TASCC BUNCH INJECTION AND PHASE CONTROL SYSTEM: REVIEW, OPERATING EXPERIENCE AND RECENT IMPROVEMENTS

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ABSTRACT

We present measurements of the performance of the bunch phase control system using our MP Tandem as an injector for the Chalk River superconducting cyclotron (SCC). We achieve less than ± 1° jitter on phase injection when ion source conditions and tandem accelerator transit-time fluctuations are acceptable. We describe the control system's sensitivity and frequency response, and give examples of its performance with two different beams.

1. INTRODUCTION

The injection beamline for the superconducting cyclotron[1,2] is shown schematically in Fig. 1. The beam produced by the ion source is pre-bunched by the low-energy buncher (LEB)[3] to a time focus at the tandem stripper to minimize straggling[4], then rebunched by the high-energy buncher (HEB)[5] to a final width of a few rf degrees for injection to the cyclotron. To achieve high-energy resolution of the output beam the phase must be controlled to within one degree; $\Delta E/E < 5 \times 10^{-4}$ requires a total bunch window of 3.7°. The LEB applies the fundamental (1f) and second harmonic (2f) of a sawtooth to a 1 mm gridded bunching gap, while the HEB applies either the second or fourth harmonic (4f) to a drift tube buncher. There is no active phase control of the HEB; it remains phase-locked to the synthesizer, with some fixed delay. The same is true of the rf drive to the cyclotron dees, hence all phasing corrections must be made on the injection beamline.

Bunches are monitored with two capacitive phase probes (CPP), one shown on Fig. 1 between the tandem and the HEB and the other (CPP2) just before the cyclotron. They are coaxial capacitive dividers that produce an output rf signal proportional to the oscillating field of the bunched beam. CPP1 is used as a timer for the phase control system, while CPP2 is used to monitor bunch arrival time and current on injection to the cyclotron. Since the CPP's do not have adequate bandwidth to measure the bunch shape in time, there are two beam pulse detectors (BPD's) on the injection beam line. BPD1 is located just before the HEB and is used for set-up and indirect monitoring of the LEB waveform and power level, and the BPD2 is located in the beam line before the cyclotron to monitor the bunch length on injection. They consist of collection electrodes and a micro-channel plate to amplify electrons produced when a thin molybdenum wire is inserted into the bunched beam. The resultant pulses are converted to a time-resolved bunch shape by a time-to-amplitude converter and pulse height analyzer in the control room. The channel separation of the system is 110 ps.

To set up the buncher waveforms and power levels, we use readback meters, the beam pulse detectors, and a four-channel oscilloscope to monitor the rf reference signal, the LEB sawtooth, CPP1 and CPP2 signals (see Fig. 2). Once each LEB resonator is tuned for minimum reverse power and the local AFC circuits are activated, the relative 2f/1f input power and phase are adjusted to produce the sawtooth shown in Fig. 2. The input power level (before the frequency doubler) is also adjusted to maximize the CPP1 signal. This is an approximation to setting the time focus at the tandem stripper gas[4].

Once the HEB is tuned for 2f or 4f operation and turned on, the HEB power is adjusted to maximize the bunched signal seen at CPP2 and minimize the bunch length seen at BPD2, assuming the LEB to HEB phasing is approximately correct. This timing can be monitored at a suitable position downstream of the slits, at BPD2 for example, by operating the bunchers separately. A typical measured bunch shape is shown in Fig. 3, for $^{127}I^{+7}$, 70.9 MeV (for I 10 MeV/u) bunched at 42.7 MHz. The measured bunch width is 3 ch FWHM, about 300 ps or 4.6° rf, including approximately 1° total phase jitter.

The major contribution to phase error and jitter in the injected bunches is low-frequency (< 100 Hz) variation in the transit time of ions from the LEB to the HEB, due to time-varying accelerating gradients in the tandem. The phase control system, shown in Fig. 4, corrects for these fluctuations by driving a phase shifter in line with the low-energy buncher labelled LEBLQA.

