Tune Resonance Phenomena in the SPS and related Machine Protection

Tobias Bär
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Content

1. SPS and the 2008 incident
2. Tune Resonance Phenomena in the SPS
3. Dynamics of Beam Losses
3. Machine Protection
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Super Proton Synchrotron

- Commissioned in 1976
- Circumference: 6.9 km
- Top Energy: 450 GeV
- Intensity: up to $5 \cdot 10^{13}$ protons
- Stored Beam Energy: up to 2.5 MJ
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SPS Incident June 27th 2008

- Beam impact of high intensity CNGS beam

(≈ $3 \cdot 10^{13}$ protons @ 400 GeV = 2 MJ)
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- Beam impact of high intensity CNGS beam
  \((\approx 3 \cdot 10^{13} \text{ protons } @ \text{ 400 GeV } = \text{ 2 MJ})\)
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3. Dynamics of Beam Losses

3. Machine Protection
Turn-by-Turn Position

- Linear Decrease of Horizontal Tune

Complete beam loss in 3 turns (69 µs)

\[ Q_H = 26 \text{ resonance} \]

LHCFAST2, 450GeV, \(1 \cdot 10^{10} \text{ p/b, 12 b, } Q_H' = -2 \cdot 10^{-3}/\text{turn} \)
Integer Resonance Crossing

• Linear Decrease of Horizontal Tune

LHCFAST2, 200GeV, $1 \times 10^{10}$ p/b, 12 b, $Q_H' = -4 \times 10^{-4}$/turn
Closed Orbit Resonance

- Influence of dipolar error on closed orbit:
  (e.g. quadrupole misalignments)

\[ \Delta x_{CO}(s) = \frac{\sqrt{\beta(s)}}{2 \sin(\pi \cdot Q)} \int F(\bar{s}) \sqrt{\beta(\bar{s})} \cdot \cos[\varphi(\bar{s}) - \varphi(s) - \pi Q] d\bar{s} \]

- \( Q_H, Q_V = \text{integer} \Rightarrow \text{diverging closed orbit} \)
Closed Orbit Resonance

MD2, 26GeV, 4\times10^{10} \text{ p/b, 12 b}

nominal LHC-Beam
Q_H=26.13

nominal CNGS/FT
Q_H=26.58
Dispersion Resonance

- Dispersion is generated by dipole magnets, transforms like orbit

\[ D(s) = \frac{\sqrt{\beta(s)}}{2\sin(\pi \cdot Q)} \int s \frac{1}{\rho(\bar{s})} \sqrt{\beta(\bar{s})} \cdot \cos[\phi(\bar{s}) - \phi(s) - \pi Q]d\bar{s} \]

- \( Q_H, Q_V = \text{integer} \Rightarrow \text{diverging dispersion} \)
Dispersion Resonance

- MD2, 26GeV, 4\times10^{10} \text{ p/b}, 12 \text{ b}
Superperiodic Resonances

• Dispersion Resonance:

\[ D(s) = \frac{\sqrt{\beta(s)}}{2 \sin(\pi \cdot Q)} \int \frac{1}{\rho(\bar{s})} \sqrt{\beta(\bar{s})} \cdot \cos[\varphi(\bar{s}) - \varphi(s) - \pi Q] d\bar{s} \]

When tune is multiple of 6 (periodicity of dipolar fields):

\[ D(s) = \frac{\sqrt{\beta(s)}}{2 \sin(\pi \cdot Q)} \cdot 6 \cdot \int_{s=0}^{\frac{C}{6}} \frac{1}{\rho(\bar{s})} \sqrt{\beta(\bar{s})} \cdot \cos[\varphi(\bar{s}) - \varphi(s) - \pi Q] d\bar{s} \]

contribution from one sextant

=> Enhanced superperiodic dispersion resonance

• Closed Orbit Resonance:

Dipolar field errors are distributed randomly

=> no strong superperiodic effect
More Resonances

Dispersion function

Chromaticity

Momentum compaction

Beta function
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Tune Decrease: $3 \cdot 10^{-4}$/turn
Tune Decrease: $1.5 \cdot 10^{-3}$/turn
Tune Decrease: $3 \cdot 10^{-3}$/turn
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New Fast Position Interlock

