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A MULTI-AMPERE HEAVY ION INJECTOR FOR LINEAR INDUCTION ACCELERATORS USING PERIODIC ELECTROSTATIC FOCUSING*

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Introduction

One of the key problems for the accelerator system for a heavy ion fusion (HIF) power plant is to provide a source of ions at the parameters, principally energy and intensity, that are well matched for the primary accelerator component. A promising candidate for the primary accelerator component is the linear induction accelerator (LIA). The LIA is well matched to the pellet requirements because it can accelerate very high intensity pulses of short (≤ 1 μs) duration. The intensity in the LIA is only limited by the capability of the beam transport system and the capacity of the injection system. Recent cost studies at LBL show that there may be some economic advantage in using multiple-charge ions. The space charge limited transport of a quadrupole system permits charge states of approximately four when the other considerations that have been previously defined[1] are included. Thus, for example, it would be possible to inject a pulse of approximately 150 μC of $^{238}U^{+4}$ in a 3 μs pulse at 100 MeV. Such a pulse, while well matched to the LIA, is far from state-of-the-art for any existing injection system and even well beyond the practical limits of systems of conventional ion sources, low-β linacs, accumulator rings, etc., that have been suggested for various HIF scenarios.

In this note, we describe two configurations for ion source and drift-tube-linac combinations that could provide the energy and intensity of accelerated ions needed for the HIF applications. The focusing for the systems is provided by a periodic structure of rectangular electrostatic lenses. Scaling rules and extensions of the ideas will be briefly described. Example systems are described that could provide 150 μC of uranium or cesium ions at 12 MeV.

The principal difficulty to be overcome in a high-intensity heavy-ion injector is, of course, space charge. The magnitude of the space-charge question can be grasped if one considers only the expression for potential depression from the outside to the center of a cylindrical beam of current I

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and velocity β:

$$\delta V(\text{volts}) = 29.98\ I(\text{amperes})/\beta \quad . \tag{1}$$

For example, for a 1 MeV $^{133}Cs^{+1}$ beam (β = .004) of 7.5 A, the potential drop within the beam is 56 kV. Because of the low velocity, solenoid focusing is weak and a very strong solenoid (several Tesla superconducting) would be needed to contain the beam. Other focusing schemes, including an electrostatic system under construction at LBL, are either unsuitable for a long pulse length (needed to get sufficient charge) or are even more forbidding than the large solenoid. The longitudinal force generated by the potential drop at the ends of a beam pulse can only be contained at accelerating gaps. Since the ends of the pulse see these longitudinal fields continuously, very strong accelerating transients must be added to the ends of the pulse to constrain the bunch length.

In attempting to design around the space charge issue, it has been suggested to consider some type of space charge neutralization or to divide the beam into several lower intensity beams. Neutralization presents some awkward problems in the presence of accelerating fields and, even though it may always be present to some degree, seems only to complicate the problem. Dividing the beam among parallel transport systems is workable but does result in the proliferation of components. In this paper, it is proposed to create a configuration of sheet beams within the main accelerating system; each sheet focused separately to permit a reduction of the space-charge depression. The advantage of the sheet-beam configuration can be seen from the comparison of Eq. (1) with the expression for the space charge depression to the midplane of an infinite sheet beam of current density j and half-thickness x:

$$\delta V(\text{volts}) = 188.37\ \frac{j(\text{amperes per unit } x^2)\ x^2}{\beta} \tag{2}$$

In the example to be considered, we will have about 2 mA/cm^2 and a half-thickness about 2 cm, so at 1 MeV (β = 0.004), δV = 377 V. This permits using a much weaker transverse focusing system and also reduces the longitudinal forces are the ends of the bunch by about an order of magnitude compared to the single beam of circular cross section.

Drift Tube Linac Configurations

There are several possible physical configurations for transport systems for a sheet beam, among which large-radius annuli and plane sheets with some edge focusing scheme are the most obvious. A stacked array of ribbon beams will be recognized as a scaled-up version of the "rail" electrode geometry employed in the LBL 60-ampere hydrogen sources for the neutral-beam injection into Tokamaks. Results in this paper show that extensive scaling of this geometry is entirely feasible for the heavy ions.

Figure 1 shows an artist's conception of an annular drift tube linac with cylindrical rings providing the transverse focusing. A section view of the annular structure is shown in Fig. 2. The inner set of focusing rings can be supported with a minimum number and size of radial rods. A simpler

