TRANSPORT OF DC AND BUNCHED BEAMS THROUGH A 25 MV FOLDED TANDEM ACCELERATOR*

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Summary

Studies of beam transport through the planned ORNL 25 MV folded tandem accelerator demonstrate efficient utilization of phase-space acceptance and the feasibility of injecting bunched beams from the tandem accelerator into the Oak Ridge Isochronous Cyclotron (ORIC). Use of a 180° bending magnet in the terminal provides outstanding charge state selection and permits better control of the high-energy beam transport than has previously been possible in conventional tandem accelerators. Time spreads introduced in bunched beams by the 180° magnet are kept within a 6° RF acceptance window at ORIC provided the beam has a crossover in the center of the 180° magnet. Ion masses from 12 to 240 amu, pre-injection energies from 150 to 500 keV and terminal voltages from 7.5 to 25 MV were studied for dc beams and beams bunched by various modulation techniques.

1. Introduction

Beam transport through a folded tandem accelerator¹ is not substantially different from that in the conventional linear tandem accelerator² except for the terminal region which is dominated by the presence of a 180° magnet. Injection problems are unchanged because beam transport to the stripper is independent of the 180° magnet. There is less freedom in the injection geometry, however, because of the proximity of the low- and high-energy beam lines to each other at the base of the accelerator. Matching the beam leaving the terminal into the high-energy acceleration stage is easier because the doubled beam path makes the terminal effectively twice as long as in the linear configuration and this additional path length is useful for good phase space matching.

Transport of bunched beams in the folded accelerator is constrained by the presence of the 180° magnet. Initially synchronous particles become dispersed in time as they pass through the magnet so care must be taken to make the particle orbits as nearly isochronous as possible. Timing problems with external magnets are, of course, the same for either linear or folded accelerators.

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500 KV INJECTOR

90° MASS ANALYZER

TO TARGET

IMAGE

90° ENERGY ANALYZER

25 MV TERMINAL

Fig. 1

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The beam shown in fig. 1 is characterized by its waist (cross-over) locations. Convergence of the beam from one waist to the next is controlled by variable lenses or by double-focusing in the case of the 90° magnets. Circular symmetry is to be maintained at each waist. Where the beam is inherently circular, quadrupole triplet lenses will be used. Quadrupole doublets or other multiplets may be required in some locations to compensate for asymmetries introduced by other accelerator components.

The negative ion beam originates within an insulated ion source platform which will operate between about 150 kV and 500 kV negative with respect to ground potential. The beam accelerates horizontally from the platform to ground potential and is then bent upward through 90° onto the axis of the low-energy acceleration stage.

The proximity of the low- and high-energy acceleration stages in the folded configuration dictated that the 90° bend take place at ground potential rather than at elevated potential. As a consequence, the 90° mass analyzing magnet has to have a mass-energy product (MxE/q^2) of ~ 120 amu MeV in order to accommodate all ions at energies up to 500 keV. The magnet will have about one meter radius of curvature and will provide mass resolution of one amu or better for the typical injected beam.

The beam will cross over either within or very close to the low-energy tube entrance, independent of injection energy or terminal voltage. This mode of low-energy injection minimizes aberrations (including chromatic aberration of bunched beams) by keeping the beam diameter small in this critical region where fringing fields produce a lens of such short focal length. The consequence, however, is a diverging beam in the low-energy stage which requires an intermediate lens to converge the beam to a waist at the stripper in the terminal.

The phase space acceptance of the accelerator is influenced by the position of this intermediate lens, by the aperture available at (or near) the lens and by the (presumably smaller) aperture subtended by the stripper. As the lens is positioned closer to the terminal the accelerator acceptance increases until eventually limited by the aperture at the tube entrance and the aperture at the lens. However, moving the lens far from the tube entrance makes injection more difficult by diminishing the range of acceptable divergence angles; that is, the increase phase space area lies in a progressively more intractable, small-angle region of phase space. Moreover, lens strength requirements increase as the lens approaches the terminal because of increased ion energy and because of a diminishing image distance (when beyond the half-way point). Having a short image distance and consequently a small waist in principle reduces the phase space increase caused by scattering in the stripper. In practice it is only the foil stripper which seriously increases phase space area by scattering and the advantages of small spot size may not be realizable for foil strippers because of attendant higher beam power density. The present intention is to place the intermediate lens about 1/3 the way up the low-energy stage. Additional dead space will be available at the 2/3 location (complementing the stripper location in the high-energy stage) if in the future it is determined that a lens should be located closer to the terminal.

