COMMISSIONING RESULTS FOR A SUBHARMONIC BUNCHER AT REA*

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Abstract

The ReAccelerator facility (ReA) at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) offers a unique capability to study reactions with low-energy beams of rare isotopes. A beam from the coupled cyclotron facility is stopped in a gas stopping system, charge bred in an Electron Beam Ion Trap (EBIT), and then reaccelerated in a compact superconducting LINAC. The original beam repetition rate at the ReA targets was the same as the LINAC RF frequency of 80.5 MHz. In order to add the capability to bunch at a lower frequency (desirable for many types of experiments using time of flight methods) a 16.1 MHz buncher has been designed, constructed, and commissioned. This paper reports the results of the commissioning of the device, and outlines some future avenues for further improvement of the properties of the bunched beam.

INTRODUCTION

Figure 1 shows the layout of the ReA facility. After charge breeding in the EBIT, the beam is transported to the accelerating section, which consists of a room temperature RFQ and a superconducting LINAC. The 80.5 MHz frequency of the ReA RFQ and LINAC has a period of 12.4 ns. This means that the time-of-flight (tof) measured at a detector is ambiguous by an integer multiple of that period. In order to reduce that ambiguity, a longer period between bunches is desired for tof experiments. One approach to increasing the period without simply discarding large numbers of particles is to bunch the particles before the accelerator at an integer divisor n of the accelerator frequency [1]. With this method, only every nth "bucket" of the accelerator is filled, and the period between bunches increases to n times the original period. The design and construction of this device was the doctoral thesis topic of D. Alt.

DEVICE OVERVIEW

This section presents a brief overview of the design of the device. For more detailed explanations of the rationale behind the design parameters, please see [2].

The basic principle of low β bunching is that for each group of particles to be bunched, a voltage is applied in the longitudinal direction which ramps linearly from strongly decelerating at the head of the bunch to strongly accelerating at the tail. The height of the ramp is chosen so that all the particles in the bunch will arrive at a focal point at the same time. In practice, a perfect linear ramp is not achievable, and an approximation is synthesized from a few Fourier components. As such, some particles will see an incorrect voltage between the end of one ramp and the start of the next one, and will not be bunched correctly.

The frequency chosen for the subharmonic buncher was 16.1 MHz, the 5th subharmonic of the LINAC frequency. This results in a final bunch separation of 62.1 ns. The amount by which the bunch can be compressed in time is determined by the voltage applied to the beam, which in turn is determined by the focal length of the device. The best compromise between efficient bunching, reasonable voltage requirements, and available space on the beamline was determined to be a focal length of 2 m upstream of the focal point at the entrance of the RFQ. The corresponding maximum voltage depends on the rigidity of the species to be accelerated - for the highest rigidity beam which can be accelerated at ReA (Q/A = 1/5) this corresponds to a peak voltage on the first mode of approximately 1700 V.

The bunching waveform is generated by a truncated Fourier series, consisting of the first three sinusoidal components of the Fourier decomposition of the repeated linear ramp. These sine waves are excited in a pair of resonant coaxial structures. The first structure is excited in the $\lambda/4$ and $3\lambda/4$ modes to generate the 16.1 MHz and 48.3 MHz components, and the second is excited in only the $\lambda/4$ mode to produce the 32.2 MHz component. While the relative amplitudes of these components in the infinite Fourier series are 1, -1/2, and 1/3, when the series is truncated these amplitudes must be modified to account for the elimination of the remainder of the series. In order to maintain amplitude and phase stability, these structures are driven by a closed loop Low Level Radio Frequency (LLRF) controller with active feedback. The voltage is applied to the beam by a pair of conical electrodes.

TESTING METHODOLOGY

To observe the time structure of the beam, a timing wire detector was used [3]. This detector consists of a rigid wire centered coaxially within a metal cylinder. A voltage difference between the wire and the cylinder maintains a radial electric field between the two. When the beam enters a hole in the cylinder and strikes the timing wire, secondary electrons are emitted by the wire and carried away by the radial field. Some of these electrons impinge on a multi-channel plate (MCP) detector which in turn sends a signal to the data acquisition setup.

