Higher Order Modes & Heating

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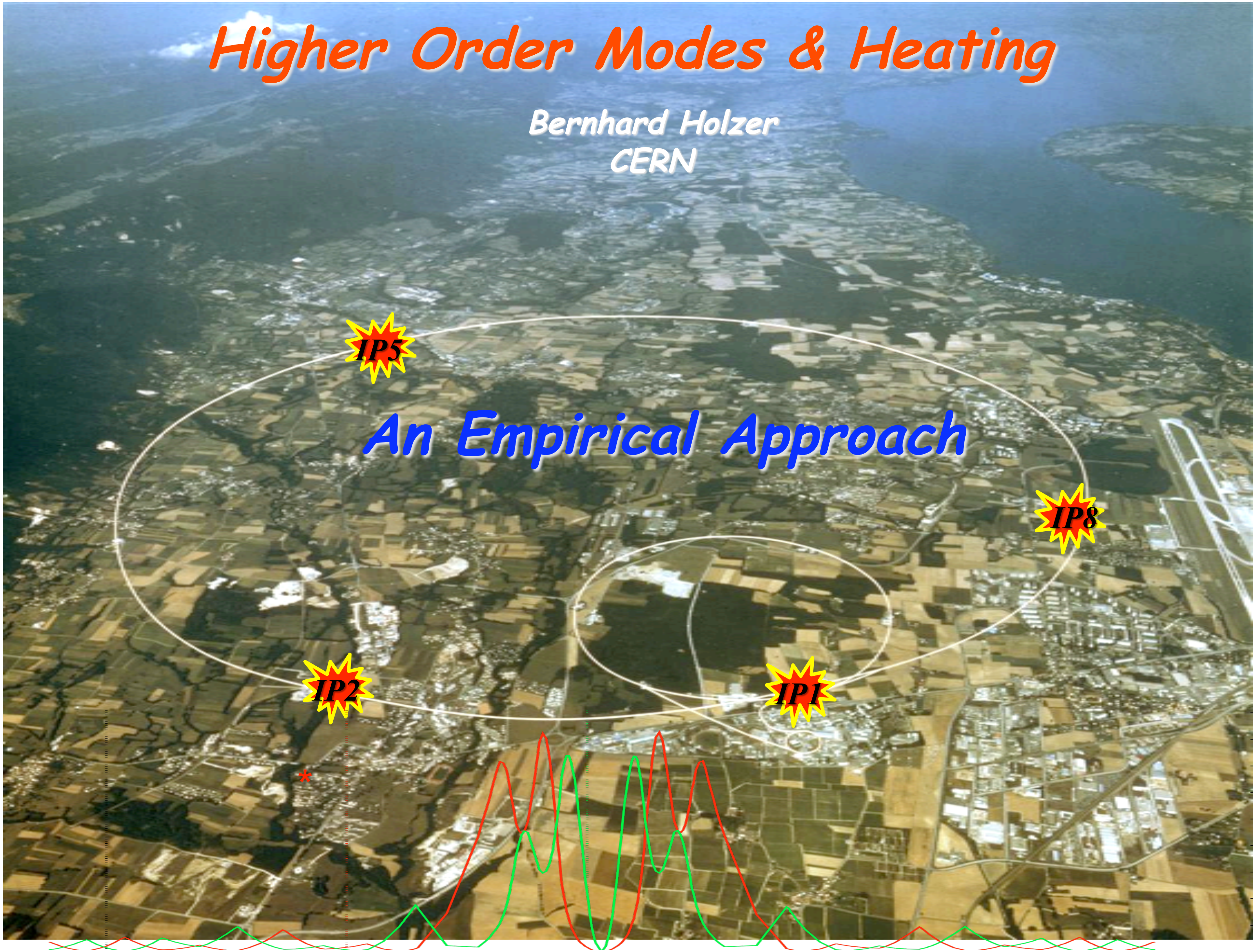
CERN

An Empirical Approach



Bibliography:

1.) H. Wiedemann: Particle Accelerator Physics II, Springer

2.) D. Brandt: Introduction to Multi Particle Effects, CAS Granada

3.) G.V. Stupakov: Wake and Impedance, SLAC

4.) A.Chao, M.Tigner: Handbook of Accelerator Physics and Engineering, Singapore : World Scientific, 1999.

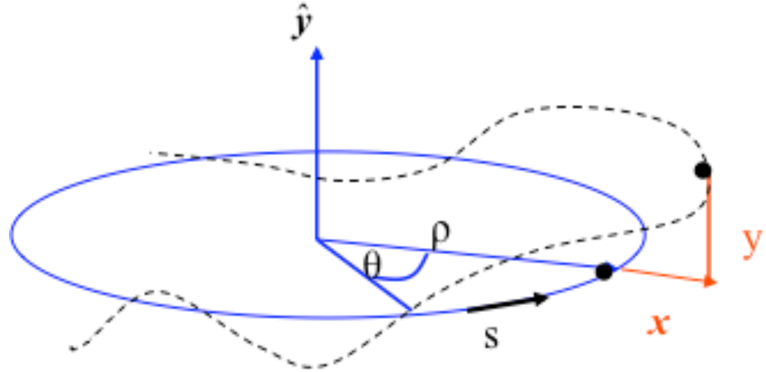
5.) A. Chao: Collective Instabilities in Accelerators, OCPA 2012

6.) A. Hoffmann: CAS, Rhodes

and a lot of material from CERN colleagues ...
E. Metral, B. Salvant, J. Uythoven, N. Mounet et al

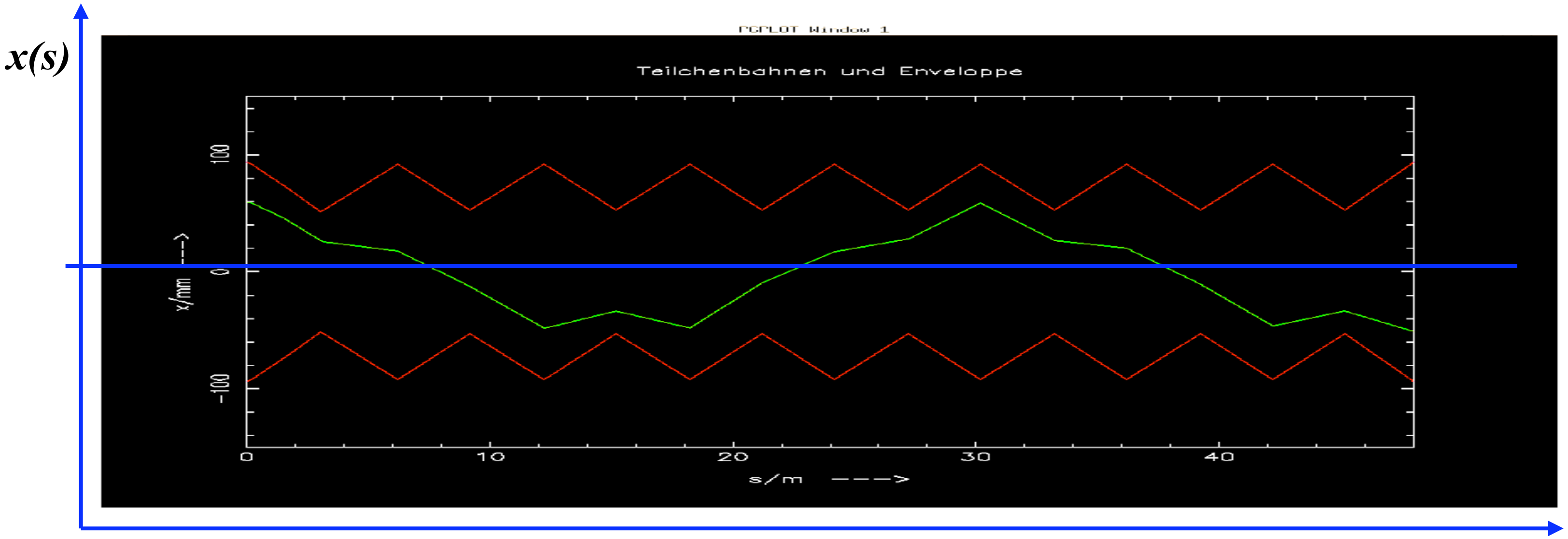
LHC Performance Workshops Chamonix 2010/ 2011/ 2012
LHC Operation Workshops Evian 2011/ 2012

Reminder: The Ideal World



Equation of Motion of a Single Particle

$$x'' + x\left(\frac{1}{\rho^2} - k\right) = 0$$

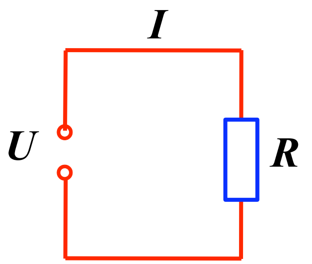


relevant parameter in this new context ... $1.6 \cdot 10^{-19}$ C
but in LHC we have $2808 \cdot 1.8 \cdot 10^{11}$ of them and
the effect of the fields generated by the beam cannot be neglected anymore.

Second Reminder:

(three definitions of impedance)

DC current:



$$U = R * I$$

Current and Voltage are related by a parameter R that is defined by the properties of the system.

G.S. Ohm

AC current:

$$U = U_0 * \cos(\omega t - \phi_u)$$
$$I = I_0 * \cos(\omega t - \phi_I)$$

or in complex notation:

$$U_C = U_0 * e^{i(\omega t - \phi_U)}$$
$$I_C = I_0 * e^{i(\omega t - \phi_I)}$$

and the physical relevant parameters we get via the real part:

$$U = \mathrm{Re}\{U_C\}, \quad I = \mathrm{Re}\{I_C\}$$

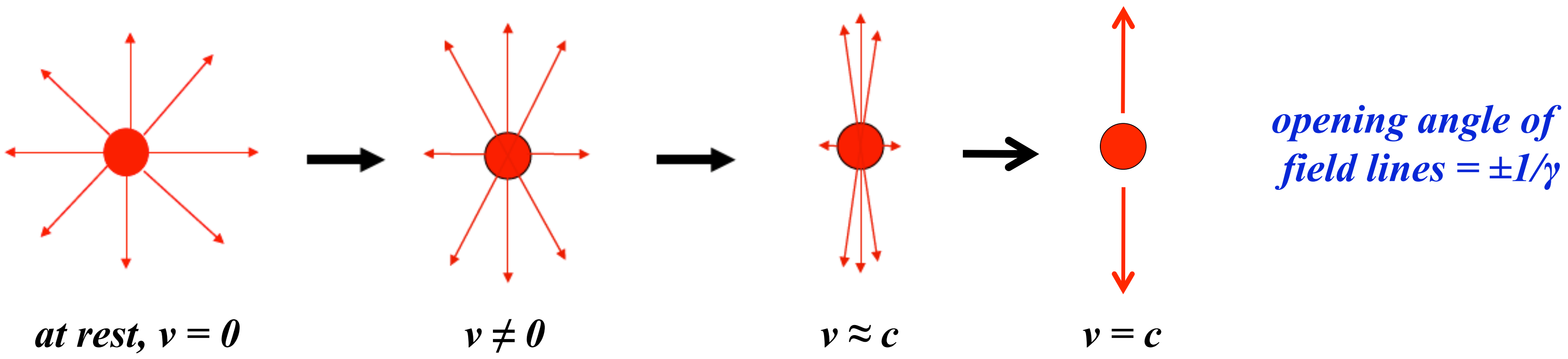
First Definition of Impedance:

Current and Voltage are again related by a parameter that is defined by the properties of the system and that we call IMPEDANCE

$$Z = \frac{U_C}{I_C} = \frac{U_0}{I_0} * e^{-i(\phi_U - \phi_I)}$$

Some general Statements:

A charged particle (bunch) always carries electromagnetic fields



An image current (of opposite sign) is travelling with the bunch along the beam pipe.
In a uniform vacuum tube of perfectly conducting material the image currents are floating without losses and no forces are generated that would act back on the bunch.

