Dc type particle acceleration by an rf field

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Abstract

Charged-particle acceleration by an electric field of constant strength corresponding to an $\underline{E}$ vector rotating perpendicularly to a static magnetic guidance field is calculated. Dc type acceleration can be achieved; in a modified version very short high-intensity pulses can be produced. The acceleration principle is suitable for heavy particles at low and medium energies. High-current accelerators economic and reliable in use should be possible.

1 INTRODUCTION

Accelerators for charged particles use either a static electric field or an electric rf field as driving force. A static field allows a genuine dc particle beam. The rf accelerators in use all need a phase correlation between particle beam and electric field $\underline{E}$. Hence there is a time microstructure in the beam.

It is the first goal of the present work to describe an acceleration principle that allows a true dc structure in the beam with the acceleration being accomplished by an rf field; in a modified version short pulses are produced. A second goal is the discussion of possible applications.

The basic principle is to apply an $\underline{E}$ field of constant strength E whose vector $\underline{E}$ rotates perpendicularly to a static magnetic field $\underline{B}$. The particles spiral with constant cyclotron frequency ω_c outward; hence $\underline{E}$ acts always in the direction of the particle velocity $\underline{v}$ (Fig. 1). As the principle is basically nonrelativistic, the treatment will also be nonrelativistic unless explicitly otherwise noted.

The acceleration principle described in this work has already been outlined to some extent in short communications [1]. However, no attention was paid to either orbit stability in space or applications other than those for muon catalyzed fusion.

Section 2 deals with the general principle and basic problems, in Section 3 several ways to use the method are described, and in Section 4 we discuss the advantages and disadvantages in comparison with techniques known up to now.

2 GENERAL PRINCIPLE

The acceleration principle described in this work is based on a magnetic field $\underline{B}$ constant in time and an electric rf field $\underline{E}$ whose vector rotates with constant angular velocity (frequency $\omega_{\rm rf}$). If we think, for sake of simplicity, of $\underline{B}$ to be uniform and of $\underline{E}$ to be at every moment also uniform, $\underline{E}$ shall be perpendicular to $\underline{B}$ (for deviations from uniformity cf. below in this Section). Particles with charge q starting perpendicularly to $\underline{B}$ stay in a plane A also per-

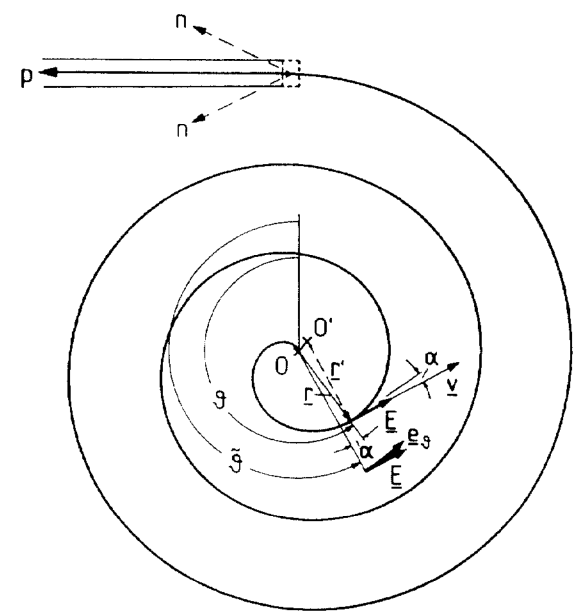

Figure 1: Sketch of the proposed design. Electric field $\underline{E}$ homogeneous in space but $\underline{E}$ vector rotating with constant angular frequency $\dot{\tilde{\vartheta}} = \omega_{\rm rf}$ around 0. Magnetic field $\underline{B}$ (in the simplest version adopted here) homogeneous and constant in time, perpendicular to plane (not indicated in drawing). Dashed lines: internal target and outgoing neutrons; this target not in place when beam of charged particles p is extracted. $\underline{r}$ and $\underline{r}'$: vectors from 0 and 0′ to momentary position of particle, respectively. α: angle between $\underline{v}$ (as well as $\underline{E}$) and $\underline{e}_\vartheta$ for particle at $\underline{r}$; simultaneously angle between ϑ and $\tilde{\vartheta}$ for particle and field, respectively. Spiral: numerical calculation of a proton trajectory starting at $t = 0$ in 0 in upward direction ($\vartheta = 0$) with $v(0) = 0$ for $E = 2\,{\rm MV/m}$, $B = 1\,{\rm T}$ and $\omega_{\rm rf} = 95.79\,{\rm MHz}$. Maximum values of radius r $r_{\rm max} = 0.4082\,{\rm m}$, velocity v $v_{\rm max} = 0.1370\,{\rm c}$ where c is the speed of light, spiral length 4.368 m and time $t = 0.21319\,\mu{\rm s}$. The calculation simultaneously confirmed that $\underline{v}$ always pointed in $\underline{E}$ direction. Strong $\underline{E}$ field chosen in order to obtain, for clarity of drawing, large orbit separation. In practice weaker $\underline{E}$ fields will be applied, with correspondingly smaller orbit separation.

