BEAM-INDUCED HEATING / BUNCH LENGTH / RF AND LESSONS FOR 2012

Elias Métral (for ICE section & collaborators & equipment groups etc. Many thanks to all!)

(20 + 10 min talk, 42 slides)

- **Observations of beam-induced heating in 2011**
- **News / work since then**
- **Several possible sources of heating => RF heating discussed only**
  - **RF heating: broad-band vs. narrow-band (long. real.) impedance**
  - **Bunch / beam spectrum**
  - **Usual solutions to avoid RF heating**
  - **Heat transfers**
  - **Synchronous phase shift as a meas. of power loss & impedance**
- **"Hot" topics: VMTSA, TDI and MKI**
- **Lessons for 2012 (and after)**

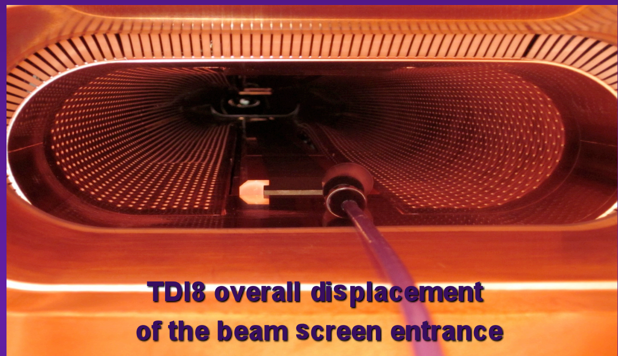
2011 run observations: Summary table (BenoitS, Evian11)

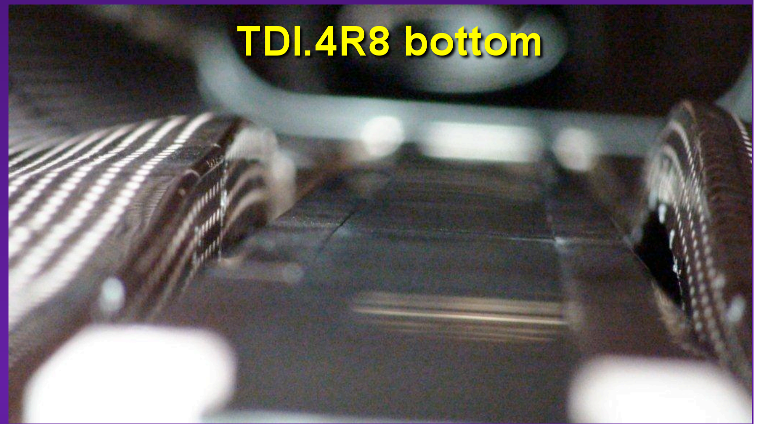
	observable	Cooling?	Limits operation?	better if bunch length increased	improves with time?	Is it happening to all similar devices
TCP_B6L7_B1	temperature	water	Yes, dump in Sept 17th interlock increase from 55 to 70 degrees	yes	no	No (1/6)
TCTVB.4R2	temperature	water	Yes, dump in October 9th interlock increase from 50 to 70 degrees	Yes	Not obvious	No (1/4)
TDI	Vacuum Temperature (outside tank)	no	Not anymore, should be put in parking position	?	no	Yes (2/2)
MKI	Temperature and Rise time and delay (soon)	no	Yes (kick strength), and temp interlock increased from 50 deg to 62 deg. Needed to wait 4h in Oct 2011	Yes	no	All are heating but MKI-8D seems to be heating more No (1/8)
Beam screen	Heat load computed from regulation response	yes	No, except in one cell Q6R5	Yes	no	No (only one)
ALFA	Temperature on the roman pots	no	Not yet (18deg increase in temperature in 2011, with margin of 40 degrees)		?	Cooling was needed in TOTEM
VMTSA	Vacuum Spring broken after May	no	Yes (spring broken and dangling fingers)		?	Yes
BSRT Mirror	Jitter in BSRT measurement		mirror is deforming and RF heating is suspected			N/A
BGI	Vacuum		Probably not a heating issue		No data	N/A

News / work since then

- **VMTSA** => (8 instead of 10) new modules installed in the LHC (shorter RF fingers + ferrite) + bench imped. meas. (see later)
- **TDI** => New observations: beam screen deformation

Benoit Salvant et al.





- **TCTVB.4R2** => Has been removed during the shutdown. TCTVB. 4L2 (i.e. not the most critical one) has been looked at and some RF fingers were found not in contact
- **TCP.B6L7.B1** => Nothing obvious by visual inspection. Xrays still to be done but might be quite difficult
- **Q6R5 (beam screen)** => Xrays performed and nothing special
- **ALFA and MKI and TDI** => More simulations performed

RF HEATING (1/17)

- **General formula in the case of *M* equi-spaced equi-populated bunches (Furman-Lee-Zotter1986)**

$$P_{loss} = M \, I_b^2 \, Z_{loss}$$

$$Z_{loss} = 2 \, M \sum_{p=0}^{\infty} \mathrm{Re}\left[Z_l \left(p \, M \, \omega_0 \right) \right] \times \mathrm{PowerSpectrum}\left[p \, M \, \omega_0 \right]$$

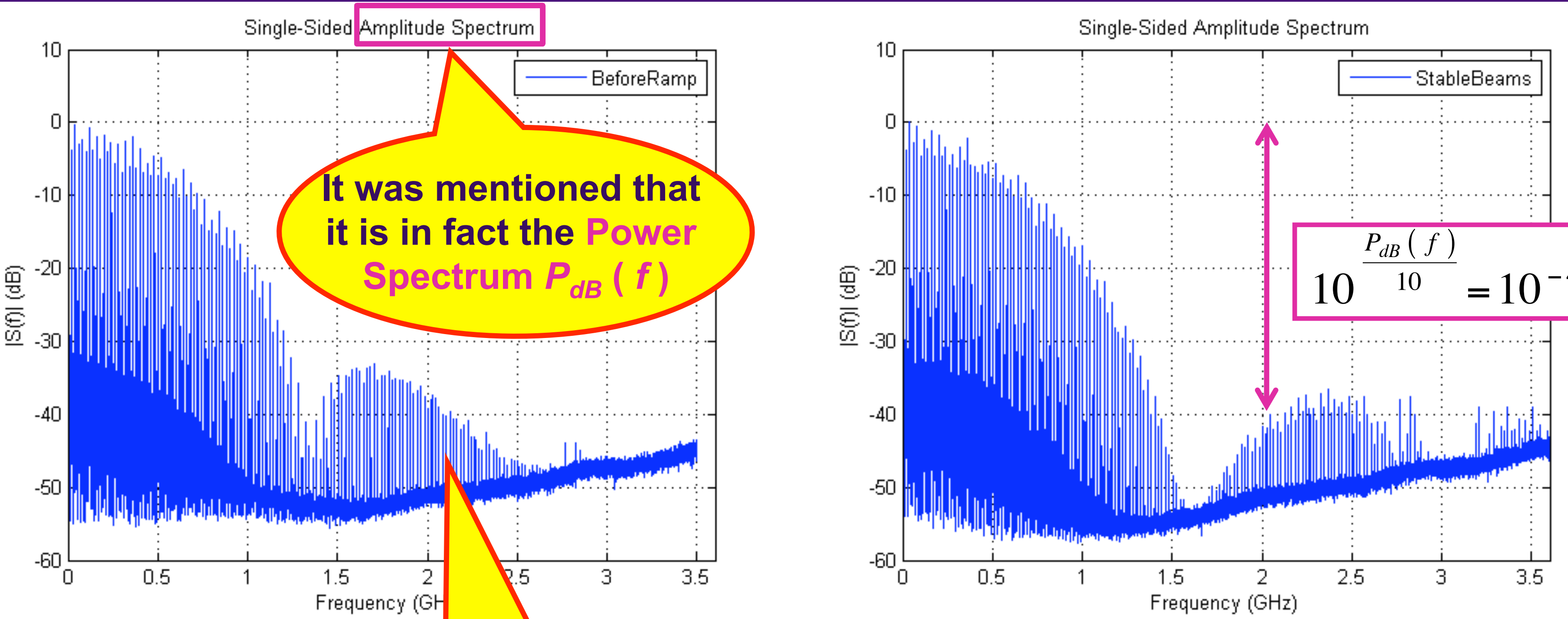
$$I_b = N_b \, e \, f_0$$

$$\omega_0 = 2 \, \pi \, f_0$$

  - **Broad-band impedance => Sum can be replaced by an integral (*M in front disappears) =>* $P_{loss} \propto M$ *(i.e. it is M times the single-bunch case)***
  - **(Very) narrow-band impedance => Only 1 term in the sum =>** $P_{loss} \propto M^2$ ***(i.e. it is NOT M times the single-bunch case)***

RF HEATING (2/17)

Measurements on B1 by ThemisM and PhilippeB on fill # 2261



It was mentioned that it is in fact the Power Spectrum $P_{dB}(f)$

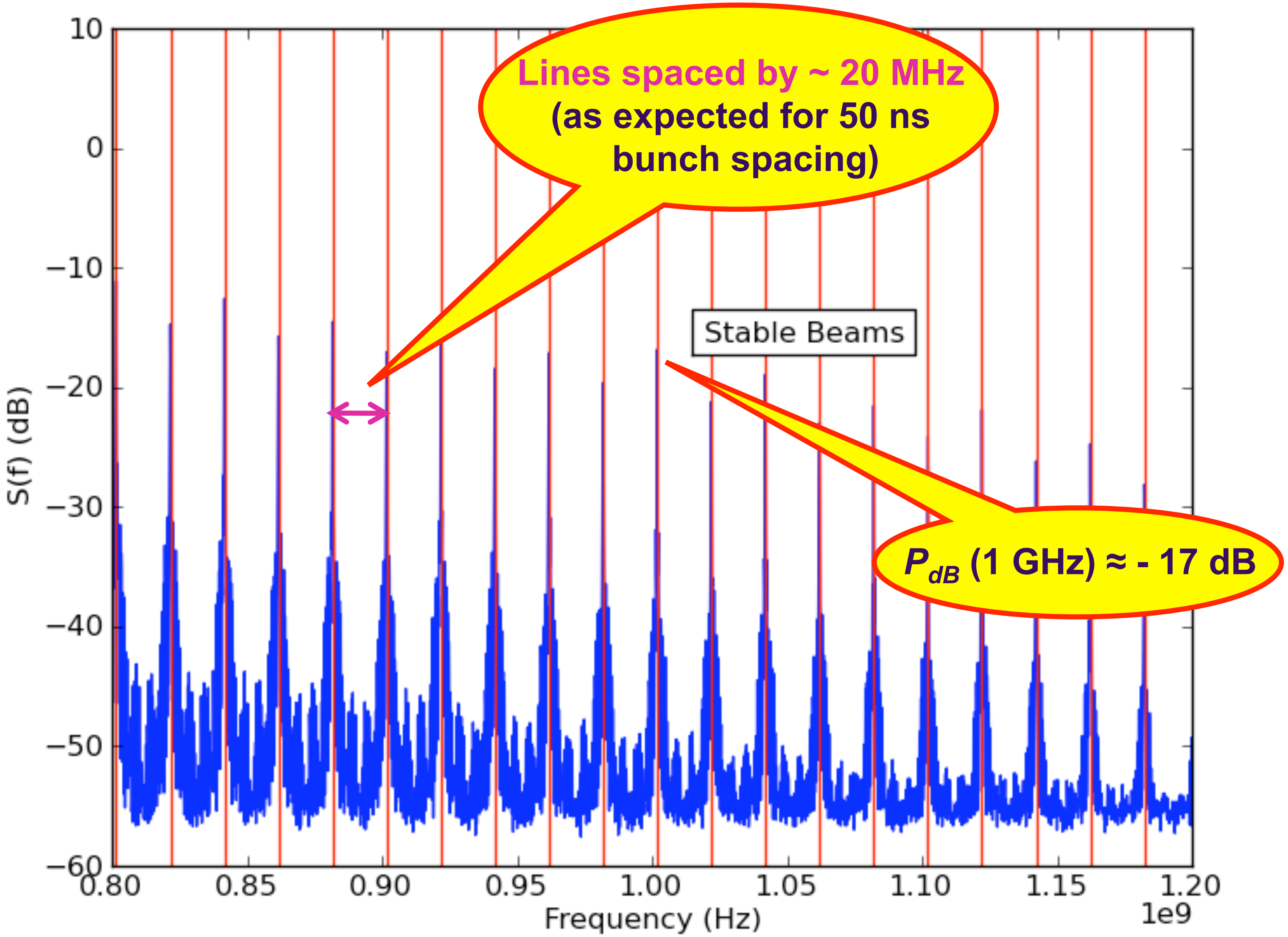
$$10^{\frac{P_{dB}(f)}{10}} = 10^{-4}$$

Coupled-bunch lines spaced by $M f_0$ ~ 20 MHz (for 50 ns bunch spacing) => It would be ~ 40 MHz for 25 ns

$$M_{50} = 1782$$

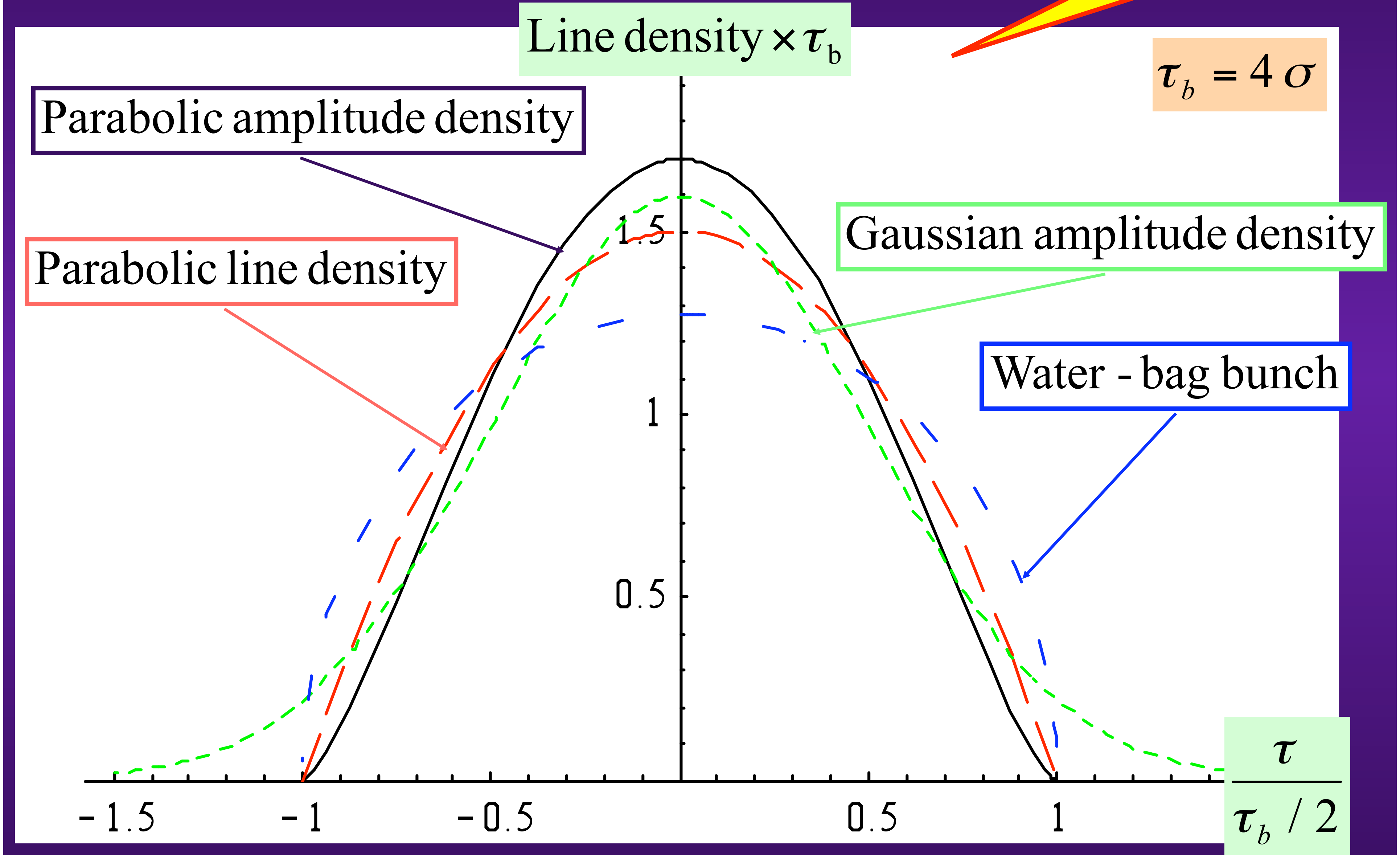
$$M_{25} = 3564$$

RF HEATING (3/17)



