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BEAM DYNAMICS GROUP SUMMARY

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This paper summarizes the activities of the beam dynamics working group of the LHC Collective Effects Workshop that was held in Montreux in 1994. It reviews the presentations that were made to the group, the discussions that ensued, and the consensuses that evolved.

1 INTRODUCTION

The CERN SPS was the first accelerator to store and collide hadron bunches - protons and antiprotons - in counter rotating beams. A relatively small number of bunches circulated in a single vacuum chamber, inside normal conducting magnets. Now used mainly as an injector to LEP, the SPS will become the final accelerator in the injection chain supplying the LHC with protons and, at least occasionally, with heavy ions.

The Fermilab Tevatron was the second hadron collider to come on the air. Still in operation, it too stores a modest number of proton and antiproton bunches in a single vacuum chamber. In contrast with the SPS, the Tevatron and all subsequent hadron colliders use superconducting magnet technology to achieve higher magnetic fields and to reduce operating costs.

Next came the DESY machine HERA, which collides electrons (or positrons) with protons. Because the proton bunches circulate in their own beam pipe, parasitic beam-beam collisions are mainly absent, and a relatively large number of circulating bunches - nominally 210 - is feasible. Superficially, this is both good and bad for single beam collective effects. The good news is that more bunches allow smaller single bunch populations to deliver the same luminosity, thereby ameliorating single bunch instabilities. In practice, of course, the population tends to remain the same, while the luminosity is increased. The bad news is that the interbunch spacing is greatly decreased, raising the potential vulnerability to multibunch instabilities.

The Relativistic Heavy Ion Collider (RHIC) is currently under construction at the Brookhaven National Laboratory. RHIC stores as many as 114 bunches of hadrons - heavy ions or protons - in two horizontally separated rings of superconducting magnets.

Chronologically last, but not least, the LHC will store as many as 2835 bunches of hadrons in two separate beam pipes inside a single superconducting magnet. Table 1 compares the bunch parameters of this list of hadron colliders.

TABLE 1: Proton bunch parameters for past, present, and future hadron colliders.

machine	number of bunches	bunch spacing [m]	bunch population N_b
SPS	6	1151.9	1.0×10^{11}
Tevatron	6	1047.2	2.0×10^{11}
HERA	210	30.2	0.3×10^{11}
RHIC	114	33.6	2.5×10^{11}
LHC	2835	7.5	$> 1.0 \times 10^{11}$

The plenary talks by F. Ruggiero[1] and S. Peggs[2] reviewed for the Montreux workshop participants the current understanding of single beam collective effects in the LHC, and in RHIC. In the "Beam Dynamics" working group sessions that followed, most of the discussions concerned one or more of the storage rings listed above. For the most part these discussions were directly or indirectly aimed at extrapolating from current experience and understanding to predict the storage performance of the LHC. Stability analyses of the PS and the SPS - critical components in the LHC injector chain - were also discussed.

The following summary of the working group activities points the interested reader towards more detailed discussions in papers submitted to these proceedings.

2 TEVATRON INSTABILITIES

S. Assadi presented a detailed review of Tevatron instabilities. The four most prominent are:

- A longitudinal coupled bunch instability that is commonly observed when the Tevatron is run in fixed target mode, with high intensity bunches of protons in most of the 1113 buckets of the 53 MHz radio frequency (RF) system. A prominent characteristic of the longitudinal impedance driving this instability is the fact that only one mode is excited. This instability is controlled by feedback, and could be cured by RF mode dampers.
- A longitudinal single bunch instability that is observed in collider mode. This is described further in the subsection immediately below.
- Head-tail instability, at all energies. The Tevatron experience is summarized in the following section, "HEAD-TAIL INSTABILITIES", along with observations from HERA and predictions from RHIC.

- An interesting and incompletely understood longitudinal single bunch phenomenon. There is a small amount of evidence of an occasional phenomenon that is tentatively labeled a "stationary microinstability" by some. See below.

2.1 Longitudinal single bunch instability

A typical long time scale plot shows that the six proton bunches in a Tevatron store start out with essentially identical bunch lengths. Sometimes, one or more of the bunches show the results of a slow instability, by which their lengths increase slowly. Having increased by perhaps 40% to a plateau value in a time of order 10^3 seconds, these bunches then cease to grow any further, for all practical purposes. The lengths of the other bunches are not so constant, but increase only with a very much longer timescale of many hours. Although this instability has been observed for many years at the 150 GeV injection energy of the Tevatron - where the beam remains only briefly - it recently began to also be observed at the storage energy of 950 GeV, where it is a more significant concern.

If the longitudinal beam profile is observed on a fast scope while this instability is in action, violent quadrupole and dipole mode oscillations are observed. The profile on a sampling scope in "persistence" mode shows large shoulders near the edges of the distribution. Tuned filters see dipole and quadrupole mode excitations that die down over the 10^3 second time scale of the instability. The instability may be controlled by the use of bunch-by-bunch RF phase feedback.

