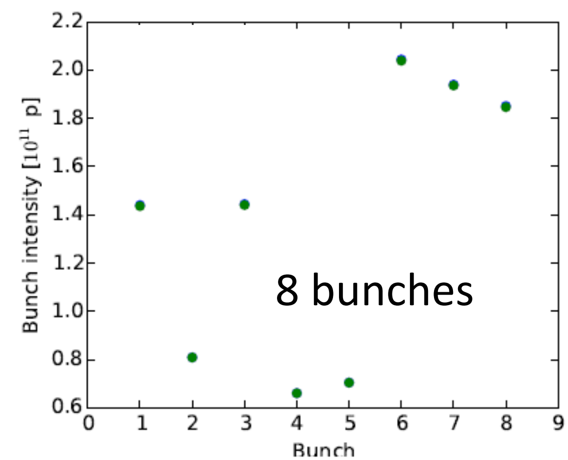
m=2 line ~ synchrotron frequency distribution

Derivative of the 400 MHz component





J. E. Muller et al., IPAC'14



(3) Loss of Landau damping is the most accurate estimation so far (see below)

Coherent synchrotron frequency shift

- Dipole oscillations → negligible effect
- Quadrupole oscillations → mismatched bunches

The shift of quadrupole oscillation frequency:

$$\omega_{2s}(N) = \Delta\omega_{inc}(N) + \Delta\omega_{coh}(N) + 2\omega_{s0},$$

where $\Delta\omega_{inc} \sim \mathrm{Im}Z_1$, $\Delta\omega_{coh} \sim \mathrm{Im}(Z/n)^{m=2}_{eff}$ and

$$\mathrm{Im}(Z/\omega)^m_{eff} = \frac{\sum_{p=-\infty}^{\infty} h_m(\omega_p) Z(\omega_p)/\omega_p}{\sum_{p=-\infty}^{\infty} h_m(\omega_p)}, \qquad \omega_p = p\omega_0 + m\omega_s$$

For a Gaussian bunch $h_m(\omega) = (\omega\sigma)^{2m} e^{-\omega^2\sigma^2}$; $\quad Z_1 \simeq \sum_{p=-\infty}^{\infty} p\, \mathrm{Im}Z(\omega_p) e^{-\omega_p^2\sigma^2/2}$

- Loss of Landau damping: $\Delta\omega^m_{coh} > \Delta\omega_s$ → $\boxed{|\mathrm{Im}Z|/n < \frac{|\eta| E}{e I_b \beta^2}\left(\frac{\Delta E}{E}\right)^2 \frac{\Delta\omega_s}{\omega_s} f_0 \tau}$

$\Delta\omega_s$ - synchrotron frequency spread inside the bunch

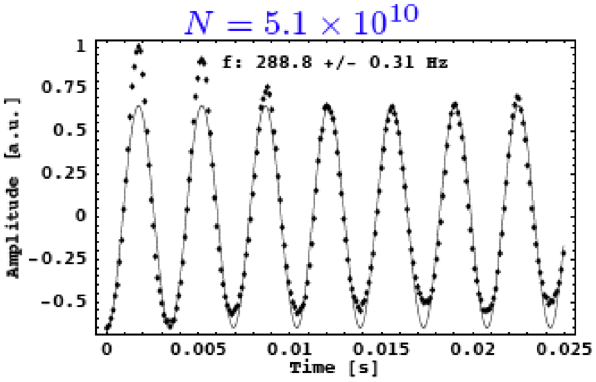
η - slip factor

F. Sacherer, IEEE Trans. Nucl. Sci. NS-20, p.825, 1973

Quadrupole synchrotron frequency shift

Measurements of **quadrupole oscillation frequency** of bunches injected with variable intensity and constant length (SPS, 26 GeV/c) from bunch length, peak amplitude and Schottky signals:

$$\boxed{f_{2s}(N) = a + b \times N/10^{10}}$$



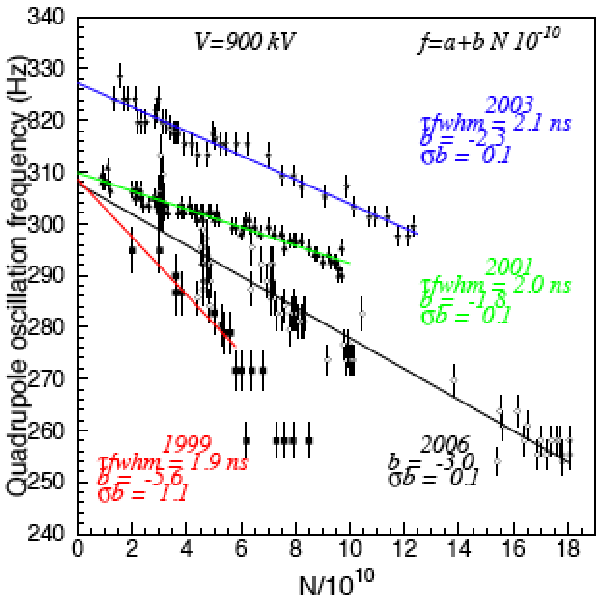
1999: before impedance reduction: **b = -5.6**

2001: SPS impedance reduction: **b = -1.8**

2003: installation of 4 extraction kickers: **b = -2.3**

2006: 5 more kickers installed: **b = -3.0**

→ Successful reference measurements

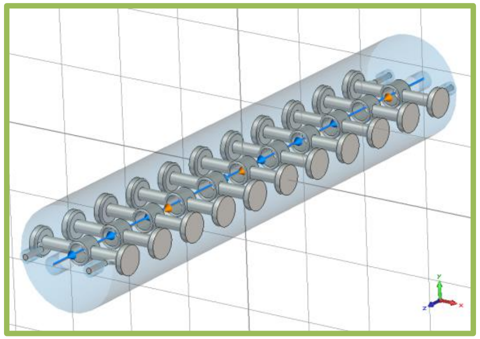


2007: a few kickers serigrafed (shielded) – but effect was not measurable anymore (increase of b)!

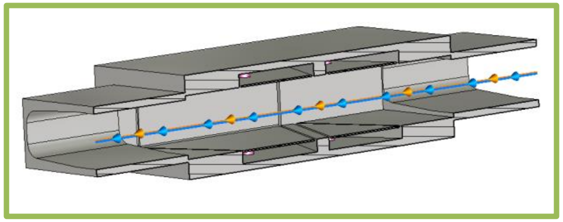
Why?

Realistic impedance model
(CERN SPS)

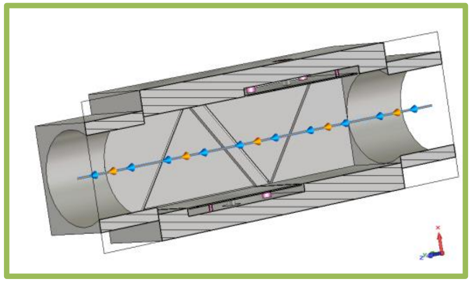
TW RF cavities:
200 MHz and 800 MHz



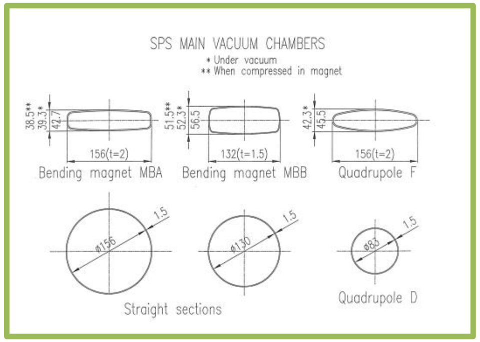
Beam position
monitor H



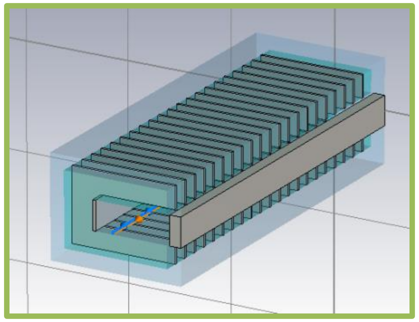
Beam position
monitor V



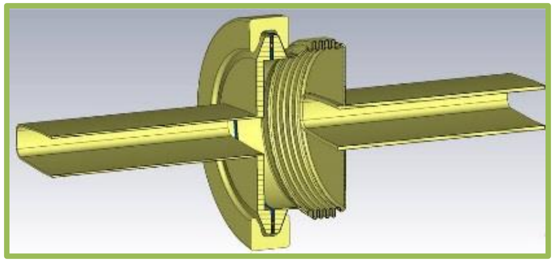
Vacuum chambers



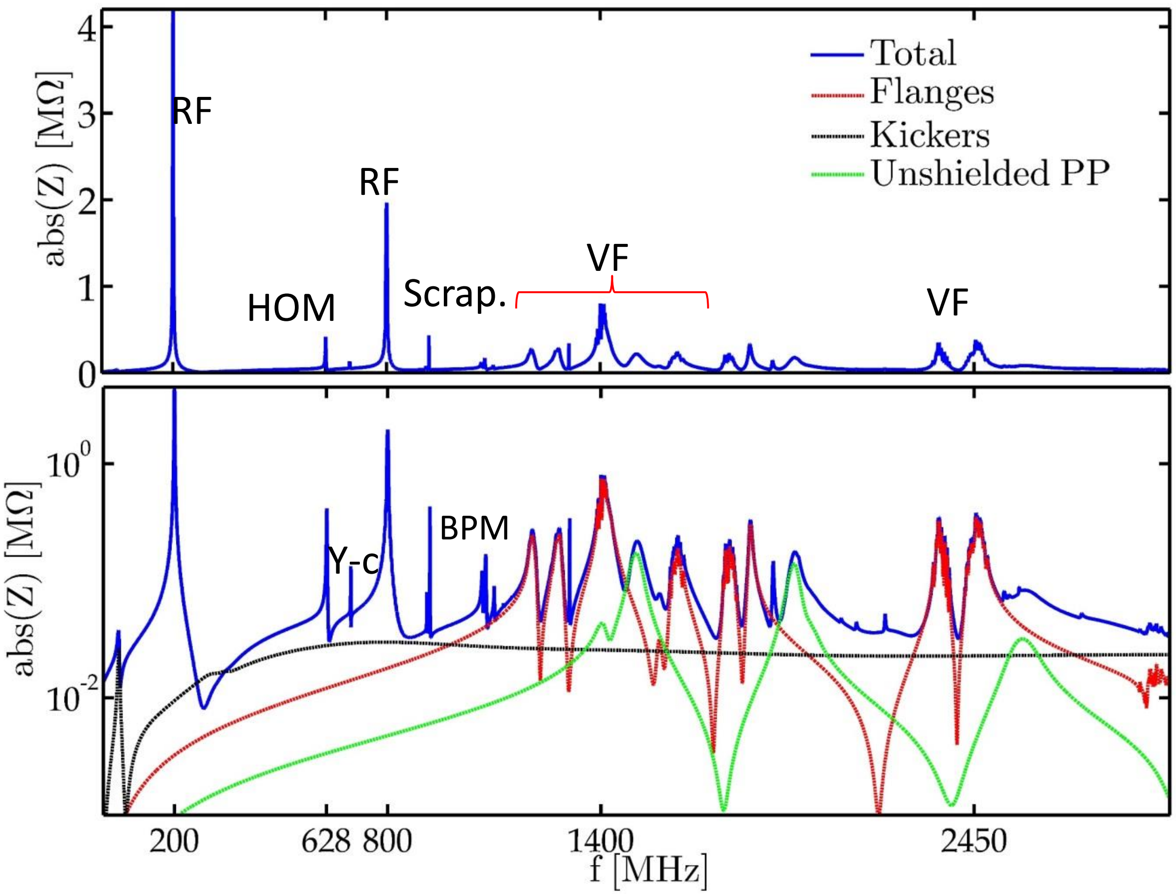
Kickers



Vacuum flanges



Present SPS impedance model



J. Varela, C. Zannini et al., 2015

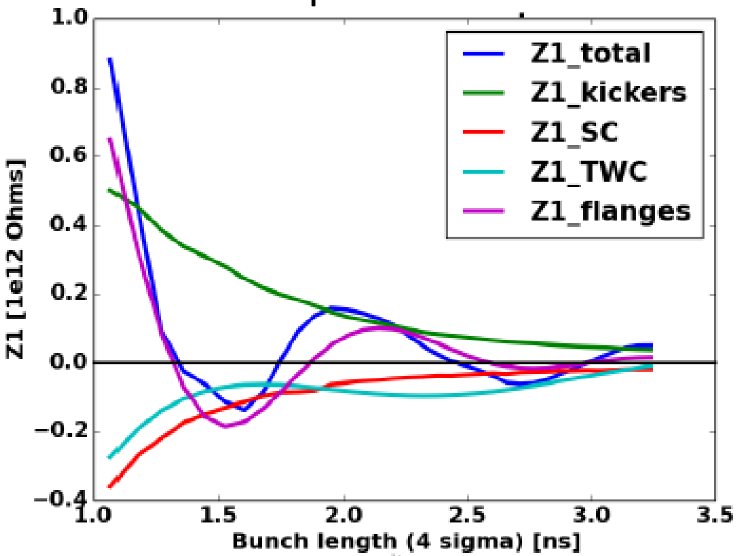
Model includes:

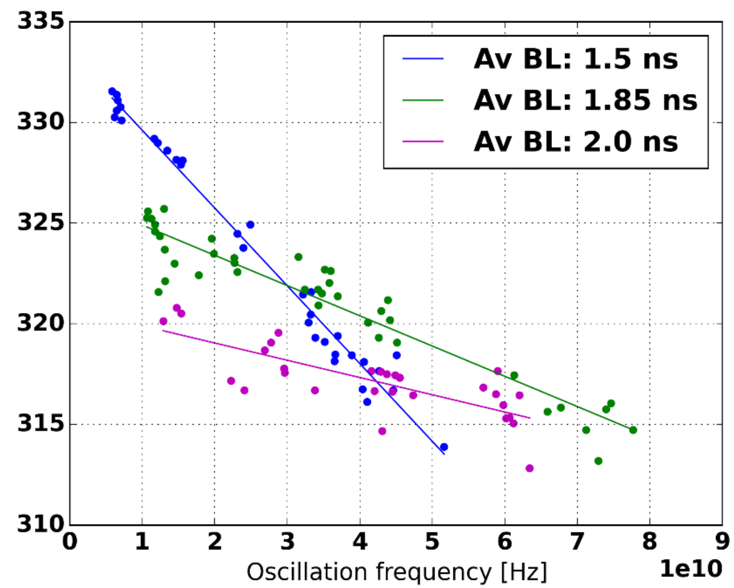
- 200 MHz cavities (2+2) + HOMs
- 800 MHz cavities (2)
- Kicker magnets (8 MKEs, 4 MKPs, 5 MKDs, 2 MKQs)
- Vacuum flanges (~500) + DR
- BPMs: BPH&BPV (~200)
- Unshielded pumping ports (~ 16 similar + 24 various)
  - non-conformal assumed 0
- Y–chambers (2 COLDEX + 1)
- Beam scrappers (3 S + 4 UA9)
- Resistive wall
- AEPs (RF phase PUs, 2) ~ 0
- 6 ZSs + PMs
- 25 MSE/MST + PMs

