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Author
Morris, D.E.

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D. E. Morris

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Donald E. Morris

Lawrence Berkeley Laboratory
University of California
Berkeley CA 94720

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A METHOD FOR INJECTING CHARGED PARTICLES ACROSS A MAGNETIC FIELD

Donald E. Morris
Lawrence Berkeley Laboratory
University of California
Berkeley CA 94720

Abstract

A new method is described for injecting charged particles across a magnetic field, in which an electrostatic reflector (bouncer) reverses the direction of the ions after they travel around a half orbit in the magnetic field. This method can be used for radial injection of charged particles into a cyclotron, or possibly into a plasma confined by a magnetic field.

Injection of ions into a cyclotron from an external source is advantagous since it permits use of sources too large to fit in the center of the cyclotron, and does not require the source to operate in the strong magnetic field of the cyclotron. It also permits easy changes of the source, and of the ions to be accelerated. The usual method of injection from an external source involves an axial hole in one pole of the cyclotron magnet.[1] The beam of ions passes through this hole to the midplane of the cyclotron. The beam is then deflected through an angle of 90° by a reflector inclined at 45° to the axis or by a helical electrostatic channel,[2] and then begins the usual circular motion in the midplane of the cyclotron. The axial injection method is complicated, especially when used in a small cyclotron. Several lenses are required to transport the beam through the axial hole, and the magnetic field in the central region is non-uniform because of the axial hole.[3] These problems are avoided by radial injection methods.

A radial injection method which is suitable for sector focussing cyclotrons was developed at the Lebedev Institute.[4] The orbit center of a particle in a magnetic field follows a path of constant field, so the hill-valley magnetic field difference in an AVF cyclotron can be used to send the beam on a trochoidal path to the center region. At the center, an electrostatic channel is used to inflect the beam into a centered orbit. When the injection energy is very small, the loops in the injection beam trajectory overlap, reducing the clearance in the electrostatic channel. In another method, developed at Saclay,[5] the ion beam was directed radially inward in the midplane across the magnetic field of the cyclotron, and the radius of curvature of the beam was increased by an electrostatic field provided by four bars, two above and two below the midplane. The bars were oriented nearly radially, with one bar of each pair positive and the other negative. The electric field of the four bars provided an effective "channel" through which the beam could be injected. When the beam reached the inner end of the bars the usual circular motion in the magnetic field began. A disadvantage of this method is the complicated and accurate shaping of the bars which is required so that the electric field will match the magnetic field profile of the cyclotron. A third method of radial injection, suitable for injection of heavy ions at relatively high energy into large cyclotrons was developed at Orsay.[6] The ions, in low ionization states were injected in the midplane, and reached the center in about a half turn. The ions were stripped in a foil positioned to give centered orbits at a higher charge state. These and other external beam injection systems have been reviewed by Clark.[7]

The new proposed method is especially suitable for small cyclotrons, and is illustrated in figure 1. The beam of particles enters the magnetic field from the right through an inflector/velocity selector, and the incoming beam is focused at A. The charged particles are allowed to travel through a semicircle A-B in the magnetic field and come to a radial focus at B. Then they are bounced or reflected by a localized uniform electric field to reverse their direction of motion. They then travel through another semicircle and focus at C. During the passage from B to C the particles are accelerated while crossing the gap between the dee and the dummy dee as in any cyclotron, and the acceleration is repeated during the return from C to B in the other half of the orbit. Since the particles have gained energy during the orbit they will miss the bouncer on their return around the enlarged orbit.

The particles will spiral out and gain energy at each dee crossing in the usual way until they reach the deflector/velocity selector and leave the magnetic field. In the arrangement shown in figure 1, the radial distance to the deflector is made smaller than the radial distance to the inflector, so that the particles can be removed before they strike the inflector. This limits the final particle orbit radius to three times the initial radius, and the final energy to nine times the injection energy.

