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A CHARGE SEPARATING SPECTROMETER FOR ANNULAR ION BEAMS*

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The need for very high currents of low-velocity heavy ions requires some new approaches to the transport and acceleration problem. One such approach, described in reference 1, would use a configuration of alternating accelerating and decelerating fields applied by rails or rings to the ion beam, which is configured in thin sheets in order to make this method of focusing effective. The annular ring configuration of the focusing structure is attractive because of the absence of end effects. In applying this system to a heavy ion injector for a linear induction accelerator (LIA), it is noted that it may be desired to accelerate multiple-charged ions in order to reduce the length and cost of the accelerator. The same conclusion can be drawn for the drift tube linac, which could be very long if only 1 or 2 MeV are gained per section. Thus, in the example parameters shown in reference 1, it is suggested that a stripping and charge-state separation system be located at the 4 MeV point between tanks No. 2 and No. 3. This report will describe an annular spectrometer system for the charge separator.

The proposed system consists of a gas-filled cell through which the singly-charged ions pass to strip off some additional electrons. This beam, consisting of several charge states, is then passed through a spectrometer which selects only that charge state chosen for further acceleration. The spectrometer is designed to use an annular-gap magnet which matches the geometry of the beam. Preliminary calculations for the acceptance and resolution of the spectrometer will be shown below.

The annular ring focusing system will continue up until the entrance aperture to the stripping cell. Within the cell, it is expected that the space charge effects will be neutralized by the plasma. A stream of electrons will likely be pulled along with the ions into the bending magnet to neutralize the excessive space charge there caused by the large number of multiple-charged ions. However, since these electrons cannot pass through the magnet, the beam emerging from the magnet will have a great deal of space charge. It may be useful to include one or more grid screens to cancel out some of the space charge. These grids could be part of a system of differential pumping baffles.

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The type and pressure of the gas in the cell will be the subject of study and experiment. However, a promising lead is offered by A. W. Wittkower and H. D. Betz[2] who report that the equilibrium charge distribution of heavy ions such as uranium passing through helium has a peak at about $q = 4$. At ion kinetic energies between 2 MeV and 15 MeV, the percentage of $q = 4$ ions exceeds 25 percent, so that as much $q = 4$ current would result as the $q = 1$ current which is injected to the stripping system. In Fig. 1, we have reproduced a curve from reference 2 showing the equilibrium charge distributions for uranium beams in helium and oxygen. Although helium is distinctly more effective in producing a high charge state at moderate kinetic energy, the differences between target gasses is not so great as to rule out something, such as N_2 or O_2, which may be pumped more easily. Both N_2 and O_2 have more than 20 percent $q = 4$ from 2 to 10 MeV. Very similar results are reported for other heavy ion species such as tantalum.

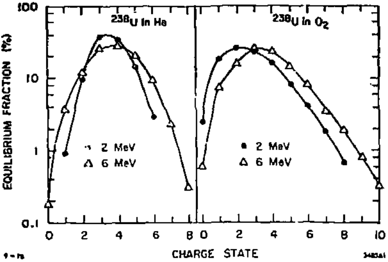

Fig. 1. Equilibrium charge state distributions of uranium ions in helium and oxygen at 2 and 6 MeV. Reproduced from reference 2.

The charge-separating spectrometer uses a pair of annular gaps with equal-strength, oppositely-directed radial magnetic fields. The annular shaped beam is first directed radially inward at a small angle, e.g., 10 milliradians, so that it has a radial slope as it is bent in the first magnet gap. The bend, which should be several times the radial slope, is in the azimuthal direction. The spectrometer resolution results from the fact that any straight trajectory which enters the side of a cylinder must eventually re-emerge at the initial radius. The distance in the axial direction between the point where the trajectory enters and leaves the cylinder is determined by the bending angle in the azimuthal magnet, and thus by the charge state, assuming that all the particles have the same nominal radial slope before bending. Within the limits of radial phase space, this requirement is met by locating the stripping gas cell after the elements which deflect the beam radially inward, i.e., immediately ahead of the bending magnet.

