Plasma Acceleration and Heating Using Hybrid Magnetic Fields

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The repulsive force between two wires with large currents flowing in opposite directions through the wires can be used to propel a light circular conductor located above a massive ring. Then the axial velocity can reach 500 km/s and an auxiliary constant magnetic field controls the radial velocity. This allows to get a high concentration of energy at any distance from the laboratory equipment. A further application could be the investigation of the equation of state of matter at high densities and the triggering of fusion reactions.

Key words: Plasma Acceleration; Plasma Reheat; Focusing.

1. Introduction

The acceleration of macroparticles to hypervelocities is a way to get the high temperatures needed for controlled fusion [1]. Remarkable results concerning nested cylindrical wire arrays were recently obtained at Sandia National Laboratories [2, 3]. In this paper we consider how to obtain very high velocities by making use of the repulsive force between two circular wires, each carrying the very same current but in opposite directions. We have already considered the case where the wires are concentrical [4] and an external magnetic field B_0 adds to the field produced by the external current. Such hybrid systems have been first considered by Wood and Montgomery [5] and Montgomery et al. [6]. We showed that velocities above 1000 km/s could be obtained at the center 0 of the concentrical conductors, resulting in various possible nuclear reactions. At present we investigate the case where the internal mobile conductor is slightly elevated with respect to the motionless external conductor. Moreover the external field B_0 is now in an opposite direction and slows down the implosion process. These features result in a drastic change of the characteristics of the accelerator. The radial force acting on the mobile conductor is strongly reduced but in return the vertical driving force becomes considerable. So a vertical jet in the z-direction is obtained. It converges at a distance $Z = 0Q$, which can be controlled by the static field B_0. This allows to unwedge the focal point $Q(0;Z)$ where a considerable density of energy and a very high temperature, possibly in the fusion range, could damage the laboratory equipment. It will be shown that the final exhaust velocity could reach the value $v_{z\text{f}} = 500$ km/s.

2. Description of the Accelerator and Magnetic Field Formulations

The proposed accelerator is sketched in Figure 1. A current I flows in a motionless stainless steel wire of diameter $D = 0.002$ m and average radius $R_1 = 0.3$ m. In cylindrical coordinates (r,z) this current generates at the point P an induction

$$\vec{B} = B_r\vec{i}_r + B_z\vec{i}_z, \tag{1}$$

where $\vec{i}_r$ and $\vec{i}_z$ are unit vectors in the radial and vertical directions.

The values of B_r and B_z, respectively, are [7]

$$B_r = \frac{\mu_0 I}{2\pi}\frac{z}{[r(R_1+r)^2+z^2]^{1/2}} \cdot \left\{M - \left[\frac{R_1^2+r^2+z^2}{(R_1-r)^2+z^2}\right]N\right\}, \tag{2}$$

$$B_z = -\frac{\mu_0 I}{2\pi}\frac{1}{[(R_1+r)^2+z^2]^{1/2}} \cdot \left\{M - \left[\frac{R_1^2+r^2+z^2}{(R_1-r)^2+z^2}\right]N\right\}. \tag{3}$$

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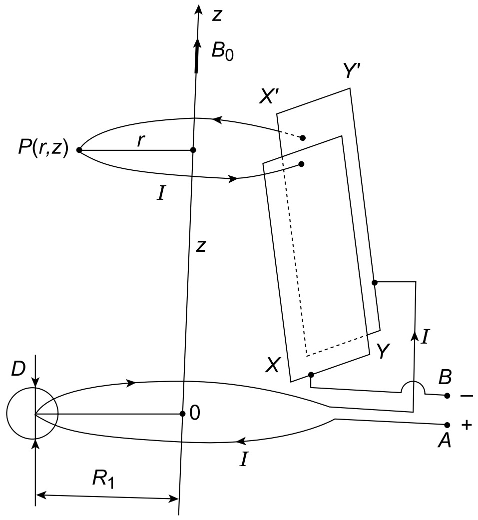

Fig. 1. Schematic diagram of the accelerator: the current I flows in the stainless steel conductor of diameter D and average radius R_1. It also flows in the opposite direction in the coaxial palladium conductor of radius r located at the height z. This conductor is propelled upwards and slides along the rails XY, $X'Y'$. B_0 is an external magnetic field which slows down the radial inwards motion of the conductor. A and B are the terminals of a Marx circuit. The figure is not to scale.

