

A SURVEY OF COLLECTIVE INSTABILITIES FOR ELECTRON, PROTON
AND ANTIPROTON BEAMS IN THE SPS

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Summary

The CERN 400 GeV proton synchrotron (SPS) will be used as a 270 GeV proton-antiproton collider in the near future, and later as a 22 GeV electron/positron injector for LEP. New RF cavities with considerably higher shunt impedance will be installed for both schemes. The stability of the bunches under these conditions has been investigated using the computer program BBI which calculates a number of beam dynamical aspects.

Introduction

The computer program EBI¹ originally conceived to calculate electron beam instabilities, has been extended to include bunched proton beams and renamed BBI for bunched beam instabilities. It is essentially based on F. Sacherer's theory² but includes a number of additional beam dynamical calculations such as potential-well and turbulent bunch lengthening, Laslett tune shifts and intrabeam scattering.

Table 1

Impedances assumed

Longitudinal	f [MHz]	Q	Z (MΩ)
Existing 18 cells of TW structure	200.222	137	4.7
Additional 64 cells of SW structure	200.3982	40,000	460
BB impedance of vacuum chamber	1300	1	0.45
First higher mode of TW (damped)	629	1000	0.865
First higher mode of SW (undamped but staggered)	340	3000	10.7
Transverse			Z (MΩ/m)
BB	1300	1	17
First damped higher mode for TW	461	840	38
First undamped higher mode for TW	939	25,000	149
First undamped but staggered SW mode	373	3000	140

The basic input to the program, besides machine and beam parameters, are a number of resonant impedances which have to be chosen judiciously to represent the effect of the beam environment. Usually, we take as first impedance a low-Q, high frequency resonator which is adapted to the (measured) low frequency inductance of the machine. This broad-band impedance (BB) is considered to represent the combined effect of all incidental cross section variations of the vacuum chamber. In addition, we take high-Q resonators such as the fundamental and the lowest undamped higher mode of the travelling wave RF structure (TW), or the additional standing wave cavities (SW). Both the longitudinal and the transverse impedances have to be specified, and been measured or estimated by G. Dome and J. Gareyte (Table 1).

Proton-antiproton collider

Later during this year, the SPS will be operated both in its standard mode as a 400 GeV proton accelerator and as a 270 GeV proton-antiproton collider. In the standard mode 2.5×10^{13} particles are injected at 10 GeV into 4620 bunches and accelerated to 400 GeV in a cycle time of about 10 seconds. In principle, the injection energy could be raised to the top energy of the PS and the transfer line (26 GeV), but the fact that the transition energy of the SPS is near 22 GeV would cause new problems.

For operation as a proton-antiproton collider, initially three, and later six, bunches of 10^{11} particles each are to be injected at 26 GeV and will be accelerated to the maximum DC energy of 270 GeV. The particles should circulate for some 24 hours with minimum blow-up and loss. Hence very slow instabilities and diffusion mechanisms become important. In particular, the RF noise diffusion³ must be reduced, not only by optimising the RF source but by increasing the RF voltage. This will require additional RF cavities, which may be high-Q standing wave cavities since they are only needed at constant energy. However, their effect on beam stability in the standard operation mode needs careful investigation.

Fig. 1 shows how during normal operation the standing wave cavities can excite multibunch instabilities which peak when the cavity frequency falls on a mode:

$$(h+n)f_0 + m f_s$$

where $h = 4620$ = harmonic number of the SPS
 $f_0 = \beta c / 2\pi R$, where $R = 1100$ m
 m, n are the mode numbers

Since f_0 changes rapidly during early acceleration many such peaks are crossed. The frequency shifts due to two of the modes are shown. The spread in synchrotron frequencies within the bunch, $\delta\omega$, is too small to appear on this graph and thus cannot provide damping. A considerable external damping is therefore required and both the shunt impedance and Q of the standing wave cavities must be reduced if the normal SPS beam is to be protected against the SW cavities.

