RF HEATING FROM WAKE LOSSES IN DIAGNOSTICS STRUCTURES

Elias Métral (35 + 5 min, 31 slides)

- **ABSTRACT:** Heating of diagnostics structures (striplines, buttons, screen vessels, wire scanners etc) has been observed at many facilities with higher stored currents. Simulations of wake losses using 3D EM codes are regularly used to estimate the amount of power lost from the bunched beam but on its own this does not tell how much is radiated back into the beam pipe or transmitted into external ports and how much is actually being dissipated in the structure and where. This talk should introduce into the matter, summarise some of the observations at various facilities and illustrate what approaches of detailed simulations have been taken

- Introduction
- Beam-induced RF heating
- Highlights from a Mini-Workshop at the DLS on 30/01/2013
- Conclusions

Diamond Light Source

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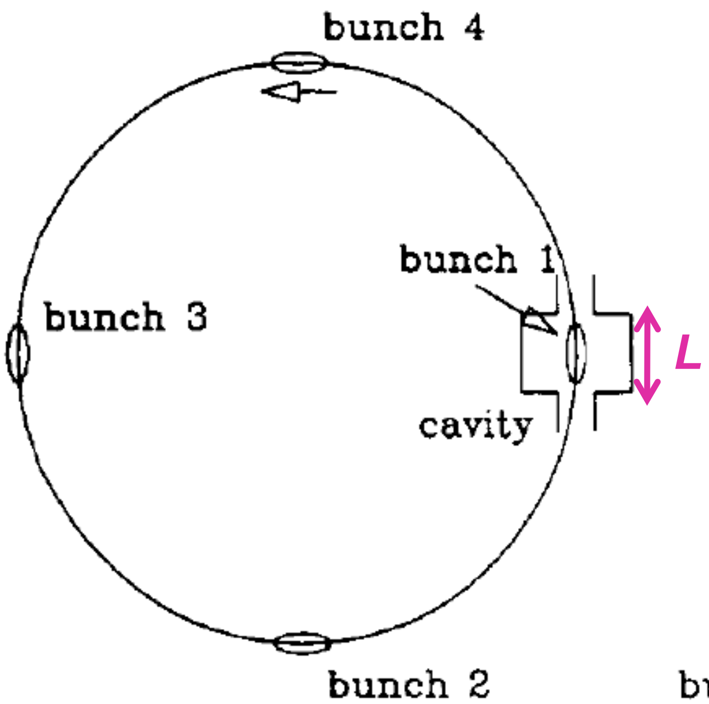
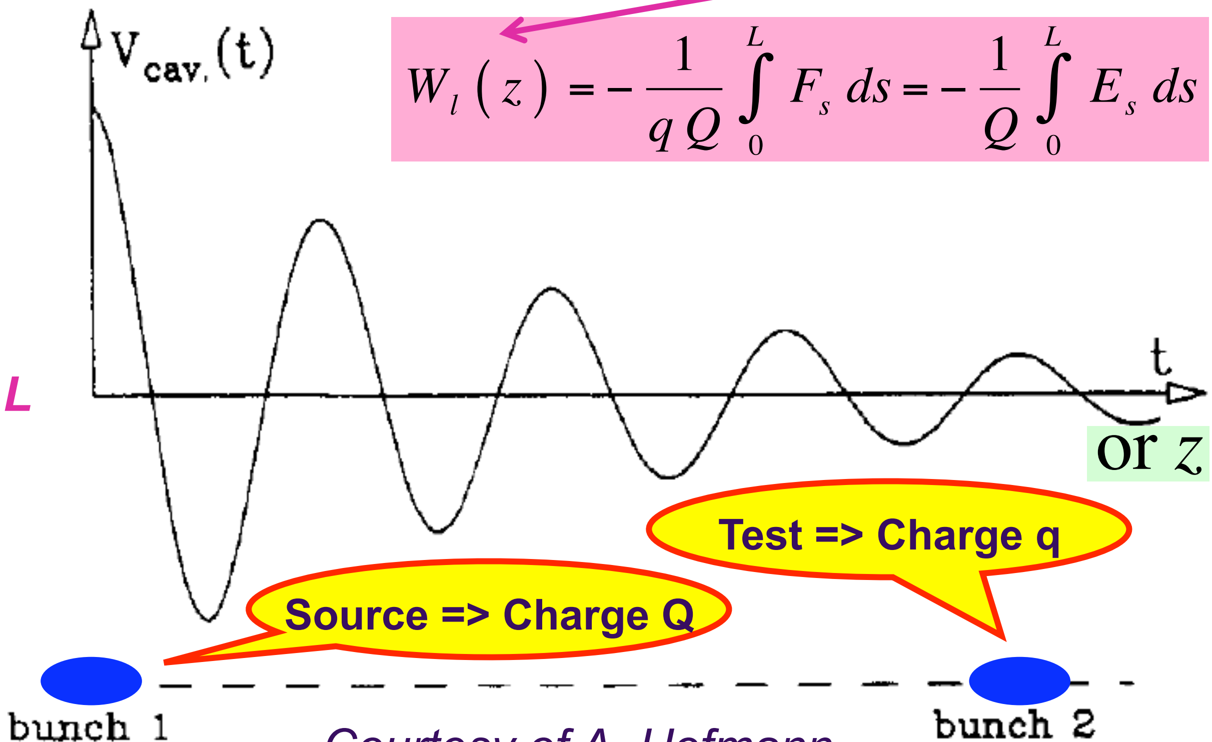
INTRODUCTION (1/2)

- **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)

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





Courtesy of A. Hofmann

INTRODUCTION (2/2)

- **Therefore, in practice the elements of the vacuum chamber should be designed to minimise the self-generated (secondary) electromagnetic fields**
  - Chambers with different cross-sections should be connected with tapered transitions
  - Non necessary cavities should be avoided
  - Bellows should preferably be separated from the beam by shielding
  - Plates should be grounded or terminated to avoid reflections
  - Poorly conductive materials should be coated with a thin layer of very good conductor (such as copper) when possible
  - Etc.

=> However, the issue with the diagnostics structures is that they are designed to couple to the beam!

BEAM-INDUCED RF HEATING (1/14)

