# On Thermonuclear Micro-Bomb Propulsion for Fast Interplanetary Missions

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**Abstract**

To reduce the radiation hazard for manned missions to Mars and beyond, a high specific impulse-high thrust system is needed, with a nuclear bomb propulsion system the preferred candidate. The propulsion with small fission bombs is excluded because the critical mass requirement leads to extravagant small fission burn up rates. This leaves open the propulsion with non-fission ignited thermonuclear micro-explosions, with a compact fusion micro-explosion igniter (driver), and no large radiator. It should not depend on the rare $He^3$ isotope, and only require a small amount of tritium. This excludes lasers for ignition. With multi-mega-ampere-gigavolt proton beams and a small amount of tritium, cylindrical deuterium targets can be ignited. The proton beams are generated by discharging the entire spacecraft as a magnetically insulated gigavolt capacitor. To avoid a large radiator, needed to remove the heat from the absorption of the fast neutrons in the spacecraft, the micro-explosion is surrounded by a thick layer of liquid hydrogen, stopping the neutrons and heating the hydrogen to a temperature of ~ $10^5$ K, which as a fully ionized plasma can be repelled from the spacecraft by a magnetic mirror.

## 1. Introduction

The central problem of propelling a space craft by a chain of thermonuclear micro-explosions is the ignition of the micro-explosions with a driver small enough to be placed in a spacecraft of realistic dimensions. Because of the low laser efficiency, I had proposed in to replace lasers with electric pulse power driven electron or ion beams, where the beams are produced by large Marx generators or a magnetically insulated torus charged up to gigavolts [1]. Unlike lasers, electromagnetic devices, and in particular electrostatic devices, have a high efficiency. Shortly thereafter, I had, in 1969, proposed at the International School of Physics "Enrico Fermi," to use thusly ignited thermonuclear micro-explosions for rocket propulsion [2]. A much more detailed analysis of this concept was published in 1971 [3]. About three years later, and apparently unaware of the earlier work, a paper with some amplification of my original idea was presented in 1972 by Hyde at the Conference of the American Institute of Aeronautics and Astronautics in New Orleans [4]. This paper attracted much attention, but unlike my earlier papers proposing relativistic electron or ion beams for ignition, it relied on ignition by laser beams. It was further developed in a paper together with Nuckolls and Wood [5], and finally in a large study by the Lawrence Livermore National Laboratory as the "Vista" concept, under the leadership of Orth [6]. All these laser ignition concepts did not take into account the scaling law for spherical implosion inertial confinement fusion targets by Kidder [7].

This scaling law obtained as follows: The energy input for ignition is

$$E \sim \frac{1}{2} M v_{imp}{}^2 \sim \rho R^3 \sim \frac{(\rho R)^3}{\rho^2} \tag{1}$$

where M is the mass of the target and $v_{imp}$ the implosion velocity. Since for thermonuclear ignition $\rho R$ is fixed by $\rho R > 1$ g/cm$^2$ for the DT reaction, one has

$$E \sim \frac{1}{\rho^2} \tag{2}$$

If $R = R_0$ is the radius at the beginning of the implosion and $R < R_0$ the final radius at the end of the implosion, one has

$$\frac{\rho}{\rho_0} = \left(\frac{R_0}{R}\right)^3 \tag{3}$$

and hence

$$E \sim \left(\frac{R}{R_0}\right)^6 \tag{4}$$

or

$$\frac{R_0}{R} \sim E^{-1/6} \tag{5}$$

This result means that the ignition energy is very sensitive to the ratio $R_0/R$, or vice-versa, the ratio $R_0/R$ is very insensitive to the energy input and is limited by the Rayleigh-Taylor instability. The latest data obtained by the laser implosion experiments of the National Ignition Facility of the Lawrence Livermore National Laboratory have shown no ignition with a laser energy input of 2MJ. Therefore, raising, for example, the laser energy tenfold, from 2MJ to 20MJ, would only decrease the ratio $R_0/R$ by the insignificant factor ~ $10^{-6}$ ~ 0.7. Together with the limitation set by the Rayleigh-Taylor instability, this all but excludes lasers as a viable means for thermonuclear micro-explosion ignition. For propulsion, the situation is even worse, because to drive the lasers, a small fission reactor power plant would have to be carried in the spacecraft, requiring a large radiator.

