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 thousands of 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 up 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 (ΔB/B < 7 × 10^{-4}), the chromaticity due to systematic sextupole fields (ΔB/B < 2 × 10^{-3} at 60 mm) and the widths of stopbands driven by random multipole errors (ΔB/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.

**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 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.

**Chromaticity**

One of our first SPS experiments was to measure and correct chromaticity \( \xi = \frac{p_dQ}{Qdp} \). 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 \( \delta \) 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.

Yet uncompensated, and with a momentum spread of $\%$ 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 $\xi$ 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 $4 \times 10^{12}$ in 50 ms (Fig. 5). Following the same procedure that we had used at FNAL 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 $\Delta Q$ necessary from octupoles would have caused significant beam loss.

Head Tail Effect

Yet another instability had to be suppressed before we reached the design intensity of $10^{13}$ pp. The head-tail or single bunch transverse instability, had been seen at the CPS and at Fermilab. The theory of this instability, 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 $6 \times 10^{12}$ ppp. Over half
the beam was lost over a second leaving the character-
istic ragged bunch pattern of Fig. 6. A negative off-
set in the $E_y$ 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 pro-
tons 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 insta-
tability. Before accelerating $10^{13}$ protons we had to
make the chromaticity slightly positive above transit-
ion 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 inten-
ded 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 $5 \times 10^{12}$ protons per pulse the head-
tail instability, although causing no loss during accel-
eration, 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 demon-
strate that the blow up could be prevented by keeping
both chromaticities positive up to 400 GeV and we ex-
tracted 8 x $10^{12}$. Soon, forced air cooling will allow
us to operate continuously in this mode. Later, stron-
ger 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 $5 \times 10^{12}$.

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 need-
ed to correct stopbands other than the $Q_H = Q_y$
coupling resonances.

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