LATEST ESTIMATES OF COLLIMATOR IMPEDANCE EFFECTS

Name given by Vos2003 but effect already in Burov-Lebedev2002

E. Métral for the RLC team

- **Reminder: A new physical regime for LHC $\Rightarrow$ "Inductive by-pass"**
- **New results since my LTC talk on 08/12/04**
  - **Measurements**
    - **Coherent tune shift from a LHC prototype collimator at the SPS in 2004**
    - **Transverse impedance from collimator bench measurements using 1 wire in 2005 (by F. Caspers and T. Kroyer)**
  - **Theory**
    - **Zotter2005's formula + extension of its validity (in 2005)**
    - **GSI result for a LHC collimator (EPAC06)**
  - **Effect of chromaticity and scans vs. gap, bunch spacing and bunch length**
  - **TCT and TCLI issue**

Reminder: A new physical regime for LHC $\Rightarrow$ "Inductive by-pass"

- **First unstable betatron line** $f_\beta^1 \approx 8 \text{ kHz}$
- **Skin depth for graphite (ρ = 10 μΩm)** $\delta\left(8 \text{ kHz}\right) = 1.8 \text{ cm}$
- **Collimator thickness** $d_{th} = 2.5 \text{ cm}$

$$\Rightarrow \quad \delta\left(f_\beta\right) = \sqrt{\frac{\rho}{\pi\,\mu\,f_\beta}} < d_{th}$$

$\Rightarrow$ **One could think that the classical "thick-wall" formula would be about right**

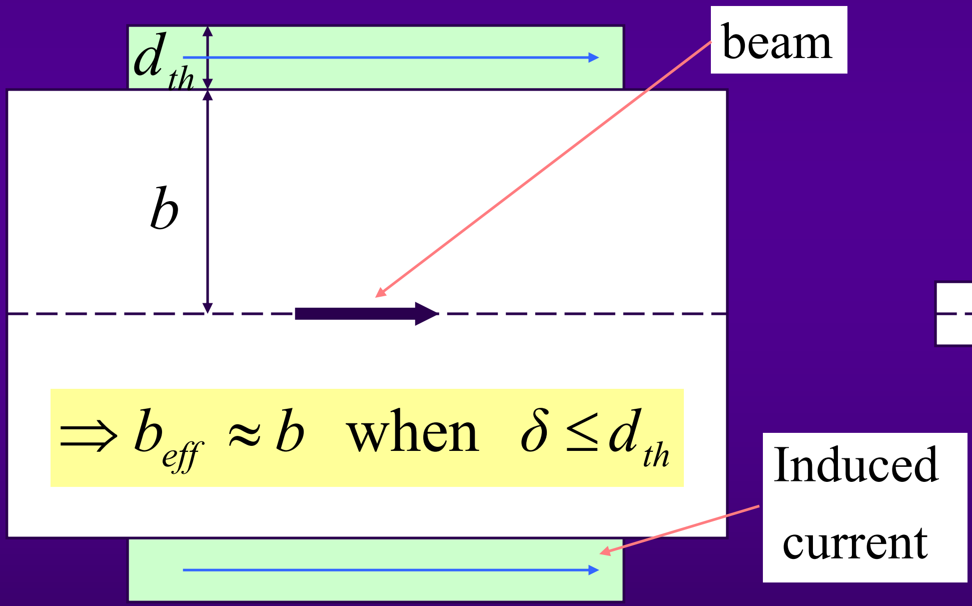
$$Z_\perp^{\text{thick-wall}}\left(f\right) \propto \frac{1}{b^3\sqrt{f}}$$

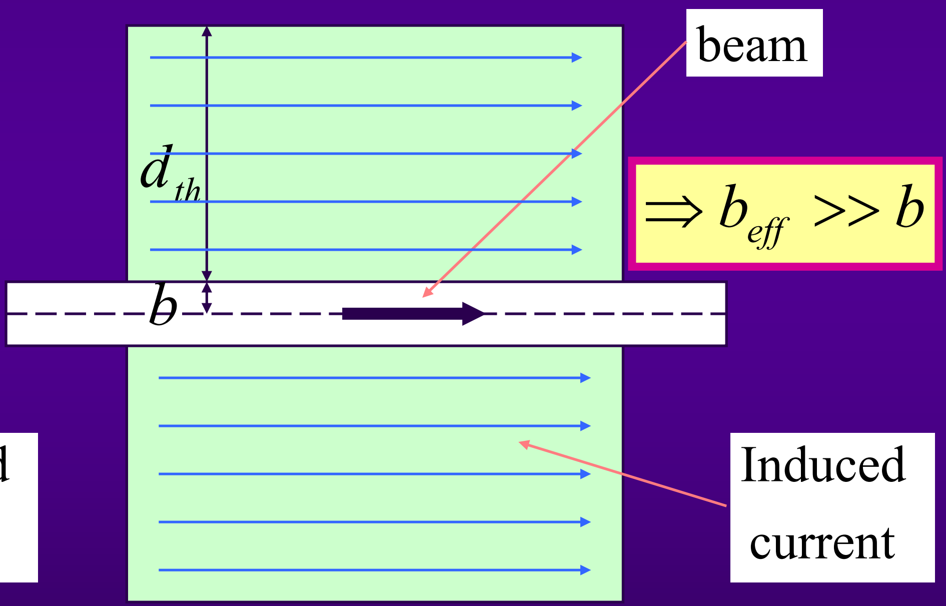
- In fact it is not ⇒ The resistive impedance is ~ 2 orders of magnitude lower at ~ 8 kHz !

