LHC IMPEDANCE STATUS AND STRATEGY

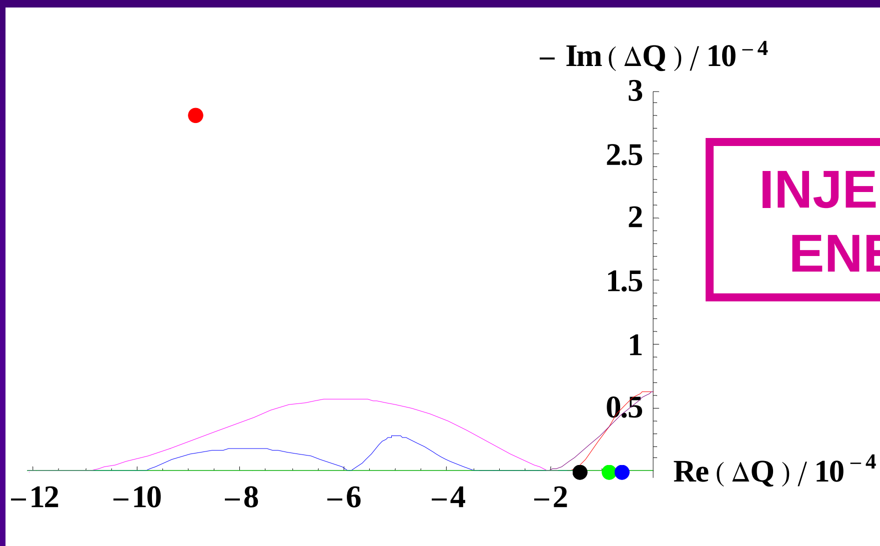
E. Métral with Hubert Medina and Benoit Salvant

- **The LHC impedance is dominated by the collimators**
- **Current work**
  - **Link the Mathematica program rewall to ZBASE $\Longrightarrow$ Hubert Medina**
  - **General program for the resistive-wall impedance (upgrade of rewall) $\Longrightarrow$ Benoit Salvant**
- **LHC collimators Phase II $\Longrightarrow$ Video conference on LHC collimation (07/03/07)**
- **Studies on TCT, TCLI, TCDQ, TCDS and TDI**
- **More details for the injection and dump septum**
- **Next important work**
- **Stability diagram at top energy before the squeeze**
- **Conclusion**

THE LHC IMPEDANCE IS DOMINATED BY THE COLLIMATORS (1/10)

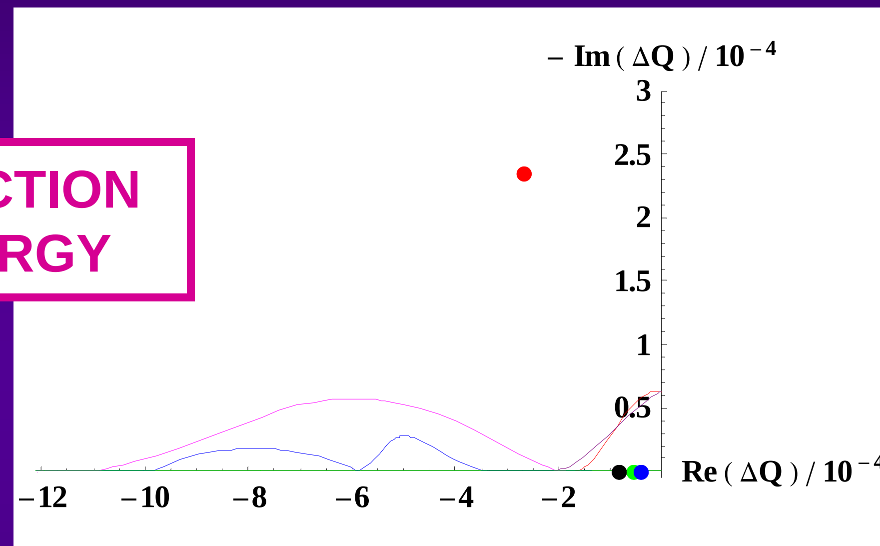
Stability diagrams (Y-plane)

With collimators



INJECTION ENERGY

Without collimators (RW + BB* effects)

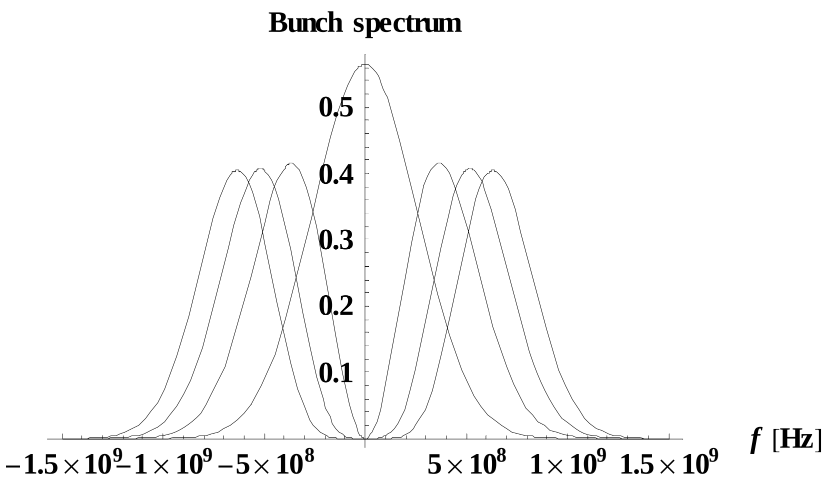


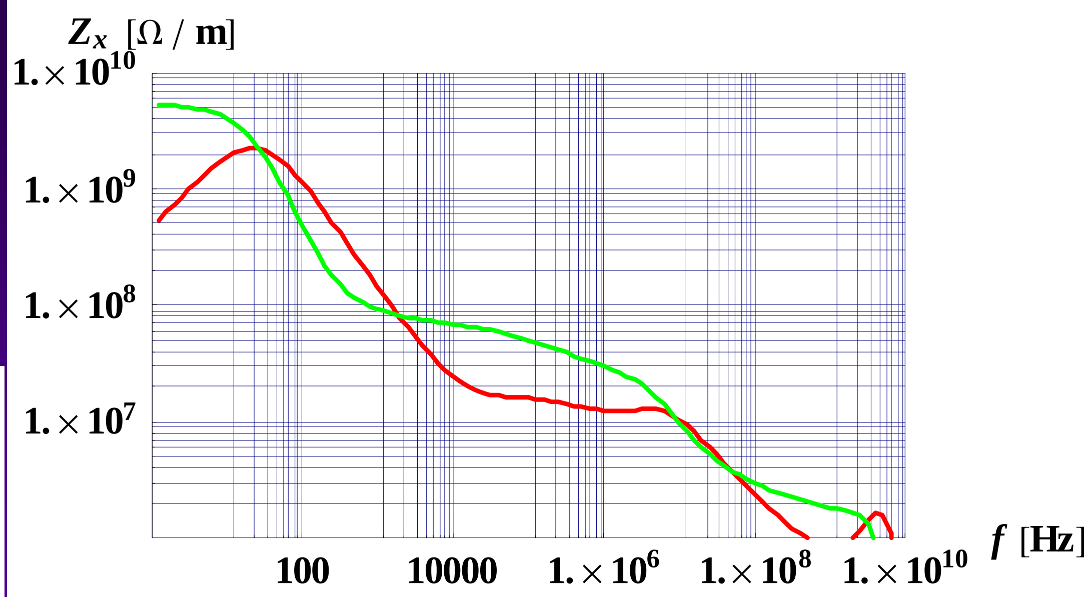
*** BB (transverse) impedance for all the collimators estimated in the LHC Design Report at** $j\,0.15\ \mathrm{M\Omega/m}$ **. The total BB is 1.34 MΩ/m**

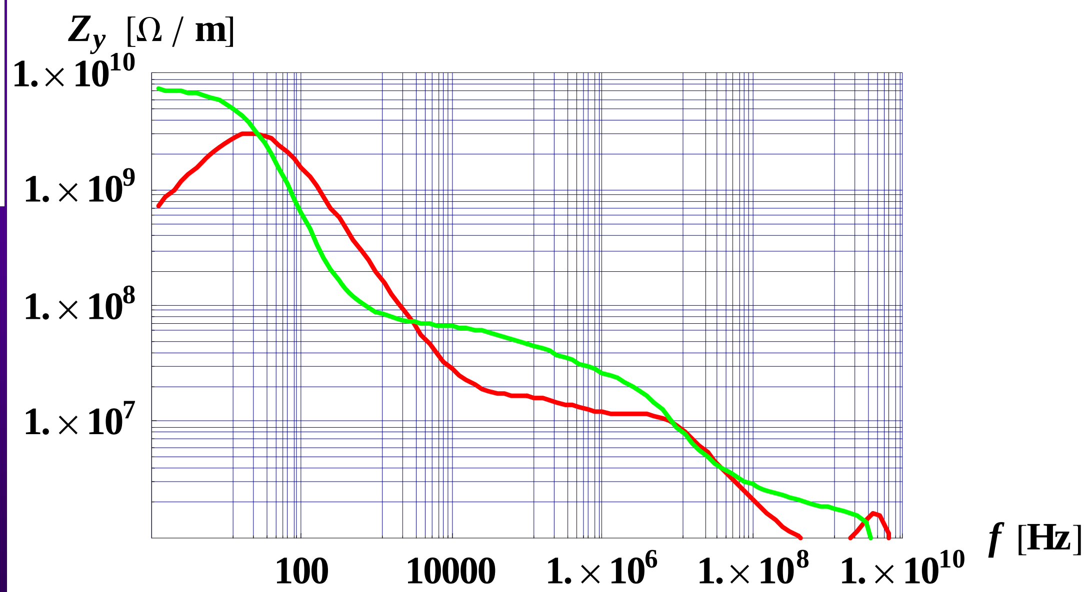
Updated estimates (with betatron functions…) are very close

