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NON LINEAR FIELDS IN THE SPS AND THEIR COMPENSATION

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Tight tolerances were placed upon non-linearities in the SPS magnet system and sextupoles installed to adjust the chromaticity of the machine. These sextupoles together with octupoles and active damping were used to adjust the SPS beam dynamics and to damp and suppress both multibunch and single bunch transverse instabilities up to 10^{13} protons per pulse.

SPS Field Tolerances

When the SPS first turn beam stopper was raised for the first time we were pleasantly surprised to find the 10 GeV beam coasted without loss for several thousand turns. Apart from indicating that there were no physical obstructions in the vacuum chamber this was the first hint that the SPS geometry and magnetic field purity were even better than we had hoped.

The magnet design and specification had been based upon a table of expected tolerances and field errors drawn up¹ as early as 1972. Throughout the construction we had checked measurements of each magnet as it was made to make sure tolerances were met, updating predictions of the closed orbit distortions due to random dipole errors ($\Delta B/B < 7 \times 10^{-4}$), the chromaticity due to systematic sextupole fields ($\Delta B/B < 2 \times 10^{-3}$ at 60 mm) and the widths of stopbands driven by random multipole errors ($\Delta B/B < 10^{-4}$).

Further confirmation of these predictions came when we scanned the Q of the machine along the $Q_H = Q_V$ diagonal, monitoring survival of the coasting beam. Fig. 1 shows the result with r.f. off. There were clearly large plateaus of high transmission in the working diamond. The influence of the third and fourth order resonances was barely perceptible although, as expected the half integer and integer stopbands killed the beam rather rapidly.

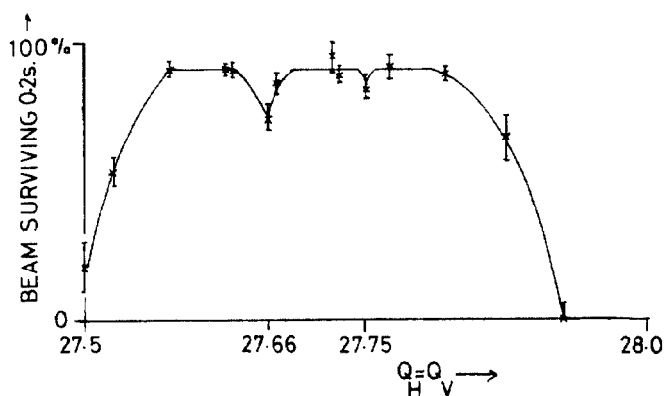


Fig. 1 Coasting beam survival for 200 ms at 10 GeV along the $Q_H = Q_V$ line

The Change of Working Point

Switching on r.f. causes synchrotron oscillations and if there is not perfect chromaticity correction, weak stopbands are repeatedly crossed. The broad

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plateaus of Fig. 1 rapidly shrink and there turns out to be little room for manoeuvre about the nominal working point of $Q_H = 27.6$, $Q_V = 27.55$. We had long suspected that fifth order structure resonances like those at 26.6 in Fig. 2 might cause beam loss with r.f. on.

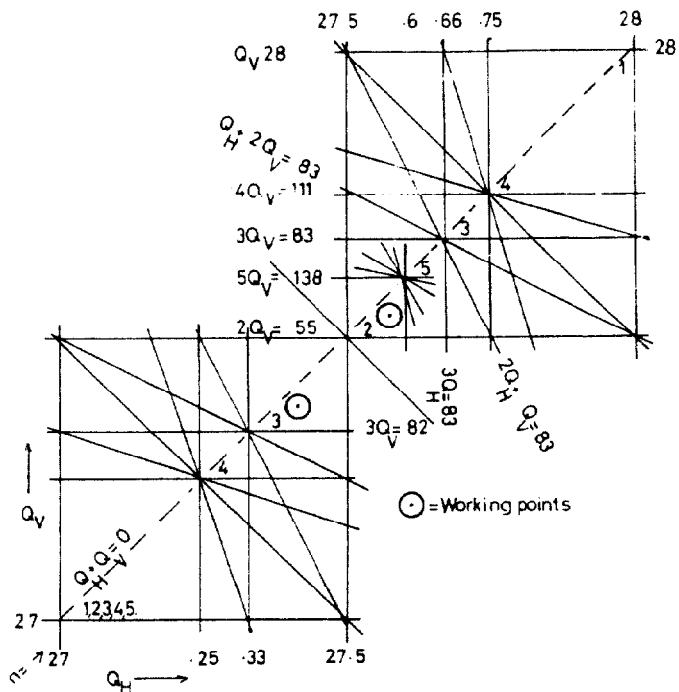


Fig. 2 SPS alternative working points showing fifth order structure resonances $5Q = 138$

