High-Current Ion-Ring Accelerator

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An accelerator concept is outlined which enables 10^{15} to 10^{18} ions in the form of a charge neutralized ion ring to be accelerated to GeV energies. A repetition rate of 10 Hz will deliver an average current in the range of 0.1 A.

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There are many applications for high-current, high-energy ion accelerators such as drivers for inertial confinement nuclear fusion [1] (ICF), intense neutron sources for transmutation of radioactive wastes [2], and other research and industrial uses. In a high-current accelerator, by definition, the number of ions in a bunch must be large. Above a critical number density space charge neutralization by electrons is essential. Charge neutralized bunches of ions, however, cannot be accelerated by longitudinal electric field E_z. For electrostatic acceleration, a transverse magnetic field which insulates the electrons has been employed successfully in intense ion diodes [3]. This technique, however, is applicable only to single stage acceleration or at most two stages [4], thus limiting the ion energy to the range of 10–20 MeV. For multistage acceleration to higher energies 100 MeV–1 GeV, the accelerating electric field must be inductive.

In this Letter, we describe a new high-current accelerator for ions in which the particle bunch of a conventional accelerator is replaced by a charge neutralized ring of ions [5] circulating in an external magnetic field B_z (Fig. 1). The self-magnetic field of the azimuthal ion current balances the repulsive pressure due to any energy spread in the ions; the zero-order self-electric field is neutralized by an equal number of low-energy electrons. The applied inductive accelerating electric field E_θ must be in the azimuthal direction and increases the ring energy by acting on the net ring current. In what follows we briefly describe (i) the ring equilibrium, (ii) techniques for creating the ring, and (iii) novel techniques for accelerating the ring to high energy.

Ring equilibrium.— An ion ring in equilibrium (Fig. 1) is completely charge neutralized and may be partially current neutralized by electrons. It consists of N ions of charge q and mass m with ion kinetic energy $\mathcal{E}=(\gamma-1)mc^2$. Elementary considerations [6] lead to $N=(g_1g_2g_3)^{-1}\zeta R/r_i$, where $r_i=q^2/mc^2$ is the classical ion radius, the field reversal factor $\zeta=\delta B/B_z|_{r=0}=g_1 2\pi \times I/RBc$, the net ring current $I=g_2 I_i$, I_i is the ion current, B is the uniform external field, R is the ring major radius, g_1 is a geometric factor of order unity depen-

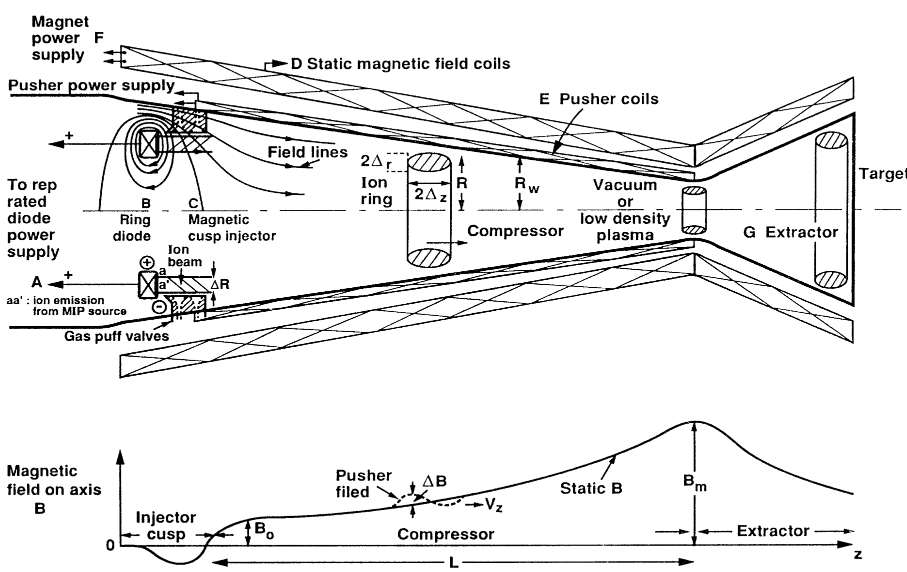

FIG. 1. Schematic of ion ring injector and compressor.

dent on ring shape, and g_2 and g_3 are defined below. Because of the diamagnetic effect of the ring current, the ring radius R is larger than the single-particle gyroradius $r_g = \bar{v}_\theta/\omega_c$ ($\bar{v}_\theta = R\Omega$ is the mean azimuthal ion velocity and $\omega_c = qB/mc\gamma$ is the cyclotron frequency). The radial force balance yields $R = r_g\{1+(I/I_A)[\ln(8R/a)-\frac{3}{4}]\}$, $\omega_c = \Omega\{1+(I/I_A)[\ln(8R/a)-\frac{3}{4}]\} \equiv \Omega/g_3$, $I_A = (mc^3/q) \times (\bar{v}_\theta/c)\gamma$, $a \equiv (\Delta_r\Delta_z)^{1/2} \ll R$, and $I = I_i - |I_e| \equiv g_2 I_i$, where $I_i = Nq\Omega/2\pi$ and I_e is the electron current.

