IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

BUNCHING SYSTEM FOR THE STONY BROOK TANDEM LINAC HEAVY-ION ACCELERATOR*

J.M. Brennan. C.E. Chen, J.W. Noe, P. Paul, G.D. Sprouse and A. Scholldorf
Physics Dept., SUNY-Stony Brook, New York 11794

Summary

A versatile high-efficiency bunching system which is used to couple the Stony Brook 9 MV tandem Van de Graaff to the recently completed superconducting heavy-ion LINAC is described. The major elements of the system are: a pre-tandem double-drift harmonic buncher working at 9.4 and 18.8 MHz, a post-tandem sine-wave beam chopper at 4.7 MHz, a pre-LINAC superconducting double-drift harmonic buncher at 150 and 300 MHz and a high voltage DC-coupled single pulse selecting beam switch.

I. Overview

The superconducting LINAC is an attractive choice for an energy booster for existing tandem Van de Graaff accelerators. An essential requirement is that a large fraction of the continuous beam from the tandem be bunched into the 100 ps phase acceptance window of the LINAC. Harmonic bunchers[1,2] are capable of compressing 60-70% of the DC beam from the ion source into approximately 1 ns bunches. Further compression is then effected immediately before injection into the LINAC by a high voltage rebuncher. Here, the rebuncher is a high frequency (150 MHz) superconducting resonator. The phase acceptance range of the rebuncher can be extended, just as for the first buncher, by employing harmonics. This relaxes greatly the requirements of the tandem buncher and allows an even greater fraction of DC beam utilization. Furthermore, if the rebuncher operates on the same fundamental frequency as the LINAC, DC beam can be injected directly into the harmonic rebuncher to fill every RF cycle of the LINAC. Debunching after the LINAC then produces an essentially continuous beam.

We have chosen double-drift harmonic bunchers, since they are optimal for the desired low operating frequency (9.4 MHz) of the pre-tandem buncher and are most readily adapted to the superconducting technology of the rebuncher. A 300 MHz Quarter Wave Resonator has been developed here for use in this application.[3] The presence of both harmonic bunchers provides the flexibility of producing either beams with pulse spacing of 106 ns or quasi-continuous beams.

Experiments using the pulsed beams would generally require high purity, that is, low dark current between pulses. Some of the 30% of the beam not bunched by the pre-tandem buncher would enter the LINAC at accelerating phases and result in full energy small satellite pulses in the output beam. To eliminate this, a sine-wave beam chopper is placed between the tandem and the rebuncher and operates at one half the pre-tandem buncher frequency (the chopper passes beam twice per cycle). Beam phase space degradation introduced by the chopper is minimal (<20% for transverse, <10% for longitudinal) because the beam is already bunched at the chopper location. In addition, the beam injection path here involves two 90° bends after the rebuncher. Beam phase at the rebuncher translates into momentum dispersion and displacement after the first 90° bend. The final clean up of the time structure is done with a vertical slit after the 90° bend. The chopper then has only to eliminate beam that would arrive outside ±150° (5.5 ns) with respect to the bunching phase. The 5.5 ns pulse width is a rather modest requirement of the chopper.

For those experiments that require pulse spacing greater than 106 ns a high voltage beam switch is installed adjacent to the chopper and deflects in the perpendicular plane. The fact that the beam is already bunched is also advantageous here since the voltage pulse rise time can be as long as the beam pulse separation, 106 ns. The system is operated in the normally on mode so that the beam is normally rejected. The voltage is pulsed off to accept a single pulse and in this way the fringe field of the deflecting plates has no effect on the selected pulse.

II. Pre-Tandem Buncher

The fundamental frequency of the bunching system is a design parameter dictated by the requirements of the experimental program carried out with the accelerator. In this laboratory a frequency of 10 MHZ was chosen. The LINAC frequency being 150.4 MHz implies that the pre-tandem buncher should work on the 16th. subharmonic of the LINAC, 9.40 MHz. At this frequency double-drift harmonic bunchers have been shown to give good bunching performance with high capture efficiency.[1]

Double-Drift Harmonic Buncher

The double-drift scheme uses two simple sine-wave bunchers, operating at the fundamental and 1st. harmonic frequencies and separated by a drift distance of ~15% of the system focal length. The first buncher overbunches strongly to focus particles at ±120° of RF phase; the second buncher, operating 180° out of phase from the first, then removes the excess modulation from the particles at low phases and will have little effect on the particles at the extreme phases. The drift space between the two allows the bunch to begin to coalesce before the second buncher and greatly improves the overall system efficiency.

