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Production of high densities of energy using a microparticle beam

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Résumé. — On considère l’accélération électrostatique de grains de poussière de fer chargés. Ces particules convergent vers le centre d’une sphère et des densités d’énergie supérieures à 2 mégajoules/cm³ sont prévisibles. La transformation de l’énergie cinétique du faisceau en chaleur aboutit à de très hautes températures pouvant éventuellement déclencher des réactions de fusion.

Abstract. — The electrostatic acceleration of charged iron macroparticles is considered. These macroparticles are directed toward the center of a sphere and energy densities above 2 megajoules/cm³ are expected. The conversion of the kinetic energy of the beam into heat results in very high temperatures, possibly in the fusion range.

1. Introduction.

High densities of energy are specially useful in various branches of physics as production of high temperatures, production of short bursts of X-rays or controlled fusion. The use of projectiles accelerated to hypervelocities is now receiving an increased interest. It looks that the first macroparticle accelerator was proposed for space propulsion by Goddard [1] in 1920. About fusion pioneer work is due to Winterberg [2], Maisonnier [3] and Linhart [1]. Pozwolski [5] has considered more specially the acceleration of heavy elements allowing to get high temperatures with lower velocities, using a Fermi acceleration process.

The electromagnetic drive of projectiles is also a possible way to reach hypervelocities and homopolar generators [6] as well as railgun accelerators [7] have been considered.

Finally the acceleration of transparent macroparticles sized in the micron range by the radiation pressure of a laser [8] would allow velocities up to 5 000 km/s. However the electrostatic acceleration of small grains of dust considered in what follow is perhaps simpler to use.

2. Dust accelerators.

Neutral clouds of positively and negatively charged dust particles (dust plasmas) have been studied by James and Vermeulen [9]. For such clouds the plasma frequency is about 10 Hz. Friichtenicht and Becker [10] accelerated macroparticles of iron (typically 0.05-1 micrometer) to 20-45 km/s using a 2 MV Van de Graaf generator. Using LaB₆ macroparticles the authors reached 112 km/s. Such projectiles were used in order to simulate micrometeors.

It can be shown that for a spherical macroparticle the charge/mass ratio is \( \frac{q}{m} = 3 \varepsilon_0 \frac{E}{\rho r} \) where \( \varepsilon_0 = 10^{-9}/36 \pi \) farad/m, \( r \) is the radius of the particle, \( E \) the electric field at its surface and \( \rho \) the density. The maximum value \( E_s \) of the electric field is about \( 10^9 \) volts/m for negatively charged particles, because field emission. For positively charged particles the value of \( E_s \) could be one order of magnitude higher and is obtained by equaling the electrostatic pressure to the tensile strength \( \sigma_m \) of the material [2]. So \( E_s = \left(2 \sigma_m / \varepsilon_0 \right)^{1/2} \) and some values are given below.

<table>
<thead>
<tr>
<th>Material</th>
<th>iron</th>
<th>copper</th>
<th>aluminium</th>
<th>lead</th>
<th>glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_m, \text{ GP}_A )</td>
<td>0.6</td>
<td>0.3</td>
<td>0.1</td>
<td>0.015</td>
<td>0.05</td>
</tr>
<tr>
<td>( E_s, \text{ volt/m} \times 10^{-10} )</td>
<td>1.16</td>
<td>0.824</td>
<td>0.475</td>
<td>0.184</td>
<td>0.237</td>
</tr>
</tbody>
</table>

For iron we select \( E_s = 10^{10} \) volts/m resulting in \( \frac{q}{m} = 34 \) C/kg when \( r = 1 \) micrometer. So an ac-
catering voltage $U = 10^7$ volts results in a velocity $v = (2 qU/m)^{1/2} = 26$ km/s in good agreement with experiments of Früchtenicht et al. [10].

In order to get high densities of energy the following conditions should be met:

i) particles of small radius, 1 micrometer or less, in order to reach high velocities;

ii) in order to eventually start fusion reactions and check Lawson criteria a very large number of dust particles should be focalised;

iii) for an efficient focalisation electrostatic interactions should be reduced: this is the main advantage of dust particles over elementary particles as electrons or ions.

The proposed configuration is shown in figure 1. A similar configuration has been proposed by Winterberg for electrons [11]. However in the case considered here the energy of the beam has not to be transferred to a target since the incident impinging macroparticles act themselves as a target. A « guard ring » (shaped as a cone and shown in dotted lines) improves the quality of focalisation. $S$ is a portion of a spherical conductor of area $A = 2$ m$^2$ and radius $R = 10$ m where 0.0345 g of iron dust have been deposited. These grains converge toward point 0.

Fig. 1. — Focalization of macroparticles by a radial electric field. Alternatively a concentric grid connected to -HT could be used.

H.T. is a high voltage source, namely a Marx circuit 10 MV, 0.1 MJ. Alternatively it is also possible to use opposite beams formed by positively and negatively charged macroparticles. Because the large value of $R$ a similar but simpler configuration may be used as shown in figure 2 where AB is a portion (2 m$^2$) of a plane and is covered with dust. The outer part of the plane acts as a guard ring and $G$ is a quasi-spherical grid. From the theory of image charges [12] it is easy to check that if $OM = 1$ m and $CM = 9$ m then $OP = 1.005$ m and $ON = 1.002$ m. Practically all the macroparticles converge toward the center 0 of $G$.

