The Possibility of Producing a Dense Thermonuclear Plasma by an Intense Field Emission Discharge*

F. Winterberg†
International Centre for Theoretical Physics, Trieste, Italy
(Received 18 March 1968)

It is shown that it may be possible to produce a dense thermonuclear plasma by irradiating a liquid or solid T-D target with electrons or ions from an intense field emission discharge. It may also be possible to generate a beam of microparticles resulting from the disintegration of the field emitter anodes by this method. The energy for the discharge can be supplied by conventional capacitor banks in the megajoule range using the Marx circuit technique, or, perhaps more efficiently, by an electrostatic energy system based on charging a superconducting ring to very high voltages.

INTRODUCTION

During the past decade great efforts have been aimed, in the field of plasma physics, at the ultimate goal of controlled thermonuclear energy release. All efforts have been based, without exception and in one modification or another, on the principle of confining and heating a plasma in a magnetic field. Although this approach showed promise in the beginning, until now all attempts to achieve the ultimate goal of controlled fusion energy release have been unsuccessful. The reason for this failure lies in the multitude of different plasma instabilities of which, at the present time, only a few are theoretically understood. There is, however, some guarded hope that late-generation devices based on multipole magnetic field configurations with large magnetic shear may lead to substantial improvements, but it should be remembered that similar hopes were raised in the past only to be frustrated by the experimental evidence of other, not anticipated, plasma instabilities.

Moreover, it was shown by Coppi, Furth, Rosenbluth, and Sagdeev[1] that the presence of a small amount of impurity ions will always lead to a drift-wave instability which cannot be stabilized by magnetic shear. To date it is difficult to see how such impurities will ever be eliminated from a thermonuclear reactor.

Because of the enormous number of difficulties associated with the problem of plasma confinement, the question has been raised if the problem of controlled thermonuclear fusion can be solved by simulating, on a small scale, the process that takes place in a hydrogen bomb. For obvious reasons, the physical process of a hydrogen bomb must be ruled out, because it depends on a trigger which consists of a critical mass of fissionable material. Since there appears to be no known way of substantially reducing the size of a critical mass, the process of a hydrogen bomb will always lead to an energy release much too large to be controllable.

However, the hydrogen bomb process could be simulated on a smaller scale if a trigger can be developed which is much smaller than that of a fission bomb, but one which is still strong enough to produce the high temperatures required to ignite a small thermonuclear explosion within a small volume of dense T-D.

The trigger must be capable of dissipating in a few nanoseconds an amount of energy in excess of 10^{14} erg into a volume of a few mm^3 of dense T-D. Such a trigger could ignite, in principle, an unlimited amount of thermonuclear material, but for purposeful power production the size of the explosion has to be limited. On the other hand, it is obvious that, for reasons of rational economy, the thermonuclear energy output should be at least equal to the energy set free by the trigger itself; that is, the thermonuclear energy output of the "microsize hydrogen-bomb" explosion should be no smaller than 10^{14} erg.

As an example, we may suppose that the explosion delivers an energy of 10^{16} erg. This would correspond to an explosive charge of 100 kg of TNT, which is very small compared with a thermonuclear explosion set free by a fission bomb. It is conceivable that the size of the explosion could be raised by a factor 10 or 100 above, up to 10^{17} or 10^{18} erg, and still be kept under conditions necessary for controlled energy release.

For the purpose of power production, it is conceivable to confine a chain of such explosions within a spherical container. A modification of the system could be used for rocket propulsion wherein the explosions would take place in the focus of a reflector, open at one side.

The decisive problem in contemplating a "microsize hydrogen bomb" is, then, the search for a trigger with the required properties.

Two schemes for such a trigger have been proposed in the past. Both of these schemes had in common the required property to dissipate a large amount of energy into a small volume of dense T-D within a few nanoseconds.

One of these schemes is based on the sudden irradiation of a dense piece of T-D by a giant pulsed laser. This method was first proposed by Basov and Krokin.[2] A detailed theoretical study of the scheme was later carried out by Dawson[3] and Engelhardt.[4] However, the enormous energies in excess of 10^{14} erg, which are required to ignite a small thermonuclear explosion, make it unlikely that this approach will be successful with the lasers available now or in the foreseeable future.

The second method, proposed first by the author and independently by Harrison, is based on the acceleration of a solid projectile (macroparticle) which would be shot at very high velocities onto a target consisting of thermonuclear material.[5,6] With this approach, the principal difficulties center on the problem of accelerating a macroparticle, consisting of 10^{22} atomic particles, to the required high velocities of 10^8 cm/sec. One way in which this goal may be achieved is by the acceleration of a superconductor in a traveling magnetic wave.[7-9] Estimates in this direction, however, indicate that such an accelerator may become many miles long. Without commenting further on this point, we would like to mention that certain means seem to exist by which the size of such an accelerator could be substantially reduced.[10-12] We also would like to refer to other ideas on macroparticle acceleration.[13]

In summary: Because of the enormous technical difficulties involved, it is hard to predict when either of the two reported schemes will ever be technically realized.

In this paper, we will present a third method for igniting a "microsize hydrogen bomb," one which may offer more promise than either of the two methods outlined above. This method is based on the irradiation of a dense T-D target by an intense field emission discharge.

I. THE CONDITIONS FOR THE IGNITION OF A SMALL THERMONUCLEAR EXPLOSION

To derive the conditions necessary to ignite a small thermonuclear explosion, we consider a sphere of liquid or solid T-D of arbitrary radius r.