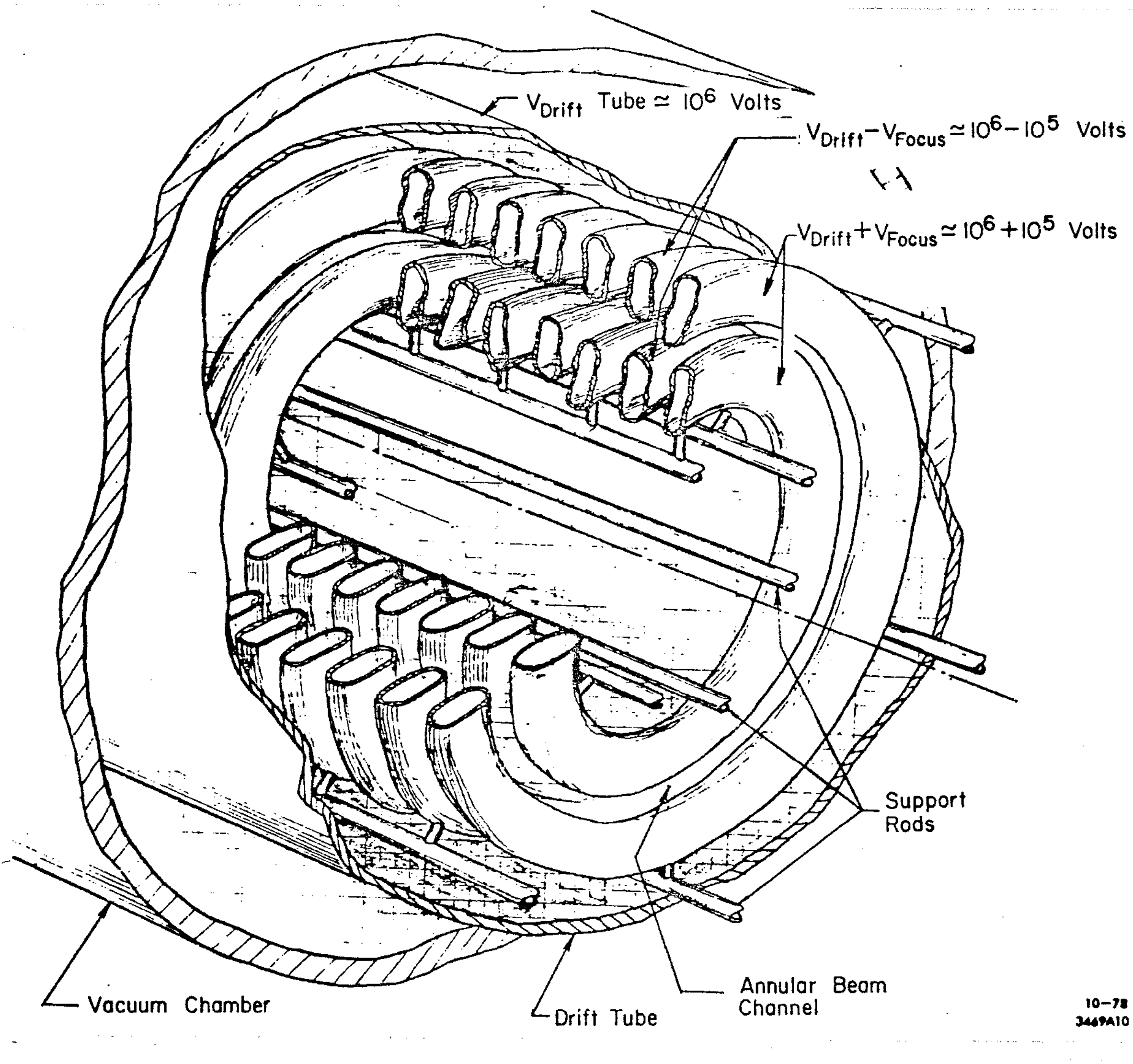

Fig. 1 Annular drift-tube linac structure. Artist's conception of annular drift tube linac with periodic focusing structure.

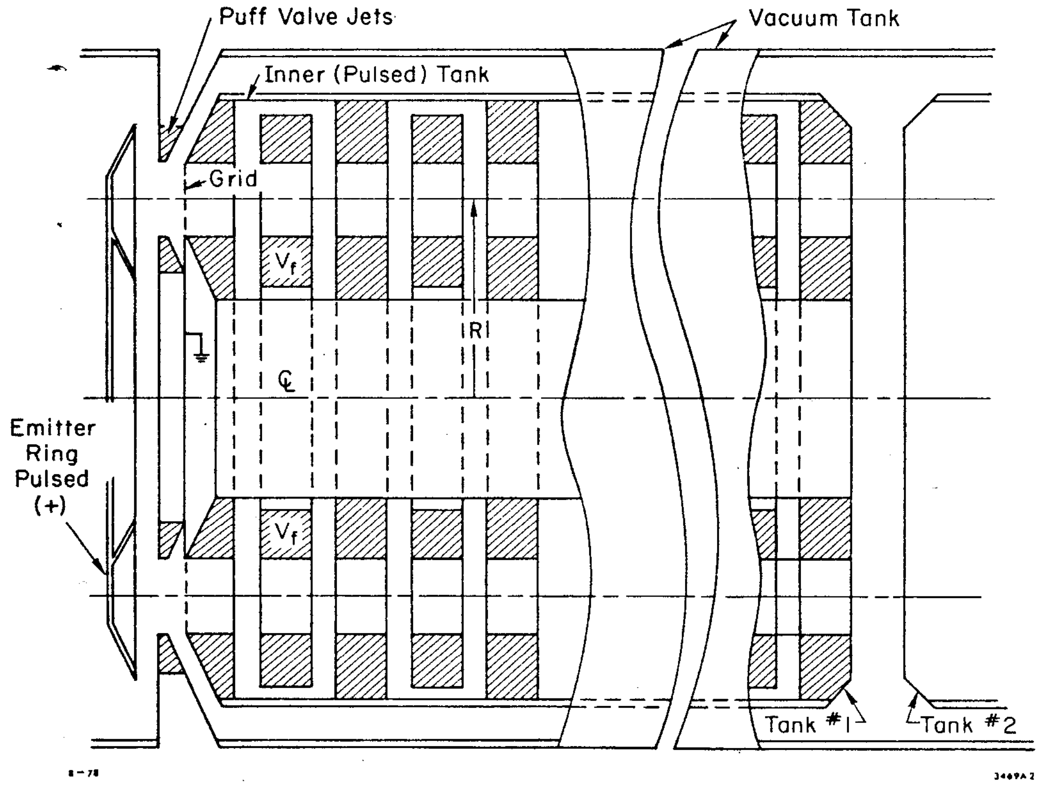

Fig. 2 Annular ion source and drift tube linac.