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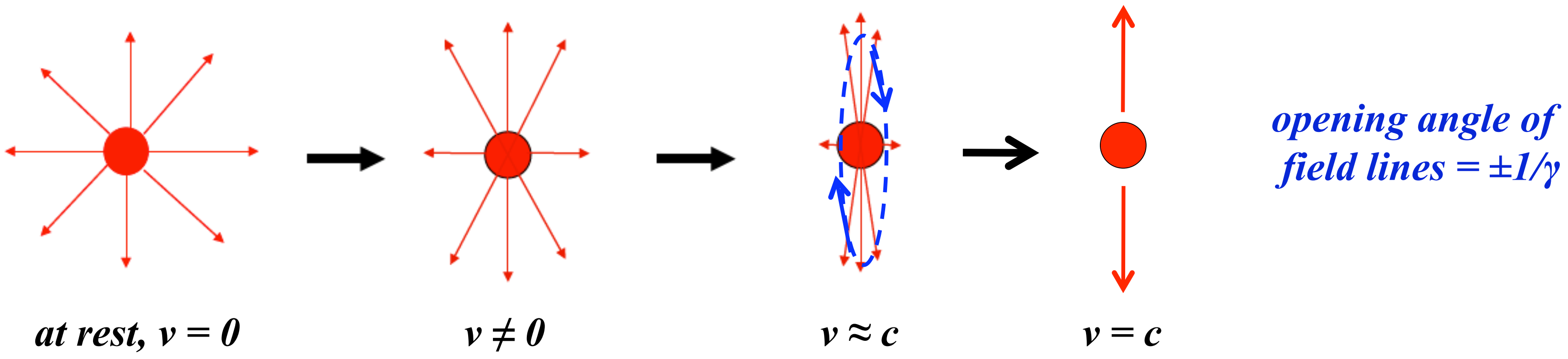


An image current (of opposite sign) is travelling with the bunch along the beam pipe.
In a uniform vacuum tube of perfectly conducting material the image currents
are floating without losses and no forces are generated that would act back on the bunch.

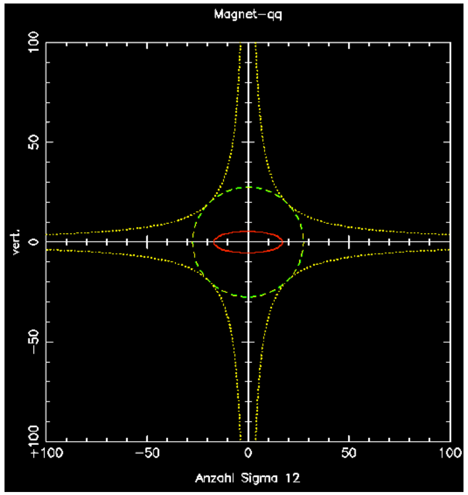
Nota bene: there is also a magnetic field (in azimuthal direction) that in ultra relativistic case
has the same but opposite force on the particle
-> no net effect on the beam at high energy
-> strong space charge forces on the particles at low energy.

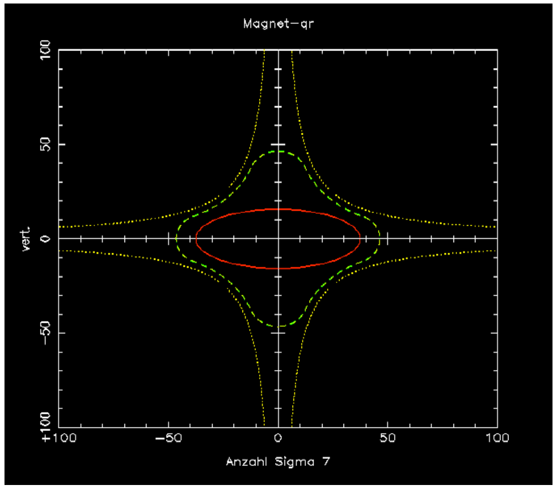
There are ***no collective instabilities and there is no heating**,*
if the following conditions are fulfilled:

the beam is ultra relativistic
the vacuum chamber is smooth
the vacuum chamber material is perfectly conducting.

Unfortunately these conditions are not realistic

Examples of vacuum chamber cross sections:

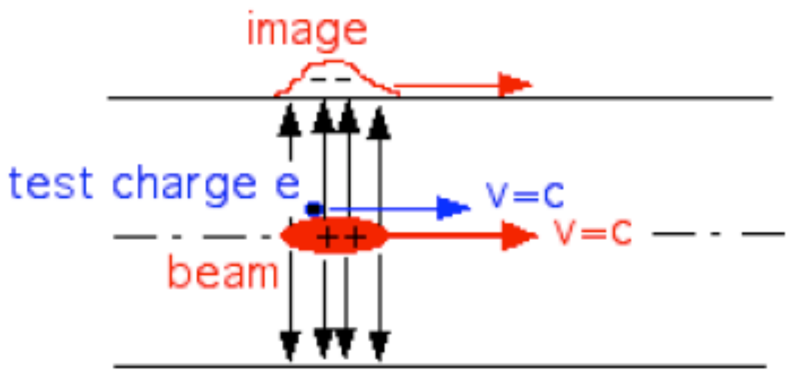




round chamber in the s.c. part of HERA

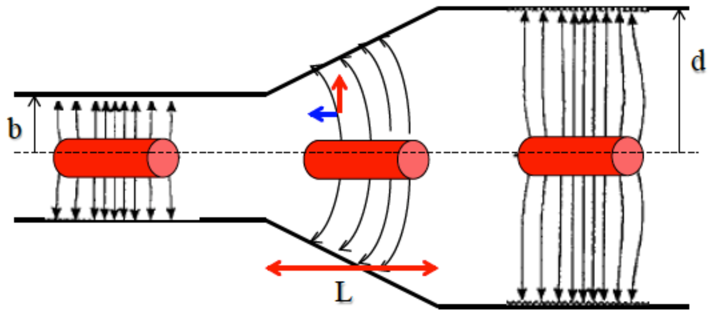
chamber optimised for very different β functions

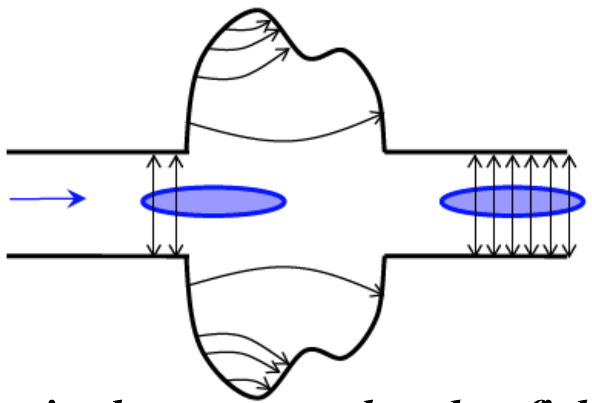
Due to these non-ideal conditions the fields created are "distorted" and act back on the beam:



A "test-particle" get affected by the fields created by the other particles in front of the same bunch
... or the leading bunches in the beam.

Effect of non-uniform vacuum chambers:

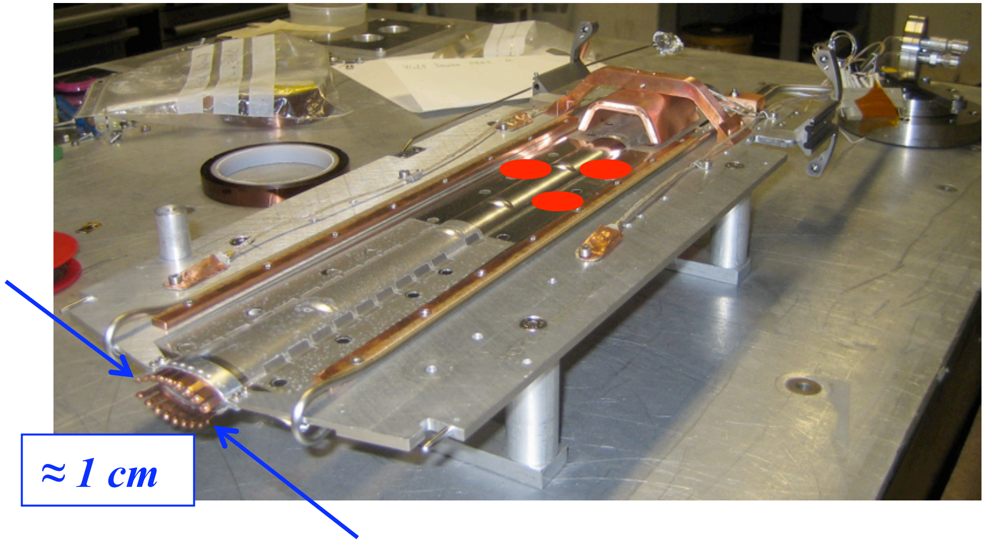




When a charged particle beam traverses a discontinuity in the vacuum chamber fields are generated that have longitudinal & transverse electrical components and change the (long / transverse) energy of the beam.