3. Electrostatic interactions.

The impact parameter for alike charged particles is $b = q^2/2 \pi \varepsilon_0 mv^2$. Taking $q/m = 34$ C/kg, $m = 3.26 \times 10^{-14}$ kg and $v_f = 26$ 000 m/s it is found that $b = 10^{-9}$ m so the distance of closest approach is of the order of 2 $b = 0.002$ micrometer. Such distance being much smaller than the radius $r$ of macroparticles the electrostatic repulsion will not prevent collision. Besides, using the theoretical values of $q/m$ and $v$ it is easy to check that $b = Er^2/U$ so the distance of closest approach is $d = 2 r^2 E/U$ and collision will occur if $d < r$ or $r < U/2 E$. Taking $E = E_s = 10^{10}$ V/m it is found that $r < 0.5$ mm. So for particles sized in the micron range collision surely occurs. However it is essential that all the particles leave the sphere at the same instant. The relaxation time for charges is $\tau = \varepsilon_0 \eta$ where $\eta$ is the resistivity. For good conductors such time is extremely small, of the order of $10^{-17}$ s for metals [13] and it seems reasonable to assume that the particles are instantaneously charged. Eventually longitudinal focalisation by an a-c electric field [14] could be used before radial focalisation but at the expense of a much more sophisticated system.

4. Expected densities of energy.

The kinetic energy of 0.0345 g of iron accelerated to 26 km/s is 11.661 kJ. Neglecting the compressibility this energy will be localized in a volume $0.0345/7.8 = 4.423 \times 10^{-3}$ cm$^3$. The corresponding energy density is 2.63 MJ/cm$^3$. The focalised macroparticles mutually heat themselves and the initial impact temperature has the value $T = Mv^2/3R = 1.5 \times 10^6$ K. Of course the equilibrium temperature
is lower because the cooling effect of free electrons and radiation; these effects are discussed in the appendix. For uranium macroparticles the temperature would be increased by a factor 238/56 = 4.25 and would reach 6.37 x 10^6 K. For a velocity of 52 km/s a temperature of 25 millions K is to be expected. So the use of uranium hydride particles could eventually result in fusion reactions.

The use of heavy elements has the further advantage to involve very high impact pressures and this could prove useful in order to study state equations.

As far iron is concerned its main advantage is to simulate the impact of micrometeors (besides iron is one of the main components of these projectiles). It is also worth while to notice that the accelerated iron macroparticles remain perfectly cold before collisions so allowing a better simulation of the impact.

Finally another point of interest is to increase the energy of the beam merely by increasing the involved mass. Referring to figure 2 the involved charge is obtained from the equation

\[ U = 9 \times 10^9 Q \left[ \frac{1}{a} - 1/(2R - a) \right] \]

where \( a = OM \) and \( R = OC \). It looks difficult to use potential difference above \( U = 10^7 \) volts and taking \( R = 10 \text{ m} \) the maximum charge is given by \( Q = a/\left[ 900 \left[ 1 - a/(20 - a) \right] \right] \) corresponding to a mass, in grams

\[ 1000 \frac{Q}{34} = 0.03268a \left[ 1 - a/(20 - a) \right]. \]

For instance taking \( a = 3 \text{ m} \) a mass of 0.12 g is found corresponding to an energy of 40 kJ.

5. Conclusion.

The acceleration processes considered look relatively simple. If the focalisation works properly and this has to be checked by experiment, with special emphasis to minimize the spreading in departure time of the particles-very high densities of energy indeed are to be expected. Moreover the involved mass is rather large and could approach the gram.

Acknowledgment.

We wish to thank the French Physical Society which encouraged us to present the above topics at the occasion of its Symposium in Strasbourg, July 6-10, 1987.

Appendix.

An important advantage of plasmas obtained by hypervelocity impact is that ions are heated preferentially, their initial temperature \( T = Mv^2/3R \) being proportionnal to their mass; the electrons remains rather cold. Such situation is exactly the contrary of conditions usually met in electrical discharges in gases where it is the hot electrons which are heating the ions.

However, for the first case, electrons will gain energy from the hot ions and will radiate it. So the equilibrium temperature will be lowered. Such effect has been already discussed for uranium projectiles [15]. We consider here the case of iron.

From the conservation of energy and assuming that the plasma radiates as a black body the equilibrium temperature is obtained from the equation:

\[ 1/2 \rho v^2 = 3/2 kT (n_i + n_e) + aT^4 \]

where \( n_i \) is the ionic density, \( Z \) the ionization number, \( n_e = Zn_i \) and \( a = 7.62 \times 10^{-13} \text{ CGS} \). The above equation can be rewritten:

\[ v = \left[ 3 kn_i (1 + Z) T/\rho + 2 aT^4/\rho \right]^{1/2}. \]

The energy invested in radiation becomes equal to the kinetic energy of the particles for the temperature \( T_c = (3 kn_i/2a)^{1/3} (1 + Z)^{1/3} \). In other words the fictitious particle density equivalent to the energy carried by photons [16] is then \( n' = 2aT_c^3/3k = 36.4 T_c^3 \text{ cm}^{-3} \). The curve \( T = T(v) \) shows an inflexion point when \( d^2v/dT^2 \) vanishes and this occurs when \( T^6 + 2 T^3 - T + 1/8 = 0 \) or \( T = 0.3929 T_c \).

Numerically \( T_c \) changes from 13.9 \( \times 10^6 \) to 33.2 \( \times 10^6 \text{ K} \) when \( Z \) varies from 1 to 26.

![Fig. 3. — The relationship between temperature \( T \) (Million K) and velocity \( V \) (km/s) for iron macroparticles. The ionization number \( Z \) is the parameter.](image-url)
Curves $T = T(v)$ are shown in figure 3 assuming $n_i = 5 \times 10^{22} \text{ cm}^{-3}$ and taking the ionization number as parameter. For low temperatures the variation of $T$ viz. $v$ is almost parabolic but at high velocities most of the energy is invested as radiation and the ionization number becomes less important.

References