BEAM TEST RESULTS USING THE AUXILIARY ACCELERATING CAVITY

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Abstract

A $\lambda/4$, 92 MHz cavity is now operating in the TRIUMF cyclotron. The device, when operating at 50 kW and at a peak voltage of 140 kV, increases the energy gain per turn from 0.32 MeV to a maximum of 0.60 MeV in the 370-520 MeV range. This reduces electro-magnetic stripping losses from 8% to 5% and lowers the beam induced tank activation by ~1/3. The cavity allows other modes of operation. In particular the cavity has been phased to oppose the fundamental rf to produce a localized flattop in the energy gain, stabilizing the precession pattern during resonant extraction. When the power is increased in flattop mode the corresponding strong phase expansion has been observed to split the longitudinal phase band into two bunches. In principle, additional cavities could further sub-divide the extracted beam time structures.

I. Introduction

The auxiliary accelerating cavity (AAC) has been described elsewhere [1] [2]. 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. When operated at 140 kV the energy gain per turn increases from the present 320 keV to a maximum of 600 keV.

The 500 MeV TRIUMF cyclotron routinely accelerates 150 μA of H^- ions. Electro-magnetic (e-m) stripping losses rise rapidly from 0 to 8% in the region from 400-500 MeV. Gas-stripping losses total ~5% for a typical tank pressure of 5×10^{-8} torr and are spread roughly uniformly throughout the machine with stripping cross-sections scaling as $1/\beta^2$ and the orbit length per energy increment scaling as β. Scraping of vertical haloes on foils defining the vertical aperture occurs at various radii through the cyclotron and account for a further ~3% of the total circulating current. Since activation scales roughly with particle energy, the electro-magnetic losses account for ~2/3 of the total tank activation. The cavity was originally conceived [3] to improve extraction efficiency for H^- extraction. However the addition of an extra higher harmonic cavity in the outer radial region to reduce losses and/or modify beam behaviour was sufficient reason to proceed with manufacture and installation after it was decided to use precessional extraction to improve extraction efficiency. [4]

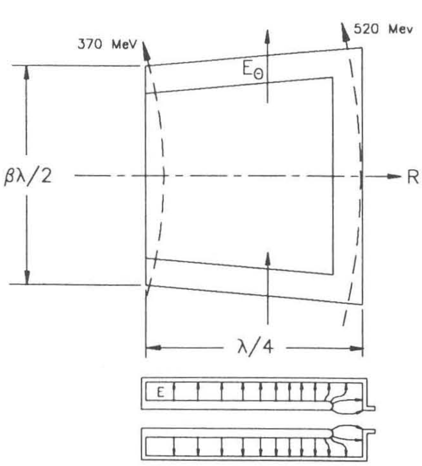

Figure 1: Schematic view of the cavity.

II. Acceleration Mode

The optimum phase of the cavity is set empirically using the time-of-flight (TOF) through the cyclotron as the main diagnostic. At the normal operating voltage, 140 kV, the TOF is reduced from 329 μsec to 303 μsec, corresponding to a reduction of 120 in the total number of turns. Even though the cavity operates at the 4^{th} harmonic of the fundamental rf, phase stability is not a problem since phase compression tends to stabilize and damp phase wander. Computer simulations prior to cavity testing predicted the total losses from gas and e-m stripping as a function of particle phase in the region from 350-500 MeV for a tank pressure of 1×10^{-7} torr (Fig. 2). Results for cavity voltages of 0, 90 kV and 150 kV are plotted. When the cavity is powered a reduction in beam loss is predicted over a full 40° of phase.

Loss reduction measurements are shown in Fig. 3 for a standard high intensity beam (148 μA equivalent at a duty factor of 80% and 35° phase width). Plotted are the

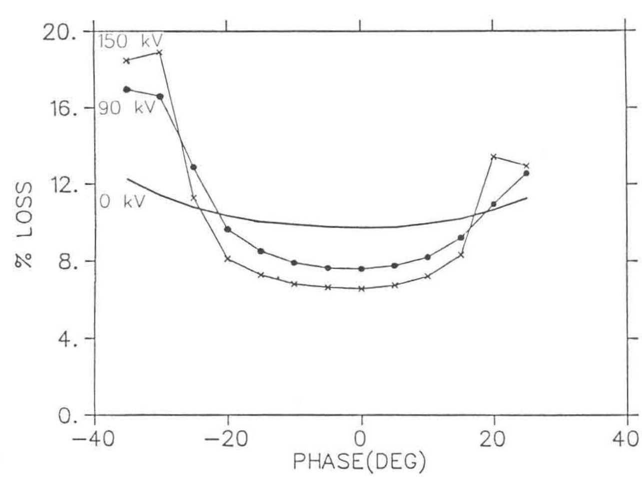

Figure 2: Results of computer simulations showing expected beam loss from gas and electro-magnetic stripping as a function of initial particle phase in the region from 350-500 MeV. Losses for cavity voltages of 0, 90 kV and 150 kV are plotted. The gas-pressure was 1×10^{-7} torr.

