A Beat Frequency Buncher

G. C. Harper and D. W. Storm

Nuclear Physics Laboratory, Box 354290, University of Washington, Seattle, WA 98195-4290

Abstract

The superconducting LINAC at the University of Washington Nuclear Physics Laboratory has been delivering heavy ion beams reliably for ten years. In that time, a number of techniques for beam tuning and beam quality evaluation have been developed. A beam bunching system with the high energy buncher operating at 13/12 of the LINAC fundamental frequency has been developed for removing unwanted, spurious pulses from ion beam that is outside of the pre-tandem, or low energy, buncher time acceptance but within the time acceptance of the LINAC. The system is synchronized so the LINAC and high energy buncher beat frequency remains in phase with the low energy buncher. On LINAC cycles not corresponding to a primary bunch, the high energy buncher bunches residual beam away hom the LINAC longitudinal acceptance rather than into it. The resonator for the new high energy buncher was constructed by shortening an existing low-β resonator.

1 Introduction

The superconducting LINAC at the University of Washington was built to fit in space already existing at the facility. Although economical, an adverse consequence of this is that the beam optics are crowded together and there is not a long enough flight path to install the usual transverse sweeper which removes the beam that lies well outside of the beam bunch in time. We operate our low energy buncher at 12.4 MHz which is 1/12 of the LINAC frequency (148.8 MHz), and we are able to bunch about 65% of the dc beam, leaving a more or less continuous distribution of beam between bunches. Our original high energy buncher operated at the LINAC frequency, so a measurable fraction of the beam outside the main bunches was captured into the 11 LINAC cycles between the main bunch. Although these beam pulses constituted a small fraction of the total, they could produce significant backgrounds in experiments depending on time-of-flight. Furthermore, the size of this background depended on how well the low energy buncher was tuned. It is easy to see, however, that when about half of the DC beam remains uncaptured by the low energy buncher and a sine wave super-conducting high energy buncher captures about 30% of this beam, that the eleven small beam bursts might each be almost 2% of the main bunch. One of our graduate students at the time, Ken Swartz, suggested that we operate the high energy buncher at 11/12 or 13/12 times the LINAC frequency, so that the high energy buncher, low energy buncher, and LINAC could all be synchronized, but so that the high energy buncher and LINAC would not be synchronized for the 11 LINAC cycles between bunches.

Our original high energy buncher was one of our low-β quarter-wave resonators [1]. There is a small cryostat which holds this single resonator, and it was necessary to put the new buncher in the same cryostat. The possibility of reducing the frequency by capacitively loading the high voltage end of the inner conductor was investigated, but the necessary capacitance would have required a very small gap. It seemed unlikely that the gap would hold voltage or that it could be made stable enough to tune the eigenfrequency of the resonator to within the required ten or twenty Hz of the desired frequency. It was clear that building a longer resonator would be expensive and difficult. Consequently we chose to shorten one of our existing resonators.

2 Principles of operation

With the high energy buncher operating at 13/12 of the LINAC frequency, the LINAC and high energy buncher beat with a frequency 1/12 that of the LINAC. Each high energy buncher cycle leads the LINAC by 30° more than the previous cycle. If a continuous beam entered the high energy buncher, and if it were bunched to the synchronous phase ϕ_s of the LINAC on one cycle, it would arrive at ϕ_s-30° on the next cycle, and so on until on the twelfth LINAC cycle it would arrive at (ϕ_s again. We operate the LINAC with a synchronous phase of—20° (using the convention that the voltage varies like cos ϕ), so the LINAC will accept particles with phase from about—40° to +20° [2] if they are at the synchronous energy. Thus we expect some beam to be captured into the LINAC cycle preceding the main cycle. The bunch after the main cycle, however, should be excluded.

To determine the attenuation resulting from the 30° offsets of the bunches, using the buncher that operated at the LINAC frequency, we shifted the operating phase by increments of 30° and recorded the beam current at the LINAC exit. We observed rejection of the bunches lagging by 30° up to 150°, with strong attenuation of bunches leading by 180° up to 30°. Although the details of this result seem counter to the conclusions drawn above, the beam entering the high energy buncher was already bunched by the low energy buncher to a point corresponding to ϕ_s The important result is that there is significant reduction of transmission when the high energy buncher phase is offset. In a better test we would have had the low energy buncher turned off.