Synchrotron frequency shift: effective impedance

Realistic ring impedance usually cannot be approximated by constant ImZ/n since its frequency dependence has a complicated structure

Effective impedance Z1 of SPS





A. Lasheen et al., 2015

→ Only effective impedance can be measured with the beam

→ Strong dependence of the synchrotron frequency shift on bunch length

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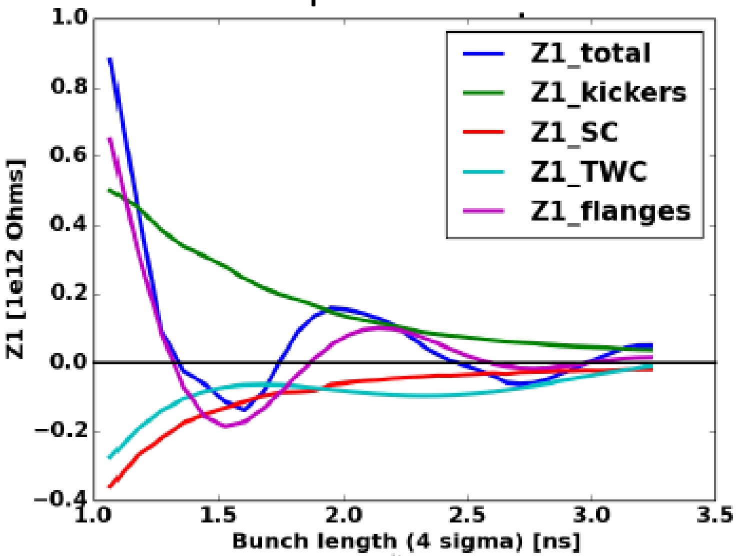

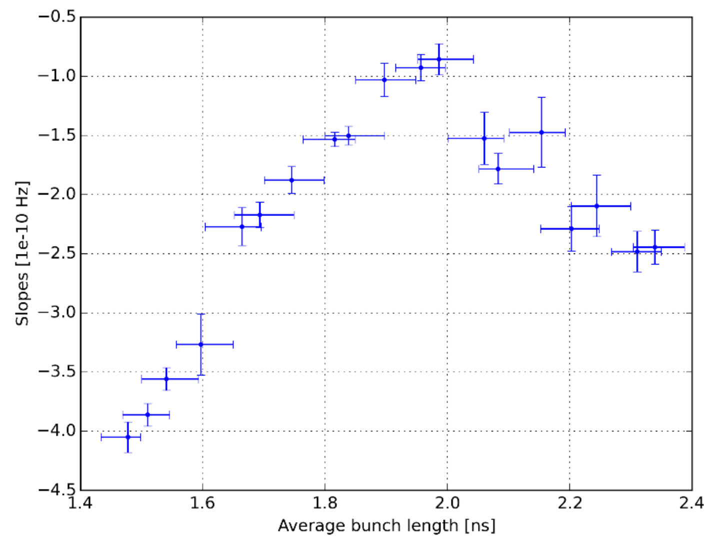

A. Lasheen et al., 2015

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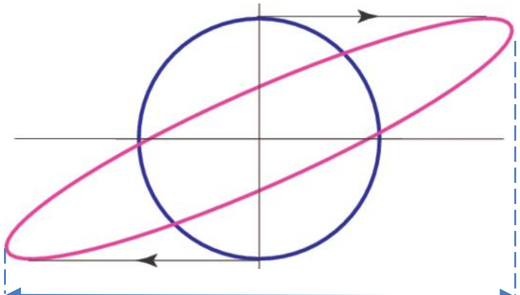
Measurements with RF off: debunching time (1/3)

For a parabolic bunch injected into the ring with RF off variation of bunch length $\tau(t)$ and peak line density $\lambda_p(t)$ with time (debunching process)

$$\frac{\tau(t)}{\tau(0)} = r(t) \quad \text{and} \quad \frac{\lambda_p(t)}{\lambda_{p0}} = \frac{1}{r(t)}$$



can be described using an exact analytical solution of equation (ImZ/n = *const*):

$$\frac{\dot{r}^2}{2} + U(r) = 0, \qquad U(r) = -\frac{\Omega^2(r-1)(1+ar)}{2r^2} \quad \text{where}$$

$$a = 1 + 2\mathrm{sgn}(\eta \mathrm{Im Z})\frac{\Omega_\epsilon^2}{\Omega^2} \qquad \Omega = \frac{2\eta}{\tau}\frac{\Delta p_{max}}{p} \quad \text{and} \quad \boxed{\Omega_\epsilon = \left(\frac{6Ne^2\eta}{\pi E_s \tau^3}\frac{\mathrm{Im Z}}{n}\right)^{1/2}}$$

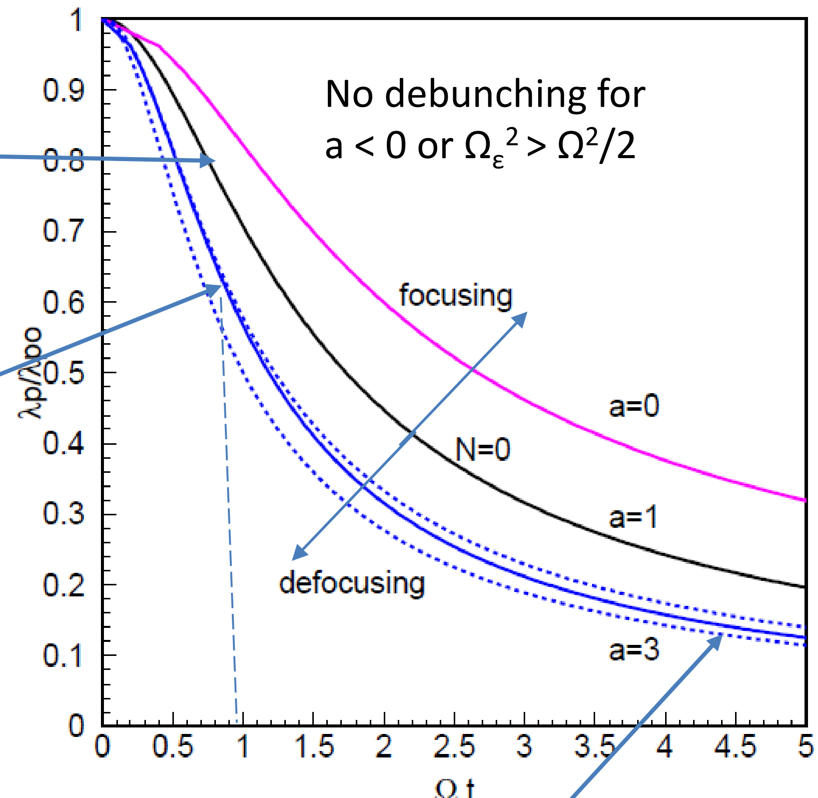
E.S., EPAC'96

Debunching time (2/3)

For N=0: $\tau(t) = \tau(0)\,[1 + \Omega^2 t^2]^{1/2}$
with debunching time $t_d = 1/\Omega$ (a=1).
For matched bunch $\Omega = \omega_{s0}$
(otherwise defined by RF in injector)

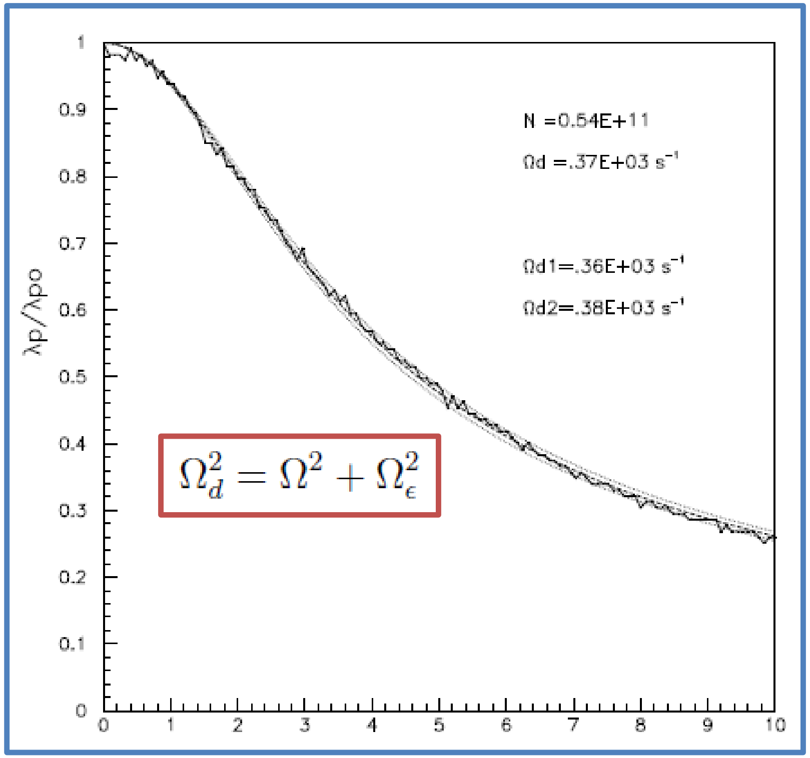
For $t \leq 1/\Omega$
$\tau(t) = \tau(0)\,[1 + (\Omega^2 \pm \boldsymbol{\Omega_\varepsilon^2})\, t^2]^{1/2}$

But… if RF is switched off for matched bunch, $\Omega^2 = \omega^2_{s0} - \Omega_\varepsilon^2$ due to potential well distortion and $t_d \approx 1/\omega_{s0}$
→ no effect can be measured

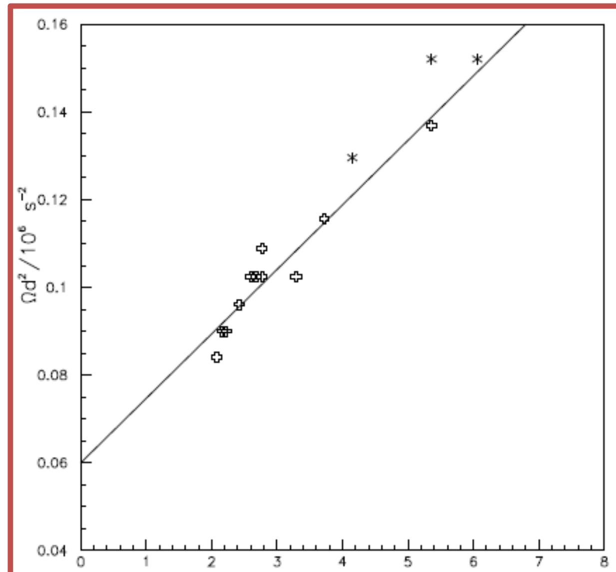


Asymptotic solution for $t \gg 1/\Omega$:
$\tau(t) \approx \tau(0)\,[1 + (\Omega^2 \pm 2\Omega_\varepsilon^2)\, t^2]^{1/2}$

Debunching time (3/3): measurements in the CERN SPS



Time [ms]



$N/10^{10}$

Measured ImZ/n = 18.7 Ohm is slightly higher then values found by other methods (with RF on) at that time (before impedance reduction), most probably due to longer bunches during debunching

Bunch length after rotation can also be used for impedance estimation!

Transverse (reactive) impedance: betatron tune shift measurements (1/2)

Measurements of coherent betatron tune shift due to effective impedance:

