20 + 10 min talk (28 slides)

SPS IMPEDANCE

Elias Métral

Work in collaboration with G. Arduini, T. Bohl, H. Burkhardt, F. Caspers, T. Kroyer, H. Medina, G. Rumolo, B. Salvant, E. Shapochnikova, B. Spataro…

OUTLINE

- **Introduction**
  - Longitudinal microwave instability observed before 2001
  - MKE kickers installed for extraction towards LHC (2003&6)
  - Fast vertical single-bunch instability at injection in 2003 (02)
  - Beam-induced heating from MKE kicker
- **Resistive-wall impedance of the MKE kickers**
- **Measurements vs. theory**
  - $\mathrm{Im}[Z_{y,eff}]$ from coherent tune shift vs. intensity
  - Fast vertical single-bunch instability intensity threshold at injection
  - $\mathrm{Re}[Z_{y,eff}]$ from head-tail growth/decay rate
  - $\mathrm{Im}[Z_l/n_{eff}]$ from quadrupole oscillation frequency shift vs. intensity
  - Power loss
- **HEADTAIL simulations in the longitudinal plane**
- **Conclusion**
- **Appendices:** Potential-well bunch lengthening, microwave instability with RF OFF, localization of impedances, BPMs, vacuum ports, RF cavities…

LONGITUDINAL MICROWAVE INSTABILITY OBSERVED BEFORE 2001

LHC Design Report

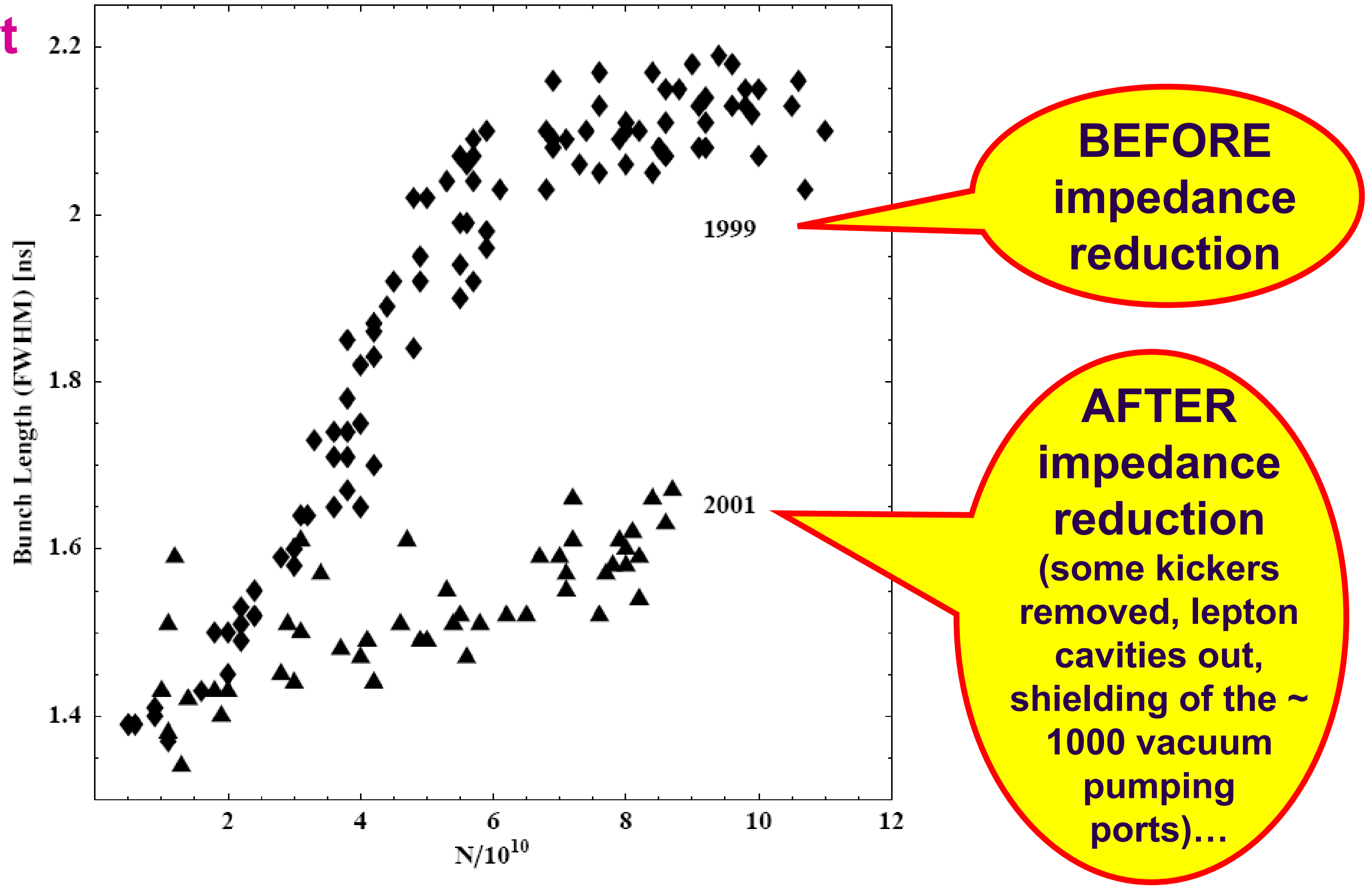


Figure 17.13: The bunch length measured 600 ms after injection as a function of bunch intensity in 1999 and 2001. Data taken at 26 GeV, ε=0.15 eVs, V=900 kV.

MKE KICKERS INSTALLED FOR EXTRACTION TOWARDS LHC

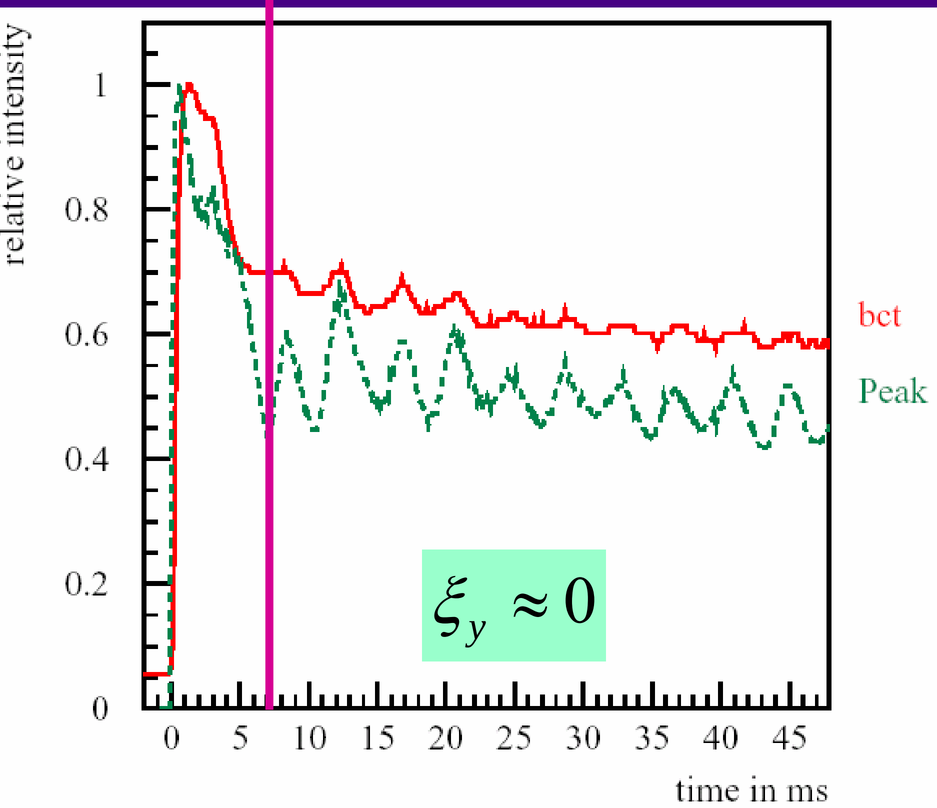
- **2001**
  - **Lepton cavities removed + impedance reduction (pumping ports) done**
  - **No MKE kickers (11 kickers in total)**
  - **Impedance reduction by ~ 2.5 in the longitudinal plane (from meas.)**
  - **Impedance reduction by ~ 40% in the transverse one (from meas.)**
- **2003**
  - **+ 5 MKE kickers in LSS4 (16 kickers in total)**
- **2006**
  - **+ 4 MKE kickers in LSS6 (20 kickers in total) – 1 MKE kicker shielded on 2 cells**
- **2007**
  - **- 1 MKE kicker and 1 MKE has been shielded (19 kickers in total)**

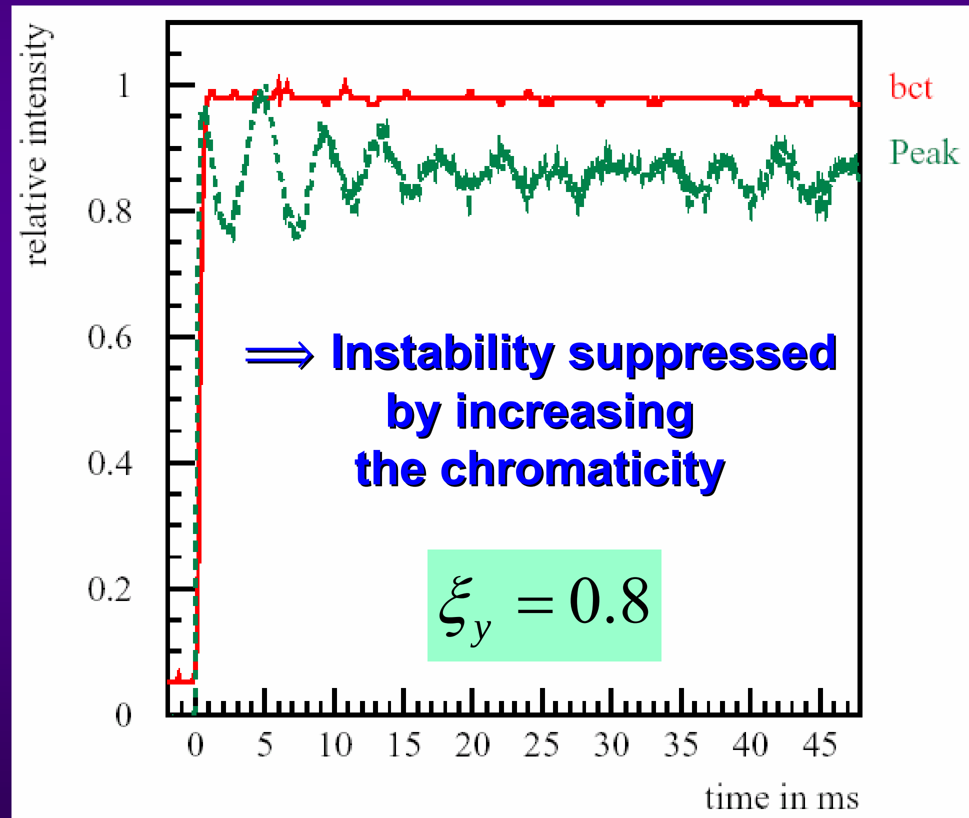
FAST VERTICAL SINGLE-BUNCH INSTABILITY AT INJECTION IN 2003 (1/3)

$p = 26\ \mathrm{GeV/c}$ $N_b \approx 1.2\,10^{11}\ \mathrm{p/b}$

$\varepsilon_l \approx 0.2\ \mathrm{eVs} < \varepsilon_l^{\mathrm{LHC}} = 0.35\ \mathrm{eVs}$

Synchrotron period ≈ 7 ms



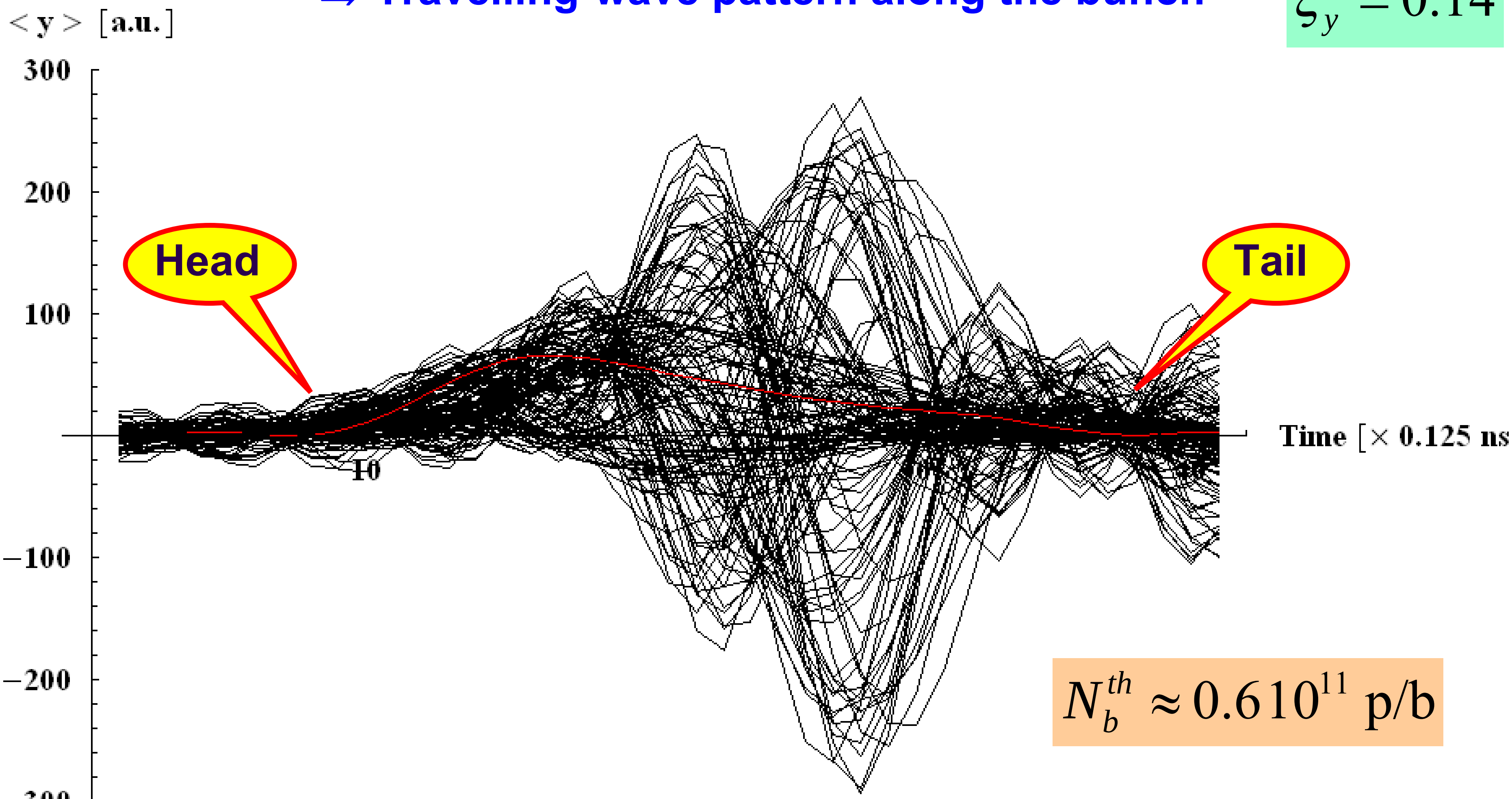


$T_{rev}^{SPS} \approx 23\ \mu\mathrm{s}$

FAST VERTICAL SINGLE-BUNCH INSTABILITY AT INJECTION IN 2003 (2/3)