A simple modification of the arrangement will overcome this limitation. The injector A can be placed below the plane of the beam as shown in figure 2, and the bouncer B1 inclined, so that a small component of its internal electric field is directed along the cyclotron axis to reduce the axial velocity of the particles to zero after bouncing. (The axial electric field can of course be provided by extra electrodes in the bouncer.) In another arrangement, a second bouncer B2 can be placed farther from the center and below the plane of the beam as shown in figure 3. From A, which is placed in or near the cyclotron beam plane, the ion beam is directed radially in to Bouncer B2 which is inclined to direct the beam to bouncer B1 in the beam plane. The ion beam is radially focussed at A, and will refocus at B2, B1, C, etc. More bouncers can be added if needed for larger ratios of energy gain. The reflecting electrodes may be shaped so as to provide small field components directed toward the centerline of the beam, and thereby provide axial focusing. This can also be accomplished by segmenting the reflecting electrode and varying the voltages on the segments.

To increase the clearance from the bouncer additional energy may be given to the ions while they go around the first orbit by adding a multiple electrode booster inside the first orbit. The idea is illustrated in figure 4. A set of "booster" electrodes is placed around the inside of the first orbit near C and connected to an RF voltage source at a harmonic of the cyclotron frequency of the ions. If the cyclotron dee is operated at a harmonic of the cyclotron frequency alternate electrodes can be connected to the dee and to the dummy dee (ground). The electrodes are spaced at half the distance the ions travel in one period of the RF. As the ions pass near the set of booster electrodes during their first orbit they will be accelerated several times and gain much more energy than the dee voltage. During their next orbit the ions will gain energy from the dee crossings, so they will not return so close to the booster electrodes. The ions will gain energy in subsequent orbits from the dee gap crossings in the usual way. It may be useful to adjust the angular position of the electrodes to give the maximum energy boost to ions which cross the dee gaps after the RF voltage has passed its peak and is falling, since such ions will experience electrostatic axial focussing during subsequent dee crossings.

There are many possible designs for the bouncer (reflector), some examples are shown in figures 5, 6 and 7. The repeller electrode is operated at a potential greater than the energy of the particle to be injected. In figure 5 the grid is connected to the grounded shielding box to provide a uniform retarding field and prevent leakage of the field out to the the region where the beam passes the bouncer after the first orbit. In figure 6 different potentials are applied to the guard rings proportional to their distances from the top opening to give a uniform electric field inside the bouncer. The opening is made small compared to the depth so that the fringing field outside the box will be small. The open bouncer in figure 7 could reflect an intense beam of charged particles, and can contain water cooling to resist destruction from bombardment by oppositely charged particles which would be attracted to the bouncer electrode.

There are several reasons why this new method of injection would be attractive for injecting ions into a cyclotron, especially one of low energy:

(1) The ions can be injected in the midplane of the cyclotron, so an axial hole in the pole piece, which could interfere with the uniformity of the magnetic field, is not required. This also eliminates the need for a vacuum seal to the pole piece, so a removable bakable dee chamber can be used.

(2) The bouncer can be made small since the magnetic field of the cyclotron focuses the beam of particles on the bouncer. This also ensures that the centers of the orbits of all of the ions lie on the line of the dee-dummy dee gap, so the particles will stay in phase as they are accelerated.

(3) The bouncer is a small simple device and is easily located in the required position. It can be made of non-magnetic materials, so that there will be no strong magnetic forces to contend with, and the uniformity of the magnetic field is not affected.

(4) With this injection method the central region of the cyclotron chamber is not used. The dee chamber can be independent of the magnet poles, and the vacuum walls of the dee chamber can be supported near the axis by a strut (figure 2). The dee chamber can be removable and bakable, which is especially desirable in a cyclotron used for mass spectroscopy or isotope dating. Space is available in the central region for an NMR Gaussmeter, for precise determination of charge/mass ratio.

