Characterization of Subnanosecond Heavy-Ion Bunches at the TASCC Superconducting Cyclotron

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Abstract

The TASCC heavy ion facility produces beams at specific energies of 4 to 50 MeV/u. We report on the fine time structure of the beam, typically bunches of 150-500 ps FWHM, at a repetition rate of 31-62 MHz. Average beam currents range from 1 to 500 enA. The ratio between peak and dark current typically exceeds 5000:1, ideal for time-of-flight experiments. We also discuss measurements of absolute beam energy by bunch time-of-flight.

I. INTRODUCTION

The Chalk River Superconducting Cyclotron (SCC) is a K=520 machine, fully commissioned in Oct. 1991. Its two pairs of dees operate in 0-mode or π-mode, from 31-62 MHz. It accelerates beams from 3 Li to 238 U up to 50 MeV/u and 10 MeV/u, respectively. Extracted currents range from 1 to 500 enA. Here we discuss the timing properties of the beam, and energy measurement by bunch time-of-flight.

Figure 1 shows the TASCC facility layout. A Tandem accelerator serves as injector for the SCC. The Low Energy Buncher (LEB) uses an rf sawtooth (up to 2 kV across a grid) to pre-bunch the beam to about 1 ns (10-20° rf), focusing at the Tandem stripper to minimize straggling. The High Energy Buncher (HEB) is a double drift tube device that rebunches the beam to a focus at the SCC stripper foil. The beam is sent to the target areas through the time-of-flight energy measurement system (described in Section 3 below).

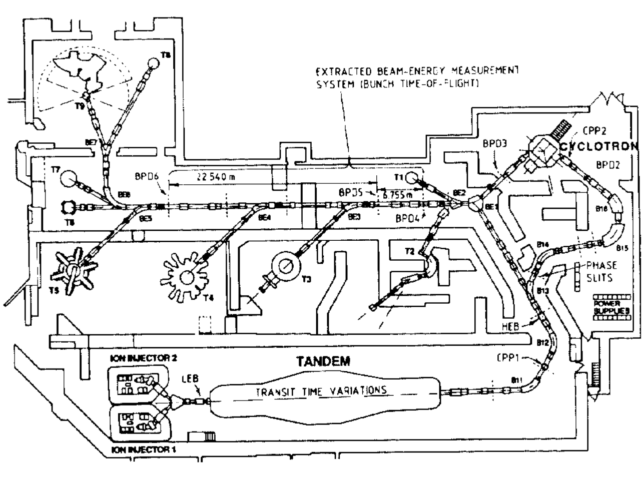

Figure 1. TASCC Facility Layout.

II. INJECTION TIMING

We have reported on the phase control system in a previous paper [1], but briefly re-cap here to point out recent modifications. A capacitive pickup (CPP1) after the Tandem provides a signal to a phase shifter at the LEB to correct for transit time variations through the Tandem, typically of order 10-30° rf. An analyzing magnet and slits after the HEB are used in another feedback loop to remove most of the unbunched current and to maintain energy stability at SCC injection by varying the HEB phase. The beam position is stabilized both vertically and horizontally using analog feedback at the object slits of the analyzer [2].

The HEB is operated the second or fourth rf harmonic, to ensure matching of the drift tube length to $\beta\lambda/2$ over the wide range of injected beams, and so not all HEB focusing buckets are filled. A recently-developed 'bucket control' computer program monitors the beam phase and coarsely resets the LEB phase to feed the desired HEB bucket after large phase shifts. These can occur after ion source or Tandem disruptions. Residual phase noise is reduced to typically $\pm 0.5°$ rf at SCC injection, with current variations less than a few percent. Much recent effort has gone into noise control, improved sensitivity of capacitive phase probes [3] and development of linear, octave-bandwidth phase modulators [4]. Our ability to bunch and phase-control a Uranium beam of <10 enA was crucial to the commissioning of the SCC.

