BEAM INDUCED RF HEATING IN THE LHC

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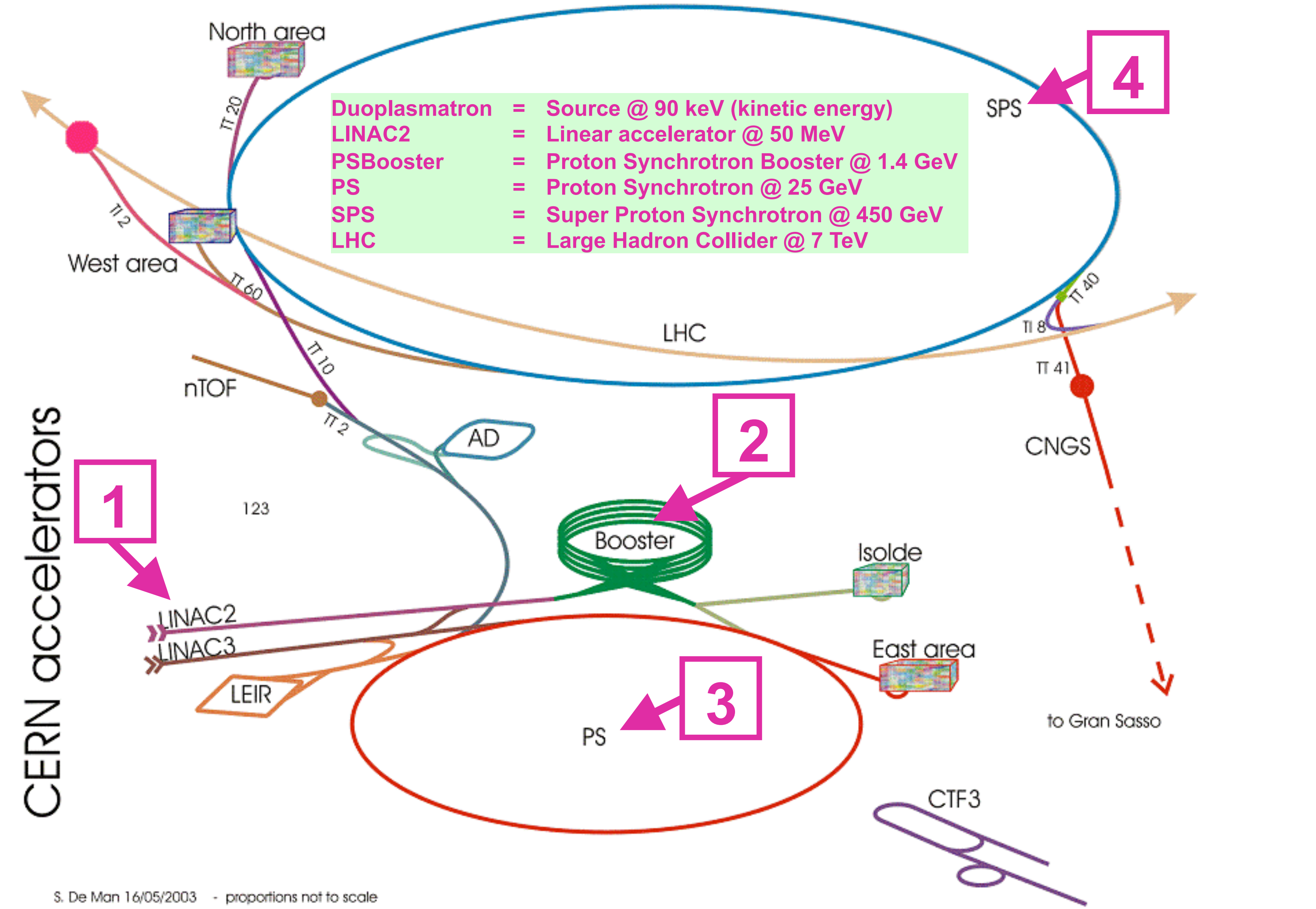
45 min, 62 slides

- **ABSTRACT for the talk: Beam-induced RF heating has been observed in several LHC components during the 2011 and 2012 runs when the bunch/beam intensity was increased and/or the bunch length reduced. This caused beam dumps and delays for beam operation (and thus less integrated luminosity) as well as considerable damages for some equipments. This contribution summarizes these observations and their current understanding**

- **HOMEWORK: Results for the simulations required on a simplified strip line structure**



LHC injector chain

RELEVANT NOMINAL LHC BEAM PARAMETERS

Beam energy	E	7 TeV (4 in 2012)
Number of particles per bunch	N_b	1.15 10^{11} (~ 1.6 in 2012)
Number of bunches per beam	M	2808 (1380 in 2012)
Revolution frequency	f_0	11245 Hz
Bunch spacing	Δt	25 ns (50 in 2012)
Rms bunch length	σ_z	7.55 cm (~ 10 in 2012)
Bunch charge	Q	18.4 nC (25.6 in 2012)
Total beam current	I_b	0.58 A (~ 0.4 in 2012)

OUTLINE FOR THE TALK

- **RF heating computations**
  - 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
- **LHC observations of beam-induced RF heating in 2011-2012**
- **RF Task Force in 2012**
  - Why do we need RF fingers and/or ferrite (absorbers)?
  - Several designs for RF fingers
  - Possible issues to consider with RF fingers
  - Typical nonconformities in warm modules found with X-rays
  - Conclusions and recommendations

RF HEATING COMPUTATIONS (1/14)

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

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

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

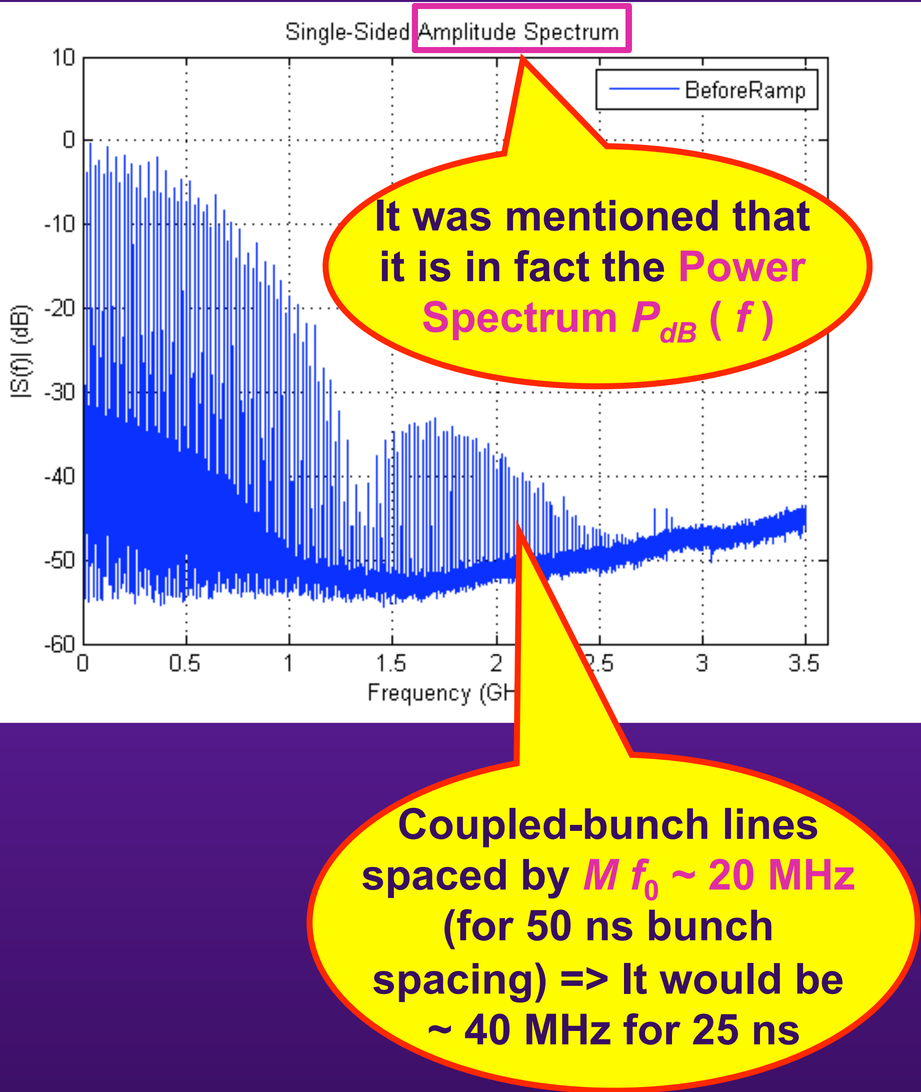
$$I_b = N_b \, e \, f_0$$

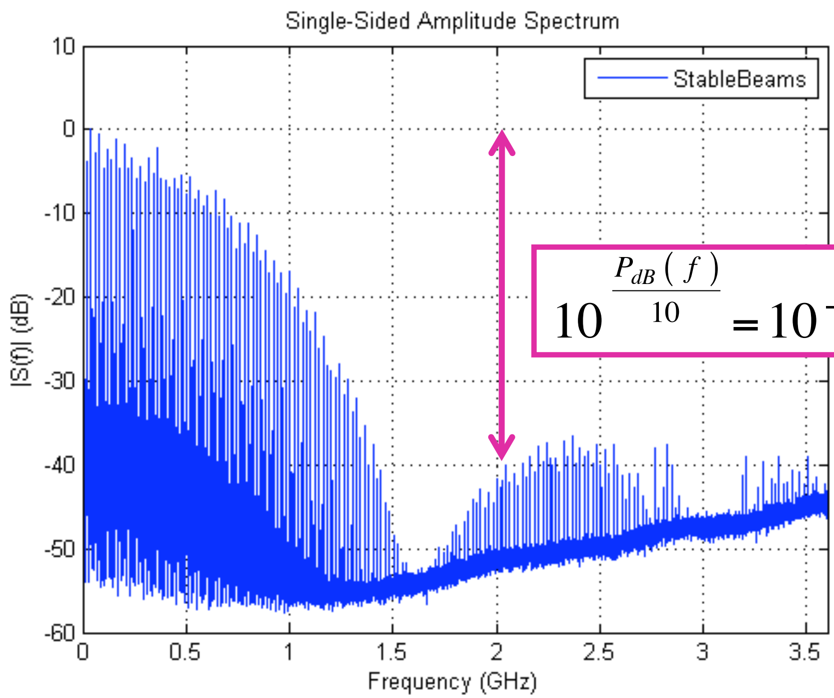
$$\omega_0 = 2 \, \pi \, f_0$$

  - **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 COMPUTATIONS (2/14)

Measurements on B1 by ThemisM and PhilippeB on fill # 2261



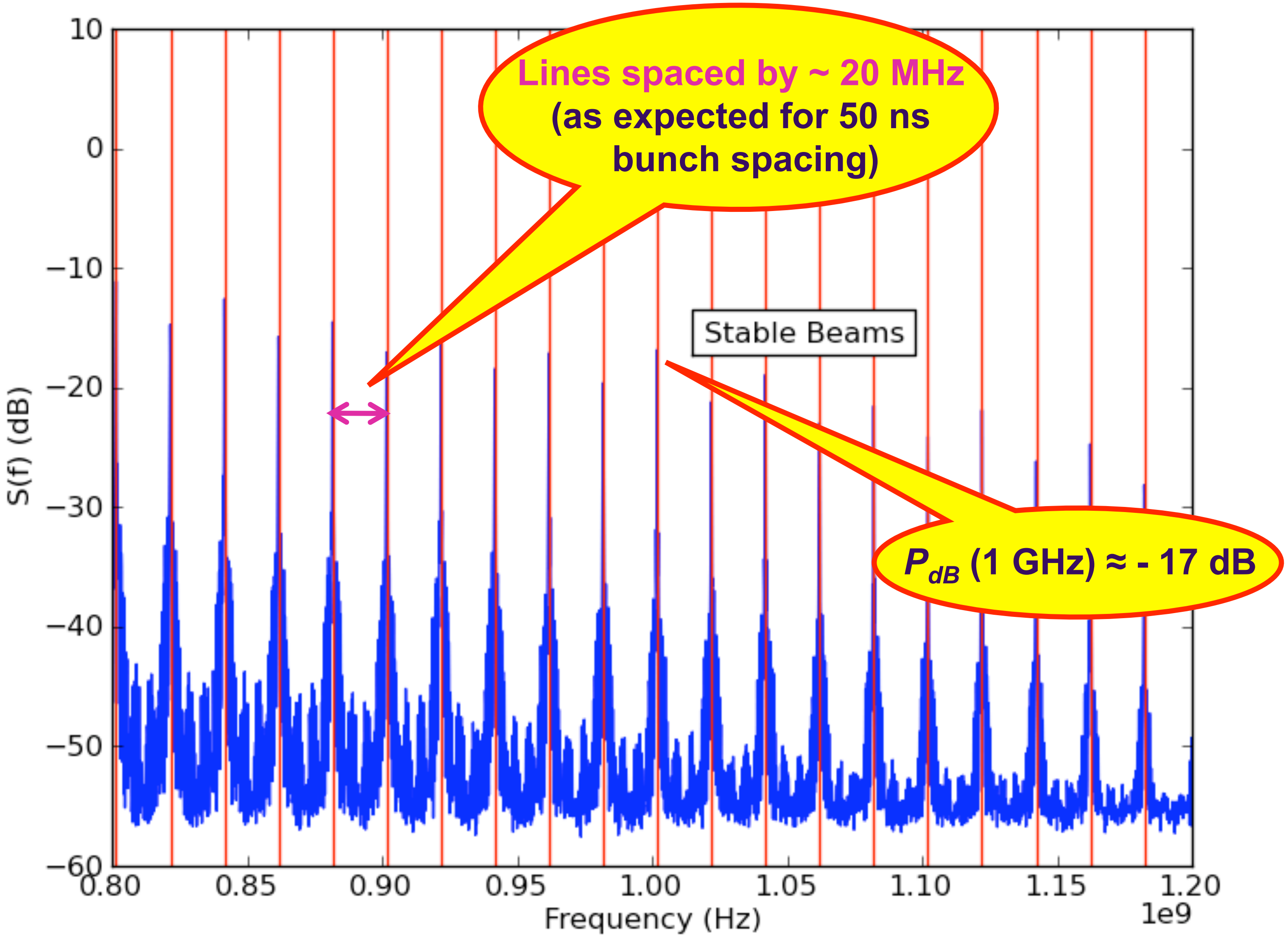


$$10^{\frac{P_{dB}(f)}{10}} = 10^{-4}$$

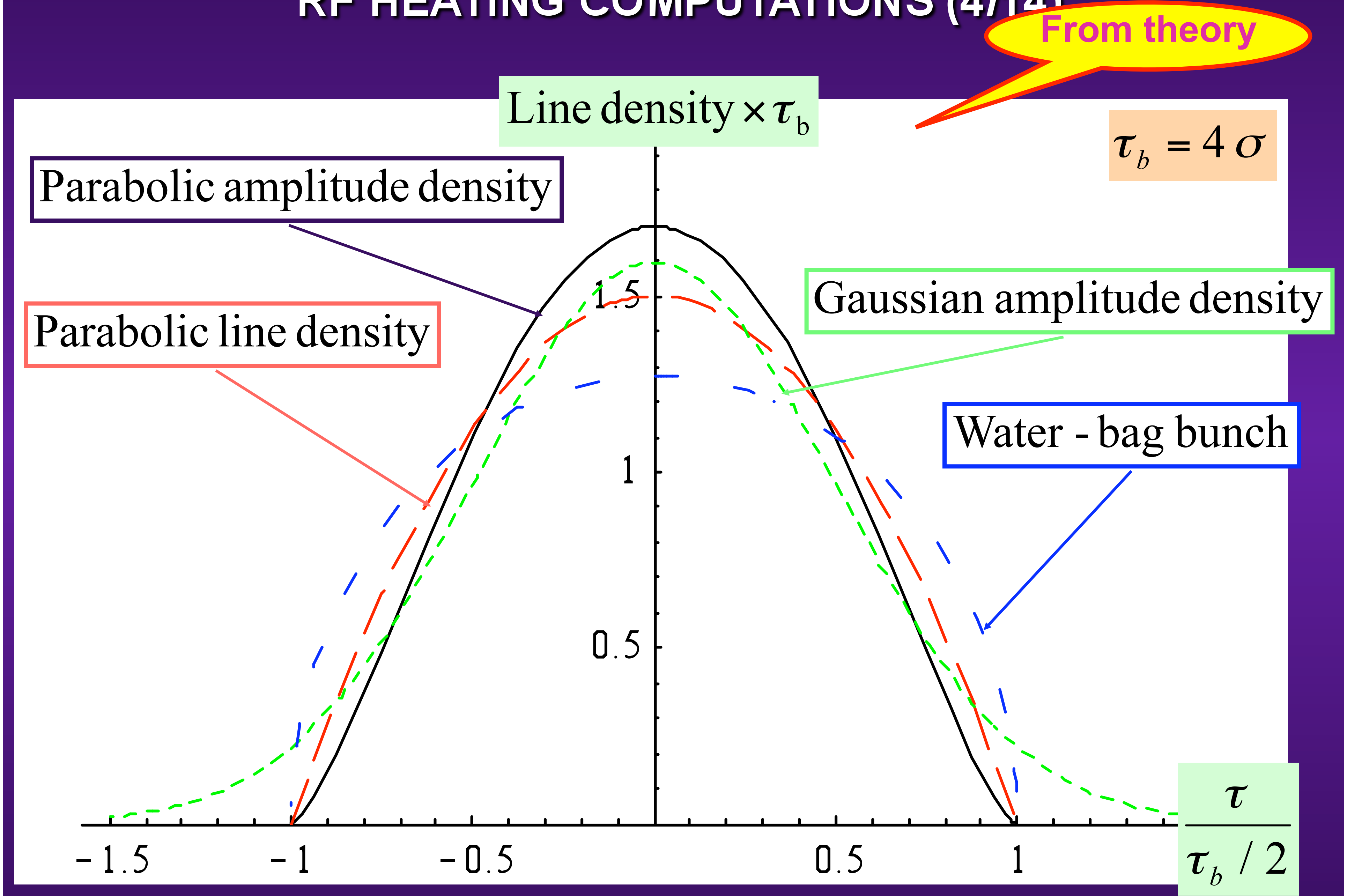
$$M_{50} = 1782$$

$$M_{25} = 3564$$

RF HEATING COMPUTATIONS (3/14)

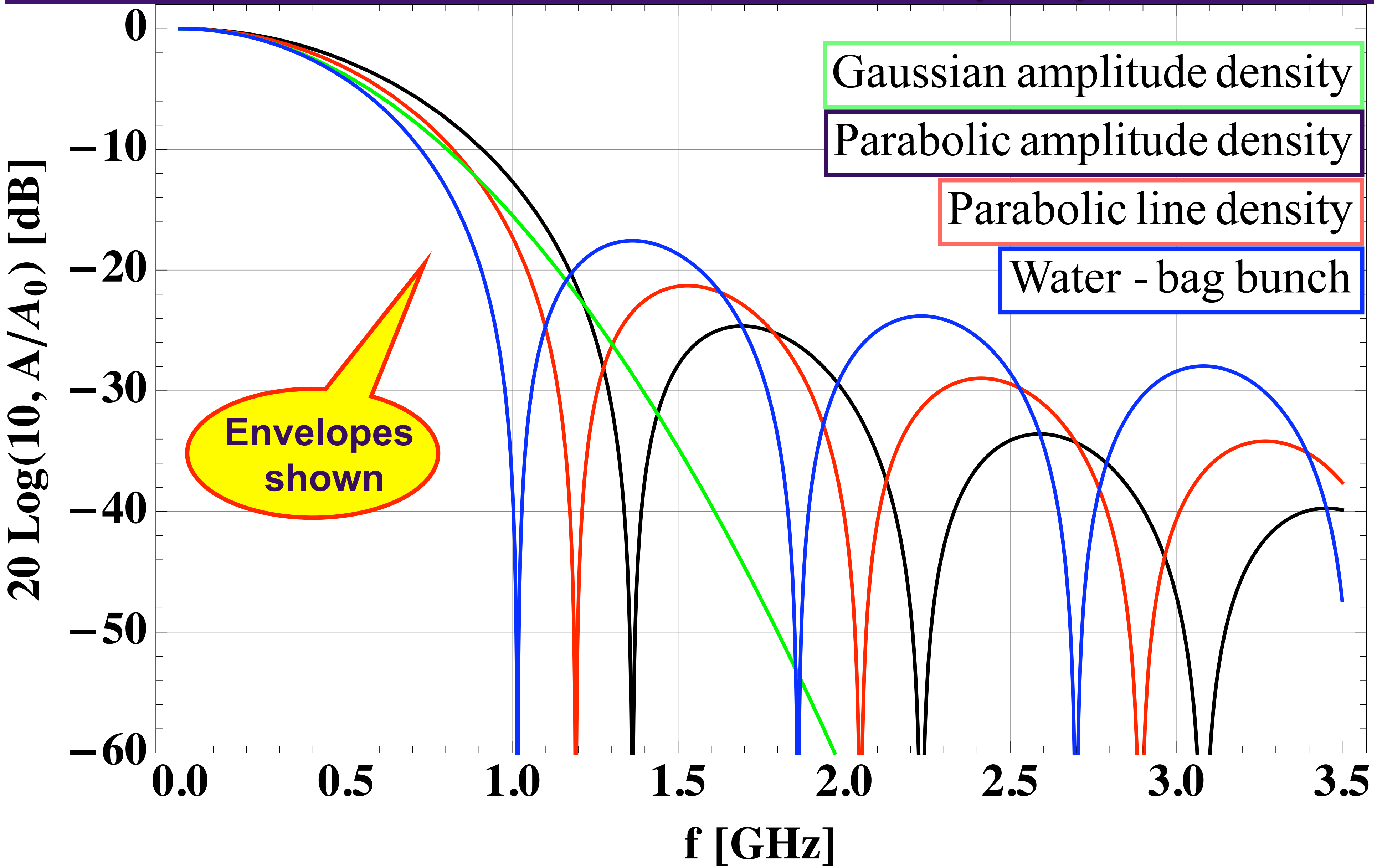


RF HEATING COMPUTATIONS (4/14)