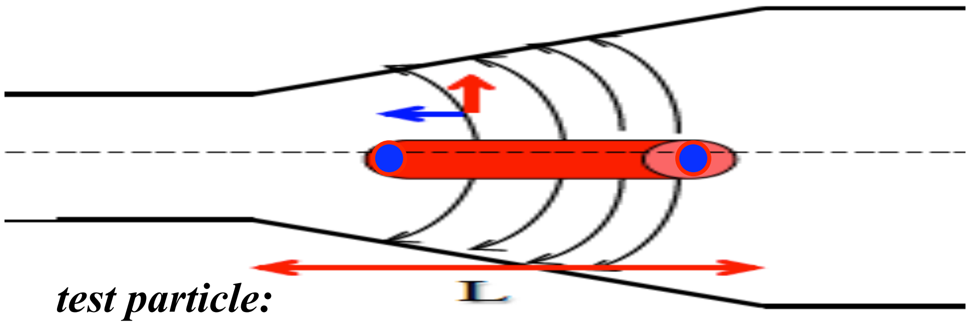
Examples:

HERA-e: Experiment Beam Pipe (HERMES target cell)



s.c. RF accelerating structure

Longitudinal Wake Fields:



test particle:
feeling the influence of
the wake-field at $\tilde{z}$

leading particle:
creating E-field (wake-field)
position z

longitudinal wake function
Integral of $E_{\parallel}$ *along interaction length*
and normalise to the charge q

$$W_{\parallel}(z-\tilde{z}) = \frac{1}{q}\int_L E_{\parallel}(s, t-\Delta z/\beta c)\,ds$$

[units] =V/C

potential

integrating over all particles ahead of the test particle and multiplying by its charge "e" gives the Wake Potential

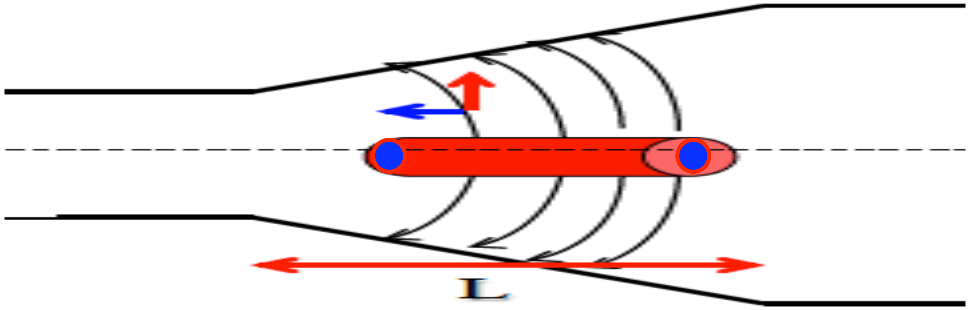
$$V_{HOM}(\tilde{z}) = -e\int_{\tilde{z}}^{\infty}\lambda(z)\,W_{\parallel}(z-\tilde{z})\,dz$$

negative sign ➔ decelerating field

Total energy loss of bunch: integrate over all slices $d\tilde{z}$

$$\Delta U_{HOM}(\tilde{z}) = -\int_{-\infty}^{\infty} e\lambda(\tilde{z})\,d\tilde{z}\int_{\tilde{z}}^{\infty}\lambda(z)\,W_{\parallel}(z-\tilde{z})\,dz$$

Longitudinal Wake Fields:



Wake functions describe higher order mode losses (HOM) in time domain.

A fully equivalent description is obtained in frequency domain.

$$V_{HOM}(\tilde{z}) = -e\int_{\tilde{z}}^{\infty} \lambda(z)\, W_{\parallel}(z-\tilde{z})\, dz$$

replace the charge density by the instantaneous current

$$I(\tilde{z},t) = \hat{I}_0\, e^{i(k\tilde{z}-\omega t)}$$

$$V_{HOM}(\tilde{z},t) = -\frac{1}{c\beta}\int_{\tilde{z}}^{\infty} I(\tilde{z},t+\frac{\Delta z}{c\beta})\, W_{\parallel}(\Delta z)\, dz$$

$$V_{HOM}(t,\omega) = -I(t,\omega)\frac{1}{c\beta}\underbrace{\int_{-\infty}^{\infty} e^{-i\omega\Delta z/c\beta} W_{\parallel}(z-\tilde{z})\, d\Delta z}_{Z_{\parallel}(\omega)}$$

Second Definition of Impedance: $Z_{\parallel}(\omega)$

The longitudinal coupling impedance relates the beam current to the induced Voltage, that is created by the wake fields and that acts back on the beam.

$$V_{HOM}(t,\omega) = -I(t,\omega) Z_{\parallel}(\omega)$$

Impedance of the vacuum components is the Fourier Transform of the Wake Fields left behind the beam

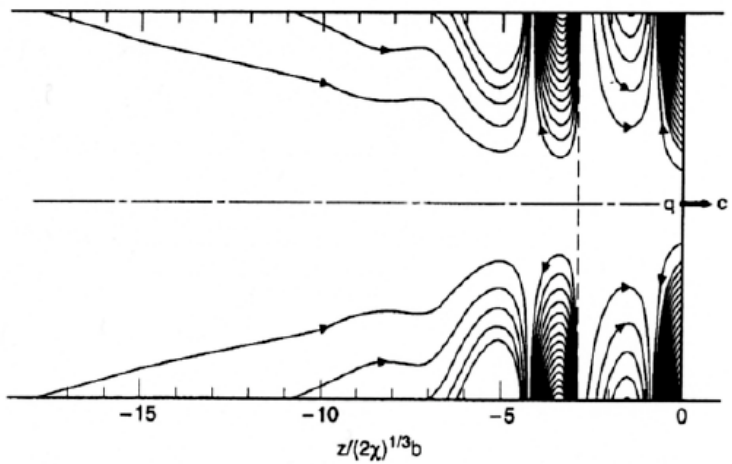
Two equivalent descriptions:

Interaction of the (test-) particle and the generated (wake-) field   (... time domain)

Like in case of cavities: sudden changes in vacuum chamber cross section act like "cavities"
-> representation of frequency dependent impedances (frequency domain).

frequency spectrum of the beam < -- > mode spectrum of the "cavity"

-> induced voltage: $V(\omega) = -Z(\omega) * I(\omega)$



Field lines of a resistive wall wake field generated by a point charge q (court. K. Bane, 1991)

Nota bene:

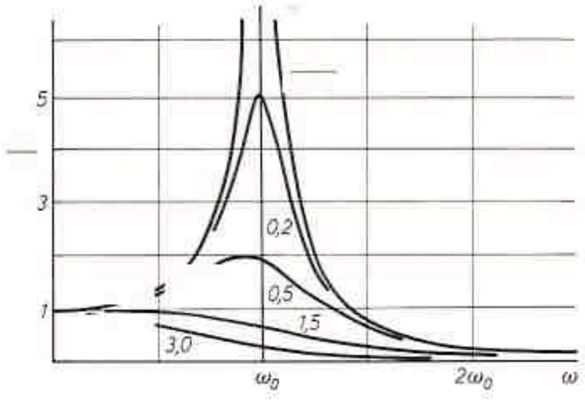
the minus sign indicates energy loss of the particles
the impedance depends on material and geometry of each piece of vacuum chamber
the coupling between beam and structure depends on the frequency spectrum of both
... and so e.g. on the bunch length !!

Wake Fields and Cavity Quality Factor Q:

Reminder: mechanical oscillations

$$F * \cos(\omega t) \quad = \quad m\frac{d^2x}{dt^2} \quad + \quad k\frac{dx}{dt} \quad + \quad Dx$$

ext. force   inertial force   damping   restoring force



Resonance in mechanical Oscillations (Gerthsen et al) for different damping

small damping (i.e. small energy losses in the system) leads to narrow resonance width

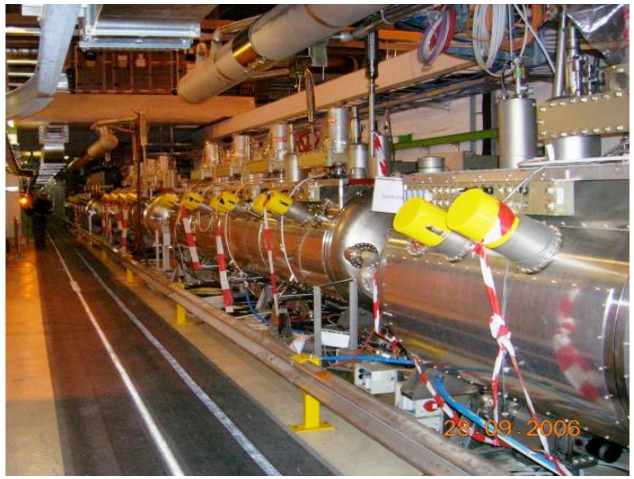
Optimising the Cavity Design:

go for small losses, e.g. s.c. cavities

Q factor:

$$Q \quad = \quad 2\pi \frac{\text{Stored Energy in the Cavity}}{\text{Energy Loss per Period}}$$

$$= \quad \omega_0 \frac{W}{P_{loss}}$$

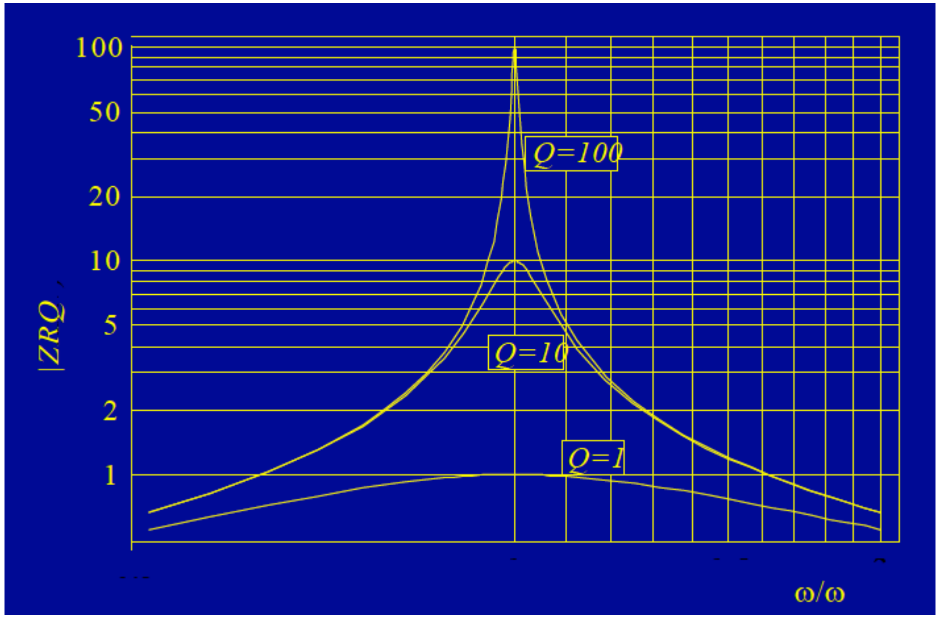


Wake Fields and Cavity Quality Factor Q:

$$Q = \omega_0 \frac{W}{P_{loss}}$$

LHC cavities:

$$Q \approx 8 * 10^4$$

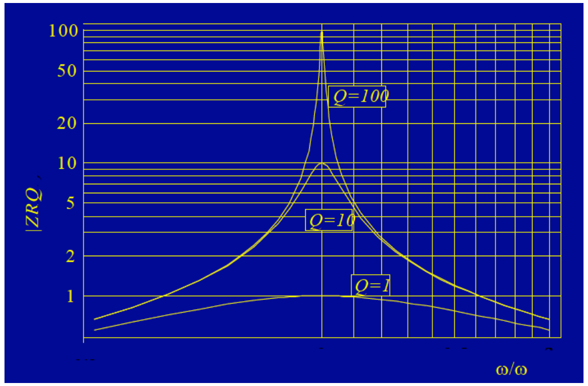


The impedance of a special vacuum component can be
broad band (Q ≈ 1), sudden change of chamber size
or narrow band (Q >> 1), the cavities (!)

narrow band impedances have a small frequency band, but exist for a long time ...
they can act even on other bunches or the same bunch after some turns
-> multi bunch instabilities

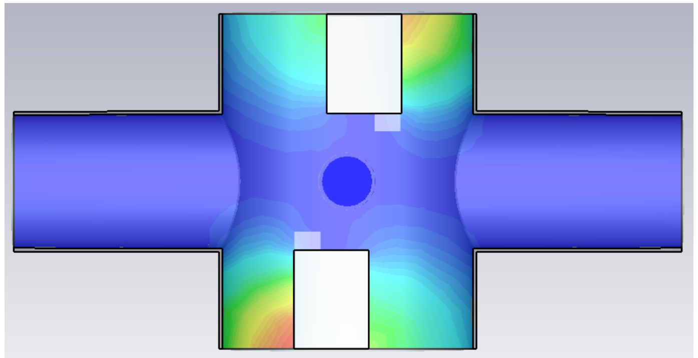
broad impedances have a broad frequency band, decay fast
-> single bunch instabilities & heating !!

