COLLECTIVE-FIELD ACCELERATION*

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The reasons for investigating collective methods of acceleration are well known. The primary motivation is to obtain larger accelerating fields than in conventional devices, and thus to be able to generate high-energy particles with relatively inexpensive accelerating machines. It is also expected that collective-field accelerators will have the capability of readily accelerating different species of particles (and even neutral bunches of particles), and also, perhaps, of accelerating larger fluxes than in conventional devices, either because of less restrictive fundamental limits or because of greater overall efficiency. And, of course, there is the motivation of simply increasing our understanding of the behavior of plasmas as an important branch of pure science, for the sake of any assistance that understanding may give to the problem of attaining controlled thermonuclear fusion, and for the insight it surely will give to the character of natural accelerators, whose existence is manifest from the presence of cosmic rays but whose detailed behavior is still largely unclear to us.

It is not surprising, therefore, that there is considerable research effort going into the study of collective-field accelerators. We shall review here the diverse methods which have been proposed for collective acceleration. In particular we shall attempt to note the various experimental programs engaged in investigating collective acceleration. Clearly our survey will be superficial, but one hopes a useful purpose is served by a compilation of activities in this field.

Our task is lightened by two circumstances. Firstly, this very conference has a few invited papers in which detailed reports will be given on a number of collective-field accelerator research programs. Secondly, Rabinovich has recently produced an extensive review of collective methods of acceleration [1]. We shall only briefly mention (for completeness) subjects covered extensively in these sources.

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1. Collective and Coherent Mechanisms

Veksler, in 1956, focused the attention of the community of particle-accelerator specialists upon the advantages and possibilities of collective-field and coherent-field acceleration [2]. In collective-field methods, the accelerating field is created by a group of charges and is proportional to their number. (An example is the electron-ring accelerator in which each ion is accelerated by a field which is proportional to the number of electrons in the ring.)

In coherent-field methods, the accelerating field on one particle is proportional to the number of particles accelerated. (An example is the acceleration of a bunch of charges by an electromagnetic wave whose wavelength is larger than the bunch size.)

Both coherent and collective mechanisms contain the possibility of obtaining very accelerating fields and the possibility of accelerating partially neutralized bunches. In coherent methods there is no need to maintain synchronism between the accelerating wave and the accelerated particles.

Coherent-field devices are, despite the attention devoted to them, still somewhat in the future, whereas collective-field devices have received considerable attention during the last ten years, and within this very year have produced ions of MeV energies.

2. Electron-Ring Accelerators

The electron-ring concept has captured the imagination of the community of accelerator specialists. Since the report from the Joint Institute for Nuclear Research, by Veksler et al. [3], at just the immediately preceding International Accelerator Conference, experimental and theoretical programs have been initiated at a number of other laboratories: The Lawrence Radiation Laboratory, Berkeley [4,5]; The Institute for Experimental Nuclear Physics, Karlsruhe [6]; and the Institute for Plasma Physics, Garching [7]. Major progress at the Joint Institute and the Lawrence Radiation Laboratory was described earlier this year [8]; invited papers at this conference will describe the present status of these programs.

Besides the experimental progress towards ring acceleration, much theoretical effort has been devoted to new methods of ring formation; namely, static-field compressors [9,10,11]. These compressors should permit electron-ring accelerators to produce very large particle fluxes.

Attention should also be called to the interesting experimental creation, by Trivelpiece et al., of low-intensity electron rings by means of pulsed magnetic mirror field [12]. Very recently, Dandl et al. have observed energetic ions and electrons produced by a plasma instability in the electron-cyclotron heated cylindrical plasma the ELMO Facility at Oak Ridge [13].

Various theoretical investigations may be found in reports from the various laboratories active in the field; they will not be reviewed here. The diffraction radiation by a rapidly moving ($\gamma >> 1$) electron ring has received an unbelievable amount of attention (as it threatens to impose a limit on the ultimate energy attainable with an electron-ring accelerator); the subject is reviewed in a contributed paper at this conference.

3. The HIPAC

During the last few years the group at AVCO-Everett [14] has been developing a collective-field device in which a partially neutralized toroidal electron cloud, which is contained by an external azimuthal magnetic field, serves to provide a deep electrostatic pontential well in which ions are stripped and contained until they undergo energetic collisions. Recent experimental progress [15] suggests optimism in regard to the utility of the HIPAC as a source of highly stripped heavy ions; its use as an accelerator is more remote.

4. Plasma Induction Accelerators

Budker's proposal, in 1956, that self-stabilized relativistic electron beams would be of interest as collective-field accelerators [16] stimulated the development of devices for generating intense electron beams. Budker and Naumov [17] developed the plasma betatron, where the neutral plasma should permit acceleration of larger currents than in conventional betatrons. Plasma betatrons have not, to date, worked up to the original expectations, and development programs at CERN and Novosibirsk have been terminated. In the opinion of Ferrari et al. [18], the limiting instability has been identified (the negative mass) and can be overcome. An active research and development program exists at the City University of New York, Queens.

