Impedance Model of the CERN SPS and Aspects of LHC Single-Bunch Stability

Benoit Salvant for the « impedance team »

March 18th, 2010

Agenda

- Context
- Objectives
- Useful notions

1. General framework to obtain a transverse impedance model
   - Context
   - Overview
   - Conclusions and next steps
2. Transverse impedance of simple models of kickers
   - Context
   - New quadrupolar theory
   - 3D simulations
   - Conclusions and next steps
3. Fast instability in the SPS
   - Context
   - HEADTAIL simulations
   - Measurements with beam in the SPS
   - Conclusions and next steps

- Sum up

Context of the CERN LHC complex
Luminosity

- **Key parameter to assess the performance of a collider**: luminosity

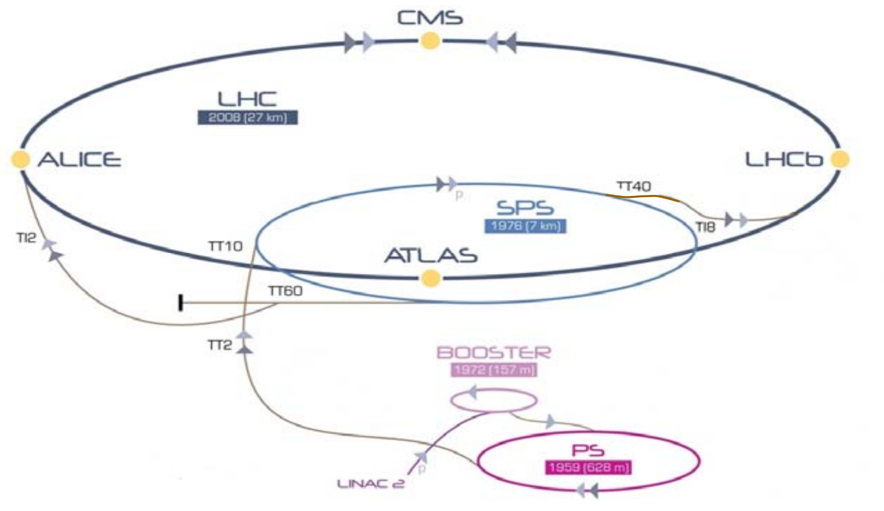
$$\mathcal{L} = \frac{N_b^{(1)} N_b^{(2)} f_{rev} N}{4\pi\sigma_x\sigma_y}$$

- $N_b^{(i)}$ = number of protons per bunch in beam i
- f_{rev} = revolution frequency
- N = number of bunches
- $\sigma_{x,y}$ = transverse beam sizes

→ High luminosity requires high intensity and low transverse beam sizes

- These dense bunches also need to be produced and accelerated in all the injectors.

→ The performance of the injectors also affects the LHC luminosity



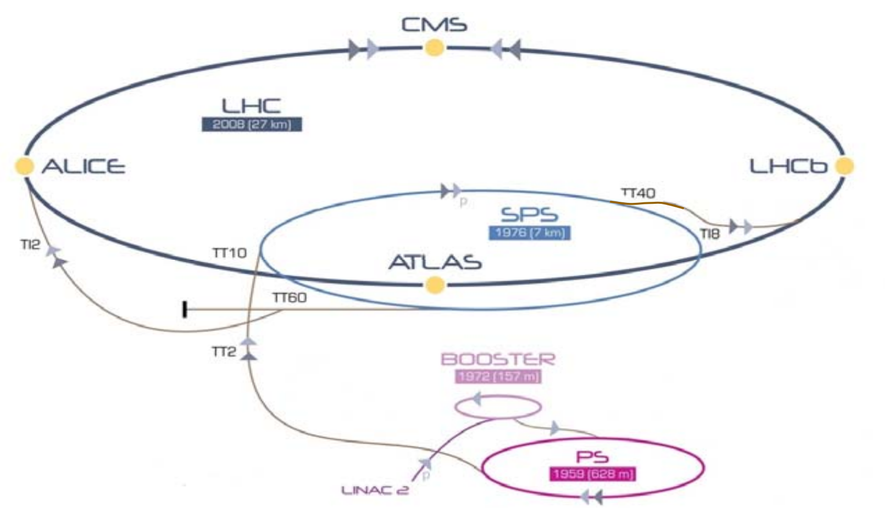
Context of the CERN LHC complex for protons:
Wakefields

- Electromagnetic wakefields are a limitation to circulating dense bunches:

  - Moving charged particles generate EM fields.
  - EM fields are reflected by the surroundings and act back on the trailing particles.
  - This perturbation can lead to beam size growth and beam losses.

More particles ➔ larger EM fields ➔ more beam losses and larger size ➔ lower LHC luminosity

→ **Wakefields in the LHC and its injectors can limit the LHC luminosity**



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Objectives

Main achievements of the PhD thesis work in collaboration with many colleagues

1) a) A general framework was defined to obtain the impedance model of an accelerator and assess its validity

   b) This full framework was implemented to the case of the SPS transverse impedance.
   → important issue for feasibility of intensity upgrade of the LHC

2) Assess the transverse impedance of the LHC collimators and LHC bellows
   → crucial issue for LHC nominal performance

In this talk, I focus on :

1) Overview of the general framework to obtain a transverse impedance model

2) New analytical formulae and 3D simulations for the transverse impedance of kickers

3) Comparison between theory, simulations and measurements of a fast instability in the SPS

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Some useful notions (1):
wakes and impedances

- **Wake potentials W(z):**
  integrated force F generated by a source bunch (1) of longitudinal distribution ρ(z) on a witness particle (2) following at a distance *z*.

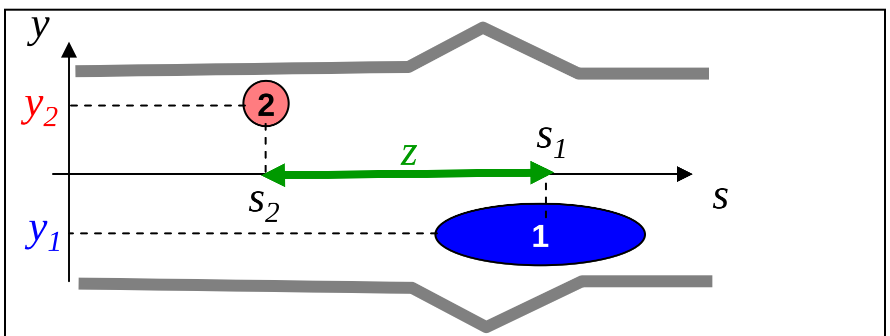
$$W_y(z) = \frac{1}{q_1 q_2} \int_{s_2=0}^{L} \left[F_y(s_2,t)\right]_{t=\frac{s_2+z}{\beta c}} ds_2$$

- **Wake functions G(z):**
  wake potential for which the source is a point charge

$$G(z) = iFT\left(\frac{FT(W(z))}{FT(\rho(z))}\right)$$

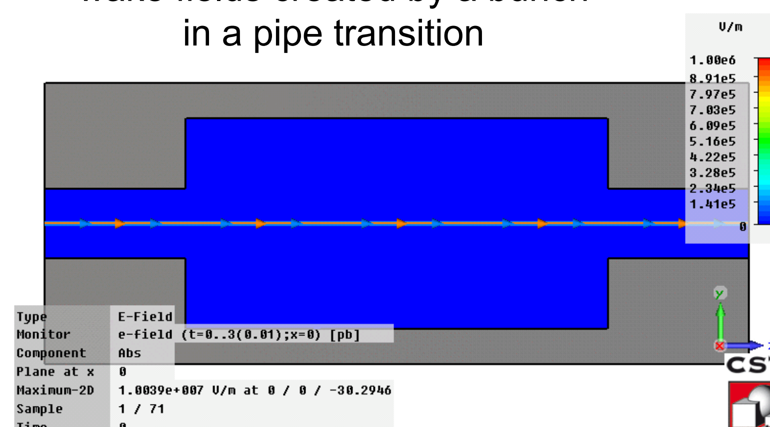
- **Beam impedance Z(ω)**
  Fourier Transform (FT) of the wake function

$$Z(\omega) = FT(G(z))$$



Accelerator element

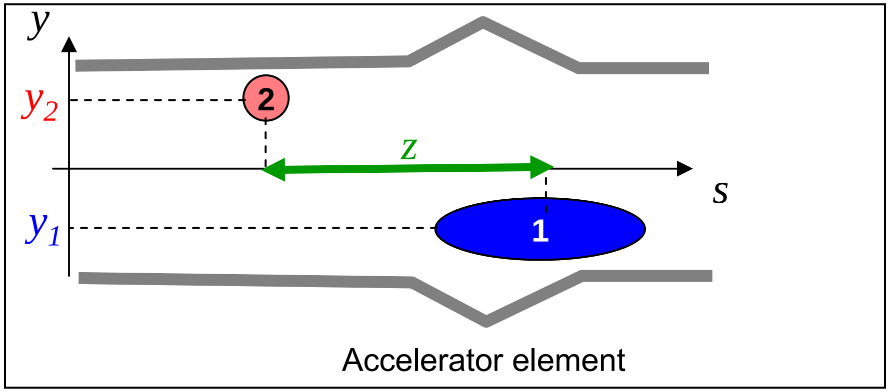
Example of 3D simulations of wake fields created by a bunch in a pipe transition



In general, larger impedances are generated by
- smaller pipe apertures
- abrupt changes of the shape of the pipe
- materials with larger losses

Some useful notions (2):
Separating the dipolar and quadrupolar impedance contributions

- Dipolar and quadrupolar contributions (resp. driving and detuning contributions) linearization of the wake dependence with the source (1) and witness (2) transverse locations



In general, we assume we can expand the wake anywhere in a transverse cross section with powers of x and y

Total vertical wake:

$$W_{y,tot}(x_1, y_1, x_2, y_2, z) = \sum_{i,j,k,l=0}^{n} A_{i,j,k,l}(z) y_1^i x_1^j y_2^k x_2^l$$

Then we classically: (1) assume top/down and bottom/left symmetries
(2) linearize for small displacements
(3) assume no coupling between the horizontal and vertical plane

(1) $$W_{y,tot}(x_1, y_1, x_2, y_2, z) = \sum_{i,j,k,l=1}^{n} A_{i,j,k,l}(z) y_1^i x_1^j y_2^k x_2^l$$ with *i,j,k,l* odd numbers

(2) $$W_{y,tot}(x_1, y_1, x_2, y_2, z) = A(z)x_1 + B(z)y_1 + C(z)x_2 + D(z)y_2$$

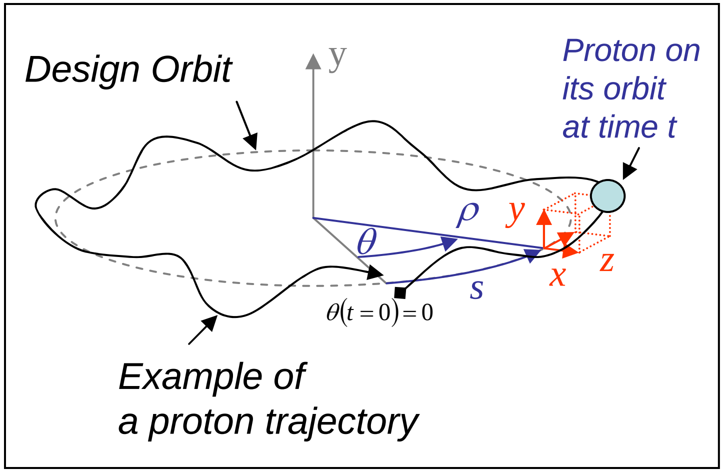
(3) $$W_{y,tot}(x_1, y_1, x_2, y_2, z) = B(z)y_1 + D(z)y_2$$

$$\boxed{W_{y,tot}(y_1, y_2, z)} = \boxed{W_{y,dip}(z)} y_1 + \boxed{W_{y,quad}(z)} y_2$$

Total wake — Dipolar wake — Quadrupolar wake

Some useful notions (3):
Beam dynamics in a synchrotron

Particles perform oscillations around the ideal trajectory of the design synchronous particle.



- Tune :
  Number of these oscillations per revolution:
  - (betatron) tune Q_x and Q_y : transverse oscillations
  - synchrotron tune Q_s : longitudinal oscillations
  - incoherent tune: oscillations of an individual particle
  - coherent tune: oscillations of the bunch center of mass

  Coherent motion decomposed in coherent modes of oscillation

- Beta function
  Envelope around all transverse particle trajectories in an accelerator
- Chromaticity ξ_x and ξ_y
  Machine parameter that introduces a tune shift for off-momentum particles

$$\xi_y = \frac{\Delta Q_y / Q_y}{\Delta p / p}$$

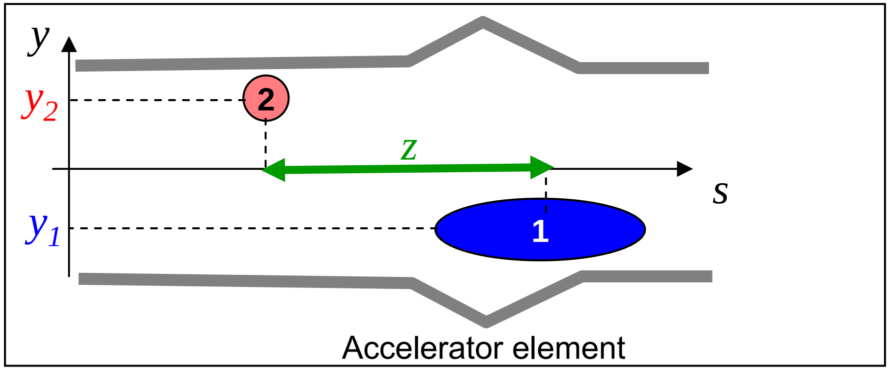
p → particle momentum

- Emittance
  area covered by the particle distribution in phase space (several conventions)
- Transverse instability
  Uncontrollable growth of the amplitude of transverse oscillations
- Transverse Mode Coupling Instability (TMCI)
  Instability caused by coupling of coherent modes if the bunch intensity is increased over a given threshold

Some useful notions (4)
Why separate the dipolar and quadrupolar impedance contributions?

$$W_{y,tot}(y_1, y_2, z) = W_{y,dip}(z)\, y_1 + W_{y,quad}(z)\, y_2$$

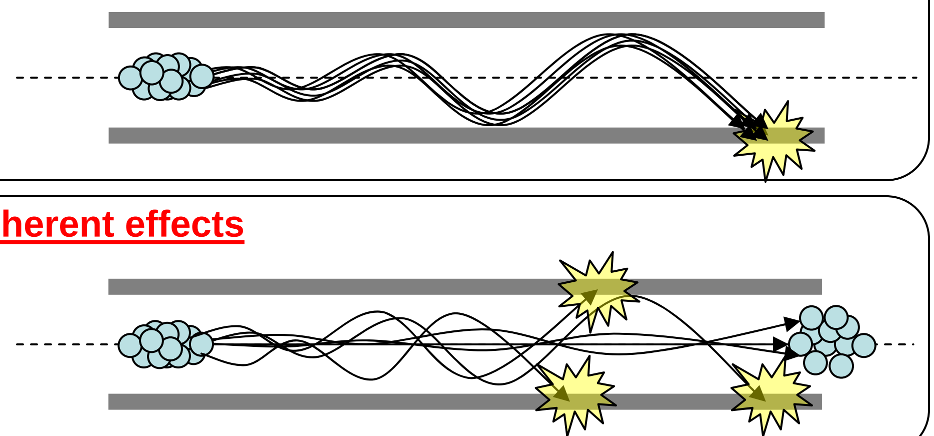
Total wake — Dipolar wake — Quadrupolar wake



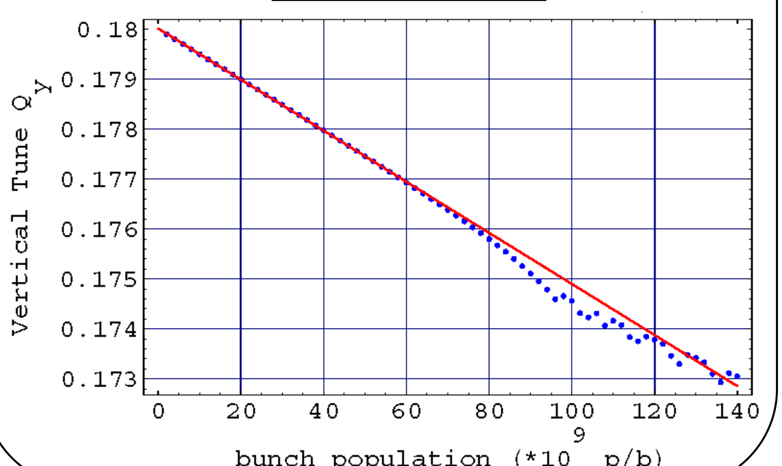
- dipolar wake leads to coherent oscillations of the bunch as a whole
  → dipolar wake drives **coherent instabilities**
- quadrupolar wake leads to oscillations that depends on the individual particle's amplitude
  → quadrupolar wakes leads to **incoherent effects** (damping and emittance growth)
- Both dipolar and quadrupolar wakes contribute to the **coherent tune shift**

Coherent instabilities

Incoherent effects



Coherent tune shift as a function of bunch intensity



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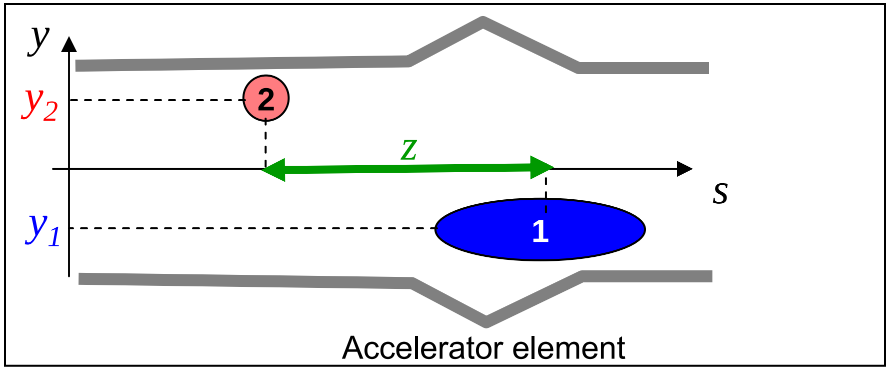
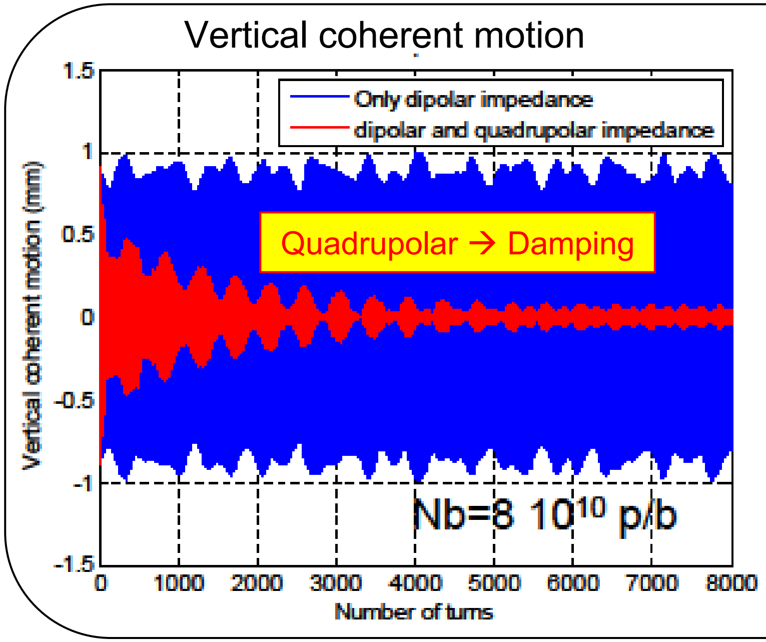
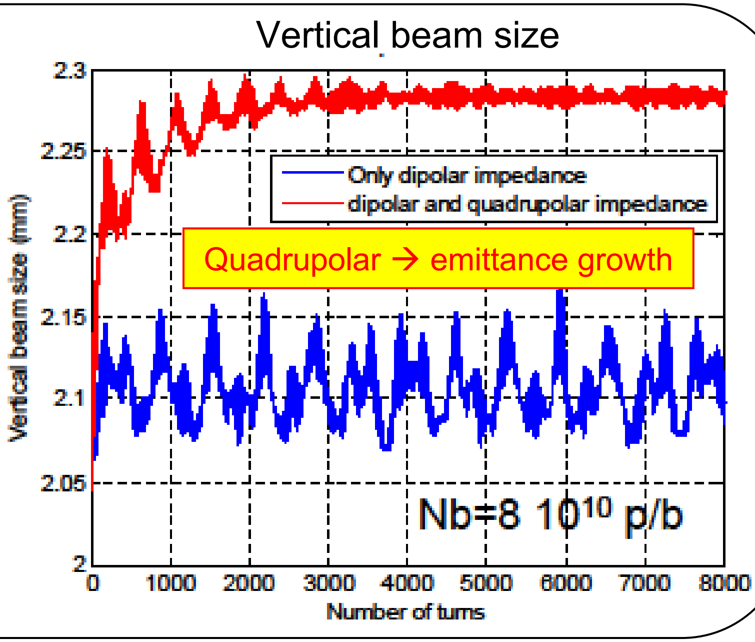


Example:
HEADTAIL macroparticle simulation of a bunch interacting with: - a dipolar impedance contribution
- both dipolar and quadrupolar impedance contributions





→ Very different impact on beam dynamics!
→ We need to separate the dipolar and quadrupolar impedance contributions

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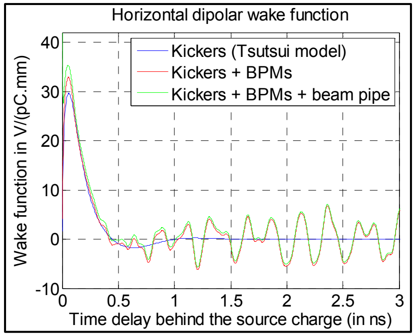


- Sum up

General framework to obtain the impedance model
Context

- Context
  – Impedance database ZBASE was created to store input files and compute the impedance of LEP and LHC with several codes (URMEL, ABCI, MAFIA).