- 6 BPMs with new hardware using logarithmic amplifiers (large dynamic range)
- Turn-by-Turn interlock processing via FPGA
- Combined Extraction Interlock System
- In commissioning phase (difficulties with position acquisition)
New Fast Position Interlock

Q_H=26 resonance

Novel Interlock

Simple Interlock

September, 30th 2010
Tobias Baer
Summary

• (Integer) tune resonance are a challenging machine protection Issue
  • (cp. complete beam loss in 3 turns)
• Integer tune resonance crossings are possible (huge oscillations)
• No clear beam loss hierarchy (especially in vertical plane)
• Protection with Turn-by-Turn Position Interlock
• Be aware of superperiodic resonances
Thank you
for your Attention

Tobias Baer
CERN BE/OP
Tobias.Baer@cern.ch
Office: +41 22 76 75379
Backup slides
Dynamics of Beam Losses

The graph shows the dynamics of particle losses and beam intensity as a function of horizontal tune. The red line represents particle losses, while the blue line indicates beam intensity. The vertical axis on the left represents normalized particle losses, and the right vertical axis represents beam intensity in arbitrary units.
Tune Slope Threshold

- 25% of particles lost
- 50% of particles lost
- 75% of particles lost

Threshold

slope of horizontal tune at $Q_h = 26$ [1/turn]

MD1, 26GeV, $1 \times 10^{10}$ p/b, 12 b
Beam Loss Pattern

Horizontal

Vertical
Horizontal Beam Losses

- slow extraction collimators (TCE/TPST)
- scraper (TIDP) and beam dump (TIDH/TIDV)
- BLM 323
Power Converter Interlock

Power converter failure of QF1 @ 400 GeV

$Q_{th} = 26$ tune resonance

Beginning of failure

PC Interlock

Measured Current

Reference

Current [A]

Time [ms]

1780
1770
1760
1750
1740
1730
1720
1710

-5
0
5
10
15
20
Failure test of RQ4.LR3 (PM event 10/03/2010 13:52:56)

Current change: -0.11%, tune change: -5\cdot10^{-4}
Acquisition Commissioning

New Hardware vs. Traditional Hardware (vertical orbit bump)

vertical position measured by new HW [mm]

vertical position measured by MOPOS [mm]

-8 -6 -4 -2 0 2 4 6 8

0 2 4 6 8

-8 -6 -4 -2 0 2 4 6 8

y = 0.60x - 0.79

y = 0.59x - 0.39

BPCE.618 V-position @ injection
BPCE.618 V-position @ 49 GeV

07 - 09.11.2009, CNGS beam
@ injection: 14GeV, 2×10^{13} p
@ 49GeV: 4×10^{13} p
Consistency Check: 
Vertical $3\pi$ orbit bump at BPCE 618
New Hardware vs. Traditional Hardware
(3π vertical orbit bump)

- Nominal Trim
- BPCE.618.V new hardware
- BPCE.618.V MOPOS

12.11.2009, CNGS beam
14GeV, 2 \times 10^{13} \text{p}

y = 1.76x - 0.07
y = 1.06x - 0.08
y = 0.97x - 0.14

vertical position measured/trimmed [mm]
fitted bump amplitude @ BPCE.618.V [mm]
Correlation between BPCE618.H and BPCE618.V (horizontal orbit bump)

- CNGS beam @ injection
- CNGS beam @ 49 GeV
- LHCFAST2 Beam @ 450 GeV
- LHCFAST2 Beam @ 450 GeV, reduced intensity

\[ y = 0.2166x + 7.9709 \]
\[ y = 0.1454x + 8.9439 \]
\[ y = 0.1332x + 7.9541 \]

vertical position measured by BPCE618.V [mm] vs.
horizontal position measured by BPCE618.H [mm]
Fast Position Interlock

- 6 BPMs with new hardware using logarithmic amplifiers (large dynamic range)
- Turn-by-Turn interlock processing via FPGA
- Algorithm compares current position with moving average of last 100 turns

Problem:

**Injection Oscillations**

- Probable solution:
  (Time dependent) Low pass filter