COLLIMATION-DRIVEN IMPEDANCE

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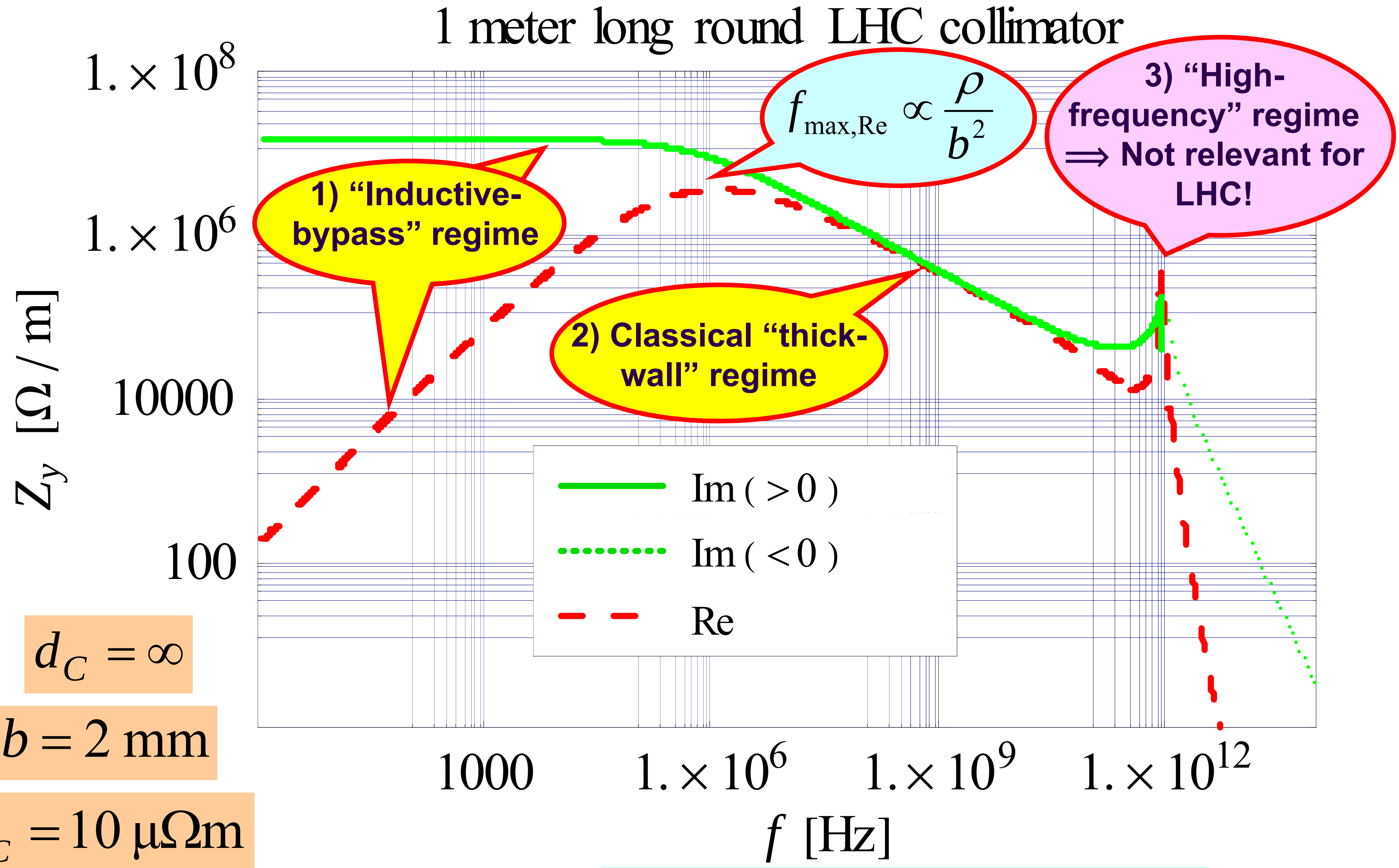
(15 + 5 min, 17 slides)

- Introduction
- Theory of the “wall” impedance
- LHC total transverse impedance
- Transverse coupled-bunch instability
- Stabilizing mechanisms
  - Landau damping ⟹ Stability diagram
  - Transverse feedback
- How can we reduce the collimator impedance? ⟹ Phase 2
- Conclusion and outlook

ZOTTER2005'S THEORY FOR 1 GRAPHITE COLLIMATOR



1) **"Inductive-bypass" regime**

$$f_{\max,\mathrm{Re}} \propto \frac{\rho}{b^2}$$

2) **Classical "thick-wall" regime**

3) **"High-frequency" regime**
⟹ Not relevant for LHC!