For cylindrical targets the situation can be very different. If ignited with intense ion beams with a current of a few mega-amperes, large enough to radially entrap the charged fusion product, the condition $\rho R \sim 1$ g/cm$^2$ has to be replaced by $\rho L \sim 1$ g/cm$^2$, where L is the length of the cylindrical target. There then, (1) is replaced by

$$E \sim \rho L R^2 \tag{6}$$

or with $\rho L = const.$

$$E \sim R^2 \tag{7}$$

independent of R, permitting lower densities for longer cylindrical targets. With intense mega-ampere ion beams below the Alfvén limit, the cylindrical targets are not subject to pinch instabilities.

It was later claimed by Hyde [8], running the fusion micro-explosion pellets of the Daedalus study by the British Interplanetary Society through the (classified) LASNEX computer code, that "he found that these pellets produced little thrust, and if re-engineered to create thrust, would melt the engine." But the Daedalus study [9] was based on my beam ignition concept, making use of the large self-magnetic beam field, ignored by Hyde. Therefore, had Hyde run beam magnetic field supported pellet ignition through the LASNEX code, he would have obtained a very different result. For the ultra-high voltage and magnetic charging techniques used for the generation of mega-ampere GeV proton beams, no onboard nuclear fission reactor is needed, as it would be needed in Hyde's "Laser-Fusion Starship."

## 2. Ignition of a Cylindrical Target with a $10^7$ Ampere-GeV Proton Beam

If a proton beam is focused onto one end of a cylindrical target, the beam not only can be made powerful enough to ignite the target, but its strong azimuthal magnetic field entraps the charged fusion reaction products within the cylinder, launching a detonation wave propagating with supersonic speed down the cylinder [10a, 10b]. There the fusion gain and yield can in principle be made arbitrarily large, because it only depends on the length of the deuterium rod.

The range of the charged fusion products is determined by their Larmor radius

$$r_l = \frac{\alpha}{B} \tag{8}$$

where,

$$\alpha = \frac{c}{e}\frac{(2MAE)^{1/2}}{Z} \tag{9}$$

In (9) $c$, $e$ are the velocity of light and the electron charge, $M$ is the hydrogen mass, $A$ the atomic weight and $Z$ the atomic number, and $E$ is the kinetic energy of the fusion products.

If the magnetic field is produced by the proton beam current $I[A]$, one has at the surface of the deuterium cylinder the azimuthal magnetic field in Gauss

$$B_\phi = 0.2I / r \tag{10}$$

Combining (8) with (10) and requesting that $r_1 < r$, one finds that

$$I > I_c \tag{11}$$

where $I_c = 5\alpha$. In Table 1 the values for $\alpha$ and $I_c$ for all the charged fusion products of the DT and DD reaction are compiled. For all of them the critical current is below $I_c = 3.84 \times 10^6$ A. Therefore, with the choice $I \sim 10^7$ A, all the charged fusion products are entrapped inside the deuterium cylinder.

For a detonation wave to propagate along a DT cylinder we can then set

$$\rho L \sim 1 \text{ g/cm}^2 \tag{12}$$

**Table 1:** *Critical Ignition Currents for Thermonuclear Reactions.*

| Reaction | Fusion Product | Energy [MeV] | A [G cm] | $I_c$ [A] |
|---|---|---|---|---|
| DT | $He^4$ | 3.6 | $2.7 \times 10^5$ | $1.35 \times 10^6$ |
| DD | $He^3$ | 0.8 | $1.12 \times 10^5$ | $5.6 \times 10^5$ |
| DD | T | 1.0 | $2.5 \times 10^5$ | $1.25 \times 10^6$ |
| DD | H | 3.0 | $2.5 \times 10^5$ | $1.25 \times 10^6$ |
| $DHe^3$ | H | 14.65 | $5.56 \times 10^5$ | $3.84 \times 10^6$ |
| $DHe^3$ | $He^4$ | 3.66 | $2.78 \times 10^5$ | $1.39 \times 10^6$ |