⇒ **Travelling-wave pattern along the bunch**

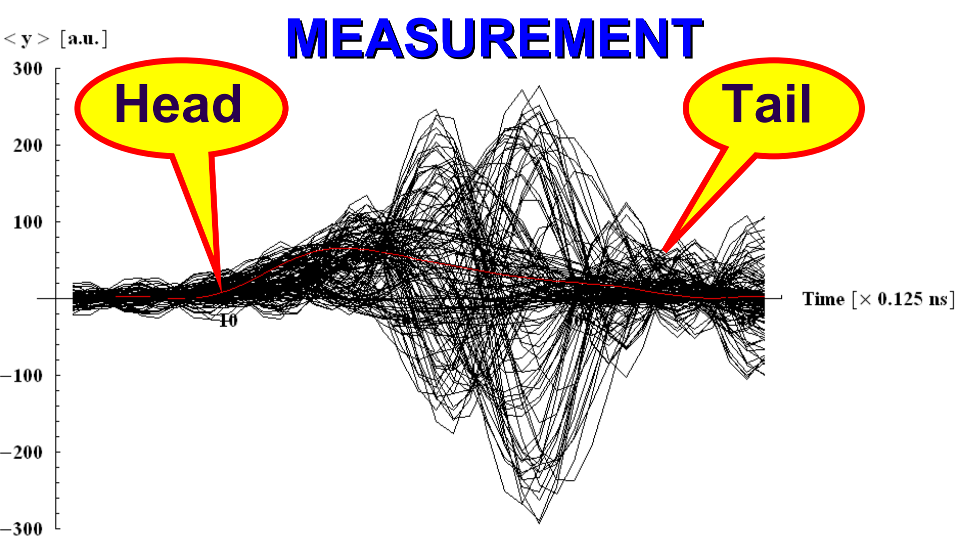
$\xi_y = 0.14$

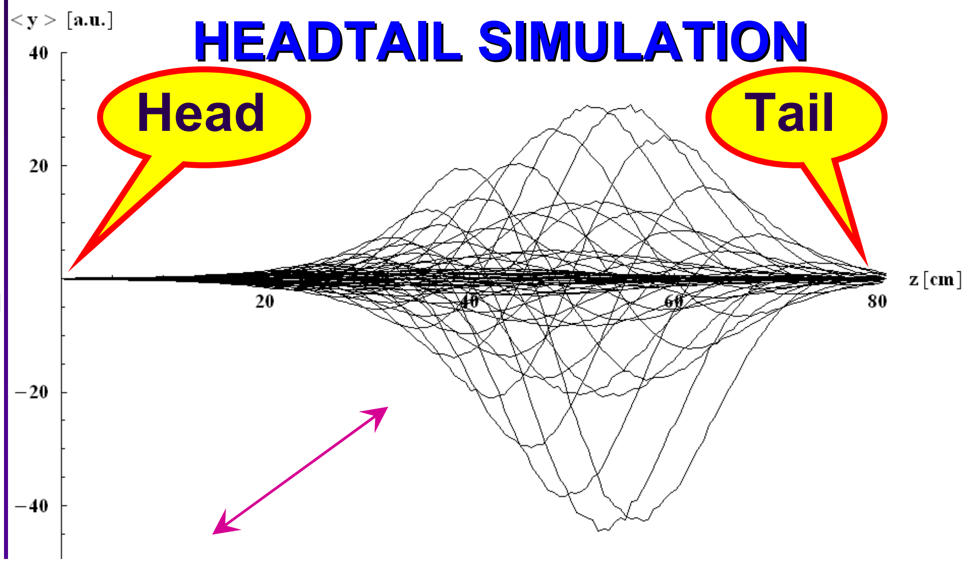


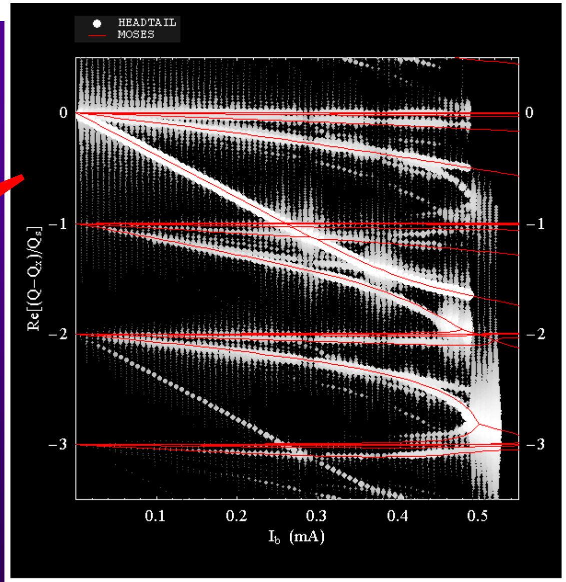
$N_b^{th} \approx 0.6\,10^{11}$ p/b

1st trace (in red) = turn 2 | Last trace = turn 150 | Every turn shown

FAST VERTICAL SINGLE-BUNCH INSTABILITY AT INJECTION IN 2003 (3/3)







See B. Salvant's talk (BB impedance)

Next steps:

- **Measure mode coupling**
- **Improve impedance model**

BEAM-INDUCED HEATING FROM MKE KICKER

- **If a part of the ferrite itself reaches temperatures above the Curie temperature, around 125°C, it looses its magnetic properties and the magnetic field strength will be reduced**

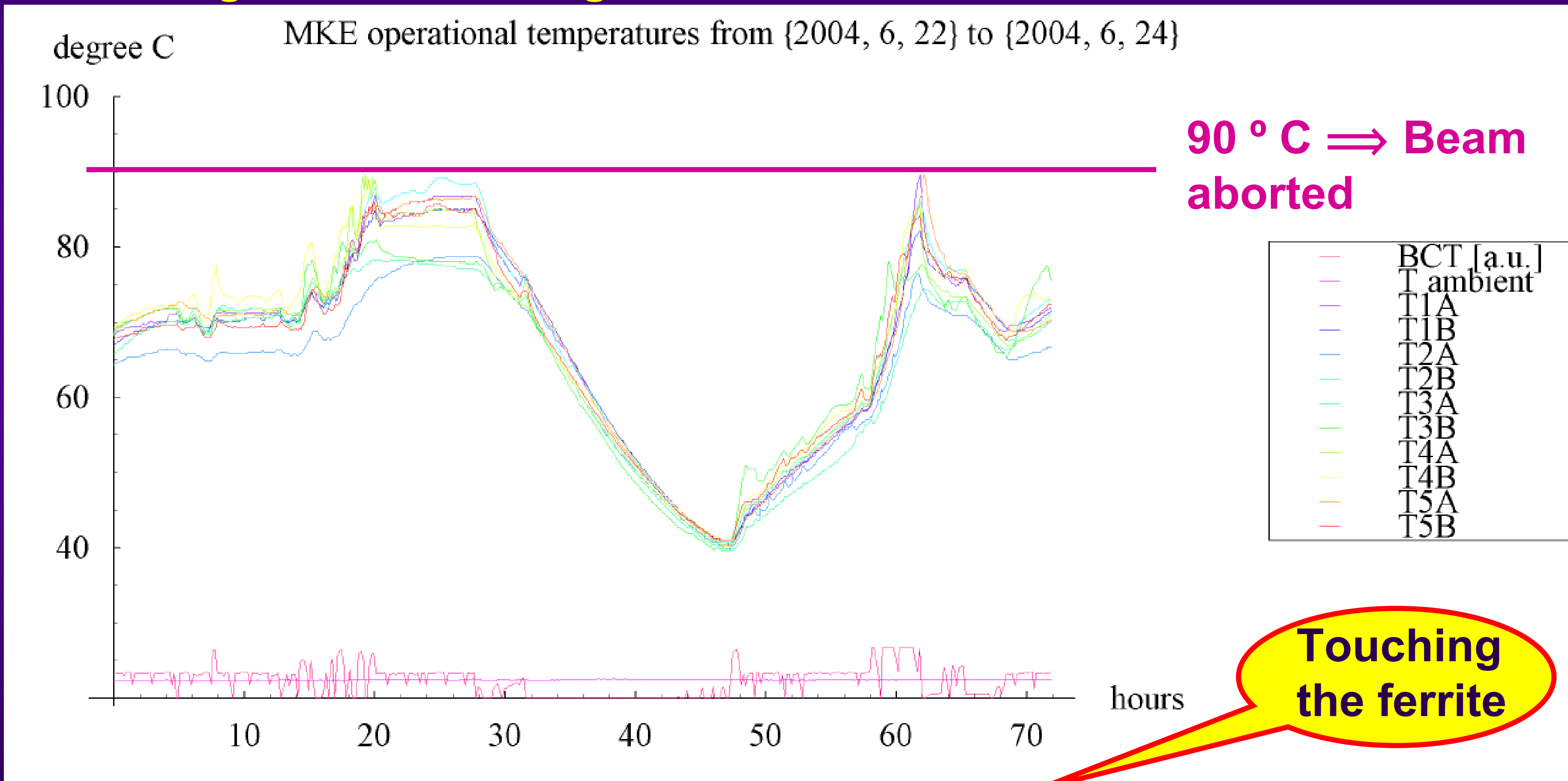
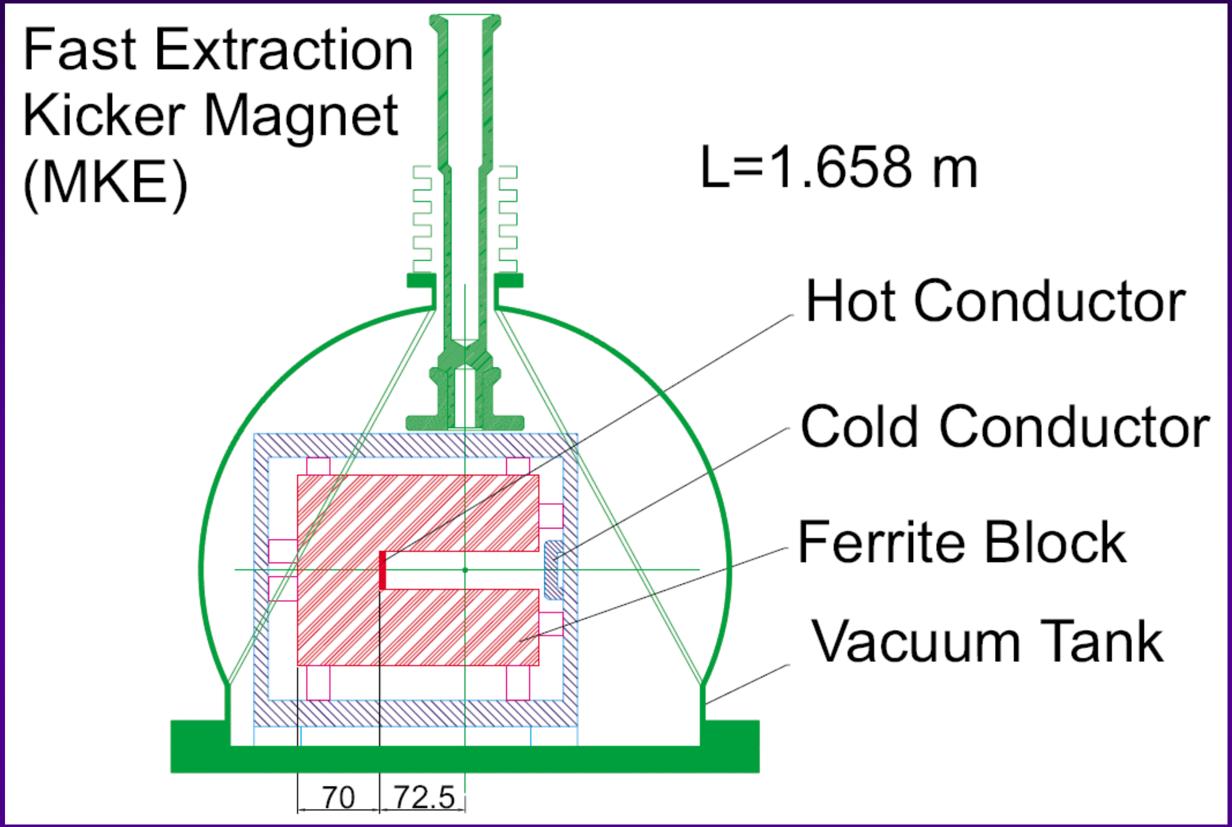
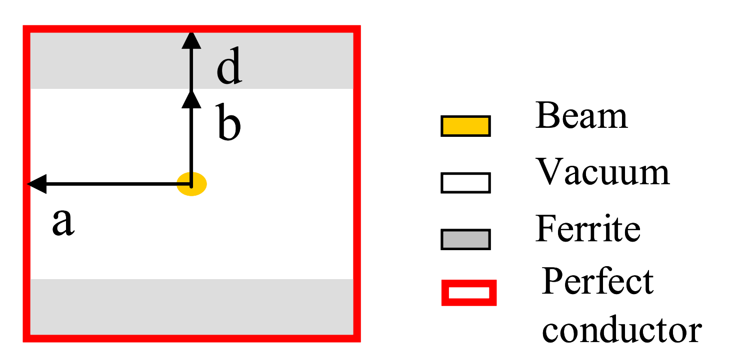


Figure 17.18: Measured MKE temperatures on the ceramic spacers during the 2004 scrubbing run.

VERTICAL RESISTIVE-WALL IMPEDANCE (1/4)

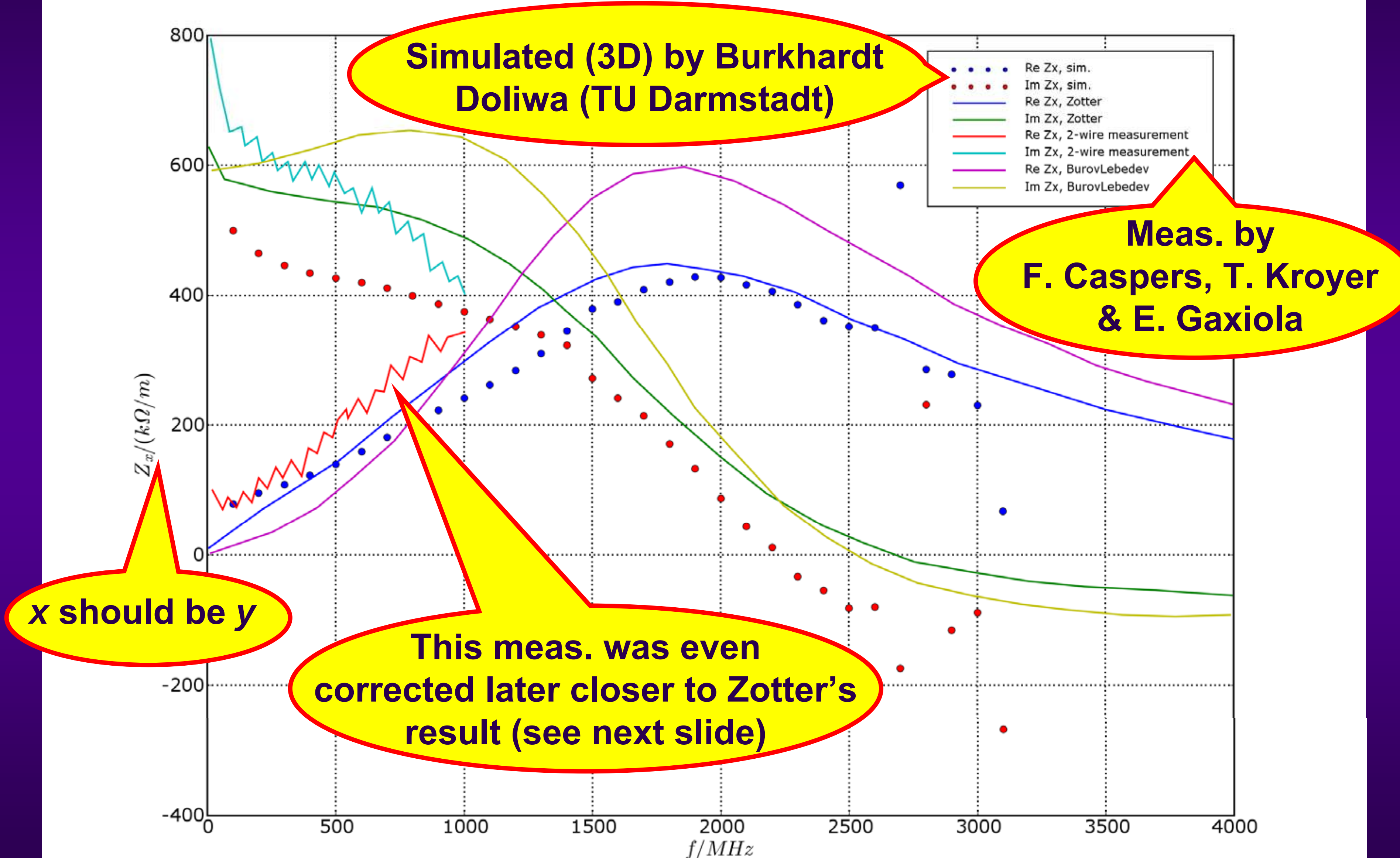


⟹ From the impedance point of view, a SPS kicker can be approximated by the following sketch