Wake Fields and Cavity Quality Factor Q:

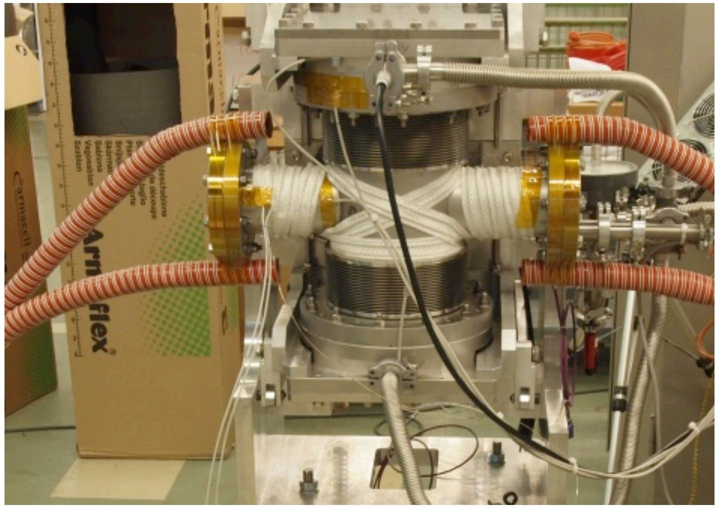


narrow band impedances

Cavities, Roman Pots, bad flange connections
kicker chambers (ceramic)
-> shielding by RF-Fingers



forward spectrometer "ALFA"

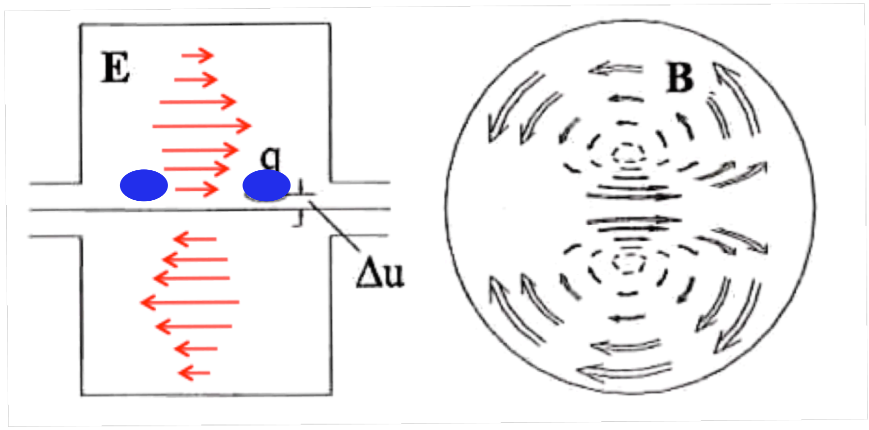


Transverse Wakefields and Panofsky-Wenzel Theorem

Transverse Forces acting on particles are generated when a bunch is travelling off-centre through a non-uniform structure
they only can be induced if there is a longitudinal wake function !!

Acting back on the beam they can amplify the beam offset and lead to instabilities.

Off-centre bunch induces a long. E-field mode that is related to an azimutal B-field ...
which leads to a transverse deflection.



$$W_\perp = \frac{\int_L \{E(t-\Delta z/\beta c) + v \times B(t - \Delta z/\beta c)\}_\perp ds}{q\Delta u}$$

Δu = beam offset
[ ] = V/Cm

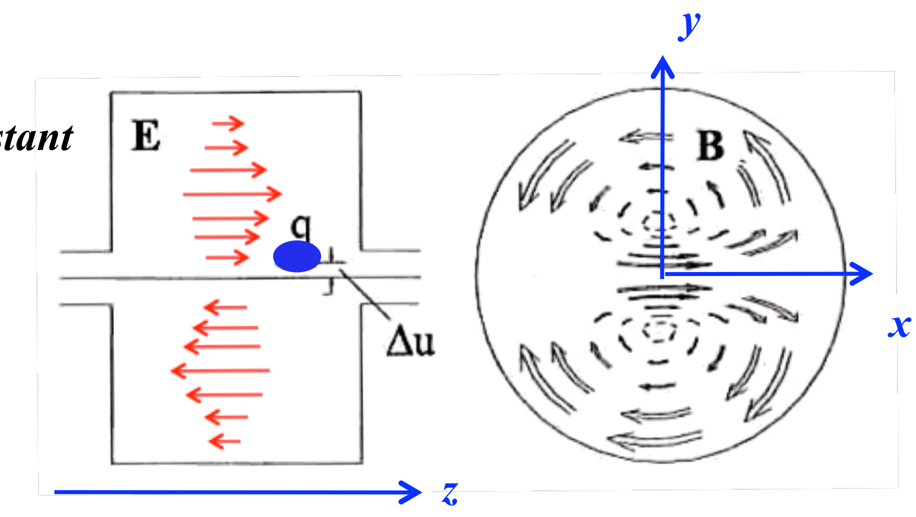
corresponding impedance:

$$Z_\perp(\omega) = \frac{-i}{c\beta}\int_{-\infty}^{\infty} e^{-i\omega\Delta z/c\beta} W_\perp(\Delta z)\, d\Delta z$$

Transverse Impedance,
[ ] = Ω/m

Transverse Wakefields and Panofsky-Wenzel Theorem

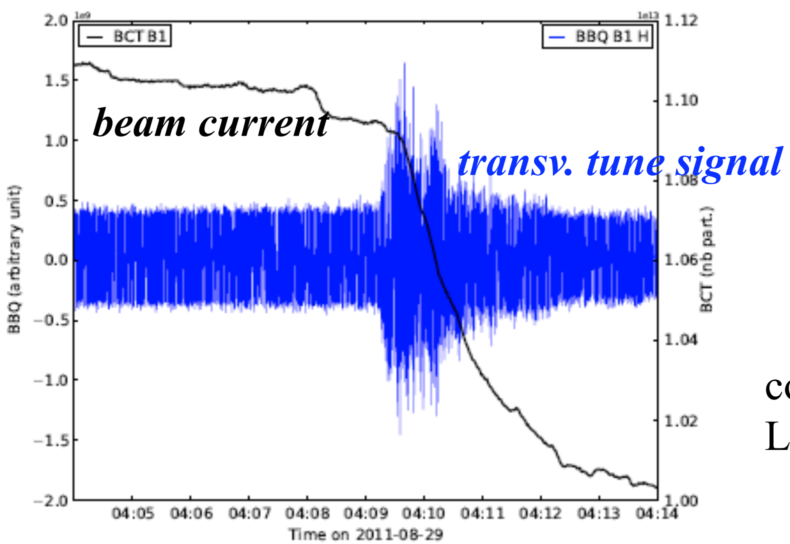
Transverse Impedance is imaginary
-> transverse amplitude grows
but particle (i.e. bunch) energy stays constant



we will observe no heating but bunch instabilities

Panofsky-Wenzel Theorem:
the longitudinal gradient of the transverse force
is given by the transverse gradient of the long. force

$$\frac{\partial}{\partial z} F_{\perp} = -\nabla_{\perp} F_{\parallel}$$

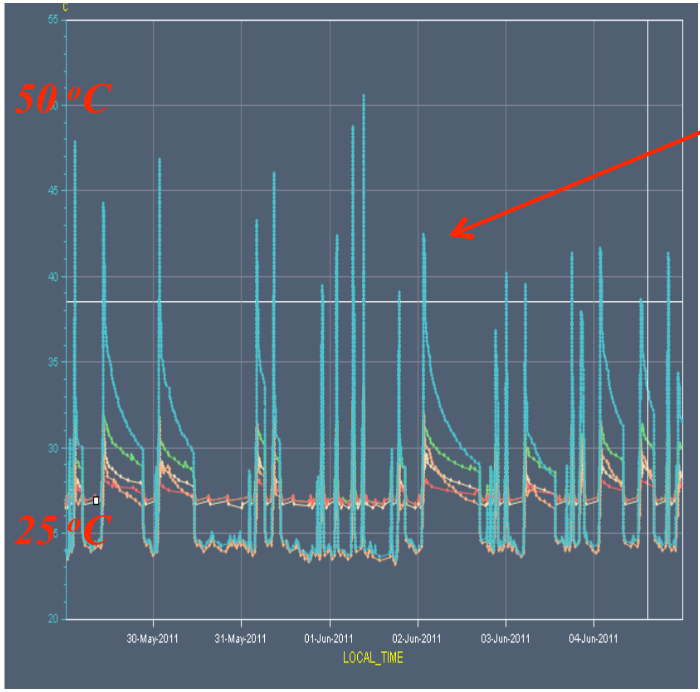


court. N. Mounet,
LHC: observed transverse bam instability

Longitudinal Impedance of single Elements: Collimators

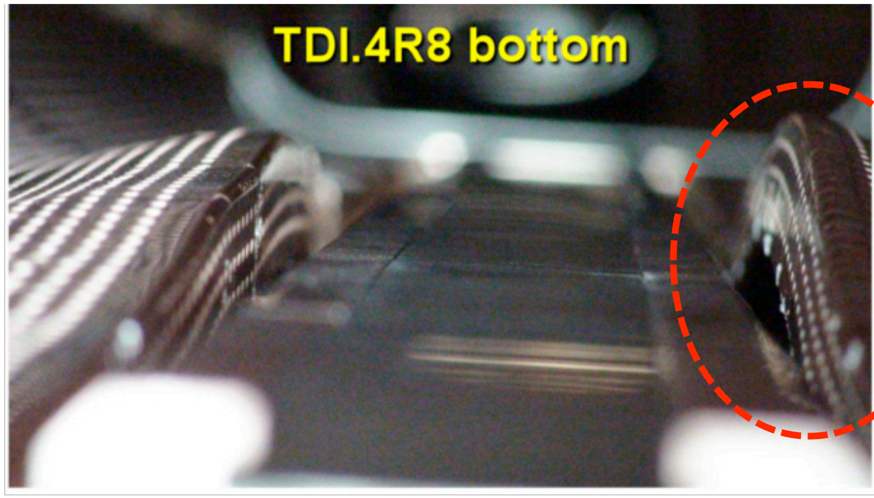
broad impedances

vacuum chamber cross sections, collimators
-> tapering



sharp temperature increase at injection & ramp
slow decrease with decaying beam current

sometimes reaching the damage level



beam screen deformation at injecton collimator

Total Resistive Impedance:
Loss Factor

... a quantity to measure or describe on beam (!) the total resistive impedance (over all frequencies)

$$k_{HOM} = \frac{\Delta U_{HOM}}{e^2 N_b^2}$$

where ΔU_{HOM} = energy loss of the bunch
N_b = number of particles in the bunch

k_{HOM} is – clearly – related to the long. wake function:

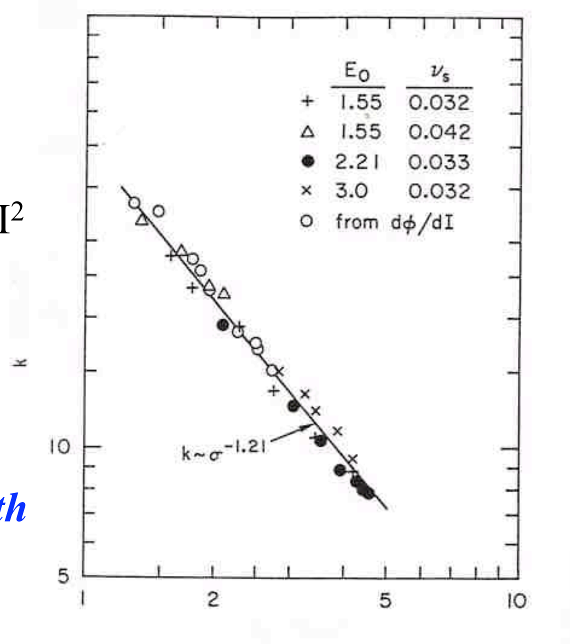
$$k_{HOM} = \frac{1}{N_b^2} \int_{-\infty}^{\infty} \lambda(\tilde{z}) d\tilde{z} \int_{\tilde{z}}^{\infty} \lambda(z) W_{\parallel}(z - \tilde{z}) dz$$

and defines the power loss of the beam

$$P_{HOM} = k_{HOM} \frac{I_0^2}{f_0 n_b} = k_{HOM} \frac{I_0}{f_0} \frac{I_0}{n_b}$$

... remember Ohm: $P = RI^2$

and it depends strongly on the bunch length



loss factor K and bunch length (Spear 1977)

Longitudinal Impedance of Single Elements: Collimators

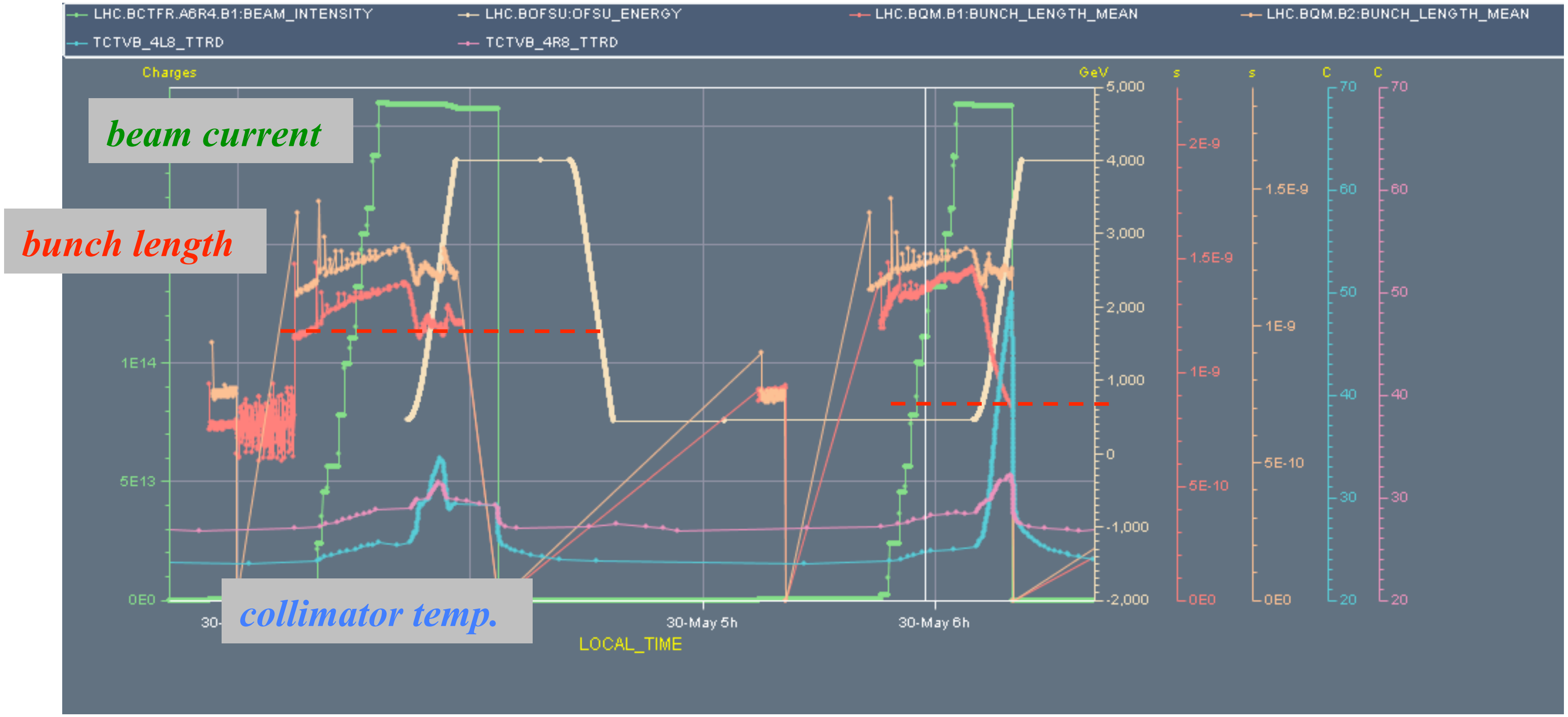
broad impedances

vacuum chamber cross sections, collimators

-> tapering

“Despite active cooling, TCTVBs in IR8 consistently heat by around 10 degrees”

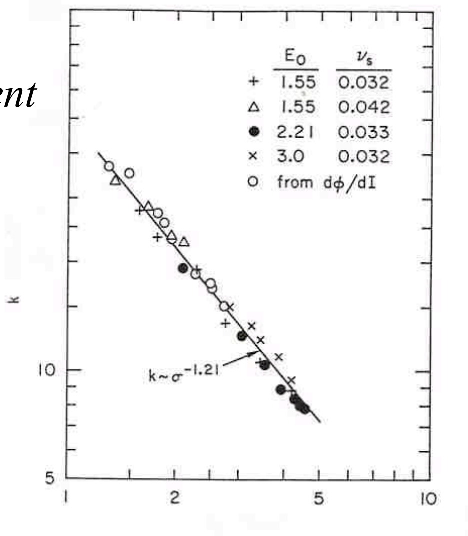
→ *Worry if bunch length is reduced in physics, but should be replaced by TCTPs after LS1*



Loss Factor Bunch Number & Bunch Length

$$P_{HOM} = k_{HOM} \frac{I_0^2}{f_0 n_b} = k_{HOM} \frac{I_0}{f_0} \frac{I_0}{n_b}$$

bunch length dependent loss factor in Spear



remember luminosity:

$$L = \frac{1}{4\pi e^2 f_0 n_b} * \frac{I_{p1} I_{p2}}{\sigma_x \sigma_y}$$

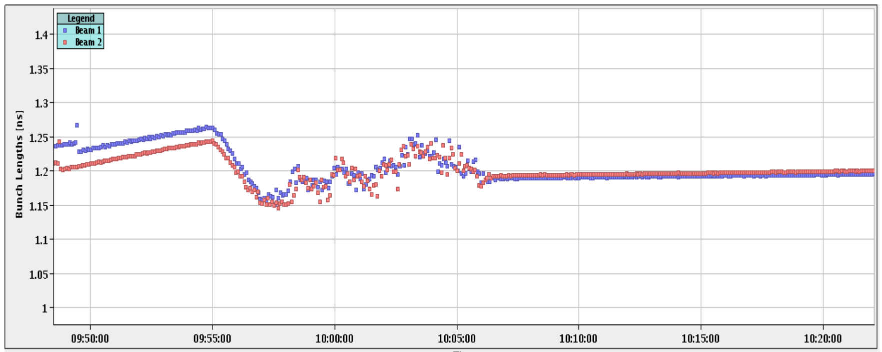
The loss factor depends on the average beam current I_0, the number of bunches the current is distributed n_b, the size of the accelerator f_0 and the bunch length !!!