Ring formation.— The ion source is a magnetically insulated pulsed powered diode. The anode is in the shape of a ring [7] (see Fig. 1) of radius R_D with an ion emission annulus of area $2\pi R_D \Delta R_D$. The anode also contains a coil which produces a cusp-shaped magnetic field in conjunction with the solenoidal magnetic field downstream. Ions accelerated across the diode gap pick up an azimuthal velocity by virtue of the conservation of canonical angular momentum $P_\theta = m\gamma r v_\theta + q\psi/c$, where $\psi = rA_\theta$ and A_θ is the magnetic vector potential. To minimize radial defocusing and axial velocity spread the anode ion emitting surface [7] must be a flux surface, i.e., ψ is constant on this surface. The magnetic cusp must be as sharp as possible. Ions above the cutoff energy pass through the cusp to form a ring; others fail to make it.

As the ring forms (for $\zeta > a/R$), the topology of the magnetic field lines has to change rapidly on the time scale of $(\omega_c/2\pi)^{-1}$. This is possible in good vacuum but the ring must also be promptly charge neutralized by electrons emitted from nearby surfaces. To capture these electrons within the beam/ring system they must be rapidly scattered. Thus, the injection region is flooded with neutral gas at $10 \sim 10^2$ mT from fast gas-puff valves which direct a supersonic jet into the cusp region [8]. Current neutralization is avoided by (i) choosing a low atomic number gas like hydrogen and (ii) providing a conducting surface close to the injected beam to line tie the magnetic field lines, i.e., to ensure that the electric field transverse to the field lines is reduced to a minimum. Beyond the cusp the ring is well formed and propagates in a tenuous low density plasma ($n_e \sim$ a few times 10^{13} cm^{-3}) and eventually in high vacuum.

The total ion charge from the ring diode for an applied voltage of V megavolts of duration τ seconds is $Q = 50\alpha_1(Z/A)^{1/2}V^{3/2}A_D\tau/d^2$ C, where d is the gap (in cm), A_D is the ion emission area (in cm^2), $q = Ze$, $m = Am_p$, m_p is the proton mass, and α_i is an enhancement factor. For $V \sim 0.6$ MV, $\tau \approx 1.5\times10^{-7}$ sec, $d = 1$ cm, $R_D = 25$ cm, $A = 1100$ cm^2, $\alpha_1 = 5$, and $Q = 9.6\times10^{-3}$ C for protons. With experimentally achieved injection efficiency $\eta_{\rm inj} \sim 0.8$ the number of protons trapped to form a ring is $N = 6\times10^{16}$ for $\zeta \sim \frac{1}{3}$ and $R \sim 25$ cm, $a \sim 5.0$ cm. Rings of ~ 400 keV protons, and $\zeta \lesssim 0.1$, $N \sim 10^{16}$ have been routinely created in the IREX facility at Cornell Laboratory of Plasma Studies [7,8].

Ring acceleration.— Ring acceleration is accomplished in two stages. In the first stage, the ring is compressed magnetically by pushing it to regions of higher static magnetic field [9]. The static magnetic field is produced by the dc excitation of solenoid coils which could be cryogenic or even superconducting if energy consumption becomes a serious issue. The ion energy is increased and the size of the ring is reduced. For applications where the ion energy is < 30 MeV, this may be the only stage that is needed. Limitations on the maximum magnetic field imposed by superconductor technology ($\lesssim 10^2$ kG) restrict the compressor stage to $\lesssim 30$ MeV. For accelerating ions to 0.1 GeV and higher, a second stage involving rf or pulsed acceleration modules may be necessary.

