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A New Collective Particle Accelerator

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A simple and novel mechanism for a collective particle accelerator is proposed. It is suggested that a density modulated intense relativistic electron beam propagating in a spatially modulated magnetic field can drag particles (electrons or ions) and accelerate them to high energies. This new mechanism can generate high particle current. A strong radial electric field exists in the mechanism ensuring radial confinement of the accelerated ions.

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A NEW COLLECTIVE PARTICLE ACCELERATOR

In the last few years there was interest in using an intense relativistic electron beam (IREB) for ion acceleration. (1-6) It has been suggested that waves "riding" on an IREB can, under certain conditions, accelerate ions. These waves can take the form of cyclotron waves, (4) slow beam waves (5) or large amplitude electrostatic "well" associated with the front of an IREB. (6) By manipulating beam parameters (e.g. current, magnetic field, geometry etc.) the phase velocity of these waves can be controlled. When the phase velocity is small enough ions can be trapped by the wave. By "accelerating" the wave (i.e. increasing its phase velocity) the trapped ions will be dragged and gain energy from the wave. If during the acceleration process an ion escapes from the wave the acceleration phase will end and the ion will be lost. The generation of these waves and the control of their phase velocity may require beam parameters which are not attainable (e.g. monochromatism of particle energy).

In this letter a new mechanism for a collective accelerator is proposed. This mechanism can accelerate ions as well as electrons and it is free of some of the problems of current collective accelerators.

The axial electric field, on axis, produced by an annular unneutralized magnetically focused IREB propagating through a drift tube of radius R is

$$E_z \approx -\left[\frac{1}{2\pi\epsilon_0}\frac{\partial Q}{\partial z}\right] \ell n \frac{R}{r_b} - \left[\frac{\mu}{2\pi}\frac{\partial I}{\partial t}\right] \ell n \frac{R}{r_b} + \frac{Q}{2\pi\epsilon_0}\frac{1}{r_b}\frac{\partial r_b}{\partial z}\,, \qquad (1)$$

Note: Manuscript submitted February 8, 1978.

where Q is the charge/length. $Q = I/v$, I is the beam current, r_b is the beam radius and v is the electron velocity. Equation (1) was obtained from Maxwell equations under the assumption that the axial characteristic length is greater than the radius of the drift tube. By covering the drift tube walls with a thin dielectric layer of thickness δR and permeability ϵ one gets from Eq. (1) (after some rearranging)

$$E_z \approx -\frac{\mu}{2\pi}\frac{1}{\beta^2\gamma^2}\frac{\partial I}{\partial t}\,\ell n\,\frac{R}{r_b} + \frac{\mu}{2\pi\beta^2}\frac{\epsilon}{\epsilon - 1}\frac{\delta R}{R}\frac{\partial I}{\partial t} + \frac{Q}{2\pi\epsilon_0}\frac{1}{r_b}\frac{\partial r_b}{\partial z} \tag{2}$$

by choosing

$$\frac{\delta R}{R} \approx \frac{\epsilon}{\epsilon - 1}\frac{1}{\gamma^2}\,\ell n\,\frac{R}{r_b} \tag{3}$$

one gets

$$E_z \approx \frac{Q}{2\pi\epsilon_0}\frac{1}{r_b}\frac{\partial r_b}{\partial z}\,. \tag{4}$$

In a case where a modulated IREB (7) is propagating through a rippled magnetic field one inserts in Eq. (4) the following:

$$Q \approx \frac{Q_0}{2}\left(\sin\left(\frac{2\pi}{\lambda}\,z - 2\pi ft\right) + 1\right), \tag{5}$$

and

$$r_b \approx r_0 + r_1 \cos\frac{2\pi z}{L}\,; \qquad r_1 < r_0, \tag{6}$$

where f and λ are the frequency and wavelength of the modulation $\lambda f = v$, r_0 is the equilibrium radius of the IREB, r_1 is the amplitude of the oscillations of the IREB due to the influence of the rippled magnetic field and L is the wavelength of the rippled magnetic field. Here we assume that the parallel velocity of the electrons is $v \approx c$.

