Acceleration of Filamentary Macroparticles to Very Large Velocities in High Voltage Diodes

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An attempt is made to explain the observed very large velocities of macroscopic particles in pulsed high voltage diodes. It is assumed that the macroscopic particle has the shape of a filament which is pulled out of the anode surface by electrostatic forces. It is furthermore assumed that a vacuum spark will originate from the tip of this filament If the current of the spark discharge is very large and the filament radius sufficiently small, it will be held together by a large magnetic field. This large magnetic field then also permits the filament to become highly charged and it is shown that this large charge in conjunction with the applied large diode field can explain the observed very high velocities.

It has been observed in rapidly rising high voltage diodes that specks of matter, after torn off from the anode surface, can impact with very high velocities on the cathode [1]. According to these experiments impact velocities of macroscopic particles up to $\sim 10^9$ cm/sec were observed. Unfortunately, no analysis of the cratering process was done from which the mass could have been estimated. The understanding of this phenomenon may be of considerable importance, since macroscopic objects attaining these large velocities and having sufficiently large masses could be used to make large scale nuclear reactions and perhaps ignite thermonuclear microexplosions.

We first show that a simple interpretation fails to explain the observed phenomenon. In this simple interpretation a speck of matter, assumed spherical in shape and attached to the anode is first charged up to a high potential. As a result of the large electrostatic forces acting on this speck, it is then torn off from the anode surface and accelerated towards the cathode. If a speck of matter with mass m acquires the charge q, and if the diode voltage is V (esu), its final velocity v is determined by

$$\tfrac{1}{2} m v^2 = q V . \tag{1}$$

Now, the maximum charge the speck can attain depends on its tensile strength σ by the circumstance that the surface electric field is limited to values for which $E^2/8\pi < \sigma$, and the maximum posible field strength is thus $E_0 = \sqrt{8\pi\sigma}$. A typical value for the tensile strength is $\sigma \simeq 10^{10}$ dyn/cm^2 and one finds that $E_0 \simeq 5 \times 10^5$ esu $\sim 10^8$ V/cm. This is also the limiting strength for field ion emission. Let us optimistically assume that the speck of matter is charged up to this maximum surface field strength. Then, if the particle has a spherical shape with radius r, the maximum attainable charge is $q = r^2 E_0$. With $m = (4\pi/3)\varrho r^3$, where ϱ is the density of the speck material, one thus obtains from Eq. (1)

$$r = E_0 V/(2\pi/3)\,\varrho\, v^2 . \tag{2}$$

The velocity of $\sim 10^9$ cm/sec was observed at a diode voltage of 8×10^6 V $\simeq 2.7 \times 10^4$ esu. Assuming altogether $\varrho \simeq 7$ g/cm^3, $E_0 = 5 \times 10^5$ esu, $v = 10^9$ cm/sec and $V = 2.7 \times 10^4$ esu one finds from (2) that $r \simeq 10^{-9}$ cm. This of course, is a much too large value. But even if the particle would be a whisker, that is a single microcrystal, with a tensile strength ~ 100 times larger, and if the velocity would be only 10^8 cm/sec, the particle radius would be not larger than 10^{-6} cm, corresponding to a mass of only $\sim 10^{-17}$ g.

We will, here propose a different mechanism which better seems to explain the reported observation. For this consider Fig. 1 displaying the anode-cathode gap of a high voltage diode. Let us assume

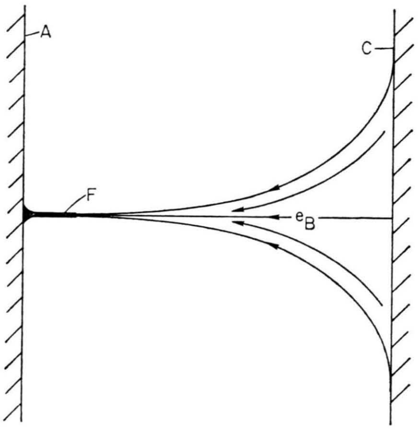

Fig. 1. A anode, C cathode, F filament of length l and radius r, e_B electron beam.

