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EXPERIMENTS WITH BEAM POSITION SENSORS

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Summary

Previous work[1] on obtaining beam centroid position information using a beam excited resonant cavity with two orthogonal TM_{110} modes was extended to a higher harmonic cavity. The cavity operated at a frequency of 3220 MHz, the fourth harmonic of the accelerator frequency, and was fine tuned by using the frequency shift caused by varying the size of the beam hole. As predicted by beam-cavity interaction theory, the cavity output signal was shown to be proportional both to the square of the beam centroid displacement and to the square of beam current, and to be well correlated with position information obtained by self-powered γ-ray detectors. A crystal and a singly balanced mixer were used to process this signal to give information of both magnitude and sign of the beam position. The cavity was used to observe the effects on beam position when slow (0.01 Hz) sinusoidal disturbances were applied to three accelerator parameters: forward power, frequency and phase. Corresponding changes in the beam position have been found. The preliminary results of an automatic beam centering control show that slow disturbances on beam position can be corrected by driving a steering magnet with the cavity signals.

Introduction

Theoretical investigations of accelerator behaviour using computer models have great influence in new accelerator designs. Refinement of these models demands experimental information of beam parameters. A program to measure these parameters for a standing-wave linac has begun at Chalk River with the cw electron test accelerator[2].

One of the parameters, which is of primary concern during accelerator operation, is the beam position. Insufficient information on beam position may lead to unnecessary beam spill. At high beam power, the associated hazards may range from system activation to melting of structural materials.

A requirement of a beam position sensor for accelerators with high beam power is non-interception of the beam. Beam excited resonant cavities are sensors of this type and they have been in use for continuous beam position monitoring in accelerators[3]. Compared to non-resonant devices, they are two orders of magnitude more sensitive and can be used for measurements down to a few microamperes. A unique characteristic of resonant cavities is their ability to distinguish between positive and negative particles accelerated in alternate bunches in a single beam. The output signals of a cavity tuned to an odd harmonic of the bunch fundamental frequency are proportional to the sum of the signals from each polarity while even harmonics provide signals proportional to their difference.

The general theory and the development of a third harmonic resonant sensor has been described previously[1] with a fundamental accelerator frequency of 805 MHz. This paper, describing experiments using a fourth harmonic cavity, is a continuation of that work. This cavity has been designed to use electric probes instead of magnetic probes. It is tuned by dimpling the outer surface and machining the beam hole accurately. The mechanical design has, therefore, become simplified and more reliable. Beam tests with the odd-even combination are not possible at the present time as particles of only one polarity were available.

Theory of Design of Resonant Sensor

The theory of beam-cavity interaction has been detailed in Ref. 1 with the cavity described as a perfect cylinder with closed ends. Recently, the effect of the beam entrance and exit holes has been analyzed[4] using a similar method as described by Russian workers[5]. It was found that the frequency dependence of beam hole size is a strong function of the cavity length. The calculated frequency shift is in reasonable agreement with experiment (Fig. 1). This frequency shift has been found to be a convenient means of fine tuning and was used to simplify the mechanical design of the present cavity. Furthermore, the analysis shows that the higher space harmonics are strongly attenuated in the radial direction and the TM_{110}-like mode dominates in the cavity interior. Details of this analysis will be published elsewhere.

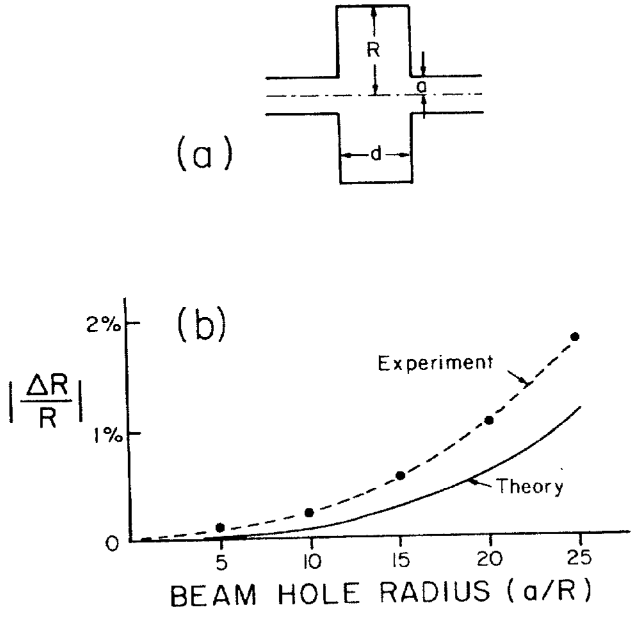

Fig. 1 Frequency shift of beam hole effect. The frequency shift is expressed as the fractional change of cavity radius ($\Delta R/R$) to return the cavity to resonance.

