Initial Operating Experience with the Auxiliary Accelerating Cavity for the TRIUMF Cyclotron

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Abstract

A 92 MHz auxiliary accelerating cavity has been installed in the TRIUMF cyclotron. It operates at the fourth harmonic of the dee frequency with a planned peak voltage of 150 kV. At full power it will almost double the present energy gain per turn in the 400-500 MeV range, reducing by 25% the stripping loss of the H^- beam. Low current beam tests have been conducted at voltages of up to 90 kV and a maximum voltage of 145 kV has been attained. The cavity has also been used to flattop the integrated energy gain per turn. A description of the cavity design and a summary of the operating experience is given.

I. Introduction

The 500 MeV TRIUMF cyclotron routinely accelerates 150 μA of H^- ions. Electromagnetic stripping, rising rapidly from 400 MeV, is responsible for ~1/2 of the total particle losses and ~2/3 of the total activation of the cyclotron. The use of additional accelerating cavities was suggested as early as 1983 [1], primarily to aid in improving the extraction efficiency for H^- extraction for injection into a KAON Factory [2]. However, even after another method of improving extraction efficiency was chosen [3], the increased energy gain per turn and consequent reduction in the number of turns, hence losses, in the outer radial region were sufficient motivation to design, manufacture and install one cavity.

The cavity operates at the fourth harmonic (92.24 MHz) of the main rf frequency and consists of a trapezoid of dimension $\lambda/4$ radially and $\beta\lambda/2$ azimuthally, so that the orbiting ion receives two acceleration impulses on each passage (Fig. 1). The peak accelerating voltage rises sinusoidally with radius, covering the energy range from 370-520 MeV. The maximum energy gain per turn will increase from the present 320 keV to 620 keV.

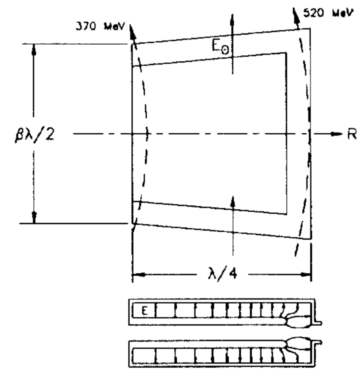

Figure 1: Schematic view of the cavity.

II. Cavity and Amplifier Design

The cavity has been described elsewhere [4]. Briefly, it consists of two halves (Fig. 2), placed above and below the beam plane, separated by 64 mm and mounted independently from the vacuum chamber floor and lid to minimize activation. All conducting walls defining the rf boundaries are made from 1.6 mm thick OFHC Cu sheets with most seams TIG welded, and then brazed together. The cantilevered hot arm is exceptionally stiff (~220 N/mm) to minimize tip vibrations (2.7 μm p-p @ 20 Hz). Cooling circuits were designed to limit the temperature rise from the skin losses (up to 8.5 W/cm^2) to below 25°C. Coarse frequency adjustment is done on assembly by shimming the hot arm to ground arm distance. Fine tuning is provided by a water cooled, hinged flap, built into each ground arm, actuated through a zero backlash linkage system. Each cavity half can be remotely installed in ~20 min.