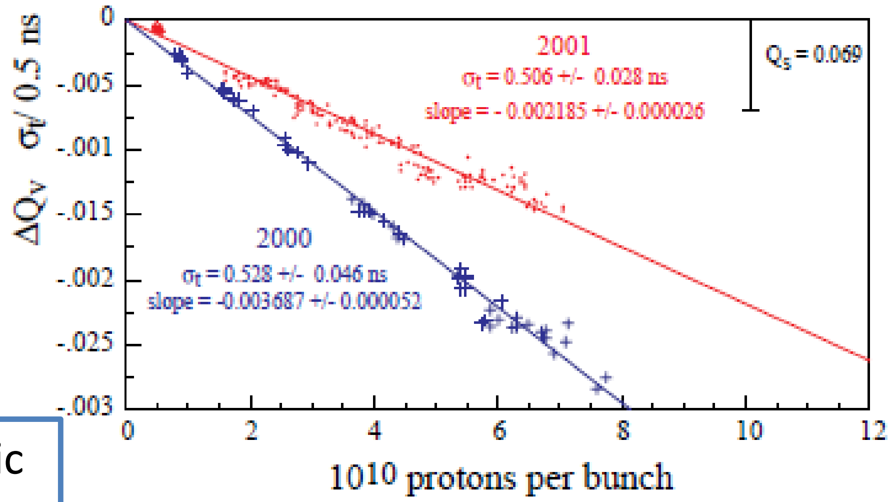
$$\Delta\omega_\beta = \frac{N\,e\,c}{4\sqrt{\pi}\,\omega_\beta\,(E/e)\,T_0\,\sigma_t}\,i(Z_\perp)_{\text{eff}}$$

$$(Z_\perp)_{\text{eff}}(\omega_\xi) = \int_{-\infty}^{\infty} Z_1^\perp(\omega)\,h_m(\omega-\omega_\xi)\,dw$$

where $\omega_\xi = \xi\,\frac{\omega_\beta}{\eta}$

For Gaussian bunch and m=0

$$h_0(\omega) = \frac{\sigma_t}{\sqrt{\pi}}\,e^{-(\omega\sigma_t)^2}$$



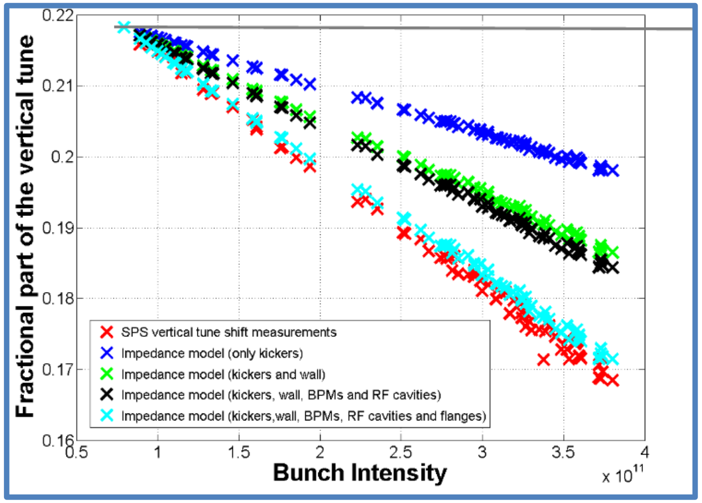
→Tune shift with intensity is one of the basic measurements of total transverse impedance
Results of the SPS impedance reduction are visible in the reference measurements [2]

year	Im Z_x MΩ/m	Im Z_y MΩ/m
2000	-0.9 ± 1.8	26 ± 3
2001	-0.35 ± 0.53	18.4 ± 0.5

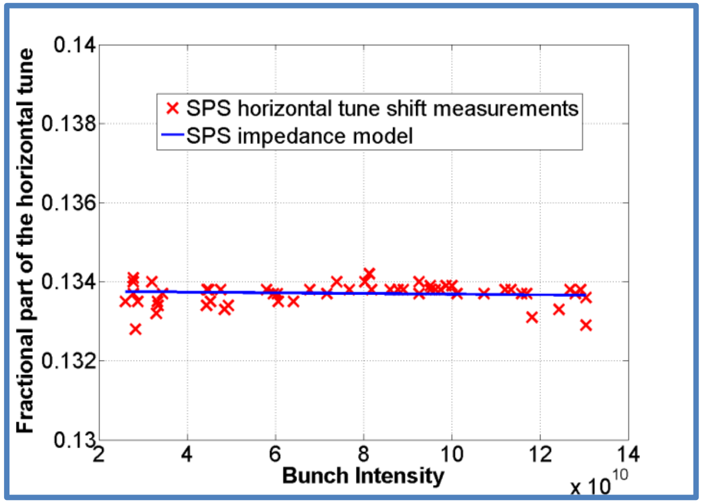
[1] F. Sacherer, Proc. 1976 Erice School, 1977
[2] H. Burkhardt, G. Rumolo, F. Zimmermann, PAC'01

Transverse (reactive) impedance: betatron tune shift measurements (2/2)

SPS vertical tune shift @ 26 GeV/c



SPS horizontal tune shift



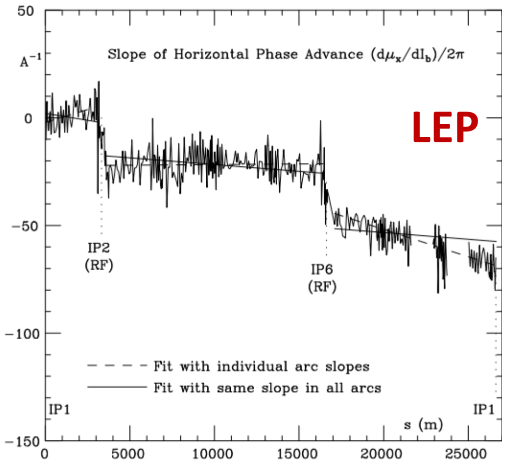
→ Present SPS impedance model reproduces about 90% of the vertical tune measured in the present Q20 optics

C. Zannini et al., PAC'15

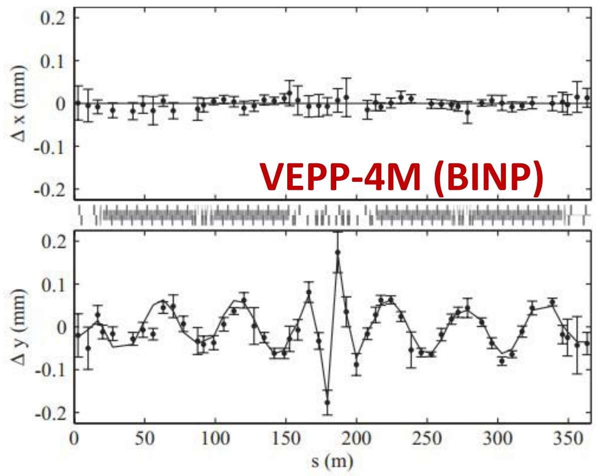
Local transverse impedance measurements

- Betatron frequency depends on current so phase advance does → local phase advance can be measured by BPMs for excited betatron motion
- Orbit bump method (effect on the orbit)
- Orbit Response Matrix fit: small lattice changes due to defocusing effect of impedance can be found (current dependent focusing errors)

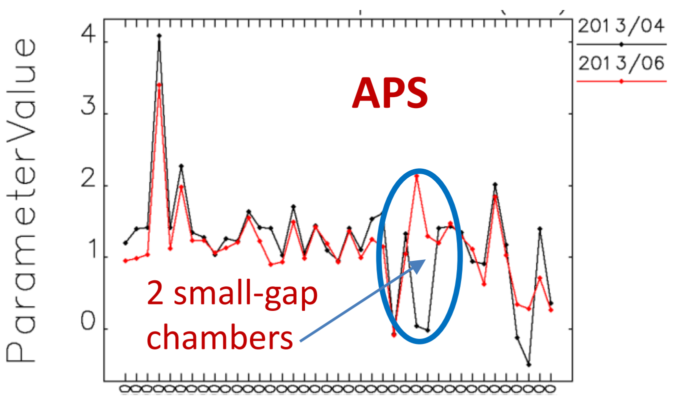
Issues: BPMs(N), orbit drifts…



D. Brandt et al., PAC'95



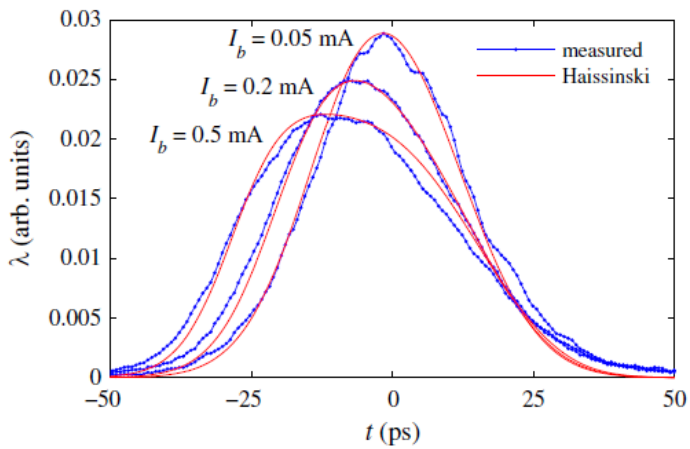
V. Kiselev, V. Smaluk, EPAC'98

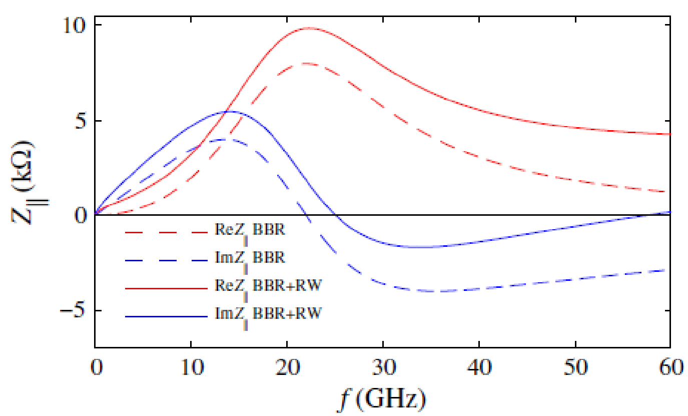


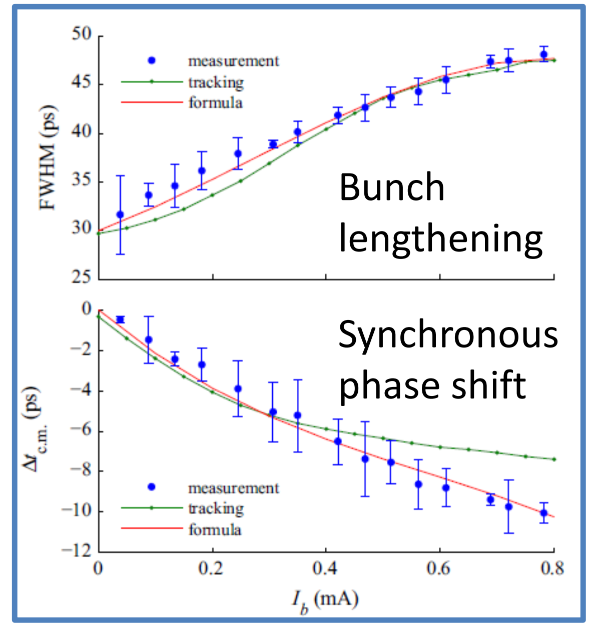
V. Sajaev, PAC 2003,
AOP-TN-2012-046

Longitudinal impedance: bunch lengthening

The measured bunch profiles and Haissinski equation fit





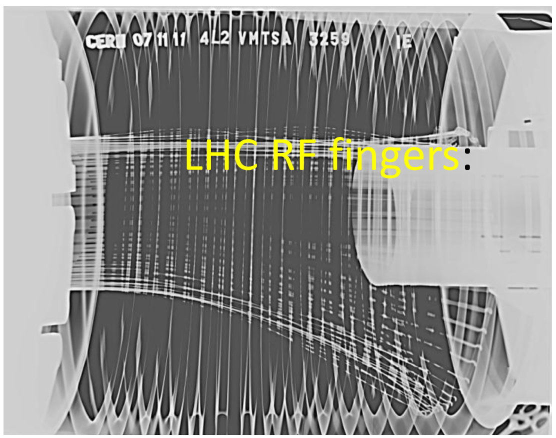


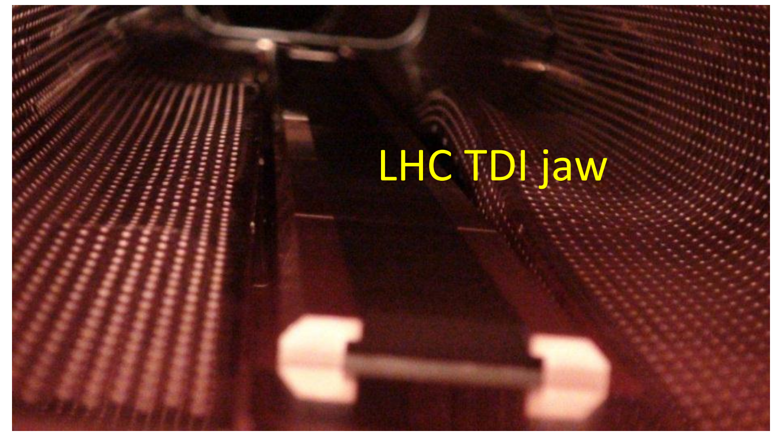
Diamond Light Source (3 GeV): beam-based (longitudinal and transverse) impedance models: broad-band resonators with Q=1 (R_{sh} and ω_r – are fitting parameters)

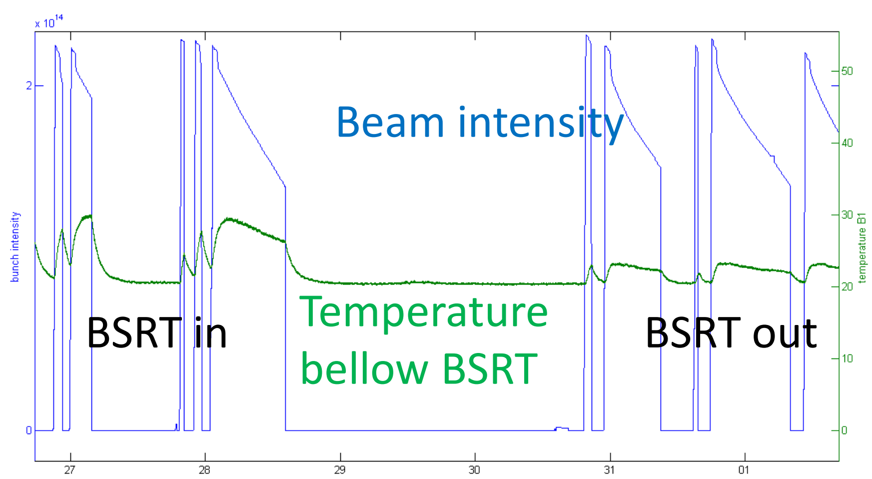
V. Smaluk et al., PRST AB 18, 2015

Resistive impedance measurements: beam induced heating (damage?)

