EXPERIMENTAL INVESTIGATION OF THE COHERENT LONGITUDINAL INSTABILITY OF RELATIVISTIC PARTICLE BEAMS

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Summary

In order to verify the theoretical predictions of stability of relativistic proton beams against coherent longitudinal oscillations driven by interaction with the surrounding vacuum chamber wall, a special high-Q cavity was built with remotely controlled tuning and damping. Already the first experiments with the cavity were successful, and the beam was driven unstable at thresholds quite close to those calculated for simplified models. These results also confer more credibility to the claim that it is necessary to continue the costly efforts of keeping the wall impedance low.

Introduction

Great efforts have been made during the construction of the ISR to minimize coupling between the beam and surrounding equipment. Nevertheless, cross-section variations of the vacuum-chamber present resonant impedances in the lower microwave region that could have led to longitudinal instability under certain conditions. However, no microwave instability was detected with a circulating beam, and the question arose how much confidence we could have in the simplified model calculations.

The existing RF and scanning cavities did not have a high enough coupling impedance to drive the beam unstable, which was verified by experiment [1]. It was therefore decided to construct an "experimental cavity" with high and variable quality factor and coupling impedance. This should then permit measurement of the threshold of instability and thereby allow a simple verification of theoretical predictions.

Design

For practical reasons - mostly of size - a frequency around 60 MHz was chosen for the fundamental mode of a resonant quarterwave coaxial cavity. As the revolution frequency is about 300 kHz in the ISR, this corresponds to a mode number a little less than 200. Since we aimed at a Z/n value of 2-3 kΩ, this means a shunt impedance of about half a Megohm. Although we designed for a high R/Q ratio, the available ceramic gap limited this value to about 50-60 Ω, i.e. a maximum quality factor of about 10 000 was desired. Actually we achieved only about Q = 6000, due to the surface imperfections of the cavity body that was made rather simply by rolling hard aluminium sheet and welding of the end plates. The cavity also had to be split in the middle in order to be able to install it around the ceramic gap that had been put into the vacuum-chamber beforehand. The resulting split would have had no influence on the quality factor of the fundamental mode except for the fact that asymmetries were introduced by tuning and damping mechanisms.

A cross-section of the cavity is shown in figure 1.

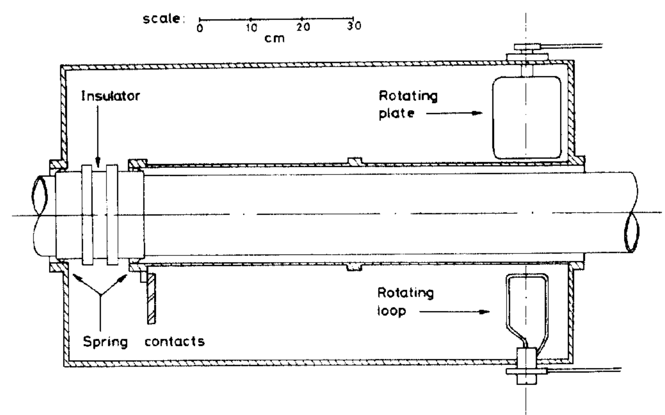

Fig.1. Cross-sectional view of cavity

Tuning over about half a MHz is done with a rotating paddle, while variable damping is introduced by a rotatable loop terminated in a coaxial 50 Ω resistor. Both devices are moved by stepping motors remotely controlled and monitored from the ISR control room.

In order to damp higher parasitic modes, two fixed loops terminated with resistors are installed in such an orientation as not to influence the fundamental. Furthermore, a large damping resistor can be lowered into the cavity by remote control in order to be safe against all interactions when the cavity is not in use. Finally, a pair of short-circuiting jaws can be put over the ceramic gap, but this operation requires opening of the cavity body.

Experimental Results

Since the completion of the cavity in June of last year, almost a dozen experiments have been performed with it on the longitudinal stability of ISR beams. From the beginning it has been possible to drive the beam unstable, this being observed both with signals from a small loop in the cavity (see fig. 2), and with signals from pick-up stations traversed by the beam (see fig. 3).

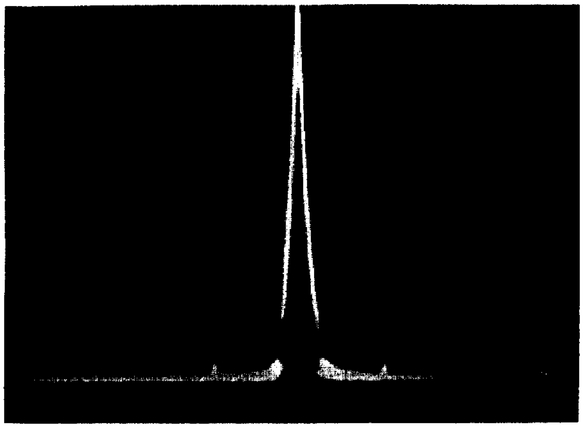

Fig. 2 : Signal from the cavity, center frequency 56.8MHz horiz.: 200 KHz/div,vert.: 10 db/div.