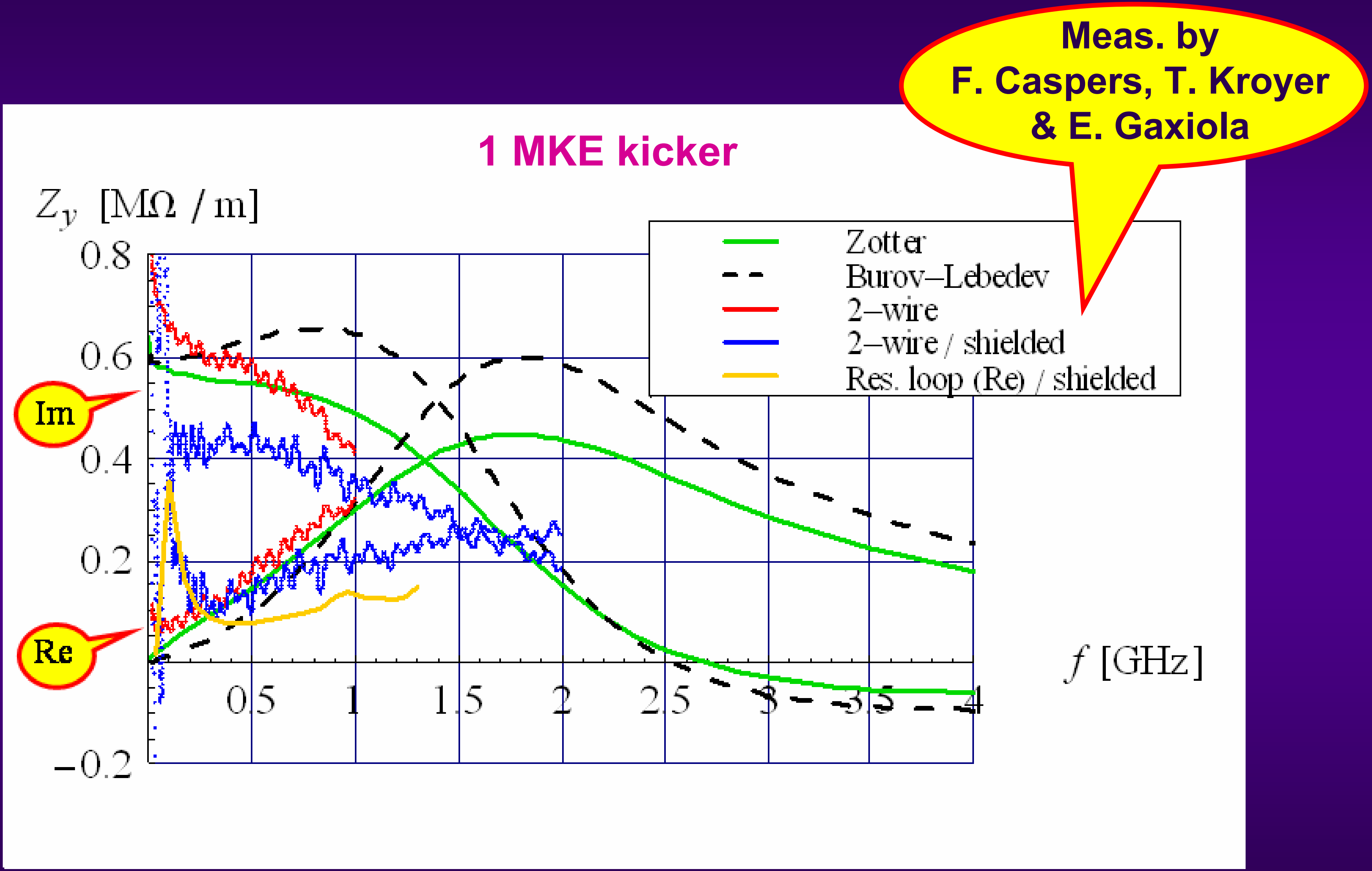


VERTICAL RESISTIVE-WALL IMPEDANCE (2/4)

1 MKE kicker ⟹ Comparison between 2 theories, 3D simul. and meas.



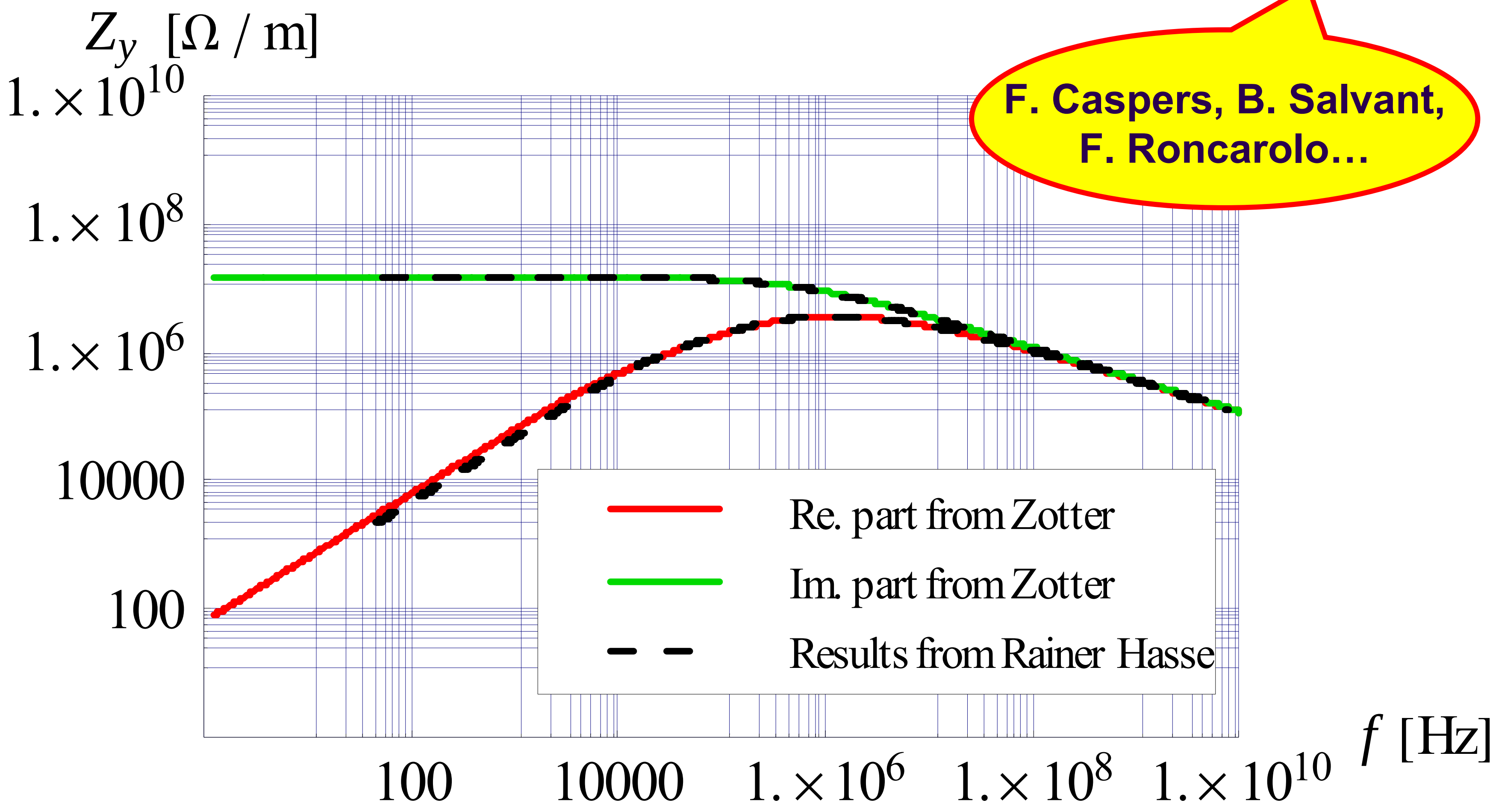
VERTICAL RESISTIVE-WALL IMPEDANCE (3/4)



VERTICAL RESISTIVE-WALL IMPEDANCE (4/4)

1 LHC collimator ⟹ Comparison between 2 theories (meas. ongoing…)

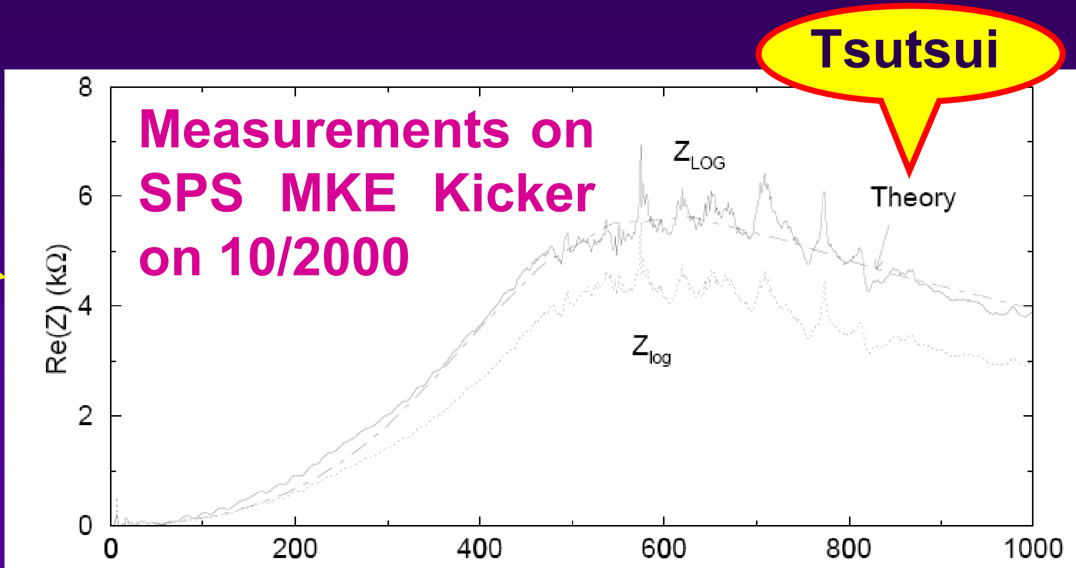
F. Caspers, B. Salvant, F. Roncarolo…

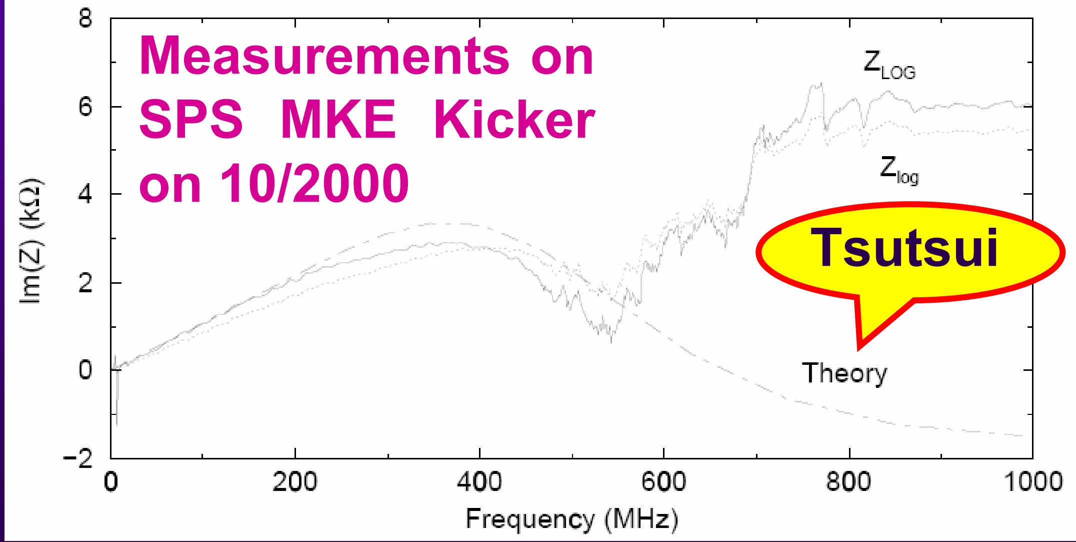


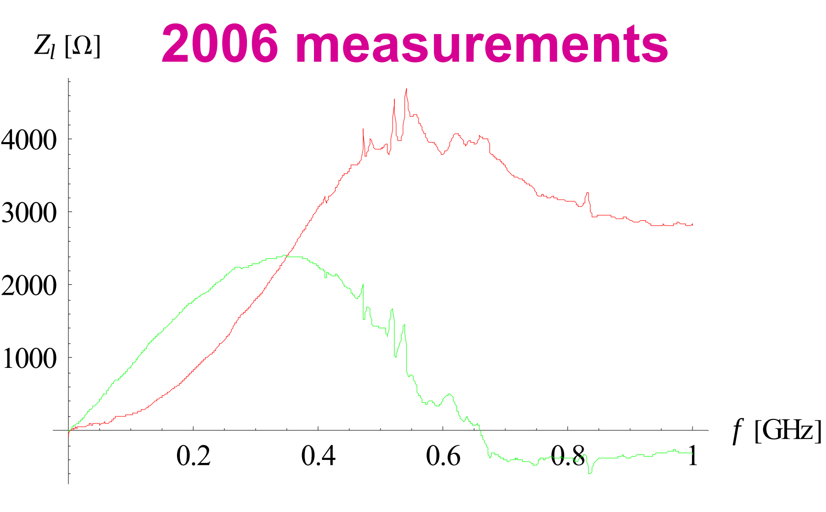
LONGITUDINAL RESISTIVE-WALL IMPEDANCE (1/2)

