TUNING THE CERN PROTON SYNCHROTRON TO FULL DESIGN INTENSITY

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The designers of the SPS, mindful of the effects of non linear fields and collective instabilities in other proton synchrotrons, foresaw careful control of the multipole content of the guide field. Tight tolerances were placed upon magnetic purity and a large number of special multipole correction magnets installed. This paper describes how these and other devices were used during the running in of the accelerator in experiments which brought the SPS to its design intensity of 10^{13} protons per burst only six months after switch on. Future improvements are discussed.

1. The SPS Design

Apertures for the separated function FODO lattice[1] of the SPS[2] were determined by adding ±5 mm vertically and ±10 mm horizontally to the bare emittances predicted for the CPS after improvement to deliver 10^{13} protons per pulse. In practice these safety margins proved adequate for the residual closed orbit distortion after correction[3].

A detailed theoretical study[4] of the machine, once parameters had been fixed, alerted SPS designers to the dangers of non-linear fields, both in exciting stopbands and in modifying the natural chromaticity of the machine in a way which varied with B, the guide field. These effects, which scale up with Q and β become particularly worrisome in synchrotrons as large as FNAL[5] and the SPS[6].

To keep stopbands down to widths which still leave clear space in the working diamond, field tolerances at the edge of the aperture in dipoles were set at $\delta B/B < 10^{-4}$ and in quadrupoles of $\delta K/K < 5 \times 10^{-3}$. Particular attention was paid to the systematic sextupole component inevitably present at low field due to the remanent field shape of the lattice dipoles and eddy currents in the vacuum chambers. Even so, it proved necessary to order two sets of 36 equally spaced sextupoles to compensate the changes in chromaticity due to these sextupole fields[7]. Uncorrected, the Q spread would otherwise have been much larger than the distance between second and third order stopbands.

Many other small individually powered multipole corrections were installed with the intention of compensating stopbands but so far only skew quadrupoles, to correct coupling on the $Q_H = Q_V$ diagonal, and normal quadrupoles, to compensate neighbouring half integer stopbands have been used, the latter only in machine development studies.

It was foreseen[4] that the low frequency transverse coupled bunch instability, the resistive wall effect,would be a danger at high intensity. Six powerful Landau damping octupoles were installed to suppress this instability up to 400 GeV.

During construction, as empirical information became available from FNAL, the wisdom of these precautions was confirmed. In addition we came to fear the single bunch head tail transverse instability at low energy and planned to use a negative chromaticity offset to suppress this effect [8]. At high energy we expected the octupoles would provide sufficient damping as they had in the CPS. Another idea which we imported from FNAL was the use of a 0 to 2 MHz transverse feedback system as a more elegant means of suppressing the resistive wall effect[9]. The tuning of the SPS to high intensity during the second half of 1976 followed closely the pattern we had foreseen[10].

2. Resonances and Field Tolerances

An early scan along the main $Q_H = Q_V$ diagonal (Fig. 1) showed that there were indeed extensive high transmission plateaus between stopbands. This was confirmed by later scans with rf on and after chromaticity correction. Apparent in these subsequent scans was a depression at 27.6 at a fifth order systematic stopband which conventional wisdom had at first led us to discount. We were not unprepared, however, since the FNAL working point had had to be displaced because of just such a resonance. One presumes that the remanent field of the dipoles contains sufficient decapole mixed with its sextupole, and broken by the sixfold superperiodicity of the lattice, to excite these stopbands at 5Q = 23 x 6.

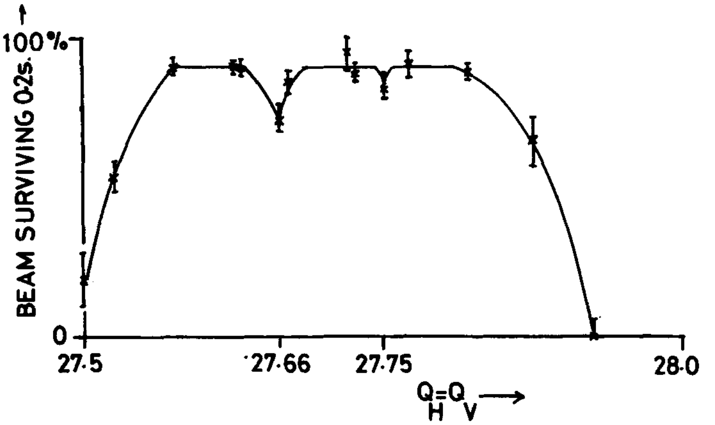

Fig. 1. Coasting Beam Survival for 200 ms at 10 GeV along $Q_H = Q_V$ Diagonal

Like FNAL we moved the nominal Q to 27.4 and later, for practical reasons connected with slow extraction, to 26.6. At both these lower working points one can kick the beam by ±15 mm vertically and ±35 mm horizontally before its 10 GeV half life drops to less than 1s. Close to 27.6 the kicks can only be half as large.