⇒ A new physical regime was revealed by the LHC collimators

Usual regime : $d_{th}, \delta < b$

New regime : $d_{th} >> b$, $\delta \leq d_{th}$



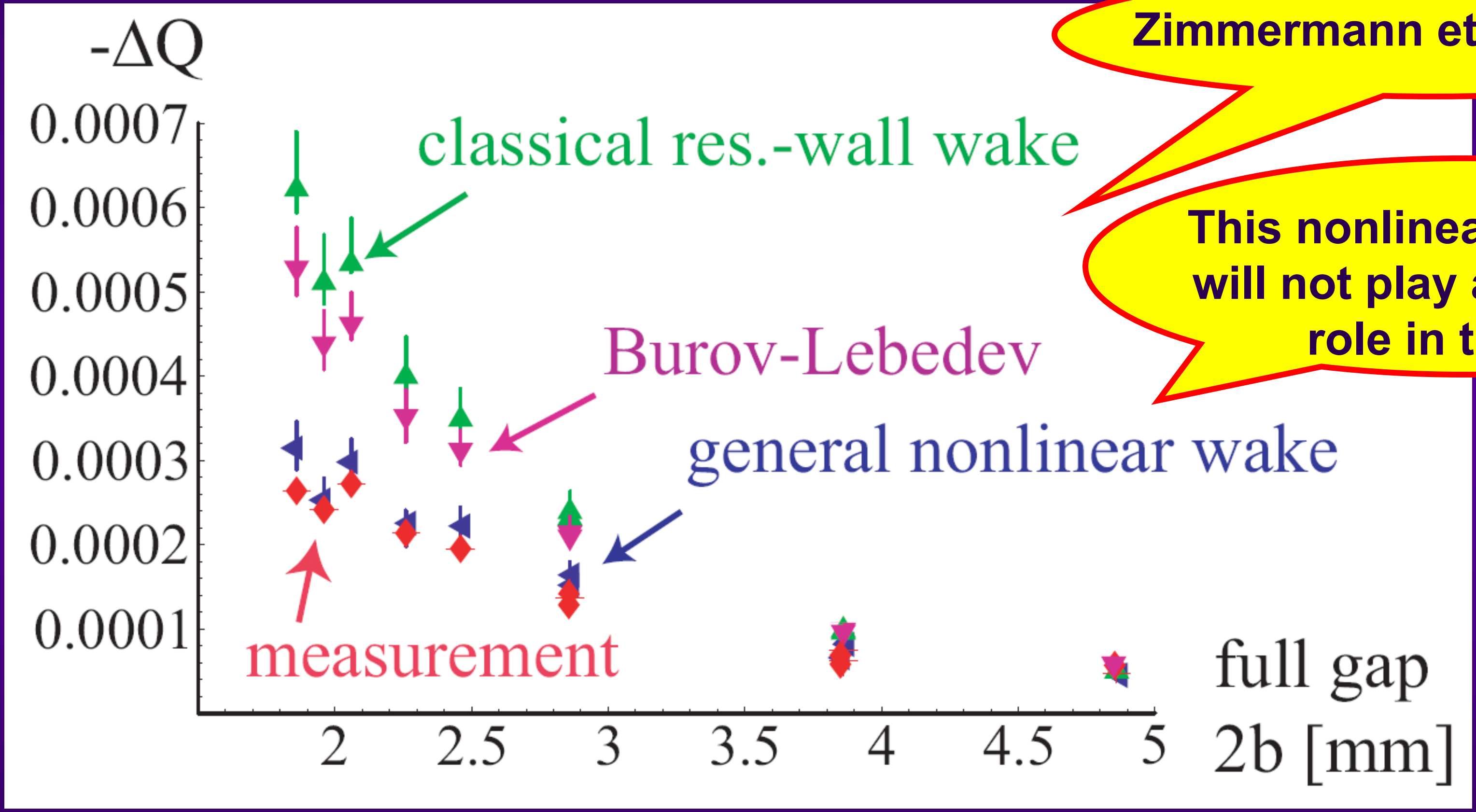


⇒ This inductive by-pass effect is therefore observed even with a single layer extending up to infinity

New results since my LTC talk on 08/12/04

MEASUREMENT 1

- Coherent tune shift from a LHC prototype collimator at the SPS in 2004



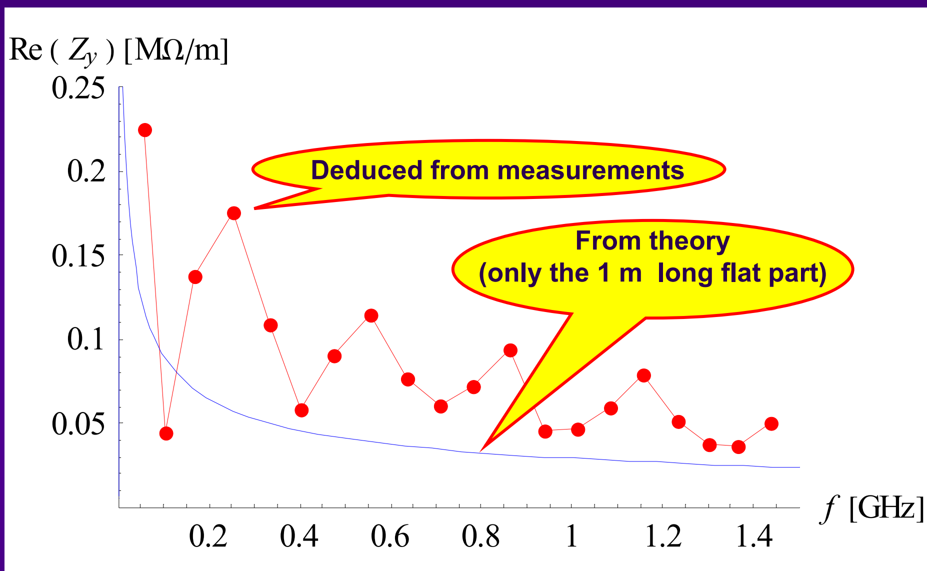
Zimmermann et al., EPAC06

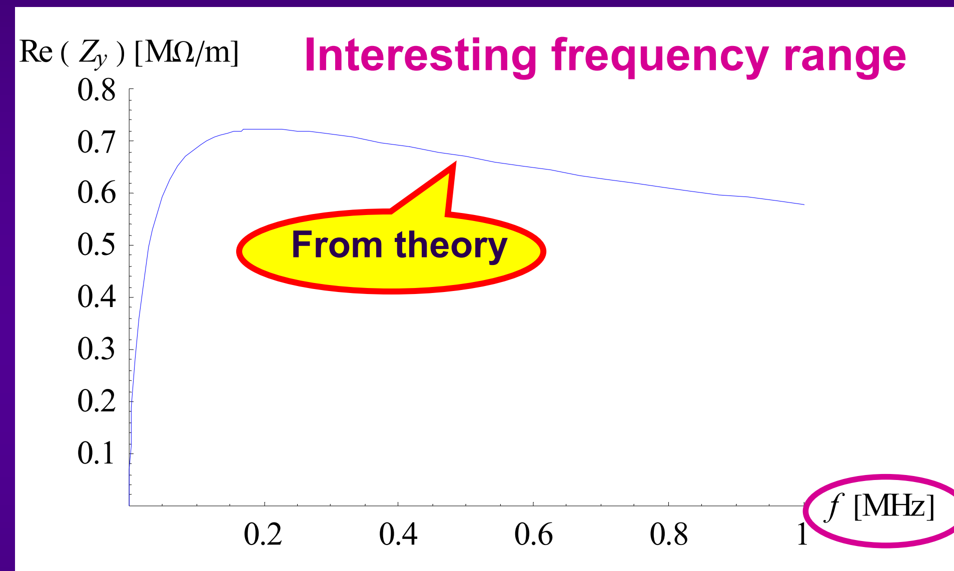
This nonlinear wake of FZ will not play an important role in the LHC

⇒ This meas. can be fully explained but **DOES NOT ADDRESS** the issue of the inductive by-pass effect

MEASUREMENT 2

- **Transverse impedance from collimator bench measurements using 1 wire in 2005**





⇒ **This meas. can be reasonably explained but DOES NOT ADDRESS the issue of the inductive by-pass effect as the frequency range is too high (from 57 MHz to 1.4 GHz) ⇒ Classical regime only!**

CERN-AB-2005-043

ZOTTER2005'S THEORY

- Zotter2004's results revealed an impedance ~ 100 times higher at 8 kHz than the one from Burov-Lebedev (BL) / Vos / Tsutsui $\Rightarrow$ This has been understood (error in the Mathematica Notebook)

