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A compact laser-driven accelerator of macroparticles

ALEXANDRE POZWOLSKI
Education Nationale, 4 rue de la Plaine, 75020 Paris, France

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Abstract

Charged transparent macroparticles of silicium carbide of radius $r = 0.5$ μm are submitted to the repeated radiation pressure of a laser beam which follows the sides of a square 3.5×3.5 m, using total reflection on three prisms. The macroparticles follow a closed path since they are deflected by a strong electric field, using magnetic insulation. After 4650 revolutions, velocities up to 106 km/s can be reached.

1. INTRODUCTION

The radiation pressure of light may accelerate macroparticles sized in the micrometer range to very high velocities. In order to avoid the vaporization and destruction of the macroparticle, Ashkin (1970, 1971) has suggested the use of transparent materials. With the object of avoiding an accelerator that is too long, Pozwolski (1998) has suggested the use of charged macroparticles driven by an electric field in order to follow a closed path. However the size of such a device could be considerably reduced by using magnetic insulation (Winterberg, 1984), which allows extremely high electric fields. The magnetic field B should be perpendicular to the electric field E and its maximum value is $E = 2.1 \times 10^8 B$ (Volt/m, tesla). In this article, we consider electric fields up to 60×10^6 volt/m, which can be safely sustained using an induction of 0.35 tesla.

2. CHARACTERISTICS OF THE LASER BEAM

We consider a laser beam having exactly the same characteristics as estimated (Pozwolski, 1998) in a previous article: cw argon laser light, TEM_{00} mode, wavelength $\lambda = 0.5145$ μm, power $P = 0.5$ W. But now the considered beam follows the sides of a square 3.5×3.5 m through the use of three prisms ensuring total reflection, as shown in Figure 1. In the next section it will be shown that the macroparticles are submitted to the beam along the segments AB, CD, EF, GH, each of them of length $l = 1.5$ m. The beam is focused so its radius is $r = 0.5$ μm. This is also the radius of the macroparticle, namely a transparent sphere of silicium carbid SiC of mass $m = 1.68 \times 10^{-15}$ kg, charge $q = 3.15 \times 10^{-13}$ C so $q/m = 187.6$ C/kg.

The driving force due to the radiation pressure of the laser beam is

$$f = 2sP/c, \tag{1}$$

where c is the velocity of light and $s \simeq 0.1$ is the reflection factor of the macroparticle (fraction of light reflected back). Numerically $f = 3.33 \times 10^{-10}$ N and the acceleration of the macroparticle is $\gamma = 1.985 \times 10^5$ m/s^2. The equivalent voltage that would produce the same acceleration along the length l is defined by:

$$U_L = m\gamma l/q = 1585.5 \text{ V}. \tag{2}$$

3. CHARACTERISTICS OF THE TRAJECTORY OF THE MACROPARTICLES

The macroparticles are injected in I after acceleration by a dc voltage $U_i = 500$ kV. Their initial velocity is $v_0 = 13.696$ km/s. They follow a circular path of radius $R = 1$ m since they are deflected by a radial electric field between a portion of two coaxial cylinders of radius $R_1 = 0.998$ m and $R_2 = 1.008$ m. We consider four sets of such portions of coaxial cylinders. The inner cylinders are grounded and the external cylinders are at a potential U. An induction $B = 0.35$ tesla, parallel to the axis of these cylinders, ensures magnetic insulation. Such a field has a negligible effect on the motion of massive macroparticles. Besides, such an effect could be cancelled if each portion of the coaxial cylinders is seg-

Address correspondence and reprint requests to: Alexandre Pozwolski, Education Nationale, 4 rue de la Plaine, 75020 Paris, France.