Recently, the group at the Technical Physics Institute of the Academy of Sciences of the USSR has started development of linear plasma induction accelerators [19], where the instabilities should be convective and hence less serious than in a cyclic device. It is to be hoped that these devices will yield larger currents than vacuum linear induction accelerators, and produce beams of better energy definition and longer pulse lengths than megavolt-switching accelerators.

It is true that Budker's original proposal is not being actively pursued at this time; but new concepts have been doveloped, and intense relativistic beams are very much of interest for collective-field accelerators.

5. Acceleration by Pulsed High-Intensity Electron Beams

Electron accelerators are now available [20,21,22] which produce pulsed electron beams with peak power between 10^{10} and 10^{12} W; namely, electron beams of a few MeV, with a pulse length of tens of nanoseconds, and a current in the 10^5 ampere range.

The acceleration of ions in arc discharges was first observed in 1930; Plyutto, in a series of experiments started in 1960, has been able steadily to increase the energy of ions produced in unstable discharges from 1 keV to the MeV range [23]. Nevertheless, much excitement has been created by the observations by Graybill and Uglum [24], early this year, of 5-MeV protons produced by a 40-nsec, 45-kA peak current beam of 1. 3-MeV electrons.

The electron beam was generated by field emission from 20 sharp needles (within a 1. 25-cm radius) separated from a foil anode by 2.0 cm. The beam having $\nu/\gamma \equiv [I(\text{amperes})/17\ 000\ \beta\gamma] = 0.8$ passed through the anode into a 50-cm-long drift-tube chamber containing gas with pressure optimally chosen for obtaining beam self-pinching. With the chamber filled with hydrogen, protons of 4.8 ± 0.9 MeV were produced having an average pulse width of 3.0 nsec and a peak current of 100 A (i.e. , approximately 10^{13} protons were accelerated per pulse). The proton energy varied quadratically with electron beam current, in the range of 30 to 45 kA. Filling the chamber with other gases, yielded accelerated D_2, He, and N_2. Independent experiments by Yonas et al [25] have already confirmed these observations and are in the process of extending them to mega-ampere beams.

Wachtel and Eastlund [26], following a suggestion of Veksler [2], have calculated the acceleration due to coherent-ion inverse Cerenkov radiation. Rostoker [27] and Putnam [28] have suggested the moving potential well associated with the head of a sharp current pulse as the source of the collective-field accelerating force.

6. Electron Beam Schemes

A large number of collective-field acceleration methods employing electron streams have been proposed, but are yet to be studied experimentally. In fact, the very first collective-field accelerator, proposed by Alfven and Wernholm [29] in 1952, was of this type.

In general, the main problem to be overcome maintain large electric fields for the purpose of accelerating ions, while not having these same fields destroy the electron streams. (In the electron-ring accelerator the coordinated electron rotary motion serves exactly this purpose.) One solution is to employ ion-electron forces to maintain self-stabilization; a second possibility is to continually replenish dissipated electrons, or —equivalently—to stream electrons, continually through the region of strong field (so each electron suffers only a small energy change, while trapped ions experience a large energy gain).

Six different proposals are discussed, in some detail, in the review paper by Rabinovich [30]. We shall, correspondingly, be very brief.

Lewis has discussed ion drag by a (longitudinal) density-modulated electron beam, emphasizing its interest because of its potential high efficiency [31].

Kovrizhnykh has suggested a method of producing a stable density modulation in an intense stream [30,32]. The electrons move parallel to a magnetic field and stream through a localized bump in the field strength. If the potential well associated with the density increase were accelerated by changing the external field, any trapped ions would be accelerated.

R. Johnson has proposed sweeping an electron beam transversely, in a method in which electrons stream through a region in which ions are trapped [33].

Askaryan has suggested three different schemes [30]. One employs the large axial electric field produced by the changing flux associated with the passage of the end of an intense bunch. The second scheme is similar to that suggested in Refs. [27] and [28] as an explanaton of the experiments on ion accelereton. The third scheme is essentially the impact-acceleration proposal of Veksler [2].

7. Plasma Waveguides

For a very long time, namely ten years, Fainberg and his group at the Physicotechnical Institute at Kharkov have been studying, both experimentally and theoretically, plasma-accelerating structures. The subject has been rather recently reviewed in a very well-written paper by Fainberg [34]. Consequently we shall limit our presentation to a few general remarks, especially as there is an invited paper at this conference on the present status of the Kharkov program.

There are two strong reasons for developing plasma waveguides: Large accelerating field strengths, concentrated in a small volume so that the stored energy is small and the wall losses are small, are a possibility. Simultaneous longitudinal and radial particle stability is, in principle, possible.

The main problems are (I) to maintain a stable plasma which will support high-intesity waves suitable for particle acceleration (namely waves with controlled phase velocity); and (II) to generate the accelerating waves with high efficiency (namely, waves restricted to a narrow part of the frequency spectrum). Progress towards solving these problems has been considerable [34] but much remains to be done.