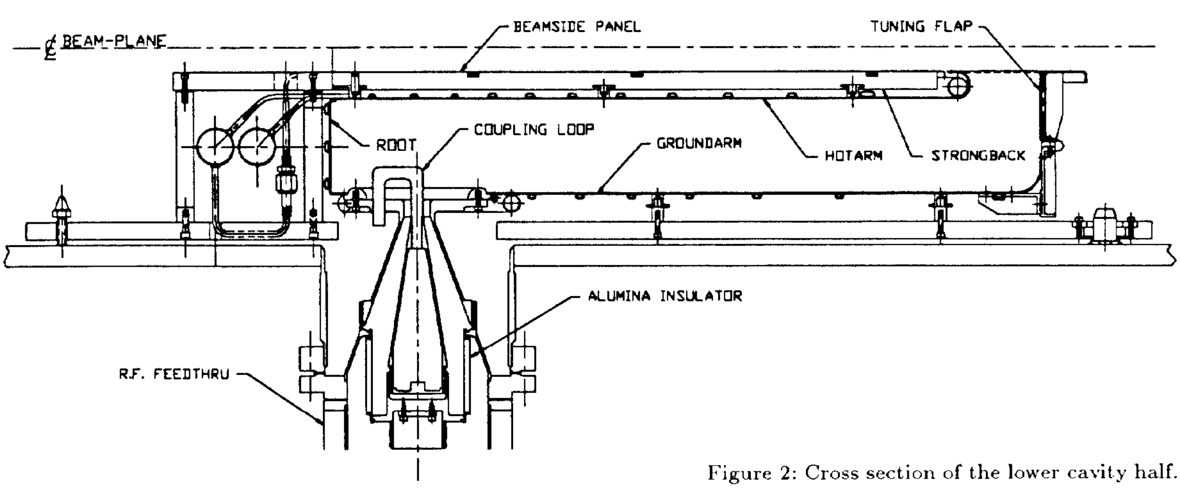

Figure 2: Cross section of the lower cavity half.

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The water cooled coupling loop is connected to a 6 inch transmission line of adjustable length via a smooth transition section. A single tetrode power amplifier can deliver 160 kW, well in excess of the power required (~120 kW) for a voltage of 150 kV and a 200 μA beam.

III. Low Level RF and Control System

A block diagram of the control system is shown in Fig. 3. The cavity voltage, sampled by a capacitive probe, is demodulated by a temperature-compensated diode detector, and feedback regulated by a Proportional-Integral-Derivation (PID) controller, resulting in a stability of better than 0.5%. The phase is regulated to better than 1° by a 40 dB dynamic range phase detector and another PID controller. The gain and frequency parameters of the PID controllers are programmable through a dedicated microprocessor embedded in a VME crate. This enables the feedback parameters to be changed in response to eventual gain variations. The microprocessor also handles automatic power-up sequencing, system status monitoring, and local display/control, and in addition, communicates with the cyclotron central control system through ethernet.

The 92 MHz rf for the cavity is generated from a phase-locked loop (PLL) referenced to the 23 MHz signal from the cyclotron dee gap. The PLL output signal is four times the frequency of the input reference, with a phase noise level less than −60 dBc at 10 kHz from the carrier. This output is split into two parts: one is used as the phase reference; the other is amplitude and phase modulated before it is used to drive the power amplifier chain. A digital frequency-hold/pull-in circuit enables the PLL to hold its frequency indefinitely when the reference signal is absent. This allows the cavity to maintain thermal equilibrium even when the cyclotron rf is turned off. If the reference signal returns at a frequency different from the previous setting, the capture process in the PLL is deliberately slowed down to enable the tuning mechanism in the cavity to follow the frequency drift until the error is less than 10 kHz. The phase loop is then closed, and the output frequency locked to the reference.

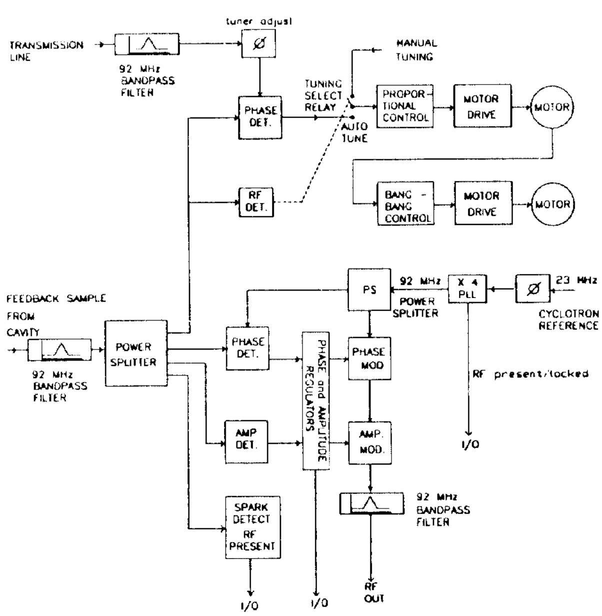

Figure 3: A block diagram of the control system.

