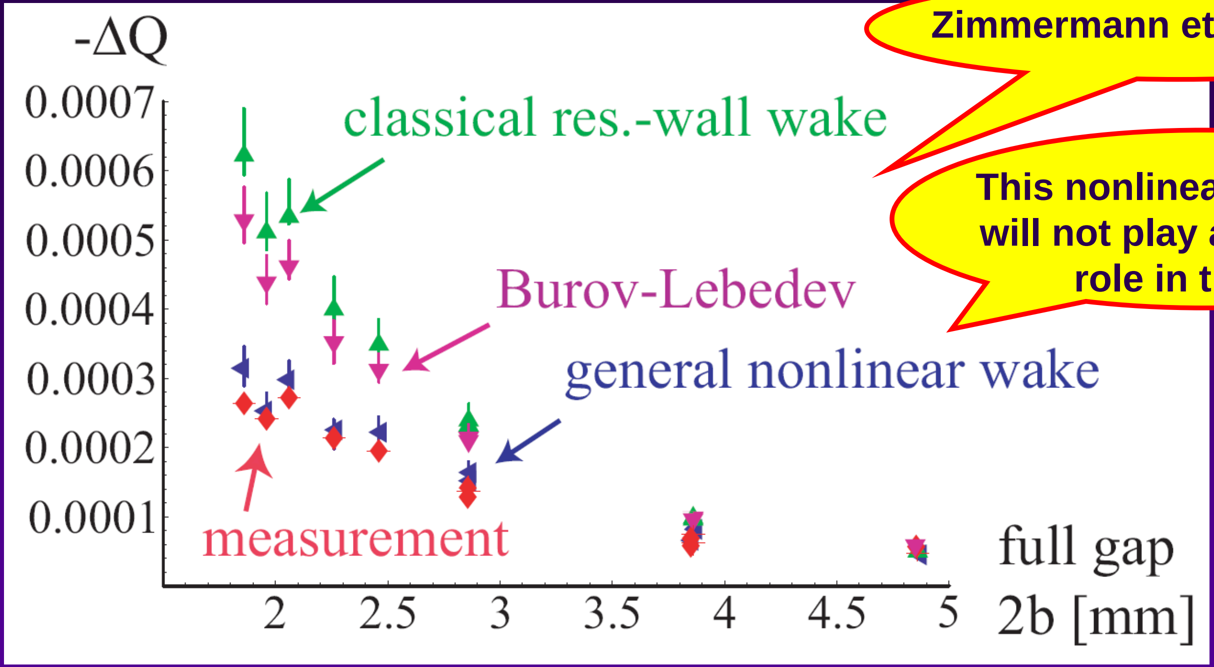
IMPEDANCE MEASUREMENTS IN 2006 FOR THE LHC PROTOTYPE COLLIMATOR

G. Arduini and E. Métral (for the RLC team)

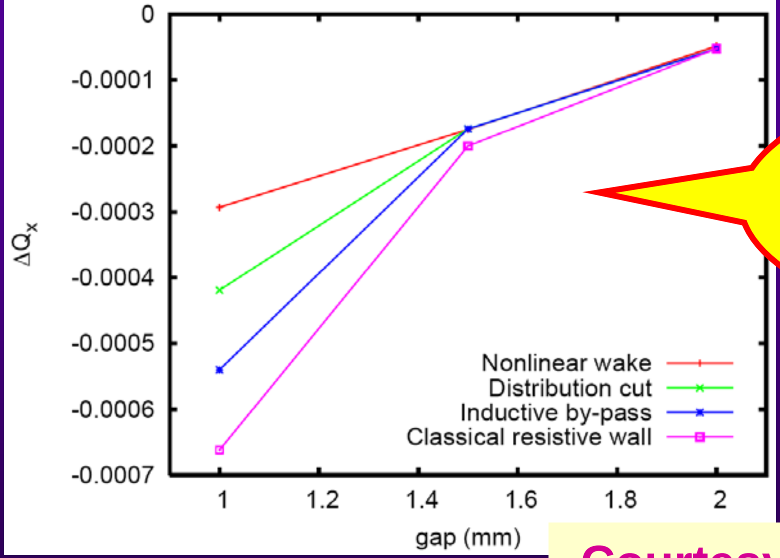
- **Review of the 2004 results ⇒ Imaginary part of the impedance**
- **Single-bunch effect ⇒ See talk at the Collimation WG (02/10/06)**
- **Multi-bunch effect ⇒ Today**
  - **Gianluigi's approach using the classical thick-wall wake field**
  - **"Extension" using the wake field with "inductive by-pass" (from Alex Koschik 2003)**
- **Results from Alex Koschik (Simulation code MultiTRISIM)**
- **(Theoretical) impedance result from Rainer Hasse (GSI)**
- **Appendices 1&2**

Review of the 2004 results



Zimmermann et al., EPAC06

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



HEADTAIL simulations reproduce the SPS tune shift measurements, confirming the nonlinear theory

Courtesy G. Rumolo

Gianluigi’s approach using the classical “thick-wall” wake field

(“Beam observations with electron cloud in the CERN PS & SPS complex”, ECLOUD’04)

