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# THE BEAM BUNCHING SYSTEM FOR THE CHALK RIVER SUPERCONDUCTING CYCLOTRON

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## Summary

The bunching system for the tandem accelerator-superconducting cyclotron is of the buncher-rebuncher type. It consists of a low energy gridded buncher before the tandem that produces a time focus at the tandem stripper, combined with a high energy buncher between the tandem and the cyclotron to correct for debunching of the beam produced by energy straggling in the stripper. To meet the cyclotron design energy resolution of 5:10$^4$ the bunch length produced at the cyclotron has to be less than three degrees in rf phase.

## Introduction

The Chalk River heavy-ion superconducting cyclotron project consists of a 13 MV MP tandem Van de Graaff accelerator injecting into a K=520 (ME/Q$^2$) superconducting cyclotron[1]. The civil construction phase of this project has now finished and installation of the beam transport elements along the injection beam line[2] to the cyclotron is well advanced. The accelerating tubes of the tandem accelerator have been successfully reversed to accommodate the new layout of beam lines and experimental areas (Fig. 1) and the first of two ion source stations is essentially complete. High voltage tests of the reconfigured accelerator and first beam tests are scheduled for this summer. The cyclotron magnet and rf system have been moved to the new building and reassembly of the magnet steel begun. Major tasks remaining are: installation of the new helium liquefier, the magnet power supply, and the rf transmitter in the cyclotron service area; installation of the injection stripping and beam extraction[3] systems in the cyclotron; completion of the computer control system; and completion of the bunching system for the injection beam line. This paper will describe the bunching system and its current status.

## The Bunching System

The Chalk River cyclotron is a four-sector isochronous cyclotron with an elegant rf system[4] comprising a coupled pair of quarter-wave resonators operating at up to 100 kV in either the zero or pi modes (resonators in phase or 180° out of phase). The rf frequency of the resonators is set at the second, fourth or sixth harmonic of the cyclotron orbital frequency (in the pi, zero and pi modes respectively) resulting in the small operating frequency range of 31 to 62 MHz.

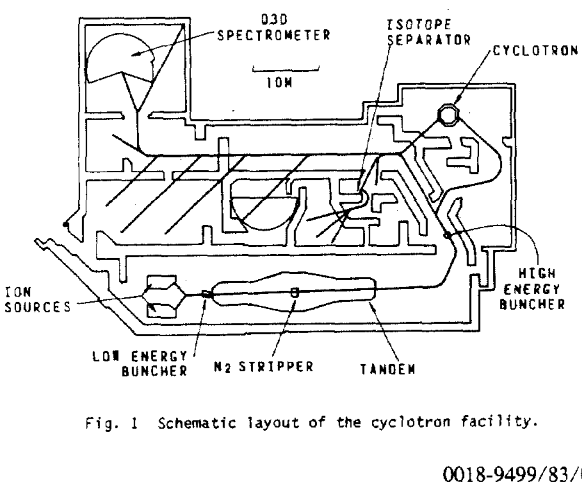


Fig. 1 Schematic layout of the cyclotron facility.

The design energy resolution of the cyclotron is 5:10$^4$ and to achieve this, the bunch length (which for an isochronous cyclotron remains essentially constant during acceleration) must be less than three degrees in rf phase. At the highest frequency, 62 MHz, this corresponds to a bunch length of 130 ps and this exacting requirement must be established at the injection orbit by the external bunching system.

The system chosen to accomplish this is of the low energy buncher, high energy rebuncher type[5]. The low energy buncher is located immediately upstream of the tandem accelerator as shown in Fig. 1. This single gridded gap buncher operates at the fundamental and second harmonic of the cyclotron rf drive frequency providing the first two terms of the Fourier series expansion of the ideal sawtooth wave form. It provides the time focus at the stripper in the tandem high voltage terminal necessary to minimize the longitudinal phase space growth produced by energy straggling in the stripper.

The energy straggling also results in a debunching of the beam beyond the tandem stripper which is most significant for the heavy, low energy ions[6]. This debunching of the beam increases with distance beyond the tandem stripper and at the high energy buncher location (Fig. 1) the debunching can be quite large for the worst ions. Fortunately these ions also exhibit a high correlation between phase and energy at that location and this makes rebunching possible. To ensure that this correlation is established and preserved, the beam line sections before and after the high energy buncher have been designed to be achromatic[2] to permit rebunching to the required 3° at the cyclotron.

