THE REBUNCHER FOR THE TANDEM-SUPERCONDUCTING CYCLOTRON BEAM BUNCHING SYSTEM

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Summary

The Chalk River Tandem Accelerator-Superconducting Cyclotron beam bunching system consists of a gridded low energy buncher between the ion source and tandem and a rebuncher between the tandem and the cyclotron. The rebuncher is a 65 mm drift tube mounted on a "quarter-wave" sliding short tuned resonator which needs only 300 watts rf to produce the required 20 kV peak voltage over the 62 to 190 MHz operating range. The buncher is operated at either twice or four times the cyclotron rf frequency, depending on cyclotron harmonic number, to make the drift tube length as close as possible to the ideal $\beta\lambda/2$. The relative phase between the two bunchers and the cyclotron must be maintained to better than 1° by the rf distribution and control system. The rebuncher, control system and initial testing without beam will be described.

Introduction

The Chalk River cyclotron[1] is a four-sector isochronous cyclotron with an rf system[2] based on 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.

The design energy spread of the cyclotron output beam is $3{:}10^4$. To achieve this, the bunch length 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 met at the injection orbit by the external bunching system. A system consisting of a low energy buncher followed by a high energy rebuncher[3] has been chosen. The low energy buncher is located immediately upstream of the tandem accelerator. 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 a time focus at the stripper in the tandem high voltage terminal[4] thus minimizing the increase in longitudinal phase space from energy straggling.

The debunching of the beam beyond the stripper is most significant for the heavy, low energy ions[5]. At the high energy buncher location this debunching can be quite large, but there is a strong correlation between phase and energy, making rebunching possible. To ensure that this correlation is established and preserved, the beam line sections before and after the high energy rebuncher have been designed to be achromatic[6] to permit rebunching to the required 3° at the cyclotron.

Design Considerations

The rebuncher should ideally provide a linear voltage ramp to modulate ion energies so that early ions are slowed and late ions speeded up to provide a new time focus at the cyclotron. At the cyclotron rf frequency, the $\beta\lambda$ values for the different beams cover a wide range which at first sight suggests that a single gap would have to be used rather than a more efficient drift tube structure. But, because of the high ion energies, a single gap would have to operate up to a rather impractical ≈ 160 kV peak voltage. This peak voltage can be reduced by the factor 1/n if the gap is operated at n times the cyclotron rf frequency. Furthermore, if n=4 is used when the cyclotron is operating with h=2 (rf frequency twice the orbit frequency) and n=2 with h=4, then $\beta\lambda$ values for different ions are similar and can be matched by a fixed drift tube length. This allows the use of an efficient resonator with the required voltage reduced another factor of two because of the two gaps, i.e., up to about 20 KV. The ratio n=2 can also be used for the lowest energies requiring h=6; here the match is not critical because the voltage required is smaller. In this way, most beams can be reasonably matched to a 65 mm drift tube operating in the 62 to 190 MHz frequency range. In Table 1 parameters for typical ions are listed. Cℓ at 23 MeV/u and U at 3 MeV/u are examples of the poorest fitting high energy and low energy ions respectively.

Estimated bunch lengths[7] are also shown in Table 1 and all except U-3 will pass during the reasonably linear portion of the sinusoidal voltage waveform. For U-3 the mismatch in $\beta\lambda$ pushes ions into more non-linear voltages and there may be significant losses that could be reduced by shortening the drift tube.

Table 1

Rebuncher Parameters

Ion	Energy MeV/u	Cyclotron Frequency MHz	Harmonic Numbers h	n	$\beta\lambda/2$ mm	Rebuncher Voltage kV	Bunch Length at Rebuncher Frequency
C	50	46.9	2	4	67	20	11°
Cℓ	23	32.2	2	4	84	18	22°
Br	20	59.9	4	2	59	12	51°
U	10	47.8	4	2	63	11	58°
U	3	32.2	6	2	46	6	109°

