collision energy studied. The largest possible value the electric dipole can have in the $n=3$ manifold is $7.35ea_0$. The direction of the electric dipole is such that the electron cloud lags behind the proton immediately after the collision takes place.

The authors would like to thank J. Macek for useful comments. This work was supported in part by the Atomic, Molecular, and Plasma Physics Program of the National Science Foundation.

[1]A. H. Mahan and S. J. Smith, Phys. Rev. A 16, 1789–1792 (1977).

[2]I. A. Sellin, L. Lijeby, S. Mannervik, and S. Hultberg, Phys. Rev. Lett. 42, 570–573 (1979).

[3]M. Lombardi and M. Giroud, Phys. Rev. Lett. 36, 409–412 (1976).

[4]R. Krotkov and J. Stone, Phys. Rev. A 22, 473–482 (1980).

[5]G. Nienhuis, in *Coherence and Correlation in Atomic Collisions*, edited by H. Kleinpoppen and J. F. Williams (Plenum, New York, 1980), pp. 121–132.

[6]Our density matrix formalism can handle any electric field orientation and strength to extract the intensity and polarization fraction (linear and circular) in any direction.

[7]M. Lombardi, M. Giroud, and J. Macek, Phys. Rev. A 11, 1114–1117 (1975).

[8]J. Burgdörfer, Phys. Rev. A 24, 1756–1767 (1981), Eq. (A1).

New Type of Collective Accelerator

Charles W. Hartman and James H. Hammer
Lawrence Livermore National Laboratory, University of California, Livermore, California 94550

(Received 7 December 1981)

Described here is a collective accelerator based on magnetically confined plasma rings. Typical rings which have been produced and which have 10-kJ magnetic energy and 0.1 to 10 C of nuclei are predicted to be accelerated magnetically to 10 MJ or higher in acceleration lengths of 100 m. Applications are discussed of current drive in tokamak fusion reactors, fueling and heating magnetic fusion reactors, transuranic element synthesis, and, for focused rings, a high-energy density driver for inertial confinement fusion.

PACS numbers: 52.75.Di, 29.15.-n, 52.55.Gb

This Letter describes a new type of collective accelerator and discusses possible applications. The accelerator is based on plasma rings,[1] confined magnetically in a nearly force-free field configuration consisting of a dipolelike poloidal field with an entrapped toroidal field. The rings, which are considered to be accelerated magnetically, have very high magnetic moment per unit of mass (~10^8 greater than superconducting pellets) and, on the other hand, may have a coulomb or more of total ion charge—greatly in excess of previous electrostatic, collective accelerators. We would like to note here that related proposals have been made to accelerate large quantities of plasma confined by the toroidal stabilized pinch,[2] and the fields of electron[3] and ion[4,5] rings.

Considering rings which have been produced experimentally, we anticipate acceleration over reasonable lengths up to kinetic energies in the 10-MJ range, and for low ion mass rings up to 1- to 10-MeV kinetic energy per nucleon. Among possible applications we discuss here are current drive, fueling, and heating of a conventional tokamak or other fusion reactor, transuranic element synthesis, and, for focused rings, a high-energy, density driver for inertial confinement systems.

Magnetically confined plasma rings have been studied for some time as possible controlled thermonuclear fusion devices. Ring formation was first demonstrated at low energy by Alfvén, Lindberg, and Mitlid in the 1950's.[1] More recently, plasma gun experiments,[6,7] shown in Fig. 1, have produced rings having typically 10-kJ magnetic energy, 10 to 20 cm major radius, 10^{19} to 10^{20} total number of ions, and a 10-eV plasma having a ratio of plasma pressure to magnetic energy density $\beta=p/(B^2/2\mu_0)$ of order 0.01. Two important aspects for the considerations here are that the lifetime of the rings is adequately long for acceleration, typically 100 μs or so, and that the rings are highly resilient, undergoing large departures from symmetry with only

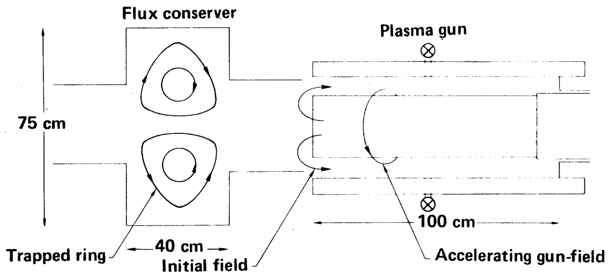

FIG. 1. The Beta II plasma gun experiment (Ref. 7) shown schematically. The initial field is established, D_2 gas is puffed in, and the gun is fired. Plasma with embedded acceleration gun field emerges from the gun stretching the initial field into the flux conserver. Reconnection of the field produces an isolated trapped ring.