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

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

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

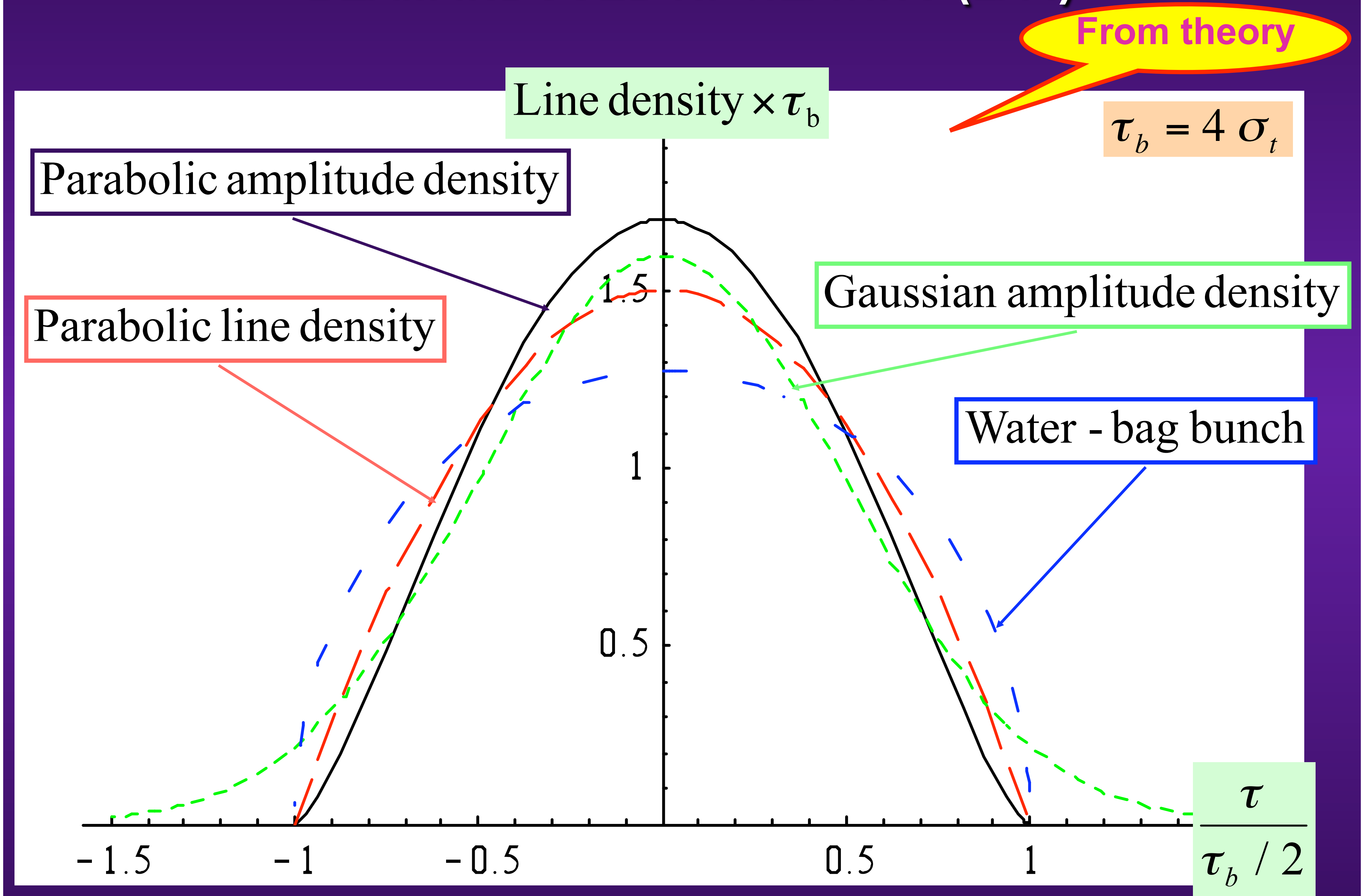
$$I_b = N_b\, e\, f_0$$

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

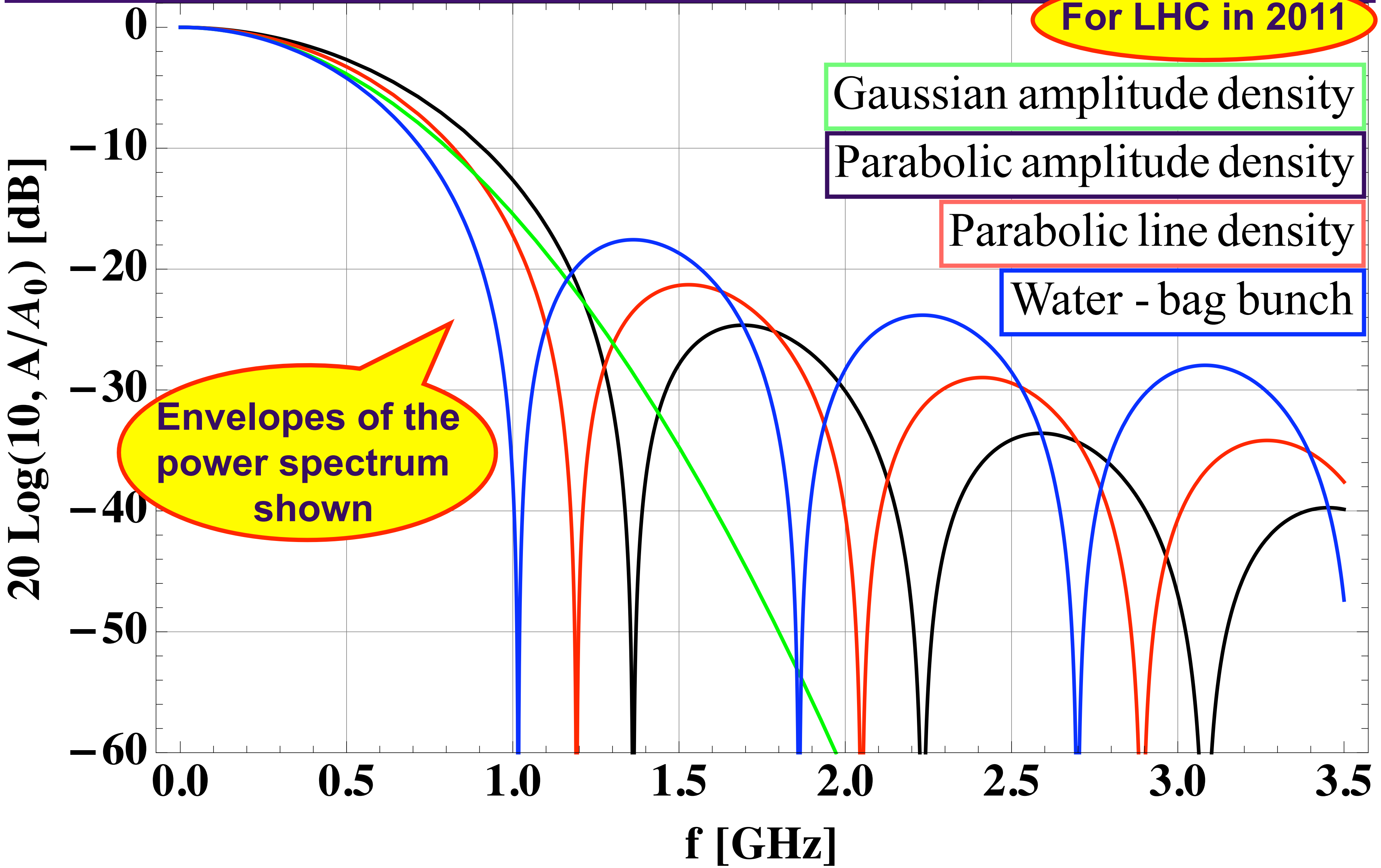
  - **Broad-band impedance (i.e. short-range wake field) => Sum can be replaced by an integral (*M in front disappears)* =>** $\boxed{P_{loss} \propto M}$

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

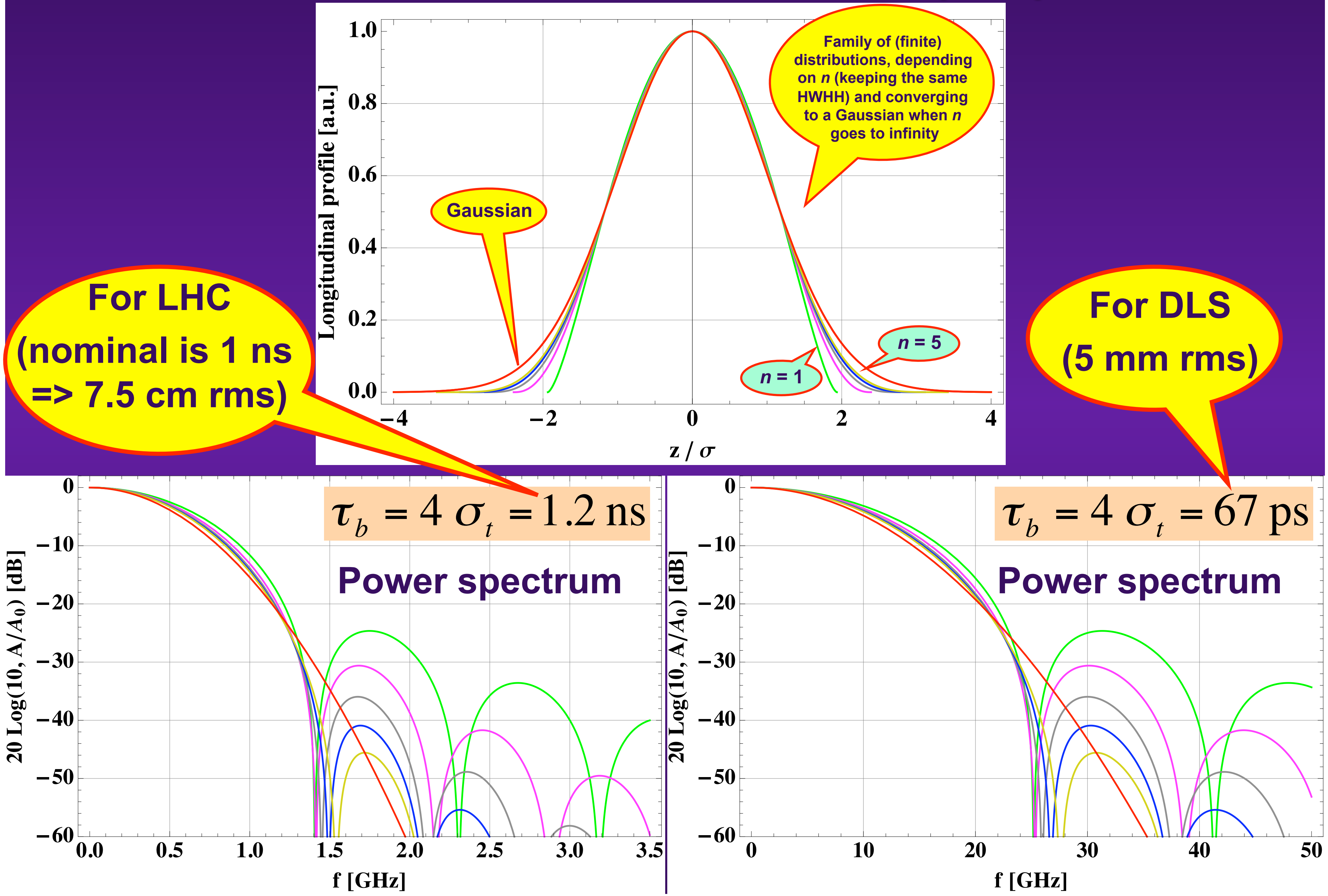
BEAM-INDUCED RF HEATING (2/14)



BEAM-INDUCED RF HEATING (3/14)