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

Bunch spectrum and total impedances







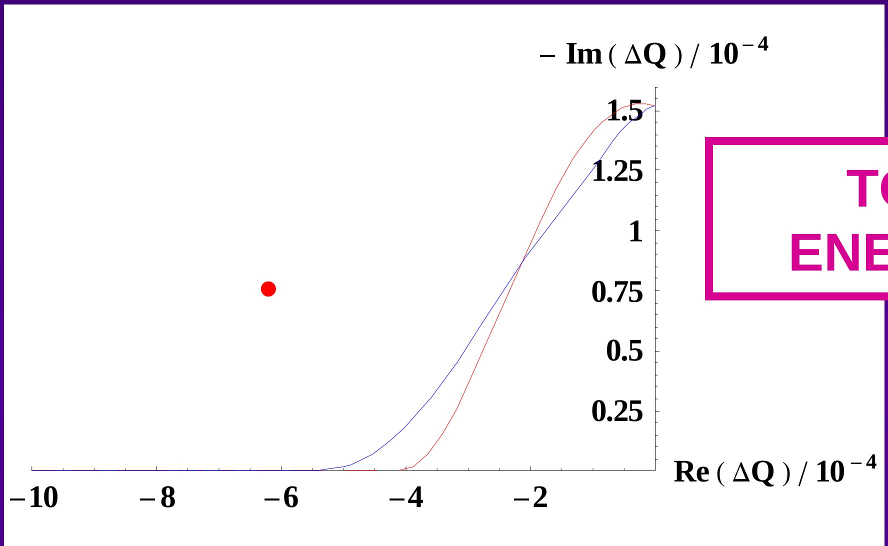
$$Q'_{x,y} = 1 \Rightarrow f_{\xi_{x,y}} \sim 40 \text{ MHz}$$

THE LHC IMPEDANCE IS DOMINATED BY THE COLLIMATORS (3/10)

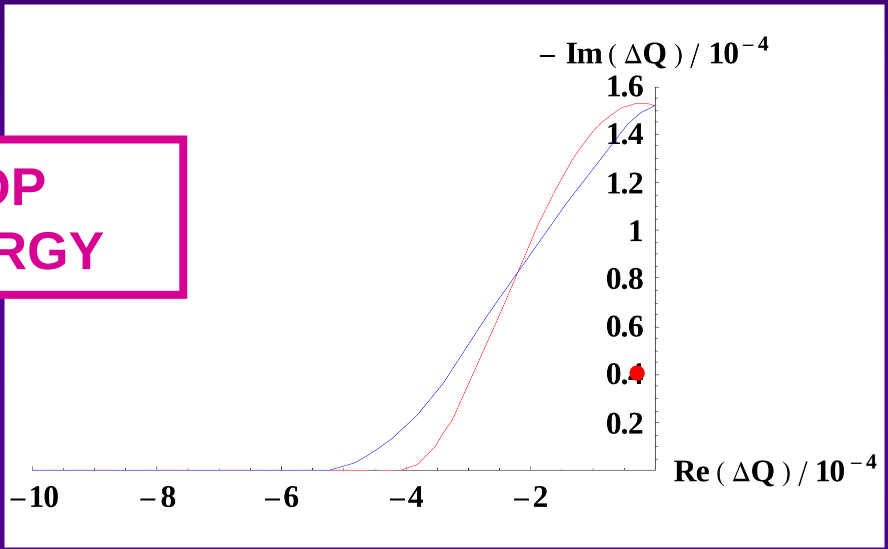
Stability diagrams (Y-plane)

With collimators

Without collimators (RW + BB* effects)



TOP ENERGY

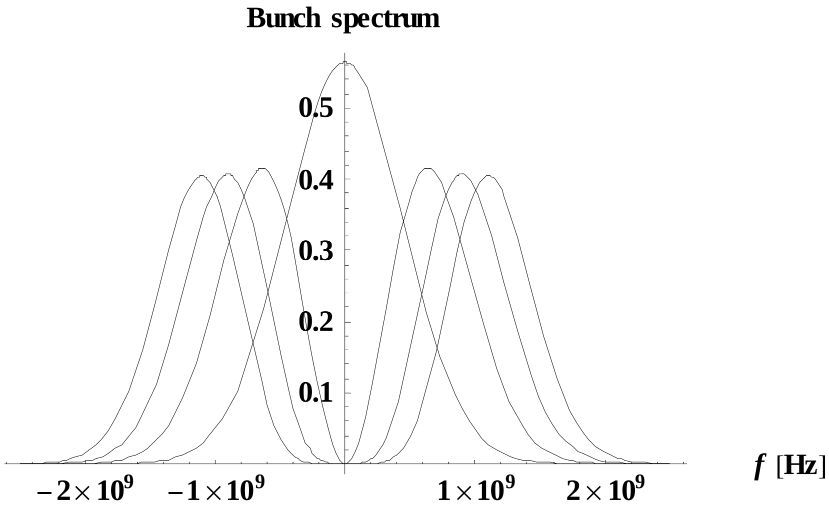


* BB (transverse) impedance for all the collimators estimated in the LHC Design Report at $j\,1.5\ \mathrm{M\Omega/m}$. The total BB is 2.67 MΩ/m

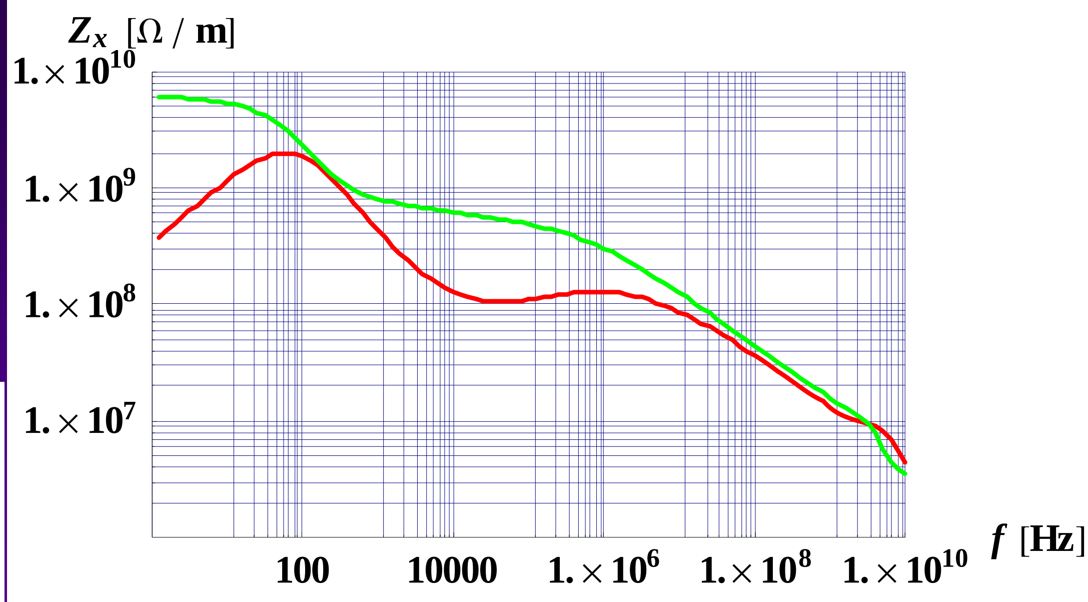
Updated estimates (with betatron functions…) are very close

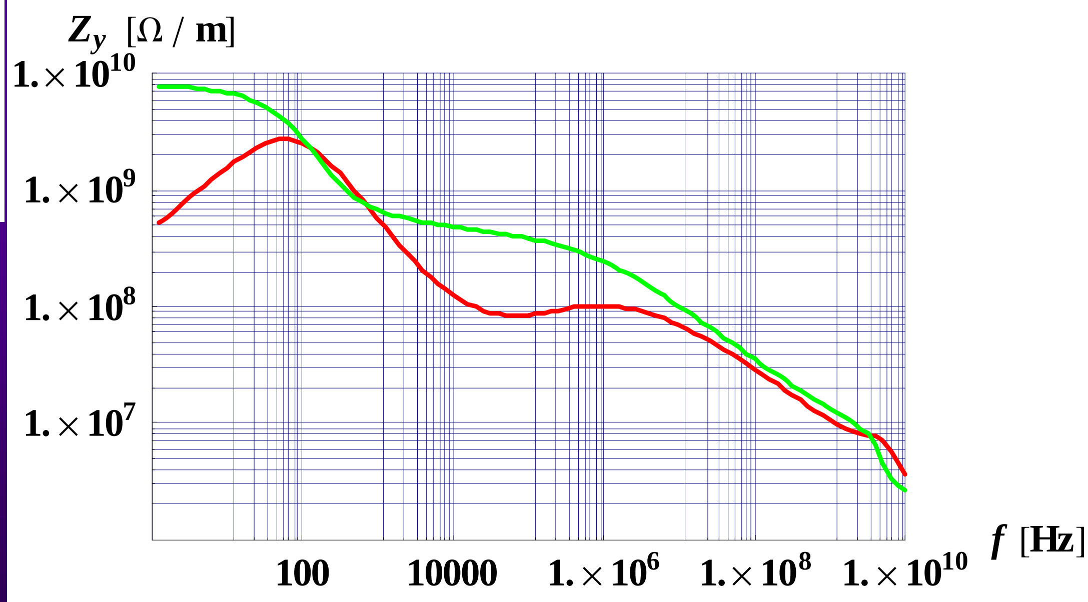
- Reminder: Tune shift for a BB impedance of *j* 1 MΩ/m = - 0.15×10^{-4}

Bunch spectrum and total impedances



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





THE LHC IMPEDANCE IS DOMINATED BY THE COLLIMATORS (5/10)

Table 5.1 Transverse resistive wall (low-frequency) impedance for the LHC without collimators. The first four columns report element name, latest relevant reference, total length in m and inner radius b in mm. The last two columns give the transverse 'effective' impedance $Z_\perp^{\rm eff}$ in MΩ/m for the slow waves at 8 kHz and at 20 MHz multiplied by $\beta/\langle\beta\rangle$, where $\langle\beta\rangle = 70$ m.

