20 + 10 min talk (28 slides)

SPS IMPEDANCE

Elias Métral

OUTLINE

◆ Introduction
  ▪ Longitudinal microwave instability observed before 2001
  ▪ MKE kickers installed for extraction towards LHC (2003&6)
  ▪ Fast vertical single-bunch instability at injection in 2003 (02)
  ▪ Beam-induced heating from MKE kicker

◆ Resistive-wall impedance of the MKE kickers

◆ Measurements vs. theory
  ▪ $\text{Im}[Z_{y,\text{eff}}]$ from coherent tune shift vs. intensity
  ▪ Fast vertical single-bunch instability intensity threshold at injection
  ▪ $\text{Re}[Z_{y,\text{eff}}]$ from head-tail growth/decay rate
  ▪ $\text{Im}[Z_{l'/n_{\text{eff}}}]$ from quadrupole oscillation frequency shift vs. intensity
  ▪ Power loss

◆ HEADTAIL simulations in the longitudinal plane

◆ Conclusion

◆ Appendices: Potential-well bunch lengthening, microwave instability with RF OFF, localization of impedances, BPMs, vacuum ports, RF cavities…
Figure 17.13: The bunch length measured 600 ms after injection as a function of bunch intensity in 1999 and 2001. Data taken at 26 GeV, $\varepsilon=0.15$ eVs, $V=900$ kV.
MKE KICKERS INSTALLED FOR EXTRACTION TOWARDS LHC

- **2001**
  - Lepton cavities removed + impedance reduction (pumping ports) done
  - **No MKE kickers (11 kickers in total)**
  - Impedance reduction by ~ 2.5 in the longitudinal plane (from meas.)
  - Impedance reduction by ~ 40% in the transverse one (from meas.)

- **2003**
  - + 5 MKE kickers in LSS4 (16 kickers in total)

- **2006**
  - + 4 MKE kickers in LSS6 (20 kickers in total) – 1 MKE kicker shielded on 2 cells

- **2007**
  - - 1 MKE kicker and 1 MKE has been shielded (19 kickers in total)
Synchrotron period ≈ 7 ms

$p = 26 \text{ GeV/c}$, $N_b \approx 1.2 \times 10^{11} \text{ p/b}$

$\varepsilon_l \approx 0.2 \text{ eVs} < \varepsilon^\text{LHC}_l = 0.35 \text{ eVs}$

$T_{rev}^{\text{SPS}} \approx 23 \mu\text{s}$
FAST VERTICAL SINGLE-BUNCH INSTABILITY AT INJECTION IN 2003 (2/3)

⇒ Travelling-wave pattern along the bunch

$\xi_y = 0.14$

$N_b^{th} \approx 0.610^{11}$ p/b

$\frac{p/b}{10} \approx \frac{th}{bN}$

$<y>$ [a.u.]

Head

Tail

$F_0$

$1^{st}$ trace (in red) = turn 2

Last trace = turn 150

Every turn shown

Elias Métral, CARE-HHH-APD BEAM'07, CERN, 05/10/07
See B. Salvant’s talk (BB impedance)

Next steps:
- Measure mode coupling
- Improve impedance model
If a part of the ferrite itself reaches temperatures above the Curie temperature, around 125°C, it loses its magnetic properties and the magnetic field strength will be reduced.

Figure 17.18: Measured MKE temperatures on the ceramic spacers during the 2004 scrubbing run.
⇒ From the impedance point of view, a SPS kicker can be approximated by the following sketch.
1 MKE kicker $\Rightarrow$ Comparison between 2 theories, 3D simul. and meas.

Simulated (3D) by Burkhardt Doliwa (TU Darmstadt)

Meas. by F. Caspers, T. Kroyer & E. Gaxiola

$x$ should be $y$

This meas. was even corrected later closer to Zotter’s result (see next slide)
VERTICAL RESISTIVE-WALL IMPEDANCE (3/4)

Meas. by F. Caspers, T. Kroyer & E. Gaxiola

1 MKE kicker

\[ Z_y \, [\text{M} \Omega \, / \, \text{m}] \]

-0.2
-0.2
0.2
0.4
0.6
0.8

Im
Re

\[ f \, [\text{GHz}] \]