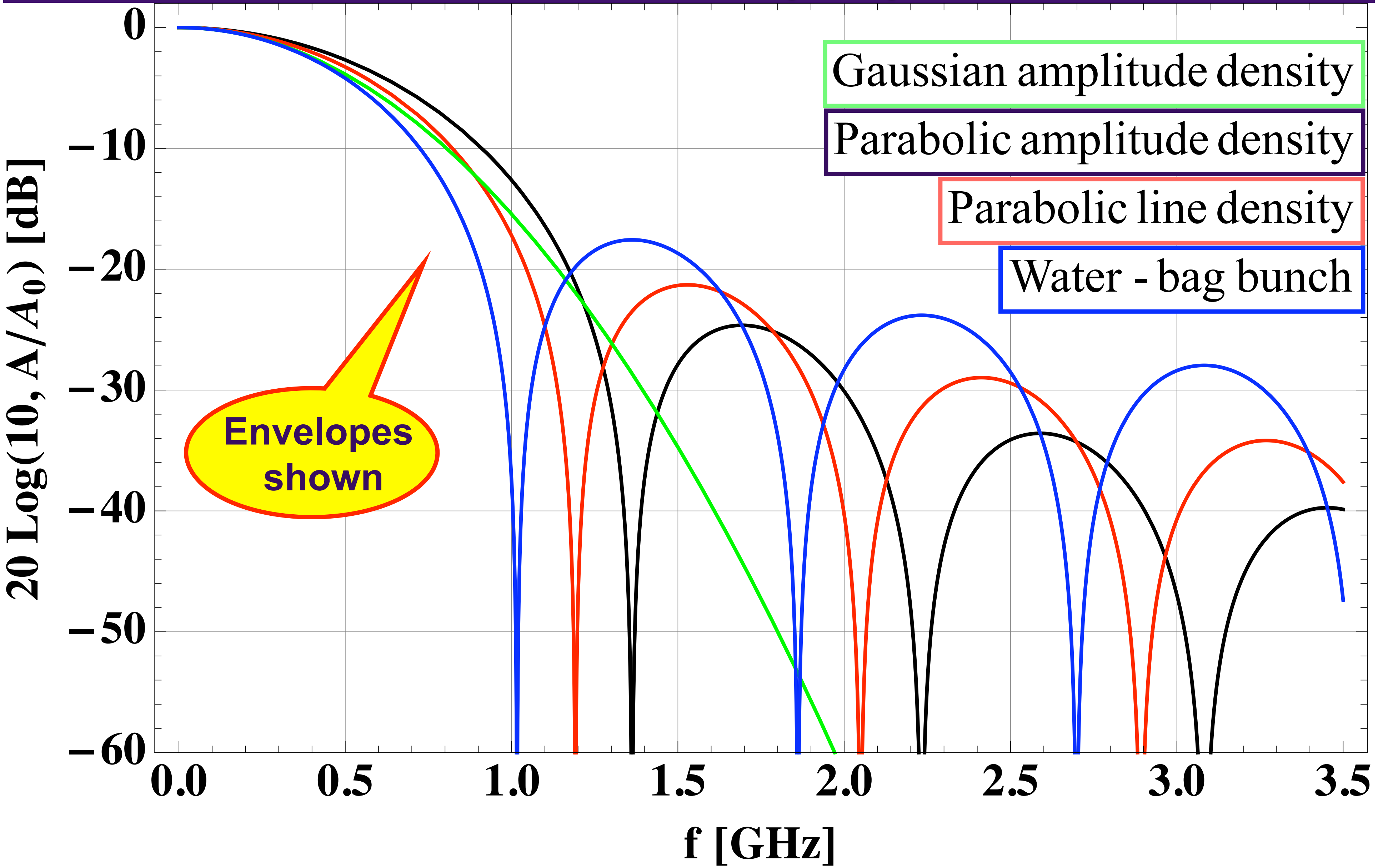
RF HEATING (4/17)

From theory

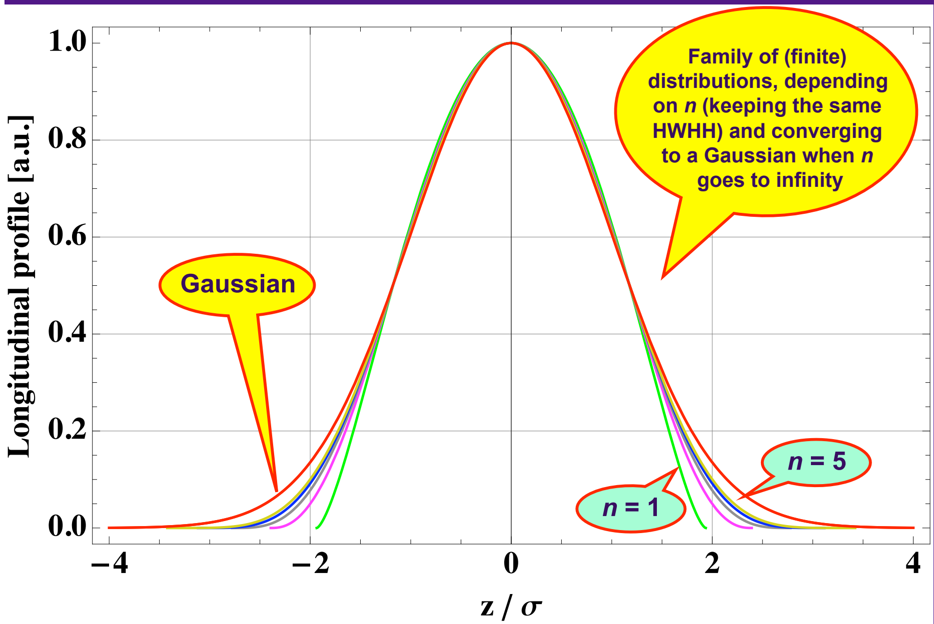


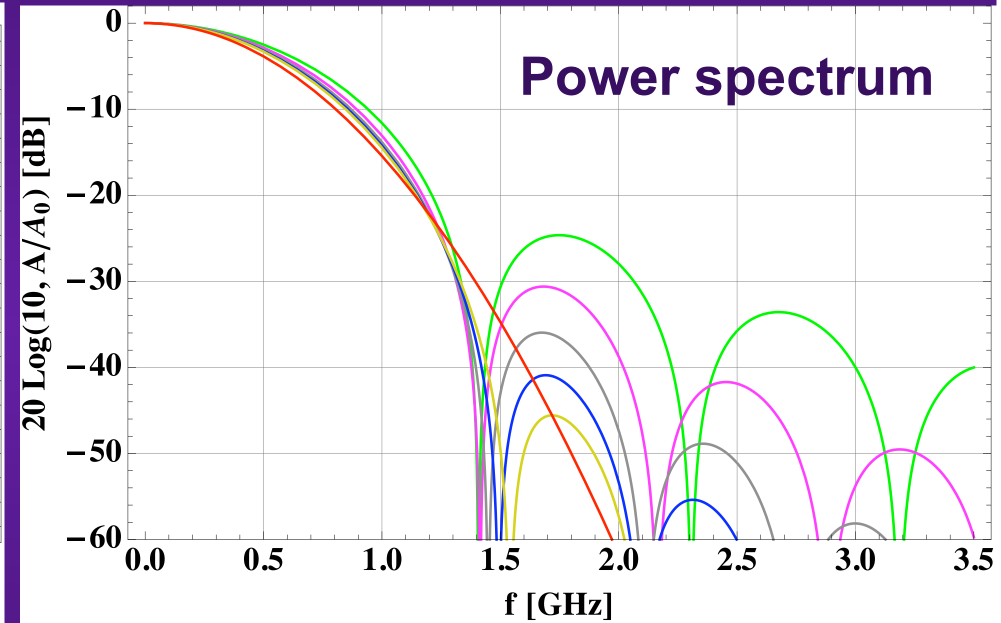
RF HEATING (5/17)

$\tau_b = 1.2$ ns



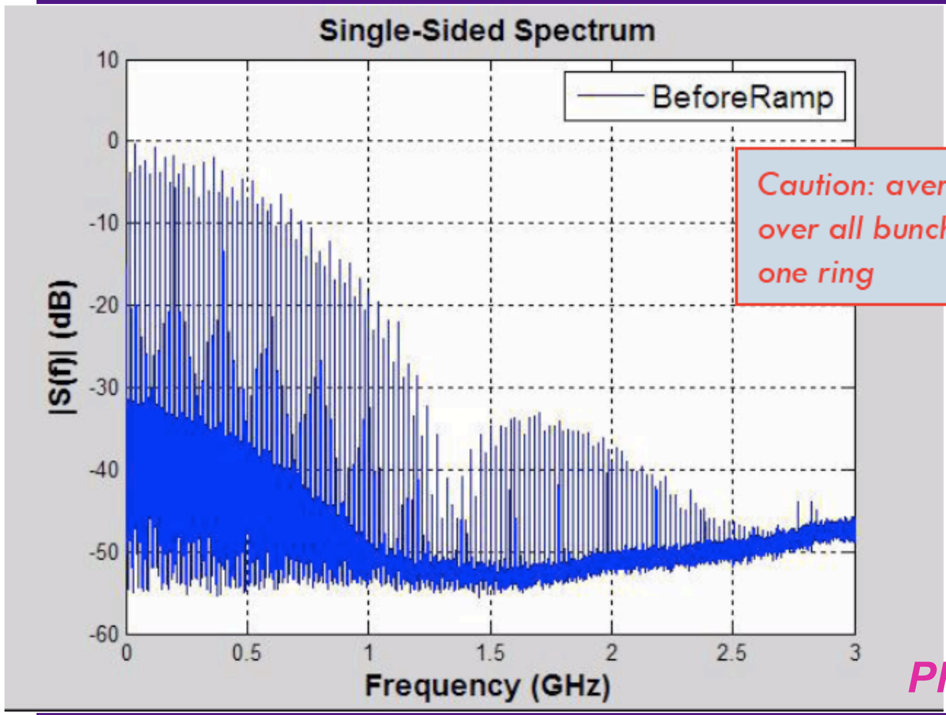
RF HEATING (6/17)



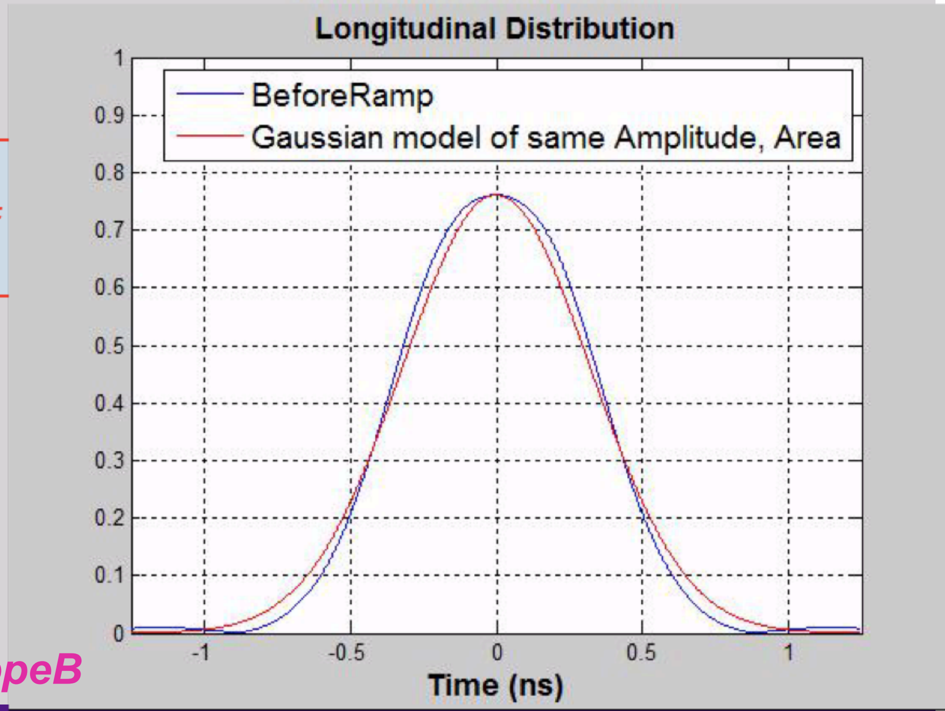


RF HEATING (7/17)

- **By taking the inverse Fourier Transform, ThemisM and PhilippeB found the following distribution**



Caution: average over all bunches of one ring

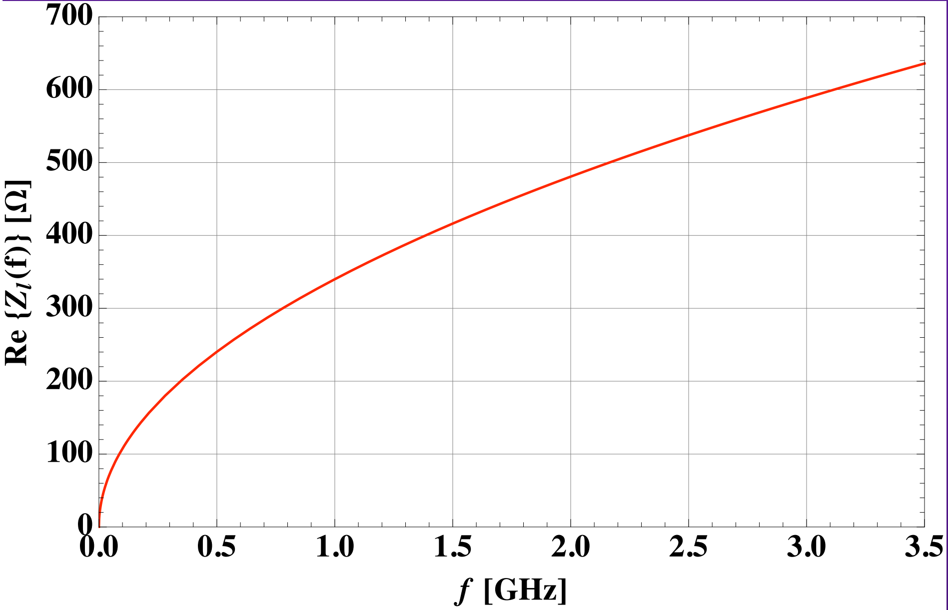


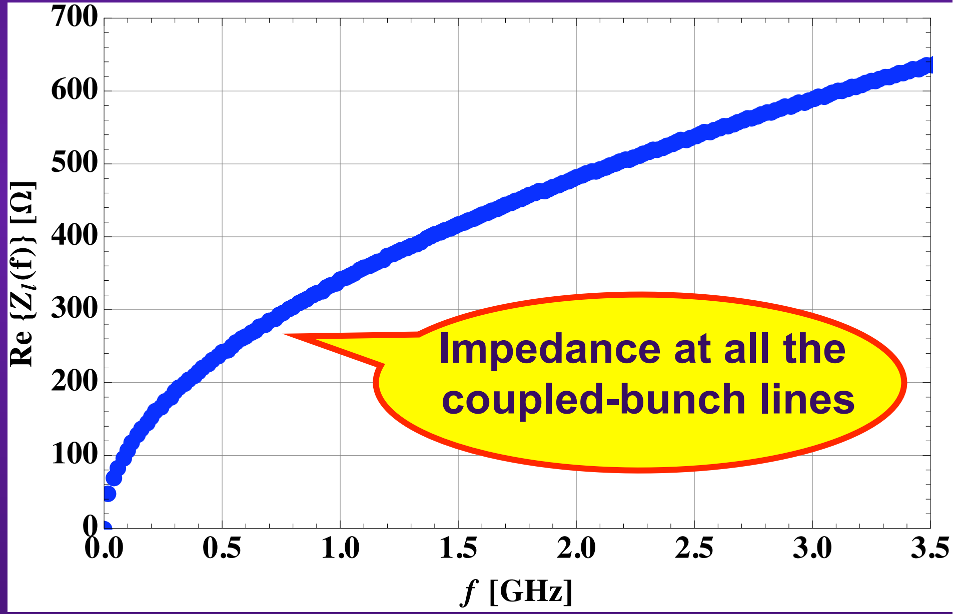
PhilippeB

- **Studies also by ThomasB and ElenaS with the PD Schottky => 2 peaks are visible**

