1. Summary

It has long been known 1) that there is a dangerous transverse deflecting mode in the RF cavities which can lead to a transverse instability. During the past few months this instability has been identified and is known to become very troublesome above about $6 \times 10^{12}$ ppp. It occurs strongly just after transition and has been successfully damped by octupoles 2). It also occurs at high energy where there is insufficient octupole strength to damp it at present. Moreover, a strong octupole field is undesirable during slow extraction as it seriously perturbs the extraction process.

Fortunately, the cavity resonance at 460 MHz is very sharp so the possibility arises to tune either the mode spectrum of the beam or the cavity frequency in order to minimise the impedance of the cavity as seen by the beam. In particular, by carefully tuning the cavity temperatures the instability could be suppressed above 150 GeV/c without the use of octupoles.

2. Theory

The offending resonance is a transverse deflecting standing wave mode at a frequency $f_0$ of 460 MHz. The Q is very high (30,000), so the 3dB bandwidth defined by $f = f_0/Q$, is only 15 kHz.

The resistive part of the impedance close to the resonance is given by
\[ Z_R(f) = \frac{1}{1 + 4Q^2 \frac{(f - f_o)^2}{f_o}} \]

and is plotted in figure 1.

Now, the beam can be only driven unstable at a quasi-infinite number of frequencies given by

\[ f_n = (n - Q) f_r \]

where \( f_n \) is the frequency of mode \( n \) and \( f_r \) is the revolution frequency (\( \approx 44 \) kHz). Therefore only modes around mode numbers 10'000 which overlap the cavity resonance could be driven. We see from figure 1 that the cavity impedance at a full width of 44 kHz is only \( \approx 10\% \) of its maximum. The possibility therefore arises to displace either the frequency of the cavity or the mode spectrum of the beam in order to minimise the impedance seen by any one of the modes.

This may be achieved by varying any of the following 3 parameters.

(i) **The cavity temperatures**

This is a very interesting method, since the fundamental accelerating mode is wide-band and therefore not affected by small temperature variations. The frequency for the 460 MHz is shifted by 7 kHz/\( ^\circ \)C.

(ii) \( Q_H \)

A change of \( Q \) of 1 integer is equivalent to the displacement of the whole spectrum by 44 kHz.

(iii) **Mean radial position**

This changes the revolution frequency and therefore displaces the mode spectrum. The sensitivity is 0.4 kHz/mm.
This method is useful for investigating the width of the resonance but is of no practical value for the suppression of the stability.

Since there are two RF cavities which resonate at slightly different frequencies, the first method is by far the most attractive because each cavity can be tuned independently to sit between the beam modes.

These considerations only apply when the mode spectrum is stationary. During the early part of acceleration up to ~150 GeV/c the revolution frequency changes by 0.44%, so about 40 modes sweep through the cavity. During this time, the Landau damping octupoles must be used.

3. Experiments

From the measurements carried out by the ARF group, we have the following data concerning the 460 MHz resonance:

Central frequency of cavity 1 at 20°: 460.730 MHz
Central frequency of cavity 2 at 20°: 460.703 MHz.

Thus, for the same temperature, cavity 1 is shifted with respect to cavity 2 by +27 kHz.

The frequency shift corresponding to one degree temperature change is 7 kHz.

The bandwidth of the cavity for the 460 MHz mode is 15 kHz, at the point where the coupling impedance is 3 db down from the peak. This means that the real part of the impedance, which is responsible for the instability, is ±7.5 kHz away from the central resonance, down by 50%. 22 kHz away (half mode separation), the real impedance is only 10% of the peak (Fig. 1).

The experimental procedure consisted in scanning the temperatures of the two cavities and observing the signal picked up by the horizontal fast transverse beam position monitor, as displayed on a spectrum analyser.
tuned at 460 MHz. The instability usually appears at transition and above. For the reasons mentioned in the first part of the report, only the high energy instability (> 150 GeV) was investigated. The measurements revealed an enormous effect of the cavity temperatures on the threshold of the instability: in "quiet" regions, one could run at a beam intensity of $8.5 \times 10^{12}$ ppp without the need of any damping octupoles; for other ranges of temperature, the maximum available octupole strength was not sufficient to stabilize a beam of only $6 \times 10^{12}$ ppp. The experimental results fit rather well with the simple model of the resonant modes sitting at various heights of the real cavity impedances. We found that the instability disappeared completely at $8.5 \times 10^{12}$ ppp when the cavity temperatures were nominally set at $T_1 = 20^\circ$, $T_2 = 24^\circ$ (the subscript 1,2 refer to the cavities).

This result can be easily justified by plotting the cavity impedances and the resonant modes on a frequency axis (fig. 1). The peaks of the two cavities are spaced by 27 kHz (separation for equal temperature) + 4 x 7 (4 degrees temperature difference) = 55 kHz.

With this separation, it is possible for consecutive modes to sit at low values of the impedance (about a factor 5 down with respect to the peak of the impedance of a single cavity). The location of the modes was calculated theoretically and confirmed experimentally by the observation of the strength of the instability for different values of the cavities frequency separation. In fact, for the mode number 10648, the resonant frequency is, for a $Q_H = 26.62$ at 150 GeV/c,$(m - Q)f_{\text{rev}} = 460.701$ MHz.

From fig. 1, we see that the frequency of the middle mode is 27 kHz lower than the peak of cavity 1 at $20^\circ$; thus $f_{\text{mode}} = 460.703$, in excellent agreement with the above theoretical value.

Figure 2 shows the resistive impedance pattern corresponding to $T_1 = T_2 = 20^\circ$. In this case, all the beam was lost; again, the experimental result is in agreement with the fact that the peak of the impedance of cavity 2 coincides with one of the mode frequencies.
The accuracy of the temperature gauge used to monitor the cavity temperatures is probably no better than \( \pm 0.5^\circ \), corresponding to \( \pm 3.5 \) kHz. This measurement error has little effect on the determination of the optimum (valleys of the impedance curves in fig. 2) and, to a lesser extent, on the worst cases (peaks). On the sloping sides of the distribution, however, the temperature error has a much greater effect on the impedance for a given mode. For this reason, it is difficult at this stage to give an estimate of the threshold impedance; we feel the order of magnitude of the threshold impedance to be about 30% of the peak impedance of a single cavity for a beam intensity of \( 10^{13} \) ppp.

To summarize the results: with the present bandwidth and impedance of the deflecting mode, we are able, by temperature tuning, to reduce the total impedance to a value \( \sim 20\% \) of the peak impedance of a single cavity. This seems to be sufficient to prevent the onset of the instability at \( 10^{13} \) ppp at high energy (> 150 GeV). More measurements are planned with a view to obtaining more accurate information about growth time, threshold, etc.

References


2. L. Evans, R. Lauckner, SPS Commissioning Report, No. 71.