Impedance effects during injection, energy ramp & store

LHC-CC10, 4th LHC Crab Cavity Workshop

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- longitudinal stability and impedance budget
- transverse impedance budget

Acknowledgments: E. Ciapala, W. Hofle, J. Tuckmantel

Beam and machine parameters

Energy	**TeV**	**0.45**	**7.0**
RF frequency	MHz	400.8 (200.4)	400.8
RF voltage	MV	8.0 (3.0)	16.0
synchrotron frequency f_s	Hz	66.08 (28.64)	23.86
revolution frequency f_0	kHz	11.245	11.245
betatron tune Q_β H/V		59.3/64.28	59.3/64.31
longitudinal emittance	eVs	0.6 (1.0)	1.0-2.5
rms bunch length	ns	0.4	0.275
nominal (ultimate) bunch current	mA	0.2 (0.3)	0.2 (0.3)
number of bunches (symmetric) M		2808 (3564)	2808 (3564)
nominal (ultimate) beam current (with symmetric bunches) I_0	A	0.7 (1.05)	0.7 (1.05)

RF systems in LHC

SPS

- Acceleration in the SPS is done by the 200 MHz RF system. The high harmonic 800 MHz RF system is used as Landau cavity for beam stability.
- For nominal bunch intensities controlled longitudinal emittance blow-up from 0.4 eVs to 0.65 eVs is required in addition. Larger emittance (0.8 eVs) will be needed for stability of ultimate intensities in SPS
- Maximum voltage (7.5 MV) to shorten bunch for transfer to LHC

LHC

- Acceleration in the LHC is done by the 400 MHz RF system. Maximum voltage 16 MV/beam (coast)
- Capture 200 MHz RF system (8 bare cavities exist, 3 MV/beam,) => postponed - not ideal solution: impedance, reliability, maintenance, cost, transfer to 400 MHz and reduced beam stability

Longitudinal stability in LHC
- general remarks

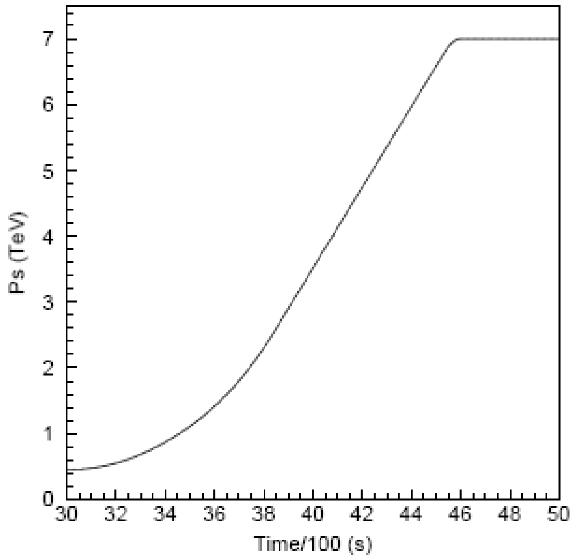
- We have feedback and feedforward systems and longitudinal damper at 400 MHz (~ 1 MHz bandwidth)
- No longitudinal bunch-by-bunch feedback - difficult to do better than natural damping

→ We rely only on Landau damping due to synchrotron frequency spread inside the bunch:

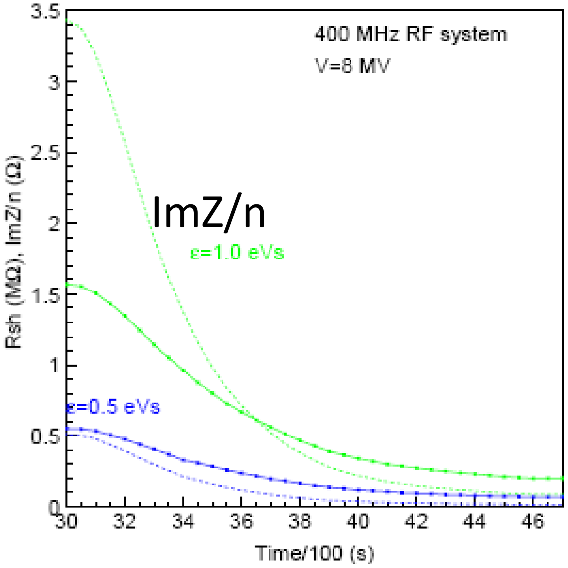
  - ImZ/n of broad-band impedance leads to the loss of Landau damping: measured in 2010
  - controlled longitudinal emittance blow-up during the ramp: in 2010 0.6 eVs @0.45 TeV → 1.75 eVs @3.5 TeV
  - proposal for Landau cavity at 800 MHz