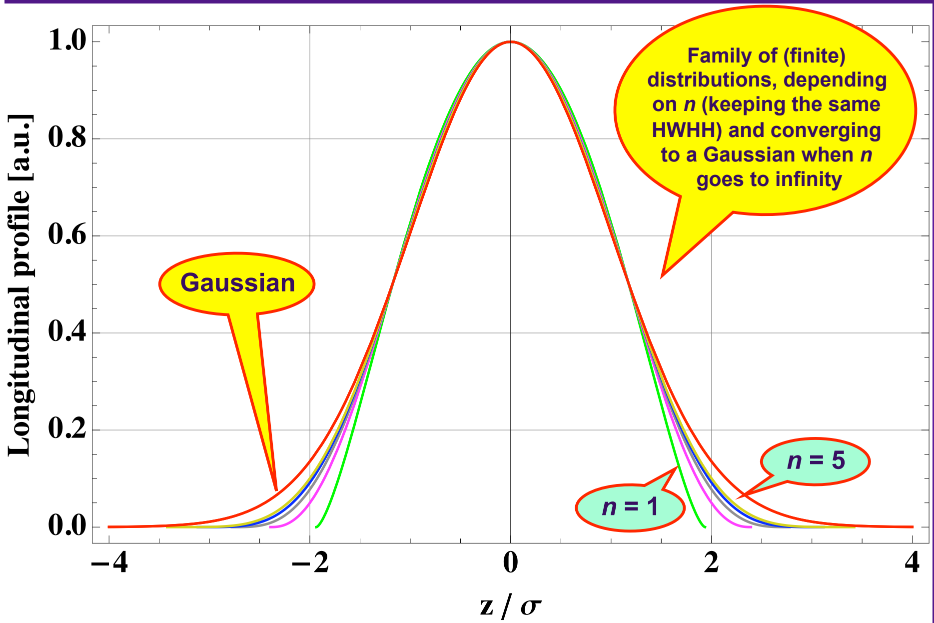


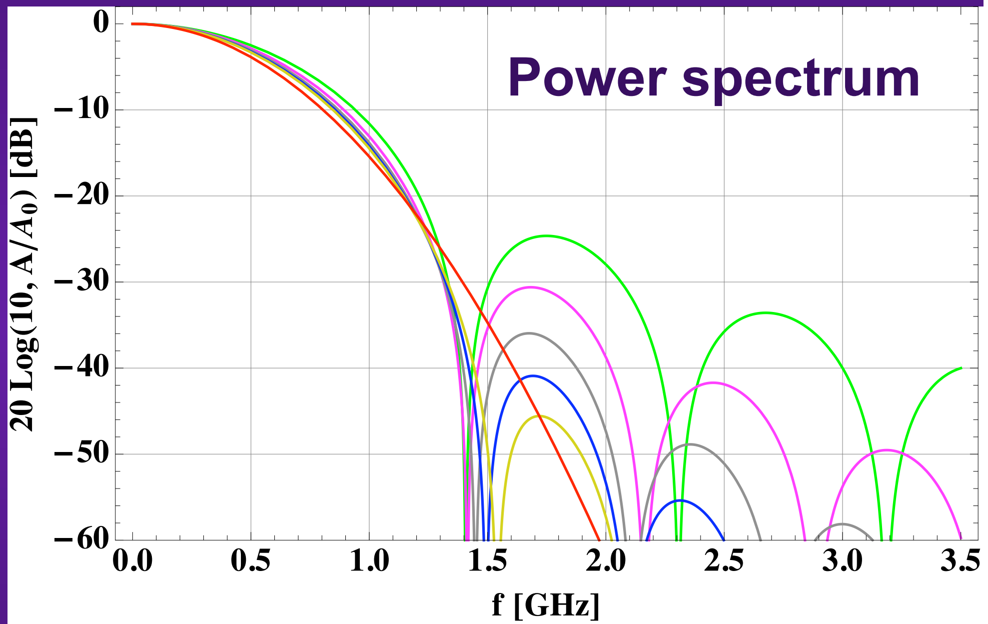
RF HEATING COMPUTATIONS (5/14)

$\tau_b = 1.2$ ns



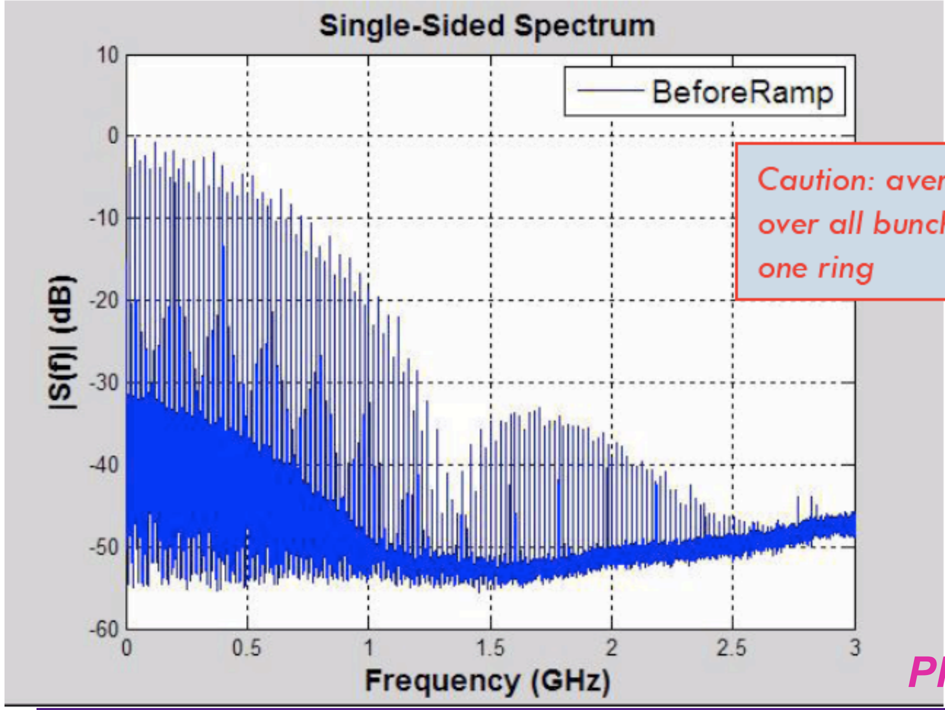
RF HEATING COMPUTATIONS (6/14)



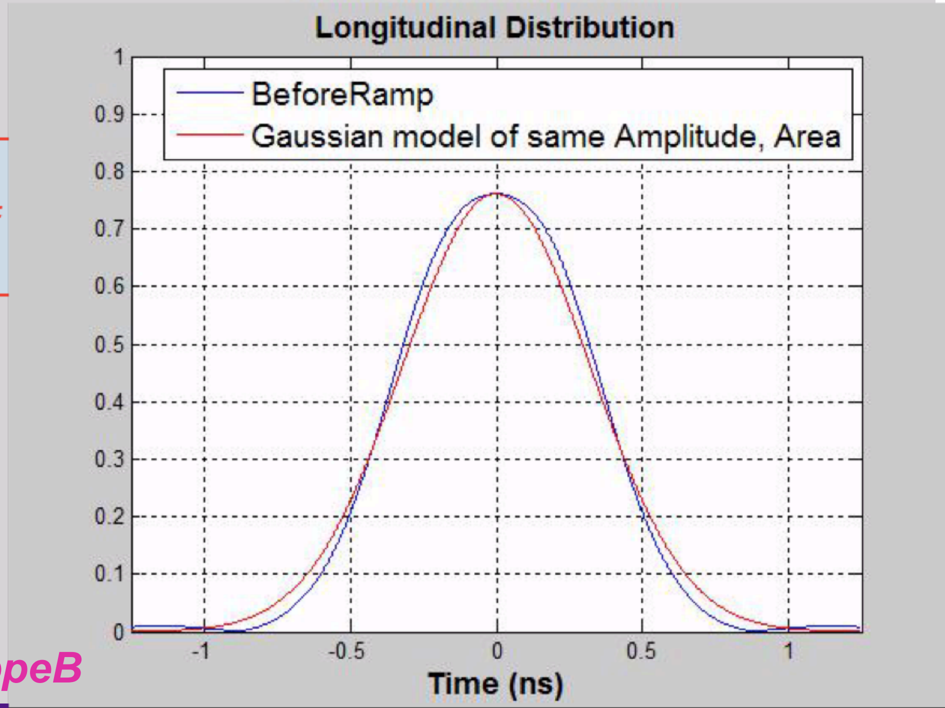


RF HEATING COMPUTATIONS (7/14)

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



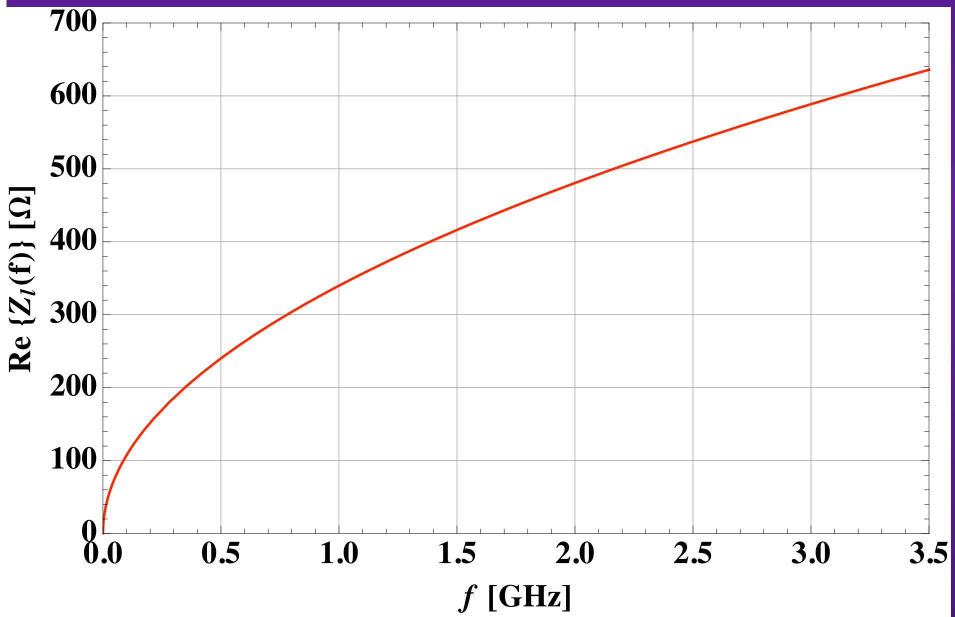
Caution: average over all bunches of one ring

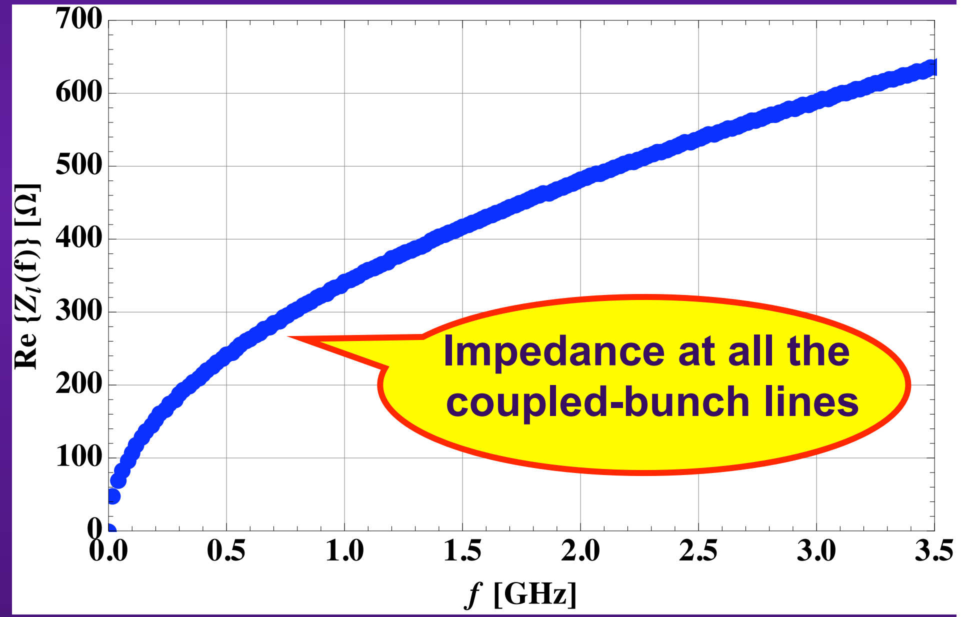


PhilippeB

RF HEATING COMPUTATIONS (8/14)

- 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

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

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

RF HEATING COMPUTATIONS (9/14)

- 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

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

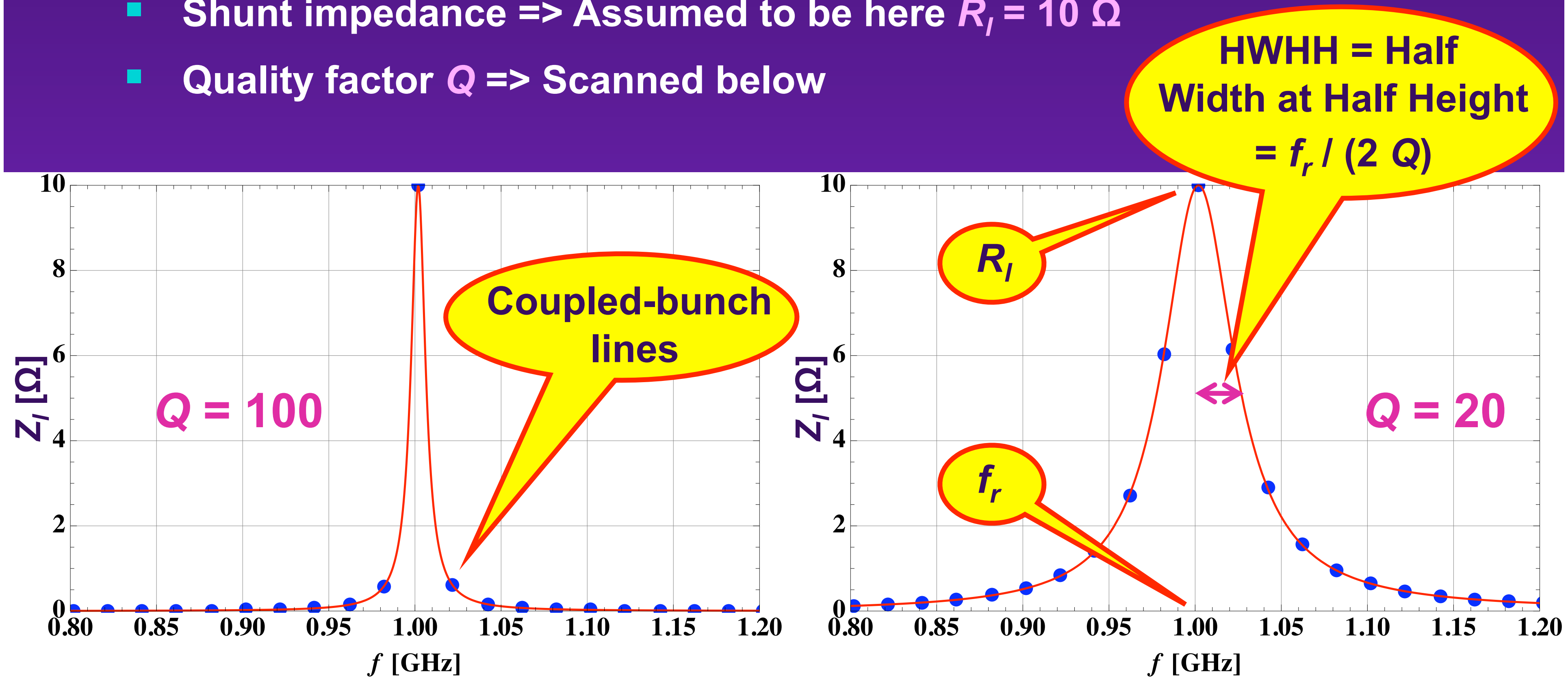
$$M_{50} = 1782 \qquad N_b = 1.4\times10^{11}\ \text{p/b} \qquad \sigma_t = 0.30\ \text{ns}$$

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

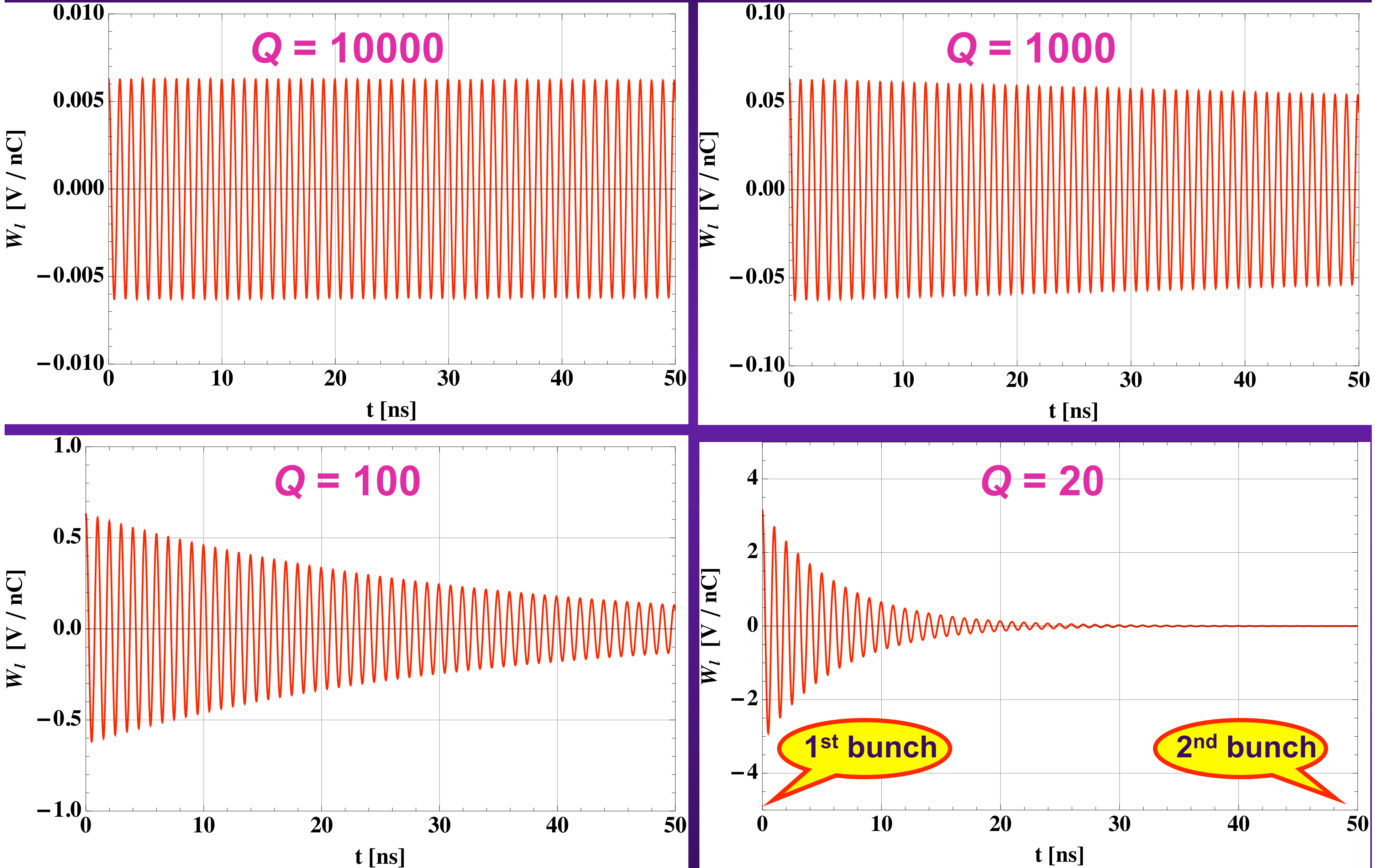
- With the 25 ns beam and 2 times more bunches, it would give a factor 2 more power

RF HEATING COMPUTATIONS (10/14)

- Consider now the case of a narrow resonance (trapped mode due to the geometry) => 3 parameters (obtained from EM simulations):
  - 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



RF HEATING COMPUTATIONS (11/14)



RF HEATING COMPUTATIONS (12/14)

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

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

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 => $P_{loss} \approx$ 52 mW

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

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

RF HEATING COMPUTATIONS (13/14)

- **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**

Heating of the ferrite can still be a pb

RF HEATING COMPUTATIONS (14/14)

- **Heat transfers**
  - **Convection: none in vacuum**
  - **Radiation: usually temperature already quite high => Improve the emissivities**
  - **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:**