$$E_z \approx -\frac{Q_0}{4\pi\epsilon_0}\left(\frac{r_1}{r_0}\right)\frac{2\pi}{L}\sin\frac{2\pi z}{L}\left[\sin\left(\frac{2\pi z}{\lambda} - 2\pi ft\right) + 1\right], \tag{7}$$

rearranging Eq. (7) one gets

$$E_z \approx -\frac{1}{4}\frac{Q_0}{\epsilon_0}\left(\frac{r_1}{r_0 L}\right)\left\{\cos\left[2\pi z\left(\frac{1}{\lambda}+\frac{1}{L}\right)-2\pi ft\right]-\cos\left[2\pi z\left(\frac{1}{L}-\frac{1}{\lambda}\right)+2\pi ft\right]+2\sin\frac{2\pi z}{L}\right\}. \tag{8}$$

Equation (8) describes two "waves" with phase velocities

$$\begin{aligned} &(1) \quad v_{\phi 1} = v\,\frac{L}{L+\lambda} \qquad \text{forward wave,} \\ &(2) \quad v_{\phi 2} = -v\,\frac{L}{\lambda - L} \qquad \text{backward wave.} \end{aligned} \tag{9}$$

Figure 1 shows the phase velocity of these waves as a function of L. The amplitude of these waves is

$$E_{z0} \approx \frac{Q}{4\epsilon_0}\left(\frac{r_1}{r_0 L}\right). \tag{10}$$

Both waves can accelerate ions but only the backward wave can accelerate electrons since it can have phase velocity approaching c.

The acceleration force acting on particles with velocity v', by this collective mechanism, is impulsive in nature. During a period $T = [(\lambda \pm L)/2]/v = (L/2)/v'$ a favorably phased particle will be under the influence of a time-average electric field $2E_{z0}$. For a subsequent period no force will act on the particle. Formally, this mechanism resembles a nonlinear Landua damping process in which a fictitious wave (the rippled magnetic field) with wavelength L and zero frequency combine with a beam wave of wavelength λ and frequency f to exert a force on a particle and accelerate it.

If electrons are to be accelerated by this mechanism the backward wave has to be used. By choosing $\lambda \approx 2L$ the phase velocity of the backward wave is c. An IREB of

80 kA current and particle energy of 3 MeV can easily be modulated with a 1 GHz frequency. The automodulation (7) technique which is used to modulate the IREB can also increase the particle energy within the beam to $V \approx 5$ MeV. Passing this beam through a rippled magnetic field with $L = 15$ cm and $r_1/r_0 \approx 0.30$ one gets $E_{z0} \approx 15$ MV/meter. Figure 2 shows schematically the proposed accelerator.

The electron accelerator can work in two modes. In the first mode the duration of the accelerated electrons is about the duration of the IREB. In that case the accelerated current I_1 and the final energy of the accelerated electrons E_f has to satisfy the relation

$$I_1 E_f \leqslant IV. \tag{11}$$

Here, each bunch loses energy continuously along the acceleration length.

In the second mode of operation the duration of I_1 is smaller than $(L/2)/c$. Only during this duration each bunch loses energy. In that case

$$I_1 E_f \leqslant IV \frac{S}{L}, \tag{12}$$

where S is the total length of the accelerator, $S >> L$ and $S \lesssim c\tau/2$ and τ is the duration of the IREB. From Eqs. (10) and (12) one gets

$$I_1 \lesssim 4\epsilon_0 V_c (r_0/r_1). \tag{13}$$

In practice I_1 may have to be smaller so as to reduce effects of two stream instability. It seems (8) that if $I_1 \approx 0.1\, I$ the growth rate of the instability will be small especially for high γ.

The final energy of the accelerated electrons will be

$$E_f = (E_z L)\frac{S}{L}\ ; \qquad S = c\tau/2 \tag{14}$$

for τ = 100 ns and for the same IREB parameters mentioned earlier one gets $E_f \approx 200$ MeV, S = 15 meters and I_1 = 8 kA.