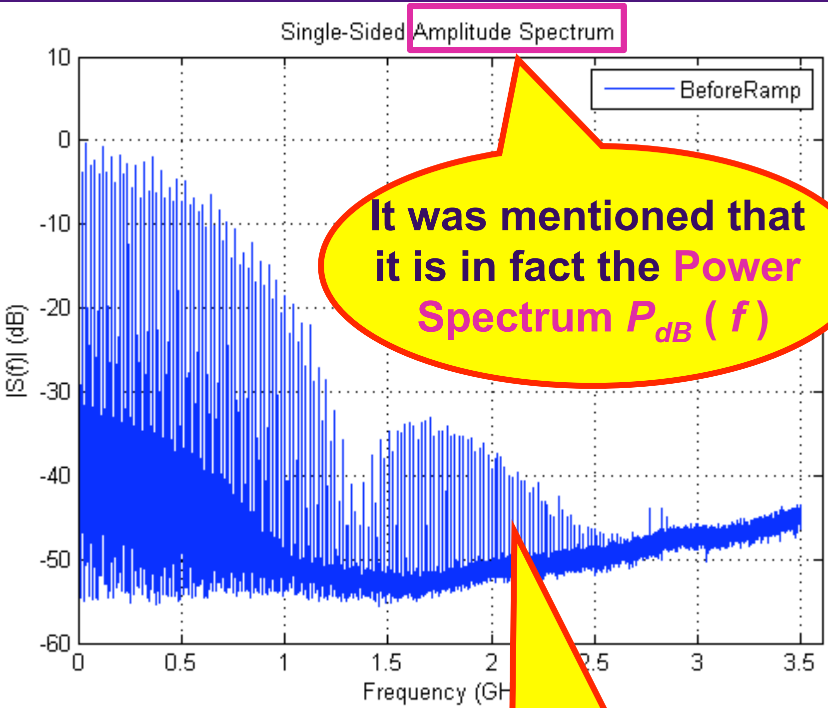


BEAM-INDUCED RF HEATING (4/14)

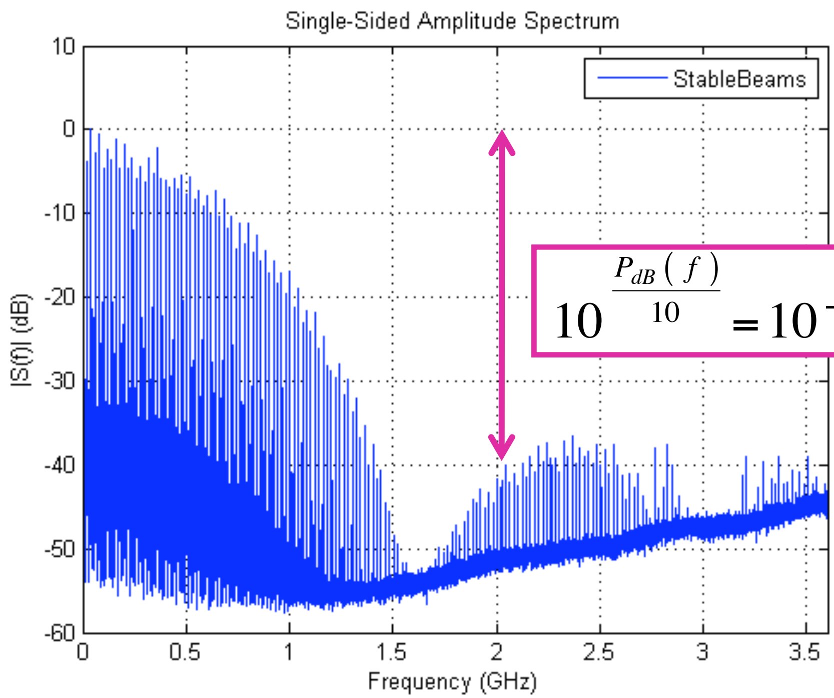


BEAM-INDUCED RF HEATING (5/14)

Measurements on LHC Beam 1 on fill # 2261



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



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

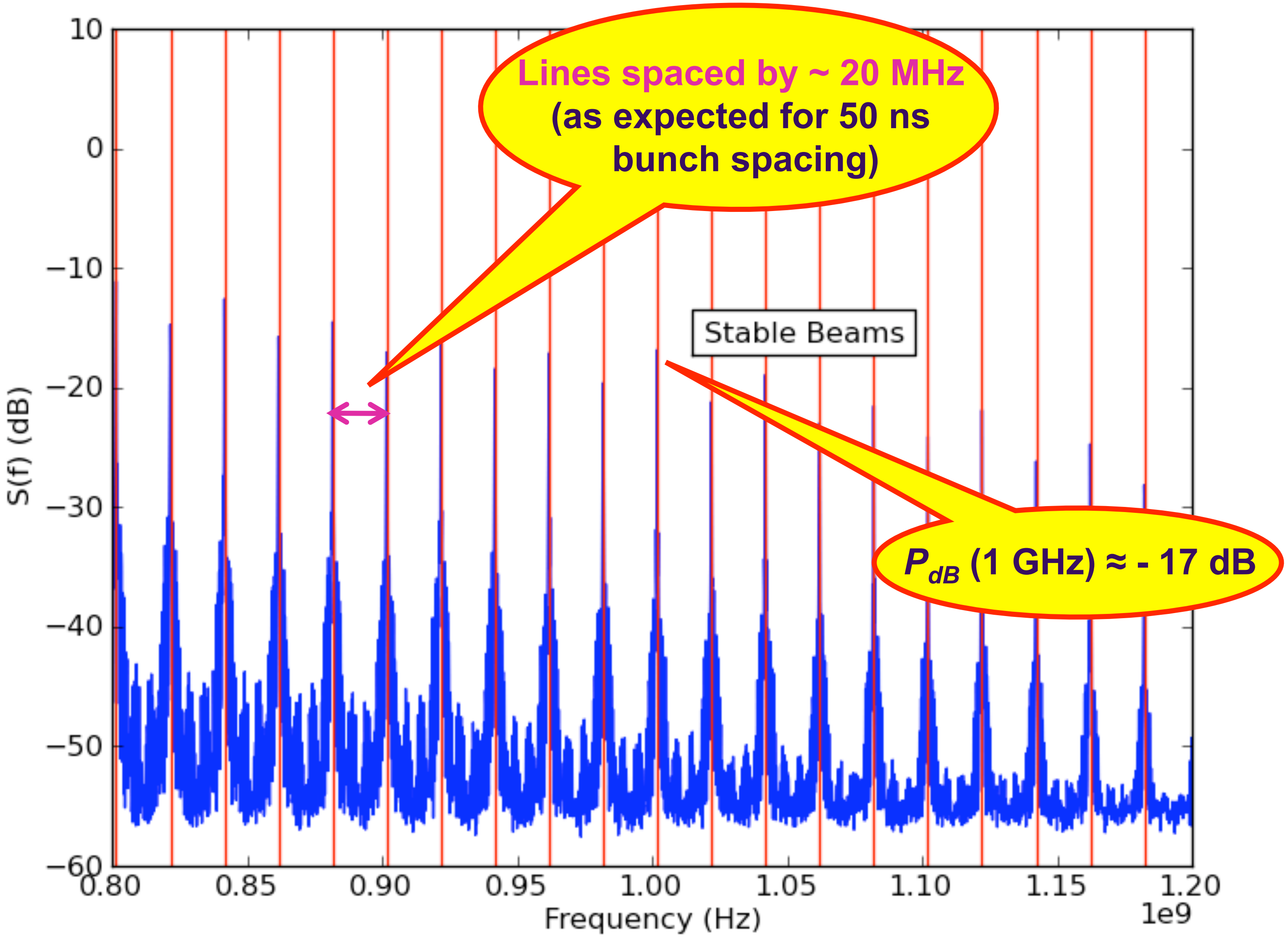
Coupled-bunch lines spaced by $M f_0$ ~ 20 MHz (for 50 ns bunch spacing) => It would be ~ 40 MHz for 25 ns

$$M_{50} = 1782$$

$$M_{25} = 3564$$

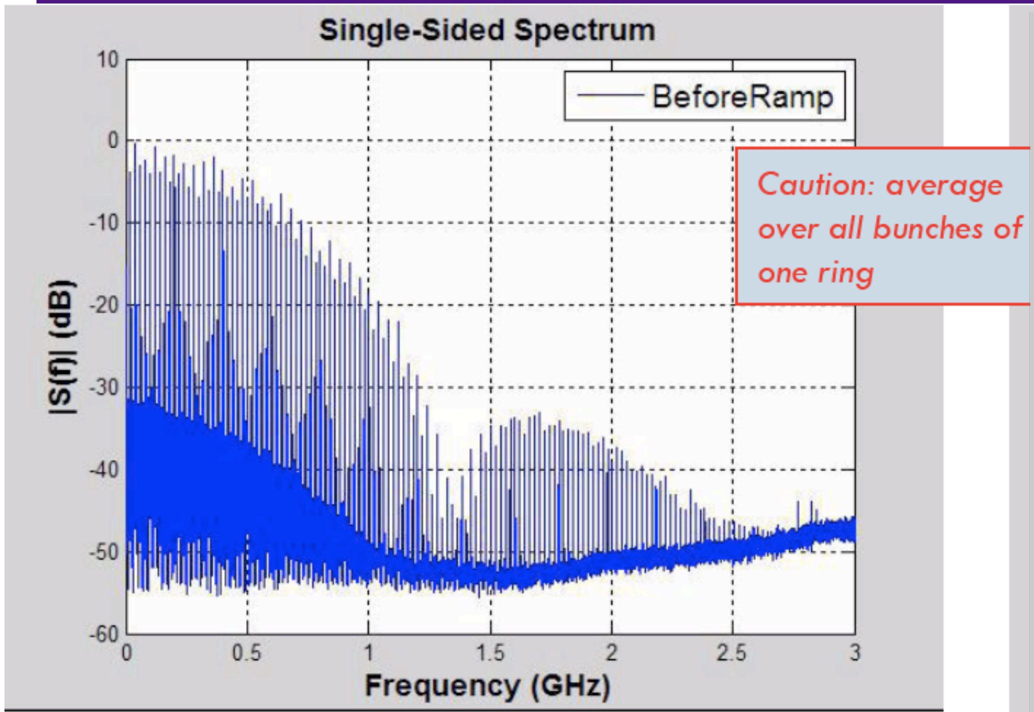
Courtesy of Philippe Baudrenghien, Themistoklis Mastoridis and Hugo Day

