The Performance of Proton Antiproton Colliders

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1 Abstract

During the physics production runs in 1988 and 1989 both the SPS and the Tevatron achieved a maximum luminosity between 2 and $3 \times 10^{30} cm^{-2}s^{-1}$ with a luminosity lifetime between 10 and 15 hours. The SPS operated for a period of about 8 months during which it produced an integrated luminosity of 8100 nb^{-1}, while the Tevatron produced 9600 nb^{-1} over a 12 month period. While the beam parameters of the two machines are quite different, and the SPS uses normal conducting magnets and the Tevatron superconducting ones, the performances of the two machines was surprisingly similar. In this paper we compare the parameters of both colliders and discuss performance limitations due to beam-beam effects, intrabeam- scattering, instabilities and persistent currents in the superconducting magnets. By comparing the two colliders we try to identify problems common to both machines, with a particular view to the next generation of hadron colliders such as the LHC and the SSC.

2 Introduction

The first hadron collider constructed in the seventies was the ISR at CERN. Two proton beams with an energy of up to 31 GeV were circulated in two separate vacuum chambers and collided with an angle, a maximum luminosity of up to $1.3 \times 10^{32} cm^{-2}s^{-1}$ was achieved. With the experience from the ISR and the development of stochastic cooling it was possible to accumulate dense $\bar{p}$ bunches in an accumulator ring and to transform the Super Proton Synchrotron (SPS) into a $p\bar{p}$ collider. The first collisions between protons and $\bar{p}$ were observed in 1981.

Some years later the Tevatron at Fermilab came into operation, a machine of about the same physical size as the SPS, but with superconducting magnets. In the Tevatron the beams collide with an energy of up to 1 TeV, compared to a beam energy of 315 GeV in the SPS. After some years of very satisfactory operation of the Tevatron and the SPS various fundamental performance limitations of hadron colliders are now well understood. It is thus appropriate to compare both colliders, their parameters, the operational procedures and the major limitations, in particular in view of the future machines. Another interesting aspect is the comparison between normal conducting and superconducting accelerator behaviour.

In the table the basic parameters of both colliders for the 1988/1989 runs are shown. The most significant numbers for the high energy physics community, the integrated and the maximum luminosity, are remarkably similar for both machines (see fig.1), although many other parameters and the operational procedures are different. In the following sections we discuss various aspects in the first phase of the operation, the setting up including injection and energy ramping, and in the second phase, the physics store. Then we discuss particular aspects of hadron colliders, the beam-beam effect and problems related to superconducting magnets. Although for the performance of $p\bar{p}$ colliders the $\bar{p}$ production and accumulation rates are essential, we limit ourselves in this paper to a comparison of only the two colliders. Other papers presented at this conference give details about the $\bar{p}$ production [1].

