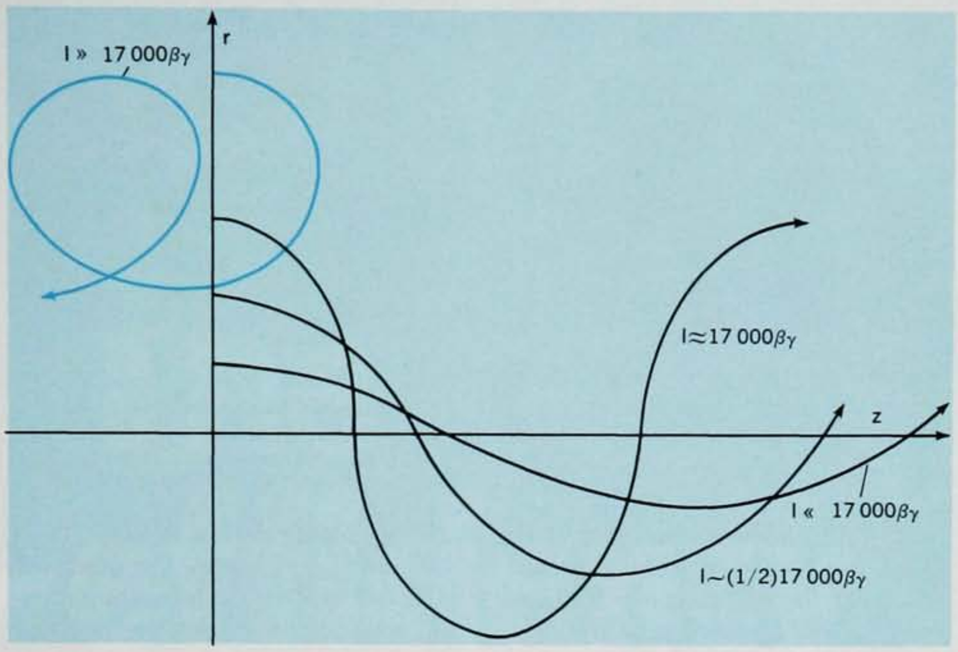
Intense MeV-Electron Beams and Prospects for Accelerators

Although the intensity of charged-particle beams was believed to have a theoretical limit, several groups have now produced relativistic-electron beams with intensities beyond the limit. Besides the interesting properties of the beam itself, the electron flux might be used for relatively inexpensive ion accelerators.



ELECTRON TRAJECTORIES in magnetic field of a uniform current-density beam. When current I exceeds Alfven's theoretical limit, $I = 17\,000\ \beta\gamma$ amperes, net electron motion is in the opposite direction (red trajectory). Several groups have now produced beams that exceed the limit, and propagation theories have been developed.

Theoretical limitation. In 1939 Hannes Alfvén[1] considered the propagation of intense beams of charged particles associated with cosmic rays. He concluded that in an electrically neutralized beam the maximal current that could be propagated is $I_A = (mc^3/e)\gamma\beta$ ($\beta = v/c$, v is the particle velocity and $\gamma = (1 - \beta^2)^{-1/2}$). For a uniform beam of radius a the self magnetic field is $B\theta = 2Ir/ca^2$ where I is the beam current. The gyroradius (Larmor radius) R_L of a particle moving in the field at $r = a$ is $R_L = (I_A/I)(a/2)$, so that the Alfvén current I_A is the current at which the gyroradius of a particle is half the beam radius. For electrons $I_A = 17\,000\ \beta\gamma$ amperes.

Trajectories of electrons in the magnetic field of a uniform current-density beam are shown in the figure on this page. When an electron is projected at a radius r such that a current greater than I_A is enclosed, the electron on the average moves in such a direction as to decrease the beam current. J. D. Lawson[2] further elaborated the significance of this limiting current.

Recent developments in pulsed power technology have allowed production of relativistic-electron beams with currents in excess of I_A. Last year S. Graybill, J. Uglam and Sam V. Nablo of Ion Physics Corp, Burlington, Mass.[3] reported stopping of a beam of about 50 000 amperes (approximately the Alfvén current) by the self magnetic field.

More recently it has been shown that currents far in excess of this limit can propagate over many meters with modest energy losses. The time-exposure photograph on this page (taken by Merrill Andrews, Hans Fleischmann and Sam Linke) shows a 100 000-ampere, 0.5-MeV beam at the plasma laboratory of Cornell.

How does one exceed the limit? Several modes of propagating currents greater than the Alfvén limit are now understood, and David Hammer and Norman Rostoker at Cornell have developed theories for these modes.