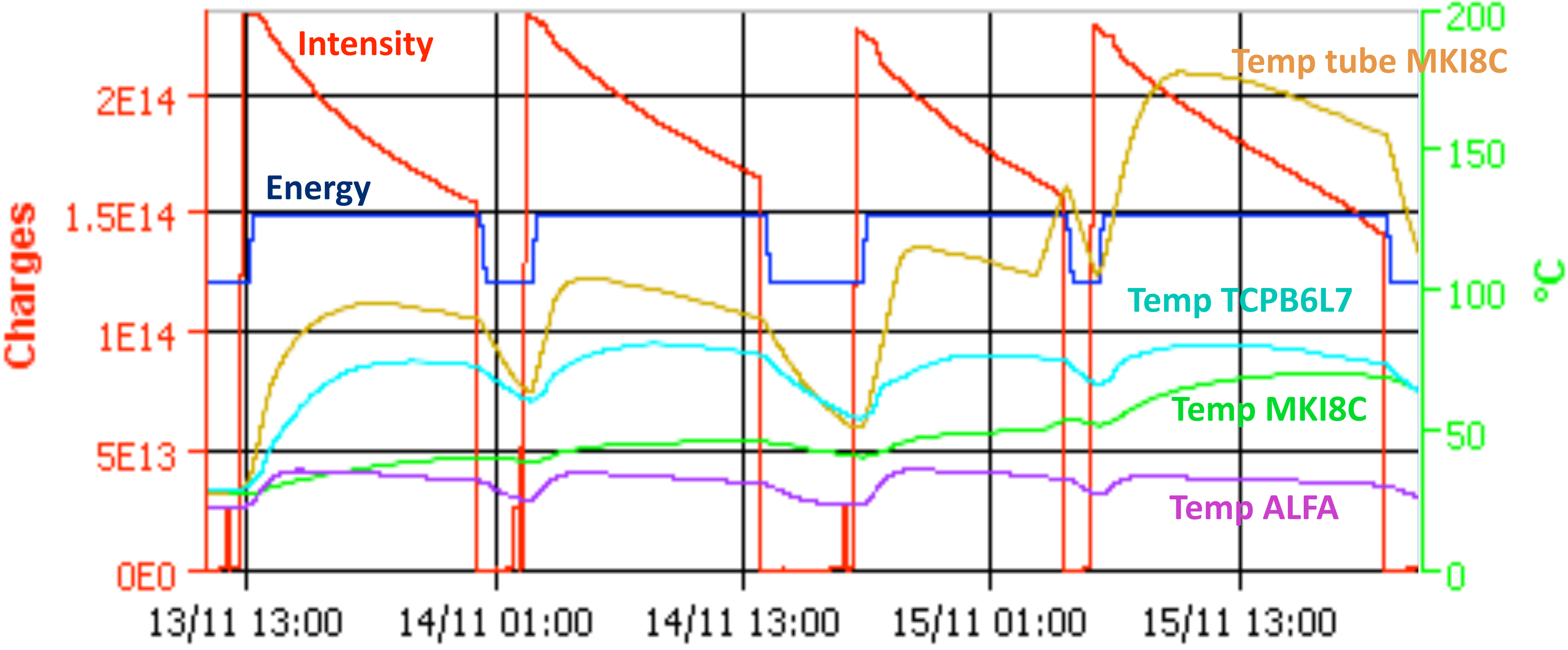
$$\Delta P_{bunch,1\rightarrow 2} = \Delta P_{bunch,2} - \Delta P_{bunch,1} = e\,\hat{V}_{RF}\,f_0\,N_b\left(\sin\phi_{s2} - \sin\phi_{s1}\right)$$

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

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

LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (1/20)

Benoit Salvant



- Example of temp. increases for kicker / collimator / detector during 4 LHC fills (Nov 2012)
- Temp. increase believed to be due to the interaction of beam-induced wake fields with the surrounding => RF heating
- Temp. increase in LHC devices can cause several issues (damage, delays, dumps)
- Other sources of heating not discussed: synchrotron light, beam losses, electron cloud

LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (2/20)

- **Heating was an issue in 2012 (as in 2011) on many LHC devices, and significantly affected operation**
- **Heavy upgrades are planned on most affected hardware during LS1 (Long Shutdown in 2013 and 2014)**
- **It is not clear that the upgrade foreseen for the TDI (Injection protection collimator) will be enough to be safe until the new design comes in LS2**
- **Choice of parameters after LS1 from heating point of view:**
  - **The longer the bunches the better**
  - **The longitudinal distribution plays a very important role for some devices, and it should be kept under tight control (in particular during the ramp)**
  - **25 ns or 50 ns bunch spacing is expected to be similar for most equipment with currently planned parameters. However, we need to watch for surprises**
- **More temperature monitoring is needed on critical devices**

LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (3/20)

Summary table 1

Benoit Salvant

Equipment	Problem	2011	2012	Hopes after LS1
VMTSA	Damage		replaced	removed
TDI	Damage			Beam screen reinforced, and?
MKI	Delay		(+ MKI8C high temperatures)	Beam screen and tank emissivity upgrade
TCP_B6L7_B1	Few dumps		Interlock increased	Cooling system checked
TCTVB	Few dumps		Interlock increased	removed
Beam screen Q6R5	Regulation at the limit		Since TS3, correlation with TOTEM?	Upgrade of the valves + TOTEM check
ALFA	Risk of damage		Due to Intensity increase	New design + cooling
BSRT	Deformation suspected			New design + cooling

LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (4/20)

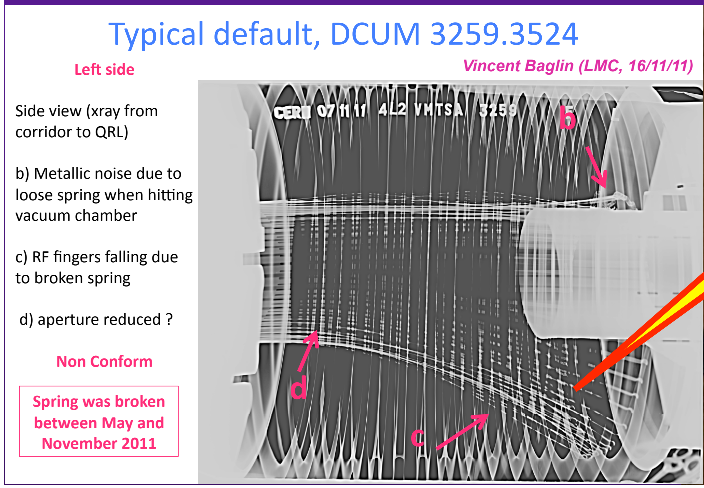
Summary table 2

Benoit Salvant

	Cooling	Has limited operation?	Type of impedance	Current estimated power loss 50 ns (1.2 ns – 1.6e11p)	power loss with 25 ns (1.2 ns -1.15e11p)	power loss with 25 ns (1 ns -1.15e11p)
VMTSA	no	No, repaired.	narrow band (before repair)	~ **0** if good contacts (>100 W if bad contacts)	~ **0** if good contacts	Will be removed
TDI	no	No, in parking position after injection	Broadband + narrow band	**40 W** (only broadband)	**40 W** (only broadband)	**50 W** (only broadband)
MKI	No	Yes, regularly delays programmed dumps and next injection by a few hours	Broadband	**100 W (15 cond.)**	**130 W (15 cond.)**	**210 W (15 cond)** **70 W (19 ciond)** **40 W (24 cond)**
TCP_B6L7	Yes (water)	Yes, 2 dumps interlock increased from 55 to 95 degrees	Broadband	**50 W**	**50 W**	**80 W**
TCTVB	Yes water	No (dump with shorter bunch length)	narrowband	To be assessed	To be assessed	Will be removed
Beam screen	yes (cryo)	No, except Q6R5 for 7TeV	Broadband (if no non conformity)	**0.1 W/m**	**0.1 W/m**	0.13 W /m No margin for cooling of current Q6R5
ALFA	no	Not yet (18deg increase in temperature in 2011, with margin of 40 degrees)	Broadband	**20 W**	**23 W**	~ **30 W**
BSRT Mirror and support	no	Yes, mirror coating is damaged and the mirror support lost its mechanical properties	Broadband (if below Curie temperature)	10 to 50 W if below Curie temperature (> 500 W above)	10 to 50 W (or > 500 W)	To be estimated

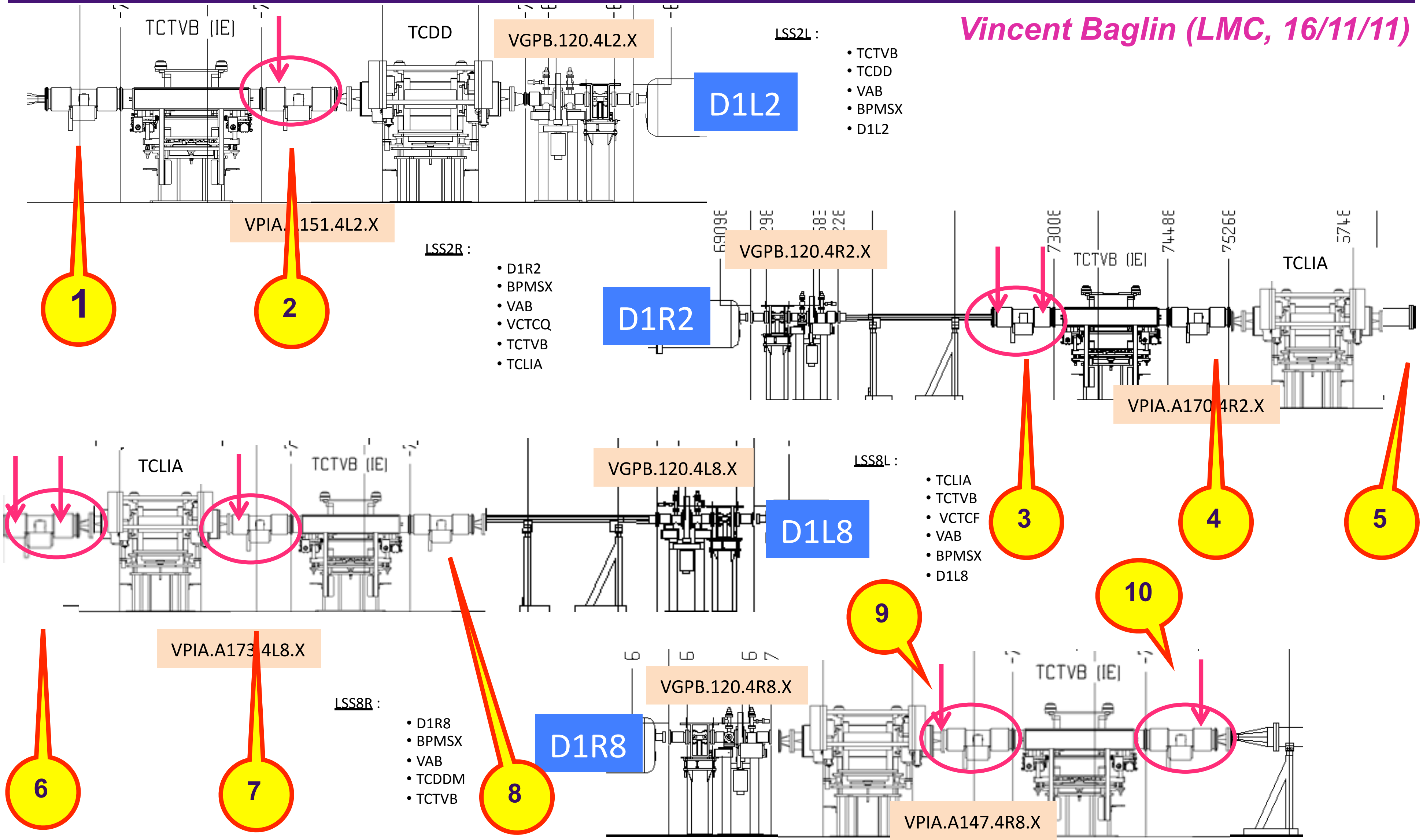
LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (5/20)

- 8 bellows, out of the 10 double-bellows modules (called VMTSA) present in the machine in 2011, were found with the spring, which should keep the RF fingers in good electrical contact with the central insert, broken
- SS spring deformed and brazed to the CuBe RF fingers with RF fingers permanently deformed => Estimated temp. of ~ 800 - 1000 °C
- 2 modules removed in 2012 and 8 modules reinstalled with new shorter RF fingers, ferrite plates and reinforcement corset => Np pb
- Will be removed during LS1 => No pb anymore



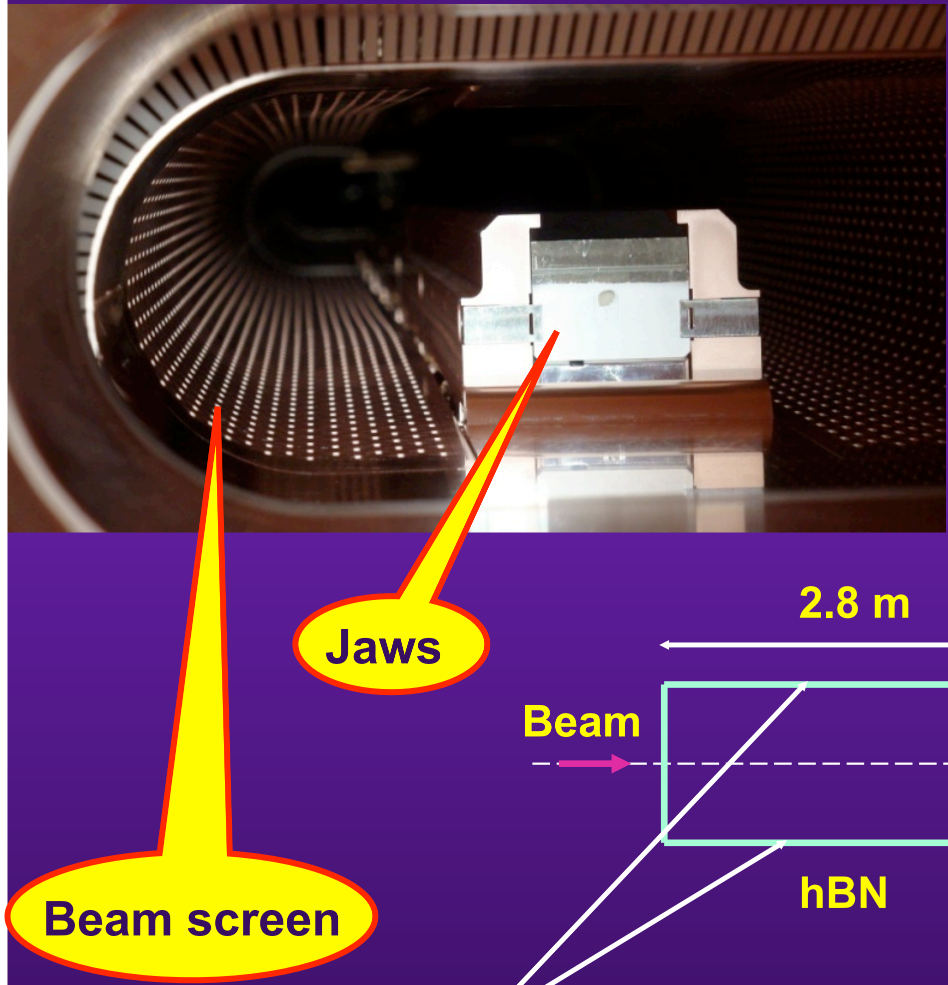
LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (6/20)

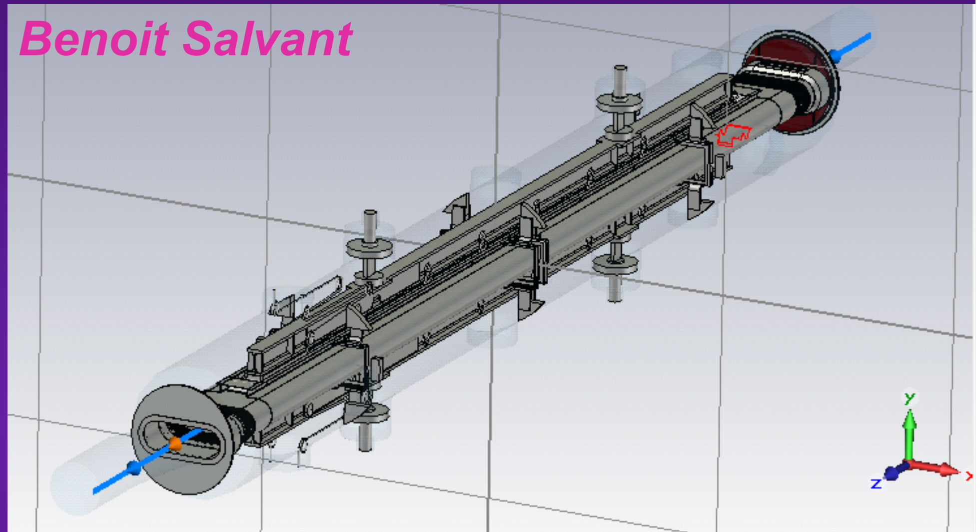
Vincent Baglin (LMC, 16/11/11)

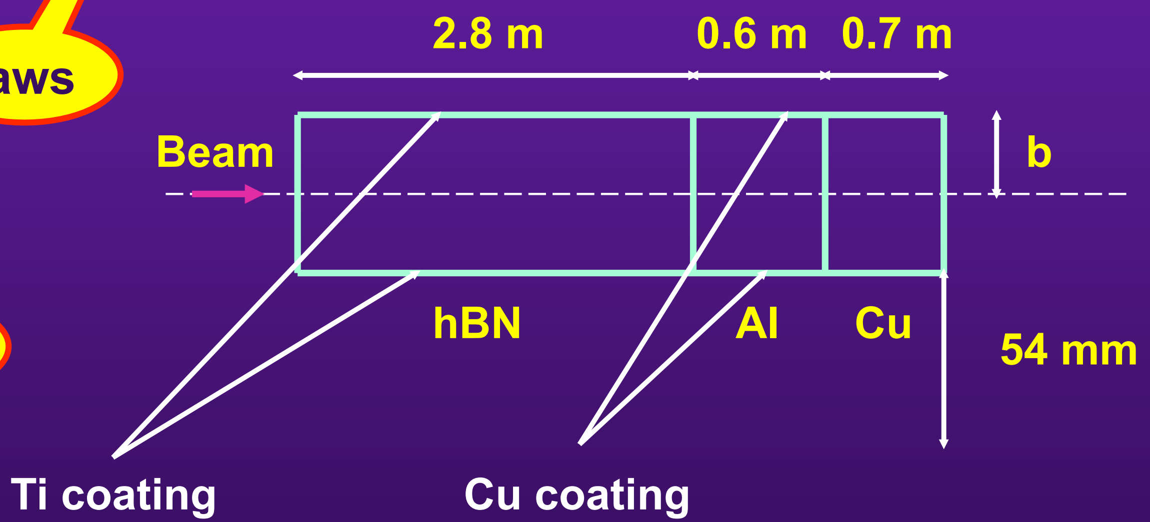


LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (7/20)