Ring compression stage.— The bore of the magnet coils R_w decreases as the field increases, maintaining approximately a constant magnetic flux $R_w^2 B$ through the length of the compressor. The pusher coils energized by a fast power supply provide the azimuthal electric field E_θ for compressing the ring. During ring compression the individual ion P_θ is conserved because of axisymmetry. Therefore for the ring as a whole the mean $\bar{P}_\theta = m_i\gamma \times R\bar{v}_\theta + (q_i/c)R\bar{\psi}$ is also conserved [5]. Since the time for magnetic flux to diffuse through the ring given by $\tau_D = 4\pi\sigma\Delta_r^2/c^2$ (σ is the plasma/ring conductivity in cgs esu) is generally much greater than the compression time τ_c, ψ is also conserved. Thus, $R\gamma\bar{v}_\theta = \text{const} = R_0\gamma_0\bar{v}_{\theta 0}$; $R^2B = \text{const} = R_0^2B_0$, $\mathcal{E}_i/B = \text{const} = \mathcal{E}_{i0}/B_0$, and $\zeta = \text{const} = \zeta_0$. Finally, from the above relation we must also have $I/I_A = \text{const}$, $a/R = \text{const}$, $I_i/I = R_0/R$, and $|I_e|/I_i = 1 - R/R_0$ where R_0 is the initial radius. Thus, even if the electron current is zero initially for $R = R_0$, it picks up as the ring compresses to maintain the magnetic flux trapped inside the ring.

Let $(R_w/B)dB/dz = k(z)$, where $k(z)$ is a constant or a slowly varying function of position. Since $R_w^2B(z) = \text{const} = R_0^2B_0$, we obtain $B(z)/B_0 = [1-g(z)/2R_0]^{-2}$, where $g(z) = \int_0^z dz\, k = k_0 z$ if $k(z)$ is constant. From now on take $k(z) = k_0 \sim 0.1$. Then $R_w(z)/R_0 = 1 - k_0 z/2R_0$.

The stored energy in the static magnetic field is $W_M = \frac{1}{8}B_0^2R_0^2LC^{1/2}$, where $B_m = B_0(1-k_0L/2R_0)^{-2}$ and $C = B_m/B_0$ is the compression factor. The length L of the compressor is $L = (2R_0/k_0)(1-C^{-1/2})$.

The ring lifetime τ is given by the slowing down time of the ring ions in the neutralizing electrons and any residual gas/plasma. In the absence of any instabilities, $\tau = \tau_0(\mathcal{E}_i/\mathcal{E}_0)^{3/2}$.

The rate of compression may scale as τ^{-1}, i.e., $(\tau_0 v_z)dB/Bdz = B_0^{3/2}/B^{3/2}$, where v_z is the velocity of the pusher coil traveling wave. Thus, $v_z(z) = (R_0/\tau_0k_0) \times (1-k_0z/2R_0)^4 = (R_0/\tau_0k_0)(B_0/B)^2$. The power required to compress one ring is given by $P_c = \alpha_3N(\mathcal{E}_{i0}/B_0) \times v_z dB/dz = \alpha_3 N(\mathcal{E}_{i0}/\tau_0)(B_0/B)^{1/2}$, where α_3 is a numerical constant of order 2–3 which takes care of losses and the fact that an equal amount of energy is invested in the ring self-magnetic energy.

The time τ_c to compress the ring to the final energy is $\tau_c = \int_0^L dz/v_z = \frac{2}{3}\tau_0[C^{3/2}-1]$. When $P(z)$ is integrated over time from 0 to τ_c, the total work done by the pulser coils is $W_c = \int_0^{\tau_c}P_c\,dt = \int_0^L P_c\,dz/v_z = \alpha_3 N\mathcal{E}_{i0}(C-1)$

which is just the difference between the final and initial ring energy.

Ring extraction.— The ring is extracted from the final stage of compression by expanding the external magnetic field. The ring acquires an axial velocity $\bar{v}_z$ which can be computed through the conservation of the total ring energy W, the canonical momentum $\bar{P}_\theta$, and the magnetic flux. Nonrelativistically, $W = N(\frac{1}{2}m\bar{v}_z^2 + \frac{1}{2}m\bar{v}_\theta^2) + \frac{1}{2}LI^2 + NT$, where $L = (4\pi R/c)[\ln(8R/a) - \frac{7}{4}]$ is the ring self-inductance and T is the thermal energy of the ions. It can be shown that $T/m\bar{v}_\theta^2$ is conserved. Thus, we obtain after taking into account the relations derived earlier, $\bar{v}_z = (2/m)^{1/2}[W/N - \lambda_1(B/B_0) - \lambda_2(B/B_0)^{1/2}]^{1/2}$, where λ_1 and λ_2 are constants dependent on the ring parameters before expansion. The term $\propto B$ originates from the conservation of $\bar{P}_\theta$ and $B^{1/2}$ term represents the ring magnetic energy.