1 MKE kicker ⟹ Comparison between Tsutsui's theory and meas.

F. Caspers et al., CERN-SL-2000-071 (AP)





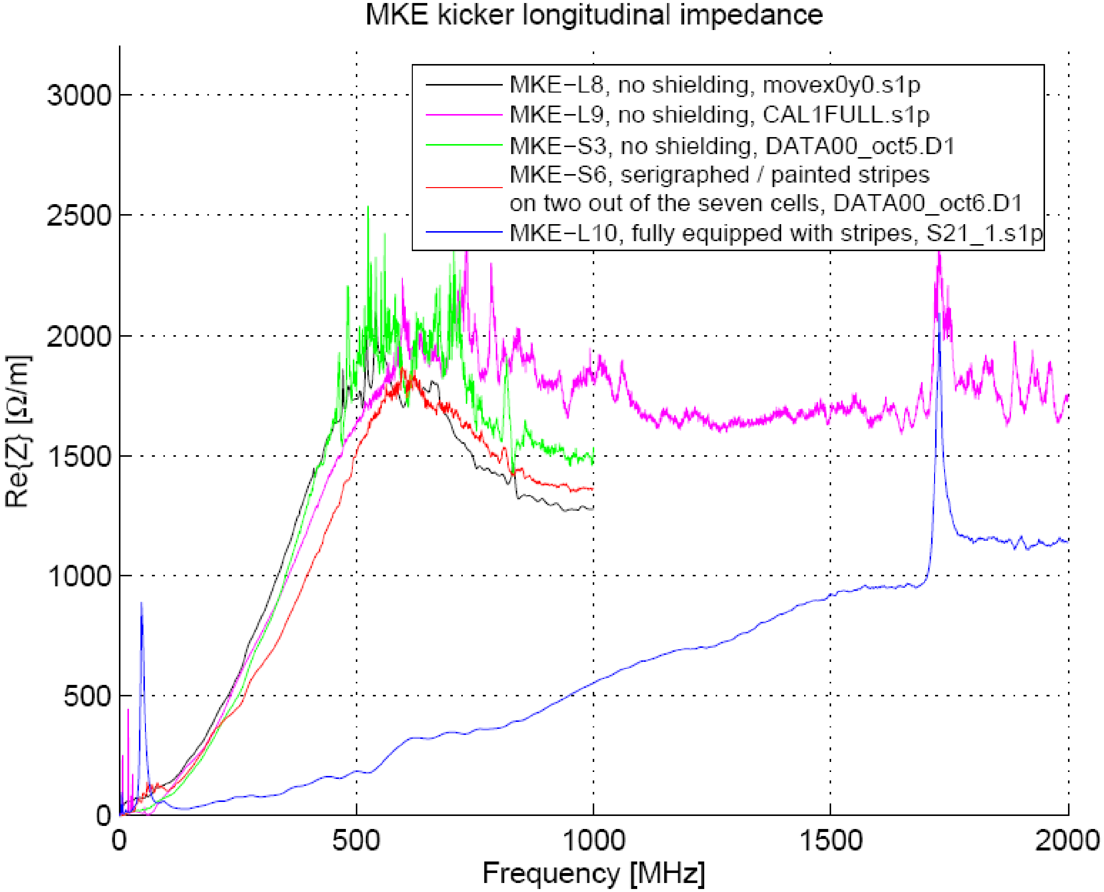


LONGITUDINAL RESISTIVE-WALL IMPEDANCE (2/2)

- In a comprehensive measurement campaign data for all types of MKE magnets was collected

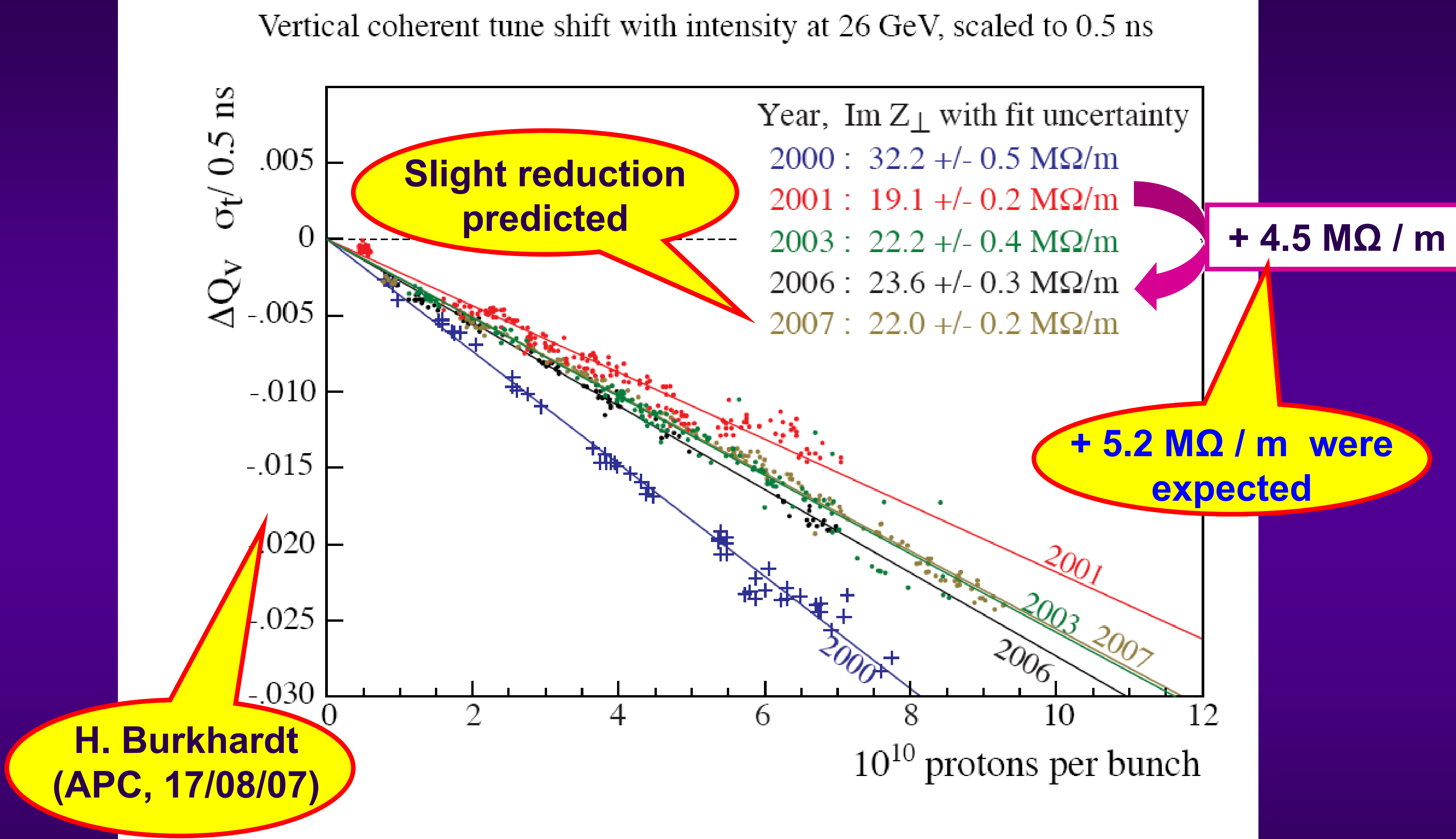
Courtesy of T. Kroyer (APC, 10/11/2006)

Printed strips in MKE-L10



⟹ **Significant reduction of the (real part here of the) longitudinal impedance (and associated power loss)**

SPS VERTICAL IMPEDANCE Im[$Z_{y,eff}$] (1/2)



Same analysis and very similar beam parameters (~ 0.5 - 0.6 ns rms bunch length)
The measured slopes can directly be compared. Estimated uncertainty ~ 10 - 20 %.

SPS VERTICAL IMPEDANCE Im[$Z_{y,eff}$] (2/2)

- **Summary and comparison between measurements and theoretical predictions (kickers contribution only)**

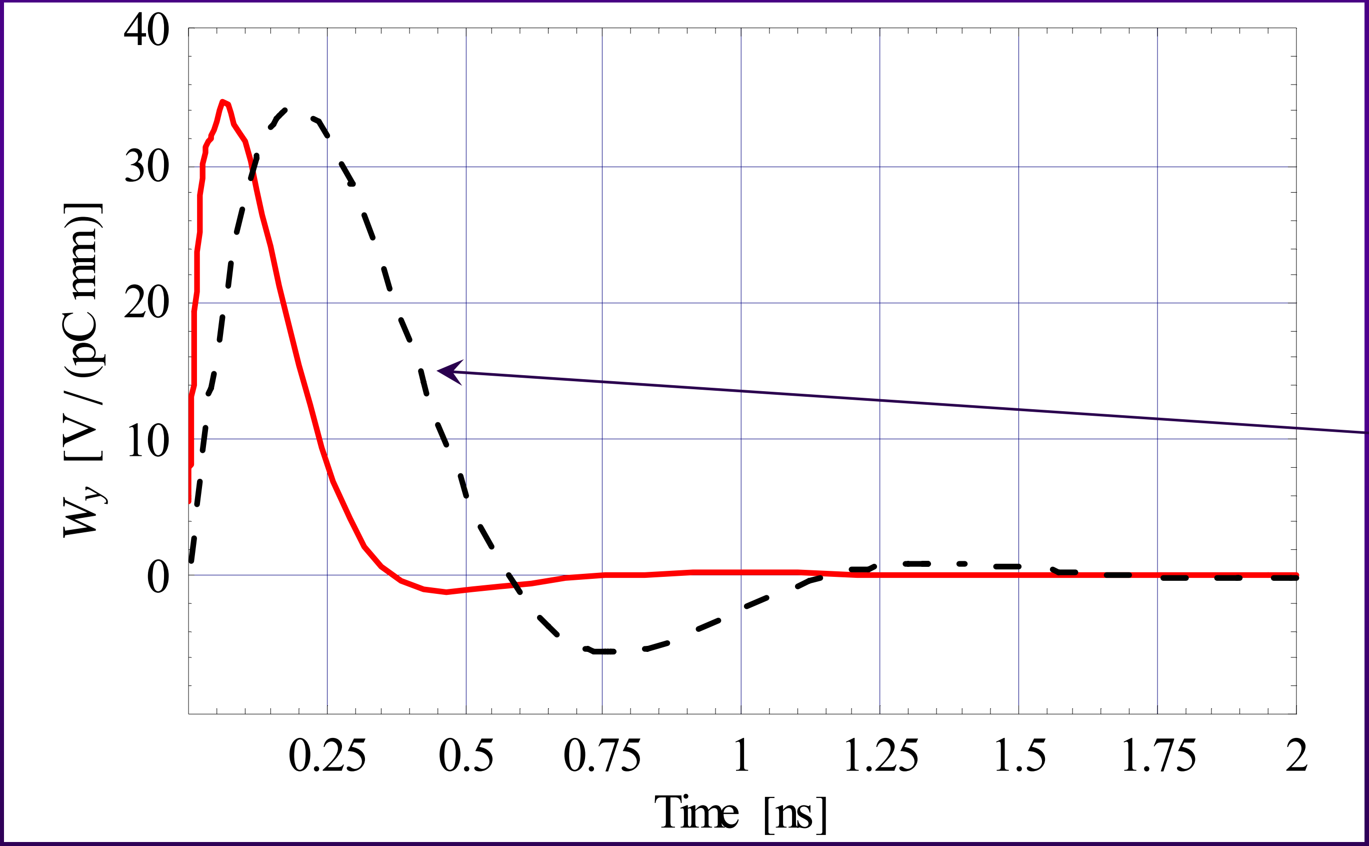
Im($Z_{y, eff}$) [MΩ/m]	Meas	delta	Theory (kickers)	delta	Error delta [%]
2001	19.1		3.5		
2003	22.2	3.1	6.4	2.9	7
2006	23.6	1.4	8.7	2.3	-39
2007	22	-1.6			

Cannot be done for the shielded kicker as we do not know the quadrupolar term!!!

- **Im[$Z_{y,eff}$] of the shielded kicker (using only the dipolar term available) = 0.24 MΩ/m**
- **Im[$Z_{y,eff}$] of the same kicker before the shielding (using only the dipolar term) = 0.27 MΩ/m**
- **Im[$Z_{y,eff}$] from the vertical space charge impedance (which contributes to the coherent tune shift!) ≈ + 2.6 MΩ/m ⟹ It is + 0.04 MΩ/m in the horizontal plane**

FAST VERTICAL INSTABILITY AT INJECTION (1/4)

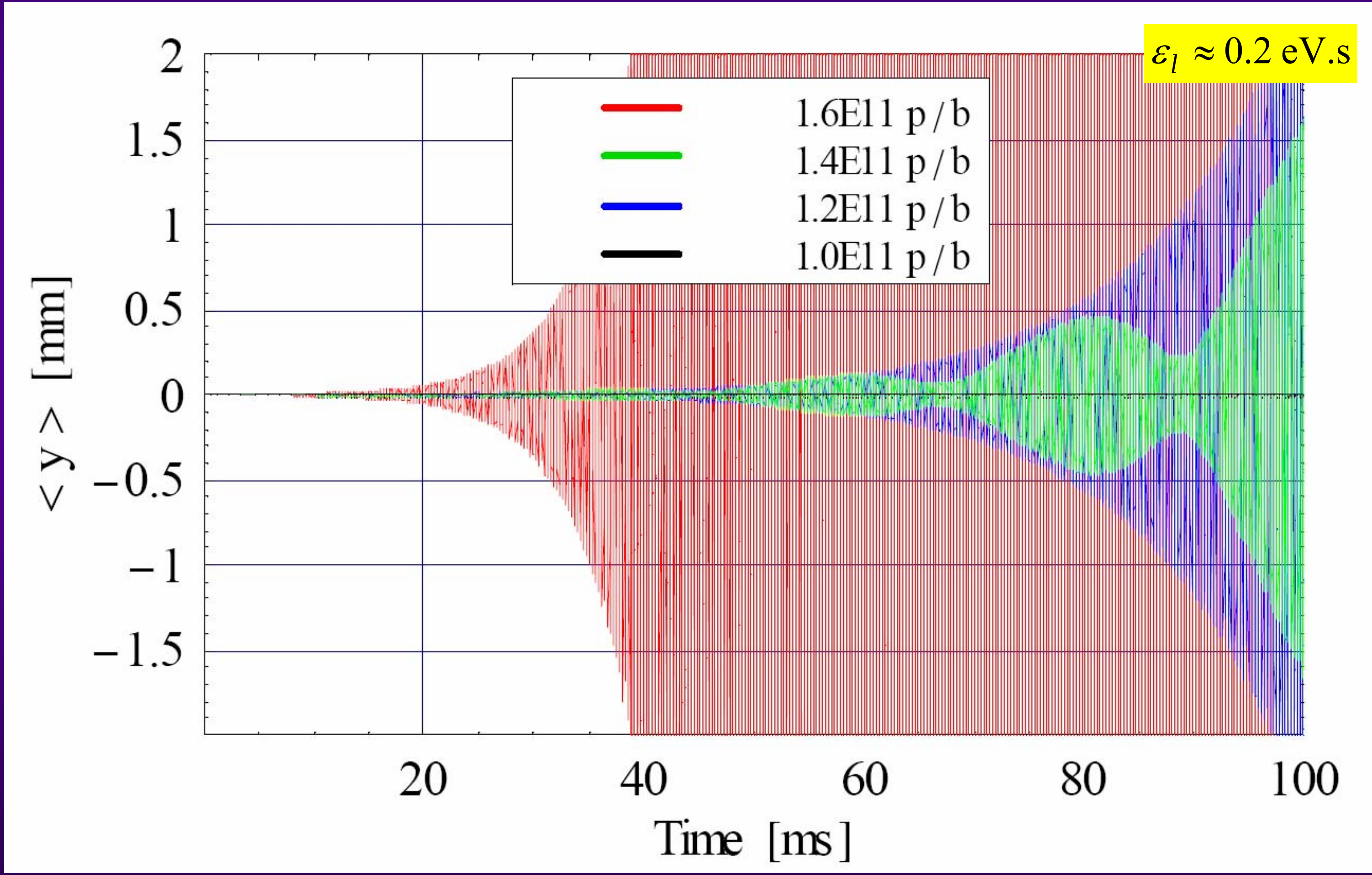
- **Wake-field obtained through ZBASE3 for the 2006 case**
- **Comparison with the BB resonator model used by B. Salvant for his mode coupling analysis**



f_r = 1 GHz
Q = 1
Z_y = 10 MΩ / m

FAST VERTICAL INSTABILITY AT INJECTION (2/4)

