IMPEDANCE STUDIES FOR LHC AND UPGRADES

Elias Métral

- **ABSTRACT:** Large values of the accelerator impedance influence the motion of trailing particles, in the longitudinal and transverse directions, leading to energy loss, beam instabilities, or secondary effects such as excessive heating of sensitive components at or near the chamber wall (the so-called beam-induced RF heating). Beam-induced RF heating has been observed in many places, for instance in several CERN 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 in operation (reducing integrated luminosity) as well as considerable damage to some equipment. Furthermore, despite the excellent performance of the LHC in 2012, with a record peak luminosity at 4 TeV corresponding to 77 % of the 7 TeV design luminosity of 10^{34} $cm^{-2}s^{-1}$, the intensity ramp-up was perturbed by several types of instabilities, one of which could not be damped at the end of the run. These limitations could be more severe in the future and therefore impedances should be treated with great care.

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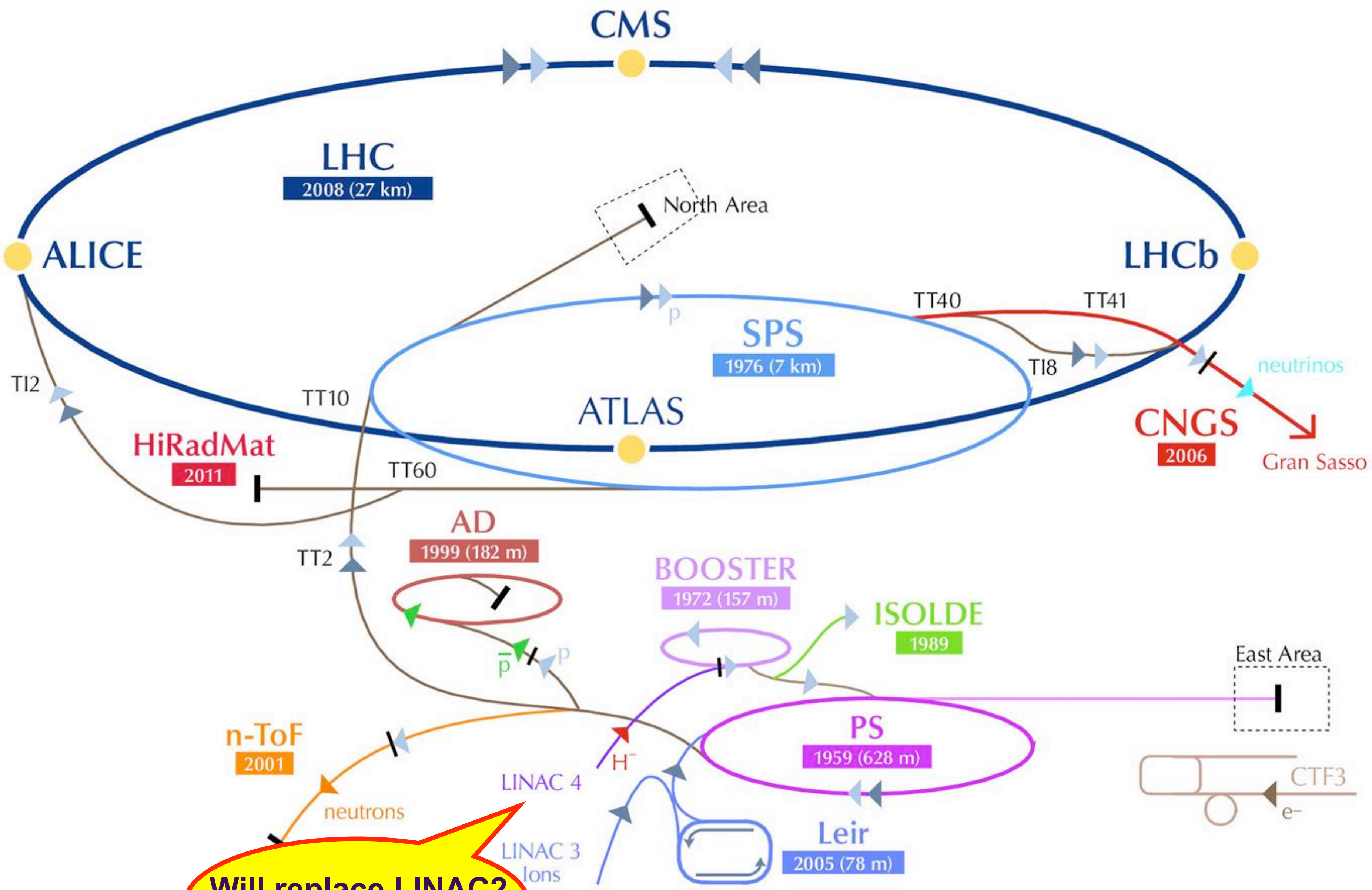
OUTLINE

- Introduction
- Impedance and related transverse instabilities
- Beam-induced RF heating
- CERN RF fingers task force in 2012
- Mini-workshop at the DLS on 30/01/2013
- Conclusion

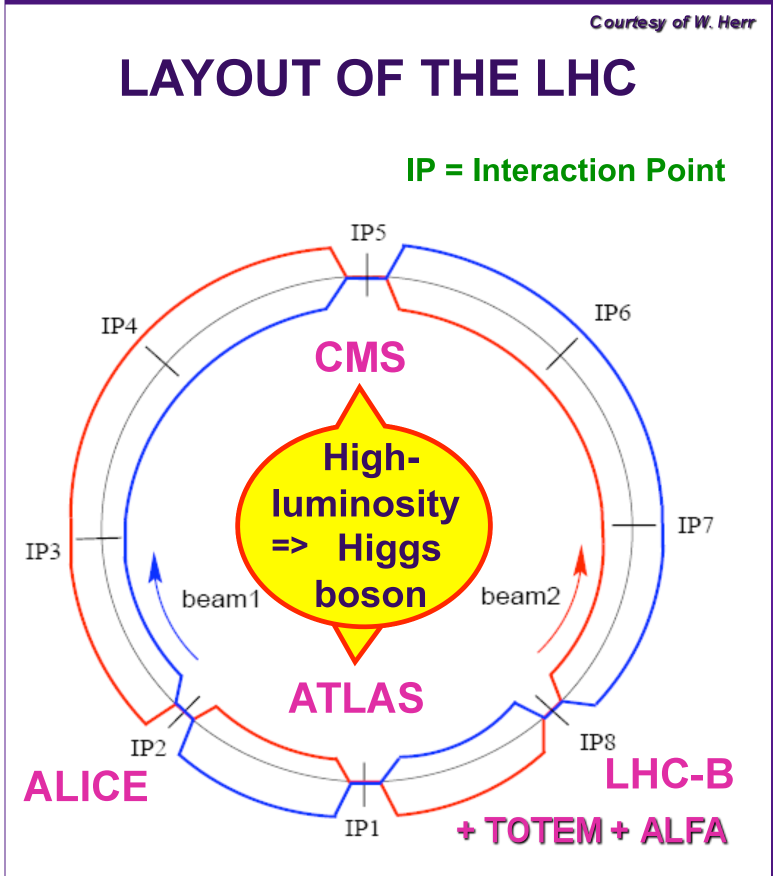
Many thanks to all the impedance colleagues, inside CERN and outside CERN => INFN, DESY, TUD, Naples, etc.

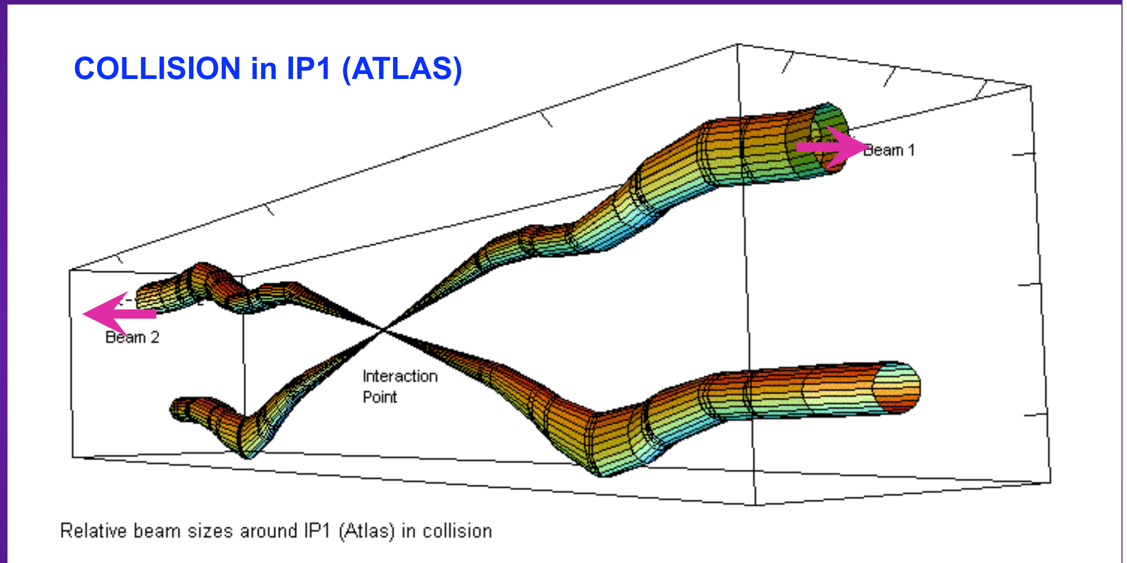
INTRODUCTION (1/7)



Will replace LINAC2 (p^+) in few years

INTRODUCTION (2/7)





Courtesy of A. Hofmann

INTRODUCTION (3/7)

- 1983 (i.e. several years before LEP started): 1st ideas / estimates for LHC

- Dec. 1994: LHC Project approved by CERN Council

- Oct. 1995: LHC Conceptual Design Report, which has served as the basis for the detailed design

- Dec. 1996: Council passed a Resolution approving the construction of the 14 TeV accelerator in a single stage (initially, the budgetary constraints implied that the LHC was to be conceived as a 2-stage project). The LHC is the 1st machine built at CERN with substantial material contribution from non-Member States. Machine hardware constructed in National Laboratories in Canada, India, Japan, Russia and USA

- 2007: LHC was finished

- 2008: LHC commissioning & inauguration

10/09/2008: LHC startup

INTRODUCTION (4/7)

- 19/09/2008: **Major incident…**

Fault in a dipole-quadrupole interconnect ("splice")

- 30/03/2010: 1st collisions at 7 TeV (3.5 + 3.5)

- 04/07/2012: Announcement of the discovery of a new particle ("Higgs-like" boson). 4 TeV beams used in 2012

- At the end of Run I (end 2012): Peak luminosity record ~ 7.7E33, i.e. 77% of design luminosity

- Long Shutdown 1 (2013-2014) => Ensure operation of the LHC > 13 TeV (6.5 + 6.5) and reliable operation of the accelerator complex

Courtesy of A. Hofmann

INTRODUCTION (5/7)

LHC 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)
Bunch spacing	Δt	25 ns (50 in 2012)
Norm. rms. trans. emittance	ε	3.75 µm (~ 2.2 in 2012)
Revolution frequency	f_0	11245 Hz
Rms bunch length	σ_z	7.5 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)

=> Bunch brightness reached: ~ (1.6 / 1.15) × (3.75 / 2.2) ~ 2.4 times larger than nominal!

Courtesy of A. Hofmann

INTRODUCTION (6/7)

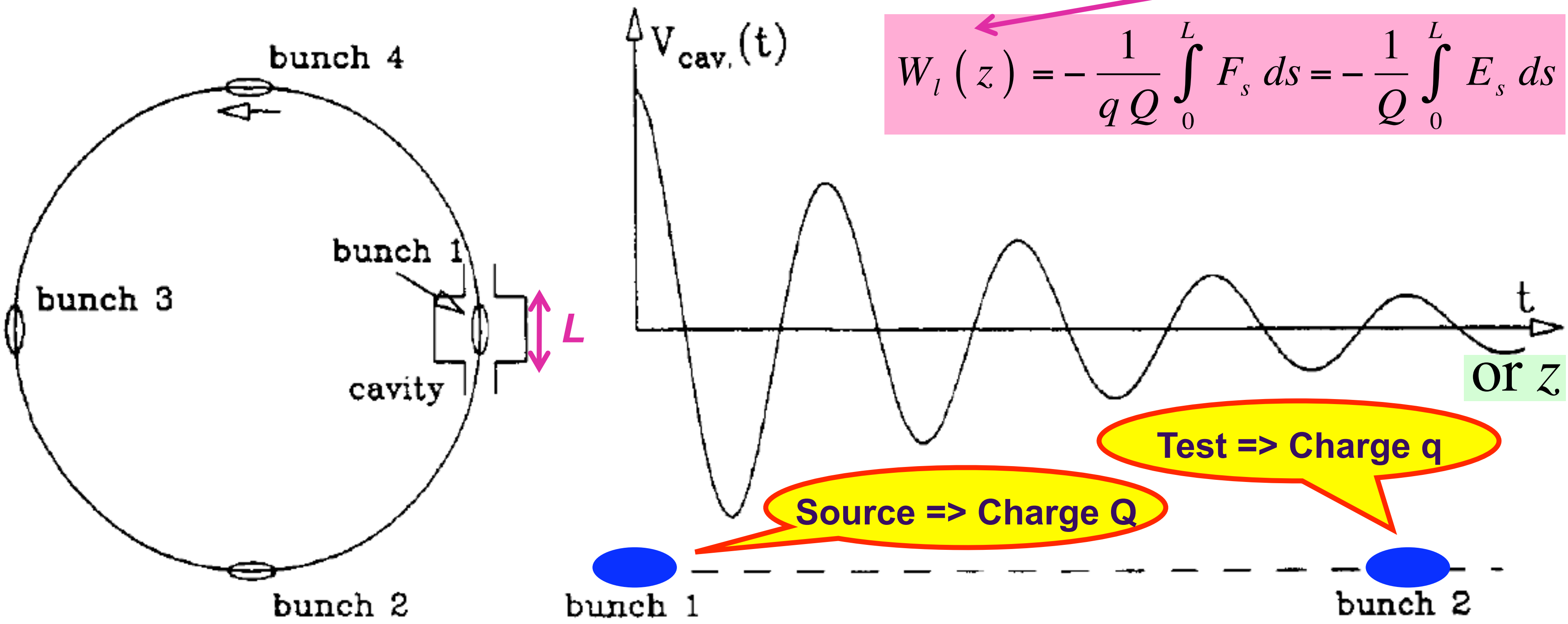
HL-LHC parameters

Parameter	nominal	25ns	50ns
N_b	1.15E+11	2.2E+11	3.5E+11
n_b	2808	2808	1404
N_{tot}	3.2E+14	6.2E+14	4.9E+14
beam current [A]	0.58	1.11	0.89
x-ing angle [μrad]	300	590	590
beam separation [σ]	9.9	12.5	11.4
β^* [m]	0.55	0.15	0.15
ε_n [μm]	3.75	2.50	3
ε_L [eVs]	2.51	2.51	2.51
energy spread	1.20E-04	1.20E-04	1.20E-04
bunch length [m]	7.50E-02	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	18.5	17.2
IBS longitudinal [h]	61 -> 60	20.4	16.1
Piwinski parameter	0.68	3.12	2.85
Reduction factor 'R1*H1' at full crossing angle (no crabbing)	0.828	0.306	0.333
Reduction factor 'H0' at zero crossing angle (full crabbing)	0.991	0.905	0.905
beam-beam / IP without Crab Cavity	3.1E-03	3.3E-03	4.7E-03
beam-beam / IP with Crab cavity	3.8E-03	1.1E-02	1.4E-02
Peak Luminosity without levelling [$cm^{-2} s^{-1}$]	1.0E+34	7.4E+34	8.5E+34
Virtual Luminosity: Lpeak*H0/R1/H1 [$cm^{-2} s^{-1}$]	1.2E+34	21.9E+34	23.1E+34
Events / crossing without levelling	19 -> 28	210	475
Levelled Luminosity [$cm^{-2} s^{-1}$]	-	5E+34	2.50E+34
Events / crossing (with leveling for HL-LHC)	*19 -> 28	140	140
Leveling time [h] (assuming no emittance growth)	-	9.0	18.3