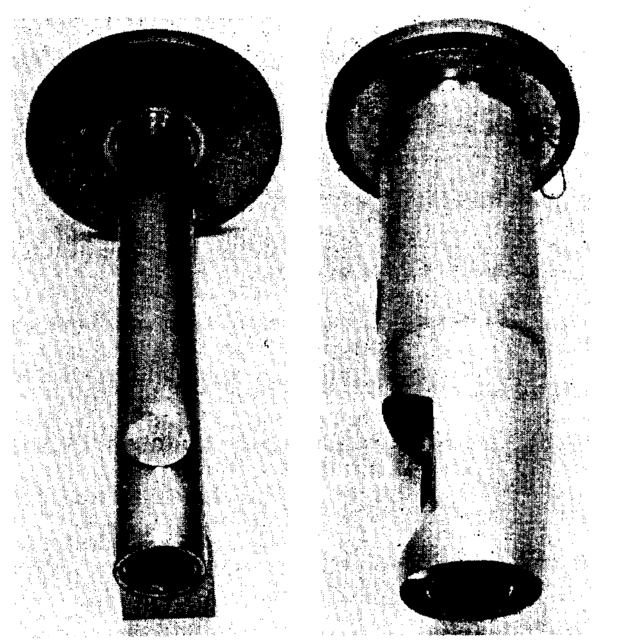

Fig. 2 The low energy buncher resonant stems (inner, fundamental frequency; outer, second harmonic). The drive power coupling loop can be seen on the right.

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## The Low Energy Buncher

The low energy buncher consists of a cylindrical cavity containing two coaxial quarter-wave stems designed (with assistance from the code SUPERFISH[7]) to be resonant at the cyclotron rf fundamental (inner stem) and second harmonic frequencies (outer stem). The stems, shown in Fig. 2, are almost equal in length as a result of both the effects of the coaxial geometry and the larger capacitive loading of the inner stem. Each stem is tuned by a rotating vane variable capacitor and these are shown in Fig. 3. The effects of the tuners are not completely decoupled and each changes the frequency of the other to a small extent. The measured Q of the two resonators without loading by the tuning capacitors is 1350 and 2000 respectively. When the resonators are tuned to their lowest frequencies these are reduced to 1200 and 1000. The frequency range of the two resonators is 24 to 68 MHz and 59 to 125 MHz respectively.

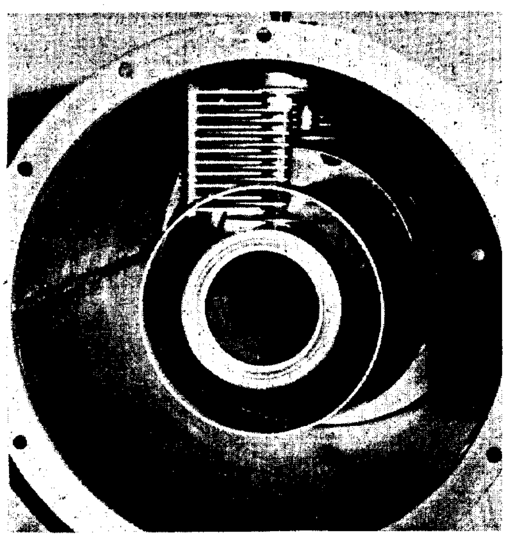

Fig. 3 The low energy buncher rotating vane tuning capacitors shown mounted on the stems. The vacuum sealing surface can be seen on the end of the inner stem.

At the base of the second harmonic stem the magnetic fields at positions radially inside and outside the stem are different in phase for the two resonances. This has been used to allow monitoring of each resonance separately by combining the signals from two probes located inside and outside the stem respectively. By orienting the probes so that their magnetic senses are either parallel or antiparallel the resultant signal can be made to be pure fundamental or pure second harmonic.