- The current distribution can be nonuniform, so that the current density and self magnetic field are concentrated in a skin depth $L < a$ near the surface of the beam. Then the limiting current will be for $R_L \simeq L/2$ or $I_{max} = (a/2L)I_A$.
- The return current (in the opposite direction) can be carried by a plasma of density greater than the beam. If the return current is mainly within the beam the self magnetic field is neutralized, that is, the net current density due to beam and plasma electrons can be negligible.
- If a magnetic guide field stronger than the self magnetic field is applied

100 000-AMPERE BEAM OF 0.5-MeV ELECTRONS at Cornell. The black lines are meter markers. The Beam diameter is 4 cm.

HIGH-INTENSITY ELECTRON ACCELERATOR at Cornell. Marx generator (right) erects a 700-kV pulse in about 300 nanosec. Then Blumlein transmission line (left) is charged to 500 kV in about 1 microsec and the energy is discharged.

in the direction of the beam, the beam can propagate without neutralization of the self magnetic field and even without electric neutralization.

Each of these propagation modes has been observed, for example by J. C. Ingraham and L. Bradley at EG & G; T. G. Roberts and Willard H. Bennett[4] of North Carolina State University, and J. Bzura, Fleischmann and Linke at Cornell.

The technology for such beams involves well known components. High voltage is usually produced by Marx generators or a Van de Graaff accelerator. A transmission line (Blumlein) is charged to high voltage and used to form a pulse of 0.25–5 MV for 20–100 nanosec. The voltage is applied to a low-impedance field-emission diode that features a thin-foil anode. Accelerated electrons pass through the anode into the drift tube that usually has a metallic-surface conductor, which may carry all or part of the return current (depending on the conductivity of the gas in the drift tube). J. Charles Martin of the UK Atomic Energy Authority has done pioneering work on these techniques.

Experiments with high-current electron beams in the US are taking place at Physics International Co, San Leandro, Calif.; Ion Physics Corp; Sandia Corp, Albuquerque, N. M.; Naval Research Laboratory, and Cornell. At the Lebedev Institute in Moscow, a program devoted to this problem is directed by Matvich S. Rabinovich.

Now that relativistic-electron beams with such large electron density (10^{11}–10^{12} cm^{-3}) and energy flux are available, one of the most interesting physics applications is the prospect for relatively inexpensive ion accelerators. Various methods for picking up or accelerating ions have been proposed.

• Cerenkov radiation of plasma waves: In the frame of reference where electrons are stationary, ions should radiate plasma waves and decelerate; therefore in the laboratory frame ions should accelerate. This mechanism was proposed by V. I. Veksler.[5] Veksler's theory has been applied to data of Nablo and his collaborators by John M. Wachtel of the Defense Atomic Support Agency and Bernard J. Eastlund of AEC.[6]

• Rostoker[7] has pointed out that when the electron beam goes through a neutral gas there must be a space-charge region at the front where the beam has not yet been neutralized. This region constitutes a potential well for ions, and ions produced at the bottom of the well will be accelerated.

• G. A. Askariyan of the Lebedev Institute suggests that if a plasmoid (a ball of plasma) carrying a current is placed in the path of the beam, the beam electrons will be reflected by the magnetic field of the plasmoid, thus accelerating the plasmoid.[8]

• An electron beam, without neutralization, in a constant guide field should have a constant density. In a method proposed by L. Kovrizhnykh of the Lebedev Institute, the electron density can be increased locally by increasing the strength of the guide field locally; this would produce a potential well for ions. Then the ions can be accelerated with a local concentration of the guide field produced by a traveling magnetic-field wave.

Nablo has reported[9] ion currents of the order of 100 amperes for about 5 nanosec when an electron beam of about 50 000 amperes is injected into a neutral gas. He observed ion energies about ten times the electron energy.

So far there are insufficient data to identify the acceleration mechanism and estimate the ultimate capability, but the chances look good that high-current relativistic electron beams will lead to economic and versatile ion accelerators.

References

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Sandia Operates Picosecond Laser at 50-Joule Output

A laser that emits 50 joules in about 2 picoseconds is now running at Sandia Laboratories in Albuquerque. Its basic input is the train of pulses from a mode-locked neodymium-doped glass laser. Garth Gobeli, Eric Jones, Paul Peercy and James Bushnell hope to use the short high-energy pulse to produce among other things thermonuclear reactions.

The laser has five neodymium-doped glass rods—a small oscillator rod and four amplifier rods ranging from 53 to 105 cm long. The oscillator generates a train of ultra-short light pulses, one of which is selected and amplified. (The final three amplifier stages were built by American Optical Co. to Sandia specifications.) Overall gain is 50 000 to 150 000, with the final stage operating in the gain-saturated mode.

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