At FNAL² we had found that the beam survival at injection was low in the neighbourhood of such resonances and this had caused us to lower the main ring working point by an integer. Presumably such resonances are driven by the weak systematic decapole component inevitably present in the remanent field of separated function dipoles. At the SPS we found a similar depression of 10 GeV beam survival with r.f. on. We went on to compare the two working points in Fig. 2, deliberately inflating the horizontal betatron amplitude by a factor 2 by kicking. Finding survival significantly better and the machine less sensitive to Q variations at the lower working point, we decided to adopt it for normal operation of the SPS.

Chromaticity

One of our first SPS experiments was to measure and correct chromaticity ($\xi = pdQ/Qdp$). Fig. 3 shows the chromaticity components as they develop during acceleration to 400 GeV. They comprise a constant term - the natural chromaticity due to the momentum dependence of quadrupole focussing strength, a term generated by the sextupole component of the remanent field in the dipoles whose influence decays away as the protons accelerate, and a B dependent term - the sextupolar fields generated by eddy currents in the vacuum chamber. The coefficients a, b and c differ in sign and amplitude in the horizontal and vertical phase planes, i.e.

in their effect on Q_H and Q_V .

It would be difficult to build dipole magnets in which the low energy time dependent terms b and c are self compensated.

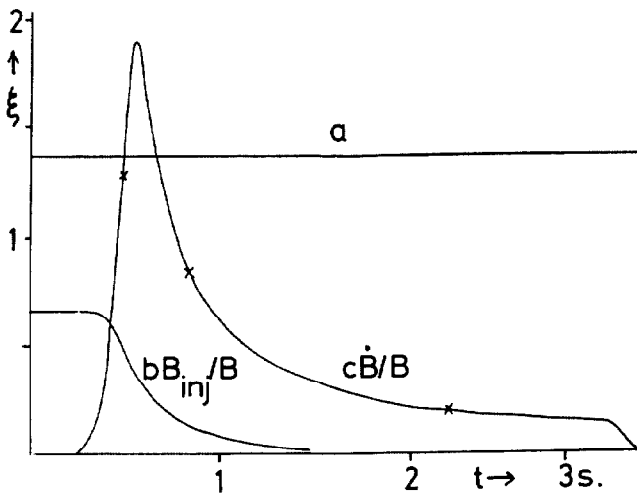


Fig. 3 Components of chromaticity during acceleration in the SPS

Yet uncompensated, and with a momentum spread of 2% from the CPS, these chromaticities lead to Q spreads as large as ± 0.3 . From the start, we had planned to use two sets of 36 series-powered sextupoles. One set at maximum horizontal beta points, near horizontally focussing lattice quadrupoles, had a predominant influence on horizontal chromaticity. The other, at vertically focussing quadrupoles where vertical beta is maximum, influenced mainly the momentum derivative of Q_V . Both sets produce a sextupole field symmetric about a vertical plane. Above 100 GeV the Q spread due to uncorrected chromaticity is rather small. The strength of these elements and power supplies was sufficient to control ξ below this energy. Computer control of their pulsed power supplies allowed us to adjust the coefficients, a , b , c , orthogonally in each plane and balance the SPS chromaticity to zero. A tracking program, LIMATRA had reassured us that 36 equally spaced sextupoles would be a necessary and sufficient number not to excite unwanted stopbands.

Our first measurements of uncorrected chromaticity (Fig. 4) showed a surprisingly good linearity at injection with little or no curvature due to octupole or decapole errors.

Leaving a and c at calculated values we adjusted b in each plane to fit the empirical slope. We then went on to verify, at times indicated in Fig. 3, that the calculated values of a and c were good fits to the curve. Experience shows that b depends on previous hysteresis of the magnet system but can be easily tuned to make the Q spread a few parts per thousand by watching the decay of coherent betatron oscillations.