$d_C = \infty$

$b = 2$ mm

$\rho_C = 10$ μΩm

Interesting frequency range for LHC
⟹ From few kHz to few GHz

SIMPLEST FORMULA FOR THE LHC COLLIMATOR TRANSVERSE IMPEDANCE (round case) (1/2)

For any relatively good conductor with $\mu_r \approx \epsilon_r \approx 1$

There are Yokoya's factors to go from round to flat (π^2 / 12 and π^2 / 24)

Coherent part (from the pipe) of the "SC" impedance

$$Z_y^{Wall}(f) = \frac{j\,L\,Z_0}{2\,\pi\,b^2\,\beta}\left(1-\beta^2\right) + \beta\,\frac{j\,L\,Z_0}{\pi\,b^2} \times \frac{1}{1 - x_2\,\dfrac{K_1'(x_2)}{K_1(x_2)}}$$

From electric images

From ac magnetic images

Modified Bessel function

$$\delta = \frac{1}{\sqrt{\mu_0\,\sigma\,\pi\,f}}$$

$$x_2 = (1+j)\,\frac{b}{\delta}$$

SIMPLEST FORMULA FOR THE LHC COLLIMATOR TRANSVERSE IMPEDANCE (round case) (2/2)

$$\frac{K_1'(x_2)}{K_1(x_2)} = \left| \begin{array}{ll} -\dfrac{1}{x_2} & \text{if } \left| x_2 \right| << 1 \\ -1 & \text{if } \left| x_2 \right| >> 1 \end{array} \right.$$

$\Rightarrow$

$$Z_y^{Wall}(f \to 0) = \frac{j\,L\,Z_0}{2\,\pi\,b^2\,\beta}\left(1-\beta^2\right) + \beta\,\frac{j\,L\,Z_0}{2\,\pi\,b^2} = \frac{j\,L\,Z_0}{2\,\pi\,b^2\,\beta}$$

From electric images only

$\Rightarrow$

$$Z_y^{Wall}(f) = \frac{j\,L\,Z_0}{2\,\pi\,b^2\,\beta\,\gamma^2} + \beta\,(1+j)\,\frac{L\,Z_0\,\delta}{2\,\pi\,b^3}$$

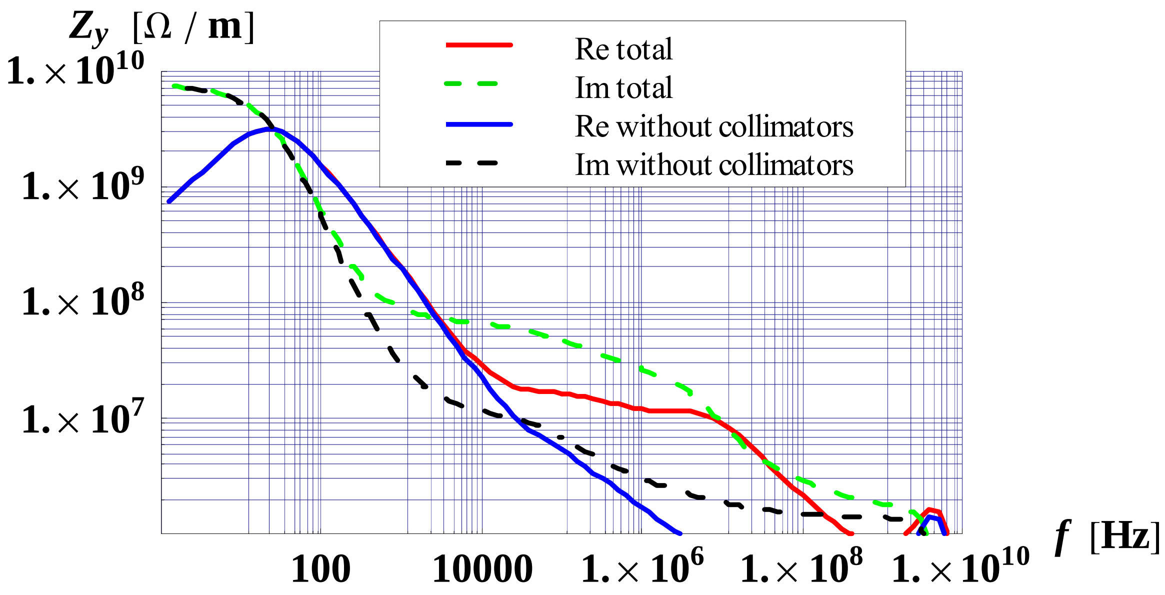
Disappears at high energy

Classical “thick-wall” regime => Main contribution from magnetic field

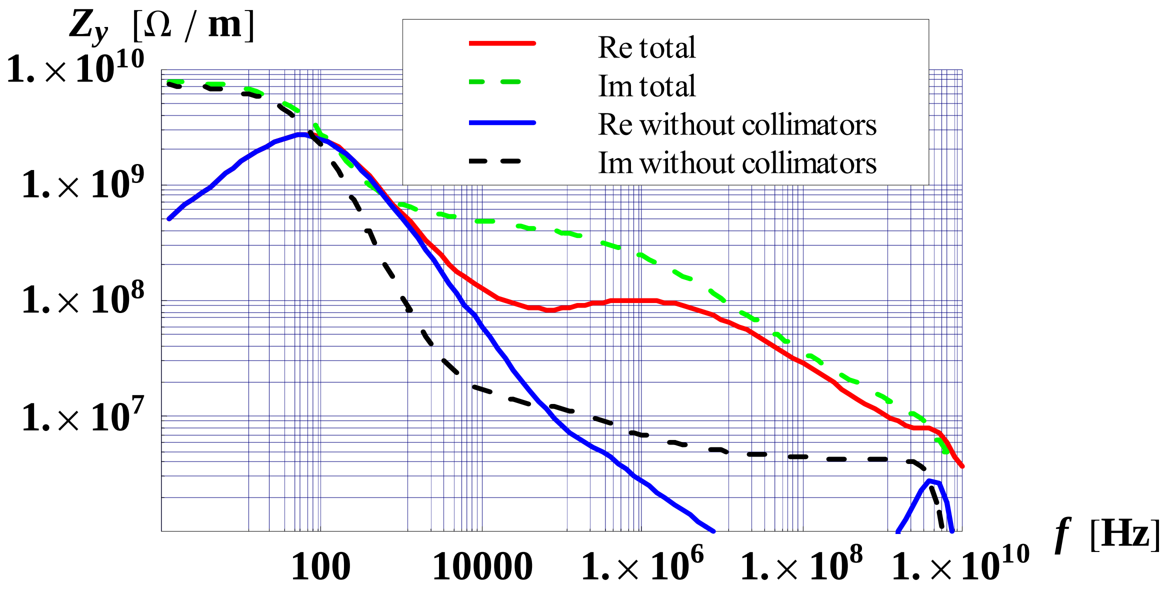
⟹ The transition between the 2 regimes are still under study (New PHD student: Nicolas Mounet): Important for the general understanding but also to define methods to measure the impedance!