Colors:
- Green: Zotter
- Black dashed: Burov-Lebedev
- Red: 2-wire
- Blue: 2-wire / shielded
- Orange: Res. loop (Re) / shielded
1 LHC collimator $\Rightarrow$ Comparison between 2 theories (meas. ongoing…)

$Z_y$ [Ω / m]

$1 \times 10^{10}$

$1 \times 10^{8}$

$1 \times 10^{6}$

$10000$

$100$

$100$ $10000$ $1. \times 10^6$ $1. \times 10^8$ $1. \times 10^{10}$ $f$ [Hz]

F. Caspers, B. Salvant, F. Roncarolo…

Re. part from Zotter

Im. part from Zotter

Results from Rainer Hasse
LONGITUDINAL RESISTIVE-WALL IMPEDANCE (1/2)

1 MKE kicker $\implies$ Comparison between Tsutsui’s theory and meas.

F. Caspers et al., CERN-SL-2000-071 (AP)

Measurements on SPS MKE Kicker on 10/2000

Tsutsui

2006 measurements

Measurements on SPS MKE Kicker on 10/2000

Tsutsui
Significant reduction of the longitudinal impedance (and associated power loss)
SPS VERTICAL IMPEDANCE Im[Z_{y, eff}] (1/2)

Vertical coherent tune shift with intensity at 26 GeV, scaled to 0.5 ns

Year, \( \text{Im } Z_{\perp} \) with fit uncertainty

- **2000**: 32.2 +/- 0.5 MΩ/m
- **2001**: 19.1 +/- 0.2 MΩ/m
- **2003**: 22.2 +/- 0.4 MΩ/m
- **2006**: 23.6 +/- 0.3 MΩ/m
- **2007**: 22.0 +/- 0.2 MΩ/m

Slight reduction predicted

+ 4.5 MΩ / m

+ 5.2 MΩ / m were expected

Same analysis and very similar beam parameters (~0.5 - 0.6 ns rms bunch length). The measured slopes can directly be compared. Estimated uncertainty ~ 10 - 20%.

Elias Métral, CARE-HHH-APD BEAM'07, CERN, 05/10/07
Summary and comparison between measurements and theoretical predictions (kickers contribution only)

<table>
<thead>
<tr>
<th>Year</th>
<th>Meas (MΩ/m)</th>
<th>Delta (MΩ/m)</th>
<th>Theory (kickers) (MΩ/m)</th>
<th>Delta (MΩ/m)</th>
<th>Error Delta (%)</th>
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<td>3.5</td>
<td></td>
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<td>3.1</td>
<td>6.4</td>
<td>2.9</td>
<td>7</td>
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<td>1.4</td>
<td>8.7</td>
<td>2.3</td>
<td>-39</td>
</tr>
<tr>
<td>2007</td>
<td>22</td>
<td>-1.6</td>
<td></td>
<td></td>
<td></td>
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</table>

Cannot be done for the shielded kicker as we do not know the quadrupolar term!!!

- \( \text{Im}[Z_{y,\text{eff}}] \) of the shielded kicker (using only the dipolar term available) = 0.24 MΩ/m
- \( \text{Im}[Z_{y,\text{eff}}] \) of the same kicker before the shielding (using only the dipolar term) = 0.27 MΩ/m
- \( \text{Im}[Z_{y,\text{eff}}] \) from the vertical space charge impedance (which contributes to the coherent tune shift!) \( \approx +2.6 \text{ MΩ/m} \) ⇒ It is +0.04 MΩ/m in the horizontal plane
FAST VERTICAL INSTABILITY AT INJECTION (1/4)

- Wake-field obtained through ZBASE3 for the 2006 case
- Comparison with the BB resonator model used by B. Salvant for his mode coupling analysis

![Graph showing vertical instability at injection](image)

- $f_r = 1 \text{ GHz}$
- $Q = 1$
- $Z_y = 10 \text{ M}\Omega / \text{ m}$
FAST VERTICAL INSTABILITY AT INJECTION (2/4)

- HEADTAIL simulations with the wake-field from ZBASE3 (table) for the 2006 case

![Graph showing fast vertical instability with time and particle distribution](image-url)

