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A COLLECTIVE ACCELERATOR AS ION SOURCE AND INJECTOR FOR A HEAVY-ION CYCLOTRON

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Summary

Experiments at several laboratories have demonstrated that collective accelerators can produce short pulses of ions with peak energies of several MeV per nucleon and peak currents in the range of 1 to 10^3 A. A particularly promising approach is the use of lasers to produce high density plasmas from solids with heavy ions of high charge state, which are then accelerated by collective effects to energies above 1 MeV/nucleon. Such a collective accelerator could be used as a combination of ion source and injector for a heavy-ion cyclotron. The ions, after passage through a stripper foil, would be accelerated in the cyclotron as single pulses, and the number of ions per second would depend on the space-charge focusing limit of the cyclotron and the repetition rate of the collective accelerator. A formula for the space-charge limit of the cyclotron for high instant beam currents is derived, and estimates of the particle intensities that could be expected are presented.

1. Introduction

Recent experiments at the University of Maryland[1-3] and at several other places[4-8] have demonstrated that copious numbers of energetic ions with energies of several MeV per nucleon can be produced by collective acceleration effects in intense relativistic electron beams (IREB). Luce, for instance, who pioneered the so-called "Luce diode",[6] which so far has produced the highest energy ions, reports the acceleration of protons to 45 MeV, and carbon, nitrogen, and fluorine ions to 7 MeV per nucleon.[7] In similar experiments at the University of Maryland with a less powerful IREB generator, proton energies of 16 MeV[1] and N, C, F ion energies of over 50 MeV were achieved.[3] Due to the pulsed nature of the electron beams, the ions are generated in short bunches. Thus, in the Maryland experiments, the proton beams had a pulse width of about 4 ns with a current peak of several kiloamperes. (However, due to the large energy distribution, the useful fraction of particles with energies near the peak of 16 MeV is probably more in the range of 100 A.) From existing experimental data, one can deduce[9] that the pulse width increases with the mass of the accelerated ions while the peak current decreases. Also, due to the nature of the collective effects, the ions with the highest charge state are preferentially accelerated in the moving space-charge well of the electron beam. Moreover, by generating the ion plasma with a laser beam, it should be possible to control the acceleration process and obtain ions of elements much heavier than those accelerated so far. No measurements of the phase-space characteristics of the ion beams from collective accelerators have been made yet. However, in view of the large number of particles available, there should be no problem in selecting a sufficiently intense bunch of ions with a well-defined small phase-space volume by standard techniques.

The successful demonstration of collective effect acceleration in various experiments raises the question of possible future developments and applications of devices that are based on these principles. Thus, one could use a collective accelerator either alone when only modest energies are required (in ion implantation, for instance) or as a combined ion source/injector for another accelerator that increases the energy to the desired range. One such latter possibility is the heavy-ion cyclotron where a collective accelerator could either replace or augment the tandem or injector cyclotron. In the following, we will examine a few aspects of this particular application. First, we will briefly discuss the basic principle of the special type of collective accelerator that appears to be most promising for use with a cyclotron. Then, in the last section, we will study the space-charge limit of a cyclotron that would apply to the single bunches with high peak current injected from a collective accelerator. (The space-charge theory is, of course, not restricted to this particular application but should be of general interest with regard to the old question of the current limit in a cyclotron.)

2. Basic Principle of the Collective Accelerator

There is a large variety of collective acceleration methods that have been proposed or that are currently being studied. A discussion of these different methods is beyond the scope of this paper. We will concentrate instead on the acceleration scheme that at present appears to be the most promising and suitable for use as a cyclotron injector. This is the method in which an intense relativistic electron beam is injected through a plasma in the anode aperture into a vacuum drift tube. It was first successfully demonstrated by Luce at Livermore, who placed a piece of insulating material into the anode of the IREB diode and used the bombardment by the beam front of the fast electron pulse to create the ion plasma. This method is now being studied and further developed by our group at the University of Maryland in a parallel effort to the electron ring accelerator (ERA) project. (The ERA injector is suitable for both types of experiments.)

