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SUGGESTION FOR A CHARGE-STATE "ENFORCER" FOR HEAVY ION ACCELERATORS*

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The design of a new type of device, a charge-state "enforcer", is described. This device, using an intense magnetic field with some static or rf electric field deflection, causes the stripping of a beam of heavy ions into a single selected charge state with nearly 100% efficiency. The requirements and limitations of the device are discussed.

A common problem for all heavy ion accelerators thus far designed is that of charge changing. This is usually done with a stripping foil or gas which intercepts the beam. The incident beam of ions is fractionated by the stripping process into a distribution of charge states, each component of which has different acceleration properties. Since an accelerator must produce a beam with a unique energy, only one of these charge states may usually be used and the others are lost. The charge state used is normally a compromise between optimum accelerator performance and high probability of formation. Even if the most probable charge state is used, however, its fraction is not large for heavy ions, ranging from 41% for ^{16}O to 17% for uranium. Clearly, this situation is far from ideal, and what one would really like is a device which would strip *all* of the beam into any desired charge state. Such a device is proposed here, and we christen it a *charge state enforcer*.

Fig. 1 shows the operation of this device. A beam of particles in a very low charge state enters from the right, and encounters an intense magnetic field produced by a superconducting solenoid. The beam strikes a thin stripper foil and is fractionated into charge states which are, on the average, of much higher charge than the incident beam. Each of these charge state groups goes into what might be called a microtron orbit[1]), and after traveling in a circular path, returns to its point of impact with the stripper foil and is stripped again. The magnetic field is adjusted so that the charge state which is to be extracted is orbited between a pair of C-shaped electric deflection plates which parallel the orbit of the ion for a sizable portion of its path length. The electric field produced by the plates deflects the selected charge state sideways in its orbit, as shown in the top view portion of fig. 1. When this charge state comes around to the stripper position, it is displaced in position enough to miss the stripper foil and pass instead into a "super tube", i.e. a tube made of superconducting material so as to act as a perfect shield against magnetic fields. When the selected charge state enters the supertube, it no longer is bent in a circular orbit by the

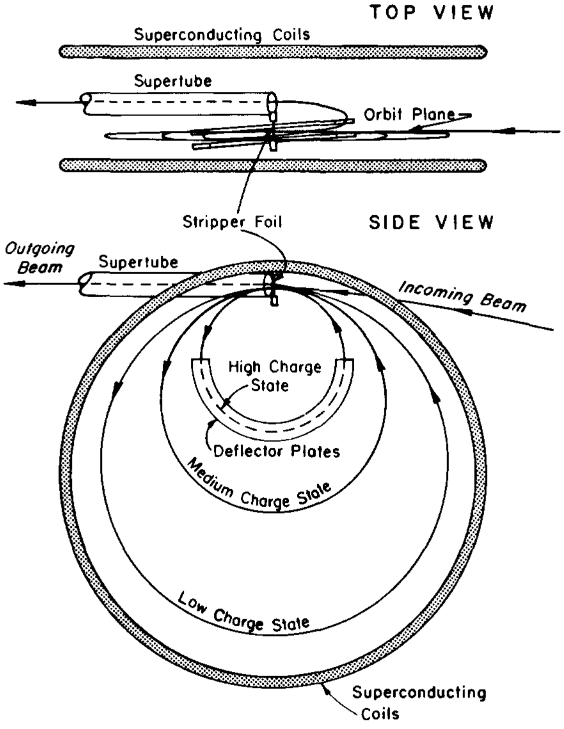

Fig. 1. Two views of charge state enforcer in operation. Beam enters high field region from right, strikes stripper foil, and its charge components go into microtron orbits which bring them back to stripper foil. Charge state which is selected for extraction travels parallel to deflector plates and is bent sideways so that its orbit intercepts entrance to supertube instead of stripper foil. It is then shielded from magnetic field and exits the device.

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magnetic field, but instead travels in a straight line, and exits from the device. The other ions are trapped in the field and are not allowed to exit until, after several collisions with the stripper foil, they are stripped into the selected charge state and are allowed to leave. Thus, even an "unpopular" charge state can, in principle, be produced with 100% efficiency by this technique.

If such an ideal device could be placed at the terminal of a tandem, it could be used to select a charge state, even a very high one, with ≈100% transmission. At the output end of a tandem, a charge state enforcer could reduce the charge of the beam by a large number of charge states and send it back through the machine for further acceleration, in the spirit of the recirculating tandem proposed by Hortig^2). At the center of a cyclotron, the device could not only deliver a high charge state into the accelerating structure of the cyclotron, but also, by applying rf to the electric deflection plates of the device, accept dc beam and dispense it only on the proper rf phase for proper acceleration in the cyclotron. In a heavy ion linac, a device of this kind could permit several strippings to very high charge states without loss of intensity, and by pulsing of the electric field plates with rf, rebunch the beam for further acceleration. At the output of an accelerator, it could prepare the beam in a high charge state so that less expensive bending magnets and quadrupole lenses would be needed, and might also average out the rf structure so that the beam would be more continuous for coincidence experiments.

