SPS impedance and intensity limitations

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CARE-HHH-2004, November 10, 2004

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Outline:

- Known SPS impedance
- Impedance measurements with the beam
  - longitudinal plane
  - transverse plane
- Intensity limitations for LHC beam and possible solutions

Acknowledgments: G. Arduini, P. Baudrenghien, H. Burkhardt, F. Caspers, E. Metral
SPS impedance

Was significantly reduced during shutdown 2000/2001:

- shielding 800 pumping ports (P. Collier, A. Spinks et al.)
- shielding MSE and MKE (B. Goddard, F. Caspers, A. Rizzo, J. Uythoven)
- removal lepton cavities (3 RF systems)
- removal non-used equipment

What do we have now:

- 2 TW RF systems
  - 2x4 sect. + 2x5 sect. cavities @200 MHz - main RF system
  - 2 cavities @800 MHz - Landau system
- 5 MKE and 3 MKP kickers with RF by-pass, 10 ZS
- Resistive-wall impedance of stainless steel chamber
- e-cloud
SPS impedance measurements with the beam

**Longitudinal plane**

- Bunch spectrum $\rightarrow$ resonant impedances, high $R/Q$ and low $Q$
- Bunch lengthening $\rightarrow$ $\text{Im}Z/n$ and high frequency $Z$
- Coherent frequency shift $\rightarrow$ $\text{Im}Z/n$
- Stable phase shift $\rightarrow$ $\text{Re}Z$
- Unstable mode spectrum of LHC beam $\rightarrow$ high $R$ and $Q$

**Transverse plane**

- Coherent tune shifts with intensity $\rightarrow$ $\text{Im}Z_T$
- Growth rate as a function of chromaticity $\rightarrow$ $\text{Re}Z_T$
- TMCI threshold $\rightarrow$ $Z_V$
- Betatron phase beating $\rightarrow$ impedance localisation
Longitudinal impedance with high R/Q and low Q (1/2)

Bunch spectrum measurements with RF off, low frequencies

1999

2001

2003

26 GeV/c. Bunch parameters: $N = 6.0 \times 10^{10}$, $\varepsilon = 0.22$ eVs, $\tau = 25$ ns

- No change in spectra from 1999 to 2000 (MSE and MST septa shielding) → source of 400 MHz was not found

- No change in spectra from 2001 to 2003 (installation of 5 MKE kickers with RF by-pass) → good damping of HOM (including 400 MHz)
Longitudinal impedance with high R/Q and low Q (2/2)

Bunch spectrum measurements with RF off, high frequencies

1996

\[ \tau = 25 \text{ ns} \]
\[ \varepsilon = 0.24 \text{ eVs} \]
\[ N = 1.5 \times 10^{10} \]

2001

\[ \tau = 25 \text{ ns} \]
\[ \varepsilon = 0.2 \text{ eVs} \]
\[ N = 2.6 \times 10^{10} \]

- Signals at 1.5, 1.9 and 2.4 GHz due to pumping ports are no longer there
- The cut-off frequency of pick-up is 2.8 GHz
Longitudinal impedance. Bunch lengthening

Bunch length (fwhm) at 600 ms after injection as a function of intensity

- Difference in slope $\sim$ factor 7
- Measurements in 1999 were done above $\mu w$ instability threshold
- Bunch parameters: $\varepsilon_{fwhm} = 0.15$ eVs, $V = 900$ kV. Scaling from 2001 measurement: single LHC bunch at 26 GeV should be stable up to ultimate intensity.
Longitudinal impedance, $\text{Im}Z/n (1/2)$

Quadrupole frequency as a function of intensity

- For these bunches:
  - the quadrupole oscillations are not damped for $N > 3 \times 10^{10}$,
  - some slow ($\sim 2$ s) instability was observed on the flat bottom for intensities above $4 \times 10^{10}$.

- Increase of $\text{Im}Z/n$ in 2003 can explain, by loss of Landau damping, recent observations for the LHC beam:
  - lowering the coupled bunch instability threshold by $\sim 30\%$.
  - increased synchrotron frequency spread (provided by voltage at 800 MHz) necessary to stabilise the beam.