Impedance limit during the cycle for nominal bunch and beam current and different emittances

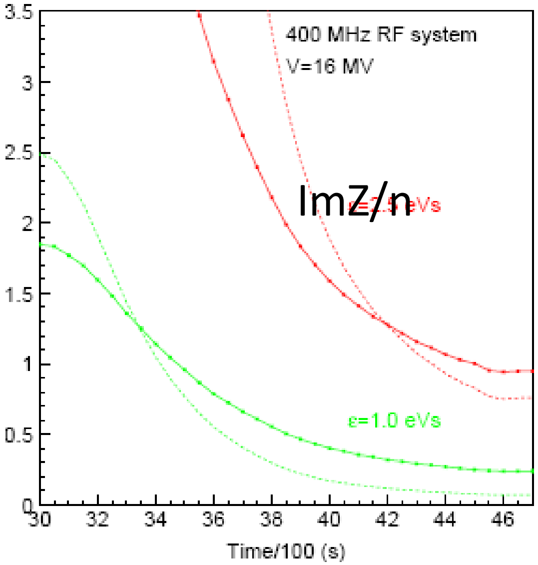
Momentum



V=8 MV@400 MHz



V=16 MV@400 MHz



→ Threshold narrow- and broad-band impedances decrease with beam energy: $R_{sh} \sim (\varepsilon^2/E)^{3/4}$, ImZ/n $\sim (\varepsilon^2/E)^{5/4}$ → controlled emittance blow-up: $\varepsilon \sim E^{1/2}$

Loss of Landau damping:
during the ramp (@1.8 TeV)

May 15 12:33:40 LHC – LHC, 00

LHC – 01

☐ Continuous Saving /user/slops/data/SPS_DATA/OP_DATA/LHC_BQM

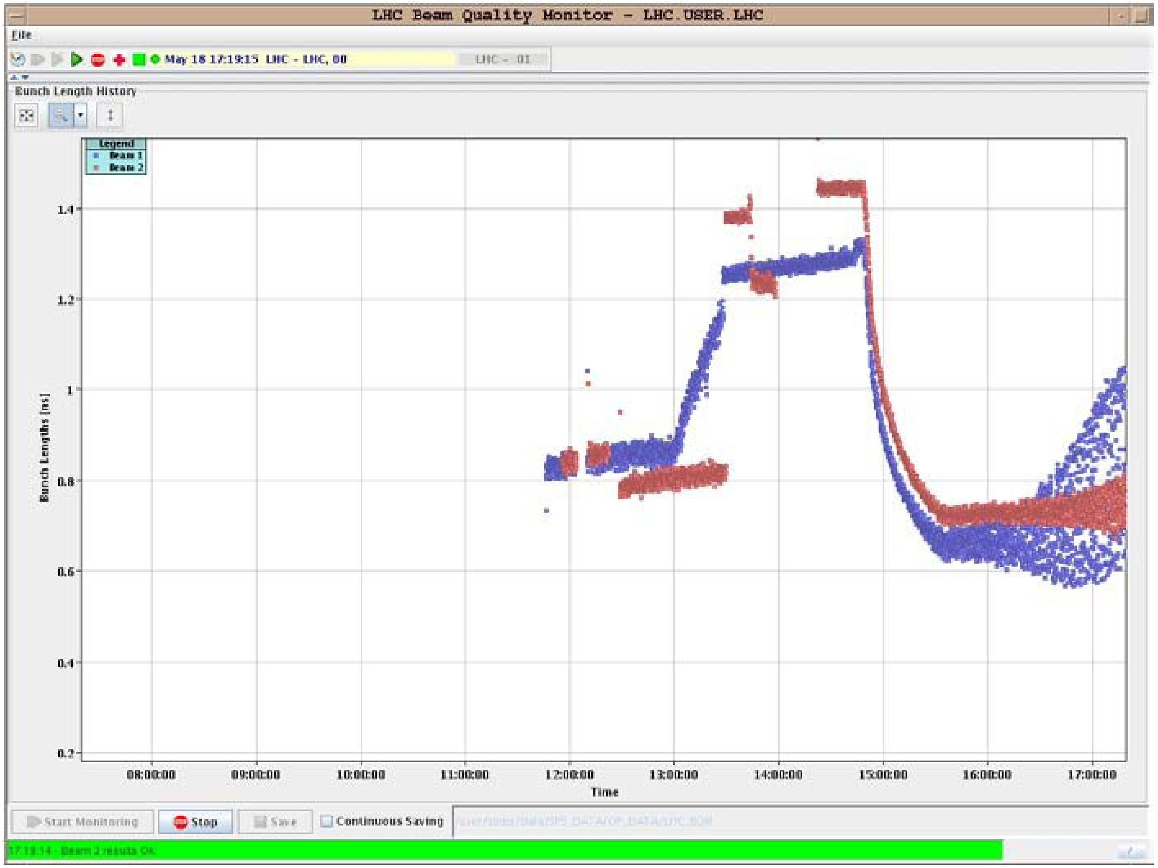
12:33:38 - Beam 2 results Ok.