(a.) The first condition is that the T-D has to be heated up to the ignition temperature of the T-D reaction, which requires that

$$T > 5\times 10^{7}\,^{\circ}\mathrm{K}. \tag{1.1}$$

(b.) In order to achieve a small thermonuclear explosion the energy generated in the T-D sphere has to be fed back into the T-D. This is the condition for detonation, and it requires that the range of the fusion products λ_F in the T-D at thermonuclear temperatures must be smaller than the radius of the T-D sphere. At densities of liquid T-D and temperatures of $5\times 10^{7}\,^{\circ}$K, this range is approximately 0.5 cm, so that the condition is given by

$$2r > \lambda_F = 0.5 \text{ cm}. \tag{1.2}$$

(c.) In order to extract more fusion energy than the thermal energy originally invested to heat the plasma up to fusion temperatures, the Lawson criterion $N\tau \geq 10^{14}$ sec/cm^3 has to be satisfied. N is the atomic number density; for liquid T-D, $N = 4\times 10^{22}$ cm^{-3}, and τ is the confinement time. The confinement time τ is determined from the fastest energy loss of the plasma. The plasma can lose energy by expansion, radiation, and heat conduction.

For an unconfined plasma, the most important energy loss results from expansion, which is determined by the velocity of sound a. At $T = 5\times 10^{7}\,^{\circ}$K the velocity of sound for a T-D plasma is approximately given by $a \simeq 10^8$ cm/sec. The time for expansion, which has to be substituted as τ into the Lawson criterion, is given by $\tau \simeq r/a \simeq 10^{-8} r$. With the above given value for N, one thus obtains from the Lawson criterion

$$r > 0.25 \text{ cm}, \tag{1.3}$$

and hence the expansion time

$$\tau > 2.5\times 10^{-9} \text{ sec}. \tag{1.4}$$

(d.) As the next important loss, we consider the loss by bremsstrahlung. The time in which a hydrogen plasma of density N and temperature T loses its energy by bremsstrahlung is given by

$$\tau_R = 2.65\times 10^{11}\sqrt{T}/N. \tag{1.5}$$

From (1.5) it follows that if $N = 4\times 10^{22}$ cm^{-3} and $T = 5\times 10^{7}\,^{\circ}$K, then $\tau_R \simeq 5\times 10^{-8}$ sec (a time larger by a factor of 20 than the minimum expansion time). From (1.5) it follows, furthermore, that the Lawson criterion is automatically satisfied, since $N\tau_R = 2\times 10^{15} > 10^{14}$ sec/cm^3.

(e.) Finally, let us consider the losses by electronic heat conduction which derive from the heat-conduction equation with a characteristic diffusion time

$$\tau_C = Nr^2/\chi\,, \tag{1.6}$$

where $$\chi = 5.3\times 10^{9} T^{5/2}\,. \tag{1.7}$$

For $T = 5\times 10^{7}\,^{\circ}$K and $N = 4\times 10^{22}$ cm^{-3} one obtains

$$\tau_C = 4.2\times 10^{-7} r^2\,. \tag{1.8}$$

For $r = 0.25$ cm, it follows then that $\tau_C = 2.6\times 10^{-8}$ sec. This time is larger by a factor of 10 than the minimum expansion time, and smaller by a factor of 10 than the time by which the plasma loses its energy by radiation.

Hence, if the only losses of the plasma are caused by bremsstrahlung and electronic heat conduction, it follows from (1.8) that the Lawson criterion will be satisfied for $r > 7.7\times 10^{-2}$ cm, since the radiation losses fulfill the Lawson criterion independently of the plasma dimension.

It would appear that the time which predominantly determines the energy losses of the plasma is the expansion time. The energy required to heat up the T-D plasma under these conditions would have to be supplied in a time shorter than 5 nsec. It is, however, very likely that this rather short time can be increased substantially by surrounding the T-D target with some heavy, high-A material. In this case, the rapid expansion of the T-D plasma could be greatly reduced, and the energy losses, consequently, would be mainly determined by the bremsstrahlung losses. Surrounding the T-D target with a heavy substance may result in the disadvantage that inverse Compton losses may significantly and adversely affect the energy balance. To what degree this effect would be important is not yet known; it would require detailed calculations of the transfer of radiation through the confining walls to determine the degree of effect. There is, however, some indication, based upon simple estimates, that the effect would be, hopefully, of minor importance.

In summary, the time τ_{in} in which the energy has to be supplied to the target is between 5×10^{-8} sec and 2.5×10^{-9} sec:

$$2.5\times10^{-9}\ \text{sec} < \tau_{in} < 5\times10^{-8}\ \text{sec}. \qquad (1.9)$$

(f.) The total energy required to heat a spherical volume of liquid T-D to thermonuclear temperatures is given by

$$E_{in} = 3NkT \times \tfrac{4}{3}\pi r^3$$
$$\simeq 5.4\times10^{13}\ \text{erg} = 5.4\ \text{MJ}. \qquad (1.10)$$

By surrounding the T-D target with a heavy substance, it may be possible to reduce the critical radius of $r < 0.25$ cm so that an input energy less than that computed from (1.10) would be sufficient. It should be noted that even a small reduction in r would result in a considerable reduction of E_{in}.

(g.) The energy given by (1.10) has to be supplied to the target within a few nanoseconds and the target must, therefore, be exposed to an energy absorption density ϵ as given by

$$\epsilon \gtrsim E_{in}/\tfrac{4}{3}\pi r^3 \tau = 3NkT/\tau$$
$$= 1.7\times10^{22}\text{–}3.3\times10^{23}\ \text{erg/cm}^3\ \text{sec}. \qquad (1.11)$$

II. IGNITION OF A SMALL THERMONUCLEAR EXPLOSION BY THE IRRADIATION OF A T-D TARGET WITH AN INTENSE ELECTRON BEAM

We shall show in this paper that there appears to exist a new and promising method by which our goal, the ignition of a small thermonuclear explosion, can be achieved. This new method is based on a recently reported technique[14–16] by which pulsed, very intense electron beams, with power outputs up to 10^{12} W and lasting for 1–10 nsec, can be generated. The electron energy in these beams is several MeV, and the total beam current is above 100 kA. The electron-beam extraction is performed by the field emission process. The energy for the pulsed field emission discharge is drawn from a large capacitor bank which utilizes the high-voltage Marx-circuit technique.

