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THE ACCELERATION OF PARTICLES BY COLLECTIVE FIELDS II

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The possibility of using the collective field of a large number of electrons to effect the acceleration of protons to high energies in a compact accelerator—or to permit acceleration of heavier ions in a manner not critically dependent on the charge-to-mass ratio of these ions—has been noted in an earlier Comment.[1] A most attractive conceptual form for such an accelerator is the electron ring accelerator (ERA) and in the present Comment we direct attention to the basic phenomena—insofar as we know them—that govern the design and operation of an ERA.

Briefly, the ERA concept visualizes the use of a compact ring of relativistic electrons that circulate in a plane perpendicular to an external magnetic field. The ring is partially neutralized by ions held in the potential well of the electrons. The electric field of these ions and the magnetic attractive forces between the circulating electrons then together act to overcome the electrostatic repulsion of the electrons and make possible the achievement of a configuration that is self-stable in the absence of external focusing fields. Acceleration of the ring with its accompanying ions, in a direction perpendicular to the plane of the ring, can be achieved (at the expense of the azimuthal motion of the electrons) by the action of a spatially decreasing magnetic guide field or, alternatively, by means of rf or pulsed electric fields. In any case the ring must provide a sufficiently strong "holding field" to permit ions to remain with the ring and thereby be carried to high energy in a short distance. An electron ring of suitable quality for this purpose might be formed by compressing a rather large and reasonably intense (e.g., ~100 A, circulating) ring in a pulsed magnetic field, thereby reducing its major and minor radii from $R \approx 20$ cm and $a \approx 1$ cm to, for example, $R \approx 3$ cm and $a \approx 0.1$ cm. A ring of this intensity ($N_e \approx 2 - 3 \times 10^{12}$ electrons) and final dimensions would produce a holding field of some tens of MV per meter.

The group at the Joint Institute for Nuclear Research, Dubna—formerly led by Veksler—has been the first in forming and compressing rings[2] and in demonstrating the acceleration of ions by means of them.[3] Major development programs, employing pulsed compressors, are in progress at Dubna, Berkeley, Karlsruhe, and Garching (Munich). Related work with static-field compression is under way at the University of Maryland and elsewhere. The possibilities and problems raised by the electron-ring concept have been reviewed recently by Keefe,[4] who also provides some details concerning the experimental program at the Lawrence Radiation Laboratory, Berkeley.

The Soviet work has already demonstrated—to a certain degree—the validity of the basic ERA concept, but, if an ERA device is to be useful, it is necessary to achieve rings of high quality; that is, rings of small dimensions and containing large numbers of electrons. Attention, therefore, must be directed to the fundamental limitations upon rings. After reviewing, in Section 1, the fundamental limits on rings, we shall discuss in Section 2 of this Comment the ultimate performance (as presently foreseen) of an ERA. Finally, in Section 3, we attempt briefly to summarize the present status of the ERA development.

1. Fundamental Limits on Rings

In this section we describe the physical phenomena that provide basic limits upon rings and the manipulation of rings. The reader will note that—not surprisingly—some of the phenomena involved are closely related to those that have concerned designers of conventional accelerators through the years, while others are more closely related to plasma phenomena, many of which have been studied as a result of the search for a practical controlled thermonuclear reactor (CTR Program).

1.1. Ring Self-Focusing

An electron ring presumably will first be formed, at the injection radius, in a magnetic field that provides substantial magnetic focusing, as would be characterized by a field-index $n = -(r/B_z)(dB_z/dr)$ appreciably greater than zero (but less than unity). Following compression, however, the field index necessarily must be virtually zero, to permit extraction and subsequent acceleration of the ring, and axial focusing must be provided by self-effects; namely, ions trapped in the ring or electric-image focusing arising, for example, from a nearby striated conducting cylinder (striated so as to reduce the defocusing image currents).[5] Alternatively, axial focusing can be obtained by an azimuthal magnetic field which in combination with the space-charge field of the ring will couple (the highly focused) radial and axial oscillations of a particle.[6]

A simple question, that as yet is incompletely answered, concerns the spatial distribution of the ions relative to the electrons (and the momentum distribution of these ions) as they may finally be formed through ionization of neutral molecules by the electron beam. As in the CTR program, it should be useful to supplement analytic work directed toward the solution of such questions (much of which has already been done) by computational "simulation experiments," in which the dynamics of a large number of mutually interacting particles (in the presence of appropriate boundary surfaces for the electric and magnetic fields) is followed, each particle being endowed with a sufficiently enhanced charge and mass that the ensemble adequately represents the situation of physical interest. Some members of the Los Alamos CTR program have recently been working with the Berkeley ERA group to develop such programs—a fine example of interdisciplinary cooperation.