- $\epsilon_t \approx 0.2 \text{ eV.s}$
- $N_b^{th} \approx 1.1 \times 10^{11} \text{ p/b}$
Fit of the wake field for the 2006 case

\[ f_r = 2.3 \text{ GHz} \]
\[ Q = 0.6 \]
\[ Z_y = 3.5 \text{ M}\Omega / \text{m} \]
MOSES computations with the fitted resonator

\[ f_r = 2.3 \text{ GHz} \]
\[ Q = 0.6 \]
\[ Z_y = 3.5 \text{ MΩ} / \text{m} \]

\[ I_b^{th} \approx 0.8 \text{ mA} \]

\[ I_b^{th} = 0.8 \text{ mA} \]
\[ \Leftrightarrow N_b^{th} = 1.15 \times 10^{11} \text{ p} \]

⇒ Consistent with HEADTAIL
Re[$Z_{y,eff}$] FROM HEAD-TAIL GROWTH/DECAY RATES MEAS.

From theory using the fitted resonator for the 2006 case

Courtesy of H. Burkhardt
E. Chapochnikova (APC, 11/05/07 & 03/08/07)

$\text{Im}[Z/n_{\text{eff}}] = -a \cdot b \cdot 2.5/(2 \cdot f_{\text{so}})$

$+ 4 \Omega = (2.2 + 1.8)$ were expected and $+ 3 \Omega = (1.8 + 1.2)$ were measured.

Slight reduction predicted.
Summary and comparison between measurements and theoretical predictions (kickers contribution only)

<table>
<thead>
<tr>
<th>Year</th>
<th>Meas</th>
<th>delta</th>
<th>Theory (kickers)</th>
<th>delta</th>
<th>Error delta [%]</th>
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- $\text{Im}[Z_l/n_{\text{eff}}]$ of the shielded kicker = 0.1 $\Omega$
- $\text{Im}[Z_l/n_{\text{eff}}]$ of the same kicker before the shielding = 0.4 $\Omega$
- $\text{Im}[Z_l/n_{\text{eff}}]$ from the space charge impedance (computed here) $\approx -1j\Omega^*$

* The contribution from space charge was already subtracted in the above given numbers
$N_b = 1.2 \times 10^{11}$ p

$M = 4 \times 72$ bunches

$\sigma_b = 0.7$ ns

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<td>4715</td>
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<tr>
<td>2007</td>
<td>10792</td>
<td>-1950</td>
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</table>

- Power loss for the shielded kicker = 407 W
- Power loss for the same kicker before the shielding = 1227 W

$\Rightarrow$ It seems that indeed a reduction by a factor of $\sim$3-4 was observed (L. Ducimetiere, private communication)
Regime of potential-well bunch lengthening

Next steps:
- Improve impedance model
- Measure mode coupling?
HEADTAIL SIMULATION IN THE LONGITUDINAL PLANE (2/3)

\[
\text{Im}\left[ \frac{Z_l}{n} \right]_{\text{protons}} \approx \frac{-4 \cos \phi_s \pi^2 \hat{V}_{RF} h(f_0 \tau_{b0})^2}{3 e} \frac{d \tau_b}{d N_b}
\]

\[
N_b^{th} \approx 1.35 \times 10^{11} \text{ p/b}
\]

\[
\text{Im}[Z_l/n]_{\text{deduced}} \approx 8.4 \Omega
\]

(10 \Omega were put in HEADTAIL)
HEADTAIL SIMULATION IN THE LONGITUDINAL PLANE (3/3)

$$\frac{Z_{l}^{BB}/p}{1.2} \times \left[ 1 - Sgn(\eta) \times \frac{3}{4} \left( \frac{Z_{l}^{SC}/p}{Z_{l}^{BB}/p} - 1 \right) \right]^{1/4} \leq \frac{(E/e)\beta^{2}}{I_{p0}} \times \left( \frac{\Delta p}{p_{0}} \right)^{2}_{FWHH,0}$$

Exactly the same as KSB in our case

$$\Rightarrow \left( N_{b}^{th} \right)_{theory} \approx 0.7 \times 10^{11} \text{ p/b}$$

FROM “THEORY”

- Regime of potential-well bunch lengthening

- Regime of μ-wave instability

$$\sigma_{z} = \sigma_{z}^{th} \times \left( \frac{N_{b}}{N_{b}^{th}} \right)^{1/3}$$