Comparison of expected and measured heating: not very accurate, but very efficient in case of problems







Benoit Salvant et al., 2012 Evian workshop

Measurement of resistive impedance: synchronous phase shift

The energy loss of the bunch per turn and per particle is defined by loss factor k

$$U_b = -e^2 N k = -e^2 N \sum_n k_n(\sigma),$$

For a Gaussian bunch the loss factor k_n due to the longitudinal impedance $Z_n(\omega)$

$$k_n(\sigma) = \frac{\omega_0}{\pi} \sum_{p=0}^{\infty} \mathrm{Re} Z_n(p\omega_0) \exp[-(p\omega_0\sigma)^2].$$

For resonator: $k = \omega_r R_{sh}/(2Q)$ for $\omega_r \tau << 1$

Any energy loss is compensated by the RF system. The shift of the synchronous phase φ_s due to energy loss U_b: $\Delta\varphi_s = U_b/(eV_{rf} \cos\varphi_s) = - eNk/(V_{rf} \cos\varphi_s)$ can be measured

(1) as a distance between two bunches

or as a variation of phase between the beam signal and

(2) reference RF signal (sent from the power amplifies to the cavity)

→ energy loss due to cavity fundamental impedance is included

(3) probe in the cavity which contains information from both applied RF voltage and the induced beam-loading voltage → beam loading is excluded

Synchronous phase shift: distance between two bunches

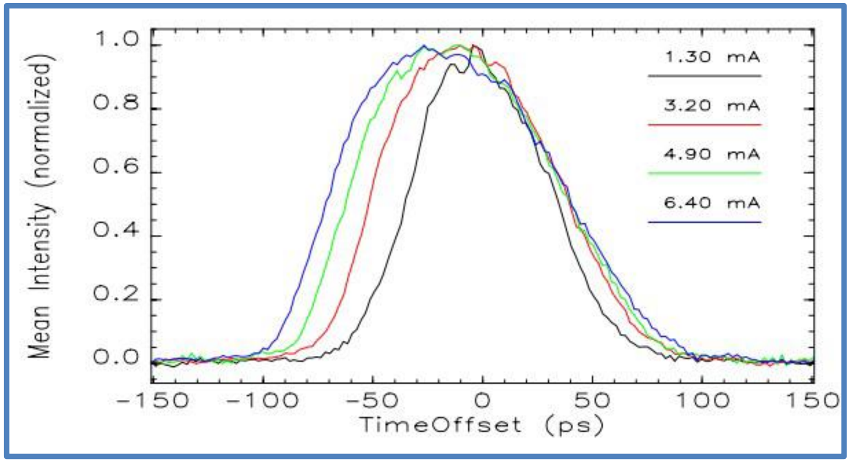
Measuring the distance between two bunches (separated by 1/2 ring) – similar to the reference RF signal (beam loading is included):

Bunch (1) - a time reference bunch (low intensity)

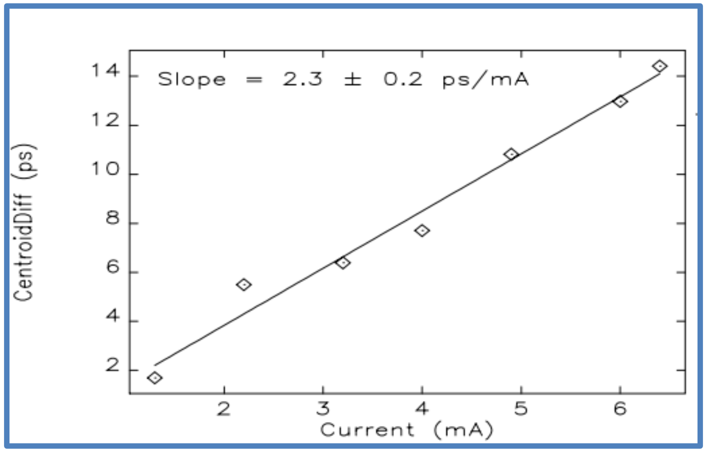
Bunch (2) with varied intensity

→ RF cavities are responsible for 70% of the total measured loss factor

Bunch profile



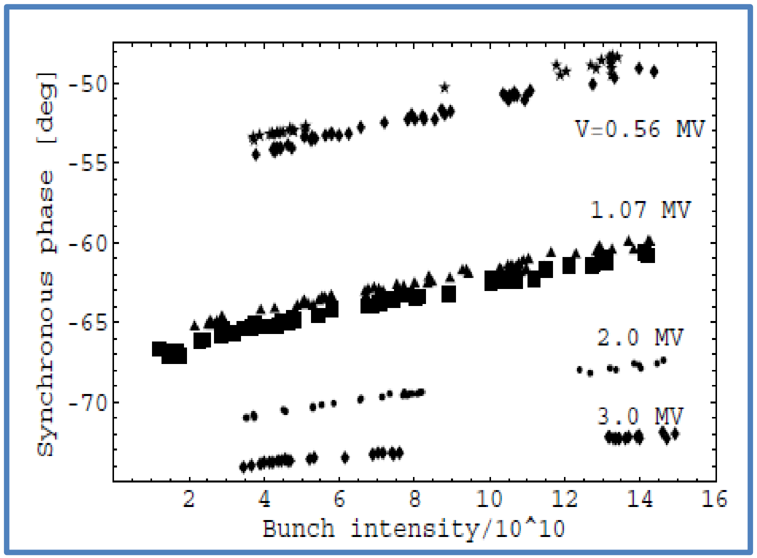
Bunch centroid shift



[1] N. Sereno et al., Proc. PAC'97

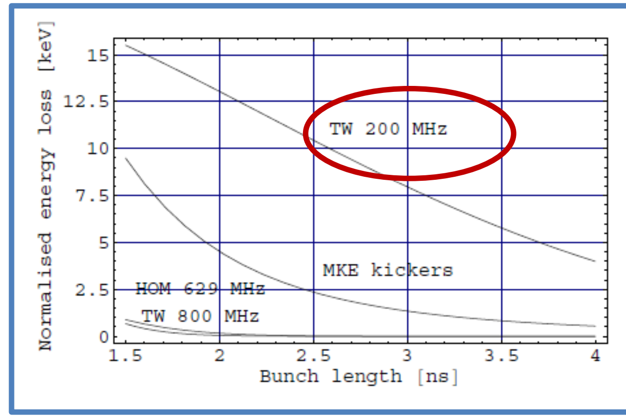
Synchronous phase shift: beam phase relative to the RF reference

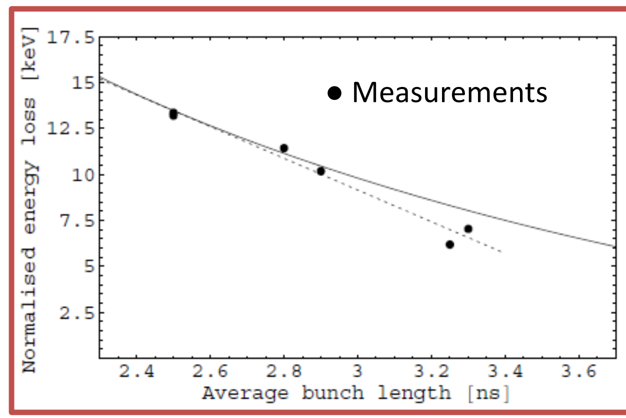
Measurements in the SPS @ 26 GeV/c
Single bunches injected in 4 different RF voltages → dependence on bunch length



$$\phi_{si} = \phi_{0i} + b_i \times (N/10^{10}) \qquad [\mathrm{deg}]$$

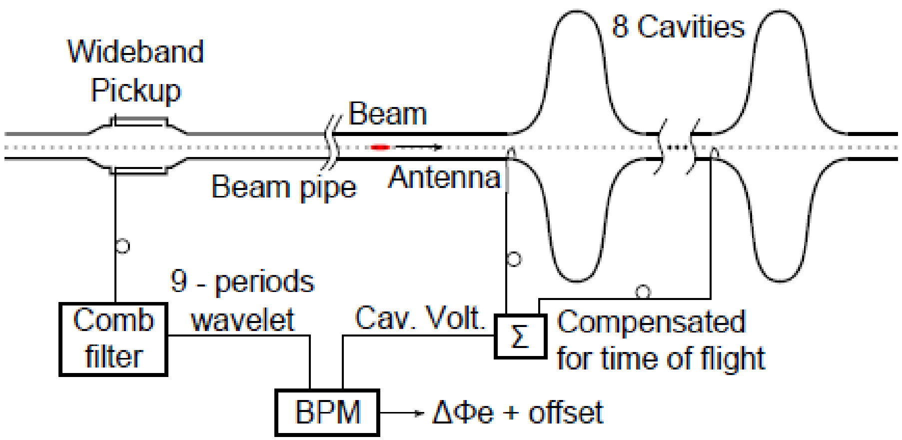
E. S. et al., EPAC'04





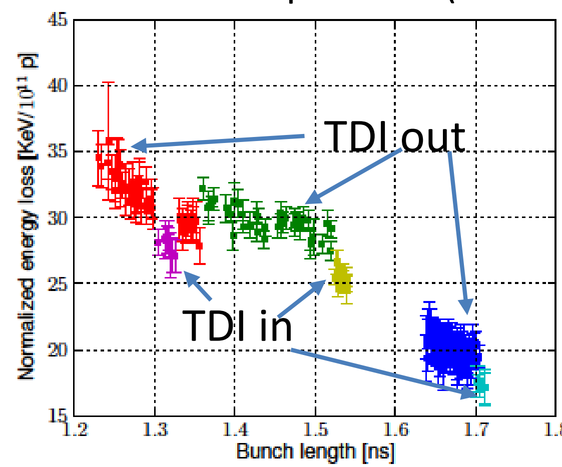
→ Losses are dominated by the main RF impedance of the 200 MHz TW system

Synchronous phase shift relative to measured RF phase: CERN LHC (1/4)



A 400 MHz wavelet is generated from the wideband PU signal and compared in phase to the vector sum of the RF voltages in Beam Phase Module (BPM)

Measured relative effect of the TDI impedance (in - out)



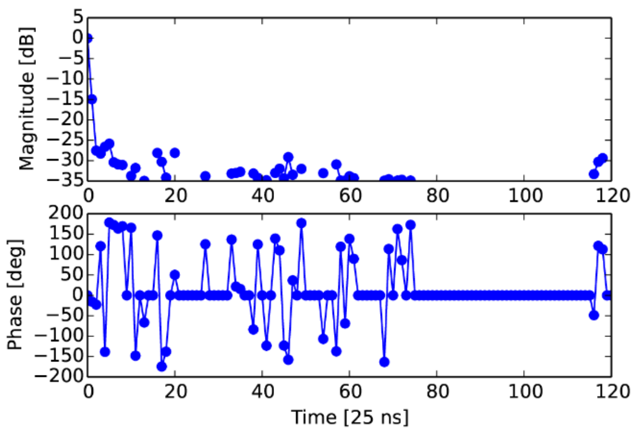
→ Effect of e-cloud on beam is similar to impedance: it causes instabilities, emittance blow-up, losses and heat load! The e-cloud density can be estimated using bunch-by-bunch synchronous phase shift (J. E. Muller et al., IPAC'14)

Very high accuracy is required to measure small shifts < 1 deg!

Bunch-by-bunch synchronous phase shift: measurements in LHC (2/4)

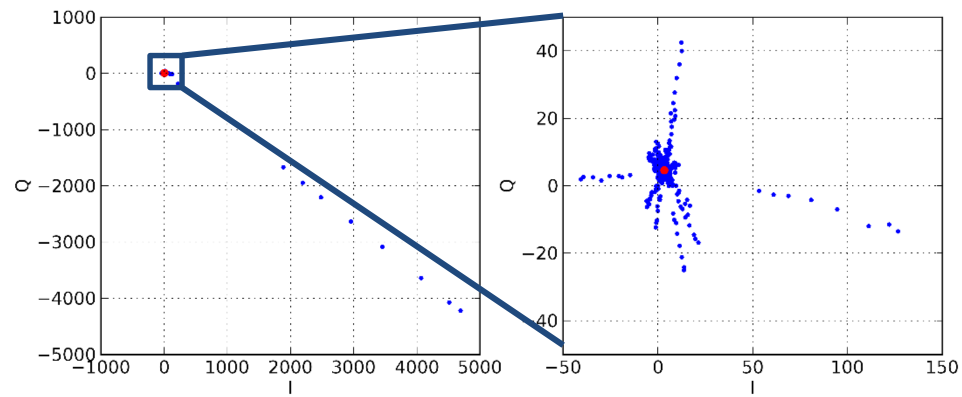
Corrections for systematic errors

(1) Reflections in the cables: affect subsequent bunches



→ Transfer function measured with a single bunch and used for correction

(2) Offset in the IQ plane (vector representation): affects single bunch

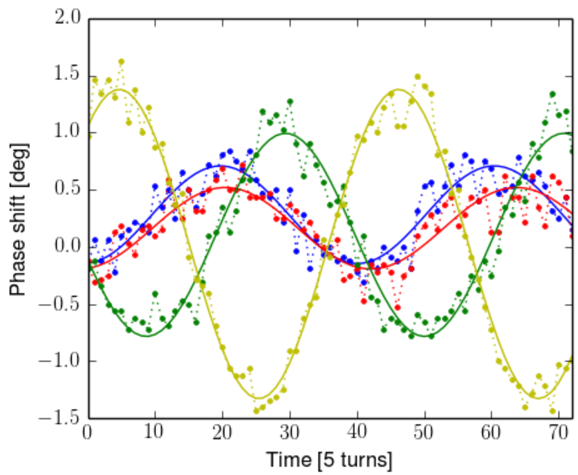


→ Measured from the noise in the empty buckets to correct the origin displacement

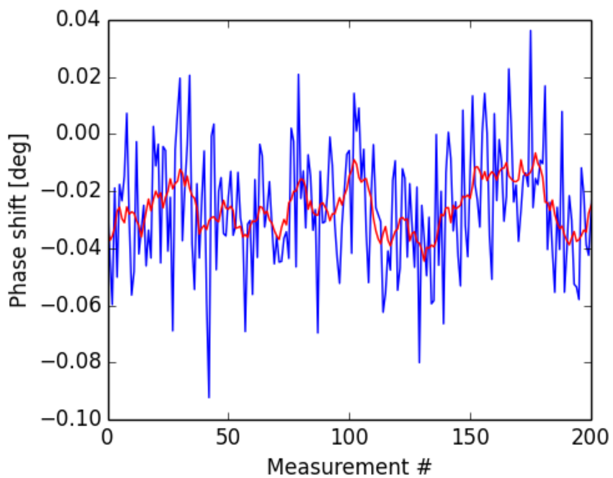
Bunch-by-bunch synchronous phase shift: measurements in LHC (3/4)

Data post-processing

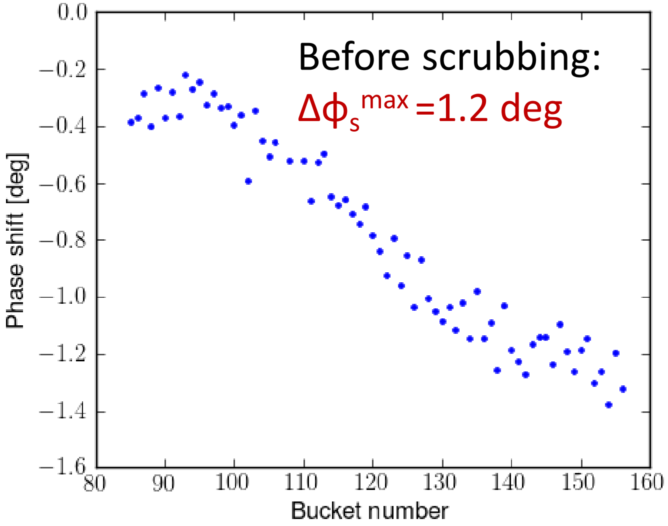
(1) Sine-wave fit of the synchrotron oscillations