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

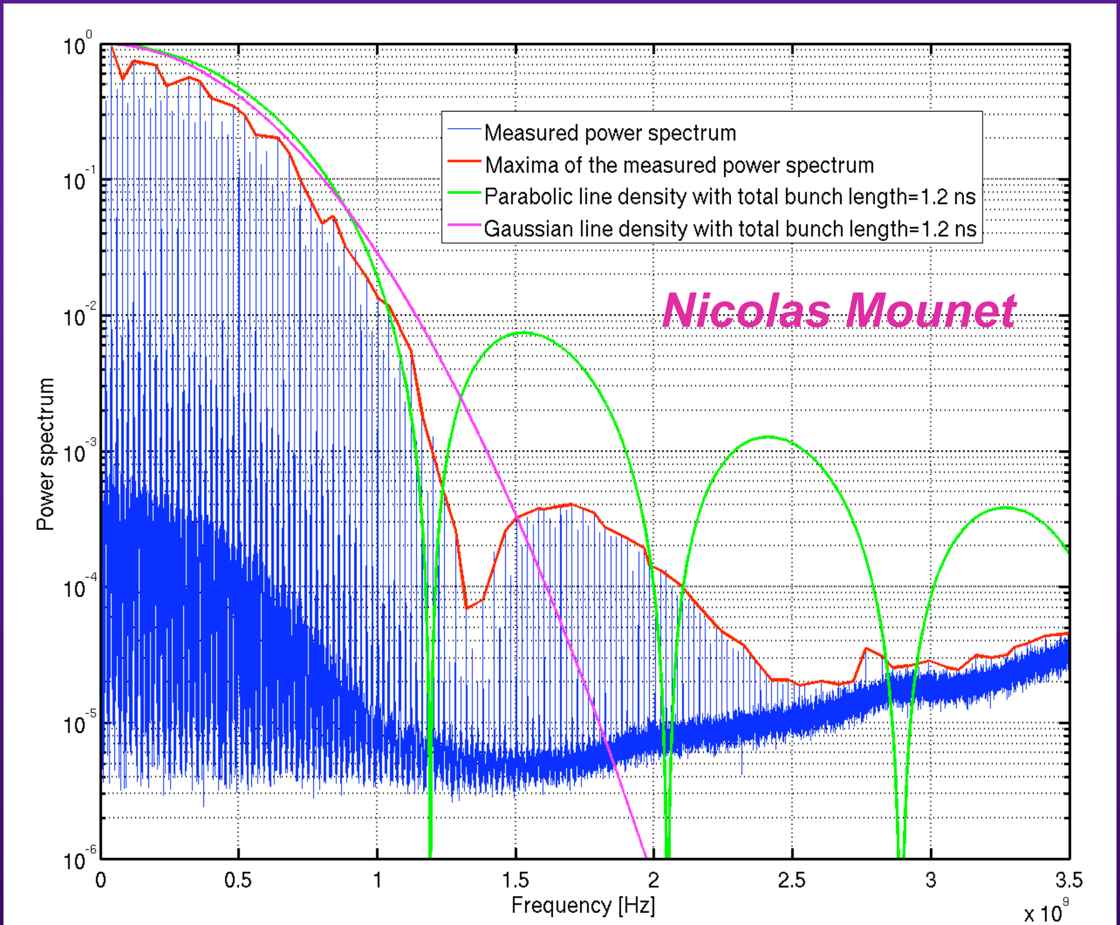




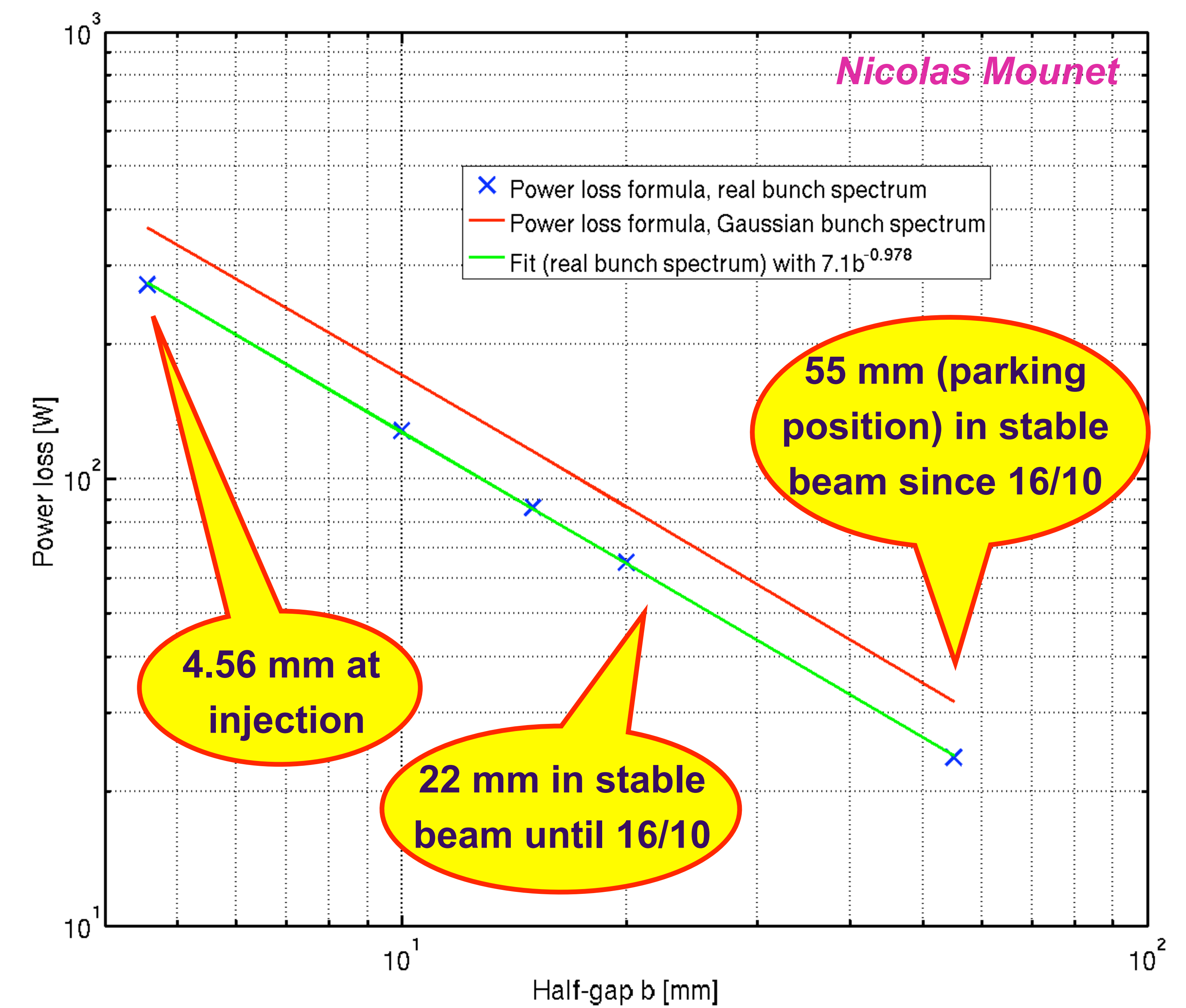


LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (8/20)

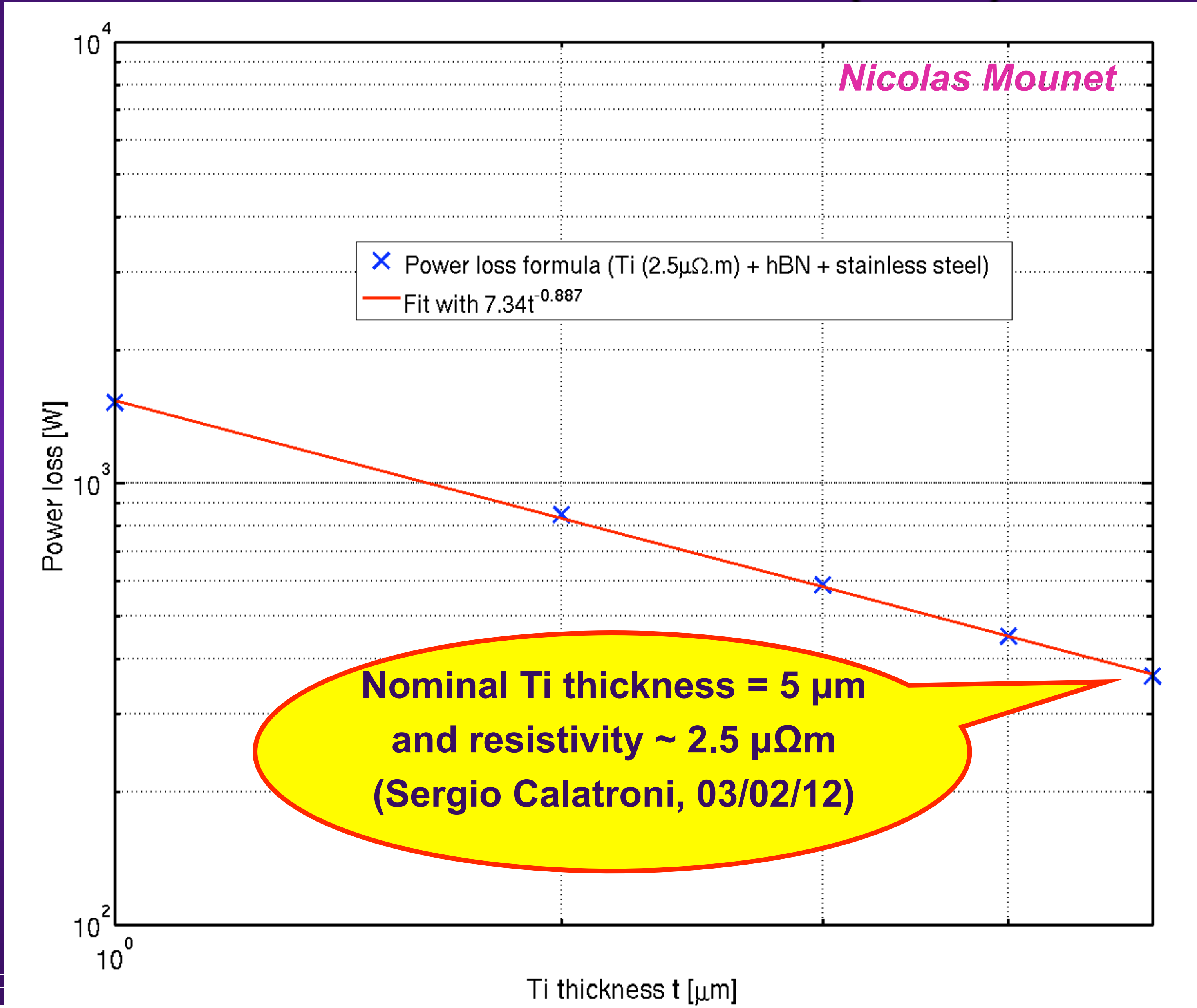
- **Power loss from resistive-wall has been re-estimated for 1380 bunches, 1.45E11 p/b, 1.2 ns 4-sigma bunch length, half gap 4.56 mm**
  - It is mainly in the Ti coating of the hBN block
  - hBN has a very good thermal conductivity => All the block heated



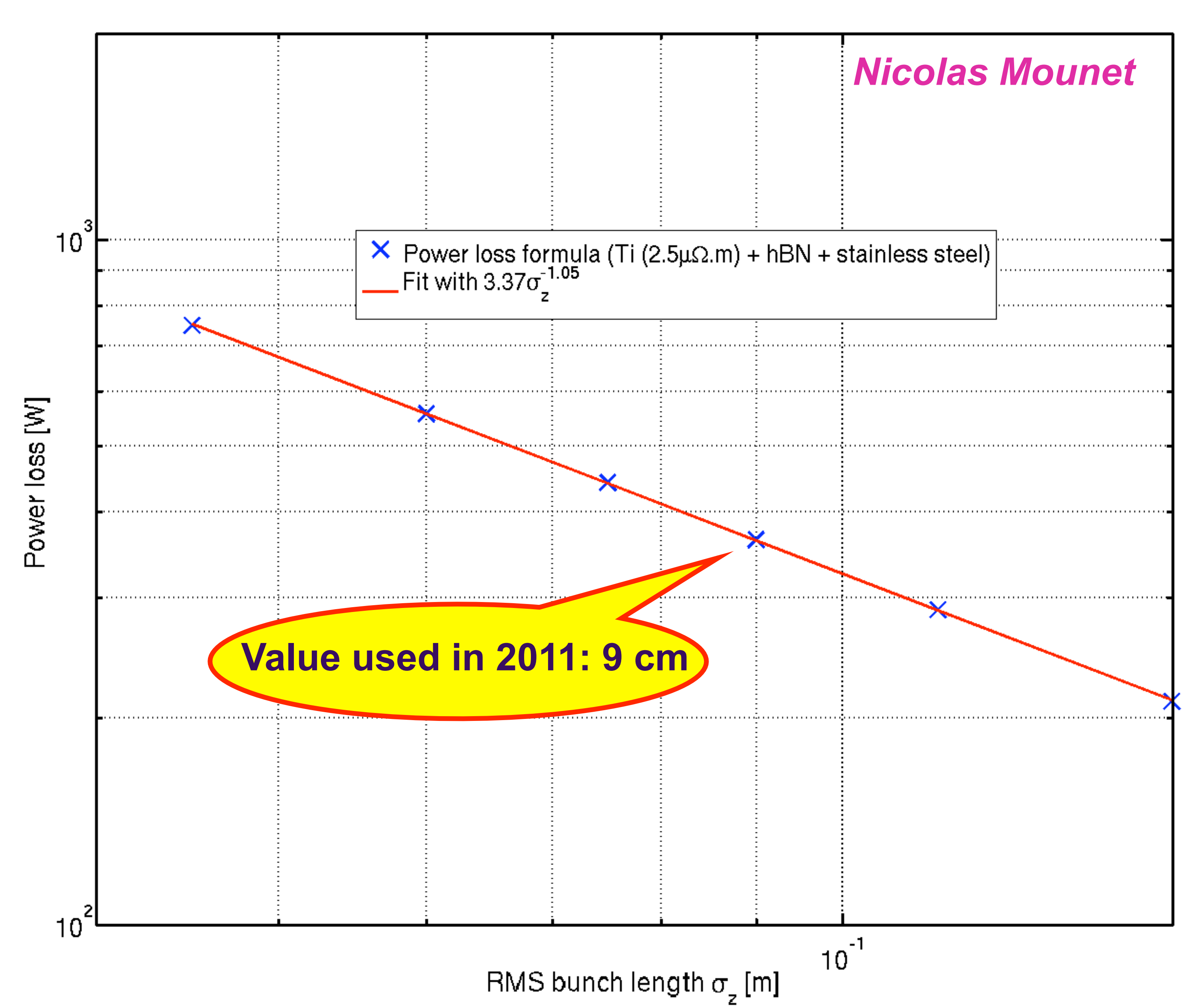
LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (9/20)



LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (10/20)

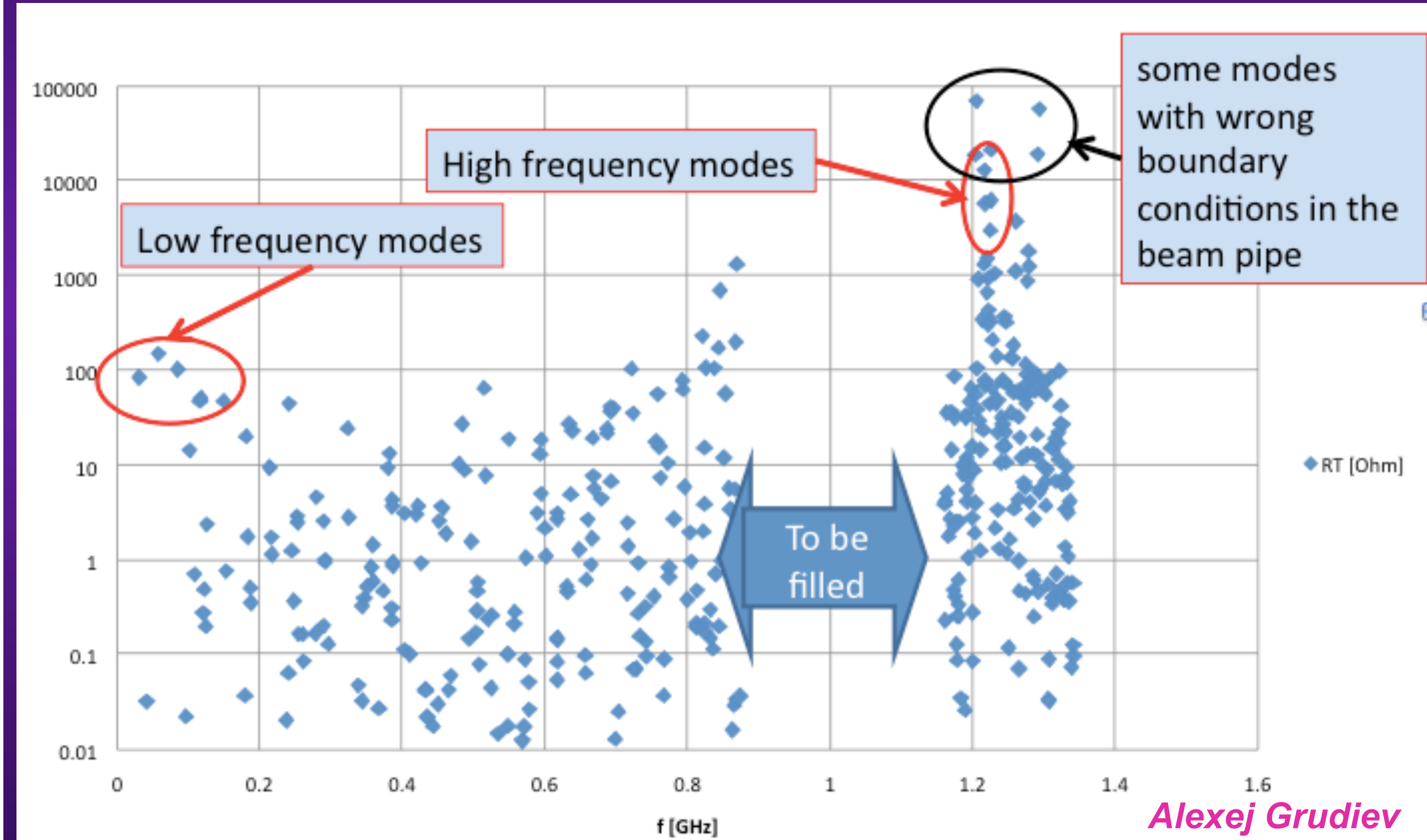


LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (11/20)



LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (12/20)

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

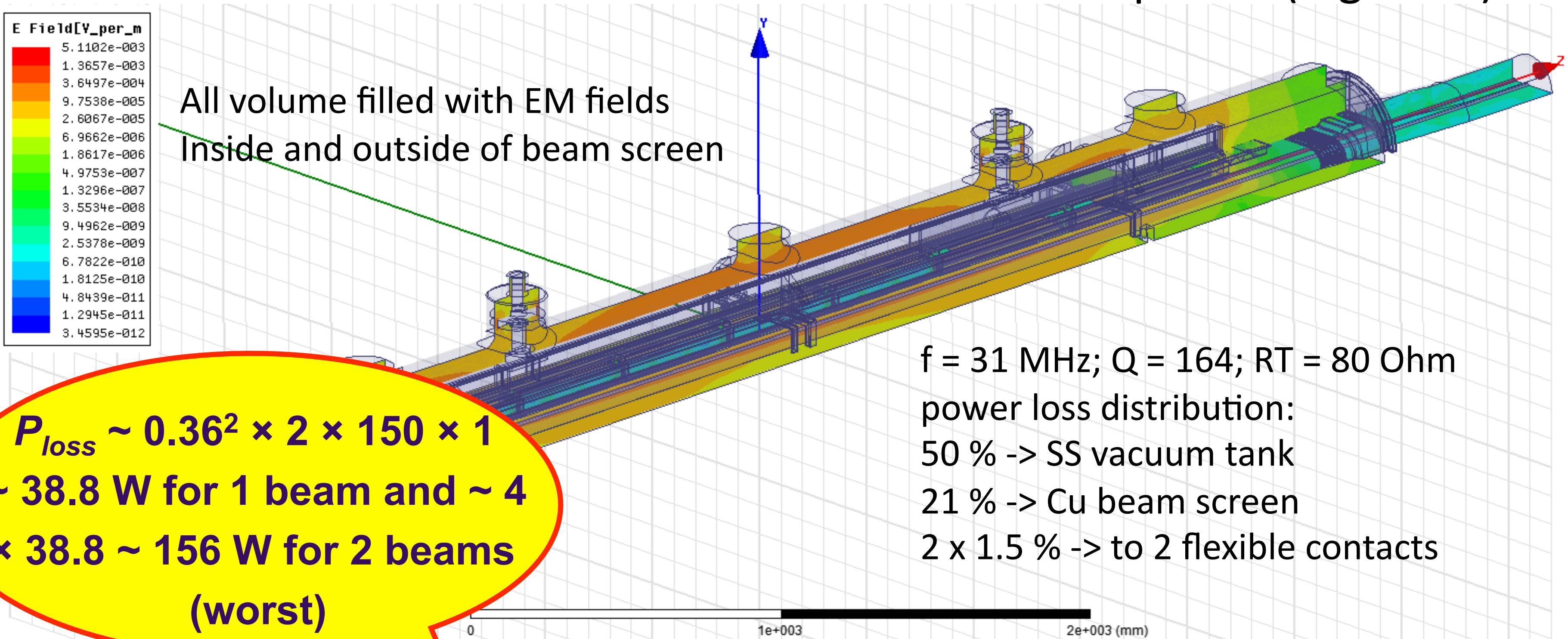


Alexej Grudiev

LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (13/20)

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

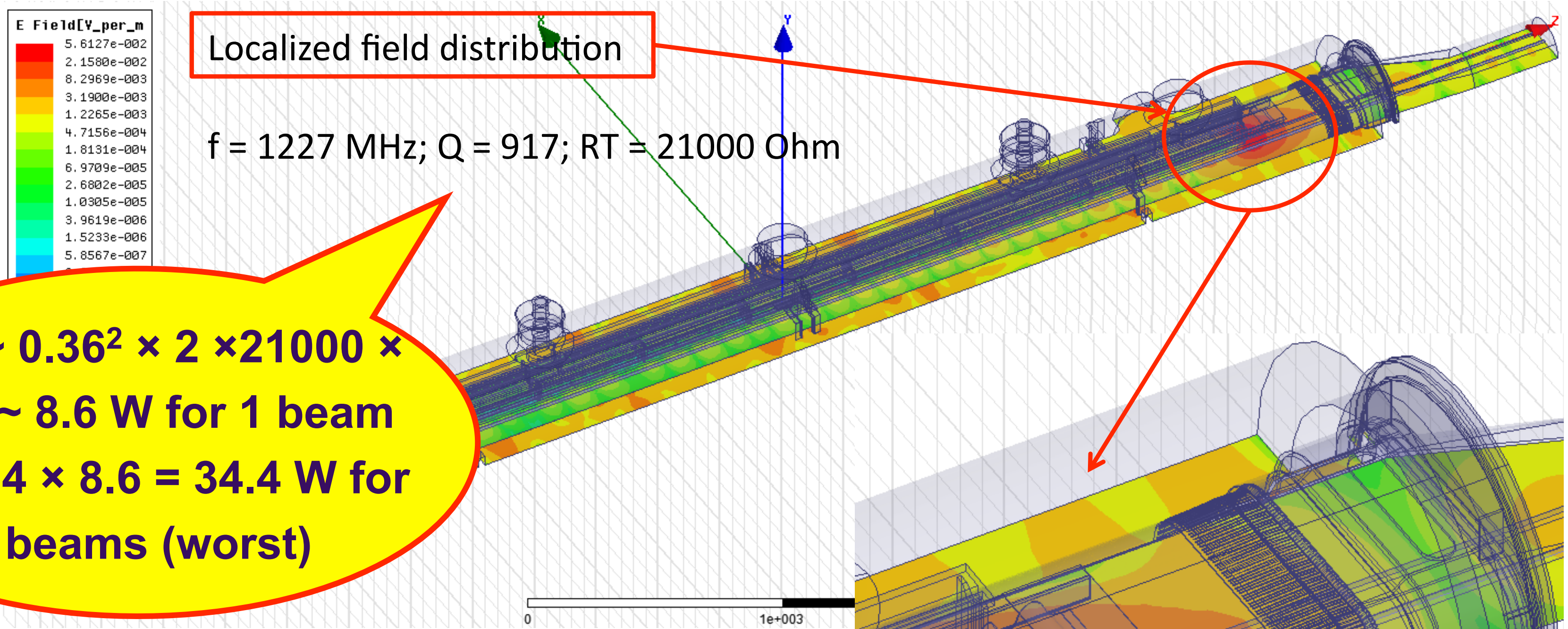
P_{loss} ~ 0.36^2 × 2 × 150 × 1 ~ 38.8 W for 1 beam and ~ 4 × 38.8 ~ 156 W for 2 beams (worst)