All of the above makes it important to understand the limiations of the device so that its real potentialities can be accurately assessed. Its limitations arise from three sources: (1) difficulty in fabrication, (2) stripper life, and (3) degradation of beam quality. Let us take these in sequence. The charge state enforcer, as described, requires extremely large magnetic fields and the use of superconducting technology. It could, of course, be constructed with large iron core magnets, but these would have to be very large indeed for energetic beams of heavy ions. The superconducting magnets would require sizeable refrigeration equipment and a liquid helium storage capacity, and its placement at a tandem terminal is problematical. It is worth noting, however, that one might be able to place such a device at the terminal of a large "up–down" tandem such as the ORNL machine currently under design, where it might also perform the function of providing the needed 180° deflection of the beam. The electric field, which must produce a significant deflection in a single orbit, may also be a problem if the needed field is too large.

It would seem that the dimensions of the proposed device would be strongly dependent on the energy of the ions of interest. Surprisingly enough, this is not the case. If we consider the product $B\bar{\rho}$, i.e. the magnetic field strength times the radius of curvature of the average charge state $\bar{Q}$ in the magnetic field, we find that $B\bar{\rho} \approx \sqrt{(2ME)}/\bar{Q}$ and $\bar{Q} \approx \sqrt{(2EZ/M)}$. Thus $B\bar{\rho} \approx M/\sqrt{Z}$ and is independent of energy to a good approximation. If M is in amu, then $B\bar{\rho} \approx 0.0578\, M/\sqrt{Z}$ T m. This gives $B\bar{\rho} = 1.43$ T m for ^{238}U, 0.77 T m for ^{79}Br, and 0.33 T m for ^{16}O. For field strengths of about 8 T (about the field strength envisioned for superconducting cyclotron magnets) this would mean that the required field would have a diameter of about 12 cm for ^{16}O, 29 cm for ^{79}Br, and 54 cm for ^{238}U. Thus the size of the proposed device is not unreasonable.

The life of the stripper foil is an even more serious problem. Because the beam recirculates until it finds the correct charge state, a very large circulating beam will be developed if an unpopular charge state is selected, with the ratio of output (or input) beam to circulating beam being just the stripper charge state fraction of the charge state selected. Thus 1 μA of an output beam with a 1% charge state fraction would require about 100 μA of circulating beam, and a particle circulating in the field would have a "half-life" of about 69 strippings before escape. A stripper foil under such

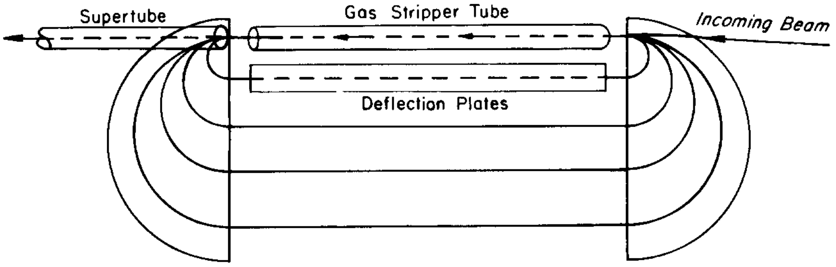

Fig. 2. Improved charge state enforcer. Magnetic field region is divided into two halves, so that gas stripper tube can be employed and long straight deflection plates can be used.

circumstances would not be expected to survive very long. Further, the heating of the foil by energy loss from the beam might cause serious problems, since this foil is placed in close proximity to the supertube. The alternative of a gas stripper does not appear particularly attractive in the geometry of fig. 1 due to the non-localization of the gas and the problems incurred by operating superconducting devices in a poor vacuum environment.

A third problem mentioned above is the beam quality degradation. At each collision with the stripper foil, the beam loses a somewhat uncertain amount of energy through straggeling, and at the same time is multiply scattered through some small but non-zero angle. On repeated collisions with a stripper foil, both of these effects will be magnified, and eventually produce a serious loss of beam quality. The magnitude of this degradation depends on the average number N of times the beam passes through the stripping foil before stripping to the selected charge state. To a rough approximation the degradation of the beam will be equivalent to that produced by a foil with a thickness of about $2N_{1/2}t$ where we note that $N_{1/2} = -\ln 2/\ln[1-F(Q)]$, where $F(Q)$ is the charge state fraction of Q, the charge state of interest. It is clear that when $F(Q)$ is small, the degradation of the beam will be a serious problem. If the emittance of the exit beam or its energy spread becomes large compared to the acceptance of the accelerator into which it is injected, then considerable beam intensity or energy resolution may be lost from the final beam.

We should also note that microtron-type orbits have radial focusing but no axial focusing, and that while the beam spot is re-imaged on the stripping foil in the plane of the orbit, it will not be focused in the axial direction. To overcome this problem it may be necessary to include additional superconducting "hill" coils to the magnet so that axial focusing is provided.

Fig. 2 shows a slightly modified charge state enforcer which may provide solutions to some of the above problems. The superconducting magnet is divided into two halves, so that the beam orbits become semicircles connected with straight lines. In this arrangement, both the stripper and the electric deflection plates are outside the fields of the superconducting solenoids, and both can be stretched out. This permits the use of long straight deflection plates for the electrostatic deflector and permits the use of a gas stripper tube. The latter would still have to be pumped so that the pressure in the vicinity of the supertube was good. The gas stripper would be thinner than any useable foil, and thus would produce less multiple scattering and energy straggeling per collision. Further, with a gas stripper, foil life would no longer be a problem.

The charge state enforcer is a new idea, and there are probably more innovations which could be incorporated in the basic scheme to improve its performance. It is clear that the real test of the utility of this concept would be a working model. In view of the payoff of a well working charge state enforcer in improving accelerator performance, it would seem that the development of such a model would justify the time, money and effort required.

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