INTRODUCTION (7/7)

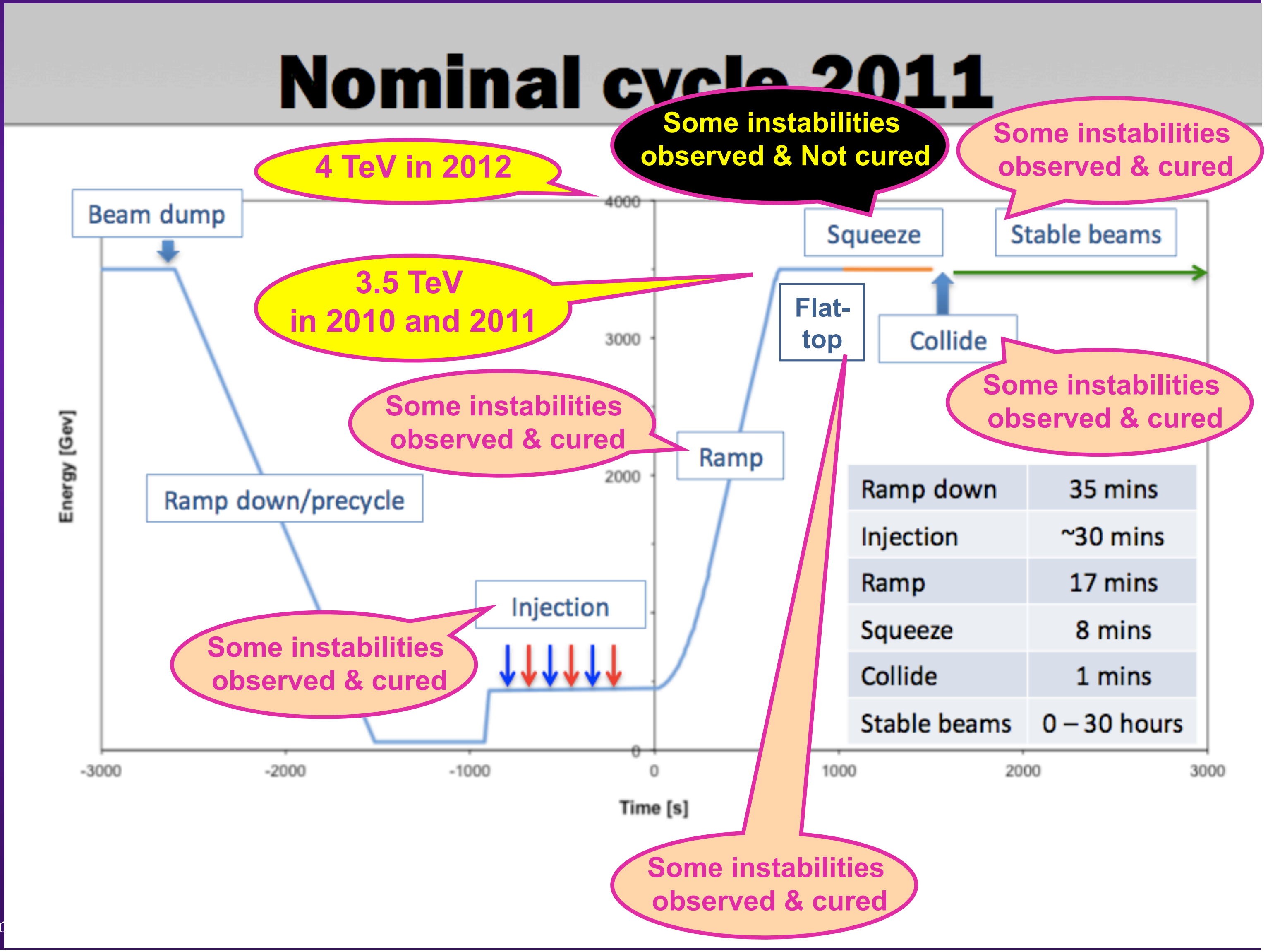
- **Wake field** = Electromagnetic field generated by the beam interacting with its surroundings (vacuum pipe, etc.)
  - Energy loss
  - Beam instabilities
  - Excessive heating => "Beam-induced RF heating"
- **Impedance** = Fourier transform of the wake field (wake function)

$$W_l\left(z\right) = -\frac{1}{q\,Q}\int_0^L F_s\,ds = -\frac{1}{Q}\int_0^L E_s\,ds$$



IMPEDANCE AND RELATED TRANSV. INSTABILITIES (1/11)

- Several types of instabilities perturbed the intensity ramp-up and 1 instability remained at the end of the Run 1 => Worry for the future…



Ramp down	35 mins
Injection	~30 mins
Ramp	17 mins
Squeeze	8 mins
Collide	1 mins
Stable beams	0 – 30 hours

IMPEDANCE AND RELATED TRANSV. INSTABILITIES (2/11)

- **Reminder: Knobs available to damp transverse coherent instabilities**
  - **Transverse tunes and tune split between the 2 beams**
  - **Coupling between the transverse planes**
  - **Chromaticities (value and sign)**
  - **(Landau) octupoles (value and sign) to increase Landau damping**
  - **Transverse damper (gain and bandwidth: not fully flat / bunch-by-bunch or flat / bunch-by-bunch)**
  - **Bunch length and / or longitudinal profile**

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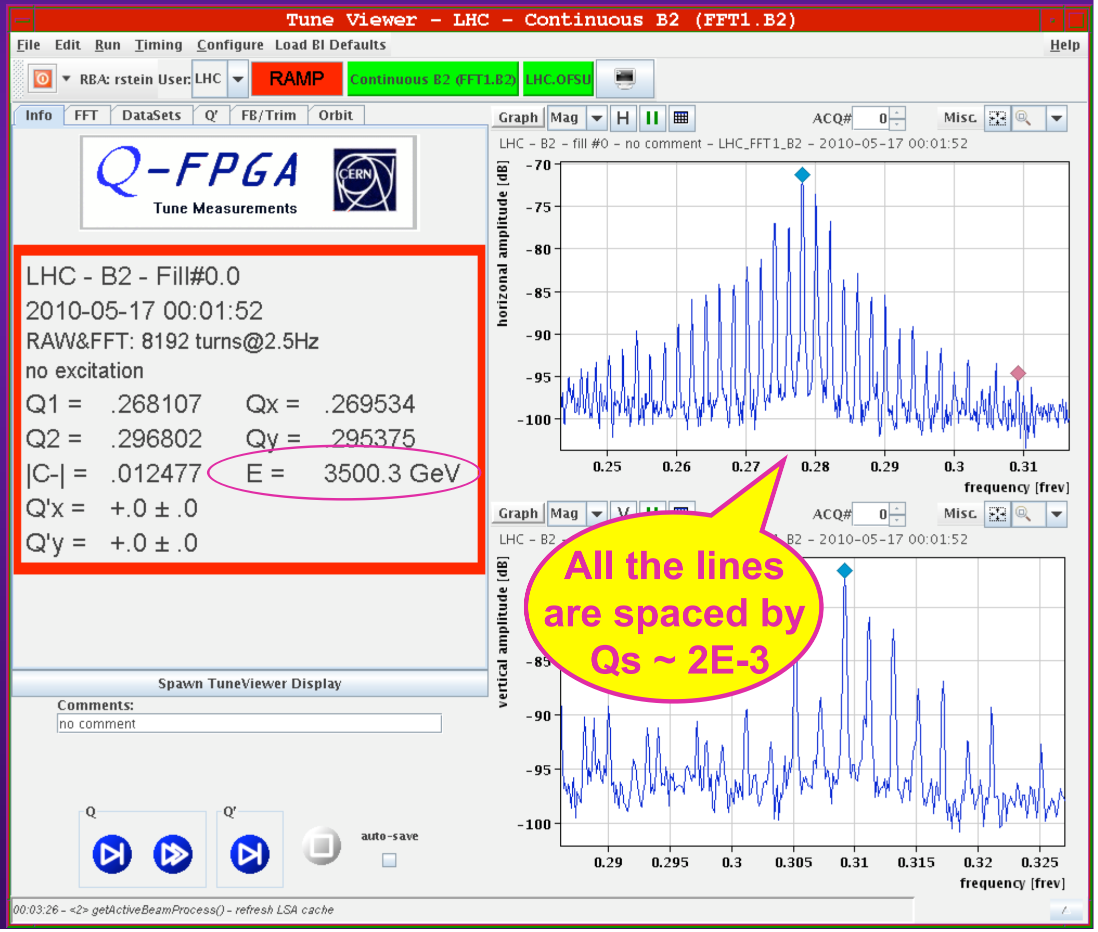
IMPEDANCE AND RELATED TRANSV. INSTABILITIES (3/11)

- **1st ramp tried with single-bunch of ~ 1E11 p/b (both B1 and B2) on SA 15/05/2010 without Landau octupoles**

=> Bunch unstable at ~ 1.8 TeV for B1 and ~ 2.1 TeV for B2

=> Famous "Christmas tree"

Dedicated study on MO 17/05/2010 at 3.5 TeV

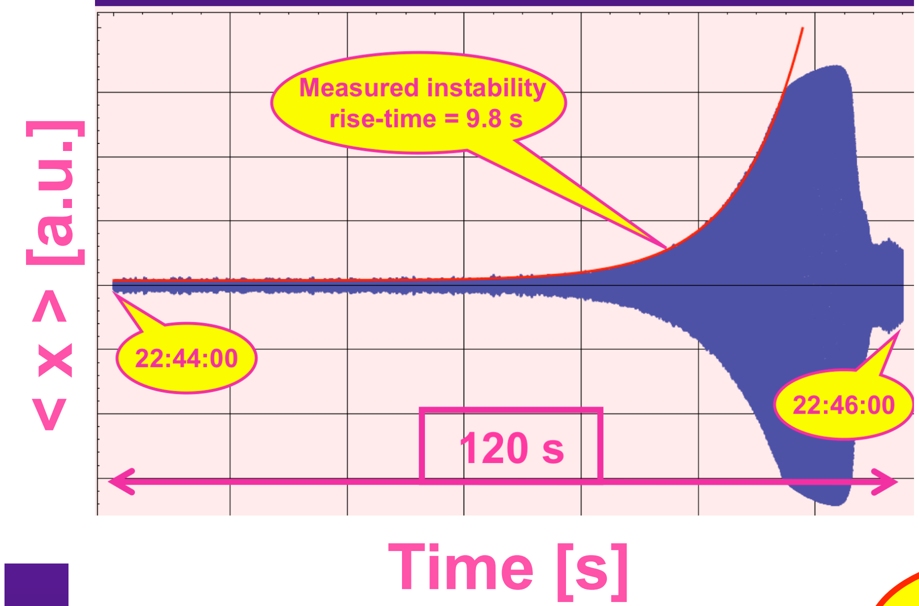


All the lines are spaced by Qs ~ 2E-3

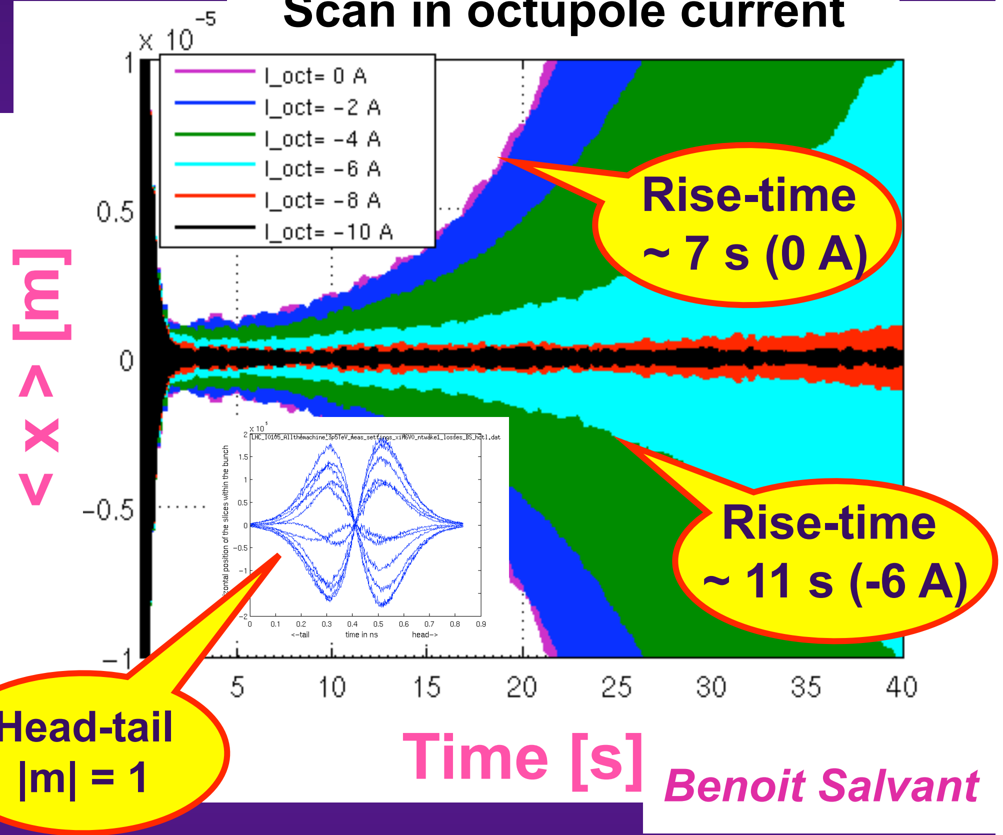
IMPEDANCE AND RELATED TRANSV. INSTABILITIES (4/11)