Single bunch:

Beam1 - $1.1\text{x}10^{11}$
Beam2 - $1.05\text{x}10^{11}$

1.05 ns ⟶ 0.35 eVs
(0.45 TeV, 5 MV)

and on flat top



17:18:14 - Beam 2 results OK.

Beam 1 - 1.1x10^{11}

•450 GeV, 5 MV:

1.25 ns - 1.3 ns ⟶ 0.5 eVs

•3.5 TeV, 8MV:

0.65 ns ⟶ 0.5 eVs

Beam 2 - 1.05x10^{11}

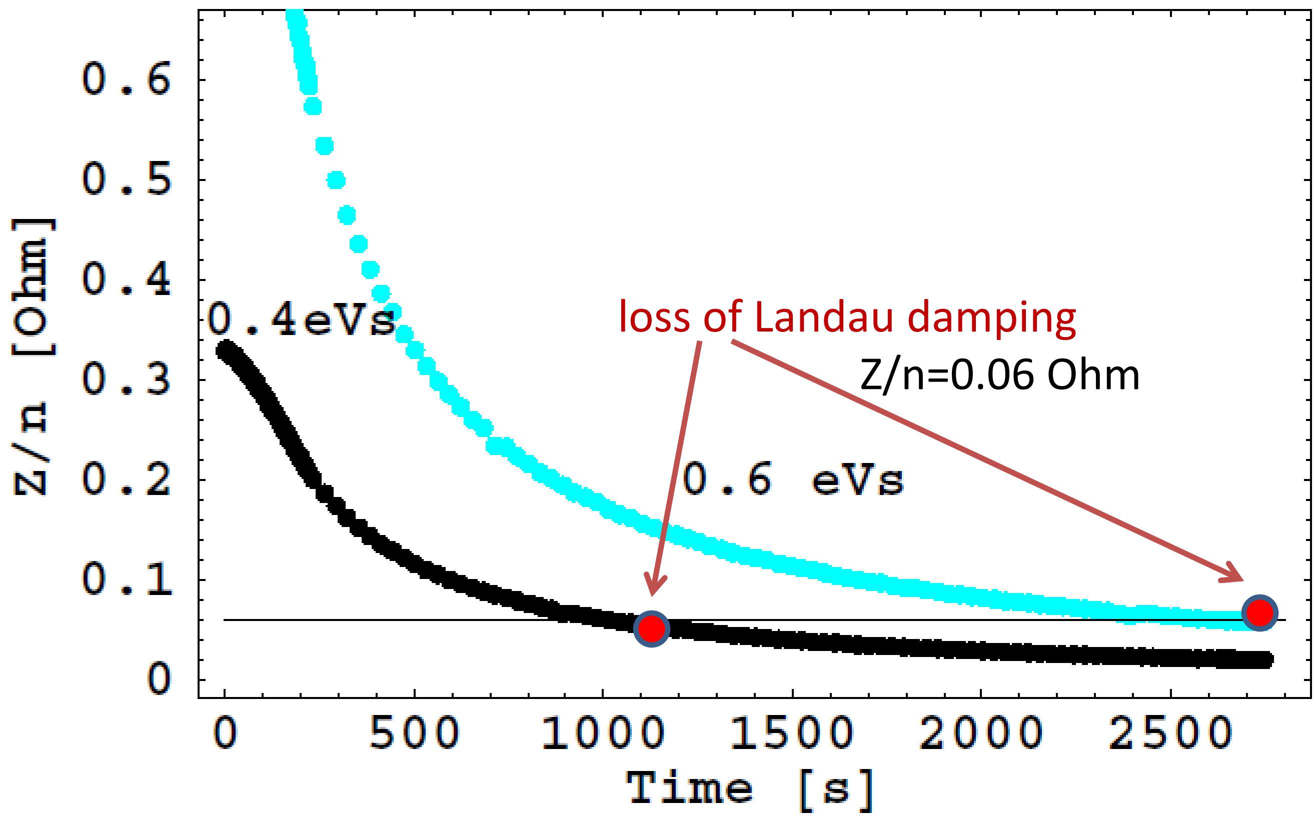
•450 GeV, 5 MV:

1.45 ns ⟶ 0.6 eVs

•3.5 TeV, 8 MV:

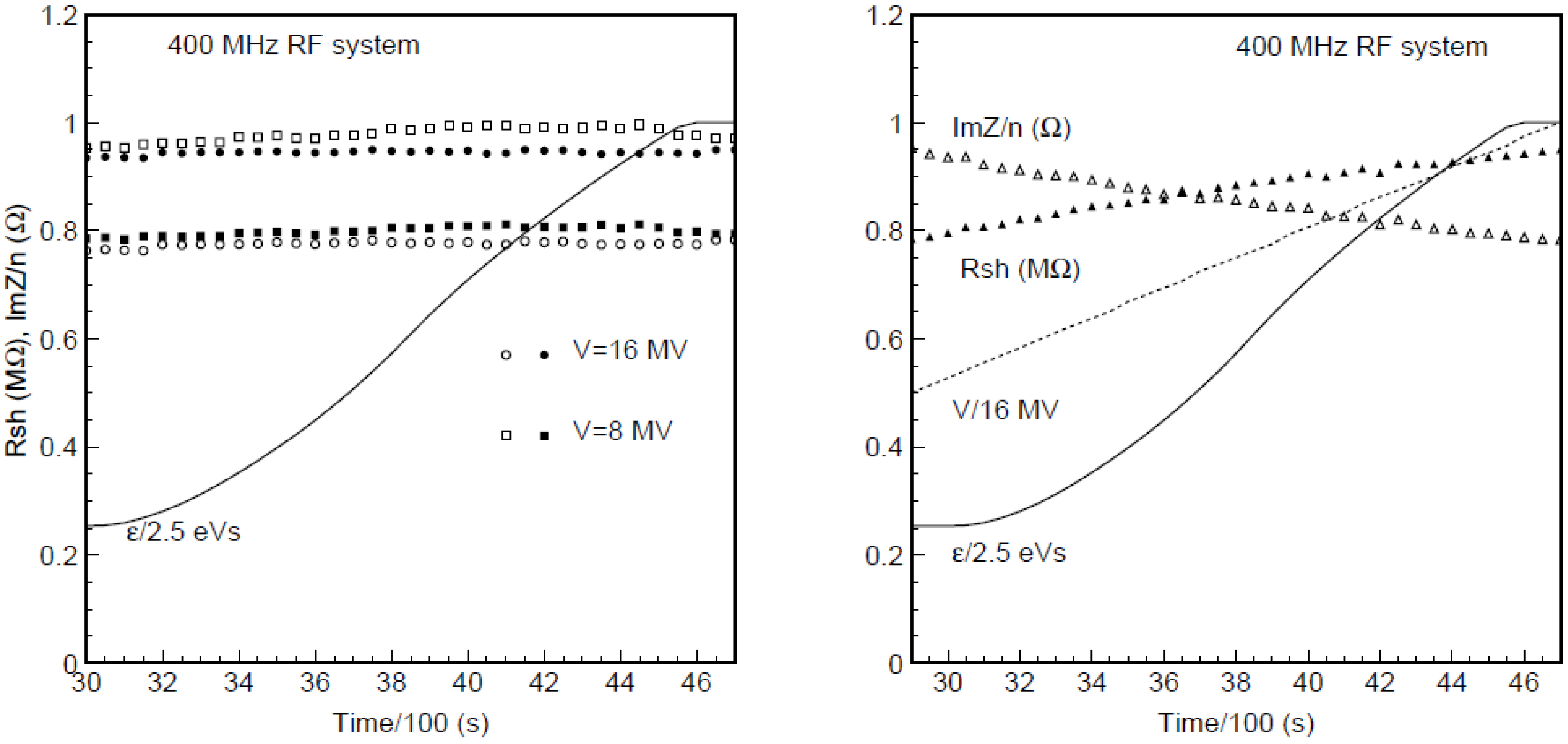
0.72 ns ⟶ 0.6 eVs

Loss of Landau damping:
threshold through the cycle