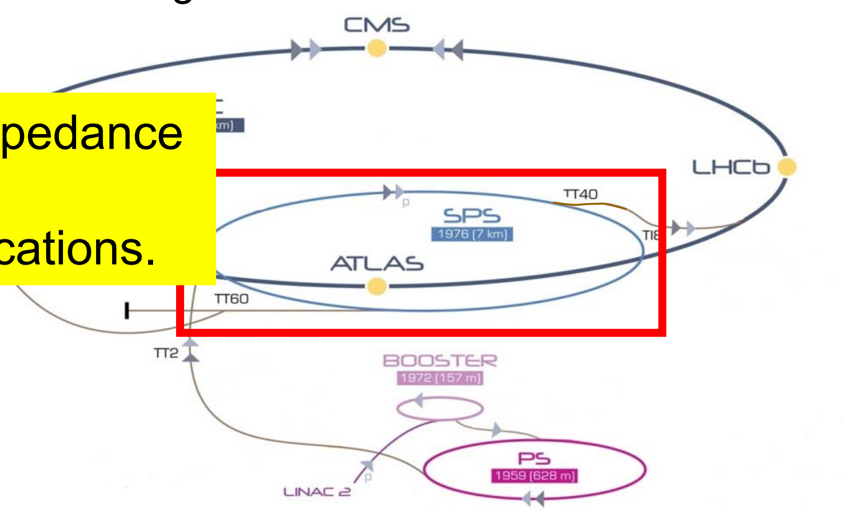
- Objectives for the impedance team:
  – Need to refurbish the code to restore the dead links and the missing libraries
  – Need to assess the feasability of using new tools that have been made available (analytical calculations, CST, HFSS, GdfidL, HEADTAIL)

- Together with E. Métral and other colleagues, we have:
  – Defined a general framework to obtain the impedance model of a machine
  – Applied this framework to the case of the SPS

General framework to obtain the impedance model
Context: Why worry about the SPS impedance?

- SPS: Super Proton Synchrotron, built in 1976 (circumference 6.9 km).
- SPS recently refurbished to be used as the injector into the LHC
  (removal of LEP elements, new ejection kickers, impedance reduction campaign in 2001)
- SPS is able to produce the nominal intensity (1.2 10^{11}p/b) and emittances for LHC
- Intensity upgrade is foreseen → multiply by three or four the intensity
- Fast transverse instability (TMCI?) limits bunch intensity to less than 2 10^{11}p/b
  → SPS transverse impedance will be one of the bottlenecks to produce large intensities
- We may increase chromaticity to push the instability threshold,
  but large chromaticities lead to slow losses and emittance growth

Need for a good understanding of the SPS impedance
to identify its major contributors
and propose possible SPS hardware modifications.



General framework to obtain the impedance model of a machine

machine measurements

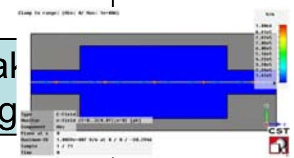
Analytical Calculations

$$\sum_{n=0}^{\infty} \frac{k_{xn}^2}{k} \frac{1}{\frac{\frac{k_{xn}}{k}(1+\mu_r\varepsilon_r)\, sh\, ch + \frac{k_{yn}}{k}(\mu_r\, sh^2 tn - \varepsilon_r\, ch^2 ct)}{\mu_r\varepsilon_r - 1} - \frac{k}{k_{xn}}\, sh\, ch}$$

iDFT

Wake function of a single SPS element

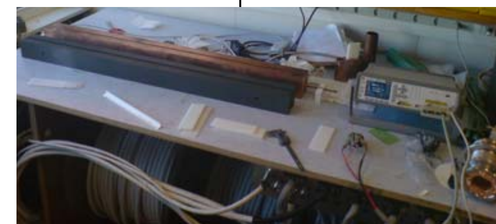
Electromagnetic Simulations



deconvolution

Wake function of a single element

Bench Measurements



Wake function of a single SPS element

HEADTAIL simulates the dynamics of a bunch of macroparticles interacting with an impedance model

Accounting for the respective beta functions

"Total" SPS Wake function

Headtail macroparticle simulations

Measured observables (Tune shift, Instability threshold…)

?

Simulated observables (tune shift, instability threshold…)

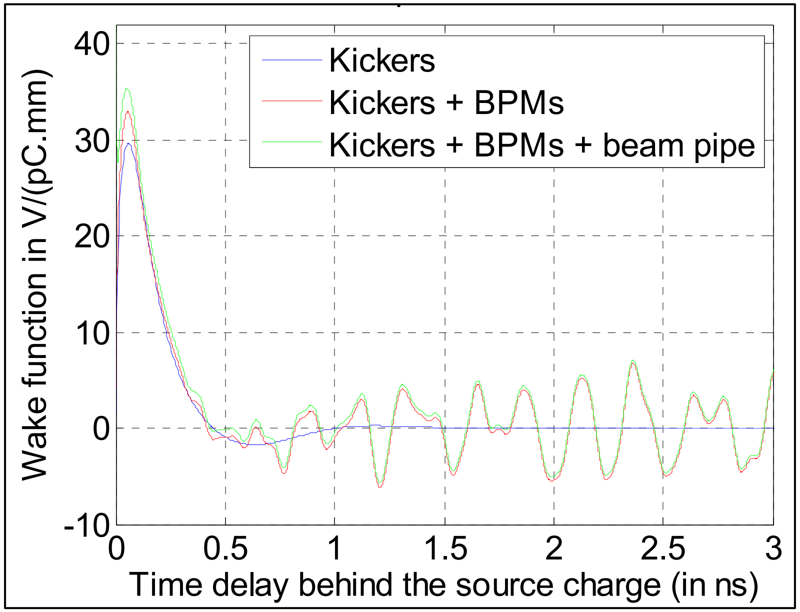
→ How much of the measured transverse impedance is accounted for in the model?
→ Which are the main transverse impedance contributors?

General framework to obtain the impedance model
Achievements and next steps

- Together with E. Métral and other colleagues, we have:
  - optimized the impedance calculation for many elements, linked MADX parameter files to ZBASE, and improved the performance of the Discrete Fourier Transforms.
  - integrated the HEADTAIL macroparticle simulation code into the database to simulate beam observables (with G. Rumolo).
  - enabled importing separately dipolar and quadrupolar tables into HEADTAIL (with G. Rumolo).
  - defined the framework to obtain the impedance of a synchrotron
  - applied this full framework to the SPS model :
    - 20 kickers (analytical calculations)
    - 106 BPHs (3D simulations)
    - 96 BPVs (3D simulations)
    - 6.9 km of beam pipe (analytical calculations)

SPS model horizontal dipolar wake function →

→ kicker : large single bunch effect
→ BPMs and beam pipe : large multi bunch effect



- Next immediate steps for the impedance team:
  - Improve the SPS model (adding more elements and refining existing models)
  - Apply this general framework to the LHC impedance model
  - Restore the full functionalities of ZBASE in this new framework

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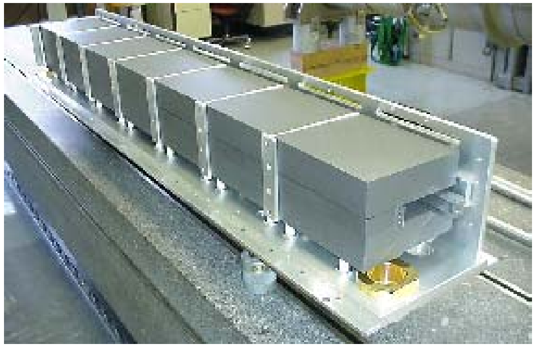
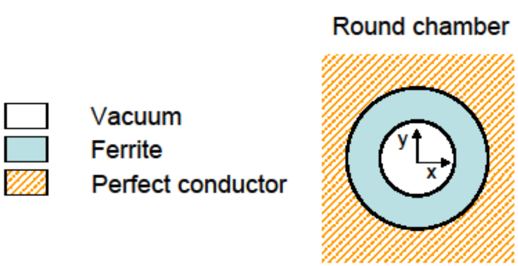


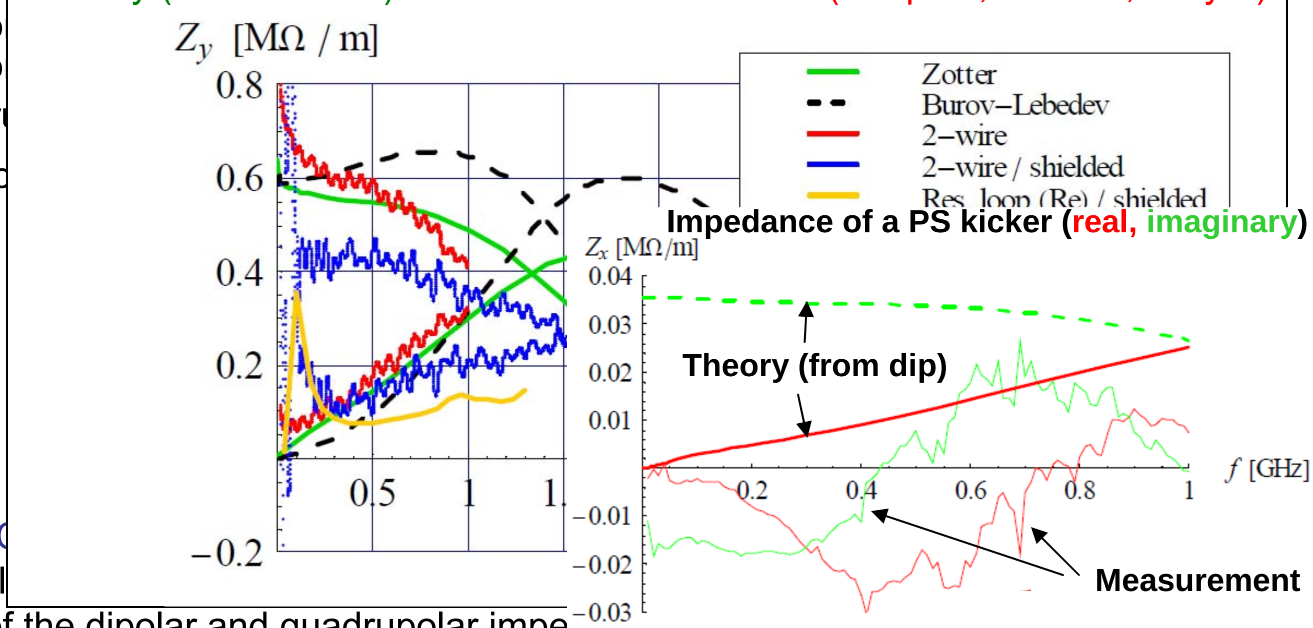
- Sum up

Transverse impedance of simple models of kickers
Context and objectives

- Context:
  - SPS beam based measurements over the years
    → SPS ferrite kickers suspected to be major contributors to the transverse SPS impedance.
  - Method to obtain the impedance of the SPS kickers:
    1. Compute impedance for a cylindrical ferrite beam pipe with Zotter/Métral model
    2. Multiply it by constant form factors to obtain the dipolar and quadrupolar impedance contributions for a flat chamber beam pipe.
  - Analytical dipolar impedance agrees with bench measurements of SPS kickers…
  - …However,
    1. Form factors can
       aperture, which i
    2. negative total ho
       negative total ho
       → Quadru
  - Tsutsui formalism also



- New tools developed with C
  - new theoretical formul
  - New 3D simulations of the dipolar and quadrupolar impe



Courtesy E. Métral

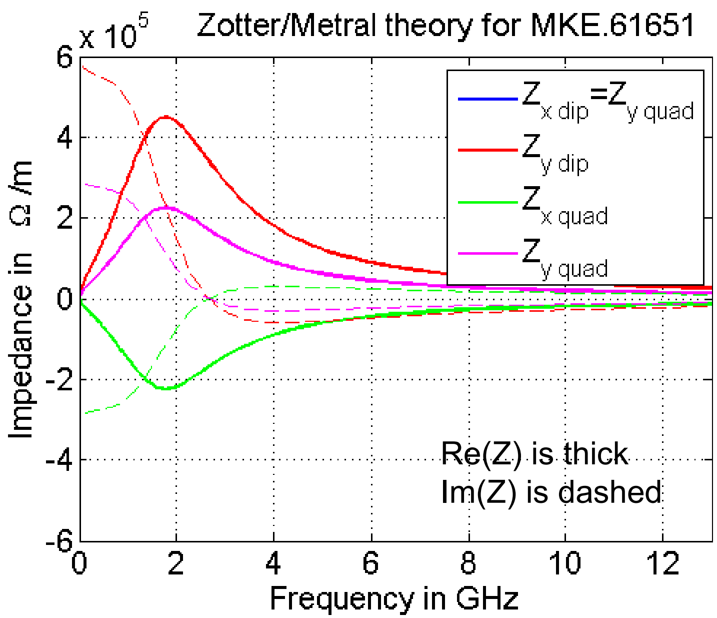
Transverse impedance of simple models of kickers
New quadrupolar contribution

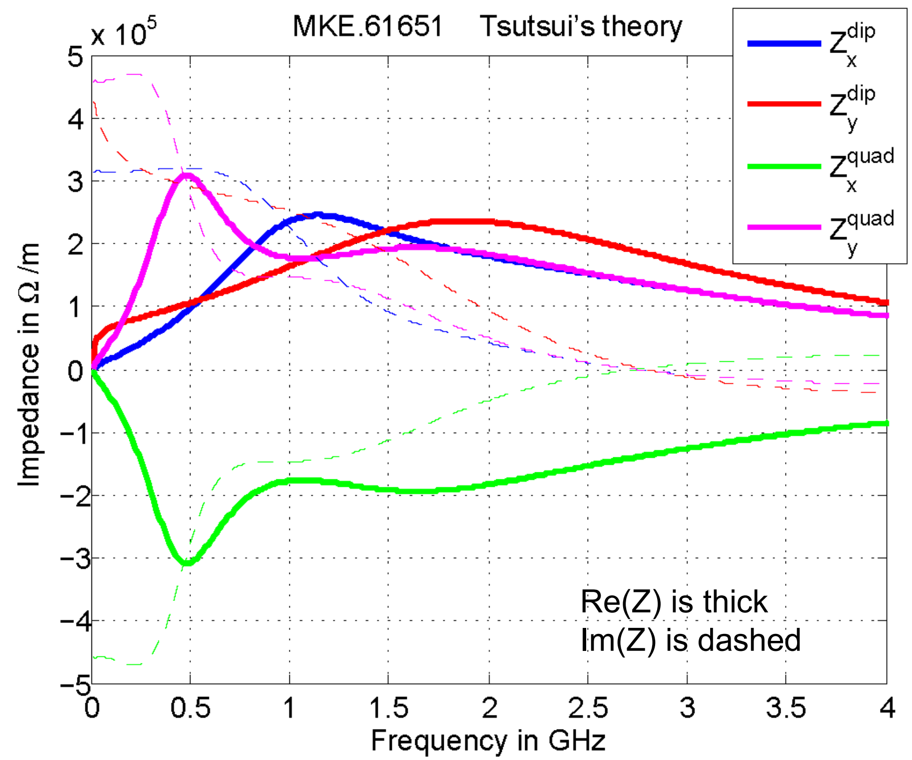
- New quadrupolar impedance was derived from the electromagnetic fields derived by Tsutsui for the longitudinal impedance (same source charge distribution)

$$\frac{Z_h^{quad}}{L} = -j\frac{Z_0}{2a}\sum_{n=0}^{\infty}\frac{k_{xn}^2}{k}\frac{1}{\frac{\frac{k_{xn}}{k}(1+\mu_r\varepsilon_r)sh\,ch+\frac{k_{yn}}{k}(\mu_r sh^2 tn-\varepsilon_r ch^2 ct)}{\mu_r\varepsilon_r-1}-\frac{k}{k_{xn}}sh\,ch}$$

$$\frac{Z_v^{quad}}{L} = -\frac{Z_h^{quad}}{L}$$

→ Analytical impedance for 1 MKE kicker



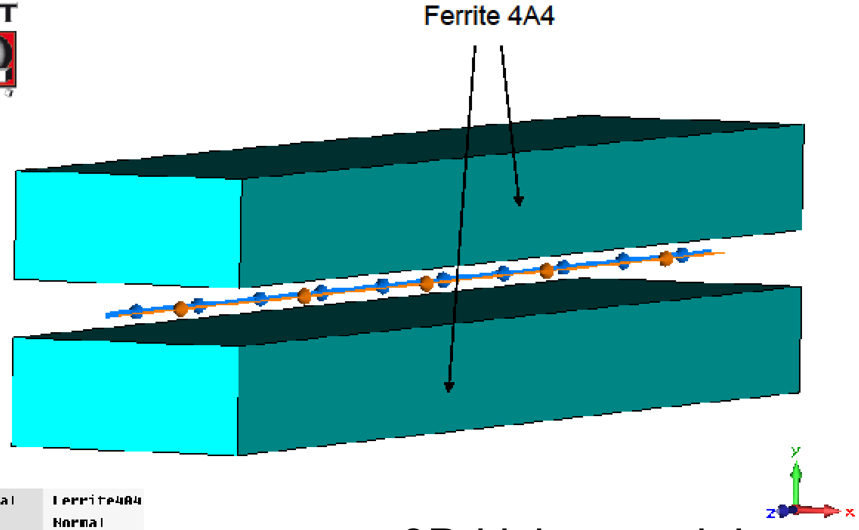


→ not possible to apply constant factors to relate the dipolar and quadrupolar contributions in Tsutsui's theory
→ Which theory is valid?
➔ **benchmark with 3D simulations**