RF HEATING (8/17)

- Consider 1st the case of the Resistive-Wall impedance => Application to the case of the LHC beam screen (neglecting the holes, whose contribution has been estimated to be small, and the weld for the moment)





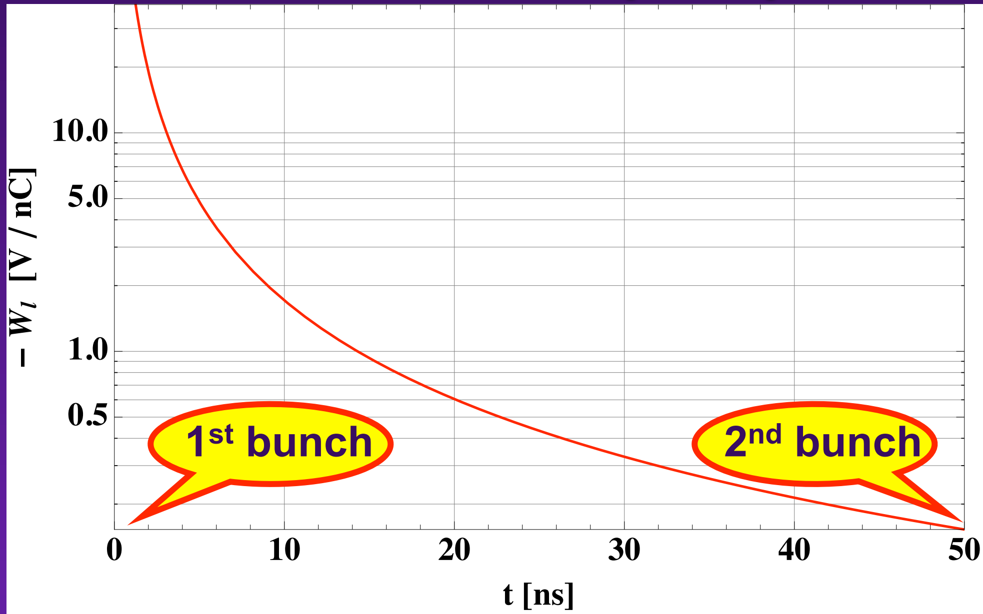
$$Z_l(f) = (1 + j)\,\frac{L}{2\pi b}\sqrt{\frac{\pi f \rho Z_0}{c}}$$

LHC circumference $= L = 2\pi R = 26658.883$ m

$\rho_{Cu}^{20K} = 5.5 \times 10^{-10}$ Ωm

$b =$ beam screen half height $= 36.8 / 2 = 18.4$ mm

RF HEATING (9/17)



$$f\left(p\, M\, \omega_0\right) = \mathrm{Re}\left[Z_l\left(p\, M\, \omega_0\right)\right] \times \mathrm{PowerSpectrum}\left[p\, M\, \omega_0\right]$$

$$\sum_{p=0}^{\infty} f\left(p\, M\, \omega_0\right) \approx \frac{1}{M\, \omega_0} \int_{x=0}^{\infty} f\left(x\right) dx$$

$$Z_{loss} = 2\, M \sum_{p=0}^{\infty} f\left(p\, M\, \omega_0\right)$$

=>

$$P_{loss} = \frac{2\, M\, I_b^2}{\omega_0} \int_{x=0}^{\infty} f\left(x\right) dx$$

RF HEATING (10/17)

- Assuming a Gaussian bunch

$$P_{loss/m}^{G,RW,1\,\text{layer}} = \frac{1}{2\pi R}\,\Gamma\!\left(\frac{3}{4}\right)\frac{M}{b}\left(\frac{N_b\, e}{2\pi}\right)^2 \sqrt{\frac{c\,\rho\, Z_0}{2}}\;\sigma_t^{-3/2} \approx 85 \text{ mW/m}$$

Euler gamma function

$$\Gamma\!\left(\frac{3}{4}\right) = 1.23$$

$M_{50} = 1782$ $\quad N_b = 1.4 \times 10^{11}$ p/b $\quad \sigma_t = 0.30$ ns

- Assuming the real power spectrum it would give the same result within few tens of %

- With the 25 ns beam and 2 times more bunches, it would give a factor 2 more power

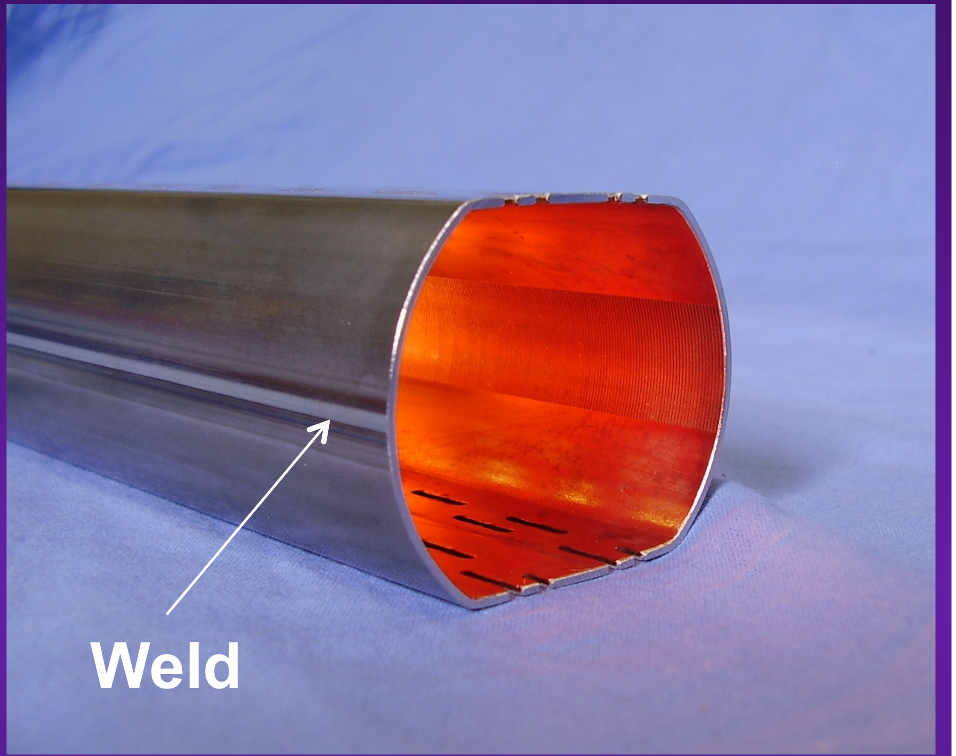
RF HEATING (11/17)

- **Consider now the longitudinal weld**

$$\rho_{Cu}^{20K} = 5.5 \times 10^{-10} \ \Omega\text{m}$$

$$\rho_{SS}^{20K} = 6 \times 10^{-7} \ \Omega\text{m}$$

$$\frac{\Delta_l^{Weld}}{2\,\pi\,b} = \frac{2}{2\,\pi \times 18.4} = \frac{1}{\pi \times 18.4} \approx \frac{1}{60}$$



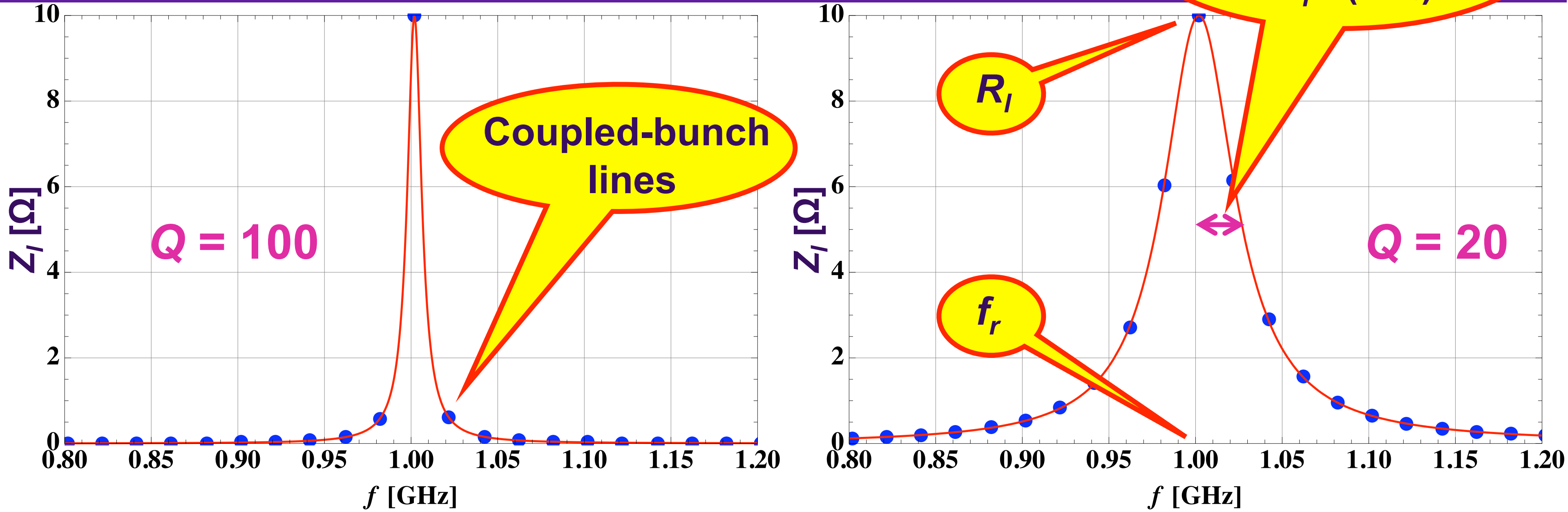
=>

$$\frac{P_{loss/m}^{Weld}}{P_{loss/m}^{G,RW,1\,\text{layer}}} \approx \sqrt{\frac{\rho_{SS}^{20K}}{\rho_{Cu}^{20K}}} \times \frac{\Delta_l^{Weld}}{2\,\pi\,b} \approx 57\%$$

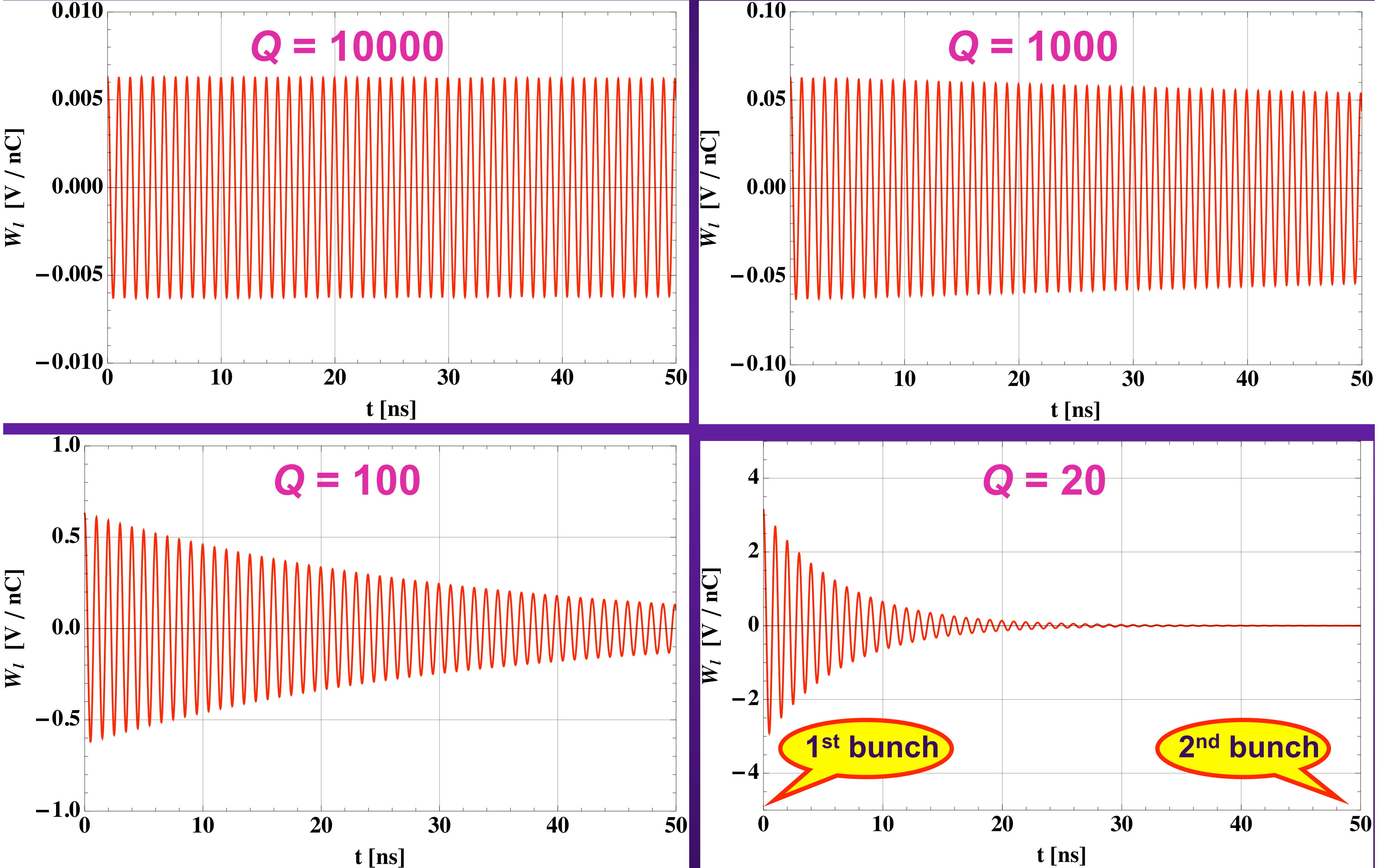
RF HEATING (12/17)

- Consider now the case of a narrow resonance (trapped mode due to the geometry) => 3 parameters:
  - Resonance frequency => Assumed to be here f_r = 1 GHz
  - Shunt impedance => Assumed to be here R_l = 10 Ω
  - Quality factor Q => Scanned below

HWHH = Half Width at Half Height = f_r / (2 Q)



RF HEATING (13/17)



RF HEATING (14/17)

- Power loss formula for the case of a (sharp) resonance (i.e. with only 1 line)

$$P_{loss} = (M\, I_b)^2 \times R_l \times 10^{\frac{P_{dB}(f_r)}{10}}$$

Total beam current

$P_{dB}(f_r)$ is the power in dB read from a power spectrum (computed or measured) at the frequency f_r

  - ✧ A.N.: M = 1380, N_b = 1.45E11 p/b => $M \times I_b = I_{total} \approx$ 0.36 A, R_l = 10 Ohm and f_r = 1 GHz => P_{dB} (1 GHz) ≈ - 17 dB (see slide 6) => $P_{loss} \approx$ 26 mW

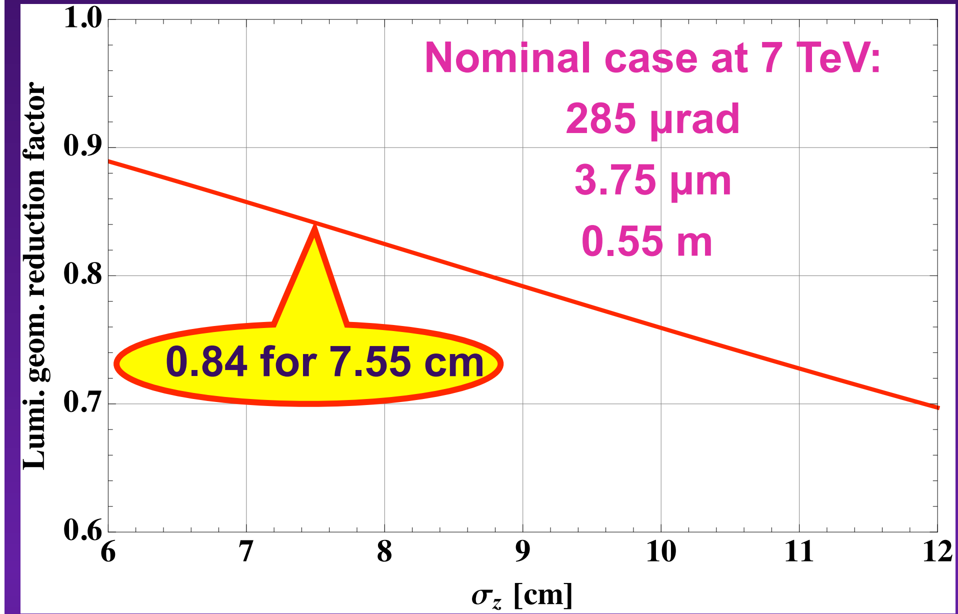
- Note that in the case of a Gaussian bunch, the power loss is