For electron cloud

$$k_{ec} = \frac{1}{pc\beta}\,\frac{e\rho_{ec}}{\varepsilon_0}\,\frac{L_{arc}}{2\pi R}$$

$$\frac{d^2 x_l}{ds^2} + \left(\frac{Q}{R}\right)^2 x_l = -k_{ec}\sum_{k=1}^{72}\left(x_l - x_k e^{\frac{i(l-k)s_{bunch}}{R}Q}\right)\chi(k-n)F_{lk} - \overbrace{k_{res}x_l}^{Quad.\quad term} +$$

$$\overbrace{+\,k_{res}\sum_{k=1}^{72}\left[x_k e^{\frac{i(l-k)s_{bunch}}{R}Q}\left(\chi(l-k-1)\sum_{m=0}^{\infty}\frac{e^{i2\pi mQ}}{\sqrt{(l-k)s_{bunch}+m2\pi R}} + \chi(k-l)\sum_{m=1}^{\infty}\frac{e^{i2\pi mQ}}{\sqrt{(l-k)s_{bunch}+m2\pi R}}\right)\right]}^{Dipolar\quad term}$$

For (classical “thick-wall”) resistive-wall

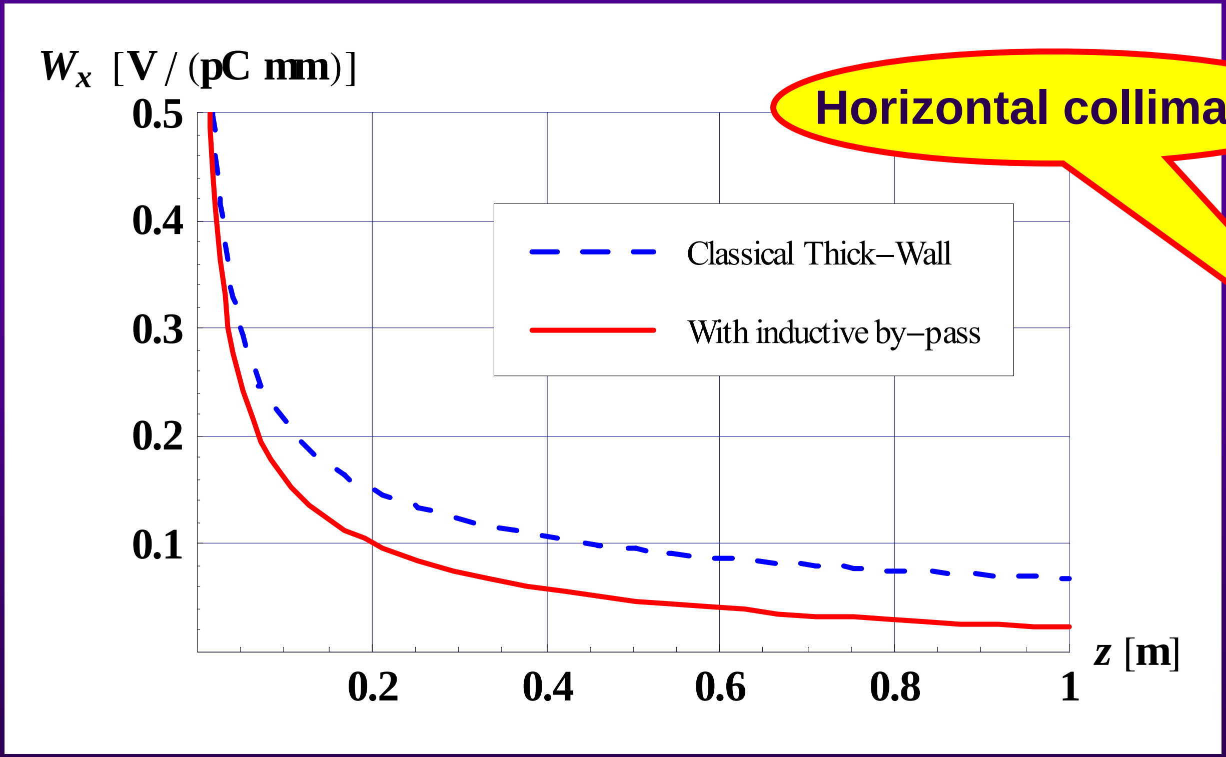
Step function

$$k_{res} = \frac{N_b e^2}{p}\,\frac{F}{\pi b^3}\sqrt{\frac{Z_0\rho}{\pi\beta}}$$

“Approximate” collimator wake-field derived by A. Koschik (2003)

From L. Vos’ formula, which is an approximation of Zotter’s (“exact”) formula

$$W^{\perp}_{m=1,\,\mathrm{ibp}}(t>0) = \overbrace{+\frac{cL}{\pi^{3/2}b^{3}}\sqrt{\frac{\mu_0\mu_r}{\sigma_c}}\cdot\frac{1}{\sqrt{|t|}}}^{\text{Classical “thick-wall” formula}} - \exp\left[\frac{4\mu_r}{b^2\sigma_c\mu_0}|t|\right]\frac{2cL\mu_r}{b^4\pi\sigma_c}\cdot\left(1-\mathrm{Erf}\sqrt{\frac{4\mu_r}{b^2\sigma_c\mu_0}|t|}\right)$$