Typical parameters	*SPS*	*Tevatron*
Injection Energy [GeV]	26	150
Top Energy [GeV]	315	900
Runtime in 88/89	8 months	12 months
Integr.Lumi 88/89 [nb^{-1}]	8100	9600
Max.init.lumi. [$cm^{-2}s^{-1}$]	2.9×10^{30}	2.0×10^{30}
Initial lumi.lifetime [h]	9 - 12 h	10 - 15 h
Integrated lumi. per store		
Best value, in nb^{-1}	95	135
Average value in nb^{-1}	40	33
p bunch intensity	12.5×10^{10}	5.5×10^{10}
$\bar{p}$ bunch intensity	7.0×10^{10}	2.5×10^{10}
Num. of bunch. per beam	6	6
Beam separation	Yes	Not yet
Number of collision points	3	12
Horizontal emittance, p	11	16
Vertical emittance, p	11	16
Horizontal emittance, $\bar{p}$	12	12
Vertical emittance, $\bar{p}$	10	12
β_h at IP [m]	1	0.55
β_v at IP [m]	0.5	0.55
Linear tune shift per IP		
on protons (H,V)	0.0037/0.0026	0.001/0.001
on $\bar{p}$ (H,V)	0.0066/0.0063	0.002/0.002
Total tune shift		
on protons (H,V)	0.011/0.008	0.012/0.012
on $\bar{p}$ (H,V)	0.020/0.014	0.025/0.025
Linear coupling	0.002 - 0.003	0.002 - 0.004
Bunch length/ store [ns]	2.4	5.5
Energy spread/ store	0.6×10^{-3}	0.25×10^{-3}
Longitudinal emitt. [eVs]	0.65	3
Synchrotron freq. [Hz]	178	39
RF-frequency [MHz]	100 and 200	53
Operational tunes (H,V)	26.685/27.680	19.411/19.405
Emitt.growth rates p/$\bar{p}$		
longitudinal [eVs/h]	$\approx 0.1/0.1$	≈ 0.06
hor. [$\pi mm - mrad/h$]	$\approx 1.3/0.7$	$\approx 0.32/0.27$
vert. [$\pi mm - mrad/h$]	$\approx 0.5/0.2$	as in h-plane .
Bunch intensity lifetime[h]	≥ 60	100 - 200
$\bar{p}$ -stacking rate	$5.80 \times 10^{10}/h$	$2.0 \times 10^{10}/h$
$\bar{p}$ stack in accumulator	1.31×10^{12}	6.5×10^{11}

Definitions for this table : Emittance $\equiv \sigma^2 \times 4/\beta$
Energy spread : σ_E, Bunch length : 4 σ_s

3 Injection and energy ramping

The SPS allows for a fast cycling. Six proton bunches are injected at an energy of 26 GeV into the SPS on a 43.2 s long injection platform. Then the magnets are ramped in about 10 s to a beam energy of 315 GeV, during the first 2 s after ramping the β-functions are squeezed to their final values. Some seconds later the beam is dumped, the magnets ramp down and the next proton injection follows. During this cycling, the machine is tuned to minimize particle losses and emittance growth.

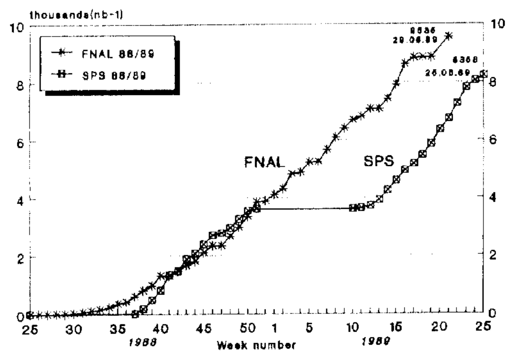

Figure 1: Integrated luminosity during 1988/1989 for SPS and Tevatron

Eventually six $\bar{p}$ bunches are injected between the injection of the last proton bunch and the start of the energy ramp, after the ramp the magnets remain at constant field during the store.

Beam losses and a growth of the emittances are mainly caused by particles crossing resonances. Resonances of order 3 and 4 are always dangerous in the SPS and have to be strictly avoided. After the injection of the $\bar{p}$ additional beam-beam resonances of higher orders are observed, in particular resonances of order 7. During injection resonances of order higher than 7 can be tolerated, because the beams are kept at 26 GeV only for a few seconds. To place the particles between the dangerous resonances, the tune spread of the beam is minimized and the tunes are carefully adjusted (see fig.2). Three different effects contribute to the

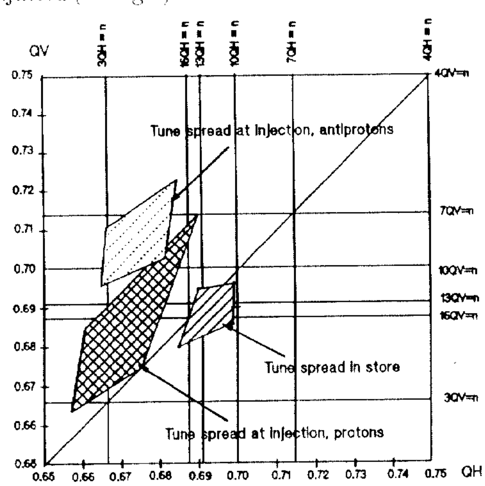

Figure 2: Tune spread in the SPS, at injection and in store

tune spread :

- The Laslett space charge detuning, which is large due to the low injection energy of 26 GeV combined with the high particle density.
- The tune spread caused by the beam-beam effect, which is of the order of the linear tune shift.
- The tune spread due to a nonvanishing chromaticity, this effect is small for the SPS and as we will discuss later, a problem for the Tevatron.