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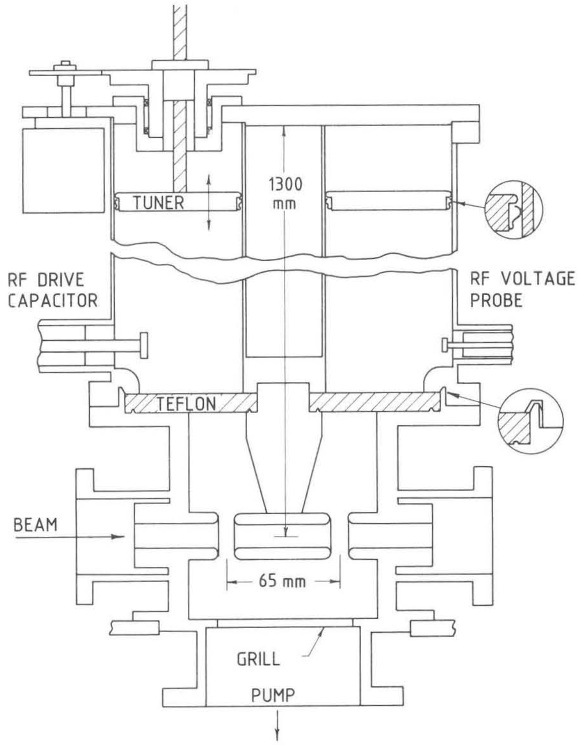

Fig. 1 Outline drawing of the rebuncher.

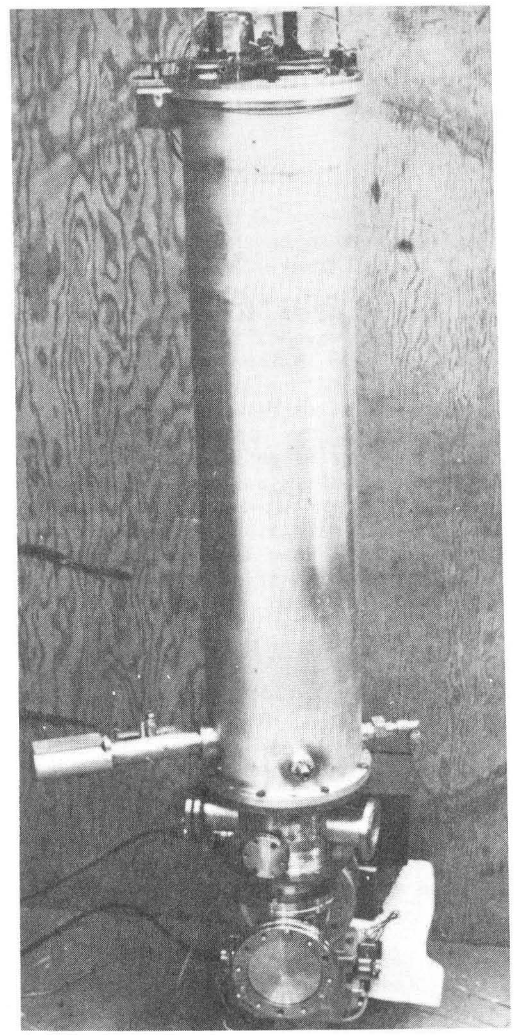

Fig. 2 Photograph of the rebuncher assembled for testing.

The Structure

The rebuncher is shown in Fig. 1 and in Fig. 2. The central stem of the resonator supports the double gap drift tube on the beam line. The gap centre-to-centre spacing is 65 mm; demountable drift tube and "noses" allow this to be altered. A teflon insulator separates the beam line vacuum from the sliding short tuner which operates in air. The sliding short is stepping motor driven through gears and three ball nut drive screws. The short position is monitored by a potentiometer geared to one of the drive screws. Sliding spring contacts on the inner and outer conductors allow the resonator to be tuned under power.

The rf drive capacitor (on the left of Fig. 1 and Fig. 3) is moved by a linear actuator to provide critical coupling at all frequencies. The capacitor on the right and two others are used for monitoring the resonator voltage.

The vacuum housing around the beam is a copper cavity with brazed joints (see Fig. 4). The vacuum seal at the teflon is made by a small ridge pressed into the teflon just inside the rf seal. (See Fig. 1 also.)

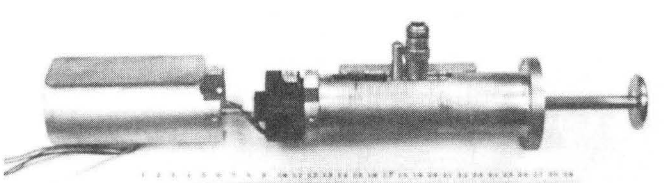

Fig. 3 Photograph of the rf drive capacitor assembly removed from the resonator.