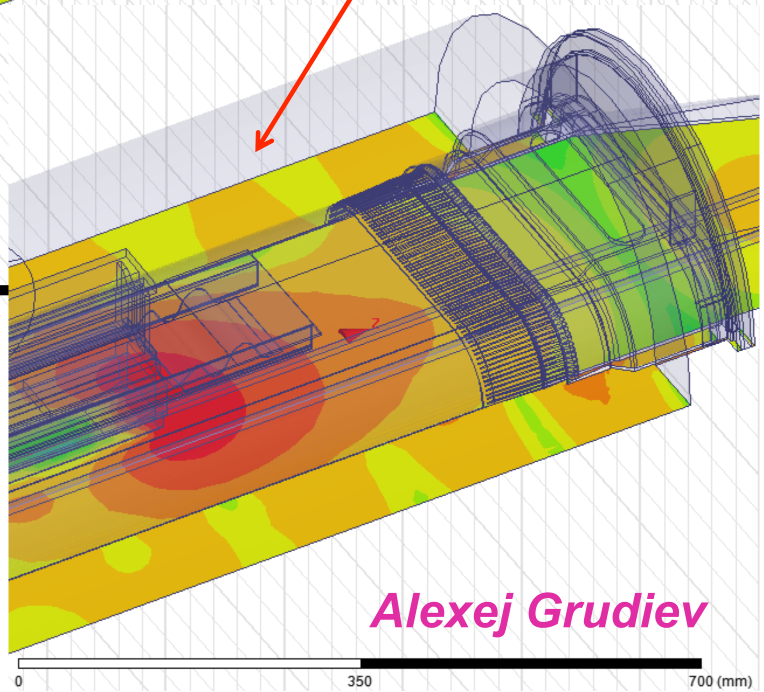
Other low frequency modes have similar field distribution:
f = 59 MHz; Q = 195; RT = 150 Ohm
f = 86 MHz; Q = 207; RT = 100 Ohm

Alexej Grudiev

LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (14/20)

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

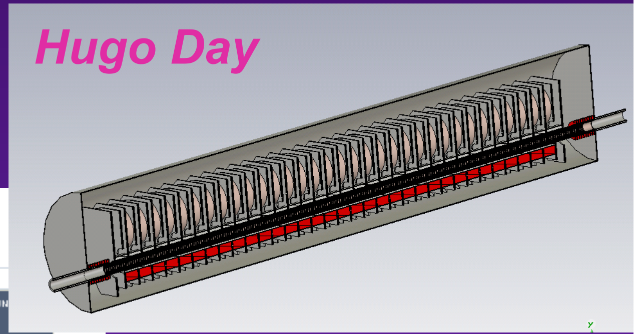




Other high frequency mode:
f = 1218 MHz; Q = 970; RT = 13000 Ohm

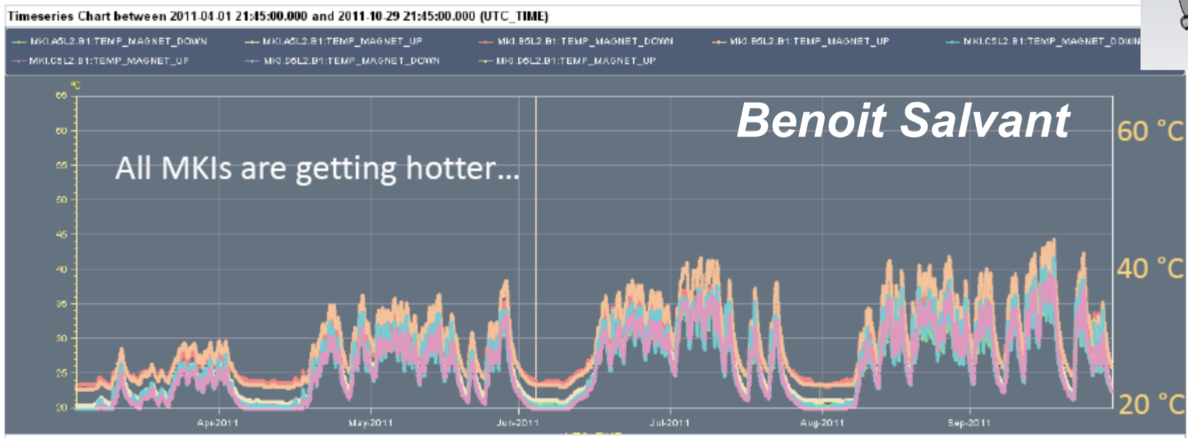
LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (15/20)

MKI (injection kicker)

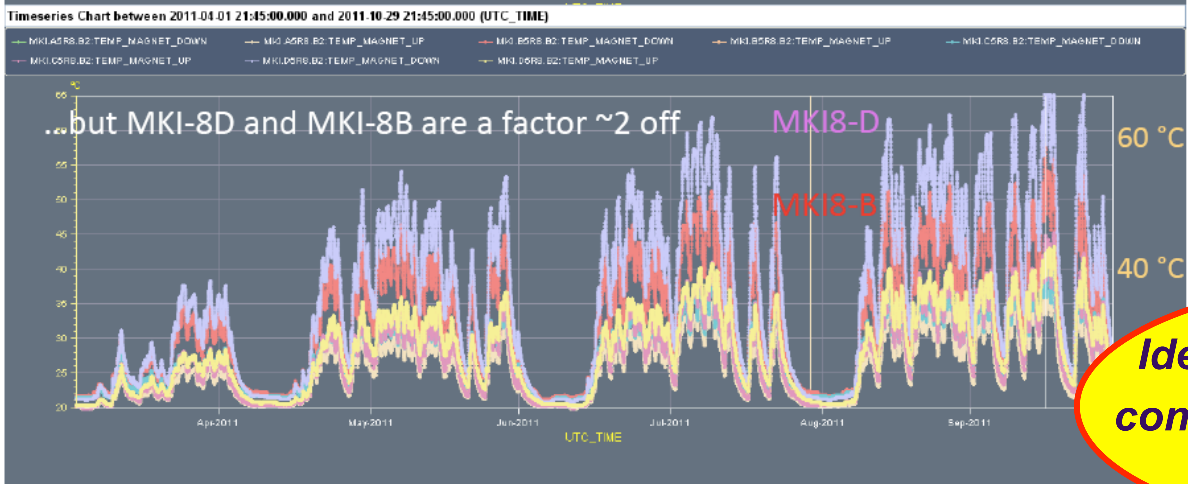


MKIs: steady temperature increase over 2011

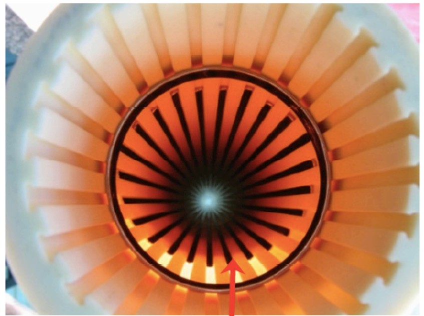
MKI
in point 2



MKI
in point 8



April 1st 2011 → October 31st 2011



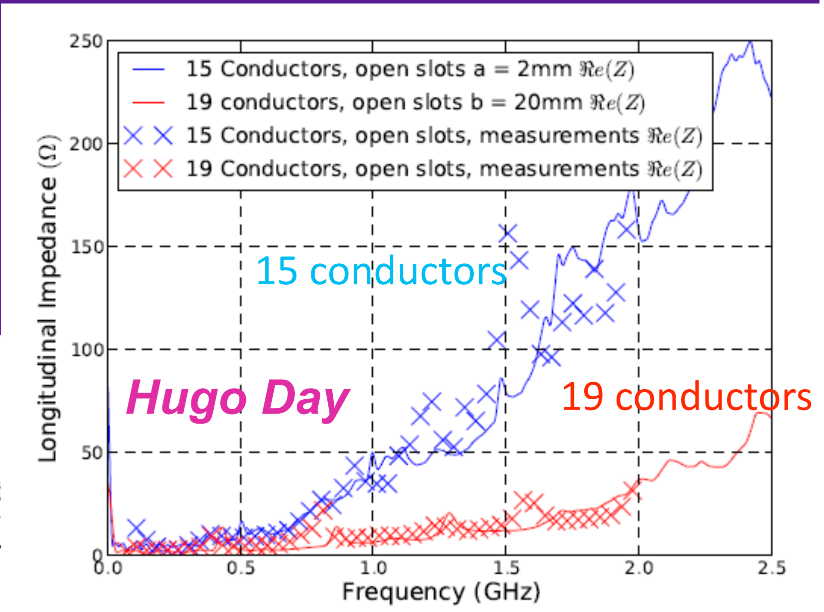
"beam-screen" of LHC Injection Kicker: ceramic tube with conductors in slots

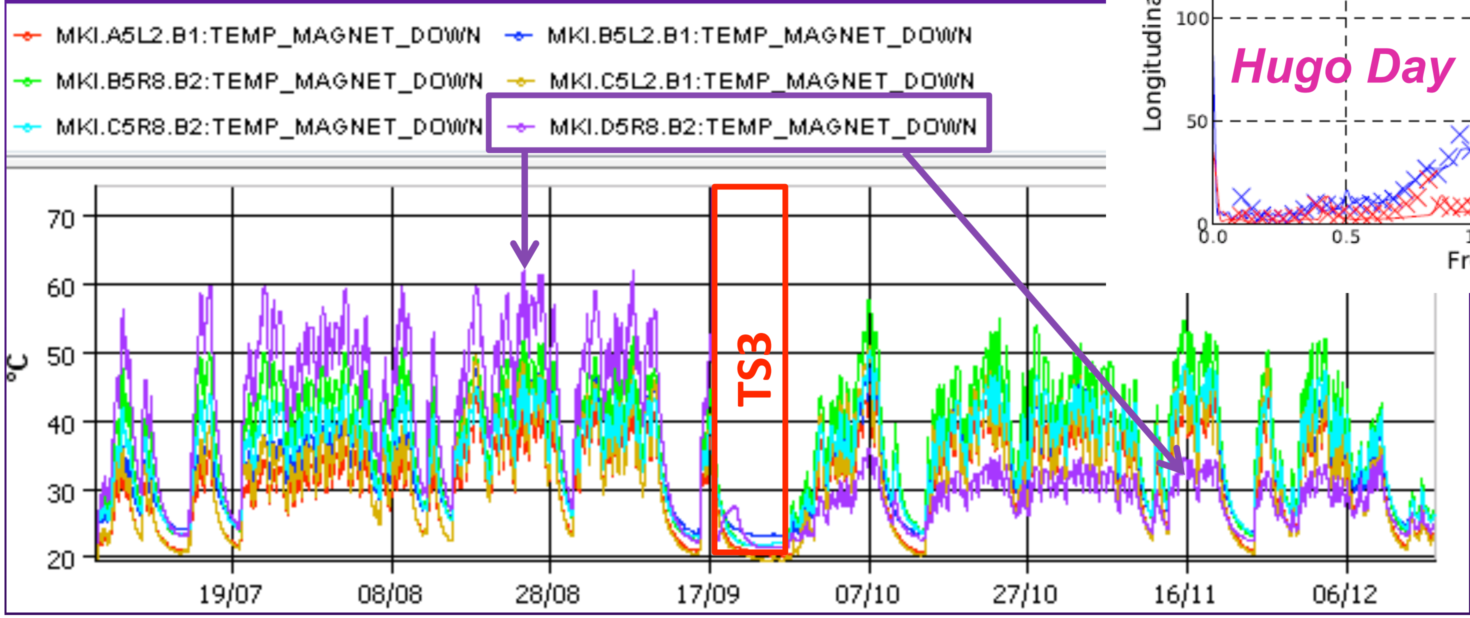
Ideally one should have 24 conductors (from impedance point of view)

LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (16/20)

- **Bench measurements and simulations predict that the new MKI design (19 conductors) would better screen the ferrite from the beam than the current MKI design (15 conductors)**
- **During Technical Stop 3, the MKI8D was replaced with a spare with 19 screen conductors**

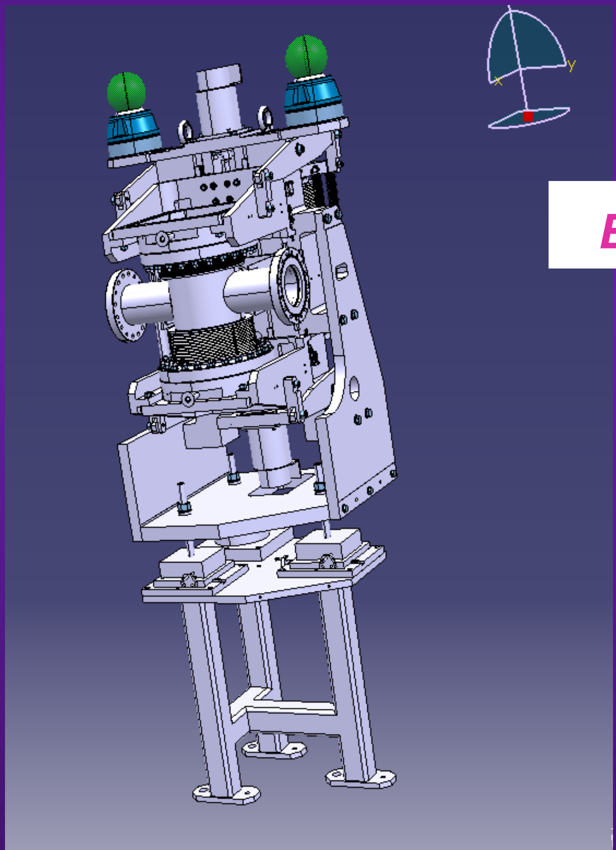
  => It had before the highest temp. and it had after the lowest one!



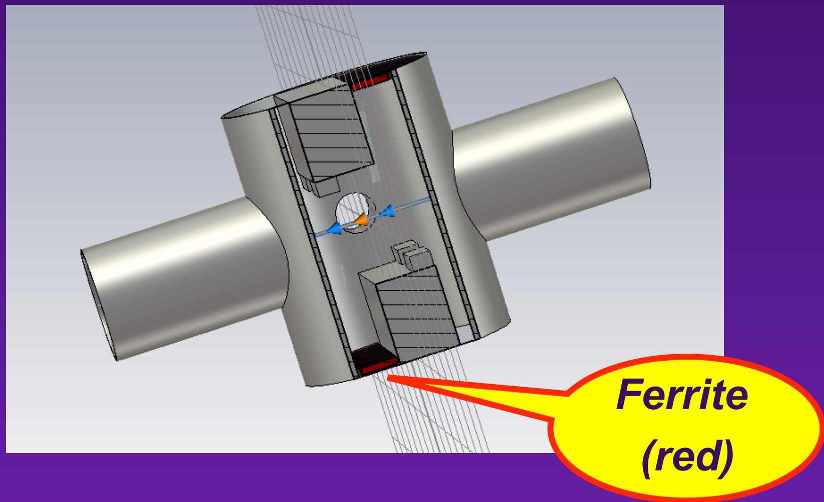


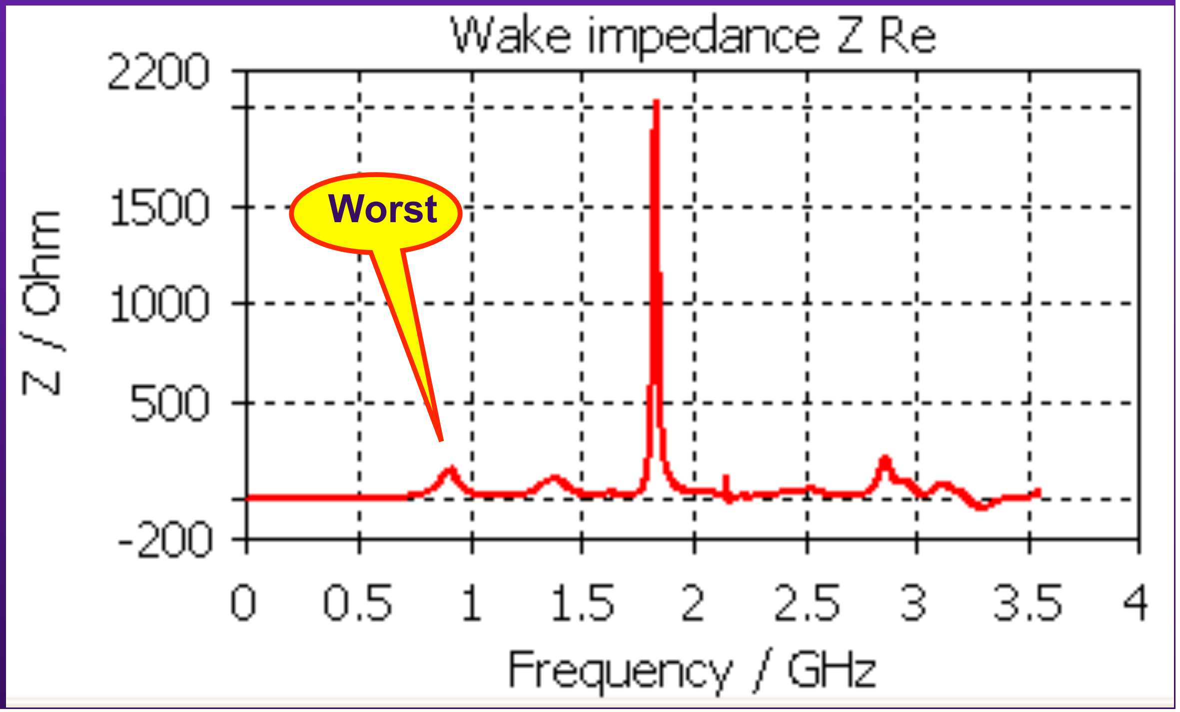
LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (17/20)

ALFA Roman Pot



Benoit Salvant





LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (18/20)

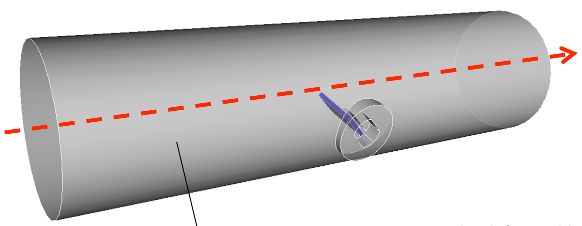
- The ALFA detectors' temperature reached 42 degrees (temp. expected to lead to detector damage = 45 degrees…)
- Temp. increase seems consistent with impedance heating of the ferrite damper ring (which is efficiently preventing more harmful heating)
- The TOTEM detector does not have this problem as it was designed with active cooling of the detector
- As emergency measures, the ALFA team removed the bake-out jackets and added some fans
- Plans: implement a new design with reduced impedance and active cooling during LS1

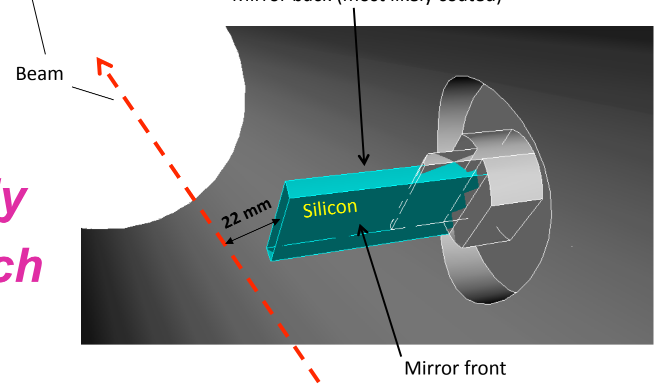
LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (19/20)

BSRT (Synchrotron Light monitor)

- **The B2 BSRT mirror and support suffered from damage that could be due to significant heating**
- **Current issue is to understand whether the Curie temperature of the ferrite has been reached => Still no clear conclusion, need to check impedance simulations with bench measurements soon**
- **Heavy effort required and planned during LS1 to find a robust design**