The tune spread due to the beam-beam effect is reduced by keeping both beams separated with one of the three available electrostatic separators. This measure was not sufficient to ensure an optimal transmission. To further reduce the tune spread, a second RF system with a frequency of 100 MHz was added to the original 200 MHz RF system [2]. This allows to inject longer bunches, reduces the tune spread due the space charge and improves the transmission (see fig.3). To counteract a longitudinal head tail instability it was necessary to combine both RF systems [3]. The proton longitudinal density is limited by the microwave

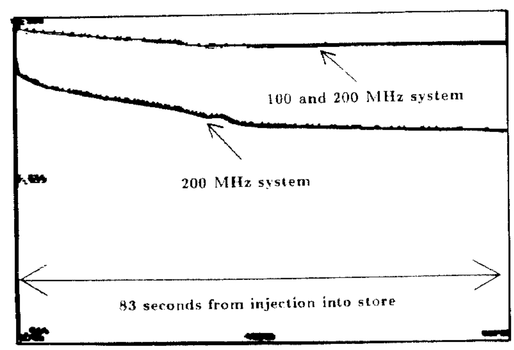

Figure 3: Transmission of a $\bar{p}$ bunch with both 100/200 MHz RF system and the 200 MHz RF system only in the SPS

instability: a longitudinal instability is observed for bunches with an intensity above 15×10^{10} particles [10].

Tevatron : Rapid cycling of the machine is impossible due to the superconducting magnets. The machine remains at injection energy while transfers are tuned up which typically takes 3 h. The proton and $\bar{p}$ injection cycle takes 500 s, acceleration to 900 GeV takes about 30 s, and the low beta squeeze an additional 150 s. As in the SPS, during this time beam losses and emittance blow up are caused by particles touching resonances, the significantly longer times associated with each step in the process requiring very detailed tune and chromatic control. A typical emittance growth of 3 π mm-mrad is observed from injection to collisions. For the Tevatron resonances of order 2 to 7 have to be avoided. These resonances are excited by nonlinearities of the magnetic field in the superconducting magnets. A significant contribution to the tune spread is also due to the behaviour of the superconducting magnets: Sextupolar field components created by the persistent currents in the superconducting magnets change the chromaticity. Together with the momentum spread in the bunch, this yields a tune spread which has to be compensated. These magnetic fields depend not only on the magnetic history (hysteresis) but also vary with time. These persistent current effects contribute to the performance limitation of the Tevatron and are discussed in a later section. The effects of space charge detuning at an energy of 150 GeV are negligible, while the tune spread caused by the beam-beam effect is independent of the beam energy. A total linear tune shift on the $\bar{p}$ exceeding a value of 0.02 - 0.025 leads to a deterioration of the machine performance. In this case emittance growth and losses of $\bar{p}$ are observed, at 150 GeV, during ramping and squeezing. The proton bunch intensities are limited to 5.5×10^{10} to avoid these problems. Single proton bunch intensities of twice this value have been obtained during study periods and are limited by longtitudinal phase space dilution during the bunch coalescing process.