3. Chromaticity

The two sets of 36 sextupoles, one at high vertical β locations, the other where the horizontal β is high, proved effective in compensating the natural, remanent and eddy current terms in the chromaticity. Fig. 2 shows a first measurement of uncorrected Q_H versus radial displacement at injection. The linearity is gratifying. By repeating this measurement near transition and at high field we were able to disentangle the three components of chromaticity and compensate them with the sextupoles, their power supplies following a digitally generated waveform. The three components agree well with estimates made on the basis of the careful measurements of all 744 dipoles as they were assembled.

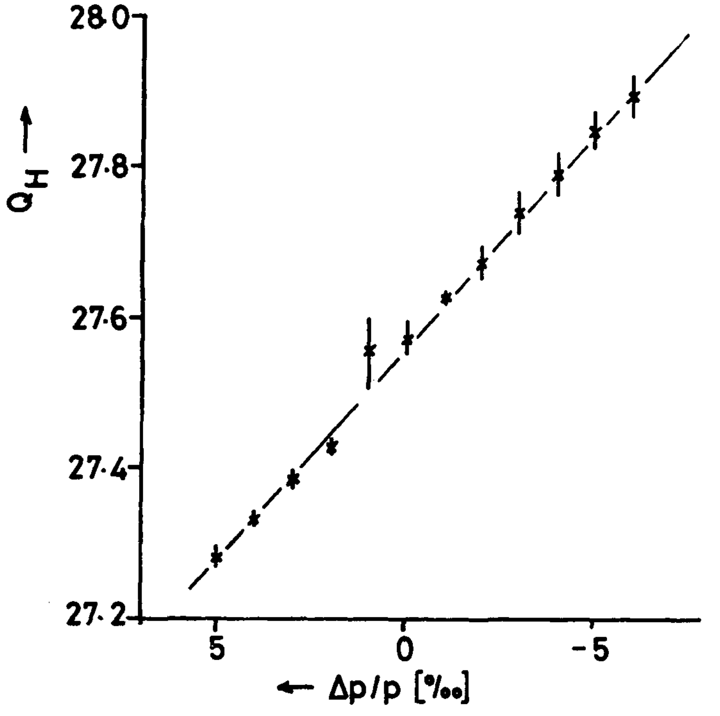

Fig. 2. Change in Q_H as the SPS Guide Field is Detuned - Slope is a Measure of Chromaticity

4. <u>Resistive Wall Effect</u>

This became apparent in injection studies at 4 x 10^{12} once the chromaticity had been made zero even before the SPS had accelerated. We used the Landau damping octupoles, and later the active beam dampers to remove this instability. Without these measures, one cannot accelerate more than 3 x 10^{12}.

5. <u>Head Tail Instability</u>

At 5 x 10^{12} before acceleration, the ragged bunch pattern characteristic of this instability appeared accompanied by beam loss. Fig. 3 shows how by applying a negative chromaticity bias at injection, transmission is restored and there is a short plateau before the Q spread leads to beam loss to resonances. The amount of offset is fortunately intensity independent. This can be seen from the shape of the second curve in which the CPS beam was extracted in half the SPS circumference.

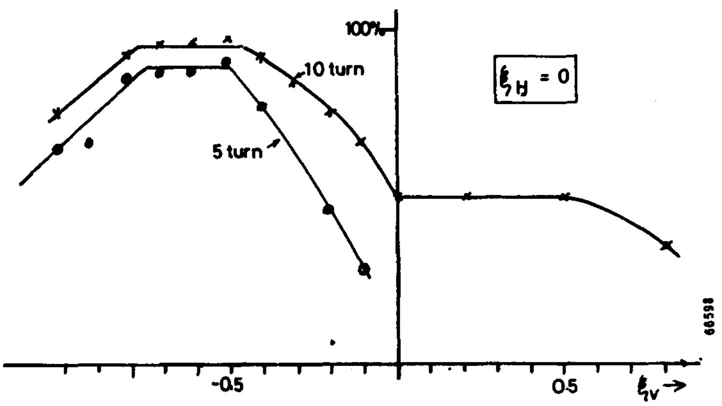

Fig. 3. Injected Beam Survival for 500 ms Improves as Chromaticity is made Negative

A small positive bias above transition suppressed the instability in that region and strong octupoles prevent the reappearance of beam loss due to any further transverse effect up to 400 GeV.

6. <u>Reaching 10^{13}</u>

Unfortunately the CPS, while it accelerates 10^{13} regularly and for sustained periods, has difficulty in accelerating the 10 to 20% extra needed to make up for the inevitable losses in 10 turn extraction and in the 200 Mhz r.f. capture process in the SPS. So, although 8 x 10^{12} has been accelerated with a single CPS load, we had to load two consecutive CPS batches to reach the magic design figure of 10^{13} protons accelerated to 400 GeV. However, this multipluse mode only extends the overall cycle time by 1.2 seconds for each additional pulse and we plan now to make two, and later three, batch multipulsing a part of regular operation. Fig. 4 shows a magnet excitation pulse and beam current trace recorded on the first occasion this procedure was used to reach 10^{13} protons per pulse, less than six months after protons were injected for the first time.