Accelerator module.— The acceleration module requires an inductive, azimuthal electric field E_θ. In the simplest configuration, this module may consist of a coil of length $L_c \gg R_c$ its radius, fed from an rf source at frequency ω with $E_\theta = (\omega r/2c)\tilde{B}_z \sin\omega t$ where $\tilde{B}_z = 4\pi nI/c$, and nI are the ampere turns/cm of the coil. Alternatively, the module is a cylindrical resonant cavity of length L_R and radius R_R operated in the TE_{0m1} mode. Within this cavity, a series of conducting cylinders with accelerating gaps of varying length l_n are provided as in an Alvarez tank [10]. In all such arrangements, the increment in the ion kinetic energy at each gap is

$$\Delta\mathcal{E}_n = q\int_0^{T_n} dt\,(\bar{v}_\theta - \bar{v}_{\theta e})\tilde{E}\sin(\omega t + \phi) = q(\bar{v}_\theta - \bar{v}_{\theta e})(\tilde{E}/\pi f)\,,$$

where $\tilde{E} = (\omega R/2c)\tilde{B}_z$; $\Delta\mathcal{E}_n$ is maximized if the phase of the ring at entry $\phi = 0$ and $\omega T = \pi$, with $T = l_n/v_z$.

During the acceleration process $m\gamma r\bar{v}_\theta$ is conserved. The ring radius changes during the acceleration but after acceleration it is the same as on entry because the guide field B is uniform and the flux enclosed within the ring is conserved. Thus, the ring azimuthal energy is unchanged and the increment in axial momentum is $\Delta p_z = \int_0^T dt\, q \times (\bar{v}_\theta - \bar{v}_{\theta e})B_r/c = q[(\bar{v}_\theta - \bar{v}_{\theta e})/v_z](\tilde{E}/\pi f)$, because $B_r = \partial A_\theta/\partial z$ and $E_\theta = -\partial A_\theta/c\partial t$. Thus, although the ring is accelerated azimuthally ultimately the energy is converted to axial motion. The number of accelerating steps S required to reach the final energy $\mathcal{E}_f$ is $S = (\mathcal{E}_f - \mathcal{E}_i)/\Delta\mathcal{E} = (\pi f/\tilde{E})(\mathcal{E}_f - \mathcal{E}_i)/q(\bar{v}_\theta - \bar{v}_{\theta e})$. For $\mathcal{E}_f$ less than a few hundred MeV the single-turn coil (Fig. 2) may be driven by a pulsed power supply which delivers a transient $\tilde{B}_z$.

A physical picture of the acceleration process is as follows (Fig. 2). The ring is phased to arrive at the coil entrance at the instant when the transient field $\tilde{B}_z = 0$. The ring therefore enters a weaker field and will be axially accelerated. At the exit $\tilde{B}_z$ is now at a positive maximum; the ring again enters a weaker field and is axially accelerated, thereby converting the azimuthal energy gained in the coil to axial energy. Furthermore, there is no restriction on the scale length of the spatial field variations with respect to ring major radius.

Recirculating accelerator.— If the number of steps S and therefore the total length of accelerator modules SL_c gets too large for high ion energy $\mathcal{E}_f$ then the accelerator modules may be configured in a circular or a closed circuit as in a synchrotron. The main consideration for this case is whether the ion rings can be guided along a circular track. It is easy to demonstrate that a charge neutralized ring will not be able to stay along a guide magnetic field $\mathbf{B}$ of radius of curvature $\mathbf{R}_c$ because of the centrifuged force $mv_\parallel^2/R_c$ where $v_\parallel$ is the ring velocity along $\mathbf{B}$. The ions in the ring drift with velocity, $\mathbf{v}_c = (cmv_\parallel^2/q) \times \mathbf{R}_c \times \mathbf{B}/R_c^2 B^2$. The displacement of the ions with respect to the electrons creates a polarization electric field $\mathbf{E}_p$ and the entire ring will drift radially outwards in the direction of $\mathbf{R}_c$ due to the $\mathbf{E}_p \times \mathbf{B}$ drift. To counteract this outward drift, we need to cancel the centrifugal force $mv_\parallel^2\mathbf{R}_c/R_c^2$ with an outward gradient in the magnetic field. The most convenient way of providing such a gradient in B is to employ the induced image currents in a highly conducting liner surrounding the ring in the vacuum chamber. Any outward shift Δr in the center of the ring induces an image current which provides a restoring force $F = (I\delta B/c)2\pi R$; δB is estimated to be proportional to $(\Delta r/R)I/c(R_L - R)$ where R_L is the liner radius. The shift Δr is obtained from balancing the centrifugal force with F, i.e., $Nmv_\parallel^2/R_L = \alpha(\Delta r/R)[I^2/c^2(R_L - R)]2\pi R$, where α is a constant of order unity which yields $\Delta r/(R_L - R) = \pi\zeta^{-1}C^{1/2}(v_\parallel^2/\bar{v}_\theta^2)R/R_c$. The requirement is to maintain $\Delta r \ll (R_L - R)$. If this relation cannot be satisfied, an external field may be necessary.