4 Storage

For the largest integrated luminosity both initial luminosity and luminosity lifetime have to be optimized. For an acceptable lifetime the particles have to be kept free from dangerous resonances, in the case of the SPS these are all resonances up to order 10. i.e. if the beam is placed onto 10th order resonances the lifetime is reduced to a few minutes. To limit the tune spread to the available space between 10th and 3rd order resonances, the beams are separated at 9 of the 12 interaction points. The tune diagram in store is shown in fig.3. During normal operation the SPS is not limited by the beam-beam effect, while this is the major limitation in the Tevatron. In this machine, with proton bunches of maximum intensity and minimum emittance the linear tune shift exceeds a value of 0.03 and some of the $\bar{p}$ are shifted onto resonances of order 7. This not only leads to emittance growth and losses at injection, but also to a reduced luminosity lifetime in store. To limit the tune spread of the $\bar{p}$ it has been operational practice to blow up the proton beam emittance by about 20 %. The tune diagram is shown in fig.4. The total tune shift in the

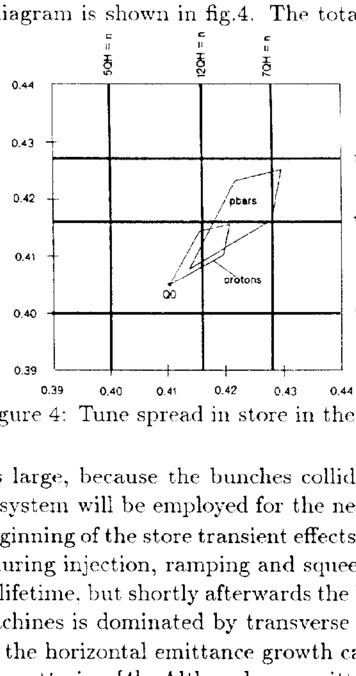

Figure 4: Tune spread in store in the Tevatron

Tevatron is large, because the bunches collide at 12 points. A separation system will be employed for the next run in 1991.

At the beginning of the store transient effects due to beam halos produced during injection, ramping and squeezing dominate the luminosity lifetime, but shortly afterwards the luminosity lifetime in both machines is dominated by transverse emittance growth. In the SPS the horizontal emittance growth can be explained by intra-beam scattering [4]. Although no emittance growth is expected in the vertical plane because of the vanishing dispersion, a small growth has been observed which is probably due to coupling. Before the 100 MHz RF system was used, the luminosity lifetime was limited to about 7 h at the beginning of a store. With the 100 MHz and the 200 MHz RF systems together, the bunches can be shaped within certain limits (see fig.5). With the additional voltage of the 100 MHz system the bucket area is increased. Larger emittance bunches can be injected and the peak density of the particles can be reduced. The use of the 100 MHz RF system not only improved the transmission, but also led to an increase of the luminosity lifetime from 7-8 h to a value of about 10-12 h at the beginning of a store. The measured emittance growth in the Tevatron for the bunch parameters already quoted is 0.32 π mm-mrad/h for the proton bunches and 0.27 π mm-mrad/h for the $\bar{p}$. Intrabeam scattering calculations have been performed using three different models [5] with measured

Figure 5: Bunch shape with both 100/200 MHz RF system in the SPS. The bunch is 6.5 ns long.

bunch parameters. While the calculations are consistent (agreement at the 25 % level), the predicted transverse growth rate is only 0.1 - 0.15 π mm-mrad/h. In addition, growth rates similar to those at high intensity have been measured at lower intensity, therefore another mechanism is needed to satisfy the observations. Possible candidates include the low beta quadrupoles and the experimental toroidal fields both of which have been shown to produce coherent excitations [6]. The bunch intensity lifetime of about 200 h is consistent with beam gas scattering and interactions at the collision point. The longitudinal emittance growth of 0.06 eVs/h agrees well with the intrabeam scattering calculations.

5 Beam-Beam effects

In this section we discuss some observations on the beam-beam effect in greater detail. The observations from the SPS and from the Tevatron both indicate that the tunes must be kept between resonance. These depend on the working point and are for the SPS the 3rd and 10th and for the Tevatron the 5th and 7th. In the SPS resonances with an order above 4 are mainly excited by the beam-beam effect, whereas in the Tevatron the influence of the multipoles of the superconducting magnets is felt up to order 7. The resonances limit the total linear tune shift, i.e. the sum of the linear tune shifts over all interaction points, to a value between 0.02 and 0.03 for both Tevatron and SPS. There is no indication, that the maximum possible tune shift for one interaction point is limited to a lower value, as it is usually quoted for e+e- colliders. In the Tevatron a maximum tune shift for one interaction point of about 0.0025 has been reached, in the SPS about 0.007.