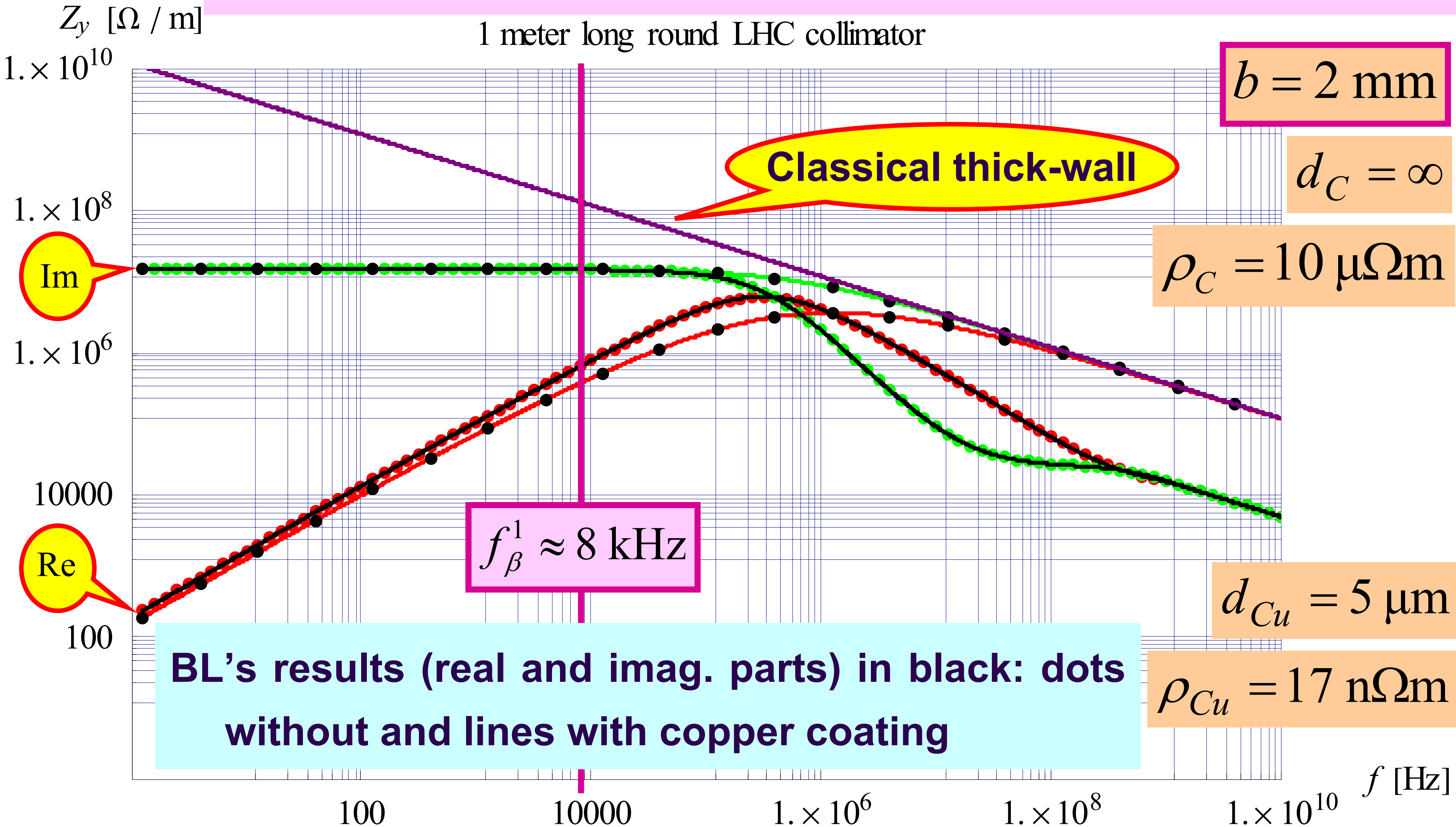
- Zotter2005's formula for the transverse RW impedance is more precise than the one of BL in 1 aspect

  $\Rightarrow$ He considers both TE and TM modes, whereas BL considers only TM mode

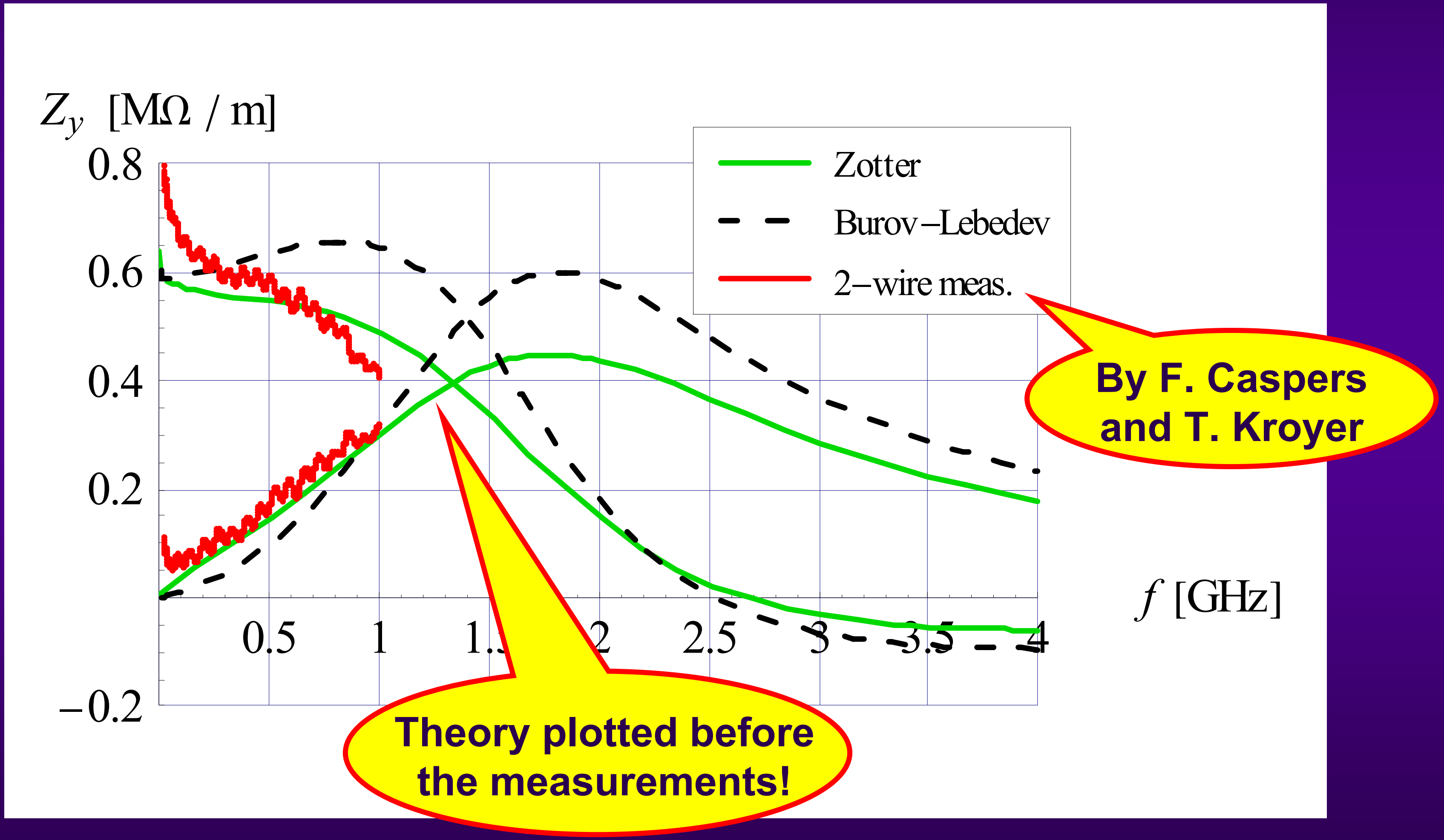
- Using Zotter's formalism I extended his formula (see CERN-AB-2005-084) in 2 aspects. The new formula is now valid
  - Without making the "low-frequency" approximation
  - Without assuming (necessarily) a good conductor for the first layer

$\Rightarrow$ This new Zotter2005's formula is therefore more "precise" than the one from BL in 3 aspects