M and N are the elliptical integrals defined by

$$M = \int_0^{\pi/2} (1 - K\sin^2\varphi)^{-1/2} \mathrm{d}\varphi,$$
$$N = \int_0^{\pi/2} (1 - K\sin^2\varphi)^{1/2} \mathrm{d}\varphi, \tag{4}$$

where $K = 4R_1 r/[(R_1 + r)^2 + z^2]$ and $\mu_0 = 4\pi \cdot 10^{-7}$ Henry/m.

The mobile conductor to be accelerated is a ring of initial coordinates $r_0 = 0.299$ m and $z_0 = 0.02$ m. It is made from a palladium $\left({}_{107}\mathrm{Pd}^{46}\right)$ wire of mass $m = 4 \cdot 10^{-5}$ kg. The density of palladium is 11500 kg/m^3. The same current I flows through this ring but in an opposite direction and the tips of the ring can slide vertically and horizontally along the two rails XY and $X'Y'$. A and B are the terminals of a (8 MV, 10 MJ) Marx circuit. It is assumed that the average value of the current is $I = 3$ MA. The field components B_r and B_z, respectively, impart an upward motion and a radial inwards motion to the mobile conductor; however, a constant magnetic field $B_0 = 3.5$ Tesla, directed upwards, considerably slows down the inwards motion.

Table 1. The position and the velocities v_r, v_z (in km/s) of the mobile ring in cylindrical coordinates r, z (in mm) as functions of the time t (in ns). The field components are B_r and B_z (in Tesla). $B_0 = +3.5$ is a static field in upward direction.

t	B_r	$B_z + B_0$	z	r	v_z	v_r
0	−29.83	−1.85	20	299	0	0
10	−29.52	−1.83	20.21	298.98	42	2.6
20	−28.61	−1.8	20.84	298.94	83.6	5.18
30	−27.21	−1.62	21.67	298.8	123.9	7.7
50	−23.7	−1.36	25.1	298.6	198.2	12.1
100	−15.18	−0.5	38.7	297.3	339	19.5
140	−10.72	−0.002	53.4	297	414	21.2
180	−7.94	0.541	71.6	295	468	19.9
200	−6.91	0.737	81.3	294.5	489	18.2
220	−6.03	0.8562	91.1	294.2	508	16

3. Equation of Motion of the Moving Conductor

Since the field equations (2) and (3) are very complicated, the trajectory of the mobile ring can be determined only by numerical calculation. At time t_i the coordinates of the moving conductor are r_i and z_i and the field components are B_r and B_z; so the vertical and radial (inwards) accelerations have the values

$$\gamma_{zi} = 2\pi r_i I(-B_r)/m, \tag{5}$$

$$\gamma_{ri} = -2\pi r_i (B_z + B_0)/m. \tag{6}$$

At time $t_{i+1} = t_i + \Delta t$, where Δt is very small, the new coordinates become

$$z_{i+1} = z_i + (1/2)\gamma_z(\Delta t)^2 + v_{zi}\Delta t, \tag{7}$$

$$r_{i+1} = r_i - (1/2)\gamma_r(\Delta t)^2 - v_{ri}\Delta t, \tag{8}$$

where v_{zi} and v_{ri} are the magnitudes of the velocity components at time t_i. So the final velocities at time t_{i+1} become

$$v_{z(i+1)} = v_{zi} + \gamma_{zi}\Delta t, \tag{9}$$

$$v_{r(i+1)} = v_{ri} + \gamma_{ri}\Delta t. \tag{10}$$

We choose 22 time intervals, each of $\Delta t = 10^{-8}$ s, and the results of the calculation are recorded in Table 1.