The signal for the cavity tuning flaps comes from an independent servo loop which compares the phase difference between the rf field at the cavity accelerating gap and at the coupling loop, and activates a pair of flap drives to maintain the phase difference at 90°. The servo loop is disabled by an additional circuit when the cavity voltage is below the multipactoring level.

IV. Commissioning

The cavity was pre-commissioned outside the cyclotron in an auxiliary vacuum vessel. Signal level measurements using an HP network analyzer and on-line modelling using a computer code, NODE [5], provided significant time saving in the pre-commissioning phase.

Installation of prototypes in the cyclotron and initial high power testing can only be done during the scheduled shutdowns that occur twice a year. The cavity was installed in April 1990, and a voltage of 100 kV was achieved in several hours. Pressure excursions in the cyclotron, probably due to rf heating, stopped the first commissioning phase at this point.

In the second commissioning session in October 1990, 145 kV was achieved, but later a failure in the high voltage vacuum feedthrough caused a premature curtailment of the test. During the repair of the feedthrough it was also noted that rf energy, leaking out of the cavity, had damaged a beam diagnostic probe a few metres away.

In subsequent tests the control system was successfully commissioned. In the latest shutdown in April 1991, top-bottom telescopic shorting contacts were added to the cavity outside the 520 MeV beam orbit, to help reduce the rf leakage. Further commissioning will commence immediately after this conference and it is expected that the design voltage will be achieved at this time.

V. Beam Tests

The first tests with beam were done during the initial commissioning. The beam induced voltage in the cavity, while tuned to the resonant frequency but not energized, was 10 kV with 100 μA circulating. Detuning the cavity by 200 kHz reduced the induced voltage to 3% of the above value. The cavity was then energized to 90 kV and a series of measurements were taken with circulating currents of low intensity. In Fig. 4 time-of-flight (TOF) measurements of the beam through the cyclotron are summarized and compared with results from computer simulations. The measurements show that, even at 90 kV, reductions of ~20 μsec or ~100 turns are possible, depending on the isochronism and beam phase width, and at 150 kV a reduction of 140 turns is expected. This would reduce the activation from electro-magnetic stripping by ~35%.

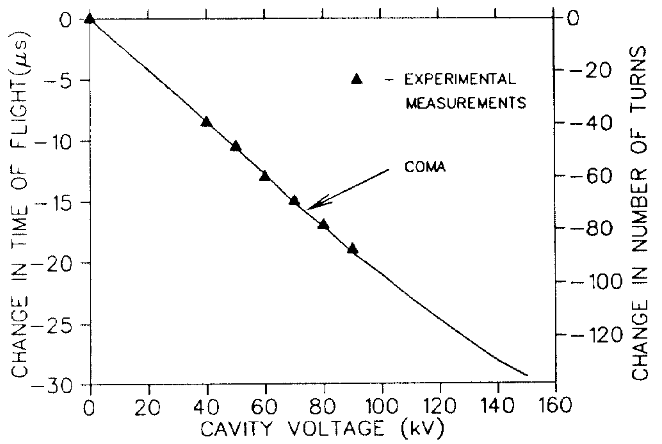

Figure 4: The reduction in the measured time-of-flight (TOF) of the beam through the cyclotron to 500 MeV for various cavity voltages is compared to the results of a computer simulation using the matrix code COMA [6]. The reduction in number of turns is also shown. (Without the cavity the beam makes ~400 turns in the cavity region.)