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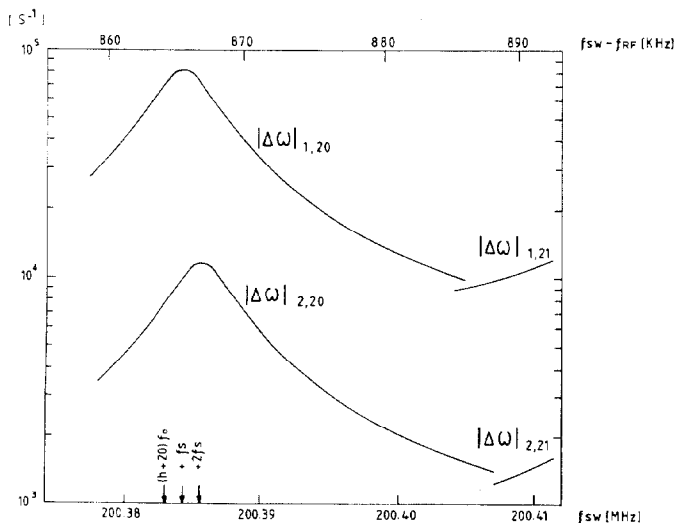


Fig. 1 Frequency shift of multibunch mode $|\Delta\omega|_{m,n}$ for 2.5×10^{13} protons in 4620 buckets at 10 GeV/c, $V = 2.0$ MV, $\phi_s = 0$, $\sigma_s = 0.34$ m.

Fig. 2 shows how the frequency shifts can be brought close to the level at which they may be Landau damped by the frequency spread with damping of a factor of several hundred. However, before this occurs the next longitudinal mode of the cavity becomes important and this must also be damped.

We cannot ignore the effect of the standing wave cavities on the antiproton bunches as they are accelerated from 26 to 270 GeV. Here again Fig. 3 shows the instability to be above the spread. One may hope to damp the cavities until they are needed at high energy but the broad band impedance of the vacuum chamber still gives a real frequency shift which for shorter bunches negates Landau damping leaving the beam prone to higher order instabilities.

Fig. 4 shows multibunch modes for 270 GeV anti-protons as a function of bunch length due only to the broad band impedance. The stable length is above the RF diffusion limit of 0.2 m. Feedback on modes $n = 1$ and 2 together with the higher voltage from the cavities will help, but there is a danger that the real shift will remain above damping.

With the impedances assumed, the beams were always stable against transverse oscillations, and Laslett tune shifts as well as intrabeam scattering⁴ were generally found acceptable.

SPS as LEP injector

In order to minimize the costs of the LEP project, it is proposed to use the existing CERN proton synchrotrons to accelerate also electrons and positrons. In particular, the SPS will be required to accelerate up to 3×10^{11} electrons or positrons in four bunches from 3.5 GeV to 22 GeV. Since already the radiation loss per turn is about 28 MeV at top energy, the installed RF voltage of 5 MV is obviously inadequate. At present, it is foreseen to use up to 64 standing wave cavities which would provide a total of 52 MV at 200.4 MHz. Because of the large impedance (460 MΩ) presented by these cavities, they must be damped (and/or compensated) during operation of the SPS in the standard or proton-antiproton mode. All our calculations assume the full number of extra cavities although smaller complements are being considered. A smaller number of cavities does not change qualitatively the problem of damping. In the "interleaved

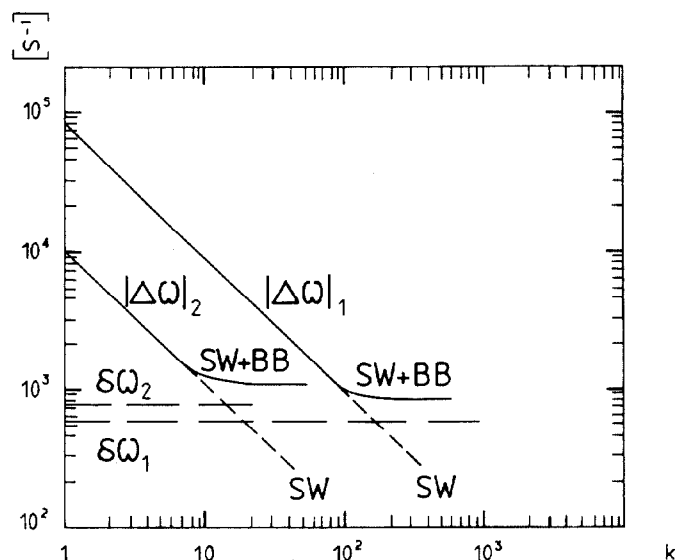


Fig. 2 Effect of damping SW cavities in Q and Z by a factor k for Fig. 1 parameters.

mode", rapid switching between operation of the SPS from LEP injector to proton accelerator must be possible and this will require a fast operating mechanism.