minor changes in lifetime. (The remarkable resilience of the rings is illustrated by the observation of tilting and off-center displacements of the order of the ring size during formation in a "pillbox"-type flux conserver[8] and of the formation of "racetrack"-shaped rings in a cylindrical conserver.[6] "Racetrack" rings are observed to live roughly half as long as axisymmetric rings. Generally, the plasma confinement time exceeds the ring lifetime, and is adequately long for acceleration.)

In consequence of the resiliency of the rings we assume that an accelerating force F_{acc} can be applied which is comparable to the force,[9] $F_{\text{eq}} \simeq U_{\text{magnetic}}/R$, necessary to maintain radial equilibrium. When we let $F_{\text{acc}} = \kappa F_{\text{eq}} = M_r \ddot{Z}$, and assume that the ring remains unchanged in size, field strength, and number of particles during acceleration, quantities of interest are

$$\frac{U_k}{U_m} \equiv G = \frac{\kappa L}{R}, \quad \tau = \frac{(2G)^{1/2}}{\kappa\Omega}, \quad V_r = (2G)^{1/2}\Omega R,$$

$$P_r = F_{\text{acc}} V_r = (2G)^{1/2}\Omega U_m,$$

and

$$E_n = \frac{GU_m}{Q}\,\text{eV}.$$

Here Z is the ring position, L is the accelerator length, τ is the time to accelerate, V_r is the final ring velocity, and P_r is the total power which must be delivered to the ring at time τ to maintain the acceleration force F_{acc}. The accelerated ring has kinetic energy U_k, magnetic energy U_m, major radius R, energy per nucleon E_n, a total number of nucleons characterized by the charge $Q = eM_r/m_p$ coulombs, and an Alfvén wave transit frequency $\Omega = (U_m/M_r)^{1/2}/R$. The

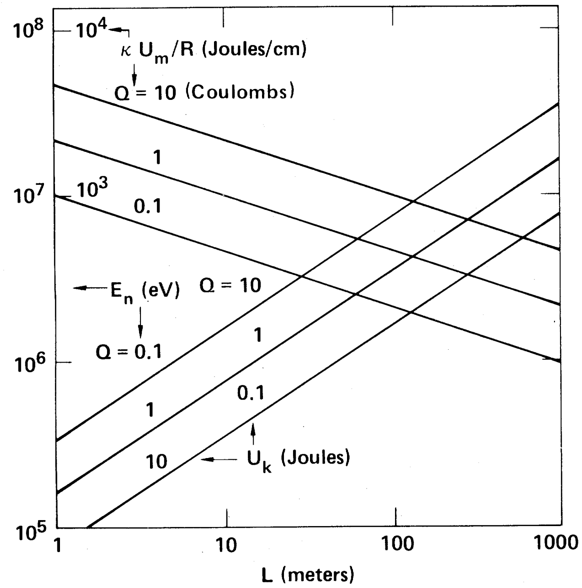

FIG. 2. Ring kinetic energy U_k, energy per nucleon $E_n = U_k/Q$, and ring magnetic energy divided by radius $\kappa U_m/R$ vs accelerator length L for several values of Q. Here the maximum power delivered to the ring is held constant at $P_r = 10^{12}$ W, and $Q = eM_r/m_p$. The quantities κ and P_r are defined in the text.

basic dynamical equations, of course, describe the plasma as a magnetized fluid which, because of charge neutrality, constrains the ions to move with the highly magnetized electron component of the plasma. Of various scaling laws which may be formulated from the above, if high U_k or E_n is desired, a limiting quantity for a given accelerator length is the power which can be delivered to the ring. In terms of P_r the scaling becomes

$$U_k \propto Q^{1/3} P_r^{2/3} L^{2/3}, \quad \tau_{\text{acc}} \propto Q^{1/3} L^{2/3}/P_r^{1/3},$$

$$E_n \propto P_r^{2/3} L^{2/3}/Q^{2/3},$$

and

$$\kappa U_m/R \propto Q^{1/2} P_r^{2/3}/L^{1/3}.$$

To minimize the accelerator length, we choose $P_r = 10^{12}$ W, in the range of present large-pulse generators, and plot the above quantities versus accelerator length L in Fig. 2. The range of $M_r = (Q/e)m_p$ corresponds to rings which have been produced recently with $m_{\text{ions}}/m_p = 1$–10. However, further significant variations in this parameter appear quite possible. Note also in Fig. 2 that $\kappa U_m/R$ falls in the range of rings which have been produced provided $\kappa \simeq 0.01$–1. For all parameters shown, $\tau < 100$ μs—less than the observed lifetime.

