PARTICLE ACCELERATION BY INVERSE-WEIBEL INSTABILITY

S. Kawata

Department of Electrical Engineering, Nagaoka University of Technology, Nagaoka 940-21, Japan
e-mail: kawata@voscc.nagaokaut.ac.jp

Abstract
A high demagnetization rate $\partial B/\partial t$ can be obtained through fast decoupling of a magnetic field from an electric circuit which generates the magnetic field. Nowadays fast decoupling is possible by present switching technologies. A high particle-acceleration gradient can be obtained in an inductive acceleration system compared with that in a conventional induction accelerator. Based on this new proposal, inductive ion and electron accelerations are investigated numerically. The mechanism presented in this paper may be considered as pseudo-inverse Weibel instability.

Introduction
A number of new particle acceleration mechanisms have been studied and proposed [1,2] in order to break through the limitation of the acceleration gradient for current accelerators. In a conventional induction accelerator [3], in which a cylindrically symmetric azimuthal magnetic field B_θ is used for the generation of an inductive acceleration field, the acceleration field is also limited, and the denagnetization rate $\partial B_\theta/\partial t$ is determined by an electric circuit structure and a magnetic core material; typically $\partial B_\theta/\partial t \simeq$ a few T/μs. [3] Here t denotes the time. Using the Maxwell equation, one can easily obtain the relation of $V = \Delta B_\theta S/\tau$, where V is an acceleration-voltage increase for a time duration τ, ΔB_θ a change in B_θ, and S the area through which B_θ penetrates perpendicularly. (3) Therefore one of the important points for attaining a high acceleration gradient is to obtain a short τ. We propose to use a magnetic field which is decoupled from the electric circuit by fast opening-switch technology, and to use the demagnetization process to obtain a large acceleration field. Based on this new proposal, inductive ion and electron accelerations are investigated numerically.

Nowadays, fast switching technologies are firmly established and available. For example, 1) a plasma opening switch provides a switching time of $\leq 5\sim10$ns. [4] 2) Another available tool is an intense high-power laser. Based on the fast opening-switch technologies, it is possible to decouple a magnetic field in the short switching time from an electric circuit that generates the static magnetic field. Consequently we may have a high acceleration gradient compared to that of a conventional induction accelerator.

Inductive Acceleration Mechanism
In order to demonstrate the generation of the large acceleration field, we perform a simple estimation and a particle simulation for ion or electron acceleration in the system (Fig.1). First, the static magnetic field, sustained by electric currents, is applied in an acceleration vacuum. Then the currents are terminated abruptly by the fast opening

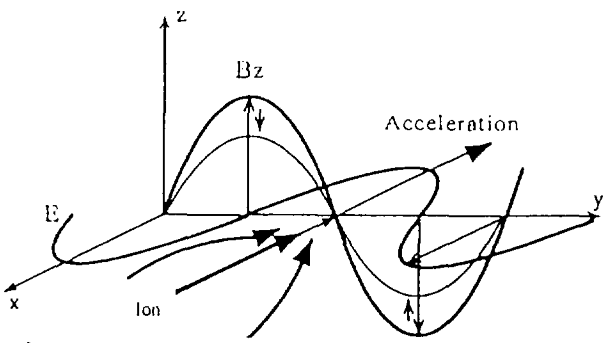

Fig. 1 A static spatially alternating magnetic field B z is first generated and is abruptly decoupled from the electric circuit which generates Bz. During the demagnetization phase a high acceleration field E is induced. Ions are accelerated by E and focused by Bz.