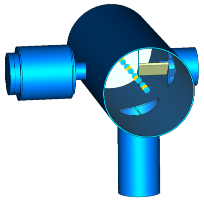
Simplified BSRT model is considered

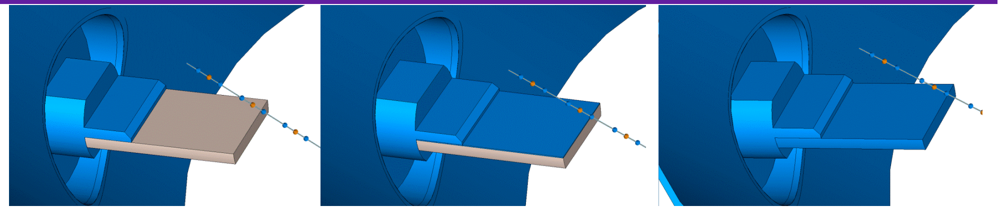




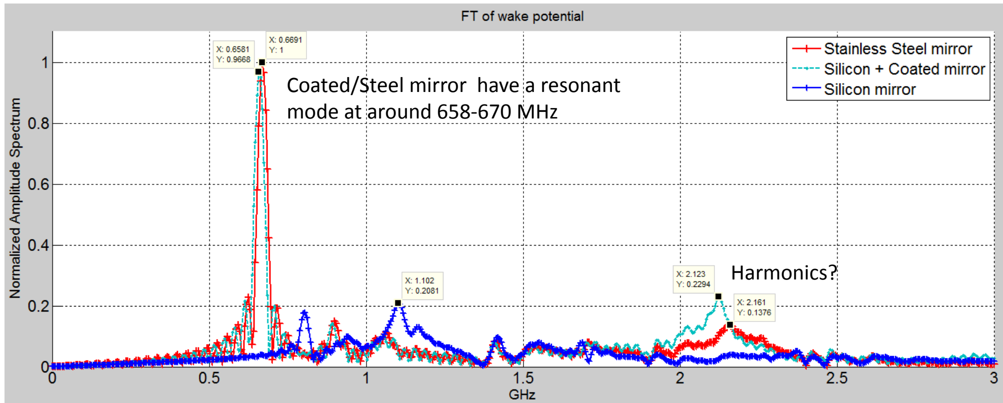
Andriy Nosych

(BSRT complete assembly)



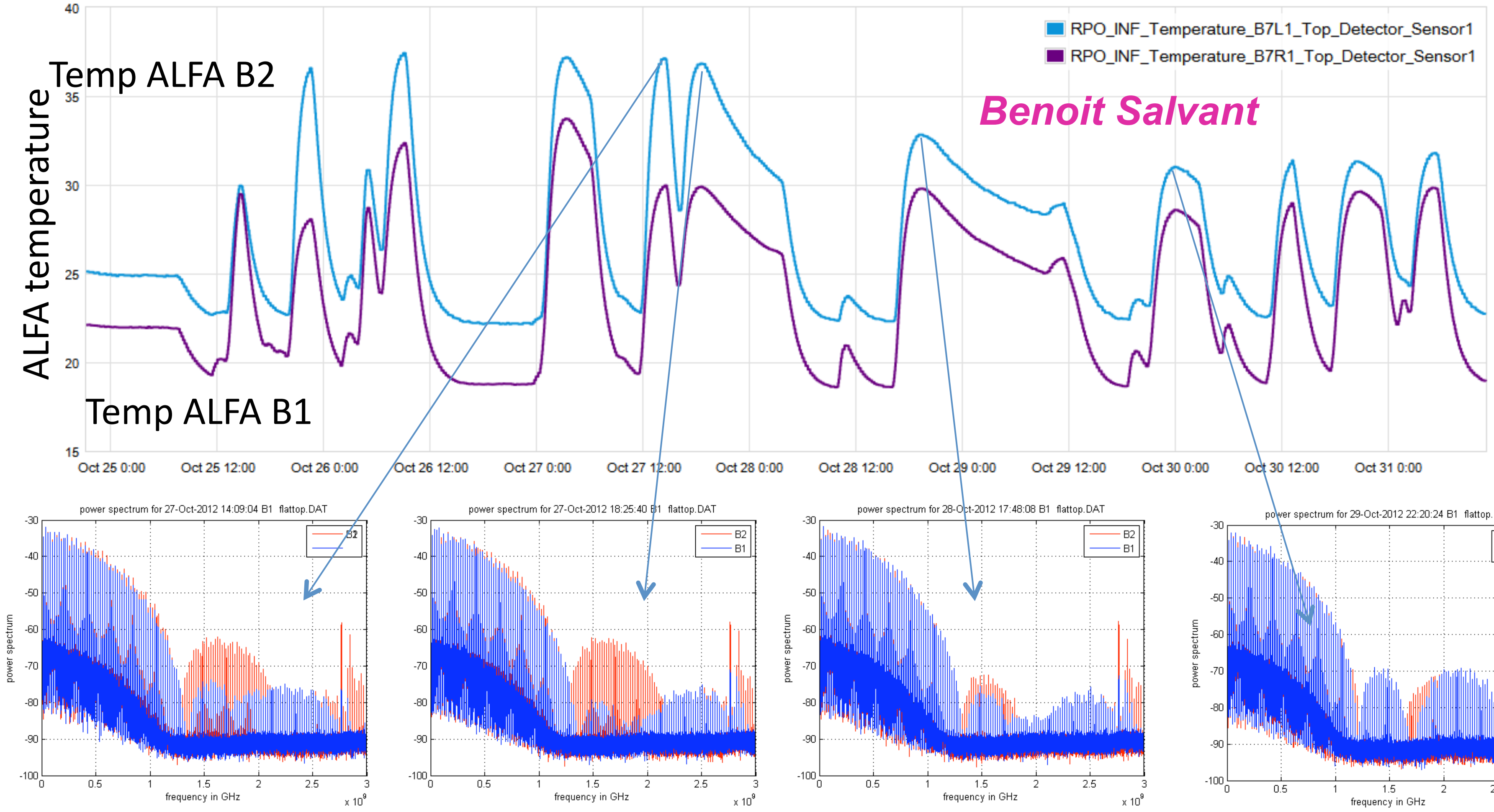


Silicon mirror (eps = 11.9,el.cond=2.5e-4) | **Silicon + coated mirror** (by putting an electric boundary on back surface) | **Stainless-steel mirror**



LHC OBSERVATIONS OF BEAM-INDUCED RF HEATING IN 2011-2012 (20/20)

Observed effect of the longitudinal distribution (power spectrum)



- Difference believed to be due to the longitudinal blow up during the ramp
- Significant increase of temperature on BSRT too

RF TASK FORCE IN 2012

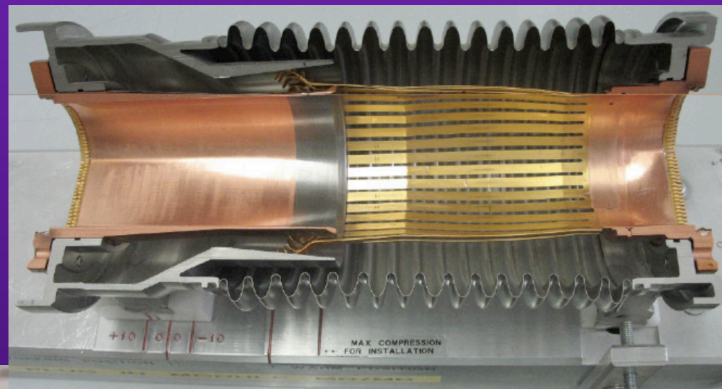
- Proposition made during the LMC meeting # 119 (18/01/2012) to review the design of all the components of the LHC equipped with RF fingers => LRFF (LHC RF Fingers) Task Force before LS1
- Web site: http://emetral.web.cern.ch/emetral/LRFF/LRFF.htm
  - 1st (kick-off) meeting: 20/03/2012
  - 20th (last) meeting: 27/11/2012

WHY DO WE NEED RF FINGERS AND/OR FERRITE? (1/3)

- To avoid having too large impedances (longitudinal or transverse) due to (big) changes of geometry for moving equipments, which can lead to
  - Beam-induced RF heating (if real part of longitudinal impedance)
  - Longitudinal or transverse beam instabilities (if real and/or imaginary parts of longitudinal or transverse impedances)

- Example of RF fingers:

  PIMs = Plug-In Modules



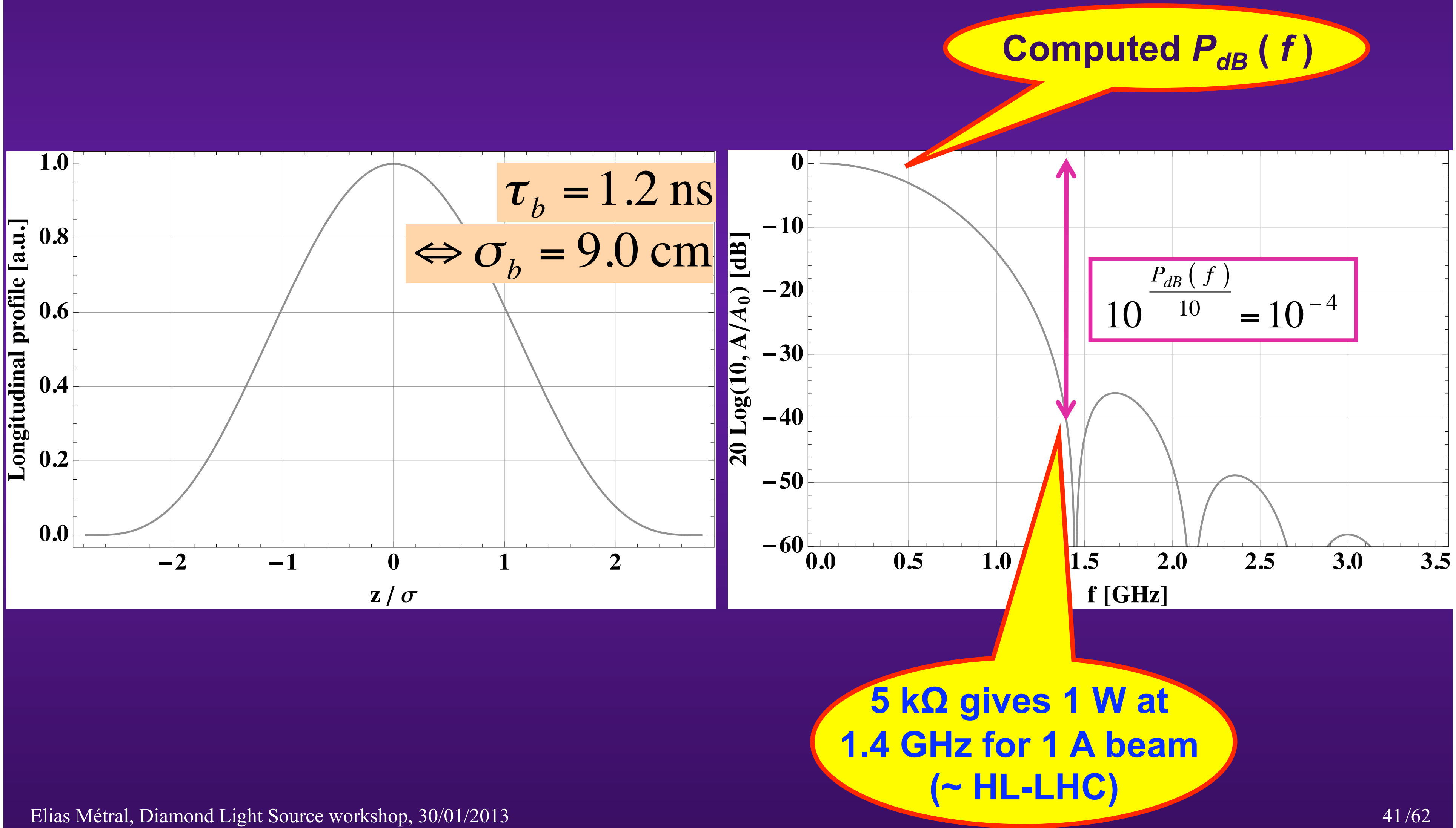
- Example of ferrite tiles:

  Installed in the new VMTSA in 2012

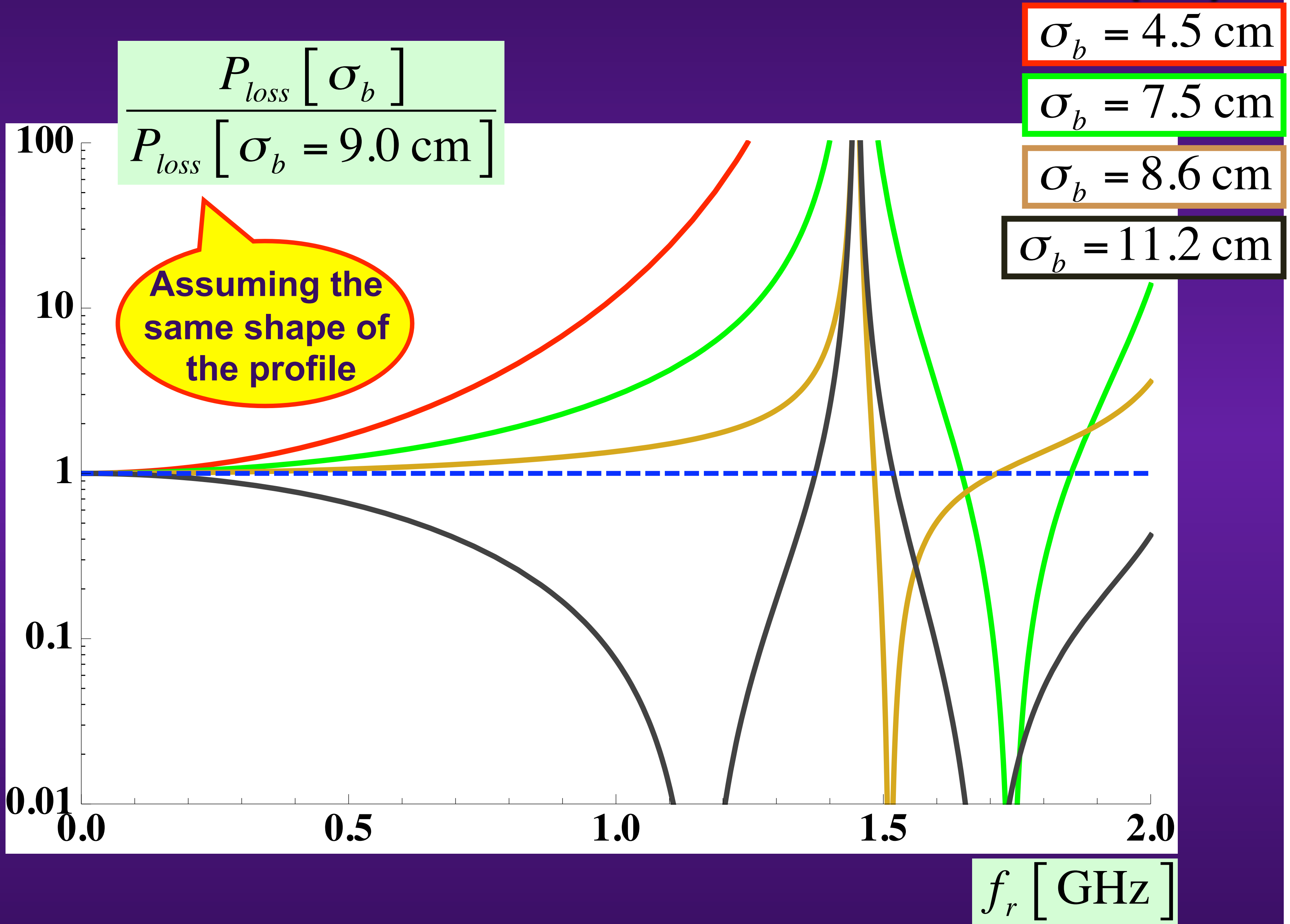
Initial dimensions (quickly available!):
~ 12 cm × 3 cm × 1 cm

WHY DO WE NEED RF FINGERS AND/OR FERRITE? (2/3)

- **Consider the following (analytical) distribution**

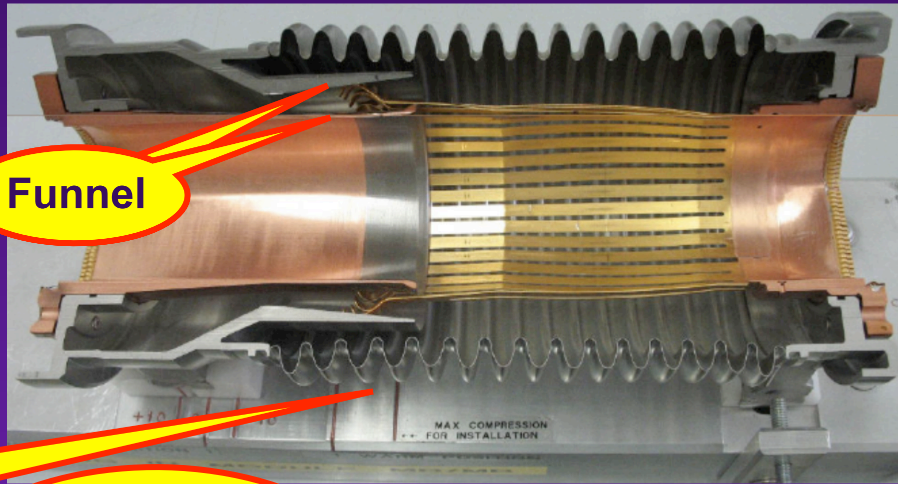


WHY DO WE NEED RF FINGERS AND/OR FERRITE? (3/3)

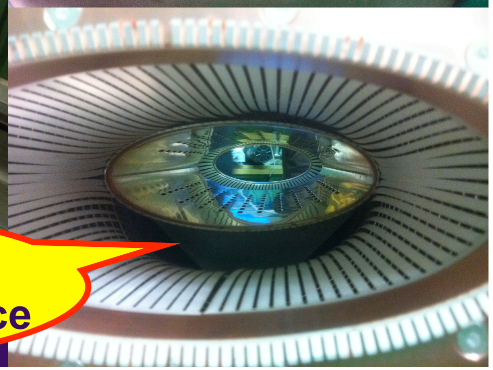


SEVERAL DESIGNS FOR RF FINGERS (1/3)

- **1) Funnel for the PIMs**
  - For case of longitudinal movement (only)
  - Good for contact / gap
  - Possible issue with buckling and aperture restriction

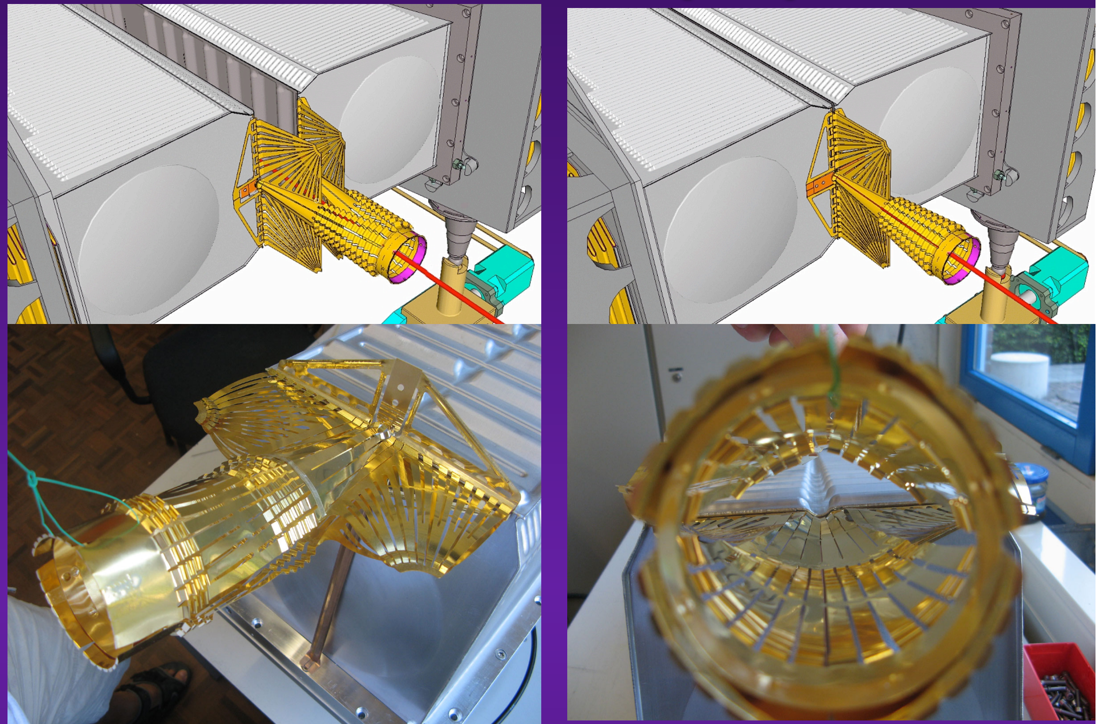


- **2) Spring for the VMTSA**
  - For case of transversal movement
  - Possible issue with contact / gap (due to elliptical shape) => RF heating
  - Possible issue with aperture restriction

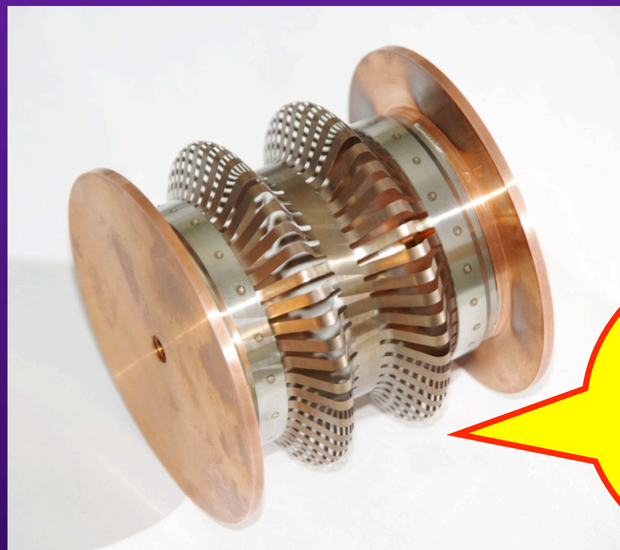


SEVERAL DESIGNS FOR RF FINGERS (2/3)

- **3) Fixed extremities for the LHCb VELO (VErtex LOcator)**
  - Seems to work very well!
  - Well-studied VELO design in terms of impedance effects paid off => No issue observed
  - Future upgrade: Reduction of the inner radius of the foil (from 5.5 to 3 − 4 mm)