2001: decrease in slope $\propto \text{Im}Z/n$ by 2.5
2003: increase in slope by $\sim 30\%$ (1.8 Ohm from 5 MKE to $\text{Im}Z/n = 5$ Ohm)
Longitudinal impedance: $\text{Im}Z$ (2/2)

Imaginary part of the SPS impedance up to 1 GHz

total

MKE kicker

MKE kicker: resonant impedance with $R_{sh} = 3 \text{ kOhm}$, $f_r = 0.5 \text{ GHz}$ and $Q = 1$ plus $\text{Im}Z/n = 0.3 \text{ Ohm}$ (fit to measurements of F. Caspers, A. Mostacci, H. Tsutsui, 2000)

• Strong dependence of effective impedance on bunch length $\tau$

• Reasonable agreement of calculations using effective impedances $\text{Im}Z^{m=1}_{eff}(\tau)$ and $\text{Im}Z^{m=2}_{eff}(\tau)$ with quadrupole frequency shift as a function of bunch length and intensity measured at 14 GeV/c
Longitudinal impedance measurements: ReZ (1/2)

Energy loss $U$ as a function of bunch length

$\bar{U} = eV \sin \phi_s / (N \times 10^{-10})$

- Measured from the synchronous phase shift with intensity. For a Gaussian bunch

\[ U_n = e^2 N \frac{\omega_0}{\pi} \sum_{p=0}^{\infty} \text{Re} Z_n(p\omega_0) e^{-(p\omega_0\sigma)^2} \]

- Contributions: 200 MHz RF system and MKE kickers, the HOM at 629 MHz, 800 MHz TW. Resistive wall impedance: $\bar{U} = 0.8$ keV for $\sigma = 0.6$ ns.

- For $\tau = 3$ ns and $N = 1.3 \times 10^{11}$ the energy loss from MKE kickers alone is 20 keV $\rightarrow 0.3$ ns gap between buckets and kicker heating with LHC beam.
Longitudinal impedance: ReZ (2/2)

200 MHz TW cavity 5/4 sections

\[ f_r = 200 \text{ MHz}, \quad Q = 130 \]

\[ R_{sh} = 6 \text{ kOhm}, \quad f_r = 0.6 \text{ GHz}, \quad Q = 0.95 \]

G. Dome, 1977

F. Caspers, A. Mostacci, H. Tsutsui, 2000
Transverse impedance (1/2)

Coherent tune shift measurements

- 2000-2001: Slope ratio: 0.023/0.038 = 0.6 → 40% reduction
- 2002-2003: Slope ratio: 0.026/0.017 = 1.53 → 50% increase
due to 5 MKE (ImZv = 15 MOhm/m to 24 MOhm/m)
- Horizontal plane - small positive shift due to resistive wake
- Growth rates measurements suggest ReZh = 7 MOhm/m and ReZv = 10 MOhm/m with Q=1 and fr = 1.3 GHz (H. Burkhardt, 2004)

H. Burkhardt, G. Rumolo, F. Zimmermann, 2001
Transverse impedance (2/2)

Fast head-tail instability

\[ \xi_y \approx 0 \]

\[ \xi_y = 0.8 \]

\( N = 1.2 \times 10^{11}, \ \varepsilon = 0.2 \text{ eVs}, \ \tau = 2.5 \text{ ns} \)

- For \( \sigma = 0.5 \text{ ns} \) and \( \varepsilon = 0.2 \text{ eVs} \) the threshold \( N_{th} \approx 4 \times 10^{10} \) (G. Arduini, H. Burkhardt, E. Metral)

- For LHC bunch code MOSES gives \( N_{th} \approx 1.25 \times 10^{11} \) (E. Metral et al., 2004) using broad-band impedance model with \( f_r = 1.6 \text{ MHz}, \ Q=0.8 \) and \( R=11 \text{ MOhm/m} \). Chromaticity and space charge help. (simulations with Head Tail code)
LHC beam in the SPS

RF system upgrade for the LHC beam

- Upgrade of feedback system (one per cavity)
- New RF feedforward system
- New longitudinal damper (0 - 3 MHz)
- New 1 MW couplers
- Transverse damper: bandwidth and gain

Intensity limitations

- e-cloud
- Injection
  - capture loss
- Acceleration
  - coupled bunch instabilities
- Flat top
  - requirements for injection to LHC
Intensity limitations for LHC beam. Transverse plane

- **Resistive wall instability** is cured by Transverse Feedback. Upgraded to 20 MHz bandwidth (W. Hofle)

Electron cloud

(G. Arduini et al., EPAC’04)

- Leads to transverse **emittance blow-up and instabilities**
  - coupled bunch in H-plane (a few MHz)
  - single bunch in V-plane affecting tail of the batch (∼700 MHz)

- **Scrubbing run** increases the threshold from $0.3 \times 10^{11}$ to $1 \times 10^{11}$

- Transverse feedback helps to damp coupled-bunch modes in H-plane with growth rates ∼40 turns

- **High chromaticity** (up to 1.5) is used as a cure for V-plane
Intensity limitations for LHC beam. Injection (1/2)

Capture loss

- Motion to the left $\rightarrow$ negative energy deviation $\rightarrow$ energy loss $\rightarrow$ accelerating bucket $\rightarrow$ reduced bucket length.

- Long bunches from PS: $(4.2 \pm 0.5) \text{ ns}$ injected into 5 ns bucket.