element	Ref.	length	b	$Z_\perp^{\rm eff}$ [8 kHz]	$Z_\perp^{\rm eff}$ [20 MHz]
		m	mm	MΩ/m	MΩ/m
Beam screen-H @low-B	[9]	23600	22	-21.4+6.3j	-1+0.3j
Beam screen-V @low B	[9]	23600	18	-29.5+8.6j	-1.5+0.5j
Beam screen-H @high-B	[9]	23600	22	-61+7.2j	-3+0.3j
Beam screen-V @high-B	[9]	23600	18	-84.4+9.9j	-4+0.5j
Interconnects	[19]	340	22	-5.3+0.5j	-
Cold-warm transitions		10	22	-0.6+0.3j	-
Warm pipe (pipe+etc.)		2400	40	-3.5+2.9j	-0.2+0.2j
MQW (2 mm Cu)		155	14.5	-4.3+4.8j	-0.3+0.3j
MQW (2 mm SS)		5		-1.4+1.6j	-0.1+0.1j
MBW (2 mm Cu)		70	22	-0.6+0.6j	-0.05+0.05j
MBW (2 mm SS)		2		-0.21+0.18j	-
TDI-H @injection		2.8		-	-0.8+4.5j
TDI-V @injection		2.8	5	-	-0.5+3j
Injection-Septum-H	[20]	22	22	-0.3	-
Injection-Septum-V	[20]	22		-0.5+0.1j	-
Dump-Septum	[20]	72	25	-1.3+0.2j	-
Injection-Kicker-H	[21]	15	19	-0.4+4j	-
Dump-Kicker-V		22.5	29	-1+5j	0+7.2j

LHC Design Report (CERN-2004-003, Vol. 1, p. 97)

THE LHC IMPEDANCE IS DOMINATED BY THE COLLIMATORS (6/10)

Table 5.2: LHC transverse resistive wall impedance budget in MΩ/m (no collimators).

	horizontal	vertical
TOTAL $Z_\perp^{\mathrm{eff}}$ @injection, 8 kHz slow wave	-40+22j	-49+26j
TOTAL $Z_\perp^{\mathrm{eff}}$ @injection, 20 MHz slow wave	-3+6j	-3+12j
TOTAL $Z_\perp^{\mathrm{eff}}$ @top energy, 8 kHz slow wave	-79+22j	-103+26j
TOTAL $Z_\perp^{\mathrm{eff}}$ @top energy, 20 MHz slow wave	-5+1j	-5+8j

Table 5.3: Vertical 'effective' impedance of the LHC collimators, normalized to $\langle\beta\rangle = 70\,\mathrm{m}$, for un-coated Carbon jaws with resistivity $\rho = 14 \times 10^{-6}\,\Omega\mathrm{m}$. The effect of the inductive bypass, of the Yokoya coefficients, and the contribution at higher harmonics of the 40 MHz bunch frequency for the slow waves at 8 kHz and at 20 MHz have been properly taken into account.

	$Z_\perp^{\mathrm{eff}}$ [8 kHz]	$Z_\perp^{\mathrm{eff}}$ [20 MHz]
	MΩ/m	MΩ/m
injection optics	-7.6+74j	33j
squeezed optics	-42+1800j	-7.2+1160j

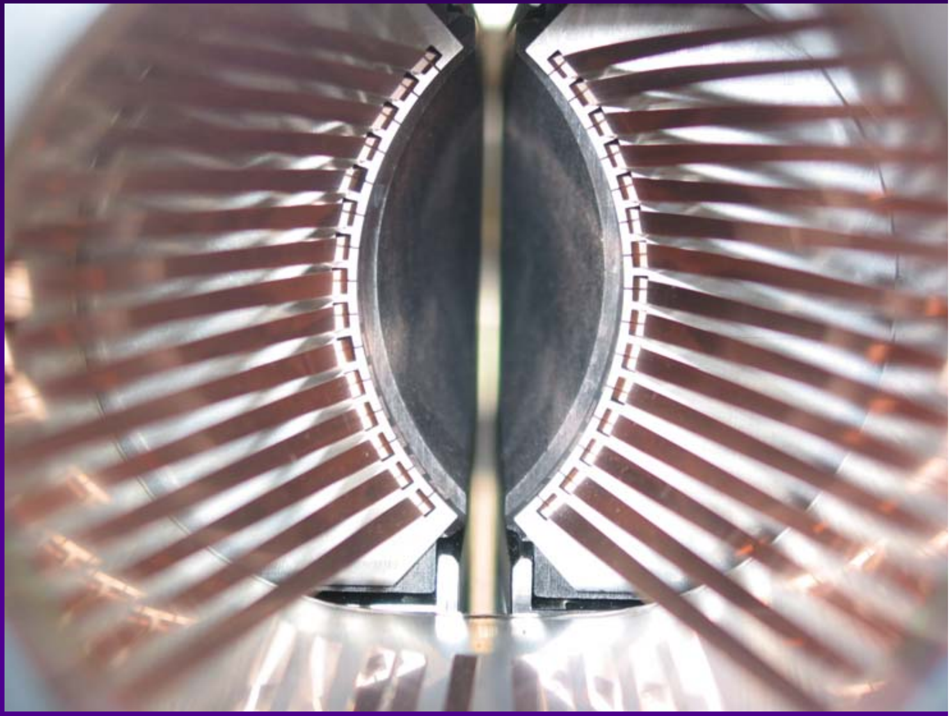
The effective impedances of the LHC Design Report are 28 (16) times larger at 7 TeV (injection) than the usual (normalized) effective impedance

THE LHC IMPEDANCE IS DOMINATED BY THE COLLIMATORS (7/10)

Table 5.4: LHC broad-band impedance budget. The first three columns report element name, latest relevant reference, and inner vertical aperture b in mm. The last two columns give the effective longitudinal and transverse impedance in the vertical plane, the latter being multiplied by $\beta/\langle\beta\rangle$, where $\langle\beta\rangle = 70$ m.

element	Ref.	b	$\mathrm{Im}(Z/n)$	$\mathrm{Im}(Z_\perp)$
		mm	Ω	MΩ/m
Pumping slots	[23]	18	0.017	0.5
BPM's	[24]	25	0.0021	0.3
Unshielded bellows		25	0.0046	0.06
Shielded bellows		20	0.010	0.265
Vacuum valves		40	0.005	0.035
Experimental chambers		-	0.010	-
RF Cavities (400 MHz)		150	0.010	(0.011)
RF Cavities (200 MHz)		50	0.015	(0.155)
Y-chambers (8)	[25]	-	0.001	-
BI (non-BPM instruments)		40	0.001	0.012
space charge @injection	[2]	18	-0.006	0.02
Collimators @injection optics		$4.4 \div 8$	0.0005	0.15
Collimators @squeezed optics		$1.3 \div 3.8$	0.0005	1.5
TOTAL broad-band @injection optics			0.070	1.34
TOTAL broad-band @squeezed optics			0.076	2.67

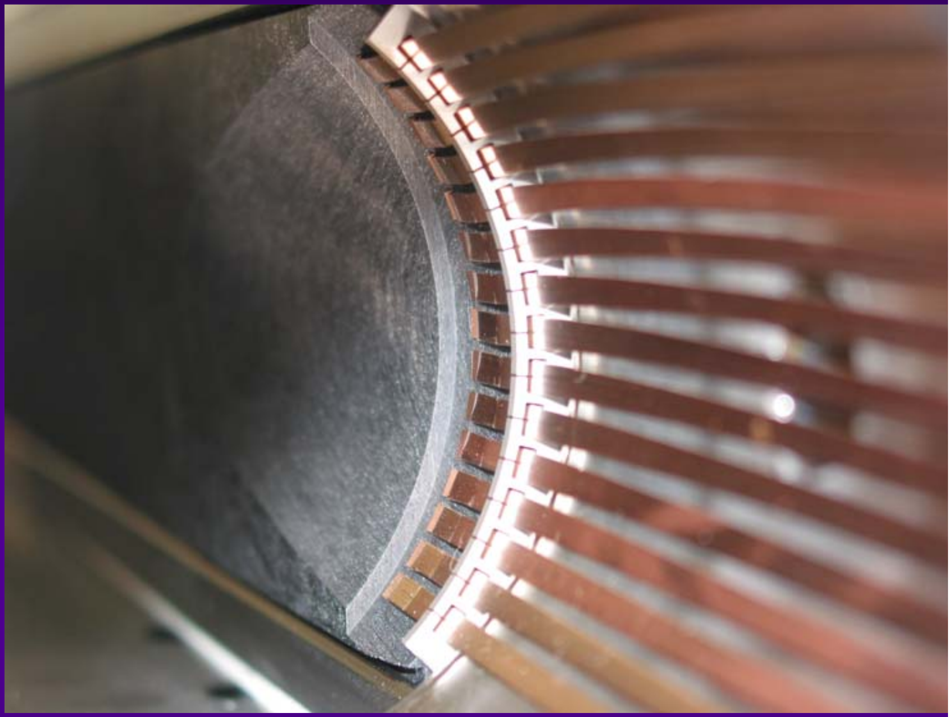
THE LHC IMPEDANCE IS DOMINATED BY THE COLLIMATORS (8/10)



Collimator prototype in the SPS **View along beam path**

Beam-based studies performed in 2004 and 2006

THE LHC IMPEDANCE IS DOMINATED BY THE COLLIMATORS (9/10)



Carbon carbon jaw | **RF contacts for a single jaw**

THE LHC IMPEDANCE IS DOMINATED BY THE COLLIMATORS (10/10)

- **RF contacts connect the moving carbon-fibre-reinforced carbon composite (CFC) jaws with the vacuum flanges**
  - **Allow for a smooth geometrical transition from the flat jaws to the round flanges and beam pipe**
  - **Guarantee electrical continuity for the beam induced currents**