The combination of a waist at the entrance to the injector acceleration tube and again at the entrance to the tandem low-energy stage yields remarkably stable phase space requirements at the ion source over

a wide range of operating conditions. Fig. 2 shows the beam size and angle requirements at the first (injector) waist as a function of injection energy and terminal voltage as required to match into a lens of 2.54 cm diameter (end apertures) located 1/3 the way up the low-energy stage and a stripper of 0.95 cm diameter in the terminal. This beam subtends 2π cm mrad MeV^{1/2} with 25 MV on the terminal and represents a practical upper limit to the phase space acceptance of the accelerator. Minimal adjustment will be required at the ion source (where lenses will be provided for this purpose as indicated in fig. 1) to compensate for wide variations in the accelerator voltage parameters.

Because the 180° magnet offers ideal charge state separation (e.g., charge +11 displaced 20 cm from charge +10 at the magnet exit), stripping necessarily takes place ahead of the magnet. In this accelerator the resulting beam of stripped positive ions expands toward the magnet with divergent half-angles ranging from 0.5 - 1.0 mrad for beam scattered by a gas stripper to 5 - 10 mrad for very heavy ions scattered from a 5 $\mu\text{g}/\text{cm}^2$ carbon foil stripper. A 180° magnet having normal (0°) entrance and exit poles to first order transports the beam component in the bending plane into a mirror image of itself (reflected across the beam axis). The transverse beam component transports through pure drift of length $\pi\rho$ where π is the angle of bend and ρ is the radius of curvature. An initially symmetric beam emerges with virtual objects in the two planes shifted longitudinally by the amount $\pi\rho$. The resulting asymmetry is difficult to correct especially since differing magnifications are required in the two planes for each different ion mass, ion energy and stripper thickness. If not properly corrected such beam asymmetry can lead subsequently to loss of beam and loading on apertures in the high-energy acceleration tubes. To achieve beam transport through the terminal region which is independent of incident beam and stripper properties it is desirable to locate lenses both preceding and following the 180° magnet. Although some corrections can be made by rotating the magnet entrance and exit pole tips it is not desirable to have adjustable controls for this purpose.

The 180° magnet will have a mass-energy product of 95 amu MeV. It will transmit 25 MeV uranium ions of charge +8 and lighter ions or less energetic ions having

Fig. 2. Variations in beam size (solid curves) and angle (dashed curves) at first waist location beyond the ion source as a function of injection energy and terminal voltage for fixed-geometry acceptance.

lower charge states. The folded tandem configuration is characterized by an enforced cutoff of low charge states for all but the lightest ion species. Fig. 3 shows how the 180° magnet separates ions by mass and charge between those transmitted and those rejected. Loss of the low charge states of heavy ions should not prove detrimental because experimental interest ordinarily focuses on the more energetic high charge states.

Time dispersion in beams of finite phase space area can be minimized by keeping the beams small at the center (90° point) of the magnet. The time dispersion for such "isochronous" trajectories in a 180° magnet is

$$\Delta t = (2/v)X_{90} \\ = (2/v)(\tan \epsilon X + \rho X'),$$

where Δt = time difference,

v = particle velocity,

ϵ = entrance pole tip angle,

ρ = radius of curvature,

X' = divergence at magnet entrance,

X = displacement at magnet entrance,

X_{90} = displacement from central orbit at 90°.

From these first-order expressions it is evident that time dispersion depends directly on spatial displacement (X_{90}) at the magnet center (90° point). For uranium ions of 25 MeV the factor $2/v$ is 4.5 ns/cm indicating 0.9 ns dispersion for a beam 2 mm wide at the 90° crossover. Adjustable slits will be placed at the 90° point in the 180° magnet. A lens between the stripper and the magnet will converge the beam to a minimum between the slits.

Fig. 4 demonstrates the effect of this lens on beams leaving the gas stripper (dashed curves) or foil stripper (solid curves) for two possible arrangements of the strippers. (A third possibility, the inclusion of the foil stripper mechanism within the confines of the gas stripper, can be visualized by combining cases shown in fig. 4). Because the beam

Fig. 3. Charge states transmitted through 180° terminal magnet as a function of ion mass for different terminal voltages. Lines of separation between ions transmitted or rejected correspond to a magnet having a mass-energy product of 95 amu MeV.

is effectively "parallel" leaving the gas stripper the relative position of gas stripper and lens is not critical over the short distances involved. Conversely, fig. 4 suggests that foil-stripped beams having large angles and occupying much larger phase space area can be focused to comparably small sizes within the 180° magnet only by locating the foil stripper as far from the lens as space in the terminal will permit. In all cases it is desirable to locate the lens as close as possible to the magnet to minimize the image distance to the slits.