The principle of the idea is explained in Fig. 1. The Marx high-voltage circuit contains n capacitors of capacitance C_i, so that in parallel alignment the total capacitance is given by

$$C_p = nC_i\ . \qquad (2.1)$$

After the spark gaps are closed, the total capacitance is given instead by aligning the capacitors in series; hence,

$$C_s = C_i/n. \qquad (2.2)$$

As a consequence, the voltage is raised instantly from its value V, before the spark gaps are closed,

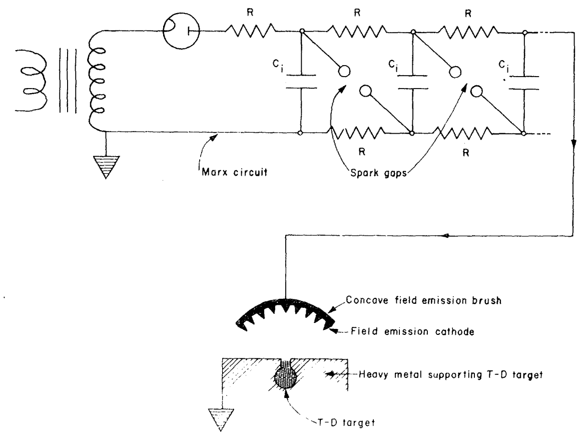

FIG. 1. The principle by which the T-D target is irradiated by an intense electron beam.

to the value nV, and the time constant for discharging the bank is reduced from

$$\tau_p = (2\pi/c)(LC_p)^{1/2} = (2\pi/c)(LnC_i)^{1/2}, \qquad (2.3)$$

to $\tau_s = (2\pi/c)(LC_s)^{1/2} = (2\pi/c)(LC_i/n)^{1/2} = \tau_p/n\ . \quad (2.4)$

By using the Marx-circuit technique, the voltage of a capacitor bank can be suddenly increased by simultaneously lowering the discharge time. If, for instance, the capacitors were charged up to a voltage of 100 kV and $n = 100$, the output voltage, after the spark gaps are closed, would be 10 MV, and the discharge time would be reduced by a factor of 100. If the time constant of the bank were $\tau_p = 10^{-6}$ sec, it would be reduced to $\tau_s = 10^{-8}$ sec $= 10$ nsec.

The high-output voltage is then applied to a brush of many field emission cathodes arranged in a concave pattern, and the electrons are focused on the T-D target. The T-D target is supported by a dense high-A material, which serves both as anode and as a means to confine the target inertially as long as possible.

The field emission current density is[17]

$$j = 1.55\times10^{-6}(E^2/W)$$
$$\times \exp(-6.9\times10^{7}\,W^{3/2}/E)\ \text{A/cm}^2. \qquad (2.5)$$

In Eq. (2.5) E is the electric field strength in V/cm which acts on the field emission cathode, and W is the work function of the emitter in eV. The work function for tungsten, a material frequently used for field emission cathodes, is $W = 4.4$ eV. The field-emission current density approaches for $E > 6.4\times10^{8}$ V/cm a saturation value given (for tungsten) by

$$j_{max} = 1.55\times10^{-6}E^2/W,$$
$$= 3.5\times10^{-7}E^2\ \text{A/cm}^2. \qquad (2.6)$$

Each field-emission cathode is in the form of a needle and the tip of the needle is a half sphere. If the radius of this half sphere is r, and the applied voltage is V, the electric field acting on the tip of the cathode is given by

$$E = V/r. \quad (2.7)$$

The maximum total current I emitted by each cathode is obtained by multiplying (2.6) by the surface area $2\pi r^2$ of a half sphere; hence,

$$I_{max} = 2.2 \times 10^{-6} V^2 \text{ A},$$

$$r < 1.6 \times 10^{-9} V \text{ cm}. \quad (2.8)$$

The inequality in (2.8) is derived from the condition that the argument in the exponential function (2.5) is small compared with 1, which is the condition for obtaining the saturation current.

The maximum total power output is given by

$$P_{max} = I_{max} V = 2.2 \times 10^{-6} V^3 \text{ W}. \quad (2.9)$$

If, for instance, $V = 10^7$ V, it follows that $r < 1.6 \times 10^{-2}$ cm, $I_{max} = 2.2 \times 10^8$ A, and $P_{max} = 2.2 \times 10^{15}$ W. If the discharge lasts 10 nsec, the total energy released will be 2.2×10^7 J $= 2.2 \times 10^{14}$ erg. In spite of the short duration of the discharge, the high current density of $j_{max} = 1.4 \times 10^{11}$ A/cm^2 seems to be intolerably high, and it is, therefore, more expedient to work with a brush of many cathodes which have been arranged in the concave pattern indicated in Fig. 1. If, for example, the tip radius for each emitter cathode is put equal to $r = 10^{-1}$ cm, under otherwise unchanged conditions, the total current density according to (2.5) is reduced by the exponential factor $\exp(-6.9 \times 10^7 W^{3/2}/E) = \exp(-6.4) = 1.6 \times 10^{-3}$, where for $r = 10^{-1}$ cm and $V = 10^7$ V one has to put $E = 10^8$ V/cm. The total current emitted from one emitter is now given by $I = 3.5 \times 10^5$ A, and the power output is $P = 3.5 \times 10^{12}$ W. The total current density on each emitter is reduced to $j = 6 \times 10^6$ A/cm^2. The delivery of an energy of 10^{14} erg in 10 nsec would, hence, require approximately 300 cathodes.