In Fig. 2, three views of the spectrometer are shown to illustrate the above discussion. The projected angle ϕ in the end view is given by

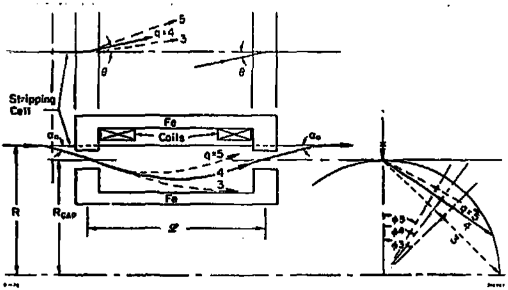

Fig. 2. Annular Charge Separating Spectrometer. Trajectories with a radially inward slope α_0, are deflected in the radial magnetic field by an angle ϕ. They then continue on a straight path towards the second gap, which must be located the correct distance $\mathscr{L}$ away from the first gap for the trajectory to pass through the gap and emerge with slope α_0 after an azimuthal shift of $2\phi_n$. Trajectory path between magnet poles is straight, but appears parabolic in the projection to the $r-z$ plane in cylindrical coordinates.

$$\phi = \tan^{-1}\left(\frac{\sin \alpha}{\sin \theta}\right) \tag{1}$$

where α is the initial radial angle after the particle is bent by an angle θ. The path of the trajectory between the gaps is a straight line, but projected on the $r-z$ plane in radial coordinates, it is parabolic with a minimum value

$$r_{\min} = R_{\text{gap}} \cos \phi . \tag{2}$$

If the half length between centers of the gaps is $\mathscr{L}/2$, then

$$R_{\text{gap}} - r_{\min} = \alpha \mathscr{L}/4 . \tag{3}$$

For the small angles anticipated in the system $\alpha \approx \alpha_0$, but for larger angles

$$\alpha = \tan^{-1}\left(\frac{\tan \alpha_0}{\cos \theta}\right). \qquad (4)$$

where α_0 is the incident radial angle. From (2) and (3)

$$\mathscr{L} = 4(r_{gap} - r_{min})/\alpha = 4R_{gap}(1 - \cos \phi)/\alpha . \qquad (5)$$

$\mathscr{L}$ is "reasonable," i.e., not greater than the diameter, for $\theta \gtrsim 10\alpha$, where $\alpha_0 \approx 10$ milliradians. A series of ray tracing computer runs graphed in Fig. 3 shows the radial path taken by three charge states: $q = 3$, 4, and 5.

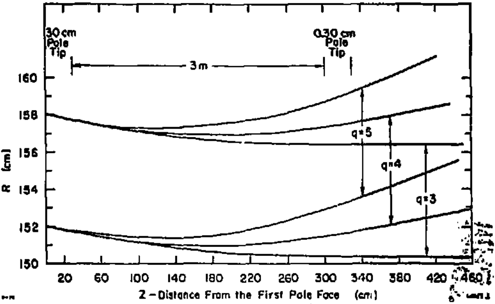

Fig. 3. Computed ray-trace plots of two trajectories at each of three indicated charge states. The bending field is 0.28 T for 4 MeV cesium ions entering with an initial slope $\alpha_0 = -0.01$.

With subsequent aperture baffles set for a symmetric configuration, the case shown in Fig. 3 would transmit $q = 4$ and eliminate all other charge states within a couple of meters drift. The next accelerating gap would then be installed just down beam of the aperture baffles. The baffles are probably just a continuation of the annular focusing structure. Not yet included in the calculation of Fig. 3 is the effect of space charge on the beam drifting between the pole gaps. It is assumed that the space charge effects there will be severe and that focusing rings will have to be installed within the drift space between the magnet poles. Part of the space charge could be eliminated if atoms with the wrong q value, particularly ± 2 or more from the desired level, could be eliminated earlier. This might be done by some slanted baffles in the first magnet gap. Such baffles would also aid the differential pumping system and help as supports for the inner iron cylinder.

Preliminary results of the ray tracing studies show that energy spread and radial divergence do not particularly affect the conclusions suggested above and shown in Fig. 3. In fact, the spectrometer appears to have some mixing effect on radial and transverse phase space which is probably beneficial since radial aberrations will have increased the radial emittance by this point in the system.

REFERENCES

1. W. B. Herrmannsfeldt, "A Multi - Ampere Heavy Ion Injector for Linear Induction Accelerators Using Perodic Electrostatic Focusing," Proceedings of the Heavy Ion Fusion Workshop, Argonne National Laboratory, September 19-26, 1978.
2. A. W. Wittkower and H. D. Betz, Phys. Rev. A, 7, 159 (1973).