The same mechanism that accelerates electrons can accelerate ions. Here, too, we use the backward wave for acceleration. (One can also use the forward wave for ion acceleration.) In addition to the acceleration force there is a radial force, generated by the IREB, focusing the ions. A simple way for looking at the focusing force is to consider the case of solid ion beam flowing within an annular IREB. Here two forces will act on an ion. The first force results from the self electric field of the ion beam. This electric field will accelerate an ion to a outward radial velocity at the radius of the IREB.

$$V_{ri} \approx \sqrt{\frac{1}{2} \frac{ZeQ_i}{2\pi\epsilon_0 M}} \tag{15}$$

where Q_i is the charge/length of the ion beam Z is the effective charge of the ion and M its mass. A second force acts on the ions when they enter the trajectories of the electrons. This force will give an ion an inward radial velocity of

$$v_{ri} \approx \sqrt{\frac{ZeQ}{2\pi\epsilon_0 M} \frac{\delta a}{a}} \tag{16}$$

where δa is the thickness of the IREB. From Eq. (15) and (16) we can see that the ion current that can be radially confined inside an IREB is

$$I_{\text{ion}} \approx 2 \frac{\delta a}{a} \frac{v_i}{v} I. \tag{17}$$

If we take I = 80 kA, $v_i/v \simeq 0.06$, Z = 1, $\delta a/a \approx 0.1$ we get that $I_{\text{ion}} \approx 10^3$ amps can be focused. Similar calculation shows that 100 amps of U^{+10} can be focused when the initial velocity of the ions is v_i = 0.006 c.

The mechanism for ion acceleration is similar to the electron acceleration discussed earlier. At the axial position where the ions start the acceleration we choose L and λ such that

$$V_{\phi 2} = -v \frac{L}{\lambda - L} = v_i (<< c).$$

For the case of $Z = 1$ $v_i = 0.06\,c$ one choses $L = 10$ cm, and $\lambda = 170$ cm. For $I = 80$ kA and $r_1/r_0 \approx 0.067$ the accelerating electric field $E_z \approx 5$ MV/m. In order to maintain the force and the ion in phase, L has to be changed. While the ion is accelerating L is changing such that $V_{\phi 2} = v_i$. At the same time $(r_1/r_0)\,L$ is being kept constant such that $E_z \approx 5$ MV/m. This easily can be done for any L up to $L = 45$ cm. When $L = 45$ cm, one gets $r_1/r_0 \approx 0.3$ and $v_{\phi 2} \approx 0.36\,c$ corresponding to energy of 67 MeV. Since values of r_1/r_0 greater than 0.3 may not be technically possible one has to increase L without increasing (r_1/r_0). In that case E_z will drop when L increases beyond 45 cm and the acceleration length will become very long. In order to avoid long accelerator and be able to get energies greater than 67 MeV the ion beam has to be injected into a second generator. At the injection point $L = 10$ cm, $\lambda = 38$ cm and $r_1/r_0 \approx 0.15$ such that $E_z \approx 11.2$ MV/m, and $v_{\phi 2} = 0.36\,c$. Changing L from 10 cm to 19 cm, $v_{\phi 2}$ increases to c. Simultaneously r_1/r_0 is being changed to 0.3 so that E_z stays constant and is equal to 11.2 MV/m. Only 100 meters of acceleration length are needed to obtain particle energy of 1 GeV.

A similar considerations can show that for a beam of U^{+10} ions to reach energy of 1 GeV it is necessary to have acceleration length of 44 meters.

For the acceleration mechanisms to work, ions with the right velocity have to be injected into the IREB. The injection mechanism is part of the acceleration mechanism. This is shown in Fig. 2. The modulated IREB is being terminated on a metal plate or foil.

The place of termination is the equator of one of the mirror magnetic field. Ions will accelerate between the metal plate and the apex of the mirror magnetic field and reach a velocity

$$v_i \approx \frac{Ze}{M} \frac{Q}{\epsilon_0} \left(\frac{r_1}{r_0 L}\right) \frac{\lambda}{c} . \qquad (18)$$

It is easy to show that with the IREB parameters discussed earlier one can get $v_i \approx 0.06\ c$ for $Z = 1$.