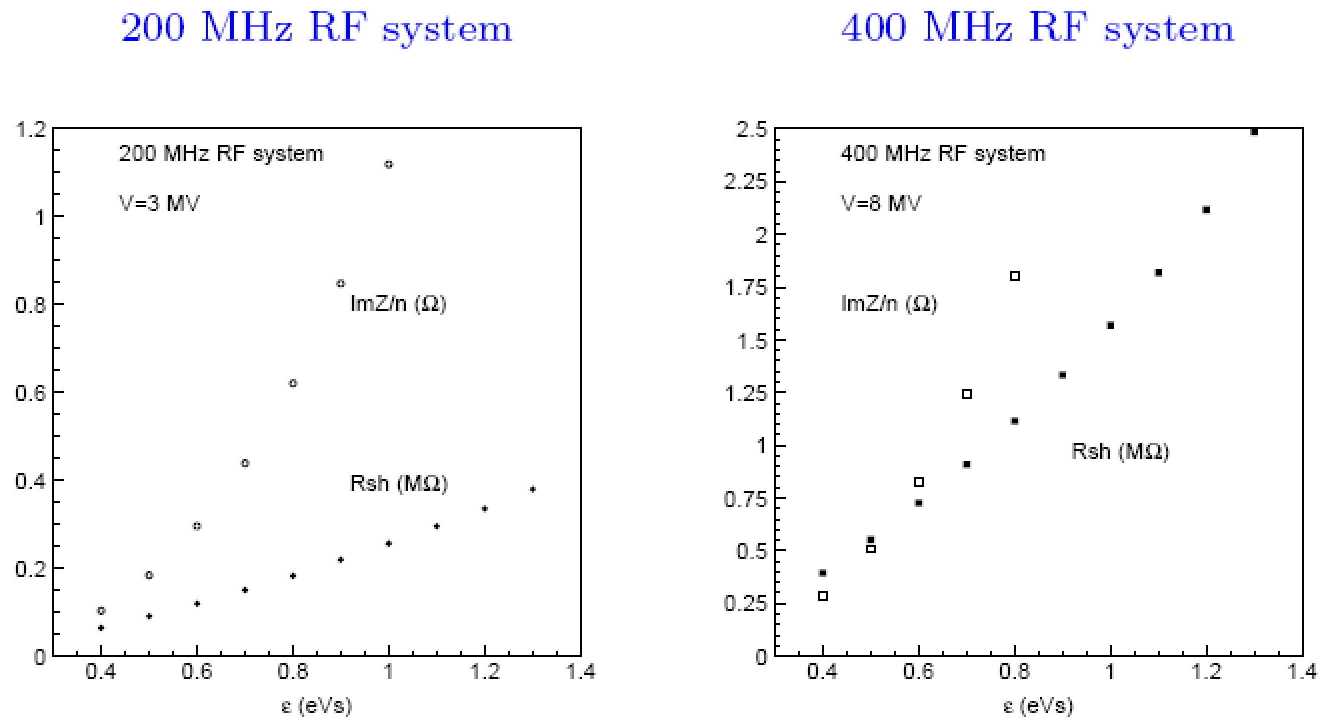


- mode m=2 → 0.09 Ohm. LHC DR impedance budget - 0.08 Ohm
- Minimum emittance for ultimate intensities is 1.5 eVs @ 7 TeV