Assuming the HEADTAIL’s threshold
CONCLUSION

- Transverse analytical estimates and measurements of the low frequency inductive effective impedance are in good agreement over the last years (relative values)
- Transverse analytical estimates and measurements of the head-tail growth/decay rates are also in good agreement over the last years (relative values)
- All the kickers can only explain ~ 50% of the longitudinal and transverse impedances ⇒ Continue the investigation (in addition to the kickers, we looked at the 108 BPMH, 108 BPMV, ~ 1000 pumping ports, the 4 TW 200 MHz cavities, TIDVG: See Appendices)
- 1 major issue in our understanding: Why the longitudinal effective impedance measured in 2007 is ~ 40% higher than in 2006, whereas a reduction was foreseen???
HEADTAIL SIMULATION IN THE LONGITUDINAL PLANE

![Graph 1: Relative Momentum Spread $\sigma_p/p$ vs Bunch Population]

![Graph 2: Longitudinal Emittance vs Bunch Population]

Elias Métral, CARE-HH-PF BEAM'07, CERN, 05/10/07
LONGITUDINAL POTENTIAL-WELL BUNCH LENGTHENING AND MICROWAVE INSTABILITY (1/2)

Using the same formula as before, \( \text{Im}\left[\frac{Z_i}{\rho}\right]_{\text{deduced}} \approx 13.4 \, \Omega \) for 2001 (4.4 \, \Omega \) were measured with \( f_{s_2} \) shift with -1 \, \Omega \) from space charge already subtracted…)

Figure 17.13: The bunch length measured 600 ms after injection as a function of bunch intensity in 1999 and 2001. Data taken at 26 GeV, \( \varepsilon = 0.15 \) eVs, V=900 kV.
Using the same formula as before, \( \text{Im}[Z_i/p]_{\text{deduced}} \approx 23.1 \ \Omega \) for 2006 (7.4 \ \Omega \) were measured with \( f_{s2} \) shift with -1 \ \Omega \) from space charge already subtracted…

Using the same formula as before, \( \text{Im}[Z_i/p]_{\text{deduced}} \approx 40.4 \ \Omega \) for 2007 (10.2 \ \Omega \) were measured with \( f_{s2} \) shift with -1 \ \Omega \) from space charge already subtracted…

E. Shapochnikova (APC, 03/08/07)
MICROWAVE INSTABILITY WITH DEBUNCHED BEAM

- Unstable bunch spectra up to 2 GHz with RF OFF ("similar" beam parameters)

2001

2007

Elias Métral, CARE-HHH-APD BEAM'07, CERN, 05/10/07
Impedance inferred from iterative SVD fit

14-GeV/c data much cleaner than 26-GeV/c data (unfortunately not available in 2004)

Impedance concentrated in a few locations – MKP & MKE kickers, ~ RF, and one other

G. Arduini, C. Carli, F. Zimmermann, EPAC 2004 ⇒ Follow-up this year by R. Calaga
BEAM POSITION MONITORS

- 108 BPMH and 108 BPMV
  - Broad-band impedance (for ALL BPMs)
  - Trapped modes (for ALL BPMs) → 4 most critical

MAFIA simulations by B. Spataro

| Im[Z/n] (Ω) | 0.02 |
| Im[Z_y] (MΩ/m) | 0.07 |

<table>
<thead>
<tr>
<th>β_x [m]</th>
<th>β_y [m]</th>
<th>f_r [GHz]</th>
<th>R_y [MΩ/m]</th>
<th>Q</th>
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→ HEADTAIL simulations revealed an instability threshold ~ 1 order of magnitude higher than measured
VACUUM PUMPING PORTS (1/2)

⇒ For all the transitions

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<th>( \text{Im}[Z/n] \ (\Omega) )</th>
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<td>( \text{Im}[Z_y] \ (M\Omega/m) )</td>
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MAFIA simulations by B. Spataro
## VACUUM PUMPING PORTS (2/2)

- **Tank gap and intermodule screening ➞ To be treated...**

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<tr>
<th>Magnet</th>
<th>Location</th>
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<th>V aperture</th>
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<td>32</td>
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</table>
RF CAVITIES

- For the 4 TW 200 MHz cavities (preliminary results)

\[ \text{Mafia simulations by B. Spataro} \]

\[ \text{\( \Im[Z_l/n_{\text{eff}}] = 2.7 \ \Omega \)} \]
TIDVG $\implies$ High energy beam dump absorber

- With or without the Titanium foil the $\text{Im}[Z_l/n_{\text{eff.}}] \ll 1 \Omega$ (preliminary results)