LHC TRANSVERSE IMPEDANCE

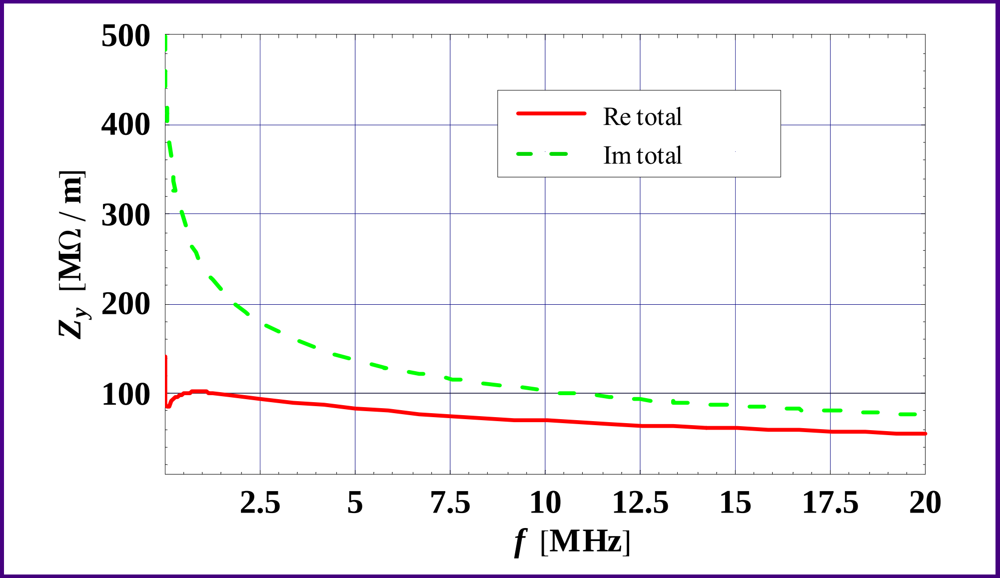
INJECTION



TOP ENERGY (after squeeze)



ZOOM (between 8 kHz and 20 MHz) OF THE LHC TRANSVERSE IMPEDANCE AT TOP ENERGY (AFTER THE SQUEEZE)



- The value of the real part of the impedance at 8 kHz (1st unstable betatron line) is ~ 141 MΩ/m
- The value of the real part of the impedance at 20 MHz (frequency limit of the transverse damper) is ~ 55 MΩ/m
- The ratio between the two values is only ~ 2.6 (it would have been 50 in the case of the classical resistive-wall theory!)

Of importance for the transverse feedback:
if the gain of the power amplifier rolls off rapidly when approaching 20 MHz, there might be some problems there… (seems OK)

STABILITY DIAGRAM (1/3)