1.2. Single-Particle Resonances

When a single-particle transverse oscillation frequency (ω_z, ω_r) is simply related to the particle gyrofrequency, ω_0, or—more generally—when

$$n\omega_r + m\omega_z = p\omega_0$$

for integers n, m, and p, there is the possibility of resonant increase in the oscillation amplitude and hence degradation in the ring quality. These resonances are driven by field variations or imperfections. They have been troublesome in practice, although it should be possible, by suitable design, either to avoid them or make the crossing of them innocuous.

1.3. Coherent Instabilities

Corresponding to the analogous situation in more conventional cyclic accelerators, instabilities of a collective nature can also arise in an electron-ring device. These instabilities can take the form either of collective transverse or collective longitudinal motion and in many cases are strongly influenced by the nature and geometrical configuration of nearby boundary surfaces. In practice, it is important to avoid pronounced electromagnetic resonance effects, either with the vacuum chamber as a whole or with a wall of dielectric material. It appears, possible, however, to accomplish this by placing suitable resistive materials on the walls, although this subject is by no means settled and is currently under active investigation.[7]

Coherent instabilities, including collective ion-electron motions, are likely to be of fundamental importance in limiting ERA performance— just as they are of fundamental importance in the CTR program. In order to suppress coherent instabilities it is necessary to employ Landau damping; i. e., to introduce a spread into the oscillation frequencies of particles in the ring. This is most practically done by introducing an energy spread, which has the undesired side effect of adding radial width to the ring. It appears, at our present level of understanding of an ERA of the type now visualized, that the balance between ring current and ring size, as dictated by the potential transverse (resistive-wall) coherent instability in the compressed state of the ring, constitutes the basic limit to a successful electron-ring device.[8]

1.4. Ring Acceleration: Self-Stability

In the presence of an accelerating force the electron and ion distributions will be polarized. A consistent solution is not yet in hand, but some simplified models have provided estimates of the maximum acceleration that the ring can experience without losing the ions.[9] One of the reasons for developing the simulation capability mentioned above is, in fact, to obtain quantitatively significant solutions to this very important and complicated question.

The limit to the external accelerating field that can be tolerated without disrupting a ring can be expressed as a limit on the internal field that is experienced by an ion in the ring, namely as a limit on the holding field E_H. Letting N_e denote the number of electrons in a ring of major radius R and minor radius a, one finds that

$$E_H \lesssim \frac{1}{\eta} \frac{N_e e}{\pi R a},$$

with $\eta \approx 2$ if image focusing is present and $\eta \approx 4$ if the focusing arises entirely from ions.

1.5. Ring Acceleration: Field Limits

The simplest means of accelerating the ring is that of "magnetic expansion," through the action of a radial component (B_r) of magnetic field. This method indeed may be adequate for achievement of moderate particle energies. For higher energies the use of rf-cavity fields or (perhaps more efficiently) the use of pulsed electric fields may be required, and a series combination of electric and magnetic acceleration sections may be particularly effective.

With magnetic acceleration, it is clear that the value of B_r must not be too great, and an accelerator for a certain final energy hence must not be too short, else the ability of the ring to hold ions will be exceeded. This restriction can impose rather stringent tolerances on the uniformity of the axial field in the acceleration region (e.g., so as to limit B_r to a few dozen gauss in an axial field of some 20 kG). Similar restrictions exist in the case of acceleration by periodically applied electric fields. In this latter case it may be useful to attempt some smoothing out of the acceleration force by also introducing some modulation of the magnetic field, suitably phased insofar as is practicable so that the B_r associated with a decreasing B_z gives acceleration in regions where the electric field is absent and a compensating negative B_r to some degree acts in the opposite sense where the electric accelerating field is strong.

1.6. Ring Acceleration: Diffraction Radiation

A heavily charged ring moving down an electric accelerating column inevitably passes near spatially varying conducting surfaces and hence will radiate energy. It can be shown that the net gain of energy by the ring will be that which would be computed neglecting such radiation losses, diminished by the energy required to pull such a ring past the same sequence of passive (unexcited) gaps or cavities. Extensive analytic and numerical effort has been devoted to the study of this problem.[10] It has been shown that although the radiation evoked by a single cavity or gap may be quite large, the radiation loss per unit length in a truly periodic structure approaches a constant as the ring speed approaches the velocity of light. Numerical computations have provided estimates of the loss for a variety of structures.[11] Further attention must still be given, however, to the magnitude of diffraction radiation in a not-quite-periodic structure of finite length.