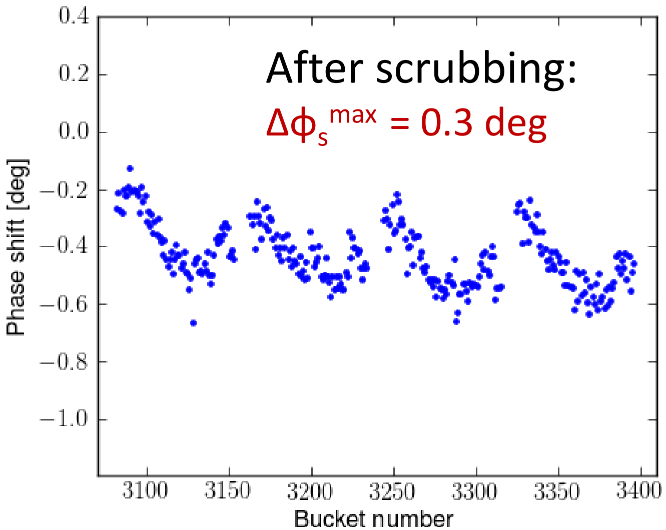


(2) Smoothing phase of each bunch over time

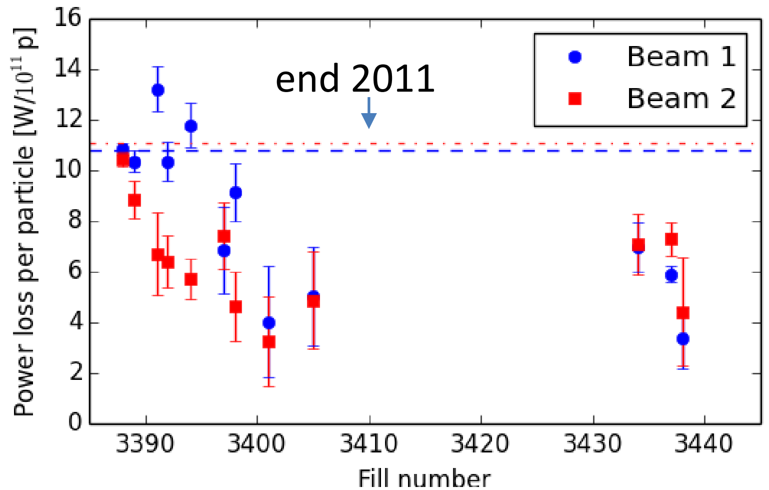


Synchronous phase shift: measurements in LHC for e-cloud (4/4)





Scrubbing effect seen from the maximum power loss per particle (2012)



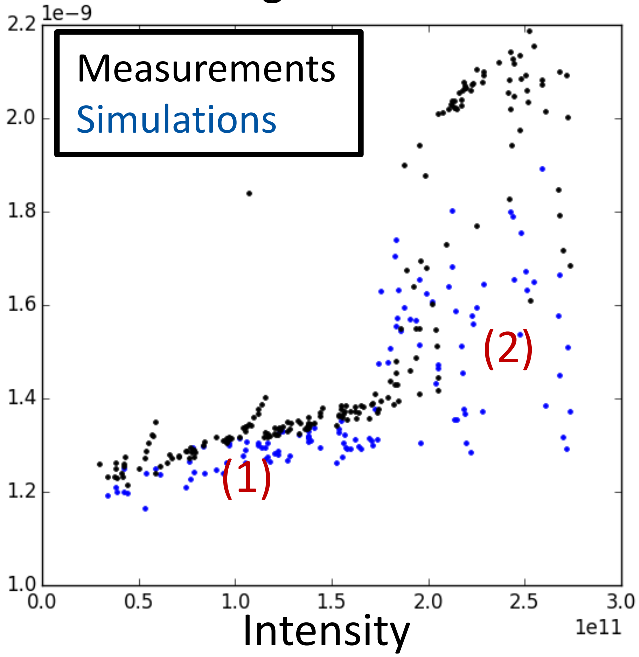
→ From 2015 this is an operational tool available in the CERN Control Center

Comparison with simulations gives good estimate of e-cloud density (see talk of G. Rumolo)

Measurements with unstable beam

Bunch lengthening: single bunch instability

Bunch length at 450 GeV



Simulations of the whole acceleration cycle using full SPS impedance model

A. Lasheen et al., 2015

SPS at 450 GeV (single 200 MHz RF system)

→ Two very different slopes in dependence of bunch length on intensity:

(1) Potential well distortion

(2) Emittance blow-up due to instability

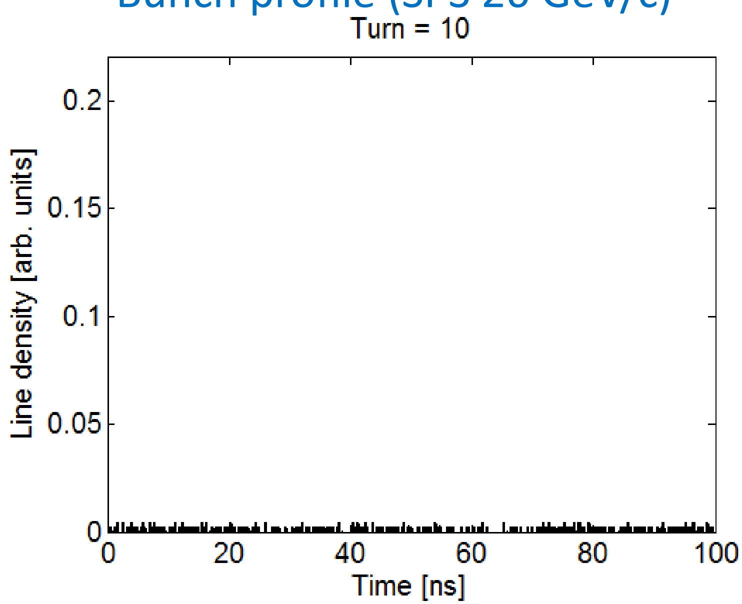
What could be a source of this instability?

Spectrum of unstable single bunches (1/4)

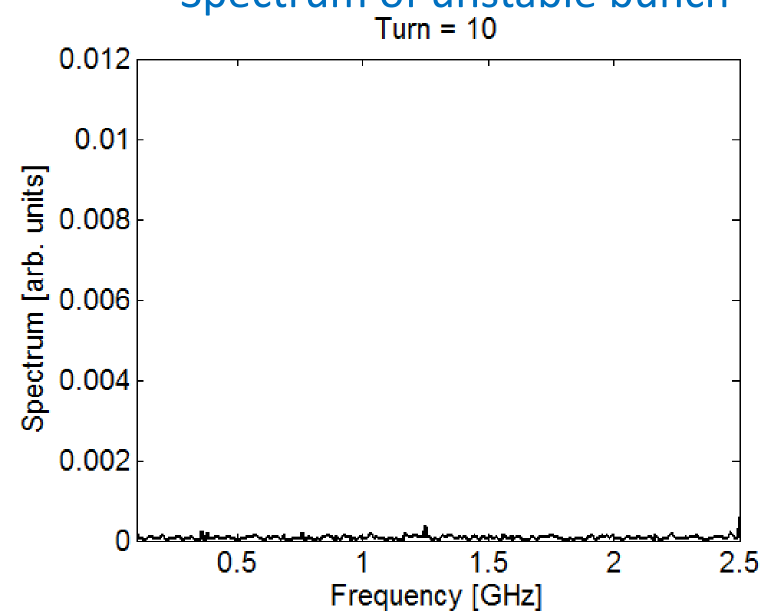
Method of measurement:

- Inject long single bunches into ring with RF off
- Bunches with low momentum spread: slow debunching and fast instability
- Measure bunch profiles or spectrum amplitude at given frequency
- Use projection of spectra to see longitudinal impedances with high R/Q

Bunch profile (SPS 26 GeV/c)



Spectrum of unstable bunch



Single bunch instability with RF off

The linearised Vlasov equation for the line density perturbation $\rho(\theta,t) = e^{-i\Omega t}\sum_n \rho_n e^{in\theta}$

$$\rho_n = -i\frac{\eta n\omega_0}{2\pi E_0}(\frac{e\omega_0}{\Omega})^2\sum_{n'} G_{n-n'}Z_{n'}\rho_{n'}$$

describes a fast microwave instability, assuming particle distribution $F(\theta,\dot{\theta}) = G(\theta)\delta(\dot{\theta})$

For a costing beam $G_{n-n'} = N\delta_{n,n'}/(2\pi)$ and $\Omega_n^2 = -i\frac{(en\omega_0)^2 N\omega_0}{2\pi E_0}\eta\frac{Z_n}{n}$

→ the negative mass instability.

Let's consider a resonant impedance with bandwidth $\Delta\omega_r = \omega_r/2Q$. Two regimes exist:

(1) Narrow-band impedance: $\Delta\omega_r \ll 1/\tau$

→We can assume for n' > 0: $G_{n-n'} \simeq G_{n-n_r}$

Then growth rate $\frac{\mathrm{Im}\Omega}{\omega_r} \simeq \left(\frac{Ne^2\omega_0|\eta|}{16\pi E_0}\frac{R_{sh}}{Q}\right)^{\frac{1}{2}}$

Instability spectrum: $\rho_n \sim nG_{n-n_r}$

→ centered at n ~ n_r with width ~ $1/\tau$

(2) Broad-band impedance: $\Delta\omega_r > 1/\tau$

→For a long Gaussian bunch assume

$$G_{n-n'} = \frac{N}{2\pi}\exp(-\frac{(n-n')^2\sigma^2}{2}) \approx \frac{N}{\sqrt{2\pi}\sigma}\delta_{n,n'}.$$

Growth rate $\Omega_n^2 \simeq -i\frac{(en\omega_0)^2 N}{(2\pi)^{3/2}E_0\sigma_t}\eta\frac{Z_n}{n}$

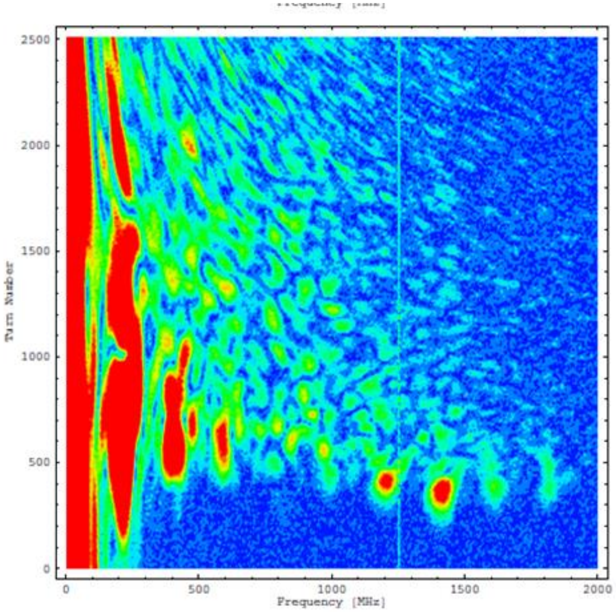
similar to a coasting beam where average current is replaced by peak.

→ Spectrum width ~ impedance $\Delta\omega_r$

Spectrum of unstable single bunches (2/4)

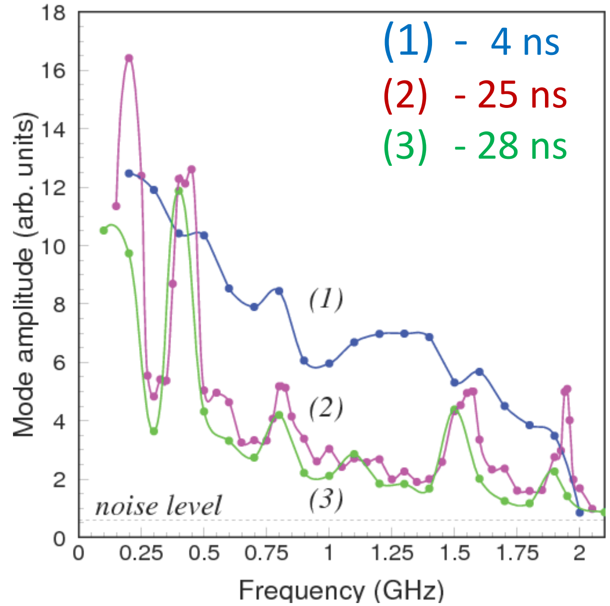
Spectrum of unstable bunch during development of instability

→ time



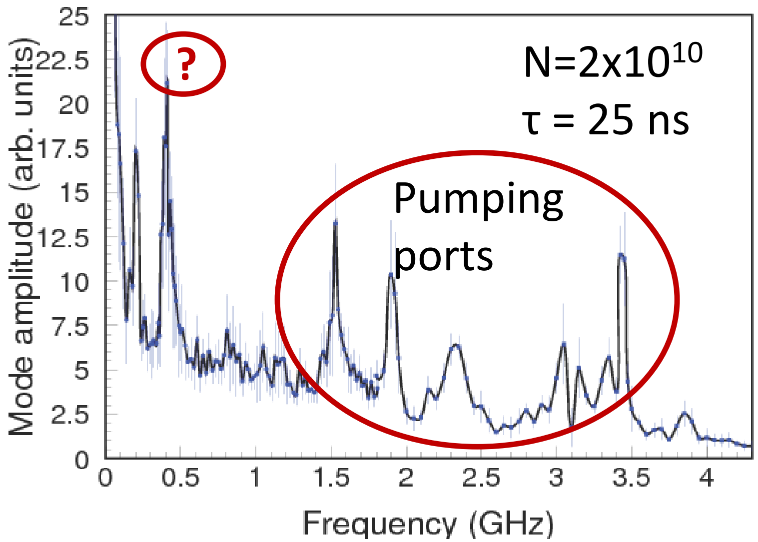
→ To have a good frequency resolution bunches should not debunch too fast: instability growth time << debunching time t_d

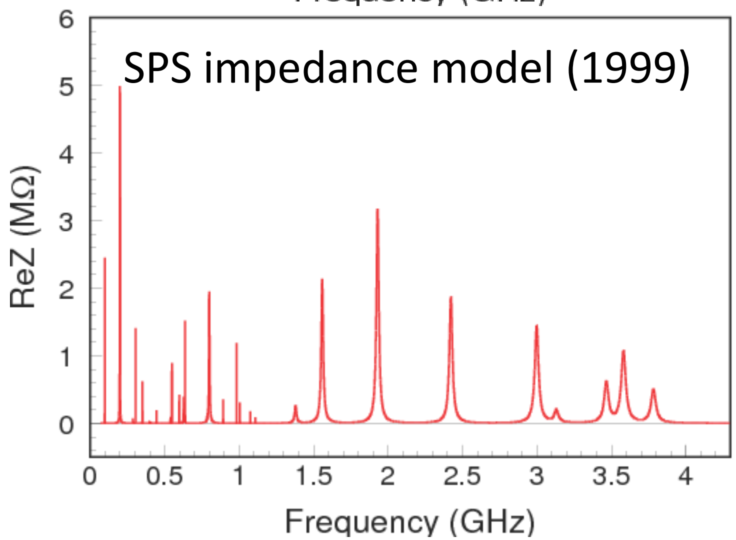
Projection of unstable spectrum measured with short and long bunches



→ Frequency resolution is defined by bunch length (SPS, 1997)

Unstable bunch spectrum: narrow-band impedances (3/4)





The TM_{mnl} modes of a cylindrical cavity with radius r_c and length z:

$$f_r = \frac{\omega_r}{2\pi} = \frac{c}{2}\sqrt{\left(\frac{l}{z}\right)^2 + \left(\frac{u_{m,n}}{\pi r_c}\right)^2}$$

$u_{m,n}$ is the n-th root of equation $J_m(u) = 0$.