The electrons, emitted simultaneously by all 300 cathodes, are focused, by the concave arrangement, onto the T-D target. Because of the fact that the electron beam has a strong, self-magnetic field, it can be confined into a narrow beam with a diameter less than 1 mm; that is, if the space charge is compensated by a tenuous plasma which can be placed in front of the target. If the electron beam is focused down to a diameter of less than 1 mm, the current density will rise above 10^{10} A/cm^2.

The question may be raised whether a beam of such a high current density will be actually stable. At the present time we are not yet in a position to answer this question with assurance. It has been shown, however, by Budker[18] that relativistic electron streams tend to be more stable than their nonrelativistic counterparts. From his analysis, which, according to his own judgment must be considered preliminary, he obtains stability against kinks for perturbations less than 0.5 cm for a relativistic electron beam of energy 10 MeV and radius 10^{-1} cm. The derived stability criterion depends upon the beam energy and radius, but not upon the electron density. Whether beam stability at the high current densities of 10^{10} A/cm^2 can be actually achieved will, in all probability, have to be decided experimentally.

If the target and the energy absorbed in it by the impinging electrons satisfy the conditions put down in Sec. I, a small thermonuclear explosion will be ignited.

It is clear that the condition for detonation and the Lawson criterion can always be satisfied by a proper size of the target. Furthermore, by choosing a capacitor bank of sufficient size, the energy requirement put down by Eq. (1.10) can be met. Actually, capacitor banks with an energy storage of about a megajoule have been built, and an even larger bank with 10 MJ is under construction. However, simply going to larger capacitor banks may raise another problem. Enlarging a capacitor bank will not only increase its capacitance C, but also its inductance L. This will result in an increase of the discharge time $\tau = (2\pi/c)(LC)^{1/2}$. But, since L and C increase linearly with the size of the bank (in contrast to the stored energy which increases with the third power of its size), this difficulty can always be overcome by making the bank large enough. In Sec. III we shall propose an unconventional energy storage system in which a much larger amount of electrostatic energy can be stored in a much smaller volume.

Experimentally[14–16] pulsed field emission discharges have been achieved with total energy outputs of 10^4 J $= 10^{11}$ erg in the time of 10 nsec. In one of these experiments,[14] the electron energy was about 10 MeV and the total beam current was 3×10^5 A. In another experiment[16] the electron beam was directed onto a solid target, and, as a result of the beam impact, strong shock waves were created.

As required by the condition (1.9), the time in all of these reported experiments was of the right order of magnitude. Also, the requirement to focus the beam on a target with a size of a few millimeters was fulfilled. But the total beam energy output was still short by almost three orders of magnitude for what would be needed to trigger a small fusion explosion.

Besides the need for a higher beam energy output which can be met by larger banks, there may arise a second problem associated with the requirement to fulfill the condition (1.9). This problem results from the long range of many cm of electrons in liquid T-D for electron energies of several MeV. For 10-MeV electrons, for instance, one obtains in liquid T-D a range of $l \simeq 30$ cm. As a consequence, only a fraction of the energy delivered by the field-emission discharge would be absorbed in the target.

Fortunately, however, the situation is much better than deduced from this single-particle picture, since the beam can efficiently deposit its energy in the target by the process of the counterstream instability.

The maximum growth rate of the counterstream instability for nonrelativistic electron beams has been derived by Buneman.[19] Although these calculations do not apply to relativistic electron beams, they can be used to obtain an order-of-magnitude estimate.[20] According to these investigations, if a stream of electrons with density n_2 is moving through a plasma with electron density n_1, the maximum growth rate σ for counterstream instability is approximately given by

$$\sigma = 0.7(n_2/n_1)^{1/3}\omega_{\mathrm{pl}}, \tag{2.10}$$

where ω_{pl} is the electron plasma frequency of the plasma with density n_1. Since the electrons move almost at the velocity of the speed of light, one obtains from (2.10) an expression for the range λ_D of the beam, over which its energy will be dissipated,

$$\lambda_D \simeq 1.4(n_1/n_2)^{1/3}(c/\omega_{\mathrm{pl}}). \tag{2.11}$$

For a current density of 10^{10} A/cm^2 and electron velocities close to c, one obtains as the beam electron density $n_2 \simeq 2\times 10^{18}$. With the target electron density $n_1 \simeq 4\times 10^{22}$ there results from (2.11) $\lambda_D \simeq 10^{-4}$ cm. This range seems to be sufficiently short to ensure complete beam absorption in the target.

To enhance beam absorption, it may be advantageous to expose the target to a strong magnetic field at the moment of discharge. In this case, the electrons from the beam which disintegrates by the counterstream instability, will be forced into circular motion. For 10-MeV electrons and a magnetic field larger than 600 kG, the electron Larmor radius will be less than 0.5 cm and thus of the dimensions of the target. A field in excess of 600 kG could be easily produced by a small theta pinch coil.

If, however, this mechanism should fail in the case envisaged for some unforeseen reasons, then there still remains the possibility of using a field-emission discharge of ions rather than one of electrons. In this case the range of the ions, by ordinary Coulomb scattering, would be already small enough to assure large beam energy absorption in the target. The employment of a field ion emission discharge will result in a number of other problems. These are discussed below.