The description of this collective accelerator will focus on the basic features rather than on technical details. Furthermore, it will be interesting and helpful to the understanding if its operation is compared with that of a conventional ion source. Let us therefore digress for a moment and recall the characteristics and limitations of a conventional ion source with which we are all familiar and which are shown in Fig. 1(a). The ions are produced in the plasma of an arc discharge and extracted by the electric field due to potential difference V_a between the extraction (or "puller") electrode and the ion source "chimney." The ion current density is usually space-charge limited (the potential variation between source and puller is shown schematically in the figure) and is given by Child's law:

$$J = 1.73\, V_a^{3/2} d^{-2} \sum_i (Z_i/A_i)^{1/2}\ \mathrm{mA/cm^2} \qquad (1)$$

where Z_i, A_i are the charge states and mass numbers of the various ion species contained in the beam, d is the gap spacing in cm, and V_a is the extraction voltage in kV. The parameter range for V_a and d, and hence the current density J, are restricted by electrical breakdown effects. Conventional sources operate

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below the breakdown limit

$$V_{B[kV]} = k\sqrt{d_{[cm]}}\ , \quad (k \approx 100)\ , \tag{2}$$

which necessitates a compromise between achieving high luminosity (small d) and sufficient focusing (high V_a). In heavy-ion sources, the output current drops rapidly for higher charge states from 10^{-3} A for light ions with charge state Z = 1 to the range of 10^{-4} to 10^{-6} A for heavy particles with high charge state (Z ≈ 10-12 is about the upper limit for conventional sources).

Figure 1(b) illustrates schematically the operating characteristics of the collective ion accelerator. An intense relativistic electron beam passes through the ion plasma into a vacuum drift tube. The electrons are produced by field emission in a diode which operates above the breakdown limit (2) at voltage V_o in the range of 1 MV or higher. This explains why electron beam currents in the range of 10 to 100 kiloamperes are achieved. At the same time, the electrical breakdown mechanism used to obtain these high currents limits the pulse width of the electron beam to the range of 20 to 100 ns. As the electron beam passes through the plasma behind the anode, it builds up a deep potential well due to its own space-charge on the downstream side of the plasma. If the electron beam current I_o is greater than the limiting value,

$$I_L = \frac{17{,}000(\gamma_o^{2/3} - 1)^{3/2}}{1 + 2\,\ln(a/b)} \quad \text{Amps.} \tag{3}$$

where $\gamma_o = 1 + eV_o/m_oc^2$, the depth of the space-charge well becomes comparable to, or greater than, the kinetic energy, eV_o, and the beam cannot propagate. A dynamic equilibrium is then established in which some fraction of the electrons passes down the drift tube while the majority of the particles are reflected back into the plasma region. The variation of the potential along the axis of the beam (from the cathode down into the drift tube) is schematically shown in Fig. 1(b). By comparison with Fig. 1(a), we see that here the space-charge well takes the function of the extraction electrode in a conventional ion source. A strong electric field E is established at the plasma surface, and, using a one-dimensional theoretical model, one obtains the expression

$$E = 2.77 \times 10^{-2}[(\gamma_o^2 - 1)^{1/2} J_o]^{1/2} \quad \text{MV/m}\ , \tag{4}$$

where J_o is the electron current density in A/m^2. This strong field, which is in the range of 100 to 500 MV/m, extracts and accelerates positive ions from the plasma. As these ions partially neutralize the electron space-charge near the plasma surface, the potential well and the associated electric field move with the ion bunch, as indicated in the figure. It takes only a few cm where the ions see an effective electric field given by (4) to obtain kinetic energies of several MeV. This, in short, is the principle of the collective ion acceleration mechanism as it is presently understood in a more qualitative than quantitative way. Many aspects still remain to be investigated and clarified. This general picture explains why the ions with highest charge state and lowest mass are preferentially accelerated. As was already pointed out, the type of ion species and charge state desired can be controlled by generating the plasma with a laser beam (or some other external means) rather than with the electron beam itself as was done in most experiments so far. Also, it should be mentioned that by using special insulated electrodes or a slow-wave structure in the drift tube downstream from the plasma one can increase the achievable ion energy appreciably. Further details may be found in the references on collective ion acceleration.

3. Cyclotron Current Limit

The ion beam from the collective accelerator would be injected into the cyclotron as a single pulse with a repetition rate of between 1 to 100 Hz. By debunching, one could stretch the ion pulse length and fill perhaps two to three rf buckets each time. In any case, the particle intensity will be determined by the space-charge limit of the cyclotron (which depends on the charge state of the ions after the beam passed through the stripping foil) and the number of pulses per second. A theoretical estimate of the space-charge limit is simplified by the fact that there are no ion bunches on neighboring orbits. To calculate this limit, the smooth-approximation presented in a recent paper on focusing of intense beams[10] (which is somewhat different from the approach used in the 1966 paper[11]) will be employed.

