TUNE RESONANCE PHENOMENA IN THE SPS AND MACHINE PROTECTION VIA FAST POSITION INTERLOCKING

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Abstract

The Super Proton Synchrotron (SPS) at CERN with a peak energy of $450\,\mathrm{GeV}$ is at the top of the LHC preaccelerator-complex. Apart from the LHC, SPS is with Tevatron the accelerator with the largest stored beam energy of up to $2.5\,\mathrm{MJ}$. The SPS has a known vulnerability to fast equipment failures that led to an uncontrolled loss of a high intensity beam in 2008, which resulted in major damage of a main dipole. The beam loss was caused by a fast tune decrease towards an integer resonance [1]. Simulations and distinct experimental studies provide clear understanding of the beam dynamics at different SPS tune resonances. Diverging closed orbit oscillations, dispersion explosion and increased beta-beating are the driving effects leading to a complete beam loss in as little as 3 turns ($70\,\mu\mathrm{s}$). Dedicated experiments of fast failures of the main power converters reveal that the current interlock systems are much too slow for an adequate machine protection. To counteract the vulnerability of the SPS, current research focuses on a new fast position interlock system which is planned to become operational in 2010.

INTRODUCTION

On June 27th, 2008 an equipment failure in the SPS led to the uncontrolled loss of a high intensity beam at $400\,\mathrm{GeV}$ with a total beam energy of about $2.1\,\mathrm{MJ}$. The vacuum chamber of a main bending magnet was punctured (cp. Figure 1) and the magnet had to be replaced. Cause of the incident was a freeze of the main timing system that inhibited the beam extraction after acceleration and resulted in an unintended tune shift towards the $Q = 26$ integer tune resonance during the ramp down of the magnets. An analysis of the data from the beam loss monitoring system revealed that the beam was lost in less than $20\,\mathrm{ms}$ which is the time resolution of the system [1].

The incident points out a vulnerability of the SPS to fast beam losses and the challenge of machine protection against tune resonances.

BEAM DYNAMICS AT TUNE RESONANCES

In 2009, dedicated experiments were made to understand the beam dynamics at different tune resonances in the SPS.

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Figure 1: Impact of a $2.1\,\mathrm{MJ}$ beam. Over a length of about $10\,\mathrm{cm}$ the vacuum chamber is punctured. Metal droplets contaminate the vacuum chamber.

The special threat of beam losses due to integer tune resonances becomes obvious when looking at the case depicted in Figure 2.

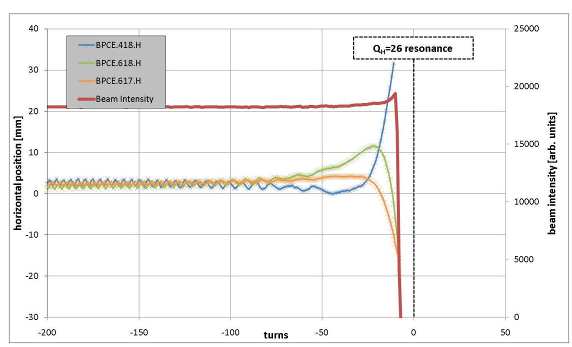

Figure 2: Beam intensity and horizontal turn-by-turn beam position at three particular beam position monitors (BPMs). **The complete beam is lost within 3 turns after the first beam losses start.**

The graph shows the horizontal beam position at three particular BPMs close to the $Q_H = 26$ integer tune resonance and the corresponding beam intensity. The horizontal tune is decreased linearly by about $-2 \cdot 10^{-3}/turn$. The beam position starts to diverge about 40 turns before the resonance is reached, leading to a complete beam loss at a tune of about $Q_H = 26.015$. Most challenging is the fact that it takes only 3 turns ($= 69\,\mu$s) to loose the complete beam after the first beam losses start. This gives practically no time for an adequate machine protection based on beam loss monitors (BLMs).

Besides these effects, tune resonances lead to a large variety of resonance phenomena. In the following a closer look is taken on the resonance phenomena that dominate fast beam losses, i.e. the resonant behaviour of closed orbit, dispersion, chromaticity and beta-beating.