In both colliders it has been observed that the beam emittances can grow or decrease. From observation in the SPS it is known that both behaviour can arise from the beam-beam effect:

- If a particle with a small amplitude is touching a resonance, the amplitude increases, the tune changes (decreases). The particle moves away from the resonance until it reaches an amplitude where its motion is stable. In this case an emittance growth is observed. No particles are lost.
- If the particle with a large amplitude is touching a resonance, its amplitude increases. The detuning is small, the particle remains in the unstable region, the amplitude increases until the particle is lost. In this case an emittance reduction together with particle losses are observed.

For resonances of high order the resonance width function increases with amplitude [7]. If one beam has a much larger emittance than the other beam, the particles in the larger beam are more susceptible to resonances of high order, as it has been observed in the SPS collider run in 1987 : In this period the proton emittance was about four times larger than the $\bar{p}$ emittance which reduced the proton lifetime to less than 10 h and created unacceptable background conditions for the physics detectors. Although the tune shift on the $\bar{p}$ was 3 times higher, only the protons were affected. The cause of this effect were resonances of the order 13 and 16. In the 1988/89 runs the proton emittance was reduced to a value only slightly larger than the $\bar{p}$ emittance, and this effect disappeared. To further understand the dependence of the beam-beam effect on the emittances, a series of experiments was done [8]. One of these experiments is discussed in the following: with one proton and one $\bar{p}$ bunch the lifetime of the bunches and the background rate in the physics detectors was measured as a function of the horizontal tune. The background rate is a good measure of the beam stability, and the rate can be separately observed for protons and $\bar{p}$. The linear beam-beam tune shift on the protons was 0.001 during this first scan. Then a part of the $\bar{p}$ bunch was scraped without touching the protons. This reduced the $\bar{p}$ emittance and intensity. After the scraping the linear tune shift on the protons was 0.0006 and the tune scan was repeated. In the first scan only a small increase of the background rate created by the protons in the region of the 16th order resonance was observed, after the scraping this rate clearly increased and the proton lifetime decreased (fig.6). This experiment shows that it is not sufficient to parametrize the beam-beam effect by only the linear beam-beam tune shift. In particular in the case of unbalanced emittances particle losses due to resonances of high order depend on the ratio between the emittances of the two beams. The Tevatron usually operates with

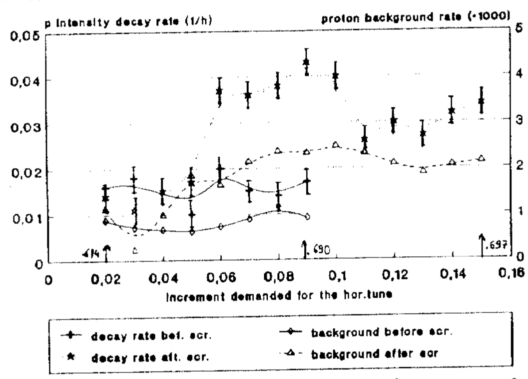

Figure 6: Intensity decay and background rate as a function of Q_h in the SPS

two beams of different emittances. This is a consequence of the controlled proton emittance blow up to limit the linear tune shift on the $\bar{p}$ at the beginning of a store. The beams are placed onto resonances of order 12, and until now no strong adverse effects have been observed from these resonances. From the experience in the SPS one would have expected to suffer from them. Why not in the Tevatron ? :

- The 12th order resonance might be weakly excited.

- Protons with large amplitudes might not touch this resonance, this assumption is supported by the tune spectra of protons and $\bar{p}$ (see fig.7, [11]).