that from the anode surface a long metallic filament of length l and radius r is pulled out by electrostatic forces prior to the breakdown by a vacuum spark. The large electric field created near the tip of the filament will then enhance the breakdown towards this tip. The vacuum spark discharge itself will be a relativistic electron beam converging onto the filament resulting in a large current flowing on the surface of the filament and producing a strong magnetic field at the filament radius r given by

$$H = 2\, I/r\, c\,. \tag{3}$$

In Eq. (3) the spark current I is measured in electrostatic units. Now, as long as the high voltage is sustained, large positive electric charges can be also sustained on the surface of the filament. In the previous case the amount of the surface charges was determined by the tensile strength σ. Here however, if $H^2/8\pi \gg \sigma$, the filament is rather held together by magnetic forces and if these magnetic forces are larger than the tensile strength much larger charges can be accumulated. The maximum electric surface field is here limited by

$$E^2/8\pi < H^2/8\pi\,,$$

that is in absolute values

$$E < H\,, \tag{4}$$

and one has $E_0 = H$. Equation (4) is incidentally also the condition for magnetic insulation. In case of a cylinder with radius r and length l one has now for the maximum attainable charge

$$q = (1/2)\, r\, l\, E_0 = (1/2)\, r\, l\, H\,, \tag{5}$$

or because of Eq. (3)

$$q = l\, I/c\,. \tag{6}$$

Since the mass of the filament is $m = \pi r^2 l \varrho$, one finds from (1) that

$$r = \sqrt{\frac{2}{\pi}} \left(\frac{I V}{\varrho c}\right)^{1/2} \frac{1}{v}\,, \tag{7}$$

or by expressing I in ampere and V in volt one has

$$r \simeq 1.5 \times 10^{-2}\, (I V/\varrho)^{1/2}\, v^{-1}\, [\mathrm{cm}]\,. \tag{8}$$

In the reported observation $I \simeq 5 \times 10^5$ [A], and one obtains $r \simeq 10^{-5}$ cm. In contrast to the simple interpretation much larger masses are now possible bacause l can become much larger than r. If for example, $l = 0.1$ cm one finds $m \simeq 5 \times 10^{-10}$ g and for the kinetic projectile energy $(1/2)\, m v^2 \simeq 10^8$ erg $= 10$ J. The discharge time was $\tau \simeq 2 \times 10^{-8}$ sec and hence $I V \tau \simeq 10^5$ J. Thus even here, only a small fraction of the energy stored in the diode actually goes into the projectile.

One may contemplate to enhance the proposed mechanism for the projectile acceleration by artificially supplying the anode with many wire-like protrusions. In this way the simultaneous acceleration of many projectiles should become possible. The wire-like protrusions could be produced by many capillars. Also, since for thermonuclear reactions velocities of $\sim 10^8$ cm/sec are sufficient [2] one may thereby be able to control the projectile velocity. If one requests that $v \simeq 10^8$ cm/sec a value for r according to Eq. (7) is being set.

Let us assume that $I V = 10^{14}$ W and that $\varrho \simeq 7$ g/cm^3, it then follows $r \simeq 6 \times 10^{-4}$ cm. If the filament is $l = 0.1$ cm, its mass is $m \simeq 10^{-6}$ g. This gives a kinetic projectile energy $(1/2)\, m v^2 \simeq 5 \times 10^9$ erg. Therefore, if one wants to use this effect for thermonuclear microexplosion ignition (which requires an energy of $\sim 10^{13}$ erg) one would have to launch several thousand filaments. The number of required projectiles is unchanged if one chooses higher projectile velocities, because the kinetic energy of one projectile is given by

$$(1/2)\, m\, v^2 = I\, V\, l/c\,, \tag{9}$$

depending only on the power $I V$ and filament length l.

It is worthwile to note that the electric field strength near the surface of the filament can become much larger than what is possible with filaments held together by tensile forces, for which the maximum electric field strength would be only $\sim 10^8$ V/cm. For example, in case of a magnetically confined filament, taking the values $I \sim 5 \times 10^5$ A, $r \simeq 10^{-5}$ cm, one has $H = 10^{10}$ G and hence $E_0 = 3 \times 10^{12}$ V/cm. For currents up to $\sim 5 \times 10^7$ A, which are possible with pulse power technology, one would have $H = 10^{12}$ G and $E_0 = 3 \times 10^{14}$ V/cm. These values represent very respectable field strengths. The large fields are only attainable if the current flows near the surface of the filament. This is not obvious since the current in heating the filament will lead to a plasma corona surrounding the filament and which can have a radius much larger than the radius of the filament. However, as it has been shown by several authors [3, 4], the bremsstrahlungslosses in a high-Z plasma, as it is realized here, can be so large that they cause rapid shrinking of the plasma corona down to the very small dimensions as required.

One may think that for a magnetic field strength of $\sim 10^{12}$ G, corresponding to a magnetic pressure of $\sim 10^{16}$ atmospheres, the matter of the filament would be completely crushed thus invalidating our model. This however, is not the case since the magnetic pressure $H^2/8\pi$ is here balanced by the electric pressure $E^2/8\pi$ if $H = E$.

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[4] J. W. Shearer, Phys. Fluids **19**, 1426 (1976).