mechanical design is shown in Fig. 3 for the configuration of flat parallel ribbons. The flat ribbons in this example have a total current equal to that carried by a single annular beam in a pipe of about 25% greater diameter than that needed for the ribbons. This assumes that the ribbon edges have been properly accounted for by counting only the current in the shaded areas. With some added mechanical intricacy, it is possible to have two or more concentric annular rings, so that the relative efficiency in utilizing the volume could favor the annular configuration. Ultimately, the choice between possible configurations will probably depend on details of the transverse recombination of the beam, and on mechanical engineering aspects. The rest of this discussion will be independent of the configuration.

Cylindrical sheets do not involve any three-dimensional calculations for fields and thus can be completely defined in available computer codes. Actually, in using the SLAC Electron Optics Program,[2] it is convenient to make the focusing calculations in rectangular coordinates, ignoring the effect of cylindrical curvature since it is assumed that the cylindrical radius is much greater than the radial gap between the rings (20 to 1 in the example case).

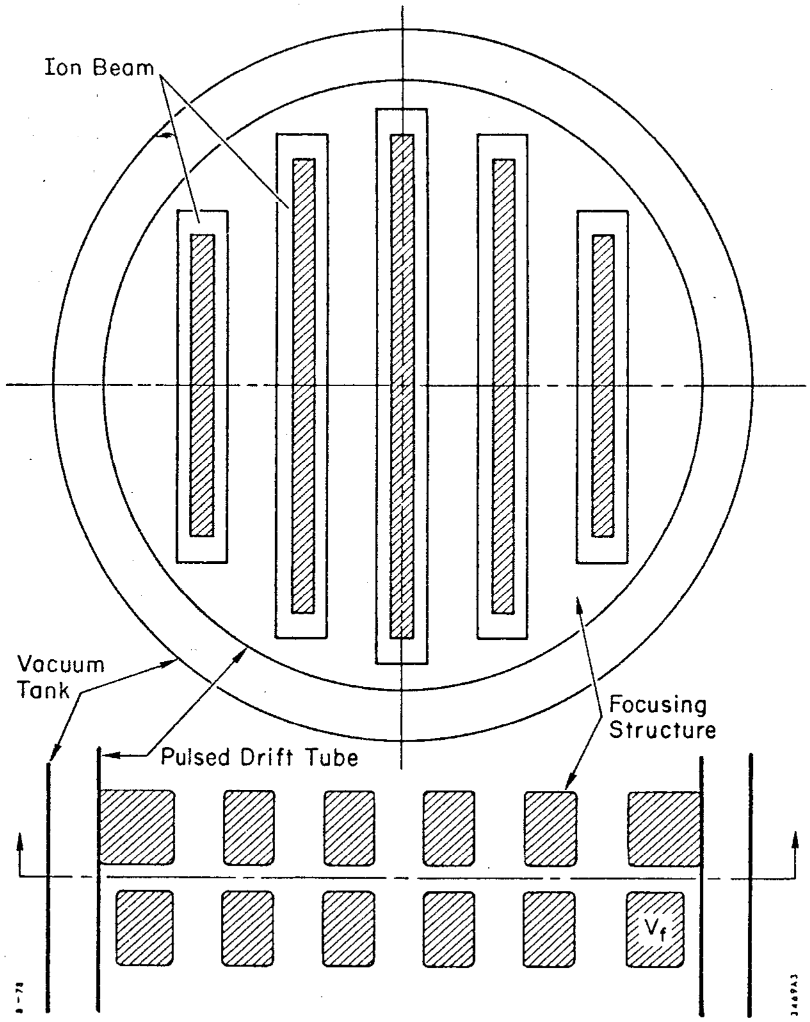

Fig. 3 Flat ribbon configuration of periodic focused drift tube linac.

The ion-source partially defines the transport system. Based on the design for a cesium ion source for the drift tube linac experiment at LBL, an ion current density of 2 mA/cm^2 or more is expected to be demonstrated to be feasible. This current density results from operating the gun at 500 kV with a second 500 kV acceleration stage into the first drift tube. The transport system consists of alternating accelerating/decelerating fields induced by static voltages on a structure as shown in Fig. 4. The structure is essentially a periodic system of rectangular Einzel lenses. The ratios of gap to width and gap to periodic spacing are not presumed to be optimized, but appear to be reasonable first choices to study the system. The beam shown in Fig. 4 is an ordered beam assumed to be injected into the structure. Figure 5 shows half of the beam, assuming mirror symmetry on the midplane of the sheet, with an expanded vertical scale to show the focusing action. It shows the result of transporting the beam through 20 sections equivalent to 17.5 meters. From the scatter plots of R' vs R shown in Fig. 6, the resulting growth in phase space appears to be substantially less than a factor of two.