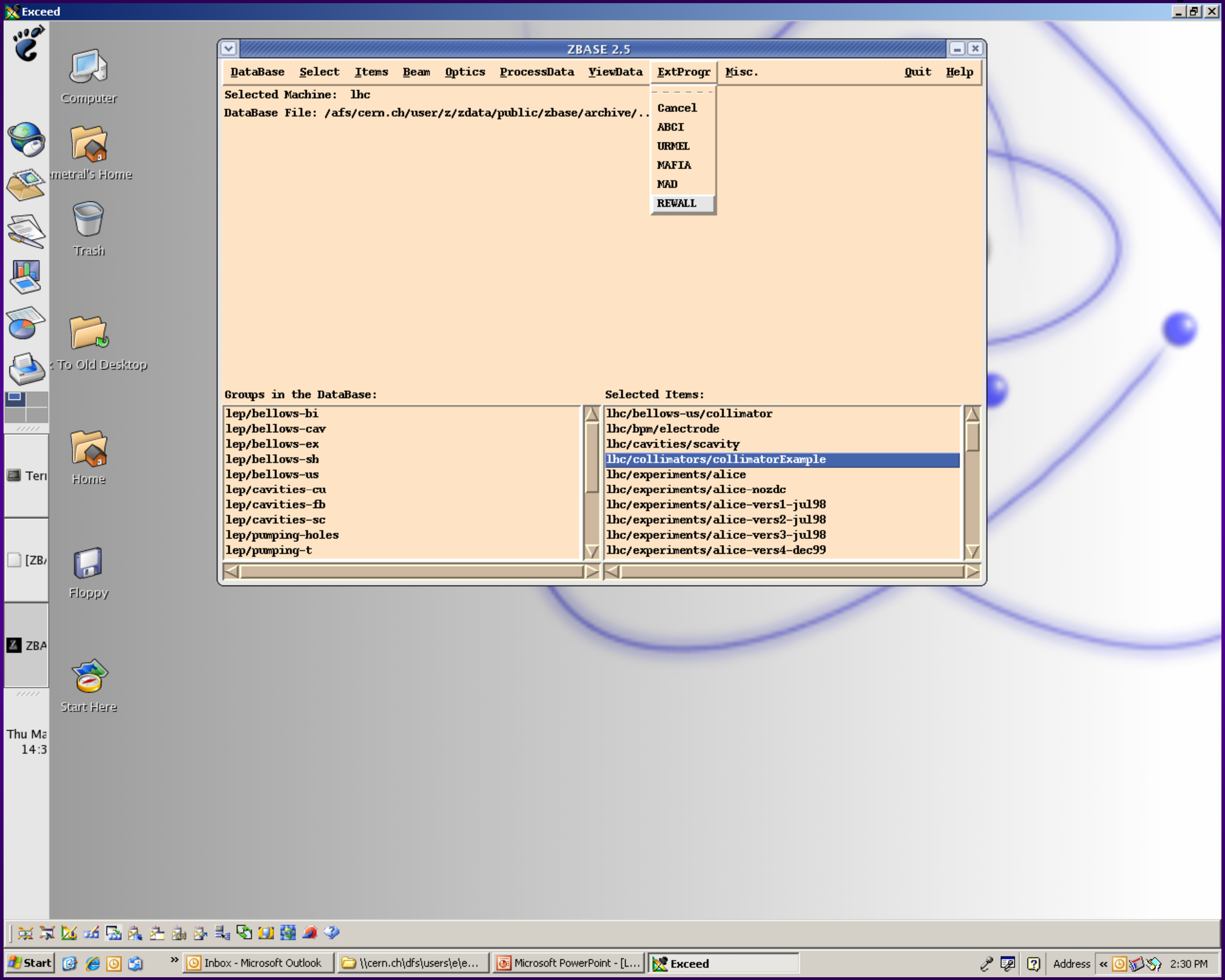
$\Longrightarrow$ **CuBe alloy of the C17410 type plated with Ag, acting over stainless steel plated with Rh (to avoid cold welding, etc.)**

LINK THE MATHEMATICA PROGRAM REWALL TO ZBASE (1/2)

- **Hubert Medina (5-month trainee student) is currently linking the program rewall (written in Mathematica) to ZBASE ⟹ Transverse impedance only and 2 layers maximum for the moment**

⟹ At the end of the summer the transverse impedance (and wake-field) of all the collimators should be available through ZBASE

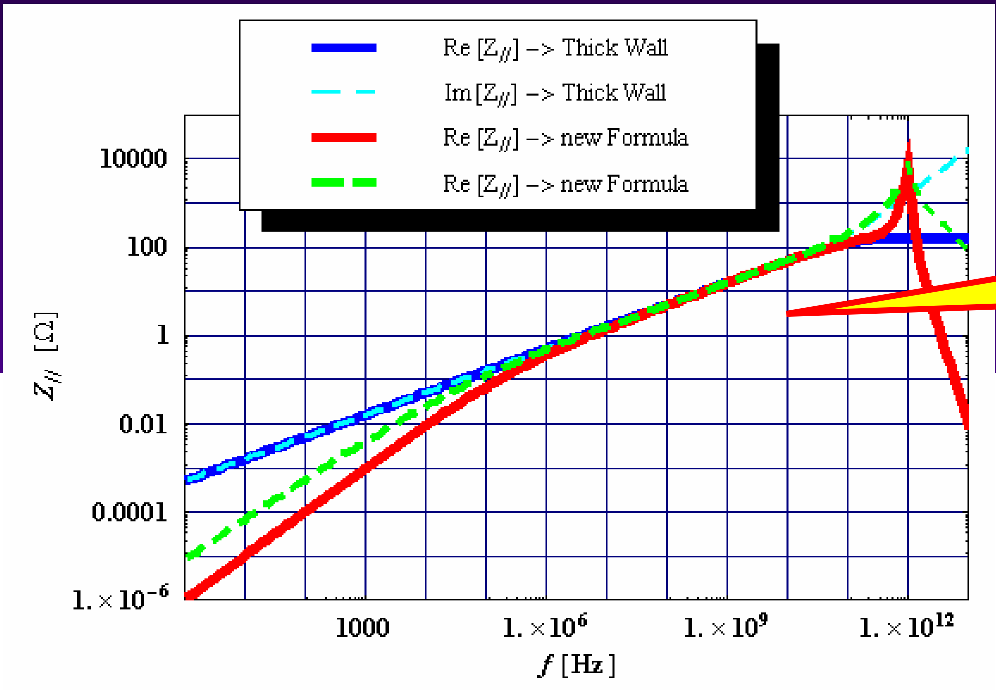
LINK THE MATHEMATICA PROGRAM REWALL TO ZBASE (2/2)



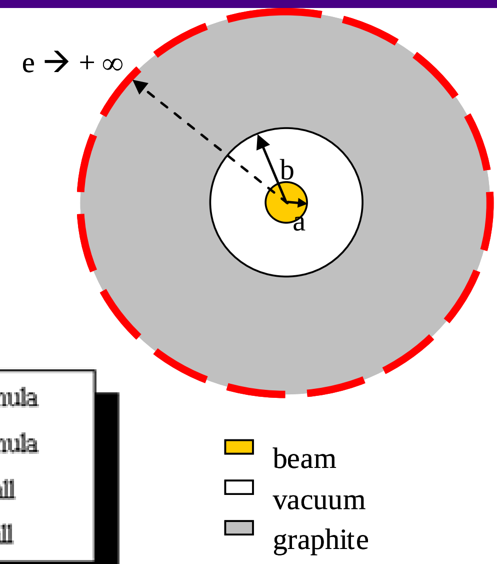
GENERAL PROGRAM FOR RESISTIVE-WALL IMPEDANCE (1/4)

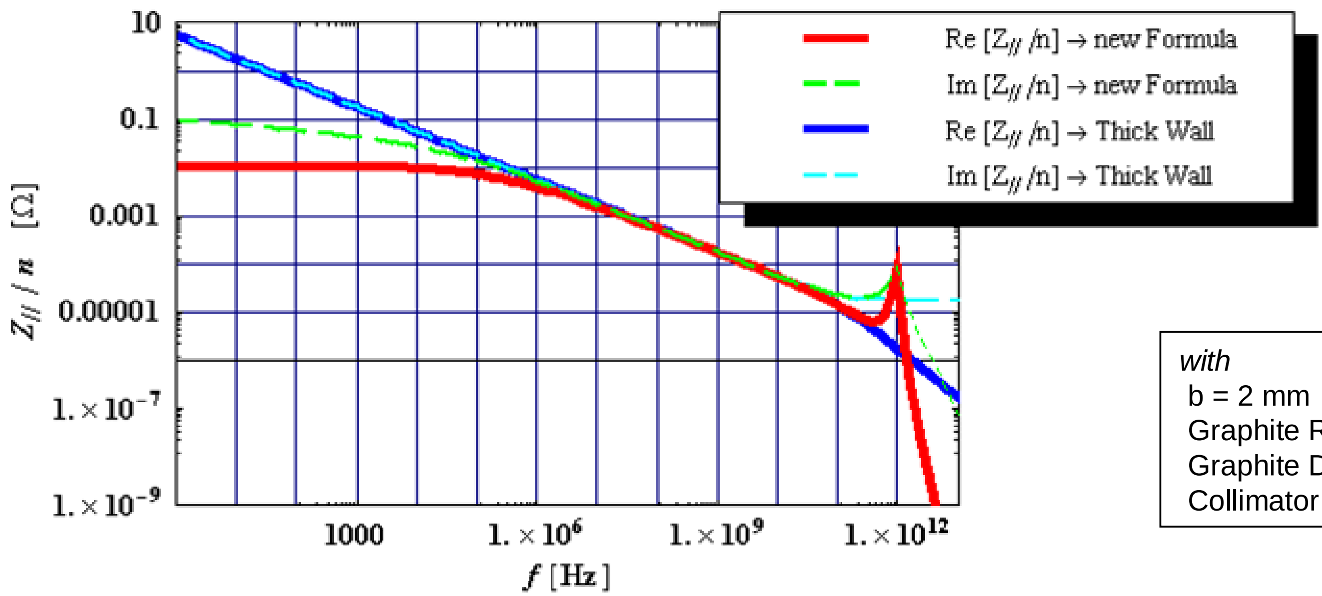
- **Benoit Salvant will upgrade the program rewall at the end of the year $\Longrightarrow$ Transverse and longitudinal resistive-wall impedance for multi-layer cylindrical structures with infinite length**
  - **Theory in longitudinal already done by Benoit**
  - **Then, next year (hopefully), rewall will be upgraded to include the effect of the finite length of a resistive object**

GENERAL PROGRAM FOR RESISTIVE-WALL IMPEDANCE (2/4)