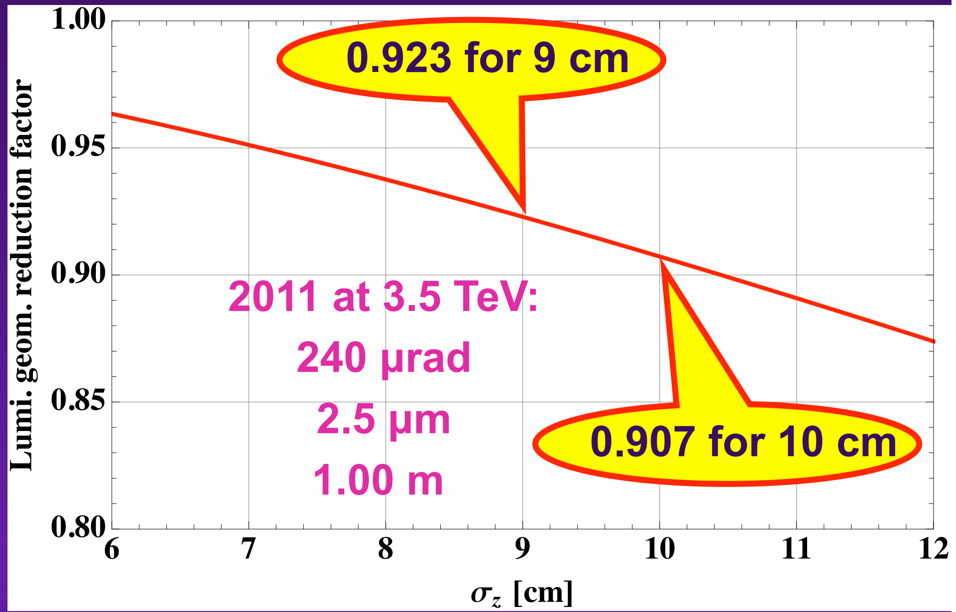
$$P_{loss}^{Gaussian} = (M\, I_b)^2 \times R_l \times e^{-(2\pi f_r \sigma_\tau)^2}$$

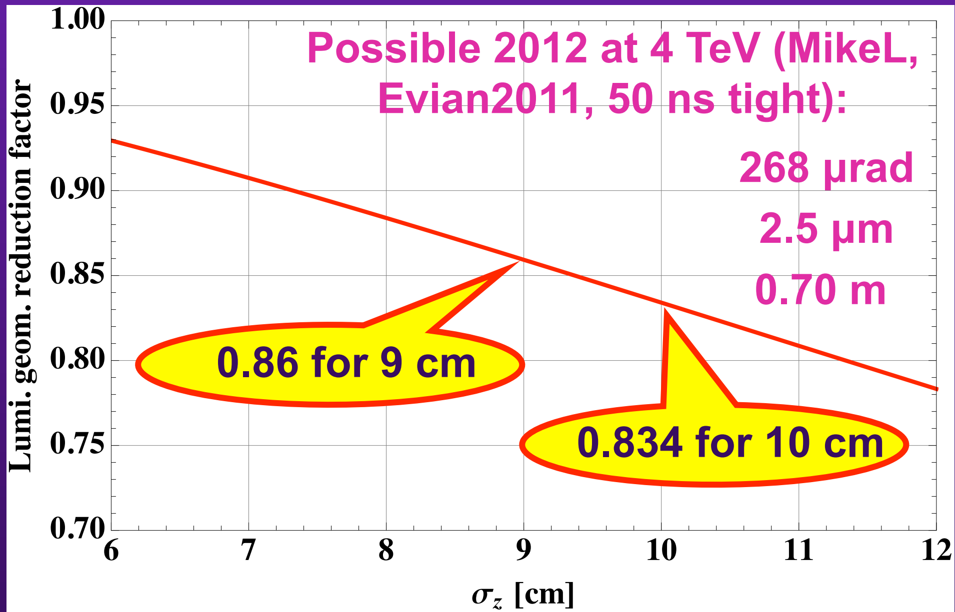
RF HEATING (15/17)

- Usual solutions to avoid RF heating => Depending on the situation
  - Increase the distance between the beam and the equipment
  - Coating with good conductor
  - Close large volumes (could lead to resonances at low frequency) and smooth transition => Beam screens, RF fingers etc.
  - Put ferrite (close to maximum of magnetic field of the mode):
    - Adding a material with losses the Q factor is decreased (by few tens, say 50), while the R / Q is conserved (depends only on the geometry)
    - => $R_2 = (R_1 / Q_1) \times Q_2$ is decreased by 50
    - => Power loss is decreased accordingly if Q still sufficiently high or less if other coupled-bunch lines are involved
    - The ferrite should absorb the remaining (much smaller) power
    - Note that the resonance frequency should also slightly decrease
  - Bunch length increase, but then lumi. geom. red. factor + possible losses from the bucket (to be studied in detail)

RF HEATING (16/17)







$$F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

RF HEATING (17/17)

- **Heat transfers**
  - **Convection: none in vacuum**
  - **Radiation: usually temperature already quite high**
  - **Conduction: if good contacts + good thermal conductivity**
  - **Active cooling => LHC strategy: All the near beam elements in the LHC are water cooled (Ralph Assmann)**

- **Synchronous phase shift as a meas. of power loss & impedance**
  - **Bunch power gain with no imped.:** $\Delta P_{bunch,1} = e\,\hat{V}_{RF}\,\sin\phi_{s1}\,f_0\,N_b$
  - **Delta bunch power due to impedance:**

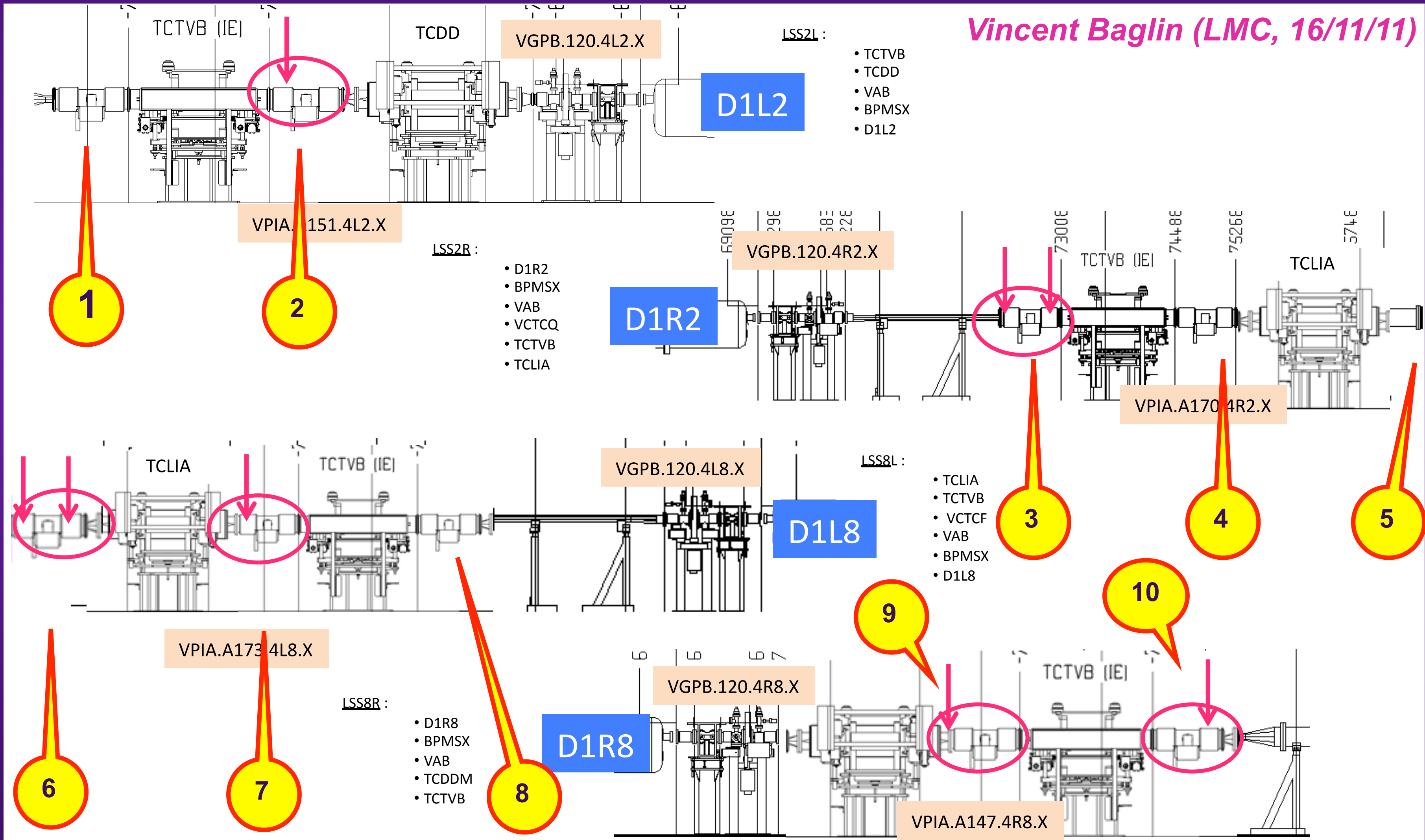
$$\Delta P_{bunch,1\rightarrow 2} = \Delta P_{bunch,2} - \Delta P_{bunch,1} = e\,\hat{V}_{RF}\,f_0\,N_b\left(\sin\phi_{s2} - \sin\phi_{s1}\right)$$

$$\approx e\,\hat{V}_{RF}\,f_0\,N_b\,\cos\phi_{s1}\,\Delta\phi_s \quad \text{with} \quad \Delta\phi_s = \phi_{s2} - \phi_{s1}$$

  - **Scaling with # of bunches *M* => Depends on the impedance!**

VMTSA (1/5)

- **10 modules (each of 2 bellows) in total in 2011. 8 bellows were found with defaults (see arrows below). 2 modules removed for 2012**



VMTSA (2/5)

Typical default, DCUM 3259.3524

Left side

Vincent Baglin (LMC, 16/11/11)

Side view (xray from corridor to QRL)

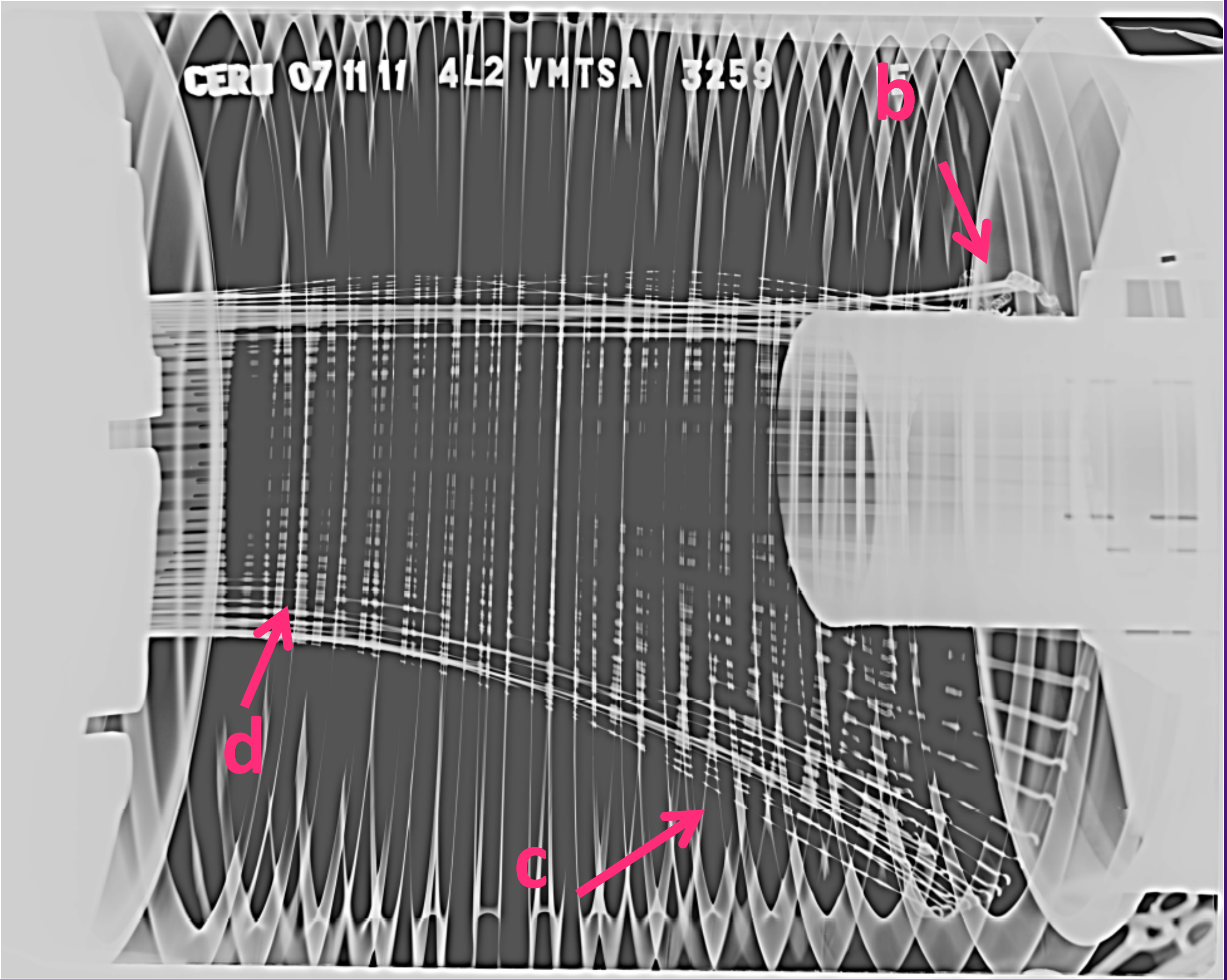
b) Metallic noise due to loose spring when hitting vacuum chamber

c) RF fingers falling due to broken spring

d) aperture reduced ?