The consensus of the working group was that this is classical single bunch instability excitation in the "standard model", on the brink of Landau damping stability. As the bunch length gradually increases, Landau damping also increases, until the instability turns itself off. Similar effects have been observed in the SPS collider.

2.2 Evidence for a "stationary microinstability"

Digitised longitudinal bunch profiles, averaged over very many turns, were shown in which the full width of the bunch is approximately half the bucket length of the 53 MHz RF system. Profiles taken from a small number of Tevatron stores show a large and very narrow feature, apparently about 0.3 nanoseconds wide, on the trailing edge of the profile. This "spike" typically occurs about half way between the tail edge of the main bunch and the following unstable fixed point of the bucket. The spike usually migrates towards the trailing unstable fixed point over a typical period of about five minutes, after which it disappears. A companion spike is *not* seen in front of the head of the bunch, implying that the feature, if it is real, is not rotating inside the RF bucket. This leads to its tentative identification as a "stationary microinstability".

Skeptics within the working group pointed out that the potential well distortions necessary to capture such a non-rotating narrow slug of charge are extreme. They maintained that it is unlikely that the microinstability is truly analogous to the situation at the Brookhaven NSLS, where a secondary bucket can be created within the fundamental RF bucket via a passive cavity component. Is the effect merely instrumental? Perhaps the feature actually *is* rotating?

The consensus of the group was that the relatively small amount of data available on this effect hampers accurate interpretation. We were unanimous in requesting more data, please.

3 HEAD-TAIL INSTABILITIES

Head-tail instabilities are seen at virtually all lepton and hadron storage rings. Fortunately, it is usually only necessary to set the chromaticities to be slightly positive (above transition) in order to stabilise the beams.

3.1 HERA observations and simulations

An extensive and impressive body of work was presented by F. Gallucio, combining both HERA beam observations and simulations results[3].

Instability is seen most prominently at injection energies. Beam position monitors show typical oscillation rise times of order $\tau \approx 1$ second, when both chromaticities are approximately zero. HERA has an unusually low synchrotron tune of $Q_s \approx 0.0006$, equivalent to a synchrotron period of $T_s \approx 0.04$ seconds. Head-tail instability is sometimes accidentally initiated by scraping the beam or by turning on the 208 MHz RF system.

The simulation results were based on a simplified model with one transverse and one longitudinal degree of freedom, in which the dominant transverse wake potential comes from 15 higher order modes measured in the RF cavities. A parametric investigation of the dependency of the instability rise time on chromaticity showed surprisingly good agreement with observation: for example, both showed that stability returns at “very negative” chromaticities.

For a broad range of chromaticity and synchrotron tune values, the observed and simulated risetimes were always very much longer than the synchrotron period, $\tau \gg T_s$. This is characteristic of the “head-tail” effect. In marked contrast, the characteristic rise time of the “strong head-tail” instability is usually extremely fast, $\tau < T_s$, and does not depend in practice on the chromaticity. Note that the strong head-tail instability is also known as the “transverse mode coupling”, “transverse turbulent”, or “transverse microwave” instability.

The consensus of the working group was that this body of work was well on the way to becoming an authoritative discussion of the head-tail instability. We recommended a more detailed exploration, by simulation, of the regime when $\tau \to T_s$, and encouraged further exploration of the chromaticity plane, especially when the betatron tunes are close together.

3.2 Tevatron experience and RHIC predictions: skew chromaticity

In his Tevatron presentation, S. Assadi showed a typical spontaneous occurrence of the head-tail instability, in which two thirds of the protons were lost in a very short period of time. Coherent excitation is visible on spectrum analysers attached to beam position monitors, not only when beam is being lost, but also in the metastable condition close to the head-tail threshold.

The Tevatron has a large energy range that results in a relatively low injection field. As in HERA, this causes persistent current effects in the superconducting magnets to be important. In storage, persistent current drifts force the horizontal and vertical chromaticities to move in opposite directions. It is normal procedure for the operators to correct for this (and other drifts) by adjusting the chromaticities and the tunes every few hours. During the 1989-1990 run, the operators reported that beam loss was sometime experienced through the head-tail instability when the fractional tunes were being *separated*, moving away from close proximity to the coupling diagonal. Machine studies later that year showed that head-tail instability can also be induced, under different carefully controlled conditions, either when the tunes are separated or when they are brought together.

S. Peggs made a presentation showing that the interaction between linear coupling and the head-tail effect in the Tevatron can be explained by introducing the concept of a “skew chromaticity” vector with two components[4]. The skew chromaticity model also explains behavior observed in RHIC simulations. Measurements at the Tevatron, in RHIC simulations, and at CESR appear to indicate that skew chromaticity is only important at large superconducting hadron colliders. It is relatively easy to ensure observed stability at the Tevatron and predicted stability at RHIC, by keeping the two eigenchromaticities slightly positive.

The working group recommended a careful evaluation of skew chromaticity effects and sources in the LHC design, possibly leading to criteria on magnetic harmonics in the bodies and ends of the superconducting magnets.