Horizontal collimator

$L = 1$ m

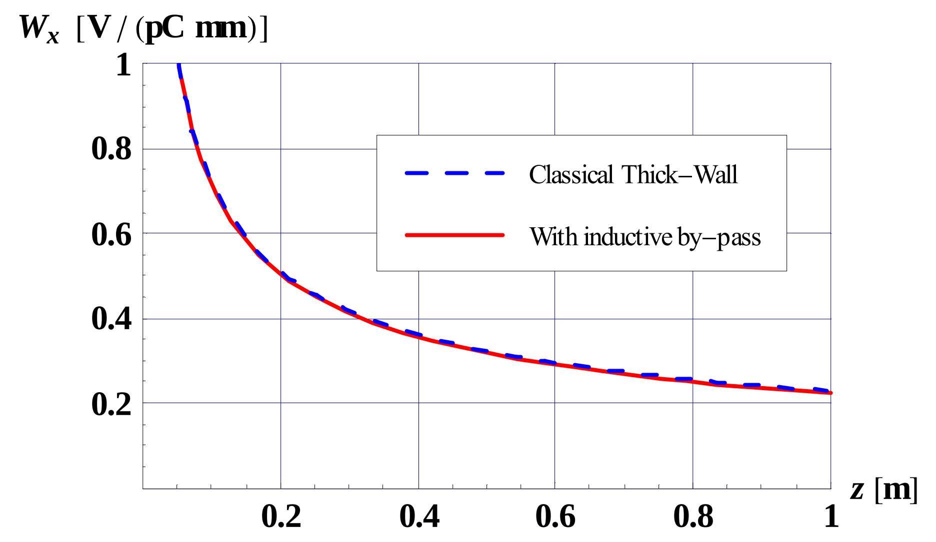
$b = 2$ mm

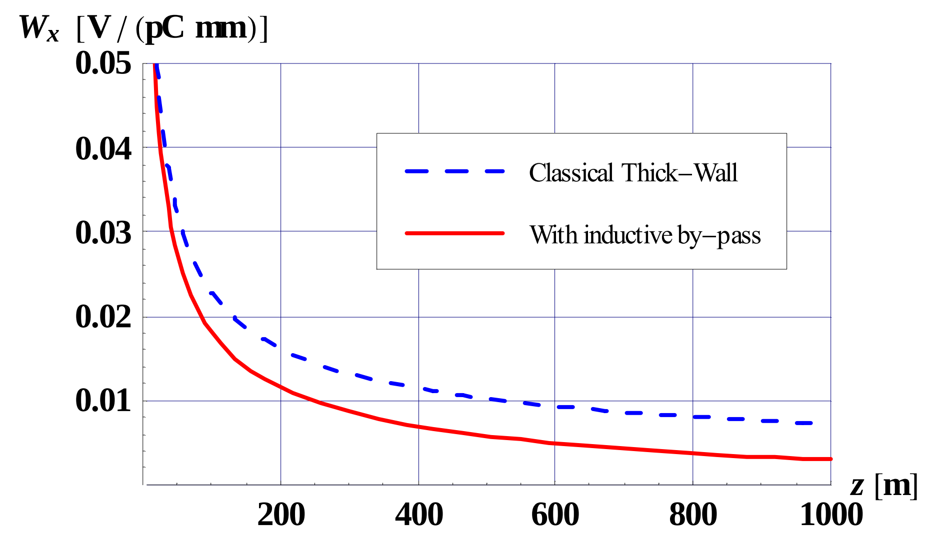
$\rho = 10\ \mu\Omega$m

$$F = \frac{\pi^2}{12} \approx 0.8$$

$$\frac{\beta_{coll}}{\beta_{av}} = \frac{23.2}{42} \approx 0.55$$

SPS resistive-wall wake-field from A. Koschik's (2003) formula





$$L = 6925 \text{ m}$$

$$b_{av} = 2 \text{ cm}$$

$$\rho = 0.73 \ \mu\Omega\text{m}$$

$$F = \frac{\pi^2}{24} \approx 0.4$$

Flat chamber

Not exactly the same

“Extension” of Gianluigi’s program (without electron cloud) using the wake field with “inductive by-pass” (from Alex Koschik 2003) and allowing the possibility to place the bunches at any positions around the machine