COMPARISON ZOTTER2005-BUROV&LEBEDEV2002

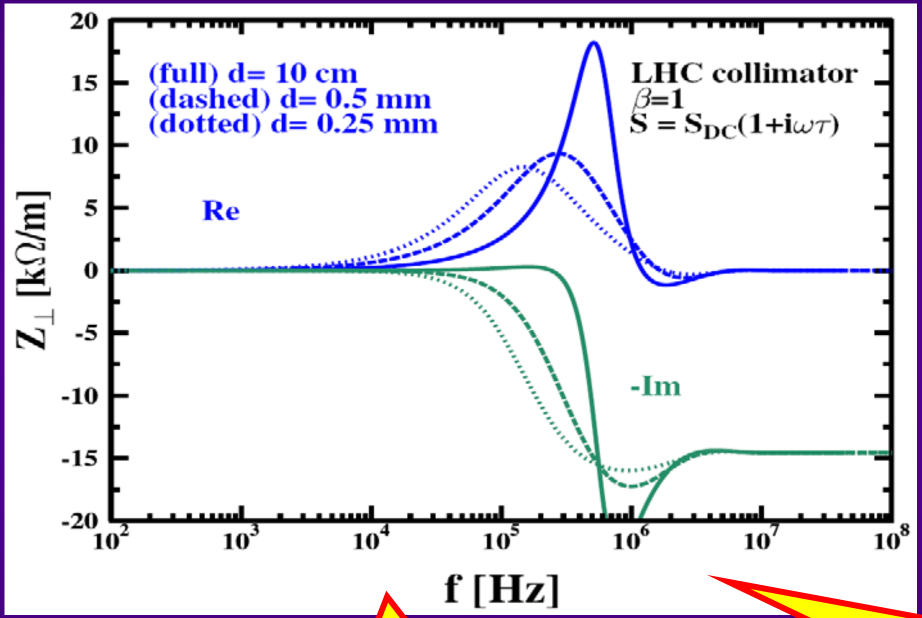


APPLICATION OF THE NEW ZOTTER2005'S FORMULA IN THE CASE OF A SPS MKE KICKER

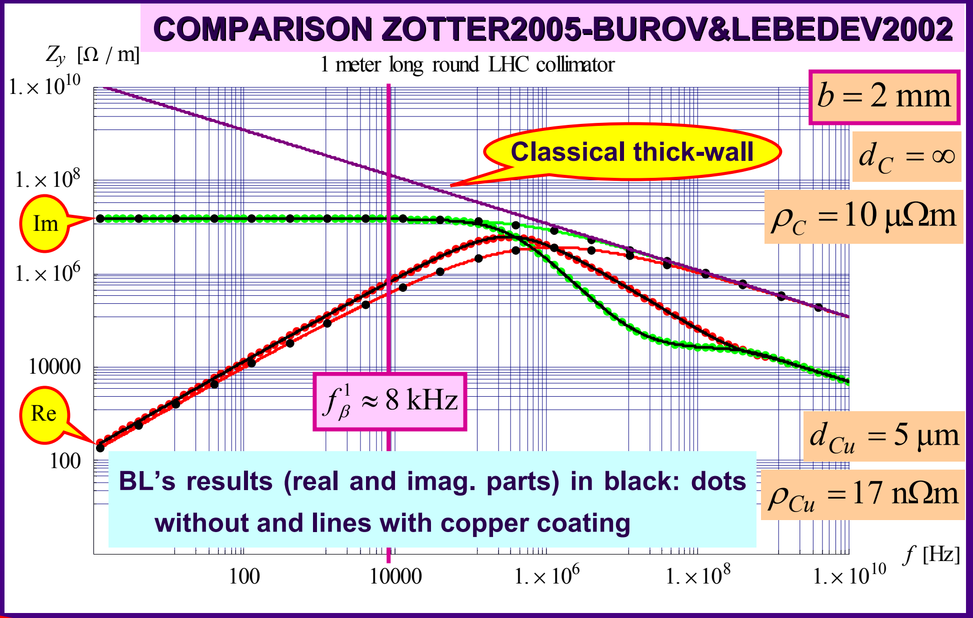


GSI RESULT FOR A LHC COLLIMATOR (EPAC06)

GSI RESULT (2006)



CERN RESULT (2005)



d = 2.5 cm for the real LHC collimators

"Transverse Coupling Impedances from Field Matching in a Smooth Resistive Cylindrical Pipe for Arbitrary Beam Energies" by A. Al-Khateeb, R.W. Hasse, O. Boine-Frankenheim, Wafa M. Daqa, I. Hofmann

- Very different results between the 2 approaches !!!
- The new result from GSI exhibits 3 main differences
  - Both 0 real AND imaginary parts of the impedance at very low frequency
  - A constant imaginary part of the impedance at high frequency
  - A peak impedance more than 100 times smaller than ours

⇒ If it is true (one has to look at it in detail), this could have a major impact on the LHC project and in particular on the collimation project as the resistive-wall impedance would no longer be a problem !!!

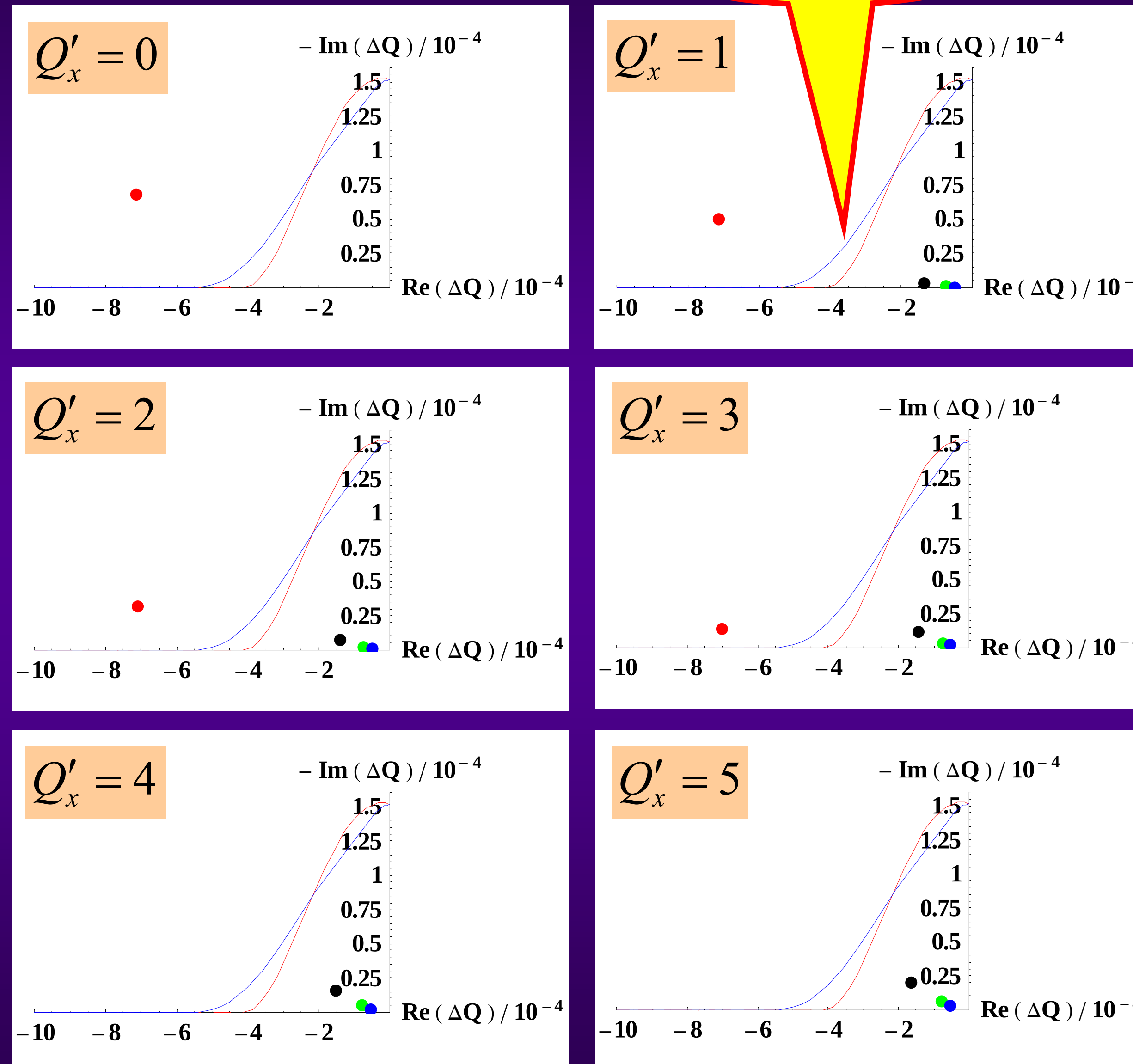
EFFECT OF CHROMATICITY

$$Q'_{x,y} = 1 \Rightarrow f_{\xi_{x,y}} \sim 40 \text{ MHz}$$

From Landau octupoles at max.