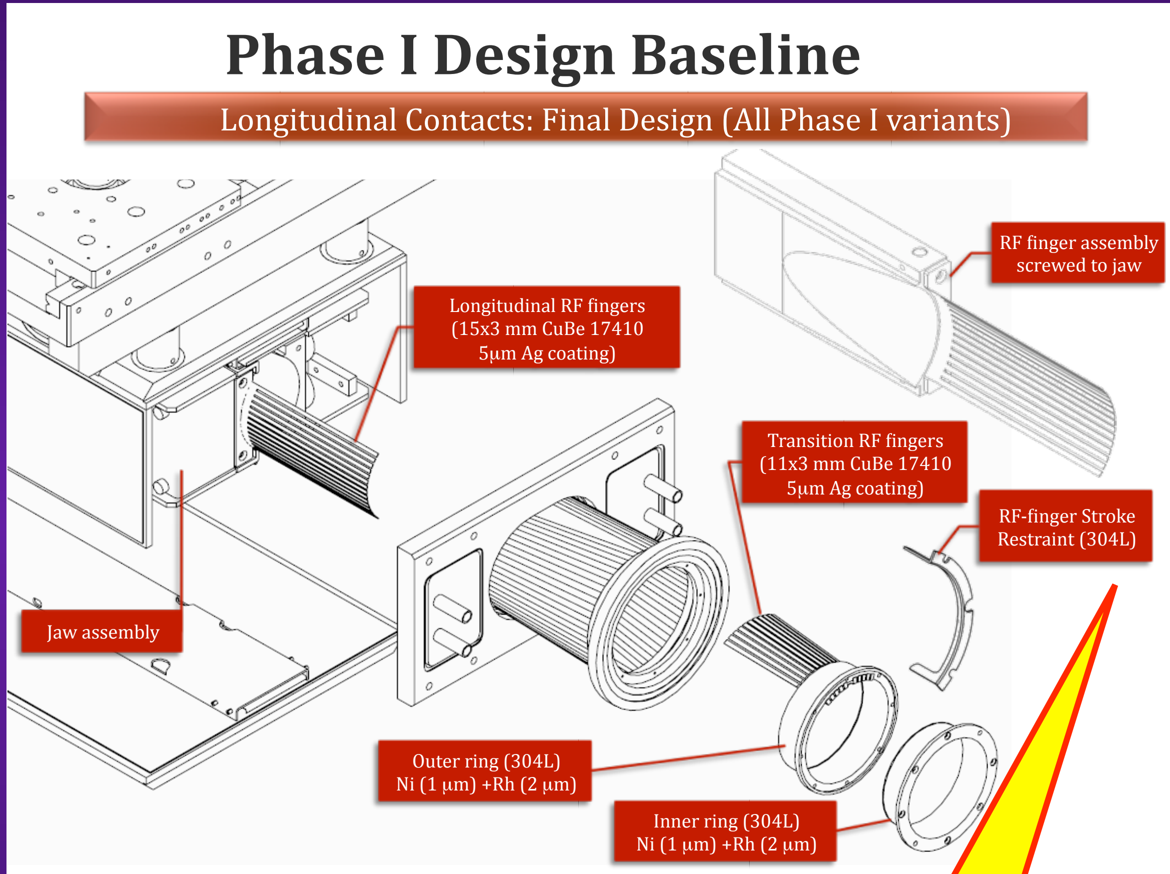
- **4) New RF design from TE/VSC**
  - 1st prototype based on 2 convolutions manufactured this year. Tests ongoing
  - Issue: Imaginary part of the longitudinal impedance (if many and not elongated)

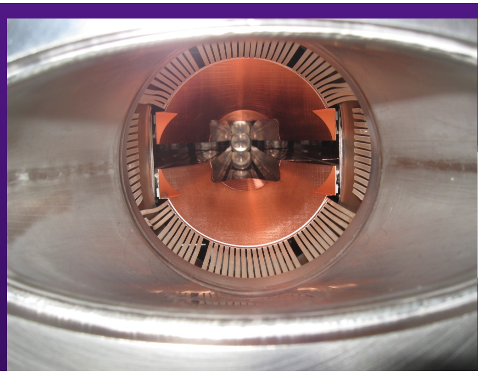


Device EM longer than mechanically due to induced current having to follow the convolutions

SEVERAL DESIGNS FOR RF FINGERS (3/3)

- **5) Longitudinal sliding contacts for collimators**
  - Initial proposal for 1st (SPS) prototype (2003)
  - Uncoated CuBe fingers sliding on C/C
  - Electrical contact resistance ~ 30 mΩ (specification: 1 mΩ) => Redesign necessary





Solution to the pb observed with the TCDD

POSSIBLE ISSUES TO CONSIDER WITH RF FINGERS

- **RF fingers for PIMs**
  - Low contact resistance < 0.1 mΩ (i.e. 3 mΩ / RF finger as there are 30 RF fingers in //)
  - No cold welding
  - Low friction
  - Good formability properties
- **RF fingers for collimators**
  - Same as above with contact resistance < 1 mΩ
  - Resistance to bake out: 250°C / 1000 h
  - Resistance to heating => Good thermal conductivity
  - Wear after many cycles "open-close of the jaws" (1500 cycles ~ 4 years)
- **Good electric contacts requires**
  - Low surface roughness
  - Soft metals (at least one)
  - No oxide layer at the surface

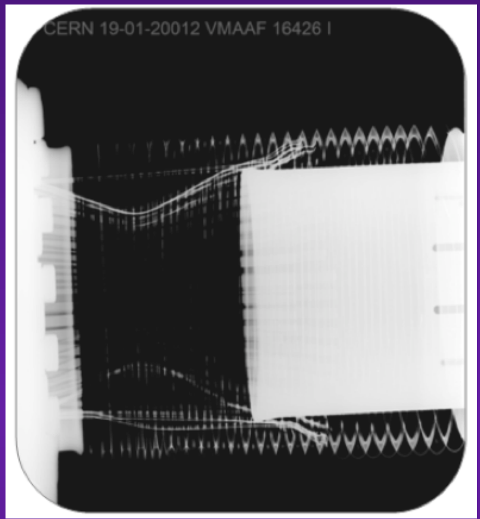
TYPICAL NONCONFORMITIES IN WARM MODULES FOUND WITH X-RAYS (1/2)

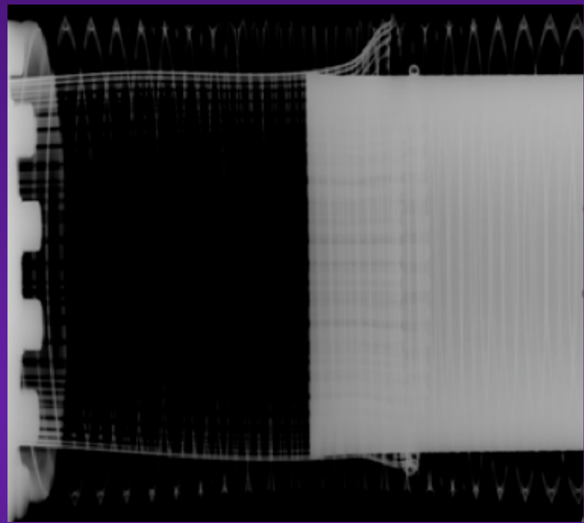
- **1800 X-rays taken**
- **92 NC (~ 5 %) => 2 types of design: circular and elliptical (VMTSA)**
- **58 vacuum sectors concerned out of 190 at room temperature (88 sectors at cryogenic temperature)**

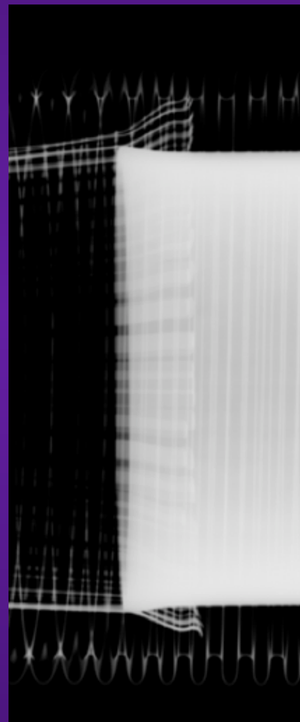
CONFORMITY

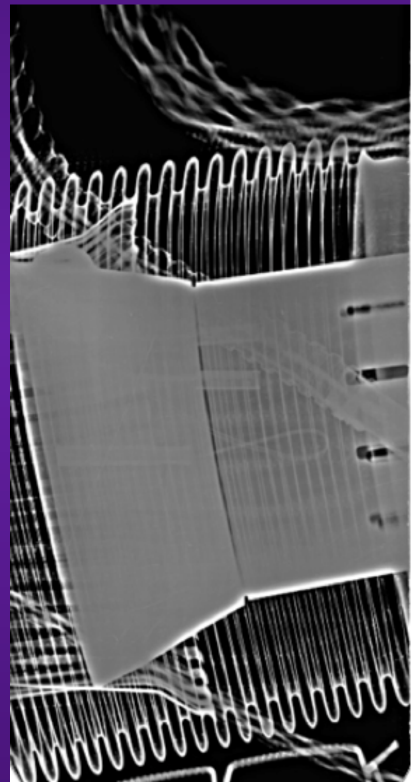
TYPICAL NONCONFORMITIES IN WARM MODULES FOUND WITH X-RAYS (2/2)

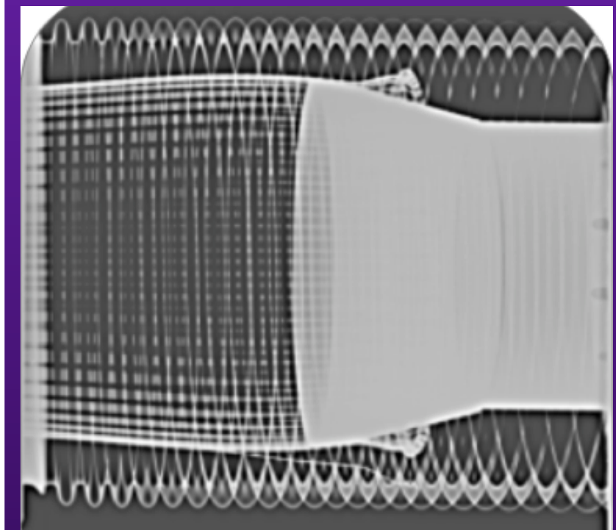
NONCONFORMITIES

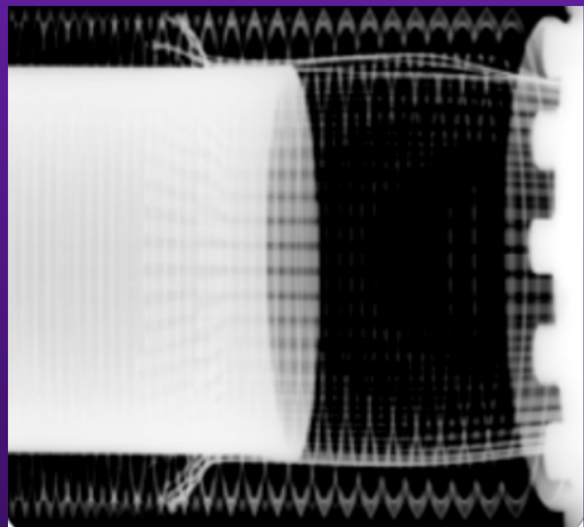








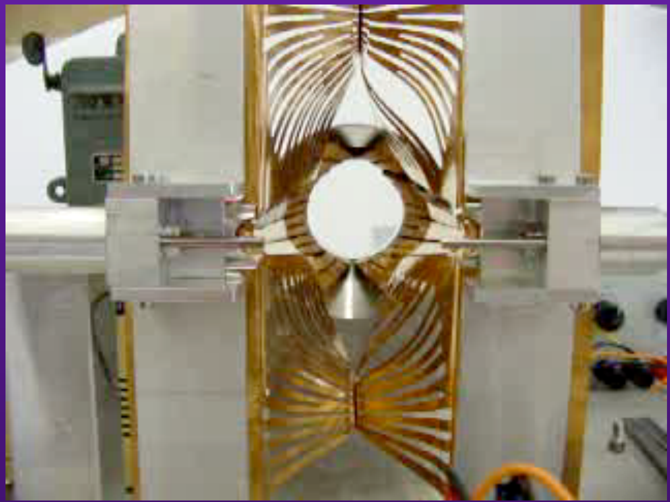




CONCLUSIONS AND RECOMMENDATIONS (1/3)

- A lot of experience has been accumulated at CERN over the past decades for the use of RF fingers and/or ferrite absorbers
- This experience needs to be (and will be) summarized in a forthcoming internal report
  - Guidelines for the use of RF fingers
  - Guidelines for the use of ferrite absorbers => Nominated "ferrite responsible persons" at CERN: Fritz Caspers and Christine Vollinger
- Several designs of RF fingers are used in the LHC depending on the requirements
  - Some have been studied in great detail

    => Takes time but it paid off!



  - New design from TE/VSC under careful checks

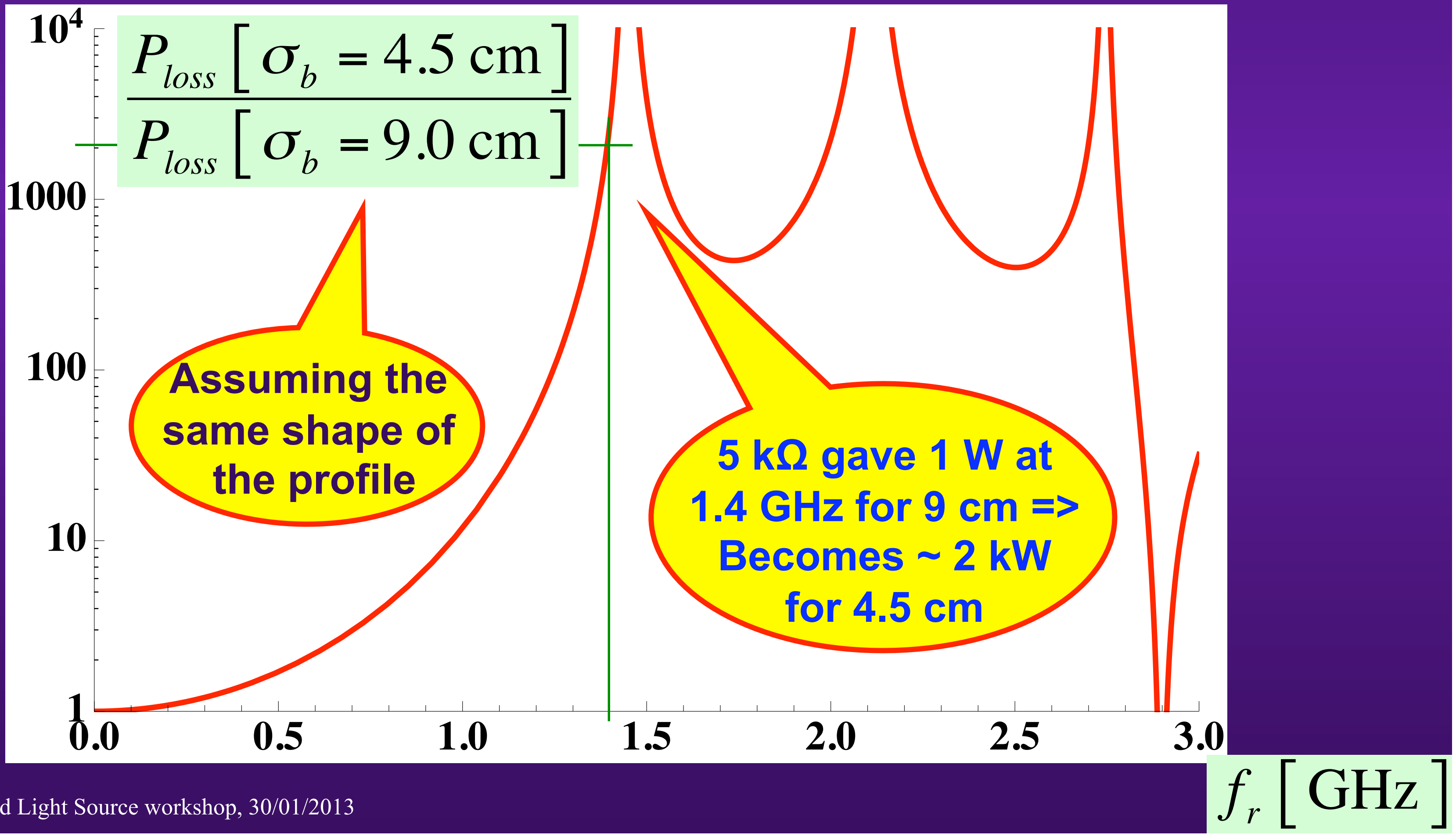
CONCLUSIONS AND RECOMMENDATIONS (2/3)

- VMTSA issues observed in 2011 have been reproduced by simulations and traced back to be due to a gap between some RF fingers and central insert
  - The spring acted as a fuse => Robust mechanical design needed
  - No issue at all this year => Our modifications during last year Xmas break's crash program were sufficient to assure a good contact
  - All the VMTSA modules will be removed during LS1
- Full list of the 92 nonconformities revealed in warm modules after X-rays campaign => Should be repaired during LS1
- For the cases studied, we didn't see any problem with impedance for conforming RF fingers => No (big) pb expected for HL-LHC bunch populations (i.e. up to 2.2E11 p/b for the 25 ns beam and 3.5E11 p/b for the 50 ns beam)

  => Top priority for the future: Robust mechanical design to keep the contacts of all the RF fingers (e.g. with funnel as for the PIMs, or fixed extremities) + Very careful installation

CONCLUSIONS AND RECOMMENDATIONS (3/3)

- **BUT the big problem is the possible very short bunch of ~ 4 cm**
  - **2012 run made with ~ 10 cm rms bunch length**
  - **Nominal (rms) bunch length = 7.5 cm (for both LHC and HL-LHC) and ~ 4 cm was also considered for HL-LHC => Needs many careful checks!!**

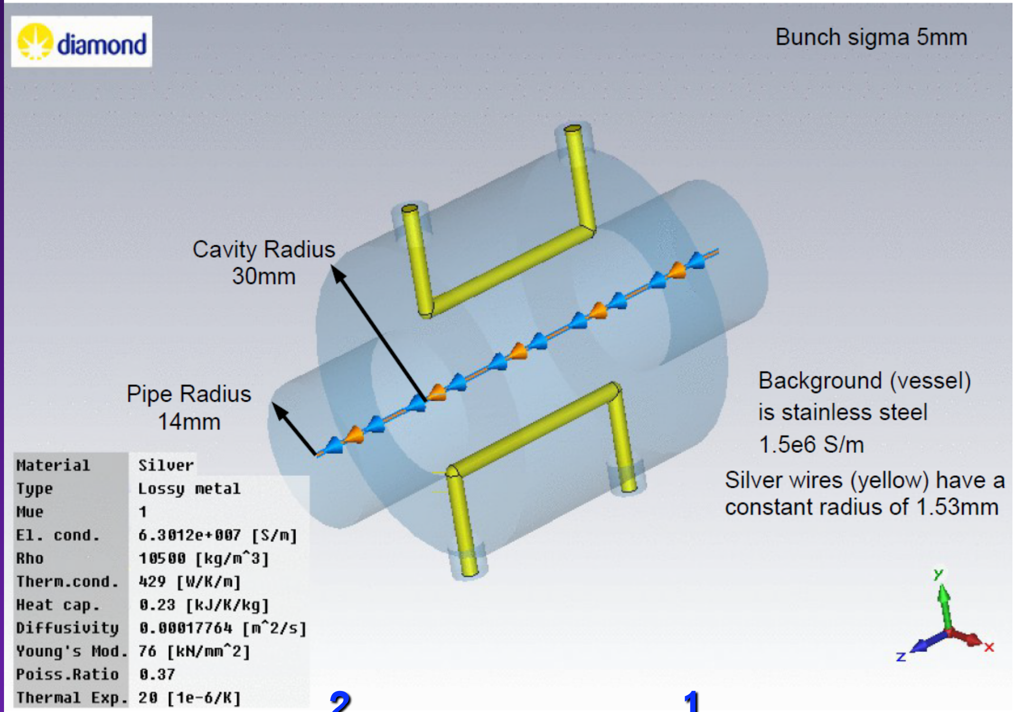


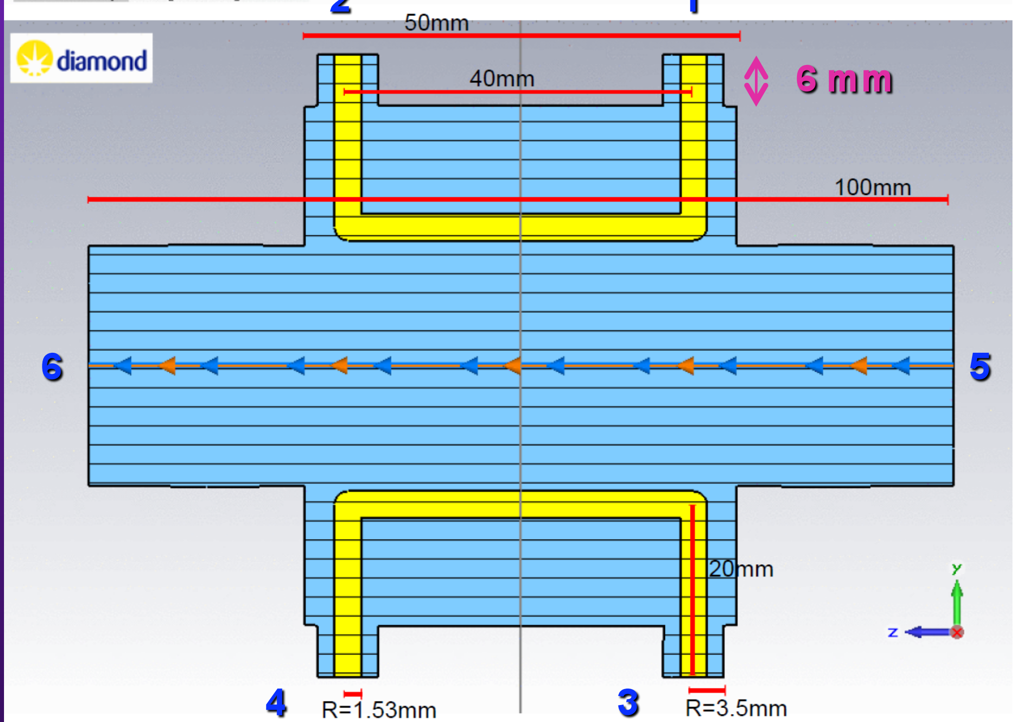
HOMEWORK

GEOMETRY OF THE STRUCTURE

Simplified strip line with the coax ports terminated (waveguide boundary)