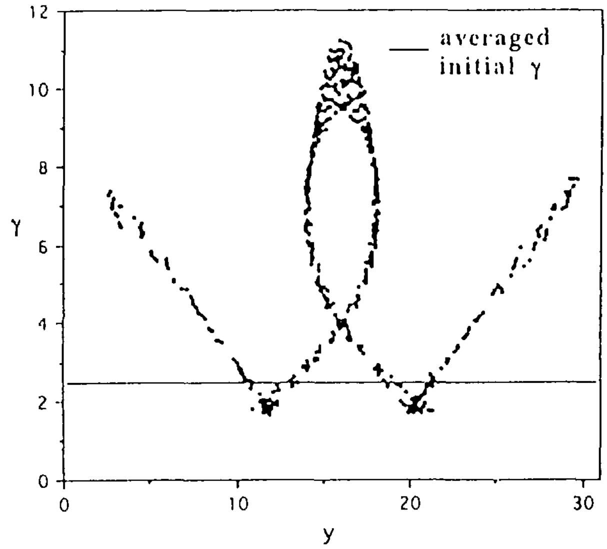

Fig. 2 A particle map by particle (PIC) simulation. The electron relativistic factor γ versus y at the maximum acceleration time. The initial electron speed is 0.9c on average, the beam initial temperature is 10 eV, and the maximum γ=11.5. A fraction of the electrons is accelerated well.

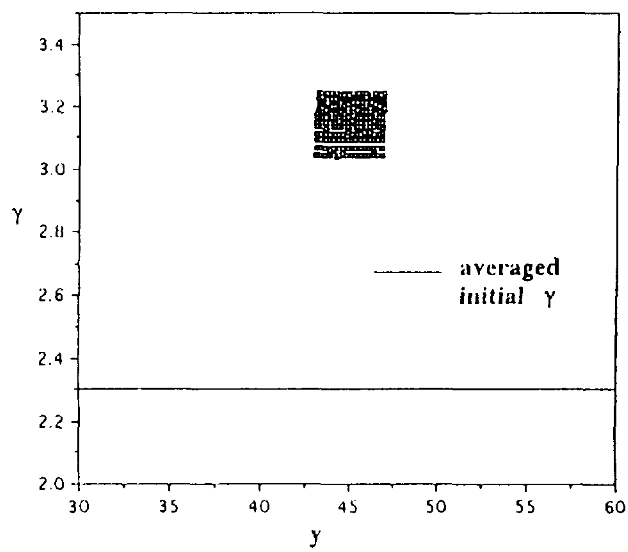

Fig.3 An ion map by particle simulation. The ion relativistic factor γ versus y at the maximum acceleration time. The initial ion speed is 0.9c on average, the beam initial temperature is 10 eV, and the maximum γ=3.24. The ions are accelerated well.

switch described above. In this paper we assume that the switching time is small compared with a characteristic time of the change in the magnetic field, based on the discussions presented above. Our analyses are performed immediately after the static magnetic field is decoupled and free from the circuit. For simplicity a spatially alternating magnetic field B_z, whose wave number is k, is employed instead of B_θ without loss of generality. The magnetic field B_z in an acceleration area induces an inductive electric acceleration field.

The magnetic field energy is converted to the energy of the inductive electric field E:

$$\frac{\partial E}{\partial t} = c\frac{\partial B_z}{\partial y}, \tag{1}$$

$$\frac{\partial B_z}{\partial t} = c\frac{\partial E}{\partial y}. \tag{2}$$

Incoming beam charged particles are accelerated by the inductive field E in the acceleration area. In addition to the acceleration, the magnetic field focuses the beam.

It is assumed that the static magnetic field is $B_z = B_0 sin(ky)$ and $E = 0$ at the time $t = 0$. As a solution [5] which satisfies these initial conditions, we obtain

$$B_z = B_0 sin(ky)cos(\omega t), \tag{3}$$

$$E = B_0 cos(ky)sin(\omega t), \tag{4}$$

$$\omega = \pm kc. \tag{5}$$

During the first period ($0 < t < \pi/|\omega|$), ions/electrons can be accelerated by this mechanism. We use this acceleration phase. The maximum acceleration field is B_0, and

$$\frac{\partial B_z}{\partial t} = -B_0 \omega sin(ky)sin(\omega t). \tag{6}$$

Therefore $|\partial B_z/\partial t| = B_0\omega = B_0 kc$, and the changing time τ in B_z is $1/(kc)$. For efficient acceleration, $\pi/(kc)$ should be comparable to or larger than the switching time duration mentioned above. When the wave number k is 1/3, $|\partial B_z/\partial t| \simeq 10^{10} B_0(Tesla)$ Tesla/s, which is rather large compared with that in a conventional induction accelerator.