We start with the K-V equations for the envelopes of the ion bunch. The beam cross section is an ellipse with uniform particle density and minor radius x_m = a in the radial direction and z_m = b in the axial direction (see Fig. 2). It is assumed that there are no ion bunches on neighboring orbits, and longitudinal (azimuthal) space-charge effects as well as image forces due to the conducting boundaries at z = ±h will be neglected for the purpose of this estimate. Furthermore, we ignore the ripple in the beam envelope due to the azimuthal variation of the focusing force or due to possible mismatch conditions. The K-V equations for a matched beam may then be written in the form

$$\kappa_r x_m - \frac{2K}{x_m + z_m} - \frac{\varepsilon_r^2}{x_m^3} = 0\ , \tag{5}$$

$$\kappa_z z_m - \frac{2K}{x_m + z_m} - \frac{\varepsilon_z^2}{z_m^3} = 0\ . \tag{6}$$

The first term in both equations represents the focusing force, the second the space-charge defocusing, and the last the effect of the emittance, $\varepsilon_r\pi$ and $\varepsilon_z\pi$, in both transverse directions. If R denotes the orbit radius, ν_r and ν_z the radial and axial frequency tunes, we have

$$\kappa_r = \nu_r^2/R^2\ , \quad \kappa_z = \nu_z^2/R^2\ . \tag{7}$$

The parameter K is proportional to the perveance of the beam and, in the nonrelativistic limit that is applicable here, it is defined in terms of instantaneous beam current I, kinetic energy W, charge state Z, and mass number A by

$$K = 6.5 \times 10^{-4}\,\frac{Z^2}{A}\,\frac{(I/Z)_{[A]}}{(W/A)^{3/2}_{[MeV]}}\ . \tag{8}$$

Note that I is the electric current while I/Z is the particle current.

Equations (5),(6) can be solved numerically for the envelopes x_m and z_m. In the zero-intensity (K→0) and the zero-emittance (ε→0) limits, one gets the analytical results

$$\frac{x_m}{z_m} = \xi = \left(\frac{\varepsilon_x\nu_z}{\varepsilon_z\nu_r}\right)^{1/2} \quad \text{for } K = 0\ , \tag{9}$$

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$$\frac{x_m}{z_m} = \xi = \frac{\nu_z^2}{\nu_r^2} \qquad \text{for } \varepsilon_r = \varepsilon_z = 0 \ . \tag{10}$$

Since in cyclotrons usually $\nu_z < \nu_r$, we see from (10) that for high-intensity beams the ratio $\xi = x_m/z_m$ is significantly less than unity. Thus, we are justified in neglecting x_m in Eq. (6), which then allows us to solve analytically for the space-charge parameter K yielding

$$K = \frac{1}{2}\,\kappa_z z_m^2 [1 - (\varepsilon_z/\alpha_z)^2] \ . \tag{11}$$

Here, α_z denotes the axial phase-space acceptance of a cyclotron defined as

$$\alpha_z = \sqrt{\kappa_z}\, z_m^2 = \frac{\nu_z}{R} h^2 \ , \tag{12}$$

where 2h is the aperture available for the beam (see Fig. 2). Our main interest is to estimate an upper limit for the instantaneous beam current that can be focused in the space-charge dominated regime where $\varepsilon_z \ll \alpha_z$. Neglecting the factor $(\varepsilon_z/\alpha_z)^2$ in the bracket on the right side of Eq. (11), setting $z_m = h$, and using Eqs. (8) for K and (7) for κ_z, we obtain the result

$$I_{[A]} = 0.77 \times 10^3\ \nu_z^2 \left(\frac{h}{R}\right)^2 \frac{A}{Z} \left(\frac{W}{A}\right)^{3/2}_{[MeV]} \ . \tag{13}$$

As indicated, current I is in amperes and W/A is the kinetic energy per nucleon in MeV. Z is the charge state of the ions after passage of the beam through the stripping foil.

The relationship between orbit radius R, magnetic field B, and kinetic energy W is given by the formula

$$R_{[m]} = 0.144\ \frac{A}{Z}\ \frac{(W/A)^{1/2}_{[MeV]}}{B_{[T]}} \ . \tag{14}$$

By substituting (14) into (13) we could get a formula that expresses the current limit in terms of the magnetic field rather than the radius. However, the initial radii are usually fixed by other considerations and Eq. (13) will thus be more useful.