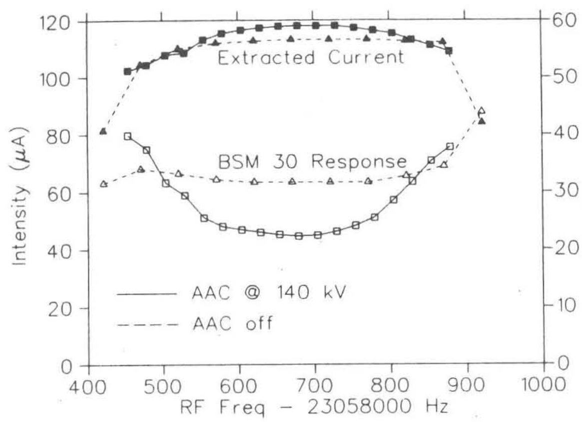

Figure 3: Experimental result showing extracted current and signal from a beam spill monitor external to the cyclotron for cavity off and for the cavity on at 140 kV. The longitudinal phase of the accelerated phase band was varied with respect to the cavity rf phase by altering the main frequency (100 Hz$\simeq$12°).

extracted current and the response from a beam spill monitor external to the cyclotron as a function of the rf frequency for the AAC off and powered (140 kV). The monitor is positioned to be selectively sensitive to e-m losses. The rf frequency is varied to scan the longitudinal phase band in the cavity region (100 Hz$\simeq$12°). As predicted the cavity reduces losses over a phase interval of ~40°. At the optimum phase the beam loss signal was reduced by 40% and the overall transmission was increased by 4%. This represents a decrease in total losses from 16% to 12% and losses weighted for energy from 12% to 8%. This reduction would allow a 33% reduction in tank activation for the same μA-hours or an equivalent increase in the μA-hours to maintain existing activation levels.

The time spectrum of the extracted beam is shown in Fig. 4. Phase compression forces from the cavity have reduced the total phase band of the extracted beam from 32° to 18° measured at 10% of the distribution maximum. This result compares well with the expected reduction given by [5]

$$E_{G1}(R_o)\sin\phi_o = E_{G1}(R_f)\sin\phi_f + \frac{E_{Gm}(R_f)}{m}\sin m(\phi_f - \phi_m) \quad (1)$$

where E_{G1} and E_{Gm} correspond to the peak energy gain per turn from the fundamental and the cavity ($m = 4$) respectively (0.32 MeV and 0.28 MeV in this case), ϕ_0 and ϕ_f correspond to the initial and final phases with respect to the fundamental and ϕ_m is the relative phase between the cavity and the fundamental (for acceleration $\phi_m = 0$).

III. Flattop Mode

In general all higher harmonic cavities can combine with the fundamental to flattop the energy gain, however as the harmonic increases the useful phase width of the flattop is reduced. The AAC can serve two functions as a flattopping cavity. Firstly the cavity can be run at relatively high voltages to flattop the number of turns (TOF) through the whole cyclotron to achieve more mono-energetic turns. The number of turns through the cavity determines the cavity voltage necessary to compensate the $\cos\phi$ dependence in the TOF. Secondly, at a somewhat lower voltage the cavity can flattop the local energy gain per turn. This is useful to control phase-dependent stretching or coherent growth at resonances or increases of the extracted emittance due to phase-dependent precession of a stretched emittance.

