

COHERENT PRINCIPLE OF ACCELERATION OF CHARGED PARTICLES

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This paper will include a very brief description of a new principle regarding the acceleration of charged particles.

In all existing accelerators of charged particles, the constant and varying electric field accelerating them is created by a powerful external source, and hence the strength of the field is independent, in the first approximation, of the number of particles which are being accelerated.

In resonance accelerators, the electromagnetic field has to be synchronized with the movement of the particles (this is of particular importance in linear accelerators). Finally, none of the existing methods permits the acceleration of neutral bunches of particles.

A new principle of particle acceleration is set forth below. Its distinctive feature lies in the fact that the particle-accelerating electric field is produced by the interaction of a geometrically small group of accelerated particles with another group of charges, plasma or an electromagnetic wave. This method has a number of important features. It appears, in the first place, that the magnitude of the accelerating field produced by this interaction and acting on each particle depends on the number of accelerated particles; more specifically, it is proportional to that number. Secondly, synchronization between the accelerating field and the motion of the accelerated bunch is automatically maintained. Thirdly, it is possible in a number of cases to create high field strengths only at those points where the accelerated particles are located. (This makes it possible to avoid breakdowns due to field emission from the metal). Fourthly, and lastly, it is possible to accelerate neutral bunches of particles.

The new method may be called "coherent", by virtue of the fact that the strength of the field acting on a single particle is proportional to the number of particles in a bunch.

Although the practical development of the ideas set forth below is still far from clear in all its details, the author assumes that it is possible, by this means, to approach the problem of constructing accelerators for very high currents and super-high energies of the order of 10^{12} eV and even more. Moreover, the author believes that the principle of "coherent impact acceleration" is the only way whereby the solution of this problem can be approached.

Theoretical studies of various aspects of the coherent acceleration method have been made by M. S. Rabinovich, A. A. Kolomenski, B. M. Bolotovskii, L. V. Kovrizhnikh and I. V. Iankov, as well as by A. I. Akhiezer, Ia. Fainberg and their collaborators. The calculations made by these theoretical workers shed light on a number of complicated problems connected with the development of the different variants of this new acceleration principle, and it therefore seems appropriate to describe the new method despite the fact that a great many problems involved still await solution.

1. *Acceleration of charged bunches by means of the medium*

It was pointed out in a paper by Tamm that the loss of energy by particles due to Čerenkov radiation could be reversed, i.e. the medium travelling at a great velocity past charged particles should be able to convey energy to the latter. Up to now, however, no attention has been paid to the possibility of developing an acceleration process of this kind by using a high density electron beam (plasma) as the moving medium. Of course, if a single charge e is used as the particle being accelerated, the effective field accelerating it will be very small. We know, however, that the losses due to ionization and to excitation of plasma oscillations—and hence the value of the reversed accelerating field—are proportional to the square of the charge. Hence, by selecting a bunch of ions with a charge number N as the charge to be accelerated, the force acting on each particle can be increased N -times.

This is due to the fact that each particle excites oscillations in the electron beam which add up coherently to produce a resultant electric field proportional to the number of charges in the bunch. The coherent addition relates to the longitudinal non-damped waves with a wave length greater than the Debye radius. In considering the acceleration of charged particles therefore, we must envisage collision parameters exceeding the Debye radius.

It can be shown that the strengths of the accelerating electric field in this case will be equal to

$$\mathcal{E} = \frac{eN\omega_0^2}{v^2} F \ln \frac{v}{D\omega_0} \quad (1)$$

where ω_0 is the frequency of plasma oscillations, v is the velocity of the electron plasma, N is the number of particles in the bunch being accelerated and F is the form factor

$$\omega_0^2 = (4\pi e^2 \rho) / m \quad (2)$$

where ρ is the electron density, and m, e are the mass and charge of an electron. The form factor F is close to unity if the bunch dimensions are small compared with the length of the plasma wave v/ω_0 .

The electron beam accelerating the bunch of charges must be stabilized in the radial direction. It is interesting to note that if, say, a longitudinal magnetic field is used to stabilize the beam, particle acceleration will occur due to a "reversal" of Čerenkov losses *).

The field \mathcal{L} at high values for N and ω_0^2 can theoretically run into many millions of volts per centimetre. To obtain an effective accelerating field with a very high gradient, however, it is necessary to use very high powers, as can easily be shown. The reason is that accelerators based on the coherent acceleration method inevitably produce a very high pulse current of accelerated particles, since effective acceleration does not take place when the number of particles in the bunch is small. It follows that, at the present stage of technical development, at any rate, the method in question seems suitable for the production of ions of not too outstandingly high energies.