The potential growth of phase space due to all causes (aberrations, instabilities, grids, scattering, etc.) in such a focusing system is limited by the height δR of the gap and the angle $\delta\Theta$ of particles which can be focused by the structure. Eventually, however, the beam must be made to converge and merge into a cylindrical beam for transport through a more conventional quadrupole or solenoid system. The merging process will result in a phase area which at best conserves the four-dimensional transverse phase area. The relevant equivalent transverse coordinate then would appear

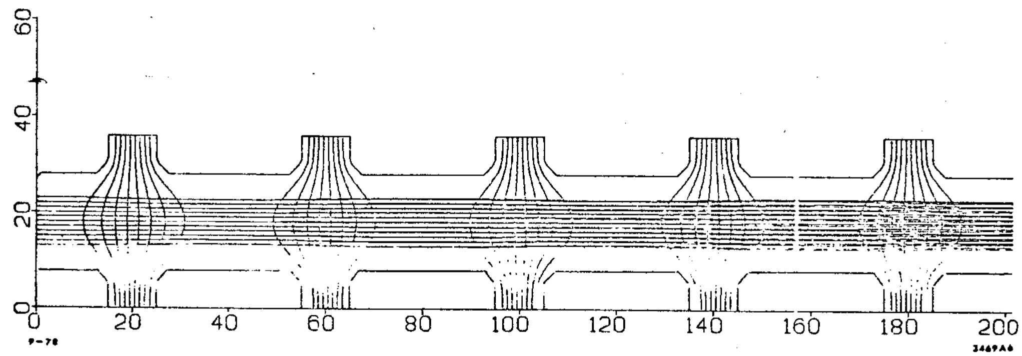

Fig. 4 Focusing structure of periodic rectangular Einzel lenses. For the annular drift tubes, the system axis is depressed by about 20 gaps, i.e., to −440 for the example case in which one mesh unit is 0.35 mm. Thus the aperture is 7 cm wide and the periodic length is 14 cm.

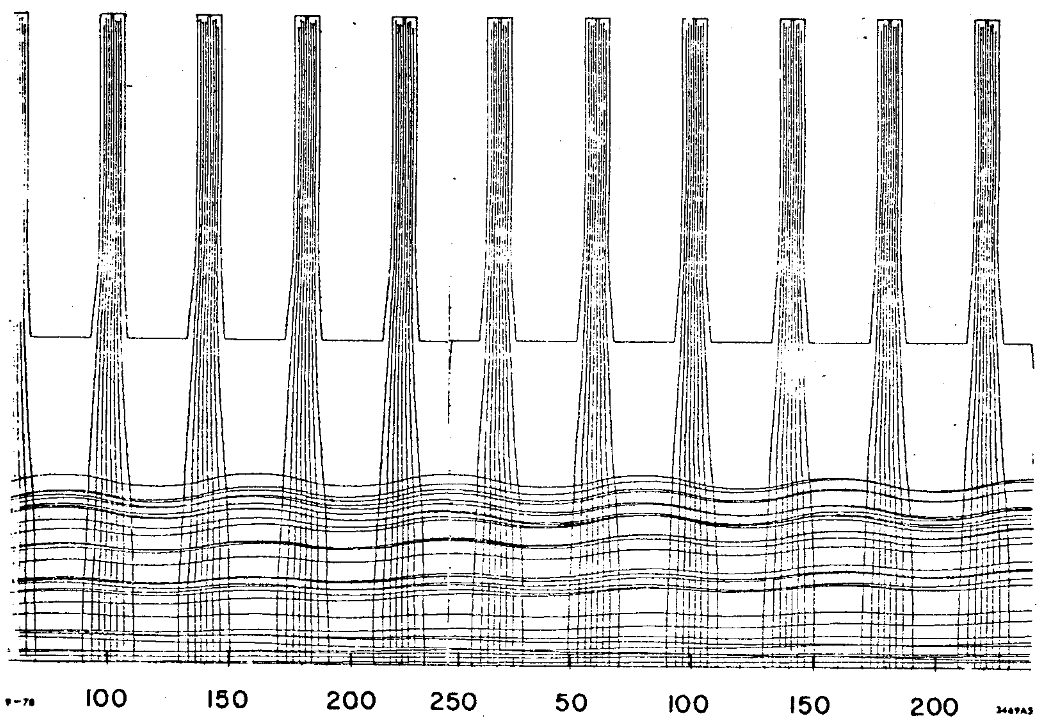

Fig. 5 View of the same structure as shown in Fig. 4 with scales distorted to show the focusing effect. The trajectories shown are in the 20th section, equivalent to 17.5 m of drift length. Midplane symmetry is assumed.