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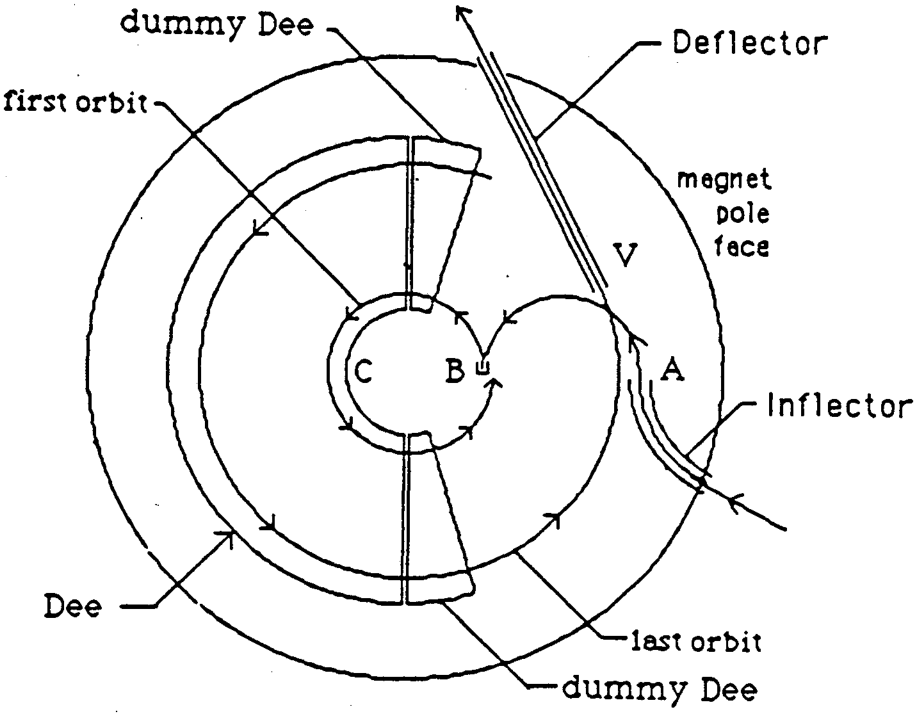

Figure 1

Figure 1: Plan view of the cyclotron chamber. The beam of particles enter the magnetic field from the right through the inflector/velocity selector, and the incoming beam is focused at A. The charged particles travel through semicircle A-B in the magnetic field and come to a radial focus at B. Then they are bounced or reflected by a localized uniform electric field to reverse their direction of motion, and travel through another semicircle and focus at C.

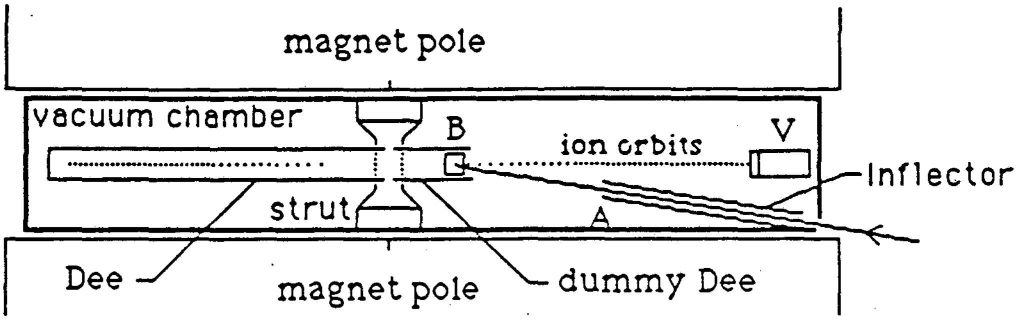

Figure 2

Figure 2: A larger ratio of final to initial energy is possible if the injector A is placed below the midplane and the particles are injected at an angle to the midplane. The bouncer B is inclined so that a small component of its internal electric field is directed along the cyclotron axis to reduce the axial velocity of the particles to zero after bouncing, or the necessary small axial electric field can be provided by extra electrodes in the bouncer. Extraction of the beam at final energy is through a deflector placed at V. The vacuum chamber walls can be supported by by a central strut as shown.