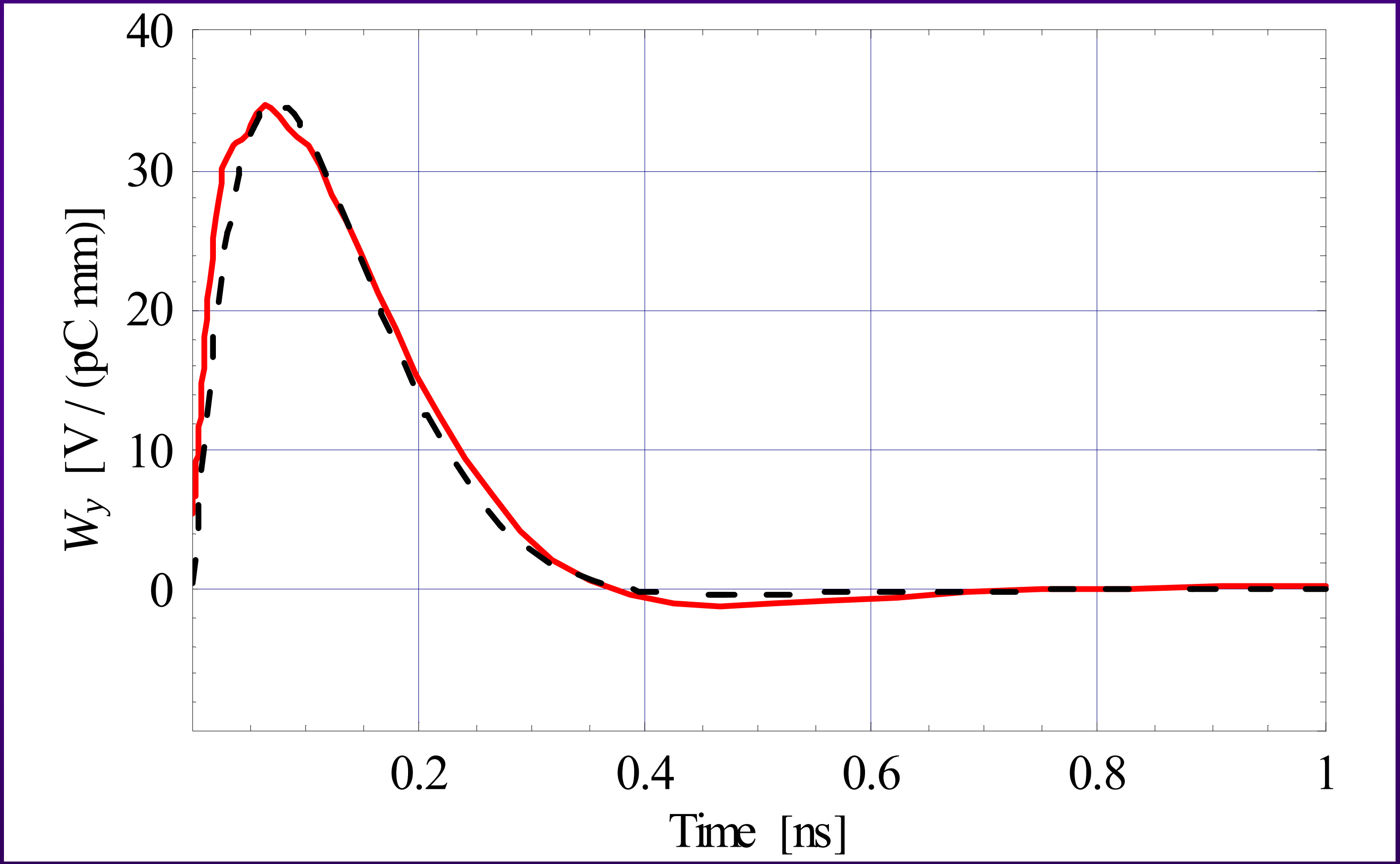
- **HEADTAIL simulations with the wake-field from ZBASE3 (table) for the 2006 case**



$N_b^{th} \approx 1.1 \times 10^{11}$ p/b

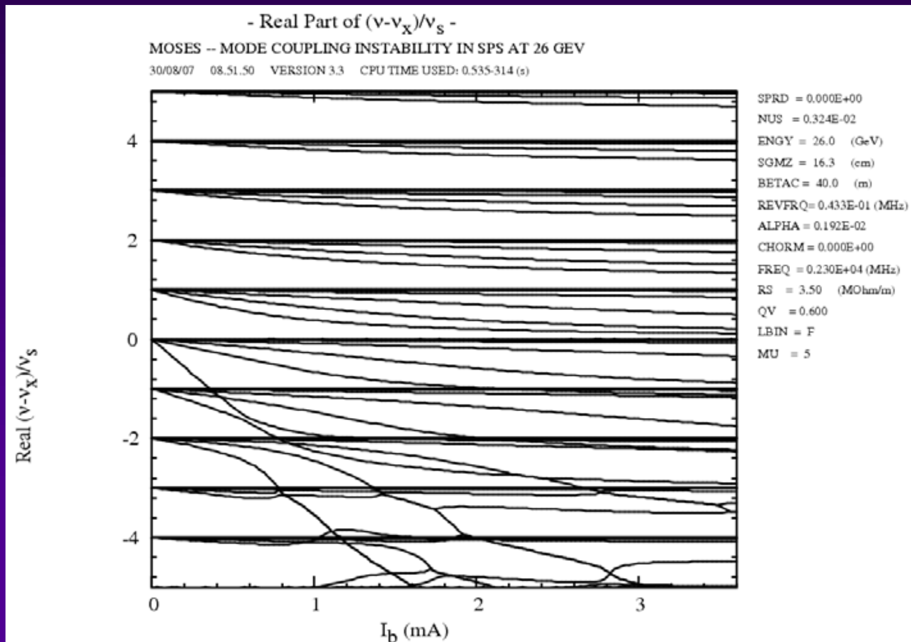
FAST VERTICAL INSTABILITY AT INJECTION (3/4)

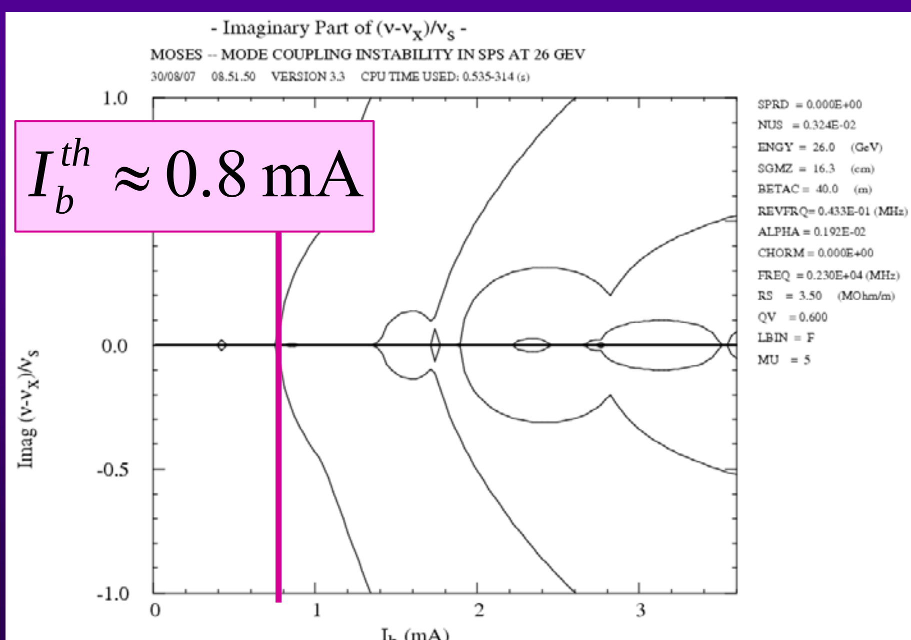
- **Fit of the wake field for the 2006 case**



f_r = 2.3 GHz
Q = 0.6
Z_y = 3.5 MΩ / m

FAST VERTICAL INSTABILITY AT INJECTION (4/4)





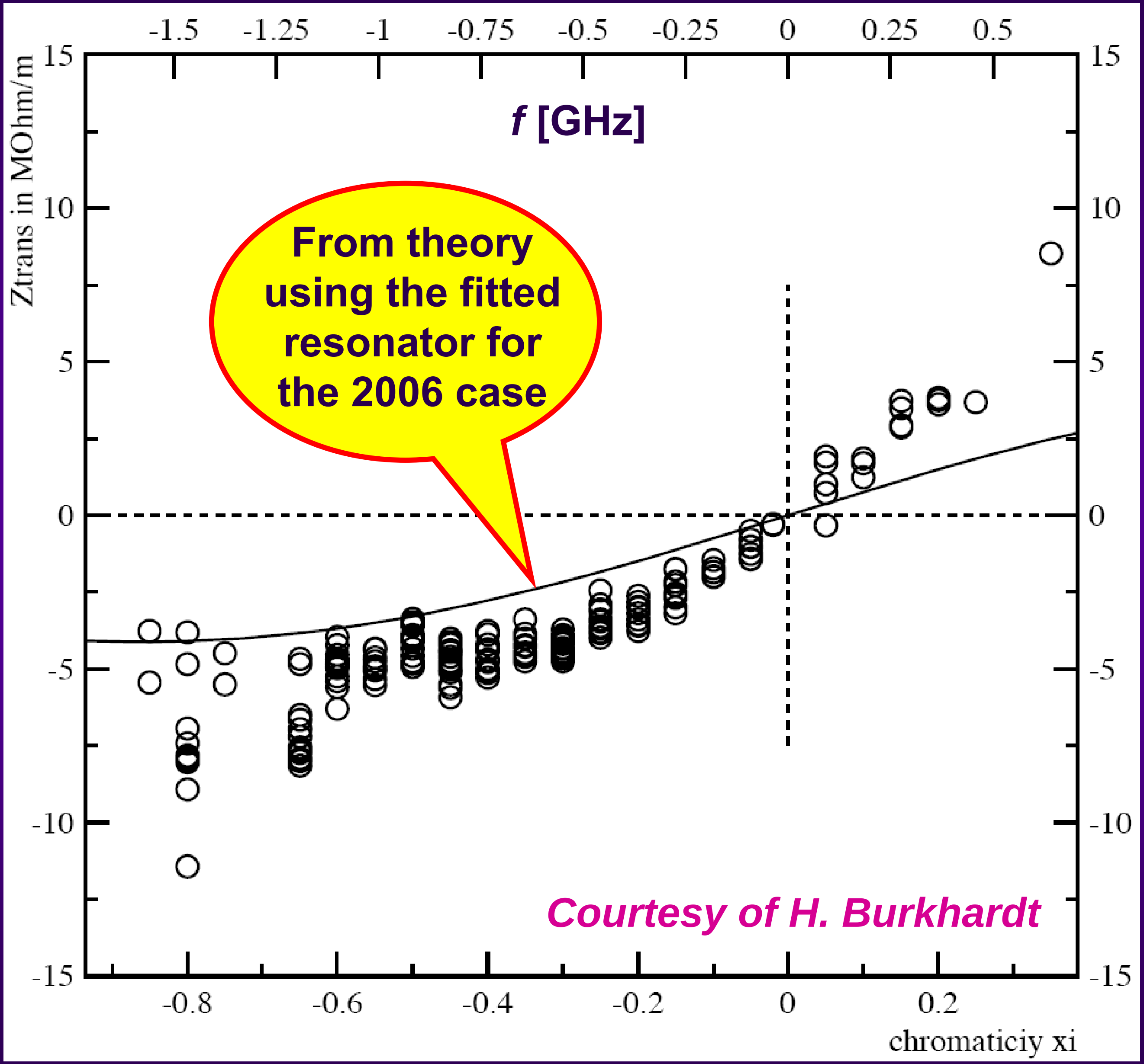
MOSES computations with the fitted resonator

f_r = 2.3 GHz
Q = 0.6
Z_y = 3.5 MΩ / m

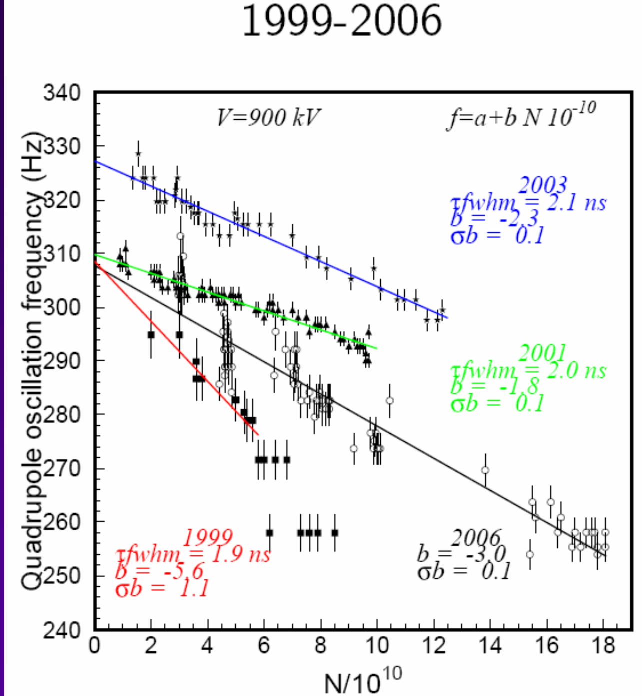
$$I_b^{th} = 0.8\,\mathrm{mA}$$
$$\Leftrightarrow N_b^{th} = 1.15\,10^{11}\ \mathrm{p}$$

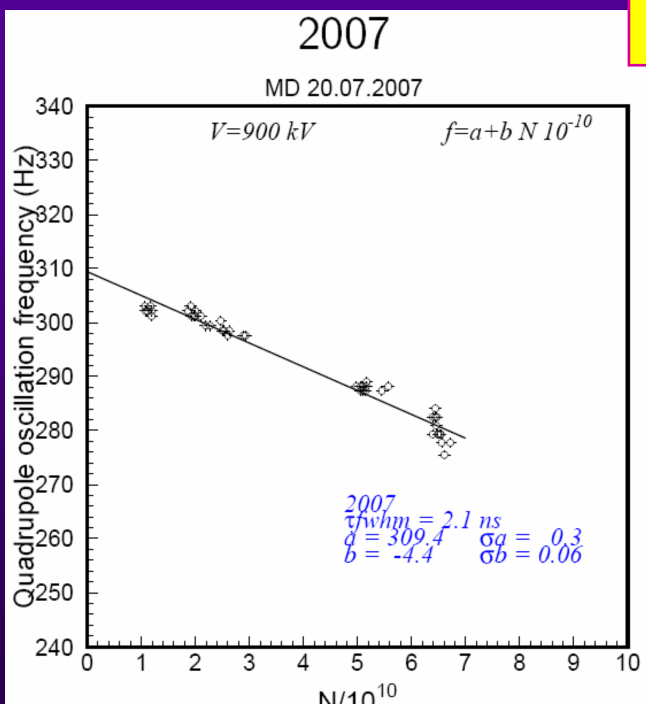
$\Longrightarrow$ Consistent with HEADTAIL

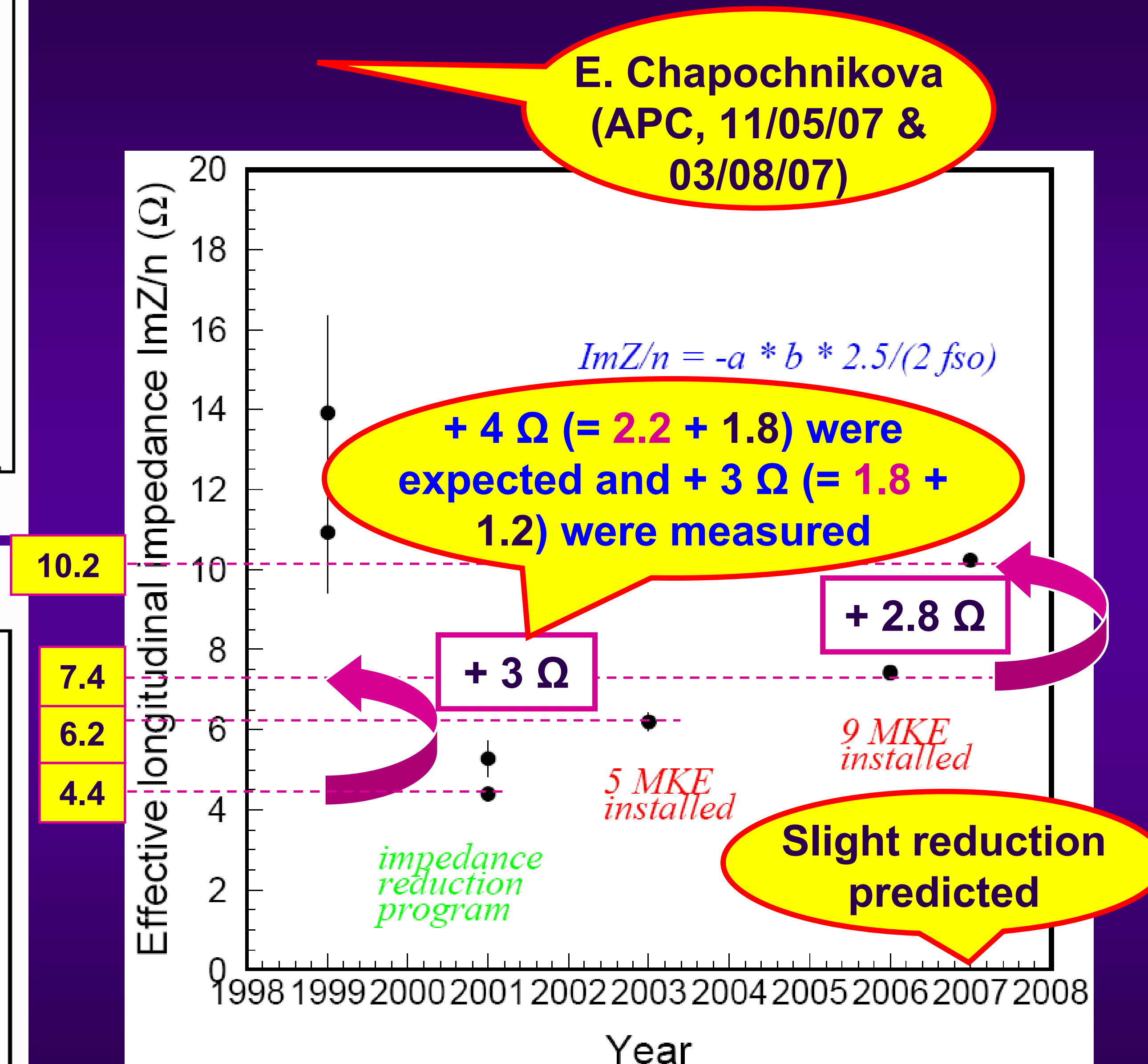
Re[$Z_{y,eff}$] FROM HEAD-TAIL GROWTH/DECAY RATES MEAS.



