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national accelerator laboratory

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Introduction

The concept of the electron ring accelerator, as it is coming to be called in this country, is the outgrowth of ideas developed by V. I. Veksler in a series of papers dating from 1956[1-3]. His first presentation was very speculative in nature and, perhaps unfortunately, was overshadowed in Western reaction by the simultaneous publication of more specific suggestions by G. I. Budker[4] and Ya. Feynberg[5] regarding the exploitation of collective effects for the purpose of accelerating particles. In particular, Budker's proposal to establish a very strong magnetic guide field through the medium of an intense beam of relativistic electrons was pursued actively, both theoretically and experimentally, in the United States, Europe, and the Soviet Union for some years. These researches met with little success and, in hindsight, only served to postpone the decision in the United States and Europe to pursue the problems of high energy physics by more conventional means.

The current surge of American interest in the electron ring accelerator follows the presentation of a paper[3] at the 1967 International Accelerator Conference describing the status of an experimental program at Dubna. The significance of this work was recognized chiefly by Dr. A. Sessler of the Lawrence Radiation Laboratory, Berkeley, California, whose enthusiasm has led to the initiation of a similar program in Berkeley and Livermore.

Professor Veksler's idea is qualitatively different in that the highly concentrated electron bunch is to be the active element in accelerating protons or heavier ions. Such a concept reduces the complexity of the developmental problem enormously, to the point where we currently feel optimistic that its feasibility can be demonstrated. The purpose of this report is to present the basic principles of the device, to record the present state of activity, and to guess at its implications for the future.

General Description

The electron ring accelerator would take advantage of the large difference in mass between electrons and ions by accelerating a packet of electrons sufficiently dense that a relatively small number of ions imbedded in the packet would be carried along by the electrostatic self-field of the electrons. For a given final velocity of the combination, the ions would have a much larger kinetic energy. For example, if protons could accompany electron bunches in a conventional electron linac of 50 MeV, they would have a final energy larger in the ratio of the rest masses; that is, 100 GeV. However, the self-field of electron bunches in present day linacs is too small by five or six orders of magnitude to retain ions for any reasonable rate of electron acceleration. In order to create an electron bunch which can hold ions and still not blow itself apart, it seems necessary to use electrons which even initially are moving at relativistic speeds, but in a plane perpendicular to the direction of acceleration. In this circumstance, the self-attractive magnetic field of the electron current largely cancels the electrostatic repulsion and the electrons can be kept bunched by the use of modest external forces. The ions, being at rest with respect to the bunch, see only the attractive electrostatic forces. The conglomeration is confined to reasonable transverse dimensions by use of an axial magnetic field which causes the electron stream to close in a circle; thus the name, electron ring accelerator.

An operating cycle is visualized as follows. An electron current of several hundred amperes at several MeV is injected transversely into a coil configuration as indicated in Fig. 1. Initially, only the outer set of coils is energized to produce a field appropriate to the injection radius. After one or more turns are trapped at injection radius, the current in the outer coils is increased, causing the ring to decrease in radius and the electrons to gain energy due to the increasing magnetic flux. When the ring is inside the radius of the middle set of coils, they are energized to continue the process, and so with the innermost coils, until the ring is well inside the inner set. During this time, the minor radius of the toroidal stream has also decreased, as a well known consequence of increasing electron energy.

Thus the bunch is established. At this time a burst of gas (hydrogen for a proton accelerator) is introduced to the chamber; the electrons serve to ionize the gas which enters the toroidal region and the resulting ions are trapped in that region by the electrostatic field of the electrons. After the desired number of ions has been produced, the current in the right-hand coil of Fig. 1 is reduced slightly and the ring moves axially out of the compressor unit toward an accelerating system. Hopefully, the ions, though small in number, are present in sufficient quantity that their attractive effect on the electrons overweighs the slight excess of Coloumb repulsion over magnetic attraction of the electrons on themselves and the ring holds itself together. This self-pinching phenomenon is well known, though it is not yet clear whether it would be strong enough to obviate the need for externally applied focusing forces.