The average equilibrium charge state $\bar{Q}$ of ions after passage through a solid stripping foil may be calculated by the formula of Nikolaev and Dmitriev[12] (see the extensive review by Betz[13]), which may be written in the form

$$\frac{\bar{Q}}{Z_A} = \left[1 + \left(\frac{3.86\sqrt{W/A}_{[MeV]}}{Z_A^{0.45}}\right)^{-1/0.6}\right]^{-0.6} \ , \tag{15}$$

where Z_A is the atomic number. For crude calculations in the case of heavy ions where A > 20, one can use the approximation

$$\bar{Q} \approx 3.6\ A^{0.45}\sqrt{W/A}_{[MeV]} \ . \tag{16}$$

Taking this formula for $Z = \bar{Q}$ in Eq. (14), one gets the simple relation for the injection radius

$$R_{[m]} = 4 \times 10^{-2}\ A^{0.55}/B_{[T]} \ . \tag{17}$$

The three equations (13), (14), (15) or (13), (16), (17) allow one to calculate the space-charge limit for the beam current in a heavy ion cyclotron with solid stripper foil. If $T = 2\pi/\omega_c$ denotes the cyclotron period, n_b the number of bunches (1 to 3) injected each cycle, $\Delta\phi$ the phase width of the ion bunch, and f the repetition frequency of the injector, the number of ions per second is given by

$$N_i = \frac{I/Z}{e}\ \frac{\Delta\phi}{2\pi}\ T\ n_b\ f \ , \tag{18}$$

where $e = 1/6 \times 10^{-19}$ C. The cyclotron period is obtained from the relation

$$T_{[S]} = 6.5 \times 10^{-8}\ \frac{A}{Z}\ \frac{1}{B_{[T]}} \ . \tag{19}$$

Following are two examples that illustrate what instantaneous currents and total number of particles can be expected for a typical set of parameter values. Assume that in each case $\nu_z = 0.3$, h = 0.02 m, $\Delta\phi/2\pi = 0.1$, $n_b = 1$, f = 50 Hz. In the first case, we take a beam of calcium ions of 4 MeV per nucleon, in the second iodine of 1 MeV per nucleon.

<u>Case 1</u>: $_{40}Ca^{20}$, $Z_A = 20$, A = 40, W/A = 4 MeV/amu.

The average charge state after stripping is found from (15) to be $\bar{Q} = Z \approx 17$. Let the injection radius be R = 0.15 m, with B = 4.5 T (we assume a superconducting cyclotron). We then find from (13) for the instantaneous particle current the value

$$I/Z = 0.6 \text{ A} \ .$$

The cyclotron period is $T = 34 \times 10^{-9}$ s, the number of ions per bunch is 1.28×10^{10}, and the total number of ions per second (with $n_b = 1$, f = 50 Hz) is

$$N_i = 6.4 \times 10^{11} \quad [s^{-1}] \ ,$$

which compares well with the number expected from a tandem/cyclotron.

<u>Case 2</u>: $_{127}I^{53}$, $Z_A = 53$, A = 40, W/A = 1 MeV/amu.

Here one finds $\bar{Q} = Z \approx 27$, and for R = .15 m, B = 4.5 T, the instantaneous particle current limit is

$$I/Z \approx 0.1 \text{ A} \ .$$

The cyclotron period is 68×10^{-9} s in this case, the number of ions per bunch 0.8×10^{10}, and per second $N_i = 4 \times 10^{11}$ $[s^{-1}]$, which again is a reasonably high number that compares well with the expected values for heavy ion cyclotrons.

4. Conclusion

Collective accelerators are capable of producing high-intensity beams of heavy ions with energies in the range of several MeV per nucleon. They thus combine the features of an ion source with those of a pre-accelerator, which makes them very attractive as possible future injectors into heavy-ion cyclotrons. The ion beams are generated in short single bunches with high peak current, and thus the number of ions per second depends on the cyclotron space-charge focusing limit and the repetition rate of the collective accelerator. A formula for the current limit in the cyclotron was derived, and estimates indicate that (with repetition rates between 10 and 100 Hz) ion intensities compare favorably with numbers expected from cyclotron facilities presently being designed. Problems that remain to be studied in future collective accelerator research are (a) the generation of heavy ions above mass 20, (b) the transverse and longitudinal phase-space properties of the ion beam and techniques to select the ions with the emittance and energy spread desired for injection into a cyclotron, (c) development of pulse repetition capability.

