LONGITUDINAL BEAM OPTIMIZATION OF THE ARGONNE SUPERCONDUCTING HEAVY-ION LINEAR ACCELERATOR

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Summary

The various aspects of optimizing the accelerator system in longitudinal phase space are discussed. There are three major components which must be properly adjusted: 1) the buncher system, which must produce a beam bunch of approximately 100 ps FWHM at the entrance to the linac, 2) the linac, which must accelerate the ions while maintaining an undistorted phase ellipse, and 3) the rebuncher/debuncher, which must be optimized to produce either a time focus on target or an improved energy resolution. Optimization of the buncher system and the linac is automatic and under computer control. Rebuncher optimization is only partially computer controlled at this time.

Introduction

In the past 3 years, the Argonne Superconducting Linac Heavy-Ion Booster has accelerated 17 different isotopes for nuclear and atomic physics experiments. Because of varying needs of beam current and maximum energy, the total number of ion types, including charge state combinations, rises to over 25. The diversity of beams makes it imperative that efficient techniques be developed for tuning the accelerator system.

Another requirement of the tuned accelerator system is fast and easy energy variability. The linac functions as a user-operated accelerator to a large degree, and many experimental programs call for frequent changes in the linac output energy. In order for this to occur efficiently, the tuneup of the accelerator must provide the system with information concerning the precise field levels and phase angles of each resonator. Once this data is stored in the computer's data base, the settings necessary for a particular energy are calculated and the linac is automatically configured to the new requirements.

The beam optimization procedures developed depend heavily on the linac control computer described in a companion article presented at this conference.[1] The beam sensing devices used consists of an array of profile monitors, faraday cups, surface-barrier detector scattering systems, and room-temperature helix resonators used as phase detectors. These devices are strategically placed along the beam line as indicated in Figure 1 of the accompanying article.[1]

Tuning the linac proceeds in a sequential fashion, starting with the bunching system and proceeding through the linac, one resonator at a time. Finally the rebuncher/debuncher is tuned, if needed, to achieve optimal conditions at the experimental station.

The remainder of the paper describes the tuning procedure employed to tune each of the major components of the linac system. The results of these efforts in terms of speed, reproducibility, and beam quality are discussed.

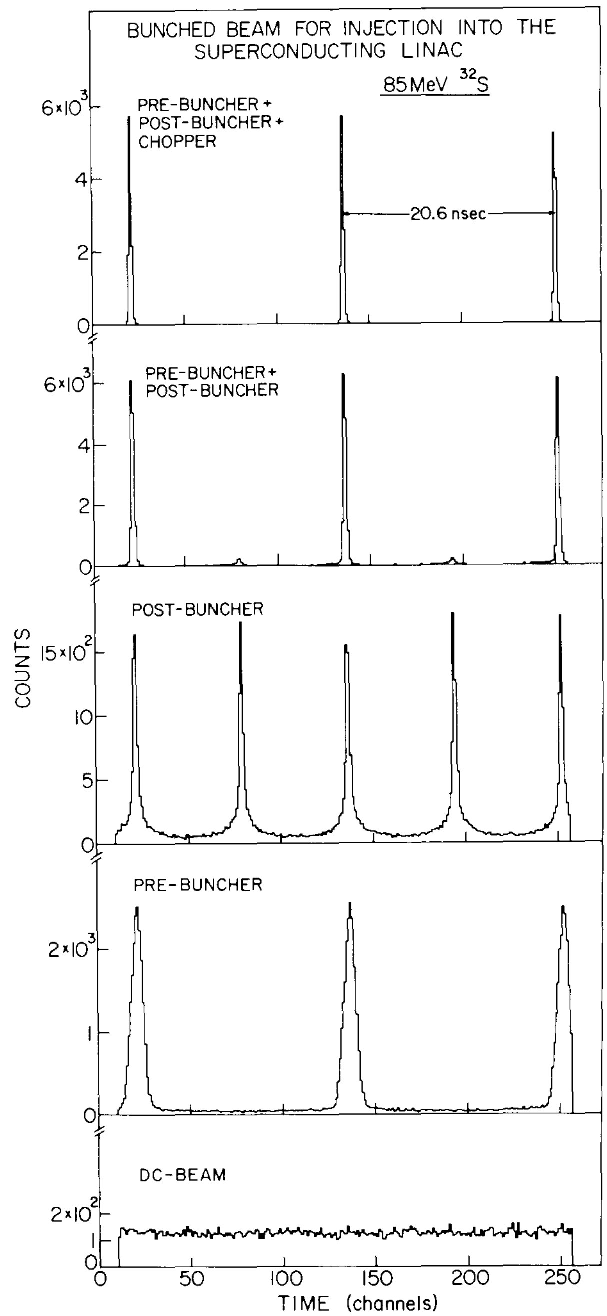

Fig. 1. Effects of the three bunching elements on the initial D.C. beam. Typically 70% of the D.C. beam is injected into the linac in approximately 100-ps wide pulses.