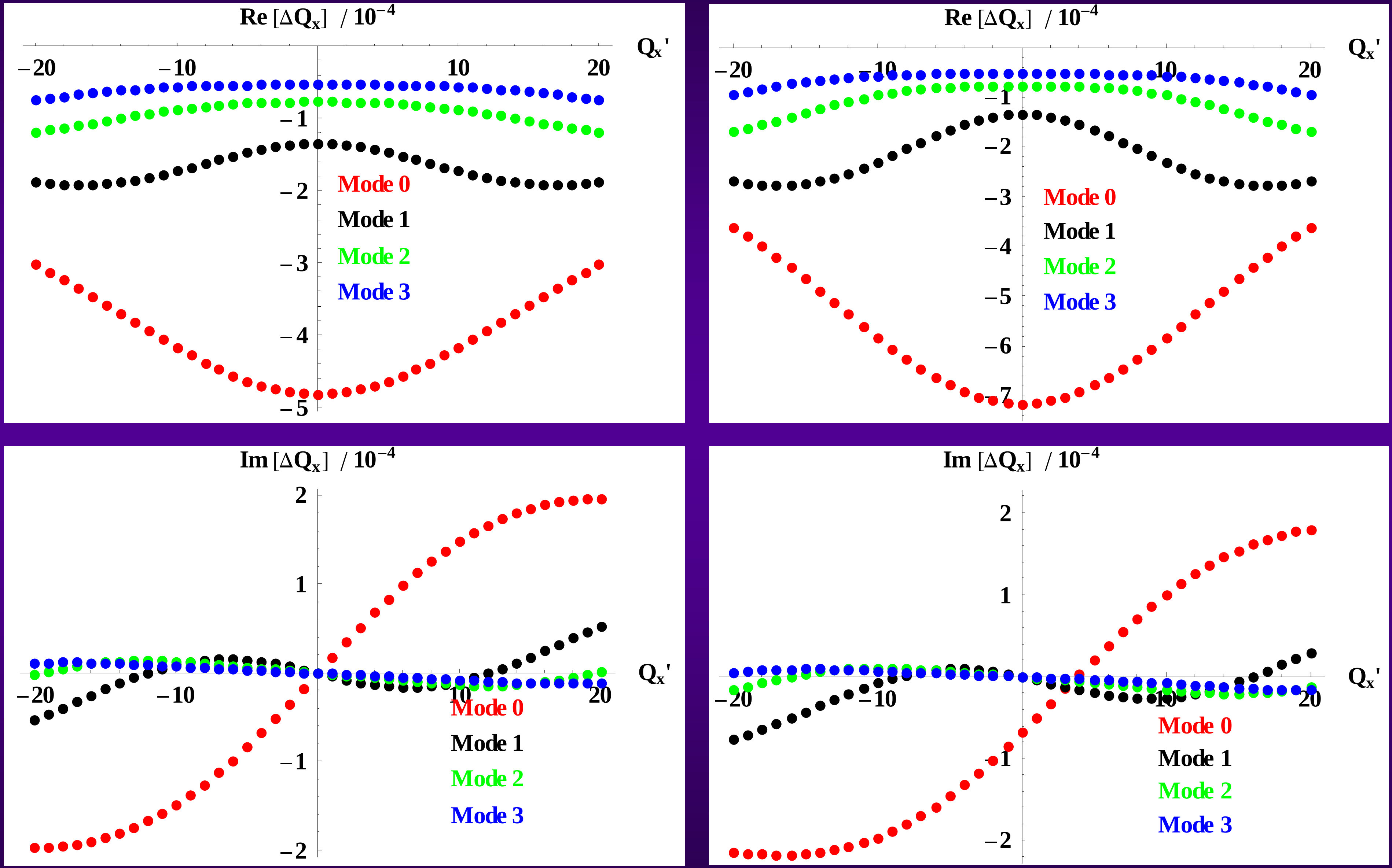
TOP ENERGY

Stability diagrams (X-plane)



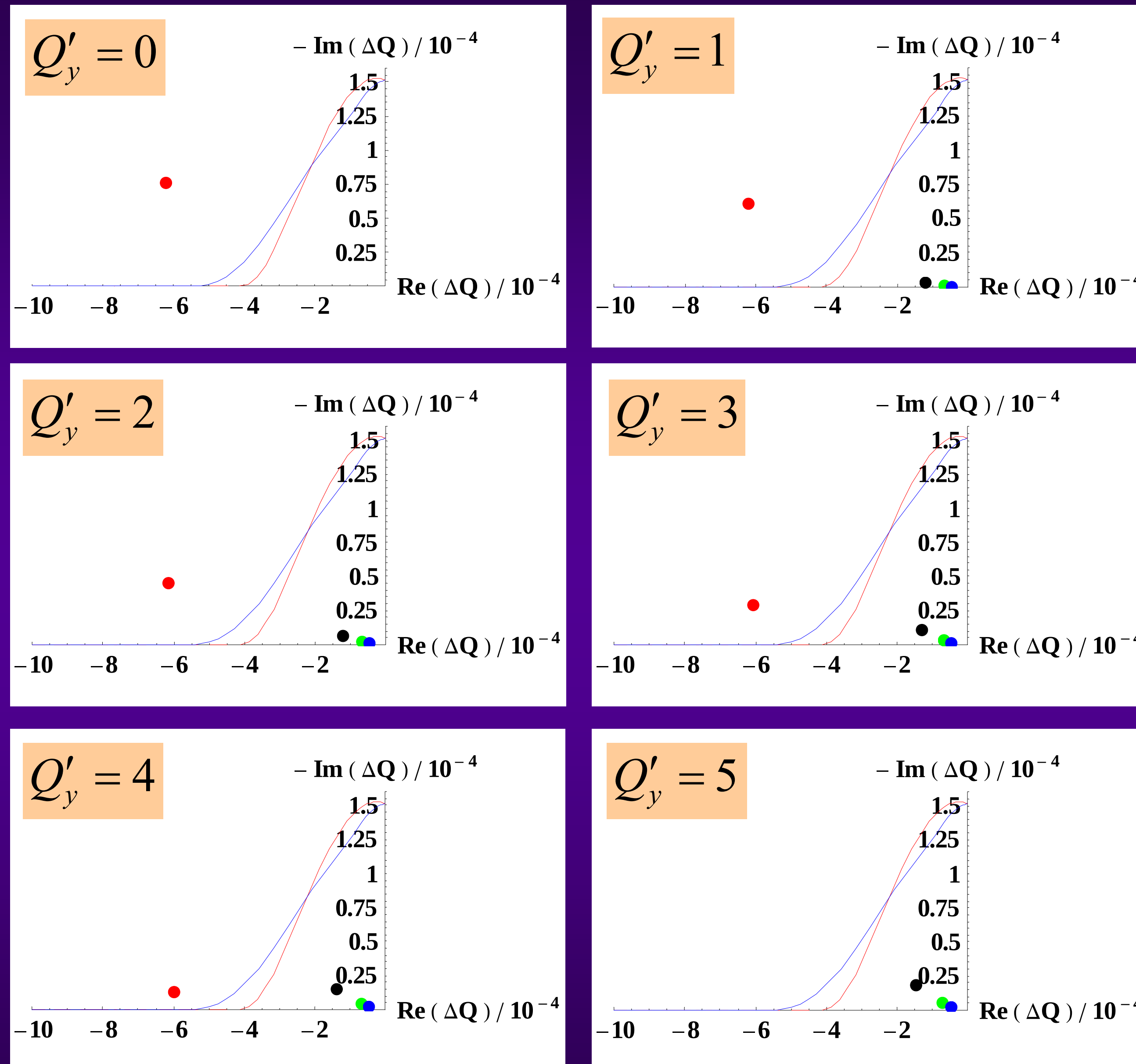
Mode 0
Mode 1
Mode 2
Mode 3

Single-bunch X-plane Coupled-bunch



Stability diagrams (Y-plane)