- From experiments on dynamic aperture is has been clearly demonstrated that tune modulation enhances the effect of resonances [9]. It is conceivable. that the Tevatron during storage conditions exhibits less tune modulation than the SPS since a single low voltage power supply provides the magnet excitation to the superconducting ring.

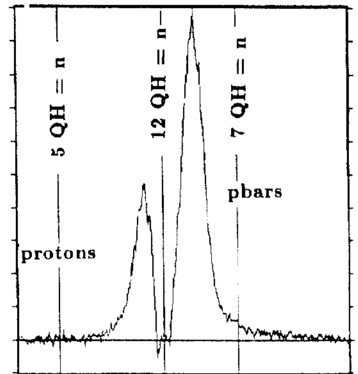

Figure 7: Proton and $\bar{p}$ tune distributions in the Tevatron [11]

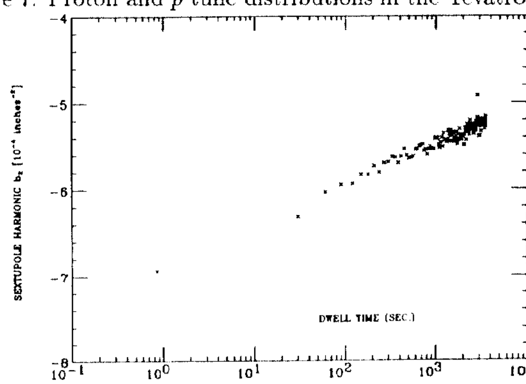

Figure 8: Slow time drift of sextupole harmonic for superconducting magnet

For a further understanding of 12th order resonances more experiments in the Tevatron are needed. A common picture of the beam-beam effect for both colliders is extremely valuable in view of the future projects.

6 Time dependent persistent currents

Persistent current effects in superconducting magnets produce a strong multipole component to the magnetic fields in the allowed harmonics [12]. The phenomonon is strongest at low fields and is highly non-linear in magnet excitation and temperature. The multipole fields also exhibit slow time drift which follows a ln(t) dependance. Fig.8 shows the sextupole harmonic of a Tevatron dipole over a 60 minute period after ramping down to injection energy. A variation of this magnitude corresponds to a change in machine chromaticity of 60 units, thus this is a very large effect if uncompensated (the chromaticity is defined as $\delta Q/\delta E \times E$). The other field harmonics demonstrate a similar behaviour. The slope and intercept of this curve can change significantly depending on the 'history' of the magnets, where 'history' includes the number of ramps prior to setting at injection energy, the length and value of flattop excitation, and the ramp rate. As well as this slow time drift, there is a rapid change at the onset of acceleration where the multipoles effectively recover from the prior decay, this is shown in fig.9. The Tevatron is only operationally sensitive to the sextupole component in the dipoles due to the relatively high injection energy (150 Gev) and the large magnet aperture (coil diameter 75 mm). Based on both magnet and accelerator data an algorithm was developed to provide feed forward compensation to the chromaticity for both the slow time drift and the rapid variation at the onset of acceleration. The sextupole settings are adjusted on a 120s cycle. The 'history' of magnets is set by ramping a fixed (6) number of times when recovering from a store to

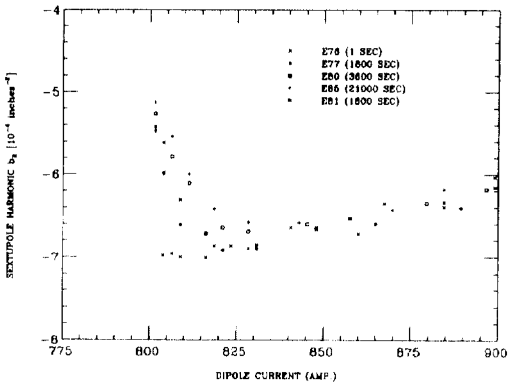

Figure 9: Sextupole harmonic for superconducting magnets at start of acceleration

sit at injection energy for the start of the next shot. Transient effects and the most rapid time variation are avoided by the simple expedient of waiting 15 mins before injecting the first beam. Under these conditions, the feed forward technique stabilizes the chromaticity to 5 units i.e. a 90% correction of the full effect. 'History' effects are still apparent in extreme situations; recovering from a quench condition and exiting gracefully from a store will produce an additional 5 units of chromatic variation in spite of the reset ramps.