The optimum values for the amplitudes of the two bunchers and the length of drift space between them were obtained with a least squares minimization computer program. The optimized values for the buncher strengths and separation are:

$$d_1/d_f = 0.52,\ d_2/d_f = 1.67,\ d/df = 0.15$$

where; d_f is the system focal length, measured from the first buncher, $d_{1(2)}$ is the focal length of buncher 1(2), and d is the separation between the two. These values correspond to a capture efficiency of 60% and yield a compression factor of ~200. They are essentially universal, being independent of beam velocity, beam energy and system frequency and focal length.

Buncher Tube Structures

Skorka[4] has shown that the minimum longitudinal phase space product is obtained by the proper choice of the injected beam energy into the tandem. One strikes a balance between low injection energy where ion source noise dominates the time factor and very high injection energy where buncher modulation dominates the energy factor. This follows from the observation that the time factor is bounded from below by the buncher aberrations and the energy factor is bounded by the tandem stripper energy straggling.

The optimum injector energy as a function of ion mass is plotted in Fig. 1. For moderate heavy ions this energy E is quite high, ~300 keV. Since the RF power required to drive a buncher increases as E^3 one must take care that impractically high power levels are not called for. This means high Q tank circuits

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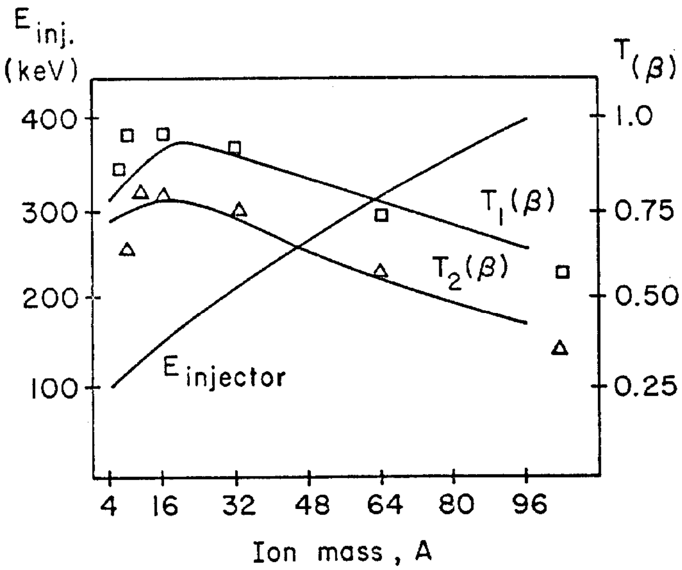

Fig. 1 Optimum injection energy and transit time factors for buncher 1 (fundamental) and 2 (1st harmonic) as a function of mass. The points are measured values, those for 1 are normalized to $T_1(\beta)$ at m=32.

and low capacitance structures. The common practice of using multiple drift tube lengths and some switching mechanism is quite costly in terms of capacitance. The structure used here, shown in Fig. 2 uses only one drift tube length for each frequency and is capable of spanning the mass range 4-100 if the beam energy follows approximately the optimum value.

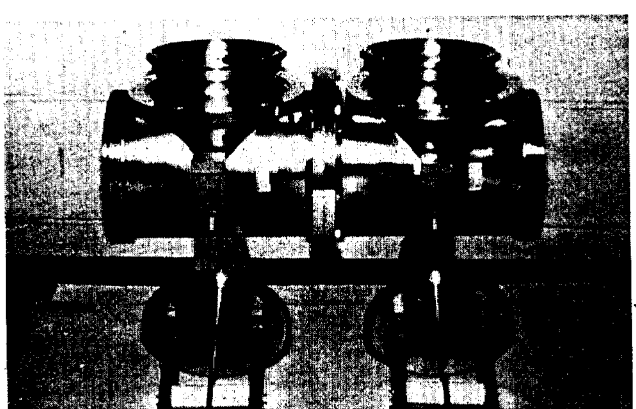

Fig. 2 Buncher high voltage structures and standard 6" Tee vacuum chamber. Buncher spacing is 27 cm.