3 regimes found
(as for the transverse)





with

b = 2 mm

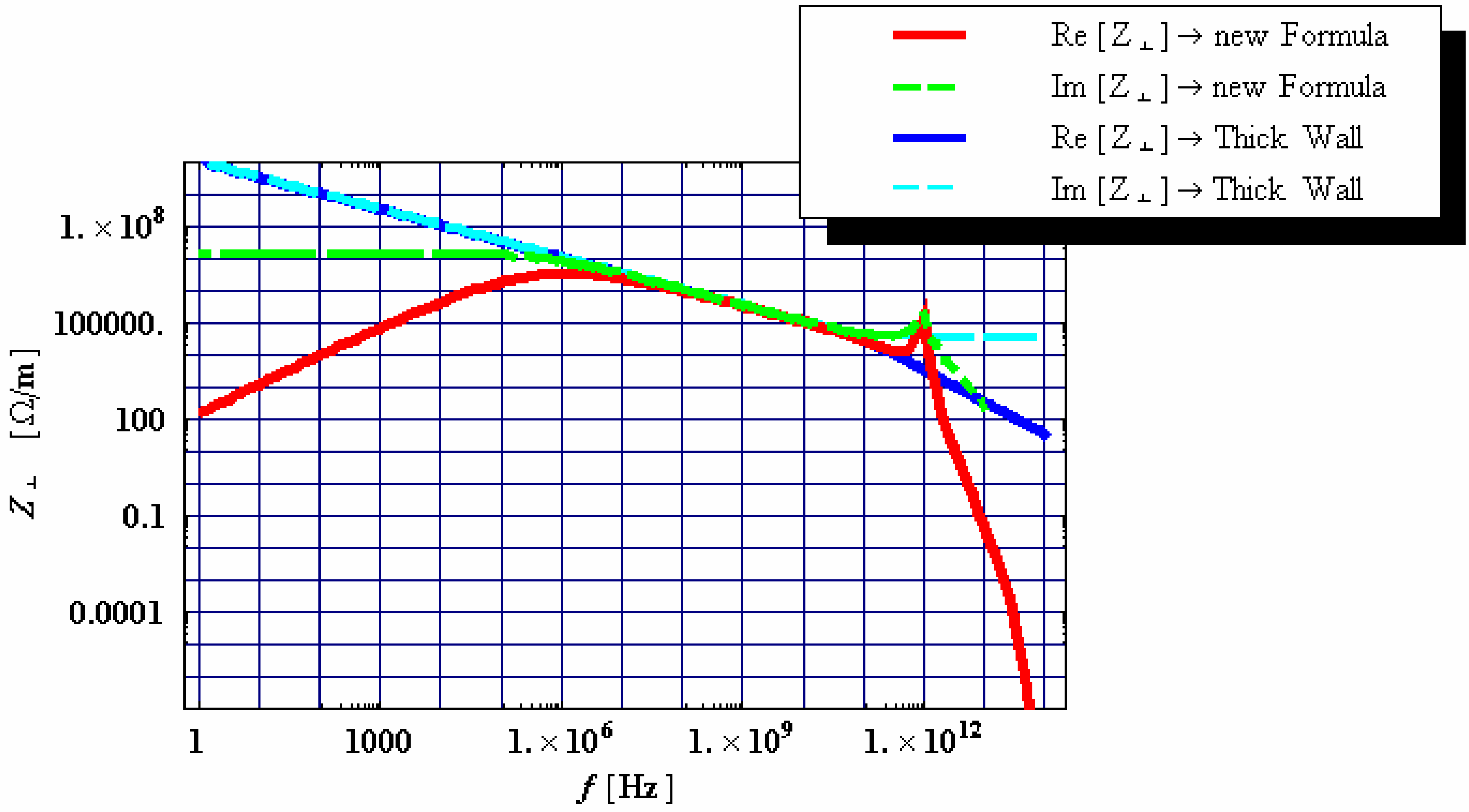
Graphite Relaxation Time = 0.8 10^{-12} s

Graphite DC conductivity = 10^5 S.m^{-1}

Collimator Length = 1 m

GENERAL PROGRAM FOR RESISTIVE-WALL IMPEDANCE (3/4)

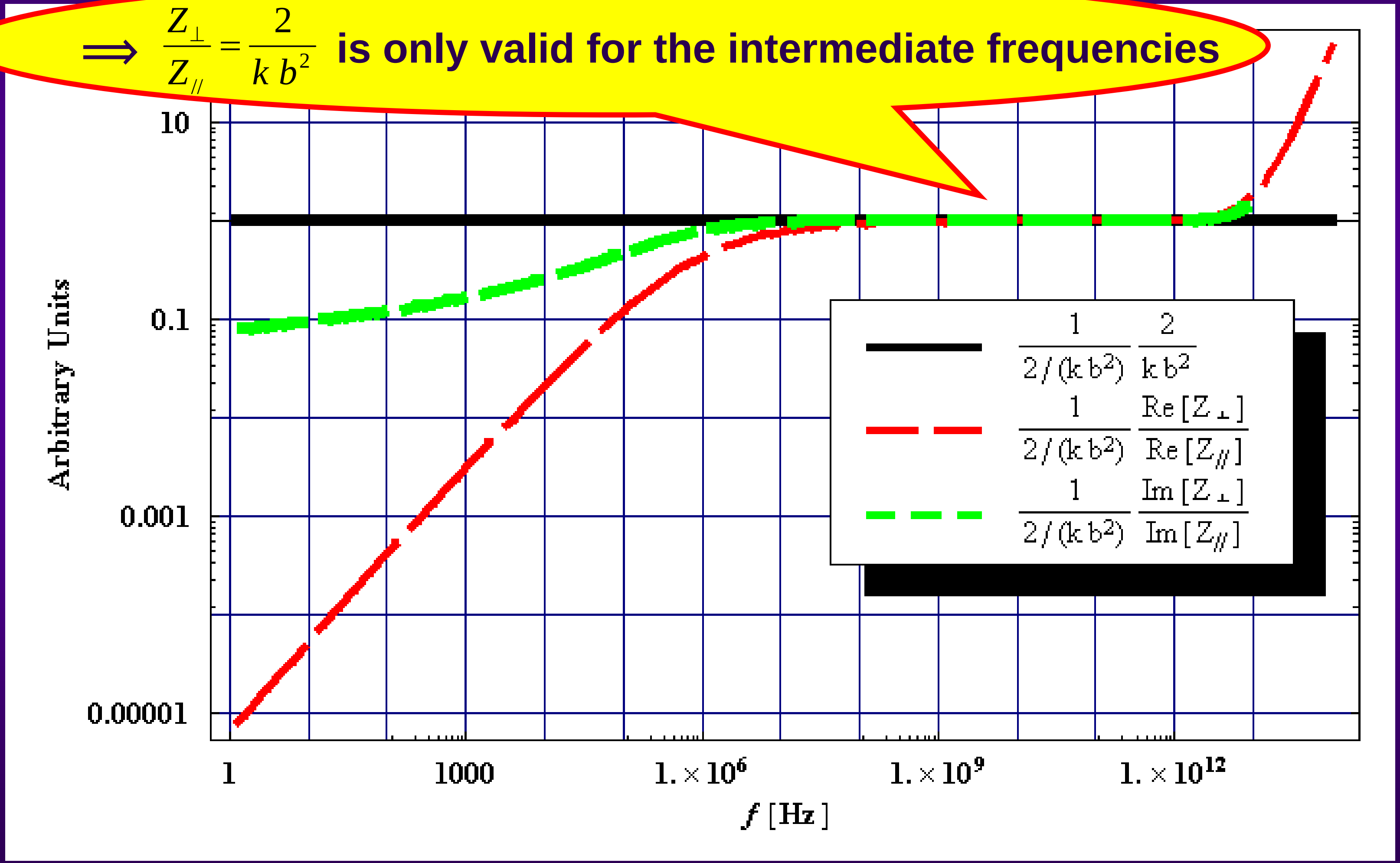
Reminder for the transverse impedance



GENERAL PROGRAM FOR RESISTIVE-WALL IMPEDANCE (4/4)

$$Z_\perp \,/\, Z_{//}$$

$\Longrightarrow \dfrac{Z_\perp}{Z_{//}} = \dfrac{2}{k\,b^2}$ **is only valid for the intermediate frequencies**

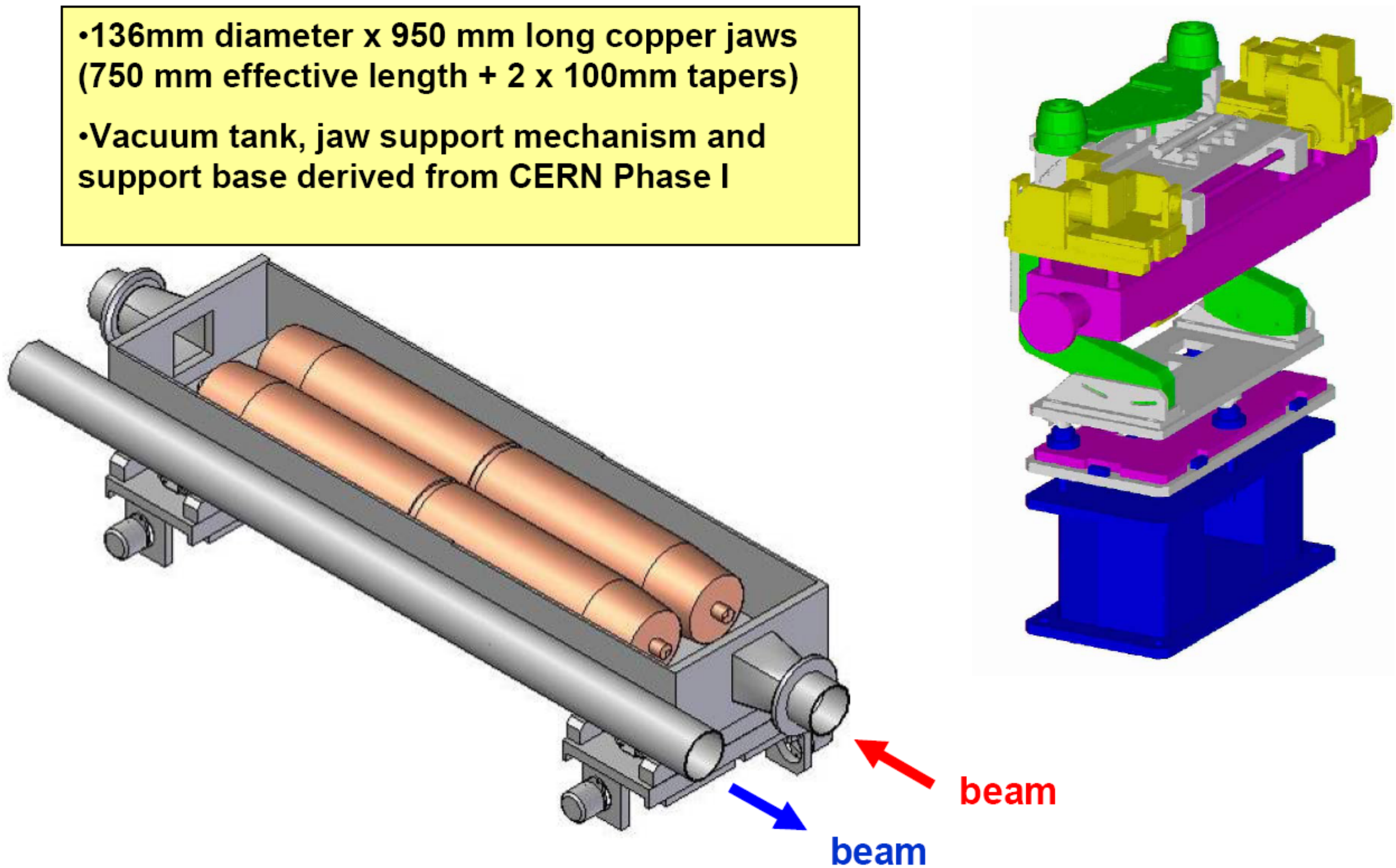


LHC COLLIMATORS PHASE II (1/4)