We conclude this section by mentioning that the electron beam hitting the target primarily heats the target electrons and not the target ions. The ions are then heated by electron-ion collisions, and the equipartition time is given by[21] ($N = 4\times 10^{22}$ cm^{-3}):

$$t_{\mathrm{eq}} = 1.5\times 10^{-21}\,T^{3/2}. \tag{2.12}$$

Inserting $T = 5\times 10^{7}$°K one obtains $t_{\mathrm{eq}} \simeq 10^{-9}$ sec. This time is short enough to heat the ions to fusion temperatures.

III. A DEVICE FOR STORING A LARGE AMOUNT OF ELECTROSTATIC ENERGY

In the approach outlined in this paper, one of the principal problems is the need for a system which can deliver an energy amount in excess of 10^{14} erg in a few nanoseconds. The experimentally tested systems of 10^{12} W with total energy outputs of 10^4 J $= 10^{11}$ erg are still too small to achieve the desired goal by almost three orders of magnitude. It has already been pointed out that an increase in the capacitance of conventional electrostatic-energy storage systems is accompanied by an undesirable increase in the discharge time τ. In order to overcome this difficulty, we shall propose here a radically different electrostatic-energy storage system.

It is well known that in ordinary capacitors the attainable voltage and maximum energy input is limited by electric breakdown. In a high-voltage capacitor with vacuum insulation, the breakdown is caused by electron field emission which results from surface irregularities. The question thus arises whether the loss of charge by field emission could be suppressed by a strong magnetic field.

We shall describe here a device which might be charged up to a much higher voltage than any other system.

For this we consider a toroidal ring, as drawn in Fig. 2. The material of this ring consists of the high-magnetic-field type-II superconductor. Furthermore, this superconducting ring must be levitated in high vacuum with the aid of externally applied magnetic fields. If toroidal currents are set up in this superconducting ring, they will cause an azimuthal magnetic field H_θ. If j is the current density in the superconducting torus, then one easily computes a surface magnetic field strength given by

$$H_\theta = 0.2\pi r j = 0.63 r j, \tag{3.1a}$$

$$\text{and } j = 1.6 H_\theta / r \ \mathrm{A/cm^2}, \tag{3.1b}$$

respectively.

The critical magnetic field for high-field superconductors of the vanadium-gallium type is above the limit posed by the tensile strength, giving an

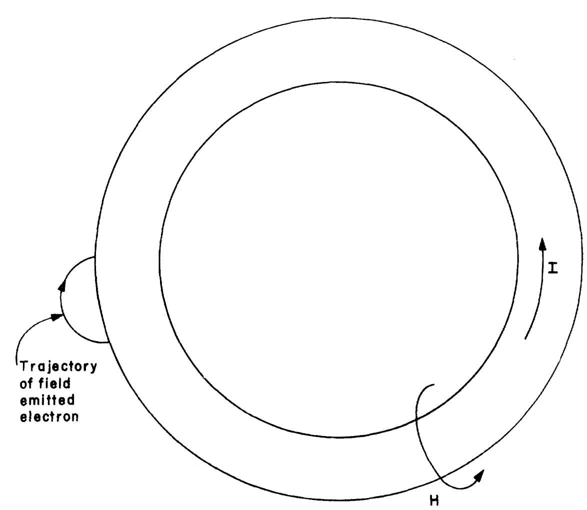

FIG. 2. Levitated superconducting ring with large toroidal currents and strong magnetic field as capacitor.

upper field strength of approximately 3×10^5 G. The critical current density is of the order of 10^5 A/cm^2. Putting, for example, $r=50$ cm and $H=3\times10^5$ G, one obtains from (3.1b) $j=10^4$ A/cm^2, which is less by one order of magnitude than the critical current density. It is now proposed to charge the highly magnetized and levitated superconducting torus to a high voltage. The strong magnetic field of the ring prevents field emission of electrons from discharging the torus. The radial electric field E_r and the azimuthal magnetic field H_θ will cause a drift motion of the electrons in a direction parallel to the circular axis of the torus, and the electrons will always be recaptured by the torus if the Larmor radius for the drift motion R_L is less than the major torus radius R. Hence,

$$R \gg R_L = mc^2 E_r / eH_\theta^2. \tag{3.2a}$$

(E_r is measured in electrostatic units.)

Obviously, in order to avoid mechanical disintegration, E_r cannot be made larger than the maximum possible value computed from the tensile strength. For this reason the maximum electric surface field is limited to 10^8 V/cm. For (3.2) we can also write in conventional units, and by expressing the electron energy in eV,

$$R \gg R_L = 1.1\times10^{-5}\, V E_r / H_\theta^{\,2}, \tag{3.2b}$$

where V is the voltage of the torus and E_r the electric surface field in V/cm.

The voltage V of the charged torus and the electric surface field E_r are related to each other by

$$V = 4rE_r \ln(8R/r), \tag{3.3}$$

where r is the minor torus radius. Inserting E_r from (3.3) into (3.2b), one has

$$R \gg R_L = 2.7\times10^{-6}\, V^2/H_\theta^{\,2} \ln(8R/r). \tag{3.4}$$

In order to levitate the ring, the levitating external magnetic coils should be not too far from the surface of the torus. If the separation distance is of the order r (the minor torus radius) the electron Larmor radius for electrons coming from the surface with an energy $mc^2 = 1$ eV, must be prevented from reaching the levitating coils. This requires that $r \gg r_L$, where r_L is the electron Larmor radius; hence, $(v \simeq c)$

$$r \gg r_L = \frac{mc^2}{eH_\theta} = 3.3\times10^{-3}\, V/H_\theta . \tag{3.5}$$

The charging of the torus may be performed during the buildup of the toroidal currents in the levitated ring. For that purpose the magnetization of the ring has to be done inductively, and for this to be possible, the superconducting material of the torus has to be embedded into a normal conductor of high conductivity. The magnetization of the torus is caused by the flux-jump effect in the superconducting ring. During the flux jump, the electric currents will for a short period of time, flow inside the normal conductor.[22]

During this inductive magnetization, the field lines coming from infinity "move" towards and penetrate into the superconducting ring. The charging of the ring can thus be performed by "attaching" to the magnetic field lines the electrons which are emitted at low energies by a glow discharge. The field lines then transport these electrons to the surface of the torus.