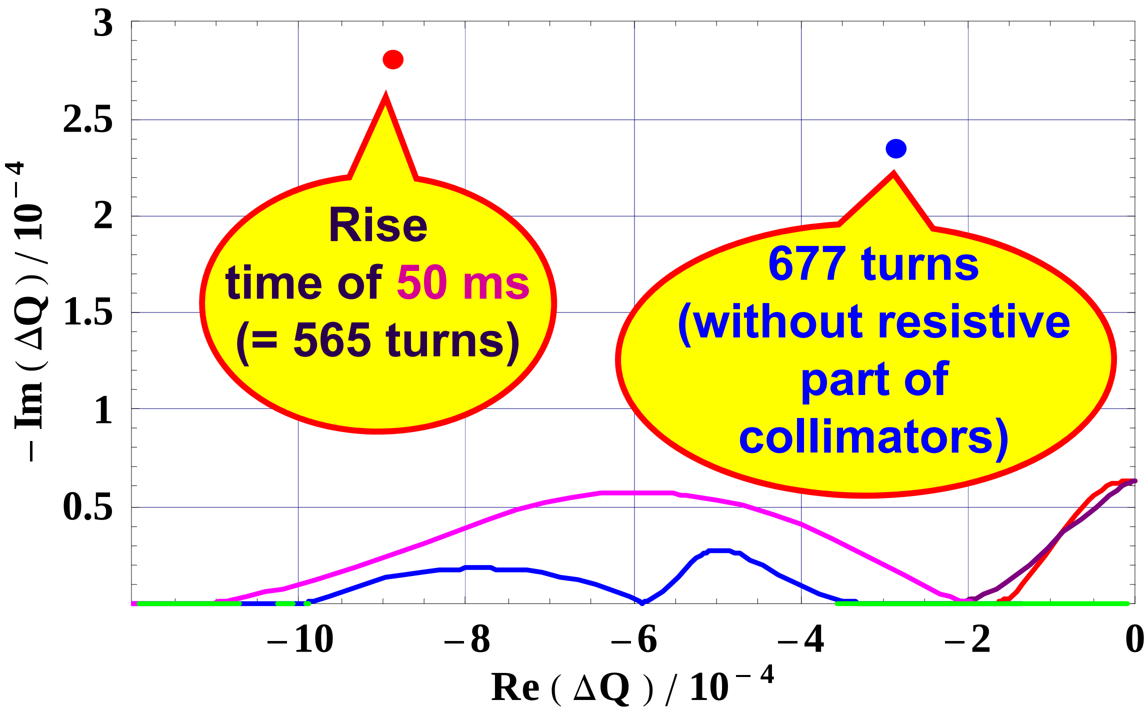
INJECTION

- Nominal case (25 ns bunch spacing and nominal intensity)

$T_{rev}^{LHC} \approx 89\ \mu\text{s}$

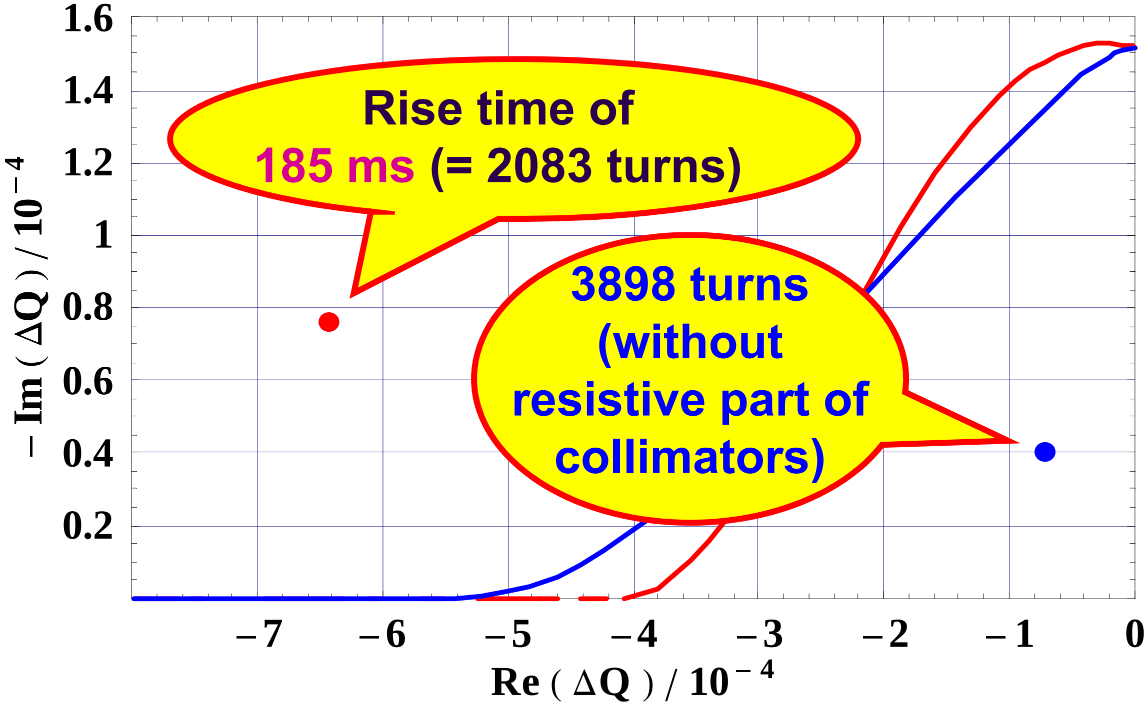
TOP ENERGY (after squeeze)

Reminder: - Im (ΔQ) / 10^{-4} = 1 $\Longrightarrow$ Rise time ≈ 1600 turns ≈ 140 ms



Rise time of 50 ms (= 565 turns)

677 turns (without resistive part of collimators)