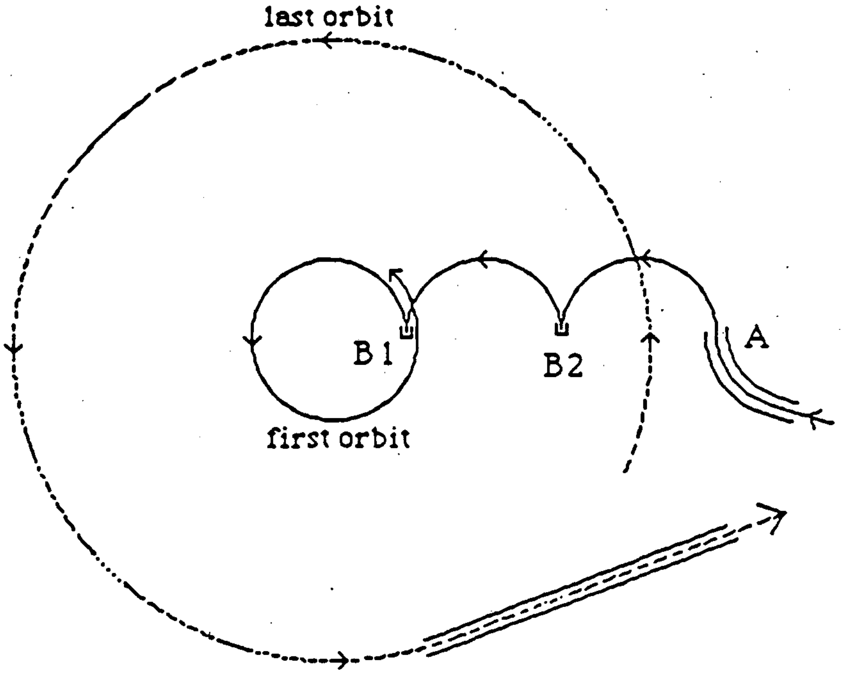

Figure 3 a

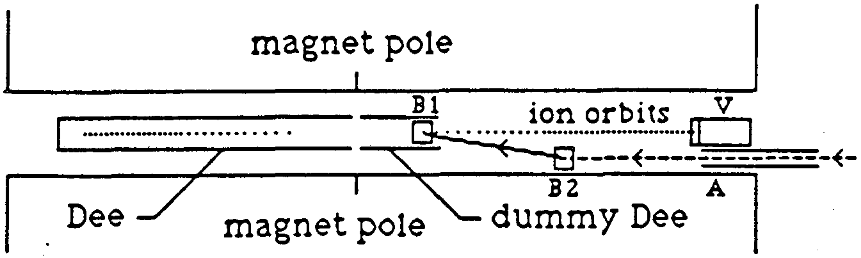

Figure 3 b

Figure 3: Another arrangement which allows a larger ratio of final to initial energy would use several bouncers. The second bouncer B2 can be placed farther from the center and below the plane of the beam as shown in figure 3. The ion beam is directed radially in from inflector A below the cyclotron beam plane to Bouncer B2, which is inclined to direct the beam to bouncer B1 in the beam plane. The ion beam is radially focussed at A, and will refocus at B2, B1, etc. To provide axial focusing the bouncer electrodes may be shaped to provide small electric field components directed toward the centerline of the beam, or the reflecting electrodes may be segmented, and the voltages on the segments varied .