It is assumed that the current is switched off when $t = t_0 = 0.22\ \mu$s, since the field component B_r responsible for the vertical acceleration, has been reduced by a factor 5. So the final coordinates are $r_f = 0.2954$ m and $z_f = 0.0911$ m and the final vertical velocity is $v_f = 508$ km/s.

The curves (a) and (b) of Fig. 2 show the increases of the vertical and radial velocities versus time. The slope

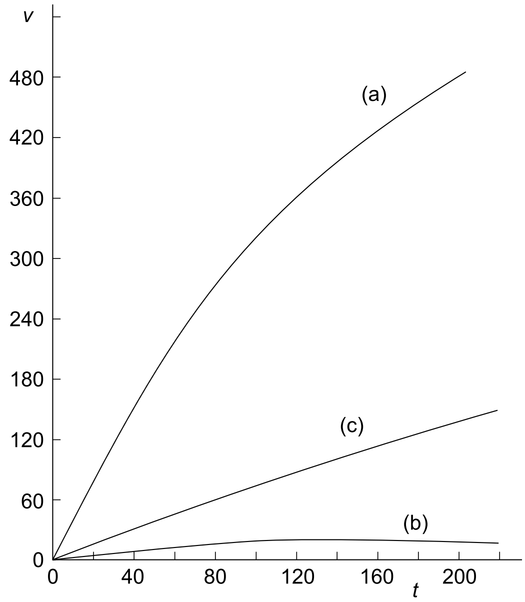

Fig. 2. The various velocities v (km/s) versus time t (in ns). (a) Vertical velocity v_z. (b) Radial velocity v_r in the presence of an external magnetic field. (c) Radial velocity v_r in the absence of an external field.

of the trajectory of the moving conductor is defined by the angle

$$\theta = \tan^{-1}(v_z/v_r). \tag{11}$$

Its initial and final values are $\theta_0 = 86.4°$ and $\theta_f = 88.2°$. The palladium particles converge at a distance O$Q = Z = z_f + r_f \tan\theta_f = 9.43$ m, where a considerable increase in temperature is to be expected. In the absence of the auxiliary magnetic field B_0, similar calculations show that the vertical velocities are practically unchanged but the radial velocities become considerable, as it appears from curve (c) in Figure 2. Then the initial and final slopes are 79.8° and 73.5°, i. e., the metallic particles converge at a distance O$Q' = Z' = 1.04$ m.

4. Stability of the Collapsing Wire

Such a problem is very important and has been discussed considering an iron wire [8]. The ohmic heating due to the high current should be limited to about 100 eV because of the runaway of the electrons [9]; then Pd^{3+} and Pd^{4+} – with respective ionization energy 78 eV and 139 eV – are expected to be present. For the considered conditions the sound velocity is $c_0 = 10$ km/s. The expansion in the x,y-directions (perpendicular to B_0) is not detrimental, but an expansion along the z-direction would result, as the collapsing wire converges towards the axis, in a filament of length $l = c_0 t_m$, where t_m is the time at which the converging macroparticles have reached the z-axis.

As long as the current flows the expansion of the wire is restained by the pinch effect which is, however, associated with the $m = 0$ and $m = 1$ ("sausage" and "kink") instabilities. A thorough discussion of Z-pinches has been edited by Spielman and Miley [10]. Since the acceleration process occurs only in 0.22 μs we admit that the plasma retains a well-defined cylindrical geometry, a result confirmed by the observation of exploding lithium wires [11]. However, when $z > z_f$, there is no current flow anymore, so the plasma expands freely at the sound velocity c_0. The points Q and Q' are, respectively, reached after the time intervals $\Delta t_1 = (Z - z_f)/v_{zf} = 1.838 \cdot 10^{-5}$ s and $\Delta t_2 = (Z' - z_f)/v_{zf} = 1.868 \cdot 10^{-6}$ s. So the colliding particles result in the formation of the high temperature plasma filament of length $l_1 = c_0 \Delta t_1 = 0.184$ m and $l_2 = c_0 \Delta t_2 = 0.187 \cdot 10^{-2}$ m. At the density of the solid state the plasma volume is $V = 3.478 \cdot 10^{-9}$ m^3; so the radius of these filaments would be, respectively, $\rho_1 = 7.757 \cdot 10^{-5}$ m and $\rho_2 = 2.433 \cdot 10^{-4}$ m.