MEASUREMENTS

(17/05/2010 at 3.5 TeV)



SIMULATIONS



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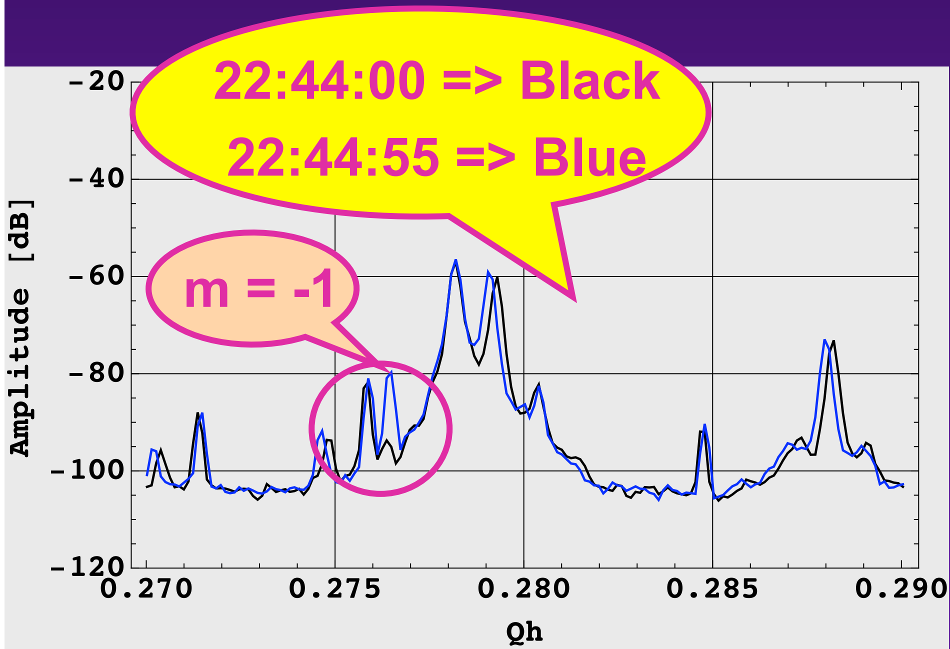
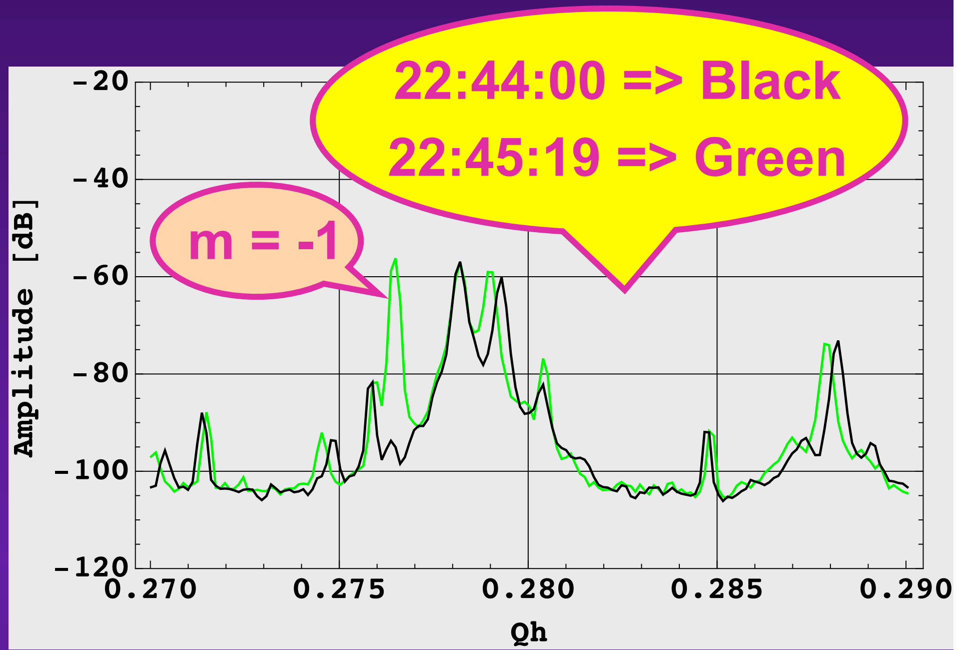
- Rise-time ~ 10 s
- - 20 A < I_{oct} for stability < - 10 A

- Rise-time ~ 10 s
- Stability for I_{oct} ~ - 10 A

IMPEDANCE AND RELATED TRANSV. INSTABILITIES (5/11)





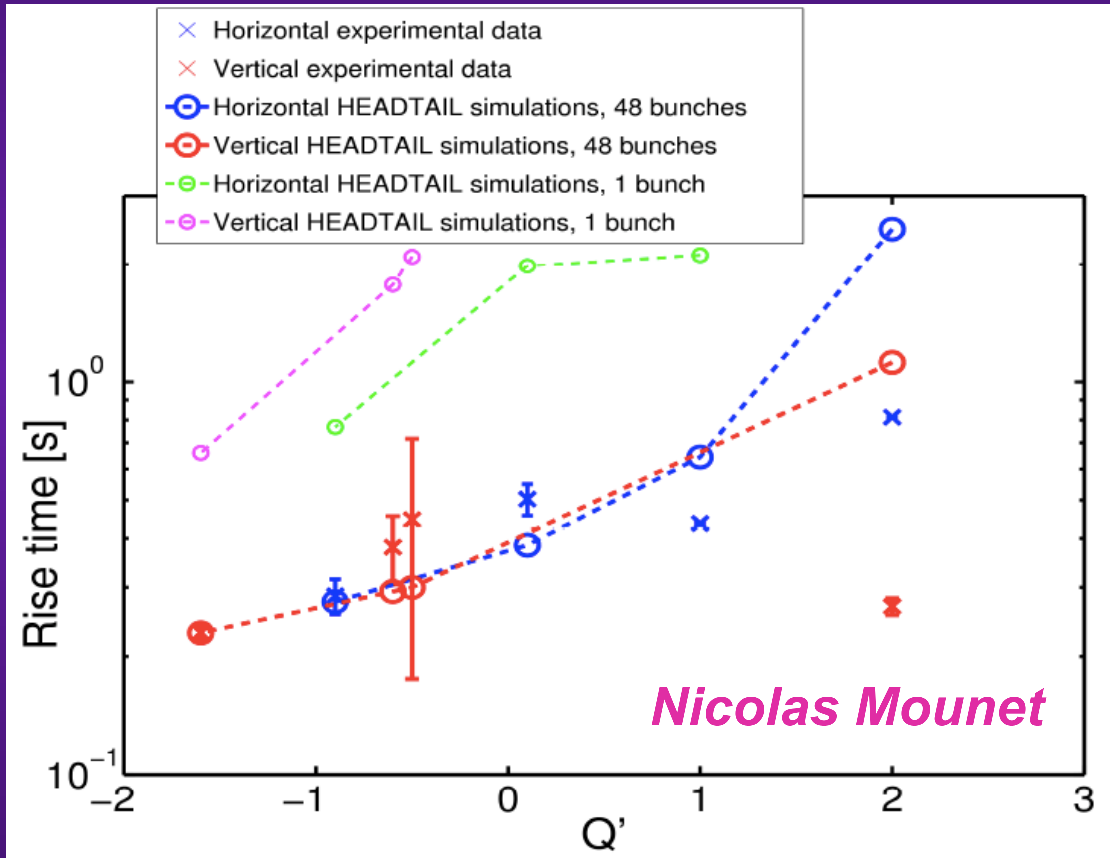
Estimation of the rise-time in frequency domain

~ 24 dB in 24 s => ~ 9 dB in ~ 9 s

=> Instability rise time ~ 9 s (consistent with time domain)

IMPEDANCE AND RELATED TRANSV. INSTABILITIES (6/11)

- **TCBI rise-time studies (for mode 0) with 48 bunches (12 + 36)**
  - **Good agreement at 450 GeV**



  - **~ 2-3 faster rise-times observed at 3.5 TeV (but uncertainty on chromaticities…)**

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IMPEDANCE AND RELATED TRANSV. INSTABILITIES (7/11)

- **Landau octupoles used at 3.5 TeV to stabilize the beam**

LOD = - LOF

Landau octupole current [A]	Beam 1	Beam 2
HEADTAIL predictions (Gaussian bunch)	120	100
Measurements	60	70

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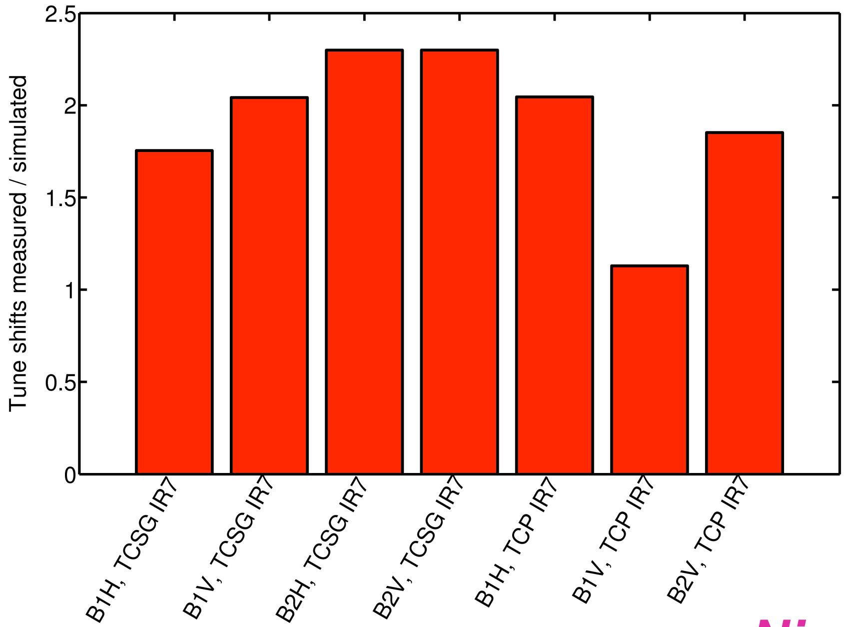
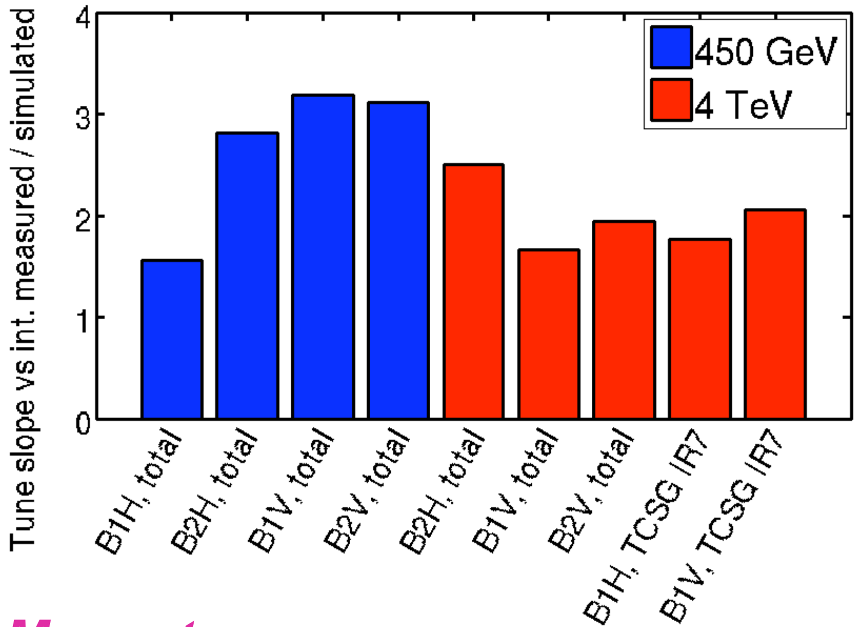
- **Simulations more critical (but uncertainty on chromaticities, transverse profile - measured by collimation team - different from Gaussian, etc.) => Reasons exist for that and some explanation can be found!**

IMPEDANCE AND RELATED TRANSV. INSTABILITIES (8/11)

- **Transverse coherent tune shifts: simulations vs. measurements**





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=> Everything was for the best in the best of all possible worlds…

IMPEDANCE AND RELATED TRANSV. INSTABILITIES (9/11)

- **Things started to get worse during the 2012 run, which was devoted to LHC exploitation but also to explore the LHC performance limits => Busy period for us!**

- **Lot of effort devoted to study the main mechanisms alone and interplays between them**
  - **Impedance, octupoles and transverse damper (and BBLR)**
  - **Impedance and beam-beam (BBLR & BBHO)**
  - **Etc.**

- **Experience from 2012 => "Full" understanding not possible**
  - **Frequent and simultaneous changes of beam parameters**
  - **Non-conclusive measurements**
  - **Different interpretation of measurements and observations**

  => More systematic measurements needed

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IMPEDANCE AND RELATED TRANSV. INSTABILITIES (10/11)