There is also the possibility that the magnetized and levitated torus can be charged up to a high electrostatic potential by an electron gun. In this case, it would be necessary that the electrons lose some of their energy in order to be trapped inside of the magnetic well. This might be accomplished by inductive coupling to external resistors, as it has been successfully demonstrated in trapping the E layer in the astron device.

Assuming, for instance, that the torus is charged up to a surface electric field strength $E = 10^6$ V/cm, and putting, for example, $R = 3\times10^2$ cm and $r = 5\times10^1$ cm, one obtains from (3.3) $V = 7.8\times10^8$ V. If the magnetic surface field strength is equal to 3×10^5 G, one obtains from (3.4) $R_L = 4.4$ cm, by which $R \gg R_L$ is satisfied. It is then verified that (3.5) is satisfied, since $r_L = 8.6 \text{ cm} \ll 50$ cm.

The capacitance and inductance of the torus are given (in electrostatic cgs units) by

$$C = \frac{\pi R}{\ln(8R/r)} = 2.4\times10^2 \text{ cm}, \tag{3.6}$$

$$L = 4\pi R\left[\ln\left(\frac{8R}{r}\right) - \frac{7}{4}\right] = 8.1\times10^3 \text{ cm}. \tag{3.7}$$

The stored electrostatic energy E_S is

$$E_S = \tfrac{1}{2} C V^2 = 8.2\times10^{14} \text{ erg}, \tag{3.8}$$

which is larger than the critical amount required to trigger a small thermonuclear explosion.

The discharge time is given by

$$\tau = (2\pi/c)(LC)^{1/2} = 3\times10^{-7} \text{ sec} = 300 \text{ nsec}. \tag{3.9}$$

(The discharge time is larger by a factor of 10 than the loss time for bremsstrahlung, but this is compensated in our example by an energy supply larger than required.)

Since the electric field is not limited to the chosen value of 10^6 V/cm and could probably be raised by a factor of 10, this means that, with our chosen torus parameters, energies even ten times higher could be stored; that is, as much as 10^{17} erg.

The energy from the highly charged torus could be drawn by a spark gap switch. An electrode would have to be moved towards the torus until breakdown occurs. Breakdown is likely to occur at a distance smaller than the electron Larmor radius in our example, 8.6 cm. The principal feature of this system is drawn in Fig. 3.

There are two remarks to be made in connection with the described system of electrostatic energy storage. One remark relates to a major disadvantage of the system which would result if

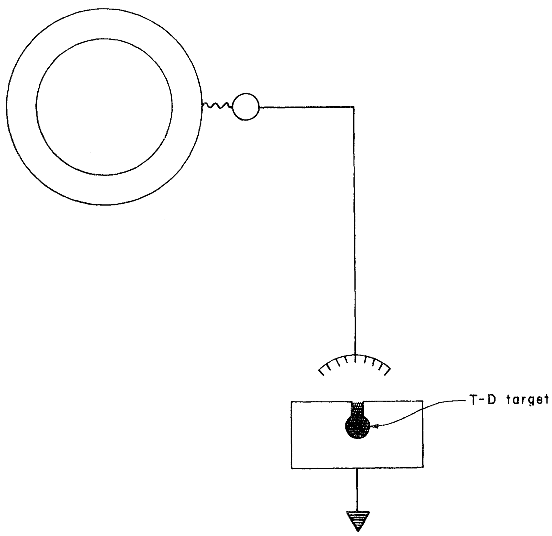

FIG. 3. The discharging of the levitated torus.

the charging of the torus could be only performed inductively. In this case, the magnetic energy would be lost prior to each new cycle of charging the torus involving a large waste of energy. This obvious disadvantage would not occur if the charging of the toroidal superconducting ring were performed by an electron gun. The torus, in this case, would be theoretically charged and discharged an infinite number of times as long as it could be kept superconducting.

For the second remark, we would like to direct attention to a system which is based on a magnetically confined electron cloud and is known as the HIPAG.[23] Although there are certain similarities between the proposed system and the HIPAG device, there are also significant differences, the most important of which are (1) the replacement of the electron cloud by a solid core, and (2) the azimuthal direction of the field in our device, as contrasted to the HIPAG in which the direction is poloidal.

The replacement of the electron cloud by a solid core has the obvious advantage of a much higher stability, but apart from this advantage, it seems difficult to see how the HIPAG device could be discharged in a way which would make it useful for our purpose. It is to be remembered that in the HIPAG device the electron cloud, trapped in a toroidal magnetic field, is surrounded by a solid conducting wall which is essential for the functioning of the device. Any attempt to discharge the electron cloud through an outside electrode will most likely result in a discharge of the electron cloud to the conducting container wall.

IV. TARGET HEATING BY AN INTENSE FIELD ION EMISSION

The possible problem of inefficient electron thermalization resulting from the large range of energetic electrons in dense matter can be greatly reduced by using, instead of a field electron emission, a field ion emission. The range of MeV protons in T-D at liquid densities and thermonuclear temperatures is of the order of cm and therefore short enough to ensure large energy absorption in the T-D target even without dissipation by the counterstream instability. The position of emitter and absorber as drawn in Fig. 1, would have to exchange their positions.