We have two systems to produce the phase correction signal. One is based on CPP1, which generates an rf signal proportional to the bunched current. This signal is amplified, filtered and phase-compared to the reference signal at a double balanced mixer (DBM). The DBM output is filtered (to reject the rf), amplified, and used to drive the 0-180° phase shifter on the LEB input, to minimize the phase error between CPP1 and the reference. The phase loop gain is adjustable, and typically set > 50 at low frequency (< 10 Hz). In practice, the CPP is usable with beam currents of 100 nA or more; it is insensitive to beam steering errors and to the transverse profile of the beam as it passes through the steering magnets. It recovers unambiguously from beam disruptions and is relatively easy to set up to produce less than ± 1° phase jitter.

Finer phase control can generally be achieved using the energy analyzing slits labelled "phase slits" in Figs. 1 and 4. Logarithmic amplifiers sense the left-right shift of the beam that accompanies a change in arrival time at the HEB; this is amplified again to produce the phase-correction signal at the LEB. The gain is set > 50 at 10 Hz, with a rolloff at 100 Hz. The sensitivity of the slits-based control system is limited by the dispersion of the analyzing magnet BI3 (≈ 1 mm per 10^{-3} $\Delta E/E$) versus that of the tandem energy analyzer (≈ 1.6 mm per 10^{-3} $\Delta E/E$). The slits system reads the response of the HEB (operating at 2f or 4f) and uses the energy shift accompanying the phase shift to drive ϕ_{LEB} (at 1f). For large phase shifts, following tandem dropouts for example, the sign of the correction signal may be wrong and control is lost, or the system may lock onto the wrong cycle at the HEB frequency, leaving a very low bunched current for the cyclotron dees, themselves phase locked at fixed delay to the HEB. For stable phase control with the HEB operating at 4f, transit time variation at the slits is limited to ± 22.5° at 1f. As well, the slits-based phase control system is sensitive to the transverse beam profile at the slits, a function of the energy and charge to mass ratio of the ions as well as the HEB power level. Its detailed setup, therefore, is quite beam-specific. The slits system provides fine control when tandem transit time variations do not exceed its control range. The slits control system automatically switches to CPP control if the slits-intercepted currents fall below an adjustable threshold[6], and back to slits control when the beam returns[6].

2. SOURCES AND EFFECTS OF TRANSIT TIME VARIATIONS THROUGH THE TANDEM

The transit time for ions from source to SCC is a function of the electrostatic potentials they encounter and their charge states. Ions leave the source at an energy of 200 keV and charge state -1, pass through the LEB with small change in energy, and into the tandem to be accelerated to the high-voltage terminal at +5 to 13 MeV, then stripped to +2 to +10 charges and accelerated to the tandem output. Most of the total transit time is spent getting to the tandem HV terminal[6,8]. Therefore, rf phasing is most sensitive to potentials changing the low-energy trajectories, i.e., the ion source energy and the accelerating voltage gradient up to the tandem HV terminal.

Instability in the ion source oven temperature, output voltage, beam emittance[7] drift, and the tandem high-voltage instabilities, at the terminal[8,9] and on the gridded lens, all contribute to transit-time variations. Examples are given for ^{127}I in reference 6. A breakdown across one of the grading resistors in the accelerating column of the tandem can also cause a phase shift greater than the bunch length[9], or the ion source cathode voltage and extracted current may change, varying the beam divergence[7] into the tandem. This changes the loading on the accelerator tubes and the detailed voltage gradient, hence drift in the transit time. To overcome this,slits were installed immediately after the source to clip the beam before injection into the tandem.

In Fig. 5 we illustrate the sensitivity of transit time to stability of the potential on the gridded lens at the low-energy end of the tandem. The voltage here is varied from 15 to 17 kV and back, and the effect monitored. The observed sensitivity is 4° (0.35 ns at 32 MHz) per 100 V variation on the supply. This agrees well with a theoretical estimate given in reference 6.

Another adverse condition occurs when the ion source current decreases with time, e.g., when the 'cone' is slowly burning out. The phase has been observed to change four half cycles or 720° in several minutes. The average jitter over a few seconds was some 35°, and the phase control system could handle this (producing a residual total jitter of ±1° or so), but in its present configuration it cannot handle monotonic drift, going unstable when the phase drifts more than 180°.

All of the above ion source/tandem injector conditions must be controlled before the bunchers can be easily set up for cyclotron injection.

To illustrate the performance of the phase control system under adverse conditions we present a series of measurements taken with $^{127}I^{6+}$, 42 MeV, done with the CPP1 to LEB control loop and monitoring at CPP2.