One of the important parameters in the above mechanism is the strength of the external magnetic field. It was found (9,10) that an IREB propagating through a rippled magnetic field produces microwave radiation and its characteristics were drastically modified. It was likewise found that a critical magnetic field existed above which very little microwave power was produced and the beam characteristics did not change.

$$B_c \simeq \frac{2\pi}{L} \frac{mc}{e} \gamma. \qquad (19)$$

For $L = 15$ cm, $\gamma = 10$, one gets $B_c \approx 7$ kG.

In summary a new collective particle accelerator is being proposed. This new type of accelerator can accelerate ions as well as electrons.

A similar idea was suggested in 1975 by A.N. Lebedev and K.N. Pazin (11). They suggested that a bunched electron beam propagating through a corrugated metal tube can support beam waves. These beam waves can be used to accelerate particles to high energies. However, there are experimental and theoretical evidence that an electron beam propagating through a corrugated drift tube is unstable. It interacts with slow rf waves (which are being supported by the structure) generating high power microwave radiation (12).

In the mechanism discussed in this paper the electron beam is propagating in a smooth metallic drift tube. The beam can interact only with fast rf waves. The interaction is very weak and under certain conditions very little microwave radiation is produced and no beam deterioration is being observed (10).

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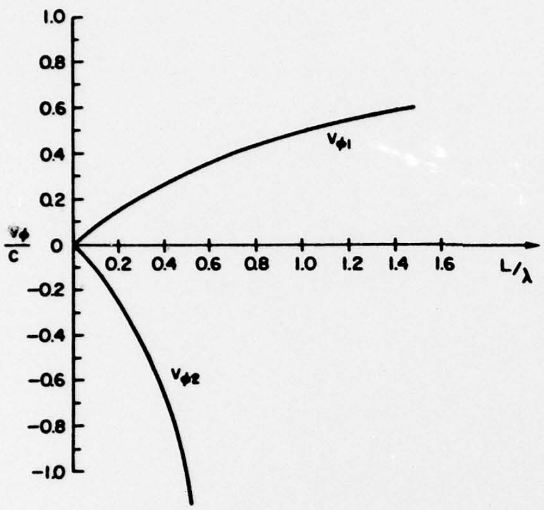

Fig. 1 — Phase velocities of forward and backward waves as a function of L/λ.

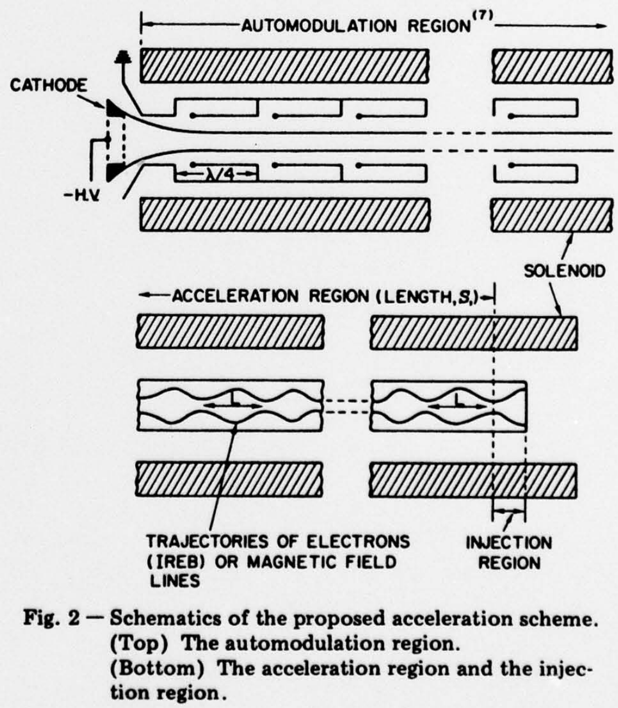

Fig. 2 — Schematics of the proposed acceleration scheme. (Top) The automodulation region. (Bottom) The acceleration region and the injection region.