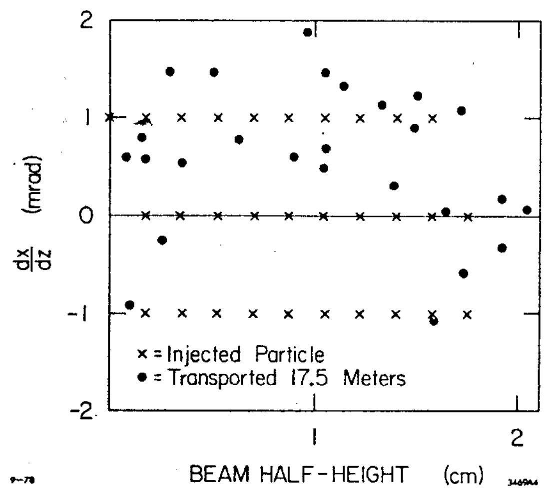

Fig. 6 Phase diagram of trajectories shown in Fig. 5. The 'x' spots indicate the injected beam, the solid dots are for the transported beam.

to be given by

$$r = \sqrt{\frac{A}{\pi}} = \sqrt{\frac{2\pi\ R\ \delta R}{\pi}} = \sqrt{2R\ \delta R} \qquad (3)$$

The normalized emittance of the beam should be less than the value assumed for the final transport system, typically $\pi\varepsilon_N \approx 2\pi \times 10^{-5}$ meter radians. Using $R = 1.5$ m, $\delta R = 0.04$ m, we find,

$$\delta\Theta = \frac{\varepsilon_N}{\beta r} = 14 \text{ milliradians} \qquad (4)$$

for 1 MeV Cs ions ($\beta = 0.004$). This is substantially greater than the $\delta\Theta < 2$ milliradians observed in Fig. 6, and is probably greater than the focusing system will transport. Thus the periodic structure appears intrinsically suited to provide a low phase-space beam to a heavy-ion accelerator, provided, of course, that the merging of the beam can be accomplished without introducing excessive dilution of the phase-space volume. Figure 7 shows the focusing properties with zero current.

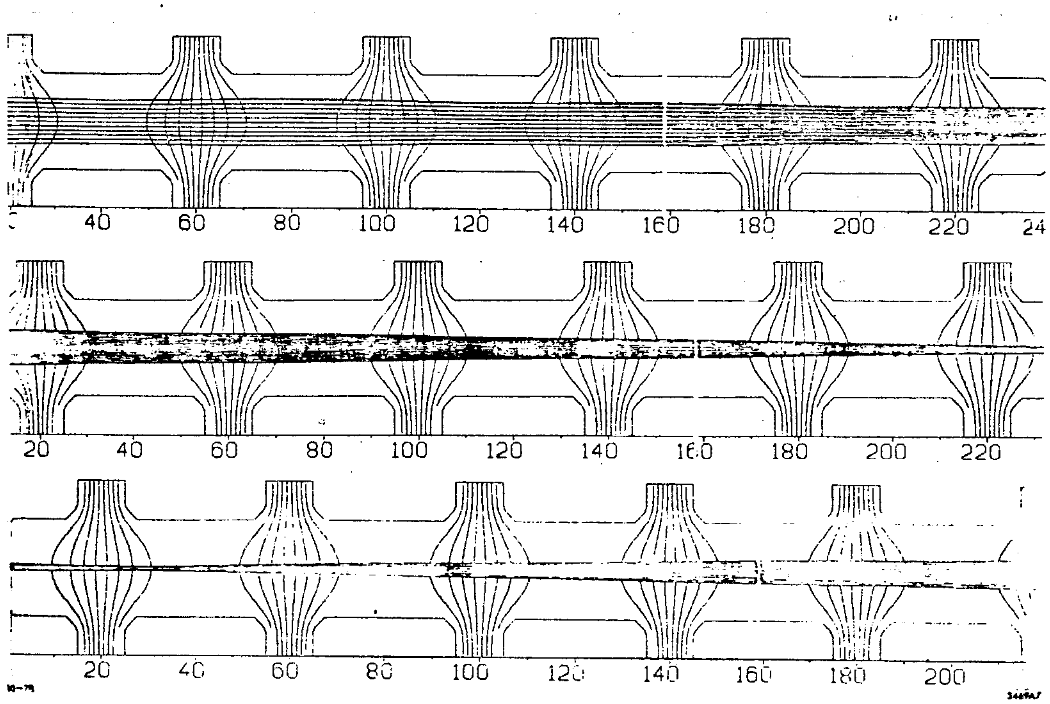

Fig. 7. Zero current case; transverse focusing for the bunch ends with no space charge.

The focusing properties of a system of periodic rectangular Einzel lenses have been estimated analytically by Lloyd Smith[3] and tested numerically in a series of calculations such as that shown in Figs. 4-6. The agreement between the two methods is remarkably good; all scaling rules have been numerically confirmed and absolute magnitudes are within a few percent. To first order in x, the focusing deflection at each gap is

$$\Delta x' \approx - \frac{qexE(x = 0)}{2T} \frac{\Delta v}{v} = - \frac{x}{g} \left(\frac{qeV}{2T}\right)^2 \tag{5}$$

where q = charge state, V = gap voltage, g = gap length and T = kinetic energy of the particle. Since these impulses occur at points separated by the periodic length of the structure ℓ, on the average

$$\frac{d^2x}{ds^2} = - \frac{x}{g\ell} \left(\frac{qeV}{2T}\right)^2 \tag{6}$$

The effect of the space charge is to cause a field E_x such that

$$\frac{qeE_x}{mv^2} = \frac{2\pi q^2e^2}{T} \rho x = \frac{2\pi qejx}{Tv} \tag{7}$$

where j is the current density. Balance is achieved for $d^2x/ds^2 = 0$ if

$$\left(\frac{1}{g\ell}\right)\left(\frac{qeV}{2T}\right)^2 = \frac{2\pi qej}{Tv} \tag{8}$$