Two basically different methods are under consideration for accelerating the ring. The simpler one, which is certainly attractive for initial studies, is merely to let the confining magnetic field decrease slowly with distance from the compressor. In this situation, the electrons should respond in the same way as particles leaving the mirror region of a plasma containment device; that is, they would maintain constant total energy in a time-independent magnetic field, but would gain axial momentum at the expense of transverse momentum. In principle, the solenoidal field could be reduced to zero, in which case the motion would be entirely axial and the trapped ions would have a velocity corresponding to several tens of GeV kinetic energy. However, the radius of the ring would simultaneously approach infinity, so that the process must be halted somewhere short of that point. A decrease in field by a factor of four would lead to a doubling of the radius of the ring and an axial velocity corresponding to one GeV proton energy; this range of operation seems a reasonable first goal. It has been pointed out that the ring radius could be held constant by introducing a second solenoid, concentric with the ring but at a smaller radius, which solenoid would control the flux linkage independently of the field at the radius of the ring. However, the mechanical problem of supporting such a solenoid without obstructing the path of the ring seems formidable.

The other mode of acceleration is by an externally applied longitudinal electric field. In its most conventional version, this would require a linear accelerator structure, in the range of 200 to 1000 Mc in frequency. The field would be built up during the compression phase and the release of the ring from the compressor would have to be synchronized with the rf cycle to insure that the ring be accelerated with reasonable efficiency. This timing problem looks difficult, but perhaps not insurmountable. An alternate possibility is to shock-excite a succession of cavities by charged pulse lines triggered from signals indicating that the ring is approaching. An accelerating field can be maintained in a reasonably sized cavity for several nanoseconds by this means, thus alleviating the timing problem and eliminating need for expensive rf hardware; on the other hand, the triggering system would require some development work and might turn out to be rather elaborate itself.

A third possibility for acceleration should be mentioned, although it has not received serious attention thus far. It was stated earlier that a longitudinal acceleration occurs if the solenoidal field decreases with distance from the compressor; this condition could be established dynamically by creating a moving crest in the field which would accelerate the ring along the solenoid on its leading edge. Indications are that it would be more complicated to produce such a magnetic wave than a more conventional electric wave.

In any of these cases of superimposed accelerating forces, the confining magnetic field would be independent of distance along the accelerator, the transverse momentum of the electrons would remain constant and the radius of the ring would remain constant. The accelerating elements could be repeated indefinitely; thus, it is conceived that the achievement of very high proton energies (100-1000 GeV) would require the use of an added accelerating structure, whereas an energy in the range of 1 GeV (or 1 GeV/nucleon for heavy ions) could be reached with a suitably designed dc solenoid and nothing else.

Formulas and Parameters

The generalities of the last section can be sharpened with the aid of a few formulas. First, it is useful to express the total energy of an electron in terms of its transverse momentum and axial velocity, which are the significant quantities in this situation. The expression is

$$W/c^2 = \gamma_{\parallel}\sqrt{m^2 + P_{\perp}^2/c^2} \quad , \qquad (1)$$

where $\gamma_{\parallel} = \left[1 - \beta_{\parallel}^2\right]^{-1/2}$, with $\beta_{\parallel}$ = axial velocity/c.

Eq. (1) shows immediately that the need to stabilize the bunch by starting with relativistic electrons compromises the original idea of exploiting the difference in rest mass between electrons and ions. With regard to axial acceleration, the electrons have an effective mass of $\sqrt{m^2 + P_{\perp}^2/c^2}$, so that the energy to be supplied to the electrons for a given final proton energy is only less by the ratio $\sqrt{m^2 + P_{\perp}^2/c^2}\,/M$, where M is the ion mass. In selecting parameters, it is therefore important to use electrons of as low energy as possible, consistent with stability of the ring against space charge blow-up and other more subtle effects. A reasonable compromise seems to be ~ 20-30 MeV in the compressed phase, which corresponds to an effective electron mass of 40-60 times the rest mass. Eq. (1) also shows the consequence of reducing the confining field without changing electron energy. In the extreme case of $P_\perp \rightarrow 0$, the resulting ion energy would be $M\gamma_\parallel c^2 = MW/m$, where M is the ion rest mass. Here the ratio of rest masses comes into full play and it would be tempting to make the initial (and constant) electron energy, W, as high as possible. Although this last formula indicates that 50 MeV electrons could yield 100 GeV protons by simple expansion in a solenoidal field, it should be remembered that the physical layout seems rather impractical.