Ring stability and lifetime.— Ion rings are expected on

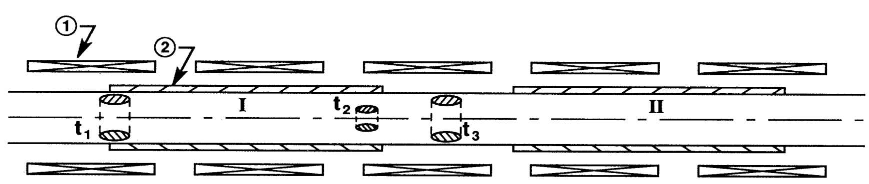

FIG. 2. Schematic of accelerator module: (1) state field solenoid, (2) single-turn coil for transient field; the transient field rises to maximum during time $t_2 - t_1$.

theoretical grounds to be fairly stable objects [7]. They have a tendency to precess which is unstable in the presence of wall dissipation for a field index $(R/B)dB/dr < 0$. However, when the field index is reversed by image currents in the conducting wall this precession is stable. Experimental studies on ion ring wall interactions would be necessary to establish ring stability in accelerators.

Ring lifetime will be determined by interaction of the ions with the neutralizing electrons and the residual gas in the vacuum chamber. A vacuum of 10^{-7}–10^{-8} torr should be more than adequate in eliminating the interaction with the residual gas as a serious concern. Hydrodynamic two-stream instability between the ions and electrons is suppressed because of the ion temperature $T > (\zeta/\pi)m\bar{v}_\theta^2$ required by pressure balance in the ring. The kinetic two-stream instability is stabilized by electron temperature. If the two-stream instability is suppressed the ring lifetime is governed by classical slowing down time of the ions against the electrons, i.e., $\tau \propto v_\theta^3$.

Parameters for 100 MeV linear proton accelerator.— Let a 10 MeV ring be delivered by the compressor and extractor stages with the guide field at 50 kG. Furthermore, let $v_{e\theta} \approx 0$; this could be arranged by passing the ring through a gas cell of length L such that flux diffusion time $\tau_0 = 4\pi\sigma a^2/c^2 < L/v_z$, transit time. Let $N = 3 \times 10^{16}$ protons, $\bar{v}_\theta = 3.0 \times 10^9$ cm/sec, $R = 8.1$ cm, $v_z = 1 \times 10^9$ cm/sec. As a simple example, let a typical accelerator module be a coil of length $l = v_z\tau/2$ energized by a pulsed power supply delivering $nI/l = 3 \times 10^5$ A/m with a period τ of 50×10^{-9} sec yielding an energy increment per coil of $\Delta\mathcal{E} = q(\bar{v}_\theta/c)R(4\pi nI/l) = 0.92$ MeV/proton. The number of such acceleration steps S to reach 100 MeV is ~ 90. A linear array of pulsed power driven accelerator modules would be adequate.

For higher energies in the GeV range, a recirculating guide-field race-track system would be required with the linear accelerator acting as an injector. The accelerator modules would most likely be rf resonating cavities, higher system repetition rate $\sim 10^3$ Hz with one or more injector/compressors, and smaller number of ions per pulse $N \sim 10^{15}$ but still with $\zeta \gtrsim 0.5$. Questions related to power supplies, frequency control, synchronization, etc., which are important for the optimization of such a system will be addressed in the future.

In conclusion, we emphasize that for accelerating a large number of ions per bunch, in the range of 10^{15} to 3×10^{17}, which have to be charge neutralized, the only means of imparting energy is for the accelerating electric field to act on the net current. This leads immediately to the concept of a charge neutral ion ring, with a net circulating current. We have shown how accelerating such rings to GeV energies and beyond could be accomplished compactly and efficiently although the examples given above are far from an optimized design. Of course, the same principle of acceleration is also applicable to unneutralized electron rings.

Discussions with John Greenly and David Hammer on injection and compression of ion rings and with Al Mondelli on acceleration in linacs were very helpful.

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