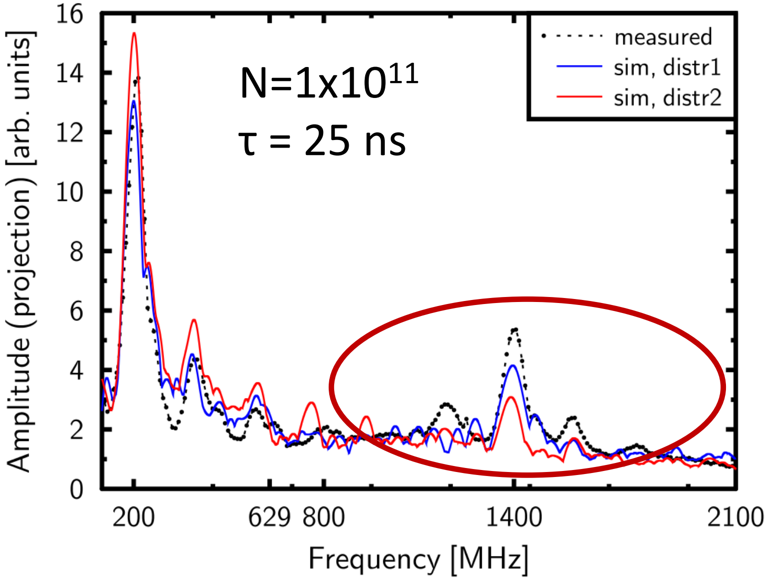
For r = 8.2 cm and z = 20 cm (typical SPS pumping port) the lowest frequencies of the TM01l and TM02l modes (l=0,1,2 …): 1.4, 1.53, 1.88, 2.34, 2.87… GHz

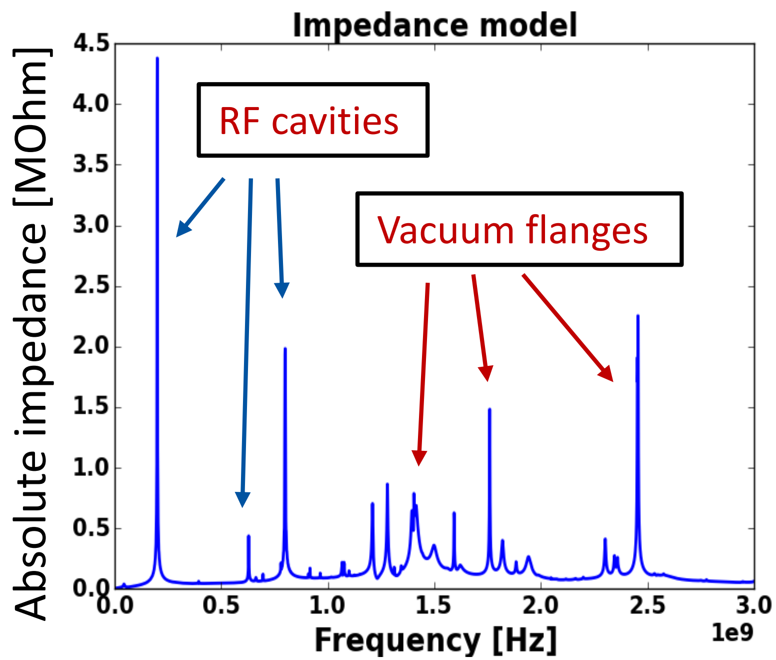
→ all visible in unstable bunch spectrum

The peak amplitude depends on R/Q of the mode (SPS: for ~900 elements with Q~50, maximum R/Q ~40 kOhm)

T. Bohl et al., PRL, 3109, 1997

Unstable bunch spectrum: narrow-band impedances (4/4)



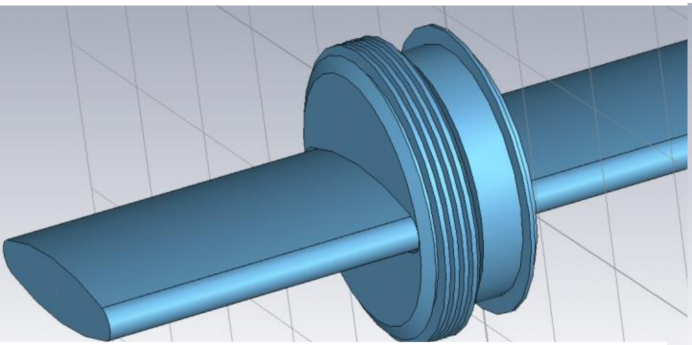


The main source of the longitudinal instability limiting the LHC beam intensity in the SPS has been identified → shielding of ~ 200 vacuum flanges is planned during the next long shutdown (2019 - 2020) together with improved HOM damping

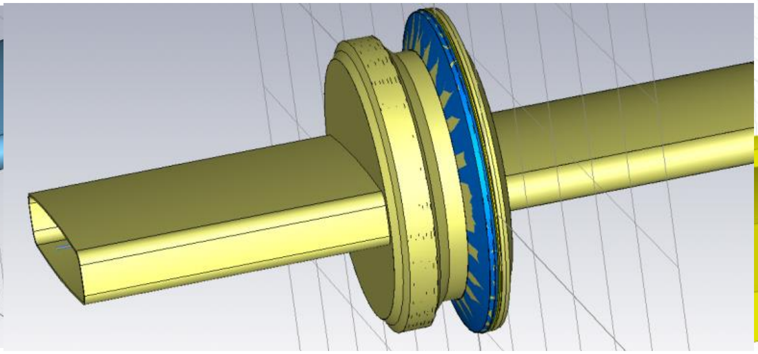
E. S. et al., IPAC'14

The SPS vacuum flanges

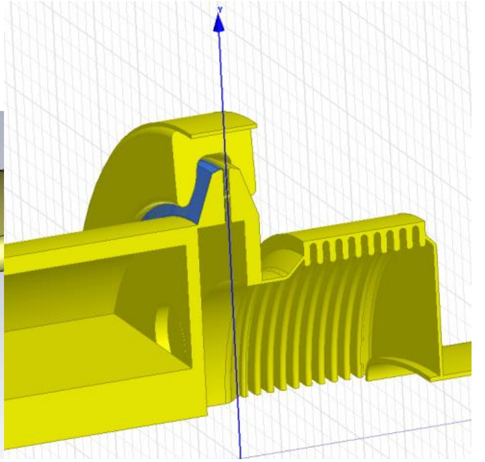
Group I – 1.4 GHz



Non-enamelled QF - QF **≈26**

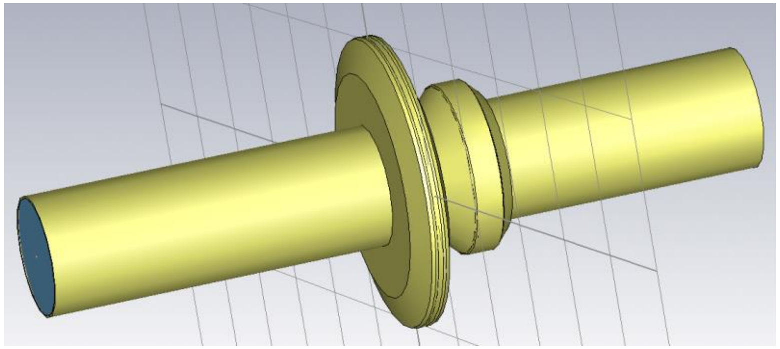


Enamelled QF - MBA **≈ 97**

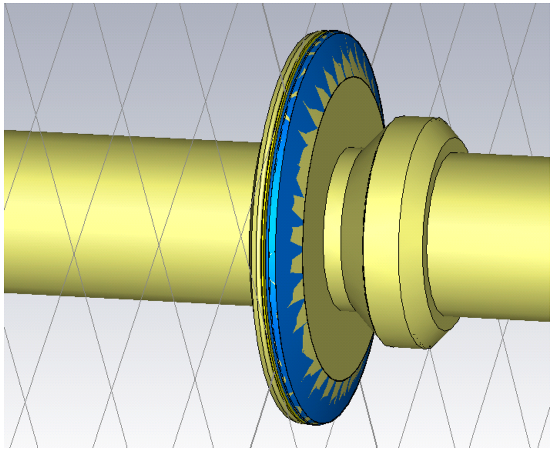


Non-shielded, enamelled BPH - QF **≈ 39**

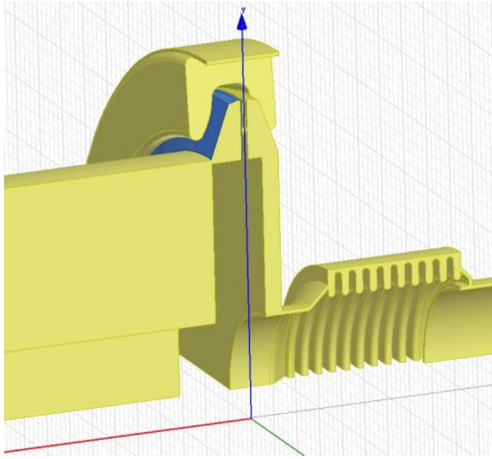
Group II



Non-enamelled QD - QD **≈75**



Enamelled QD - QD **≈ 99**



Enamelled BPV - Q**≈ 90**

Spectrum of multi-bunch beam (1/2)

- Let's consider a narrowband resonant impedance at unknown $\omega_r = \omega_0 p_r$.
- The unstable spectrum of multi-bunch beam has components at

$$\omega = (n + l\,M)\omega_0 + m\omega_s, \quad -\infty < l < \infty,$$

n=0, 1… M-1 is the coupled-bunch mode number, M is number of equidistant bunches in the ring and m=1, 2,… is the multipole number

- On the spectrum analyzer negative ω appear at $[(l+1)\,M - n)]\omega_0 - m\,\omega_s$
- Measured mode n is not sufficient to determine ω_r since $n + l\,M \approx \pm p_r$ and **l** is not known. Smaller is M, more possibilities exist
- Similar spectrum at $n + l\,M$ and $(l+1)\,M - n$, but above transition internal synchrotron sidebands correspond to impedance at higher frequency and external – at lower (the opposite for $\gamma < \gamma_t$) → high frequency resolution

→ Measuring n for different M (with $M_1 \neq kM_2$) can help to determine ω_r

[1] F. Sacherer, F. Pedersen, Theory and performance of the longitudinal active damping system for the CERN PS Booster, NS-24, N3, p.1396, 1977

Spectrum of multi-bunch beam (1/2)

The amplitude of spectral lines: $j_k = g_{kp}/g_{pp}$

in single RF: $g^m_{kp} \sim \int F' J_m(kr)\, J_m(pr)dr$ $(r_{max} \approx \omega_0\tau/2)$

