IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

COLLECTIVE ELECTROSTATIC SUPER-ACCELERATOR

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Summary

A new accelerator concept with the potential to reach order of magnitude larger particle energies is proposed. In the concept a large cylindrical cloud of charged particles is radially injected and compressed inside a long solenoid by a rising magnetic field. The cloud is permitted to expand axially and as a result, the particles positioned near the head of it attain very large energies. If the compressing magnetic field rises to $\sim 10^5$ G in about $\sim 10^{-5}$ sec, and if the solenoid is $\sim$ 10 km long, the attainable particle energies are $\sim 10^{13}$ eV, and if two expanding clouds collide the equivalent stationary target energies for electrons are as large as $\sim 10^{20}$ eV and for protons $\sim 10^{17}$ eV. Using megagauss magnetic flux compression techniques the attainable particle energies can reach $\sim 10^{14}$ eV, with equivalent colliding beam energies of $\sim 10^{22}$ eV for electrons and 10^{19} eV for protons.

Detailed Description

To study the basic properties of matter requires the availability of ever higher particle energies. We therefore propose here an entirely new accelerator concept explained in Fig. 1. As shown in the radial cross section, Fig. 1a, a cloud of electrons or ions is radially injected and compressed by a solenoidal magnetic field rising in time. By the buildup in electric space charge the radially confined and compressed cloud expands axially, with more charges continuously injected as the head of the expanding cloud moves down the solenoid (see Fig. 1b). The front of the rising magnetic field is thereby programmed in such a way, that it travels down the solenoid with its phase velocity equal to the expansion velocity of the cloud. For the feasibility of this concept the phase velocity of the travelling magnetic field does not have to match precisely the expansion velocity, because of the strong selfconfining azimuthal magnetic field produced by the expanding cloud. The axial electric field in the cloud is large only near its two ends, falling off rapidly in an axial direction towards its center. It is for this reason that the particles positioned at the head of the cloud will be primarily accelerated to high energies. With a maximum magnetic field of $\sim 10^5$ Gauss, the electric field at the front end of the cloud can be as large as $\sim 10^7$ V/cm and it therefore follows that with an accelerator of this type which is 10 km long energies of $\sim 10^{13}$ eV could be reached. For two colliding clouds this would result in an equivalent energy of $\sim 10^{20}$ eV for electrons and of $\sim 10^{17}$ eV for protons.

To produce the travelling magnetic field along the accelerator requires to discharge a series of capacitors or magnetic storage devices along the entire length to the accelerator. The radial injection of the charges and subsequent magnetic compression is here done in a very similar way as in the HIPAC device[1].

To obtain some quantitative estimates we first have to know the dependence of the axial electric field within a cylindrical cloud of charged particles. Assuming that the particles are uniformly distributed within the cloud and introducing a cylindrical coordinate system with the position z = 0 at the one end and the position $z = z_0$ at the other end of the cloud, one finds by a simple approximate calculation that the axial electric field E_z for $z < z_0$ near the position $z = z_0$, is

$$E_z \simeq \frac{\pi r^2 ne}{z_0 - z + r} \qquad \text{[esu]} \qquad , \qquad (1)$$

where r is the radius of the cloud and n its number density of particles with the charge e. The field reaches its maximum E_{max} for $z = z_0$, given by

$$E_{max} = \pi rne \qquad \text{[esu]} \qquad , \qquad (2)$$

and which is about the same as the field of a uniformly charged sphere of radius r. Instead of eq. (1) we write

$$E_z = \frac{r}{z_0 - z + r} E_{max} \qquad . \qquad (3)$$

According to eq. (3), the axial electric field falls off rapidly for $\Delta z = z_0 - z > r$. Therefore the axial electric field is large only near the head of the cloud and which is the reason why the electric repulsion axially expanding the cloud selectively converts electrostatic energy stored in it into kinetic energy of the few particles positioned at its head. The electric energy is primarily stored in the radial electric field component

$$E_r = 2\pi ner \qquad . \qquad (4)$$

The maximum particle number density in the cloud is determined by the two conditions for magnetic insulation[2] requiring that