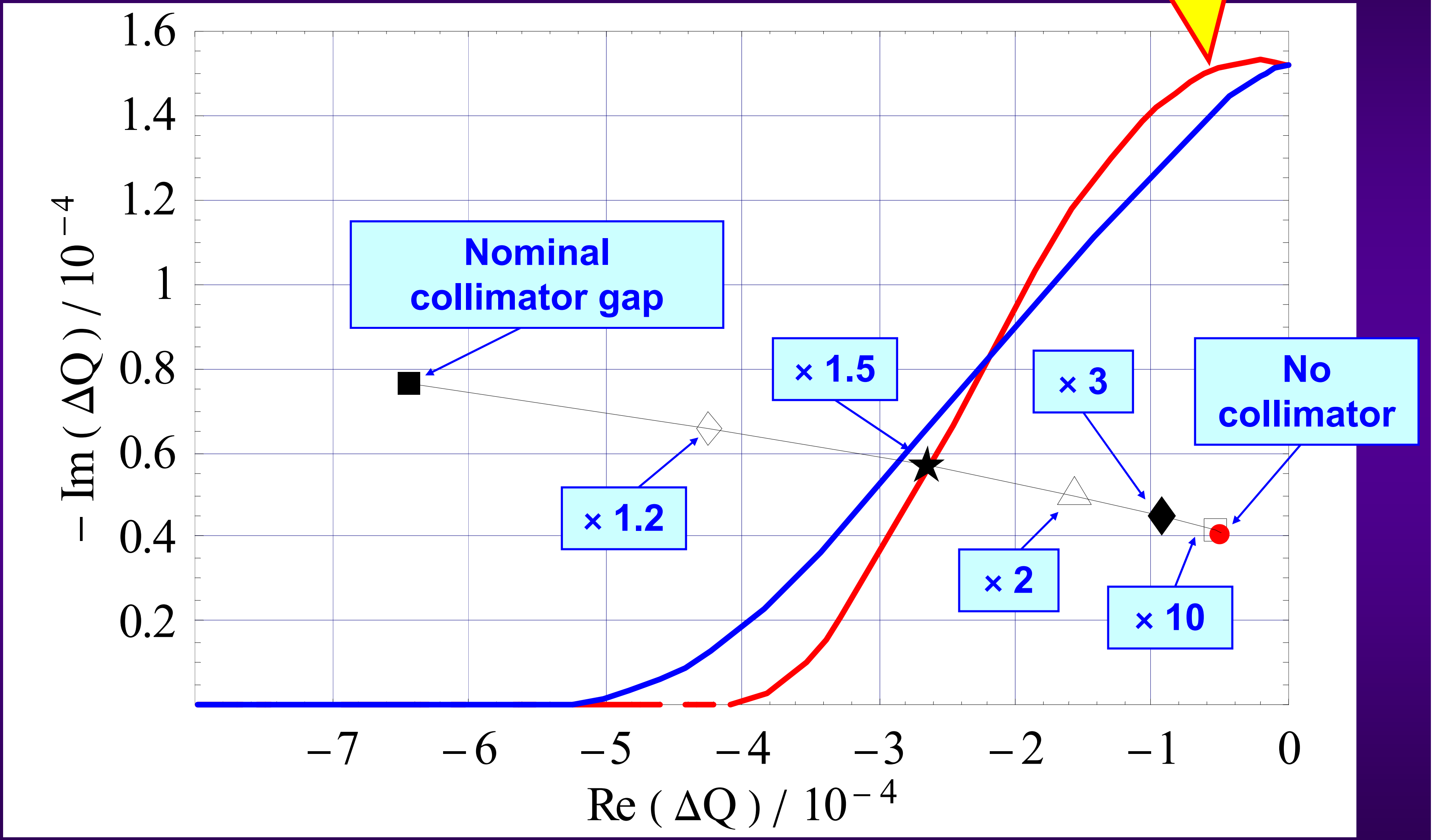
Rise time of 185 ms (= 2083 turns)

3898 turns (without resistive part of collimators)

STABILITY DIAGRAM (2/3)

- **Scan of the gap of the collimators (top energy)**

From Landau octupoles at max.