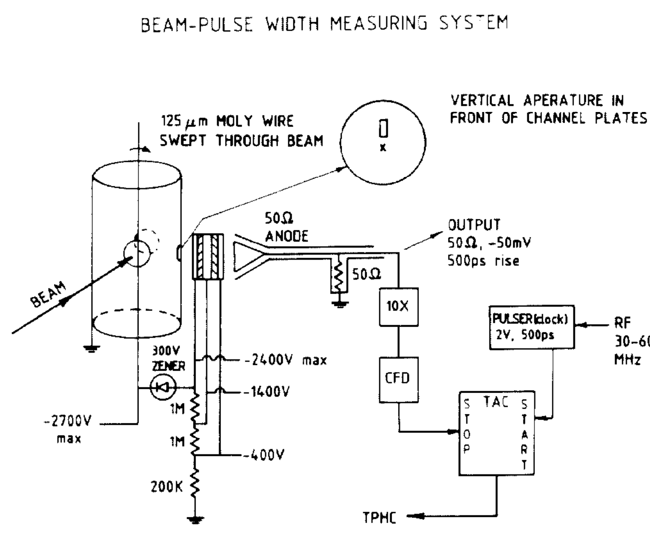

Figure 2. Beam Pulse Detector.

Bunch lengths are measured [5] with Beam Pulse Detectors (BPD) (shown in Figure 2). A 0.25 mm molybdenum wire at -2 kV is inserted into the beam. Ions hitting the wire produce primary electrons, with a (low) probability proportional to instantaneous beam current. They are accelerated through a small slot to a 'chevron' micro-channel plate to create secondaries with a gain of 10^4 and a transit-time jitter of $\sim$50 ps (manufacturer's data). Collected at a conical 50 Ω anode, they produce pulses of 500 ps risetime, and $\sim$1 ns width. The overall detection efficiency is roughly 10^{-3} pulse per bunch. The electron pulse arrival time is strongly correlated with the instantaneous ion current, thus, a histogram of arrival time with respect to the rf clock represents the bunch shape in real-time. Data is accumulated over several seconds and includes residual phase noise. The electronic time resolution of the system is about 60 ps [5].

Figure 3 shows the time structure of the beam measured at SCC injection, with (a) the HEB alone (at 4th harmonic), (b) the LEB alone and (c) both bunchers, with phase control properly set up. About 60% of the DC beam from the Tandem is bunched as shown. 72% of the bunched beam is in one of the HEB focusing buckets, with the rest divided between the defocusing HEB buckets and the out-of-phase focusing buckets. Typically 65-85% of the bunched beam is in the desired bucket, for an overall bunching efficiency of 40-50%. The bunch width measured at SCC injection is 200 ps FWHM, or about 2.4° rf at f = 33.4 MHz for a 24 Mg beam at 37.7 MeV. Typical injected bunch widths are in the range of 2.5-6°, depending on the frequency, the details of beam production in the ion source and straggling in the Tandem (straggling is worse for heavier beams).

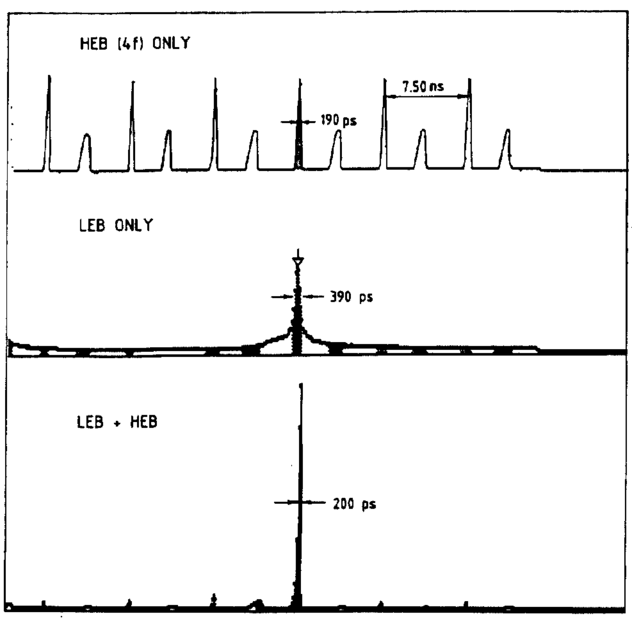

Figure 3. Injection Timing with Low and High-Energy Bunchers ^{24}Mg 37.7 MeV, f = 33.4 MHz.