Another useful expression is that for the electric field at the perimeter of an electron beam of circular cross-section. The field is given by:

$$eE_{max} = \frac{Ne^2}{\pi aR}, \qquad (2)$$

where N = total number of electrons in the ring,

R = major radius of the ring,

a = minor radius of the ring.

This expression is independent of the charge distribution over the cross-section of the ring and should indeed be the maximum value of the field for any reasonable distribution. Since this is the field which is to accelerate the ions, the desirability of the compression phase is evident in that it serves to decrease both major and minor radii and thus increase the available accelerating field.

One can now establish a condition on the rate of axial acceleration of the ring by an external electric field. We have two relations:

$$M\, d/dt\, (\gamma_{\parallel}\beta_{\parallel}) = e[E_{int} - E_{ext}]$$

and

$$\sqrt{m^2 + P_{\perp}^2/c^2}\;\; d/dt\; \gamma_{\parallel}\beta_{\parallel} = eE_{ext},$$

where E_{ext} is the externally applied axial electric field and E_{int} ($<E_{max}$) is the electron self-field at the center of gravity of the trapped ions. Equating accelerations yields:

$$E_{max} > \left[\frac{M}{\sqrt{m^2 + P_{\perp}^2/c^2}} - 1\right] E_{ext} \sim \frac{M}{P_{\perp}/c}\, E_{ext}; \qquad (3)$$

that is, the external field must be smaller than the internal by the ratio of the effective masses. For the case of no external electric field, but a decreasing solenoidal magnetic field, the corresponding condition is

$$\frac{1}{B}\frac{dB}{dz} < \frac{2eE_{max}}{M\gamma_{\parallel} c^2}\,. \qquad (4)$$

Principally on the basis of these formulas, a parameter list can be drawn up. The numbers given in Table I are those selected for the first experiments at LRL, but are not very different from those already in use by the Dubna group (Ref. 3).

It is interesting to note in the parameter list that the ratio of minor to major radius of the ring would be very small which means that the configuration would resemble a loop of thread rather than a smoke ring. For this reason,

Table I

	Injected	Compressed
Electron energy (MeV)	4.5	25.0
Circulating current (amps)	380.0	2000.0
Major radius (cm)	20.0	3.7
Minor radius (cm)	0.5	0.1
Field at orbit (gauss)	750.0	2×10^4
Max internal electric field MeV/cm		1.3
Max external accel. field KeV/cm		40.0
Compression time (μsec)		200.0
Repetition time (sec)		30.0
No. of electrons/pulse	10^{13}	10^{13}
No. of protons/pulse		10^{11}

the original appellation, "smokatron" has been discarded as being inappropriate. The point at issue is, in fact, substantive, since the achievement of a high internal field depends strongly on the achievement of a small minor radius. Within the range of possible external accelerating fields, the length of an accelerator needed to produce a given final proton energy is determined by the internal field; for example, an internal field of 1 MeV/cm would yield 100 GeV protons in a distance of $10^{11}/10^6$ cm, or one kilometer. For a given number of electrons in the ring, the minor radius is therefore a critical parameter in determining the physical layout of a possible accelerator. However, the nature of the injection process is such that the minor radius should increase approximately as the square root of the number of electrons injected; Eq. (2) would indicate that it might be wise to increase the number of electrons per pulse even though the minor radius would then be somewhat larger.

Current Status

Our knowledge of the Soviet work consists of the conference paper[3] and information obtained by Dr. D. Keefe of LRL, who visited Dubna a short time later. They have succeeded in injecting and compressing the electron ring, but although they are equipped both with a long solenoid and a set of linear accelerator cavities, they have not yet been able to accelerate the ring (Feb. 1968). This latter fact is in contradiction to Keefe's interpretation of his discussions but, regrettably, has been verified directly by Dr. V. Sarantsyev, who is in charge of the Soviet effort. The lack of success in acceleration does not imply a failure of the idea; it is very likely that the work has just not progressed that far, but we have no clear picture as to how actively it is being pursued.