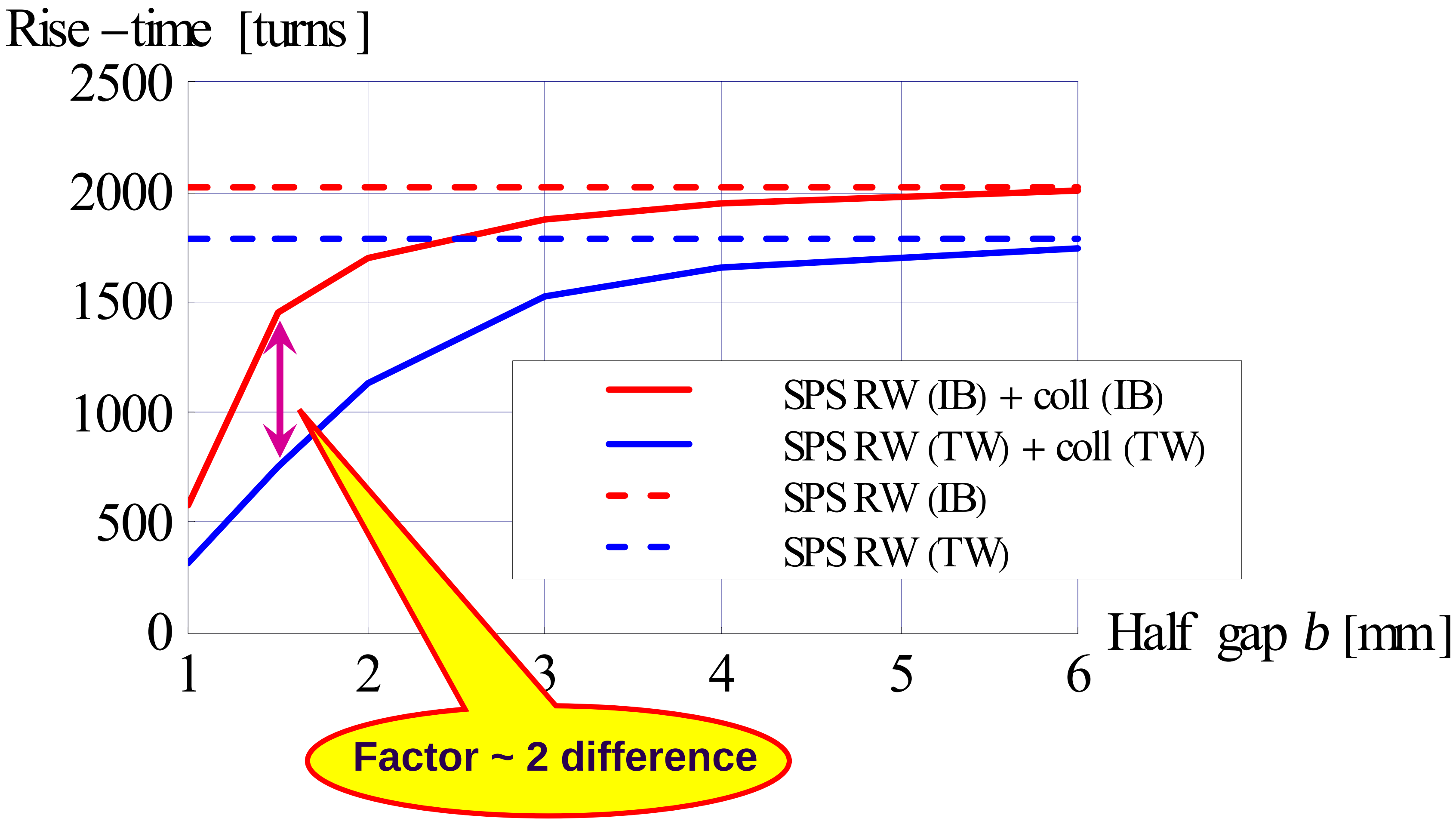
Summary of the rise-times (in SPS turns) for 1 batch of 72 bunches (1.15×10^{11} p/b) at 270 GeV/c and $m = 1$ (1/2)

Imp. Half gap *b*	SPS RW (TW)	SPS RW (IB)	Coll (TW)	Coll (IB)	SPS RW (TW) + Coll (TW)	SPS RW (IB) + Coll (IB)
6 mm	1788	2026	82117	214984	1750	2006
4 mm	1788	2026	24331	43713	1666	1949
3 mm	1788	2026	10265	19033	1523	1879
2 mm	1788	2026	3041	5801	1126	1708
1.5 mm	1788	2026	1283	2471	747	1458
1 mm	1788	2026	380	694	314	583

$$Q_x = 26.13$$

$$\tau = \frac{\tau_1\,\tau_2}{\tau_1 + \tau_2}$$

Summary of the rise-times (in SPS turns) for 1 batch of 72 bunches (1.15×10^{11} p/b) at 270 GeV/c and $m = 1$ (2/2)