Constant thresholds during the cycle for ε ~ √E

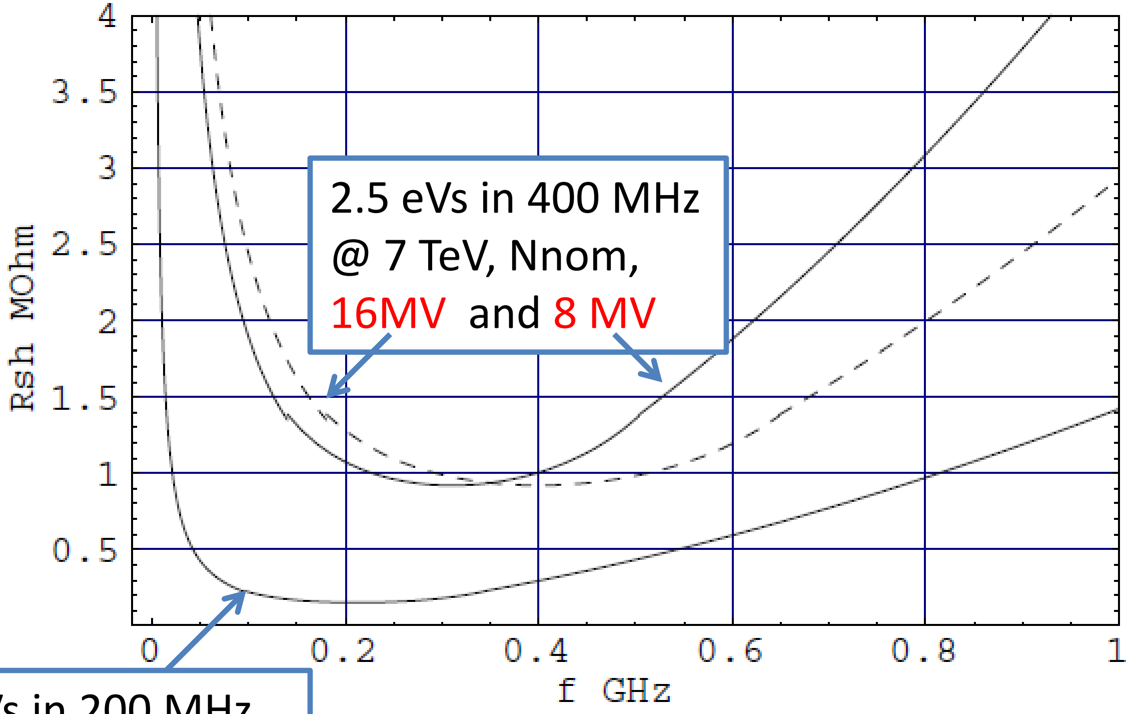


Stability on 450 GeV flat bottom



- 200 MHz: 120 kOhm limit for emittance of 0.7 eVs and nominal intensity or 1 eVs and ultimate intensity (symmetric filling) + factor ½ for different distribution (F). The 400 MHz RF can be used as Landau system
- 400 MHz: 600 kOhm limit for 0.7 eVs, nominal intensity (sym. filling)

Impedance budget: frequency dependence



2.5 eVs in 400 MHz
@ 7 TeV, Nnom,
16MV and 8 MV

0.7 eVs in 200 MHz
@ 450 GeV, Nnom

Beam stability in 400 MHz RF system

- Limit of 600 kOhm for 2.5 eVs at 7 TeV, nominal intensity (symmetric bunches)
- Factor 1/2 for different bunch distribution (formfactor F)
- Factor 2/3 for ultimate intensity

➢ 200 kOhm in frequency range (100-600) MHz,

relaxed ~ $(2\tau f_r)^{5/3}$ outside minimum at $f_r \approx 0.4/\tau$,

(τ is 4 σ bunch length)

Summary:
longitudinal impedance budget

- LHC Design Report: HOM damping below 60 kOhm
  (defined by stability in a single 200 MHz RF at 0.45 TeV)
- For nominal intensity
  - 400 MHz RF: 300 kOhm for 2.5 eVs @ 7 TeV
    (100 kOhm for 1.5 eVs – possible from single bunch stability – loss of Landau damping)
  - 200 MHz RF: 60 kOhm for 0.7 eVs @0.45 TeV
    (the 400 MHz RF can be used as Landau system)

→Limit: 40 kOhm for ultimate intensity
or 20 kOhm for two identical cavities (HOMs)

Transverse coupled-bunch instability (narrow-band impedances)