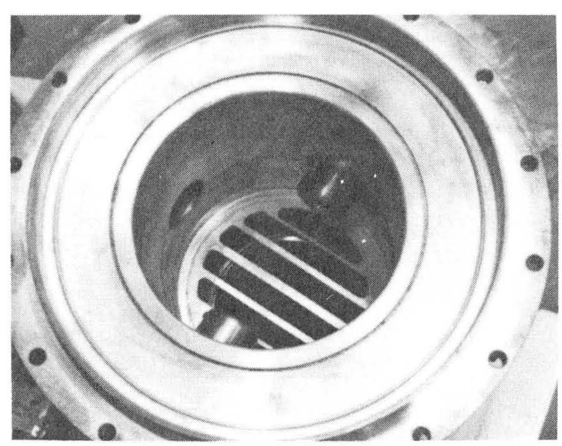

Fig. 4 A view into the copper vacuum cavity. The "noses" of the drift tube assembly can be seen on either side and the vacuum port grill on the bottom.

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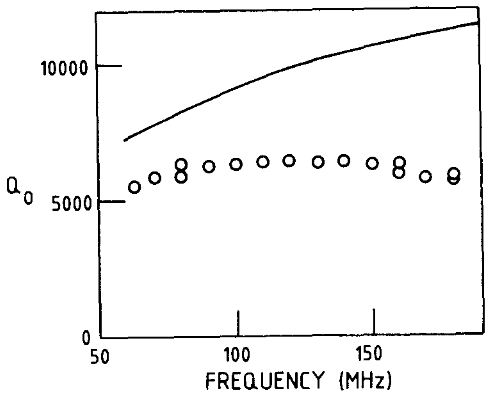

Fig. 5 The measured Q of the resonator compared with the analytic estimate.

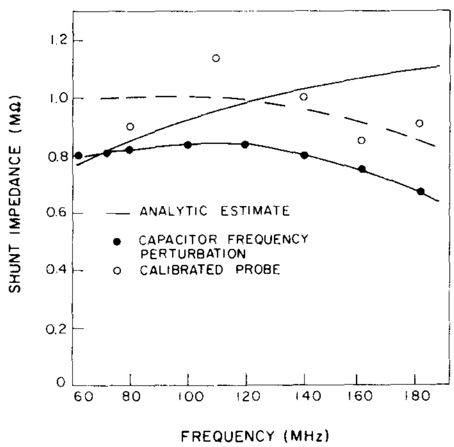

Fig. 6 The shunt impedance vs frequency measured by two methods compared with an analytic estimate.

Cold Tests

The tuning range covers the required 62 to 190 MHz. The resolution of the stepping motor drive is 1.5 steps per kHz at 100 MHz giving 20-30 steps across the resonance peak. The backlash in the drive mechanism is about 12 steps. Full range travel requires about 5 minutes.

The Q was obtained by measuring the resonance width at 3 db below the peak in a weak coupling transmission measurement. The measured Q is shown in Fig. 5 with the calculated Q for an ideal capacitively loaded quarter wave resonator. The difference is attributed to the higher losses in the more complex buncher cavity which are inadequately modeled in the calculations.

The shunt impedance was measured by two methods and the results are shown in Fig. 6 compared with the analytic estimate for an ideal resonator. In the capacitor frequency perturbation method, the frequency perturbation caused by placing a small capacitor across the accelerating gap was measured. This gave the effective capacitance of the resonator, and with the measured Q, the shunt impedance. In the calibrated probe method, a high power voltage probe was calibrated at low power. The shunt impedance can be calculated from the power and voltage at a level where the power can be measured. These results indicate that an rf drive power of 250-300 W is required for the nominal 20 kV maximum voltage required (Table 1).

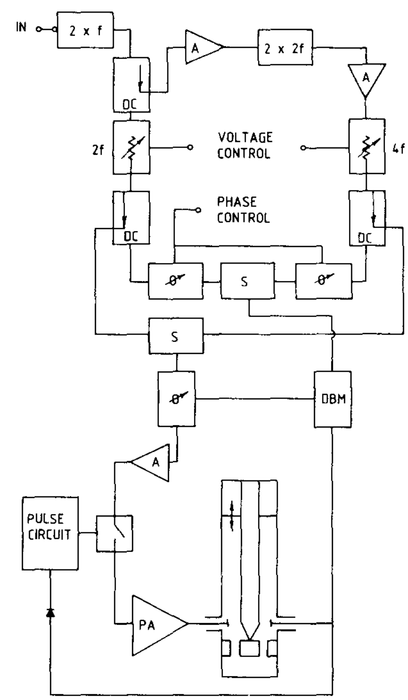

Fig. 7 The rf drive modulator showing the generation of the 2f and 4f signals to drive the power amplifier and to provide reference signals to stabilize the phase.