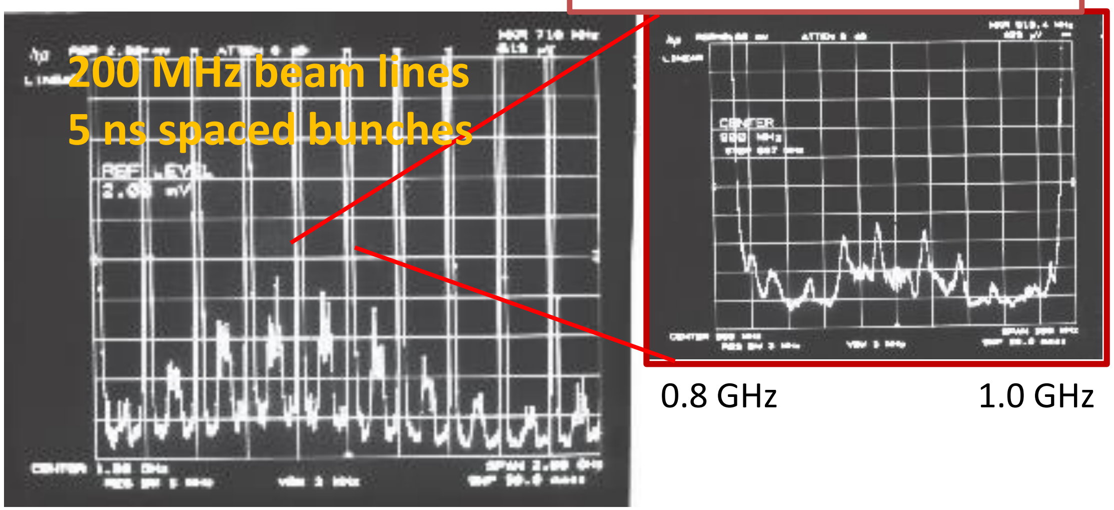
Spectrum envelope with maximum at f_{max}:

if $f_{max}\tau < 1$ → $f_r < 1/\tau$

if $f_{max}\tau > 1$ → $f_r \sim f_{max}$

→ f_r can be identified

→ R_{sh} from growth rate measurements

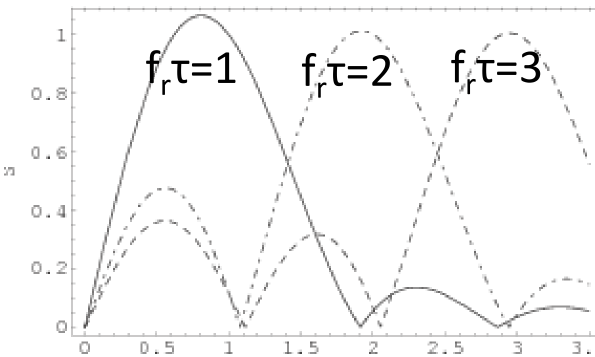


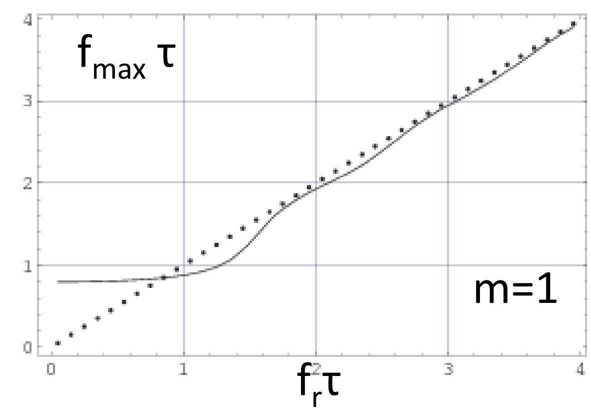
0 2 GHz

0.8 GHz 1.0 GHz

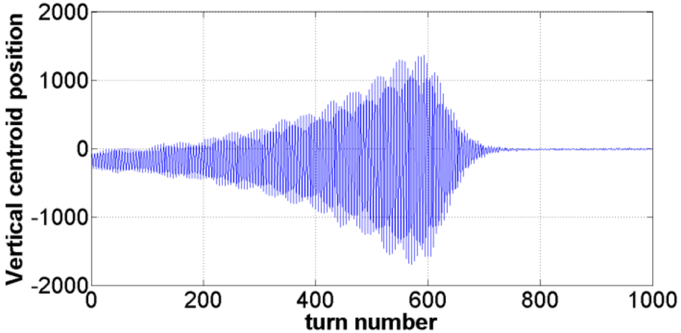
SPS: known HOMs at 629, 912 MHz…

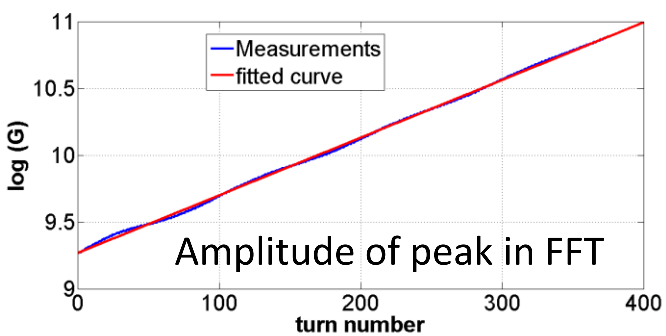
Spectrum envelope (m=1)





Head-tail growth rate as a function of chromaticity





Effective impedance is a convolution of Z with longitudinal spectral density

$$h_0(\omega) = \frac{\sigma_t}{\sqrt{\pi}} e^{-(\omega\sigma_t)^2}$$

where $\omega \rightarrow (\omega - \omega_\xi)$ and chromatic frequency is

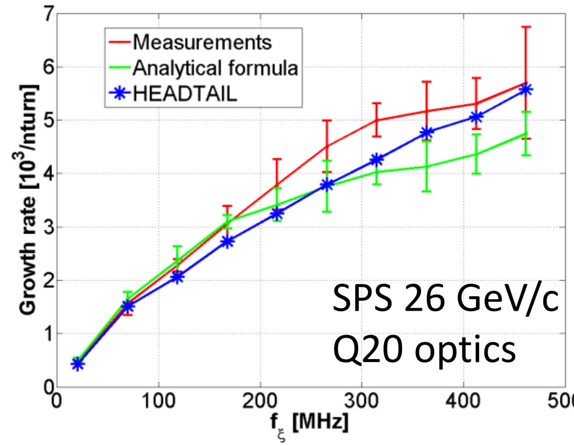
$\omega_\xi = 2\pi f_\xi = \omega_\beta \xi/\eta$,

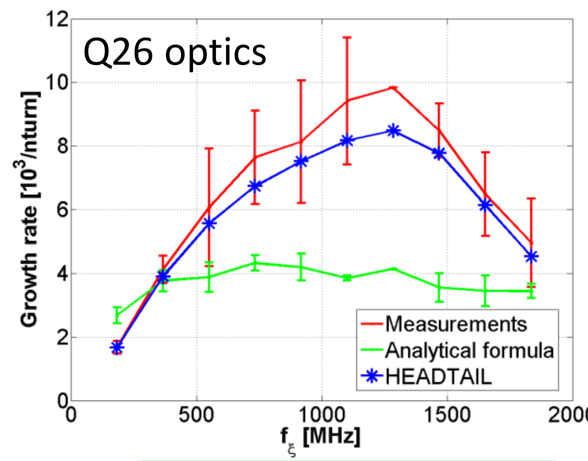
ξ is chromaticity,

η - slip factor

→ By varying ξ on can sample frequency dependence of the transverse impedance

→ Good agreement with simulations

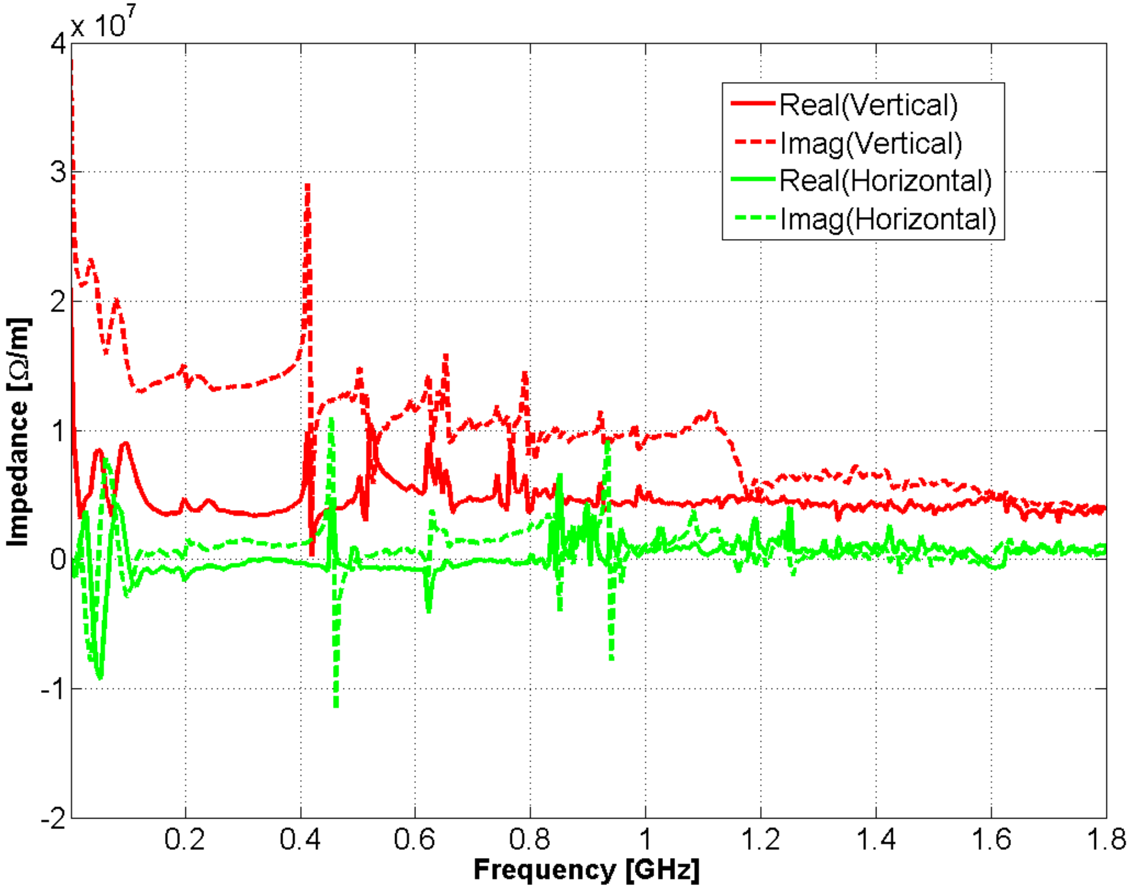




$$\tau^{-1} = \Gamma\left(\frac{1}{2}\right) \frac{\mathrm{Re}\left[Z_{\perp,dip}^{eff}(\xi)\right] N r_0 c^2}{8\pi^2 \gamma Q_\perp \sigma_z}$$

[1] F. Sacherer, Erice School, 1976
[2] A. Chao, Physics of collective beam instabilities
[3] C. Zannini et al., IPAC'15, talk at CERN

SPS transverse impedance model

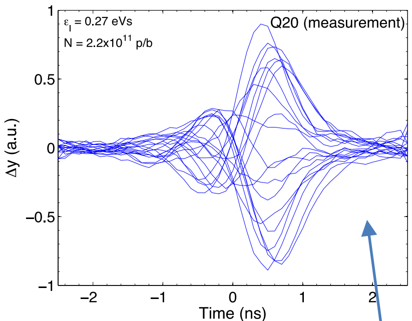


C. Zannini et al.

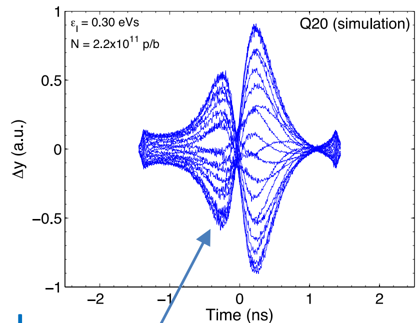
Transverse Mode Coupling Instability threshold

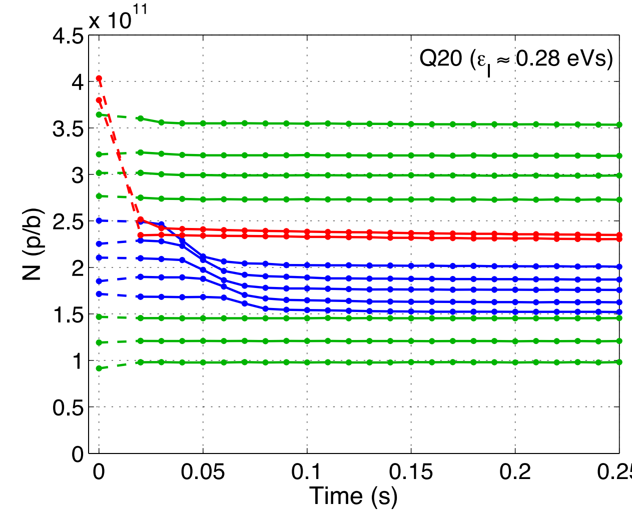
CERN SPS, 26 GeV/c

measurements: m=1



HEADTAIL simulations

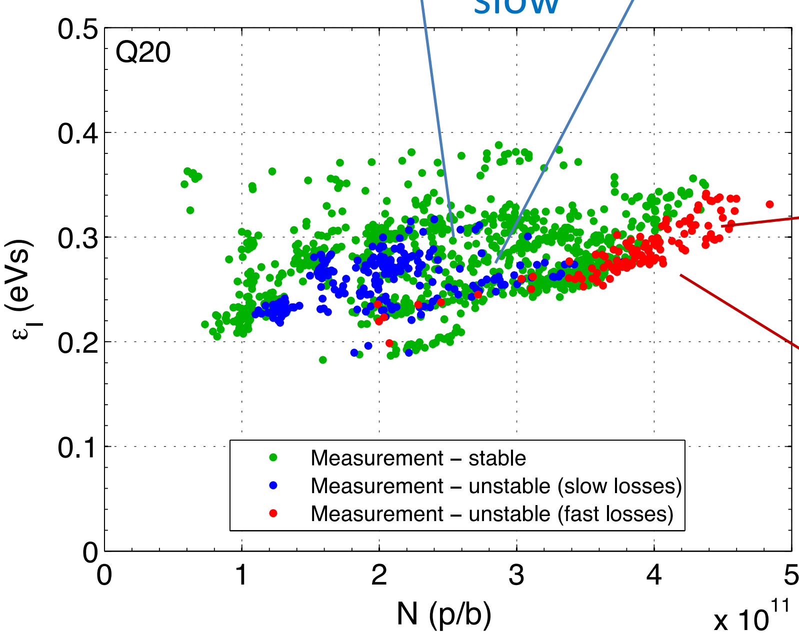




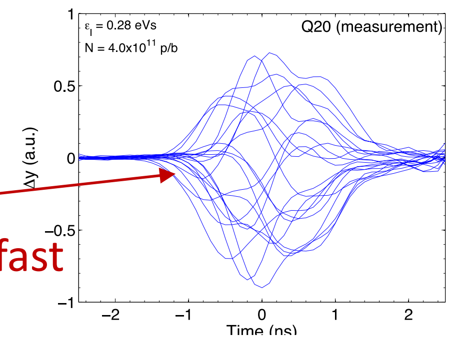
fast

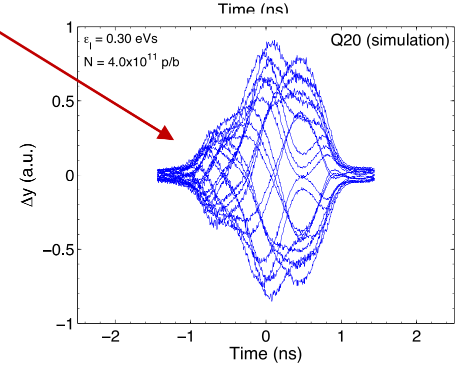
slow

slow



fast





For long bunches TMCI threshold:
$N_{th} \sim \varepsilon_L |\eta| Z_{eff}/\beta_y$

→ Instability island is reproduced in simulations

H. Bartosik et al., IPAC'14

Instability thresholds: loss of Landau damping in LHC

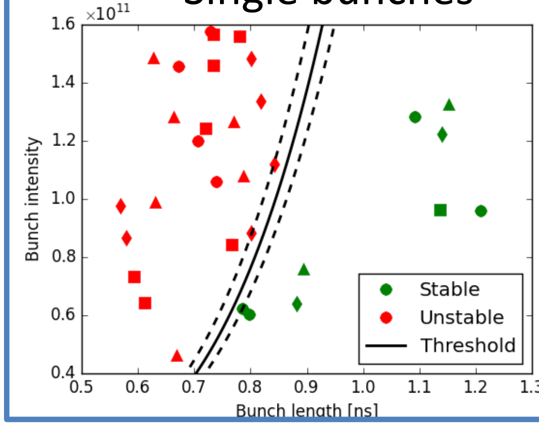
→ Most accurate method to estimate longitudinal LHC impedance so far!