To test the first case the longitudinal phase width of the beam was reduced from the standard 35° used for high current operation, to 5° by phase selection in the centre region. The phase band was scanned with respect to the accelerating field by varying the rf frequency, and the TOF was recorded. In this case the phase change varies in proportion to the turn number N yielding a TOF that varies with frequency as

$$TOF \propto \frac{d\phi}{dn}/sin(N \cdot \frac{d\phi}{dn}) \quad \text{where} \quad \frac{d\phi}{dn} = 2\pi h\frac{\Delta f}{f}. \quad (2)$$

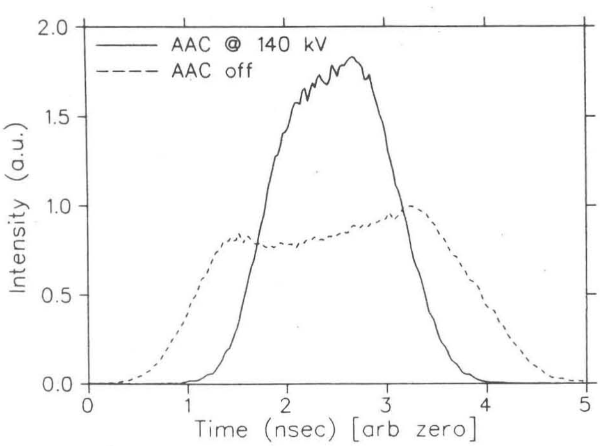

Figure 4: Time structure of the extracted beam with AAC off and AAC powered at 140 kV. Phase compression forces from the cavity have reduced the extracted phase band from 32° to 18° measured at 10% of the peak (1 nsec=8.3°).

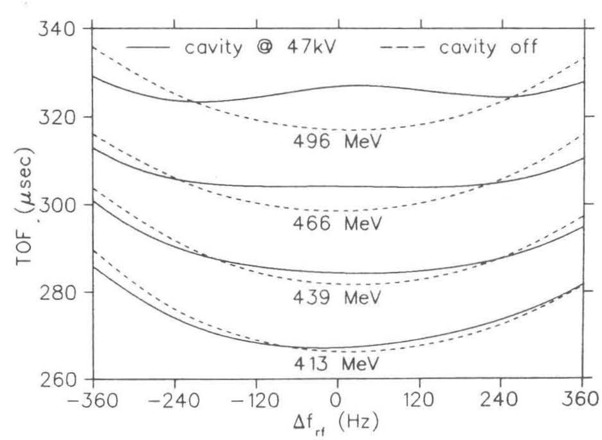

Figure 5: Measured TOF curves, after smoothing, for four different energies as a function of rf frequency for *cavity off* dashed curve) and *cavity on* at 47 kV (solid curve). The cavity was phased to give the best flattop at 466 MeV.

The AAC was powered to flattop the phase dependence of the TOF. Fig. 5 shows the measured TOF response at various radii within the AAC for the cavity @ 47 kV (solid lines) and off (dotted lines). The cumulative effects of the opposing cavity field produce flattening of the response curve at only one energy. The variations in the phase of the minimum TOF for each curve are due to radial variations in the cyclotron isochronism.

The second type of flattopping was tested with the 11.5 MHz rf deflector (RFD) being used to drive a coherent radial oscillation at ν_r=3/2 to initiate precessional extraction [4]. The coherent amplitude gained is proportional to the average radial kick and the number of turns in the resonance region and varies with particle phase as $\cos(\phi/2)/\cos\phi$, while the rate of radial advance of the centre of precession (AEO) varies as $\cos\phi$. Flattopping of the local energy gain per turn can be used to equalize both the number of turns from the ν_r=3/2 resonance to extraction and the coherent amplitude growth for a finite phase band. The advantages of this equalization are explored in another paper in these proceedings [6].

The precession of the coherent oscillation can be measured by observing the radial beam density on a differential probe. Peaks in the density plot occur at a position where the maximum radial advance for one precession cycle has lead to a build up of turns. An experimental radial scan is shown in (Fig. 6) for a narrow phase band (ϕ_o=0) and for the same phase band shifted by 24°. Such density scans were taken for various rf frequencies corresponding to different central phases and were repeated with the cavity flattopping at 15 and 30 kV. Stability of the precession pattern was characterized by measuring the position of the 4^{th} precession peak for each case(Fig. 7). The stability of the peak of a 40° phase band improves by more than a factor of two when the flattoping voltage is 15 kV. Local optimization of the AAC phase should lead to further improvements. Computer simulations show that when properly phased the cavity should virtually eliminate phase-dependent variations in the precession pattern for the ±20° bunch required by the KAON Factory [6].