- Increase of capture voltage $V$ (matched voltage: 750 kV, used: 2 MV) helps, $\sin \phi_s = U/(eV)$. Even better for 2 MV increased to 3 MV after 100 ms. Works only for 1 batch (full bucket?) Recapture of lost particles? $\rightarrow$ satellite bunches
Intensity limitations for LHC beam. Injection (2/2)

- Strong dependence on batch intensity, much less on total (number of batches) or bunch intensity
- Reduction of relative loss for 75 ns bunch spacing (5% loss for 16 bunches with $1.2 \times 10^{11}/b$)
- Flux of particles from bucket on the flat bottom, after injection
- In 2004 reduction of losses along the flat bottom with new working point: $(26.19, 26.13) \rightarrow (26.13, 26.19)$ (G. Arduini)
Intensity limitations for LHC beam. Acceleration (1/3)

Beam parameters

Coupled bunch instabilities

- Localised instability during the cycle
- Single batch with $2 \times 10^{10}$/bunch is unstable at $\sim 280$ GeV (16 s)
- The 800 MHz RF system is used in bunch-shortening mode during the whole cycle to increase synchrotron frequency spread
- Preventive emittance blow-up by
  - mismatched voltage at injection (2 MV instead of 700 kV) gives 0.4 eVs
  - beam excitation on the ramp (at 15 s) with band-limited noise around $2f_s$ on 200 MHz voltage amplitude
Intensity limitations for LHC beam. Acceleration (2/3)

Effect of the 800 MHz RF system

Voltage programmes

200 MHz RF system
\( q_p = 0.95, \varepsilon = 0.5 \text{ eVs} \)

Bunch length

\( \varepsilon = 0.45 \text{ eVs} \)

Threshold impedance

\( \varepsilon = 0.45 \text{ eVs} \)

Total voltage: \( V = V_{200} \sin \phi + V_{800} \sin (4\phi + \Delta \phi). \)

The 800 MHz RF system in BS mode, phase \( \Delta \phi = \pi - 4\phi_s \),

amplitude: in 2002 - \( V_{800} \simeq V_{200}/10 \), in 2003: \( V_{800} = 600 \text{ kV} \)
Intensity limitations for LHC beam. Acceleration (3/3)

Mode spectrum of bunch position at the end of the cycle

- Each frame at 0.1 s interval starting at 17 s
- Bunch position → dipole mode
- 72 bunches, (1-36) bunch modes
- Unstable mode $n = 18 \rightarrow \sim 10$ MHz
- The 200 MHz RF system: HOM at 629 MHz
Intensity limitations for LHC beam. Flat top

Beam parameters on the flat top

Bunch length

- 4 batches of 72 bunches with $4\sigma$ average bunch length of $1.6 \pm 0.2$ ns are obtained at 450 GeV for intensity of $1.15 \times 10^{11}$/bunch with voltage $V_{200} = 7$ MV and $V_{800} = 0.7$ kV $\rightarrow \varepsilon_{2\sigma} = 0.6$ eVs.

- For stable beam the bunch to bunch phase on the flat top is inside 130 ps.

- The $2\sigma$ emittance contains $\sim 85\%$ of particles for a Gaussian bunch limited at separatrix. $\rightarrow$ The 200 MHz capture system in the LHC for ultimate intensities?
Summary (1/2)

Main intensity limitations in the SPS for LHC beam

- Intensity dependent capture loss (∼8%), the exact reason is not clear
- Coupled bunch instabilities are cured, but
  - the 800 MHz in BSM increases the peak line density
  - emittance blow-up leads to extra losses at injection to LHC with 400 MHz bucket
- Beam loading in 200 MHz and 800 MHz (efficiency as a Landau cavity)
- e-cloud and possibly fast transverse instability for more MKE kickers or higher bunch intensities. Cure by chromaticity in conjunction with high voltage increases losses.
Summary (2/2)

Possible improvements:

- **Further SPS impedance reduction** (MKE shielding, improved passive damping of HOM at 629 MHz, search for transverse impedances...)

- **Shorter bunches from PS** with the same or larger emittance (extra RF voltage in the PS)

- **Increased voltage of 800 MHz RF system** (1 more cavity in operation in 2005)

- **Emittance blow-up** increases the threshold of coupled bunch instability on the flat top $\propto \varepsilon^2$ (0.75 eVs for ultimate intensity)

- **The 200 MHz RF system in the LHC** for capture

- Capture loss studies (RF noise, e-cloud, machine resonances...)
In September 2004 during extensive MDs fixed target (CNGS) beam with total intensity of $5.3 \times 10^{13}$ was accelerated in the SPS from 14 GeV/c to 400 GeV/c with $\sim 10\%$ beam loss.

This is 15% above CERN intensity record of 1997 and almost twice more than presently used for physics.

This is also slightly above ultimate total intensity of LHC beam in the SPS (“only” $4.9 \times 10^{13}$ but in 1/3 of the ring)

Team:

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plus a lot of help from Operation Group