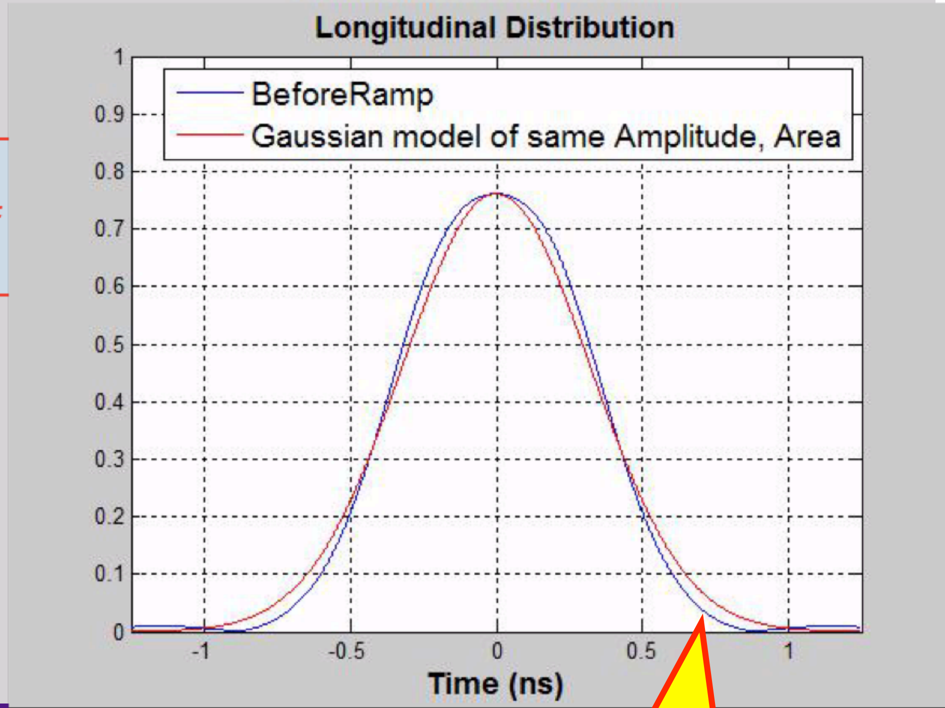
BEAM-INDUCED RF HEATING (6/14)



BEAM-INDUCED RF HEATING (7/14)

By taking the inverse Fourier Transform, the following distribution is found



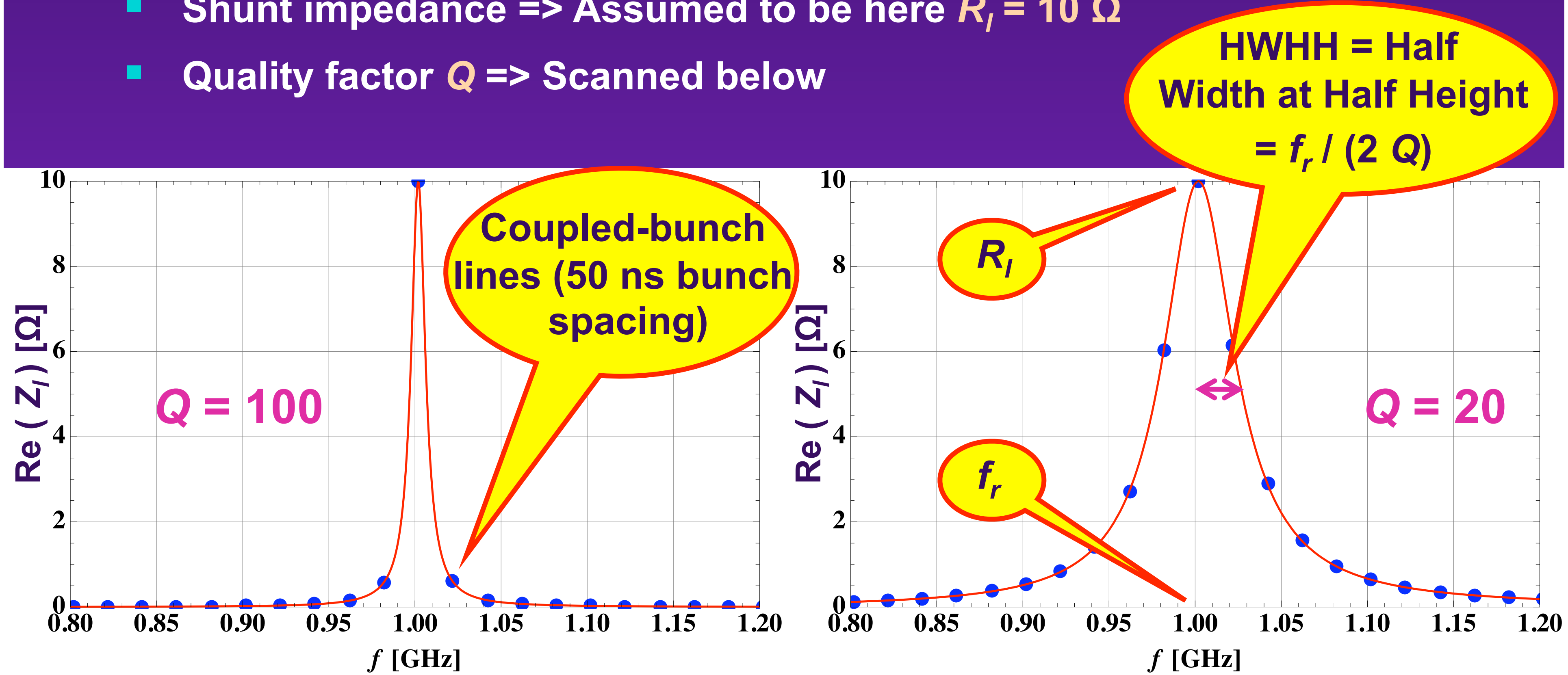


Courtesy of Philippe Baudrenghien and Themistoklis Mastoridis

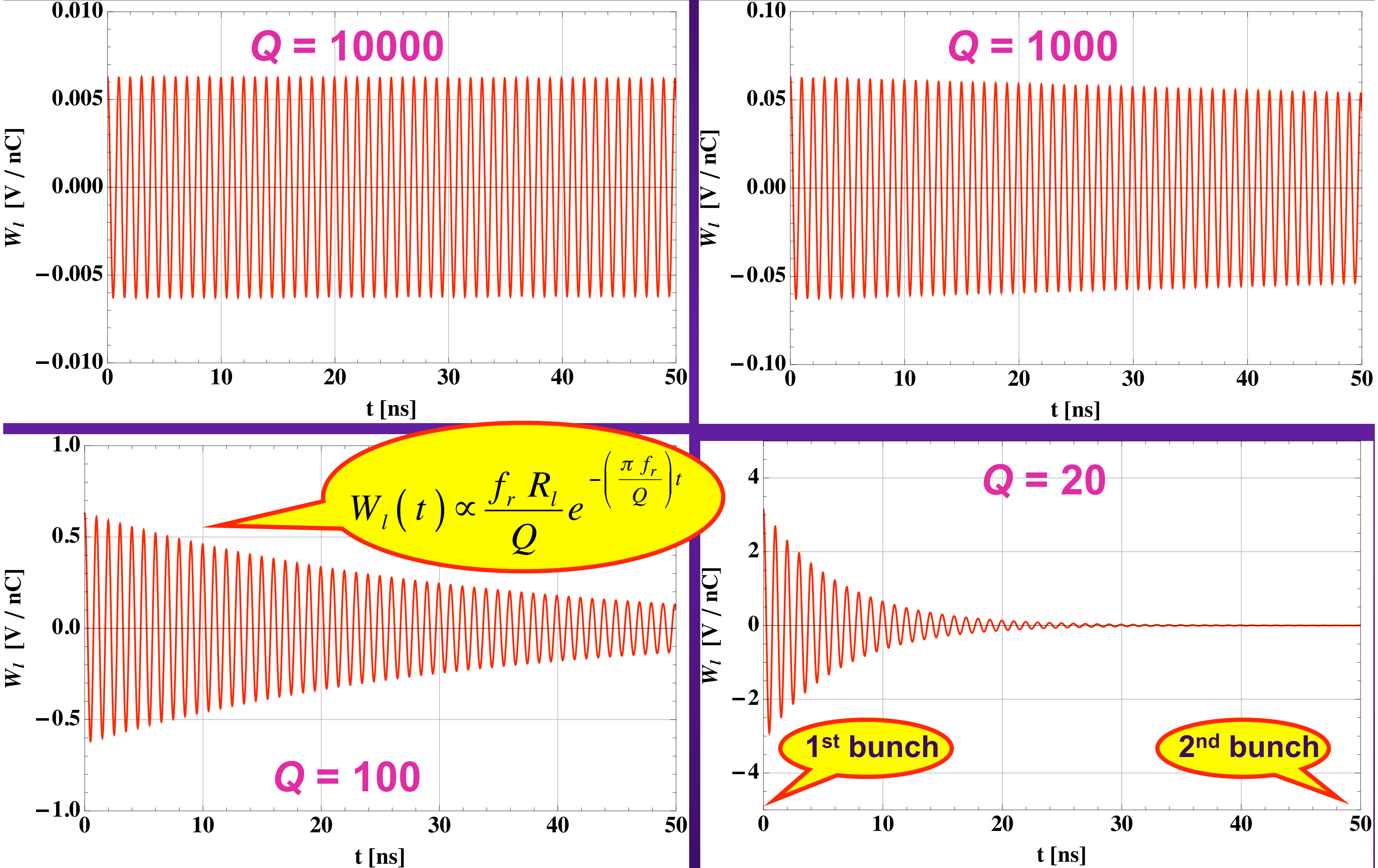
~ consistent with the previous *n* = 3 theoretical distribution