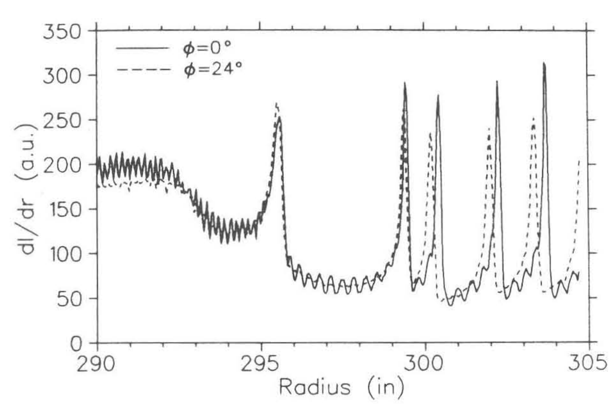

Figure 6: Radial scans using a differential probe showing the beam density pattern produced by the RFD for an optimized phase band and for a phase band off-set by 24°. Phase dependent amplitude growth at the ν_r=3/2 resonance and a $\cos\phi$ dependence in the rate of advance of the precession center account for the difference.

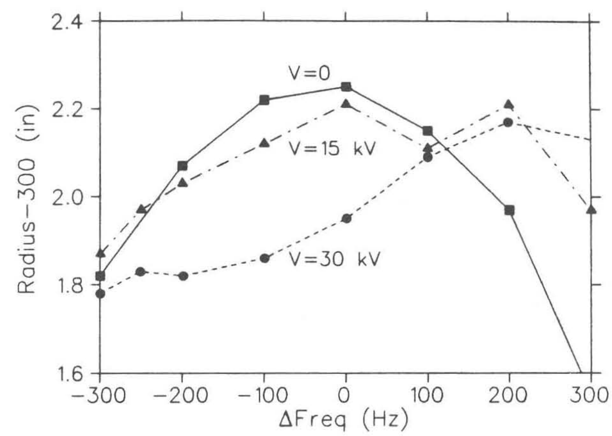

Figure 7: Position of the 4^{th} peak of the RFD induced beam density modulation as a function of rf frequency (beam phase) and cavity flattopping voltage.

IV. Phase-Splitting Mode

A cavity operating at the m^{th} harmonic and phased to oppose the fundamental ($m\phi_m = 180°$) will expand the longitudinal phase band according to Eq. 1. For cases where the peak energy gain from the cavity exceeds that from the fundamental an unstable fixed point occurs in phase space at the energy at which $E_{Gm}(E) = E_{G1}(E)$ and phase ϕ=0. Particles slightly off-phase skirt around a forbidden region defined by

$$\frac{m \cdot \sin\phi}{\sin m\phi} = \frac{E_{Gm}(E)}{E_{G1}(E)}. \tag{3}$$

In this case the longitudinal bunch could be split into two without loss of beam intensity. This idea could be used to further split the bunches with additional cavities at still higher harmonics, leading to a time structure at extraction compatible with a much higher frequency than the fundamental accelerating frequency [7]. In this study we present the results of an experiment demonstrating the proof of principle.

At the maximum voltage of 140 kV the cavity energy gain is less than that from the fundamental (E_{G4}/E_{G1} = 0.88). To produce the phase-splitting effect the isochronism was shifted from the ideal so that over the radial range of the AAC the effective energy gain from the fundamental was reduced while the AAC was phased to oppose the circulating beam. The simulation results shown in Fig. 8 illustrate how the *phase-slipping* of the fundamental rf can produce phase-splitting. In Fig. 9 we present an experimental result mirroring the simulation of Fig. 8. The phase shift of the beam with respect to the fundamental is accomplished by adjusting the rf frequency. A final time spectrum of the resulting extracted beam compared to the time structure with the cavity off is shown in Fig. 10. Complete phase-splitting is evident with the two sub-bunches separated by 7.6 nsec.