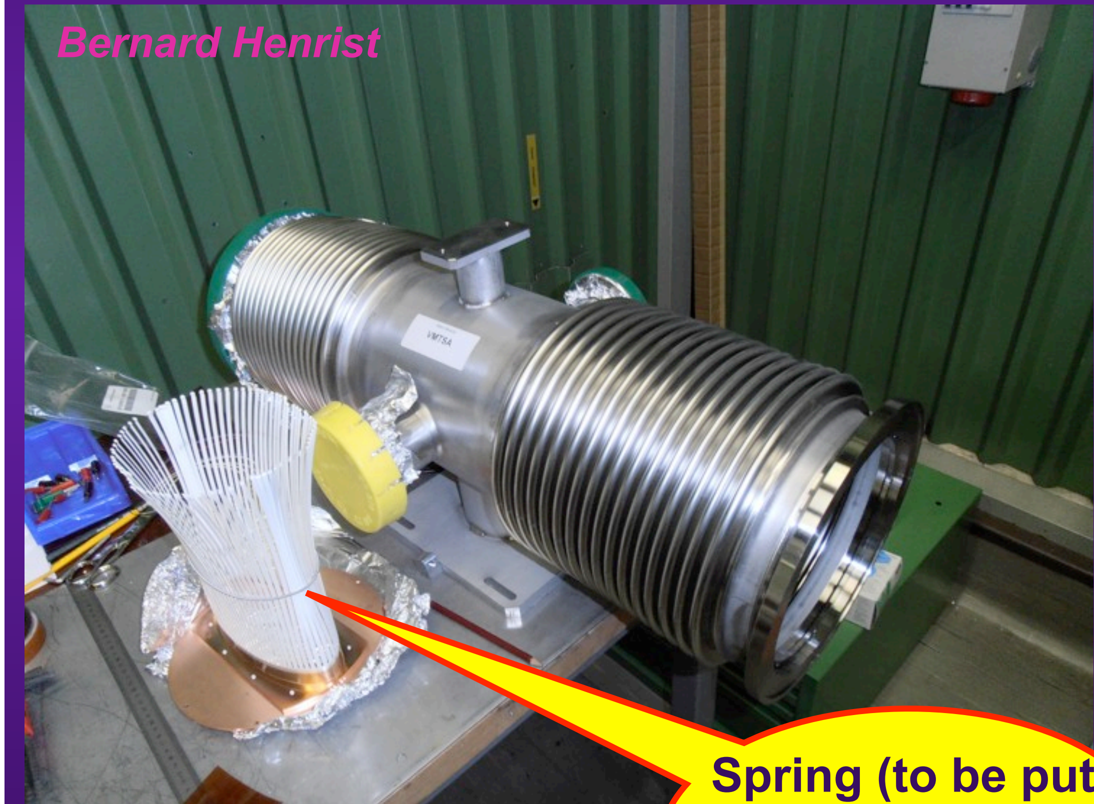
Non Conform

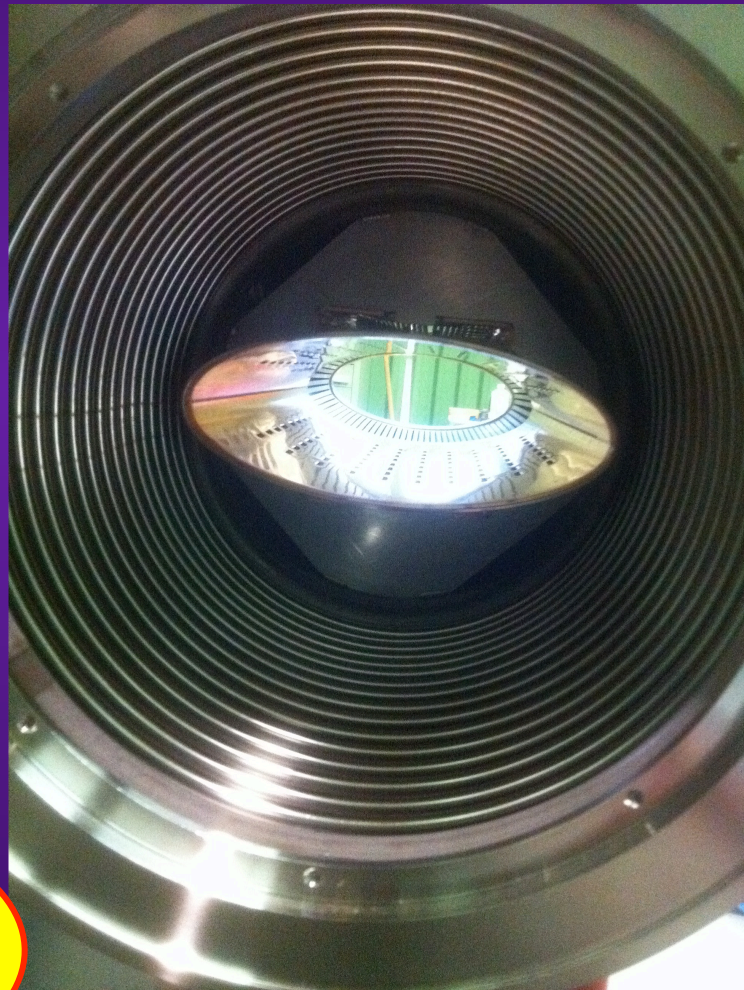
Spring was broken between May and November 2011



VMTSA (3/5)

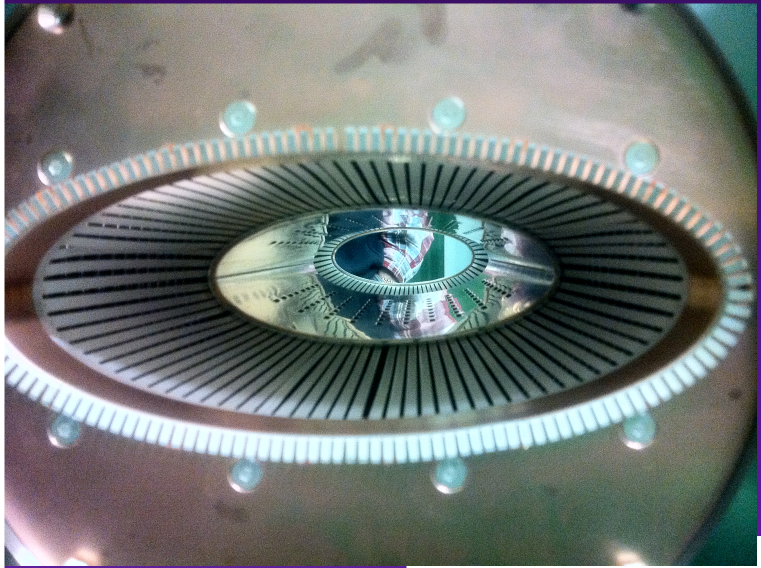
- **Why? Is it an impedance problem? => Bench impedance measurements with 1 wire (and simulations ongoing)**



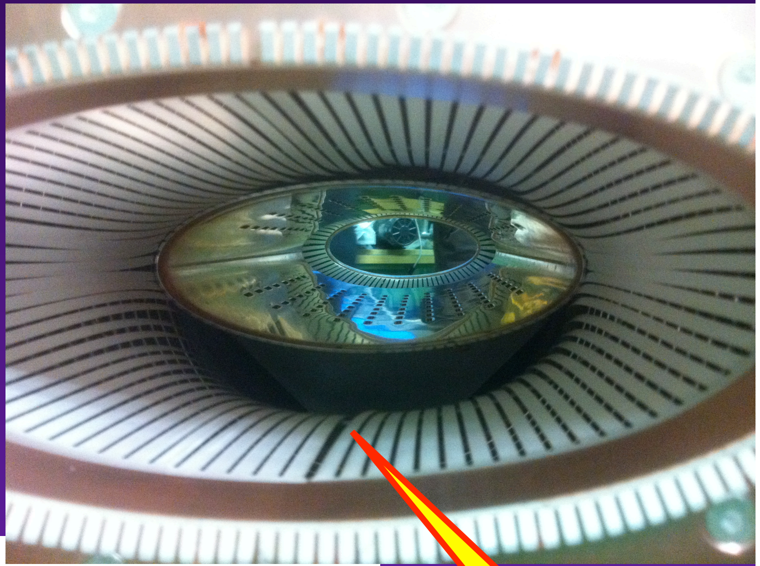


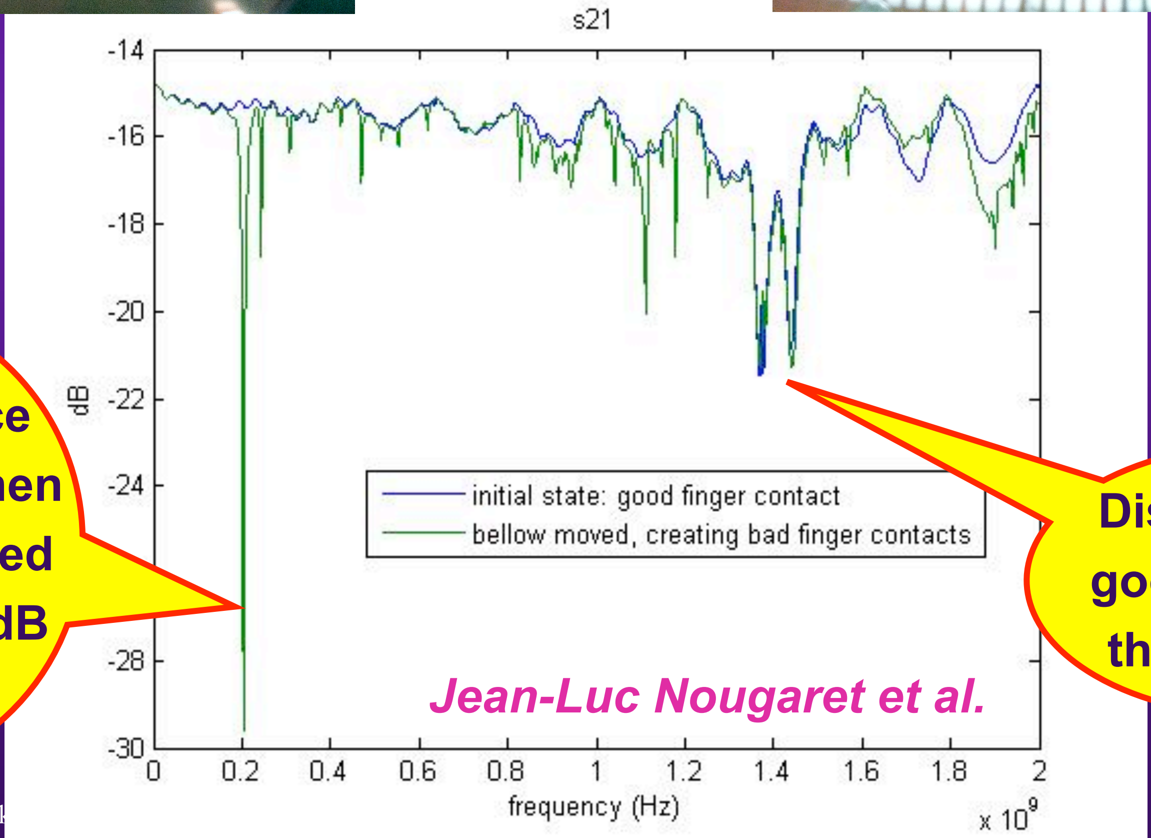
Spring (to be put at the extremity of the RF fingers)

VMTSA (4/5)



→ Spring jumped back by moving laterally the bellow by few mm





Spring

Huge resonance at ~ 200 MHz when the spring jumped back! => ~ - 15 dB in S_{21}

Disappear with good contact at the end plates

Jean-Luc Nougaret et al.

VMTSA (5/5)

- Longitudinal impedance can be deduced from S_{21}

$$Z_l = -2\, Z_{ch} \ln\left(\frac{S_{21}}{S_{REF}}\right)$$

$$S_{REF} = e^{-j\omega \frac{L}{c}}$$

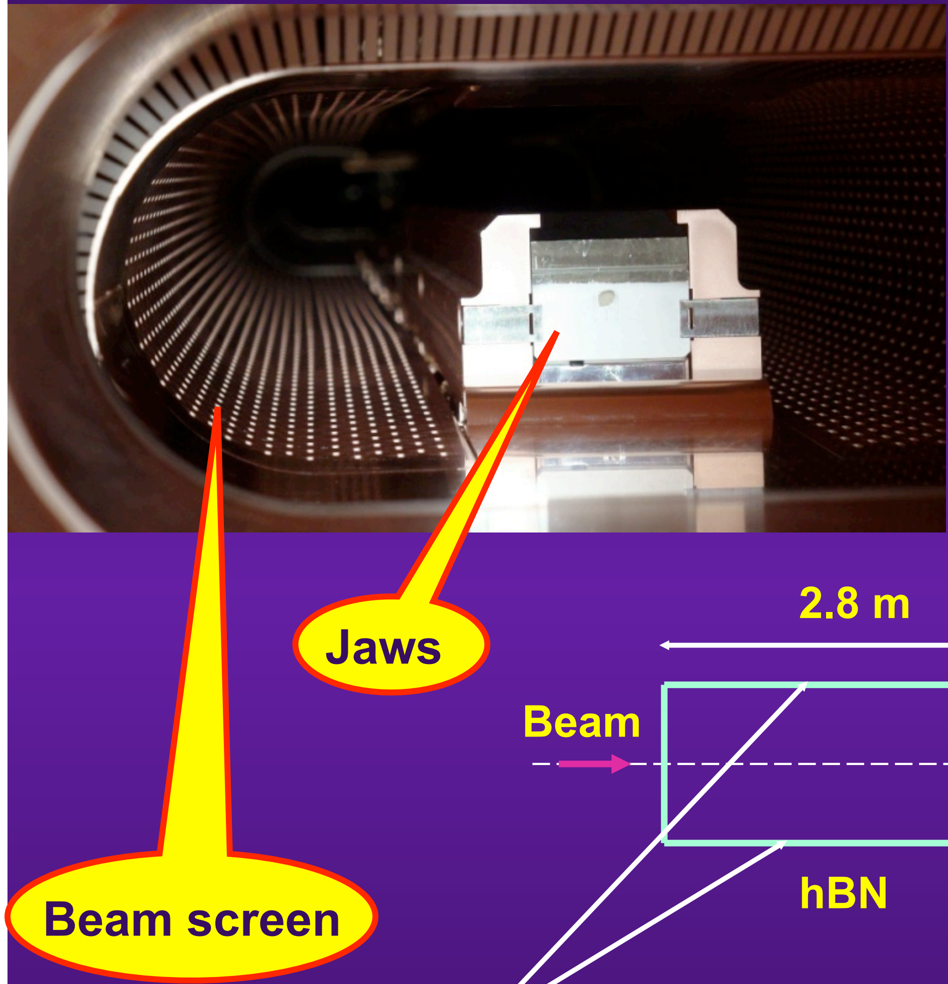
=> Numerical application for the real part of the impedance

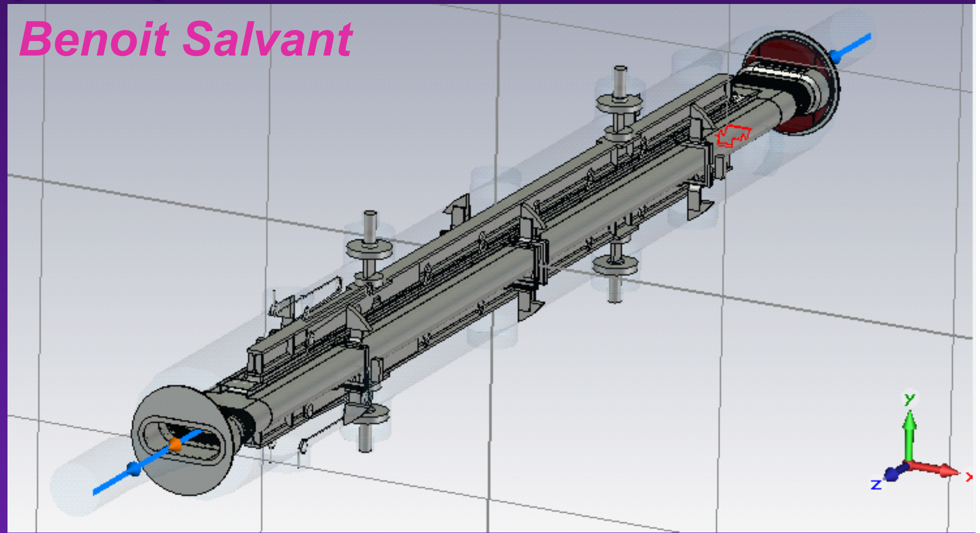
- Z_{ch} was measured and found to be ~ 270 Ω
- We use $S_{REF} = 1$

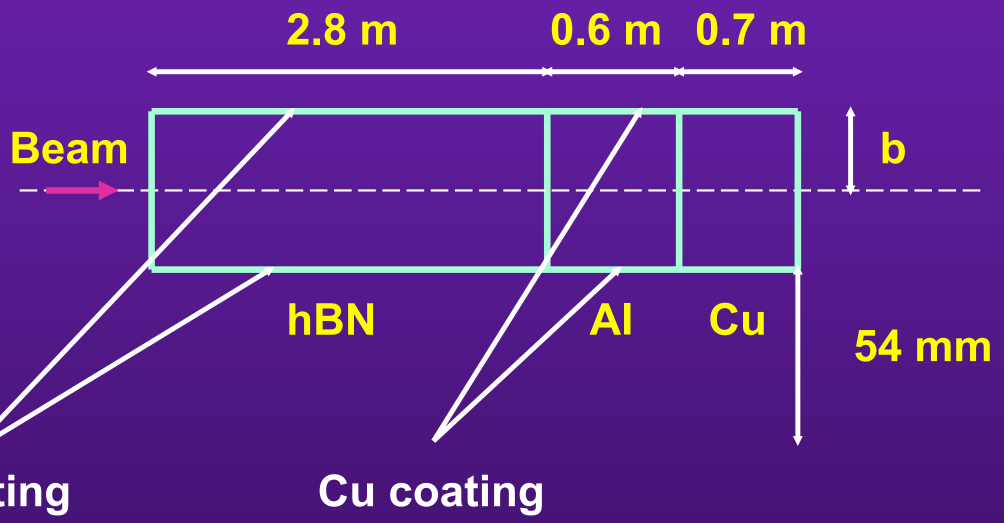
=> $$Z_l = -2\, Z_{ch} \ln\left(\frac{S_{21}}{S_{REF}}\right) = -2\, Z_{ch} \ln\left(10^{\frac{S_{21}[\,\mathrm{dB}\,]}{20}}\right) \approx 2 \times 270 \times \ln\left(10^{\frac{15}{20}}\right) \approx 930\ \Omega$$