- Instability thresholds are determined by
  - betatron frequency spread:
    - system nonlinearities
    - octupoles
    - space charge
    - long range beam-beam
  - synchrotron frequency spread (m>0)
  - chromaticity

- In LHC there is a bunch-by-bunch transverse feedback system (20 MHz bandwidth) to damp injection oscillations and unstable rigid bunch motion

➢ Estimate which growth rate can be damped without significant transverse emittance blow-up with present transverse damper HW

Instability growth rate (1/2)

- A resonant transverse impedance with resistive part Z_T [Ohm/m] at resonant frequency $\omega_r=2\pi f_r$ will drive coupled-bunch mode (n, m) $f_r=(n+pM+Q_\beta)f_0+mf_s$ with the growth rate

$$\frac{1}{\tau_m}=\frac{1}{m+1}\frac{1}{4\pi Q_\beta}\frac{cI_0Z_T}{E/e}F(\omega_r\tau-\omega_\xi\tau)$$

f_0 and f_s are revolution and synchrotron frequency,

M is number of (symmetric) bunches,

Q_β is betatron tune, $\omega_\xi = Q_\beta\,\omega_0\xi/\eta$, ξ is chromaticity,

Formfactor F(x) for water-bag bunch: F(0)=1 (the worst mode m=0),

$F(x > 0.5) \approx 0.5$

Instability growth rate (2/2)

- Growth rate ~ 1/E → maximum at low energy
- At 450 GeV, for nominal intensity and $Z_T = 1$ MOhm/m ($\xi=0$): minimum $\tau_{inst} = 0.15$ [s]
- Condition $\tau_{inst} > \tau_d$ gives

  Z_T [MOhm/m] $< 0.15/(1-x/1.6)/\tau_d$, $x = (f_r - f_\xi)\tau < 0.8$

  Z_T [MOhm/m] $< 0.3\,(0.5+x)/\tau_d$, $x > 0.8$

  τ_d [s] is the damping time by transverse damper,

  τ is the bunch length, typically $1.0\text{ ns} < \tau < 1.5\text{ ns}$

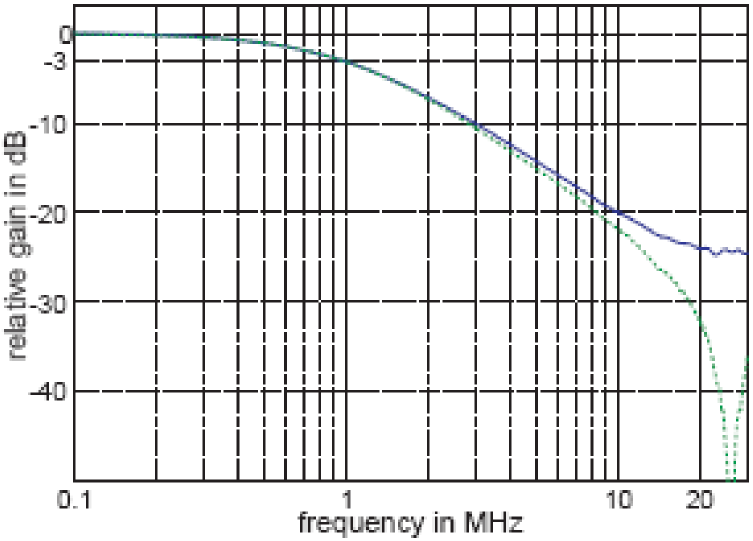
- For ultimate intensity factor 2/3

Damping time (1/2)

- Specifications of the transverse feedback (W. Hofle et al.): damping time τ_d =3.6 ms, but
  - simultaneous injection oscillation damping
  - resistive wall instability growth time ~17 ms at injection for ultimate intensity (E. Metral, 2008)
  - decoherence time 68 ms (for tune spread 1.3 x10^{-3} and chromaticity $\xi \neq 0$)
  - strict budget for transverse emittance blow-up (2.5%), 2.2% blow-up at ultimate intensity
  - gain roll-off for high frequencies
- Damping times achieved in LHC in 2010 in talk of W. Hofle

Damping time (2/2)

Power amplifier frequency characteristics



→ roll-off of gain for kicker and tetrode anode voltage (W. Hofle et al., EPAC'08)

- Frequency roll-off: -1 dB at 1 MHz and -24 dB at 20 MHz

  → $\tau_{d\ max} = 60$ ms

➢ Crab cavity impedance (for x=0)