pendicular to $\underline{B}$. The electric field is

$$\underline{E} = \underline{E}(t) = E\underline{e}_{\vartheta}[\tilde{\vartheta}(t)] \tag{1}$$

where $\underline{e}_{\vartheta}[\tilde{\vartheta}(t)]$ is a unit vector in ϑ direction in a cylindrical coordinate system r, ϑ, z, with $\tilde{\vartheta} = \omega_{\mathrm{rf}} t$ (cf. Fig. 1). The angular frequency ω_{rf} of $\underline{E}$ shall be constant:

$$\dot{\tilde{\vartheta}} = \omega_{\mathrm{rf}} = const. \tag{2}$$

$\underline{E}$ is applied to a particle of mass m that starts with kinetic energy $W_{\mathrm{k}} = 0$ at time $t = 0$ in the center 0. As we want $\underline{E}$ to point always in the direction of the velocity $\underline{v}$ we assume that this is fulfilled at $t = t_1$ and that

$$\omega_{\mathrm{c}} = \omega_{\mathrm{rf}} \tag{3}$$

holds. At a given moment $t_1 > 0$ the particle will be subject to two forces (in the laboratory reference frame): the force due to $\underline{E}$ along the direction of $\underline{E}$ and the force due to $\underline{B}$ perpendicular to the velocity $\underline{v}$ and the magnetic field $\underline{B}$. $\underline{v}$ and $\underline{B}$ yield a momentary rotation around a momentary center $0'$ (not identical with 0) with the angular velocity (not depending on the longitudinal acceleration)

$$\omega_{\mathrm{c}} = \frac{qB}{m}. \tag{4}$$

Hence the particle trajectory is turned around with just the same angular velocity as the $\underline{\mathrm{E}}$ vector. Because the angular velocity of a nonrelativistic particle in a magnetic field is a constant, we have the same ω_{c} for any time $t > t_1$.

Apparently the particle trajectory is for $t > t_1$ part of a branch of a spiral. We recognize the behavior of a particle starting at 0 (as pointed out with $W_{\mathrm{k}} = 0$ at $t = 0$) by considering the behavior of the time-reversed system. The time-reversed particle is assumed to move at t_1 with opposite velocity -$\underline{v}$. It will be decelerated by $\underline{E}$ and spiral inward. Finally it comes, for a moment t_0, to rest at 0 (immediately it will start to spiral outward along the "opposite" branch of the spiral but this does not matter here). We now turn back to our original particle starting in 0 at $t = 0$ with $W_{\mathrm{k}} = 0$ and being subject to $\underline{E}$. Apparently it moves in opposite direction to the time-reversed particle on the original branch of the spiral. Hence, eqs. (3) and (4) being fulfilled, the particle will always move along the branch of the spiral.

As the electric force $q\underline{E}$ acts always in the direction of the velocity $\underline{v}$, the particle momentum p and kinetic energy W_{k} increase linearly and quadratically with time t, respectively:

$$p = qEt \qquad W_{\mathrm{k}} = \frac{q^2E^2}{2m}t^2. \tag{5}$$

In practice $\underline{E}$ and $\underline{B}$ need not to be uniform. As in the case of the isochronous cyclotron it will be sufficient that the values averaged over an azimuthal angle $\Delta\vartheta = 2\pi$ yield approximately the correct values of ω_{c} and ΔW_{k}, respectively,

$$\omega_{\mathrm{c}} \approx \frac{q < B >}{m} \qquad \Delta W_{\mathrm{k}} \approx 2\pi < r > q < \underline{E} \cdot \frac{\underline{v}}{v} > \tag{6}$$

where ΔW_{k} is the energy gain in one turn. This enables us to obtain axial stability of the trajectories in the same way as in the isochronous cyclotron. Similarly a relativistic mass increase can be accounted for by a certain increase of $< B >$.