Factor ~ 2 difference

Effect of the beam momentum on the rise-time

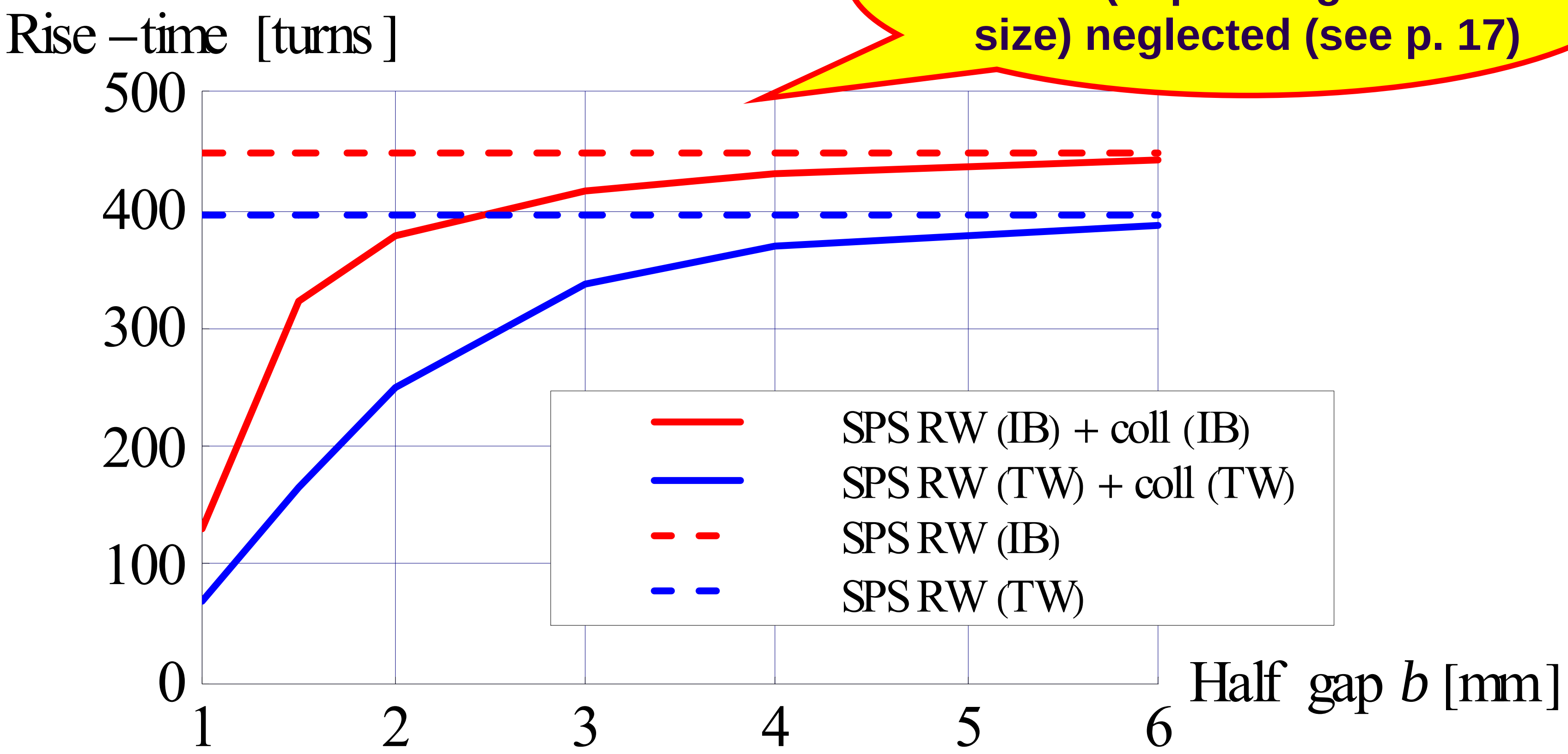
◆ The rise-times are proportional to the momentum ⇒ At 26 GeV/c, the rise-times will be 10.4 times smaller

Effect of the intensity per bunch on the rise-time

◆ The rise-times are inversely proportional to the intensity per bunch ⇒ At 5×10^{10} p/b, the rise-times will be 2.3 times larger

Summary of the rise-times (in SPS turns) for 1 batch of 72 bunches (5×10^{10} p/b) at 26 GeV/c and $m = 1$ (2/2)

⇒ Rise-times of page 8 × 0.22



Losses from scraping by the collimator (depending on the beam size) neglected (see p. 17)

Effect of m on the rise-time (in SPS turns)

Imp. m	SPS RW (TW)	SPS RW (IB)	SPS RW (TW) + Coll (TW) with b = 1 mm	SPS RW (IB) + Coll (IB) with b = 1 mm
1	1788	2026	314	583
10	1236	1914	217	302
100	1412	1926	247	
1000	1343			
10^6	1315			
Infinity	1314			

The rise-times for $m > 1$ are ~ 20-30% smaller than the one with $m = 1$

Effect of several batches on the rise-time (in SPS turns)

Imp. # batches	SPS RW (TW)	SPS RW (IB)	SPS RW (TW) + Coll (TW) with *b* = 1 mm	SPS RW (IB) + Coll (IB) with *b* = 1 mm
1	1788	2026	314	583
2	1247	1437	219	
3	923		162	
4	711		125	

Gaps of 225 ns (i.e. 8 non-occupied positions)

4 batches of 24 bunches spaced by gaps of 207 non-occupied positions

Imp. *b* [mm]	SPS RW (TW)	SPS RW (IB)	SPS RW (TW) + Coll (TW)	SPS RW (IB) + Coll (IB)
1	2058	2940	361	419
1.5	2058	2940	860	1090

Comparison between time domain and frequency domain analysis with equi-populated equi-spaced bunches

$\Rightarrow$ 924 bunches

Time domain analysis

$m = 1 \Rightarrow$ 227 turns = 5.2 ms

$m = \infty \Rightarrow$ 143 turns = 3.3 ms

Bunch length = 0

Frequency domain analysis

417 turns = 9.6 ms

Bunch length (4 σ) = 2.8 ns

Results from Alex Koschik (Simulation code MultiTRISIM)