8. Magnetic Dissipation Acceleration

A new idea for the acceleration of a plasma, due to S. I. Syrovatskiy, is presently under experimental investigation at the Lebedev Physics

Institute. This writer has only learned of the work by means of a brief summary [35], and consequently restricts his remarks to a few lines.

The basic concept is to have plasma in a static magnetic field having a large spatial gradient. An externally applied electric field causes an $\vec{E}\times\vec{B}$ plasma motion which is so arranged that the plasma density decreases while it moves into a region of larger magnetic gradient. At a critical point the field is no longer carried by the plasma, displacement currents develop, and a large electric field (suitable for acceleration) is generated. The various necessary conditions on the fields, the geometry, and the plasma are briefly mentioned by Rabinovich [35].

9. Coherent Acceleration by Electromagnetic Waves

Of course conventional accelerators use electromagnetic waves for acceleration, as does a plasma waveguide (Section 7), but not for coherent acceleration. It might be remarked, apropos of electromagnetic waves, that a number of workers have been intrigued by the possibility of employing lasers for (noncoherent) acceleration [36], but even presently available tera-watt power levels are only adequate to produce electrons with tens of MeV energy [37].

The basic concepts of coherent acceleration were discussed by Veksler [2]; the extensive literature since that time is covered in a critical review article by Motz and Watson [38]. Some discussion may be found in Refs. [34] and [39].

Theoretical and experimental work has, in general, been confined to rf frequencies (although it has been suggested that coherent acceleration might be possible at laser frequencies [40]). The basic theoretical problem is plasma stability during the acceleration process. Much attention has been given to a configuration in which a static magnetic field (in the direction of the wave vector) is employed, the field strength being adjusted to give (approximate) resonance between the rf frequency and the cyclotron frequency.

Experimental work has been in progress for more than five years at the Lebedev Physics Institute and the Radiation-Technology Institute, Moscow, and Saclay, France at [41]. So far, the Soviet work has primarily been devoted to identifying modes of instability of a dense plasma, although acceleration of ions (in a rf-cyclotron-resonance device) to a few keV has been accomplished by Consoli et al. at Saclay [41].

10. Opinions

It is wrong to think that science consists of opinions, but it is equally wrong to think that opinions do not influence the course of science. Thus, in a review paper it is appropriate not only to report, in as impartial a way as possible, the present status of activity, but also, in a clearly separated manner, to express editorial opinions concerning the importance of and the prospects for progress in the various endeavors. In this section the writer, as suggestions for his colleagues' reflection and discussion, presents a few of his opinions concerning collective-field accelerators.

The author's enthusiasm for electron ring accelerators is well documented. As a high-energy accelerator (more than a GeV/nucleon) it seems the closest of all the collective-field devices to success; as an accelerator for extreme energies (more than a TeV) it is the only collective-field device that presently appears not to require new inventions. The question of diffraction radiation is still open, although this writer believes that it does not impose a limit on the ultimate energy capability of the device; static compressors appear to leave the ultimate average intensity capability equally open.

The plasma induction accelerators are, to this author, most interesting as sources of beams for collective-field accelerators. They are subject, however, to severe competition from the new class of megavolt switching devices, and perhaps will be of interest only for intense, energetically homogeneous beams of very long pulse length (in the microsecond range).

The HIPAC, as an ion source, the author finds an interesting device. He is, at this point, not very responsive to the plasma waveguide schemes. They seem to be difficult to develop and not to offer any particular advantages over superconducting linacs.

The acceleration by electron streams is a most exciting development, but the future of this work is presently unclear. Further experimental and theoretical work is required before the limits on ion energy and conversion efficiency can be ascertained. Perhaps the straightforward approach (as in the present experiments) is limited, but a number of the theoretical schemes look like attractive possibilities for the future.

In the area of coherent acceleration the writer considers the situation not very advanced, at present, as far as high energy is concerned. Perhaps electron rings will someday be the basis of a high-energy coherent-acceleration device: either through the use of electromagnetic-wave acceleration of rings, or, more interestingly, as the essential componets of an impact accelerator [8]

In summary, the development of a number of different collective field devices for the low-energy regime appears likely, and their characteristics can be expected to afford a wide spectrum of different capabilities. For high energies, only the electron-ring accelerator presently appears to be a serious possibility, whereas the lure of coherent acceleration remains as attractive as ever; and, although not so remote as when first suggested by Veksler, nevertheless, it is still a goal for the future.

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ДИСКУССИЯ

Джелепов: Имеются ли идеи относительно возможностей растяжки импульса?

Sessler: No one has been able, to the best of my knowledge, to think of a method to increase the duty factor of an electron ring accelerator. It is, of course, possible to couple an electron ring aceelerator to a storage ring ("beam stretcher") and thus improve the duty factor. Finally, it should be noted, that the very narrow pulse of ions can be advantageous for certain experiments.

Файнберг: Какова глубина потенциальной ямы в ускорителе HIPAC и чему равно умножение напряжения?

Sessler: Recent experimental resulte on the HIPAC may be found in Reference [15].