To be able to use the cavity as a buncher, the voltages present on the resonant stems are applied to the beam travelling along the cavity axis. The aperture required to accommodate beam sizes for the many different ion species is 31 mm and to ensure that the transit time factor is both high and radially constant over this large aperture a gridded accelerating gap is necessary. Each grid plane consists of an array of 0.013 mm diameter tungsten wires spaced 1 mm apart mounted on a copper support as shown in Fig. 4. To take up the thermal expansion caused by beam heating of the wires they are tensioned after stringing by an O-ring pressure pad. The two supports are mounted on polystyrene spacer posts to form the complete accelerating gap assembly.

The accelerating gap voltage is monitored by an integral capacitive divider in the grid assembly. The gridded accelerating gap is the high impedance component of the divider. The gap capacitance is 32 pf and to tap $\lesssim 1\%$ of the gap voltage of 1 kV rms the low impedance component of the divider must be in excess of 3000 pf; its impedance is low enough to avoid any signal dependency on frequency. The low impedance component is formed from 0.025 mm thick mylar aluminized on both sides which can be seen in Fig. 4.

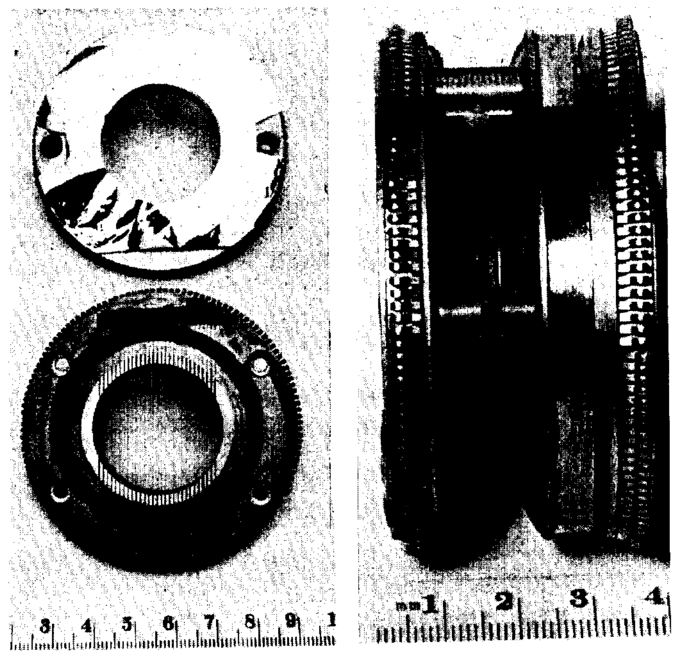

Fig. 4 One plane of the grid assembly showing the 0.013 mm diameter tungsten wires. The mylar sheet for the low impedance capacitive divider is shown above. The grid assembly is shown on the right.

The integral grid and capacitive divider can be installed in the buncher by simply sliding it into place in the beam line section of the cavity where it is held by the rf finger contacts (Fig. 5). This evacuated section is formed by sealing the central stem to the cavity end wall with a thick teflon insulating gasket. This allows easy removal of the grid for maintenance without the need to disassemble the cavity itself and leaves the tuners, coupling loop and pick-up probes in air.

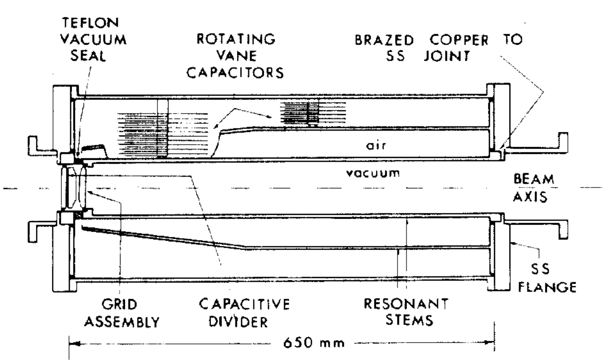


Fig. 5 Cross-section of low energy buncher showing insertion of grid assembly.

The rf drive to the cavity is generated by mixing the fundamental and its second harmonic (produced by frequency doubling) and amplifying the mixed signal to 50 W with a single broad band solid state amplifier. The phase and amplitude of both frequencies are variable. The cavity is driven through a single fixed inductive loop which can be seen in Fig. 2. This couples reasonably well to both resonances over the entire frequency range.