Transverse impedance of simple models of kickers

CST Particle Studio 3D simulations

CST Particle Studio is a commercial code that simulates the wake potentials from 3D models



Material	Ferrite4A4
Type	Normal
Epsilon	12
Disp. mue	General 1st order model (fit)
El. cond.	1e-006 [S/m]

3D kicker model

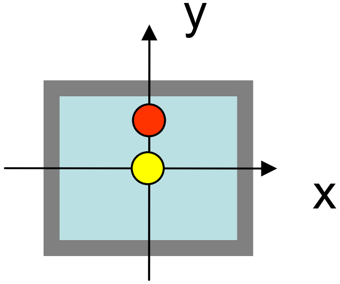
Kicker structure

Strategy to obtain dipolar and quadrupolar wake potentials from time domain CST simulations

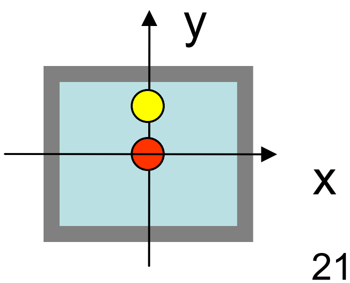
$$W_{y,tot}(y_1, y_2, z) = W_{y,dip}(z)\,y_1 + W_{y,quad}(z)\,y_2$$

Total wake — Dipolar wake — Quadrupolar wake

W_y dipolar



W_y quadrupolar



Beam

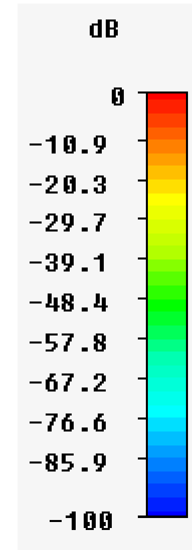
Wake integration

Transverse impedance of simple models of kickers

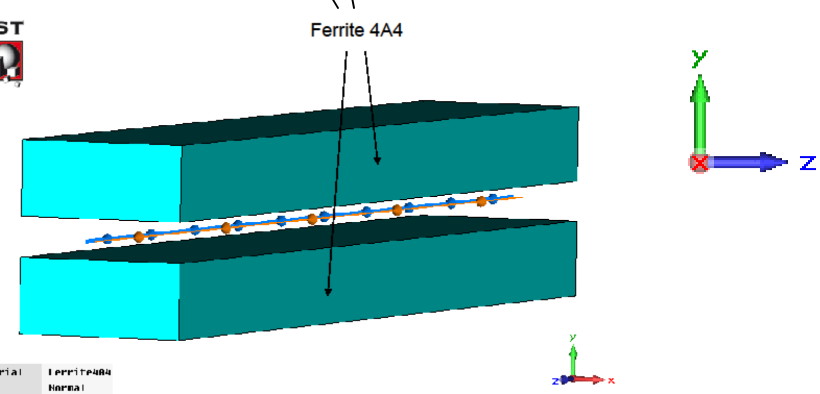
CST Particle Studio 3D simulations

Vertical electric field

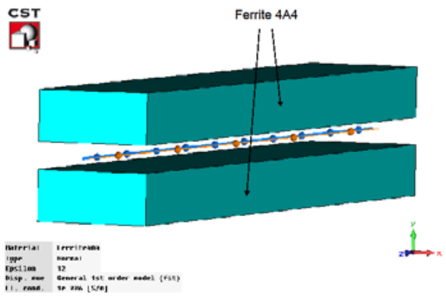
1.7 million mesh cells
Simulated Rms Bunch length 2 cm



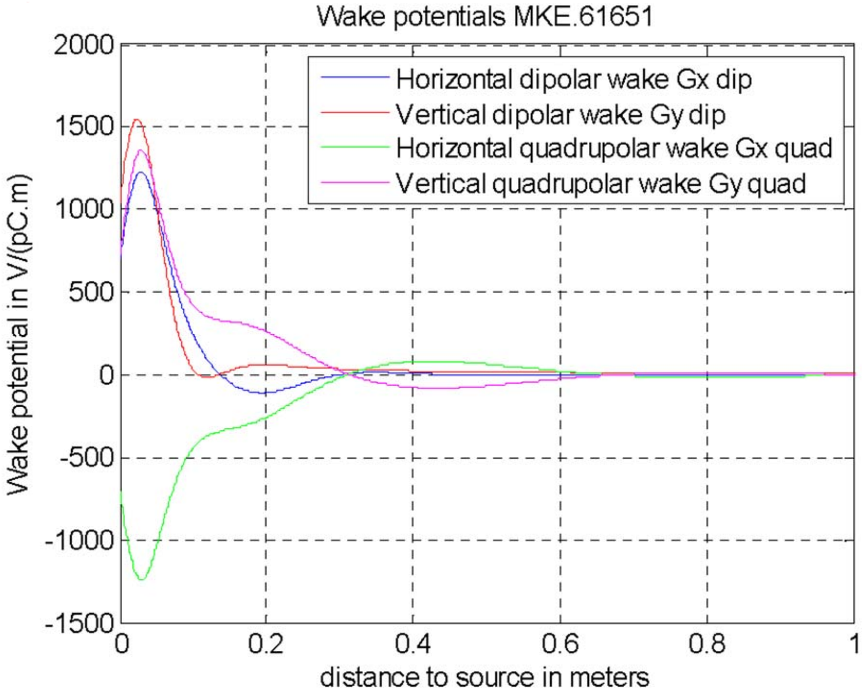
Type	E-Field
Monitor	e-field (t=0..3(0.1);y=0) [pb]
Component	y
Plane at x	0
Maximum-2D	349065 V/m (= 0 dB) at 0 / 0.5 / 1.69133
Sample	1 / 51
Time	0

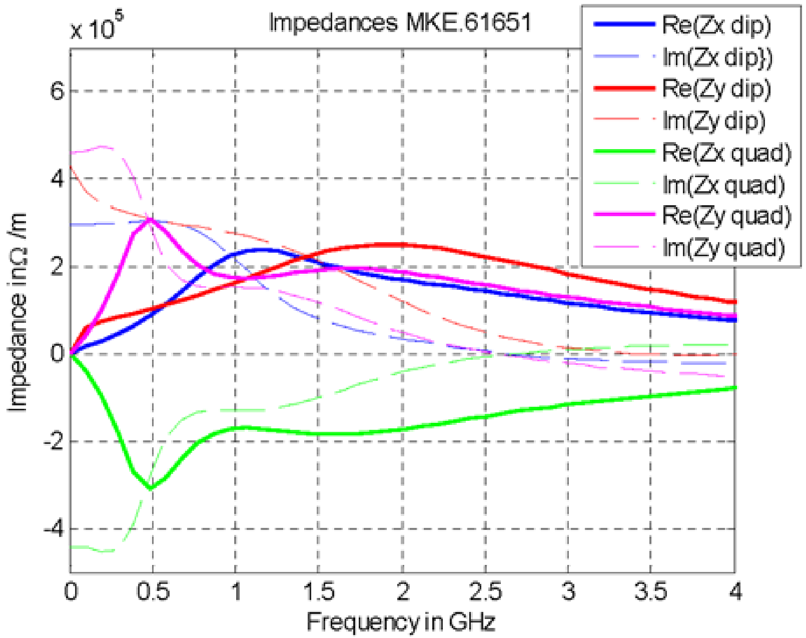


Transverse impedance of simple models of kickers
CST Particle Studio 3D simulations



1.7 million mesh cells
Simulated Rms Bunch length 2 cm



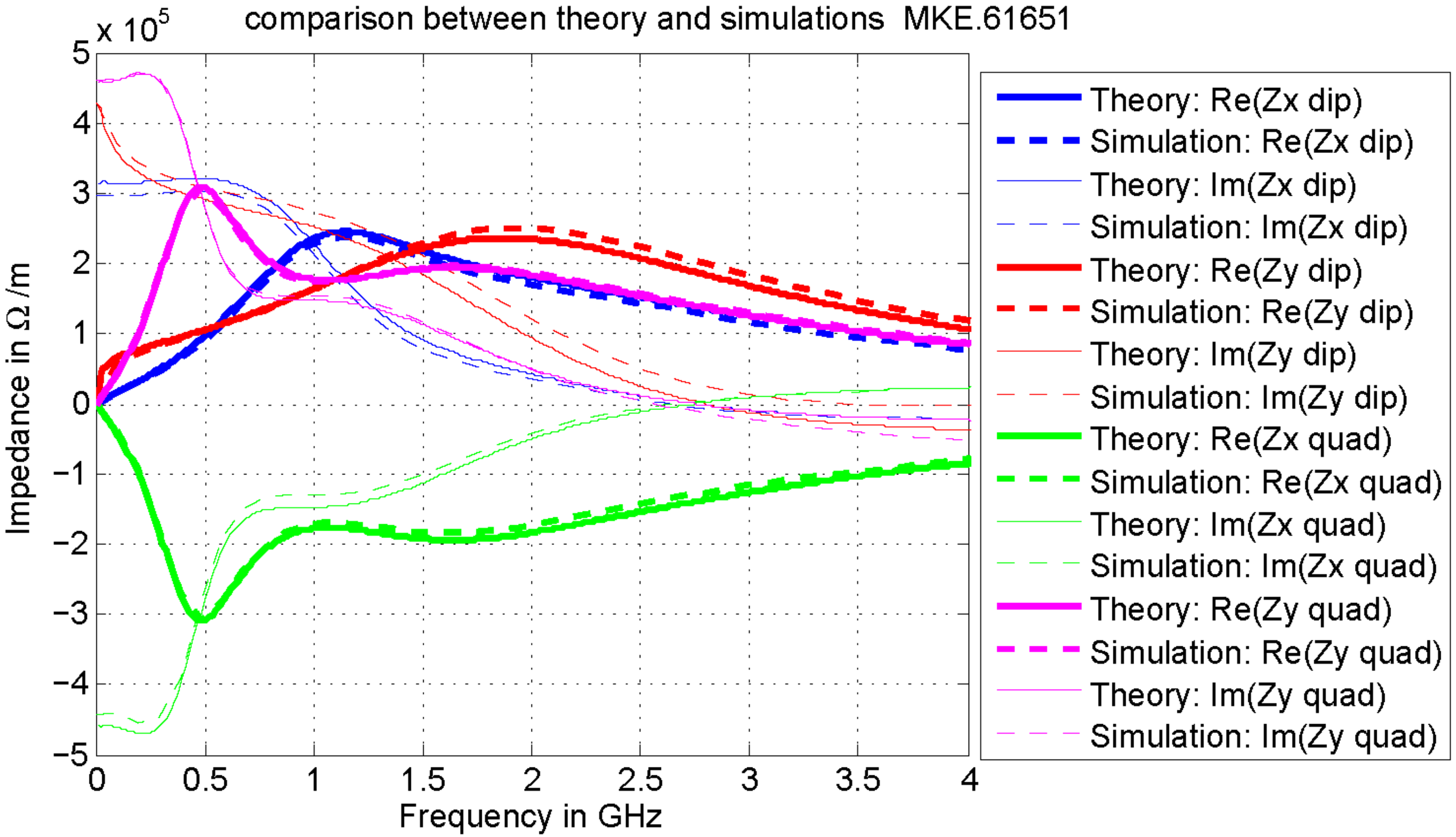


DFT and deconvolution

Let's compare with the theory…

Transverse impedance of simple models of kickers

Comparison between theory (with new quadrupolar) and new simulations



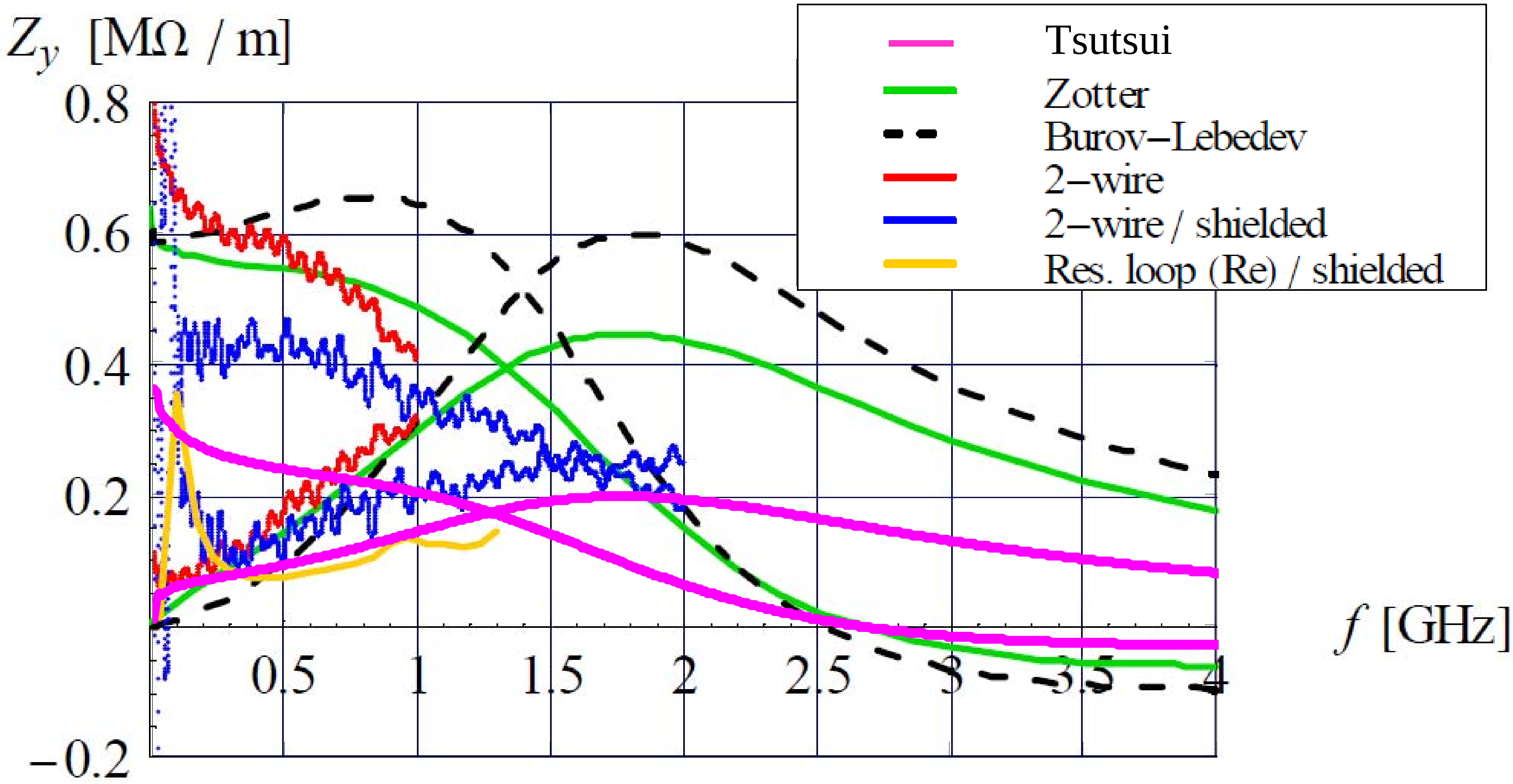
(1) Good agreement between Tsutsui's dipolar and the new quadrupolar impedance theories with impedance obtained from 3D simulations

(2) This confirms our suspicions about using the constant form factors for kickers

(3) Gives more confidence in the new theory and in the CST simulations

(4) |Im(Zx quad)| > Im(Zx dip) as predicted by previous measurements

Comparison between Tsutsui, Zotter/Metral and 2 wire measurements



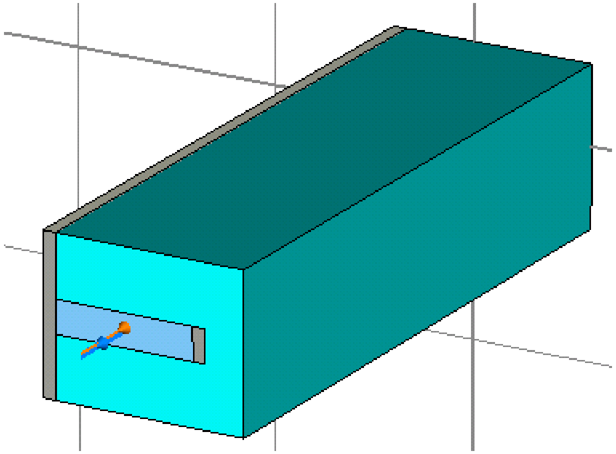
Tsutsui formula much lower than both 2 wire measurements and Zotter/Metral formula

- → we still need to understand this difference
- → refine the simple kicker model (cells, external circuits, gaps)
- → redo experiments with a focus on getting both the dip and quad impedance

Transverse impedance of simple models of kickers
Summary and next steps

- Summary:
  - New theoretical formulae for the quadrupolar impedance in the frame of Tsutsui formalism
  - New 3D simulations of the dipolar and quadrupolar impedance of simple models of kickers
  - Good agreement between theory and simulations!
  - Method with constant form factor should be applied with care if the material are not good conductors

- Immediate next steps:
  - Bench measurements of a single SPS kicker cell
  - 3D CST Simulations of improved models with separated cells, external circuits, shielding,.