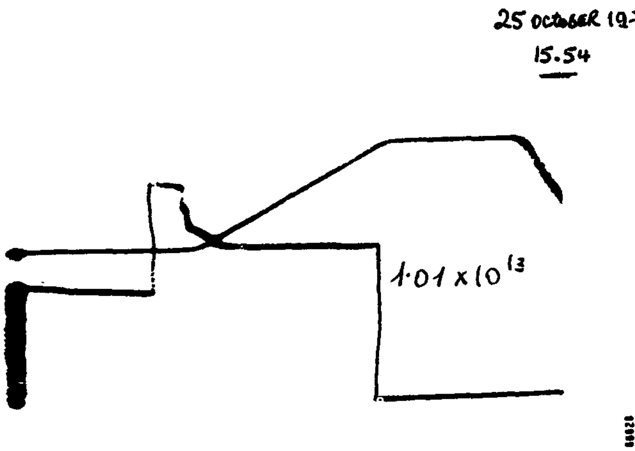

Fig. 4. 2 Batch Injection Produced the Design Intensity

7. Future Plans

Above the design intensity one expects to run into a regime where improvements in the hardware and extensive machine studies are required. One can already see substantial losses in the early part of acceleration in Fig. 4. At least part of this loss has been identified as associated with a quadrupole deflecting mode in the r.f. cavities at 460 MHz which, along with a longitudinal mode at 628 MHz /11/ which tends to restrict intensities when the SPS works with an intermediate flat top at 200 GeV, will hopefully disappear when damping systems now being installed in the cavities become operational. The need to empirically damp parasitic modes seems to be common to all machines with high frequency r.f. systems.

Another effect being studied is a transverse instability which blows up emittance at high energy so that, although 10^{13} protons have been extracted at 200 GeV, operational 400 GeV extracted intensities are typically 6×10^{12} /12/. We have demonstrated by stretching the chromaticity sextupoles to their thermal limit that this blow up disappears if one maintains a slight positive chromaticity up to 400 GeV and present improvements in sextupole cooling will make this operational. It is not yet clear however that this is just a manifestation of the head tail effect blowing up emittance to the point where the octupoles stabilize it. It may very well be due to the 460 MHz transverse cavity mode and therefore be susceptible to a more direct cure.

Before going much higher than 10^{13} we shall have to augment r.f. voltage to overcome beam loading and eliminate the switch from CPS to SPS r.f. frequency which leaves the coasting beam prone to microwave instability 100 mseconds after injection in the SPS. Considerable additional hardware will be required to effect these improvements which will take some time to manufacture and install.

Meanwhile, we are relearning the procedures for tuning the machine at 200 and later 270 GeV with a view to using the SPS as a $p-\bar{p}$ storage ring of as part of a p-e colliding facility. Initial results are encouraging. The SPS vacuum is 5×10^{-9} Torr which should give over 12 hours lifetime at 200 GeV and at 270 GeV, the maximum thermal limit of the magnet power supplies, over 24 hours. We have already reached this lifetime at 200 GeV with beams of 10^{12} protons, with r.f. on and a machine bare of corrections. So far obstacles to storing higher intensities seem to be the need for careful control of Q and chromaticity rather than esoteric instabilities.

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ДИСКУССИЯ

Э.С.Масунов: Какие трудности (в смысле проявления неустойчивости сбанчированного пучка) возникают при переходе на рабочую частоту 200 МГц?

E.J.Wilson: We always expected to have to identify and damp higher cavity modes at high proton intensity. This proves to be the case. It was also necessary, incidentally, with the Fermilab 50 MHz cavities. A longitudinal mode at 628 MHz has been damped. The next one is a transverse mode at 460 MHz. The claims for cheapness and reliability of the 200 MHz system have I think been fulfilled.

Э.А.Мяэ: Используются ли все системы коррекции магнитного поля, которые были подготовлены для SPS ?

E.J.Wilson: We use chromaticity sextupoles and octupoles for Landau damping. Although we also have taken precautions of installing many small multipole correcting magnets, we do not need to use them in regular operation for stopband correction . The exception is a set of skew quadrupoles which we use to compensate coupling at injection. We have also compensated halfinteger stopbands in machine experiments and will perhaps have to do more of this operationally as the intensity goes up.

Э.А.Мяэ: В связи с хорошими результатами по коррекции орбиты в SPS используется ли полностью весь аксептанс ускорителя?

E.J.Wilson: The vertical aperture is full but the horizontal aperture is not filled at injection. Later, when we come to inject several CPS bunches each extracted over a small number of turns we will no doubt find the spare horizontal aperture usefull. In any case we think we were wise to design magnets with poles as wide as we did. A smaller width would have reduced the field quality and left too little room for slow extraction.

П.Р.Зенкевич: Вы сообщили, что в SPS наблюдалась резистивная неустойчивость. Какие есть основания считать, что эта неустойчивость связана именно с конечной проводимостью стенок камеры?

E.J.Wilson: The instability which we name "Resistive wall" is certainly a collective, transverse effect with a frequency spectrum below 2 MHz, which matches the resistive wall theory.