BEAM-INDUCED RF HEATING (8/14)

- Consider 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



BEAM-INDUCED RF HEATING (9/14)



BEAM-INDUCED RF HEATING (10/14)

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

$$\boxed{P_{loss} = R\, I^2 \times F \times G}$$

Describes the off-resonance effect ($0 \le G \le 1$)

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

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

Describes the frequency dependence ($0 \le F \le 1$)

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

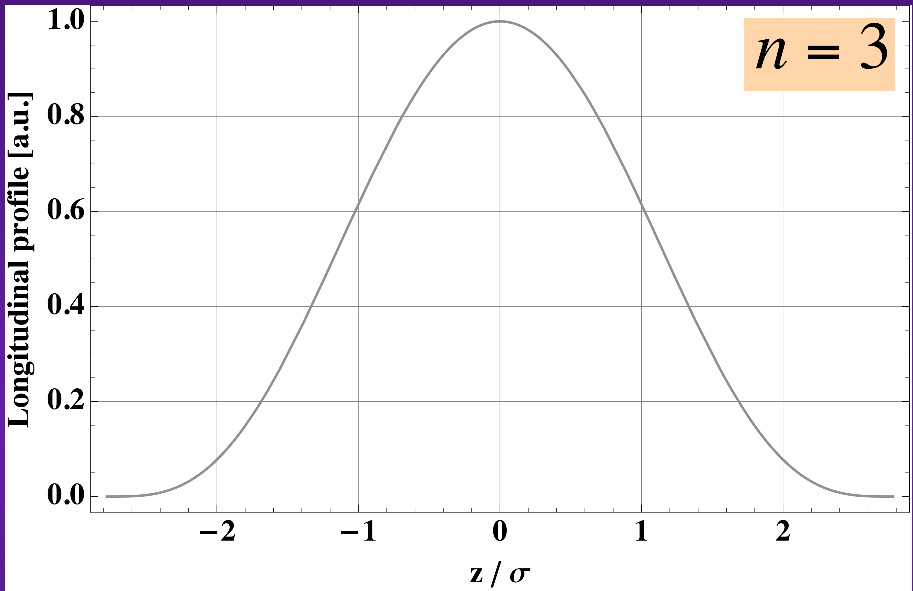
f_b is the bunch frequency

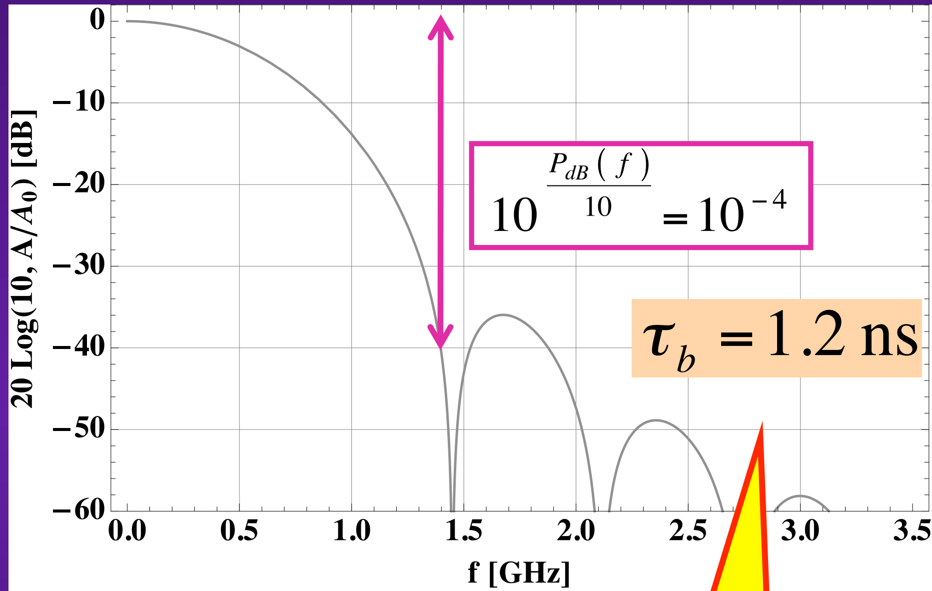
$$F = 10^{\frac{P_{dB}(f_r)}{10}} \quad , \quad G = \frac{\Delta^2}{\Delta^2 + \sin^2\left(\frac{\pi\, f_r}{f_b}\right)} \quad , \quad \Delta = \frac{\pi\, f_r}{2\, Q\, f_b}$$

BEAM-INDUCED RF HEATING (11/14)

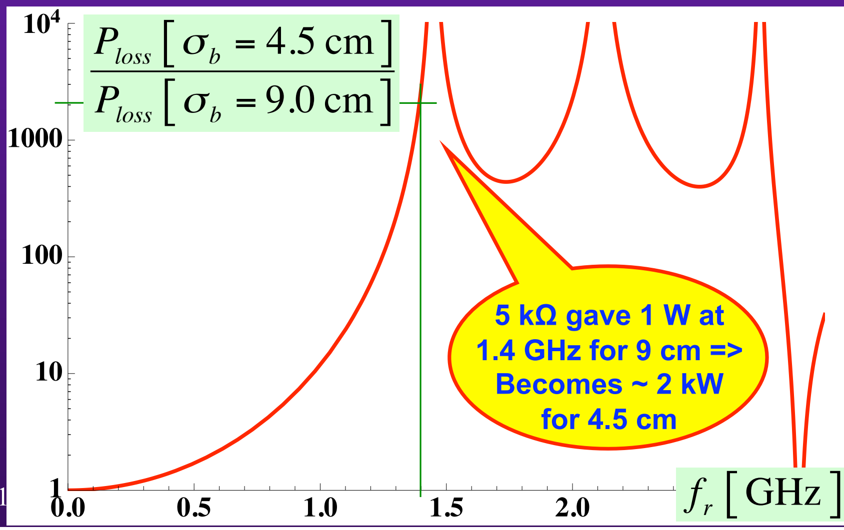
- **Huge effect of the bunch length and / or longitudinal profile**