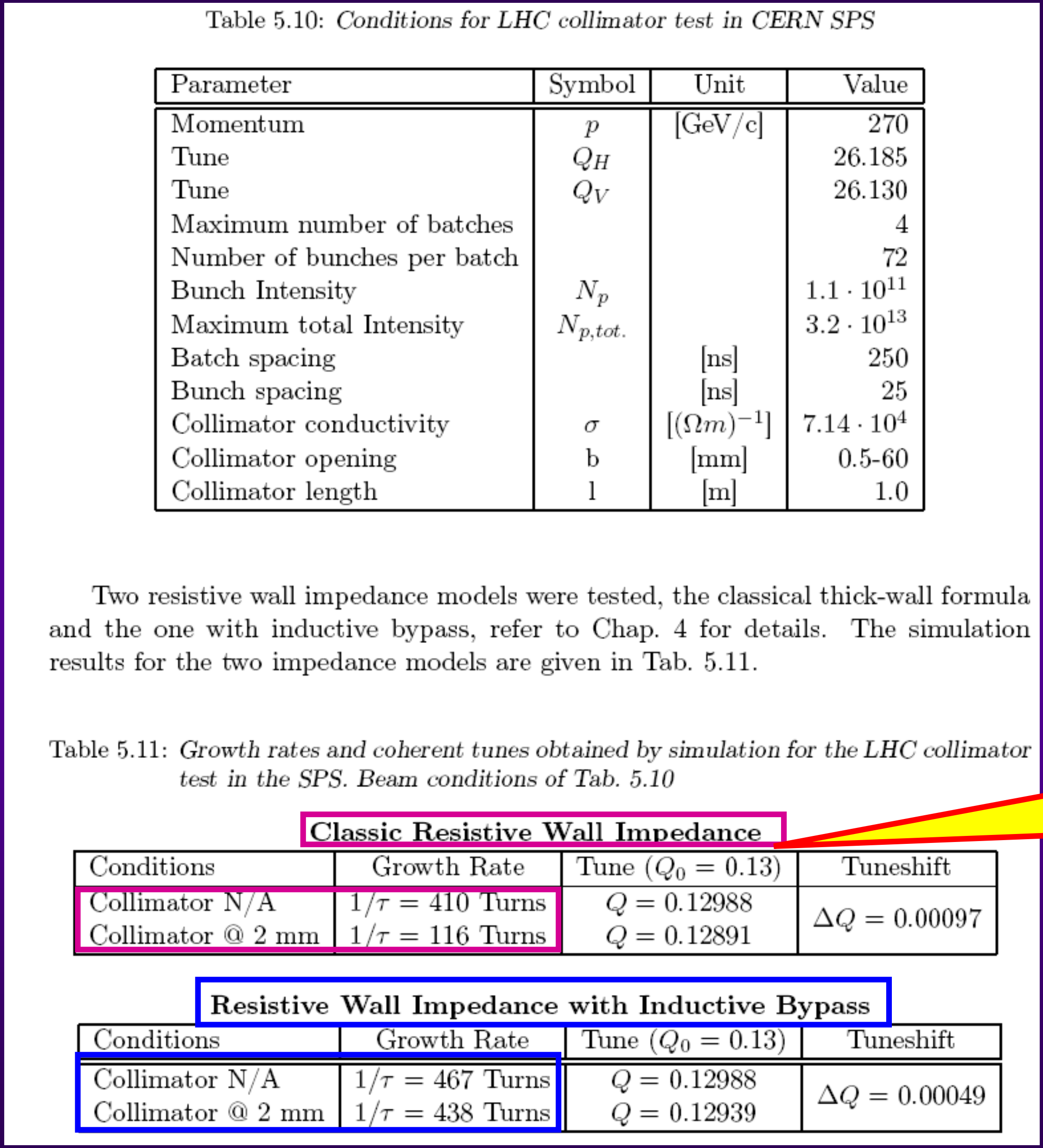


Table 5.10: *Conditions for LHC collimator test in CERN SPS*

Parameter	Symbol	Unit	Value
Momentum	p	[GeV/c]	270
Tune	Q_H		26.185
Tune	Q_V		26.130
Maximum number of batches			4
Number of bunches per batch			72
Bunch Intensity	N_p		$1.1 \cdot 10^{11}$
Maximum total Intensity	$N_{p,tot.}$		$3.2 \cdot 10^{13}$
Batch spacing		[ns]	250
Bunch spacing		[ns]	25
Collimator conductivity	σ	$[(\Omega m)^{-1}]$	$7.14 \cdot 10^4$
Collimator opening	b	[mm]	0.5-60
Collimator length	l	[m]	1.0

Two resistive wall impedance models were tested, the classical thick-wall formula and the one with inductive bypass, refer to Chap. 4 for details. The simulation results for the two impedance models are given in Tab. 5.11.

Table 5.11: *Growth rates and coherent tunes obtained by simulation for the LHC collimator test in the SPS. Beam conditions of Tab. 5.10*

Classic Resistive Wall Impedance

Conditions	Growth Rate	Tune ($Q_0 = 0.13$)	Tuneshift
Collimator N/A	$1/\tau = 410$ Turns	$Q = 0.12988$	$\Delta Q = 0.00097$
Collimator @ 2 mm	$1/\tau = 116$ Turns	$Q = 0.12891$	

Resistive Wall Impedance with Inductive Bypass

Conditions	Growth Rate	Tune ($Q_0 = 0.13$)	Tuneshift
Collimator N/A	$1/\tau = 467$ Turns	$Q = 0.12988$	$\Delta Q = 0.00049$
Collimator @ 2 mm	$1/\tau = 438$ Turns	$Q = 0.12939$	

in PHD thesis (2004)