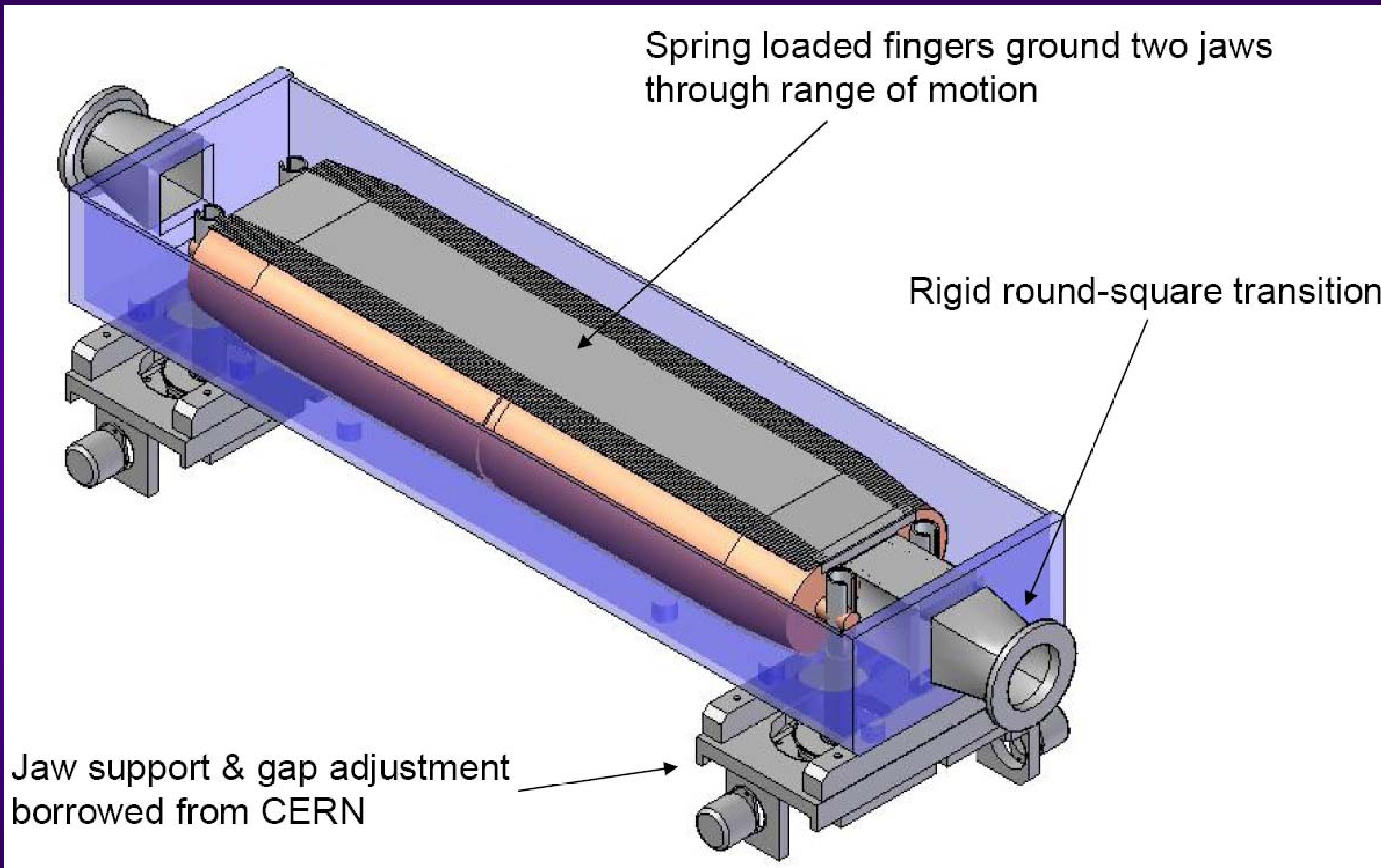
- **Pictures from the presentation "LARP Rotatable Collimators for LHC Phase II Collimation" by Tom Markiewicz/SLAC (26/10/06)**

•136mm diameter x 950 mm long copper jaws (750 mm effective length + 2 x 100mm tapers)

•Vacuum tank, jaw support mechanism and support base derived from CERN Phase I



LHC COLLIMATORS PHASE II (2/4)



LHC COLLIMATORS PHASE II (3/4)

⟹ Discussions on design principles for collimator RF shielding

In conclusion

⟹ **SIMULATIONS should be performed for the slots etc… (geometric part)**

⟹ **MEASUREMENTS should be performed for the contact resistance**

LHC COLLIMATORS PHASE II (4/4)

Ex: RF contacts for the (~2500) LHC beam vacuum interconnects

- **SUMMARY: A very strict requirement for low electrical resistance in the LHC has led to the need for a highly optimised RF bridge design. Using a combination of a high conductivity CuBe alloy with gold (on the RF fingers) and rhodium (hard brittle material, on the static part) coatings (few μm) has allowed the resistance to be lowered by more than 2 orders of magnitude (factor ~250) from that achieved in the LEP machine**

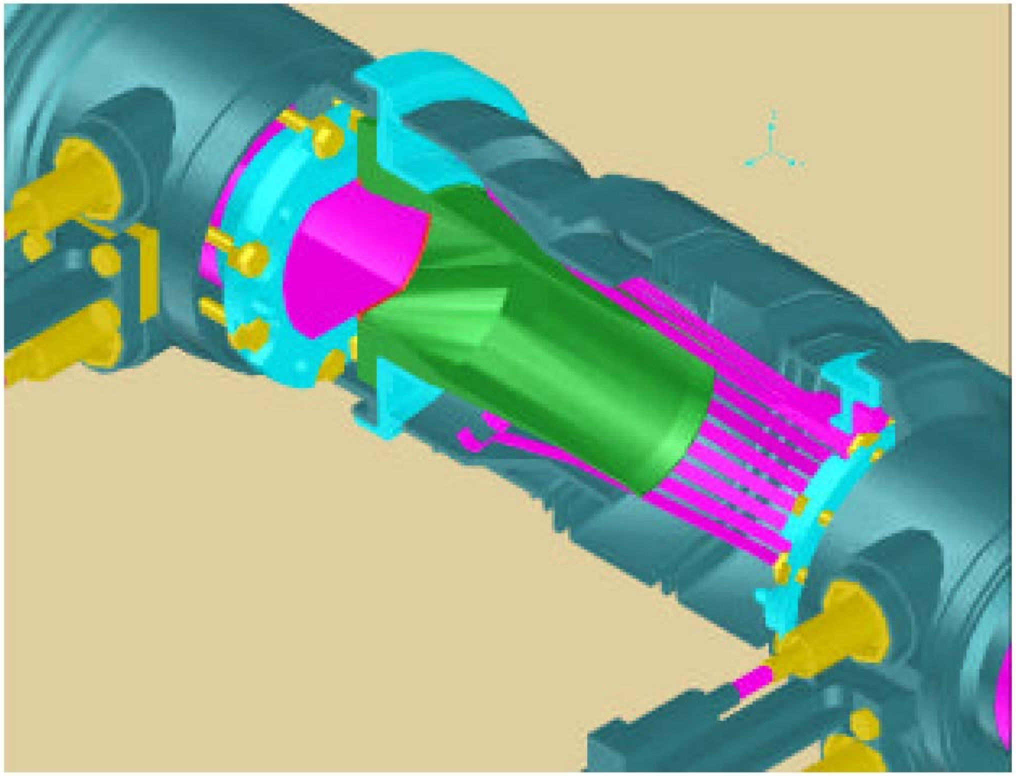


Figure 2: Part-sectioned view of the beam vacuum interconnect, showing plug-in module

S. Calatroni et al., LHC project Report 491

TCT AND TCLI

- **See RLC meeting on 07/04/2006: "TCT and TCLI in the LHC" (A. Grudiev, E. Métral and F. Ruggiero)**

  ⟹ http://ab-abp-rlc.web.cern.ch/ab-abp-rlc/Meetings/2006/2006.04.07/EM-StrategyForTheTCTAndTCLIInTheLHC_RLC_07-04-06.pdf

TCDQ, TCDS and TDI

- **See RLC meeting on 19/09/2006: "Follow-up for the TDI" (E. Métral)**

  ⟹ http://ab-abp-rlc.web.cern.ch/ab-abp-rlc/Meetings/2006/2006.09.19/TDI_FollowUp_19-09-2006.pdf

- **See RLC meeting on 26/09/2006: "Follow-up for the TCDQ &TCDS & TDI concerning the RF fingers" (A. Grudiev and E. Métral)**

  ⟹ http://ab-abp-rlc.web.cern.ch/ab-abp-rlc/Meetings/2006/2006.09.26/TCDQ&TCDS&TDI_FollowUp_26-09-2006.pdf

LHC INJECTION SEPTUM MSI (1/3)