Slits at 90° in the 180° magnet provide several useful advantages, including: a) limiting time dispersion in pulsed beams, b) charge separation, c) mass selection for beams composed initially of isotopic mixtures of hydrides, d) definition of transmitted phase space, e) shadowing of high-energy tubes from stray beam when terminal voltage fluctuates, f) signal sources for regulation of charging system. Reducing the aperture between the slits improves isochronism and provides a cleaner beam for injection into the high-energy stage. The waist defined at these slits becomes a stable object point for the remainder of the beam transport system. Particles of different rigidity pivot about the center of the magnet and will appear to originate from the slit aperture. As a consequence the beam should remain spatially stable at each subsequent waist downstream although the beam may fluctuate in angle because of terminal voltage changes, etc.

A lens is required downstream of the 180° magnet to match efficiently the beam diverging from the slits into the long high-energy acceleration stage. The best phase space match occurs when the beam has a waist near the middle of the high-energy stage. Some con-

Fig. 4. Schematic representation of beam envelopes for paired gas and foil strippers. Size of waist from "parallel" gas-stripped beam (dashed curves) is nearly independent of gas stripper position. Waist size for divergent foil-stripped beam (solid curves) is sensitive to foil position. A small waist (a) is preferable.

vergence of the beam is produced by fringing fields at the tube entrance. This varies inversely with charge λ as $f = 4 \lambda / q$ where f is the focal length of a circular tube aperture, λ is the active column length and q is the ion charge. There exists some charge state for which the fringing fields provide all the convergence required; beyond this a net divergence is required for the matching lens for optimum operation. Fortunately, for the present design this transition occurs in the region $q = 25 - 30$ so the matching lens can be a net converging lens for all ions likely to be accelerated.

A second foil stripper can be inserted in the high-energy acceleration stage about 1/3 the way down from the terminal (see fig. 1). The terminal lens system will converge the beam to a minimum size at this second stripper with a diameter not more than about 5 times the beam diameter at the first (terminal) stripper for beams scattered to angles larger than about 2 mrad per mm radius and with a diameter less than the original beam diameter at the first stripper for beams of divergence less than about 0.4 mrad per mm radius. Application of charge state selection after the second stripper is not being considered at present and some scattering of beam from the second stripper into the high-energy acceleration tubes is anticipated. Provision will exist for installing a lens at the 2/3 column location for further beam control if this is found desirable.

Post acceleration transport of the beam through the 90° energy analyzing magnet (mass-energy product 320 amu MeV) will be conventional. Beam diameter at the high-energy quadrupole lens will typically be about 2.5 cm. For a beam of 10π cm mrad MeV^{1/2}, which equals or exceeds the anticipated geometrical emittance limit of the accelerator, the beam diameter at the object and image slits of the 90° energy analyzing magnet would be about 5 mm. Typical beams will be about 2 mm diameter and very high quality beams will be under 1 mm. The geometric energy resolution of the 90° magnet for slits set at ± 1 mm will be about one part in 10^3 . Realizable energy resolution should be about one order of magnitude better.

The injection line for ORIC is designed for isochronous beam transport. The beam is bent from the vertical by a 22.5° magnet located downstream of the high-energy quadrupole lens. The beam is minimized in diameter at isochronous regulating slits located about 4.4 meters downstream of the 22.5° magnet. Beam size at these slits will be about 25% larger than for the same beam minimized at the object slits of the 90° magnet. The beam then expands into a 67.5° magnet which completes the bend onto the horizontal ORIC injection line. Both magnets will have a mass-energy product of about 735 amu MeV. Time dispersion would be about 0.7 nsec for the extreme 10π cm mrad MeV^{1/2} beam and a negligible 0.15 nsec for a more realistic beam of 2π cm mrad MeV^{1/2}.

3. Beam Bunching

The "monoenergetic" acceptance window for ion beams accelerated within ORIC includes about 6° of the cyclotron RF period for ions up to about mass 150 amu and only 2° of the period for heavier masses which ORIC will accelerate using third harmonic. The corresponding time interval varies from roughly 1.0 to 2.5 ns for masses 12 through 150 amu, respectively, and from 0.8 to 1.2 ns for masses 150 through 240 amu, respectively. Efficient utilization of the tandem accelerator and ORIC requires that as much as possible of the injected beam be compressed into this preferred time window and that little or no beam be in-

jected during the remainder of the RF period. Several approaches to chopping and bunching the beam for this purpose are being studied.

The function of the buncher is to modulate the dc beam velocity in such a way that portions of the beam initially separated in space are made to arrive at ORIC at the same time. The amount of modulation should be large compared to the velocity distribution (or "noise") intrinsic to the ion source yet small compared to the velocity increment which occurs during one turn through the cyclotron. Bunching will be performed in the vertical beam line between the 90° mass analyzing magnet and the entrance to the low-energy acceleration stage.

