ACCELERATION OF CHARGED PARTICLES IN RUNNING OR STANDING ELECTROMAGNETIC WAVES

G. A. ASKAR' YAN

P. N. Lebedev Physics Institute, Academy of Sciences U.S.S.R.

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THE average Lorentz force acting on a charged particle in the field of, say, a plane electromagnetic wave depends not only on the amplitudes but also on the phase shift between the oscillating-particle velocity and the magnetic field of the wave. For example, in the absence of free-particle momentum spread this average force is zero in a traveling wave. In a standing wave it is different from zero and is directed towards the nodes of the wave field (cf., for example, references 1 — 3), but the spatial sinusoidal variation of this force does not allow us to utilize it for prolonged acceleration over distances exceeding $1/4$ of a wavelength. It is therefore of interest to investigate in general the conditions that can give rise to the existence of a unidirectional average force of sufficient magnitude acting on particles in a traveling or in a standing wave.

The average force depends on the resonance properties of the motion of the particles (arising as a result of the application of special kinds of external fields or of the utilization of plasma resonances etc.) and on the spread in the transverse momentum of the particles (as a result of radiation or of collisions with other particles in the bunch, in the plasma stream, or in the stationary plasma). In the general case, the resonance frequency ω_0 and the dissipation coefficient γ may vary spatially. It will be shown that a special choice of these two quantities may lead to a directed continuous acceleration of particles, independent of the sign of the charge, through the spatially periodic field of the standing wave.

It can be easily shown that the average Lorentz force acting on each charge in the running wave is given by

$$f_{av} = {}^1/_2 r_0 E_0 H_0 \gamma \omega^2 c / \{(\omega_0^2 - \omega^2)^2 + \gamma^2 \omega^2\}$$

(E_0, H_0 — are the field amplitudes, $r_0 = e^2/mc^2$ is the "classical radius" of the charge), i.e., if the frequency of the wave and the characteristic parameters of the oscillations are chosen appropriately acceleration becomes possible even for unbunched particles.

Let us consider the case when dissipation predominates over the inertial and resonance factors, which occurs, in particular, near resonance. When $|\omega_0^2 - \omega^2| \ll \gamma\omega$; $f_{av} \sim r_0 E_0 H_0 c/\gamma$, i.e., as damping decreases the force increases. The possibility of accelerating particles near resonance in the case of small damping associated not with radiation by particles, but, for example, with small collision losses, will make it unnecessary to bunch the particles compactly, which is difficult to achieve, and will also allow direct acceleration of heavy weakly-radiating particles. However, if the losses are associated with radiation, then $\gamma = {}^2/_3 \omega^2 N r_0/c$ (N is the number of particles in the bunch), therefore the total force is given by $f_{av} \approx E_0 H_0 c^2/\omega^2 N$; for $N r_0 \omega/c > |1 - \omega_0^2/\omega^2|$. In this case bunching the particles increases the range of working frequencies, but a further increase in the number of particles in the bunch diminishes the force acting on each particle of the bunch.

In the opposite case when the frequency spread is sufficiently great the acting force is proportional to the dissipation coefficient. For example, if damping is associated with radiative processes, then

$$f_{av} = N r_0^2 E_0 H_0 \omega^4 / 3(\omega_0^2 - \omega^2)^2.$$

This case leads to the expression for the force acting on each particle: $f \sim N$, which is characteristic of the coherent method of acceleration proposed by V. I. Veksler.

The use of bunches also permits one to achieve, in order to produce the required phase shift, a large dissipation of the transverse components of the momenta of the particles on collisions within the bunch without any appreciable dissipation of forward motion.

It is evident from the above that it is possible by various methods to vary within wide limits the phase shift between the velocity of oscillation and the electric field of the wave. This circumstance may be utilized not only in order to increase the efficiency of acceleration in a traveling wave, but also for the production of a spatially variable phasing of particle oscillations needed for continuous acceleration in a standing-wave field. The transition to standing waves not only allows a sharp reduction in the power of the power supply, but also guarantees efficient acceleration of a rarefied unbunched plasma or one that is weakly bunched (in order for the ions to be entrained by the electrons).