On the other hand, the mechanism presented in this paper may be considered as pseudo-inverse process of the Weibel instability. [6,7] In the Weibel instability an anisotropic-plasma energy is converted to magnetic field energy: a magnetic field perturbation, whose wave number is k, causes a filamentation of the electron particle stream in a direction perpendicular to both k and B_z. The filamentation enhances the perturbation of B_z. During the growth of B_z an inductive electric field decelerates the electrons. Consequently the electron energy is converted to the magnetic field energy in the Weibel instability. In our mechanism, we use a pseudo-inverse process of the Weibel instability, although the acceleration takes place in a vacuum. The magnetic energy is converted to electron energy through the energy of the inductive electric field, which accelerates electrons.

Numerical Simulation for Inverse-Weibel-Instability Acceleration

A 2.5-dimensional (x, y, v_x, v_y, v_z) particle (PIC) simulation is also performed with the following initial and boundary conditions: a sinusoidal magnetic field ($B_0 sin(ky)$) is applied in the entire computation space domain (2.5cm in x and 5cm in y), where the amplitude B_0 is 1Tesla. In both the x and y directions, 32 space grids are employed in the computation. The wavelength $2\pi/k$ is 5cm in the simulation. An electron beam, whose size is 3.12mm in width (along the x axis) and 5cm along the y axis, moves in the $+x$ direction and an average speed of $0.9c$ and a temperature of 10eV, and is located initially at the left side of the computational area. A cyclic boundary condition is used in both the x and y directions. The computations are performed until electrons pass through the computation space in the x direction. Figure 2 shows an electron map in the y-γ space at the end of the computation for the electron beam number density n of 10^{12} /cm^3. Here γ shows the relativistic factor. Figure 2 shows that some electrons are accelerated well by this mechanism. The maximum electron γ is 11.5, and the initial one is 2.30. For this particular case, the acceleration gradient is about 183MeV/m, which is a reasonable value, because the theoretical acceleration gradient from eq.(3) is $E = B_0 = 300$MeV at maxinum.

Ions are also accelerated well in this system with the following example parameter values: the computational space area is 0.5 m in the x direction and 1.0m in the y direction. The wavelength $2\pi/k$ is 1 m in the simulation. B_0 is 10 Tesla. An ion beam, whose size is 12.5 cm in width (along the x axis) and 25 cm along the y axis, moves in the $-x$ direction with an average speed of $0.9c$ and a temperature of 10eV, and is located initially at the right side and the center in y of the computational area. Figure 3 shows an ion map in the y-γ space at the end of the computation for the ion beam number density n of 10^9 /cm^3. Figure 3 shows that some ions are accelerated well. The maximum ion γ is 3.24, and the initial one is 2.30. For this particular case, the acceleration gradient is about 1.76 GeV/m.

Conclusions

We proposed a new method to obtain a high $\partial B/\partial t$ for an inductive charged-particle acceleration. The magnetic field, which is free from the electric circuit, induces a large acceleration field. The acceleration-gradient value itself is determined by the magnitude of the magnetic field employed and the wave number k. Our results showed that a high acceleration gradient can be obtained, compared with those of conventional accelerators. The present fast switching technologies make this method possible.

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[4] Cooperstein, G. and Ottinger, P.F. (ed.), *IEEE Trans. Plasma Sci.* **PS-15**, No.6, (1987).

[5] If we use a cylindrically-symmetric system and an azimuthal magnetic field $B_\theta = B_0 j_1(\omega r/c) cos(\omega t)$ as a more practical example instead of B_z, we obtain $E = B_0 j_0(\omega r/c)\ sin(\omega t)$. Here j_n is the Bessel function of the first kind of integral order n, and r the radius. In this example the essential points of our results described in the text do not change.

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[7] Weibel, E.S., *Phys. Rev. Lett.* **2**, (1959)83.