1.7. Injector Brilliance

It conceivably could be the case that the performance of an ERA would not be limited primarily by the phenomena that control the quality of stable rings, but simply by the characteristics of electron sources available for producing such rings. This, however, does not appear to be the case; pulsed linear induction accelerators already have been built that give beams of adequate energy and brightness (particle density in 6-D phase volume), and they operate reliably and at a sufficiently rapid repetition rate. The design of a linear induction accelerator constructed explicitly to serve as an injector into an ERA compressor has been described by Keefe,[4] and experimenters at Berkeley have been pleased with the performance of this recently completed component. Techniques for the efficient injection of the electron beam into the compressor remain to be adequately mastered, but this latter problem—although very important—should involve no fundamental restrictions beyond those previously discussed.

2. Performance Expectations for an ERA

One could well argue that the physical phenomena described above are so fundamental that an increased understanding of them is certain to make a valuable contribution to the development of related fields of applied physics and, as such, provide sufficient justification for the extensive world-wide effort being devoted to development of the ERA. It is only candid to report that this argument has rarely been heard, but rather ERA enthusiasts have pointed to the expected performance of the ion accelerator itself as the primary justification of their activities.

The most comprehensive study to date of the expected performance features of an ERA is that presented in Ref. 8, and it is primarily upon this work that we draw in this section. We refrain from attempting to delineate the special uses to which the beam from such an accelerator could be advantageously applied, as in the fields of particle physics, solid-state physics, and biomedicine.

2.1. Ring Formation

Substantial thought has been put into devising compressors that have various advantages with respect to the pulsed type. One interesting class of compressors employs only static fields and thus potentially would permit a very high repetition rate for ring formation (see Ref. 4 for a further description and references pertaining to this class of compressors). One important flexibility that can be invoked in the design of a pulsed compressor is to vary independently the magnetic flux linking the ring and the magnetic field at the ring orbit. A second possibility is to retain the ring in a compressed or overcompressed state for an extended period, so that substantial synchrotron damping can occur.[12] It must be noted, however, that this last procedure can impose quite stringent requirements on the degree of vacuum to be maintained in the compressor if unacceptable loading of the ring by ions from the residual gas is to be avoided—unless some practicable means for subsequently shaking these ions loose from the ring can be devised.

Granting the freedom in compressor design just described, it can be shown that it is possible to design a compressor that will produce a ring of any reasonably desired (stable) character, without violating the theoretical stability conditions at any time during the compression cycle. The injector requirements in practice are not difficult to meet, although for some desired rings the injector energy may necessarily be high. Thus, if our understanding of the stability conditions is correct, neither injectors nor compressors need be considered when investigating the possible performance of an ERA.

2.2. Optimum Performance

The various phenomena described in Section 1 put severe limits on an ERA. One must require ring stability (positive axial focusing and a ring current below the instability thresholds) in the presence of acceleration (with diffraction radiation), and clearly the low electron number and large minor dimensions (which relax the instability conditions) are in conflict with a large acceleration field (and hence a compact and inexpensive device). If we further impose certain practical limits—namely, a limit on the average external accelerating field, $E_{ext.}$, and a limit on the axial magnetic field, B_z, in the acceleration column—then there is only one degree of freedom left in the choice of parameters, and this may be eliminated by maximizing the number of ions accelerated per ring.

We shall not burden the reader with details of the calculations, all of which may be found in Ref. 8, but confine ourselves to a numerical example in which all of the phenomena described in Section 1 have been evaluated reasonably well; and, in particular, the axial field B_z has been taken as 20 kG and the average accelerating field $E_{ext.}$ as 5 MV/m. One finds that the "optimum ring" has a major radius of 1.2 cm, a minor radius of 0.4 mm, a number of electrons $N_e = 1.3 \times 10^{13}$, and a number of ions $N_i = 2. \times 10^{11}$. Such a ring, if accelerated in an electric column and then in a magnetic acceleration section, could take ions to 65 GeV in a total length of only 400m—a performance that certainly would be impressive.

3. Present Status

As our readers will recognize, the numbers presented above were derived primarily from theoretical considerations and in many respects were based on formulas for which a sound experimental foundation as yet does not exist. It is appropriate, therefore, to end this Comment with some remarks concerning the accomplishments, to date, in development of an ERA.

Rings of high intensity ($N_e > 10^{12}$) have been formed by the Dubna and Berkeley groups. The Berkeley group reported[4] achieving rings with a holding field of 12 MV/m, which, although highly encouraging, is between one and two orders of magnitude below the field that we have previously indicated as desired in an optimum ring. The only work on the acceleration of rings containing ions is that of the Dubna group, who have reported[3] the acceleration of N^{3+} to 60 MeV in an accleration length of 25 cm. These rings have characteristics that lie within an order of magnitude of an optimum ring, but much work clearly remains to improve such rings and to extend the acceleration distance to several hundred meters. The progress already achieved, however, appears to point with some promise to the beginning of a new ERA.

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