Agenda

- Context
- Objectives
- Some definitions

1. General framework to obtain a transverse impedance model
   - Context
   - Overview
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2. Transverse impedance of simple models of kickers
   - Context
   - New quadrupolar theory
   - New CST 3D simulations
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3. Fast instability in the SPS
   - Context
   - HEADTAIL simulations
   - Comparison with MOSES calculations
   - Measurements with beam in the SPS
   - Conclusions and next steps

- Sum up

Fast transverse instability in the SPS
Context

- Context:
  - Beam measurements of single bunches of protons at injection in the SPS (G. Arduini, T. Bohl, H. Burkhardt, E. Métral, E. Shaposhnikova et al).
  - Longitudinal emittance lower than nominal

    → Instability is observed at high intensity.
  - This instability has characteristics of a TMCI:

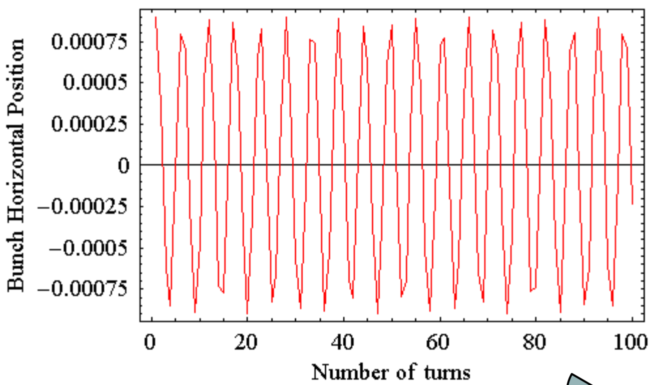
    → very fast, travelling wave pattern and stabilized by vertical chromaticity .
  - However, this not a proof that it is a TMCI.
  - First HEADTAIL simulations by E. Métral and G. Rumolo focused on the instability threshold and travelling wave

- With the help of many colleagues from BE/ABP, BE/BI, BE/OP and BE/RF, we performed
  - a benchmark of MOSES calculations and HEADTAIL simulations
  - experiments with beam in the SPS to study this fast instability
  - a comparison of HEADTAIL simulations with an improved SPS impedance model to the bench measurements
  - And concluded on the validity of the impedance model

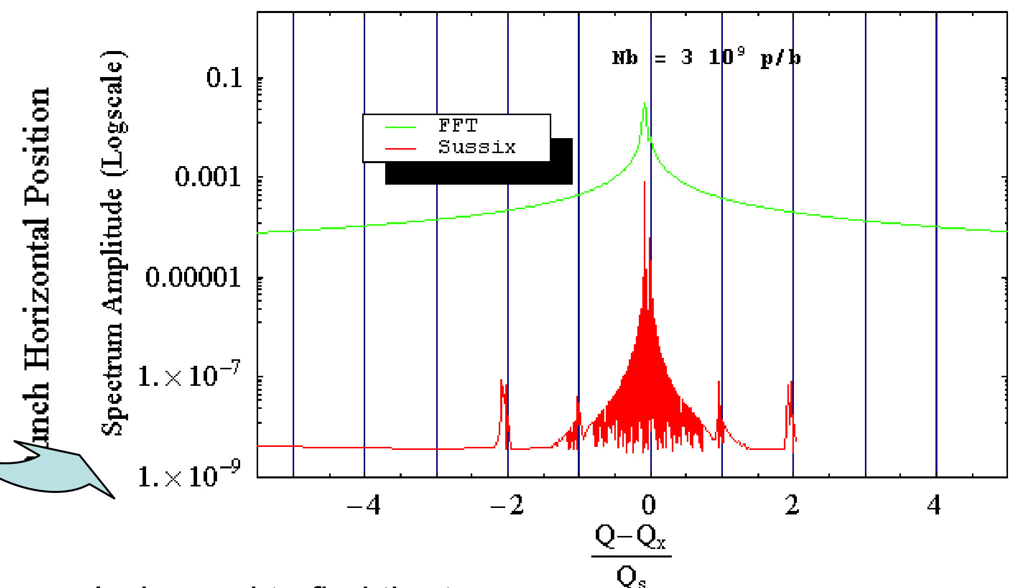
Fast transverse instability in the SPS

Getting the mode spectra from HEADTAIL Simulations

1. Extract the position of the centroid of the bunch (vertical or horizontal) turn after turn → simulated BPM signal
2. Apply a classical FFT to this simulated BPM signal (x)
3. Apply SUSSIX* to this same simulated BPM signal (actually $x - j\,\beta_x x'$)
4. Translate the tune spectrum by Q_{x0}=0 and normalize it to Q_s



Betatron oscillations



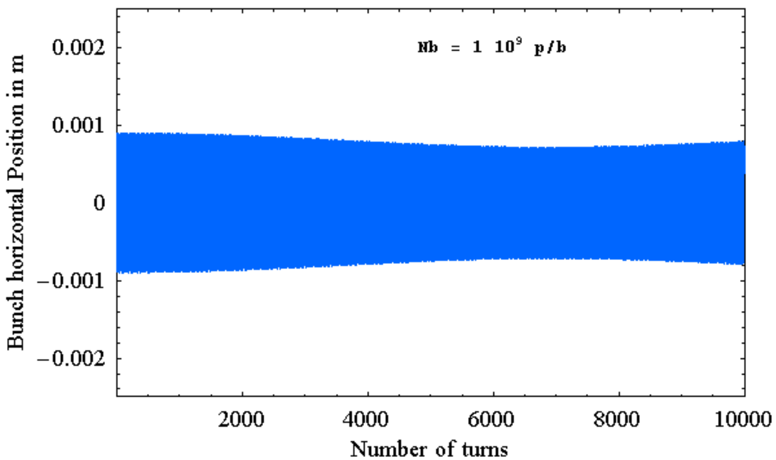
SUSSIX is an iterative interpolated frequency analysis used to find the tunes (R. Bartolini and Schmidt, 1998 – J. Laskar, 1993)

Higher sensitivity of SUSSIX to observe the sidebands

Fast transverse instability in the SPS

What do HEADTAIL simulations predict?

HEADTAIL simulated coherent bunch transverse position at a BPM location

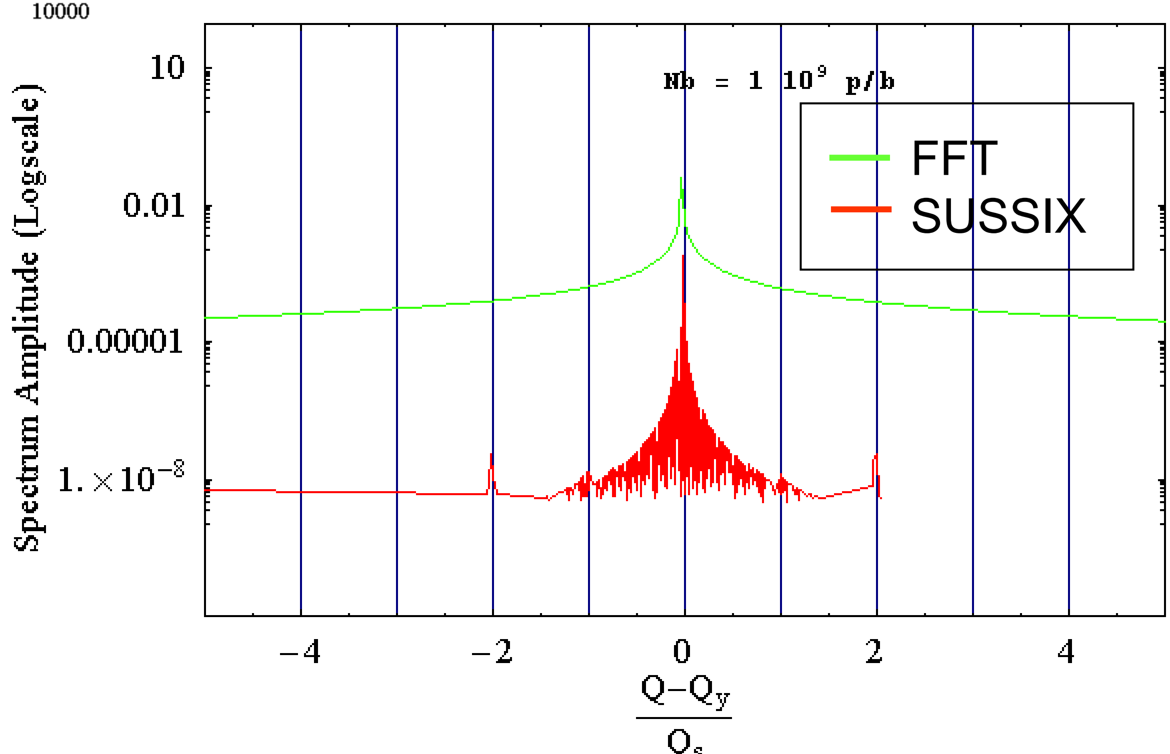


HEADTAIL simulation parameters:
Simple analytical case

- Analytical transverse impedance (broadband)
- Round beam pipe
- No space charge, no spread, no chromaticity
- Linear longitudinal restoring force

FFT
or
SUSSIX

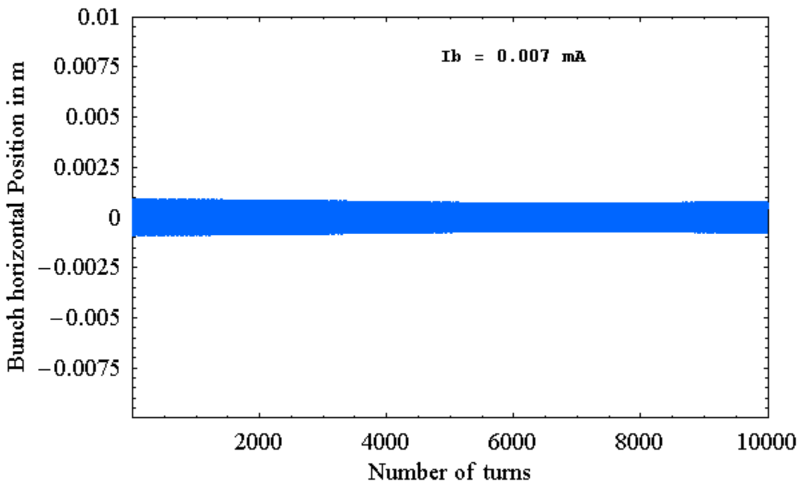
HEADTAIL Simulated mode spectrum



Fast transverse instability in the SPS

What do HEADTAIL simulations predict?

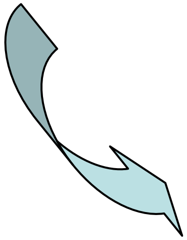
HEADTAIL simulated coherent
bunch transverse position at a BPM location



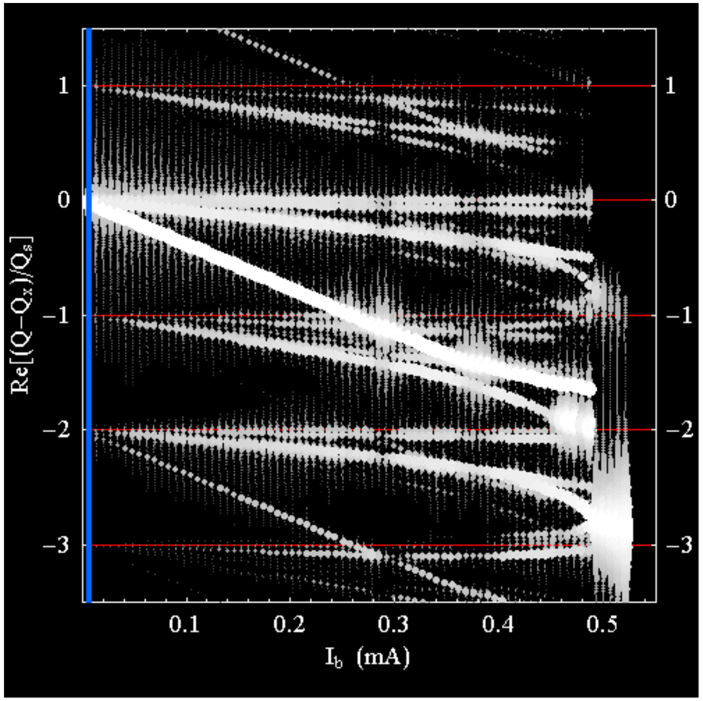
HEADTAIL simulation parameters:
Simple analytical case
- Analytical transverse impedance (broadband)
- Round beam pipe
- No space charge, no spread, no chromaticity
- Linear longitudinal restoring force

→ Transverse modes are observed to shift, couple and decouple with current

SUSSIX



HEADTAIL Simulated mode spectrum



HEADTAIL predicts a TMCI:
large coupling between transverse modes -2 and -3

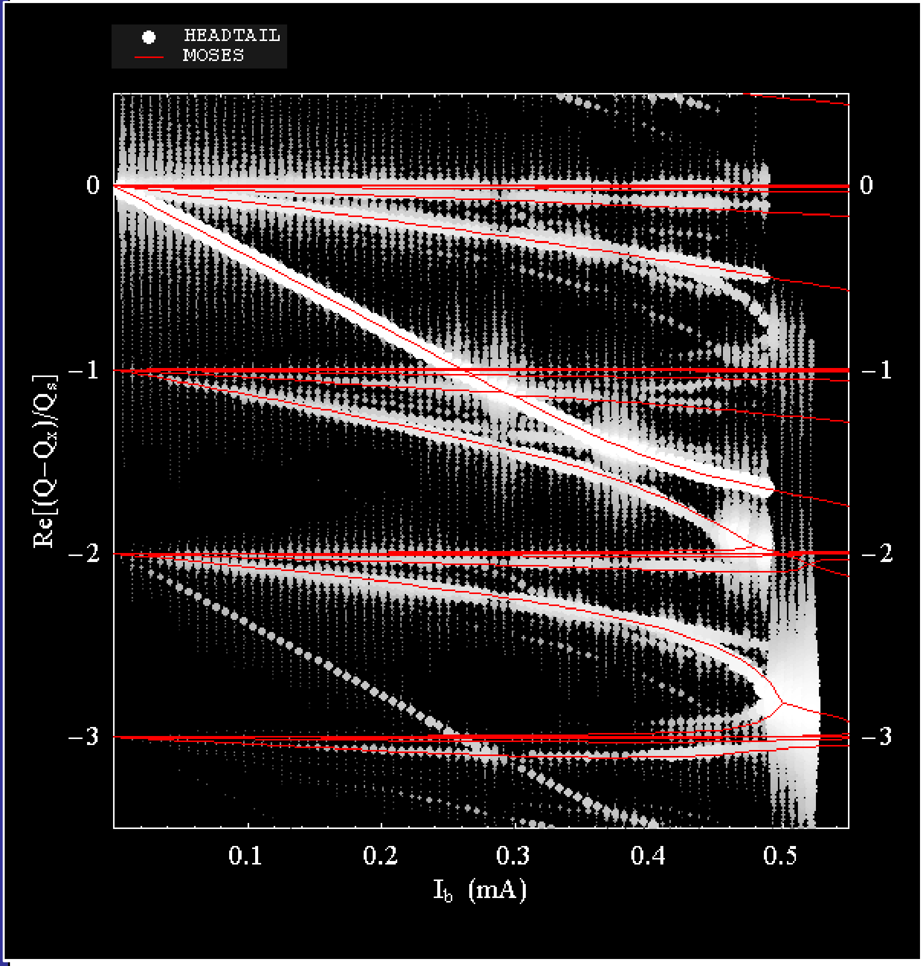
New observables of the TMCI:
- several intensity thresholds
- abrupt shift of the observed tune at the last threshold

Fast transverse instability in the SPS

Benchmark between HEADTAIL simulations and MOSES calculations

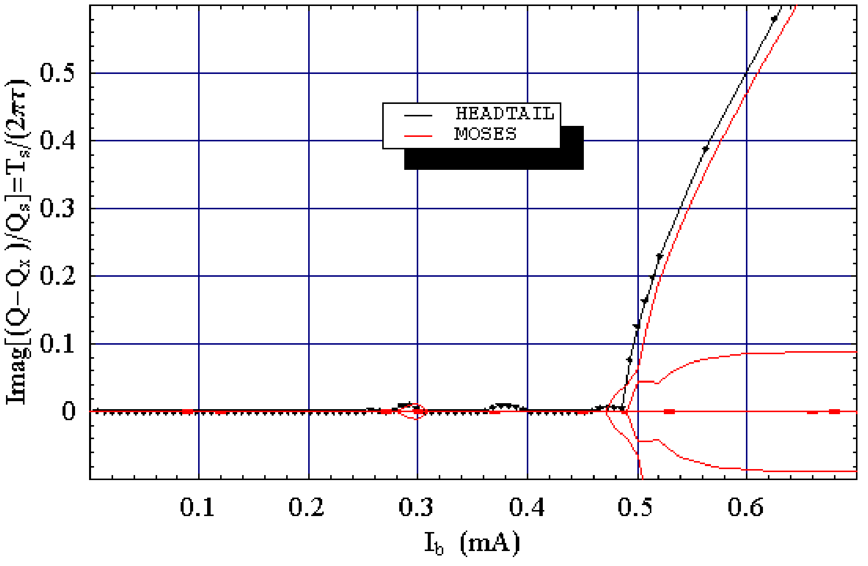
MOSES computes the tune shifts of coherent modes of oscillations of a bunch interacting with an impedance.
(Y.H. Chin, 1988)

MOSES and HEADTAIL mode spectra Vs current



HEADTAIL and MOSES parameters:
- Analytical transverse impedance (broadband)
- Round beam pipe
- No space charge, no spread, no chromaticity
- Linear longitudinal restoring force

MOSES and HEADTAIL growth rate Vs Current

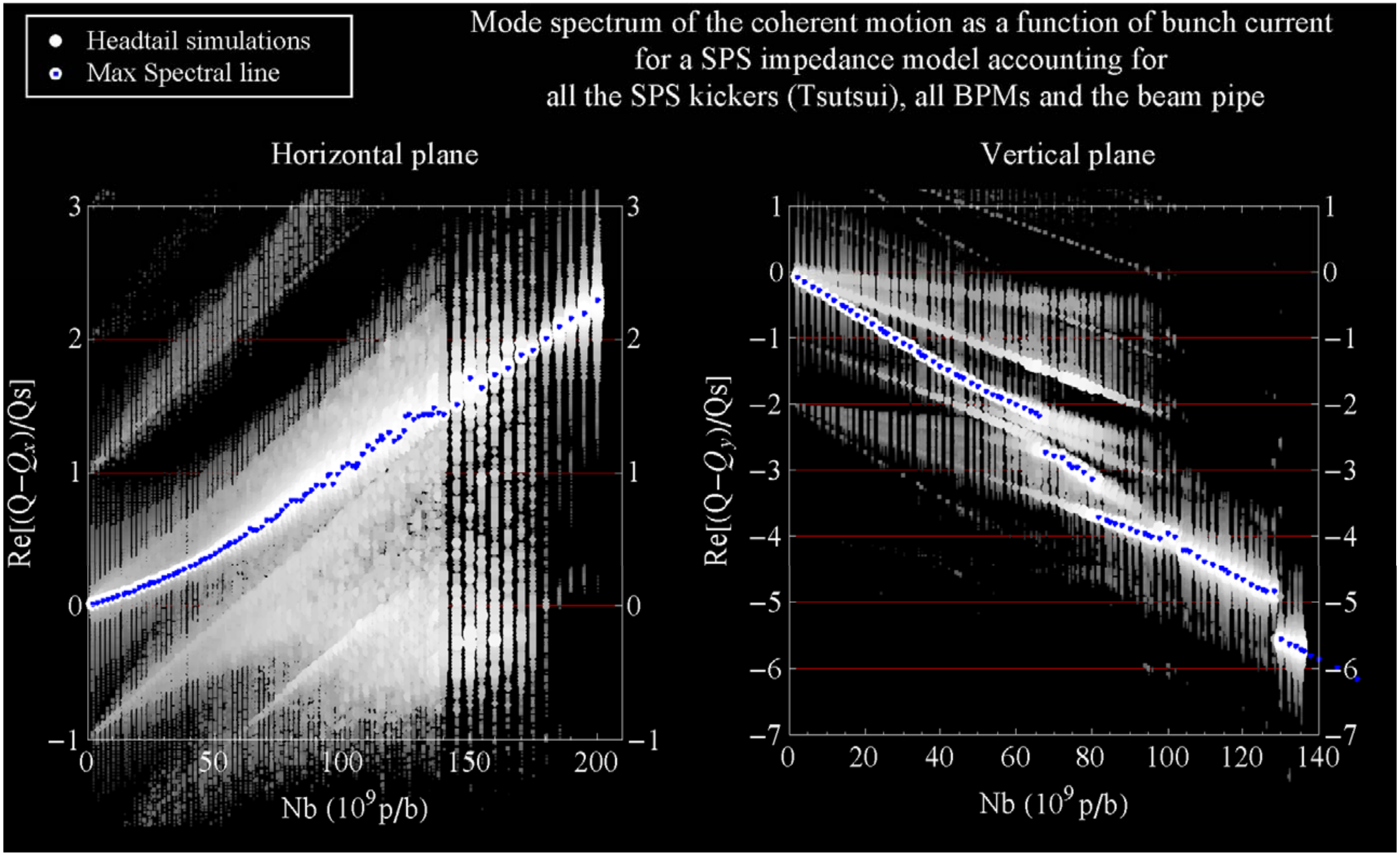


→ Very good agreement between MOSES calulations and HEADTAIL simulations.