- **Lot of effort to refine the LHC impedance model**

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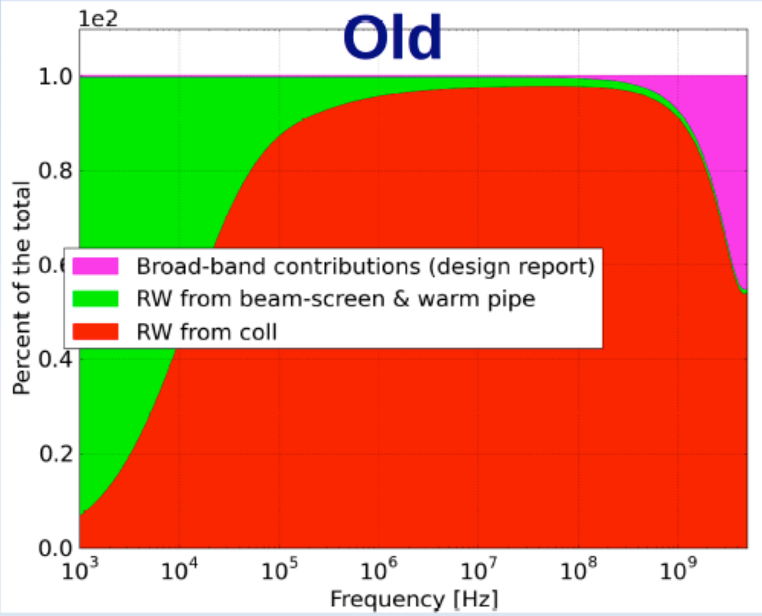
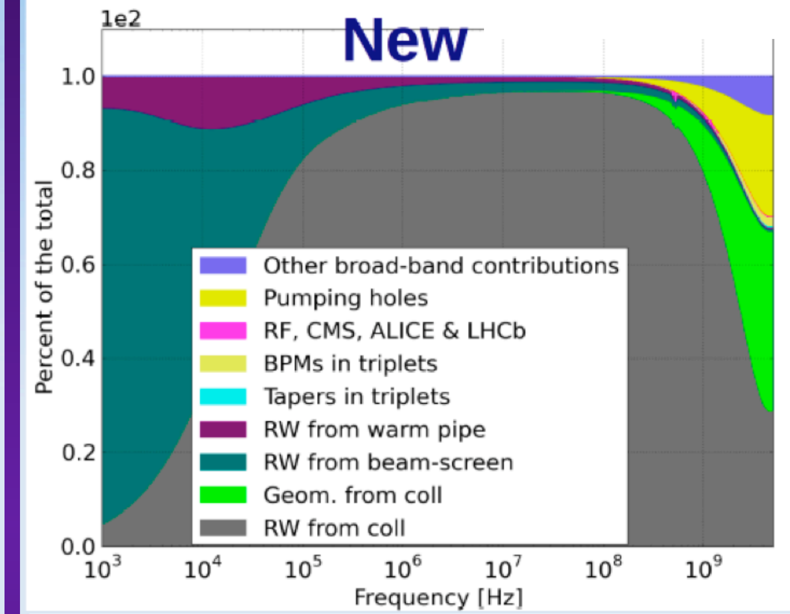
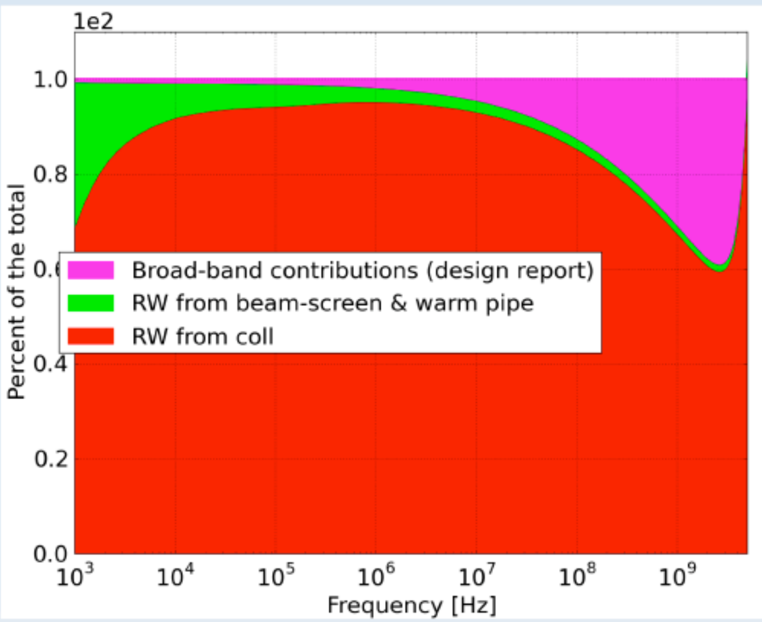
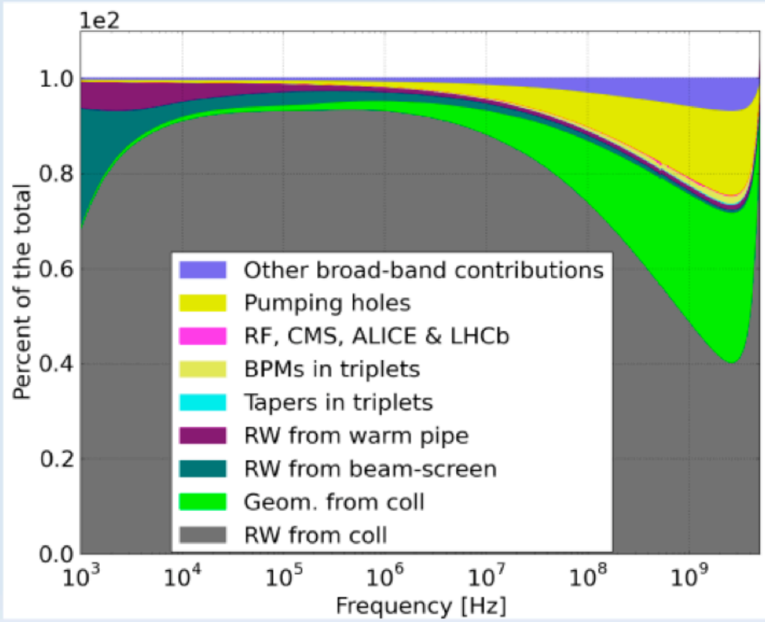
Real part





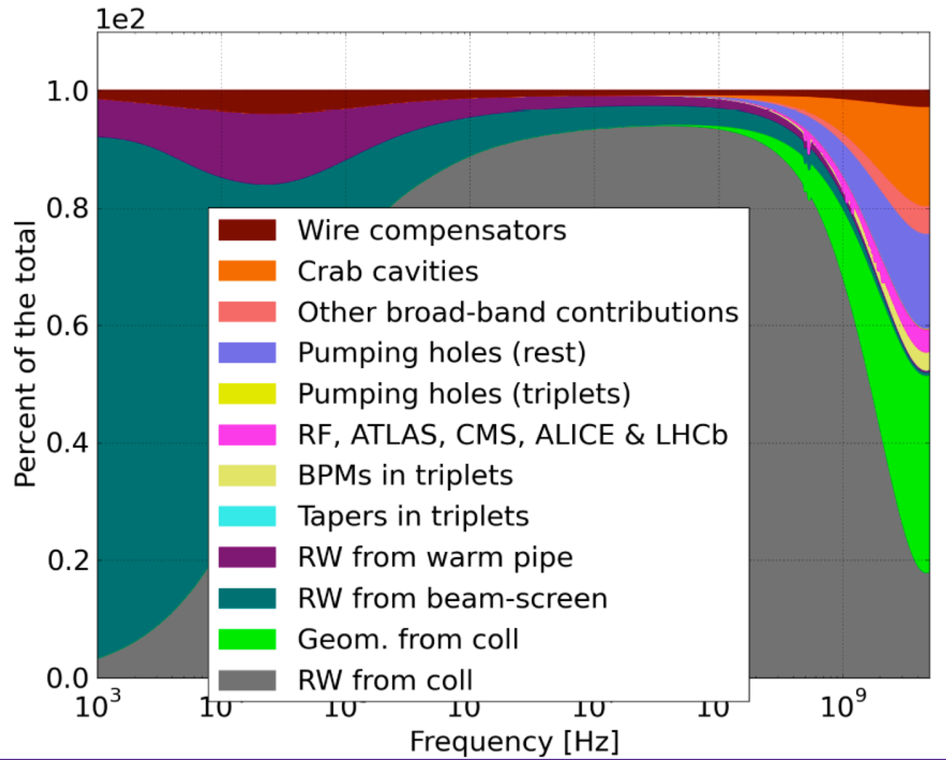
Imag. part

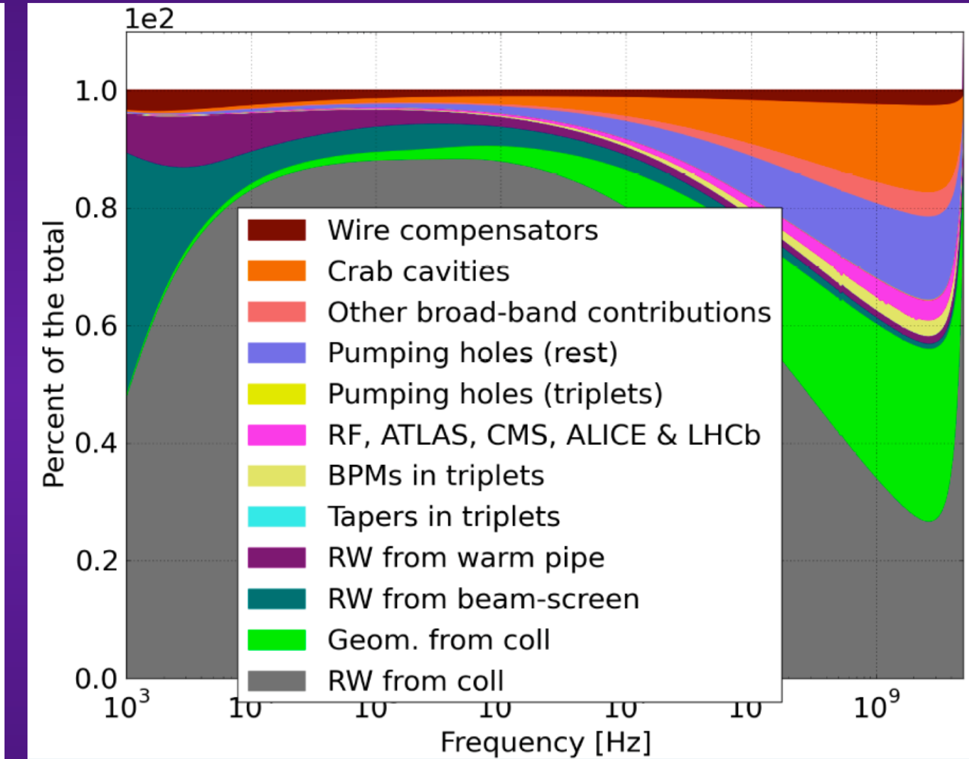




IMPEDANCE AND RELATED TRANSV. INSTABILITIES (11/11)

- **First estimate of the HL-LHC impedance model**





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BEAM-INDUCED RF HEATING (1/9)

- **Observed in several equipment during the 2011-2012 runs when bunch/beam intensity increased and/or bunch length reduced**

equipment	Problem	2011	2012	Hopes after LS1	OK for HL-LHC?
VMTSA	Damage			removed	removed
TDI	Damage			Beam screen reinforced, copper coating on the jaw	New design underway
MKI	Delay			Beam screen and tank emissivity upgrade	Current upgrade may not be enough
TCP_B6L7_B1	Few dumps			Cooling system checked	400 W expected for 7 kW cooling
TCTVB	Few dumps			removed	removed
Beam screen Q6R5	Regulation at the limit			Upgrade of the valves + TOTEM check	Upgrade should be sufficient
ALFA	Risk of damage			New design + cooling	No forward physics after LS3?
BSRT	Deformation suspected			New design + cooling	New design underway

Temp. estimate: ~ 800-1000 °C

Damage
Limits operation
Worry that can limit operation
Should be fine

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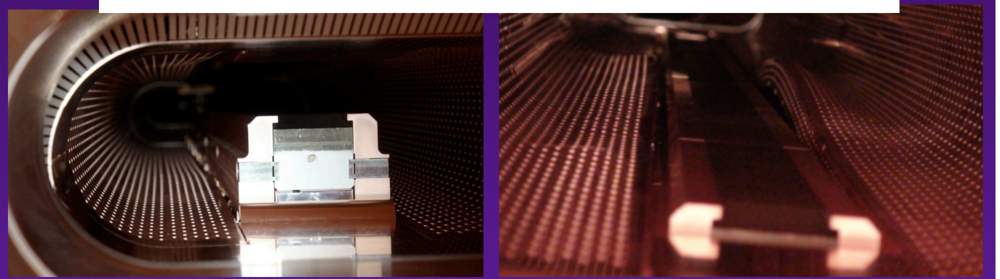
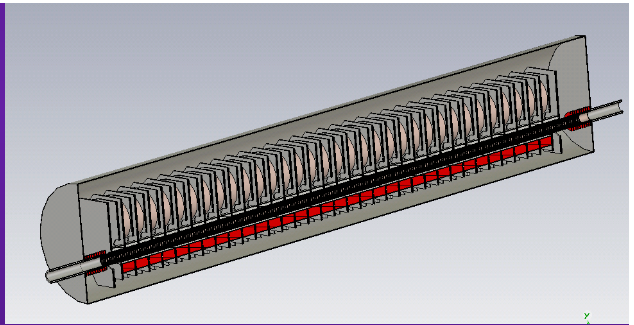
BEAM-INDUCED RF HEATING (2/9)