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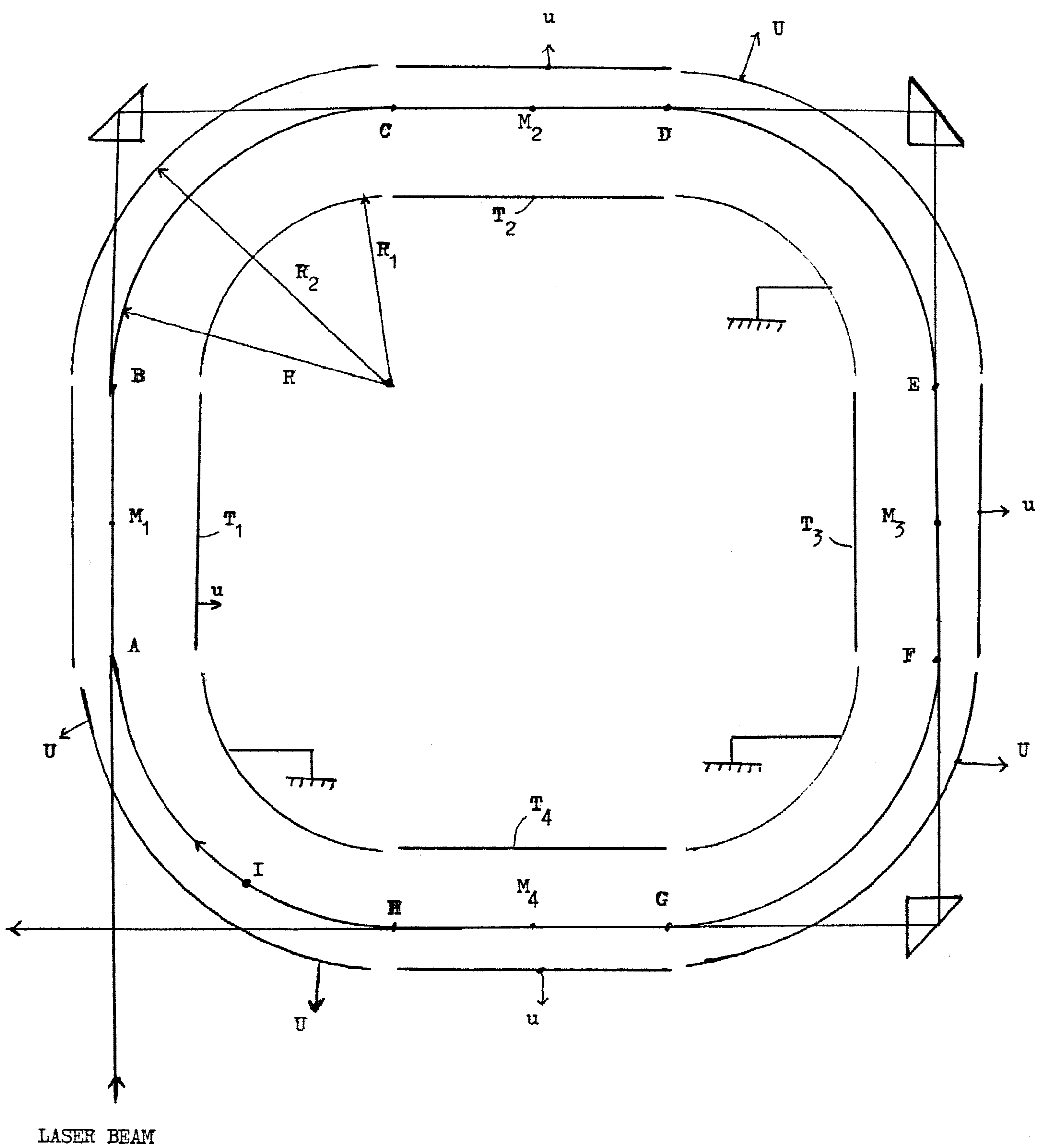

Fig. 1. The laser beam follows the sides of a square 3.5 × 3.5 m, using total reflection on three prisms. The transparent charged macroparticles are accelerated by the laser beam along the segments AB, CD, EF, and GH, each of length $l = 1.5$ m. The potential difference U between the portions of coaxial cylinders of radius R_1 and R_2 results in a circular path of the macroparticles; they travel along the following arcs of a circle: HA,BC,DE,FG, each of them of radius R. The tubes T, maintained at the potential u of the orbit, act as a shielded line.

mented, as shown in Figure 2, using, respectively, an upwards and a downwards induction in each segmented portion.

The electric field acting on a macroparticle is

$$E = aU/R, \tag{3}$$

where $a = 1/\mathrm{Log}(R_2/R_1) = 100.3$. For a macroparticle of velocity v the required condition for a circular orbit is

$$U = mv^2/qa = (2/a)U_t, \tag{4}$$

where U_t is the accelerating voltage that would result in a velocity v. The potential along the circular orbit is

$$u = bU, \tag{5}$$

where $b = a\,\mathrm{Log}(R/R_1) = 0.2008$. The tubes T_1, T_2, T_3, T_4 are at the potential of the orbit followed by the macroparticle, which is shielded from stray fields. So the initial potential of the external cylinders should be $U_0 = (2/a)U_i = 9970$ V and the potential along the orbit is $u_0 = 2002$ V; this is also the initial potential of the tubes T.

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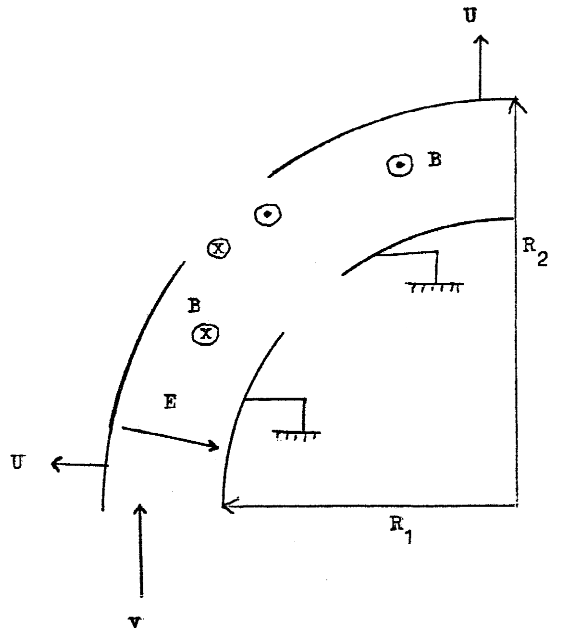

Fig. 2. Magnetic insulation is obtained by a vertical magnetic field B perpendicular to the electric field E between the coaxial cylinders which can be segmented in two parts. In the lower part of the figure the magnetic field is directed upwards ($\otimes$); so for a charged particle of velocity v the electromotive field vB is directed along the electric field. In the upper part of the figure the magnetic field is directed downwards ($\odot$) and the vB field is in the opposite direction of E. Furthermore since $vB \ll E$, the motion of the macroparticle is practically undisturbed by the magnetic field.