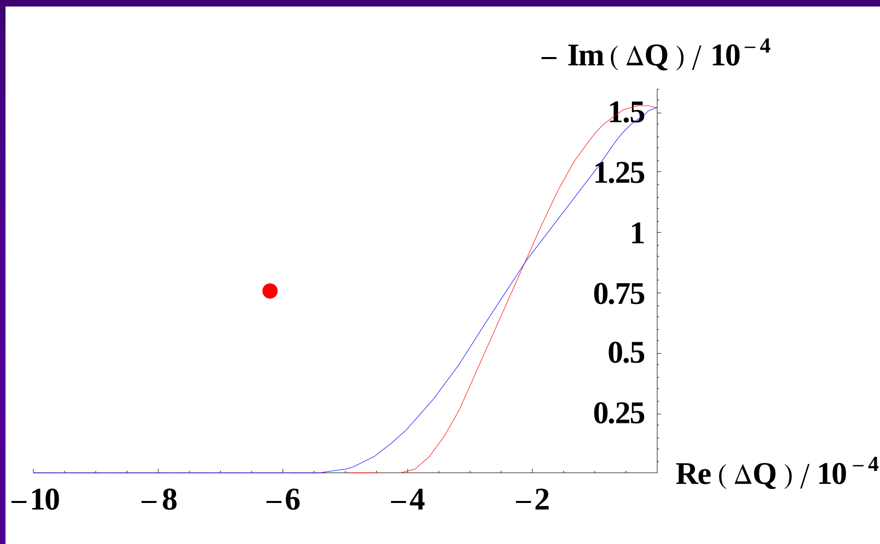
Mode 0
Mode 1
Mode 2
Mode 3

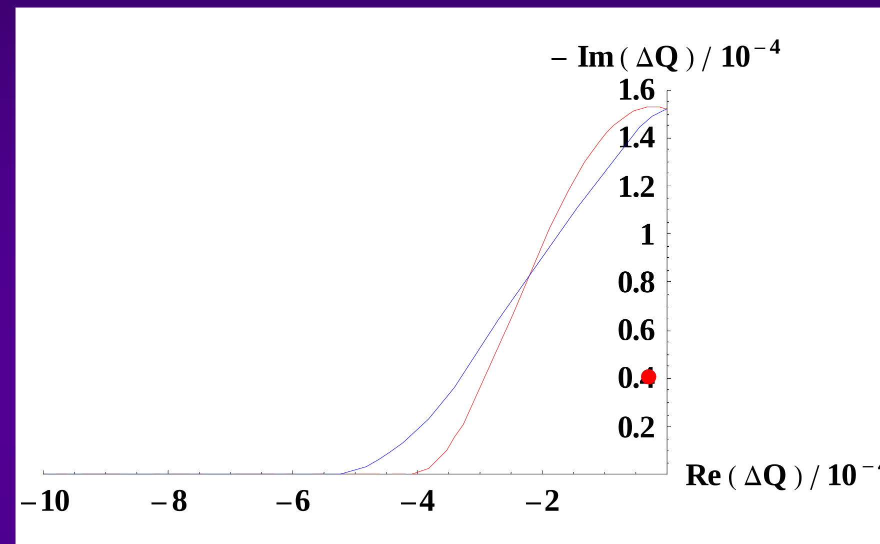


Stability diagrams (Y-plane)

With collimators

Without collimators (RW + BB* effects)





* BB (transverse) impedance for all the collimators estimated in the LHC Design Report at $j\,1.5\ \mathrm{M\Omega/m}$. The total BB is 2.67 MΩ/m

Updated estimates (with betatron functions…) are very close

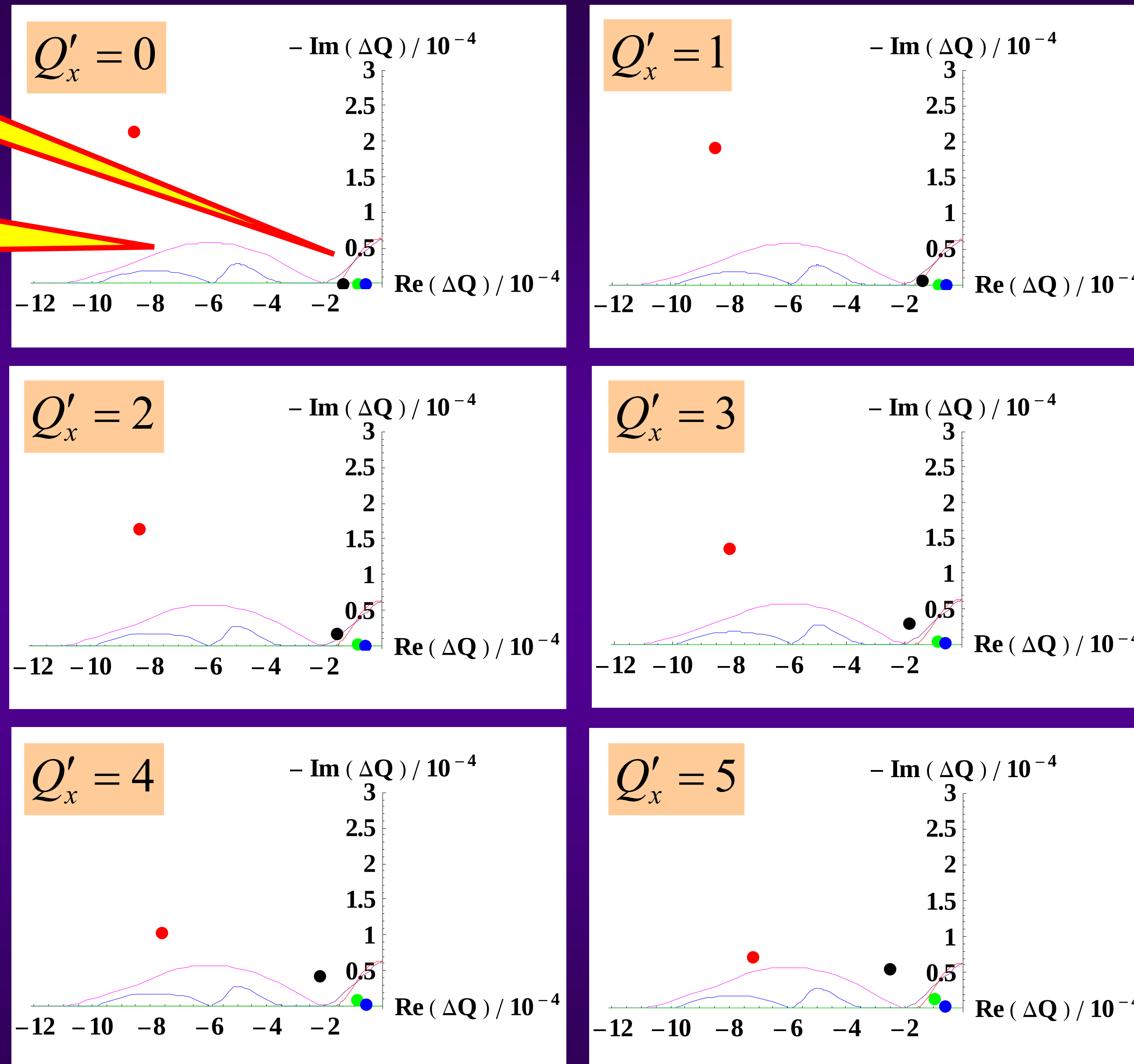
- Reminder: Tune shift for a BB impedance of *j* 1 MΩ/m = - 0.15×10^{-4}

From nonlinearities

From nonlinearities + space charge (2D)