In this country, the growing interest led to the assemblage of a working party at LRL for the week of January 29, 1968, followed the next week by a more formal symposium.[6] These sessions were attended by accelerator and plasma physicists from the United States and Europe (unfortunately, no Soviet scientists were able to accept invitations) and led to general agreement that the idea was viable and, in fact, very promising. It was, of course, recognized that a myriad of problems will require solution before the device can be competitive with present acceleration, but no insurmountable difficulties came to light.

At the Livermore branch of LRL there exists both a suitable electron gun, which has been in use for some years as injector for the Astron controlled fusion experiments, and facilities for handling pulsed coils of the type needed for a compressor. A joint Berkeley-Livermore experimental program is well under way; the hardware for injecting and compressing should be in place some time this summer. In the meantime, a program of theoretical study will continue at LRL-Berkeley, hopefully assisted by interested parties at BNL, NAL, and other laboratories.

Future Developments

As a tool for high energy physics, which aspect is of most direct interest to NAL, such a device has attractive features. One might hope to increase the number of electrons per pulse to 10^{14} and the number of protons to 10^{12}; at what seems a feasible repetition rate of 10/sec, the average proton intensity would then be 10^{13} sec. A guess at beam quality, made by considering the radial and axial oscillations of the protons in the electrostatic well of the electrons, leads to a predicted 1% energy spread, largely independent of energy, and an emittance smaller than in existing AG synchrotrons at the same energy. The protons could presumably be easily separated from the electrons at the end of an accelerating column by violating condition (3) or (4), but the beam structure would be quite unusual. Though the emittance might be small, the protons would have to be collected somehow from their ring-shaped distribution in order to be put on a target. Furthermore, the ring would be Lorentz-contracted in the axial direction from its original length of a millimeter or so, which would imply an on-target time of about 10^{-13} sec. It has been argued that such a short time is acceptable or even favorable for certain experiments, but it seems clear that some means of providing a reasonable duty factor would be essential to make the device truly competitive. The addition of a storage ring has been suggested, but not studied in any detail.

LRL has made a cost estimate for a 70 GeV accelerator, assuming that the parameter list of Table I will survive the forth-coming experimental investigation of the properties of such an electron ring. The entire complex of injector, compressor, super-conducting solenoid, rf accelerating system, and housing and auxiliary equipment would cost in the neighborhood of 20M$. A superconducting storage ring for 70 GeV protons is estimated at an additional 15-20M$. These figures correspond to the 106M$ estimated for accelerator components and housing in the NAL proposal. Thus there is no reason at this time to believe that the electron ring concept offers a break-through in cost per GeV of high-energy accelerators, though much depends on the progress of the experiments at Dubna and LRL, and on our ability to exploit the results in terms of possible technological simplifications. It will certainly be a matter of years before the merits of this ingenious idea can be properly evaluated.

REFERENCES

[1] V. I. Veksler, "Coherent Principle of Acceleration of Charged Particles," in _Proceedings of the CERN Symposium on High Energy Accelerators_, Geneva, Switzerland, 1956, p. 80.