The stopping length of single GeV protons in dense deuterium is much too large to satisfy (12). But this is different if the stopping length is determined by the electrostatic proton-deuteron two-stream instability [11]. In the presence of a strong azimuthal magnetic field the beam dissipation is enhanced by the formation of a collision-less shock [12], with the thickness of the shock by order of magnitude equal to the Larmor radius of the deuterium-tritium ions at a temperature of $10^9$ K. For a magnetic field of the order $10^7$ G it is of the order of $10^{-2}$ cm, with the two-stream instability alone, the stopping length is given by

$$\lambda \cong \frac{1.4c}{\varepsilon^{1/3}\omega_i} \tag{13}$$

where $c$ is the velocity of light, and $\omega_i$ the proton ion plasma frequency, furthermore $\varepsilon = n_b/n$, with $n$ the target number density and $n_b = 2 \times 10^{16}$ cm$^{-3}$ the proton number density in the beam. For a 100-fold compression one has $n = 5 \times 10^{24}$ cm$^{-3}$, with $\omega_i = 2 \times 10^{15}$ s$^{-1}$. One there finds that $\varepsilon = 4 \times 10^{-9}$ and, $\lambda \cong 1.2 \times 10^{-2}$ cm. This short length, together with the formation of a collision-less magneto-hydrodynamic shock, ensures the dissipation of the beam energy into a small volume at the end of the rod. For a deuterium number density $n = 5 \times 10^{24}$ cm$^{-3}$ one has $\rho = 17$ g/cm$^3$, and to have $\rho L \sim 1$ g/cm$^2$, then requires that L ~ 0.06 cm. With $\lambda < L$, the condition for the ignition of a thermonuclear detonation wave is satisfied. The ignition energy is given by

$$E_{ign} \sim 3nkT\pi R^2 L \tag{14}$$

where $T \approx 10^9$ K.

For a 100-fold compression, one has $\pi r^2 = 10^{-3}$ cm$^2$, when initially it was $\pi r^2 = 10^{-1}$ cm$^2$. With $\pi r^2 = 10^{-3}$ cm$^2$, $L = 0.06$ cm one finds that $E_{ign} \sim 10^{15}$ erg or ≈ 1 GJ. This energy is provided by the $10^7$ Ampere-GeV proton beam lasting $10^{-8}$ s. The time is short enough to ensure the cold compression to high densities. For a $10^3$-fold compression, found feasible in later fusion experiments, the ignition energy is ten times less.

The ignition energy can still be much smaller if the tip of the rod is made of DT, which after its ignition acts as the trigger for a detonation in deuterium. Such a target configuration is shown in Fig. 1, where the deuterium rod, to which the DT is attached, is radiatively compressed by the X-rays released from DT and D burn behind the detonation front of the deuterium. In this way the amount of the expensive tritium isotope can be kept at a minimum.

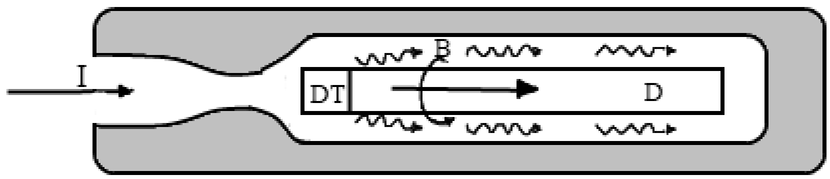


**Figure 1:** *Cylindrical Target with DT triggered D burn.*

The gain is there only dependent on the length of the deuterium rod. For a GeV proton beam with $I = 10^7$ A, the power is $P = 10^{16}$ W, and it lasts $10^{-8}$ s, feasible with the discharging of a magnetically insulated gigavolt capacitor, the energy delivered to the target is large enough to ensure ignition. With the DT assisted ignition an energy of about 10 MJ may be sufficient.

### 3. Dissipating the Neutron Energy in a Shell of Liquid Hydrogen Surrounding the Target

In DT fusion about 80% (in D fusion less) of the energy is released into neutrons, which cannot be deflected by a magnetic mirror, and still worse would heat the spacecraft, therefore requiring a large radiator. While this poses a problem for deep (interstellar) missions requiring the largest possible specific impulse, for less ambitious missions within the solar system, in particular missions to Mars, a nice solution exists for this problem: surrounding the neutron-releasing micro-explosion with a sufficiently thick layer of liquid hydrogen, stopping in it the neutrons and heating it to high temperature to render it a fully ionized plasma which can be deflected by a magnetic mirror. For missions to Mars it has the additional bonus that it increases the thrust by lowering the exhaust velocity of the order 100 km/s., which optimal for this mission.