Improvements over the feedforward compensation will be needed both at the Tevatron for higher luminosity operation, and for the next generation of hadron colliders. Real time feedback systems based on continuous monitoring of the chromaticity by RF frequency modulation of the beam are feasible but undemonstrated. Correcting higher order multipoles than sextupole could be accomplished by a feedback system using direct field measurements with an harmonic probe in a reference magnet running in series with the accelerator elements. Potential problems with this technique arise from the capability of using a single device to represent the behaviour of a ring wide ensemble of magnets and their temperature environment.

7 Conclusions

The concept of hadron colliders, demonstrated so successfully by the ISR and over the past decade by the SPS, has been more recently extended into the regime of superconducting accelerators at the Tevatron. The fundamental issues of beam dynamics are relatively well understood and a coherent picture of hadron colliders is emerging. The basic limitation to the production of very high luminosities is the beam-beam effect which requires the avoidance of resonances of order 10-16 in the working diagram to ensure adequate lifetime. There are indications that superconducting accelerators may be less sensitive to the highest order resonances than conventional ones. Working points close to the integer may tolerate larger beam-beam tune shifts than those demonstrated to date. The useable single bunch intensities are limited by the intrabeam scattering process diluting the phase space densities. Bunch shaping techniques are effective at the factor of two level. For the next generation colliders both the effects of the beam-beam interaction and intrabeam scattering can be alleviated by the use of many weak bunches colliding only at the experimental regions rather than a few very dense ones.

The major difference between the SPS and the Tevatron concerns their performance at low energies, where the time dependance of the persistent currents fields in the superconducting magnets presents major problems. Future colliders with their long fill and acceleration times will also be sensitive to these effects. It is crucial that a detailed understanding of the magnet performance is available at the design stage of future accelerators to ensure sucessful performance. Operational experience in the more demanding regime of the HERA accelerator will be welcome in this regard.

With the understanding and experience gained from currently operating machines, soon to be joined by the HERA project, we can be confident that a solid framework of knowledge has been established to allow us to approach the future colliders with assurance.

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References

[1] B.Autin et al.,Antiproton Accumulator Complex Performance, these proceedings.
J.Peoples, AIP Proc.184,Vol.II, p.1846, 1987.

[2] D.Boussard, T.Linnecar, The 100 Mhz RF system for the CERN Collider, EPAC 1988, Rome, 7-12 June 1988.
T.Linnecar, CERN-SPS/RF-Note 89-4, 1989.

[3] D.Boussard, Long.Head-Tail Instability in the CERN-SPS Collider, these proceedings.

[4] L.Evans, 12th International Conference High-Energy Accelerators, Batavia, 1983, p229.

[5] D.Finley, Fermilab Note TM-1646, December 1989.

[6] D.Herrup et al., 1989 IEEE Particle Accelerator Conference, Chicago, Volume 3, p.1824.

[7] L.Evans, The Beam-Beam Interaction, CERN SPS/83-38.

[8] K.Cornelis, M.Meddahi, R.Schmidt, The Beam-Beam effect in the SPS...., these proceedings.

[9] D.Brandt et al., Influence of Power Supply Ripple..., on the dynamic aperture of the SPS..., these proceedings.

[10] L.Evans, $p\ \bar{p}$ in the SPS, International Conference High-Energy Accelerators, Novosibirsk, August 7-11, 1986.

[11] G.Jackson, 1989 IEEE Particle Accelerator Conference, Chicago, Volume 3, p.860.

[12] D.A.Finley et.al., IEEE Particle Accelerator Conference, Pg.151 March 1987.