A rotating-$\underline{E}$-vector field of constant field strength in the center 0 can be produced by four electrodes supplied with sinoidal voltages of equal amplitudes and phases differing by $\pi/2$ [1]. Around 0 we shall find approximately correct $\underline{E}$ values and almost correct $< \underline{E} >$ values. As we are in the nonrelativistic regime we need not to worry about the magnetic fields correlated to $\underline{E}$. A more sophisticated set-up producing the desired rotating-$\underline{E}$-vector field within any given limits over a large volume is achieved by applying a (large) number of long bars in $\underline{B}$ direction as electrodes all on the mantle of a cylinder of radius r exceeding the maximal radius reached by the particles while orbiting within $\underline{B}$. These electrodes are then fed by rf-voltages varying evenly within an azimuth of 2π over a phase of 2π; if one wants to shorten the set-up one can use electrodes similar to staves building up a barrel.

3 APPLICATIONS

Some features of the proposed acceleration method which are important for possible applications shall be summarized:

1. With a continuously emitting ion source in the center 0 the electric current within the accelerator is a genuine dc-type current.
2. The electric and particle currents hitting an electrode (or target), for example shaped as a concentric ring around 0, are of genuine dc type.
3. With an extended target behind an extraction channel of correct length (cf. Fig. 1) the electric and particle currents hitting the target are also genuine dc-type currents.
4. The electric current on the target as in # (3) corresponds to a saw-tooth voltage.
5. The energy plot $W_{\mathrm{k}} = W_{\mathrm{k}}(t)$ of the particles hitting the target has a saw-tooth shape.
6. With a radially extended internal target the particle and electric currents at this target are extremely sharply pulsed in time.
7. With a pulsed ion source in the center 0 the electric and particle currents hitting the target as in # (3) will be pulsed according to the ion source pulsing.
8. The use of a pulsed ion source enables us to extract the beam by standard methods, e.g. by an electrostatic deflector with septum foil.

The proposed acceleration principle will be particularly applicable for heavy particles at low and medium energies. The extracted beam may be expected to be of excellent quality although it is not monoenergetic. However, the energy is strictly correlated to time. Hence the energy is very well known at any moment.

The electric losses in an accelerator are proportional to E^2 but the energy gain is proportional to E. The proposed scheme allows low E. Hence it is extremely economic. As there is no time structure in the internal beam that is of basic importance for the acceleration scheme to work, space charge should not be a serious problem even in the case of a high-current accelerator.

4 DISCUSSION

The proposed acceleration principle is basically different from all acceleration principles known so far. We may consider the fact that particles can be accelerated in the dc mode in proportion to the applied rf field as an interesting fact of its own. It has some analog in unipolar induction.

The above intellectual point does not mean that practical application is excluded or unlikely. On the contrary one may envisage a broad band of future applications:

a Low or medium energy accelerator for research.

b Medium energy accelerator as injector for a high-energy accelerator.

c Low or medium energy accelerator for isotope production and radiation treatment.

d Medium energy accelerator for a neutron source needed for an inherently safe fission reactor [2].

The expected extremely sharp pulse at a radially extended target (# 6 of the foregoing section) may be very advantageous for nuclear physics applications.

Today's linear accelerators and isochronous cyclotrons operate with strong electric fields: linear accelerators to limit the necessary length and isochronous cyclotrons to ensure orbit separations large enough for efficient beam extraction. This makes them not only non-economic but also unreliable and not to easy to operate. An accelerator built according to the acceleration principle proposed here needs no strong electric fields. Hence it is expected to share the advantage of economy with that of easy and very reliable operation. The latter point is particularly important for medical and industrial applications [(c) and (d) in the above listing].

A disadvantage of the proposed acceleration principle is the lack of any development and practical experience.

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5 REFERENCES

[1] H. Daniel, "A new acceleration principle for μ revitalization", Proc. Int. Symp. on Muon and Pion Interactions with Matter, Dubna, USSR, July 1987, pp. 233-234.
H. Daniel, "Can we reactivate sticking muons ?", SIN Newsletter, vol. 20, pp. 46-47 (1988).
H. Daniel, "A new form of accelerator for charged particles", Nucl. Instr. Meth., vol. A 268, p. 273 (1988).
H. Daniel, "'Cheap' muon production and artificial muon reactivation", Muon Catalyzed Fusion, vol. 5/6, pp. 335-347 (1990/91).

[2] H. Daniel and Yu.V. Petrov, "Feasibility study of an inherently safe subcritical fission reactor", Petersburg Nuclear Physics Institute, Gatchina, Russia, Preprint 1892 (1993).