Bunching

The bunching system for the superconducting linac consists of three elements. First a pre-tandem room-temperature buncher[2] operating at 48.5 MHz with a sawtooth-like waveform bunches 70% of the D.C. beam into 1 ns wide pulses at the terminal of the tandem. The sawtooth waveform is produced by adding three harmonics to the fundamental frequency. The relative amplitudes and phases are locked to the fundamental, so that only the fundamental amplitude need be changed for different ion species or injection energies. This amplitude is calculated by the computer and set manually by the operator. No manual tuning has been necessary for optimum performance after the relative phases and amplitudes of the harmonics are adjusted once.

The second element of the bunching system is a vertically sweeping electrostatic sinusoidal chopper. The chopper removes the tails of the bunched beam from the pre-tandem buncher. The criteria for proper tuning of the chopper is that the transmission function be approximately 1.0 ns wide and that the pulse be centered in the transmission window. The later requirement translates into maximum beam transmitted as a function of chopper phase angle.

The chopper is under direct computer control. The chopper amplitude and phase are calculated and set automatically by the computer. The calculated amplitudes require no further adjustment, but the calculated phases can occasionally be improved by manual adjustment. The phase error is generally less than five degrees and often zero. This manual fine-tuning will be computerized in the near future when the computer will have direct control of faraday cups and can read the output from a new electrometer recently obtained.

The last element of the bunching system is the superconducting buncher. This unit is a single low-beta (.062c) split-ring resonator which is operated at a phase angle of 90° in order to produce a time waist at the first linac resonator. The time waist must have a width of approximately 100 ps in order for the longitudinal phase ellipse to be transmitted through the linac without distortion.

The beam pulse time resolution can be observed at the entrance to the linac with a scattering foil and surface-barrier detector located at that point. The amplitude can then be varied for minimum observed time width and the phase adjusted for no energy gain from the buncher. A more common technique employed is to observe the time width and the energy gain using a surface barrier detector system located at the linac exit. The field required to form a time waist at that point is scaled in order to achieve a time waist at the linac entrance. Adjustments to this value are made to produce the desired minimum in the energy width curve for the first resonator. The results of numerous measurements in this manner provided the calibration data needed to compute directly the amplitude of the superconducting buncher. The calculated phase angle is manually adjusted to achieve zero energy gain. Operating the superconducting buncher with zero energy gain serves as a useful reference for reproducing previous tuneups. In general, the phase angle requires manual optimization in order to obtain zero energy gain. The error is generally only a few degrees but this can produce significant phase shifts because of the drift space to the first resonator. The final correction to the phase angle for the superconducting buncher is currently being added to the computer routines.

The use of the computer for setting the bunching system parameters has reduced to about one minute the time required to set the bunching system. The bunching system functions in an essentially trouble-free mode and requires no additional adjustments during a run. The action of the bunching system on a beam is shown in Figure 1. A significant benefit to calculating and setting the bunching system prior to other tuning is that the chopper serves as a time-of-flight filter which, along with the analyzing magnet, unambiguously determine the ion and charge state combination being accelerated. For certain ions such as nickel, the location of the second stripper foil in front of the analyzing magnet can result in two charge-state combinations that have nearly identical magnetic rigidity at the analyzing magnet. If the tandem control system locks on the wrong ion species, it is immediately obvious since the chopper will not transmit the incorrect species. This has proved useful to the tandem operators on many occasions.

Tuning the Linac

Tuning the linac resonators consists of determining the resonator phase setting which produces maximum energy gain, setting the phase angle to a value which produces a phase-focusing condition, and determining the energy gain of the beam from the resonator being tuned. The amplitude is predetermined, based on the operating history of each resonator. This procedure is performed for each resonator in the linac in a sequential manner, beginning with the first resonator in the linac.

Two detection systems may be used for tuning the linac. The first system consists of a silicon surface barrier detector which detects particles elastically scattered by a gold foil in a forward direction. The second system is a time-of-flight system which employs a room-temperature helix $\lambda/2$ resonator as a beam pulse detector.

The surface-barrier detector system has the advantage that both timing and energy information are independently available. Pulse width information is also available which allows some inferences to be made concerning the shape of the longitudinal phase ellipse. But the surface-barrier detector also has significant disadvantages. These include: calibration difficulties, detector deterioration, pulse-height defect for heavy ions, and (probably most important) a high degree of sustibility to beam steering in the linac because of the collimation required in the detector system.

The helix resonator phase detector has the advantage that its response is largely independent of beam current, thereby allowing the tuning of beams with low intensity. Beams of 0.1 - 1.0 na are detectable with the helix resonator. Also because of the large acceptance of the resonator, the detection system is not so sensitive to beam steering effects in the linac. The disadvantages of the resonator is that information concerning the beam phase ellipse is sacrificed. During routine tuning, we find that phase ellipse information is not critical. Therefore this loss of information is not very serious.

The procedure followed for tuning a resonator is the same for both detection systems. The steps involved are:

1) Measure the energy into the resonator.
2) Detemine the approximate peak in the acceleration curve.
3) Measure the energy gain as a function of phase angle in the vicinity of the peak.
4) Fit these results in order to determine the phase setting which produces the maximum energy gain.
5) Set the resonator phase to the desired value.
6) Store results of scan and proceed to the next resonator.