$$E_r \leq 0.62 H_z \qquad , \qquad (5)$$

and

$$\omega_p^2 < 2\omega_c^2 \qquad . \qquad (6)$$

H_z is the externally applied magnetic field rising in time, ω_p is the plasma frequency and ω_c, the cyclotron frequency. From inequality (5) it follows

$$n \leq \frac{0.62 H_z}{2\pi er} \qquad , \qquad (7)$$

and from inequality (6)

$$r > \frac{E_r}{H_z} \frac{mc^2}{eH_z} \qquad . \qquad (8)$$

Combining (5) and (8) yields

$$r > 0.62 \frac{mc^2}{eH_z} \qquad . \qquad (9)$$

For electrons this is $r \gtrsim 10^3/H_z$ and for protons $r \gtrsim 2 \times 10^6/H_z$. For $r \sim 1$ cm this is easy to satisfy for electrons. For protons it could still be satisfied with $H_z \sim 3 \times 10^5$ G leading to $r \sim 10$ cm, still a reasonable value.

For the axial velocity within the cloud we assume an uniform expansion model of the form

$$v_z = v_{max} \frac{z}{z_0} \qquad , \qquad (10)$$

where v_z is the average axial expansion velocity at the position $z < z_0$. The uniform expansion model incorporates the assumption of uniform cloud density, which according to eq. (4) implies a constant radial electric field, because if $\partial n/\partial z = 0$ then also $\partial E_r/\partial z = 0$.