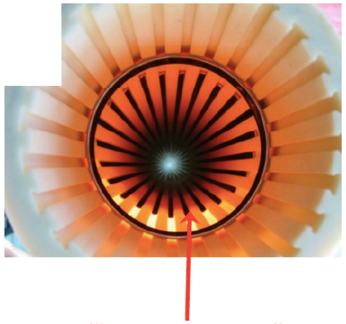
VMTSA = Double-bellow module

TDI = Injection Beam Stopper



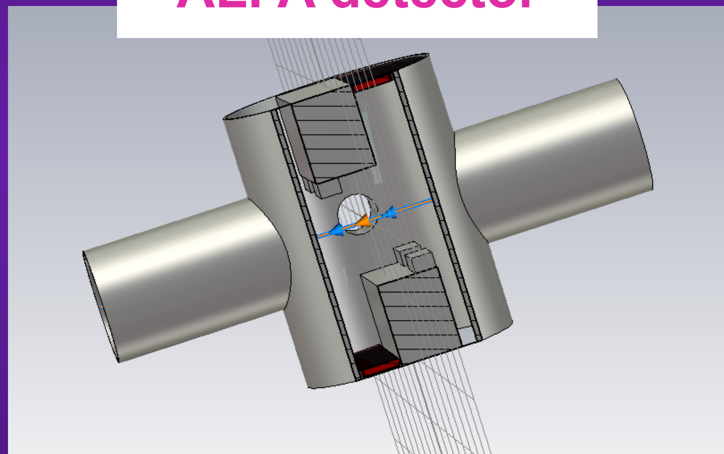
MKI = Injection kickers



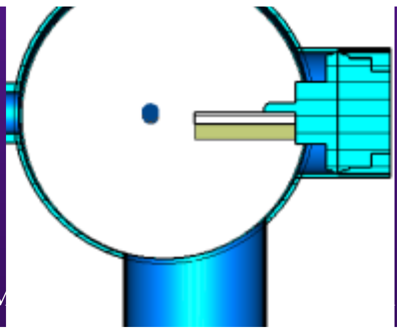


"beam-screen"
of LHC Injection Kicker:
ceramic tube with
conductors in slots

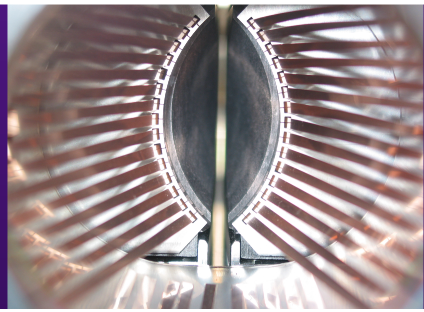
ALFA detector



BSRT = Meas. of transv. emittance



TCP collimator



Beam screen

BEAM-INDUCED RF HEATING (3/9)

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

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

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

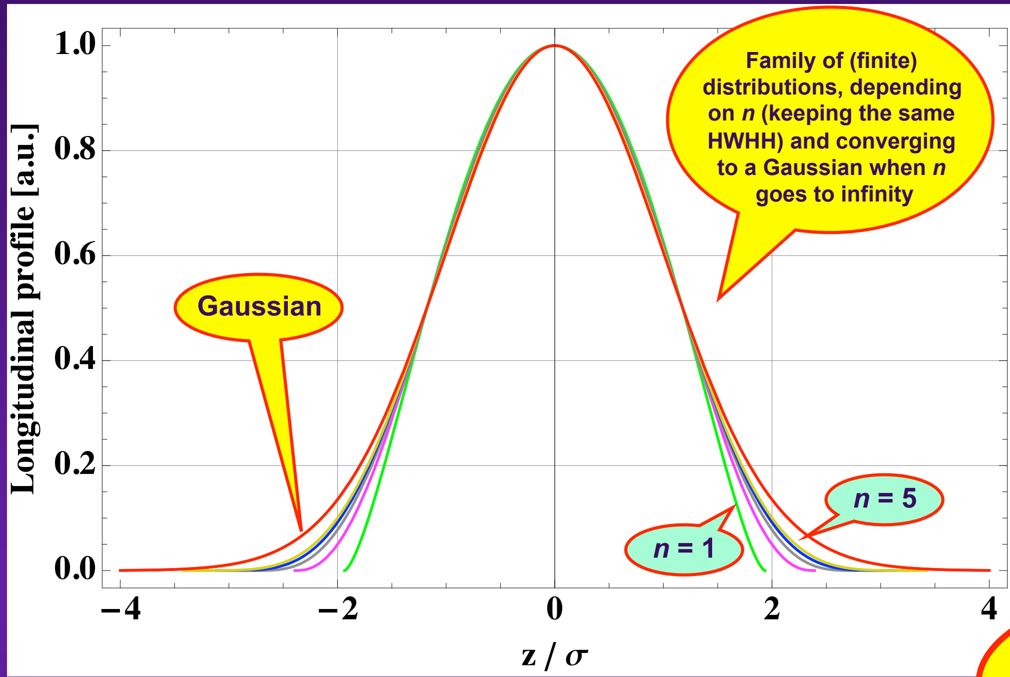
$$I_b = N_b \, e \, f_0$$

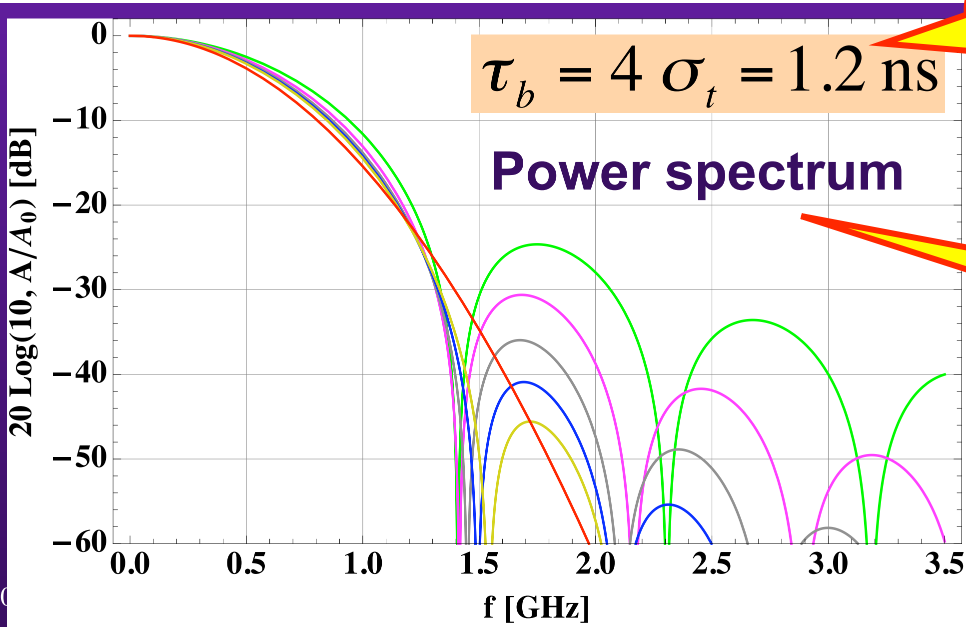
$$\omega_0 = 2 \, \pi \, f_0$$

  - **Broad-band impedance (i.e. short-range wake field) => Sum can be replaced by an integral (*M in front disappears*) =>** $P_{loss} \propto M$

  - **Narrow-band impedance (i.e. long-range wake field) => Only 1 term in the sum =>** $P_{loss} \propto M^2$

BEAM-INDUCED RF HEATING (4/9)





For LHC in 2011 (=> 9 cm rms)

Envelopes shown

BEAM-INDUCED RF HEATING (5/9)

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

  => Valid when $$Q >> \frac{f_r}{2 \, f_b}$$

  Bunch frequency

$$P_{loss}^{On-resonance} = R \, I^2 \times F$$

$$F = 10^{\frac{P_{dB}\left(f_r \right)}{10}}$$

$R = 2\,R_l$, i.e. using the Linac convention (LinacOhm)

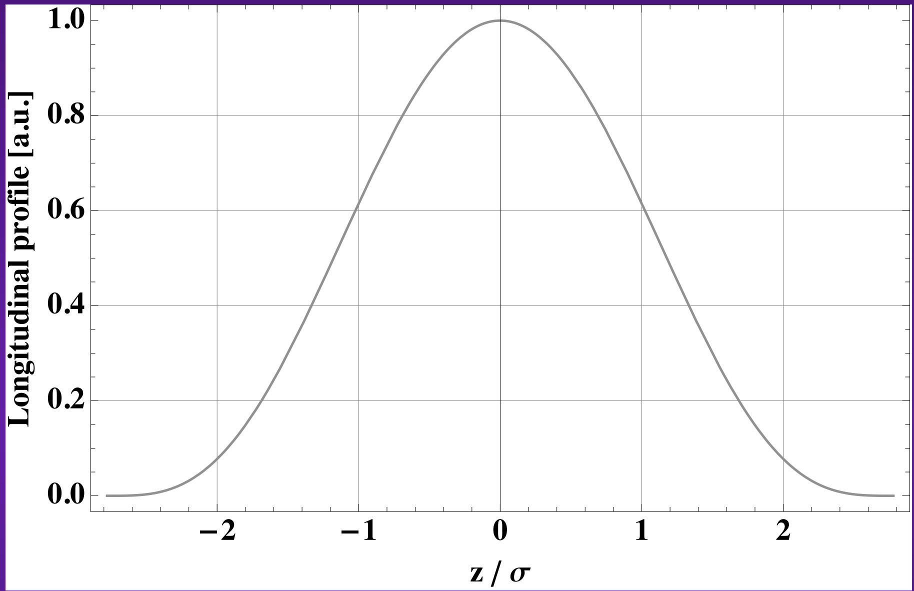
I = Total beam current [in A] = $M \times I_b$

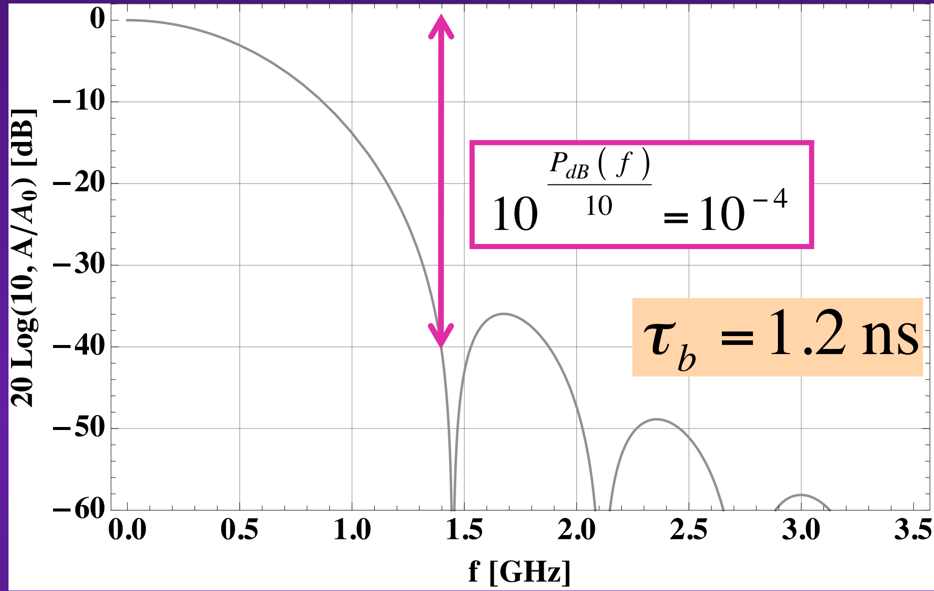
$P_{dB}\left(f_r \right)$ is the power in dB read from a power spectrum (computed or measured) at the frequency f_r

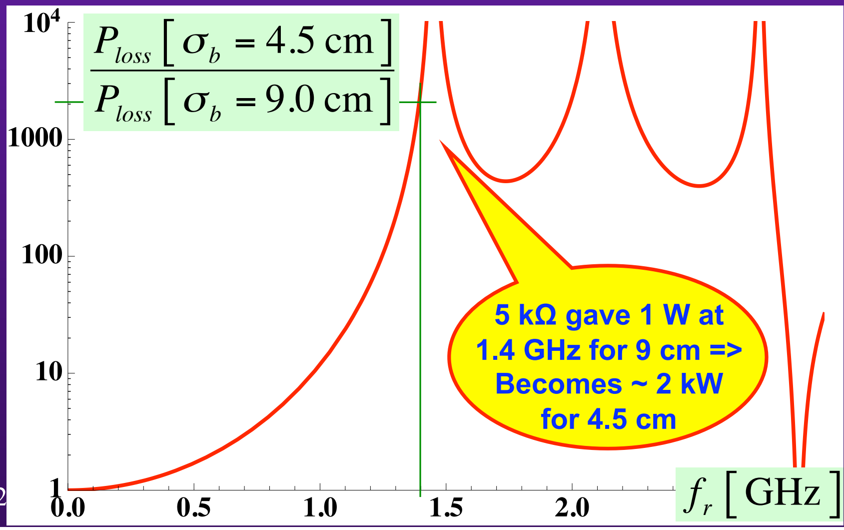
- **In the case of a Gaussian bunch** $$F = e^{-\left(2 \pi f_r \sigma_t \right)^2}$$

BEAM-INDUCED RF HEATING (6/9)

- **Huge effect of the bunch length and / or longitudinal profile**
  => Ex. with a 1 A beam and a shunt impedance R_l = 5 kΩ at 1.4 GHz







BEAM-INDUCED RF HEATING (7/9)