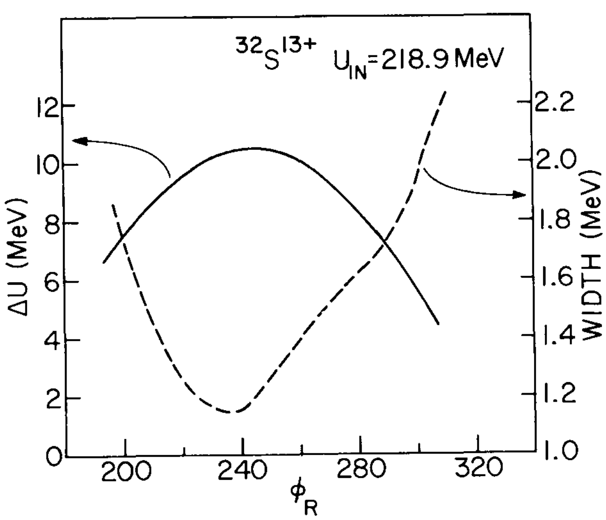

Fig. 2. Energy gain (ΔU) and full width at half maximum (width) as measured using a surface-barrier-detector scattering system for one resonator during a linac tuneup.

Although the word "energy" is used above, the prescription is the same for the helix phase detector. Here a phase change (flight time change) is measured which can be converted immediately into an energy gain.

The tuning procedure is completely under computer control. All that is normally required is to maintain sufficient beam current at the diagnostics area. An example of the results of a resonator scan using the surface-barrier-detector system is shown in Figure 2.

The tuning time of the whole linac generally requires 1.5 to 2 hours, and the best time observed is 30 minutes. The helix phase detection system is still undergoing development and certain straightforward improvements should reduce the tuning time with that system by at least 30%.

The linac tuning procedures are performed at the maximum operating field levels. Once performed at the maximum energy, any intermediate energy is obtained by a simple request at the linac control console.

Rebuncher/Debuncher Tuning

The rebuncher/debuncher is a single high-beta (.105 c) split-ring resonator. Its tuning relies on the detector system in use by the experimentalist. The linac control system can accept the data and scan the rebuncher in a manner similar to the tuning of resonators in the linac to determine the phase setting to produce zero energy gain and the bunching condition. The amplitude and phase angle are then manually adjusted to produce the optimum conditions. Future plans call for automating this procedure in order to improve the tuning speed and make the system more compatible to quick energy changes.

Results of Tuning Procedure

The primary result of the linac tuning process is to provide an efficiently accelerated beam without distortion of the phase ellipse. The litmus test of the success of the procedure and the overall operation of the accelerator system is the quality of the delivered beam at the experimental station. Experiments now scheduled at the linac are designed to be most sensitive to, and to make use of, the good timing potentially available from the linac.

The results of various timing tests using the rebuncher in the bunching mode are tabulated in Table 1. These tests indicate that bunch widths of ≤120 ps are readily obtainable. The results obtained in the ^{34}S tests are significantly worse than in the other tests and reflect the poor timing observed from the pretandem buncher. For sulfur the bunch width from the pretandem buncher is usually ≤1.1 ns but in this case even the rather large width of 1.3 ns could be obtained only by reducing the source aperture to the relatively small value of 1/8" diameter. Interestingly there was no other indication of a problem in the system. Within four days the source failed and had to be repaired. It has been found that beam-bunch timing is a sensitive measure of system operation, albeit a hard to interpret one.

Table 1. Results of timing resolution tests with the superconducting linac system.

Ion	System* Configuration	Tandem energy(MeV)	Linac energy(MeV)	Pre-tandem buncher timing (ns)	Measured timing resolution on target (psec)	Beam timing resolution (corrected) (psec)
$^{12}C^{5+}$	A	510	110.3	.62	119	108
$^{16}O^{6+,8+}$	A	56.0	108.7	1.0	105	93
$^{28}Si^{8+,13+}$	B	76.5	229.0	1.1	118	117
$^{34}S^{8+,13+}$	A	76.5	163.0	1.3	210	194

*Refer to Figure 1, Ref. 1: (A) D cryostat located in B position. Measurements made in 65" chamber. (B) B cryostat removed, 4 m drift distance between A and C cryostat. Measurement made in 18" chamber.

The other timing results are in fair agreement with ray tracing calculations based on the assumption that the linac is injected with a vertical phase ellipse of 100 ps width and total area of 40 keV-ns in longitudinal phase space. If the timing resolution observed is at the phase space limit, then the time resolution will be determined by the initial phase space area of the beam and also the relative distances between the linac exit, the rebuncher, and the experimental chamber. We plan to continue this investigation by looking at the effects of various phase-space area-changing components in the tandem injection system such as stripper foils and energy defining slits. We will combine these measurements with direct measurements[3] of the beam-energy width from energy-loss straggling in the stripper foils that make use of the pulsed-beam structure using time-of-flight techniques.

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