The average Lorentz force acting on each particle in a high-frequency standing wave depends on the longitudinal coordinate z

$$f_{av} \approx {}^1/_2 r_0 E_0 H_0 \{(\omega_0^2 - \omega^2)\,\omega c \,/\, [(\omega_0^2 - \omega^2)^2 + \gamma^2\omega^2]\} \sin 2hz.$$

In order to achieve cumulative acceleration of particles it is necessary that in those regions of space where sin 2hz changes sign the factor $\{\ldots\}$ should either change sign or have a different magnitude. (In estimating the average force we can, as before, restrict ourselves in certain cases to a consideration of the effect on the forced vibrations, since the possible excitation of characteristic oscillations gives no average contribution not only in the presence of real damping or of a spread in the phases of excitation of free oscillations, but also as a result of the fact that the characteristic oscillations have a frequency different from the frequency of the magnetic field of the wave.) In the case of a more complicated, say sinusoidal, spatial variation of the resonance parameters, we can easily demonstrate the fact that the space average of the accelerating force is different from zero by making use of solutions of the Mathieu equation, or by assuming for the sake of simplicity that the variations of the resonant frequency are small and by restricting ourselves to the first approximation. The cumulative contribution in the latter case will be determined by integrals of terms of the type $\sin\{2\pi(2/\lambda - 1/l)z + \varphi\}$ in the case when the spatial period l of the frequency variation is equal to one half of the wavelength of the radiation λ. Such zonal damping of the reverse acceleration by local constant external fields or by a local choice of the regime of dissipation will enable us to obtain continuous acceleration of plasma particles over long paths within the stationary field of a standing wave of large amplitude.

The simplest choice of the spatial variation of the oscillation parameters may be made by means of increasing or decreasing the axial magnetic field in those "quarter wavelength" regions in which it is required to alter the direction or the magnitude of the acceleration. This field will give rise to spatially-periodic variation of the amplitudes and the phases of the forced oscillations either because of a change in the cyclotron resonance frequencies, or because of a change in the characteristic plasma resonances (these changes may occur due to a change in plasma density when it is compressed in the regions of increased magnetic field) etc. Such a "corrugated field" may also help the focusing of the beam of particles undergoing acceleration.

In the method of acceleration under discussion the effective accelerating field intensity acting on the electrons may be made sufficiently large compared to the amplitude of the electric wave field. The efficiency of acceleration can also be increased by a transition from a linear resonator to a circular resonator utilizing repeated traversals of the wave field.

It is evident that similar devices may be used not only for the acceleration of plasma, but also for retarding and for turning back charged particles leaking out of storage systems.

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CONCERNING THE PRODUCTION OF COMPOUND NUCLEI IN THE INTERACTION BETWEEN ATOMIC NUCLEI

A. S. KARAMYAN, Yu. B. GERLIT, and B. F. MYASOEDOV

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It is natural, when investigating the interaction between multiply-charged ions and nuclei of various elements, to inquire about the extent to which these reactions proceed by complete fusion of the colliding nuclei with subsequent evaporation of neutrons. A useful criterion for such a reaction are the curves of the cross section of a reaction involving the emission of a specified number of

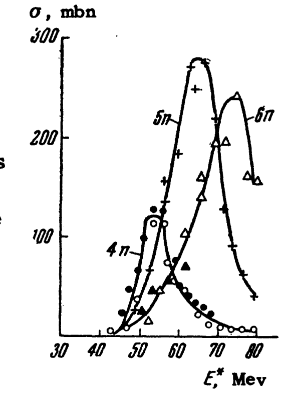

FIG. 1. Dependence of the cross sections of the reactions Au(N, (4–6)n) on the excitation energy of the compound nucleus Em[211].