Following beam dropout, the CPP1 signal must be used to re-establish the right phase bucket. The tandem exhibits frequent 'roll offs' (beam loss due to sparks in the tandem or source) and the beam stabilizes back to a different phase in Fig. 6(a). The phase control system can then only produce usable beam for short periods of time, with breaks when the beam drops out (see Fig. 6(b)). Coarse manual adjustments to the LEB phase and the dee phase are necessary to compensate for step changes in the transit phase when the beam is re-established.

3. RECENT IMPROVEMENTS AND PERFORMANCE

With increased operating experience, further reductions in injection phase jitter were possible, to approach the design goal of stability of ± 0.8° for $\Delta E/E \leq 5 \times 10^{-4}$. By late 1987, accumulated operating experience with the Model 860 ion source and aperture slits and improvements to the tandem stability had effectively eliminated transit-time drift and reduced transit-time fluctuations to the point where the slits-based phase control system could be re-enabled. As well, oscillations in the feedback loops at high gain were limited to frequencies above 1 kHz, while the observed transit-time variations were generally below 100 Hz. Some measurements were taken of the spectrum of transit-time variations through the tandem, with a view to increasing the dc-100 Hz gain while suppressing the kHz oscillations. It was found that the system as it stood had more than adequate frequency response to handle the spectrum of uncorrected transit-time variations produced by the ion source-tandem variation. Most transit-time variations occur at frequencies below 20 Hz, a consequence of the mechanics of the tandem. It was decided to add time integration to the system, to reduce gain at higher frequencies and allow an increase in lower frequency gain without inducing oscillation.

A simple 33 Hz low-pass filter was added on each of the CPP1 and slits branches of the phase control loop. This allowed an increase in loop gain of another factor of 5 for a final phase gain of 50 at 10 Hz.

Finally, we present the results of the performance of the phase control system with two beams recently injected into the cyclotron. The measuring device is a vector voltmeter that phase-compares two rf signals at a time. Each of the three time records shown was taken at a separate time, and so a transient that appears on one record does not appear on the others.

Figure 7 shows the injected phase jitter of $^{127}I^{6+}$, 42 MeV, bunched at 32 MHz, without phase control, under slits control, and under CPP1 control. Figure 8 shows comparable measurements of injection phase jitter of $^{79}Br^{6+}$, 85 MeV, bunched at 60 MHz. In all cases, the injection phase jitter was reduced by a factor of 10 or more under control, with the slits system outperforming the CPP-based control system by a factor less than two. The injection phase jitter obtained was approximately ± 0.5° (HWHM) on both beams, well within the jitter necessary to ensure an energy spread in the extracted cyclotron beam $\Delta E/E < 5 \times 10^{-4}$.

Plans for ongoing development of the system include full-cycle (0-360°) phase detection and control, bunch length and timing measurements on the extraction beamline, and high-resolution turn broadening measurements within the cyclotron.

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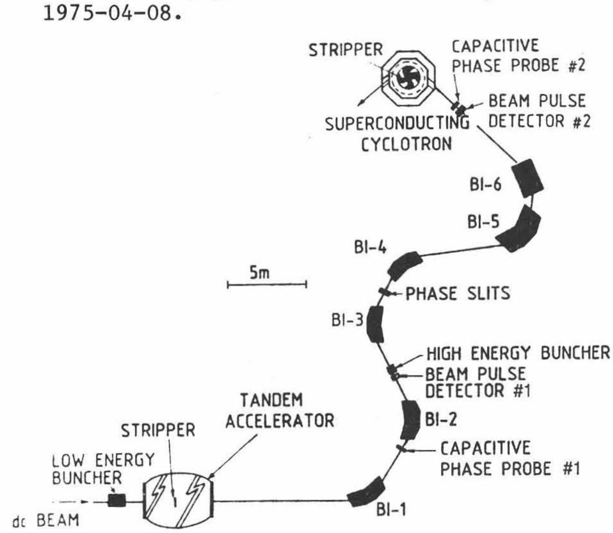