→ Good agreement of measurements and simulations (full LHC model or ImZ/n = 0.08 Ohm)

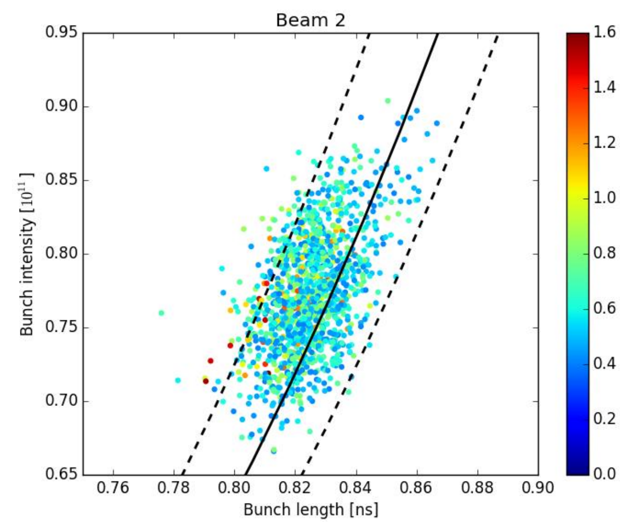
$$Z_{th} \propto \frac{\varepsilon^{\frac{5}{2}}}{N_b\, V^{\frac{1}{4}}\, E^{\frac{5}{4}}}$$

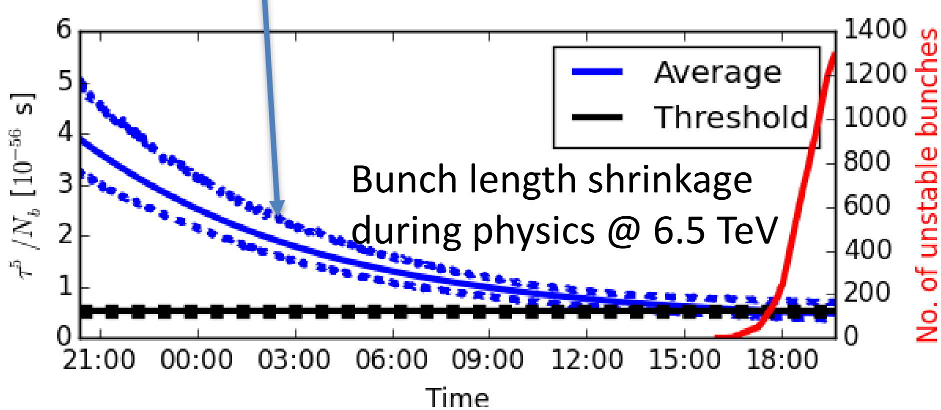
$$\rightarrow Z_{th} \propto \frac{\tau^5}{N_b}$$

Single bunches



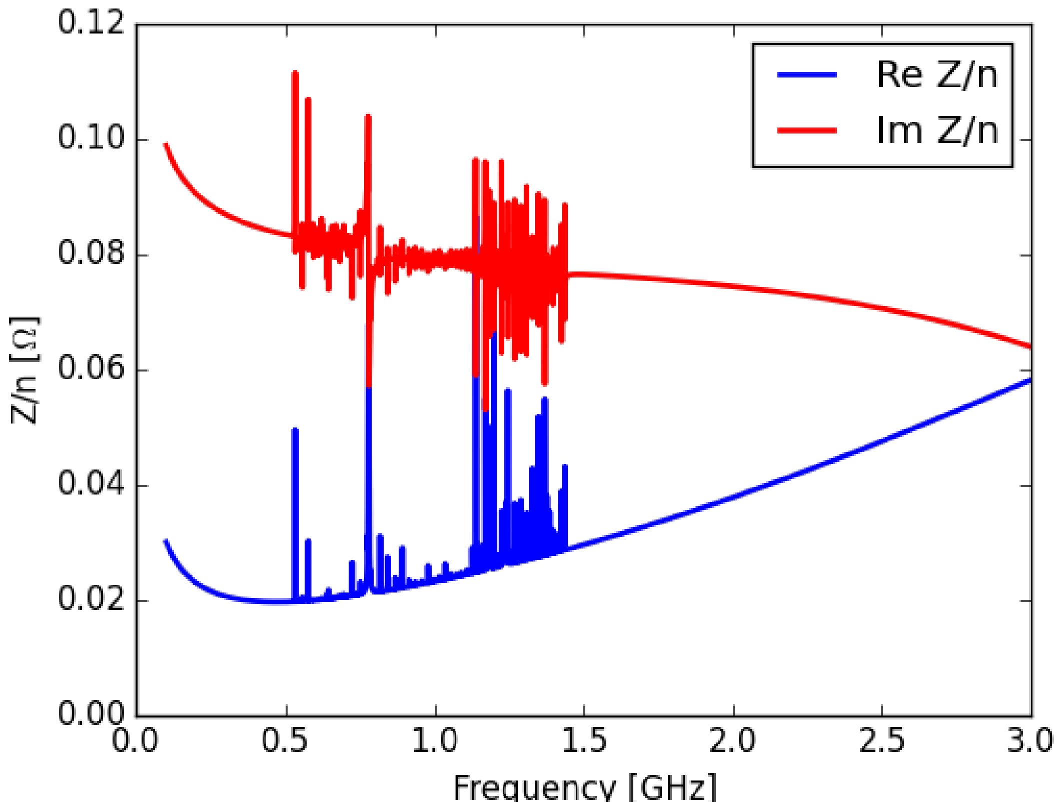
LHC bunches





J. E. Muller et al., 2015

LHC longitudinal impedance model: Z/n



N. Mounet et al.

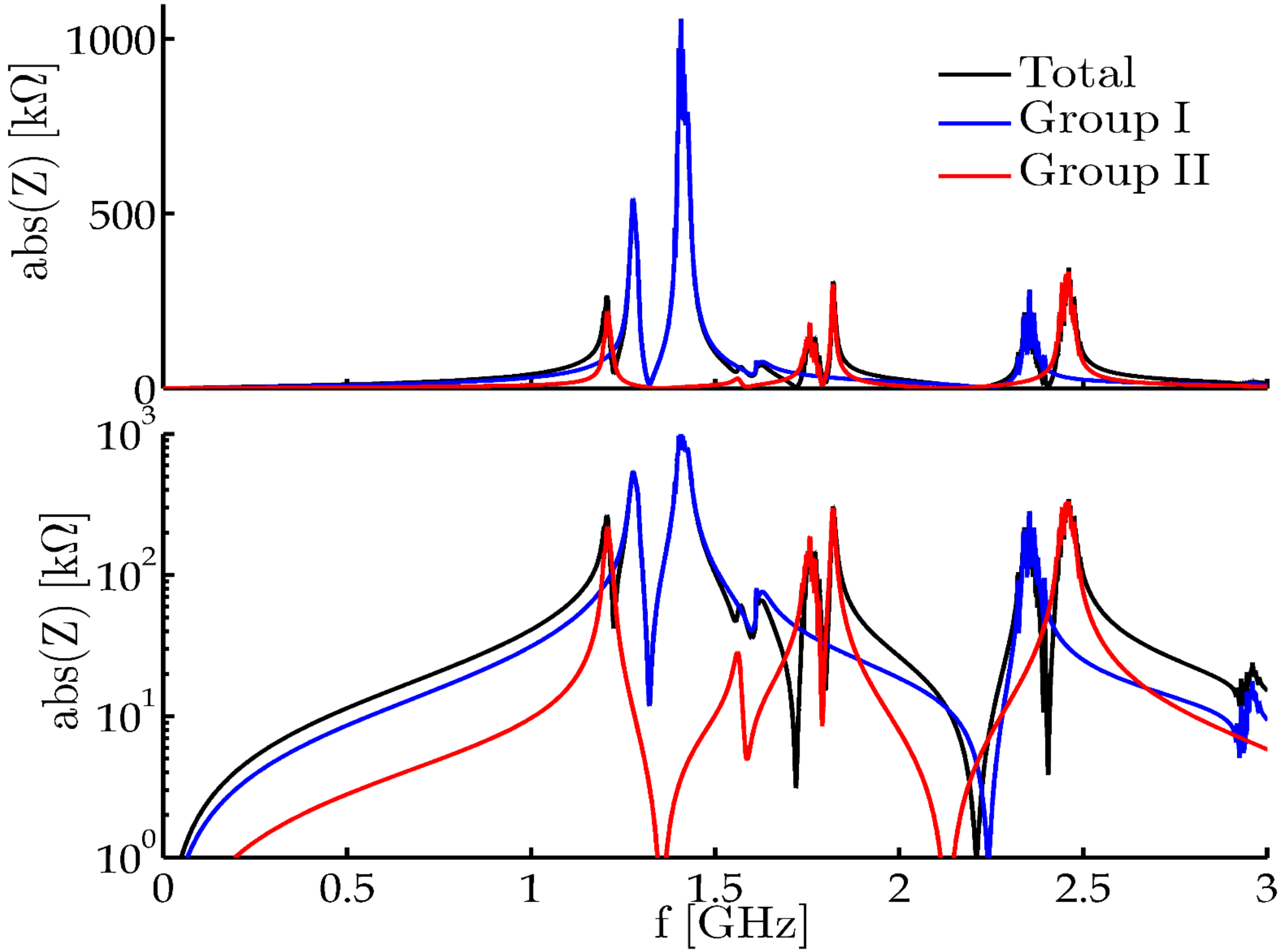
Summary

- Due to careful initial design ring impedances become smaller → more elaborated methods are required to measure them with beam even in proton machines.
- Numerical simulations of various collective effects become more advanced and can be used for beam tests of impedance.
- Measurements with stable beam are mainly used for testing existing impedance models.
- Measurements with unstable beam may contain important information about parameters of the dominant impedances.

Other methods (not discussed here)

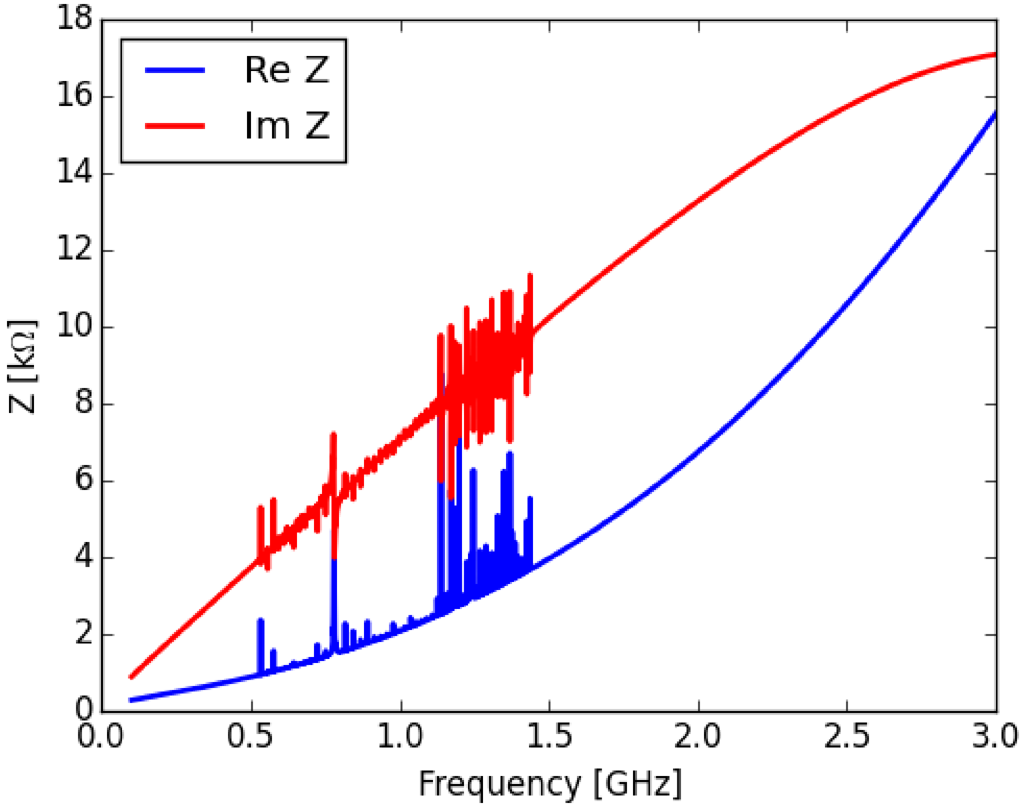
- Transfer functions– D. Moehl and A. Sessler, 1971 (continuous beam)
- Longitudinal impedance variation with transverse displacement – G. Nassibian and F. Sacherer, NIM 159, 1979
- Direct wake-field measurement with 2 bunches and spectrometer (W. Cai, C. Jing, article in Handbook of Accelerator Physics and Engineering, 2nd edition, edited by A. Chao et al.)
- Localised loss factor or orbit distortion due to parasitic energy loss (TRISTAN, LEP)
- ...

The SPS vacuum flanges



Scattered resonances, J. Varela

LHC longitudinal impedance model



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