Several embodiments of the ring accelerator are possible; we consider two in this note. First, since the basic field structure of the ring is dipolar, a traveling magnetic mirror field exerts a force $F_{acc} = -\mu\nabla B_{ext}$ in the usual manner. Stability of the ring is important, particularly against a 180° tilting of the ring. One method of stabilizing against tilt is to spin the ring at near Alfvén speed.[10] A second method of acceleration is to extend the coaxial gun electrodes and accelerate the ring by a toroidal field injected by capacitor banks fed through insulating breaks in the outer electrode (Fig. 3). This configuration, a "super gun" or coaxial rail gun, appears in preliminary estimates to avoid the tilt instability during acceleration.

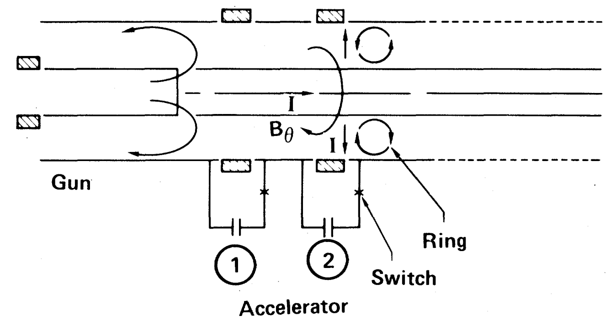

FIG. 3. An extended gun accelerator. Here a ring is produced as described in Fig. 1 and accelerated by B_θ field injected behind the ring by successively firing accelerator banks 1, 2, etc. Current flows in the center conductor as indicated and returns radially at the interface of the accelerating B_θ and ring field and through the gun and accelerator capacitor banks. It is assumed that sufficient plasma is present at the interface to support current flow.

Having accelerated the ring to large U_k/U_m, a potentially useful aspect is that it can be focused to a small size by arranging to direct radially inward a force on the order of F_{acc}. A simple possibility is to pass the ring into an appropriately shaped conducting funnel. As viewed by the ring, the funnel appears as a compressing liner where scaling laws and numerical calculations[11] indicate that the ring compression (even if tilted) should be self-similar, i.e., radial focusing is accompanied by axial contraction. A detailed study of the focusing limits has not yet been made; however, rough estimates suggest that radius/axial compression ratios of 10 to 100 may be possible. Roughly, the focal distance is $L_{focus} \simeq (2G)^{1/2}R$ for an inward force of $2F_{eq}$, where R is the initial ring radius and $G \gg 1$.

Next, we consider applications of accelerated rings, progressing from low to high kinetic energy. The first application is in employing the ring magnetic field as a "flux-pump"-like drive to maintain a tokamak reactor current in steady state. Here we note that a ring maintained in equilibrium by a uniform external magnetic field undergoes no energy change for "slip"-type displacements normal to the symmetry axis. Consequently, a ring injected in the equilibrium condition should drift across the confining toroidal field of the tokamak with little loss of energy. Growth of the tilting instability, however, should lead to eventual reconnection of the ring and tokamak fields. Both the injected ring and the tokamak have net helicity in their fields, $K = \int \vec{A} \cdot \vec{B}\, d^3V$, and, from the point of view of Taylor's minimum energy theory,[12] reconnection conserves $K = K_{tokamak} + K_{ring}$. After injection, the tokamak relaxes to a symmetric minimum energy state but with increased toroidal current corresponding to the increased K. Estimates[13] of the efficiency of this method of current drive suggest that without bootstrap current, thermonuclear Q values of $Q \approx 800\, R_{ring}/R_{tokamak}$ are achievable against current drive losses.