Vacuum chamber components behave like cavities -> represent frequency dependent impedances With the given frequency spectrum of the beam strong coupling to the vacuum components can appear if impedance and beam have a large component at the same frequency.
-> loss factor and heating depend strongly on bunch length

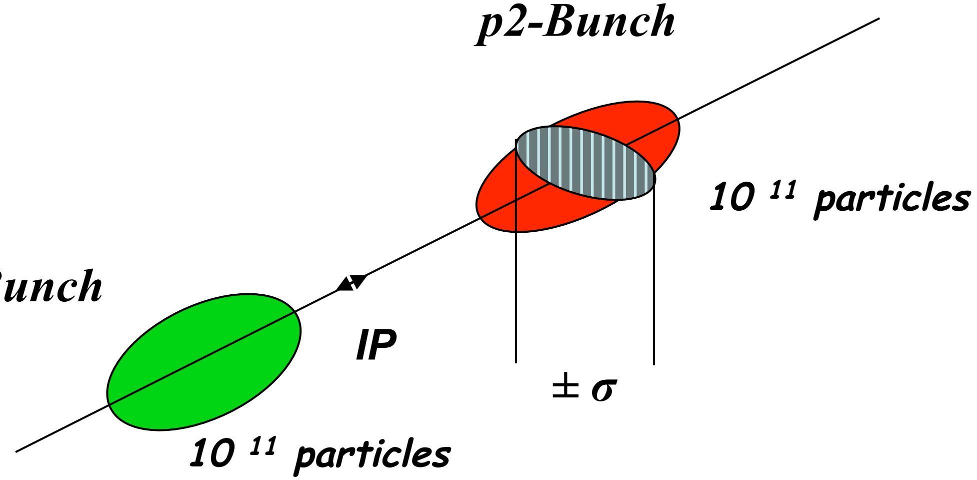
$$V(\omega) = -Z(\omega) * I(\omega)$$

LHC bunch length control during acceleration

adiabatic damping (= $E^{1/4}$)
increase in Voltage (= $V_{rf}^{1/2}$)
counter act via rf noise to keep $\sigma_l \approx 1.2$ ns



Luminosity



Example: Luminosity run at LHC

$\beta_{x,y} = 0.55\ m$

$\varepsilon_{x,y} = 5 * 10^{-10}\ rad\ m$

$\sigma_{x,y} = 17\ \mu m$

$f_0 = 11.245\ kHz$

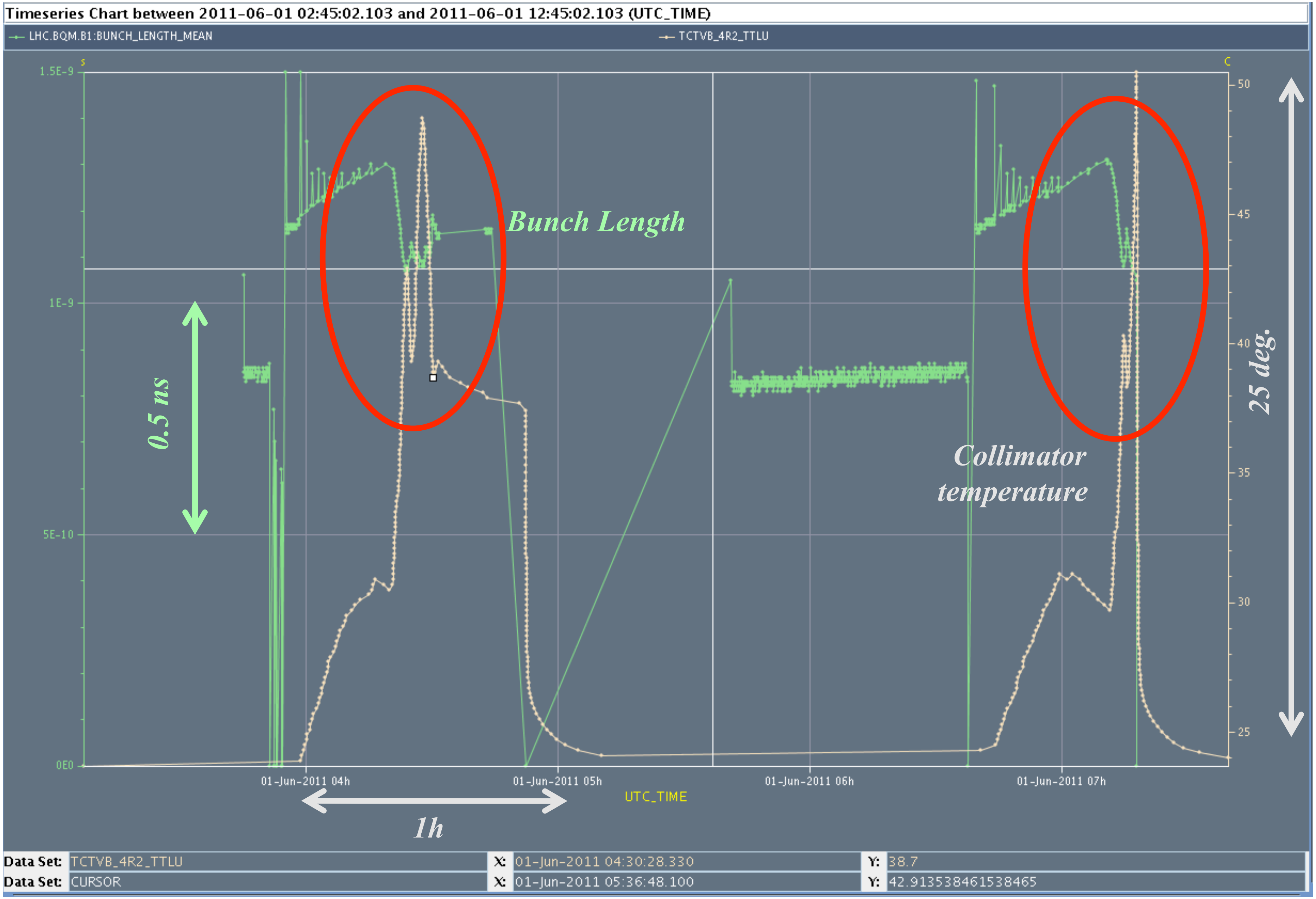
$n_b = 2808$

$$L = \frac{1}{4\pi e^2 f_0 n_b} * \frac{I_{p1} I_{p2}}{\sigma_x \sigma_y}$$

$I_p = 584\ mA$

$$L = 1.0 * 10^{34}\ \frac{1}{cm^2 s}$$

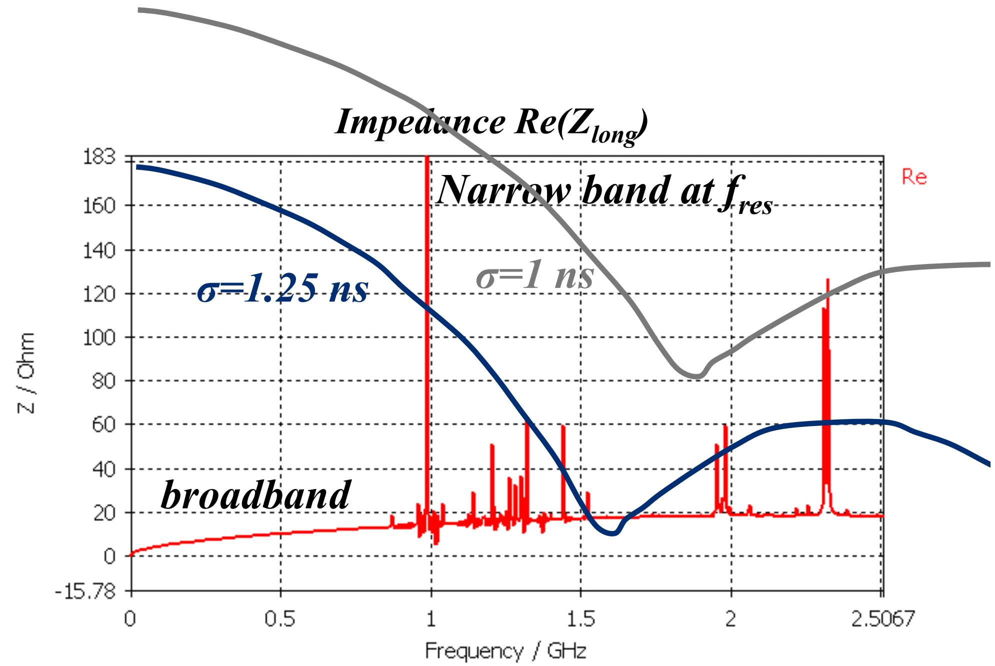
LHC Bunch Length Effect

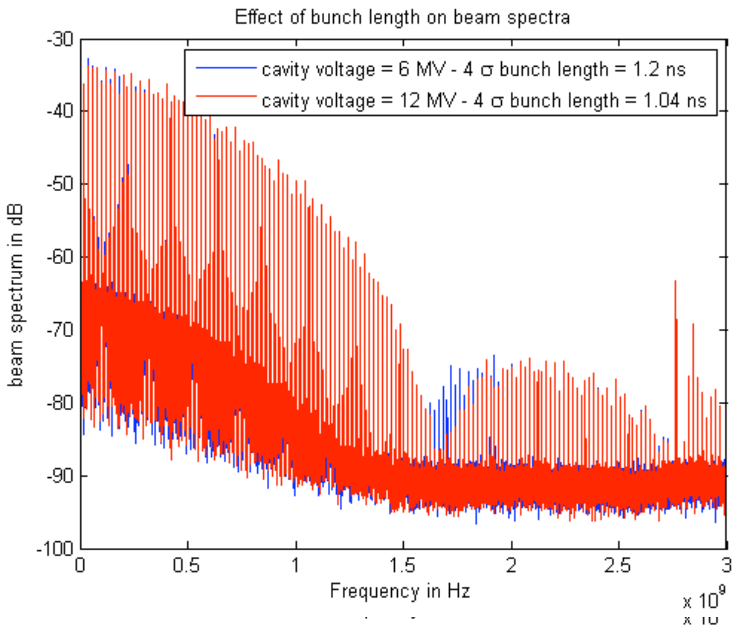


Effect of bunch length on HOM heating

Power lost by the beam in a device of impedance Z_{long} (Calculation for LHC, M=2808 bunches N_b=1.15 10^{11} p/b)

$$P_{loss} = 2(eMN_b f_{rev})^2 \left(\sum_{p=1}^{\infty} \mathrm{Re}\left[Z_{long}(2\pi pMf_{rev})\right] \times Powerspectrum(2\pi pMf_{rev}) \right)$$