Closed Orbit

Dipolar field errors lead to a distortion of the closed orbit which has a $\frac{1}{\sin(\pi Q)}$ resonant behaviour for integer tune values [2]. The closed orbit resonance is the major cause of the diverging beam positions shown in Figure 2. Measurements and simulations reveal that especially the nominal tunes of LHC-type beam ($Q_H = 26.13$ and $Q_V = 26.18$)[1] are remarkably close to the $Q = 26$ integer tune resonance (cp. Figure 3). An erroneous decrease of the tune will directly drive the closed orbit into resonance.

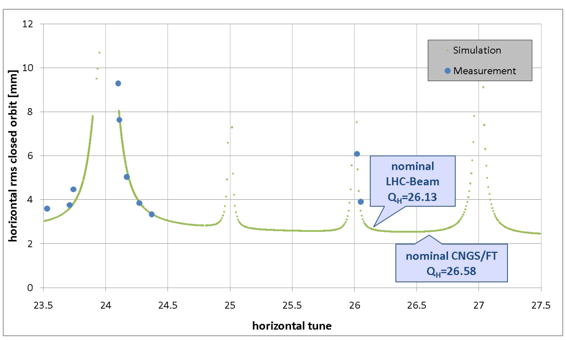

Figure 3: Simulation and measurement of the horizontal rms closed orbit as a function of the horizontal tune. The vertical tune is at nominal LHC-beam settings: $Q_V = 26.18$.

Dispersion

Like the closed orbit, the dispersion has a $\frac{1}{\sin(\pi Q)}$ resonant behaviour for integer tunes [2]. However, simulation and measurement reveal an enormous $Q_H = 24$ superperiodic[2] tune resonance (cp. Figure 4). Due to the momentum-spread[3], this enormous dispersion resonance leads to diverging transversal beam size and related beam losses.

[1]Since the horizontal working point is closer to the $Q = 26$ integer tune resonance, this article mainly focuses on the horizontal plane.

[2]The SPS is constructed of six similar sextants, each consisting of 18 FODO cells.

[3]The momentum-spread $\frac{\Delta p}{p}$ in the SPS is about 1‰.

[5]For the dispersion measurement it is crucial to take into account that also second order dispersion and momentum compaction factor have a broad resonant behaviour for superperiodic tune values.

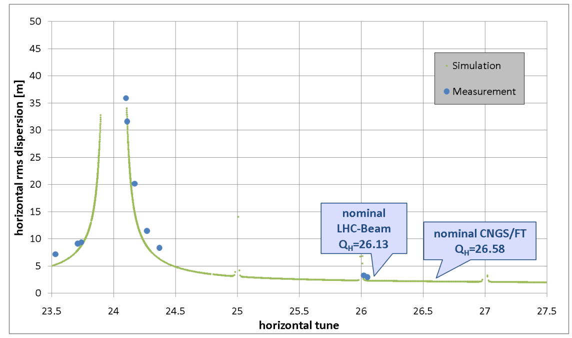

Figure 4: Simulation and measurement of the horizontal dispersion as a function of the horizontal tune[5].

Whereas the resonance condition for closed orbit distortion and dispersion are the same, the origins of both effects are different, what accounts for the different resonance behaviour. The dispersion has its origin in *dipolar fields* that are dominated by the main bending fields that are distributed *periodically* around the accelerator. This leads to an extreme superperiodic dispersion resonance. In contrast, the closed orbit distortion is generated by dipolar field *errors* that are predominantly induced by quadrupole misalignments [2]. These misalignments are to first approximation distributed *randomly*. Additional systematic components, coming for example from magnet errors, add to the dipolar field errors. As a result, the superperiodic $Q_H = 24$ closed orbit resonance shown in Figure 3 is far less pronounced than the superperiodic dispersion resonance.

Chromaticity

The correction of the negative natural chromaticity by sextupoles is proportional to the dispersion at the sextupole [3]. Thus, the resonant behaviour of the dispersion function at the superperiodic tune resonance also implies a resonant behaviour of the chromaticity (cp. Figure 5). As given by the $\frac{1}{\sin(\pi Q)}$ proportionality the dispersion function changes sign at the resonance. The inversion of the dispersion orbit leads to an inverse effect of the chromaticity correction and a negative chromaticity below the superperiodic $Q_H = 24$ resonance. In this regime the beam will be lost due to head-tail instabilities.