- Power loss: P_{loss} ~ $0.36^2 \times 930 \times 0.7$ ~ 85 W for 1 beam and ~ 4 × 85 = 340 W for 2 beams (worst case)
- Conclusion: No impedance problem foreseen when the RF contacts are OK => 1st recommendation: Improve the RF contacts

TDI (1/13)







=> 2 contributions: resistive-wall (from the jaws) and trapped modes

TDI (2/13)

- **Observations during the 2011 run**
  - Vacuum pressure increase after ~ 1-2 h in stable beam, maximum reached and then decrease:
    - Started on May 1st, 2011 for TDI.4R8
    - Started on August 6th, 2011 for TDI.4L2
  - Heating at both extremities (meas. after installation of thermocouples) on TDI.8R => Delta from 8 to 17 deg
  - Since fill # 2219 (16/10) the TDI ½ gap was increased from 22 mm to 55 mm (parking position) in stable beam
    - Pressure => Remains in the few 1E-8 mbar range
    - BUT, temperature increase remains
  - Higher impedance than expected from simulations and from previous measurements in 2010 => See NicolasM's talk at Evian11
  - Unstable positions meas., unexpected aperture restriction in P2…

TDI (3/13)

- **=> Inspection was requested**
  - Check the hBN metallization + shielding foil (large imp. meas.)
  - Identify possible aperture restrictions for B1 between TDI and TCTVB left of point 2 evidenced by the aperture measurements conducted in preparation of the 2011 ion run

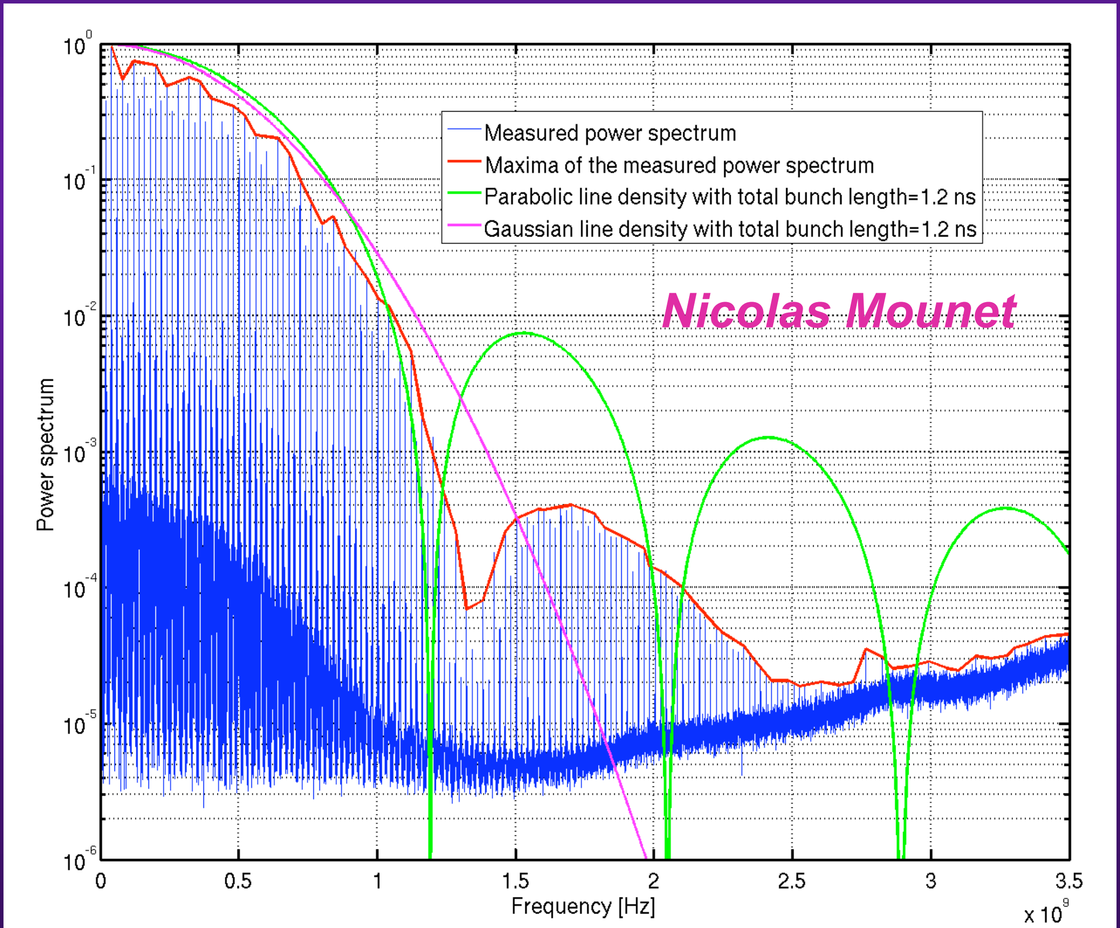
- **Conclusions of the visual inspection**
  - Ti coating seems to be OK
  - But, deformation of the beam screen in P8 mainly and to a smaller extent in P2 also
  - Soft copper used for the beam screen instead of copper coated stainless steel

TDI (4/13)

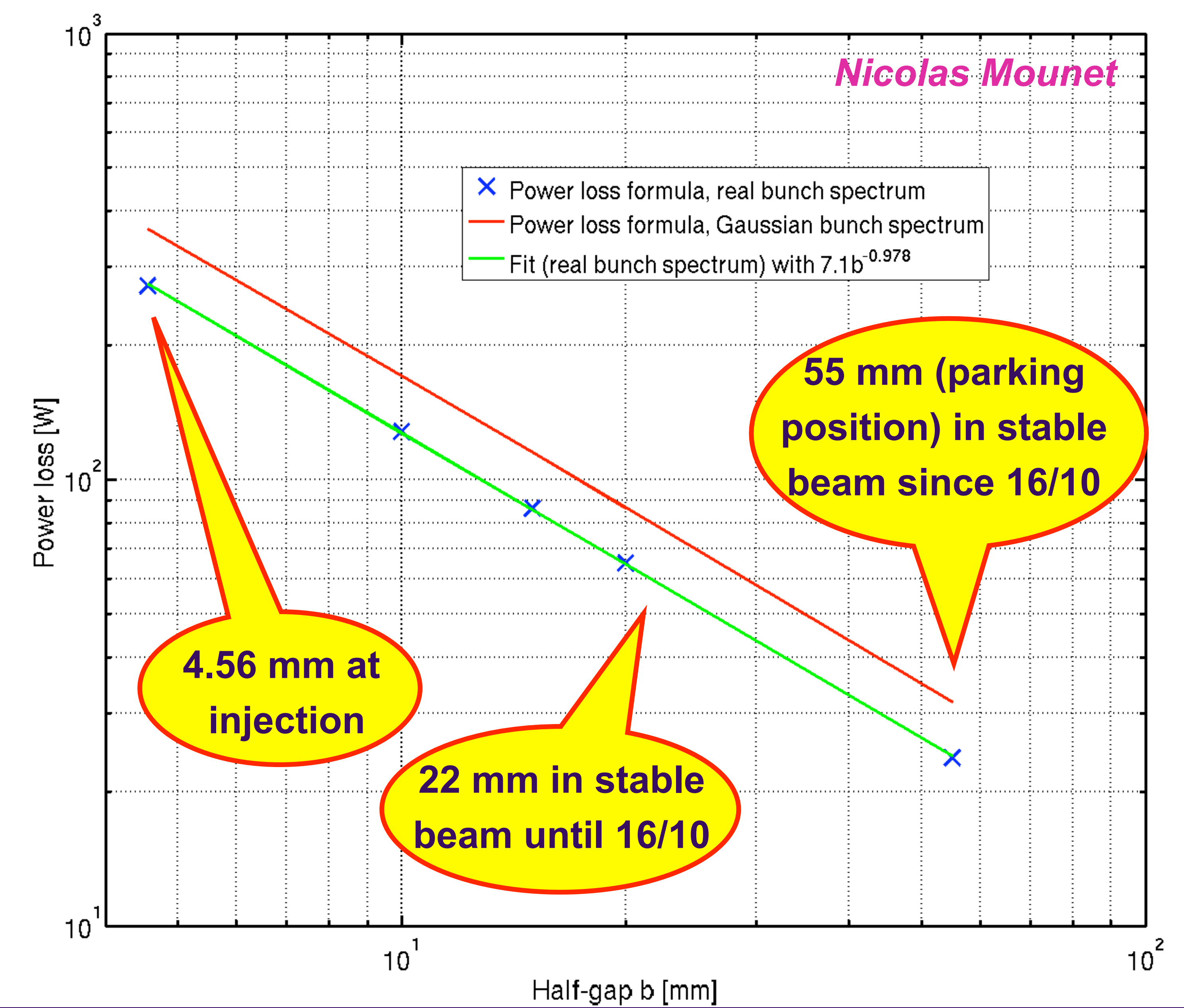
- **What is the role of the impedance? => Reminder on past predictions**
  - Power loss due to resistive-wall (jaws) ~ 200 W
  - Water cooling present on the Al frame holding the blocks – but clamped, not brazed. Capacity 20 kW => How much cooling at block surfaces?
  - Trapped modes and beam screen => Work done in the past to minimize them (simulations and measurements done with some limitations) => Not expected to be a big problem
  - No cooling of the beam screen
  - Nominal TDI operation: Should be IN only for injection (~ 20 min for nominal case) and then fully retracted (~ 55 mm half gap) => No impedance issue foreseen in the fully retracted position

TDI (5/13)

- **Power loss from resistive-wall has been re-estimated for 1380 bunches, 1.45E11 p/b, 1.2 ns 4-sigma bunch length, half gap 4.56 mm**
  - **It is mainly in the Ti coating of the hBN block**
  - **hBN has a very good thermal conductivity => All the block heated**

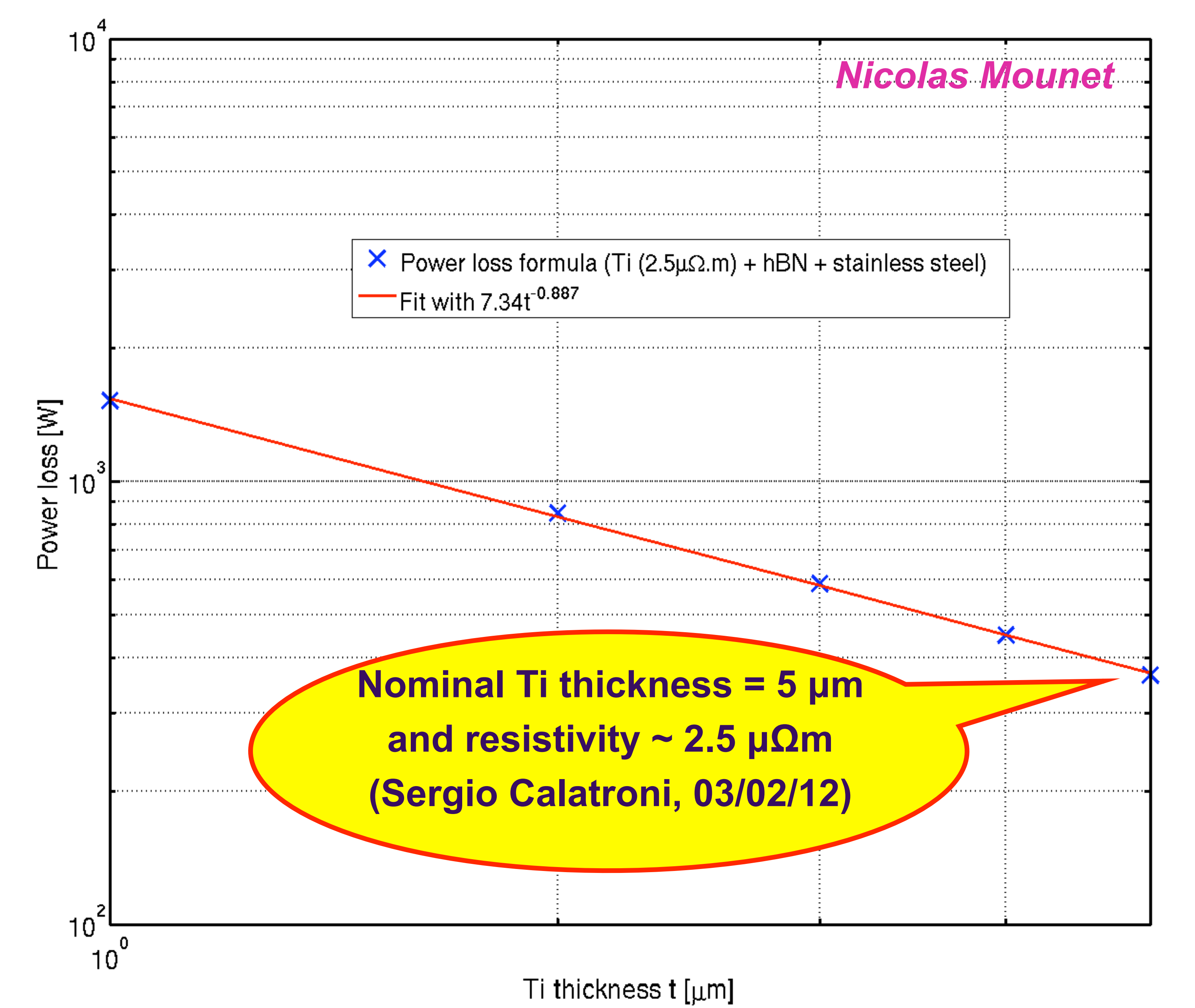


TDI (6/13)