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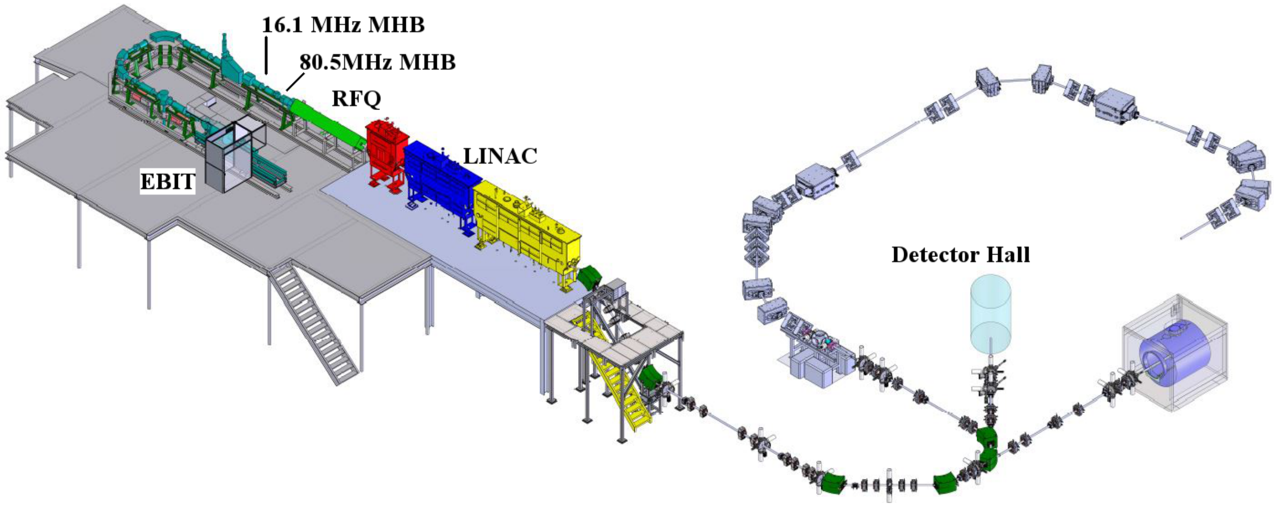

Figure 1: Layout of the NSCL ReAccelerator, including the location of the 16.1 MHz buncher.

To analyze the MCP signal, the output of the detector was connected to the "Start" input of a time-to-amplitude converter (TAC). The "Stop" input was connected to a signal generator synchronized with the accelerator RF clock, divided to produce a signal with a period of 248.4 ns. The result was that each time a signal was detected from the MCP, the TAC produced a signal with amplitude proportional to the delay between that signal and the next "Stop" signal. These amplitudes were histogrammed using a multi-channel analyzer (MCA) and Ortec Maestro software to produce a time spectrum of the incident beam. (Note: because higher amplitudes correspond to longer delays, and thus *earlier* signals, these histograms show time increasing to the *left*.)

COMMISSIONING RESULTS

Beam Simulations

In order to calibrate the results of the testing, the effects of the buncher were first simulated using MATLAB. (Shown along with testing results in Figures 2 and 3.) The x axis indicates peak voltage of the first mode of the accelerating wave as seen by a particle on the central beam axis. The y axis shows the full width half maximum (FWHM) of the time width of the simulated bunch at the focal point. As the voltage is increased the FWHM decreases until the best focus is achieved. If the voltage continues to increase past the optimum, the beam becomes overfocused, and the spectrum eventually bifurcates into two peaks.

The minimum achievable FWHM is determined by the energy spread of the initial beam, and can be easily understood by conservation of emittance. The greater the initial energy spread, the greater the area occupied by the beam in time / energy phase space, and the larger the time spread of the beam after the 90 degree rotation in phase space corresponding to the optimum bunching voltage. The figures show curves for a number of simulated energy spreads.

Single Mode Results

Measurements were conducted in Feburary, 2016, using a beam of $^{40}Ar^{13+}$ at 12 keV/u taken from the EBIT. Time spectra were taken using a timing wire detector located 1.73 m downstream of the buncher, and the FWHM for each peak fitted using the IPF.M peak fitting routines in MATLAB. Unfortunately, only the first two modes were available for testing at the time of these tests, as the third mode proved unstable under the configuration of the LLRF module and the resonant cavity hardware at the time.

The results of these measurements for the 16.1 MHz mode are shown in Figures 2 and 3 superimposed on the simulation results for each mode. It is important to note that the actual measurement results gave the FWHM as a function of the control system readout, not the on-axis voltage used for the simulation. By scaling the x-axis of the results, the beam voltage to control readout relation can thus be directly calibrated. In future operation, this type of measurement will be used to calibrate the control system readout to give the on-axis peak voltage. Also of note is the fact that this measurement to simulation comparison allows for direct measurement of the energy spread of the initial beam from the EBIT. In this case, the energy spread is seen to be about 0.15%, consistent with the design specification of approximately 0.2%.

Combined Mode Results

Once each mode was calibrated, both modes were turned on, and the beam was sent through the RFQ and LINAC to a timing wire after the third cryomodule of the accelerator. The beam was accelerated to an approximate energy of 1.5 MeV/u and the time structure measured in the same method as before. The resulting spectrum is shown in Fig. 4. The primary peaks show the desired bunching separation of 62.1 ns between peaks. Faraday cup readings indicate that approximately 50% of the initial beam current from the EBIT was preserved at the end of the LINAC. By comparison, with the 80.5 MHz buncher, 75% of the beam is preserved, and with no bunching whatsoever, 30% of the beam remains.