It should be stressed that formula (1) was deduced for a linear approximation of the plasma, and that it cannot, of course, be applied to high energy transfers although there is no doubt that the energy transfer coefficient can be made sufficiently high.

A most important problem in developing the proposed variant is that of the production and stability of the bunches. Whereas transverse stability is easily achieved with the aid of the electron beam space-charge, the bunch is unstable longitudinally. To achieve longitudinal stability, additional action is necessary, such as modulating the density of the electron beam. The modulated beam causes longitudinal focusing of the particles when they are in the density loop and defocusing when the bunch is in the density node. As shown by Rabinovich, focusing similar to that in strong-focusing accelerators occurs at definite ratios for electron beam density, modulation wave length and number of particles in the beam. It is important to note also that bunches which are not absolutely stable can be used if the acceleration time is very short. The particles in the bunch can be accelerated to high energies if the bunch alters its dimensions during acceleration time by a quantity which is small compared with the plasma wave length.

II. Coherent "impact" acceleration

The interaction mechanism between an electron beam and an ion bunch has been considered above. It seems reasonable to apply this mode of ion acceleration for producing high currents of accelerated particles when the ion energies sought are not very high. However, where the problem is to produce ions accelerated to maximum possible energies, it seems more promising, at least in principle, to use an alternative mechanism of coherent "impact" interaction based on the peculiar behaviour of relativistic particles. This may seem fantastic, but to my mind it might be a possible development.

Let us consider the collision of a fast relativistic particle of mass M_1 with a particle at rest the mass of which M_2 is substantially less than M_1 . It is well known that if the condition $M_1 \gg M_2 \gamma$ is fulfilled, the particle at rest will receive the following energy as a result of this "head-on" collision :

$$W \approx M_2 c^2 \cdot \gamma^2, \text{ where } \gamma = \frac{1}{\sqrt{1 - v^2/c^2}} \quad (3)$$

Let us now assume that the "primary" relativistic particle of mass M_1 consists of N_1 particles with mass m_1 and that the "secondary" particle similarly consists of N_2 particles of mass m_2 . If, during the time of impact, the internal degrees of freedom of such bunches are not excited to fairly high energies and if the condition $N_1 m_1 \gg N_2 m_2 \gamma$ is fulfilled and the impact is "head-on", then every particle of mass m_2 will gain energy (3) as a result of this collision.

For the collision to be "head-on", the impact parameter p must, of course, comply with the inequality :

$$p \ll B \text{ where } B = \frac{N_1 N_2 e^2}{m_0 c^2}$$

$$\text{As usual, } m_0 = \frac{m_1 m_2 N_1 N_2 \gamma}{(m_1 N_1 + m_2 N_2 \gamma)}$$

Let us now consider the condition in which all N_1 particles of mass m_1 constituting the "primary" particle moving with velocity v , and all N_2 particles of mass m_2 constituting the "secondary" particles, are concentrated in the spherical volume of radius $a \ll b$. In that case, obviously, we can ignore—at least quantitatively—the transfer of energy to the internal degrees of freedom of the bunches : in other words, we can consider the collision of two such bunches (of which one is at rest and the other possesses velocity $v \approx c$) as a collision of classical relativistic particles. With an impact of that kind, therefore,

* There is, of course, an inverse effect which has so far remained unnoticed. It has been pointed out by the author that a particle bunch (or a single particle) moving through an electron plasma placed in a magnetic field will emit Čerenkov radiation. This radiation might seemingly play a part in radio emission in the upper strata of the atmosphere of hot stars, which are characterized by strong magnetic fields. A detailed theoretical exposition on this point is given in a paper by A. A. Kolomenski¹).

a very high energy will be transferred to each particle of mass m_2 of the bunch at rest.

If, for instance, the bunch at rest “consists” of protons and the relativistic bunch of electrons (or protons) * with $\gamma = 10^2$, then each of the protons at rest will obtain the enormous energy of $W = m_p c^2 \cdot 10^4 = 10^{13}$ ev. as a result of the collision.

An essential point is that there is no necessity for the stable existence of super-dense bunches of relativistic particles.** All that is necessary is that the bunch should exist for a substantially longer period than the period of impact. Naturally, the absolute number of particles N_1 which have to be concentrated, even for a short time, in the relativistic bunch, must be very high. This circumstance, it seems, is the main difficulty in the way of carrying this very alluring idea into effect.***

III. Radiative acceleration of quasi-neutral particle bunches

Let us now consider acceleration of a particle bunch by an electromagnetic wave as another variant of the coherent method of acceleration which might permit an approach to the “impact” method.

One of the main difficulties as regards the coherent acceleration of charged bunches lies in the fact that the Coulombian repulsion of charges prevents the formation of bunches containing a sufficient number of charged particles. In the variant now being considered, however, use can be made of quasi-neutral bunches containing roughly equal numbers of ions (or positrons) and electrons²⁾.