Such narrow bunches produce well-separated turns in the SCC, making diagnostics easier. We use single-turn extraction, with a combination of (first harmonic) magnetic field shaping and electrostatic deflection. The energy spread of the beam is limited to a theoretical value of 1 - cos (HWHM) $\sim 3 \times 10^{-4}$ for a 3° bunch, assuming isochronism. Beam extraction efficiency is between 40% and 100%, depending on the electrostatic deflector gap and magnetic field details (e.g. there is loss of radial focusing at outer radius due to loss of isochronism).

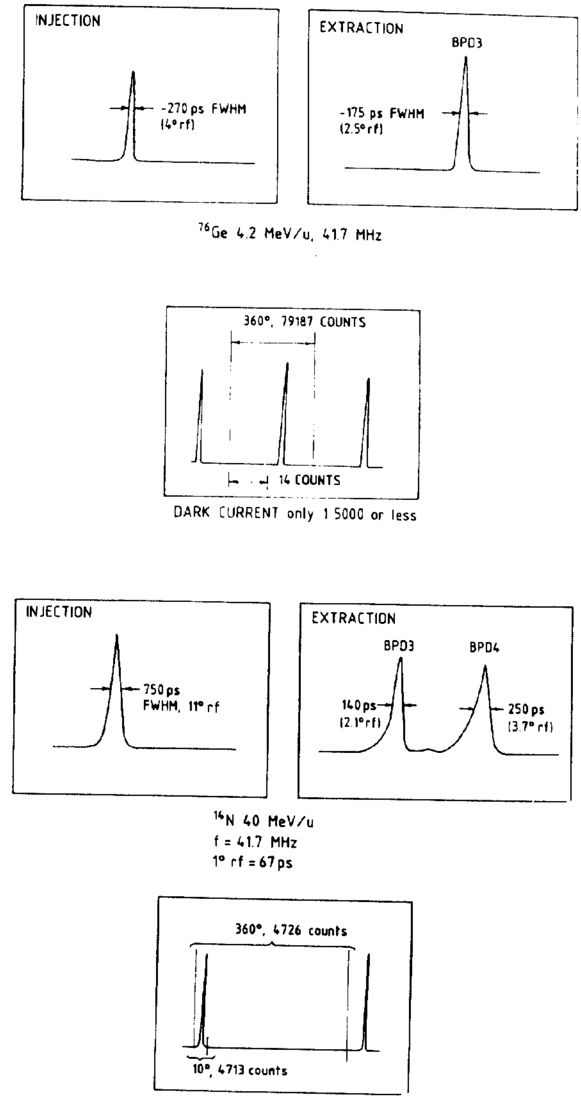

Figure 4. Bunch Widths and Current Contrast on Extraction.

The bunch length of the extracted beam is usually less than at injection, both because of the bunch compression due to the increasing DEE voltage with radius in the SCC itself [6,7] and because of aperture-clipping within the machine [8]. Figure 4 shows the bunch length for two different beams, at injection, on extraction (at BPD3), and analyzed at BPD4 in the target area. In the first case (76 Ge, 4.2 MeV/u, 41.71 MHz), the bunch length is 270 ps FWHM (4° rf) on injection, and 175 ps FWHM (2.5°) at extraction. In the second case (14 N, 40 MeV/u, 41.69 MHz), the injected bunches are purposely wide, 750 ps FWHM (11°) on injection, 140 ps (2.1°) at extraction (BPD3), and 250 ps FWHM (3.7°) at BPD4, after an additional 6 m drift and the dispersion of the analyzing magnet (BE1 in Fig. 1). The injected bunches were made wide and the current high to maximize output current. Extraction efficiency was low due to limited deflector voltage, with much of the accelerated beam clipped on the deflector electrode. The deflector performance has since been greatly improved; this is reported in another paper in this conference [9]. In both cases, the bunch timing at extraction has an extraordinary level of time-contrast, that is, the ratio between instantaneous bunched current and the dark current between bunches, of at least 5000:1. This is of interest for time-of-flight experiments.

III. TIME-OF-FLIGHT ENERGY MEASUREMENT

We have built a system to measure the absolute beam energy [10] along the straight section of the extraction beamline (shown in Fig. 1). The bunch time-of-flight (BTOF) energy measurement system consists of an array of three Beam Pulse Detectors (BPD's) on the extraction beamline (BPD 4,5,6 in Fig. 1). The bunches are time-resolved by each detector, and from the time-of-flight over the 29m path length, the velocity and energy are calculated.