Fast transverse instability in the SPS

HEADTAIL simulation with an improved SPS impedance model

BPMs + beam pipe+ kickers (Tsutsui model for the kickers)



→ positive horizontal tune shift, as observed in SPS beam measurements since many years!
→ observed vertical tune is carried by several coherent modes until the large instability

Fast transverse instability in the SPS

Measurements with beam in the SPS

Measurement conditions

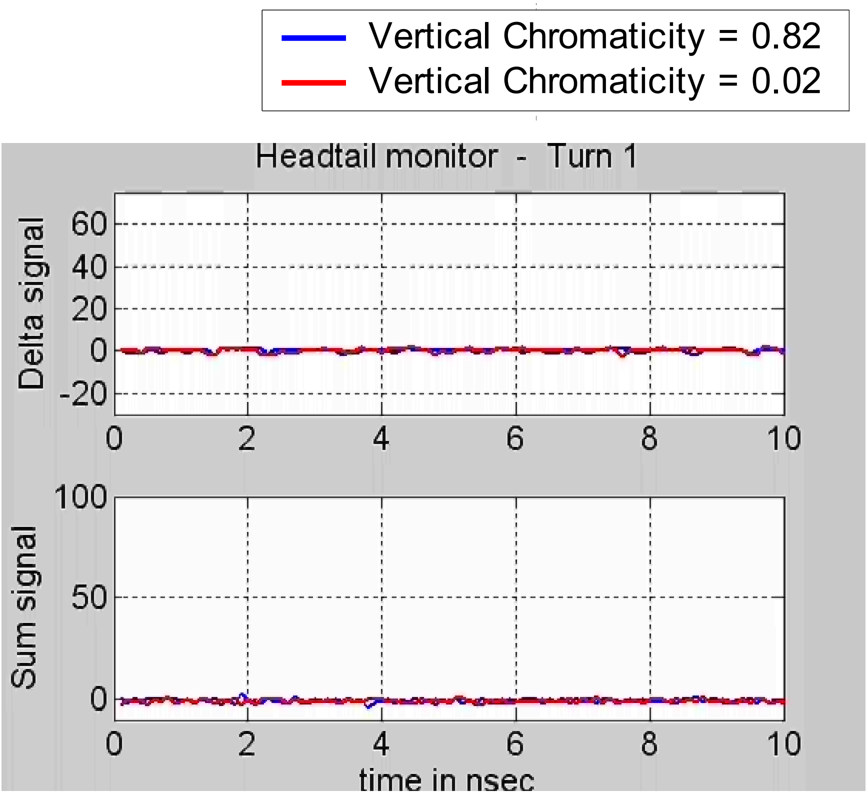
- Single LHC-type-bunch, except low longitudinal emittance (< 0.2 eVs)
- Positive vertical chromaticity as low as possible
- High horizontal chromaticity
- Octupoles used to « correct » amplitude detuning and non linear chromaticity
- Attempt to match RF voltage, but oscillations remain.
- Instrumentation: BCT, Qmeter, Headtail monitor, 2 BBQ, WCM.

Data measured with SPS wideband pickup (Nov 4th 2007)

- High bunch population: 1.2 10^{11} p/b
  → Above fast instability threshold

Transverse bunch distribution

Longitudinal bunch distribution

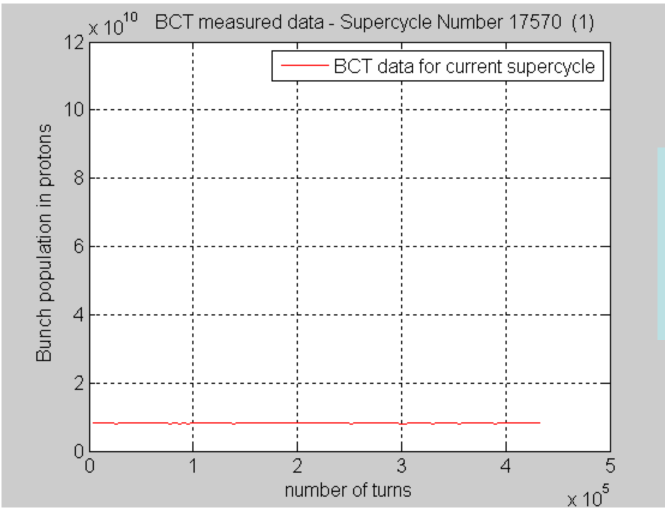


Low chromaticity leads to a fast instability with travelling wave
→ same fast instability that was observed in the past

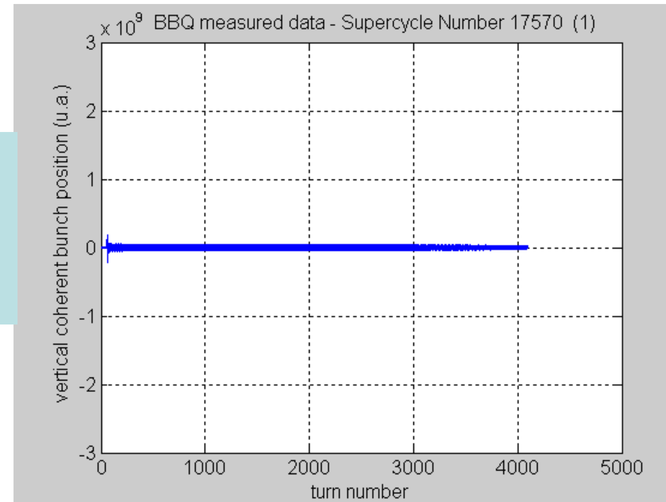
Fast transverse instability in the SPS

Measurements of tune shift with intensity

Bunch intensity= f(turns)

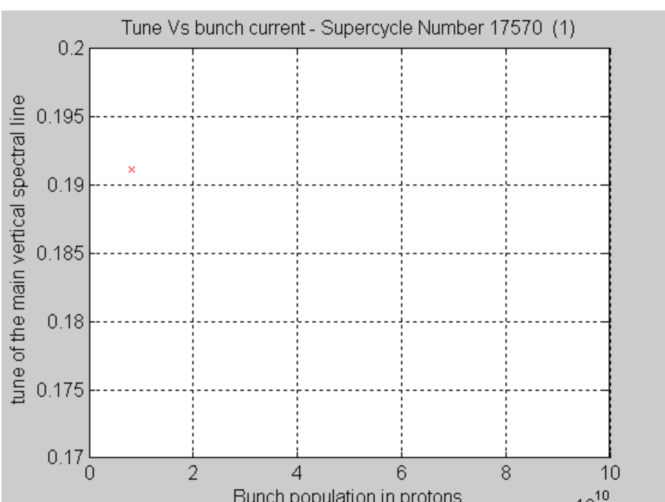


Vertical coherent motion= f(turns)

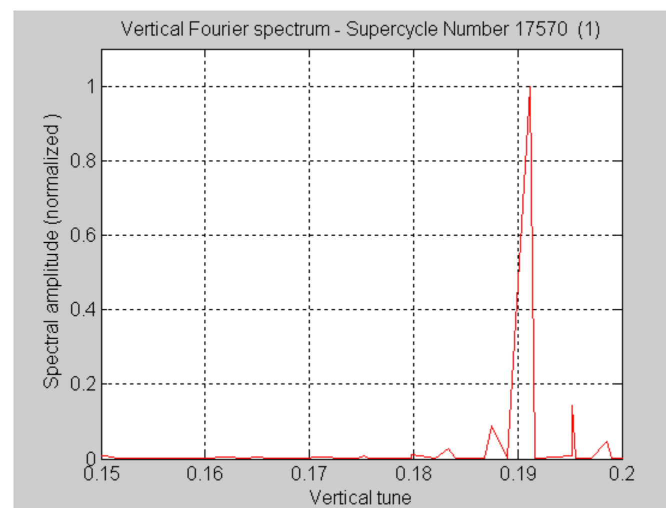


July 4th 2007
SPS fast instability experiment

Coherent tune = f(intensity)



Tune spectrum



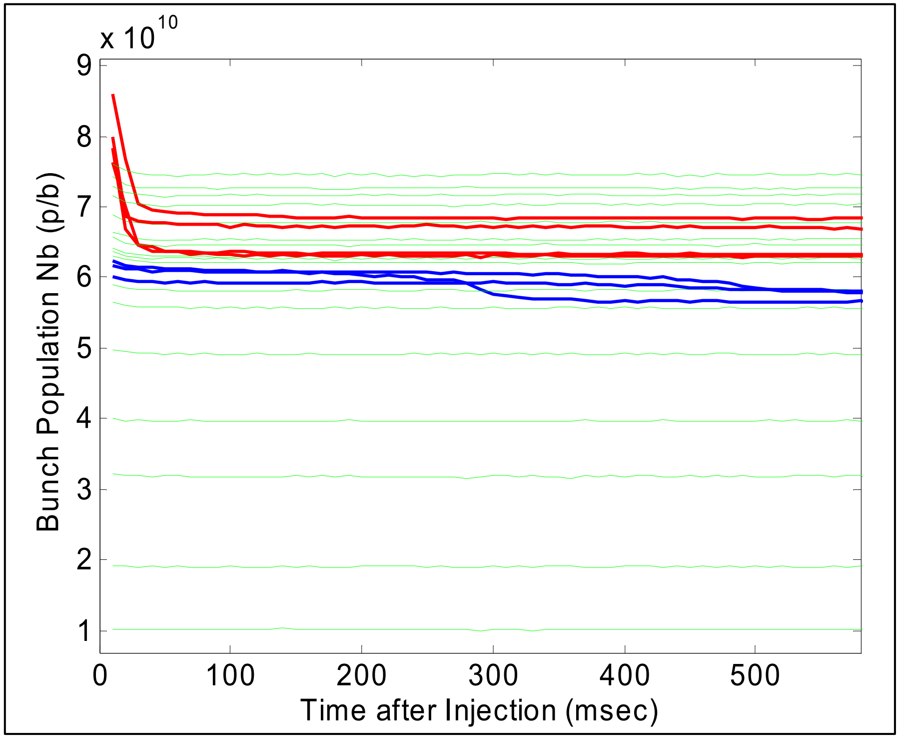
Now let's compare to HEADTAIL simulations

Fast transverse instability in the SPS

Measurements and HEADTAIL simulations: beam losses

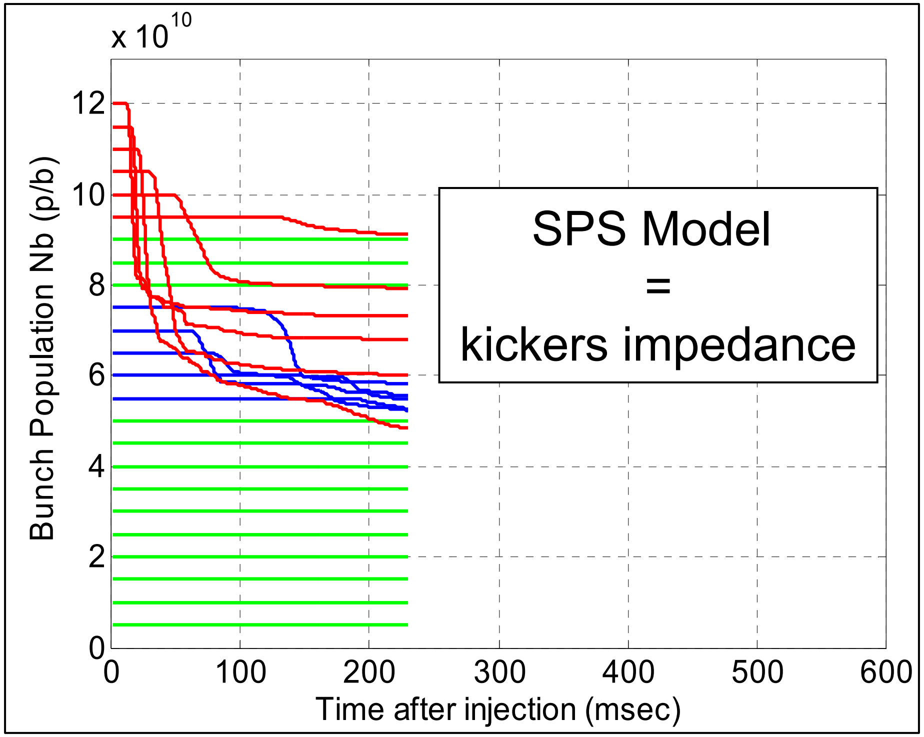
SPS Measurements (Nov 4th 2007)

- Stable beam → $N_b \in [0; 6[$ & $]6.3;7.6]$ 10^{10} p
- Unstable beam → $N_b \in [6; 6.3]$ 10^{10} p
- Unstable beam → $N_b > 7.6$ 10^{10} p



HEADTAIL simulations

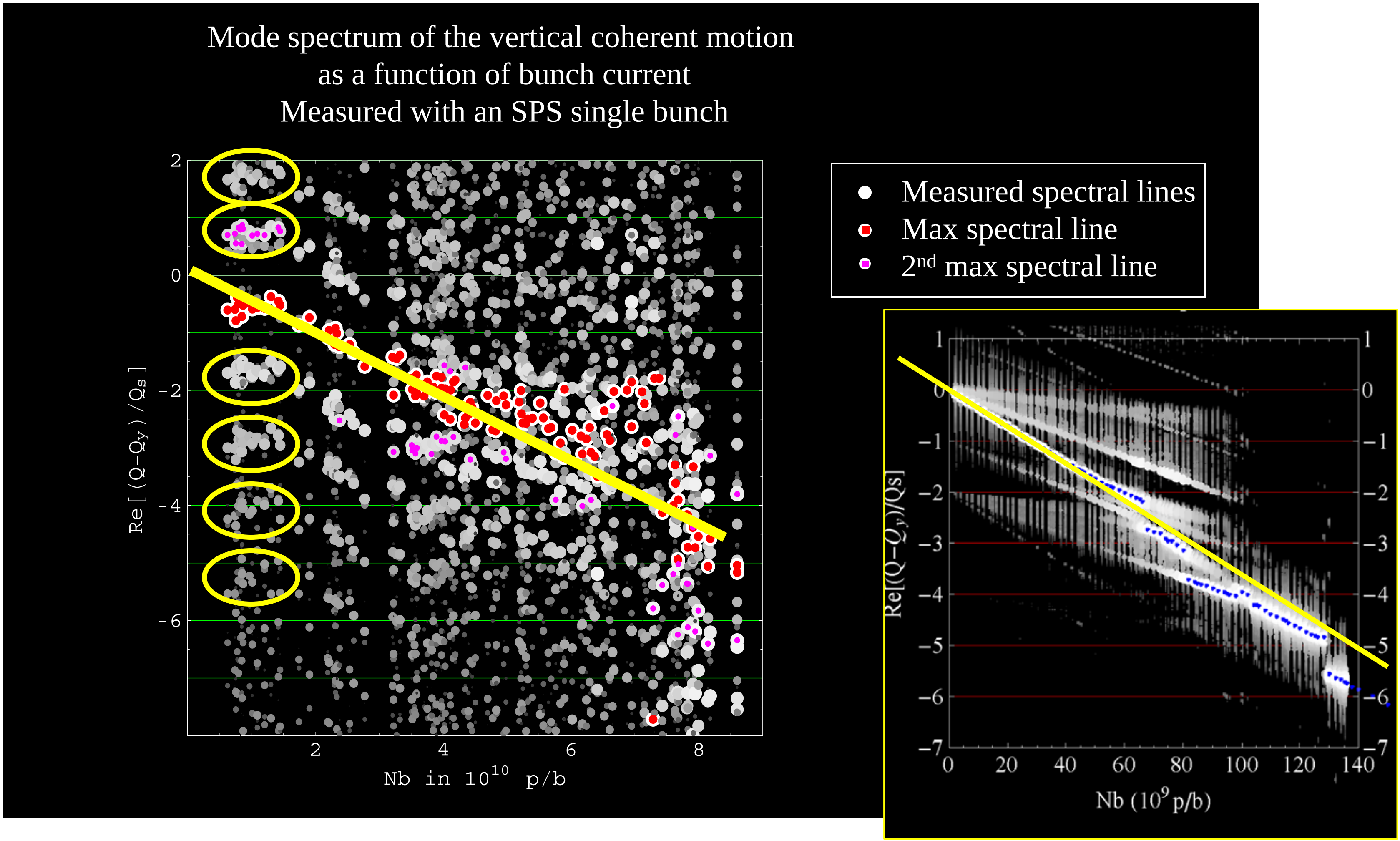
- Stable beam → $N_b \in [0; 5]$ & $[8;9]$ 10^{10} p
- Unstable beam → $N_b \in [5.5; 7.5]$ 10^{10} p
- Unstable beam → $N_b > 9.5$ 10^{10} p



→ Similar pattern of beam losses between simulations and experiments

Fast transverse instability in the SPS

Measurements and HEADTAIL simulations: mode spectra



→ Vertical tune shift with intensity
→ strong sidebands even at low currents (most likely non zero chromaticity)
→ complicated behaviour of the main mode and the second mode.
→ Indication that the mode that leads to the instability is not mode 0

Fast transverse instability in the SPS
Summary and next steps

- Benchmark of MOSES calculations and HEADTAIL simulations for a simple model of impedance. The instability simulated by HEADTAIL is proved to be a TMCI.

- From HEADTAIL simulations, improved SPS impedance model accounts for:
  - about 60% of the measured vertical SPS tune shift and main instability threshold
  - 90% of the measured horizontal SPS tune shift

- Found new features indicating a TMCI (several intensity thresholds and tune step).

- Next steps
  – Improve the current SPS model (adding new elements and improve their 3D model).
  – Continue to follow the changes of hardware to trace the impedance sources
  – Use localization of impedance technique to identify impedance contributors.

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   - Context
   - HEADTAIL simulations
   - Measurements with beam in the SPS
   - Conclusions and next steps

- Sum up

Conclusions

- It is important to separate the dipolar and quadrupolar impedance contributions.
  → The dipolar impedance drives coherent instabilities
  → The quadrupolar impedance damps coherent motion and leads to emittance growth.

- New tools: example of kickers
  - New theoretical formulae for the quadrupolar impedance in the frame of Tsutsui formalism
  - New 3D simulations of the dipolar and quadrupolar impedance of simple models of kickers
  - Good agreement between theory and simulations

- From HEADTAIL simulations, improved SPS impedance model accounts for:
  → 60% of the measured vertical SPS tune shift and main instability threshold
  → 90% of the measured horizontal SPS tune shift

- Complicated wake function leads to complicated mode spectrum.
  → Monitoring the tune shift only gives information on the total impedance, when the main objective is reducing instabilities i.e. minimizing the dipolar impedance.

Ongoing work and next steps

- Refine current impedance models for the kickers (cells, serigraphy, external circuits,etc.)
  → Carlo Zannini, Hugo Day et al
- Dipolar and quadrupolar simulations and/or measurements of other potential sources of impedance (pumping ports, RF cavities)
  → Olav Berrig, Bruno Spataro et al
- Include new theories and simulations to improve the longitudinal impedance model together with BE/RF-BR.
- Implement this framework to obtain the LHC impedance model
  → Nicolas Mounet et al
- Use localization of impedance technique to identify impedance contributors.
  → Rama Calaga et al
- Thorough study of the stability of the nominal bunch in the SPS (0.35 eVs longitudinal emittance)

Acknowledgments

- The « impedance team »:
G. Arduini, R. Calaga (BNL), F. Caspers, A. Grudiev, H. Medina, E. Métral, N. Mounet, D. Quatraro, F. Roncarolo, G. Rumolo, E. Shaposhnikova, B. Spataro (INFN), C. Zannini, B. Zotter.

- The «control room team »:
T. Bohl, M. Gasior, W. Hőfle, R. de Maria (BNL), G. Papotti, S. Redaelli, R. Steinhagen, R. Tomás, J. Wenninger, S. White, PSB, PS and SPS supervisors and operators.