The first laser acceleration process occurs along AB and the macroparticle arrives in B with a velocity

$$v_1 = [2q/m(U_i + U_L)]^{1/2}. \tag{6}$$

When the macroparticle is in M_1, the middle of tube T_1, the external cylinders are raised to the potential

$$U_1 = (2/a)(U_i + U_L), \tag{7}$$

and the tubes T are at the potential $u_1 = bU_1$. The subsequent acceleration processes occur along CD, EF, and FG. After n accelerations, the total accelerating potential is

$$U_{tn} = U_0 + nU_L. \tag{8}$$

The potential of the external cylinders and the potential of the tubes T are

$$U_n = (2/a)U_{tn} \tag{9}$$

$$u_n = bU_n. \tag{10}$$

The potential rise, from U_{n-1} to U_n, occurs when the macroparticle is in M_n, in the middle of the tube where the nth acceleration occurs.

4. TIMING OF THE POTENTIAL VARIATIONS

The time origin is chosen at the first transit of the particle through A: $t_{A_1} = 0$. The velocity in M_1 is

$$v_{11} = [2q/m(U_i + U_L/2)]^{1/2}, \tag{11}$$

and the transit through M_1 occurs at the time $t_{11} = (v_{11} - v_0)/\gamma = 5.4703 \times 10^{-5}$ s. When the particle arrives in B, after the first acceleration, its velocity is v_1, given by Eq. (6), and the transit through B occurs at the time $t_1 = (v_1 - v_0)/\gamma$.

The second laser acceleration begins in C at the time $t_{C_2} = (v_1 - v_0)/\gamma + \pi R/2v_1$, the velocity in the middle M_2 of tube T_2 is $v_{22} = [2q/m(U_i + 3/2\ U_L)]^{1/2}$ and the transit through M_2 occurs at

$$t_{22} = (v_{22} - v_0)/\gamma + \pi R/2v_1 \tag{12}$$

More generally, for the nth acceleration, the arrival in M occurs at the time

$$t_{M_n} = (v_{M_n} - v_0)/\gamma + \left(\frac{\pi R}{2}\right) S_{n-1} \tag{13}$$

where

$$v_{M_n} = \{2q/m[U_i + (n - 1/2)U_L]\}^{1/2} \tag{14}$$

$$S_n = \sum_1^n 1/v_i, \tag{15}$$

and the final velocity is

$$v_n = [2q/m(U_i + nU_L)]^{1/2}. \tag{16}$$

Some numerical values are given in Table 1, where $N = n/4$ is the number of revolutions.

Table 1. *Numeric values for various numbers of revolutions.*

N	n	v_n (km/s)	U_n (kV)	t_{M_n} (ms)	S_n (ms/m)
	1	13.718	10.002	0.0547	0.0789
	2	13.74	10.033	0.278	0.146
	3	13.762	13.762	0.502	0.218
1	4	13.783	10.097	0.725	0.291
	5	13.805	10.128	0.938	0.363
2	8	13.869	10.223	1.614	0.58
5	20	14.124	10.602	4.247	1.436
2500	10000	78.335	326.12	667.12	217.31
4650	18600	106.1	598.02	953.37	310.53

The variations of the potential of the external cylinders U_n and the velocity v_n are given, namely the number n of accelerating processes. $N = n/4$ is the number of revolutions. S_n and t_{M_n}, respectively, are the sum of the inverse of the velocities and the successive arrival times in M.

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5. FINAL RESULTS AND CONCLUSION

After 4650 revolutions, the final velocity is 106 km/s and the potential of the external cylinders reached 598 kV. In the considered device, the macroparticle is submitted to the laser beam on the major part of its trajectory and therefore the effect of gravity is negligible since the laser beam also brings about a radial acceleration, about one half the value of the longitudinal acceleration, which constantly maintains the macroparticle inside the beam (Ashkin, 1971).

Another point of interest is the possibility of accelerating a set of macroparticles together. They should be located along a vertical line, perpendicular to the plane of Figure 1, and with a minimum spacing D, chosen so that the laser radial driving force $f/2$ should be larger than the electrostatic repulsion between adjacent macroparticles. Thus,

$$D = q(2\pi\varepsilon_0 f)^{-1/2} = 2.3 \times 10^{-3}\ \mathrm{m} \tag{17}$$

where ε_0 is the permittivity of free space. In practice it looks possible to use simultaneously beams of macroparticles which are 3 mm apart.

As previously pointed out, the main interest of such macroparticles accelerated to hypervelocities is the generation of high bursts of power and the simulation of micrometeors (Friichtenicht & Becker, 1971).

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