Nominal collimator gap

× 1.2

× 1.5

× 2

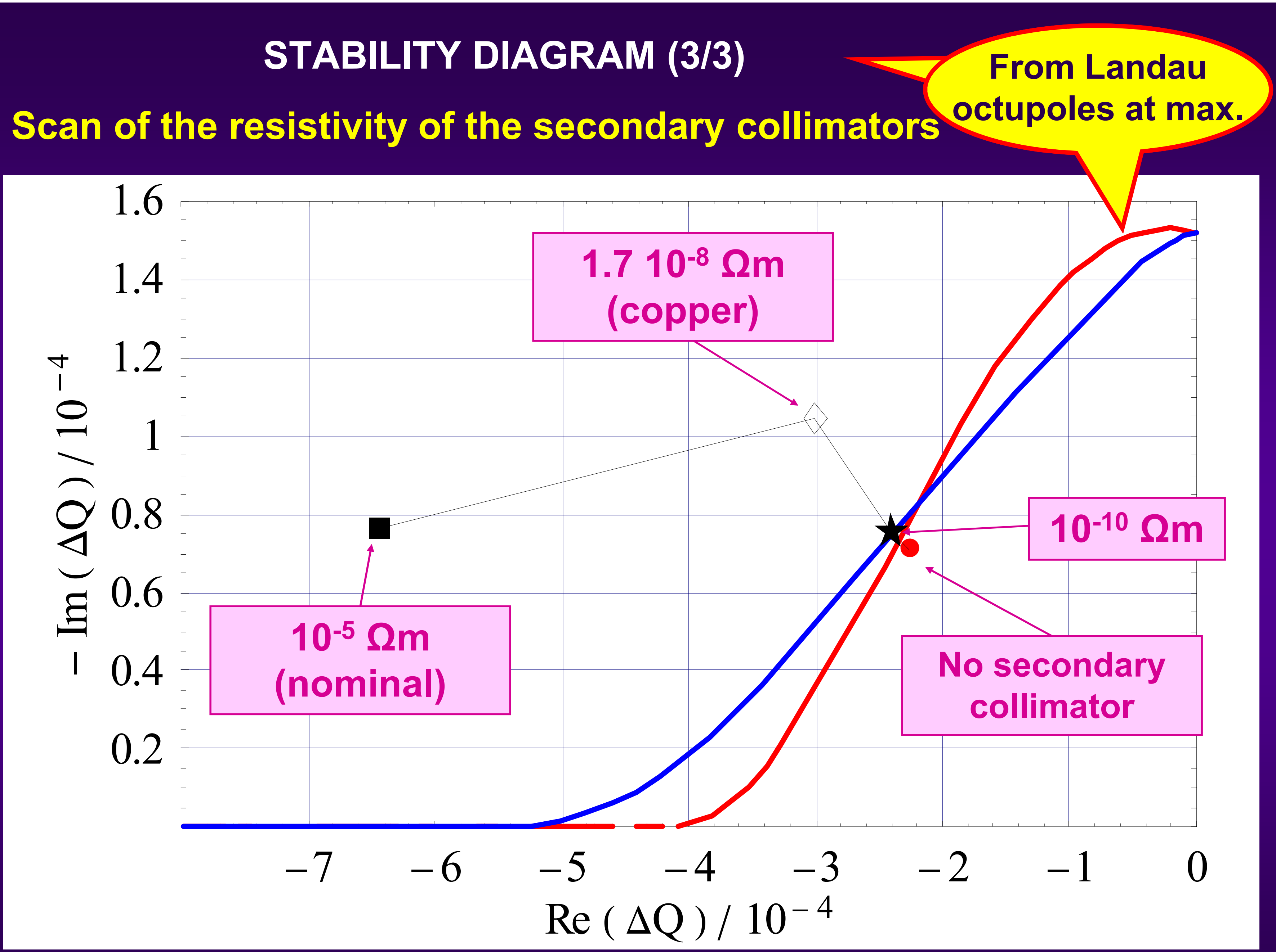
× 3

× 10

No collimator

STABILITY DIAGRAM (3/3)

- **Scan of the resistivity of the secondary collimators**



From Landau octupoles at max.

$1.7\ 10^{-8}\ \Omega m$ (copper)

$10^{-10}\ \Omega m$

$10^{-5}\ \Omega m$ (nominal)

No secondary collimator

TRANSVERSE FEEDBACK (1/2)

- The transverse feedback system should be able to damp instability rise-times of (We take a safety margin of a factor 2 compared to what was computed in the previous slides)
  - AT INJECTION ENERGY
    - ~ 280 turns (i.e. ~ 25 ms) at injection for nominal intensity
    - ~ 190 turns (i.e. ~ 17 ms) at injection for ultimate intensity
  - AT TOP ENERGY (AFTER THE SQUEEZE)
    - ~ 1040 turns (i.e. ~ 93 ms) at injection for nominal intensity
    - ~ 705 turns (i.e. ~ 63 ms) at injection for ultimate intensity

TRANSVERSE FEEDBACK (2/2)

- According to W. Hofle:
  - In the SPS ~ 20 turns damping is achieved in the vertical plane on a regular basis
  - The normal operating mode of the feedback should be at gains corresponding to 20-40 turns damping

    $\Longrightarrow$ It seems therefore feasible to damp the foreseen instability rise-times both at injection and top energy
  - The issue of the noise at top energy: K. Ohmi et al. (PAC 2007, LHC Project Report 1048) has estimated from numerical calculations that we can run in the LHC at a gain of 0.1 (10 turns damping) with a monitor resolution of 0.6% of σ and still have a luminosity life-time of one day. The corresponding required resolution is 7.2 μm at 450 GeV (σ = 1.2 mm) and 1.8 mm at 7 TeV (σ proportional to $\gamma^{-1/2}$). If the gain can be reduced, then the requirement for the monitor resolution can be relaxed. The improvement in monitor resolution required for LHC when compared with the SPS can be achieved due to the increased number of bits used and the higher signal power available from the coupler type pick-up

HOW CAN WE REDUCE THE COLLIMATOR IMPEDANCE?

- The transverse impedance (both RE and IM parts) of the LHC can be decreased by increasing the gap of the collimators ⟹ Trade-off between impedance reduction and cleaning efficiency