- The « 3D simulation teams »:
L. Haenichen, W. Mueller (TU Darmstadt), C. Boccard, A. d'Elia, A. Grudiev, E. Jensen, T. Kroyer, B. Spataro (INFN), colleagues from EN/MME and EN/MEF.

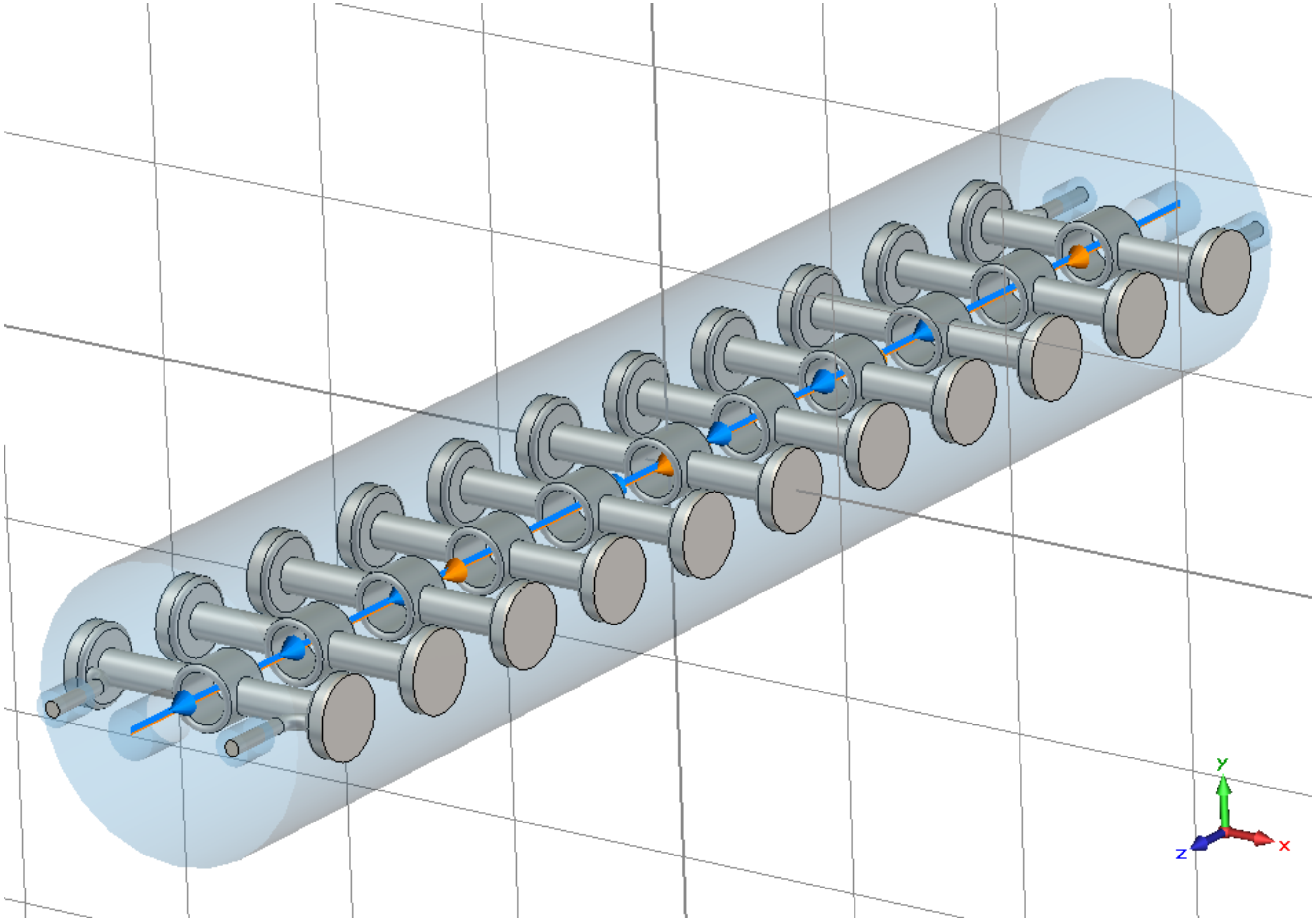
- The « software, hardware and support teams »:
O. Aberle, R. Assmann, M. Barnes, J. Evans, J. Jowett, D. Rivoiron, J. Serrano, colleagues from BTE desktop as well as BE/RF, TE/ABT and EN/STI workshops.

- And of course…

- The « supervisor team »:
Elias Métral and Lenny Rivkin

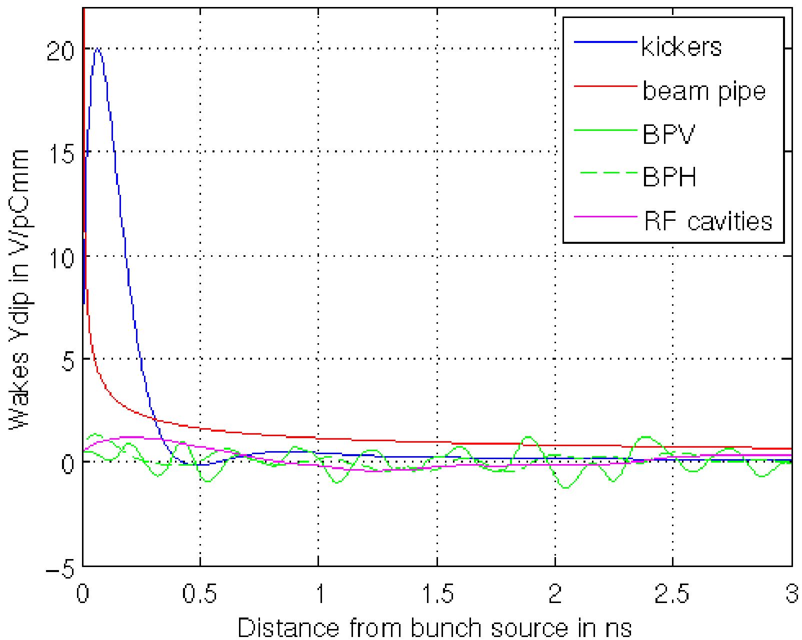
Thank you very much for your attention!

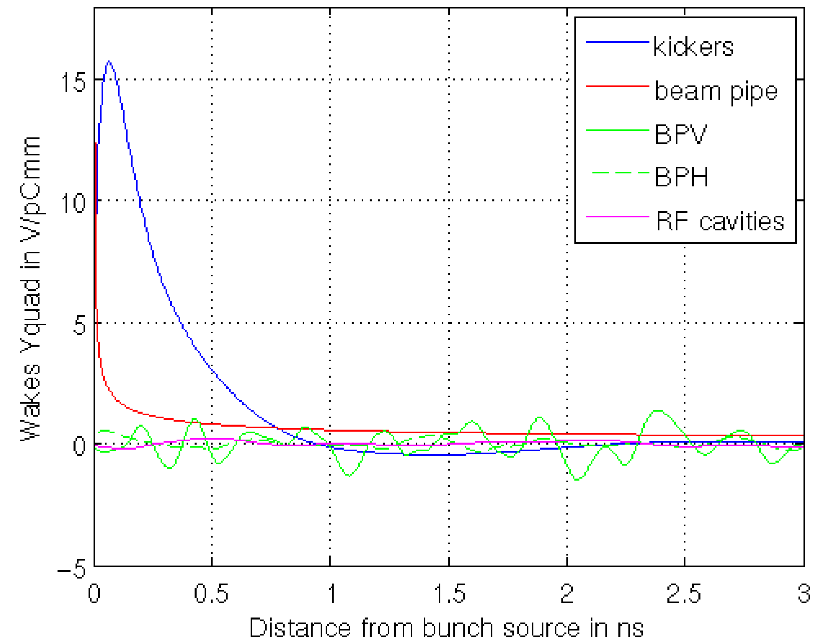
Bonus: adding 3D simulations of TW 200 MHz cavities



Together with B. Spataro (INFN)

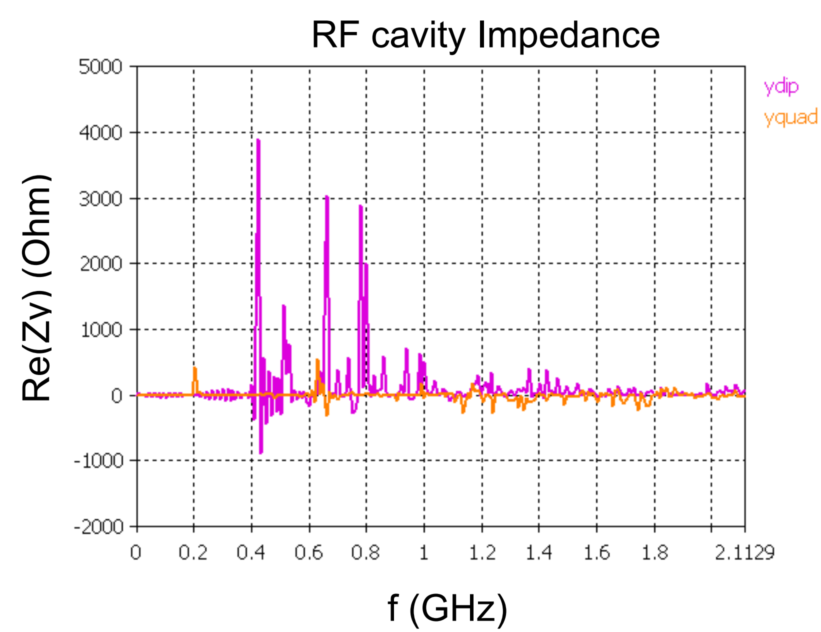
Dipolar wake "functions" for RF cavities imported into HEADTAIL





- Wake seems small with respect to the kickers

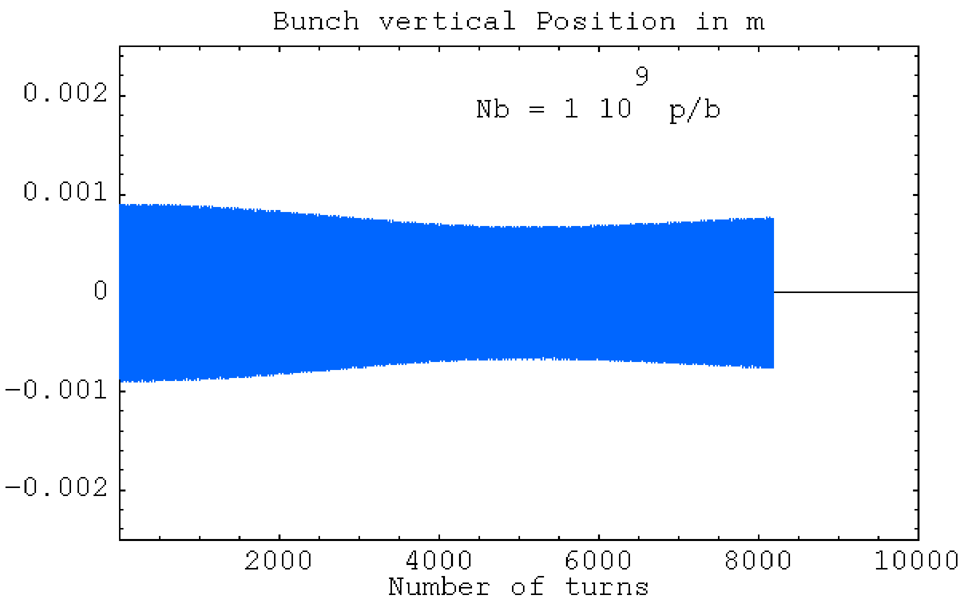
- However, large impedance peak at 400 MHz



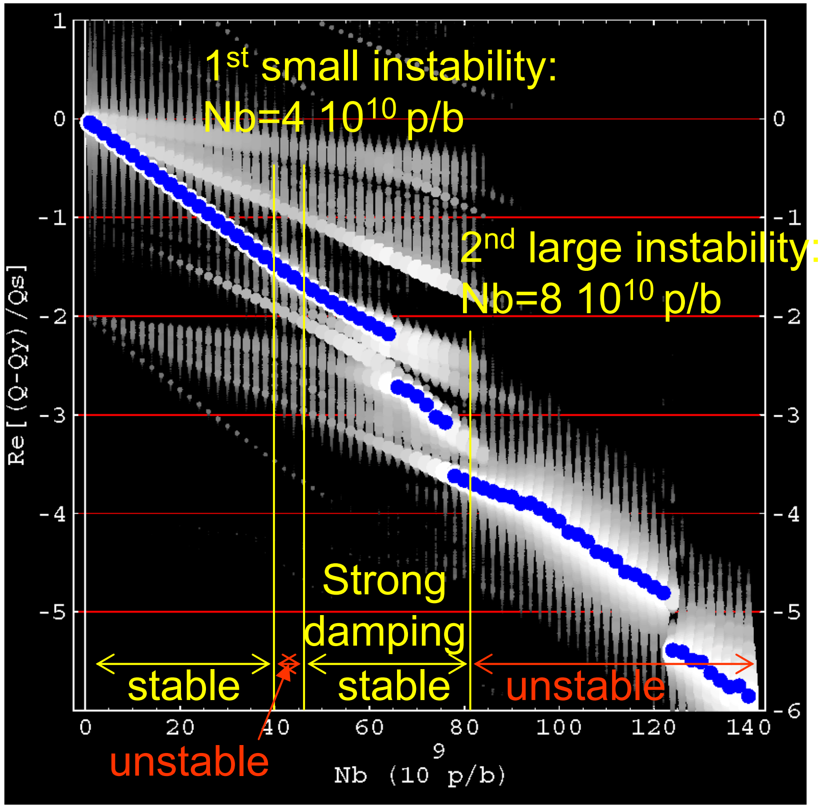
Preliminary results:including the TW 200 MHz accelerating cavities

Model includes :

- 106 BPHs (CST 3D simulations)
- 96 BPVs (CST 3D simulations)
- 6.911 km beam pipe (Zotter/Metral analytical calculations for a round pipe including indirect space charge, transformed with Yokoya factor)
- 20 kickers (situation during 2006 run, analytical calculations with Tsutsui model)
- 2 TW 200 MHz cavities (4 sections of 11 cells) without couplers
- 2 TW 200 MHz cavities (5 sections of 11 cells) without couplers



Mode spectrum as a function of bunch current



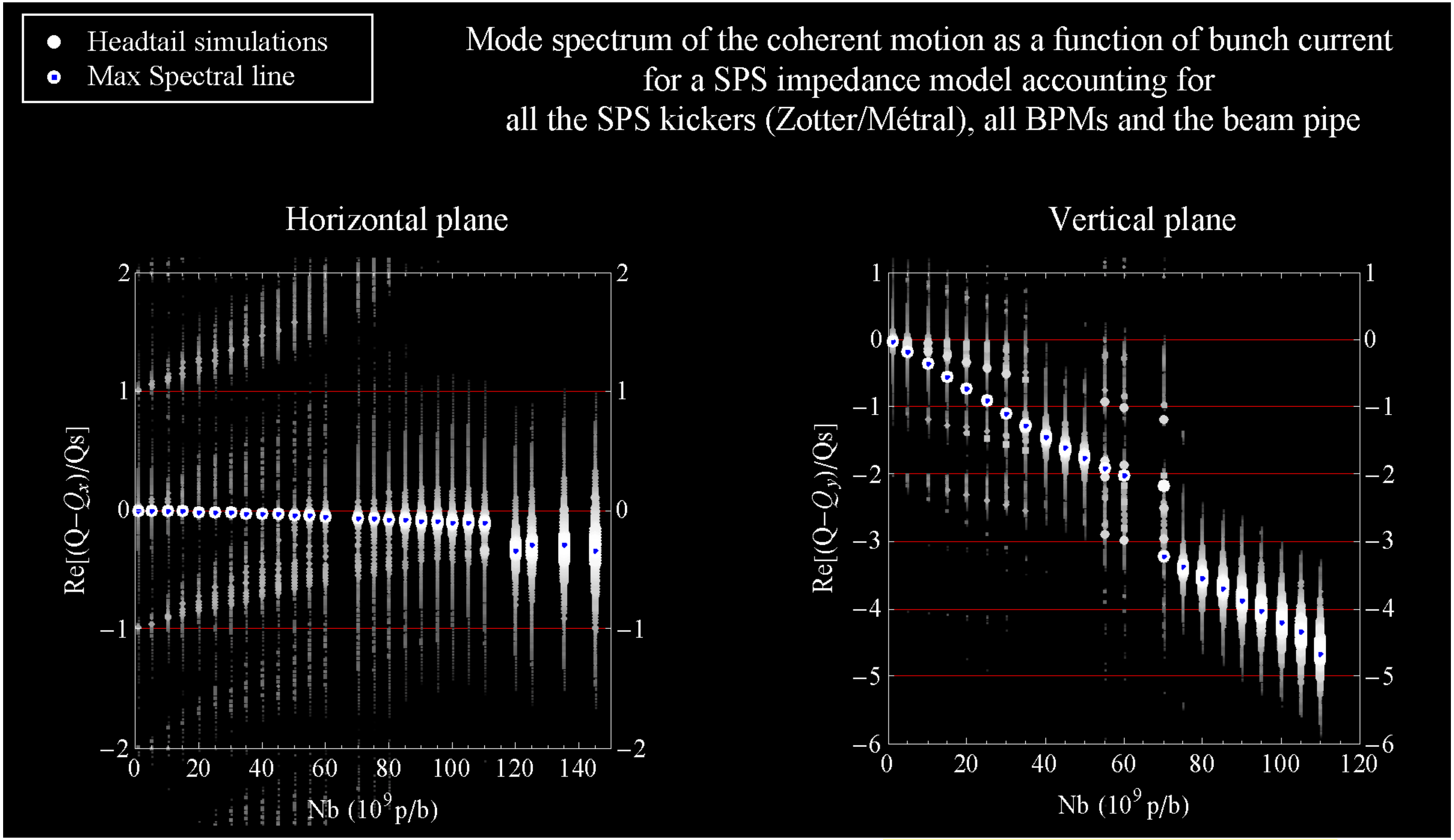
With the RF cavities,
(1) the tune shift is not changed much
(2) the threshold falls to 8 10^{11} p/b…
(3) … due to the coupling between modes -1 and -2

As a conc

Fast transverse instability in the SPS

HEADTAIL simulation with an improved SPS impedance model (1)

BPMs + beam pipe+ kickers (Zotter/Métral model with Yokoya factors for the kickers)



Negative horizontal tune shift

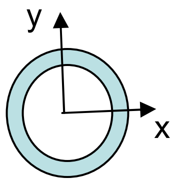
TMCI in the vertical plane

Yokoya factors

Why worry about beam impedance?
Yokoya Factors

Example: case of an ultrarelativistic beam in a good cylindrical conductor

cylindrical structure (radius a)

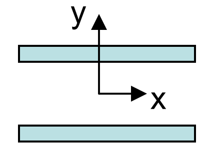


$$Z_{x,tot} = Z_{cyl}\, x_{source}$$

$$Z_{y,tot} = Z_{cyl}\, y_{source}$$

Only dipolar impedance

Flat chamber structure (half gap a)



$$Z_{x,tot} = Z_{cyl}\left(\frac{\pi^2}{24} x_{source} - \frac{\pi^2}{24} x_{witness}\right)$$

$$Z_{y,tot} = Z_{cyl}\left(\frac{\pi^2}{12} y_{source} + \frac{\pi^2}{24} y_{witness}\right)$$

dipolar and quadrupolar impedance

Yokoya factors

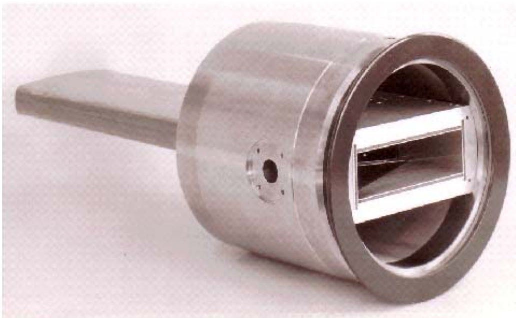
→ Yokoya form factors relate the flat chamber impedance to the cylindrical impedance

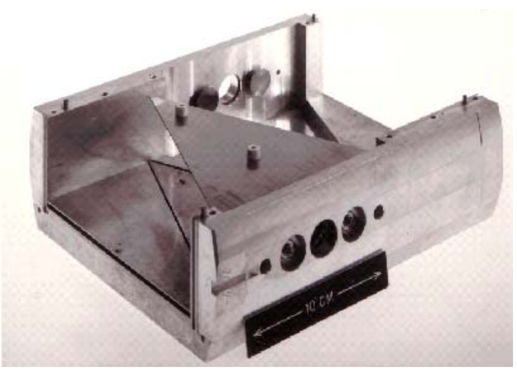
→ These factors are constants of frequency.