The system specifications and characteristics are as follows:

- specific energies 4 - 50 MeV/nucleon
- velocities β 0.09 - 0.32
- bunch repetition rate 31 - 62 MHz
- typical counting rate 5 - 100 KHz
- range of detectable currents 1 to > 100 enA
- flight path 6.755 m + 22.540 m (three detectors)
- time-of-flight 300 - 1100 nS
- transverse spatial resolution 0.25 mm (wire diam.)
- time-of-flight determined to $\pm$85 ps
- detector position surveyed to $\pm$2 mm
- ACCURACY OF ENERGY MEASUREMENT:
  $\delta E/E_{abs}$ $\pm 3 \times 10^{-4}$ for 4 MeV/u, β =.09, 41.7 MHz
  (e.g. Ge 4.2)
  $\delta E/E_{abs}$ $\pm 9 \times 10^{-4}$ for 50 MeV/u, β =.32, 46.2 MHz
  (e.g. C 50)

A representative result is shown in Fig. 5. The injected bunch pattern is shown in Fig. 5(a), with a FWHM of 330 pS, or 6.2° rf with a 'bucket efficiency' of 88%. For 127 I at 15 MeV/u, β =.18, 52.09 MHz, the bunches are $\beta\lambda \sim 1.03$ m apart in the beam-line. Each detector in the extraction array (BPD 4,5,6) produces a bunch footprint at 19.2 ns intervals, as shown in Fig. 5(b),(c). Using one pair of detectors, the velocity and energy can be determined to within 1/n, where n is the number of bunches between the detectors. Using three detectors, n is determined uniquely, and the absolute energy found to within $\delta E/E < 10^{-3}$.

We have now done measurements of absolute energy of five beams, in seven runs, from 4.2 to 25 MeV/u. Small energy changes of order 10^{-3} can readily be detected and the SCC tuning corrected as needed.

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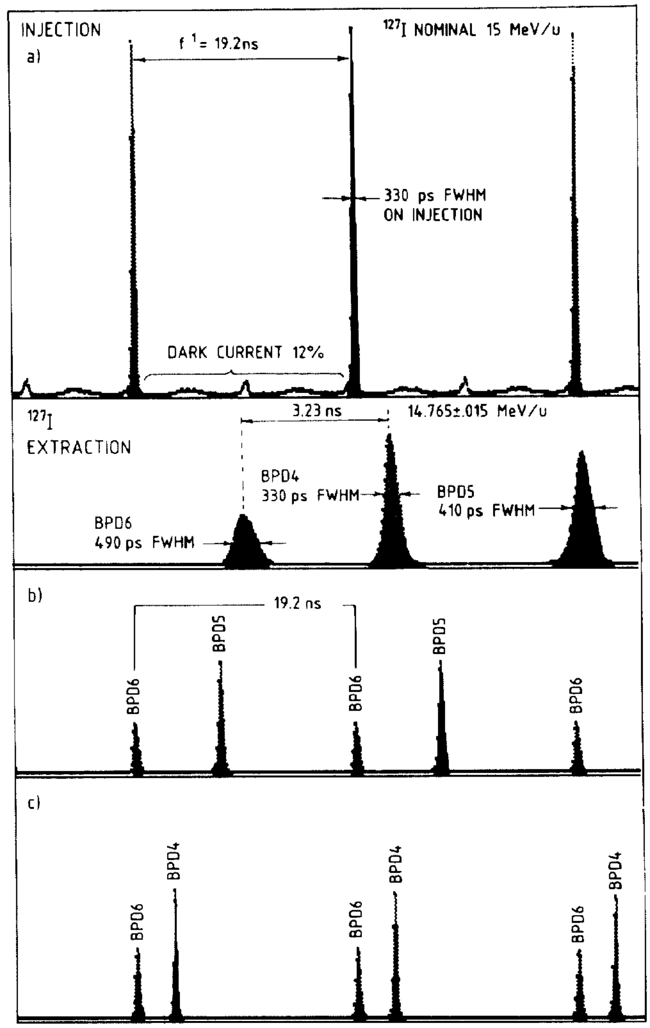

Figure 5. Injection and Extraction Timing, Bunch Time-of-Flight System.

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