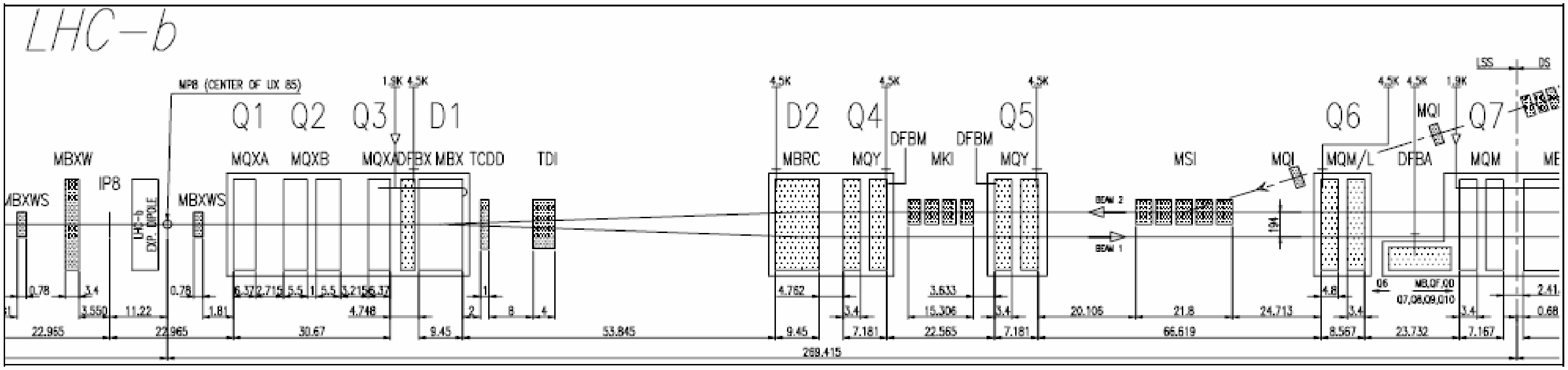


Figure 16.1: Schematic layout of the injection region right of IP8

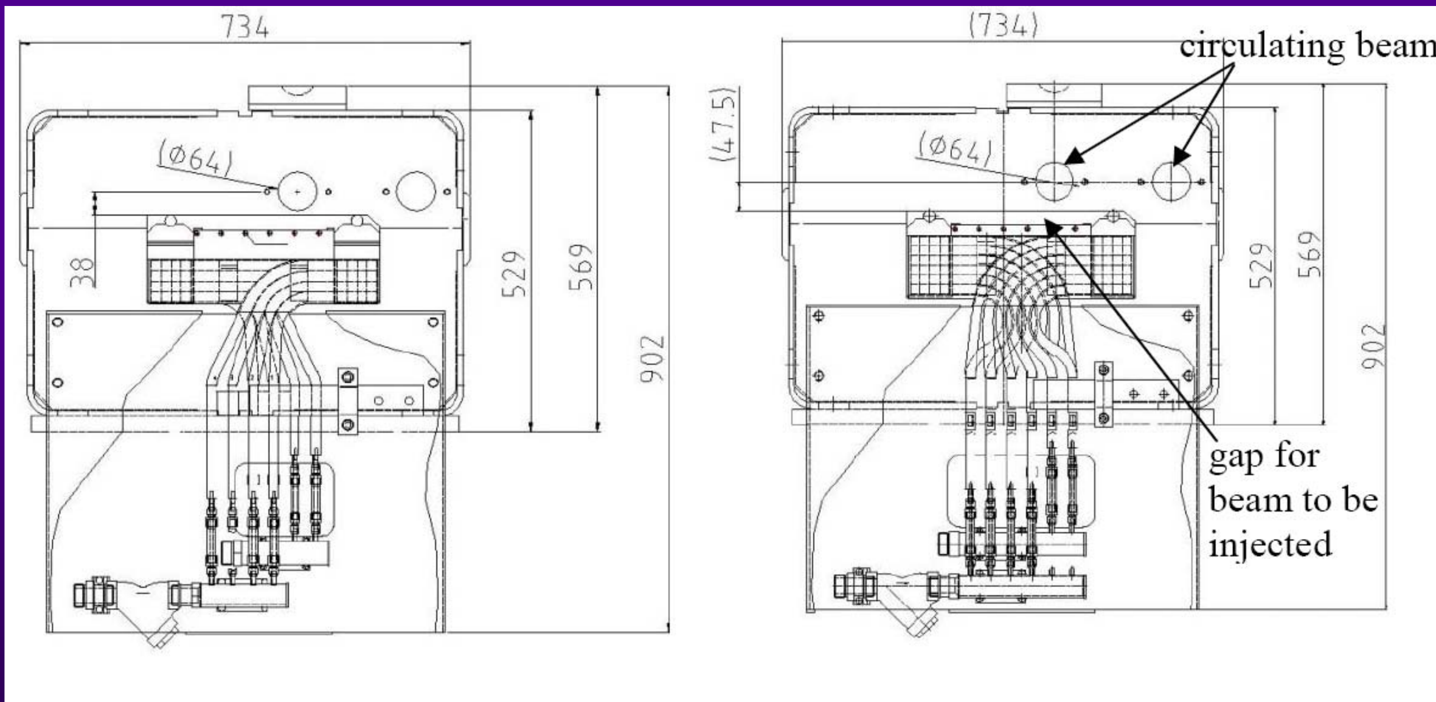


Figure 16.2: MSIA (left) and MSIB (right) connection front face view

LHC INJECTION SEPTUM MSI (2/3)

B. Goddard et al.,
LHC Project Note 387

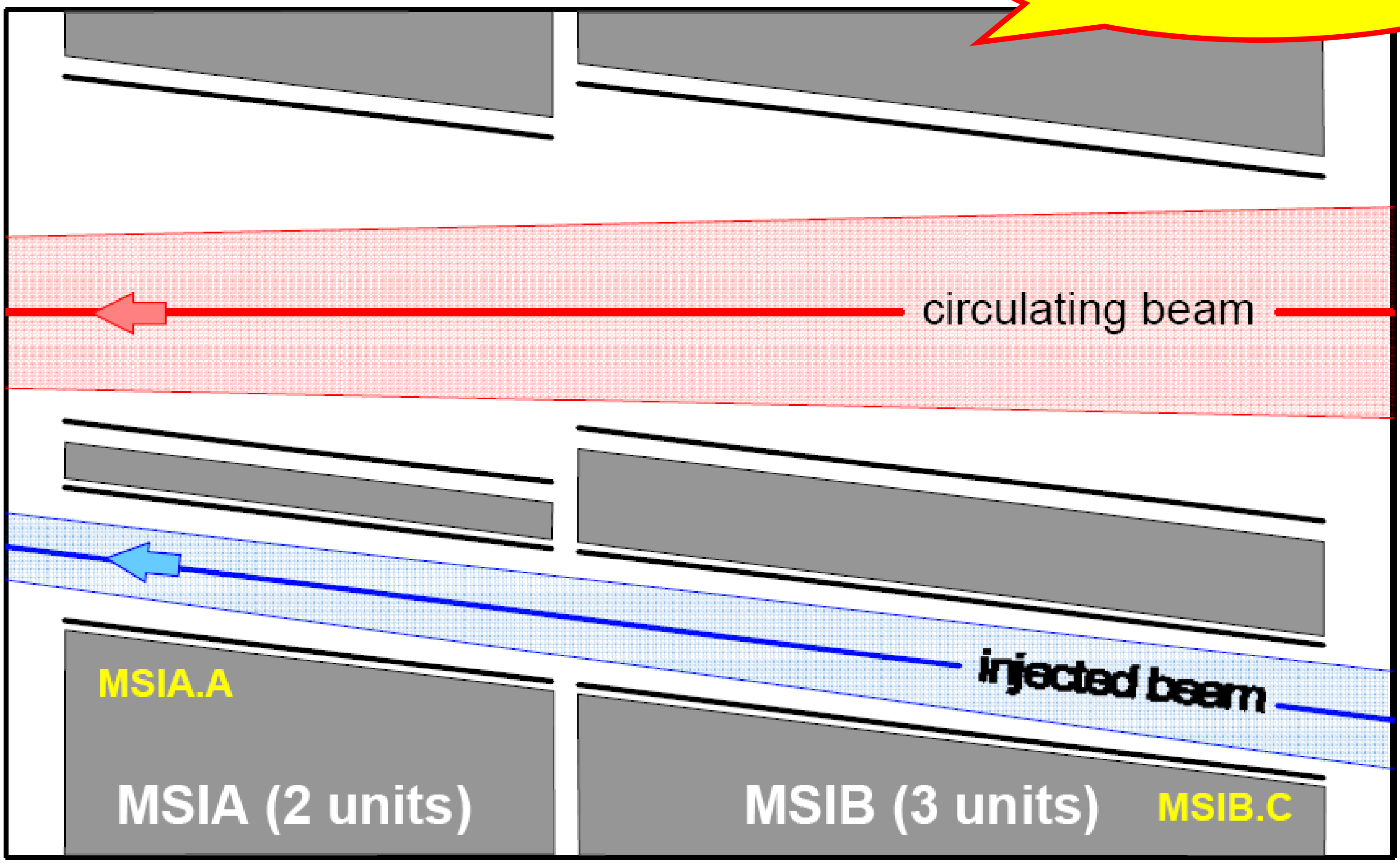


Figure 1. Vertical alignment of MSI septa

LHC INJECTION SEPTUM MSI (3/3)

From the LHC Design Report (Ch. 16)

- **MSI = 3 MSIB + 2 MSIA**
- **Total length = 21.8 m (5 times 4 m long modules + gaps between)**
- **~ circular geometry with a radius of 22 mm (effective radius due to the angle of the chamber…)**
- **Mu-metal (with a thickness of 0.9 mm) used to shield (at low frequencies) the holes where the beam is circulating**
- **Copper coating of 0.4 mm ("for aperture reasons a baseline thickness of 0.4 mm was chosen")**
- **Skin depth in copper at 8 kHz = 0.7 mm > copper thickness of 0.4 mm**
- **I think L. Vos considered only the copper layer to make his computation. To be more precise, one now needs some information about the mu-metal used**

  ⟹ Conductivity, permittivity and permeability (vs. frequency)? It is also needed for the dump septum

I contacted M. Gyr, B. Goddard etc… but no answer yet

LHC DUMP SEPTUM MSD (1/2)

From the LHC Design Report (Ch. 17)