SPS LONGITUDINAL IMPEDANCE $Im[Z_l/n_{eff}]$ (1/2)







SPS LONGITUDINAL IMPEDANCE Im[Z_l/n_{eff}] (2/2)

- **Summary and comparison between measurements and theoretical predictions (kickers contribution only)**

Im(Z_l/n_{eff}) [Ω]	Meas	delta	Theory (kickers)	delta	Error delta [%]
2001	4.4		1.2		
2003	6.2	1.8	3.4	2.2	-18
2006	7.4	1.2	5.2	1.8	-33
2007	10.2	2.8	4.4	-0.8	-450

- **Im[Z_l/n_{eff}] of the shielded kicker = 0.1 Ω**
- **Im[Z_l/n_{eff}] of the same kicker before the shielding = 0.4 Ω**
- **Im[Z_l/n_{eff}] from the space charge impedance (computed here) ≈ - 1 *j* Ω***

* The contribution from space charge was already subtracted in the above given numbers

POWER LOSS

$N_b = 1.2\,10^{11}$ p $\qquad M = 4 \times 72$ bunches $\qquad \sigma_b = 0.7$ ns

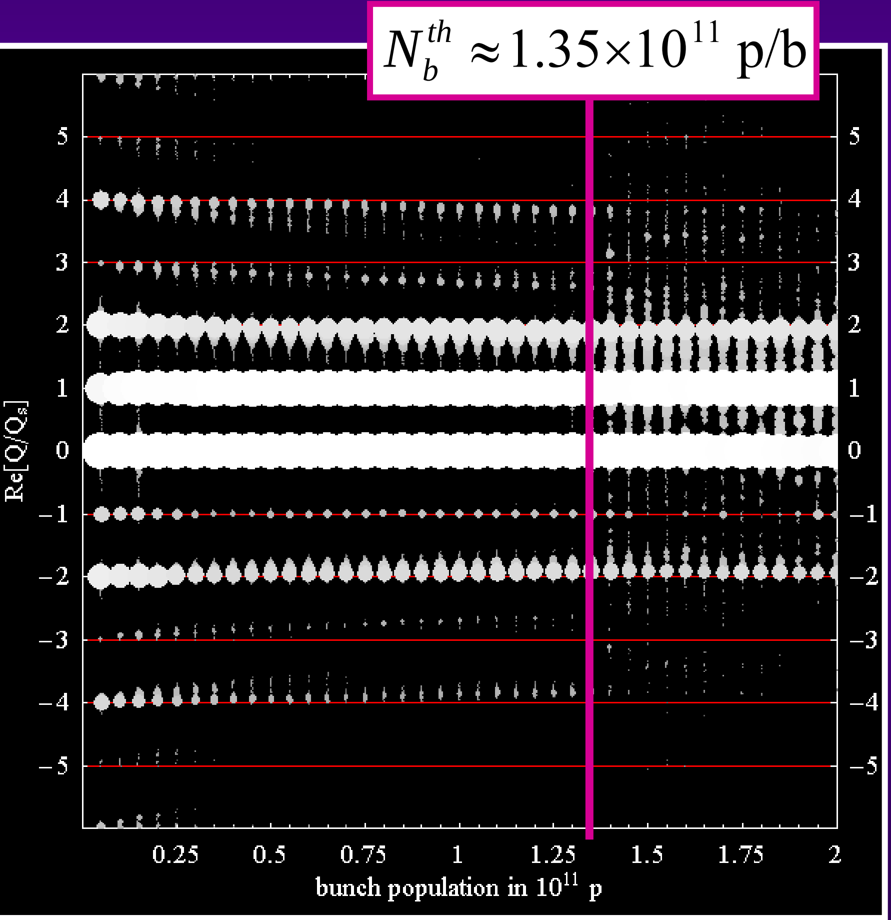
Power loss [W]	Theory	delta
2001	2085	
2003	8027	5942
2006	12742	4715
2007	10792	-1950

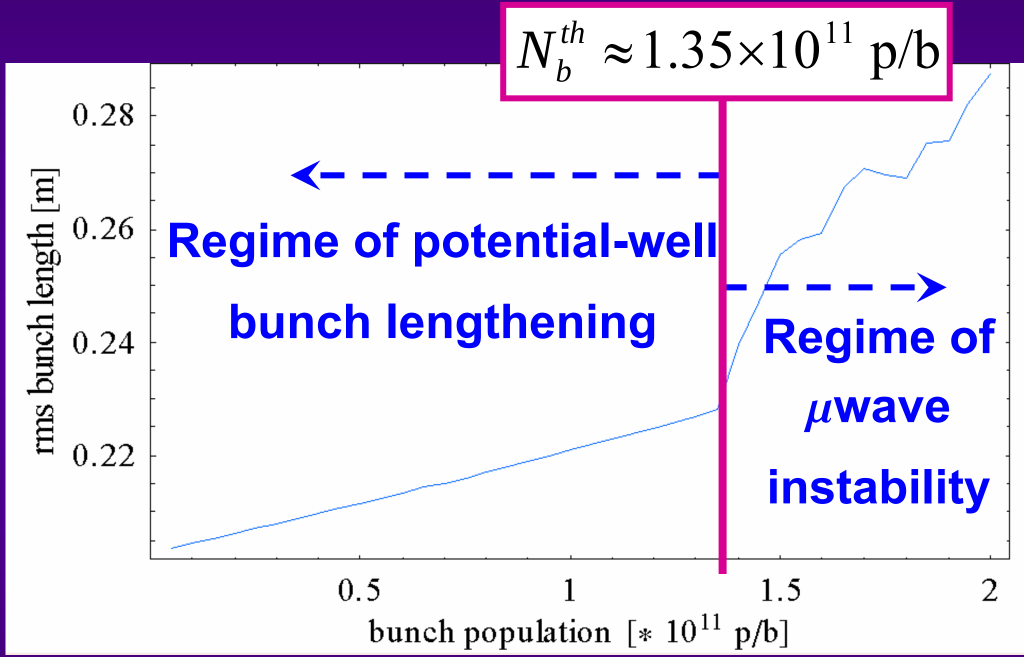
- **Power loss for the shielded kicker = 407 W**
- **Power loss for the same kicker before the shielding = 1227 W**

$\Longrightarrow$ **It seems that indeed a reduction by a factor of ~3-4 was observed (L. Ducimetiere, private communication)**

HEADTAIL SIMULATION IN THE LONGITUDINAL PLANE (1/3)

f_r = 1 GHz
Q = 1
$(Z_l / p)_{f=0} = j \times 10\ \Omega$

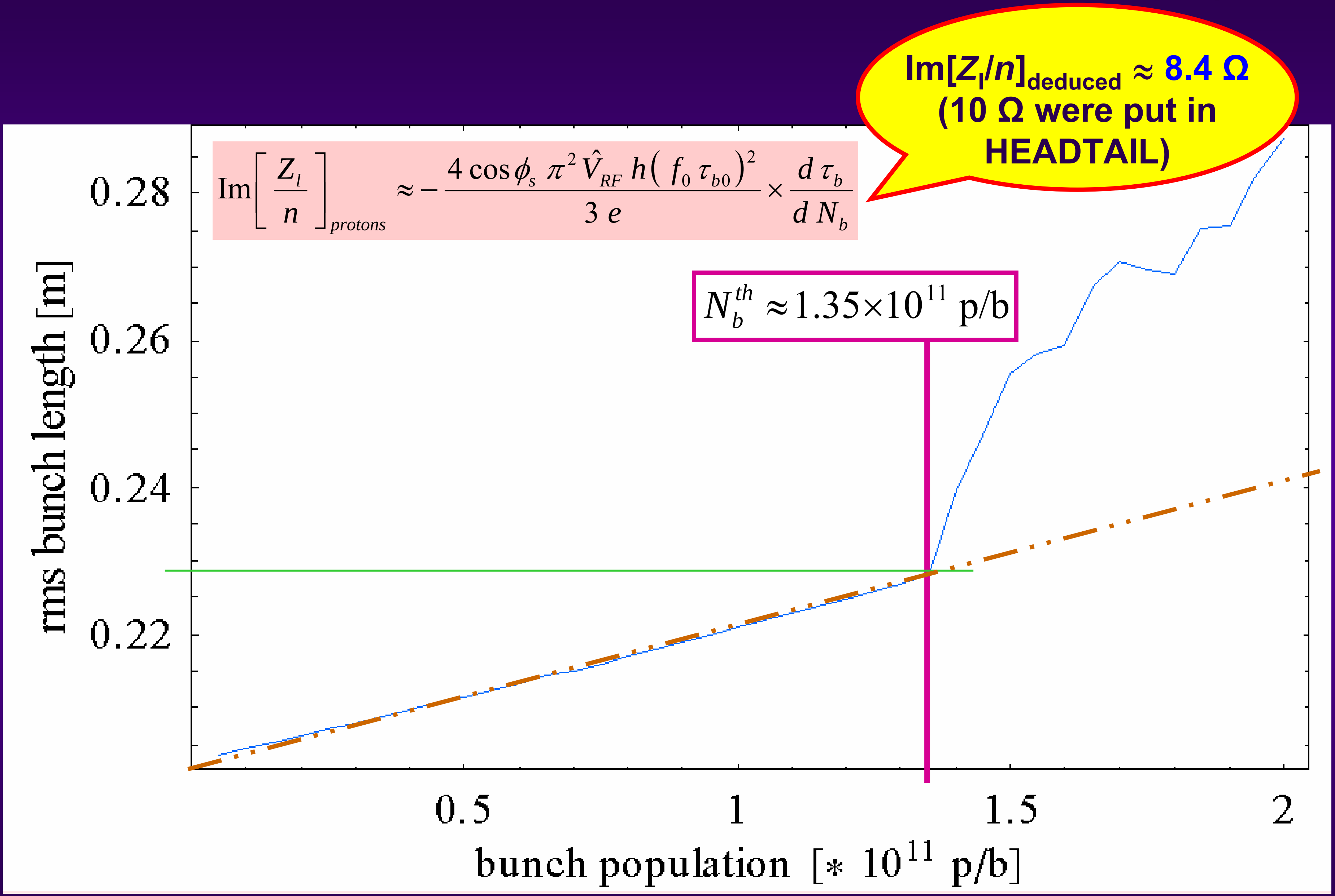




Next steps:

- **Improve impedance model**
- **Measure mode coupling?**

HEADTAIL SIMULATION IN THE LONGITUDINAL PLANE (2/3)



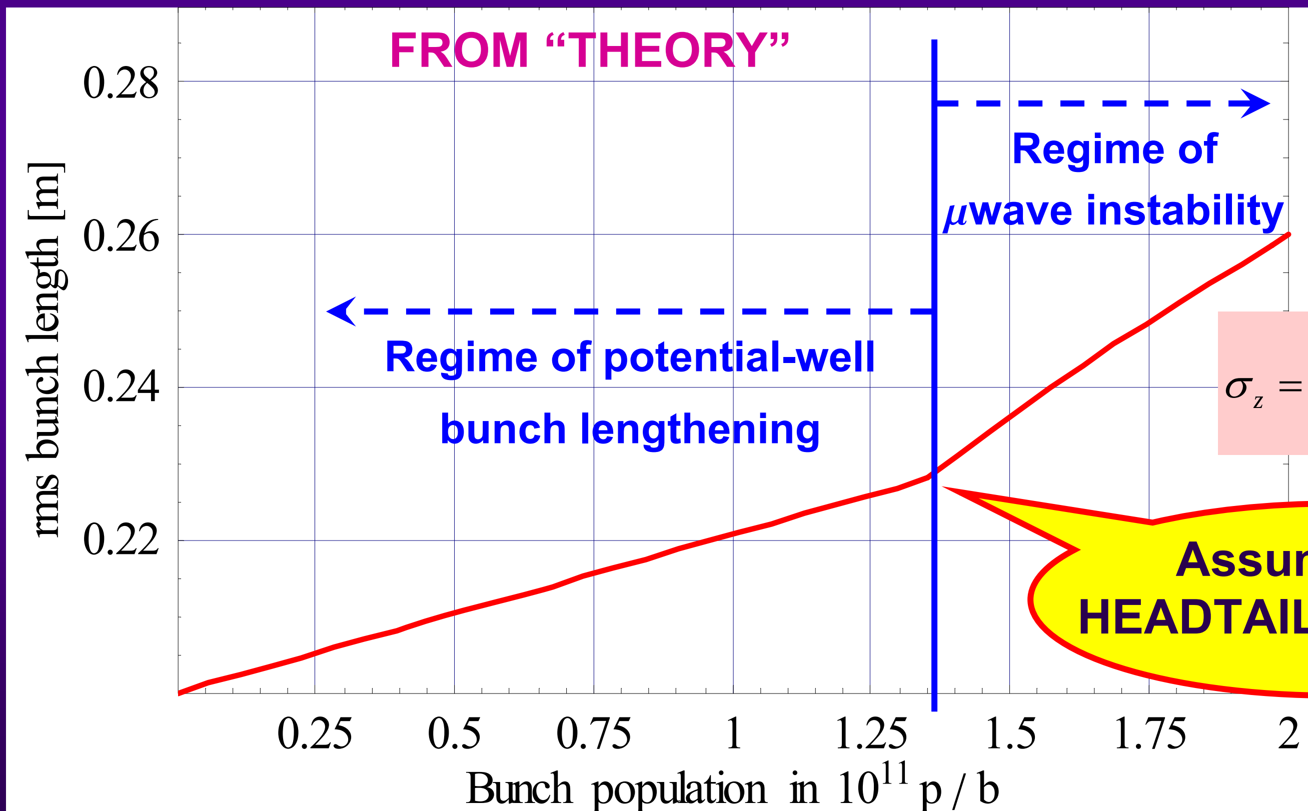
HEADTAIL SIMULATION IN THE LONGITUDINAL PLANE (3/3)

$$\frac{\left|Z_l^{BB}/p\right|}{1.2}\times\left[1-Sgn(\eta)\times\frac{3}{4}\left(\frac{\left|Z_l^{SC}/p\right|}{\left|Z_l^{BB}/p\right|}-1\right)\right]^{1/4}$$

$$\leq\frac{(E/e)\,\beta^2\,|\eta|}{I_{p0}}\times\left(\frac{\Delta p}{p_0}\right)^2_{\mathrm{FWHH},0}$$