Beta-Beating

Quadrupolar field errors induce beta-beating. The beta-beating has a $\frac{1}{\sin(2\pi Q)}$ dependency that leads to resonant behaviour for integer and half-integer tunes [4]. A simulation of the maximal beta-functions is shown in Figure 6. The related blow up of the transversal beam size dominates the beam losses at half-integer resonances.

Since the closed orbit distortion, dispersion and chromaticity scale with the beta function, they are also influenced by the resonant beta-beating.

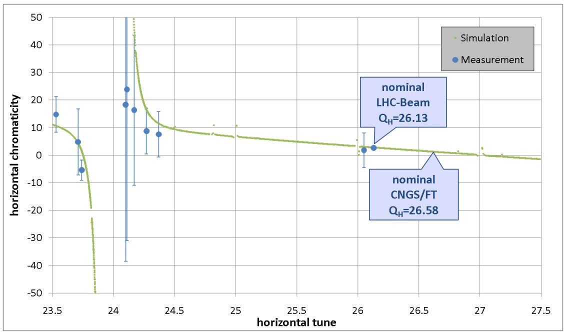

Figure 5: Simulation and measurement of the horizontal chromaticity as function of the horizontal tune.

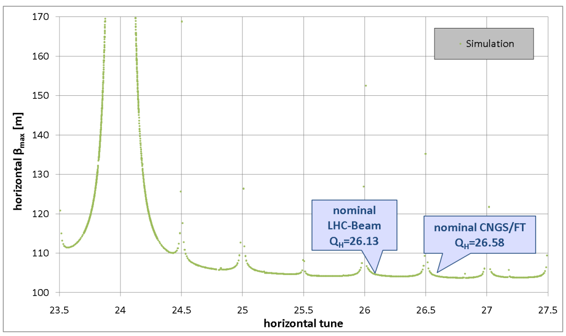

Figure 6: Simulation of the maximal horizontal beta-function.

MACHINE PROTECTION

The experiments and simulations as well as the 2008 incident underline the threat of fast beam losses due to tune resonances. Very localized beam losses in as little as 3 turns make the $Q = 26$ integer tune resonance under nominal conditions by far the most critical one.

Present Machine Protection Systems

The BLM system in the SPS has a time resolution of $20\,\mathrm{ms} \hat{=} 870\,\mathrm{turns}$. It is by no means capable of protecting the SPS against fast beam losses in a few turns.

The SPS main quadrupole circuits are protected by an interlock on the quadrupole currents. Tests at $400\,\mathrm{GeV}$ revealed that the interlock system has a delay of $12\,\mathrm{ms}$. In contrast, an experimental power cut showed that under nominal LHC-beam conditions the $Q_H = 26$ integer tune resonance would be reached in $7.7^{+0.4}_{-0.5}\,\mathrm{ms}$. Thus, no protection against fast equipment failures is provided.

New Fast Turn-by-turn Position Interlock

The experimental studies showed that in the vicinity of an integer tune resonance the beam position typically starts to oscillate at least $\approx 30\,\mathrm{turns}$ before beam losses are measurable. Based on this, a new beam position interlock system, operating on a turn-by-turn base will counteract the vulnerability. For the position acquisition six stripline coupler BPMs in two groups with a betatron phase advance of about $45°$ between two BPMs are used. The acquisition hardware is based on logarithmic amplifiers that provide a large dynamic range. Each turn ($23\,\mu\mathrm{s}$) an FPGA does the interlock processing and sends a hardware beam dump signal in case the current beam position is out of a reference window around the average position.

Additionally, an extraction interlock to LHC and CNGS target is based on the system. For each BPM, it compares the average position of about 50 turns to a reference window. The interlock processing is done in the front end. The total processing time for the extraction interlock is about $1.5\,\mathrm{ms}$.

For post analysis a post mortem position acquisition of the 1024 turns prior to a beam dump signal are logged.

Currently, the commissioning of the position acquisition and the extraction interlock is ongoing. First tests with the hardware turn-by-turn position interlock are expected during summer 2010.

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