which can be rewritten for ions of mass number A as

$$\left(\frac{eV}{m_ec^2}\right)^2 = \left(\frac{m_p}{m_e}\right) \frac{4\pi e}{m_ec^3} (g\ell A\beta j/q) \tag{9}$$

which, when solved for the focusing voltage, becomes

$$V(kV) = 594.6 \, (g\ell A\beta j/q)^{1/2} \quad . \tag{10}$$

In the example of Fig. 4, the effective gap is about $\ell/2$, $\ell = 14$ cm, $\beta = 0.004$, A = 133, and $j = 2$ mA/cm^2, which yields V = 191 kV. The actual value found from the numerical work was 170 kV for the above parameters. Note that if we had estimated the effective gap to be $\ell/3$, the prediction would be V = 156 kV, so that it might be concluded that the effective gap lies between $\ell/2$ and $\ell/3$ for this case. More significantly, the numerical results confirmed the dependence of the focusing voltage on $T^{1/4}$, $I^{1/2}$, and $A^{1/2}$, as predicted in (9) and (10).

Example Case: 7.5 A of Cesium

As an existence proof example we will examine a design for an ion source/ injection system for a 7.5 A cesium source capable of injecting 150 μC in a 20 μsec pulse at a low integer value of q, e.g., q = 4.

The system begins with a contact ion source whose design is based on the gun being built at LBL for a beam transport experiment. This gun, which is described in more detail in Ref. 4, is designed to emit between 1.4 and 2.0 mA/cm^2. The thin ribbon version of the same gun is shown in Fig. 8. The grid on the right side covers the entrance to the periodic focussing system described above. The emitting surface is pulsed to about +500 kV and the drift tube, which begins at the gridded ring, is pulsed to -500 kV. The middle electrode in the gun is the grounded cesium injector which provides a puff of cesium to the emitting surface just prior to pulsing the gun.

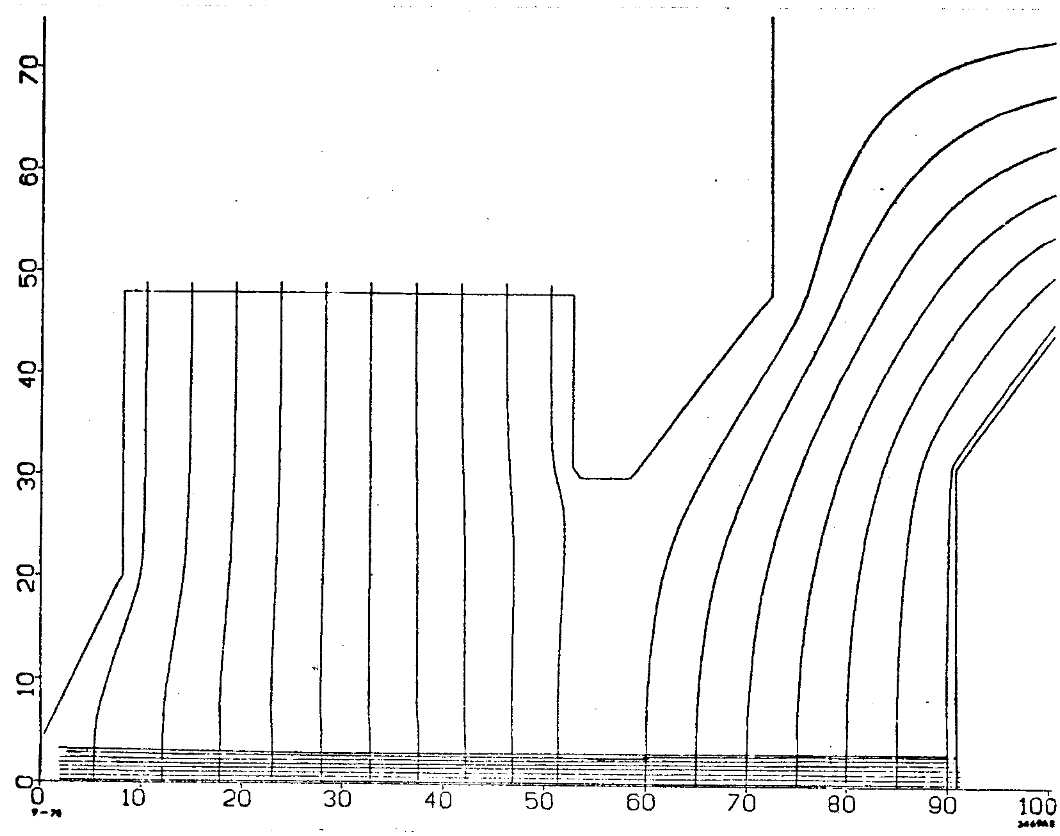

Fig. 8 Rectangular "ribbon beam" gun with emitting surface 3.5 cm wide. The grounded center electrode is used for the puff value cesium injector which sprays cesium on the hot emitter prior to each pulse. Midplane symmetry is assumed.