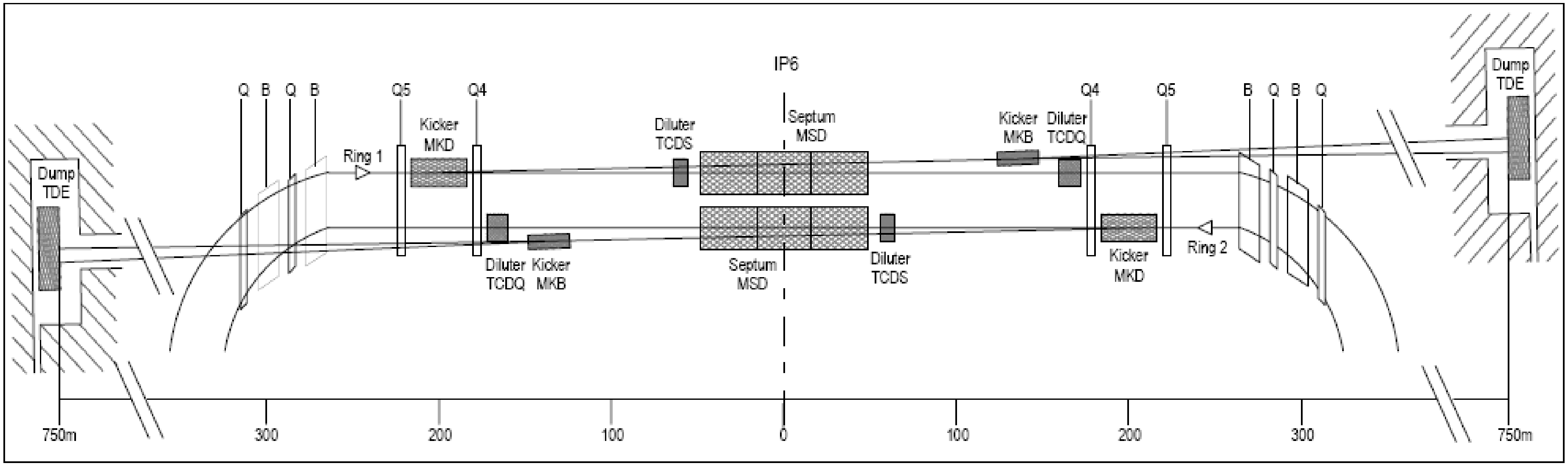


Figure 17.1: Schematic layout of beam dumping system elements around LHC point 6.

- **MSD = 15 steel septum magnets of 3 types MSDA, MSDB and MSDC**
- **Total length = 73.2 m (15 times 4.46 m long modules + gaps between)**
- **~ circular geometry with a (effective) radius of 25 mm**
- **Mu-metal (with a thickness of 0.9 mm) used to shield (at low frequencies) the holes where the beam is circulating**
- **Copper coating of 0.5 mm (“for impedance reasons”)**

LHC DUMP SEPTUM MSD (2/2)

B. Goddard et al., LHC Project Note 388

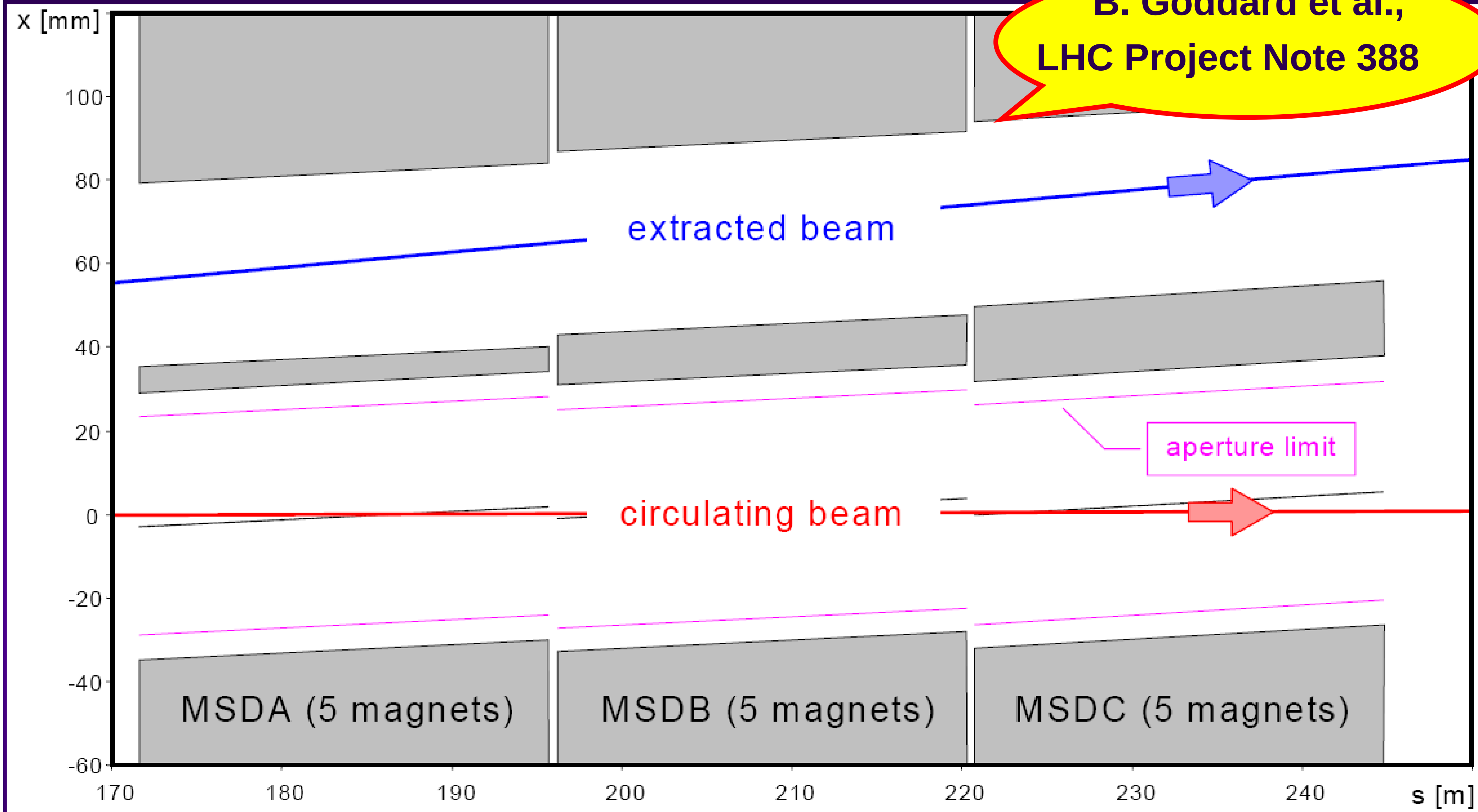


Figure 1. Horizontal alignment of MSD septa

NEXT IMPORTANT WORK

- **Study in detail the transverse coupled-bunch instability and its stabilisation all along the cycle**

LHC Design Report (Ch. 5)

5.4.2 Transverse feedback system

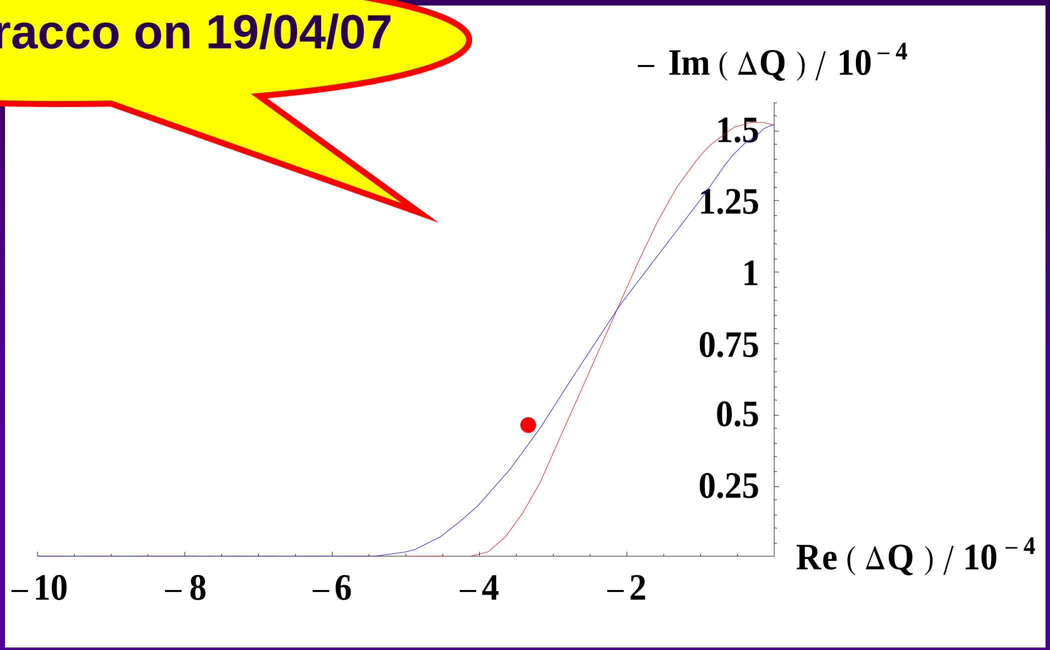
A transverse feedback system is required to damp coupled-bunch instabilities caused by the narrow-band impedance, and in particular the resistive wall instability, at injection and during acceleration to 7 TeV. Since the feedback system can only dump rigid ($m = 0$) head-tail modes, higher order head-tail modes have to be stabilized by Landau damping or (slightly) negative chromaticity. On the other hand, operation with the transverse feedback and large betatron tune spread may lead to a significant emittance growth [35] and should be avoided. Therefore the LHC strategy is to switch off the feedback system before the end of the energy ramp and to ensure Landau damping of *all* the head-tail modes by proper control of the tune spread using the arc octupoles.

- **Feedback at injection + acceleration**
- **Landau octupoles (and chromaticity?) at top energy before collisions**
- **Beam-beam tune spread in collision…**

⟹ A student or fellow could study this in detail (using the code MTRISIM from A. Koschik) to propose an operational procedure

STABILITY DIAGRAM AT TOP ENERGY BEFORE THE SQUEEZE

Sent to C. Bracco on 19/04/07



$\Longrightarrow$ **Nominal beam almost stable!**

CONCLUSION

- **The LHC impedance is dominated by the collimators, and in particular the resistive-wall effect**
  - **Hubert is linking the program rewall to ZBASE $\Longrightarrow$ At the end of the summer the transverse impedance (and wake-field) of all the collimators should be available through ZBASE**
  - **Benoit will upgrade rewall by the end of this year (T+L)**
  - **The effect of the finite length might be added next year**

- **I am waiting for the conductivity, permittivity and permeability (vs. frequency) of the mu-metal used for the septa to make a more precise estimate of their impedance**

- **Next important subject $\Longrightarrow$ Study in detail the transverse coupled-bunch instability and its stabilisation all along the cycle (student or fellow?)**