  $Z_T < 2.5$ [MOhm/m]

  (The same threshold from betatron frequency spread)

- Formfactor F_m for different longitudinal particle distribution (not water-bag) – up to factor 1/4
- n_c identical cavities: factor $1/n_c$
- Weight function $\beta/\langle\beta\rangle$ if beta-function at Crab cavity location is different from average

Summary: transverse impedance budget

- For nominal intensity at 450 GeV threshold determined by the damping time of 60 ms is 2.5 MOhm/m. With margin for particle distribution - 0.6 MOhm/m
- Approximate frequency dependence
  - $0.6/(1-f_r/1.6)$ MOhm/m for f_r [GHz] < 0.8
  - $1.2\,(0.5+f_r)$ MOhm/m for f_r [GHz] > 0.8

→ 0.8 MOhm/m at 0.8 GHz for ultimate intensity and 0.4 MOhm/m for 2 identical cavities

- Additional factor proportional to local beta-function $\beta/\langle\beta\rangle$

Conclusion

Longitudinal impedance budget

- determined by preserving natural Landau damping
- most strict requirement from capture 200 MHz RF system (not installed)
- worst at high energy - controlled emittance blow-up to keep threshold constant during the cycle

Transverse impedance budget

- determined by bunch-by-bunch FB damping time
- worst at low energy

Spare slides

Longitudinal stability

Threshold for coupled-bunch instability (equally spaced bunches) due to resonant impedance with frequency $f_r = f_0 n_r = pMf_0 + nf_0 + mf_s$

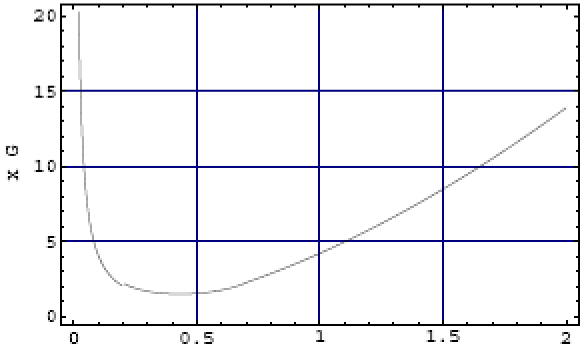
$$R_{sh} < \frac{|\eta| E}{e I_0} \left(\frac{\Delta p}{p}\right)^2 \frac{\Delta\omega_s}{\omega_s} \frac{F}{f_0 \tau} xG(x),$$

f_0 is the revolution frequency, $\eta = 1/\gamma^2 - 1/\gamma_t^2$, I_0 is the average beam current, $\frac{\Delta p}{p}$ is the relative momentum spread, $\frac{\Delta\omega_s}{\omega_s}$ is the relative synchrotron frequency spread, $F \sim 0.3$ is defined by the particle distribution.

(*V. Balbekov, S. Ivanov, 1984*)

Function

$$xG(x) = x \min\{J_m^{-2}(\pi x)\},$$
$$x = f_r \tau$$



$f_r \tau$

Warning: definition of transverse shunt impedance R_s

- Resonant impedance in [Ohm/m]

  $Z_T(\omega)=D(\omega)\, R_s/[1+jQ(w-w^{-1})]$,

  where $w=\omega/\omega_r$

  $\rightarrow Z_T(\omega_r)=D(\omega_r)\, R_s$

- A. Chao, K.Y. Ng

  $D(\omega)=c/\omega$, $D(\omega_r)=c/\omega_r$
- A. Zotter, S. A. Kheifets

  $D(\omega)=\omega_r/(j\omega)$, $D(\omega_r)=1/j$
- S. Y. Lee

  $D(\omega)=2c/(b^2\omega)$, $D(\omega_r)=2c/(b^2\omega_r)$,

  b – beam pipe radius
- G. Dome

  $D(\omega)=\omega_r^2/(c\omega)$, $D(\omega_r)=\omega_r/c$

- At the resonant frequency

  $Rs=|V_T|^2/(2\,P)$,

  where P is the power loss in the cavity walls and HOM damper for a given level of deflecting voltage V_T on the cavity axis (``circuit” definition, = ½ ``linac” Rs)

- Measured R_s [Ohm] $= Z_T\ c/\omega_r$

- Calculated - …