In a manner similar to that described above, rings injected across the confining field of a tokamak, tandem mirror, or other conventional fusion device may, after tilting and reconnection, inject fuel such as tritium, or energetic ions. Rings formed with predominantly high-energy electrons (0.1 to 1 MeV) may provide a means of forming hot electron mirror cells without high frequency electron-cyclotron resonance heating.

At high kinetic energy (10 MJ or so) and with focusing, it appears possible to concentrate short pulses of ion bombardment with very high power density for purposes of driving an inertial fusion pellet. Consider for example a ring having initial radius $R_0 \simeq 10$ cm, and $N = 6 \times 10^{18}$ ions, $U_m = 10$ kJ ($B \simeq 10$ kG) which is accelerated to $U_k = 10$ MJ. During compression in the focusing funnel, $U_m \propto 1/R$ (magnetic flux ψ is constant on the short time scales). If the conventional magnetohydrodynamic stability limit $\beta_{max} \simeq 0.1$ holds, and is limited by enhanced electron thermal conduction rather than plasma loss, focusing to a final radius $R_f = 0.2$ cm increases U_m to 500 kJ $\ll U_k$ (U_{plasma} is small) and increases $B \sim 1/R^2$ to 25 MG. Since the compression is self-similar, the ring length is reduced to $l \simeq 0.2$ cm. The ring velocity depends on the mass; however, taking $V_r \simeq 10^8$ cm/s, the focused ring could potentially deliver 10 MJ to a 0.1-cm^2 target in 2 ns. The ion current density at this level is 5×10^9 A/cm.[2]

If, instead of maximizing the total kinetic energy of the ring, high energy per nucleon is desired, a low-mass ring is required. From Fig. 2 for $10 \lesssim L \lesssim 100$ m and $Q=0.1$, proton kinetic energies in the range 1 to 10 MeV are predicted. For purposes of creating transuranic nuclei, several percent of mass 100- to 200-amu nuclei could be added which would be accelerated along with the ring to the same kinetic energy per nucleon as the protons.

In summary, we have considered a new type of collective accelerator which potentially can bridge the many orders of magnitude gap between conventional particle accelerators and accelerated solid pellets. At high power input with reasonable accelerator lengths, presently achievable plasma rings that are accelerated and focused may provide access to particle fluxes and pulsed power levels not heretofore available under controlled laboratory conditions.

This work was performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

[1]H. Alfvén, L. Lindberg, and P. Mitlid, J. Nucl. Energy 1, 116 (1960).

[2]T. Ohkawa, General Atomic Internal Report No. GAMD-1888, 1960 (unpublished).

[3]H. Fleischmann, private communication, and in Proceedings of the Collective Accelerator Meeting, Dubna, U.S.S.R., 1976 (unpublished).

[4]R. N. Sudan, Phys. Rev. Lett. 41, 476 (1978).

[5]C. A. Kapetanakos, Naval Research Laboratory Memo Report No. 4093, 1979 (unpublished).

[6]T. R. Jarboe *et al.*, Phys. Rev. Lett. 45, 1264 (1980).

[7]W. C. Turner *et al.*, in Proceedings of the Third Symposium on Physics and Technology of Compact Toroids, Los Alamos Scientific Laboratory, December 1980, Los Alamos Scientific Laboratory Report No. LA-8700-C (unpublished), p. 113.

[8]C. W. Hartman *et al.*, "3-Dimensional Aspects of Compact Torus Formation and Translation", in Proceedings of the IEEE Conference on Plasma Science, Santa Fe, New Mexico, May 1980 (to be published), paper 2D3.

[9]V. D. Shafranov, in *Reviews of Plasma Physics*, edited by M. A. Leontovich (Consultants Bureau, Rev. New York, 1976), Vol. 2, p. 103.

[10]S. I. Itoh and K. Itoh, Hiroshima Institute for Fusion Theory Report No. 36, January 1981 (unpublished).

[11]E. Hameiri and W. Grossman, in *Proceedings of the U.S.-Japan Joint Symposium on Compact Toruses and Energetic Particle Injection, Princeton, 1979* (Princeton Plasma Physics Laboratory, Princeton, N.J., 1980), p. 118.

[12]J. B. Taylor Phys. Rev. Lett. 33, 1139 (1974).

[13]J. H. Hammer and C. W. Hartman, "Current Drive, Heating and Fueling by Compact Torus Injection," Mirror Theory Monthly, 15 September 1981 (available from Lawrence Livermore National Laboratory).