  => Ex. with a 1 A beam and a shunt impedance R_l = 5 kΩ at 1.4 GHz



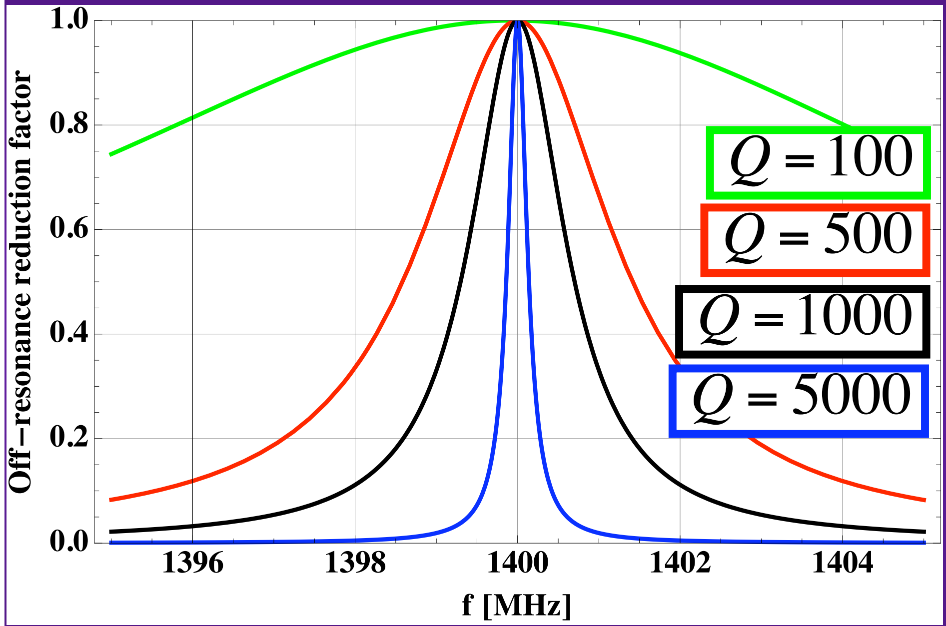


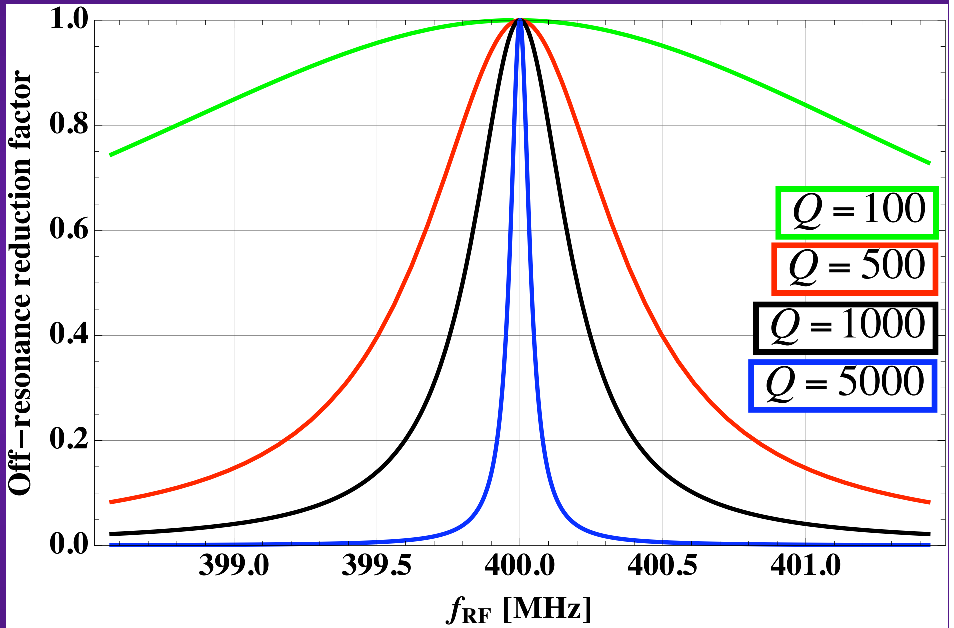
For LHC in 2011 (=> 9 cm rms)



BEAM-INDUCED RF HEATING (12/14)

- **Off-resonance effect**





Assuming f_r = 1.4 GHz

BEAM-INDUCED RF HEATING (13/14)

- **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)
    - 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 (14/14)

- **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**

MINI-WORKSHOP AT THE DLS ON 30/01/2013 (1/11)

- 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 (2/11)

- **With these huge amounts of power lost by the beam, it is important to study in detail**
  - **How much of the power removed from the beam is radiated back into the beam pipe or transmitted into external ports (where present)?**
  - **How much is actually being dissipated in the structure, and where?**
  - **Final question to answer: what is the impact of the dissipated power in terms of deformation, stresses or potential damage?**

MINI-WORKSHOP AT THE DLS ON 30/01/2013 (3/11)

- **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

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

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

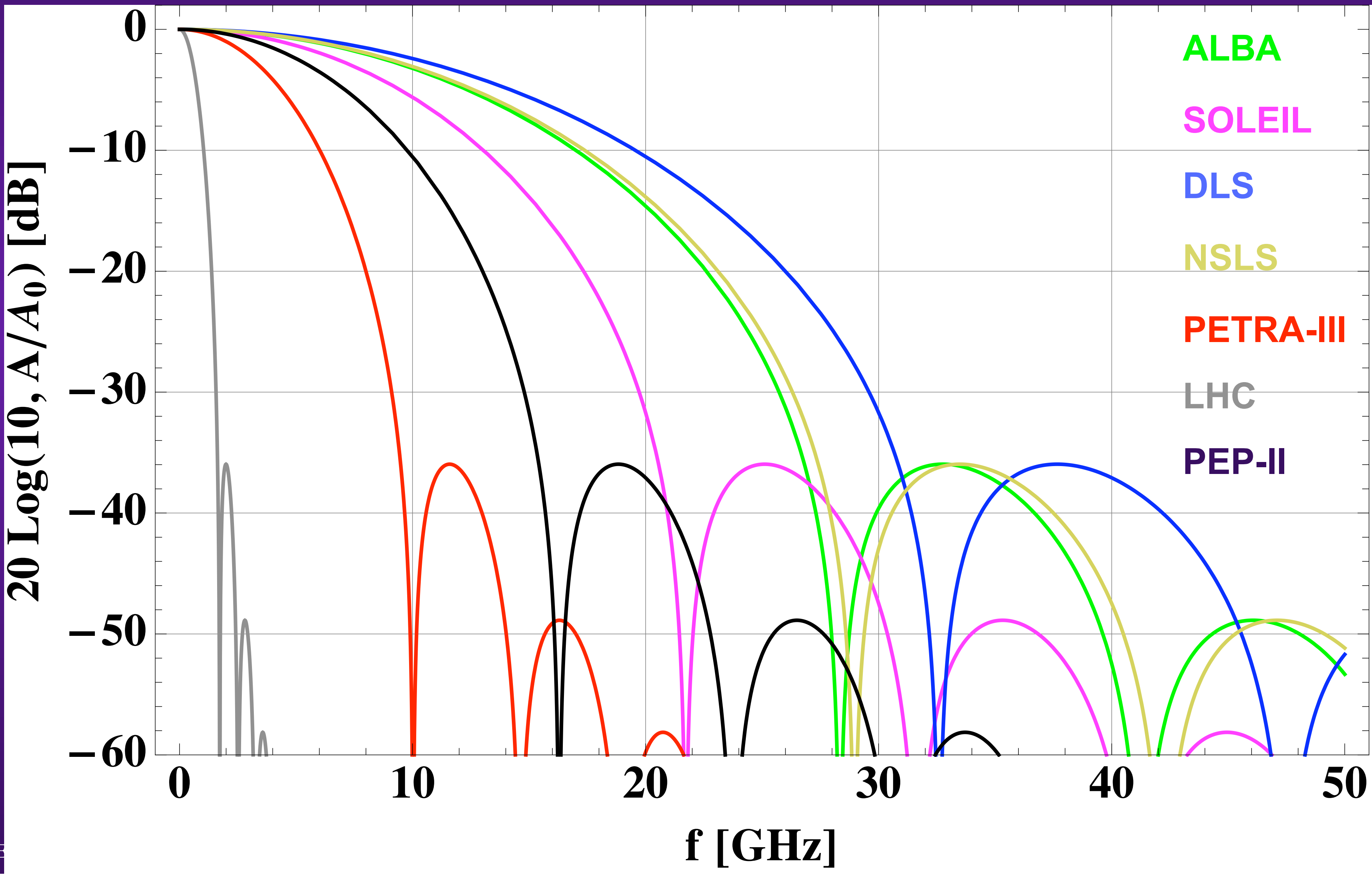
Monopole longitudinal wake potential

Normalized charge density of the bunch

Incoherent => Coherent effect between bunches not included here

MINI-WORKSHOP AT THE DLS ON 30/01/2013 (4/11)

- Comparison between the ≠ power spectra for the ≠ machines



MINI-WORKSHOP AT THE DLS ON 30/01/2013 (5/11)

- A dedicated experiment at DLS was also discussed => COLDDIAG (= COLD vacuum chamber for DIAGnostics), whose aims are threefold
  - Measure the beam heat load on a cold bore simulating the liner of superconducting Insertion Devices (IDs) with different operating conditions
  - Gain a deeper understanding in the beam heat load mechanisms
  - Study the influence of the cryosorbed gas layer on the beam heat load

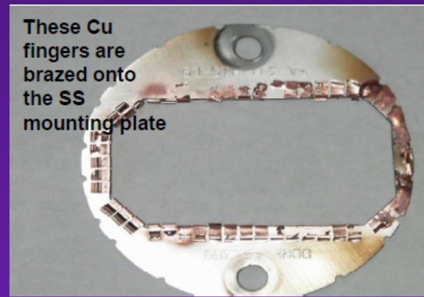
=> Measurements and their analysis is work in progress and will continue both on the experimental and theoretical sides

MINI-WORKSHOP AT THE DLS ON 30/01/2013 (6/11)

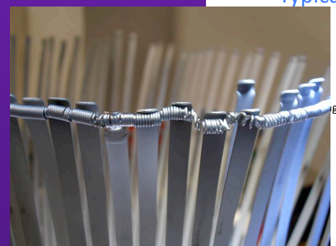
- **Different methods applied to study beam-induced RF heating**
  - Time domain wake field simulations to get the loss factor
  - Time domain long-range wake field simulations
  - Eigenmode simulations to identify critical modes
  - Identification of dangerous regions from the different modes
  - Thermal simulations using all power distributed according to mode to get temperature distribution
  - Damping of some critical modes
  - Etc.