3.3 Transverse high order head-tail instabilities in the PS

R. Cappi presented data taken in December 1993 that show the presence of a high order head-tail instability in the PS, under conditions similar to those expected during LHC operation[5]. The instability rise time was slow, in the range $0.1 - 0.3$ seconds, and resulted in 20% to 30% losses. Neither transverse feedback nor octupole excitation had a discernible effect. Most surprising was the fact that incoherent space charge tune shifts of $\Delta Q_{sc} \approx -0.4$ did not appear to stabilise the situation.

Experiments were performed at the nominal 1 GeV flat bottom, and at the 1.4 GeV flat bottom that is foreseen for LHC operation. This slight increase in energy was observed to be enough to stabilise the beam.

4 TRANSVERSE MODE COUPLING IN THE SPS

T. Linnecar and E. Shaposhnikova reported that, *for leptons*, the MOSES code is remarkably accurate in predicting transverse mode coupling (TMC) thresholds in the SPS, so long as an appropriate and large set of modes are selected. A standard broadband single resonance impedance model ($f = 1.3\text{GHz}, Q = 0.95, Z_{\|}/n = 20\Omega, Z_{\perp} = 23\text{M}\Omega$) reproduces observed TMC and longitudinal microwave thresholds at the critical time of injection into the SPS. Agreement is satisfactory for lepton bunches with rms bunch lengths in the range $0.04\text{m} < \sigma < 0.30\text{m}$, at injection. The PS also confirms that lepton TMC models are accurate.

To date, however, there is no world evidence of *proton* TMC instability. Nonetheless, it is expected that proton TMC and microwave instabilities will both be important at injection into the SPS, when it works with LHC parameters. Using the nominal LHC bunch population of $N_b = 1.0 \times 10^{11}$, it appears to be possible to find a working point in $(\sigma_{long}, \epsilon_{long})$ space that is both TMC and microwave stable, and that respects existing transfer line aperture constraints. "Ultimate" LHC parameters, with $N_b = 1.7 \times 10^{11}$, currently rely on the microwave instability to blow ϵ_{long} up from about 0.5 eVs to about 0.8 eVs, immediately after SPS injection.

The working group recommended that the effects of space charge (and other) betatron detuning on proton TMC be studied, and recommended further consideration of whether microwave blow up can be relied on at injection. We endorsed the conclusion of T. Linnecar and E. Shaposhnikova, that "*new* data on the microwave instability, and *any* data on the transverse mode coupling instability for protons in the SPS, are required".

5 FEEDBACK

W. Höfle presented the nominal longitudinal feedback design[6]. The 400 MHz RF cavities in the LHC are common to both beams, so that both 3μs abort gaps affect beam loading - as do potential changes in the layout of interaction points. A 200 MHz feedback system acting separately on each beam is foreseen, to damp synchrotron oscillations at injection and to suppress longitudinal coupled bunch instabilities. A damping time of $3T_s$ at injection is expected to limit the longitudinal emittance growth to about 10%.

The transverse feedback system is designed to damp ±2mm systematic errors of a newly injected batch, and ±2mm random errors within the bunch, in 30 turns. With a bandwidth of 1 MHz, and a maximum strength of 70 kV.m, this corresponds to a 2.5% maximum growth of the nominal transverse emittance. It is assumed that natural transverse dipole mode growth times caused by accelerator components will be limited to $\tau > 100$ turns, in order for transverse feedback to be effective on transverse coupled bunch instabilities, with a reasonable safety margin. In some extreme conditions, parasitic beam-beam collisions are speculated to shift the closed orbit of "PACMAN" bunches, near the abort gap, by as much as 1 σ. It is far from clear that it would be practical to correct these errors using a transverse feedback system.

6 LONGITUDINAL SINGLE BUNCH STABILITY

R. Baartman presented a new single bunch stability criterion, developed jointly with M. D'Yachkov[7]. They modify the matrix eigenvalue approach of Oide and Yokoya, with segmented action space. They use this framework to perform a self-consistent calculation of the intensity at which the incoherent spectrum shows a tune minimum (versus action) at $Q = 1/2Q_{s0}$, half the unperturbed synchrotron tune. If particles are present at this action, the dipole and quadrupole modes will couple. There is some evidence in KEK streak camera data of double peaks consistent with this picture.

With a single resonance broadband impedance model, this approach implies that the Keil-Schnell and Boussard criteria for the LHC are conservative by a factor of about two. This begs the question of how well one expects to know the LHC impedance environment - the province of a different working group.

7 CONCLUSIONS

The beam dynamics working group did not find any "show stopping" beam instabilities that severely threaten LHC performance. However, we did find some topics where further work and analysis is desirable, both at CERN and elsewhere. Very briefly:

- We support further investigation of the "stationary microinstability" at the Tevatron, and the head-tail instability at HERA.
- We recommend a careful evaluation of skew chromaticity effects and sources in the LHC design, possibly leading to criteria on magnetic harmonics.
- We recommend that the effects of space charge (and other) betatron detuning on proton transverse mode coupling be studied, and support further consideration of whether microwave blow up can be relied on at injection into the SPS.

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