Vertical collimator assumed. New simulations in progress…

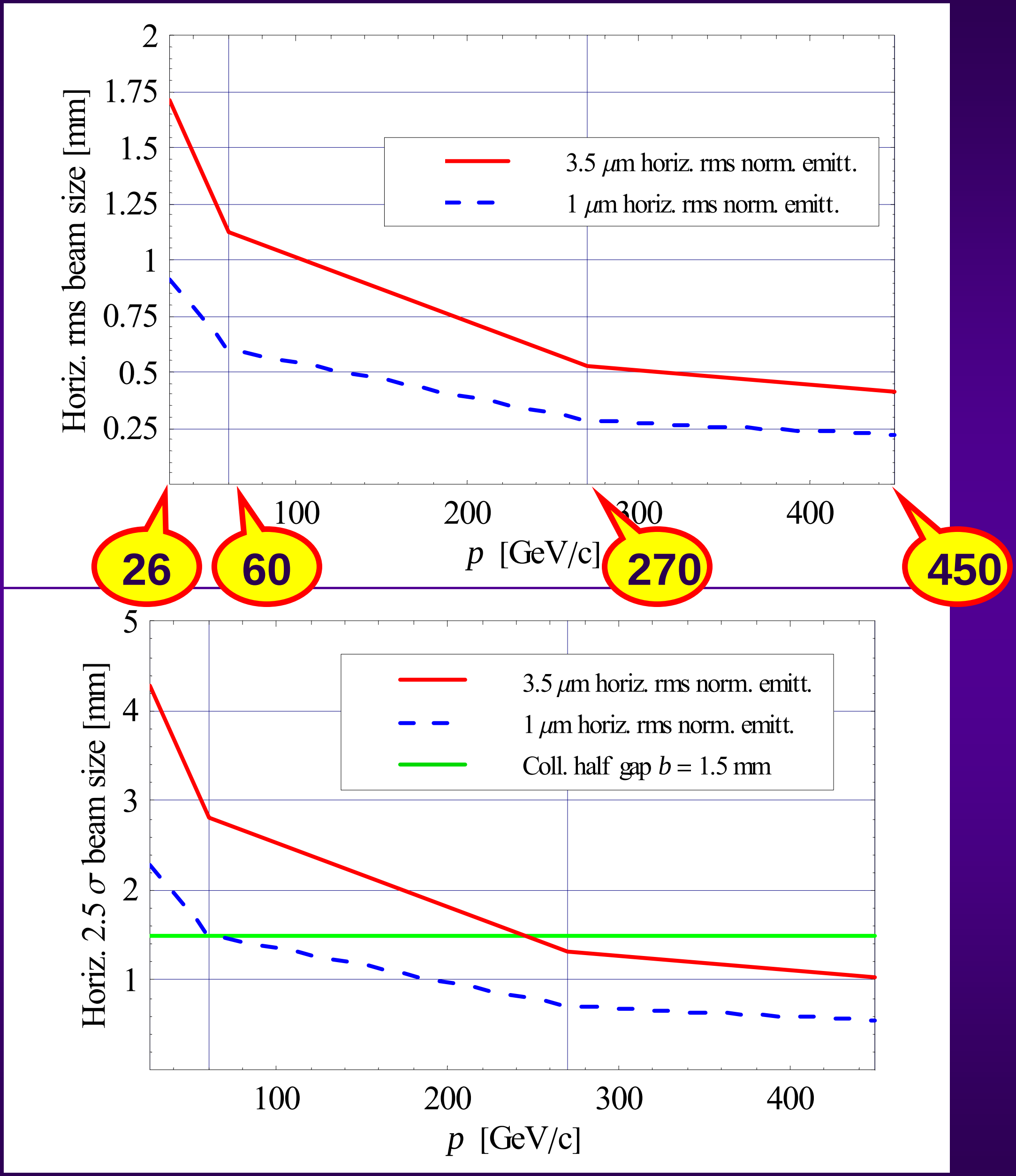
Conclusions

- A factor ~ 2 difference is predicted between SPS RW (TW) + coll (TW) and SPS RW (IB) + coll (IB) for 1 train of 72 bunches with a collimator half gap *b* = 1.5 mm (and *m* = 1)

- To measure this, one should be able to close the collimator to a half gap *b* = 1.5 mm (⇒ Go to high energy to have a small beam size or reduce the intensity) AND the beam should be unstable without the collimator, which was not always the case in 2004 (⇒ Go to low energy to have smaller rise-times, *60 GeV/c was proposed by F. Zimmermann*, or increase the intensity per bunch or the number of batches, *but minimizing the gaps*)…

- One should also try to avoid the horizontal coupled-bunch instability from ecloud… ⇒ The optimum solution still needs to be found, scaling the rise-times of p. 8 and looking at beam size vs. beam energy (p. 17)

Appendix 1: Horizontal beam size vs. beam momentum



Appendix 2: (Theoretical) results from Rainer Hasse (GSI) (1/2)