Resistive Wall Effect

As at FNAL, as soon as the chromaticity of the SPS had been made zero there was so little Q spread in the beam that the resistive wall instability (coupled bunch, low frequency, transverse) began to appear, removing half the injected beam of 4×10^{12} in 50 ms (Fig. 5). Following the same procedure that we had

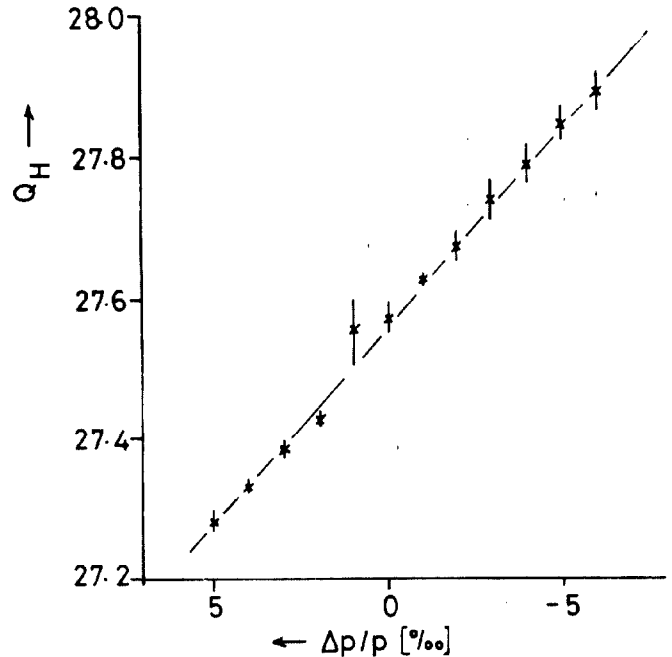


Fig. 4 Change in Q_H as the SPS guide field is detuned - the slope is a measure of chromaticity

used at FNAL³ we first powered six Landau damping octupoles to damp the instability. A considerably smaller $\Delta Q = 0.015$ is needed when one uses octupoles rather than sextupoles for this. Later we brought horizontal and vertical active transverse feedback systems into operation to cure the instability up to 10^{13} protons per pulse. At this intensity the ΔQ necessary from octupoles would have caused significant beam loss.

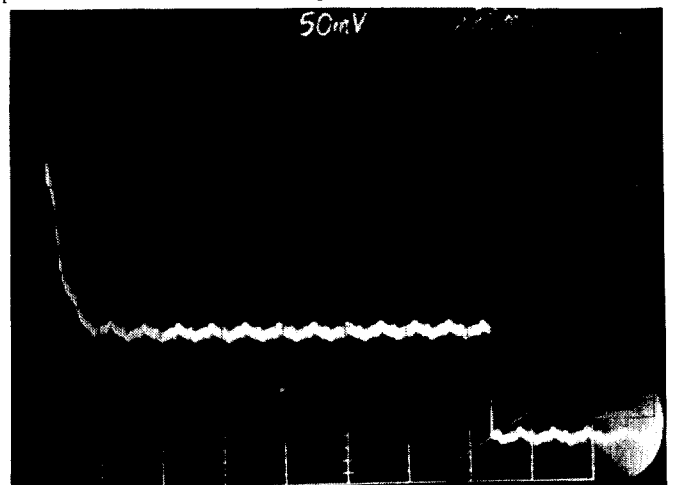


Fig. 5 Sudden loss due to resistive wall instability at injection

Head Tail Effect

Yet another instability had to be suppressed before we reached the design intensity of 10^{13} ppp. The head-tail or single bunch transverse instability, had been seen at the CPS and at Fermilab. The theory of this instability⁴, based on the impedance of the beam pipe at high frequencies, describes this instability qualitatively but does not lead one to expect its

occurrence in large accelerators. Nevertheless we had seen and cured it at FNAL by making the chromaticity somewhat negative at injection. We found that this was necessary in the SPS.

At the SPS the effect first appeared at injection in the vertical plane at about 6×10^{12} ppp. Over half the beam was lost over a second leaving the characteristic ragged bunch pattern of Fig. 6. A negative offset in the ξ_y progressively suppressed the instability and there is a short plateau before the chromatic Q spread leads to beam loss to resonances. Fig. 7 shows suppression to be equally effective when all the protons are extracted over five CPS turns to fill only half the SPS turns thus doubling the charge per bunch.