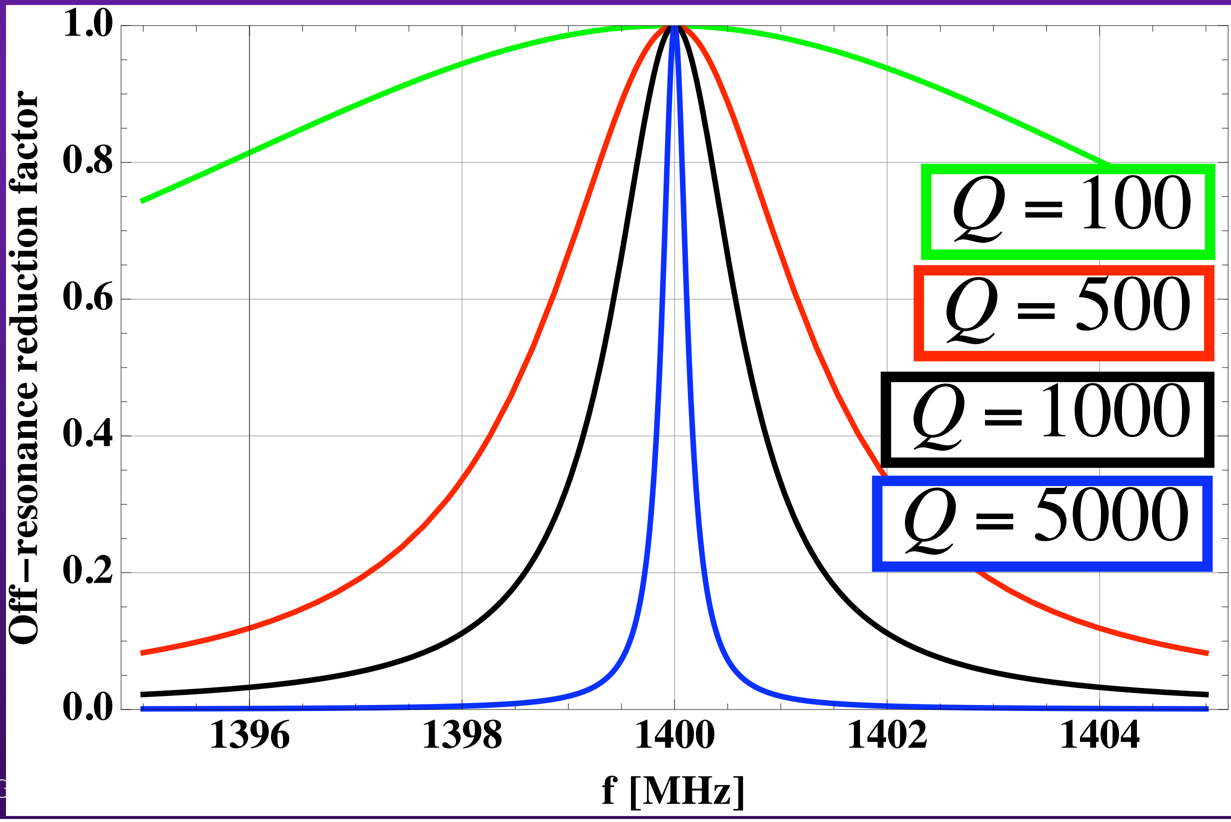
- **Off-resonance effect**

=> Valid when Q >> 1 and Δ << 1

$$G = \frac{\Delta^2}{\Delta^2 + \sin^2\left(\frac{\pi\, f_r}{f_b}\right)}$$

$$\Delta = \frac{\pi\, f_r}{2\, Q\, f_b}$$

$$P_{loss}^{Off-resonance} = P_{loss}^{On-resonance}\, G$$



BEAM-INDUCED RF HEATING (8/9)

- Usual solutions to avoid RF heating => Depending on the situation
  - Increase the distance between the beam and the equipment
  - Coat with a good conductor (if resistive losses and not geom.)
  - Close large volumes (could lead to resonances at low frequency) and add a smooth transition => Beam screens, RF fingers etc.
  - Put some ferrite with high Curie temperature and good vacuum properties (close to maximum of magnetic field of the mode and not seen directly by the beam) or other damping materials (AlN-SiC Ceralloy 13740Y as in PEP II => S. Novokhatski):
    - Power loss can be significantly decreased
    - The ferrite should absorb the remaining (much smaller) power => Still potential issue of heating due to bad contact / conduction
  - Increase the bunch length (if possible). The longitudinal distribution can also play a very important role for some devices, and it should be kept under tight control

BEAM-INDUCED RF HEATING (9/9)

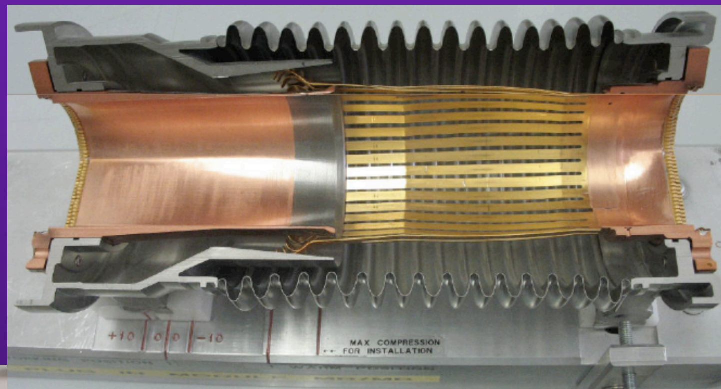
- Improve the subsequent heat transfer:
  - Convection: none in vacuum
  - Radiation: usually, temperature already quite high for radiation to be efficient. One should therefore try and improve the emissivities of surrounding materials
  - Conduction: good contact and thermal conductivity needed
  - Active cooling: LHC strategy was to water cool all the near beam equipment
- Try and design an All Modes Damper (AMD) if possible, to remove the heat as much as possible to an external load outside vacuum, where it can be more easily cooled away. This can also work together with a damping ferrite
- Install temperature monitoring on critical devices to avoid possible damages

CERN RF FINGERS TASK FORCE IN 2012 (1/9)

- **Why do we need RF fingers (and or ferrite)? => 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



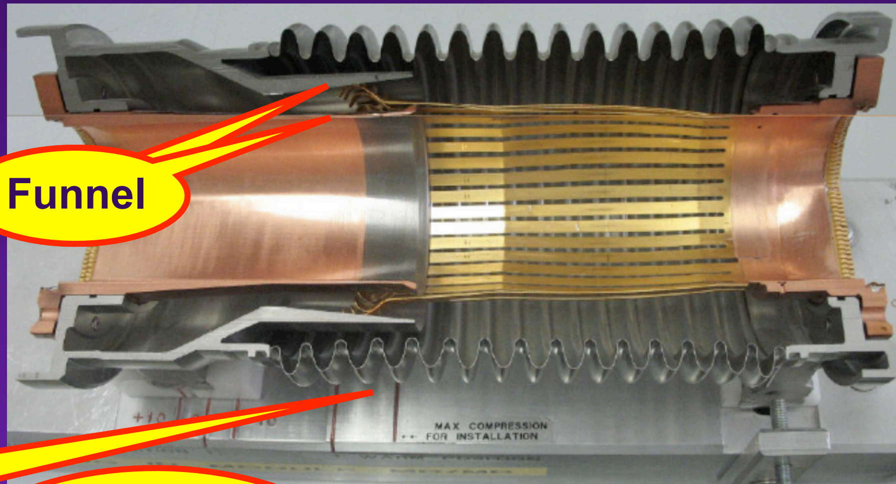
- **Example of ferrite tiles:**

  Installed in the new VMTSA in 2012

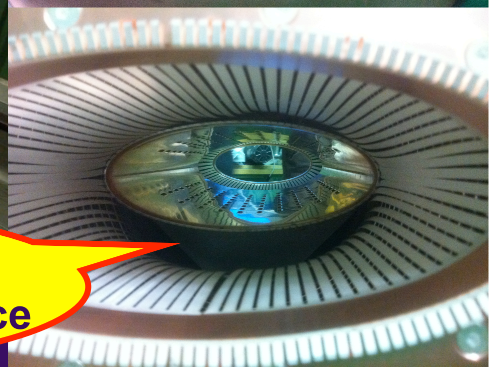
Initial dimensions (quickly available!): ~ 12 cm × 3 cm × 1 cm

CERN RF FINGERS TASK FORCE IN 2012 (2/9)

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

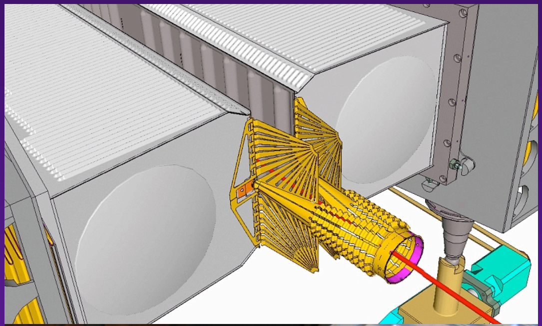


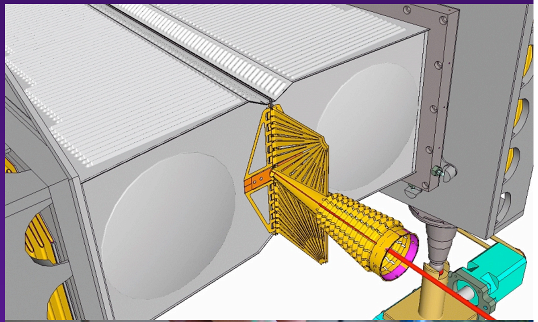
- **2) Spring for the VMTSA**
  - For case of transversal movement
  - Possible issue with contact / gap (due to elliptical shape) => RF heating
  - Possible issue with aperture restriction

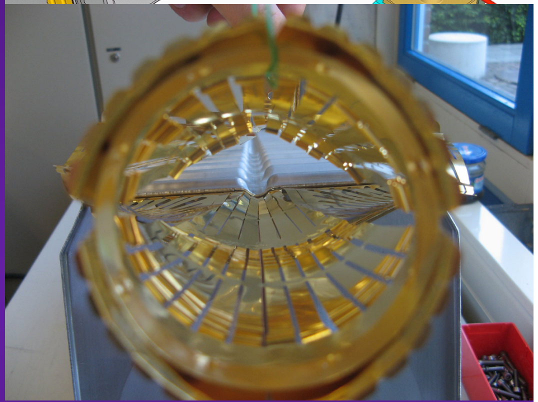


CERN RF FINGERS TASK FORCE IN 2012 (3/9)

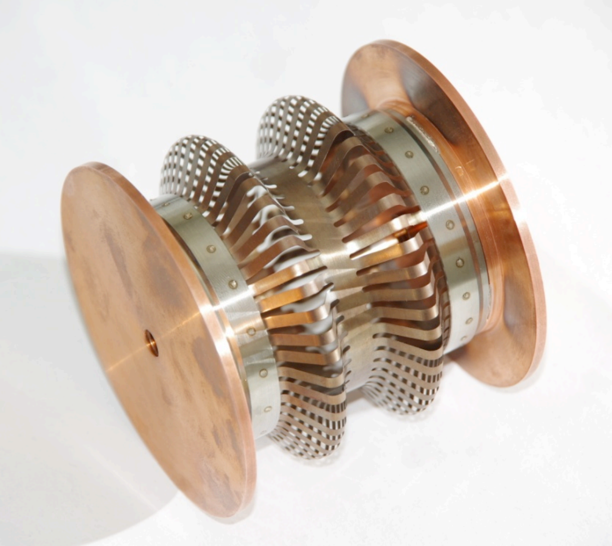
- **3) Fixed extremities for the LHCb VELO (VErtex LOcator)**
  - Seems to work very well!
  - Well-studied VELO design in terms of impedance effects paid off => No issue observed





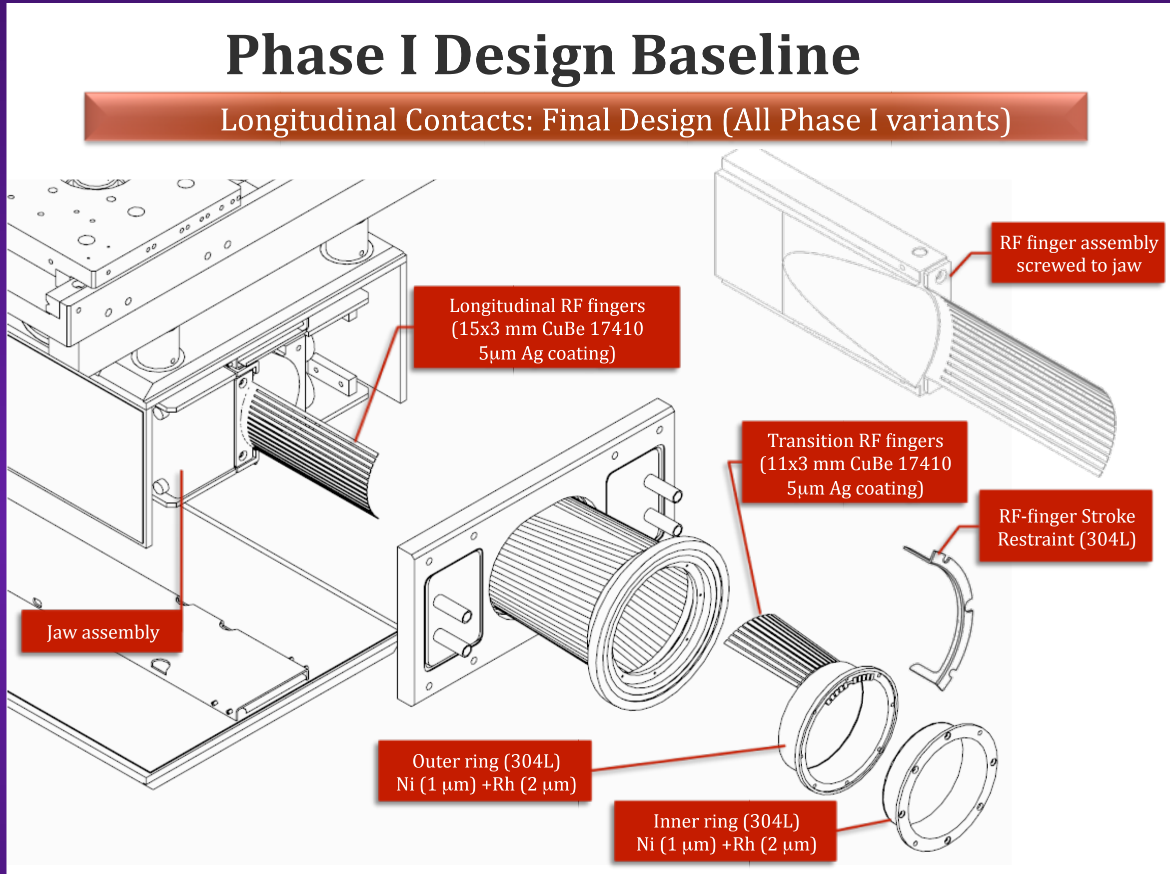


- **4) New RF design from TE/VSC**
  - 1st prototype based on 2 convolutions manufactured in 2012
  - Issue: Imaginary part of the longitudinal impedance (if many and if not elongated)



CERN RF FINGERS TASK FORCE IN 2012 (4/9)