Electronics

The probes on the cavity could be divided into two orthogonal pairs (A_1, B_1) and (A_2, B_2) which, in this case, corresponded to vertical and horizontal directions respectively (Fig. 2). The probes were devised so that one pair could pick up only one mode, and therefore, beam position information only in the

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vertical or horizontal directions. Each pair of signals was processed by identical electronic circuits, therefore subscripts on the signals will be dropped in the following description.

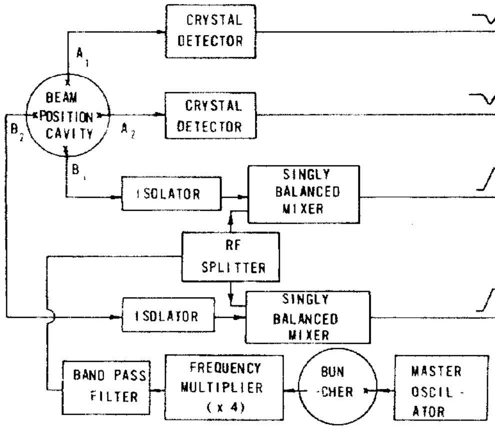
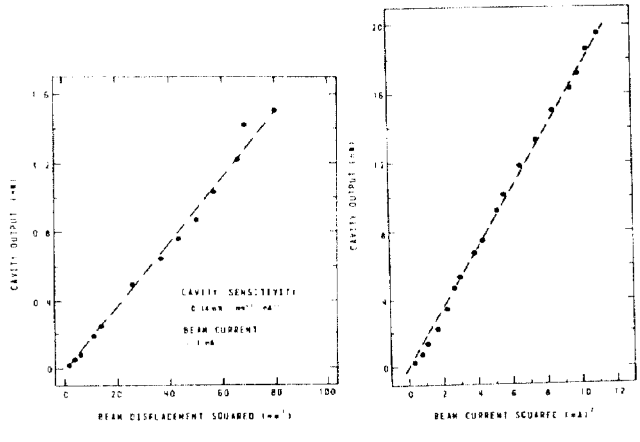


Fig. 2 Schematic of electronic setup.

Signal A went directly to crystal detectors (HP423B, Hewlett Packard) to give a voltage which varied almost linearly with the squared magnitude of the beam displacement and was unipolar. Signal B went to a singly balanced mixer (ZMA-3B, Mini-Circuits Laboratory) to be compared with the reference fourth harmonic signal derived from the rf field in the buncher of the accelerator. The output of the mixer was bipolar with the sign depending on the relative phase of the reference and signal B, which could be either 0° or 180° depending on which side the beam was displaced from the cavity axis. Therefore, one can derive the magnitude of the displacement from signal A′ and sign from signal B′.

Beam Calibration

Theoretically, the magnitude of the cavity output power is proportional to the square of the product of beam displacement from cavity axis and the fourth harmonic of the beam current. When the magnitude of the fourth harmonic component in the beam remains constant, it can be replaced by the total beam current. These proportionalities are shown experimentally for this cavity in Fig. 3.



(a) (b)

Fig. 3 Dependences of cavity output power on beam displacement and beam current.

Figure 4 shows the output signals from the crystal and mixer when the beam centroid was swept from one side of the cavity axis to the other side using a steering magnet. As expected, the crystal signal fell to zero when the beam centroid passed through zero displacement, and the mixer signal changed sign when the beam centroid traversed across the cavity axis. Around zero displacement, the mixer signal was varying linearly with displacement. In fact, this signal can give both the magnitude and sign of beam displacement in this range. This range, according to a laboratory test, corresponds to mixer input powers below 1 mW.