It is here proposed to place the thermonuclear target in the center of a liquid hydrogen sphere, with the target to be ignited by a GeV ion beam—passing through a pipe (see Fig. 2). To increase energy output, the hydrogen sphere can be surrounded by a shell made from a neutron absorbing boron. The energy released as energetic α-particles by the absorption of the neutrons in the boron not only increases the overall energy output, but also compresses the hydrogen sphere. Following the ignition and burn of the target, the hydrogen is converted into an expanding hot plasma fire ball used for propulsion.

For this idea to work, the radius of the liquid hydrogen sphere must be large enough to slow down and stop the neutrons, but not be larger than is required to keep its temperature at or above $10^5$ K. This condition can be met for liquid hydrogen spheres of reasonable dimensions.

As in fission reactors, the neutron physics is determined by the slowing down and diffusion of the neutrons in the blanket. Assuming that the radius of the target is small compared to the outer radius of the neutron-absorbing blanket, one can pproximate the neutron source of the burning target as a point source.

We use the Fermi age theory [13] for the slowing down of the neutrons from their initial energy $E_0$ to their final energy $E$. The neutron-slowing down is determined by the Fermi age equation

$$\frac{\partial q}{\partial \tau} = \nabla^2 q \tag{15}$$

where the "age" $\tau$ is given by:

$$\tau(E)=\int_E^{E_0}\frac{D}{\xi\sum_s E}\,dE \tag{16}$$

*D* is the neutron diffusion constant

$$D=\frac{1}{3\sum_s(1-\mu_0)} \tag{17}$$

with $\Sigma_s$ the macroscopic scattering cross section, $\Sigma_s = n\sigma_s$, where $n$ is the particle number density in the blanket, and $\sigma_s$ is the scattering cross section. Futhermore,

$$\mu_0=\frac{2}{3A} \tag{18}$$

is a scattering coefficient for a substance of atomic weight *A*. For hydrogen, one has $A = 1$ and hence $\mu_0 = 2/3$, making $D = 1/\Sigma_s$. The logarithmic energy decrement of the neutron deceleration is given by:

$$\xi=1+\frac{(A-1)^2}{2A}\ln\frac{A-1}{A+1} \tag{19}$$

For $A = 1$, one has $\xi = 1$.

Setting $E_0 = 14$ MeV (DT reaction), E = 10 eV ($10^5$ K), and using the neutron physics data of the Brookhaven National Laboratory [14], one finds that $\tau \cong 6 \times 10^2$ cm$^2$, and $\sqrt{\tau} \cong 20$ cm. For water, one has, by comparison for the $E_0 = 2$ MeV fission energy, neutrons slowed down to the thermal energy $E = 2 \times 10^{-2}$ eV, $\tau = 33$ cm$^2$, and $\sqrt{\tau} = 5.7$ cm. However, for the production of a $10^5$ K fire ball, water is unsuitable because at these temperatures most of the energy goes into blackbody radiation. For this reason alone, hydrogen is to be preferred.

The expression for $\tau$ given by (16) ignores neutron absorption during the slowing down process. If taken into account, one has to multiply $\tau(E)$ with the resonance escape probability p($E$) given by

$$\mathrm{p}(E)=\exp\left(-\frac{1}{\xi}\int_E^{E_0}\frac{\sum_a}{\sum_a+\sum_s}\frac{dE}{E}\right) \tag{20}$$

where $\Sigma_a = n_a\sigma_a$ is the macroscopic absorption cross-section, with $n_a$ as the particle number density of the neutron absorbing substance, and $\sigma_a$ is the microscopic absorption cross-section. For graphite-moderated reactors $p \approx 0.5$. For large $\sigma_a$ and even if $n_a << n$, p($E$) can substantially reduce $\tau$ and hence the stopping length.

Another important number is the slowing down time for the neutrons, given by

$$t_0 = \frac{\sqrt{2M}}{\xi \overline{\Sigma}_s}\left(\frac{1}{\sqrt{E_{th}}} - \frac{1}{\sqrt{E_0}}\right) \tag{21}$$

where M is the neutron mass.