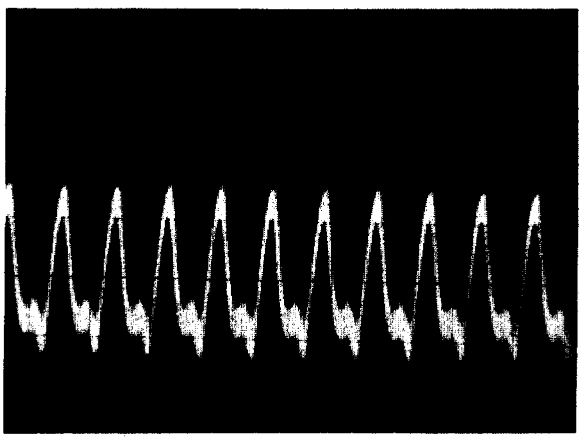

Fig. 3 : Beam envelope from transverse pick-up horiz.: 20 nsec/div, vert.: 100 mV/div.

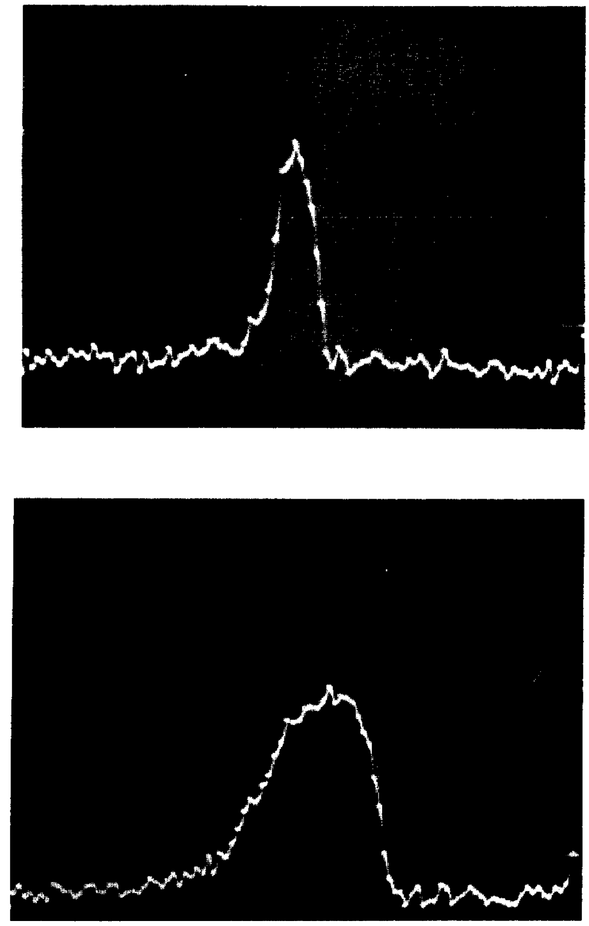

Fig. 4 and 5 : Schottky scan before and after blow-up, center frequency 1490 MHz, hor.:10kHz/div, vert.:linear.

In addition, the instability leads to a widening of the momentum spread, which could be seen directly with the so-called "Schottky-scan", i.e. with a strongly amplified and smoothed signal of the shot-noise created by the protons in the circulating beam (see figs. 4 and 5).

The agreement of the measured thresholds with the theoretical stability criteria was quite good when we used values of the momentum spread measured by independent methods. With the improvement of the phase-space density of the ISR beam in the course of the year the critical coupling impedance decreased from over 1000 Ω to below 200 Ω. Measurements were done at the four standard energies of the ISR (11.5, 15, 22, and 26 GeV/c) and at various current levels.

Increasing the current by stacking of several pulses led to a surprise that could be explained quickly : the critical coupling impedance that we had expected to go up, actually decreased at first, went through a minimum and then increased slowly for higher currents of a few amperes (see fig. 6). The reason for this behaviour is the increase in stacking efficiency that causes only a small increase in momentum spread for a large increase of current.

Measurement of the absolute signal level showed that the modulation of the beam remained below 15% when we increased the impedance of the cavity slowly. Later, a coaxial switch was installed that allowed sudden disconnection of the damping resistor. With this device, the modulation depth increased to over 40%. However, we have never seen actual bunching through of the beam by this passive cavity.