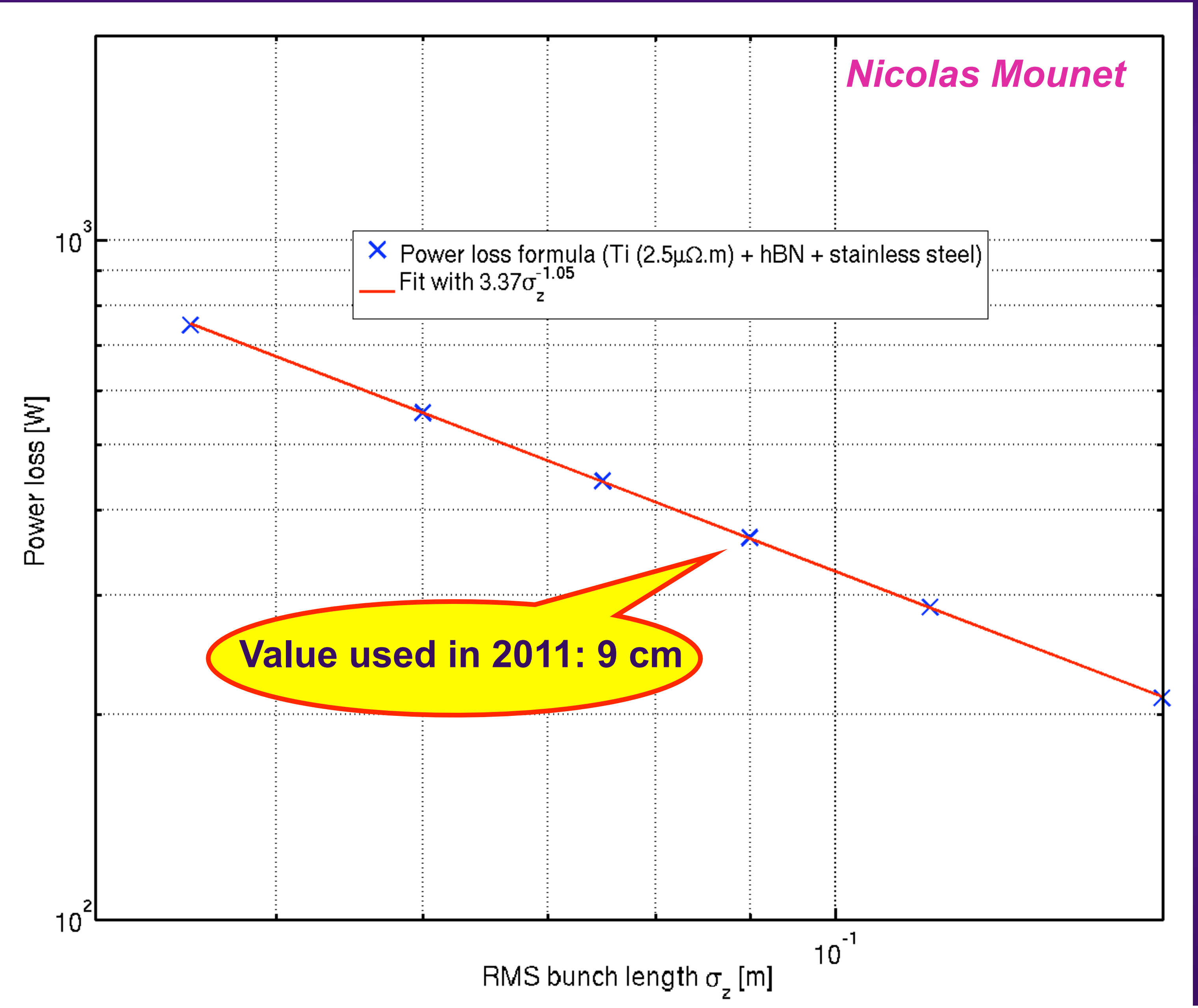
Nicolas Mounet
Power loss formula, real bunch spectrum
Power loss formula, Gaussian bunch spectrum
Fit (real bunch spectrum) with 7.1b$^{-0.978}$
55 mm (parking position) in stable beam since 16/10
4.56 mm at injection
22 mm in stable beam until 16/10
Power loss [W]
Half-gap b [mm]
10^3
10^2
10^1
10^1
10^2

TDI (7/13)



Nicolas Mounet
Power loss formula (Ti (2.5μΩ.m) + hBN + stainless steel)
Fit with 7.34t^-0.887
Power loss [W]
Ti thickness t [μm]
Nominal Ti thickness = 5 μm
and resistivity ~ 2.5 μΩm
(Sergio Calatroni, 03/02/12)

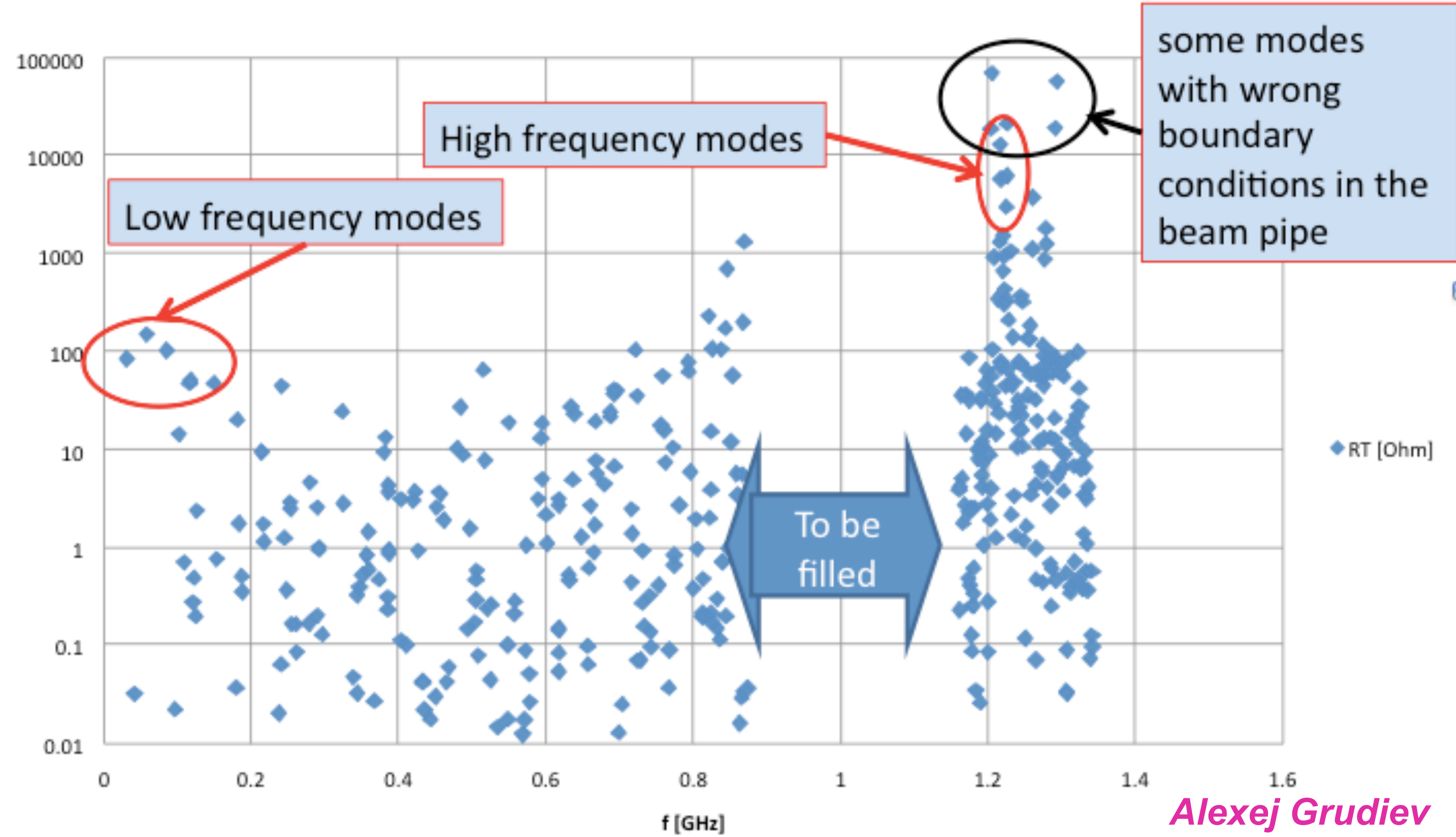
TDI (8/13)



Nicolas Mounet
Power loss formula (Ti (2.5µΩ.m) + hBN + stainless steel)
Fit with $3.37\sigma_z^{-1.05}$
Value used in 2011: 9 cm
10^3
10^2
Power loss [W]
10^{-1}
RMS bunch length σ_z [m]

TDI (9/13)

- **Power loss from trapped modes estimated with the 3D model (done in fall 2011) for a half gap of 8 mm (still work in progress)**

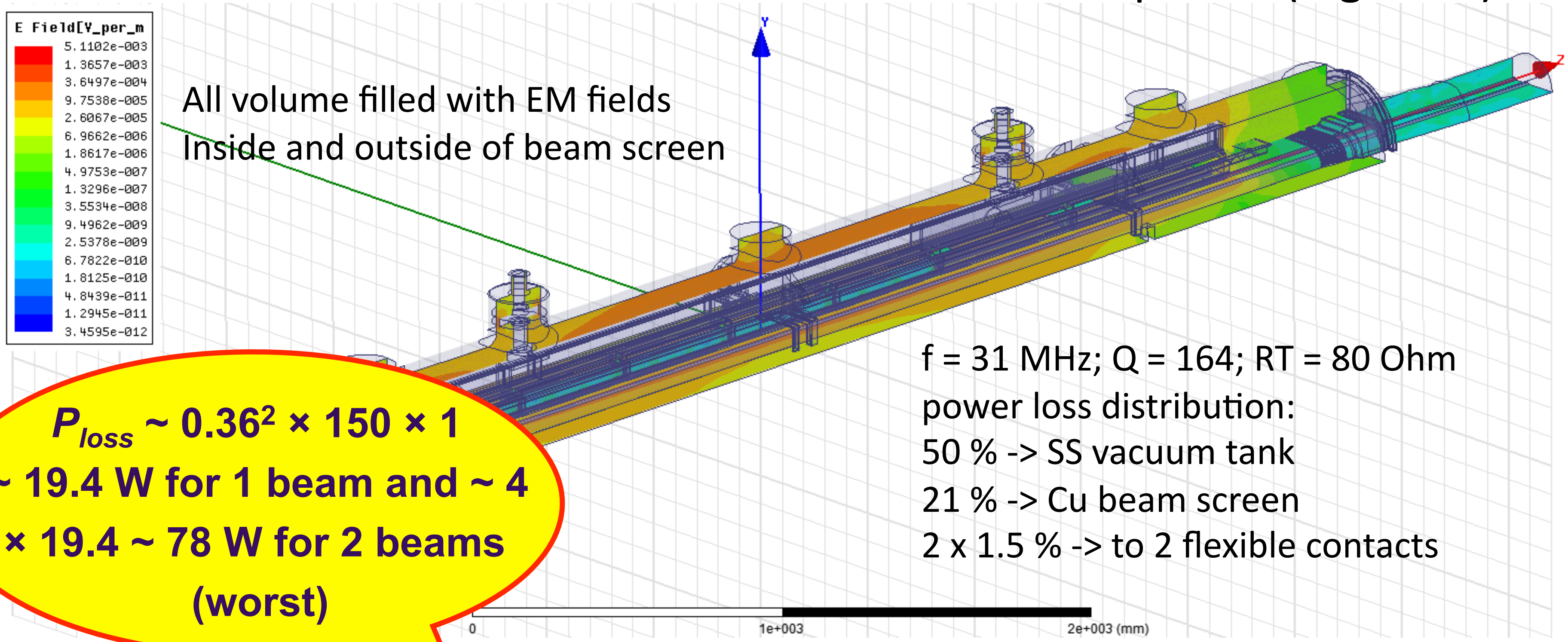


Alexej Grudiev

TDI (10/13)

Low frequency mode at 31 MHz

Electric field distribution in horizontal and vertical planes (log scale)



All volume filled with EM fields
Inside and outside of beam screen

f = 31 MHz; Q = 164; RT = 80 Ohm
power loss distribution:
50 % -> SS vacuum tank
21 % -> Cu beam screen
2 x 1.5 % -> to 2 flexible contacts

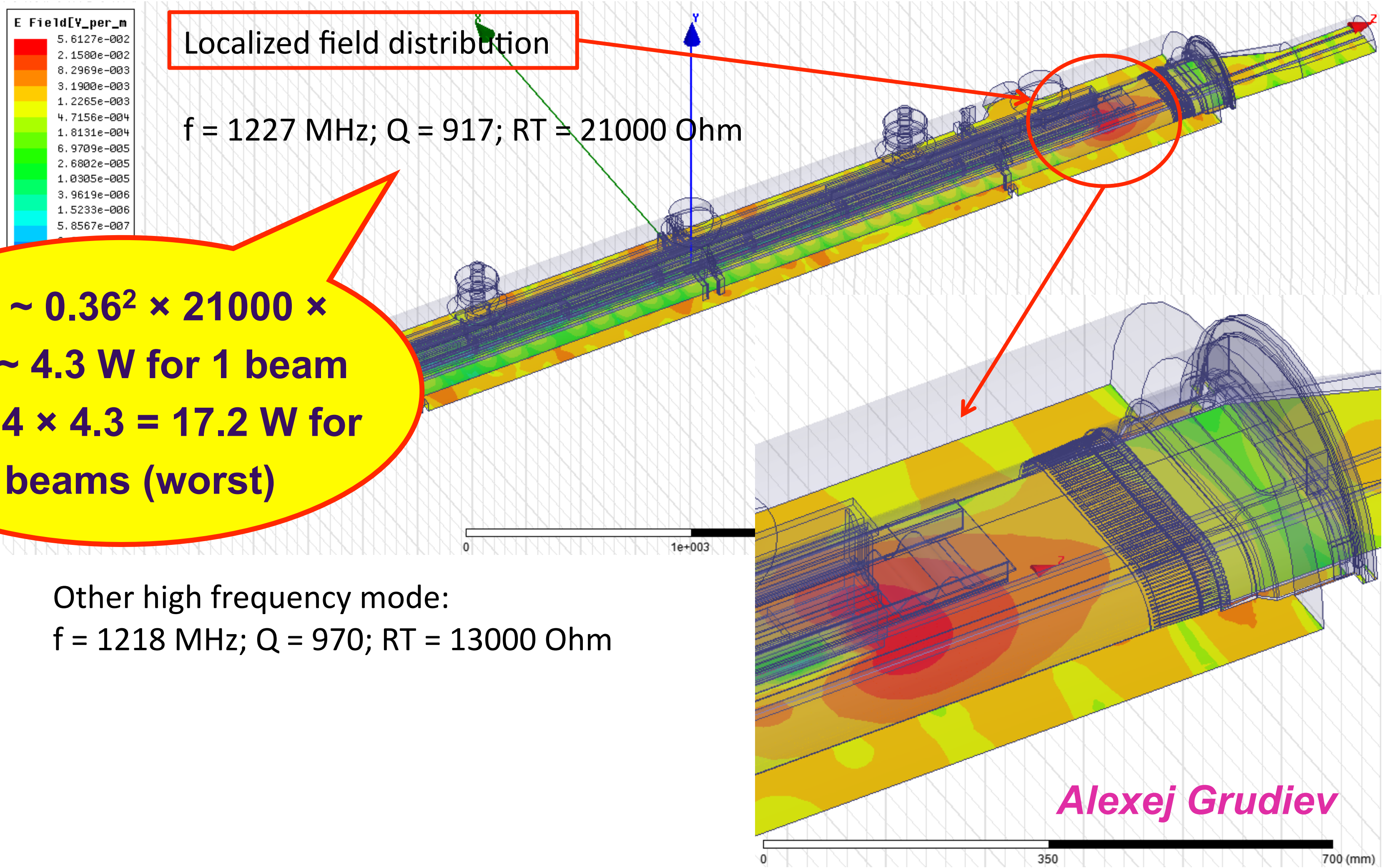
P_{loss} ~ 0.36² × 150 × 1 ~ 19.4 W for 1 beam and ~ 4 × 19.4 ~ 78 W for 2 beams (worst)

Other low frequency modes have similar field distribution:
f = 59 MHz; Q = 195; RT = 150 Ohm
f = 86 MHz; Q = 207; RT = 100 Ohm

Alexej Grudiev

TDI (11/13)

High frequency mode at 1227 MHz (preliminary)
Electric field distribution in horizontal planes (log scale)



Localized field distribution

f = 1227 MHz; Q = 917; RT = 21000 Ohm

P_{loss} ~ 0.36^2 × 21000 × 10$^{-2.8}$ ~ 4.3 W for 1 beam and ~ 4 × 4.3 = 17.2 W for 2 beams (worst)

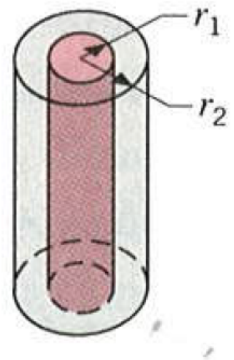
Other high frequency mode:
f = 1218 MHz; Q = 970; RT = 13000 Ohm