Simulaions and measurements of SPS BPMs

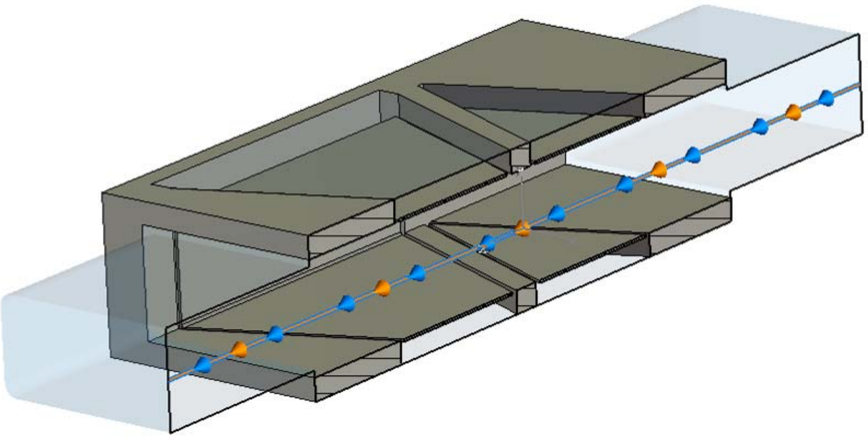
CST simulations of more complicated structures: SPS BPMs

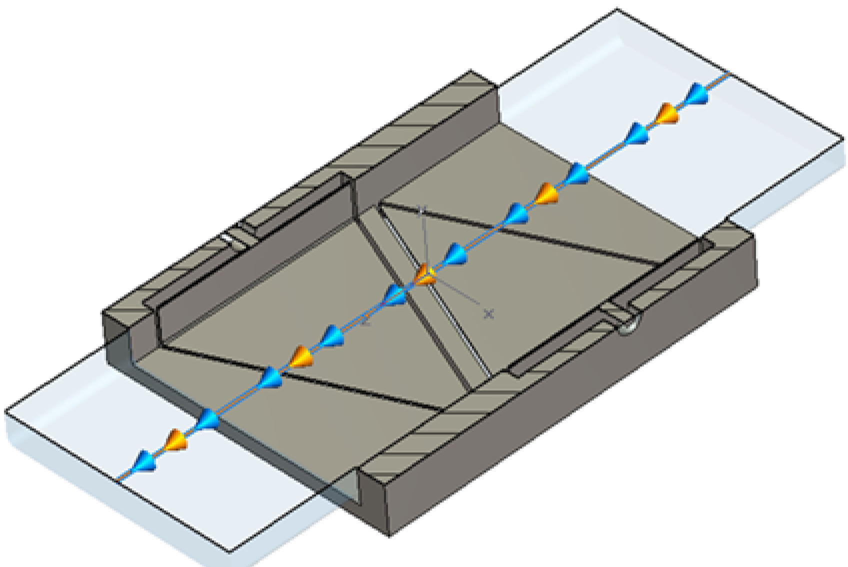
SPS BPH



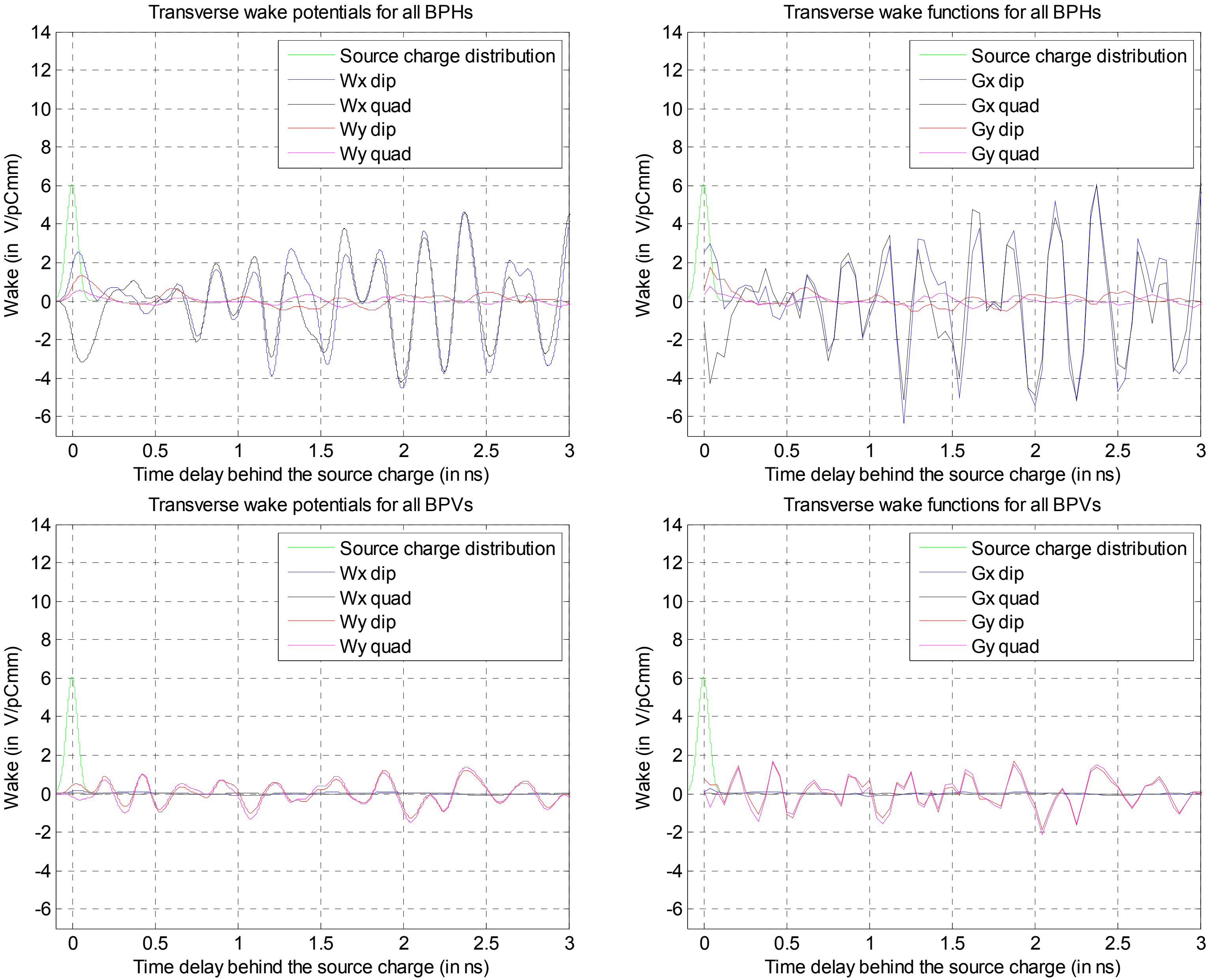


SPS BPH model geometry





Transverse dipolar and quadrupolar wakes for all the SPS BPMs

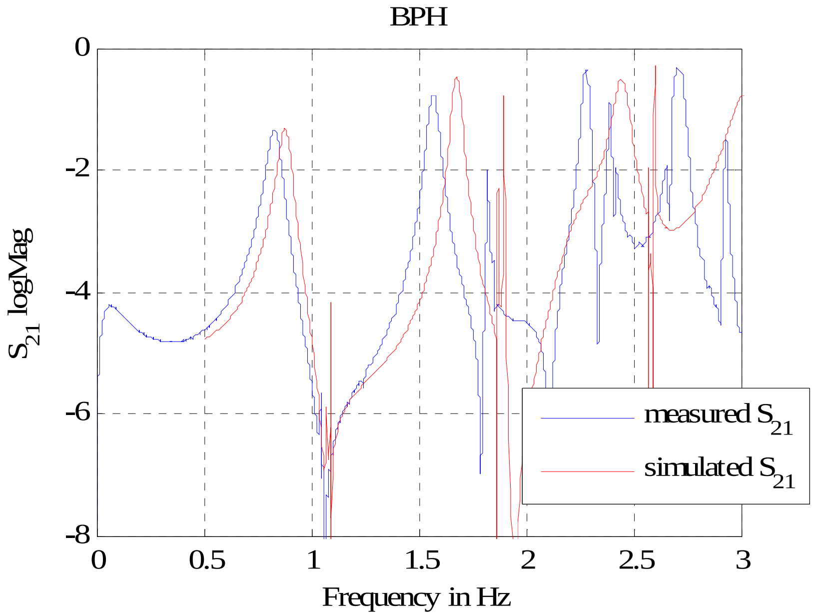


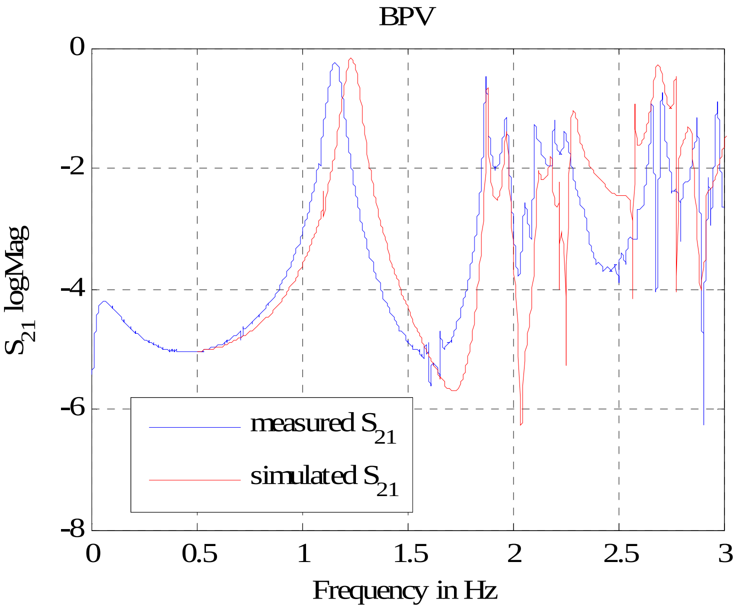
Small contribution next to the bunch, but oscillations last for a very long time and may affect following bunches

However, since we were not very experienced at the time, we'd like to check a bit the CST results…

Comparison between scattering parameter S_{21} from CST simulations and RF measurements

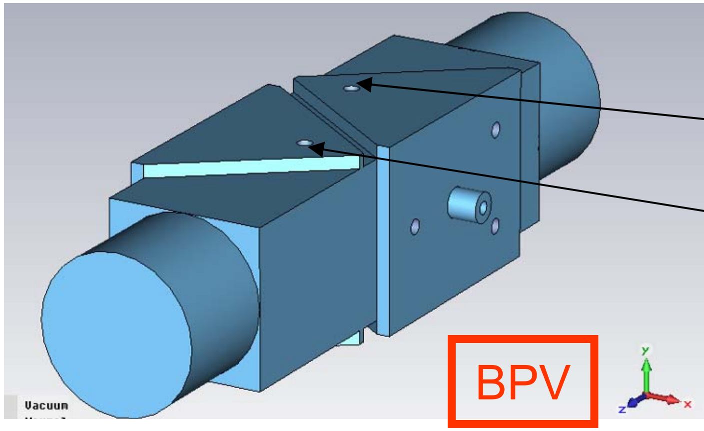
- Transmission measurement between electrode ports (S_{21})
- More convenient than wire measurement in this case (small signal expected, radioactive device, no need to recondition)



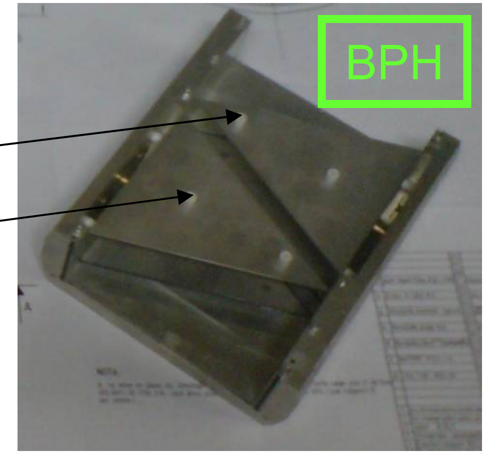


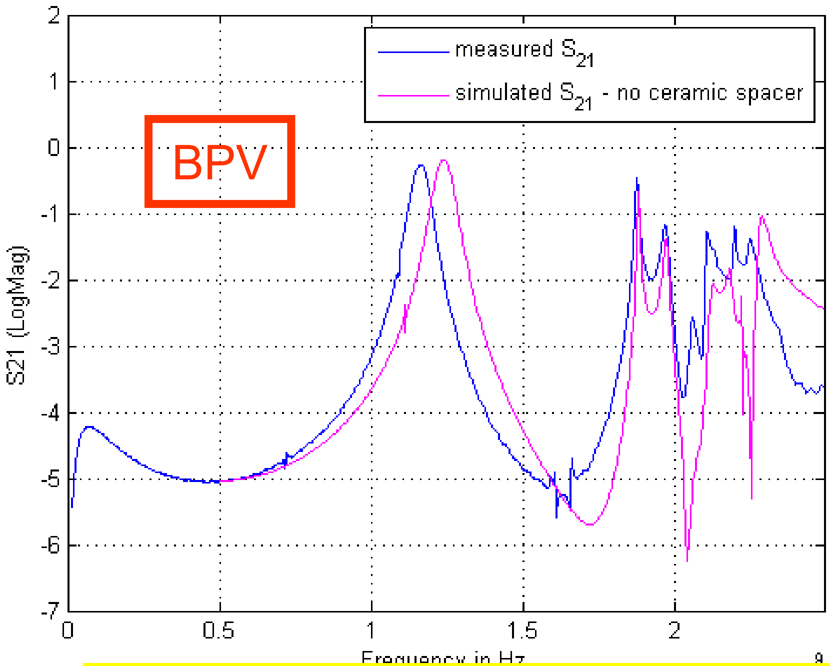
Comparison between simulated and measured S_{21}

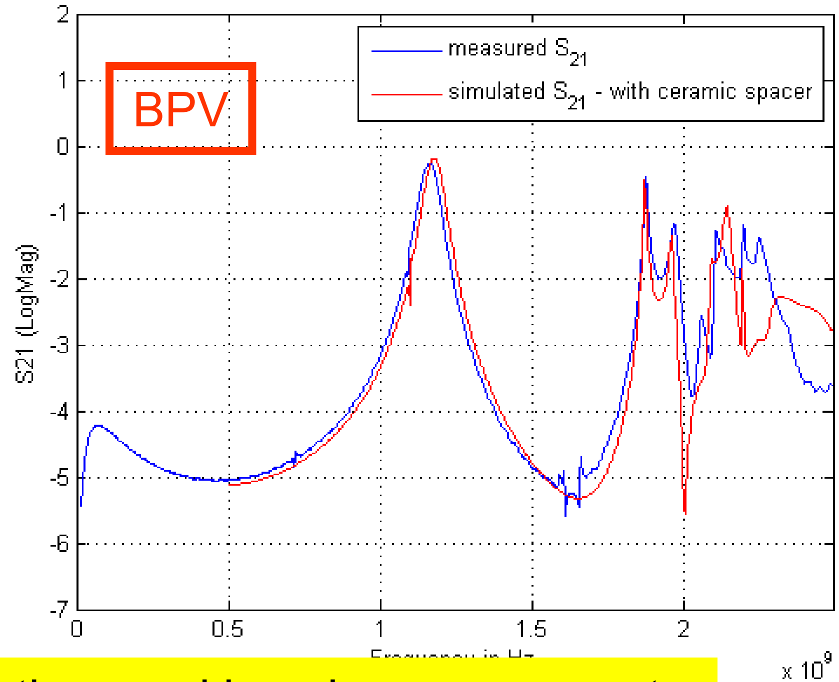
Adding the ceramic spacers



Ceramic insulator spacers designed to mechanically stabilize the thin electrodes





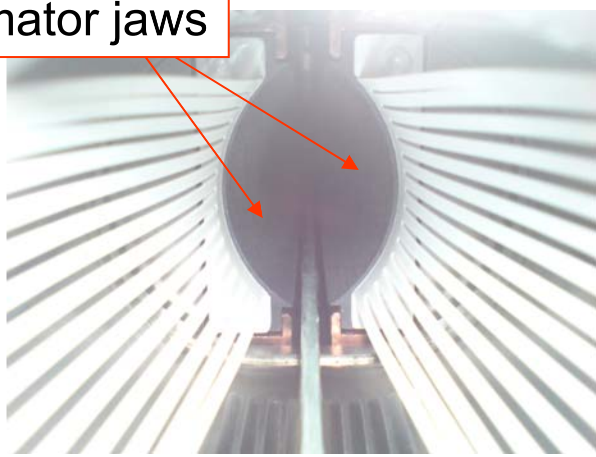


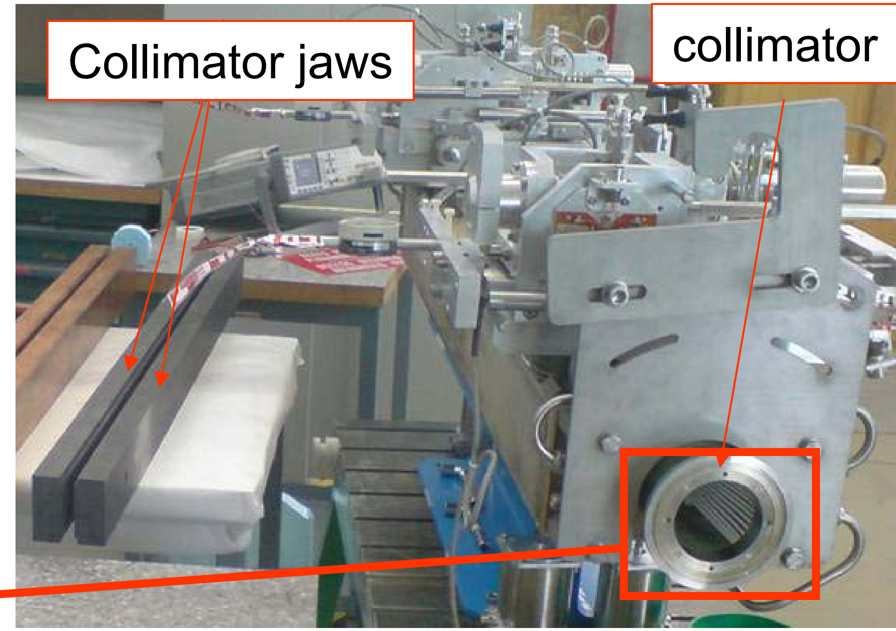
Good agreement between CST simulations and bench measurements

LHC collimator wake fields

Collimators should intercept protons on wrong trajectories to prevent damage to the superconducting LHC magnets:

- small aperture for the beam (gap of 2 mm)
- made of graphite (low conductivity)





Transverse wake fields created by the LHC graphite collimators are a concern for beam stability, in particular at very low frequencies (kHz to MHz)

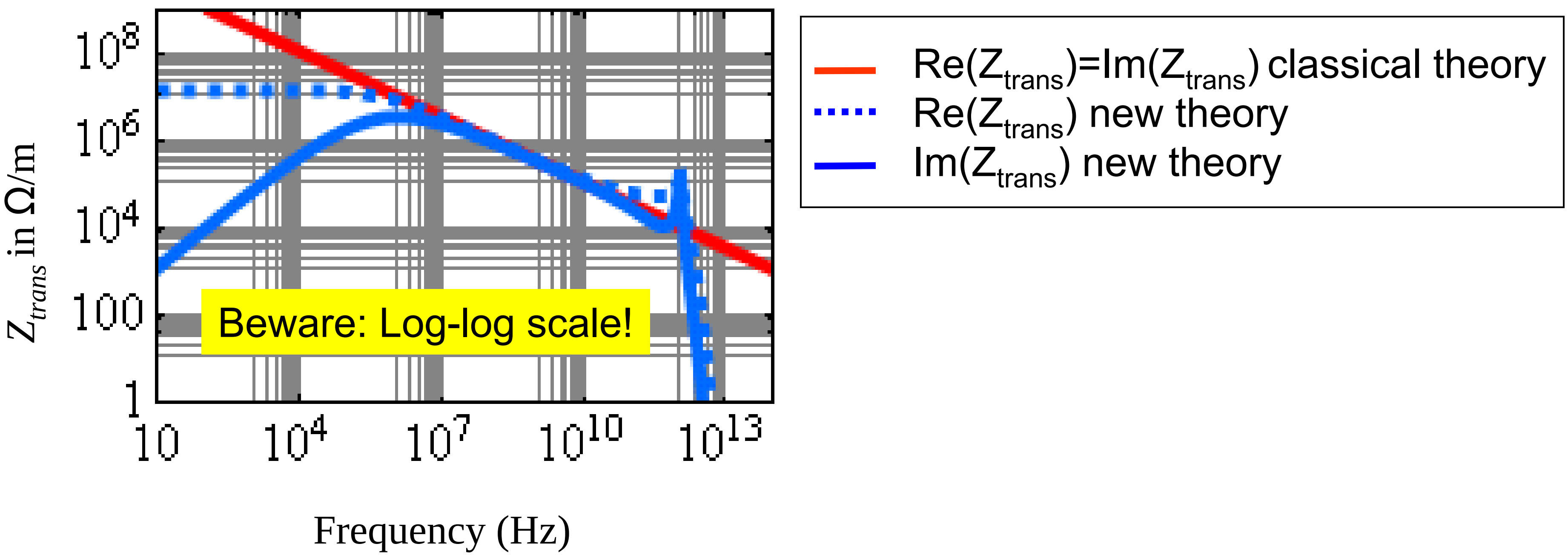
Objectives: → assess the impedance of the LHC collimators
→ check the validity of the ''new'' impedance theories

Method: → Compare impedance theory with bench measurements

Collimator transverse impedance from theory

- Solve Maxwell equations with a source beam and axisymetric boundary conditions
- A new formalism developed by E. Metral and B. Zotter uses less approximations than the classical theory.

Comparison between transverse impedance theories as a function of frequency - $Z_{trans}(f)$

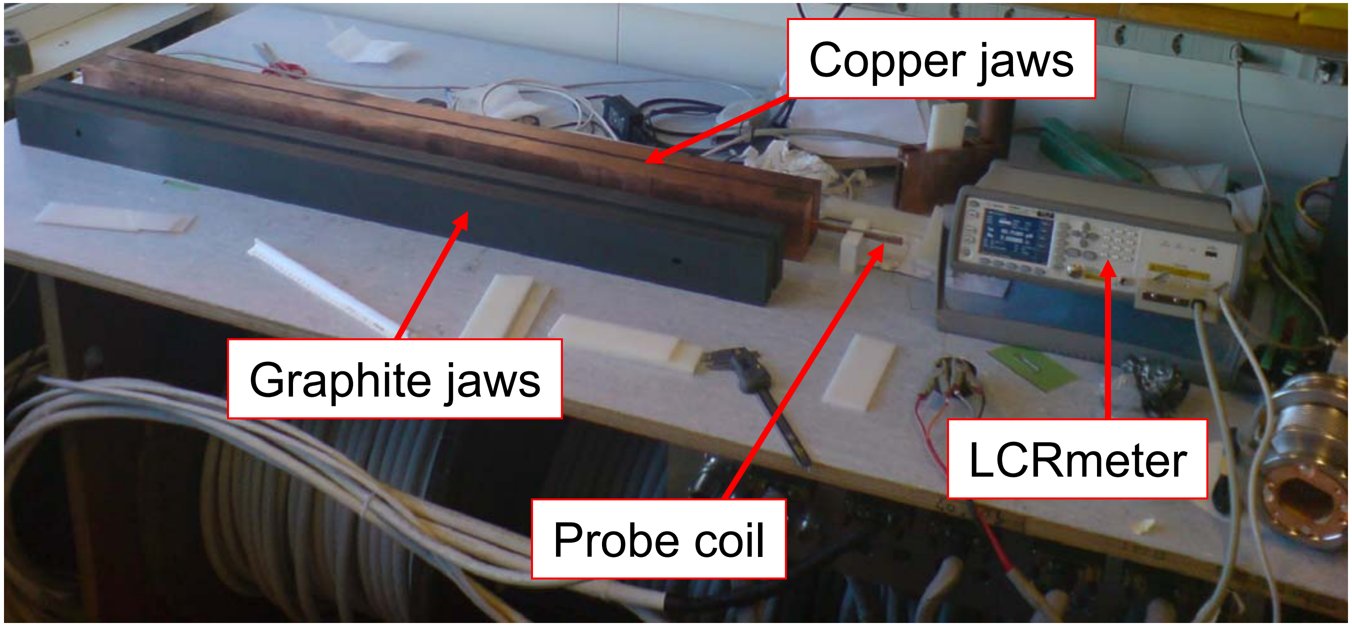


New theory gives much lower impedance at low frequencies than the classical theory

Which theory should we trust?

Setup for bench measurements

RF bench measurements with a coil → « simulates » a particle beam



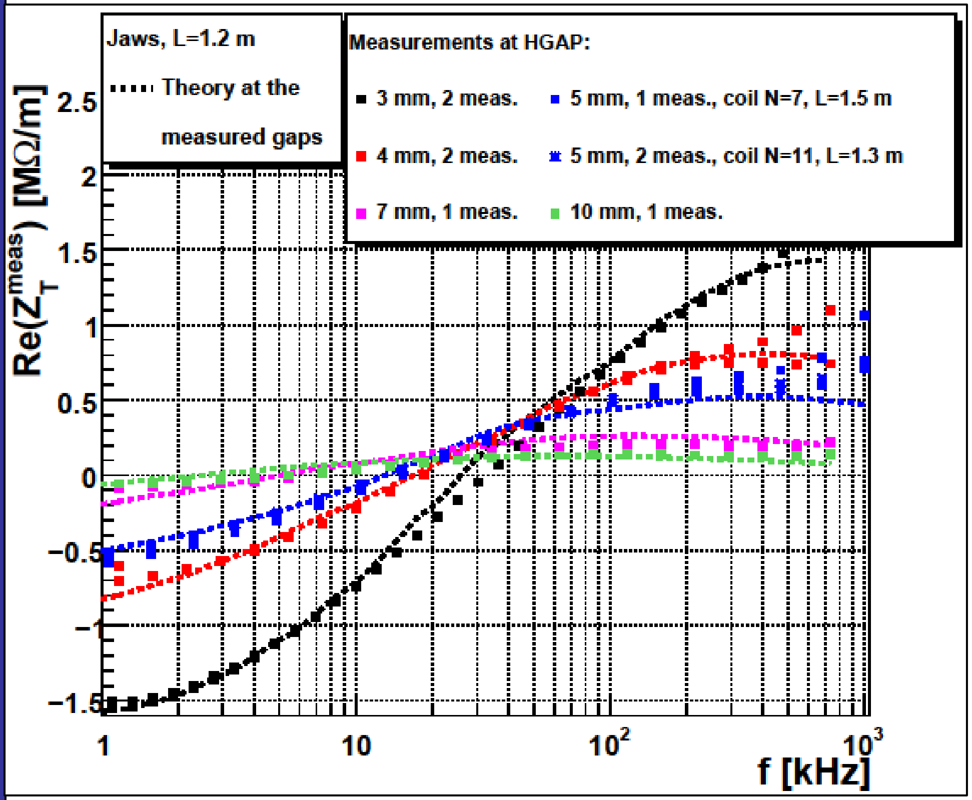
The electrical impedance of the coil Z_{coil}
can be linked to the transverse dipolar beam impedance of the device Z_T

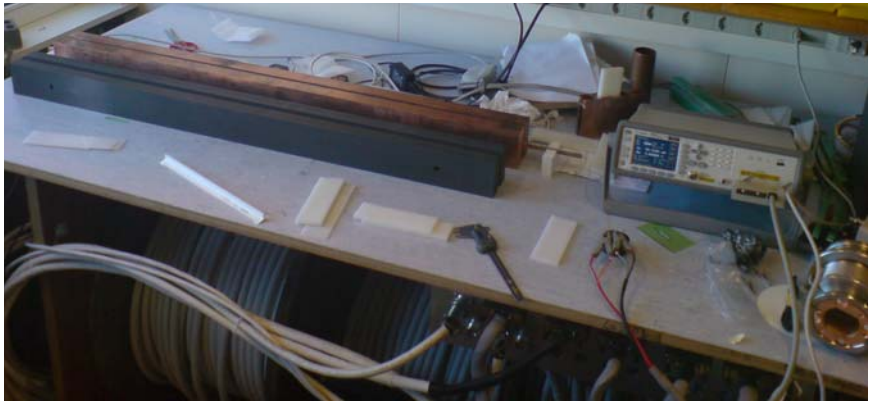
$$Z_T^{meas} = Z_T^{device} - Z_T^{reference} = \frac{c}{\omega N^2 d^2}\left(Z_{coil}^{device} - Z_{coil}^{reference}\right)$$

Δ(Beam impedance)

Measured with LCRmeter

Impedance bench measurement of collimator jaws





Theory
Measurement
Each color is a different gap

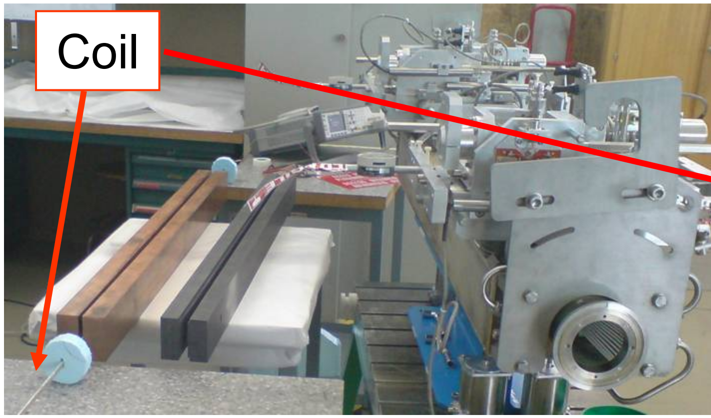
$$Z_T^{meas} = Z_T^{device} - Z_T^{reference} = \frac{c}{\omega N^2 d^2}\left(Z_{coil}^{device} - Z_{coil}^{reference}\right)$$

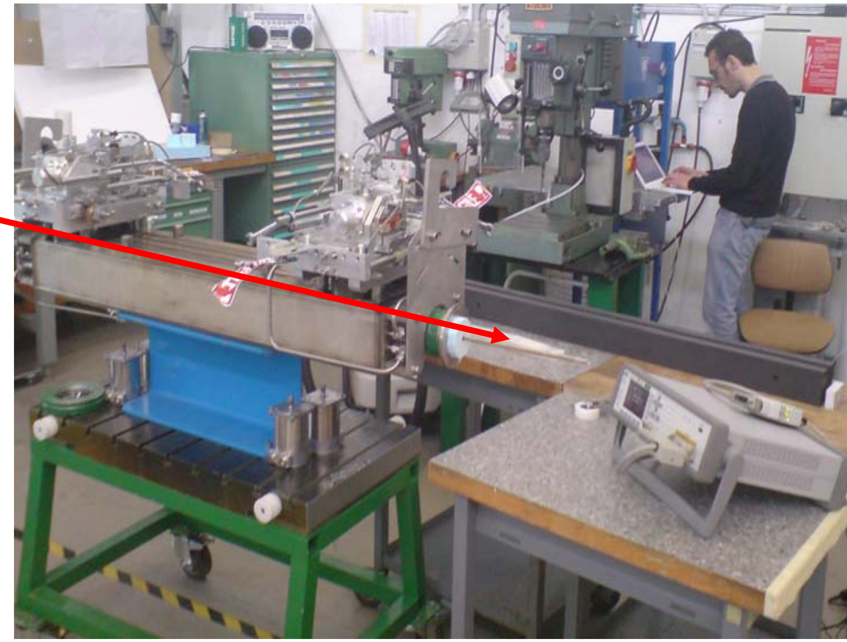
Nota: since the impedance difference is plotted, it can become negative if $Z_{copper} > Z_{graphite}$, which is the case at low frequencies.

Very good agreement of measurement with new theory.

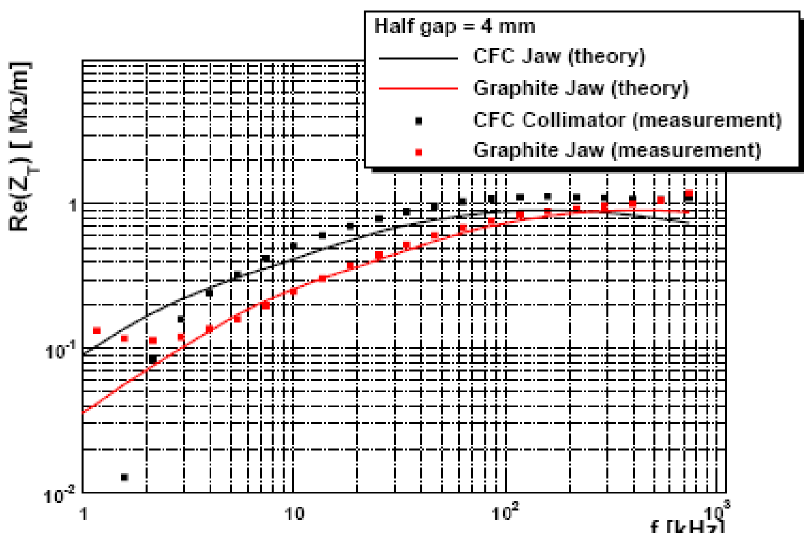
Impedance bench measurement of collimator assembly

Following the results with jaws, one collimator assembly was made available for us:

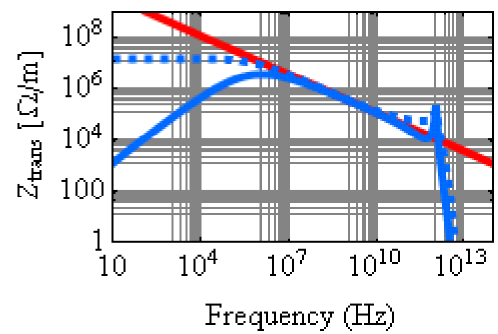




Comparison between measurements and new theory



Recall old theory and new theory →



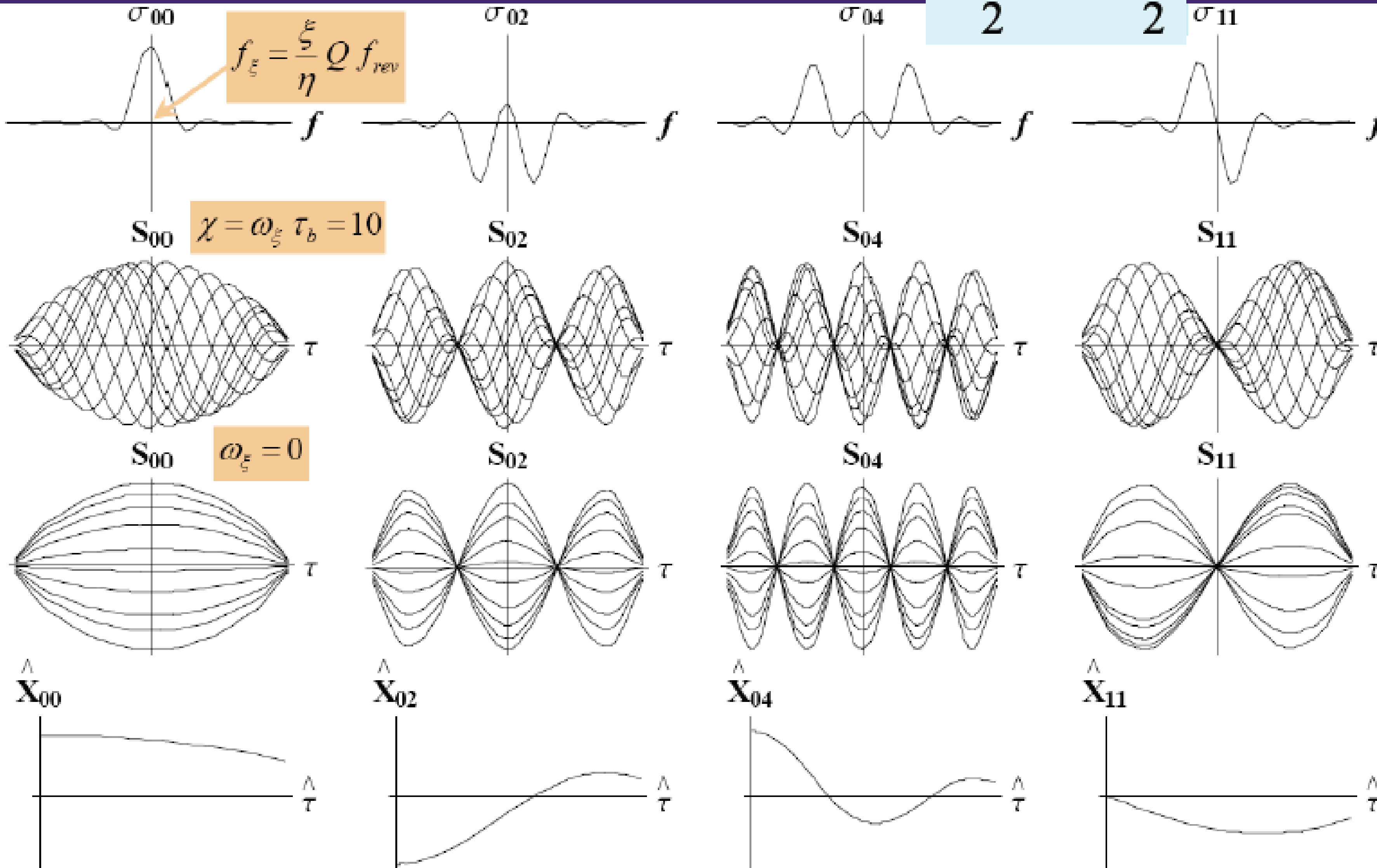
Good agreement of measurement with new theory → Great news for LHC!

HEAD-TAIL INSTABILITY (24/43)

$0 \le \hat{\tau} \le \tau_b / 2$

$-\frac{\tau_b}{2} \le \tau \le \frac{\tau_b}{2}$

$Q = x.13$



HEAD-TAIL INSTABILITY (25/43)