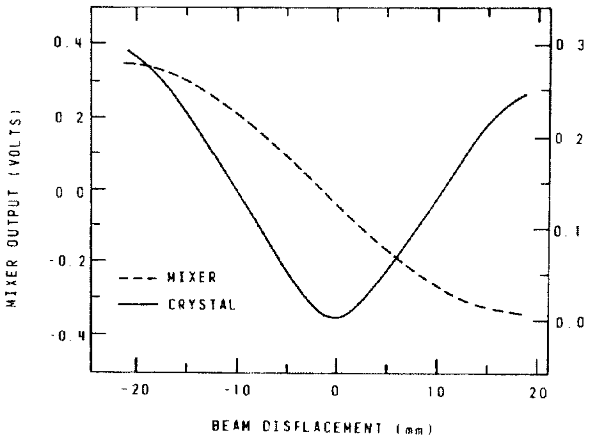


Fig. 4 Crystal and mixer output signal as a function of beam displacement.

During the experiment, the beam position at the beam dump was monitored using self-powered detectors (SPD) to compare with position information obtained from the cavity. SPD's have been used extensively in reactor control[6]. These detectors operate on the principle that, when two electrodes of dissimilar materials are placed close together but insulated from one another and exposed to gamma radiation, a current is generated and flows in the external circuit. The current results from differences in electron emission and collection properties of the two materials and is a function of the effective atomic numbers and geometry of the electrodes. Usually, the material with higher atomic numbers will become positive. An array of SPD's can be used to monitor beam position because of the forward peaking of the bremsstrahlung angular distribution for electrons with energies greater than a few MeV.

Figure 5 is an arrangement to show the correlation between the cavity signals and the SPD signals when the beam was swept horizontally by a steering magnet at a frequency of 0.65 Hz. The signals from the cavity and two vertically placed SPD's are shown in Fig. 6. As the beam crossed a SPD, the SPD output peaked. The peak was repeated on the return traverse of the beam and formed a doublet with the first peak. The troughs between the doublet corresponded to the extremities of the sweep. The cavity signal had a saw-tooth shape with the maxima and minima also corresponding to the extremities of the sweep. One can see excellent correlations between the cavity and SPD signals.

Beam Experiment

The cavity was used to study the effect on beam position when slow (0.1 Hz) sinusoidal disturbances were applied to the forward power, phase, and frequency of a β=1 biperiodic structure operating at a gradient of 0.7 MeV/m^2. A tightly bunched beam of 1.2 mA at 805 MHz was injected into the 3.3 m long structure.

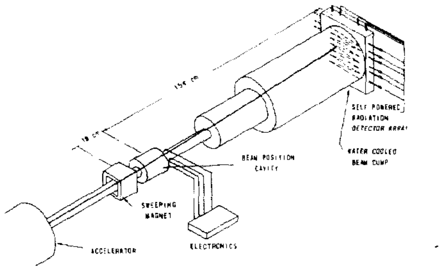


Fig. 5 Experimental setup to correlate beam position information from cavity and self-powered detectors.

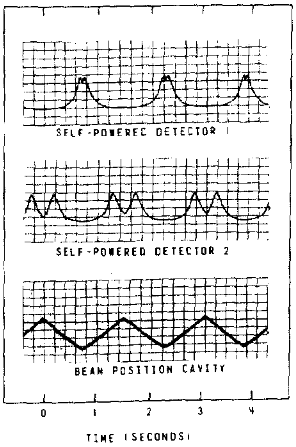


Fig. 6 Correlations of beam position information from self-powered detectors and cavity.

Figure 7 (a), (b) and (c) shows the effects on beam position as each of the three parameters was independently varied. In the cases of forward power and phase, corresponding sinusoidal oscillations on the beam position were observed. By changing the forward power by 15 kW, the beam was displaced by 2 mm. By changing the phase by 140°, the beam was displaced by 8 mm. In the case of frequency disturbance, it was found that the 0.01 Hz oscillation was completely compensated by the automatic tuner (see tuner potentiometer in Fig. 7 (c)) installed in the accelerator, and only a small and gradual change of the beam position was observed probably corresponding to the frequency change coming from a slow increase of the temperature of the accelerator structure and its cooling water. The temperature of the cooling water is automatically adjusted by the computer to keep the tuner within range.