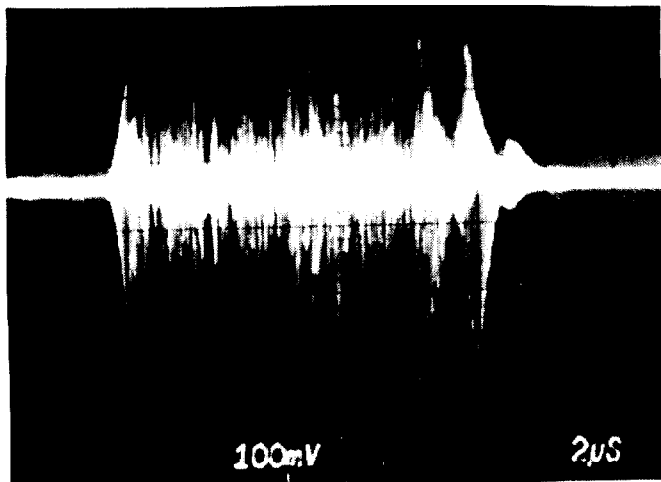


Fig. 6 Ragged pattern of bunches in a single turn intensity display following head-tail instability

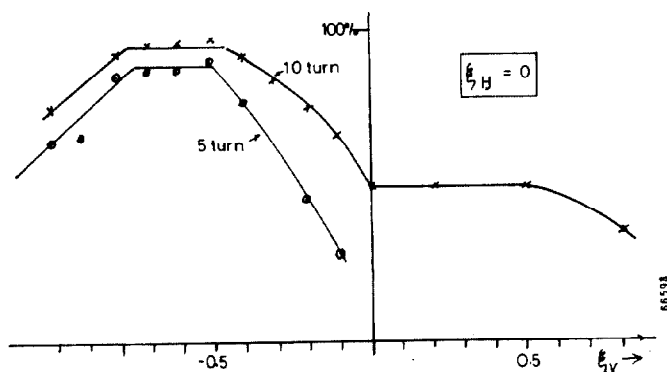


Fig. 7 Injected beam survival for 500 ms improves as chromaticity is made negative suppressing head-tail effect

The SPS, perhaps because of its short bunches, perhaps because of the absence of intrinsic field non-linearity, it particularly sensitive to head-tail ins-

tability. Before accelerating 10^{13} protons we had to make the chromaticity slightly positive above transition and up to 100 GeV where the sextupoles, intended only for correcting single particle effects, became too weak to cancel the natural chromaticity of the machine. Landau damping octupoles, originally intended to combat the resistive wall instability, but now freed by the operation of active damping, proved strong enough to prevent beam loss between 100 and 400 GeV so that we were able to accelerate more than the design intensity of 10^{13} protons.

However, when we came to extract the beam, we found that above 5×10^{12} protons per pulse the head-tail instability, although causing no loss during acceleration, was dilating the emittance before the resulting Q spread from the octupoles became large enough to stabilize the instability. The 400 GeV beam was too big for the extraction channel.

By running the air cooled chromaticity sextupoles well above their design current we were able to demonstrate that the blow up could be prevented by keeping both chromaticities positive up to 400 GeV and we extracted 8×10^{12} . Soon, forced air cooling will allow us to operate continuously in this mode. Later, stronger sextupoles will be installed. Meanwhile, we find that lengthening the r.f. bunch at 200 GeV eliminates the need for either octupoles or sextupoles above 200 GeV, at least up to 5×10^{12} .

Had one been able to predict it, a small positive chromaticity shim on each dipole magnet would have made the task of the sextupoles much easier. This is a point for future accelerator designers to consider.

Once other limitations in longitudinal phase space have been overcome we expect these measures to allow us to accelerate and extract substantially more than 10^{13} protons per pulse by injecting more than one CPS cycle before accelerating in the SPS.

Conclusions

The transverse phenomena in the SPS have been mastered to the point that we have reached the design intensity in spite of unexpected sensitivity to the head-tail instability. The tight magnet tolerances have led to very clean single particle dynamics and encourage us to hope that the full intensity potential of the SPS has not yet been explored. We have not needed to correct stopbands other than the $Q_H = Q_V$ coupling resonances.

References

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