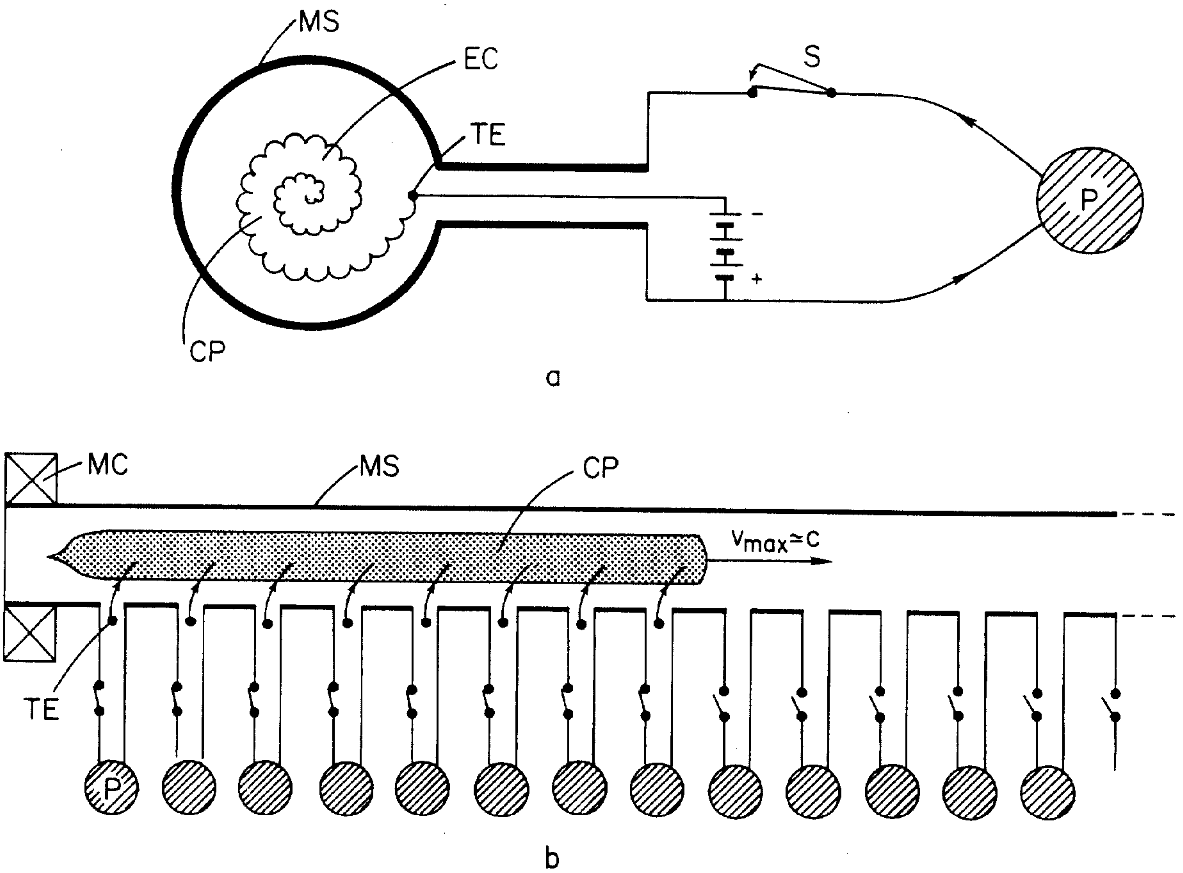

Fig. 1. a radial and b axial cross section: MS magnetic solenoid, CP charged particle cloud in particular electron cloud EC, TE thermionic emitter, S switch, P power supply, MC magnetic mirror coil.

Furthermore, assuming $\partial n/\partial r = 0$ and steady state with $\partial n/\partial t = 0$, continuity requires that

$$\frac{1}{r}\frac{\partial}{\partial r}(rv_r) + \frac{\partial v_z}{\partial z} = 0 \quad . \tag{11}$$

With eq. (10) one then obtains from eq. (11)

$$v_r = -\frac{1}{2}\frac{r}{z_0}v_{max} \quad , \tag{12}$$

or since $v_{max} \simeq c$, one simply has

$$v_r/c \simeq -(1/2)(r/z_0) \quad . \tag{13}$$

According to eq. (13) the radial injection velocity, required to keep a constant charge density in the cloud, is rather low, which is significant since it permits slow inductive charging of the cloud.

The energy of the particles in the expanding cloud is given by

$$\varepsilon_z = (1 - v_z^2/c^2)^{-\frac{1}{2}}\varepsilon_0 \quad , \tag{14}$$

where $\varepsilon_0 = mc^2$. Using eq. (10) this is

$$\varepsilon_z = [\gamma_{max}^2 - (\gamma_{max}^2 - 1)(z/z_0)^2]^{-\frac{1}{2}}\varepsilon_{max} \quad , \tag{15}$$

where $\gamma_{max} = (1 - v_{max}^2/c^2)^{-\frac{1}{2}}$ and $\varepsilon_{max} = \varepsilon_0\gamma_{max}$. Near the position $z = z_0$ eq. (15) can be approximated as follows

$$\varepsilon_z \simeq [1 + 2\gamma_{max}^2(1 - z/z_0)]^{-\frac{1}{2}}\varepsilon_{max} \quad . \tag{16}$$

The distance $\Delta z = z_0 - z$, where $\varepsilon_z = (1/10)\varepsilon_{max}$ is $\Delta z \simeq 50\gamma_{max}^{-2}z_0$. For electrons $\gamma_{max} \sim 10^7$ and for protons $\gamma_{max} \sim 10^4$. It thus follows that in the uniform expansion model the particle energy is strongly peaked towards the end of the cloud, which, in conjunction with the strongly peaked axial electric force, is a justification for the uniform expansion model as a first approximation.

The electric current at the head of the expanding cloud is given by

$$I = \pi r^2 nev_{max} \simeq \pi r^2 nec = \frac{rc}{2}E_r \quad , \tag{17}$$

or using inequality (5)

$$I \lesssim 0.62(rc/2)H_z \quad . \tag{18}$$

The azimuthal magnetic field produced by this current is $H_\phi = 2I/rc$ and one finds that

$$H_\phi \lesssim 0.62 H_z \quad . \tag{19}$$

This strong selfmagnetic field ensures good radial confinement for the head of the cloud even if the traveling magnetic wave, externally producing H_z, is with it not in perfect phase. Since for $z < z_0$, H_ϕ is proportional z/z_0, it also helps to confine the cloud for $z < z_0$ at positions z where in the traveling magnetic wave H_z has not yet reached its maximum value.

The externally applied magnetic field rising in time induces an azimuthal electric field E_ϕ computed from Maxwell's equation

$$E_\phi = -\frac{r}{2c}\dot{H}_z \quad , \tag{20}$$

which in conjunction with the axial magnetic field leads to a radial drift motion

$$v_r = c\frac{E_\phi}{H_z} = -\frac{r}{2}\frac{\dot{H}_z}{H_z} \quad , \tag{21}$$

and which, in order to satisfy continuity, has to be set equal to the radial velocity given by eq. (13). This results in

$$\dot{H}_z/H_z = c/z_o \quad . \tag{22}$$

Eq. (22) gives the characteristic rise time τ_H of H_z

$$\tau_H = H_z/\dot{H}_z = z_o/c \quad . \tag{23}$$

For $z_o \simeq 10^6$ cm one finds $\tau_H \sim 3 \times 10^{-5}$ sec, and which is sufficiently long to use cheap magnetic energy storage devices.