Usually the signal level diminished initially quite quickly, but then remained stable for several minutes. It appears that the modulated beam is in a rather stable situation that does not filament out as expected. Decrease of the signal finally occurs in many sudden steps, as shown in fig. 7. Fig. 8 shows a typical rise of the instability with a rise-time of about 25 msecs. With the sudden removal of the damping resistor the rise-time should be considerably faster.

One experiment was done with bunched beams. While it was found that the instability could still be excited, the cavity had a somewhat different effect on the momentum spread : in addition to a blow-up, the centre of the distribution was decelerated quite rapidly to a lower momentum.

Conclusions

The original reason for the construction of the cavity, i.e. the absence of microwave signals in spite of large impedances in this frequency region, has become

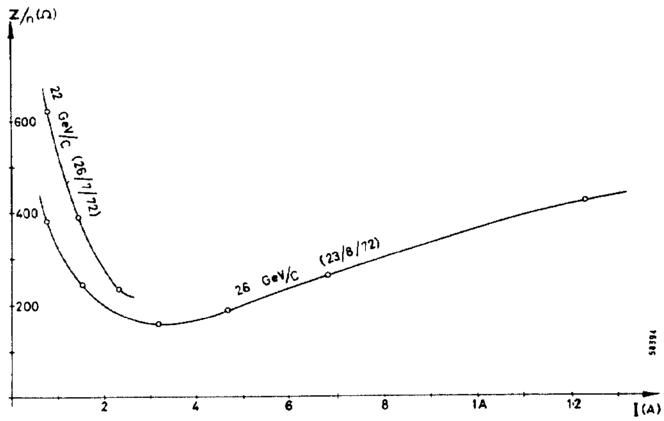

Fig. 6 : Critical coupling impedance versus stacked current

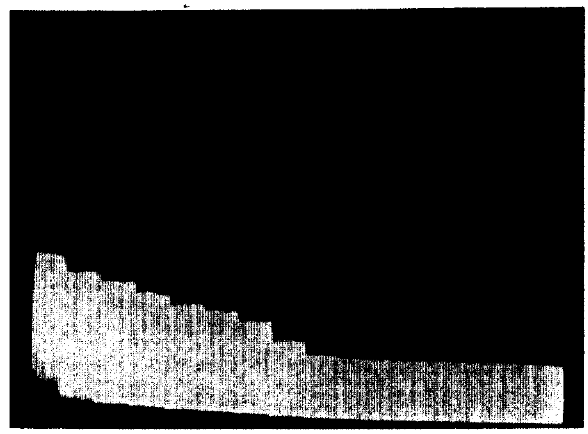

Fig. 7 : Decay of instability signal, horiz.: 10 sec/div, vert.: 10 db/div.

a bit doubtful in the meantime. Microwave signals are now seen regularily at injection of the beam, and remain tens of seconds before dying away. However, it has not been proven so far that this is due to longitudinal interactions.

We found that the experimental cavity has well verified theoretical predictions, and is now a dependable device to measure the critical coupling impedance of the ISR beam. It can even be used to measure the momentum spread of small currents, although the measurement destroys the original value. The stability criteria due to Laslett, Neil, and Sessler [2], and reformulated by Keil and Schnell for impedances, have been shown to be valid also for resonant impedances, although they were originally only derived for frequency independent ones.

Future Plans

After the yearly shut-down of the ISR, some more refined measurements are foreseen with the cavity. Also it seems desirable to find a way to achieve full bunching with a passive device, as this might be useful for luminosity improvement of the ISR. Finally, there is still some desire to build a cavity at higher frequency to check the stability criteria in or near the microwave region.

Acknowledgement

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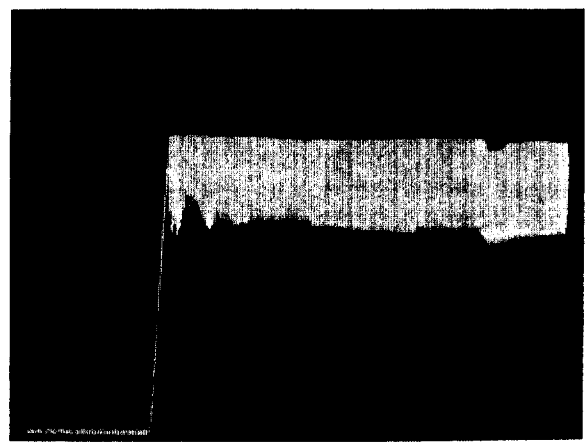

Fig. 8 : Rise of instability signal, horiz.: 1 sec/div, vert.: 10 db/div.

References

1) H. Frischholz, B. Zotter : Longitudinal Instability Tests with an RF cavity, Run 121, ISR-TH/BZ (9.11.1971).

2) A.M. Sessler : Beam Surrounding Interactions and the Stability of Relativistic Particle Beams, IEEE Transactions NS-18 (1971) p. 1039.