3 Resonator modification

The low-β quarter-wave resonator has a cylindrical outer conductor with 9 cm inside radius. The inner conductor is 4 cm in radius at the shorted end. It tapers beginning 11.4 cm from the shorted end to a 2 cm radius cylinder 12.7 cm long between the end of the taper and drift tube. We have developed a simple numerical calculation relating the taper geometry, length, and end load capacitance to the frequency of a quarter-wave resonator [3]. In this calculation we assume the resonator is a transmission line with varying characteristic impedance. The line is short circuited at one end and loaded with a capacitance at the other. The varying characteristic impedance is calculated from the radius of inner and outer conductors as if they were of constant radius. The load capacitance is determined empirically from the known eigenfrequency and radii, and its value agrees with estimates made using the geometry of the drift tube. The calculation predicted that the frequency would increase by a factor of 13/12 if 45 mm were removed from the 2 cm radius part of the inner conductor.

Because of the cylindrical symmetry of the resonator, and because these resonators are made of copper which is lead plated, removal of the required 45 mm was straightforward. This surgery was done in two steps, with a check of the frequency resulting after most, but not all, the 45 mm piece was removed. However, the final amount of material removed was within 0.2 mm of the prediction. The parts were rejoined by vacuum brazing, using the same techniques that were used to braze in the side drift tubes when the resonators were originally built. When removed from the furnace, the braze did not exhibit a smooth fillet at the surface of the copper, but there was a space about 1 mm deep from the edge which had voids. We ground out this space, leaving a smooth groove which we could plate. Fortunately, the location of the braze joint was near a point in the resonator where electric and magnetic energy densities are the same, so this modification did not alter the frequency more than a few kHz. The resonator was plated with a lead-tin mixture (1.8% tin by weight) using a technique similar to that used at Stony Brook [4] and prepared for testing.

4 Resonator Performance

During tests we found much stronger multipacting than we had experienced with our low-β resonators. (Our high-β resonators exhibit significantly less multipacting than the low-β ones.) With the low-β resonators, we are usually able to process in a day or two all the multipactor levels that can be reached at 80 °K. With the new resonator we were able to process the lowest levels and to outgas the lead, but there was a series of levels that were reached with about 50 W that we could not pass in a week of our usual pulsing. Noé has reported [5] a technique using Freon at temperatures around 60 °C when more traditional multipactor processing had been unsuccessful. To our knowledge, this technique had not been used except at Stony Brook.

After consultation with Noé, we warmed up the test cryostat to room temperature and the resonator to 60 °C. The pumping valve was closed and Freon-11 was introduced to bring the vacuum to 2 x 10^{-3} Torr as read with an ion-gauge. CW RF power was applied about 20% (forward power) in excess of that required to initiate discharges or multipacting. At first discharges were observed with maximum voltage below the multipactor level. As time progressed, the Freon pressure dropped and the voltage that could be reached increased. After about an hour we reached the troublesome multipactor levels. The system was pumped down and new Freon added, bringing the ion gauge reading to 1 x 10^{-3} Torr. In another hour we had removed all but the highest multipactor level that we had observed previously. That one was removed in another two hours. In all cases, the ion gauge reading would decrease during the RF processing after the cryostat had been closed to both vacuum pumping and the Freon inlet.

We observed, however, that the multipacting would return when the resonator was left at good vacuum and room temperature. After repeating the Freon processing a few times, we quickly cooled to 80 °K, at which point the resonator did not exhibit any multipacting.

One more level appeared when the resonator was superconducting, but this one was processed away with a few minutes puulsing.

After the resonator was installed in thue buuncher cryostat we repeated the Freon processing. This time the multipacting reappeared during the cooldown to 80 °K. Because the Freon would freeze ouut at 80 °K, we introduced He into the vacuum. We were able to remove the multipacting by a few minutes of RF processing with He at 5 x $l0^{-5}$ Torr ion gauge reading. Finally, when the resonator first was operated at 4.3 °K, some multipacting reappeared, but was processed away by pulsing, and now the resonator can be turned on and off without multipacting.

The resonator has a low-field Q of l.8 x $l0^{8}$ and can reach 2.5 MV/m at l0 W. This is not as good as most of our low-ß resonators, but is more than sufficient for the buncher.

5 Operation in the LINAC

The resonator controllers that we uuse in our LINAC are broad band enough to operate at the higher frequency of the new buncher. The power amplifiers and circulators are relatively narrow band, however, so we puurchased a broad band l00 W amplifier module and a 162 MHz circulator. The clock frequency was produced by mixing the low energy buncher clock with the LINAC clock. Since the low energy buncher clock is obtained by dividing down the LINAC clock, the beat frequency between the LINAC and buncher is guuaranteed to remain in phase with the low energy buncher. The new high energy buncher was been installed abouut a year ago and tested with the modified electronics. In a preliminary measurement, we found that the small pulses associated with LINAC cycles preceding the main bunch were less thuan 0.l4% of the main bunch. It was not possible to set meaningful limits on the size of the pulses associated with LINAC cycles immediately following the main bunch, because of a tail on the late side of the timing pulse.

References

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