## The High Energy Buncher

The high energy buncher is a 65 mm long drift tube on a quarter-wave sliding short tuned resonator (Fig. 6). This double gap buncher ideally requires that the gap-to-gap separation be $\beta\lambda/2$ whereas the $\beta\lambda$ of the ions ranges from 150 to 680 mm. However, by operating the buncher at harmonic $h_b$ of the rf frequency it is possible to obtain $\beta\lambda/2$ values reasonably close to the fixed 65 mm drift tube length. Harmonic operation also reduces the voltage required of the buncher although it also increases the fraction of a cycle occupied by the bunch length. These parameters are listed in Table 1 for some limiting ions. The bunch lengths are reasonable and the maximum voltage of 20 kV acceptable.

TABLE I

High Energy Buncher Parameters

| Ion | Energy MeV/u | RF Frequency MHz | Buncher Harmonic Number $h_b$ | $\beta\lambda/2$ mm | Buncher Voltage kV | Bunch Length at buncher frequency |
|---|---|---|---|---|---|---|
| C | 50 | 46.9 | 4 | 67 | 20 | 11° |
| Cl | 23 | 32.2 | 4 | 84 | 20 | 37° |
| C | 20 | 60.2 | 2 | 67 | 17 | 11° |
| U | 10 | 47.8 | 2 | 63 | 11 | 58° |

An advantage of the drift tube buncher is that the shunt impedance is high and the power required is estimated to be less than 200 W, which is within the range of a broad band solid state amplifier.

## Phase Control

The phase of the beam bunches reaching the cyclotron must be constant to $\lesssim 1°$ to be able to obtain the required cyclotron energy resolution and this corresponds to a timing accuracy of 50 ps. Transit time jitter, resulting in significant phase excursions, can be caused by microdischarges occurring in the tandem accelerating column. These variations can be up to nanoseconds in amplitude with millisecond duration and have to be compensated by a phase control loop to lock the phases of the low and high energy bunchers together.

This is accomplished by making use of the correlation that exists between the energy and phase of the beam at the high energy buncher location (Fig. 1). A beam intercepting slit located at the energy dispersion point of the bending magnet system immediately after the high energy buncher provides a signal proportional to the phase error between the bunchers which is then used to adjust the low energy buncher phase.

The high energy buncher, however, operates at a harmonic of the low energy buncher and it is possible that for large excursions the feedback loop could lock to a different cycle of the high energy buncher frequency. Since the high energy buncher and cyclotron are each locked in phase relative to the reference rf signal, this would result in a phase error between the cyclotron and the low energy buncher. The design must be able to accommodate this and a beam phase detector located before the high energy buncher will be used in the feedback loop as a coarse control to bring the low energy buncher within the correct cycle of the high energy buncher frequency. A beam phase scanner is planned for this role but a resonant cavity detector[8] is also being considered.

Phase stable heliax cable will be used for the cable runs to the bunchers and for phase monitoring lines. Tests on the cyclotron drive system have demonstrated stability to better than 1° and so no phase stabiliziation is required for initial operation. The high energy buncher, because of its relatively high Q, may require local phase stabilization.

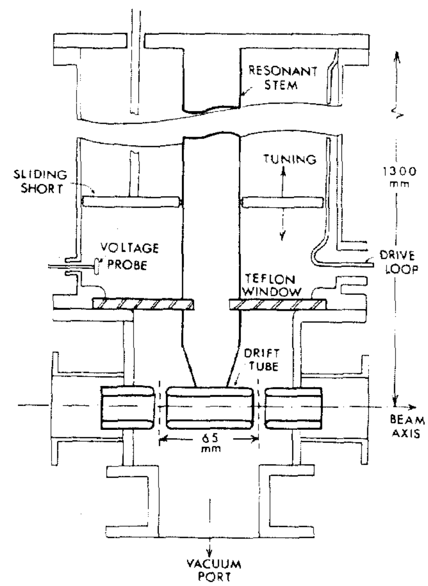


Fig. 6 The high energy buncher quarter-wave resonator.

## Status

A prototype low energy buncher has been built and the tuning, coupling, resonance monitoring and grid voltage measurement problems successfully addressed. Vacuum and high power tests are scheduled for the spring.

The high energy buncher design is complete and fabrication is underway with first tests scheduled for the summer. The phase control system needed for stable operation has been specified and work is in progress on circuit components.

## Acknowledgements

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