Since the electrons or positrons remain only a few seconds in the SPS only rather fast instabilities are of concern for these particles. Besides a certain amount of bunch lengthening, they appear to be stable when the RF is properly tuned.

Fig. 5 shows the instabilities to be expected at 3.5 GeV as electrons are injected. Radiation damping is even faster at higher energies.

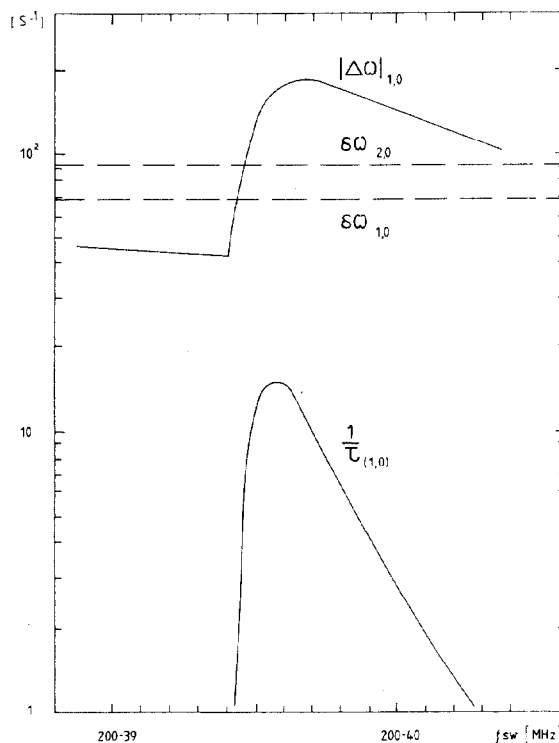


Fig. 3 Frequency shifts, inverse growth rates and Landau spreads for 6×10^{11} anti-protons in 6 bunches at 270 GeV. $V = 5$ MV, $\phi_s = 0^\circ$, $\sigma_s = 0.3$ m.

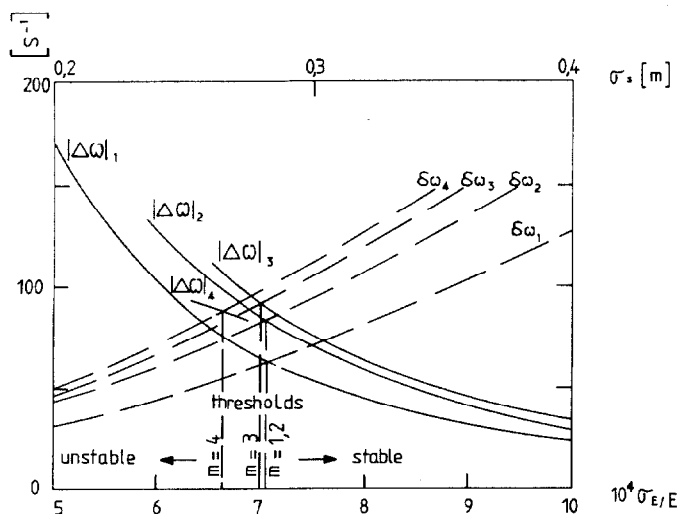


Fig. 4 Variation of shift and Landau spread for $n = 2$ to 5 modes as a function of bunch lengths for 6×10^{11} antiprotons in 6 bunches at 270 GeV. $V = 5$ MV.