For liquid hydrogen $t_0 \approx 10^{-5}$ s. This time is much longer than the time of the DT micro-explosion, but it must be about equal to the inertial expansion time of the fire ball with an initial radius *R*. For an expanding plasma fire ball of initial radius *R* and expansion velocity *V*, one has

$$t_0 \cong \frac{R}{V} \tag{22}$$

At a temperature of $10^5$ K, the expansion velocity is $V \approx 30$ km/s and setting $R \cong \sqrt{\tau} = 20$ cm, one has $t_0 \cong 10^{-5}$ s. For liquid hydrogen where $n = 5 \times 10^{22}$ cm$^{-3}$, the total number of hydrogen atoms in a spherical volume with a radius of 20 cm is of the order $N = 2 \times 10^{27}$. Heated to a temperature of $T = 10^5$ K, the thermal energy of the fire ball is of the order $E \cong NkT \approx 3 \times 10^{16}$ erg = 1 ton of TNT. For a DT target requiring an ignition energy of 1-10 MJ, this requires a gain of the order 300. The subsequent deuterium burn could increase the gain ~ tenfold, reaching a hydrogen temperature up to $10^6$ K with an expansion velocity $V \approx 100$ km/s.

**4. Spatial Distribution of the Decelerated Neutrons**

Making the point-source approximation for the neutrons released from the DT fusion micro-explosion, their spatial distribution by the Fermi age equation is

$$\mathrm{q}(r,t) = \frac{e^{-r^2/4\tau}}{(4\pi\tau)^{\frac{3}{2}}} \tag{23}$$

The slowing down of the neutrons is followed by their diffusion which is ruled by the diffusion equation in spherical coordinates

$$D\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial\phi}{\partial r}\right) - \Sigma_a\,\phi + S = \frac{\partial n}{\partial t} \tag{24}$$

Where $\phi$ is the neutron flux, $\Sigma_a = n\sigma_a$, with $\sigma_a$ the neutron absorption cross-section. *S* is the neutron source given by pq.

Surrounding the hydrogen by boron, the diffusion equation must be solved with the boundary condition for the neutron flux in the hydrogen A, and boron B

$$\left.\begin{aligned} \phi_A &= \phi_B \\ D_A\frac{d\phi_A}{dr} &= D_B\frac{d\phi_B}{dr} \end{aligned}\right\} \tag{25}$$

Because of the very large neutron absorption cross section for thermal (or epithermal) neutrons, only a comparatively thin layer of boron is needed. The 3 MeV of energy released in charged particles by the neutron absorption of neutrons in boron can be simply added to the neutron energy of the thermonuclear micro-explosion.