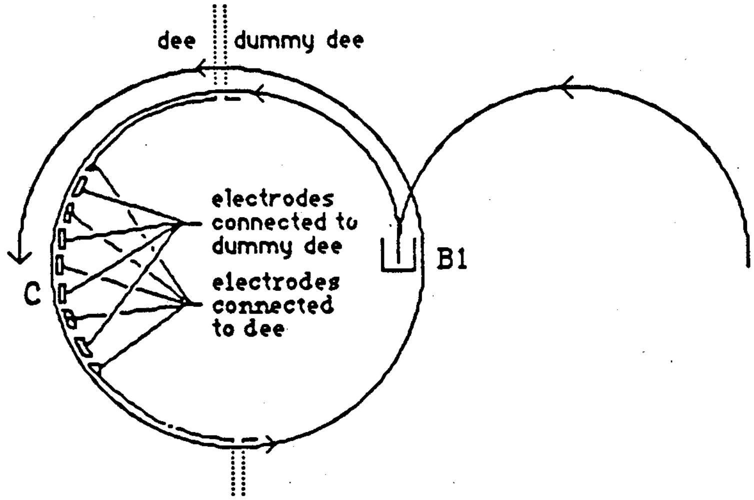

Figure 4

Figure 4: A device may be added to give additional energy to the ions while they go around the first orbit to increase the clearance from the bouncer. A set of "booster" electrodes is placed around the inside of the first orbit near point C and connected to an RF voltage source at a harmonic of the cyclotron frequency of the ions. If the cyclotron Dee is operated at a harmonic of the cyclotron frequency alternate electrodes can be connected to the Dee and to the dummy Dee (ground). The electrodes are spaced at half the distance the ions travel in one period of the RF. As the ions pass near the electrodes during tbeir first orbit they will be accelerated several times and gain much more energy than the Dee voltage.

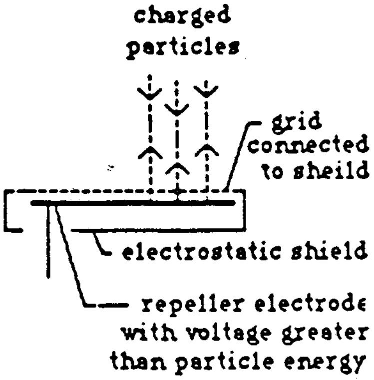

Figure 5

Figure 5: The bouncer (reflector) may be enclosed in a shielding box with a grid as the cover. This provides a uniform retarding field and prevents the fringing field from extending out into the region where the beam passes the bouncer after the first orbit. However, the grid may be damaged by a high beam current.

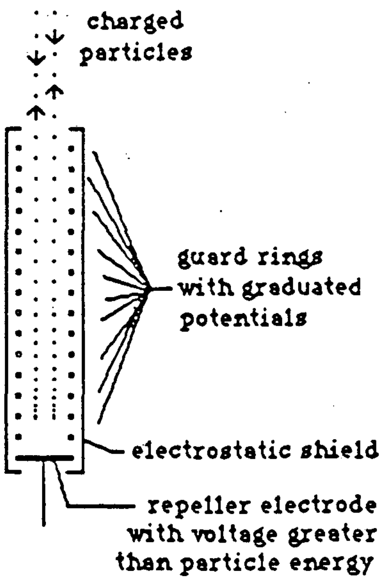

Figure 6

Figure 6: In this bouncer design the beam penetrates the interior of the sheilding box in which a uniform electric field is established by guard rings on which different potentials are applied in proportion to the distance from the opening. The size of the opening is made small compared to the depth so that the fringing field outside the box will be small.

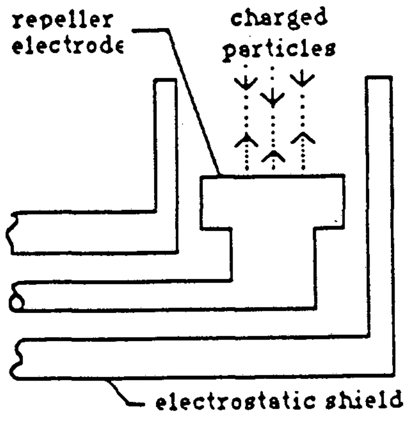

Figure 7

Figure 7: An intense beam of charged particles could be reflected by a bouncer of this design and water cooling could be incorporated to resist destruction by bombardment by oppositely charged particles which would be attracted to the bouncer electrode.