For field ion emission, the ions cannot be extracted as easily from the emitter as can electrons. In order to obtain a strong field ion current, the emitters have to be artificially supplied with a gas.[24] A continuous current, for instance, can be obtained by a flow of neutral atoms impinging on the emitter, but, as is required for our purpose, this method will not lead to a very strong ion current.

An effective way to produce a high field ion current could be as follows (see Fig. 4):

Each emitter anode has a bore with an open end at the emitter tip. The other end of the bore is subjected to high gas pressure which results in an outflow of gas from the emitter tip. If the electric field at the tip is high enough, the gas atoms will be stripped of their electrons. The electric field necessary to produce field ionization is, for most materials, of the order of 10^8 V/cm. Therefore, if this condition is met, an intense current by field ion emission will result.

We assume that the voltage at each emitter is $V = 10^7$ V and the electric field is $E = 10^8$ V/cm. The radius of the tip for one emitter is then given by $r \simeq V/E = 0.1$ cm.

If the bore in the emitter has the radius $r_0 < r$, and if the gas escaping from the end of the bore has an atomic number density n, the flux of particles F escaping through the bore is given by

$$F = na\pi r_0^2, \tag{4.1}$$

where $a = (\gamma kT/m)^{1/2}$ is the velocity of sound. Furthermore, since $n = p/kT$, it follows

$$F = \pi r_0^2 (\gamma/mkT)^{1/2} p\,. \tag{4.2}$$

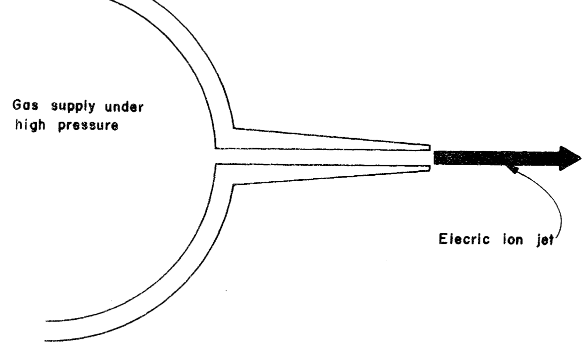

FIG. 4. Gas supply for field ion emission.

If the discharge lasts a time τ and the applied voltage is V, and if it is assumed that every gas atom is ionized, the total energy delivered by one emitter is given by

$$E_{in} = FeV\tau = \pi r_0^2(\gamma/mkT)^{1/2} peV\tau . \qquad (4.3)$$

We will assume that the gas supplied to the emitter is deuterium and, furthermore, that $r_0 = 5\times10^{-2}$ cm, $V = 10^7$ V, $p = 10^9$ dyn/cm^2, $\tau = 10^{-8}$ sec, $T = 10^{2}$°K, $m = 3.32\times10^{-24}$ g and obtain $E_{in} = 6.9\times10^{12}$ erg. Therefore, according to condition (1.10), a number of ten emitters will supply to the target enough energy to trigger a small thermonuclear explosion.

Finally, in order to confine the ion current, as in the case of field electron emission, the space charge again has to be compensated, which also can be done here by a tenuous plasma in front of the target.

V. TARGET HEATING BY MICROPARTICLES

Finally, it may even be possible to heat the target by a stream of microparticles resulting from the disintegration of the emitter anodes.

If an electric field exceeding the critical value of 10^8 V/cm is suddenly applied to the electrodes, it is conceivable that the electrodes might disintegrate momentarily in a cloud of many small microparticles. The anode material should disintegrate to a size of the microparticles for which the mechanical stress can compensate the electric stress.

If the tip of each anode has a radius r and an electric charge q, the electric field at its surface is given by

$$E_0 = q/r^2. \qquad (5.1)$$

It is assumed that the tip disintegrates into n equal microparticles of radius r_n. If the initial charge is evenly distributed, each microparticle will have a charge q_n given by

$$q_n = q/n, \qquad (5.2)$$

and a radius r_n

$$r_n = rn^{-1/3} . \qquad (5.3)$$

At the radius r_n, the electric surface field acting on each microparticle has to be equal to the critical electrical field $E_c \simeq 10^8$ V/cm $\simeq 3\times10^5$ esu; hence,

$$E_c = q_n/r_n^{\,2} = q/r^2 n^{1/3} = E_0 n^{-1/3} . \qquad (5.4)$$

On the other hand, E_0 is expressed by the applied voltage and tip radius by $E_0 = V/r$; hence,

$$V/r = E_0 n^{1/3} . \qquad (5.5)$$

In order to heat the target to a temperature of 10^{8}°K the microparticles must attain a velocity of $v = 10^8$ cm/sec. In this respect, the outlined approach has considerable similarity to considerations in a paper on microparticle acceleration quoted above.[5]