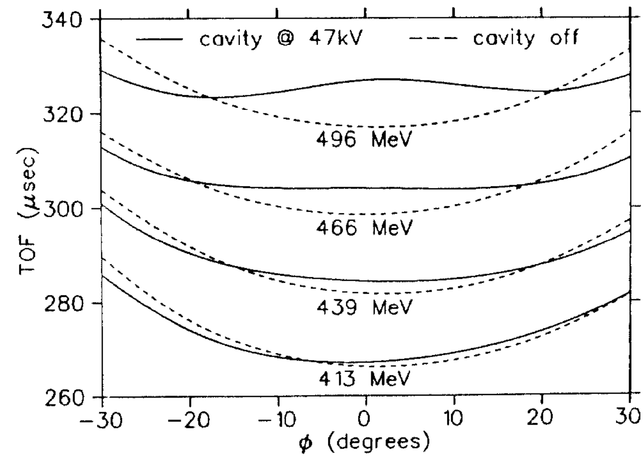

Figure 6: Measured then smoothed TOF curves for four different energies as a function of initial phase for *cavity off* (dashed curve) and *cavity on* at 47 kV (solid curve). The cavity was phased to give the best flattop at 466 MeV.

Lower voltages were used to investigate the use of the cavity in flattopping the energy gain per turn. In an isochronous cyclotron the TOF is dependent on the energy gain per turn and the degree to which the magnetic field is isochronous. The time-variation of the fundamental accelerating field is responsible for a cosine-like phase dependence in the energy gain per turn, and hence the TOF is also affected. This variation in the TOF with phase can be reduced substantially, producing a flattopping effect, by adding a higher harmonic cavity opposed to the fundamental. The higher the harmonic number of the cavity, the narrower would be the resultant flattop. The cavity voltage determines the number of turns through the cavity necessary to reach the optimum flattop condition.

For the test the initial beam phase width (23 MHz) was reduced from the nominal 30° used for high current operation, to 5° by inserting radial slits in the centre region. The position of the phase-band with respect to the accelerating field was then altered by scanning the rf frequency, and the TOF was recorded. In Fig. 5 the measured TOF values to 500 MeV are plotted as a function of initial phase for various cavity voltages. At 36 kV an optimal flattop occurs over a phase range of ~30°. The slightly asymmetric result at 48 kV shows the effect of the cavity field being slightly out of phase with respect to the fundamental, prior to optimization.

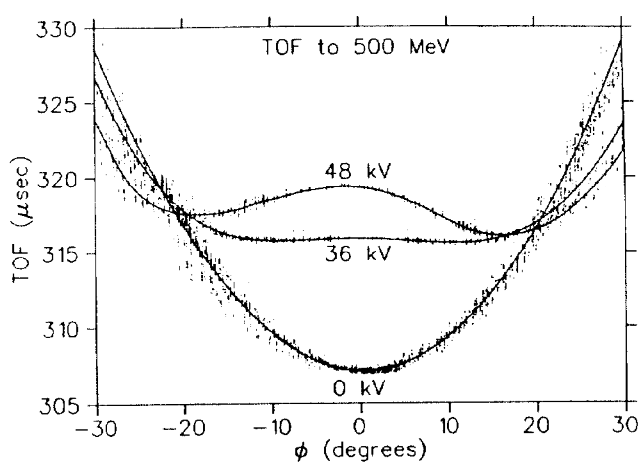

Figure 5: Measured TOF values to 500 MeV as a function of the initial phase for three different cavity settings, 0 kV, 36 kV and 48 kV, with the cavity phased to oppose the fundamental. Smooth curves are plotted through the experimental data points.

The cavity was then powered to 47 kV and phased to give the optimum TOF flattop at an energy of 466 MeV. At this setting the TOFs to various other energies were also recorded (Fig. 6). *Cavity on* results are compared with the corresponding *cavity off* data. The figure shows how the cumulative effects of the opposing cavity field produce optimal flattopping at only one energy. The variations in the phase of the minimum TOF are due to radial variations in the cyclotron isochronism.

VI. References

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