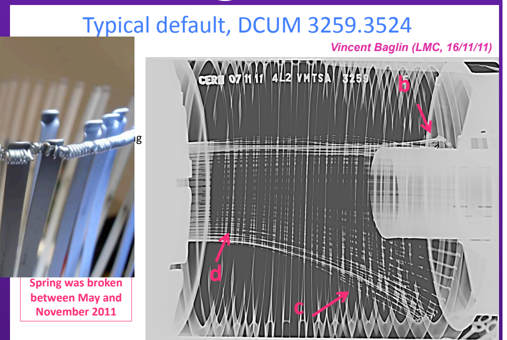
MINI-WORKSHOP AT THE DLS ON 30/01/2013 (7/11)

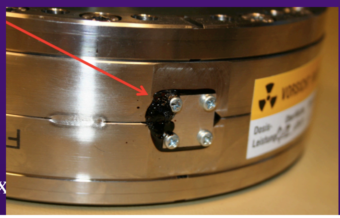
- It was reminded that the beam-induced RF heating of a machine can sometimes impose more stringent requirements on the vacuum chamber structures than those from beam instabilities and several examples of heating and damages were presented



  - Melted materials (RF fingers)
  - BPM buttons falling down
  - Mirror and support of a synchrotron light monitor damaged
  - High detector background
  - Wake fields outside the beam chamber
  - Operation delays
  - Beam dumps
  - Etc.







MINI-WORKSHOP AT THE DLS ON 30/01/2013 (8/11)

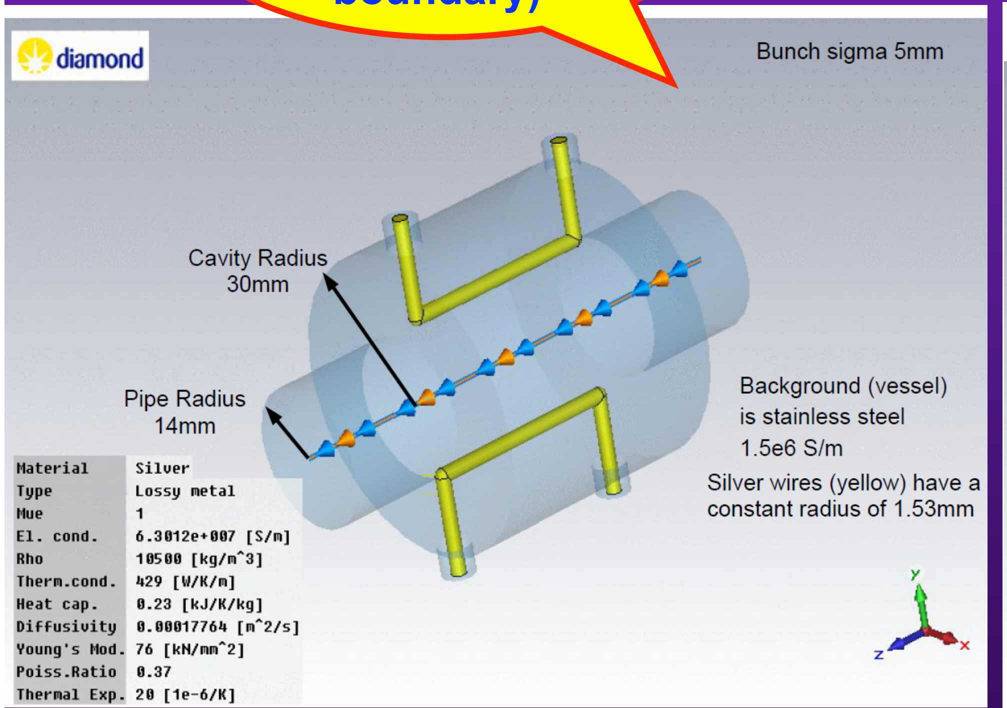
- **Several simulation codes used**
  - GdFidL (1st 2 talks and 8th one)
  - CST (3rd, 4th, 6th, 7th , 8th talks) => Thermal studies also (input power and field distribution to get temperature distribution)
  - MAFIA, NOVO and Omega3P (5th talk)
  - ECHO (8th talk)
  - Temperature and stress distribution => ANSYS

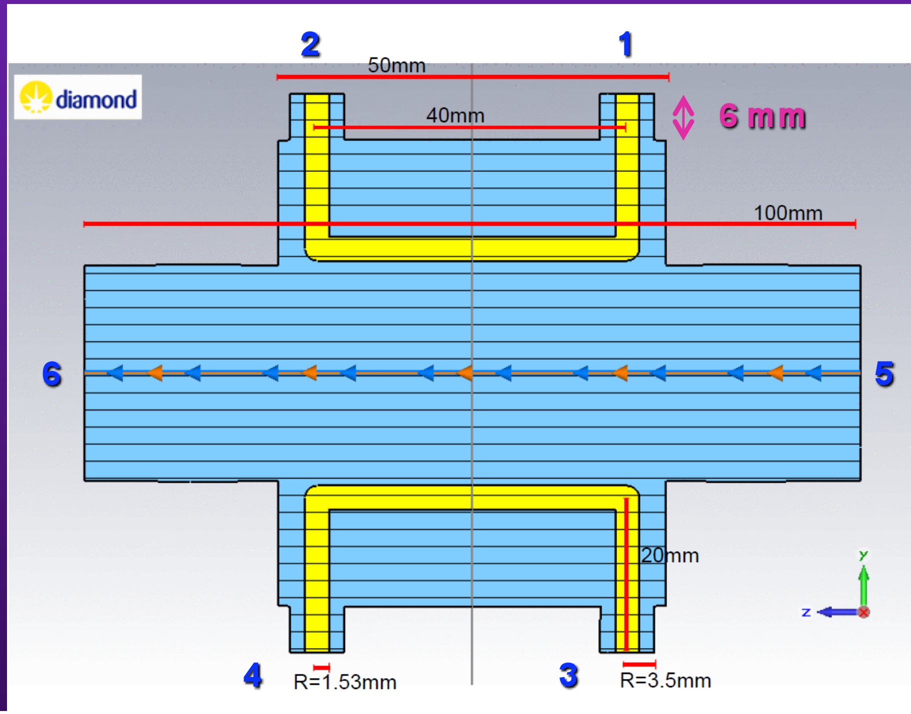
- **It was already noticed during the PEP-II time that large amounts of energy can travel through the beam pipe, but it was not quantified. At that time, they had to found rapid fixes**
  - Some designs were changed to avoid sources of wake losses where possible
  - Ceramic tiles were added to localise the losses
  - Water-cooling was also added to almost everything

MINI-WORKSHOP AT THE DLS ON 30/01/2013 (9/11)

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

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





K_{loss} = 858 mV/pC
Bunch length 5mm
Simulation time = 1h x4
16core 3.1GHz CPU 64GB ram, 128GB SSD

‘Homework’