- **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



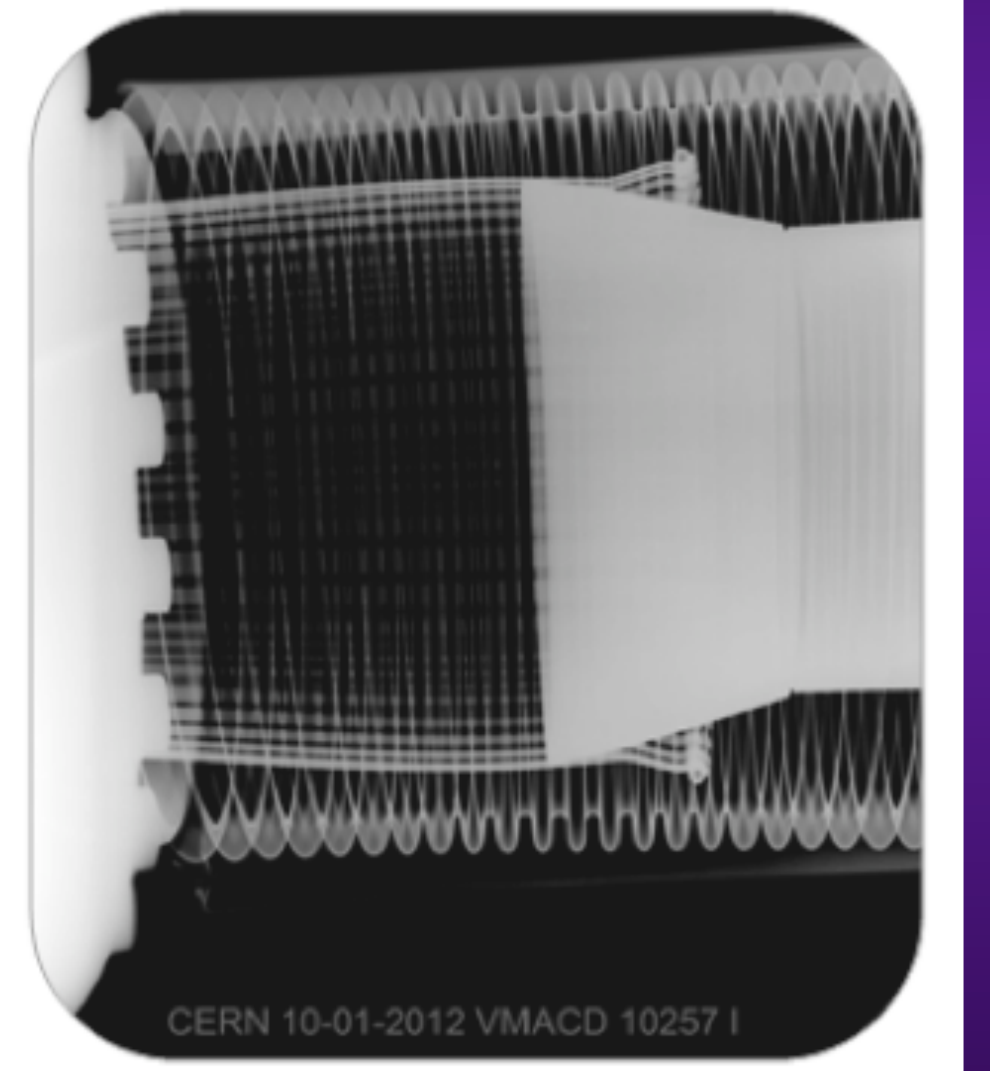
CERN RF FINGERS TASK FORCE IN 2012 (5/9)

- **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

CERN RF FINGERS TASK FORCE IN 2012 (6/9)

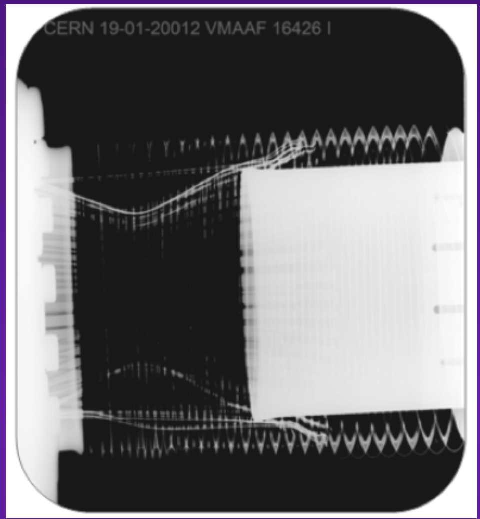
- 1800 X-rays taken in 2012
- 92 Nonconformities (~ 5 %) => 2 types of design: circular and elliptical (VMTSA)

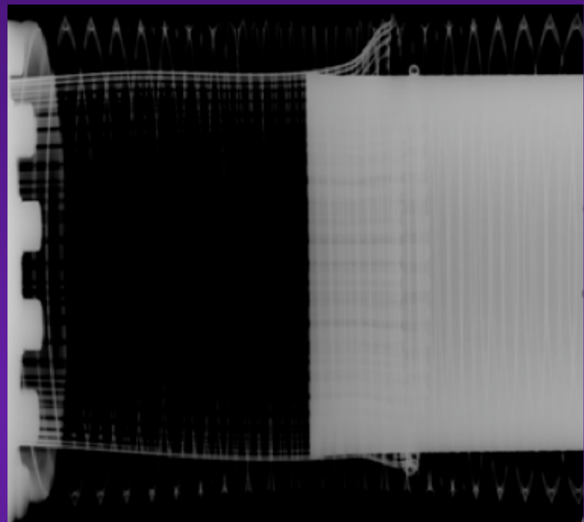
CONFORMITY

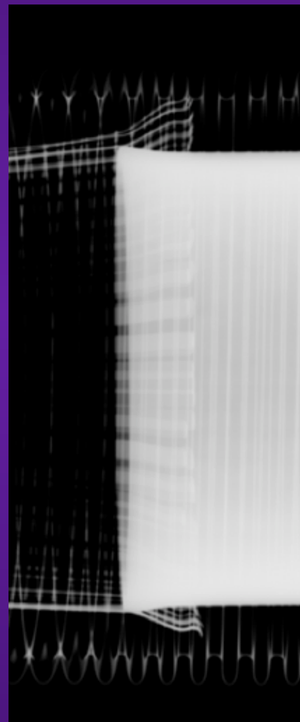


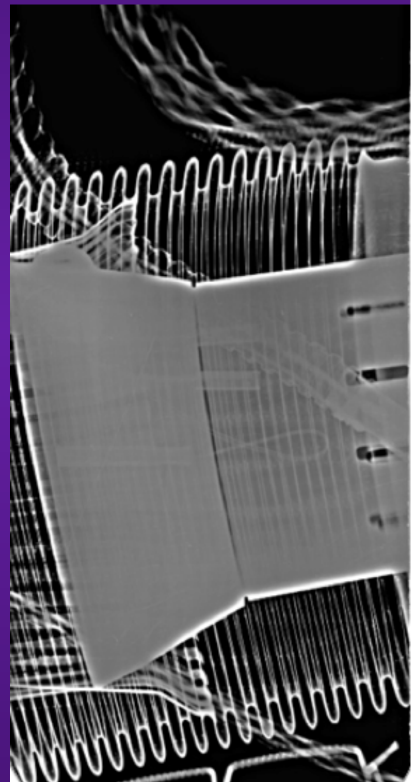
CERN RF FINGERS TASK FORCE IN 2012 (7/9)

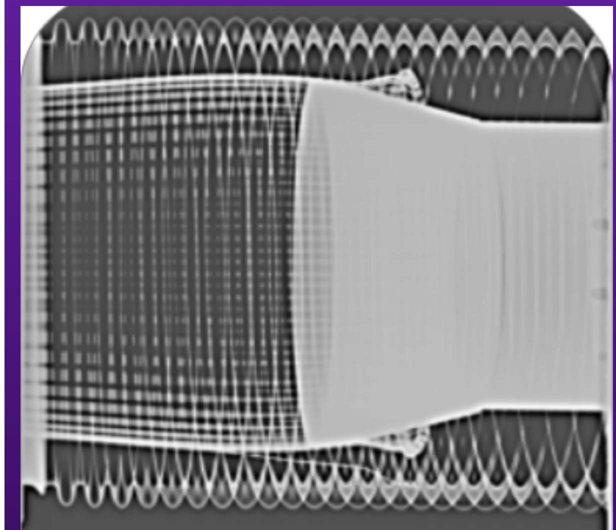
NONCONFORMITIES

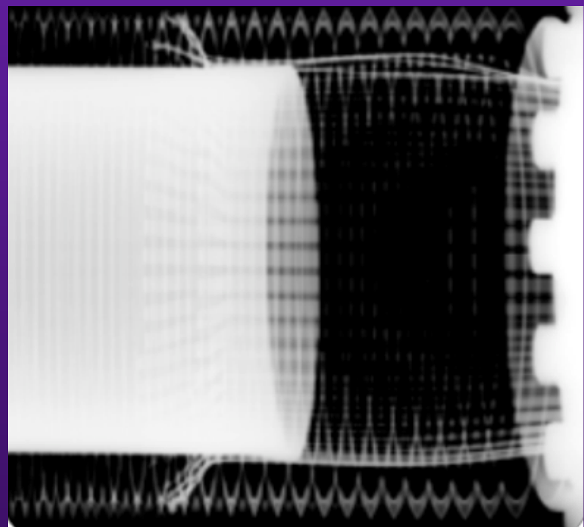












CERN RF FINGERS TASK FORCE IN 2012 (8/9)

- **Guidelines for RF fingers**
  - CuBe => Grade important in case of bake-out as for collimators (=> C17410)
  - CuBe is a good conductor but still has too an high surface impedance => Coating needed to increase surface conductivity, reduce contact resistance and avoid cold welding => 2 possible solutions to avoid cold welding
    - Putting a diffusion barrier between the 2 metals (i.e. an oxide layer) => Bad for electrical contact
    - Choosing metals with low solubility => Adopted solution: Au-Rh for the PIMs (Ag-Rh is quite similar). The contact surface on the insert should be electro-polished before putting the Rh coating
  - Collimators needs a bake-out at 250°C => Au cannot be used at this temperature because of the diffusion of Cu into Au => Ag used
  - For the MKI injection kickers, SS (instead of CuBe), but still Au plated, is used for the RF fingers because of the bake-out at ~ 300°C (CuBe would lead to a very small residual elasticity of ~ 20% only)
  - Top priority: Try and achieve robust mechanical designs to keep the contacts of all the RF fingers and do a very careful installation

CERN RF FINGERS TASK FORCE IN 2012 (9/9)

- **Guidelines for ferrite**
  - If RF fingers cannot be used or in case of nonconformities, some trapped modes might be created and ferrite tiles can be used to damp these modes
  - The ferrite should be put at (or close to) the maximum of the magnetic field of the mode to be damped (at the metallic wall), which is deduced after detailed electro-magnetic simulations, assuming known electro-magnetic properties of the ferrite. The ferrite should not be seen directly by the beam (if possible) and depending on the frequency of the mode to be damped, the ferrite type and thickness need to be optimized
  - Furthermore, the ferrite should be compatible with UHV (Ultra High Vacuum) and even if the ferrite will considerably reduce the power loss (by lowering the quality factor Q of the resonance, while keeping R / Q ~ constant), the remaining power loss will be absorbed by the ferrite which will heat and might reach its Curie temperature (and therefore lose its damping properties) if the heat transfer is not optimized

MINI-WORKSHOP AT THE DLS ON 30/01/2013 (1/5)

- A mini-workshop on "Simulation of Power Dissipation and Heating from Wake Losses in Accelerator Structures" took place on 30/01/2013 at the DLS => http://www.diamond.ac.uk/Home/Events/Past_events/Simulation-of-Power-Dissipation---Heating-from-Wake-Losses.html

Organised by G. Rehm

Programme

9.00-9.45	**T. Guenzel** *Heatload distribution in the ALBA stripline kicker on the basis of eigen mode simulations*
9.45-10.30	**R. Nagaoka** *Some experiences at SOLEIL regarding the beam-induced heating of the vacuum components*
10.30-11.00	**Coffee break**
11.00-11.45	**D. Lipka** *Heating of a DCCT and a FCT due to wake losses in PETRAIII, simulations and solutions*
11.45-12.30	**A. Morgan** *Analysis of time domain wake potential and port signals for calculation of radiated and dissipated power due to wake losses*
12.30-13.30	**Lunch**
13.30-14.15	**A. Novokhatski** *Analysis of wake field effects in the PEP-II SLAC B-factory*
14.15-15.00	**E. Metral & F. Caspers** *Beam induced RF heating in the LHC*
15.00-15.30	**Coffee break**
15.30-16.15	**S. Casalbuoni** *Beam heat load due to geometrical and resistive wall impedance in COLDDIAG*
16.15-17.00	**A. Blednykh** *Wake loss simulations at NSLS-II*

Why are we worried?

- Diagnostics systems are *designed* to couple to the beam.
- Wake loss factor is large enough to give uncomfortably large amounts of energy being lost from the beam.
- We plan to go to higher currents and shorter bunches.