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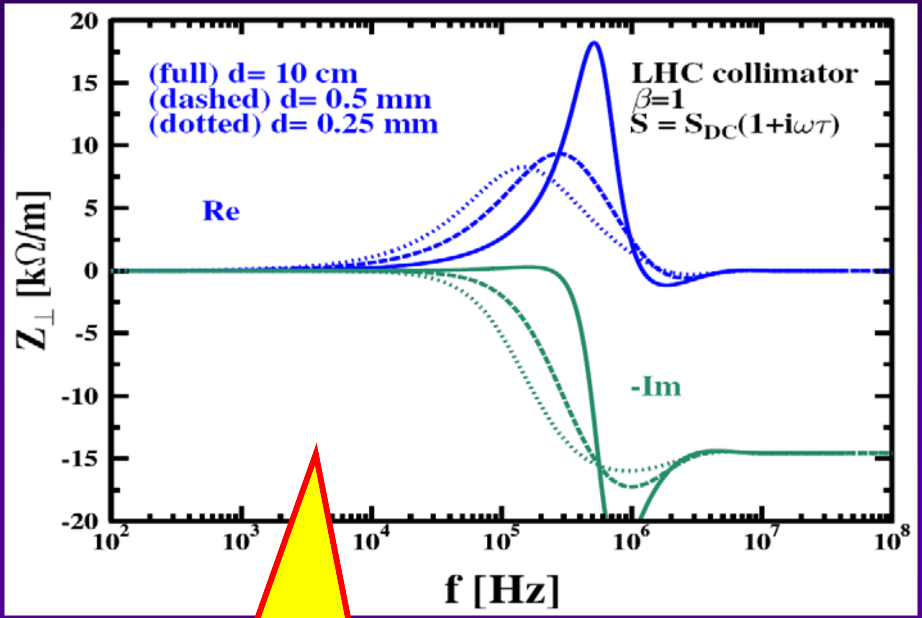
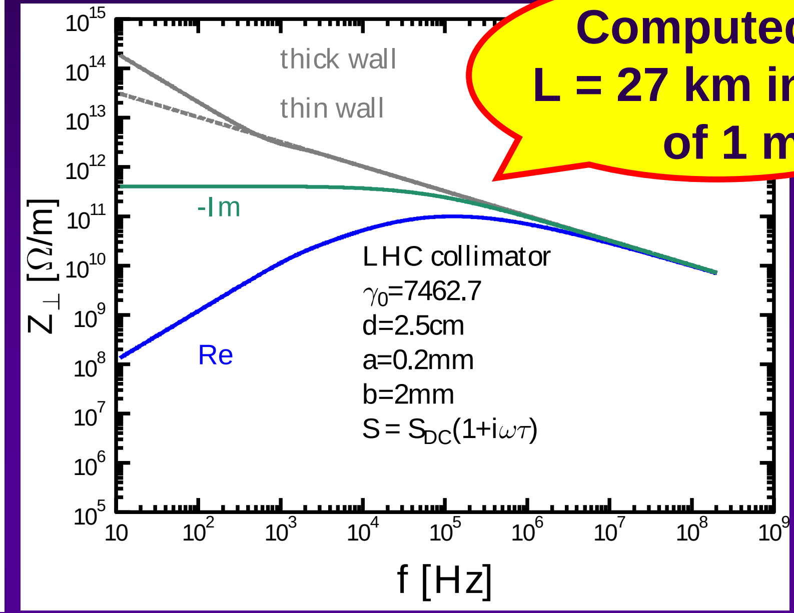


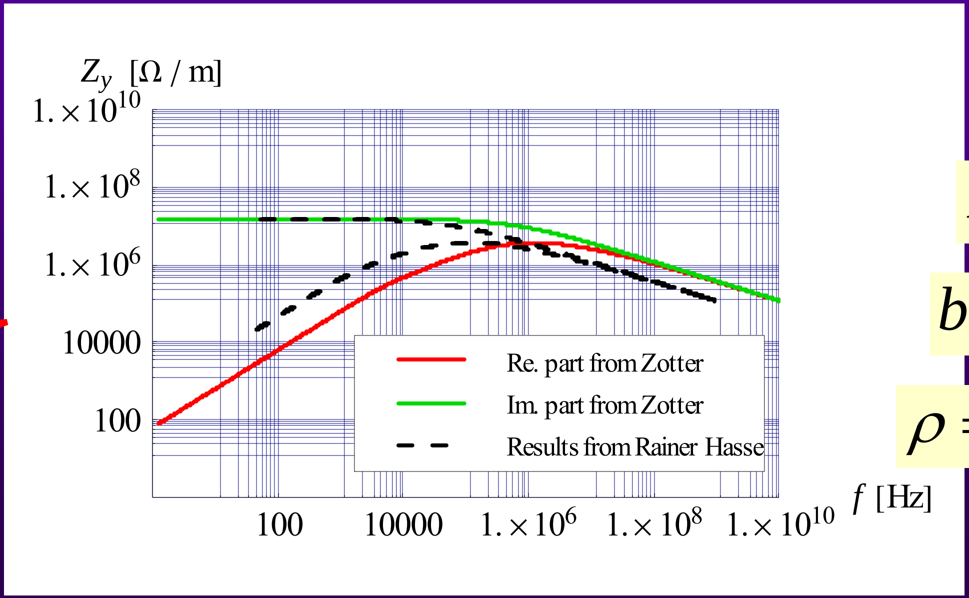
d = 2.5 cm for the real LHC collimators

On 28/09/06



Computed for L = 27 km instead of 1 m

On 07/10/06



For 1 m, but wrong resistivity (1 $\mu\Omega$m)

$L = 1$ m

$b = 2$ mm

$\rho = 10\ \mu\Omega$m

Appendix 2: (Theoretical) results from Rainer Hasse (GSI) (2/2)

On 13/10/06 (this morning)