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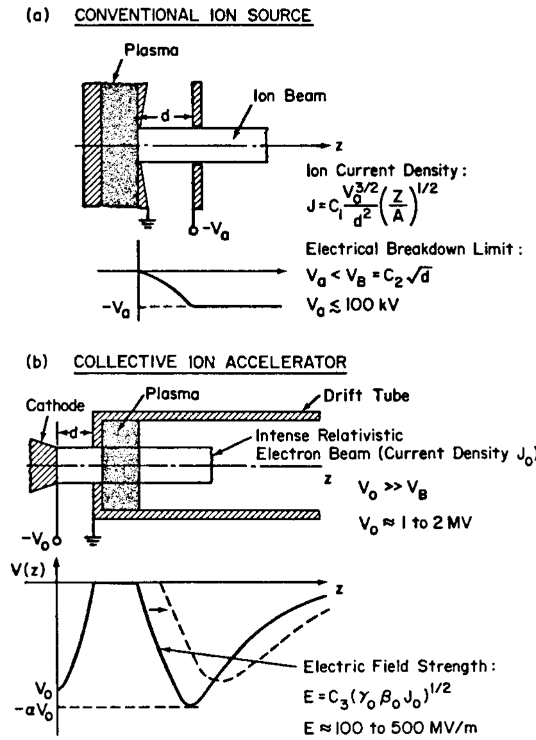

Fig. 1 Schematic diagram illustrating the principles of operation of a conventional ion source (a) and a collective ion accelerator (b).

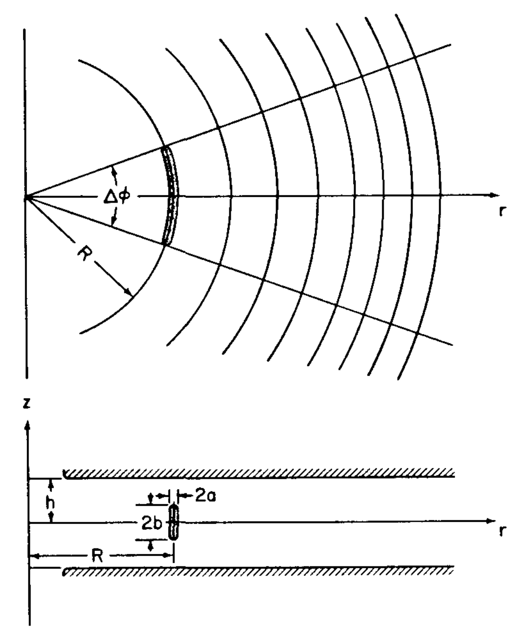

Fig. 2 Geometry of ion bunch in a cyclotron.

** DISCUSSION **

H. BLOSSER: What is the schedule for getting data on the phase space characteristics – energy spectrum and emittance – which are, of course, the key quantities in knowing whether this source will be useful in accelerators?

M. REISER: I would have liked to talk to Dr. Enge about detection methods. Obtaining the phase-space data is not easy because these are at the moment just single-shot experiments. At present, we use nuclear reaction techniques, and now we will also use a small mass spectrometer. Our first goal, however, is to go to a higher mass, to see how high in mass one can go with the collective method. That's our goal for the next year or two. As far as emittance and other characteristics are concerned, we have to first get a better reproducibility and develop the phase-space measurement devices. I would say three years from now we will begin to have a better idea of the phase-space distribution.

T. KUO: What is the electron beam intensity in order to produce 4 x 10^{11} particles/s of Ni ions?

M. REISER: What you need is an electron beam with peak energy of 1 MeV, peak current of 10 to 30 kA, 50 ns and a repetition rate of somewhere between 10 and 100 c/s.

W. JOHO: Did you estimate the energy spread induced by the longitudinal space charge between source and, let's say, a 10 m flight path to injection?

M. REISER: There is no beam transport system that can handle intense beams like several kA peak current of protons. So you transport the ions for a certain distance together with the electrons in a self-focused stream until the longitudinal space charge has debunched the ions. Then you chop the ions into two or three bunches that you inject into the cyclotron. But in the cyclotron itself, you also have some longitudinal debunching, and I have not calculated that at this point.

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