5. Estimate of the Obtained Temperatures

At the velocity $v_{zf} = 500$ km/s the kinetic energy of a palladium atom is $W = 2.221 \cdot 10^{-14}$ J = 138860 eV. But an energy of 1 eV corresponds to a temperature $T_E = 2$ eV/3 $k = 7729.4$ K, where e is the magnitude of the electronic charge and k the Boltzmann constant. So the mutual collisions of the palladium particles would result in the extremely high initial temperature $T_i = 1.073 \cdot 10^9$ K. But at such hypervelocity impact it is likely that the palladium atoms will become completely ionized; such process involves [12] an energy loss $U_y = 133680$ eV and the temperature would drop to $W - U_y = 5180$ eV or $4 \cdot 10^7$ K. Moreover the equilibrium temperature after equipartition with the $Y = 46$ electrons – on account of ionization – would come down to $T_f = (W - U_y)/(Y + 1) = 8.52 \cdot 10^5$ K, and then the sound velocity is $c = 10.5$ km/s. So the estimated lifetime of the filament at the points Q and Q' would be $\tau_1 = \rho_1/c = 7.38 \cdot 10^{-9}$ s and $\tau_2 = \rho_2/c = 2.315 \cdot 10^{-8}$ s.

6. Possibility of Fusion Reactions and Conclusion

The hypervelocity impact of macroparticles is an efficient method [1, 13] to trigger fusion reactions. The final temperature looks rather small but the $N = 2.25 \cdot 10^{20}$ ions stand for an electrical potential energy $NU_y = 4.81$ MJ; so the density of electrical energy has the huge value $W_{\mathrm{el}} = NU_y/V = 1.385 \cdot 10^{15}$ J/m^3.

Then the density of energy due to radiation looks quite negligible since its value is $W_{\mathrm{r}} = \alpha T_{\mathrm{f}}^4$ where $\alpha = 7.62 \cdot 10^{-16}$ J/m^3 K. But during the recombination process and in the presence of deuterium and tritium, these isotopes of hydrogen will be superheated according to various processes:

$$\mathrm{Pd}^{46+} + \mathrm{D}^+ + \mathrm{e}^- \longrightarrow \mathrm{Pd}^{45+} + \mathrm{D}^+ + 28330\,\mathrm{eV}, \quad (12)$$

$$\mathrm{Pd}^{46+} + \mathrm{D}^+ + 2\mathrm{e}^- \longrightarrow \mathrm{Pd}^{44+} + \mathrm{D}^+ + 56800\,\mathrm{eV}. \quad (13)$$

Because of conservation of momentum the fraction $M_{\mathrm{Pd}}/(M_{\mathrm{Pd}} + M_{\mathrm{D}}) = 107/109 = 98.16\%$ of the energy released during recombination is carried by the light ions, and the increases in temperature according (12) and (13) reach $2.15 \cdot 10^8$ K and $4.31 \cdot 10^8$ K. These temperatures look high enough to possibly result in a triggering of fusion reactions.

The advantage of a static magnetic field like B_0 is to keep the thermonuclear reaction at a safe distance from the laboratory equipment. If an uranium wire is used then the reaction

$$\mathrm{U}^{92+} + \mathrm{D}^+ + \mathrm{e}^- \longrightarrow \mathrm{U}^{91+} + \mathrm{D}^+ + 129300\,\mathrm{eV}$$

would result in an increase in temperature reaching $9.91 \cdot 10^8$ K and possibly fusion could happen without having recourse to tritium. Note that use of $_{238}$U (or $_{232}$Th) to assist the ignition of thermonuclear microexplosions has been brilliantly demonstrated by Winterberg [14].

In conclusion, the ability of palladium to absorb hydrogen and the superheating following its recombination point out the usefulness of this element to trigger fusion reactions. However, for practical applications, it seems necessary to experimentally confirm that the rates of the reactions (12) and (13) are high enough.

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