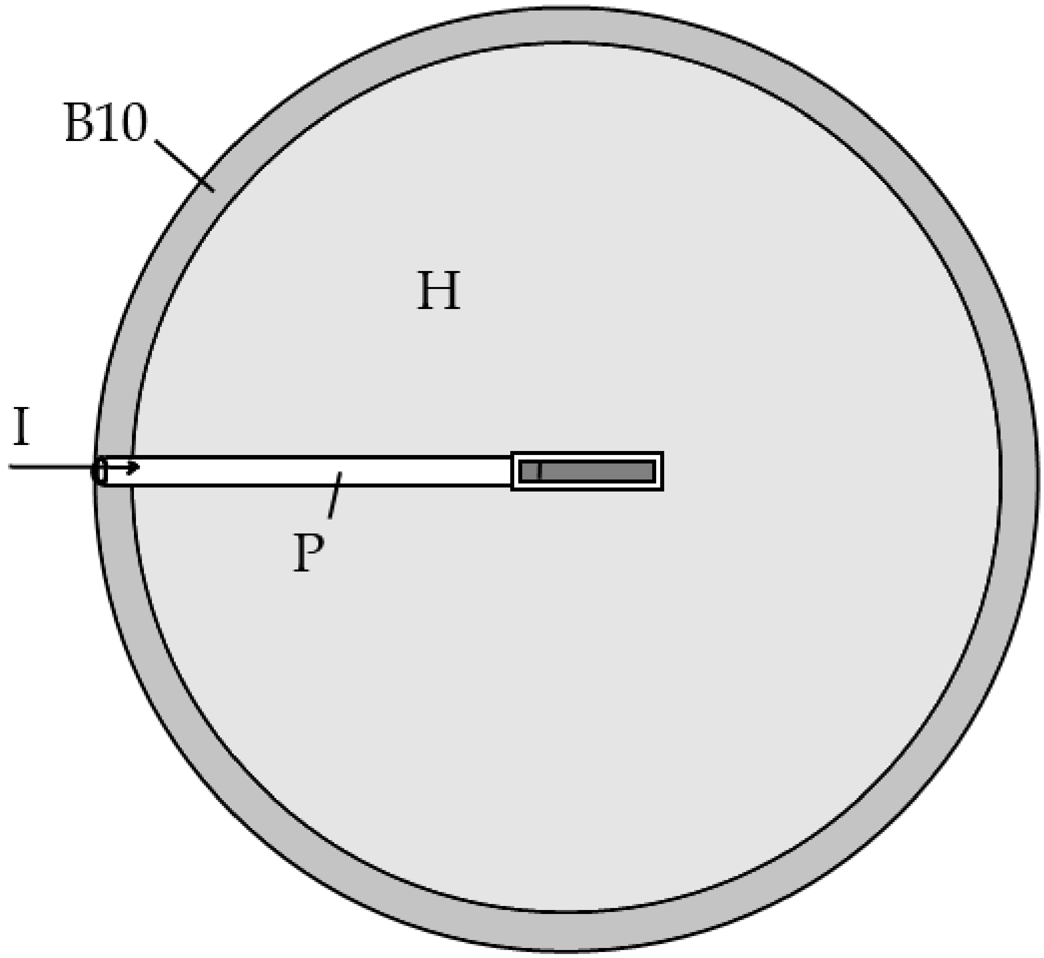


**Figure 2:** *Cylindrical fusion target placed inside a shell of liquid hydrogen. I is the proton beam to ignite the target, with I projected through a thin pipe P. H is liquid hydrogen, B10 solid boron.*

## 5. On Magnetic Insulation and Inductive Charging

There are two concepts which are of great importance for the envisioned realization of this idea:

1. The concept of magnetic insulation, which permits the attainment of ultrahigh voltages in high vacuum [1].
2. The concept of inductive charging, by which a magnetically insulated conductor can be charged up to very high electric potentials [15].

### 5.1 Concept of Magnetic Insulation

In a greatly simplified way magnetic insulation can be understood as follows: If the electric field on the surface of a negatively charged conductor reaches a critical field of the order $E_c \sim 10^7$ V/cm, the conductor becomes the source of electrons emitted by field emission. The critical field for the emission of ions from a positively charged conductor is ~ $10^8$ V/cm. Therefore, if in a high voltage diode the electric field reaches ~ $10^7$ V/cm, breakdown will occur by electric field emission from the cathode to the anode. But if a magnetic field, of strength $B$ measured in Gauss, is applied in a direction parallel to the negatively charged surface, and thus perpendicular to the direction of the magnetic field, and if $\boldsymbol{B} > \boldsymbol{E}$, where $\boldsymbol{E}$ (like $\boldsymbol{B}$) is measured in electrostatic cgs units, the field emitted electrons make a drift motion parallel to the surface of the conductor with the velocity ($c$ velocity of light)

$$v_d = c\frac{\vec{E}\times\vec{B}}{\vec{B}^2} \tag{26}$$

To keep $|v_d|/c = E/B < 1$, then requires that $E < B$. Let us assume that $B = 2 \times 10^4$ G, which can be reached with ordinary electromagnets, requires that $E \leq 2 \times 10^4$ esu = $6 \times 10^6$ V/cm. A conductor with radius of $l \sim 10$ m = $10^3$ cm, can then be charged to a voltage of the order $El \leq 6 \times 10^9$ Volts.

This idea, however, can only work if the magnetically insulated conductor is surrounded by an ultrahigh vacuum, and if it has a topology for which the magnetic field lines are closed in the vacuum, generating an azimuthal magnetic field. The simplest configuration having the required property is a torus, with toroidal currents [1]. This requires that the torus is a superconductor levitated in ultrahigh vacuum. The vacuum of space is for this end ideally suited, suggesting that the spacecraft must have the topology of a torus.

However, to use the spacecraft as a capacitor to generate by its discharge an intense proton beam, it must be charged to a large positive electric potential. There then, it is surrounded by an electron cloud in the vacuum, and is magnetically insulated against the electron cloud by the large azimuthal magnetic field set up in the spacecraft by large toroidal currents.