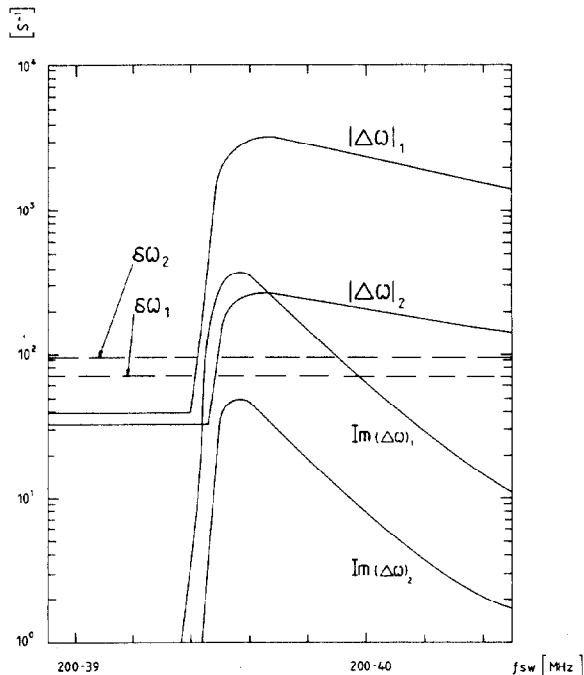


Fig. 6 1.4×10^{13} protons in 140 bunches at 270 GeV/c for e-p with LEP, $\sigma_s = 0.3$ m, $V = 5$ MV.

Electron-proton collisions

Once LEP has come into operation, it will be possible to collide the electrons in that machine with protons in SPS bypass. For a good luminosity of these collisions, one needs about 140 bunches of 10^{11} protons each in the SPS. While this project is still in the far future, we have made a first attempt to calculate the stability of the proton bunches under these conditions. Some results are shown in Fig. 6.

Conclusions

Operation of the SPS in its standard mode as 400 GeV proton accelerator will require strong damping of additionally installed high-Q cavities used for proton-antiproton or LEP injector operation. In the proton-antiproton mode, the bunch length is a very critical parameter and a compromise may have to be chosen between the minimum length required for stability and the reduction of lifetime with increasing length due to RF noise diffusion. In general electrons are stable.

References

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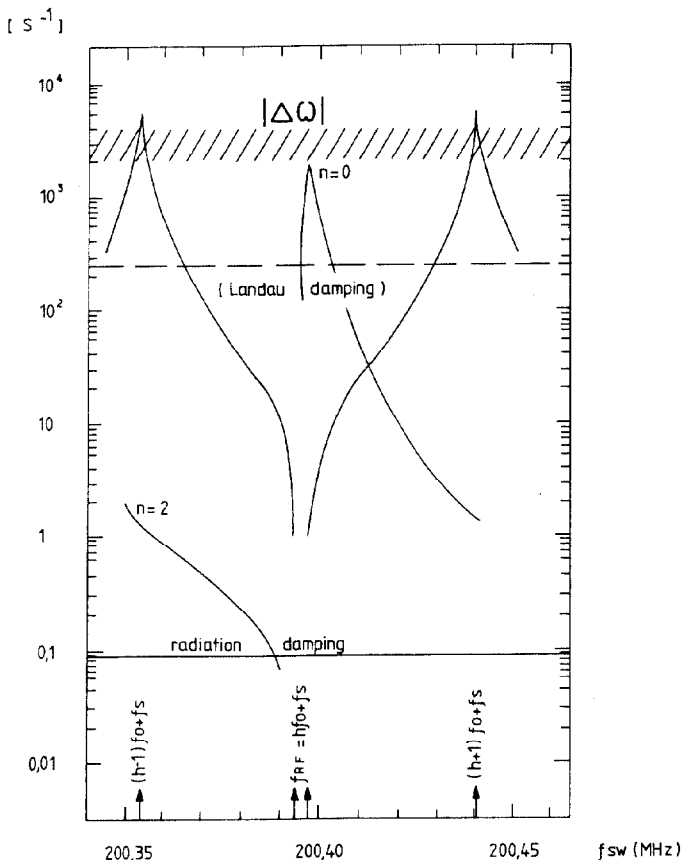


Fig. 5 Instabilities for 3×10^{11} electrons in 4 bunches at 3.5 GeV/c for LEP filling.