Alexej Grudiev

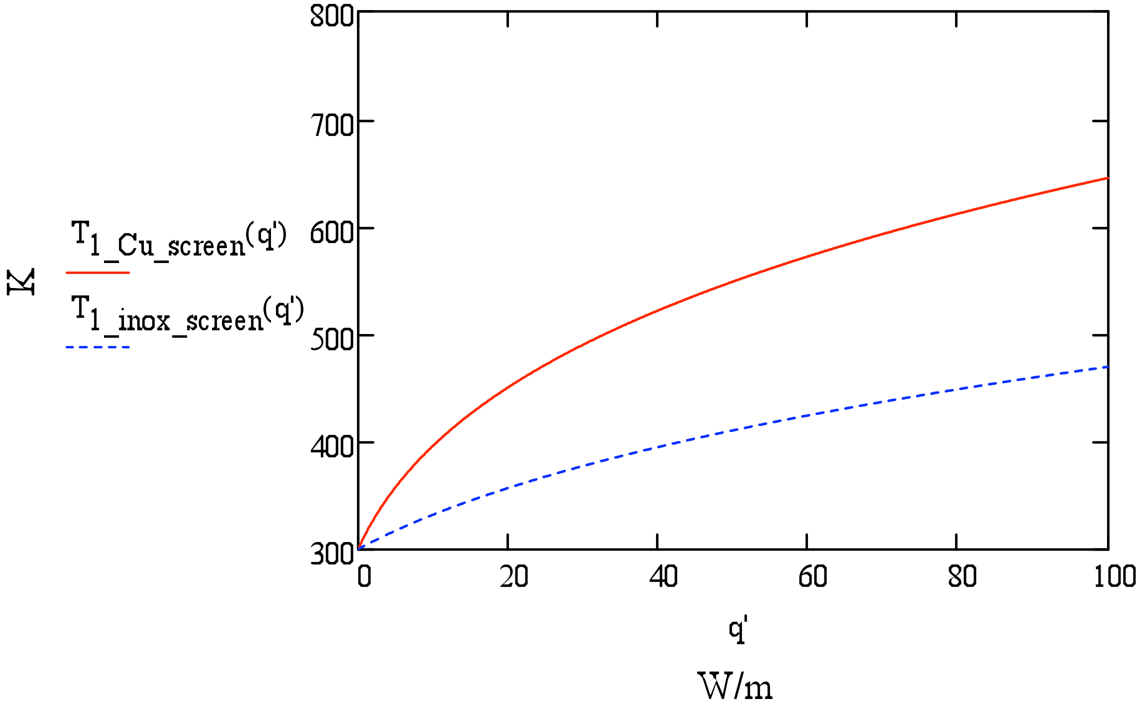
TDI (12/13)

Beam screen temperature estimation

- Radiation between diffuse gray surfaces in an enclosure
- Steady state heat exchange between two infinitely long concentric cylinders
- Vacuum tank at room temperature (T2)
- Beam screen (inner cylinder) temperature (T1) calculated for a given heat input per unit length (q')



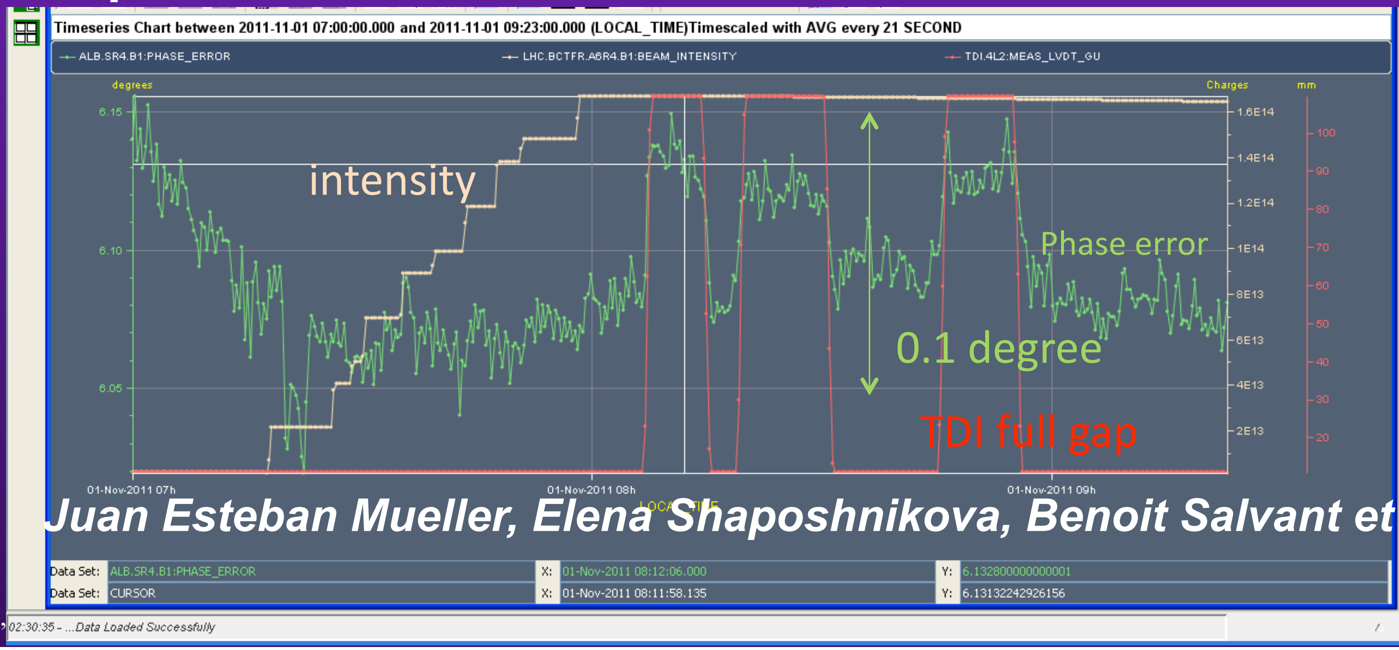
$$q_{12} = \frac{\sigma A_1 (T_1^4 - T_2^4)}{\dfrac{1}{\varepsilon_1} + \dfrac{1-\varepsilon_2}{\varepsilon_2}\left(\dfrac{r_1}{r_2}\right)}$$



Delio Duarte Ramos

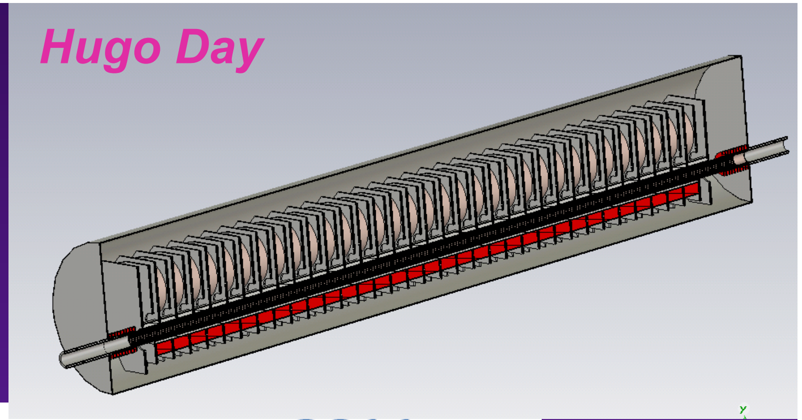
TDI (13/13)

- **Synchronous phase shift measurements during MDs**
  - **Increase of power loss of ~ 1 to 2 kW when closing the TDI jaws from parking to 4.7 mm half gap**
  - **Seems to be ~ linear with the number of bunches => Would mean that it is mainly dominated by a broad-band impedance, i.e. resistive-wall? Reminder: ~ 300-400 W predicted => Higher Ti resistivity and/or smaller thickness? Could explain also the larger transverse impedance…**



Juan Esteban Mueller, Elena Shaposhnikova, Benoit Salvant et al.

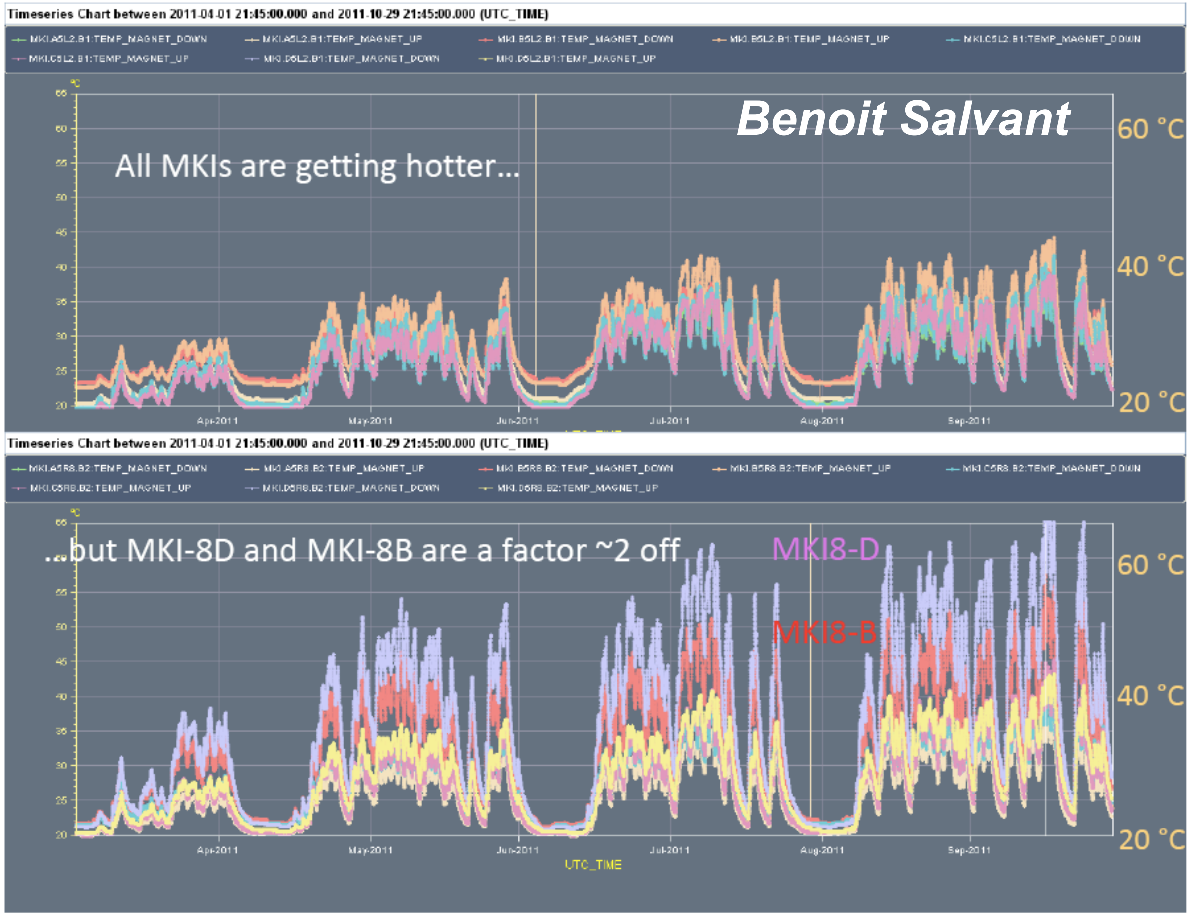
MKI (1/3)



MKIs: steady temperature increase over 2011

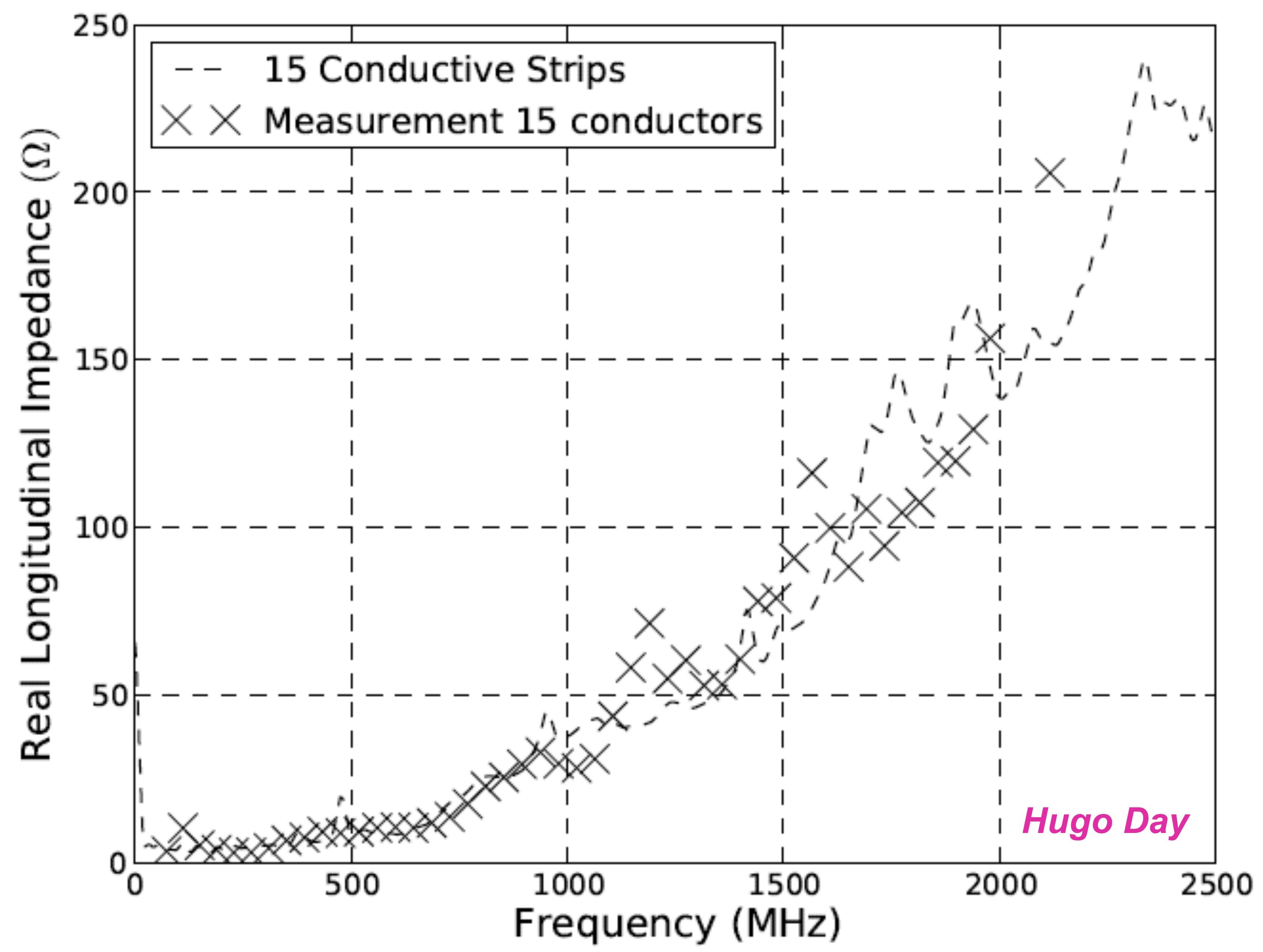
MKI
in point 2

MKI
in point 8



April 1st 2011 → October 31st 2011

MKI (2/3)



15 Conductive Strips
Measurement 15 conductors
Real Longitudinal Impedance (Ω)
Frequency (MHz)
0
50
100
150
200
250
0
500
1000
1500
2000
2500
Hugo Day

MKI (3/3)

Hugo Day

Original design but then reduced to 15 due to HV electrical breakdown

	25ns		50ns	
	1.1ns (W)	1.2ns (W)	1.1ns (W)	1.2ns (W)
24 Screen Conductors	44	43	17	16
15 Screen Conductors	150	133	78	68
No Screen Conductors	4817	3703	3067	2663
15 long, 9 short	138	127	69	62
No Metalisation	47660	40637	30187	27841
No Damping Ferrites	28	27	15	14
No Screen	4904	4314	3120	2745
Alt Screen 1	75	74	33	33

Assuming 1.15E11 p/b => It is 1.7 times higher for 1.5E11 p/b

LESSONS FOR 2012 (AND AFTER)

- **VMTSA:** No impedance problem if good RF contacts => Task force suggested / approved by recent LMC to check all the RF contacts => Discussion with MiguelJ ongoing
- **TDI:** Jaws should be IN only for injection (~ 20 min in nominal case) and then should be fully retracted. Is the beam screen deformation a consequence of the impedance with small gap? Can we add a Cu coating on the Ti flash? => Would gain a lot if needed for scrubbing…! Cooling?
- **MKI:** Impedance simulations now in very good agreement with past measurements => No surprise with the impedance. Might need to wait few h before injecting. MKI8D should be changed in August 2012 with 24 screen conductors instead of 15, i.e. lower heating. Future: improve cooling system? high-Curie temperature ferrite? etc.
- **ALFA detector (not a worry for the LHC machine but for the experiment):** Remove it for high intensity? (as in the design report?) => Time needed to remove and re-install it: few days?. Install some cooling (as TOTEM) during LS1