### 5.2 Concept of Inductive Charging

To charge the spacecraft to the required gigavolt potentials we choose for its architecture a large, but hollow cylinder, which at the same time serves to act as a large magnetic field coil. If on the inside of this coil thermionic electron emitters are placed, and if the magnetic field of the coil rises in time, Maxwell's equation $curl\vec{E} = -(1/c)\partial\vec{B}/\partial t$ induces inside the coil an azimuthal electric field:

$$E_\phi = -\frac{r}{2c}\dot{B}_z \tag{27}$$

where $B = B_z$ is directed along the z-axis, with $r$ the radial distance from the axis of the coil. In combination with the axial magnetic field, the electrons from the thermionic emitters make a radial inward directed drift motion with the velocity

$$v_r = c\frac{E_\phi}{B_z} = -\frac{r}{2}\frac{\dot{B}_z}{B_z} \tag{28}$$

By Maxwell's equation $div\vec{E} = 4\pi ne$, this leads to the buildup of an electron cloud inside the cylinder resulting in the radial electric field

$$E_r = 2\pi ner \tag{29}$$

This radial electric field leads to an additional azimuthal drift motion with the velocity

$$v_\phi = c\frac{E_r}{B_z} \tag{30}$$

superimposed on the radially directed inward drift motion $v_r$.

For the newly formed electron cloud to be stable, its maximum electron number density must be below the Brillouin limit:

$$n < n_{\max} = B^2/(4\pi mc^2) \tag{31}$$

where $mc^2 = 8.2 \times 10^{-7}$ erg is the electron rest mass energy. For $B = 2 \times 10^4$ G one finds that $n_{max} \approx 4 \times 10^{13}$ cm$^{-3}$. To reach with a cylindrical electron cloud of radius $R$ a potential equal to $V$ requires an electron number density $n \approx V/\pi eR^2$. For $V = 10^9$ Volts = $3 \times 10^6$ esu and $R = 10^3$ cm, one finds that $n \sim 2 \times 10^9$ cm$^{-3}$, well below $n_{max}$.

## 6. Space Craft Architecture

The way propulsion is achieved is straightforward and explained in Fig. 3. The mini-fusion bomb F is catapulted into the focus of a parabolic magnetic reflector R, made from steel and placed inside a large magnetic field coil C.

The wall of the magnetic mirror is insulated against the hot plasma of the expanding fire ball by the thermomagnetic Nernst effect. It generates currents in the boundary layer between the cool wall and the hot plasma of the fire ball, producing a magnetic field between the wall and the fire ball just sufficiently strong to repel the fire ball from the wall [15].

At a temperature of $T \approx 10^5$ K the exhaust velocity is about equal to the thermal expansion velocity of a hydrogen plasma which at this temperature is $V \cong 30\,\text{km/s}$, with higher exhaust velocities up to 100 km/s reached with a temperature 10 times higher.

Using the entire space craft as a large, magnetically insulated capacitor, inductively charged up to gigavolt potentials, leads to an electron cloud in the vacuum surrounding the spacecraft [17]. For the injection of the GeV proton beam into the pipe reaching the DT target as shown, the liquid hydrogen sphere must be grounded against the electron cloud surrounding the spacecraft. This can be done by a small plasma jet emitted from the surface of the hydrogen sphere as shown in Fig. 4. The jet can be produced by a laser beam heating the material making up the jet.

For the recharging of the entire space craft to gigavolt potentials by inductive charge injection, the electromagnetic pulse induced in the induction loop surrounding the rocket propulsion chamber is used to radially inject electrons at the top of the spacecraft into the rising magnetic field of an auxiliary coil. Apart from a different design of the rocket propulsion chamber, this is the same kind of inductive charge injection proposed for pure deuterium bomb propulsion [17].