- The beam will be stabilized at injection by a transverse feedback

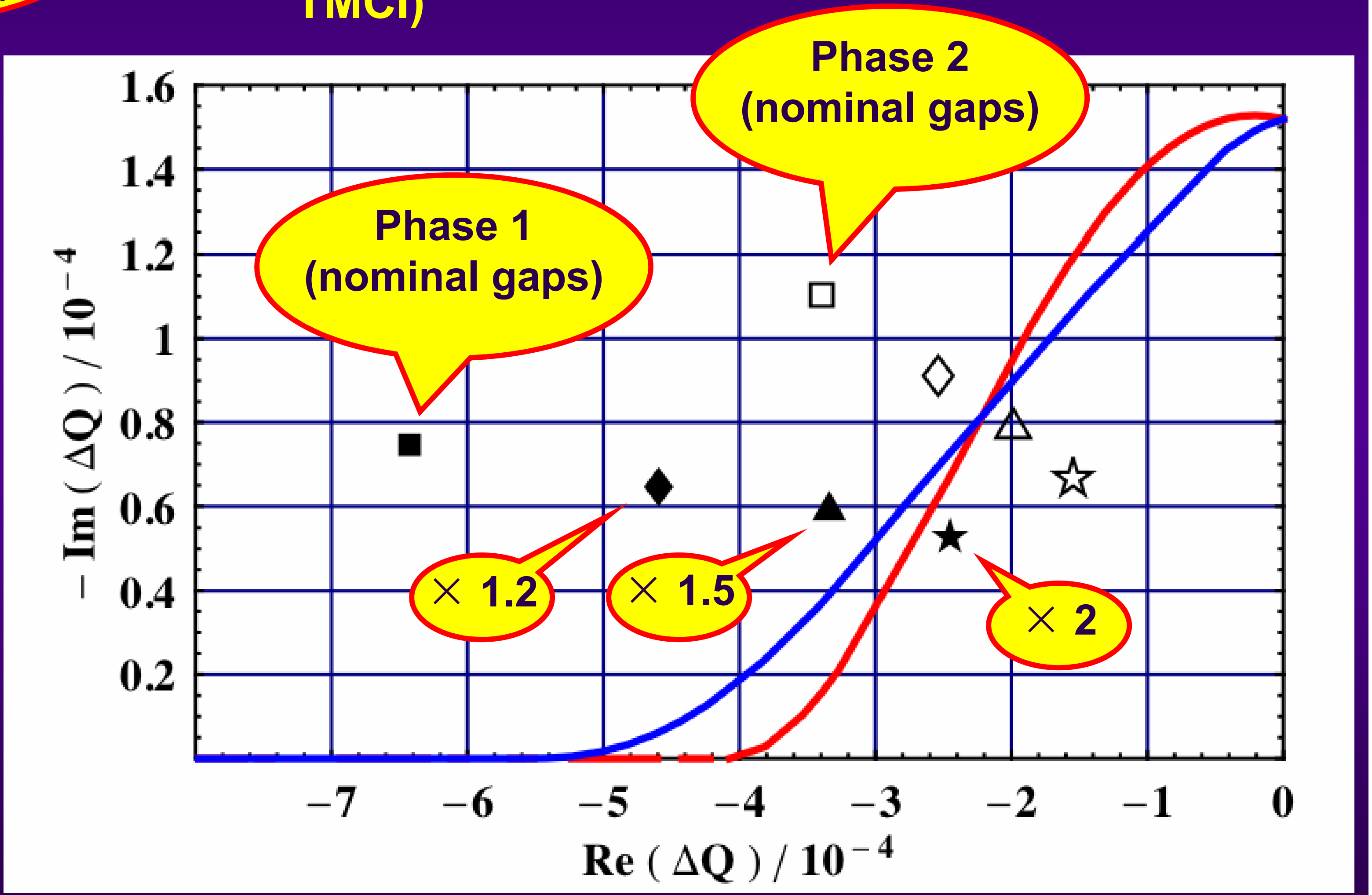
- At top energy:
  - If one can stabilize the beam at top energy by transverse feedback ⟹ One could help the feedback system even more by reducing the REAL part of the collimator impedance (in particular until ~ 20 MHz) ⟹ Use ceramics?
  - If one wants to stabilize the beam at top energy by Landau damping ⟹ One should try and reduce the IMAGINARY part of the collimator impedance (this has a huge effect compared to the rest of the machine!) ⟹ Use good conductors (copper collimators). Furthermore, the feedback should also be able to stabilize the beam in this case

1st ROUTE: COPPER SECONDARY COLLIMATORS

For Phase 2, 17 collimators are added to the 44 of Phase 1 (with gaps changed)

TCSM.5L3.B1
TCSM.4R3.B1
TCSM.A5R3.B1
TCSM.B5R3.B1
TCSM.A6L7.B1
TCSM.B5L7.B1
TCSM.A5L7.B1
TCSM.D4L7.B1
TCSM.B4L7.B1
TCSM.A4L7.B1
TCSM.A4R7.B1
TCSM.B5R7.B1
TCSM.D5R7.B1
TCSM.E5R7.B1
TCSM.6R7.B1
TCRYO.AR7.B1
TCRYO.BR7.B1

⟹ 2 advantages: Closer to stability limit (better for coupled-bunch instability) + reduce the imaginary Broad-Band impedance (better for TMCI)



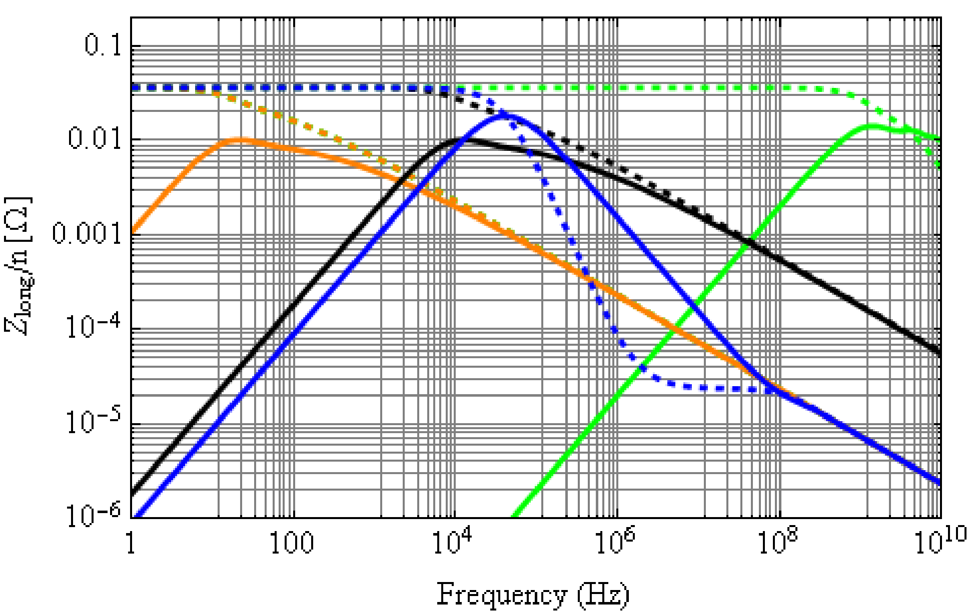
2nd ROUTE: SECONDARY COLLIMATORS MADE OF CERAMICS?