Exactly the same as KSB in our case

$$\Longrightarrow \quad \left(N_b^{th}\right)_{theory}\approx 0.7\times 10^{11}\ \mathrm{p/b}$$



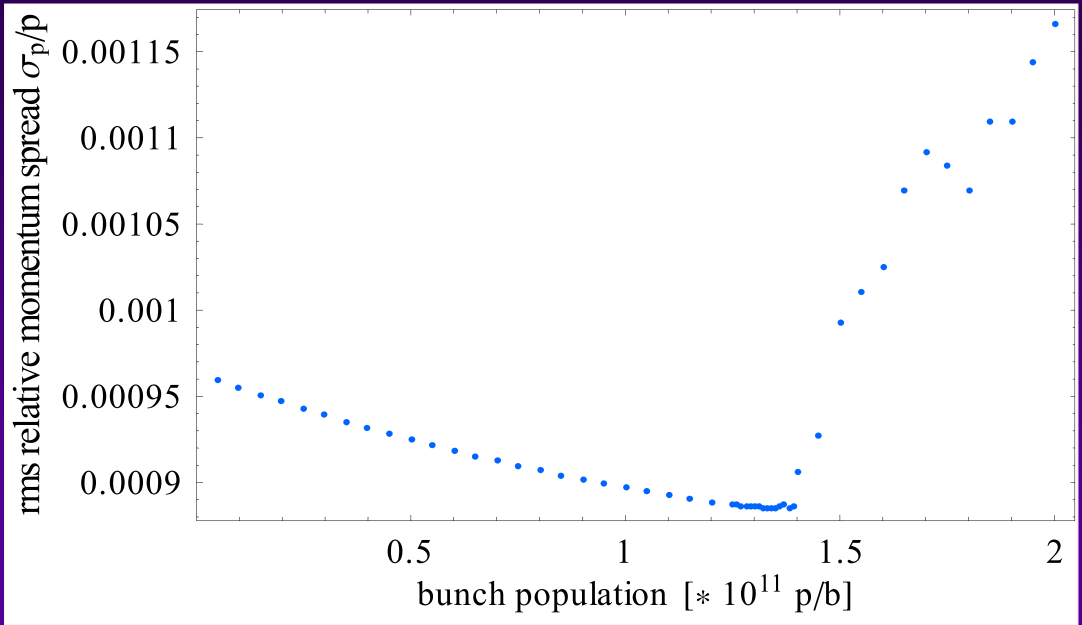
$$\sigma_z=\sigma_z^{th}\times\left(\frac{N_b}{N_b^{th}}\right)^{1/3}$$

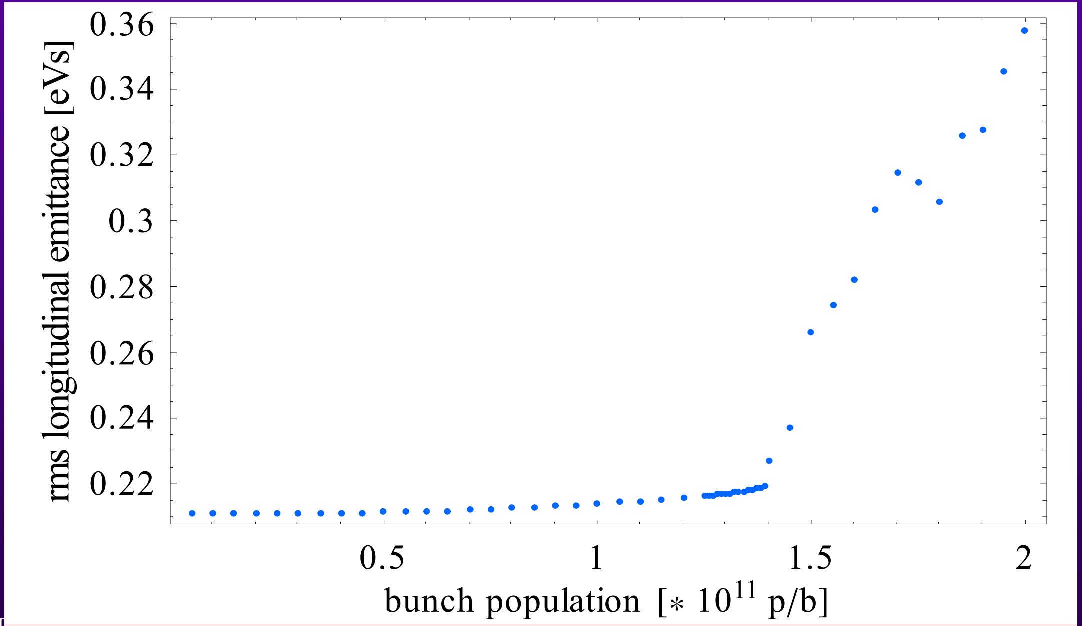
Assuming the HEADTAIL's threshold

CONCLUSION

- Transverse analytical estimates and measurements of the low frequency inductive effective impedance are in good agreement over the last years (relative values)
- Transverse analytical estimates and measurements of the head-tail growth/decay rates are also in good agreement over the last years (relative values)
- All the kickers can only explain ~ 50% of the longitudinal and transverse impedances $\Longrightarrow$ Continue the investigation (in addition to the kickers, we looked at the 108 BPMH, 108 BPMV, ~ 1000 pumping ports, the 4 TW 200 MHz cavities, TIDVG: See Appendices)
- 1 major issue in our understanding: Why the longitudinal effective impedance measured in 2007 is ~ 40% higher than in 2006, whereas a reduction was foreseen???

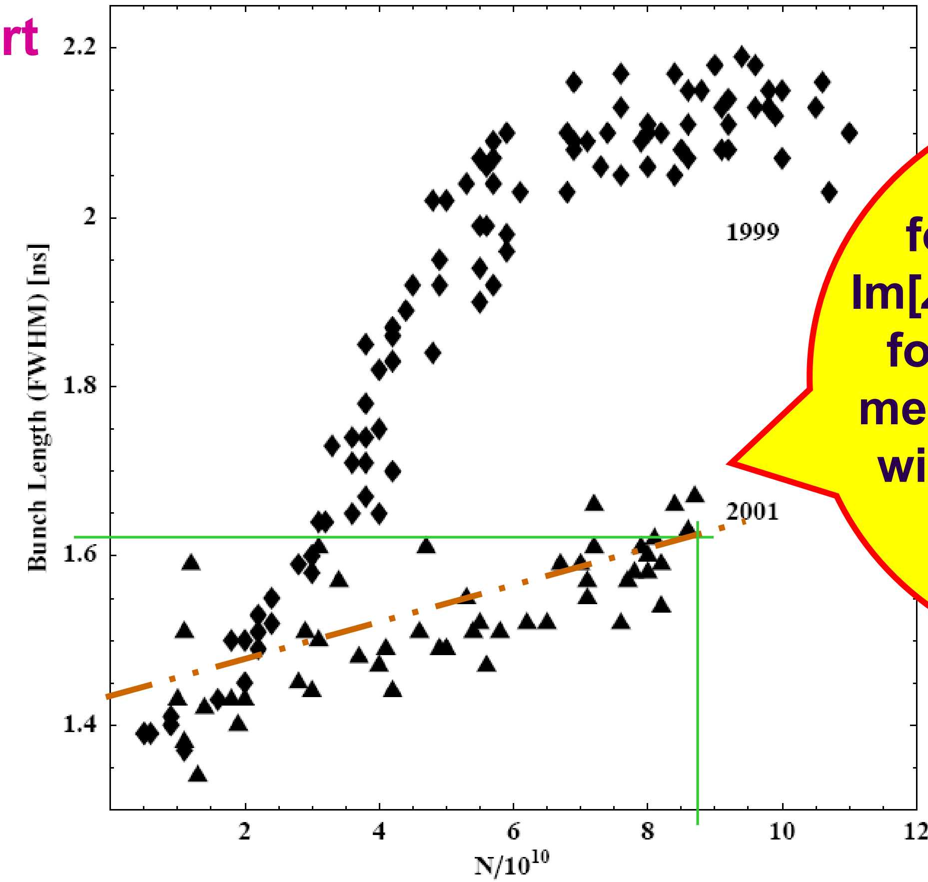
HEADTAIL SIMULATION IN THE LONGITUDINAL PLANE





LONGITUDINAL POTENTIAL-WELL BUNCH LENGTHENING AND MICROWAVE INSTABILITY (1/2)

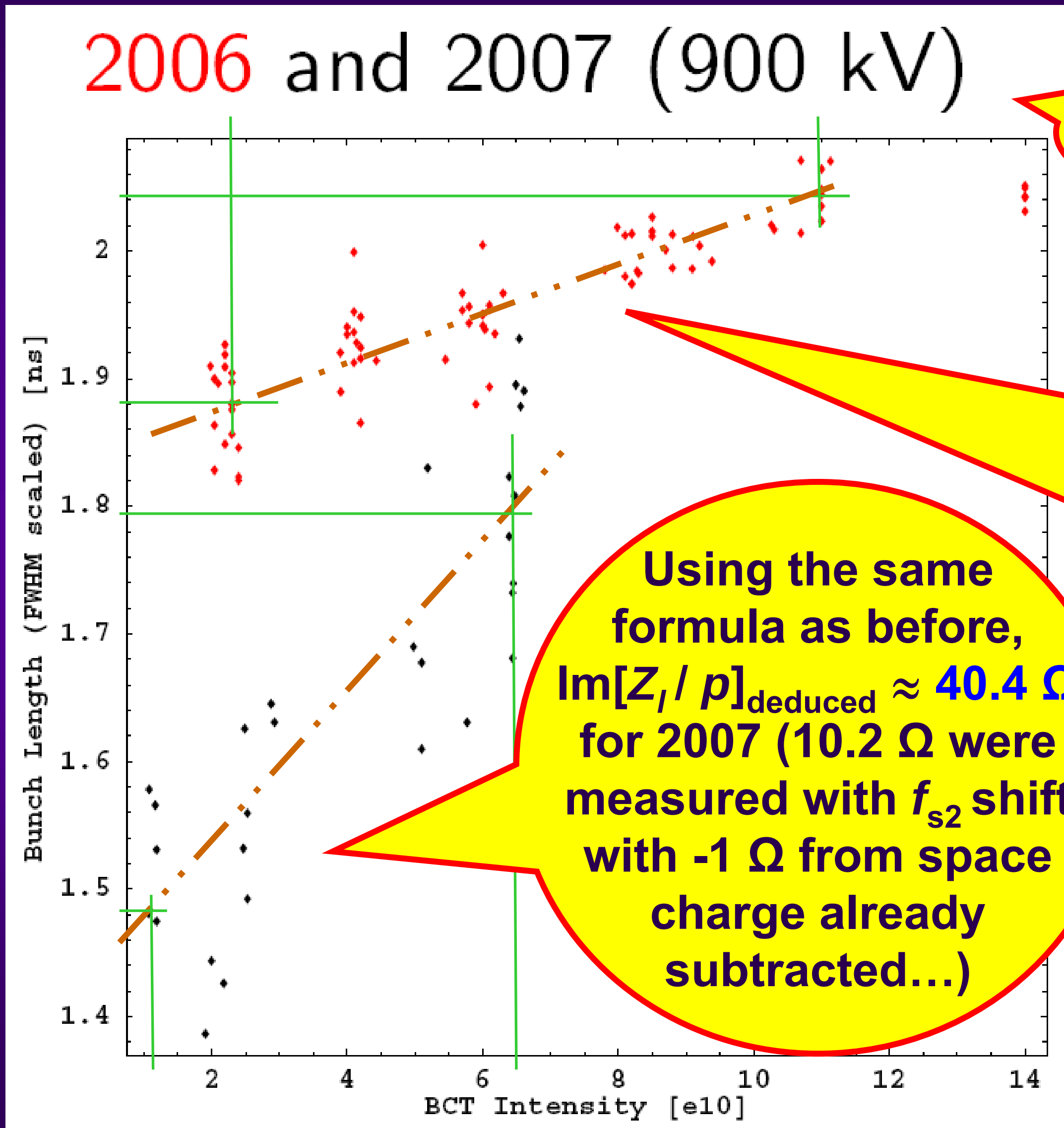
LHC Design Report



Using the same formula as before, $\mathrm{Im}[Z_l / p]_{deduced} \approx$ 13.4 Ω for 2001 (4.4 Ω were measured with f_{s2} shift with -1 Ω from space charge already subtracted…)

Figure 17.13: The bunch length measured 600 ms after injection as a function of bunch intensity in 1999 and 2001. Data taken at 26 GeV, ε=0.15 eVs, V=900 kV.

LONGITUDINAL POTENTIAL-WELL BUNCH LENGTHENING AND MICROWAVE INSTABILITY (2/2)



E. Shapochnikova (APC, 03/08/07)

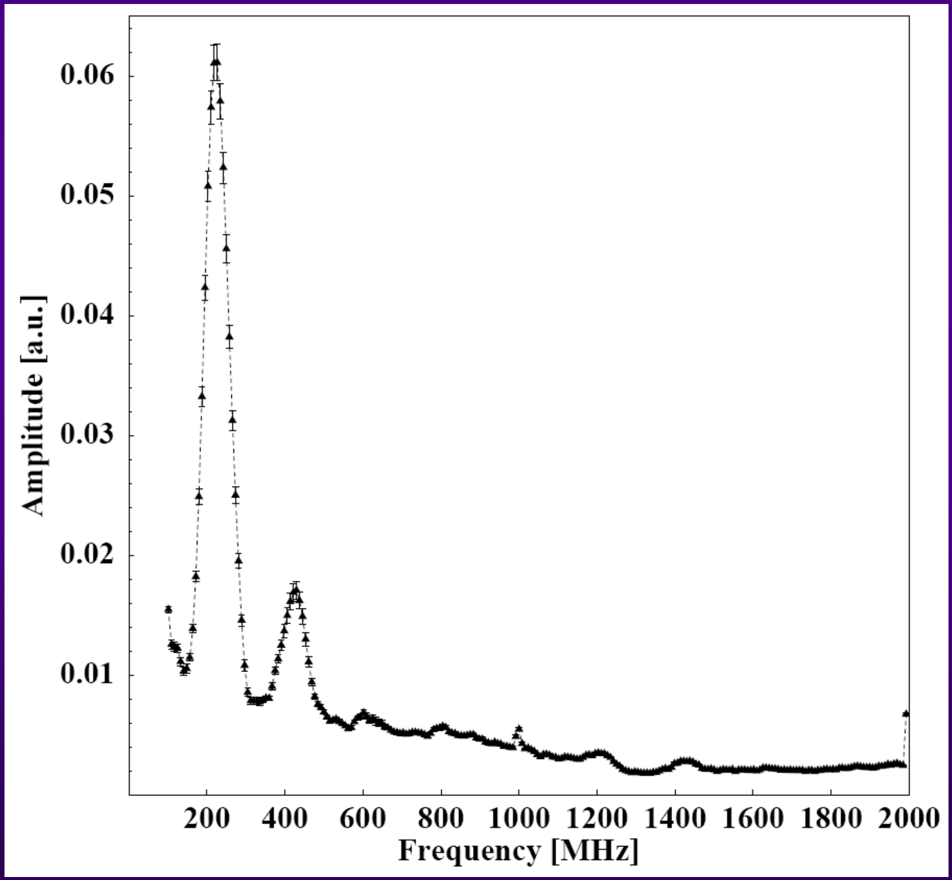
Using the same formula as before, $\mathrm{Im}[Z_l / p]_{deduced} \approx$ 23.1 Ω for 2006 (7.4 Ω were measured with f_{s2} shift with -1 Ω from space charge already subtracted…)