Also plotted in Fig. 1 are the transit time factors $T(\beta)$, which relate the actual voltage drop seen by the the beam to the RF voltage on the buncher drift tube. The transit time factor is well represented by the analytical form

$$T(\beta) = \sin\left(\frac{\pi}{2} \cdot \frac{\beta_o}{\beta}\right) \cosh^{-1}\left(\frac{\pi g'}{\beta\lambda}\right)$$

where β = the beam velocity, v/c,
λ = the RF free-space wave length

$$g' = \text{effective gap} = \sqrt{(\text{true gap})^2 + (\text{tube bore})^2} = \sqrt{5^2 + 15^2} = 16 \text{ mm}$$

β_o = optimum velocity, 2(tube length)/λ

The first factor reflects the phasing of the beam in drifting from the first to the second gap and the second factor accounts for the changing RF voltages as the beam traverses the extended region (g') of electric field. $T(\beta)$ also depends on the radius of the beam from the buncher tube center line, being higher at the outer radii where the extent of the field distribution is less. This effect leads to a multiplicative factor which is independent of the tube bore and is given approximately by $1+(\pi r/\beta\lambda)^2$. A 9 mm collimator between the bunchers ensures that this factor is always less than 7%.

Figure 1 shows some measured values for $T(\beta)$ obtained with $^{12}C^-$, $^{16}O^-$, $^{24}C_2^-$, and $^{32}S^-$ ions injected at various energies. Bunched beams were detected at the 0° port of the tandem analyzing magnet via a fast secondary-electron emission detector which uses a micro-channel plate electron multiplier (rise time <0.5 ns). Secondary electrons are emitted when the beam impinges on a thin (0.002") tungsten wire which is held at -2 kV to quickly accelerate the electrons to the detector and swamp out the distribution of initial electron energies. Typical time spectra are shown in Fig. 3.

The buncher voltages that truly correspond to the measured focal lengths are deduced by the double peak method proposed by Chen[5]. This method takes into account that the minimum pulse width occurs when the beam is actually somewhat overbunched. Measuring the double peak separation when the beam is strongly over-bunched gives a reliable means of adjusting the buncher focal length precisely to the target distance.

Effective target distances were calculated in a computer program that sums the effective drift lengths of all the accelerating sections of the tandem, the dead spaces within the tandem and the drift length to the target according to standard formulas. The physical distance to the entrance of accelerating tube is 205 cm and the total effective distances ranged from 213 cm to 240 cm, depending on beam injection velocity and tandem terminal voltage.

The optimum velocity β_0 was chosen at a somewhat high value, 0.00425, in order to extend the mass range to m=4. The fall-off of $T(\beta)$ at high mass is mitigated by the fact that heavy ions need less voltage to bunch than light ions at a given energy since they are slower. The drift tube length for the second buncher is ~15% less than half that of the first one even though the β_0 is essentially the same. This was done in anticipation of the asymmetrically distributed fields about the gaps that occur when the length to bore ratio is not large[1].

The two insulators supporting each drift tube are Alumina, Al_2O_3 (Alsimag 614 made by 3M Technical Ceramics Division). They are very strong when used in compression, have negligible dielectric losses, and are thermally stable.

Tank Circuits

The tank circuits for the bunchers are conventional lumped-element LC parallel-resonance circuits. The inductors are wound from 3/8 inch copper tubing on a 5 inch diameter teflon coil form with a pitch of 0.6 inch/turn. Tuning is done with 5-25 pf vacuum-variable high voltage (20 kV) capacitors. The circuits are enclosed in 12 inch cubical aluminum boxes equipped with fans for forced air cooling. Relevant parameters are listed in Table 1.

Table 1

f MHz	Turns	L (μH)	C (pf)	Q	Shunt Impedance M Ω
9.40	10.5	10.0	29	800	3.7
18.80	4.0	2.86	25	1300	3.5

Direct coupling is used to match the tank circuits to the 50Ω output impedance of the driver power amplifiers. This is done by tapping onto the inductor very near the grounded end. The precise location of the tap for critical coupling is found empirically by observing the reflected power wave form when the drive power is pulsed.