The first drift tube consists of a large tank containing the drift tube focusing structure as described earlier. The length of each drift tube is determined by the drift length $\beta c\tau$ of a pulse. The thickness of beam ribbon that can be transported, which is determined by the focusing strength, in turn determines the transverse length of the ribbon stack, or circumference of annular beams. Thus, using 2 mA/cm^2 from the gun, it is possible to transmit a 1 MeV beam 3.5 cm thick with a focusing voltage of 170 kV. A circumference or total length of 1070 cm by 3.5 cm wide for the emitting surface provides 7.5 A. At 1 MeV, $\beta c\tau$ for the cesium beam is 24 m for 20 μsec. Adding 2 m for pulse rise and fall times makes the total drift tube 26 m long. By double pulsing each structure, that is, first negative to pull the beam in and then positive to expel it, the total system is made shorter and more effective. From the 1 MeV assumed for the injected beam, the energy could be increased to 3 MeV in the second drift tube, which would need to be 46 m long, if the succeeding pulses are all 1 MV. Table I provides a summary of the parameters through the third drift section.

Example Case: 7.5 A of Uranium

Everything in the previous section can be extended to the case of uranium (or other high mass) ions provided that a large area ion source[5] can be developed. In Table II, the parameters for a uranium drift tube structure are given by scaling from the values in Table I. A lower current density (1 mA/cm^2) has been assumed to avoid uncomfortably high focusing voltages. This results in a larger area needed for the emitter but, by way of partial compensation, all the drift lengths are shorter due to lower values of v/c for the same kinetic energy. The emitting surface area requirement could be met by three concentric rings in the annular structure, or by a large ribbon structure. Of course, trade-offs of current and pulse length are always possible.

Accelerating, Bunching and Combining

After several drift tube sections the beam velocity will become large enough that further acceleration in electrostatic focused drift tubes will be uneconomic. The drift tube gap voltages could be programmed to begin to bunch the beam, at least to the point of preventing the bunch from becoming physically longer with each acceleration. Bunching may extend the use of drift tubes until the beam reaches velocity and bunch lengths that make the LIA more economic; 100 MeV and 3 μsec for example. However, it is likely that the focusing structure will give way to a "conventional" cylindrical beam fairly soon. Thus the requirements specified by Faltens and Keefe[1] would be met by the system already described. The beam would have to be combined into a "solid" cylinder before entering a magnetic focusing system such as they describe. Combining the beam can be accomplished by deflecting the beam inward along a converging trajectory and then causing it to flare out straight as it enters the next accelerating and/or focusing structure. These deflections are made by putting slightly different average dc voltages on the inner and outer sets of focusing rails. Figure 9 shows the deflection of a beam with a voltage difference of about 5% of the focusing voltage. Once deflected, the beam continues along the converging path provided, of course, that focusing is provided with an increasing strength since as the area decreases, the current per unit area increases. Although there will be

TABLE I

CESIUM
DRIFT-TUBE LINAC PARAMETERS

GUN :	V = +0.5 MV	I = 7.5 A	$j = 2\ mA/cm^2$	
(1 m)	Emitter: Ion Cs^{+1}	Length = 1071 cm	Width = 3.5 cm	
	Pulse:	Q = 150 μC	τ = 20 μsec	
TANK #1:	V_1 = -0.5 MV	I = 7.5 A	T = 1 MeV	
(27 m)	V_f = -170 kV	β = 0.004	τ = 20 μsec	q = +1
	V_2 = +1.0 MV	L = βcτ + 2 = 26m	T = 2 MeV	βcτ = 24 m
TANK #2:	V_1 = -1.0 MV	I = 7.5 A	T = 3 MeV	q = +1
(71 m)	V_f = -224 kV	β = 0.07	τ = 20 μsec	βcτ = 44 m
	V_2 = +1.0 MV	L = 46 m	T = 4 MeV	
STRIPPER AND CHARGE SEPARATING SPECTROMETER:				
(78 m)	Separate to select q = 4		β = 0.008	T = 4 MeV
	L = 3.6 (magnet) + 2 × 1.7 (stripper) = 7 m			
TANK #3:	V_1 = -1.0 MV	I = 7.5 A	T = 8 MeV	q = +4
(146 m)	V_f = -141 kV	β = 0.011	τ = 20 μsec	βcτ = 66 m
	V_2 = +1 MV	L = 68 m	T = 12 MeV	

NOTES: V_1 and V_2 are respectively the first and second pulsed voltage levels for the drift tube. V_f is the static focusing voltage applied to one set of rings relative to the others which are at V_1 or V_2. Cummulative lengths are shown in parenthesis.

TABLE II

URANIUM
DRIFT-TUBE LINAC PARAMETERS

GUN :	$V = +0.5$ MV	$I = 7.5$ A	$j = 1$ mA/cm^2	
(1 m)	Emitter: Ion Cs^{+1}	Length = 2142 cm	Width = 3.5 cm	
	Pulse:	$Q = 150$ μC	= 20 μsec	
TANK #1:	$V_1 = -0.5$ MV	$I = 7.5$ A	$T = 1$ MeV	$q = +1$
(21 m)	$V_f = -140$ kV	$\beta = 0.003$	$\tau = 20$ μsec	$\beta c\tau = 18$ m
	$V_2 = +1.0$ MV	$L = \beta c\tau + 2$ = 20m	$T = 2$ MeV	
TANK #2:	$V_1 = -1.0$ MV	$I = 7.5$ A	$T = 3$ MeV	$q = +1$
(47 m)	$V_f = -184$ kV	$\beta = 0.0052$	$\tau = 20$ μsec	$\beta c\tau = 24$ m
	$V_2 = +1.0$ MV	$L = 26$ m	$T = 4$ MeV	
STRIPPER AND CHARGE SEPARATING SPECTROMETER:				
(54 m)	Separate for $q = 4$		$\beta = 0.006$	$T = 4$ MeV
	$L = 3.6$ (magnet) $+ 2 \times 1.7$ (stripper) $= 7$m			
TANK #3:	$V_1 = -1.0$ MV	$I = 7.5$ A	$T = 8$ MeV	$q = +4$
(107 m)	$V_f = -117$ kV	$\beta = 0.0085$	$\tau = 20$ μsec	$\beta c\tau = 51$ m
	$V_2 = +1$ MV	$L = 53$ m	$T = 12$ MeV	