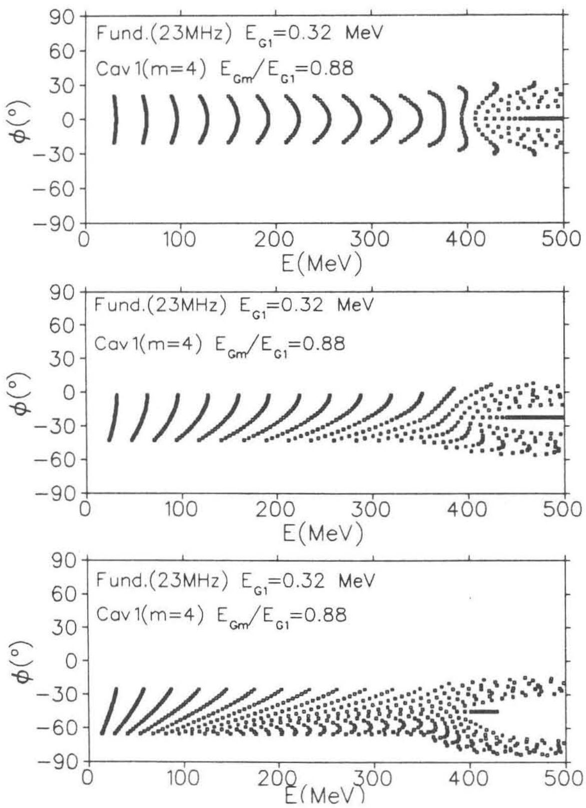

Figure 8: Simulation showing how phase-splitting can occur even when $E_{G1} > E_{G4}$. From top to bottom, the beam is progressively slipped in phase with respect to the fundamental rf prior to the cavity. In each case the phase of the 4^{th} harmonic cavity is adjusted to oppose the beam. In the bottom plot the bunch has slipped to a point where the AAC field can overcome the energy gain from the fundamental rf and splitting results. See Fig. 9 for an experimental demonstration of these simulations.

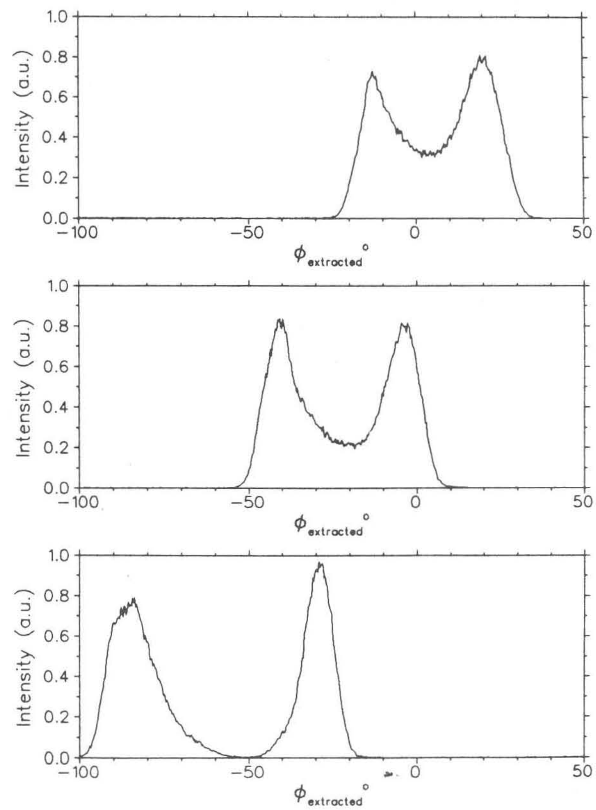

Figure 9: An experimental result mirroring the simulation result of Fig. 8. Shown are the distribution of the beam in longitudinal phase space at three different rf frequencies with the phase of the AAC adjusted to oppose the beam. From top to bottom, the beam is progressively slipped in phase with respect to the fundamental rf. In the bottom plot the bunch has slipped to a point where the AAC field can overcome the energy gain from the fundamental rf and splitting results.

V. References

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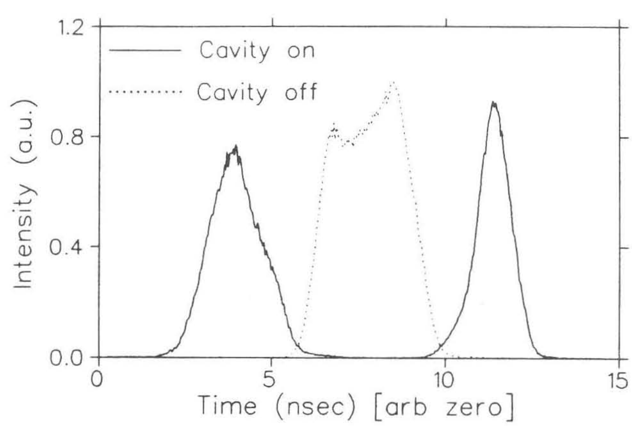

Figure 10: Experimental result showing the time spectrum of the extracted beam with the AAC ($E_{G4}(R_f)/E_{G1}(R_f)$=0.88) phased to oppose the circulating beam (solid line) and with the cavity off (dotted line).