Control Circuit

Successful operation of harmonic bunchers relies on accurate adjustment of the amplitudes and relative phase of the constituent harmonics. The high Q tank circuits that must be used are susceptible to significant phase fluctuations between the driving power source and the resonating voltage as the resonant frequency varies over a range comparable to the bandwidth. An attractive feature of the double-drift scheme is that the harmonics are completely de-coupled electrically. Nevertheless, if long term stable operation is to be achieved active feedback stabilization of the amplitude and phase of the bunchers must be employed.

Phase control is achieved with a phase locked loop scheme where the phase reference signal derives from the LINAC reference oscillator divided by 16 or 8. Phase adjustment is provided by a 360° voltage controlled phase shifter between the tank circuit pick-up signal and theloop phase comparator. A high quality temperature compensated VCO keeps loop stress to a minimum and gives essentially instantaneous lock-up upon turn on.

The amplitude feedback circuit compares the detected value of the pick-up voltage, after it passes through an adjustable attenuator, with a standard level. Amplitude adjustment is done by varying the adjustable attenuator. The amplified error signal controls the drive power to the tank circuit in a closed-loop fashion to keep the detected value equal to the standard level. This inverse programming approach has the advantage that the RF levels inside the control circuit are always the same. Linear response to the amplitude control knob (or remote programming voltage) is provided by an analog voltage divider before the variable attenuator.

A specialized feature relevant to the double-drift buncher control is that the standard level can be switched between two values having the correct ratio between double-drift and simple buncher amplitudes independently of the specific amplitude. This feature is very useful in tuning the double-drift buncher (see below).

Tuning

Figure 3 illustrates the straightforward tuning of the system. The amplitude of each buncher is first separately adjusted for a time focus at the target. With the first buncher off, the phase of the second buncher is set such that the bunches arrive symmetrically about the arrival time from the first buncher. The two amplitudes are then adjusted by the above mentioned factors, 1/0.52 and 1/1.67, and both bunchers are turnturned on.

The measured capture efficiency from these data is that 66% of the beam falls within the range bounded by the full width at 1/10 maximum limits of the peak (∿3 ns). Full width at half maximum is 1.4 ns. No discernable change in transmission through the tandem was observed when the bunchers were in operation.

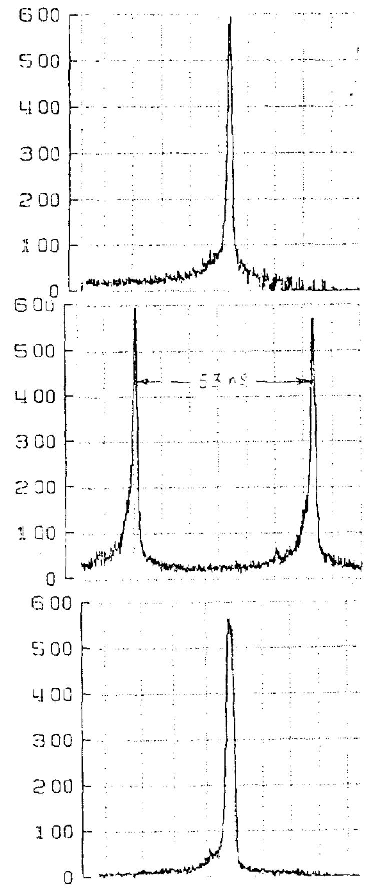

Fig. 3-Timing spectra and tuning procedure for double-drift buncher.

a) First buncher only.

b) Second buncher only phase adjusted for symmetry about a.

c) Both bunchers on with amplitudes adjusted for double-drift bunching.

Acknowledgement

The authors are indebted to the technical staff of this laboratory for skillful implementation of these designs. In particular the work of Mr. C. Pancake and Mr. A. Morrongiello was vital to the success of this project. One of us, Pr. C.E. Chen would like to acknowledge the support of a Fong Shu-Chuen Fellowship through the Committee for Educational Exchange with China.

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*Supported in part by the National Science Foundation.