The microparticles attain a velocity in the applied electric field which is computed from

$$\tfrac{1}{2} mv^2 = q_n V, \qquad (5.6)$$

where $m = \tfrac{4}{3}\pi\rho r_n^{\,3} = \tfrac{4}{3}\pi\rho r^3/n, \qquad (5.7)$

and ρ is the material density of the microparticles. From (5.6), (5.7), and (5.2) one obtains

$$(2\pi/3)\rho v^2 r^3 = qV , \qquad (5.8)$$

but since $q = E_0 r^2 = Vr$, one has

$$V/r = (2\pi\rho/3)^{1/2} v . \qquad (5.9)$$

From (5.5) and (5.9), it thus follows that

$$n = (2\pi\rho/3)^{3/2}(v/E_c)^3 , \qquad (5.10)$$

and $r = V/(2\pi\rho/3)^{1/2} v . \qquad (5.11)$

In order to set off a small thermonuclear explosion, the energy supplied to the target must be larger than E_{in}. The range of the microparticles in the target is of the same order as their radius, and is therefore smaller than $r \simeq 0.25$ cm. If N is the number of emitter anodes, the condition for the ignition of a small fusion explosion is thus given by

$$N\tfrac{4}{3}\pi r^3 \tfrac{1}{2}\rho v^2 = E_{in} , \qquad (5.12)$$

and because of Eq. (5.9),

$$N = (2\pi\rho/3)^{1/2} E_{in} v/V^3. \qquad (5.13)$$

Assuming the values $\rho = 7.0$ g/cm^3, $E_{in} = 10^{14}$ erg, and $v = 10^8$ cm/sec, we obtain

$$N = 3.8\times10^{22}/V^3 . \qquad (5.14)$$

From Eq. (5.14), it follows that a smaller number of emitter anodes is required for increasing voltage V. Putting, for instance, $V = 7.8\times10^8$ V $= 2.6\times10^6$ esu, which is a typical value for the levitated magnetic capacitor described in Sec. III, one has $N \simeq 2\times10^3$. Let us, furthermore, assume that $E_c = 3\times10^5$ esu. One then obtains, from Eq. (5.10), $n = 2.1\times10^9$, and from Eq. (5.11), $r = 0.7\times10^{-2}$ cm; hence, $r_n = 5.5\times10^{-6}$ cm.

CONCLUSION

The several estimates presented in this paper indicate that a dense thermonuclear plasma can be produced by an intense field emission discharge and irradiation of a dense T-D target. It is furthermore shown that if presently available experimental setups are increased in their dimension, one can hope to reach critical conditions under which the ignition of a small thermonuclear explosion, and thus the release of a small amount of fusion energy, becomes possible. If the heating is done by field discharge of a stream of microparticles, the approach has some similarities to the macroparticle approach to nuclear fusion which has a similar goal.

ACKNOWLEDGMENTS

This work was carried out with the support of the National Aeronautics and Space Administration while the author was on a visit to the International Center for Theoretical Physics of the International Atomic Energy Agency in Trieste, Italy. Special thanks are given to Professor Abdus Salam and the IAEA for their kind hospitality during this visit.

---

*Supported in part by the National Aeronautics and Space Administration, U.S.A., under Grant NGR-29-001-016. This paper is based on the International Centre for Theoretical Physics Report No. ICTP35/1967, November, 1967. Presented at the A. E. C. Sherwood theoretical meeting May 6–7, 1968, University of California, Berkley, Calif.

†Permanent address: University of Nevada, Reno, Nevada.

[1]B. Coppi, H. P. Furth, M. N. Rosenbluth, and R. Z. Sagdeev, Phys. Rev. Letters 17, 377 (1966).

[2]N. G. Basov and O. N. Krokin, in Proceedings of the Third International Conference on Quantum Electronics, Paris, 1963, edited by P. Grivet and N. Blounberger (Columbia University Press, New York, 1964).

[3]J. M. Dawson, Phys. Fluids 7, 981 (1964).

[4]A. G. Engelhardt, Westinghouse Research Laboratories Report No. 63-128-113-R2, 1963 (unpublished).

[5]F. Winterberg, Case Institute of Technology Plasma Research Program, Technical Report No. A21, 1963 (unpublished), and Z. Naturforsch. 19a, 231 (1964).

[6]E. R. Harrison, Phys. Rev. Letters 11, 535 (1963).

[7]F. Winterberg, Nucl. Fusion 6, 152 (1966).

[8]F. Winterberg, J. Nucl. Energy: Pt. C 8, 541 (1966).

[9]C. Maisonnier, Nuovo Cimento 42B, 332 (1966).

[10]F. Winterberg, Plasma Phys. 10, 55 (1968).

[11]F. Winterberg, Nucl. Fusion 7, 289 (1967).

[12]J. P. Somon, Laboratorio Gas Ionizzati (EURATOM) Internal Report, 1966 (unpublished).

[13]E. R. Harrison, Plasma Phys. 9, 183 (1967).

[14]F. C. Ford, D. Martin, D. Sloan, and W. Link, Bull. Am. Phys. Soc. 12, 961 (1967).

[15]S. E. Graybill and S. V. Nablo, Bull. Am. Phys. Soc. 12, 961 (1967).

[16]F. J. Grundhauser, J. L. Brewster, J. B. Barbour, F. M. Charbonnier, and W. P. Dyke, Bull. Am. Phys. Soc. 12, 961 (1967).

[17]W. Finkelnburg, Structure of Matter (Academic Press, Inc., New York, 1964).

[18]G. J. Budker, in Proceedings of the CERN Symposium on High Energy Accelerators, Geneva, 1956, CERN Report No. CERN-56-25, 56-26 (unpublished), p. 68.

[19]O. Buneman, Phys. Rev. 115, 503 (1959).

[20]The relativistic correction can be approximately taken into account by substituting into ω_{pl} of Eq. (2.10) resp. (2.11) twice the reduced relativistic mass of two counterstreaming electrons, resulting in no substantial change of the computed ranges up to several MeV.

[21]L. Spitzer, Physics of Fully Ionized Gases (Interscience Publishers, Inc., New York, 1962).

[22]J. J. Hanak, R.C.A. Review 25, 551 (1964).

[23]G. S. Janes, R. H. Levy, H. A. Bethe, and B. T. Feld, Phys. Rev. 145, 925 (1966).

[24]Handbuch der Physik, edited by S. Flügge (Springer-Verlag, Berlin, 1956), Vol. XXI, p. 233.