NOTES: V_1 and V_2 are respectively the first and second pulsed voltage levels for the drift tube. V_f is the static focusing voltage applied to one set of rings relative to the others which are at V_1 or V_2. Cummulative lengths are shown in parenthesis.

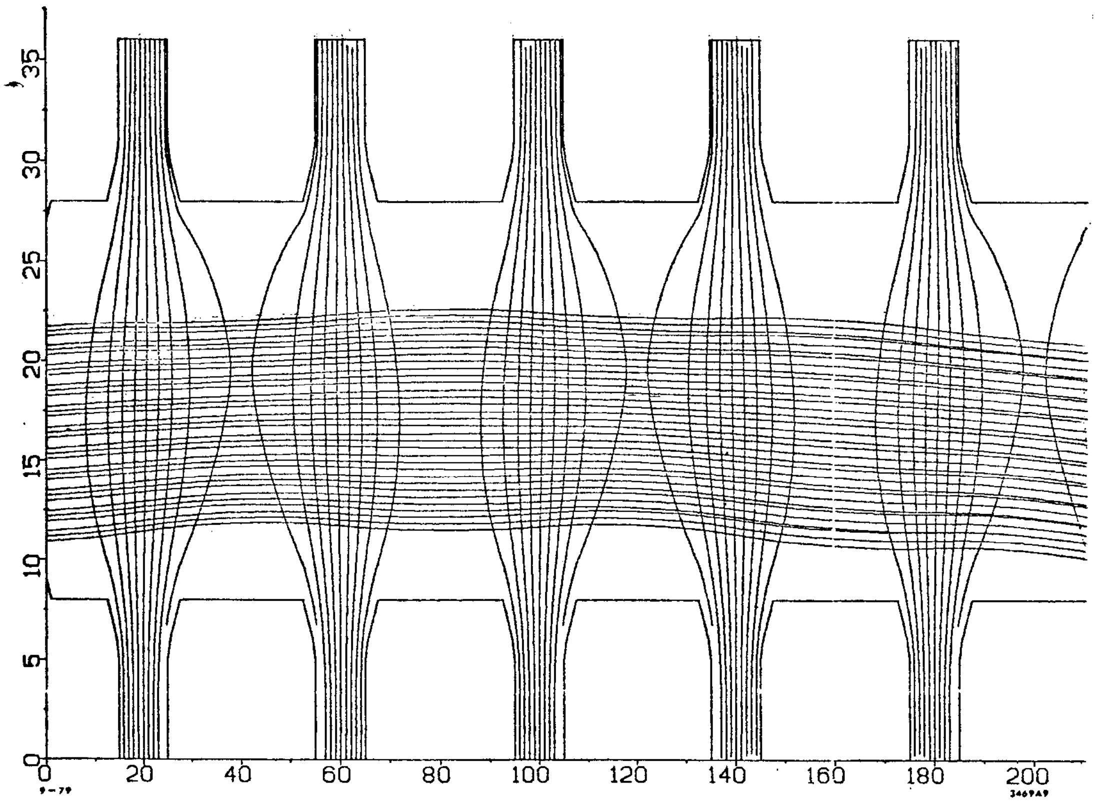

Fig. 9 Deflection within the annular focusing structure is needed for the charge separator and for recombining the beam into a cylindrical beam for further acceleration in a conventional transport system. By making the average potential different in the inner and outer focusing structures, the beam is caused to deflect toward or away from the axis.

inevitable phase space dilution in this process, it presently appears as if the emittance of the electrostatic structure will be substantially below the values needed for transporting beams of the required intensity in the induction linac. Thus the phase space dilution is needed for matching the LIA transport system.

Summary and Conclusions

The problem of providing a high intensity pulse of heavy ions requires some special tricks to avoid extremely expensive solutions to the space charge problem. Spreading the beam out between rectangular Einzel lenses arrayed as a periodic structure appears to provide a workable solution to the problem. The configuration suggested here should be considered as an existence proof that this is a valid approach but it has not yet been at all optimized. Presumably one would like to transport the highest possible current with the lowest possible focusing voltage. However, it is also necessary to consider the clearance between the beam edge and the aperture as well as the aberrations that typically result from getting too near the focusing elements. The example cases appear to be conservative in all design respects. If the periodic structure is extended to higher velocities than those considered here, the practical limits on voltage standoff will have to be considered. To offset the $\beta^{1/2}$ voltage dependence, it is possible to reduce the gap and length dimensions which were shown in Eq. (10) to reduce the focusing voltage proportionately to $(g\ell)^{1/2}$.

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