$\varepsilon_r = 5$ $\rho = 1\,\Omega\mathrm{m}$

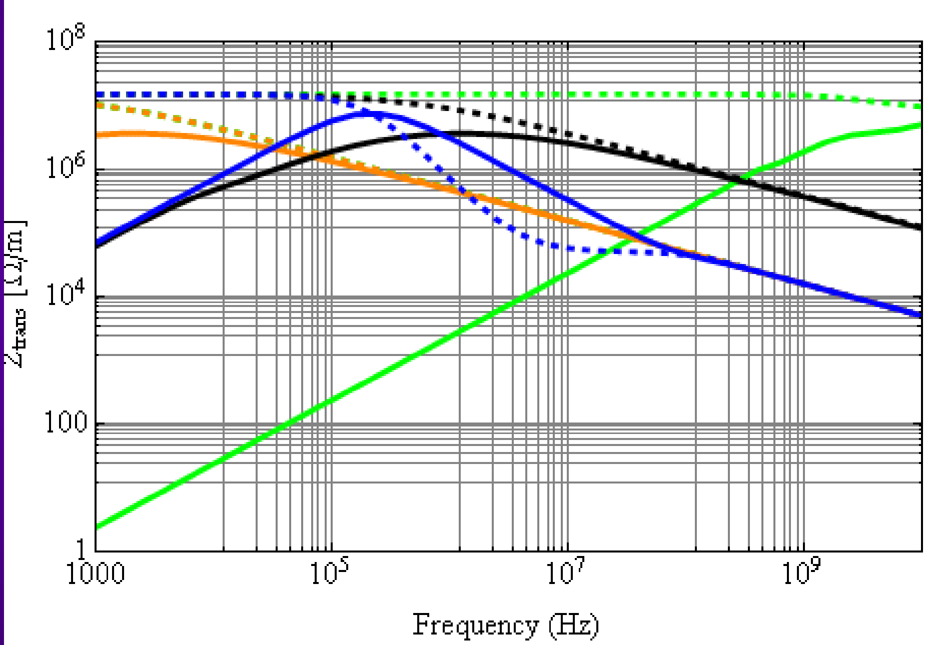
$L = 1\ \mathrm{m}$

$b = 2\ \mathrm{mm}$

LONGITUDINAL



TRANSVERSE



Real part → full
Imaginary part → dashed

- 🟩 **2.5 cm ceramic + vacuum**
- ⬛ **2.5 cm graphite + vacuum**
- 🟧 **2.5 cm copper + vacuum**
- 🟦 **10 μm copper coating + 2.5 cm ceramic + vacuum**

REMINDER ON SINGLE-BUNCH INSTABILITIES (1/2)

LOSS OF LANDAU DAMPING FOR THE LONGITUDINAL DIPOLE MODE

$= \tau_b \, f_{rev} = 1\,\text{ns} \times 11245.5\,\text{Hz}$

35640

16 MV

$$\left|\frac{Z_l(n)}{n}\right|_{eff} \le \left|\frac{Z_l(n)}{n}\right|_{eff}^{\max} = \frac{3\pi^2}{32} \times \frac{h^3 \hat{V}_{RF} \, B_0^5}{N_b \, e \, f_{rev}} \times F_{PWD} \approx 0.6\,\Omega$$

1.15E11 p/b

~ 1

Reminder: In the LHC Design Report (Vol. 1, chap. 5) the effective Broad-Band impedance was estimated to ~ 0.1 Ω for the squeezed optics ⟹ If the imaginary part of the longitudinal impedance is increased (too much) then one could be limited by this mechanism. To be followed-up with Elena Chapochnikova

REMINDER ON SINGLE-BUNCH INSTABILITIES (2/2)

TMCI FOR THE TRANSVERSE PLANE

$= 7\text{E}12$

$= 2\text{E} - 3$

$$\frac{\Delta Q^{y}_{0,0}}{Q_s} < -1 \quad \Longrightarrow \quad \mathrm{Im}\left(Z_y^{eff}\right) < \mathrm{Im}\left(Z_y^{eff}\right)_{\max} = \frac{4\,\pi\,\left(E_t\,/e\right)\,\tau_b\,Q_s}{N_b\;e\;\beta_y^{av}}$$

$$\approx 134\ \mathrm{M\Omega/m}$$

$= R\,/\,Q_y = 71.5\ \mathrm{m}$

Reminder: The effective Broad-Band impedance is estimated to ~ 30 MΩ/m for the squeezed optics $\Longrightarrow$ To be checked. If the imaginary part of the transverse impedance is increased (too much) then one could be limited by TMCI

CONCLUSION AND OUTLOOK

- Theory of "wall" impedance
  - Similar results obtained from several formalisms in the low-frequency regime (assuming infinitely long pipe), as well as with simulations and measurements
  - Next steps (work of the new PHD student Nicolas Mounet):
    - Study of transition between the 2nd and 1st frequency regime
    - Multi-bunch $\Longrightarrow$ Wave velocity ≠ Beam velocity
    - Finite length (preliminary results revealed "no" changes: Tbc)
    - Extension of HEADTAIL code to multi-bunch
- Strategy for the stabilization of the transverse coupled-bunch instab.
  - Transverse feedback: at injection and top energy (seems OK)
  - If pb $\Longrightarrow$ Landau octupoles (up to a certain intensity limit)
- Phase 2: Copper and copper coated ceramics collimators are studied
- The best way to reduce the collimator impedance remains to open the gaps!