FIG. 1 INJECTION BEAMLINE

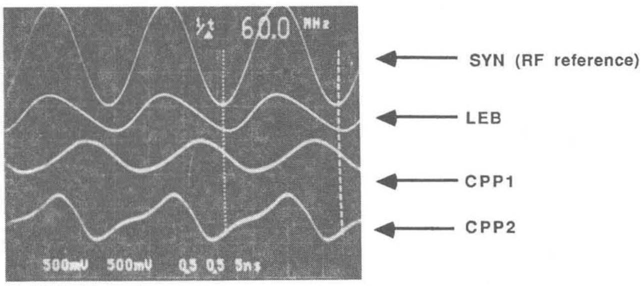

FIG. 2 BUNCH MONITORING SYSTEM AS SEEN ON OSCILLOSCOPE IN CONTROL ROOM

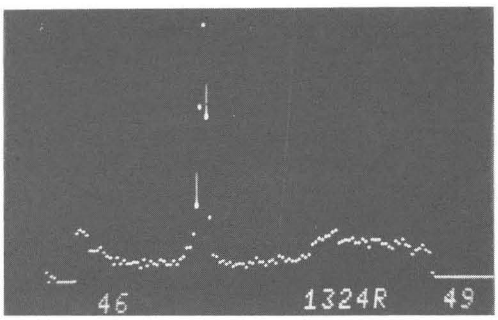

FIG. 3 FINAL BUNCH WIDTH TO CYCLOTRON, $^{127}I^{7+}$ 71 MeV, 43 MHz, 300 ps FWHM, 4.6° RF, INCLUDING 1° TOTAL PHASE JITTER