Modulator

The modulator circuit to produce the rf drive to the power amplifier and to provide phase stabilization is shown in Fig. 7. A phase stable transmission line brings the reference signal from the phase control circuit at the frequency synthesizer. This signal is at the cyclotron rf frequency, f, and is first doubled in frequency and divided by a directional coupler into two main branches. One branch, with a variable attenuator, provides a 2f signal that is divided again in a second directional coupler. One signal goes through a combiner (splitter) to drive the power amplifier (PA). The other provides a phase settable reference for the double balance mixer (DBM) in the phase stabilization circuit. For the upper part of the frequency range, a second doubler in the other main branch provides a 4f signal through the combiners. Operation at 2f or 4f frequency is selected by setting maximum attenuation in unwanted branch and the required amplitude in the other branch.

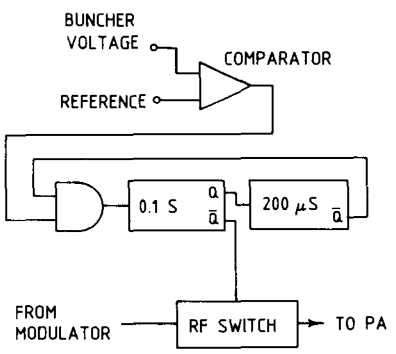

Fig. 8 The pulsing circuit for multipactor breakthrough. With no buncher voltage the rf is pulsed on for 200 μs every 0.1 s. If the buncher voltage rises beyond the multipactor level, which is only a few watts, the comparator signal to the "And" gate holds the rf switch on continously.

To overcome multipactor loading at ≈ 1 watt power level, a pulse circuit was built. The circuit that drives the rf switch to give a fast turn-on is shown in Fig. 8. If the buncher voltage is below the reference level, the timers pulse the rf for 200 μs every 0.1 s. If the buncher voltage comes up, having broken through multipactoring, the rf stays on continuously.

Power Testing

The buncher was set up on a 60 L/s sputter ion vacuum pump for testing up to the 50 W level using an available power amplifier. A sputter ion pump was used to match the standard pumps used throughout the beam line. The vacuum pressure, measured by ion pump current, was in the range 3 $\times 10^{-5}$ to 6 $\times$ 10^{-4} Pa. Normal operation up to 50 watts had little effect on the pressure but a continuous multipactor discharge would drive the pressure up rapidly.

A prototype modulator and control circuit were used in these tests. Figure 9 shows the observed multipactoring limits. The upper curve shows the power level required to break through multipactoring. Once in cw operation, the power could be reduced but at the lower curve multipactoring started again. The buncher cannot be operated below the lower curve with the ion pump on. The buncher was operated up to 190 MHz with the power supply for the sputter ion pump turned off until cw operation was established.

Status

The rf drive and control circuits are being completed, with control computer interfacing for high power testing to full voltage before installation in the beam line.

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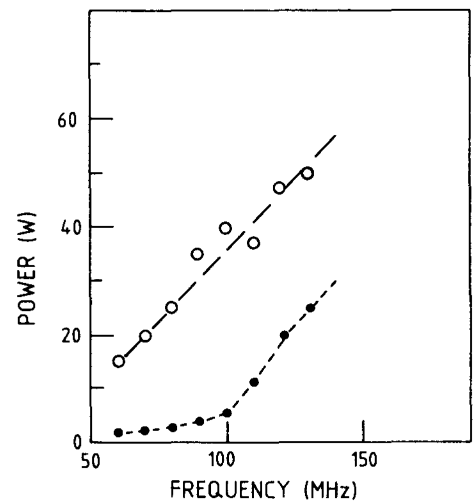

Fig. 9 The pulsed power required to breakthrough the multipactoring is shown by the upper curve. The lower curve shows where the multipactoring starts again as the power level is reduced. These tests were limited by the output of the power amplifier but indicate that operation at high frequencies is possible above about 80 watts.

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