- **Beam condition: 1 bunch of 1 nC with 5 mm rms bunch length**





RESULTS (1/9)

Olav Berrig and Benoit Salvant

1) Wake loss factor, energy lost by beam

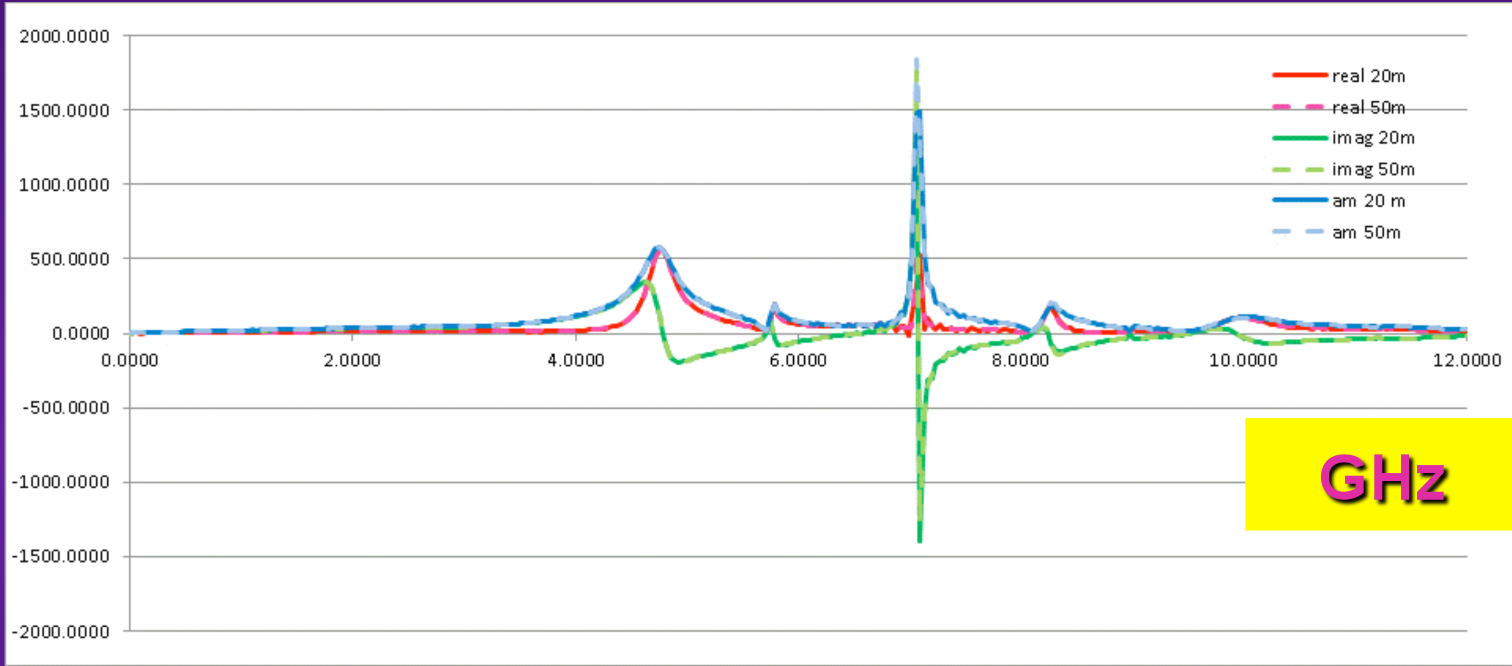
- Wake loss factor => $k_{loss} \approx$ 0.86 V / pC

- Energy loss by the bunch => $E_{loss} \approx$ 0.86 V / pC × (1 nC)^2 ≈ 860 nJ

RESULTS (2/9)

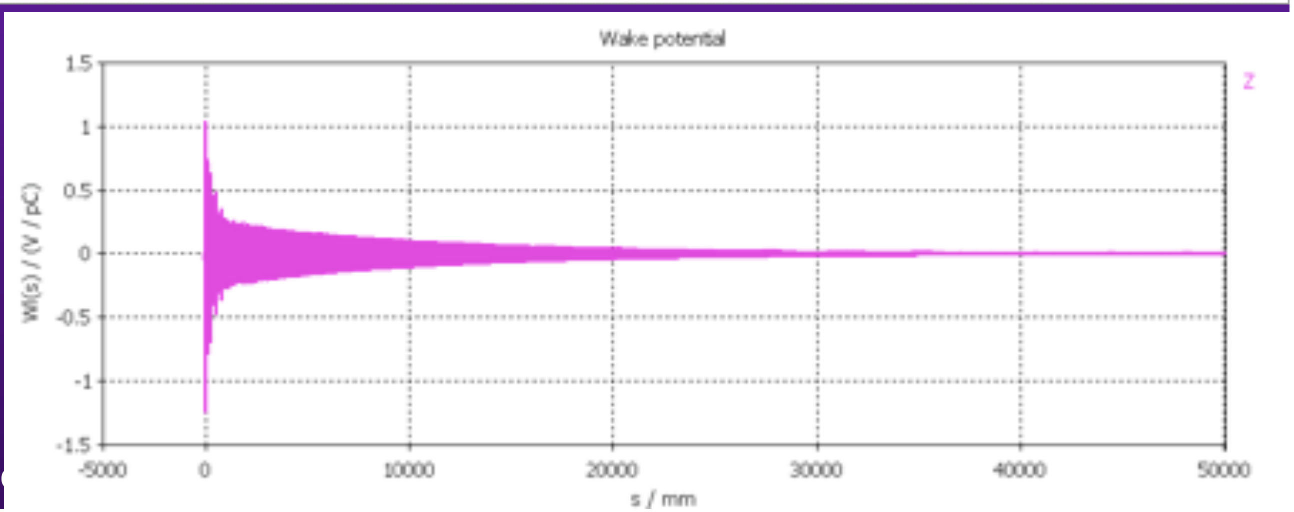
2) Wake impedance

Ω



GHz

Wake potential



RESULTS (3/9)

3) Frequencies and Q factors of the 3 strongest resonances

fr => 4.8 GHz, 5.8 GHz, 7.1 GHz

Q (deduced from half width at half maximum) => 5, 15, 40

$$Q = \frac{f_r}{2\,\Delta f_{\mathrm{HWHM}}}$$

RESULTS (4/9)

4 and 5) Energy radiated into beam pipe ports upstream and downstream and into coax ports 1-4

=> 119 × 2 + 246 × 2 + (44 + 1.3) + (51 + 4) ≈ 830 nJ

Port 1 = Port 3 => 119 nJ

Port 2 = Port 4 => 246 nJ

Port 5 => 44 + 1.3 (2 modes) = 45.3 nJ (discussion about first ns)

Port 6 => 51 + 4 (2 modes) = 55 nJ

$$\text{Energy} = \int dt \left(\text{port signal} \right)^2$$

$$\text{port signal} = \frac{V}{\sqrt{Z}}$$

RESULTS (5/9)

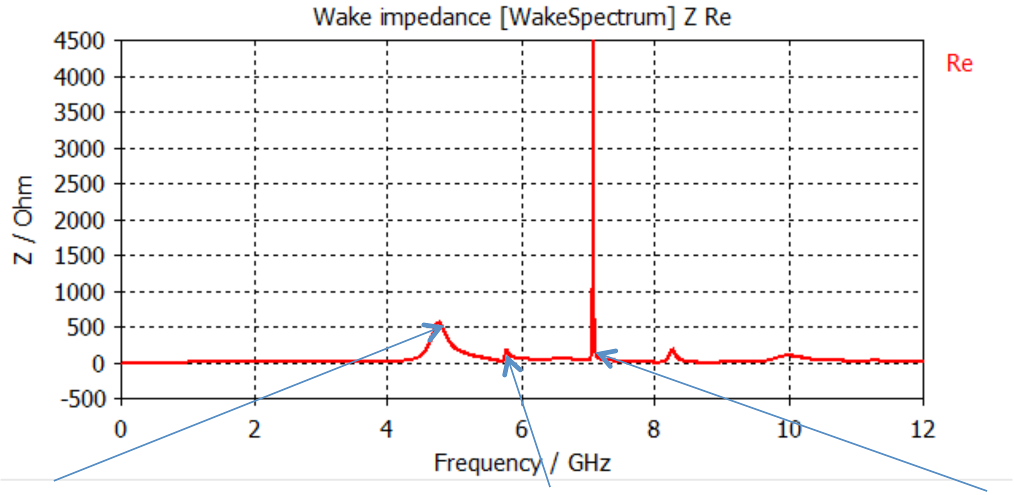
6) Energy deposited into structure, if possible separate for strip line and vessel

=> ~ 860 – ~ 830 ≈ 30 nJ on both strip line and vessel

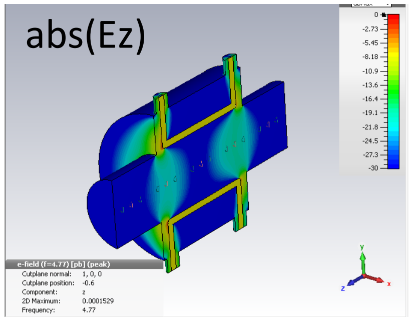
=> ~ 94 % of remaining energy loss in vessel (i.e. ~ 28 nJ) and ~ 6 % in stripline (i.e. ~ 2 nJ) => See next slide

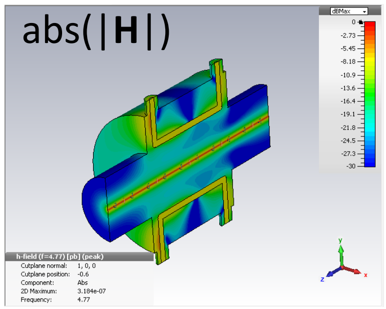
Ongoing

RESULTS (6/9)

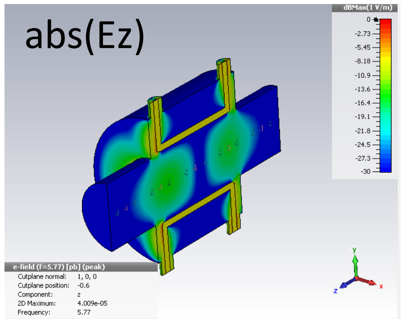


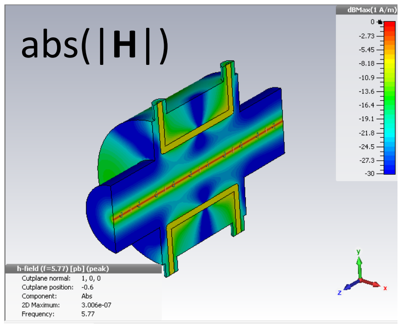
f=4.77 GHz (2 10^{-25} J)
(90 % in vessel, 10% in stripline)



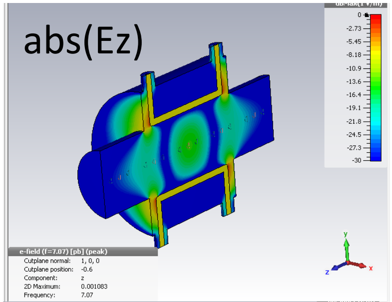


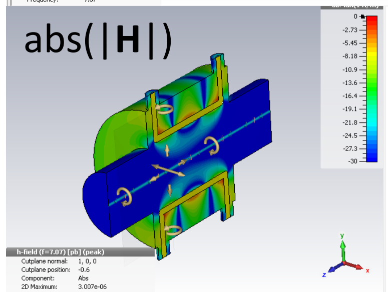
f=5.77 GHz (2 10^{-25} J)
(94 % in vessel, 6% in stripline)





f=7.07 GHz ***(3 10^{-23} J)***
(94 % in vessel, 6% in stripline)





RESULTS (7/9)

1) What software you used for simulation, including version number and module

=> CST Particle Studio (TD) and CST Microwave Studo (FD)

Build version: 2012.6 Release from 2012-09-29 (change 226220)

2) What hardware you have been simulating on, and how long the simulation took (roughly)

=> TD: 12 CPU, RAM of 128 GB, # mesh cells = 1324800 (without use of symmetry), ~ 1h30 for 20 m wake length

3) If you did a time domain simulation, how much time did you simulate (what length of wake potential) and what time steps

=> 20 m wake length. Also 50 m (linear in time)

RESULTS (8/9)

4) If you did an Eigen mode simulation, what frequency range you searched and how many modes you found

=> 2 solvers: AKS (Tetrahedral or Hexahedral) and JDM (uses in simulation losses in the material, whereas in AKS uses it as perturbation, and JDM is very slow)

=> Don’t have much experience in simulating ports in eigenmode… To be continued…

RESULTS (9/9)

OS Name	Microsoft Windows Server 2008 R2 Enterprise
Version	6.1.7601 Service Pack 1 Build 7601
Other OS Description	Not Available
OS Manufacturer	Microsoft Corporation
System Name	CAEVMSRV48
System Manufacturer	Dell Inc.
System Model	PowerEdge R710
System Type	x64-based PC
Processor	Intel(R) Xeon(R) CPU X5650 @ 2.67GHz, 2660 Mhz, 6 Core(s), 6 Logical Processor(s)
Processor	Intel(R) Xeon(R) CPU X5650 @ 2.67GHz, 2660 Mhz, 6 Core(s), 6 Logical Processor(s)
BIOS Version/Date	Dell Inc. 2.0.13 [1.1.22], 4/20/2010
SMBIOS Version	2.6
Windows Directory	C:\Windows
System Directory	C:\Windows\system32
Boot Device	\Device\HarddiskVolume1
Locale	United States
Hardware Abstraction Layer	Version = "6.1.7601.17514"
User Name	Not Available
Time Zone	W. Europe Standard Time
Installed Physical Memory (RAM)	128 GB
Total Physical Memory	128 GB
Available Physical Memory	108 GB
Total Virtual Memory	224 GB
Available Virtual Memory	204 GB
Page File Space	96.0 GB
Page File	C:\pagefile.sys

APPENDIX

Some formulae and linac-accelerator convention

Shunt impedance

Accelerator definition: r

$$V = \int_0^L E_z e^{j\frac{\omega z}{c}} dz$$

Store energy of the mode

$$r = \frac{V^2}{P}; Q = \frac{\omega_0 U}{P}; \quad \frac{r}{Q} = \frac{V^2}{\omega_0 U}$$

$$V = 2qk_l; k_l = \frac{U}{q^2}; \quad k_l = \frac{V^2}{4U}$$

$$k_l = \frac{\omega_0}{4}\frac{r}{Q}$$

P is the power dissipated into the wall

RLC-circuit definition: R

$$Z_l(\omega) = \int_0^\infty W_l(\tau) e^{j\omega\tau} d\tau$$

$$k_l = \frac{1}{\pi}\int_0^\infty \Re\{Z_l(\omega)\} d\omega$$

$$\omega_0 = \frac{1}{\sqrt{LC}}; Q = R\sqrt{\frac{C}{L}}$$

$$Z_l(\omega) = \frac{R}{1 + jQ(\omega/\omega_0 - \omega_0/\omega)}$$

$$k_l = \frac{\omega_0}{2}\frac{R}{Q}$$

$$r = 2R$$

$$Q_{Mat} = \sqrt{\frac{\sigma_{Mat}}{\sigma_{Cu}}}\, Q_{Cu}$$

Use loss(kick) factor instead of impedance

Some other useful formulae

- **Total longitudinal loss factor (for 1 bunch) => In V / C**

$$k_{loss} = \int ds \, W_{//}^{0}(s) \, \lambda(s)$$

Monopole longitudinal wake potential

Normalized charge density of the bunch

- **Energy loss of the bunch with charge Q => In J**

$$E_{loss}^{1 \text{ bunch}} = k_{loss} \, Q^2$$

- **Energy loss for M independent bunches => In J**

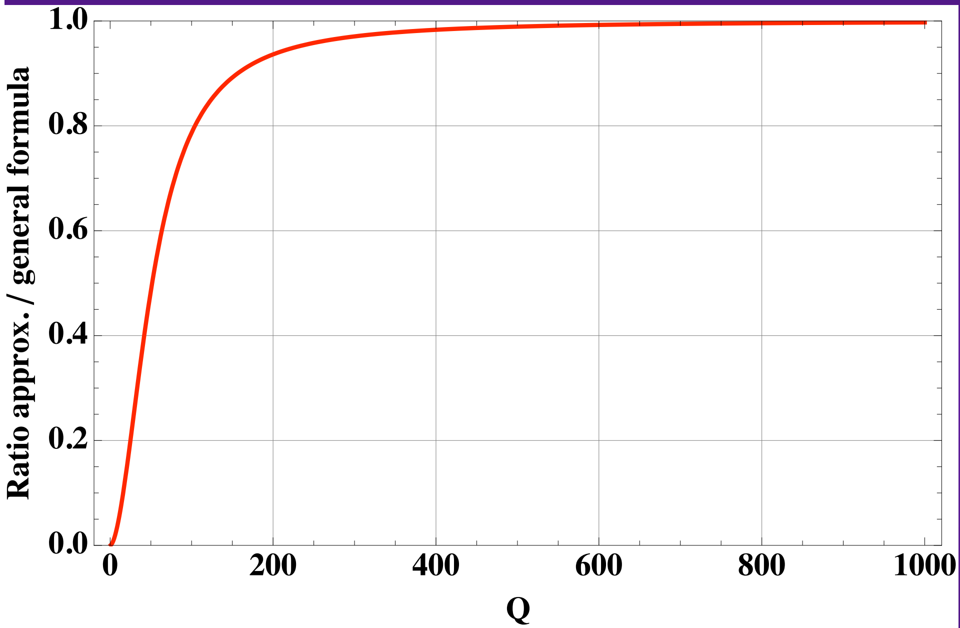
$$E_{loss}^{M \text{ bunches}} = M \, E_{loss}^{1 \text{ bunch}}$$

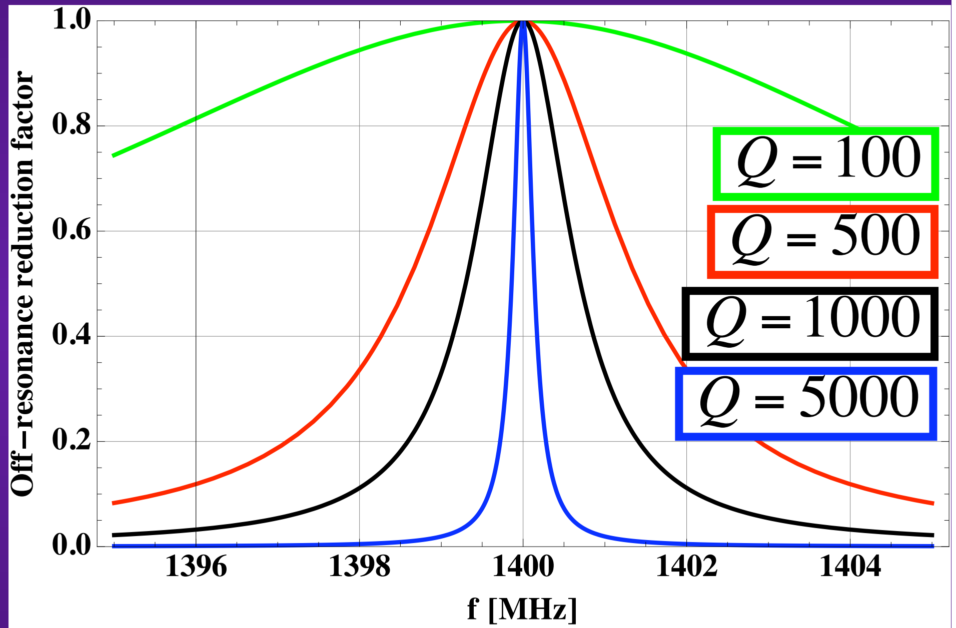
- **Power loss for M independent bunches => In W**

$$P_{loss}^{M \text{ bunches}} = \frac{E_{loss}^{M \text{ bunches}}}{T_{rev}}$$

Approximate formula for a sharp resonance and off-resonance effect for the power loss

- **Consider the case considered before => A possible resonance at 1.4 GHz in the LHC**





- Assumption: f_{RF} = 400 MHz (2.5 ns bucket length)

  => $f_b = f_{RF}$ / 10 = 40 MHz (i.e. 25 ns bunch spacing)
- f_r = 1400 MHz = Assumed resonance frequency of a trapped mode

  => $f_r = p_r \times f_b = p_r \times f_{RF}$ / 10 with p_r = 35
- Below is plotted the off-resonance reduction factor vs. RF frequency, assuming a trapped mode at f_r = 1400 MHz