Let us consider qualitatively the mechanism of acceleration of a bunch by a plane electromagnetic wave. As is known, an electron located in the field of a plane electromagnetic wave with an energy density $W = (E^2 + H^2)/8\pi$ is acted upon by an average force F_1 , directed along the wave propagation and equal to $F_1 = \sigma_T \cdot \bar{W}^{av}$ (4) where $\sigma_T = 8\pi r_0^2/3$ is the Thomson scattering cross-section and r_0 is the classical electron radius. The force F_1 is very small but if we have an electron bunch of radius a , the force acting on the bunch will be proportional to $N^2 \sigma_T$ where N is the number of electrons in the bunch. The force per electron thus increases N times. We assume, of course, that the following conditions are fulfilled :

$$K_1 a < 1 \text{ and } K_2 a < 1 \quad (5)$$

where K_1 and K_2 are the wave vector moduli in the surrounding medium and in the bunch respectively.****

The problem of bunch stability during the acceleration is not important.

Where the quasi-neutral bunch consisted of positrons and electrons, it would probably remain stable during acceleration, but if it contained ions and electrons the radiative forces would tend to detach the electrons from the ions. This action is opposed by Coulombian forces. Where the Coulombian forces of mutual attraction between the ions and electrons are greater than the radiative forces, it is possible, in this case also i.e. (in presence of the ions) that the whole bunch would be accelerated while remaining quasi-neutral. Rabinovich and Kovrizhnikh have shown that the action of the electromagnetic wave on the bunch in some cases produces a force which compresses the bunch in all directions.

The calculations so far made by Rabinovich, Kovrizhnikh and Iankov cannot be regarded as a satisfactory solution of the problem of determining how the bunch behaves in the field of the electromagnetic wave. The calculations are only in the nature of rough estimates which, nevertheless, permit an approximate determination of the magnitude of the accelerating force and a general idea of the stabilizing features.

The constant magnetic field H_0 directed along the axis Z (in the direction of the wave propagation) may have a substantial effect on the stability as well as on the magnitude of the accelerating force.

In order to produce bunch acceleration in practice, very great electromagnetic powers will be required—not less than in similar linear accelerators for high currents. However, the coherent method should permit the acceleration of bunches containing a very large number of particles—a result unobtainable by other methods. The anticipation is that it will be possible in due course to use these quasi-neutral bunches for “impact” acceleration.

The above remarks are in the nature of a qualitative exposition of physical principles underlying a new mecha-

* The impact of a relativistic bunch of electrons with a proton bunch at rest would, of course, produce a bremsstrahlung. However the latter would not have an adverse effect in all circumstances.

** Generally speaking the “secondary” bunch may consist of a single proton or of a small number of protons.

*** It is possible that the practical realisation of coherent “impact” interaction would be considerably facilitated if the polarized relativistic quasi-neutral bunch of plasma were used as the “primary particle”.

**** M. Rabinovich has shown that the above result is easily obtainable by treating the quasi-neutral bunch in the first approximation as a rigid dielectric sphere. The dielectric constant of such a sphere is equal to $\epsilon = 1 - (\omega_0^2)/\omega^2$ where ω is the frequency of forced oscillations and ω_0 is the “plasma frequency”. ($\omega_0^2 = 3.2 \times 10^9 N_1$, where N_1 is the number of electrons per cm^3). The same result was obtained by L. Kovrizhnikh, who calculated the action of an electromagnetic wave on a plasma sphere in a hydrodynamic approximation.

nism of acceleration and cannot, of course, be considered as fully worked out even as far as the main features are concerned.

We are also considering variants of coherent acceleration other than those discussed above.

It is interesting, in conclusion, to envisage the possibility of generating primary cosmic rays by one of the above-mentioned mechanisms. Radial fluxes of high velocity electrons can effectively transfer their energy to ion bunches

formed in the plasma of the upper strata of the atmosphere of hot stars. Unlike all known acceleration mechanisms, the energy acquired by the nucleus in this case proves proportional to Z^2 and not to Z .

The Čerenkov radiation of bunches moving inside a plasma placed in a magnetic field may, as mentioned earlier, be an essential factor in the radio-emission of stars. Neither of these possibilities has so far been taken into consideration by physicists.

LIST OF REFERENCES

1. Kolomenski, A. A. (Radiation of an electron moving uniformly in electron plasma placed in a magnetic field.) Doklady Akad. Nauk SSSR, 106, p. 982-5, 1956.
2. Veksler, V. I. (The use of coherent interaction of neutral bunches with an electro-magnetic wave.) (unpublished.)