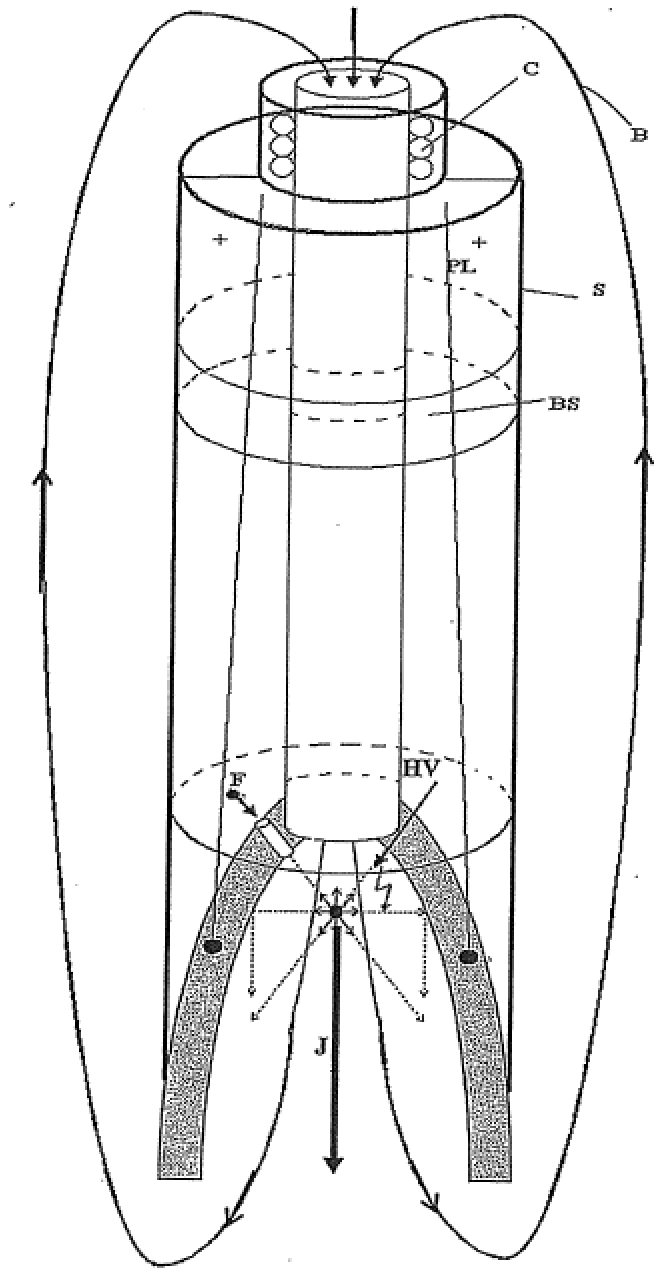


**Figure 3:** *Spacecraft architecture, with the spacecraft acting as a large toroidal gigavolt capacitor to ignite thermonuclear micro-explosion; F, mini-fusion bomb assembly shot into focus of magnetic mirror; J, plasma jet; HV, GeV proton beam; B, magnetic mirror field; BS, biological shield; PL, payload.*

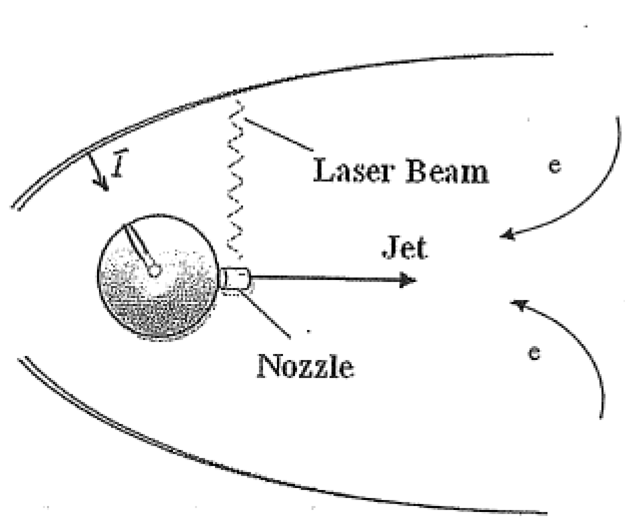


**Figure 4:** *Grounding of the hydrogen sphere against the electron cloud surrounding the spacecraft by a small, laser driven jet; e, electrons. I, GeV proton beam.*

## 7. Conclusion

Because it uses the entire spacecraft as a gigavolt capacitor to be discharged into an intense ion beam for ignition, the proposed concept is expected to be superior to all other designs intended to reach Mars in the shortest time possible, because all the other designs depend on a massive radiator. To reduce the mass of the radiator, "droplet" radiators have been proposed, but they suffer from the loss of droplet mass by evaporation. This not only applies to the VISTA and ICAN concept, but also to various electric propulsion concepts. None of them can compete with the compact gigavolt capacitor ignition concept ideally suited for the high vacuum of space.

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