Superimposed on the radial drift motion is an azimuthal, one, which, using inequality (5), is

$$v_\phi = c\frac{E_r}{H_z} \lesssim 0.62c \quad . \tag{24}$$

The resulting particle motion in the rϕ plane is hence a spiraling cycloid as shown in Fig. 1a. The azimuthal drift motion leads to a large angular momentum which permits to confine the cloud at the end of the solenoid by a magnetic mirror field with $H > H_z^{max}$.

The total beam current can be estimated by inequality (18):

$$I \leq 0.62 \times 5rH_z \quad [A] \quad . \tag{25}$$

Assume that $r \sim 1$ cm and $H_z \sim 10^5$ G, it follows that $I \sim 3 \times 10^5$ A. In a steady state situation a radial current has to be supplied by inductive charging. The density of this charging current is given by

$$j_r = \frac{I}{2\pi r z_o} \quad . \tag{26}$$

For the above given values of I, r and z_o one finds $j_r \sim 5 \times 10^{-2}$ A/cm^2. This low value suggests to use thermionic emitters along the entire accelerator.

Eliminating n from eq. (2) by inequality (7) and putting $H_z = H_z^{max}$ we have

$$E_{max} = 0.31H_z^{max} \quad . \tag{27}$$

The maximum particle energy over the distance z_o is then given by

$$\varepsilon_{max} = eE_{max}z_o = 0.31eH_z^{max}z_o$$

$$\simeq 10^2 H_z^{max} z_o \quad [eV] \quad . \tag{28}$$

If we assume that $H_z^{max} = 10^5$ G and $z_o = 10^6$ cm, we find $E_{max} \sim 10^7$ V/cm and $\varepsilon_{max} = 10^{13}$ [eV]. For electrons this corresponds to $\gamma_{max} \sim 10^7$ and for protons to $\gamma_{max} \sim 10^4$, which for two clouds colliding head on corresponds to stationary target energies $\sim 10^{20}$ eV for electrons and $\sim 10^{17}$ eV for protons.

With 10^{13} eV and a current of $\sim 3 \times 10^5$ A the beam power is $\sim 3 \times 10^{18}$ Watt. Since the highly energetic particles are positioned within a segment of the cloud of the order $\Delta z \sim r \sim 1$ cm, the beam pulse lasts for $\tau \sim z/c \sim 3 \times 10^{-11}$ sec with a total pulse energy of $\sim 10^7$ Joule. The particle number density in the beam is $n \sim 10^{13}$ cm^{-3}.

With repetitive implosive flux compression techniques, megagauss magnetic fields can be produced[3]. In this case $H_z^{max} = 10^6$ G, making $E_{max} \simeq 10^8$ V/cm and $\varepsilon_{max} = 10^{14}$ eV. The maximum γ-value for electrons is here $\gamma_{max} \sim 10^8$ and for protons $\gamma_{max} \sim 10^5$, corresponding to stationary target energies of 10^{22} eV and 10^{19} eV. To generate the pulsed megagauss magnetic fields by flux compression techniques inertial confinement fusion thermonuclear microexplosion reactors could be used as the primary energy source. Since the fireball of a thermonuclear microexplosion expands with a very high speed, typically 10^7 - 10^8 cm/sec, very large pulse power by magnetohydrodynamic energy conversion is here attainable. Therefore, a marriage of inertial confinement fusion and high energy particle accelerator techniques may at an affordable prize open up energies about $\sim 10^6$ times higher than presently possible. This may have a profound impact on the future of high energy physics.

As a final remark we would like to mention that a circular accelerator also based on the HIPAC concept but using induced electric fields rather than space charge fields was previously proposed by N. Rostoker at al.[4]. However, it does not promise the enormous particle energies predicted in our scheme. Its purpose was rather to serve as an energy storage device.

References

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