INJECTION ENERGY

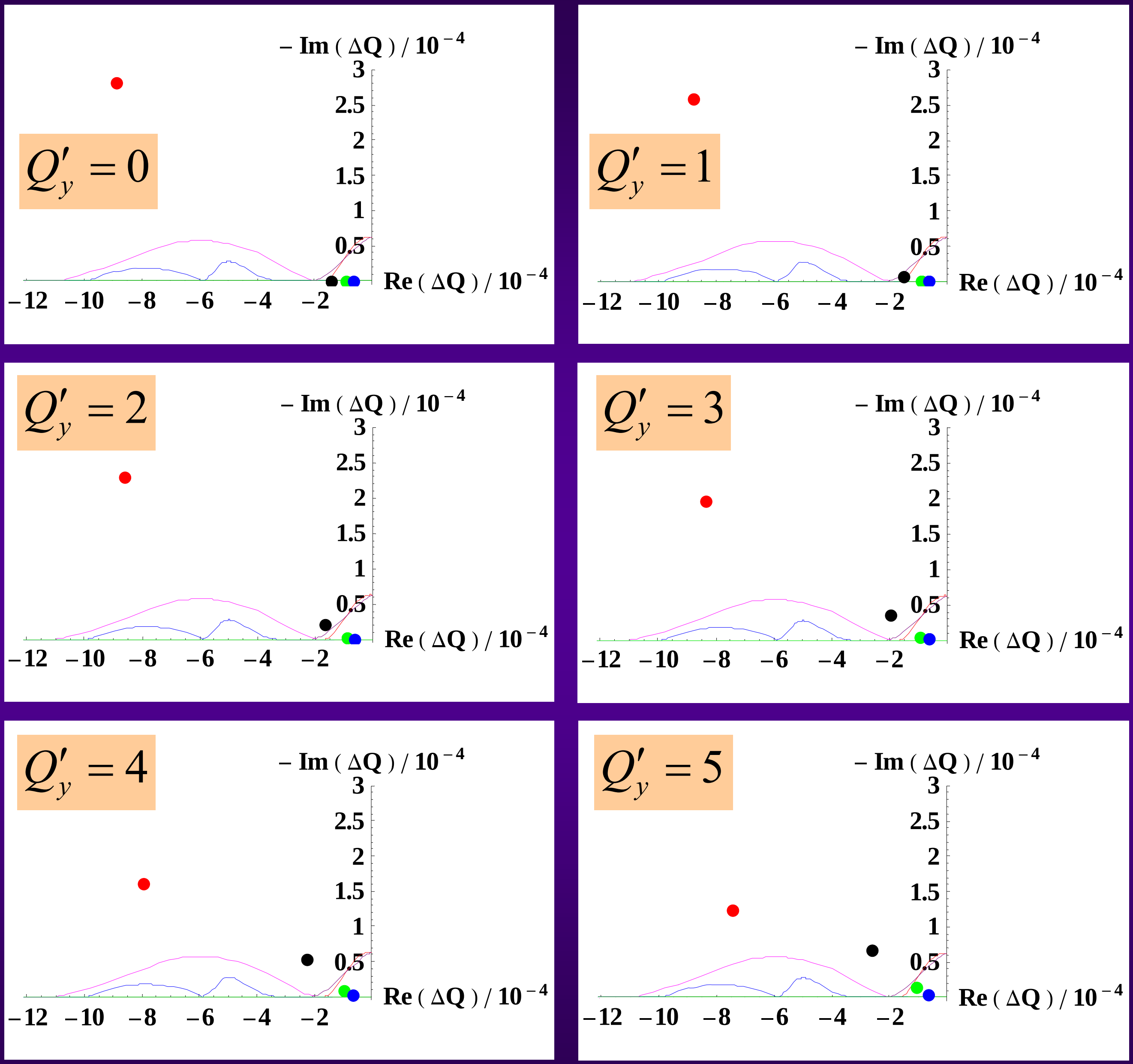
Stability diagrams (X-plane)



Mode 0
Mode 1
Mode 2
Mode 3

INJECTION ENERGY

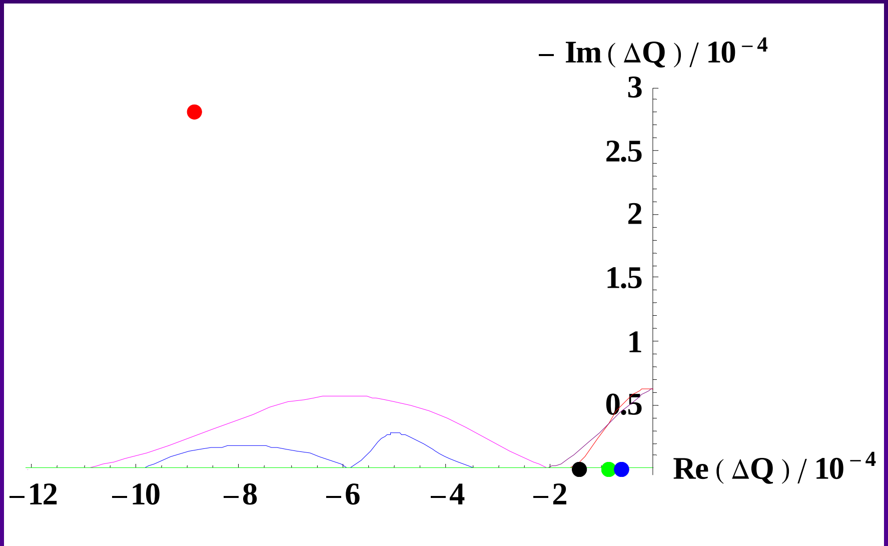
Stability diagrams (Y-plane)



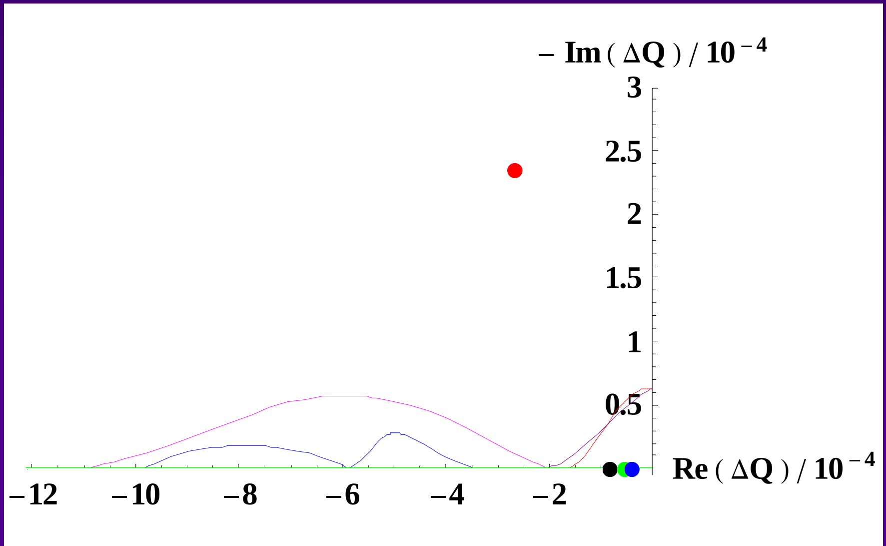
Mode 0
Mode 1
Mode 2
Mode 3

Stability diagrams
(Y-plane)

With collimators



Without collimators (RW + BB* effects)



*** BB (transverse) impedance for all the collimators estimated in the LHC Design Report at $j\,0.15\ \mathrm{M\Omega/m}$. The total BB is 1.34 MΩ/m**

Updated estimates (with betatron functions…) are very close

- **Reminder: Tune shift for a BB impedance of *j* 0.1 MΩ/m = - 0.13×10^{-4}**

SCAN VS. GAP, BUNCH SPACING AND BUNCH LENGTH

- **1) SCAN VS. GAP**
  - **1.1) For n most critical**
    - The real part of the tune shift scales between 1/b^2 and 1/b^3 (it is about 1/b^2.5)
    - The imaginary part of the tune shift scales as 1/b^2
  - **1.2) For n = 3499**
    - The real part of the tune shift scales between 1/b^2 and 1/b^3 (it is about 1/b^2.5)
    - The imaginary part of the tune shift scales (roughly) as 1/b
  - **Reminder: What is called the most critical (coupled-bunch) mode n is the (usual) one giving the largest imaginary part of the tune shift, but n = 3499 (= M - [Qx] - 1) gives the largest real part, and if we take the modulus it is the latter one which is the most critical**

- **2) SCAN VS. BUNCH SPACING (assuming a constant bunch intensity)**
  - The real part of the tune shift is almost constant (it is the "famous“ almost single-bunch effect due to the inductive bypass)
  - The imaginary part of the tune shift scales as ~ 1/bunch spacing

- **3) SCAN VS. BUNCH LENGTH**
  - **3.1) For n most critical**
    - The real part of the tune shift scales as ~ 1/(bunch length)^(1/4)
    - The imaginary part of the tune shift is constant
  - **3.2) For n = 3499**
    - The real part of the tune shift scales as ~ 1/(bunch length)^(1/5)
    - The imaginary part of the tune shift is constant

TCT AND TCLI ISSUE (1/5)