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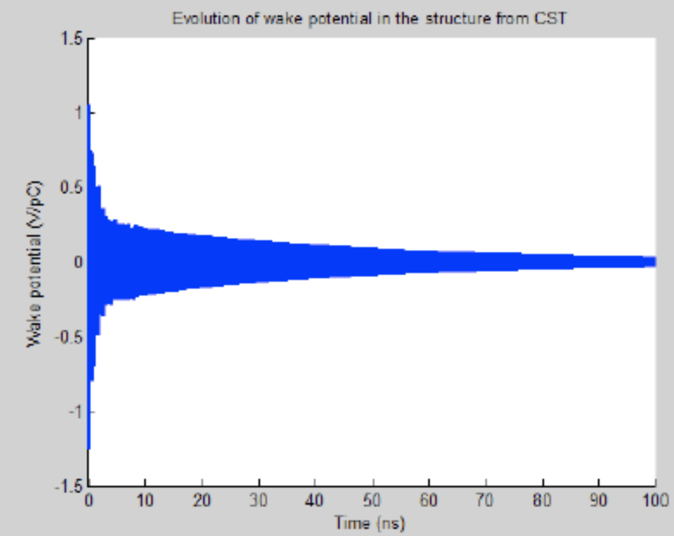
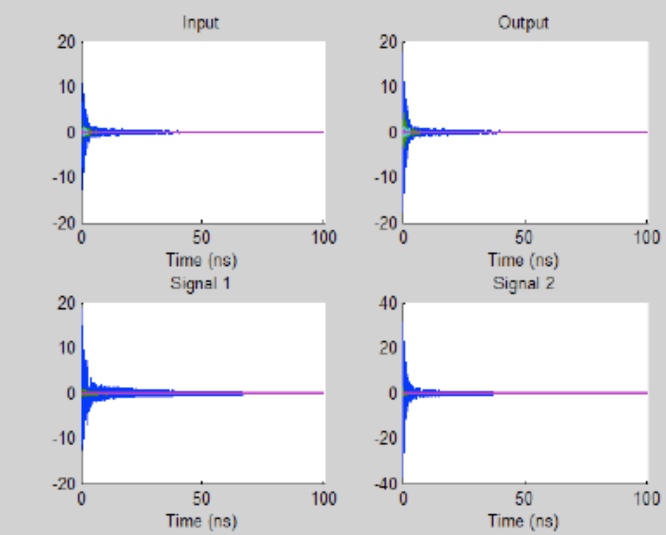
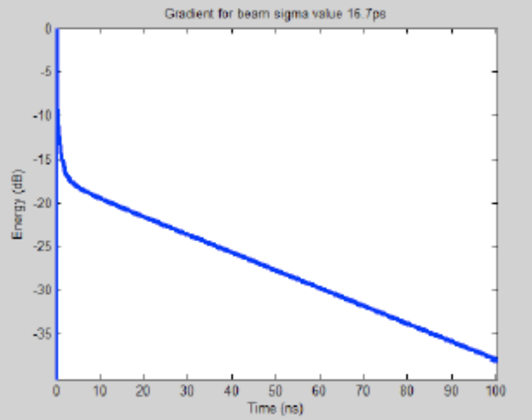
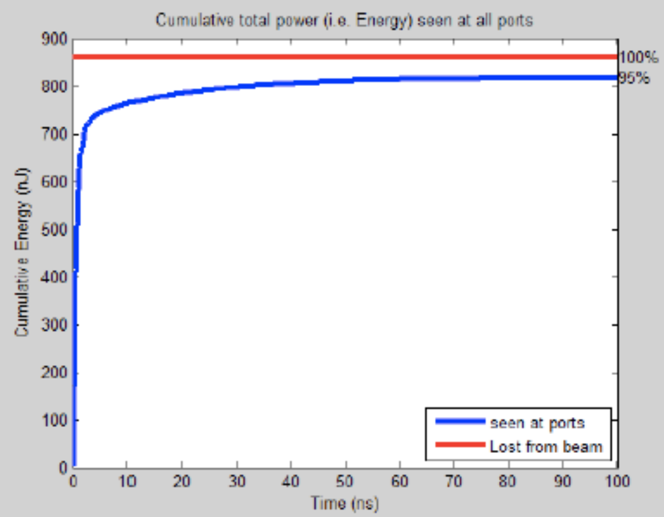
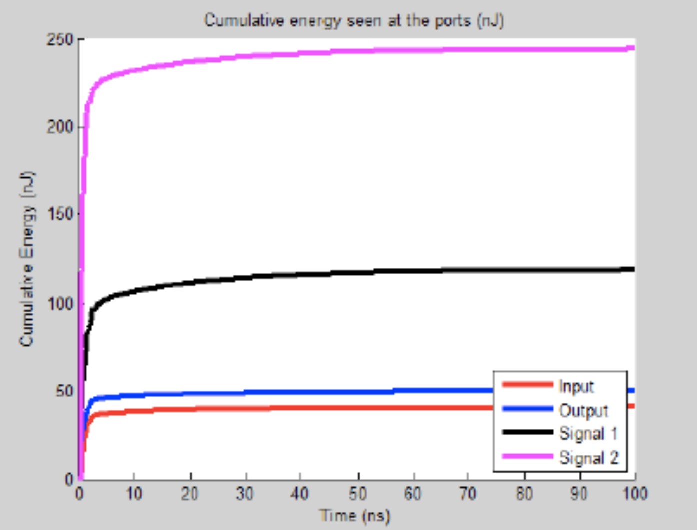






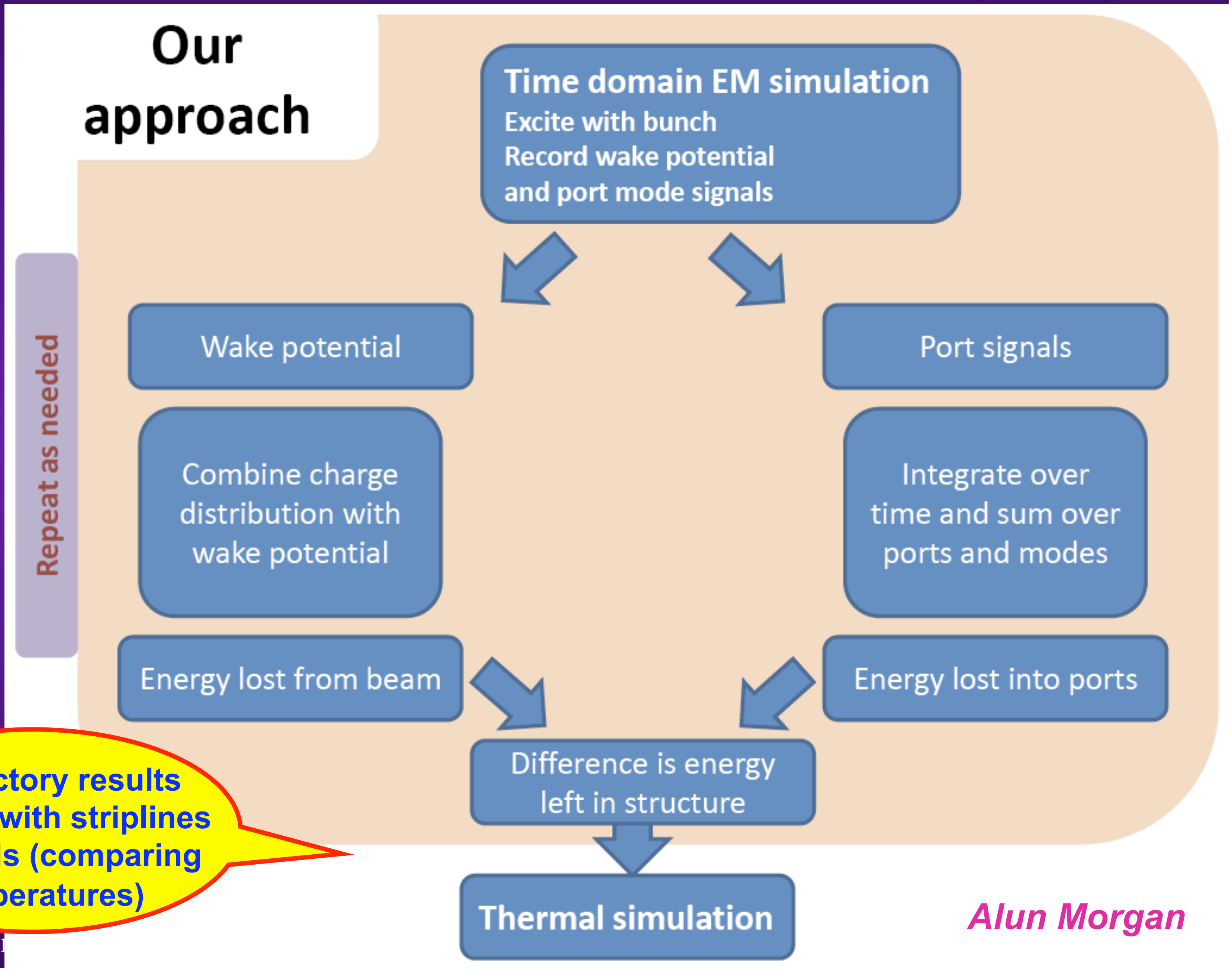




11% down the beam pipe
84% into the signal ports
5% left in structure

Losses in structure
25% Striplines
70% vessel
5% error

MINI-WORKSHOP AT THE DLS ON 30/01/2013 (11/11)



Satisfactory results obtained with striplines and BPMs (comparing temperatures)

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CONCLUSIONS (1/2)

- Beam-induced RF heating is a very important mechanism, which can limit the performance of an accelerator and which can impose sometimes more stringent requirements on the vacuum chamber structures than those from beam instabilities. Several examples of heating, damages, beam dumps or delays have been observed in many machines, and therefore it should be treated with great care
- One of the main point raised at the recent mini-workshop which took place at the beginning of the year at DLS, is that for several structures, such as striplines, a large fraction of the power is sent down the beam pipe => Will / could act as an additional heat load on nearby structures
  - How can this be correctly taken into account to accurately localize all the power losses?
  - Do we need to simulate also the adjacent structures?

CONCLUSIONS (2/2)

- Integrated calculation of dissipated power distribution from wake losses is not available at the moment already for a short-range wake field (i.e. single bunch) and the most important and critical case is a long-range wake field with a train of bunches to simulate the coherent case
- Some approximated methods are used at the moment but the post-processing analysis is quite complicated and time consuming, and one often needs many simulation runs
- None of the demonstrated methods discussed during the DLS workshop is fully consistent, and these methods can be used only as a first step

=> More discussions should take place with the code developers to tackle these different challenges!

ACKNOWLEDGEMENTS

- Many thanks to all the people working at CERN on the important issue of beam-induced RF heating and to the organisers and participants to the mini-workshop at the DLS at the beginning of the year, for the very fruitful discussions!