Using the same formula as before, $\mathrm{Im}[Z_l / p]_{deduced} \approx$ 40.4 Ω for 2007 (10.2 Ω were measured with f_{s2} shift with -1 Ω from space charge already subtracted…)

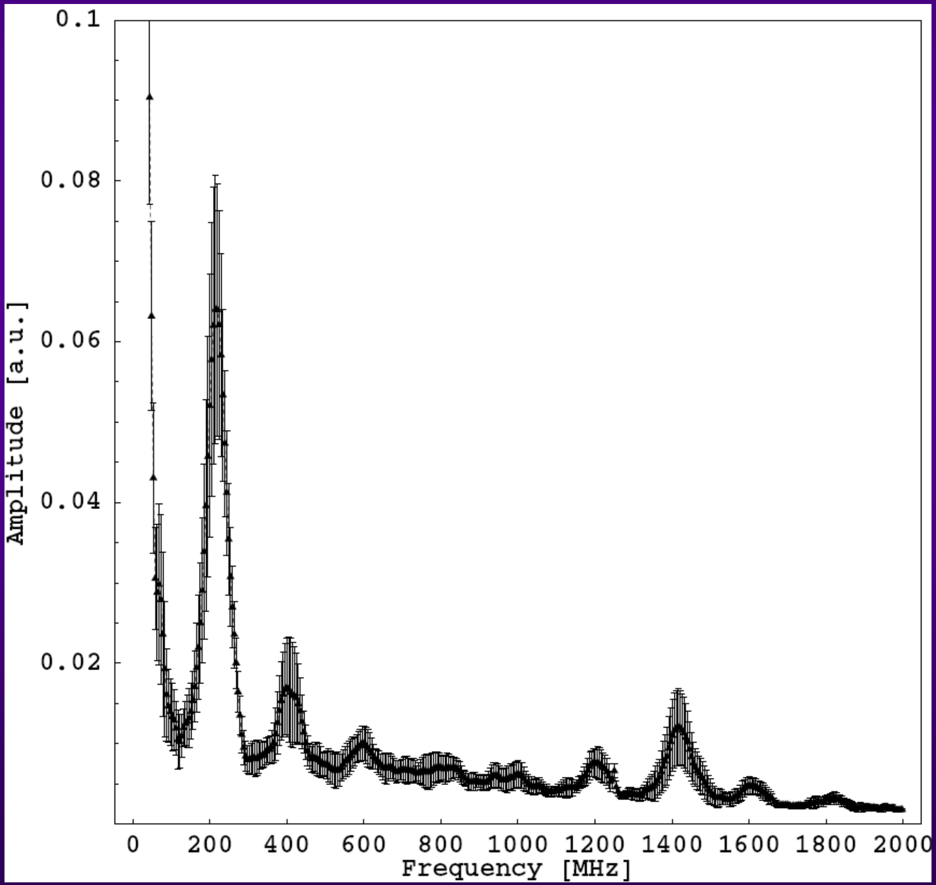
MICROWAVE INSTABILITY WITH DEBUNCHED BEAM

- **Unstable bunch spectra up to 2 GHz with RF OFF ("similar" beam parameters)**

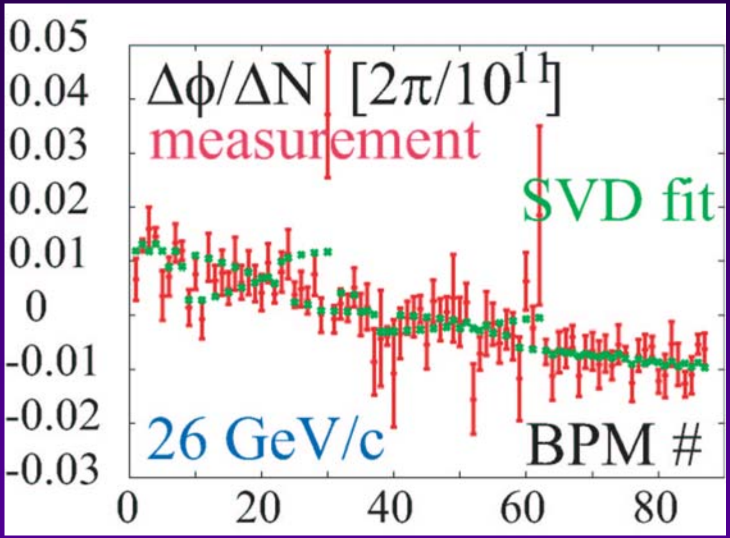
2001

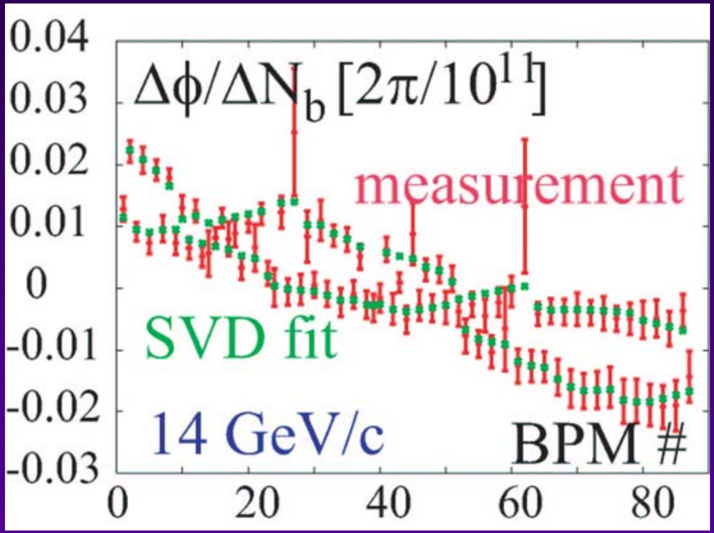


2007



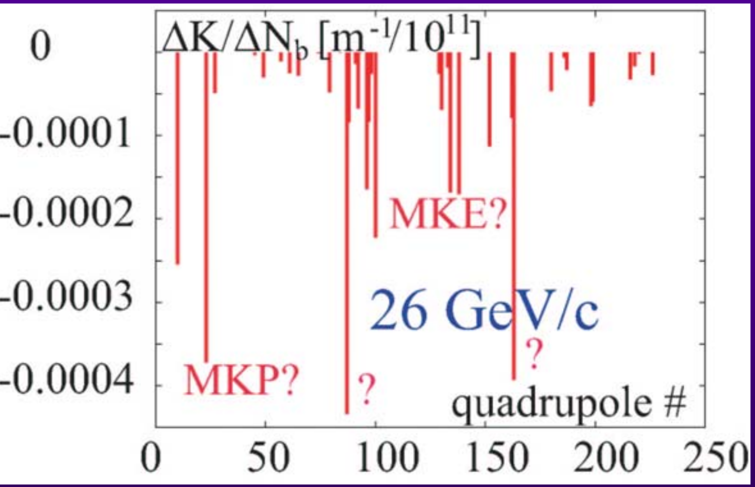
LOCALIZED SPS IMPEDANCE FROM PHASE BEATING VS. INTENSITY

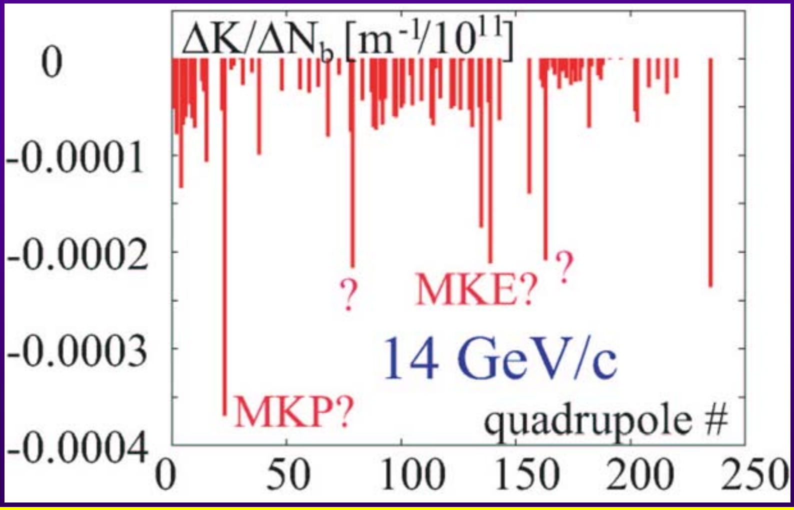




14-GeV/c data much cleaner than 26-GeV/c data (unfortunately not available in 2004)

IMPEDANCE INFERRED FROM ITERATIVE SVD FIT





Impedance concentrated in a few locations – MKP & MKE kickers, ~ RF, and one other

G. Arduini, C. Carli, F. Zimmermann, EPAC 2004 ⟹ Follow-up this year by R. Calaga

BEAM POSITION MONITORS

MAFIA simulations by B. Spataro

- **108 BPMH and 108 BPMV**
  - **Broad-band impedance (for ALL BPMs)**

$\mathrm{Im}[Z_l/n]$ (Ω)	0.02
$\mathrm{Im}[Z_y]$ (MΩ/m)	0.07

  - **Trapped modes (for ALL BPMs) $\Longrightarrow$ 4 most critical**

β_x [m]	β_y [m]	f_r [GHz]	R_y [MΩ/m]	Q
103	21	0.537	500	1951
103	21	1.836	254	3367
22	101	0.786	180	2366
22	101	2.270	222	5880

$\Longrightarrow$ HEADTAIL simulations revealed an instability threshold ~ 1 order of magnitude higher than measured

VACUUM PUMPING PORTS (1/2)

MAFIA simulations by B. Spataro

$\Longrightarrow$ **For all the transitions**

Im[Z_l/n] (Ω)	0.02
Im[Z_y] (MΩ/m)	0.20

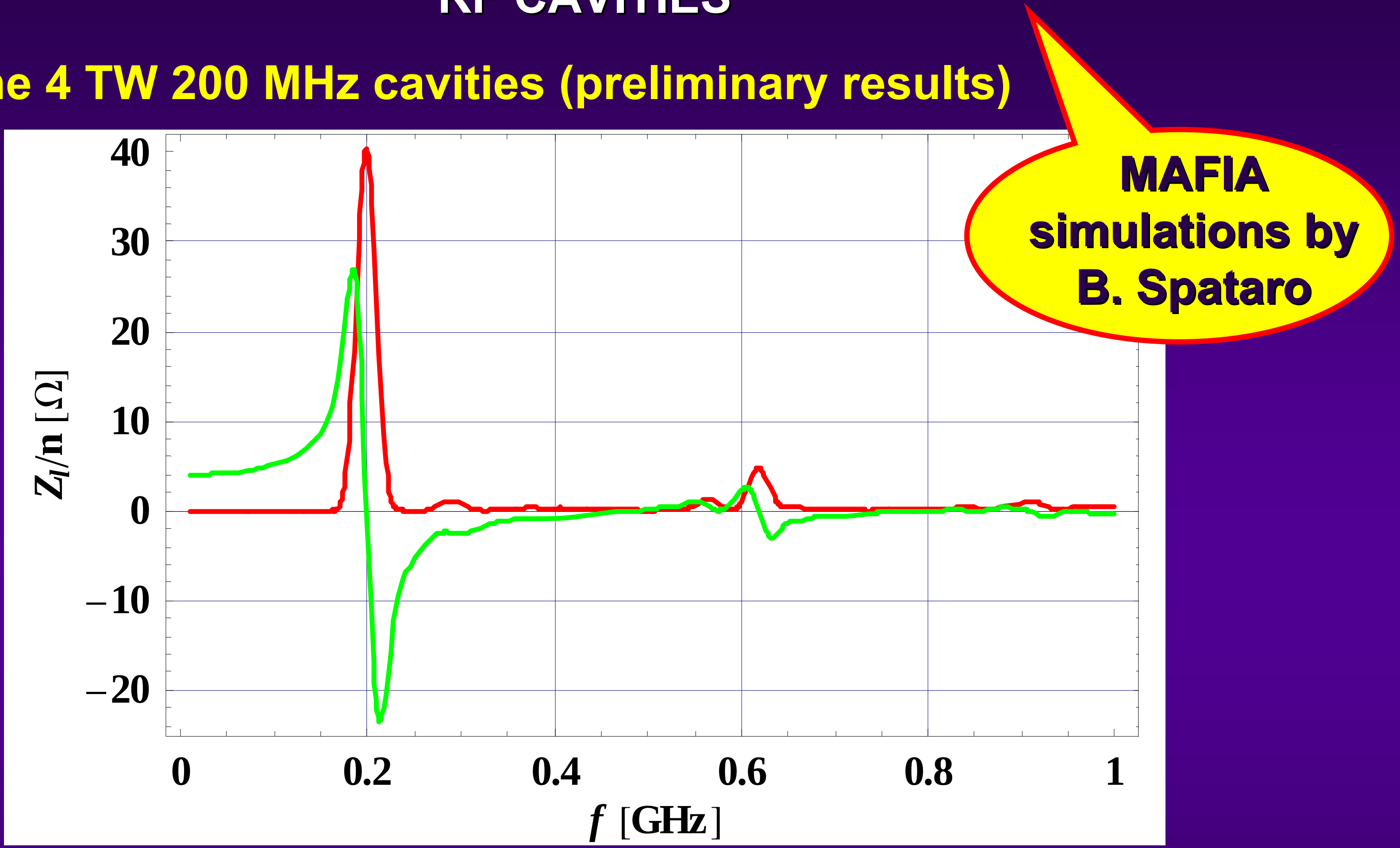
VACUUM PUMPING PORTS (2/2)

- **Tank gap and intermodule screening ⟹ To be treated…**

Magnet	Location	H aperture	V aperture	Tank gap screening	Intermodule screening
MKP-S I, 5 module	LSS1 MKP-S 11931	100	61	yes	yes
MKP-S II, 5 module	LSS1 MKP-S 11936	100	61	yes	yes
MKP-S III, 2 module	LSS1 MKP-S 11952	100	61	yes	yes
MKP-L IV, 4 module	LSS1 MKP-L 11955	140	54	no	no
spare MKP-S I, 5 module	storage	100	61	yes	yes
spare MKP-S III, 2 module	storage	100	61	yes	yes
spare MKP-L IV, 4 module	(under reconstruction)	140	54	under project	under project
MKQH	LSS1 MKQH 11653	135 *	33.9	No	not applicable
MKQV	LSS1 MKQV 11679	102	56	No	not applicable
MKDH-1	LSS1 MKDH-1 11751	56	97.1	No	not applicable
MKDH-2	LSS1 MKDH-2 11754	56	97.1	No	not applicable
MKDH-3	LSS1 MKDH-3 11756	60	106.1	No	not applicable
MKDV-1	LSS1 MKDV-1 11731	75	56	No	not applicable
MKDV-2	LSS1 MKDV-2 11735	83	56	No	not applicable
spare MKDV-2	AB-BT lab	83	56	No	not applicable
MKE-L2	LSS4 MKE-L 41631	147.7	35	yes	not applicable
MKE-L5	LSS4 MKE-L 41634	147.7	35	yes	not applicable
MKE-S4	LSS4 MKE-S 41637	135	32	yes	not applicable
MKE-S7	LSS4 MKE-S 41651	135	32	yes	not applicable
MKE-L1	LSS4 MKE-L 41654	147.7	35	yes	not applicable
MKE-L10	LSS6 MKE-L 61631	147.7	35	yes	not applicable
MKE-L9	LSS6 MKE-L 61634	147.7	35	yes	not applicable
MKE-S6	LSS6 MKE-S 61637	135	32	yes	not applicable
spare MKE-L8	storage	147.7	35	yes	not applicable
spare MKE-S3	storage	135	32	yes	not applicable

RF CAVITIES

- **For the 4 TW 200 MHz cavities (preliminary results)**



$\Longrightarrow$ $\mathrm{Im}[Z_l/n_{eff}] = 2.7\ \Omega$

TIDVG ⟹ High energy beam dump absorber

- **With or without the Titanium foil the $\mathrm{Im}[Z_l/n_{eff}] << 1\ \Omega$ (preliminary results)**