- Per beam, there are
  - 1 TCTH and 1 TCTV at each interaction point $\Rightarrow$ 4 TCTH and 4 TCTV
  - The 4 TCTH are all of the same type (1-beam pipe)
  - 2 TCTV at D2 (i.e. where the 2 beams are well separated $\Rightarrow$ 1-beam pipe) at points 1 and 5
  - 2 TCTV at D1 (i.e. where the 2 beams are not separated $\Rightarrow$ 2-beam pipe and large cavity created) at points 2 and 8
  - In addition there is also 1 TCLI (TCLIA.4R2.B1) used only at injection (1-beam pipe) and 1 TCLI (TCLIB.6R2) used also only at injection (but 2-beam pipe)

- The 4 TCTH, the 2 TCTV at D2 and the TCLIA.4R2.B1 are all (the 7) of the same type (= 1-beam TCS-type device), and of the same type of the collimator prototype used in the SPS in 2004. For this we have measurements of the trapped modes by FC and TK, and simulations by AG. Conclusion: All this is known and OK

TCT AND TCLI ISSUE (2/5)

- **The new result is for the 2 TCTV at D1 and for the TCLIB.6R2 (2-beam devices), which have been followed-up by AG. And this is for this 3 devices (2 used at top energy and 1 used at injection) that the Broad-Band impedance is quite high. For the trapped modes we think we will be able to damp them with ferrites (opening the RF bypass for the ferrite to be effective or keeping the RF bypass but creating a small cavity to put the ferrite)**

TCT AND TCLI ISSUE (3/5)

- **Conclusion: A (full) gap of 12 mm is needed for 2 devices and 30 mm in case of more than 2 devices**

Broad Band impedance of the TCTV/TCLI for different gap size

BB transverse impedance of a cylindrical taper, Yokoya 1988, CERN SL/90-88

$$Z_T^{(1)} = -\frac{iZ_0}{2\pi} 2I_1;$$

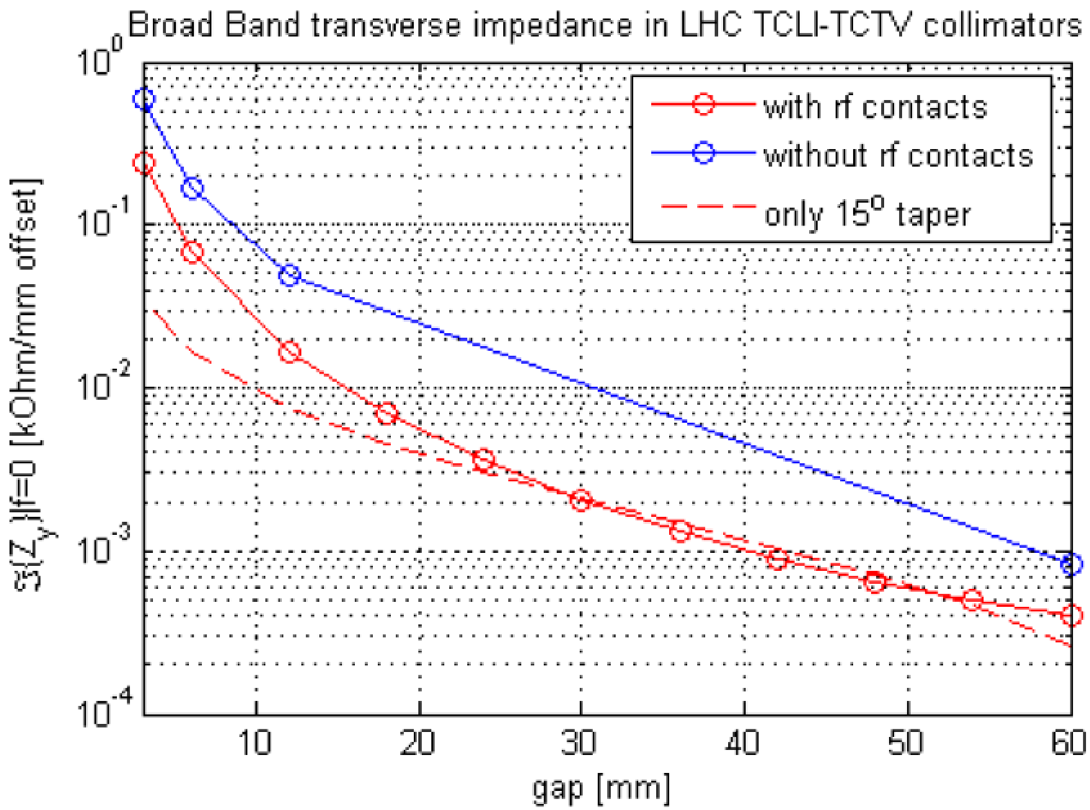
$$I_1 = \theta\left(\frac{1}{a} - \frac{1}{b}\right);$$

$$\theta = 15^o;$$

$$a = 3\,mm;$$

$$b = 70\,mm;$$

$$Z_T^{(1)} = 20\,k\Omega / m$$



For parallel plate geometry: $Z_y^{(1)} = Z_T^{(1)} \times 1.64 = 35\,k\Omega / m$

TCT AND TCLI ISSUE (4/5)

- ⇒ 12 mm is chosen to have a BB impedance per device which is about 1% of the total BB impedance of the design report (*j* 2.67 MΩ/m at top energy), i.e. ~ *j* 0.02 MΩ/m in the previous plot

- However this result is obtained for the nominal case where $\beta \approx \beta_{av}$ (~ 70 m)

- If, as discussed with RA, the beam is squeezed in 2 and 8, the β function will increase to ~ 660 m, i.e. by a factor 10

  ⇒ In this case, the impedance will increase by a factor 10

  ⇒ The impedance has to be reduced by a factor 10

  ⇒ The full gap has to be increased from 12 mm to 30 mm (see previous plot). In this case the BB impedance is similar to the 1-beam TCS-type device

  ⇒ This limits the squeeze in 2 and 8*

* Reminder: The TCTV primary function is shadowing the triplet, which half aperture is ~ 10 mm ⇒ It should be at ~ 8 mm (half gap) maximum to play is role

TCT AND TCLI ISSUE (5/5)

- **The TCLI is used only at injection and to protect the arc**
  - **The TDI alone protects until ~ 50% of the nominal intensity**
  - **For higher intensities, the TCLI (graphite) is absolutely needed**

- **A full gap of 12 mm is also chosen for the TCLIB.6R2 to have a BB impedance which is the same percentage of the total BB impedance of the design report (*j* 1.34 MΩ/m at injection) as for the 2 TCTV at D1 at top energy**

$$\frac{2 \times 0.02}{2.67} = \frac{0.02}{1.34}$$

CONCLUSION (1/2)

- Zotter2005's formula has been compared to other approaches from Burov-Lebedev2002, Tsutsui2003 (theory and HFSS simulations) and Vos2003 ⇒ Similar results obtained in the new (Burov-Lebedev2002) low-frequency regime

- The new (extended) Zotter2005's formula has been used to compute the transverse impedance of a SPS MKE kicker and a very good agreement has been obtained with 2-wire measurements from F. Caspers and T. Kroyer

⇒ "Very" confident in our impedance model!

- … Even if new results from GSI published at EPAC06 reveal that the impedance could be very different and much smaller ⇒ To be analyzed in detail

CONCLUSION (2/2)

- Coherent tune shift measurements from a LHC prototype collimator at the SPS in 2004 are in agreement with our theoretical predictions but do not address the issue of the inductive by-pass effect

- Transverse impedance from collimator bench measurements using 1 wire in 2005 (by F. Caspers and T. Kroyer) are also in agreement with our theoretical predictions but do not address the issue of the inductive by-pass effect

- Coupled-bunch instability induced by the collimators
  - At injection ⇒ Should be damped by a feedback (which should be able to damp instabilities with rise-times of few tens of ms)
  - At top energy ⇒ Should be damped by octupoles + (controlled) chromaticity (but then other problems may happen…)

- Estimated max. intensity? ⇒ Few tens of % of the nominal one…

A good control of the tunes and chromaticities will be needed to increase the intensity