An ideal buncher would pack 100% of the incident dc beam into the available time window at ORIC. Unfortunately, such a device would require driving signals having a complex waveform and high harmonic content. It is far more practical to operate the buncher sinusoidally although this entails a substantial loss in operational efficiency. A practical, two-gap klystron buncher operated sinusoidally can compress from 20 to 30% of the beam into the 6° RF window.

Calculations have been carried out to determine the performance of both one and two buncher systems for ions from 12 to 238 amu with energies from 150 to 600 keV. Contributions to time spread included intrinsic source noise, finite beam size, fringing of electric fields, imperfect velocity modulation and dispersion in the 180° terminal magnet. Estimates of space charge interaction suggest that this will be a small effect compared to other perturbations for beams of realistic intensity; therefore, for simplicity, space charge was not included in the calculations.

The buncher can be operated at ORIC rotational frequency (4.5 - 14.5 MHz) or at sub-harmonic frequencies of narrower range (say 5 MHz $\pm$ 20%). Buncher operation of the Nth sub-harmonic has the disadvantage that beam must be compressed into a buncher phase of 6°/N; tuning requirements, however, are less stringent. The studies indicate that a double drift system^{5,6} consisting of a pair of ungridded klystron bunchers located $\sim$ 50 cm on either side of the beam waist at the image of the 90° mass analyzing magnet (between the magnet and the low-energy acceleration stage, see fig. 1) has several attractive features. With the first buncher operating at ORIC rotational frequency and the second at twice rotation frequency, modulating the beam 180° out of phase, we find:

- 1) From 50% to 70% of the dc beam can be bunched into the 6° window at ORIC.
- 2) Buncher separation is not critical and in practice can range from less than 70 cm to more than 120 cm. The smaller spacing produces a very compact bunch. The larger spacing provides greater phase acceptance.
- 3) Peak-to-peak RF voltage requirements are less than 7 kV for the first buncher and less than 4 kV for the second. Voltage precision of $\pm$ 1% is quite adequate.
- 4) Time spreads introduced by the fringing fields are small enough to obviate the use of grids.
- 5) Performance is essentially constant for all ions up to mass 150 amu.
- 6) Operation at ORIC rotational frequency results in optimum buncher element lengths being nearly constant (ion drift length per cycle is typically 10-12 cm).

Fig. 5. Final phase distribution at ORIC as a function of initial phase angle for idealized buncher (solid curve) and for realistic buncher (points about curve). Points along diagonal show the beam energy modulation.

Calculated Performance of Double Klystron Buncher System.

Fig. 5 illustrates the performance of a double-drift buncher system having the following properties:

	Buncher 1	Buncher 2
Diameter	3.0 cm	3.0 cm
Length	25.0 cm	12.5 cm
Location	5.0 m	3.9 m
RF Frequency	8.48 Mhz	16.96 Mhz
RF Amplitude	2.44 kV	1.29 kV

The curves in fig. 5 were computed for 107 amu ions injected at 400 keV and accelerated to 250 MeV by the tandem accelerator. The solid curve represents the final phase distribution at ORIC as a function of initial phase for idealized bunching (with RF amplitudes somewhat different from the above). The points about the solid curve result from the more realistic calculations which include 100 eV random source noise, fringing fields for 3.0 cm diameter elements (no grids), a beam of 1.5 cm diameter, and 0.7 ns dispersion in the 180° magnet. About 65% of the beam arrives within a 6° phase angle at ORIC. The set of points running diagonally through fig. 1 shows the amount of energy modulation caused by bunching.

While performance of the double-drift system is attractive, operation is more complex than for a single klystron buncher. Two RF drives are required, one operating on the second harmonic. The second buncher has to be adjustable in phase through $360^\circ \pm 1^\circ$ relative to the first. In practice, this should be no more difficult than phase locking the entire system to ORIC. The choice of ORIC rotational frequency (which is not inherent to the double-drift system) requires broad range tuning of both bunchers. The component locations described are adequate provided source noise is (as anticipated) less than 200 eV; higher noise levels can be overcome only by increasing the beam velocity modulation which, in turn, requires moving the buncher system closer to the tandem accelerator in order to shorten the flight time to ORIC. It is very desirable to keep the buncher and RF components outside the accelerator pressure vessel. This appears to be possible using the system described.

Beam which falls outside the 6° acceptance window can be eliminated by a sweeping device or "chopper" located near the buncher or, alternatively, a chopper located between the tandem accelerator and ORIC. If 50% (or more) of the beam is being bunched then a chopper preceding the buncher must not seriously perturb the dc beam for 180° (or more) of the RF cycle. As the chopper is moved along the flight path this condition relaxes so that a chopper between the tandem and ORIC need pass beam only for 6° (or 2°) of the cycle. Such a post-acceleration chopper operating synchronously with the ORIC rotational frequency can also serve as a phase detector for the bunched beam and is being considered for inclusion in the total beam pulsing system.

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