A note on the "satellite" bunches visible in Fig. 4. As mentioned earlier, the bunching voltage is not a pure linear ramp - it is an approximation synthesized from only two (in this case) sine waves, and as such particles at the head and tail of each group of particles will see an incorrect voltage rather than the perfect linear ramp. Most of those particles will fall outside the acceptance of the RFQ, but some will enter the acceptance for undesired accelerator buckets. Those particles become the satellite bunches visible here. During the current experiment, 13% of the particles reaching the final detector were contained in satellite bunches. Simulation suggests that the number could be reduced with better tuning and calibration, as well as by the addition of the third bunching mode. However, some satellite bunches are inevitable unless the length of the initial beam pulse can be reduced below that of the linear portion of the bunching waveform.

FUTURE PLANS AND CONCLUSION

While these results represent an important proof of concept for the device, further development is necessary before the device can reach its full potential in support of the NSCL / FRIB experimental program. In particular, physical and software improvements to the hardware and LLRF module are planned which will allow the third buncher mode to extend the linear portion of the bunching waveform, thus increasing buncher efficiency. Once these improvements are carried out and the buncher controls more thoroughly calibrated, it is predicted that the buncher should be able to reach on the order of 95% of the beam in the main bunch. In the longer term, various options are being explored for cleaning the satellite bunches more completely.

In conclusion: A 16.1 MHz subharmonic buncher has been designed, constructed, and tested for the ReA linear accelerator at NSCL / FRIB. This device has been successfully shown to bunch beam with a period of 62.1 ns between primary bunches with no more than 13% of the beam remaining in satellite bunches after the LINAC. Future modifications are planned to improve the performance and usability of the device with the hope that it will soon be made available to users of the facility.

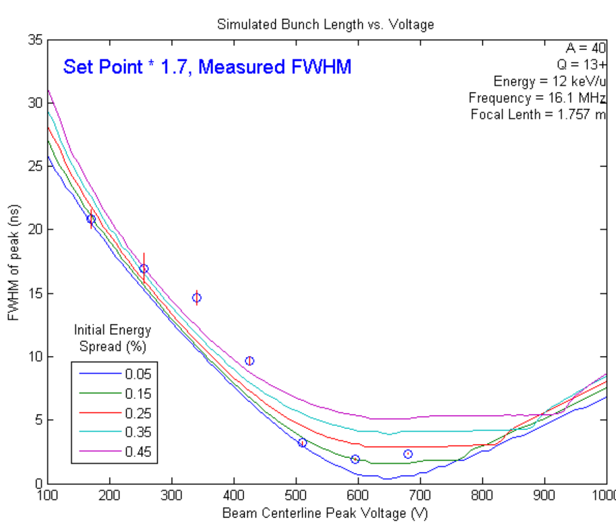

Figure 2: Measured pulse widths overlaid on simulated FWHM vs. voltage curves for the 16.1 MHz mode.

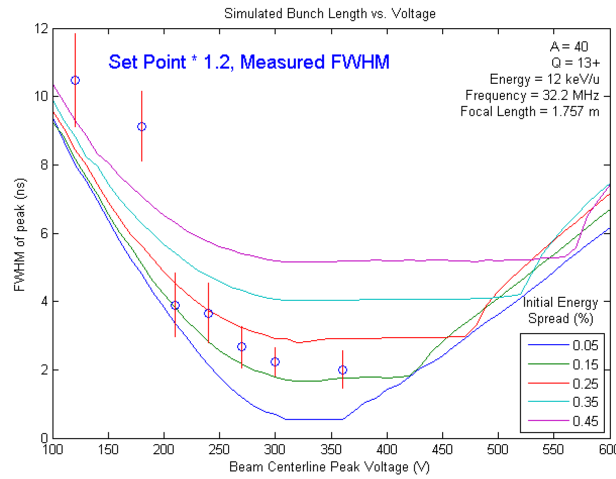

Figure 3: Measured pulse widths overlaid on simulated FWHM vs. voltage curves for the 32.2 MHz mode.

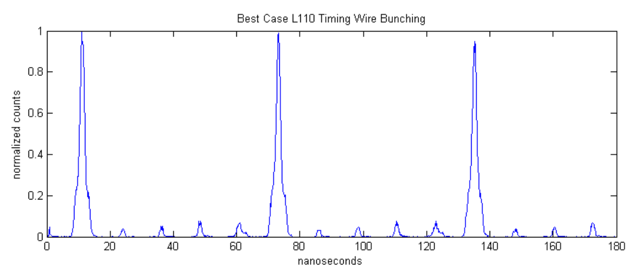

Figure 4: Time spectrum for bunched beam after the LINAC.

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