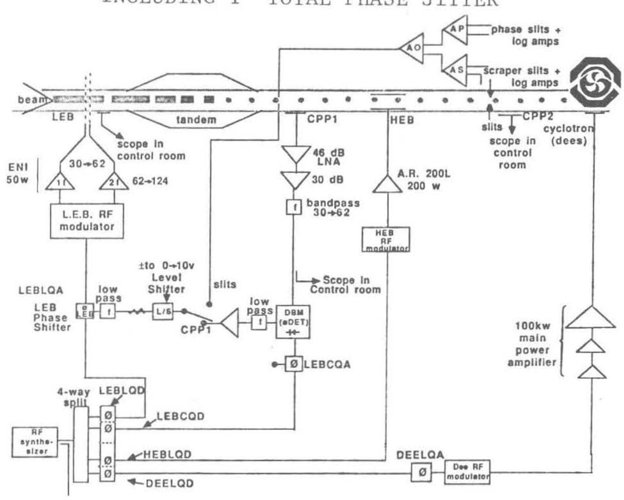

FIG. 4 BUNCH PHASE CONTROL SYSTEM

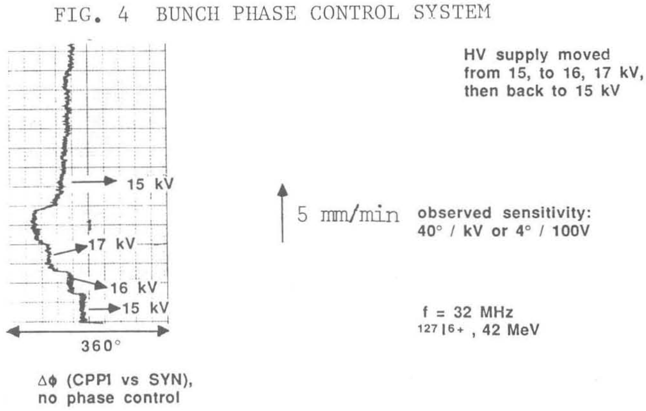

FIG. 5 EFFECT OF TANDEM GRIDDED LENS HV STABILITY ON TRANSIT TIME VARIATION

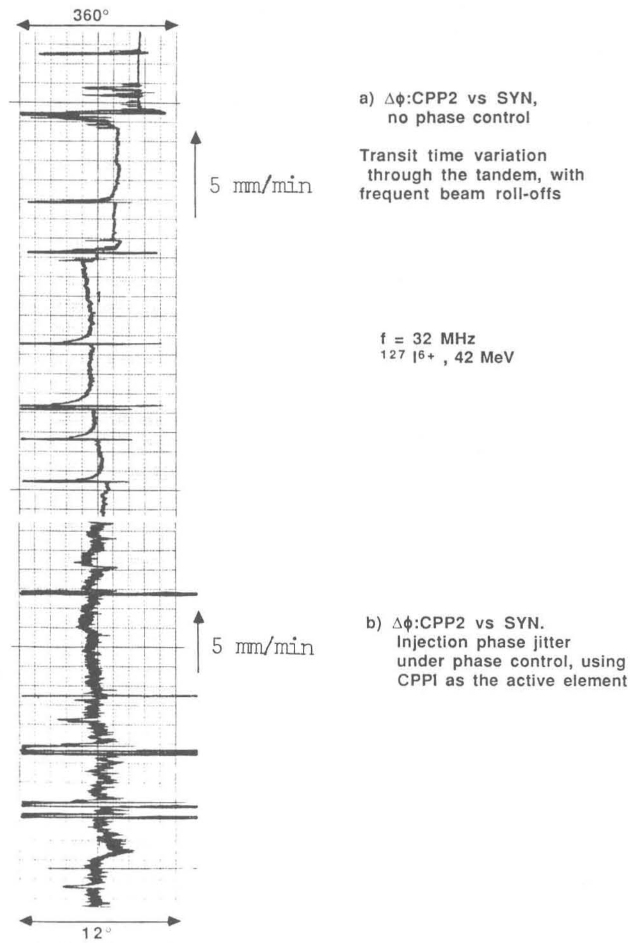

FIG. 6 RESPONSE OF PHASE CONTROL SYSTEM TO SEVERE TRANSIT TIME VARIATIONS

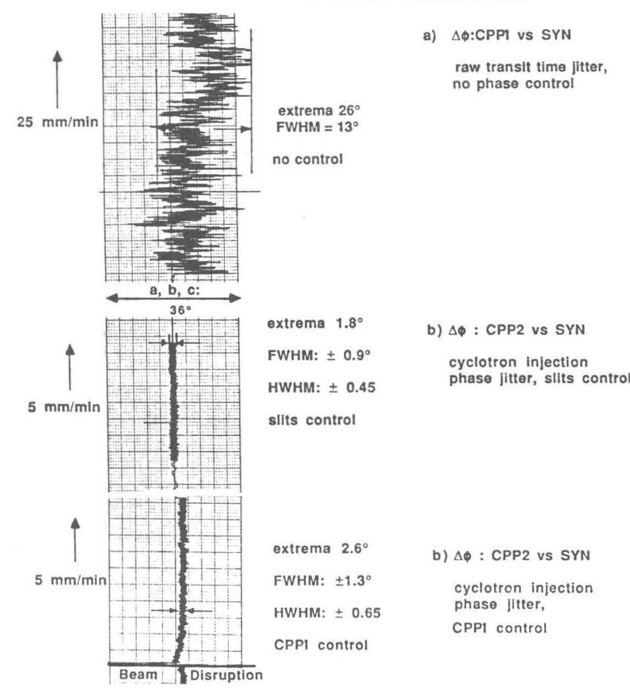

FIG. 7 INJECTION PHASE JITTER TO CYCLOTRON $^{127}I^{6+}$, 42 MeV, 32 MHz

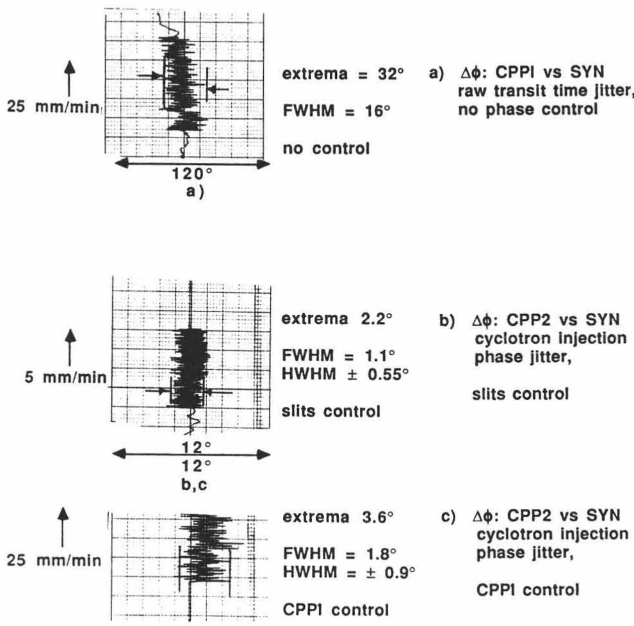

FIG. 8 INJECTION PHASE JITTER TO CYCLOTRON
$^{79}Br^{6+}$, 85 MeV, 60 MHz