To understand the overall system stability of the accelerator, it is necessary to know the frequency distribution of disturbances in the beam position. This time dependence is also a critical parameter in a future experiment to study parity violation effects in the photo-disintegration of the deuteron near threshold[7]. The cavity signals were, therefore, examined with a spectrum analyzer. The main disturbance was caused by a nearby sweeping-magnet system of 0.65 Hz and 25 Hz. In addition, there was a 60 Hz displacement which was probably due to beam transport magnet current ripple. However, a more interesting finding was a 10 kHz ripple resulting from the frequency modulation of the master oscillator for resonance control[8]. At this frequency, the position variation is ± 0.5 mm. Higher harmonics of this disturbance were also present. The observation of this high frequency disturbance indicates the capability of the cavity in picking up fast disturbance in beam position.

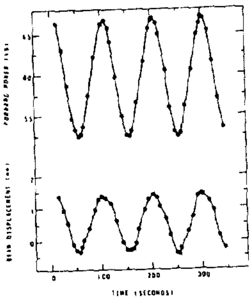


Fig. 7(a)

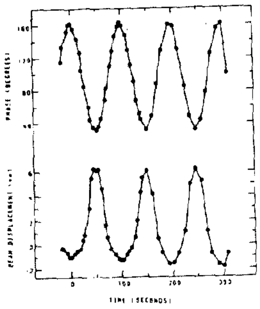


Fig. 7(b)

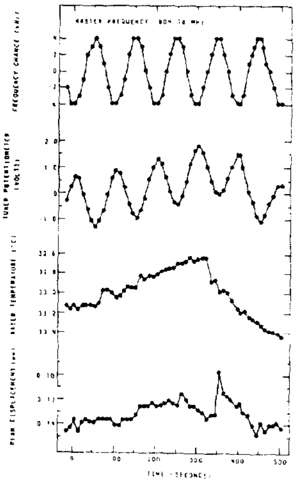


Fig. 7(c)

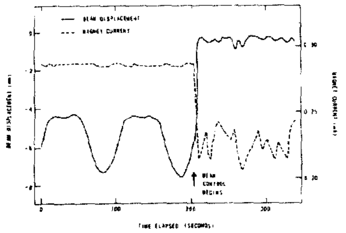


Fig. 8

Fig. 7 Effects on beam position when slow (0.01 Hz) Hz) sinusoidal disturbances were applied to the forward power, phase, and frequency of a cw linac.

Fig. 8 Beam position control experiment.

The beam position variation caused by accelerator disturbances can be corrected by a steering magnet driven by position error information fed back from the cavity. A computer program was written to achieve this closed loop control. Figure 8 shows an attempt of this automatic control to correct a slow oscillation (0.01 Hz) caused by disturbing the phase of the accelerator structure. This preliminary work indicates that a microprocessor based automatic beam centering control can be built.

References

1. J. McKeown, IEEE Trans. Nucl. Sci., NS-26 (3), 3423-3425 (1979).
2. J.S. Fraser et al., Proc. of 1972 Proton Linear Accel. Conf., LA-5115, 226 (1972).
3. Z.D. Farkas et al., Proc. of 1976 Proton Linear Accel. Conf., Atomic Energy of Canada Limited, Report AECL-5677, 300 (1976).
   H. Herminghaus et al., Nucl. Instr. and Meth. 138, 1 (1976).
4. Private communication, Y.M. Shin, University of Saskatchewan.
5. L.G. Lomize et al., Accelerator Complex for Medium Energy Physics, Academy of Science, USSR, Proc. of the Radiotechnical Institute, No. 16, Moscow, 1974.
6. R.B. Shields, Atomic Energy of Canada Limited, Report AECL-3564 (1970).
7. A.B. McDonald, Atomic Energy of Canada Limited, Report AECL-6851 (1980).
8. J. McKeown et al., Proc. of 1976 Proton Linear Accel. Conf., Atomic Energy of Canada Limited, Report AECL-5677, 291 (1976).