- Current settings imply 189W lost in striplines
- Planned settings imply 313W lost in striplines

Alun Morgan

MINI-WORKSHOP AT THE DLS ON 30/01/2013 (2/5)

- **Several machines were discussed**

	M	$Q = N_b\, e$ [nC]	f_0 [kHz]	I_{beam} [A]	W / (V / pC)	σ_z [mm]
ALBA	448	0.8	1118.6	0.4	319	4.6
SOLEIL	416	1.3	844.5	0.44	551	6
DLS	900	1.0	533.8	0.5	520	4
NSLS	1080	1.2	378.8	0.5	611	4.5
PETRA-III	40	19.2	130.1	0.1	1921	13
LHC	2808	18.4	11.2	0.58	10691	75.5
PEP-II	1700	12.9	136.3	3	38838	8

$$k_{loss} = \int ds\, W_l(s)\, \lambda(s)$$

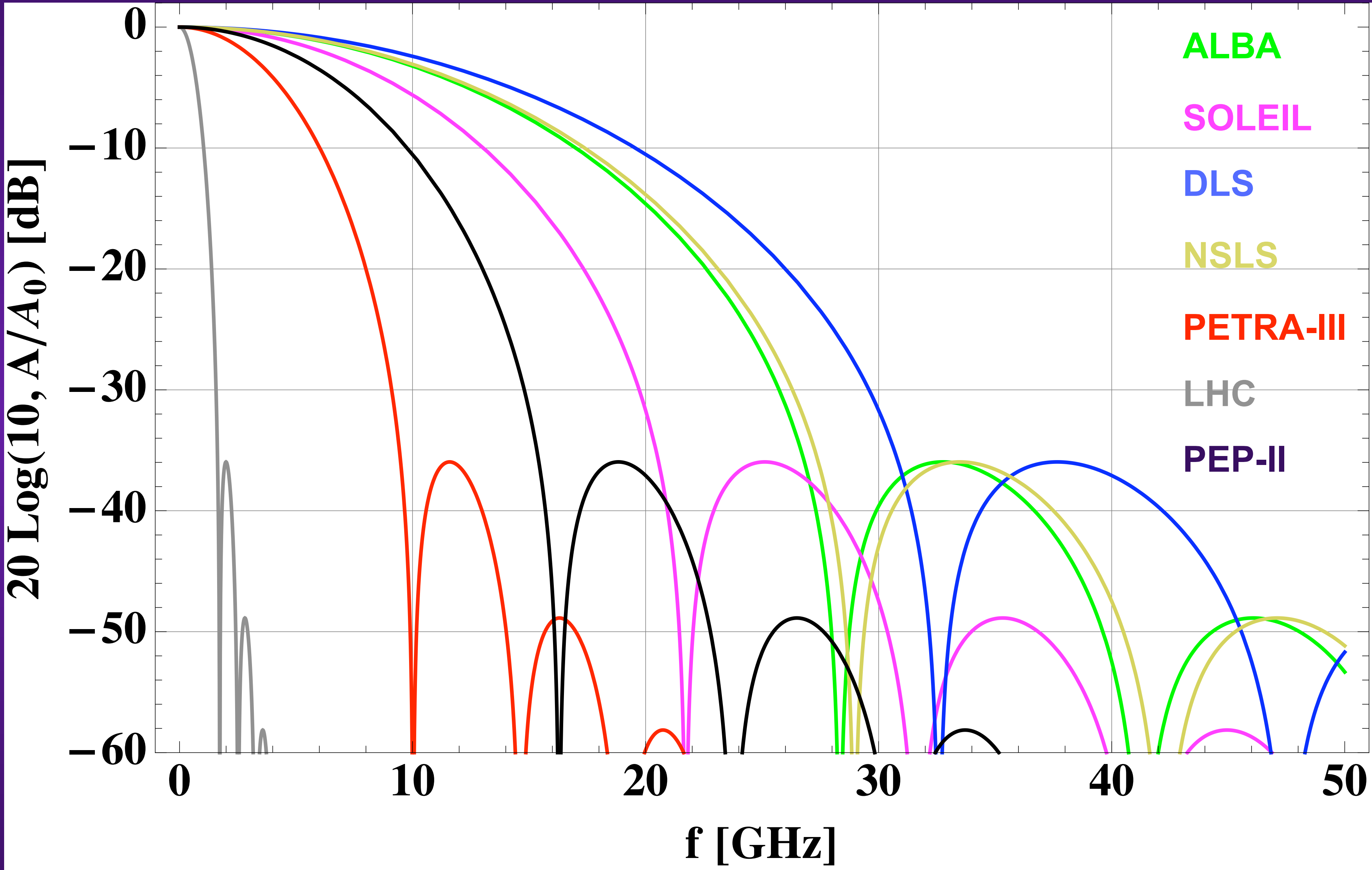
$$\frac{P_{loss}^{Incoh}[\mathrm{W}]}{k_{loss}[\mathrm{V/pC}]} = M\, Q[\mathrm{nC}]^2\, f_0[\mathrm{kHz}]\, 10^{-3}$$

Monopole longitudinal wake potential

Normalized charge density of the bunch

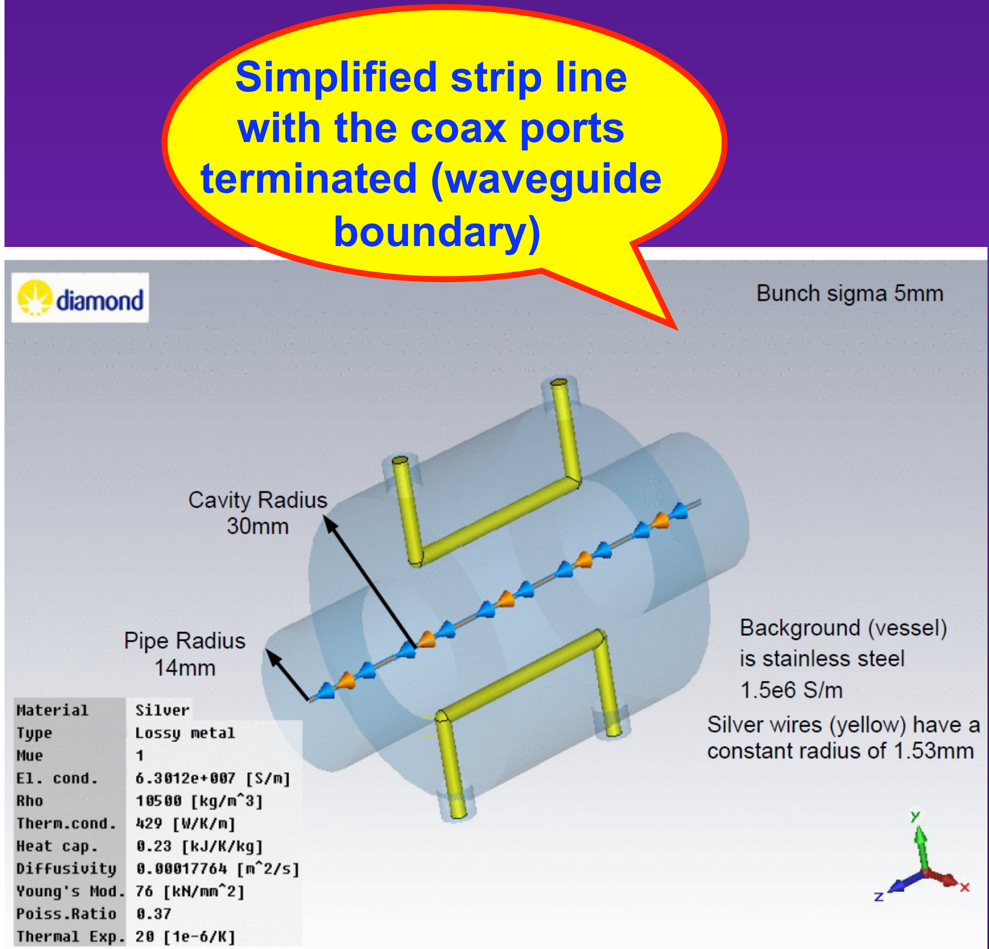
Incoherent => Coherent effect between bunches not included here

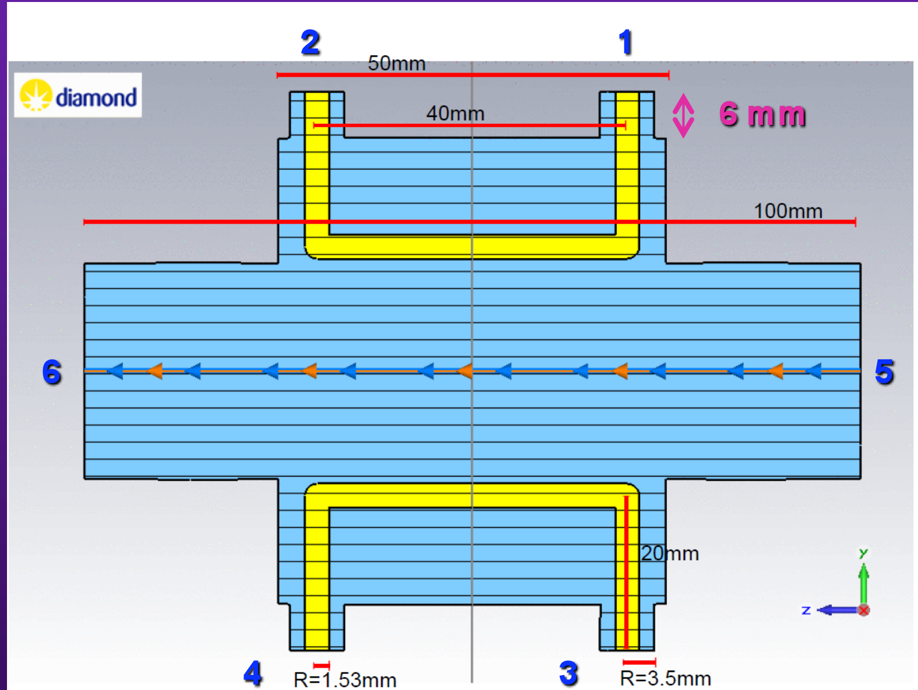
MINI-WORKSHOP AT THE DLS ON 30/01/2013 (3/5)



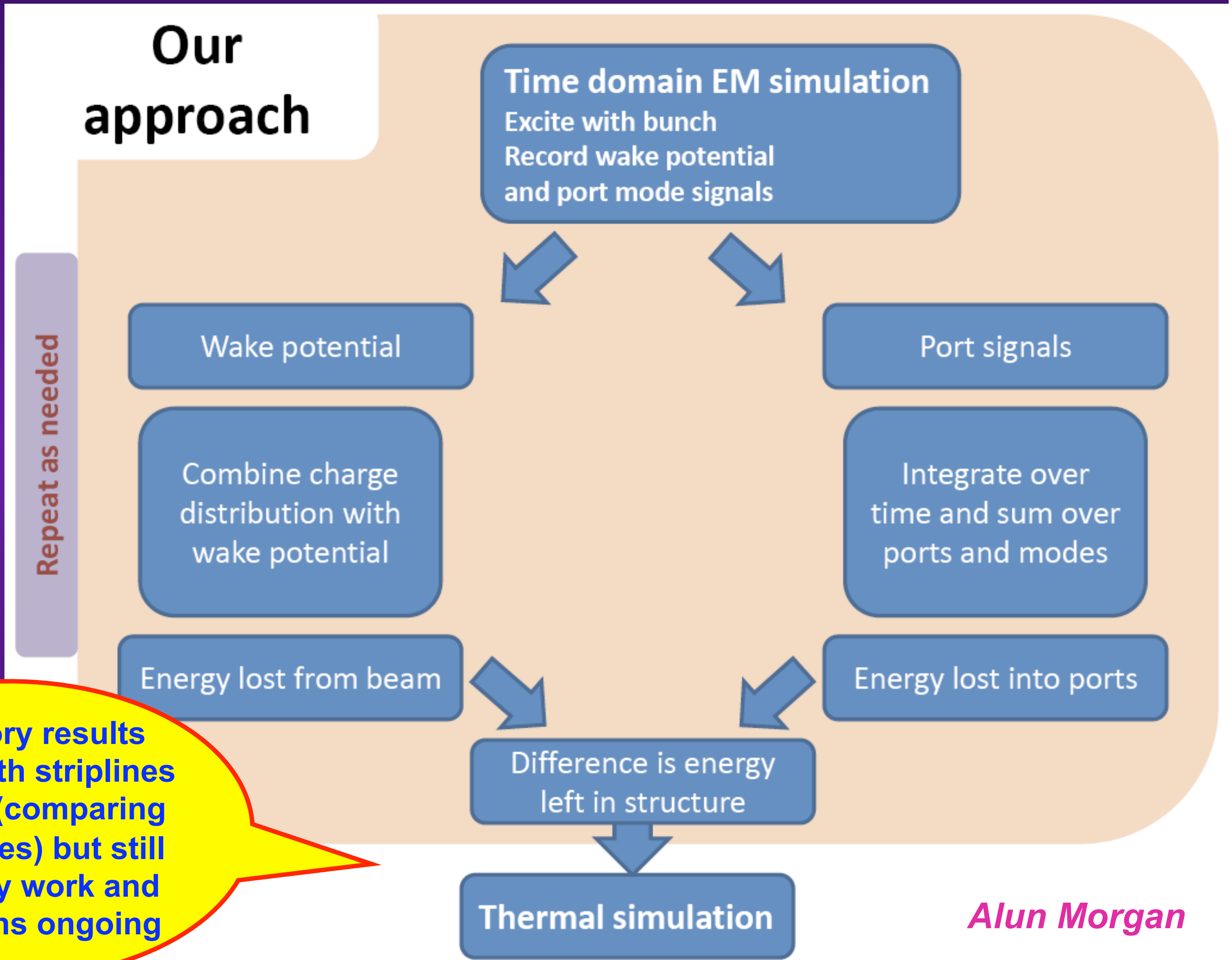
MINI-WORKSHOP AT THE DLS ON 30/01/2013 (4/5)

- **A homework was proposed by the workshop organisers (before the workshop) on a simplified version of the stripline, with a single bunch of 1 nC and an rms bunch length of σ = 5 mm**





MINI-WORKSHOP AT THE DLS ON 30/01/2013 (5/5)



Satisfactory results obtained with striplines and BPMs (comparing temperatures) but still not an easy work and discussions ongoing

Alun Morgan

CONCLUSION (1/2)

- Great success for the LHC performance
  - ~ 1.6E11 p/b instead of nominal 1.15E11 p/b => + ~ 40%
  - ~ 2.2 μm instead of nominal 3.75 μm => - ~ 40%

  => Bunch brightness: ~ (1.6 / 1.15) × (3.75 / 2.2) ~ 2.4 times larger than nominal!

  - Both transverse damper and Landau octupoles are needed and work well! High chromaticity used at high energy

- However,
  - The End-Of-The-Squeeze Instability could not be cured (not understood yet) => Potential worry for future operation at higher energy, higher beam intensity and higher beam brightness
  - Many beam-induced RF heating issues

CONCLUSION (2/2)

- **Lot of work at CERN on impedances over the last few years**
  - **LHC and HL-LHC**
    - **Impedance and related (transverse) instabilities**
    - **Beam-induced RF heating**
  - **LHC injectors within the LIU (LHC Injectors Upgrade) project**
    - **SPS, PS and PSB => Reliable impedance models under development**

- **Next important event for impedance studies**

=> Workshop on "Electromagnetic Wake Fields and Impedances in Particle Accelerators", Erice (Sicily, Italy), 23-29/04/2014 **(Organisers: V. Vaccaro and E. Métral)**

=> Everybody welcome!