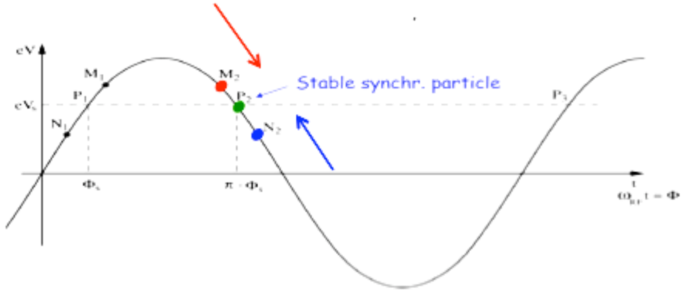




court. E. Metral

Phase Shift due to Impedance Effects

$$k_{HOM} = \frac{\Delta U_{HOM}}{e^2 N_b^2}$$



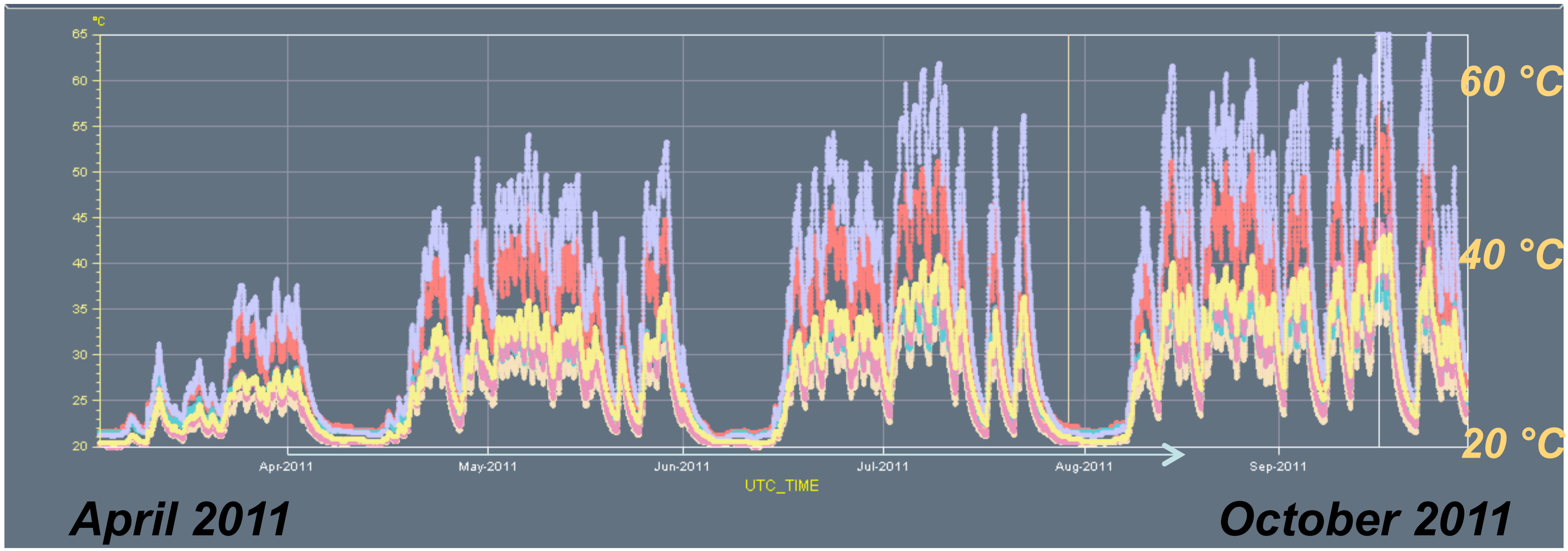
energy loss has to be compensated by the RF system ***and leads to change in synchr. phase***

$$\Delta U_{HOM} = e N_b V_{rf} \sin(\phi_s - \phi_{s0})$$ ***where $\phi_{s\,0}$= synchr. phase at small (zero) current***

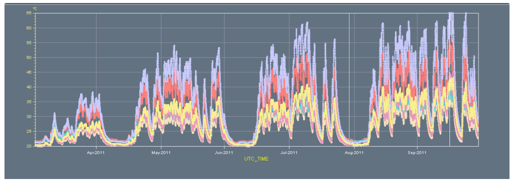
energy loss depends on the stored beam current and the number of bunches

energy loss leads to heating of chamber components ***and depends strongly on the bunch length.***

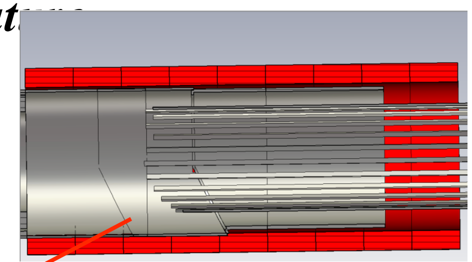
Example: Temperature increase of LHC injection kickers



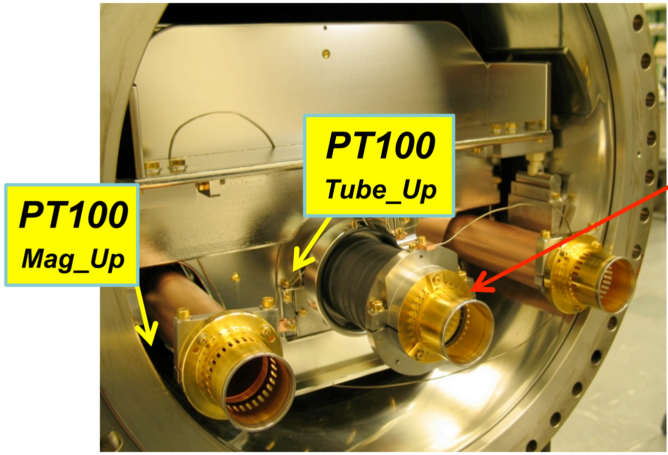
LHC MKI8 Heating
a cavity like object

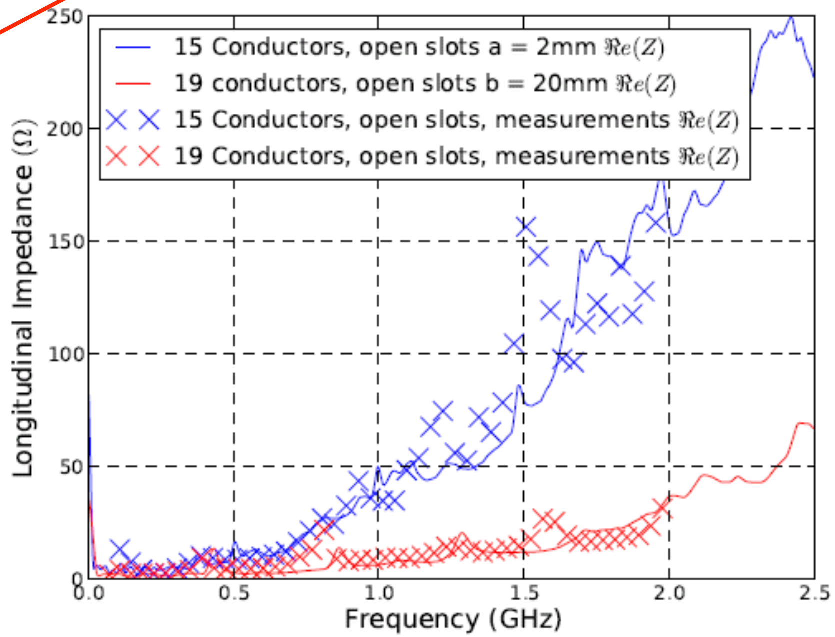


strong heating of injection kicker observed ...
as a function of the stored beam current
reaching in-tolerable limits for the ferrite temperat



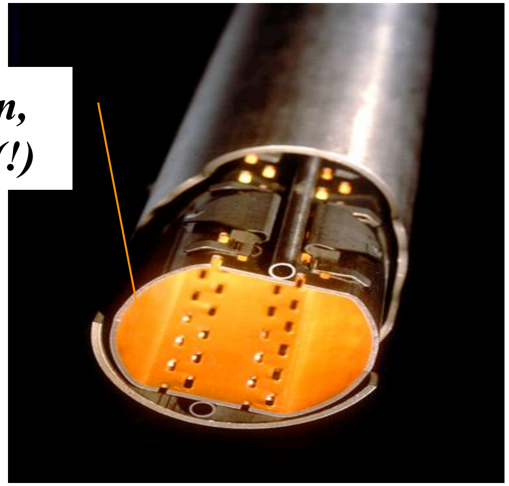
ceramic (!) beam pipes are equipped with
conducting stripes (15 in 2011)





Reduced Impedance, loss factor and heating eff
by improved shielding stripes

Impedances in an Accelerator



LHC beam screen, with Cu coating (!)

Resistive Wall Impedance:

$$\frac{Z_{\parallel}(\omega_n)}{n} = (1+i)\frac{\bar{R}}{n\, r_w\, \sigma\, \delta_{skin}}$$

r_w = *vacuum chamber radius*
δ_{skin} = *skin depth*
$n = \omega_n / \omega_0$

improve your vacuum chamber conductivity

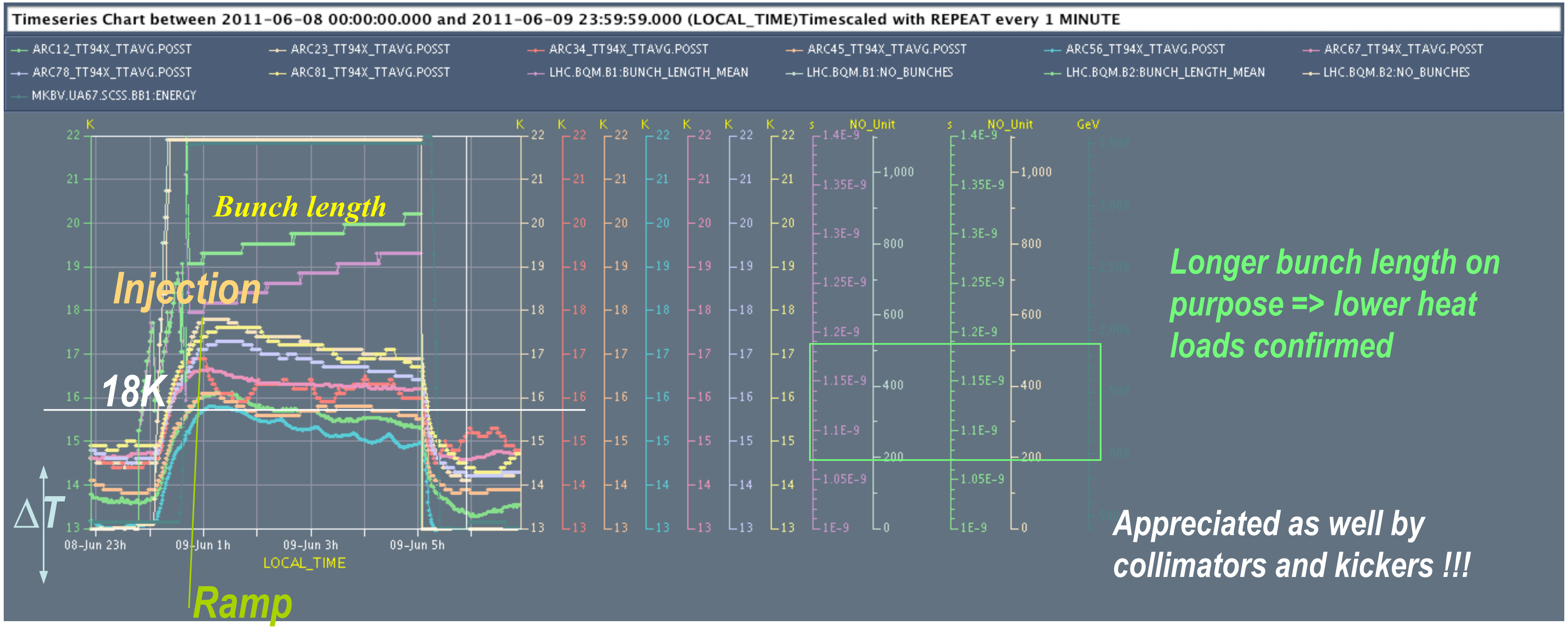
Cavity-like Impedance:

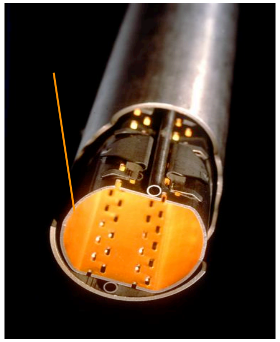
$$\frac{1}{Z_{\parallel}(\omega)} = \frac{1}{R_S}\left(1 + iQ\frac{\omega^2 - \omega_r^2}{\omega\omega_r}\right)$$

Q = *cavity quality factor*
R_s = *cavity shunt impedance*
ω_r = *resonance frequency*

cavities cannot be avoided ...
but cavity-like objects
-> shielding

Effect of bunch length on HOM heating: Beam Screen Temperature & Cryo Load



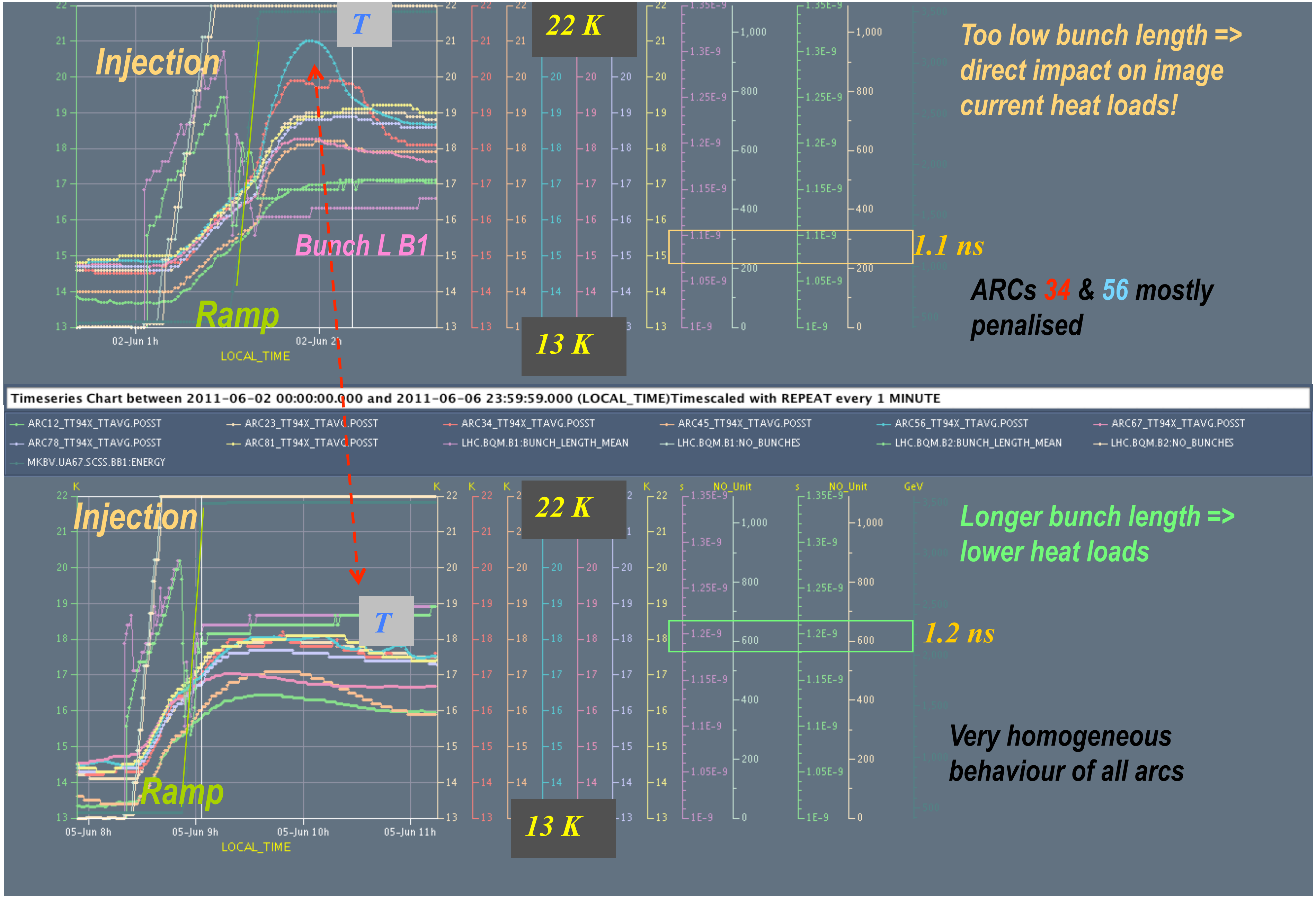


Temperature increase (Peak - before injection) for 1092 bunches:

- ***Maxi: ΔT = +4.5K (1836, short bunch: 1.12ns-1.14ns)***
- ***Avg: ΔT = +3.6 K***
- ***Mini: ΔT = + 2.6K (1859, longer bunch:1.22ns-1.27ns)***
- ***About 2.0K for injection, rest for ramp effect***

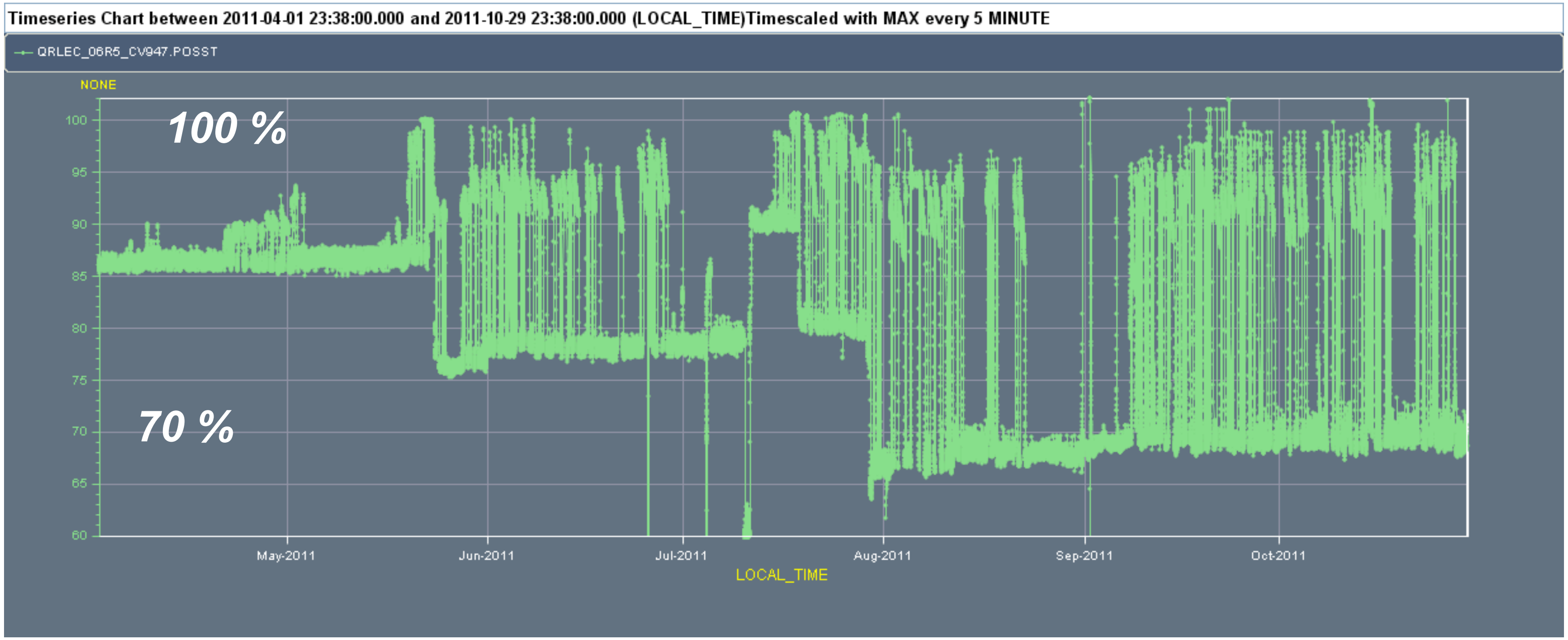
court. S. Claudet

Effect of bunch length on HOM heating: Beam Screen Temperature & Cryo Load



Effect of bunch length on HOM heating:
Beam Screen Temperature & Cryo Load

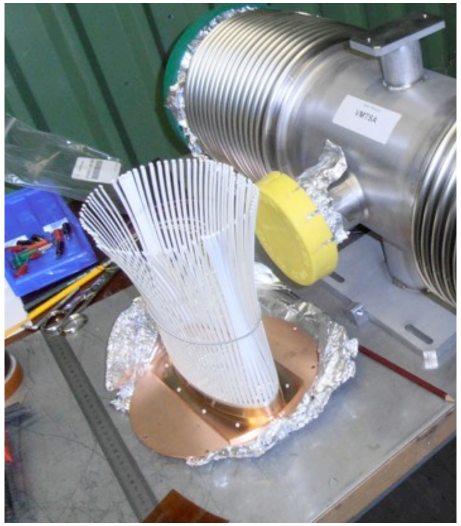
Valve control of CRYO to compensate for beam screen heating
during 25ns scrubbing we got up to 100% of possible He flow -> at the limit



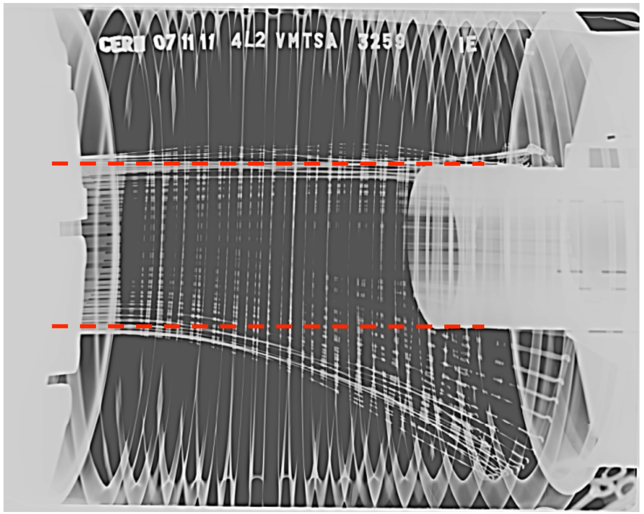
Reducing the Narrow Band Impedance

avoid cavity like objects ... or shield them by metallic stripes (Kicker example) or "RF-fingers"

example: injection kicker: ceramic chamber & metallic stripes
***any kind of** bellows connections*



strong heating observed in some bellows
investigation via x-ray-photograph



Sche Scha