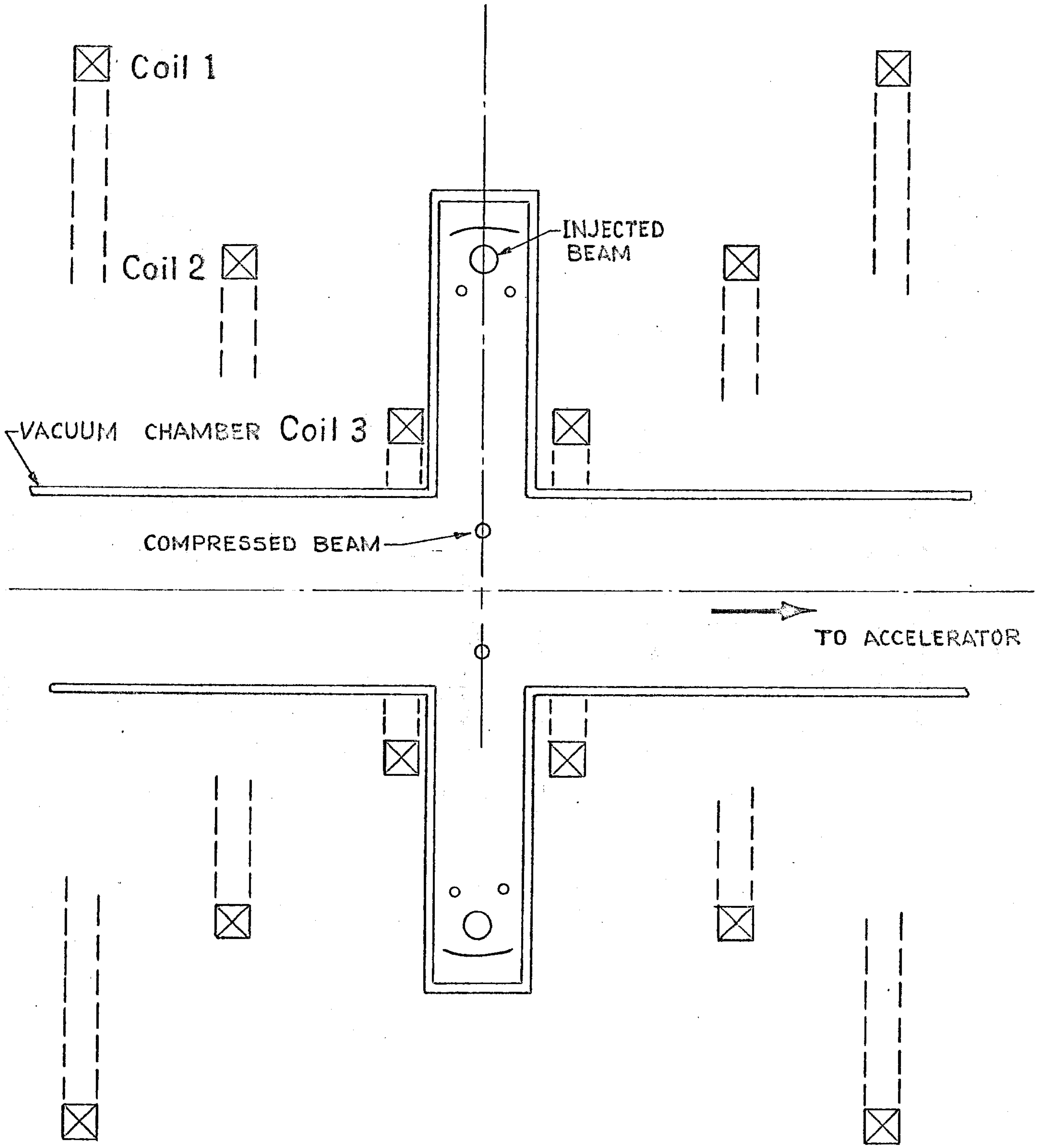
[2] V. I. Veksler and V. N. Tsytovich, "On Coherent Impact Acceleration," in _Proceedings of International Conference on High Energy Accelerators_, Geneva, Switzerland, 1959, p. 160.

[3] V. I. Veksler, et. al., "Collective Linear Acceleration of Ions," in _Proceedings of the Sixth International Conference on High Energy Accelerators_, Cambridge, Massachusetts, 1967, p. 289.

[4] G. J. Budker and A. A. Naumov, "Relativistic Stabilized Electron Beam," in _Proceedings of the CERN Symposium on High Energy Accelerators_, Geneva, Switzerland, 1956, p. 68.

[5] Ya. B. Feynberg, "Use of Plasma Wave Guides as Accelerating Structures in Linear Accelerators," in _Proceedings of the CERN Symposium on High Energy Accelerators_, Geneva, Switzerland, 1956, p. 84.

[6] _Symposium on Electron Ring Accelerators_, Lawrence Radiation Laboratory Report UCRL-18103, Feb. 1968.



COMPRESSION UNIT
FIG. 1