

Matter-Antimatter GeV Gamma Ray Laser Rocket Propulsion

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Abstract

It is shown that the idea of a photon rocket through the complete annihilation of matter with antimatter, first proposed by Sanger, is not a utopian scheme as it is widely believed. Its feasibility appears to be possible by the radiative collapse of a relativistic high current pinch discharge in a hydrogen-antihydrogen ambiplasma down to a radius determined by Heisenberg's uncertainty principle. Through this collapse to ultrahigh densities the proton-antiproton pairs in the center of the pinch can become the upper GeV laser level for the transition into a coherent gamma ray beam by proton-antiproton annihilation, with the magnetic field of the collapsed pinch discharge absorbing the recoil momentum of the beam and transmitting it to the spacecraft. The gamma ray laser beam is launched as a photon avalanche from one end of the pinch discharge channel.

1. Introduction

The idea of the photon rocket was first proposed by Sänger [1], but at that time considered to be utopian. Sänger showed if matter could be completely converted into photons, and if a mirror can deflect the photons into one direction, then a rocket driven by the recoil from these photons could reach relativistic velocities where the relativistic time dilation and length contraction must be taken into account, making even intergalactic trips possible. The only known way to completely convert mass into radiation is by the annihilation of matter with antimatter. In the proton-antiproton annihilation reaction about 60% of the energy goes into charged particles which can be deflected by a magnetic mirror and used for thrust, with the remaining 40% going into 200 MeV gamma ray photons.¹ With part of the gamma ray photons are absorbed by the spacecraft, a large radiator is required, greatly increasing the mass of the spacecraft.

Because of the problem to produce antimatter in the required amount, Sänger [2] settled on the use of positrons. There, the annihilation of a positron with an electron produces two 500 keV photons, much less than two 200 MeV photons optimally released in the proton-antiproton annihilation reaction. But even to deflect the much lower energy 500 keV gamma ray photons, would require a mirror with an electron density larger than the electron density of a white dwarf star.

Here, a much more ambitious proposal is presented: The complete conversion of the proton-antiproton reaction into a coherent GeV gamma ray laser beam, with the entire recoil of this beam pulse transmitted to the spacecraft for propulsion.

This possibility is derived from the discovery that a relativistic electron-positron plasma column, where the electrons and positrons move in an opposite direction, has the potential to collapse down to a radius set by Heisenberg's uncertainty principle, thereby reaching ultra high densities [3]. Because these densities can be of the order 10^{15} g/cm³, comparable to the density of a neutron star, has led the Russian physicist B.E. Meierovich to make the following statement [4]: "This proposal can turn out to be essential for the future of physics."

The most detailed study of the matter-antimatter, hydrogen-antihydrogen rocket propulsion for interstellar missions was done by Frisbee [5]. It was relying on "of the shelf physics," while the study presented here goes into unknown territory.

The two remaining problems are to find a way to produce anti-hydrogen in the quantities needed, and how to store this material. A promising suggestion how the first problem might be solved has been proposed by Hora [6] to use intense laser radiation in the multi-hundred gigajoule range. This energy appears quite large, but the energy to pump the laser could conceivably be provided by thermonuclear micro-explosions to pump such a laser.

1. Magnetic Implosion of a Relativistic Electron-Positron-Matter-Antimatter Plasma

Let us first consider the pinch effect of an electron-positron plasma, where the electrons and positrons move with relativistic velocities in the opposite direction. For a circular cross section of this plasma the magnetic pressure of the electron-positron current will implode this plasma by the pinch effect. For non-relativistic currents the pinch effect is highly unstable, but as theory and experiments have shown, intense relativistic electron beams propagating through a space charge neutralizing plasma, seem to be quite stable, and the same should be true for two counter streaming relativistic electron and positron beams.

¹ A comparatively small amount goes into muons and neutrinos which are here ignored.

The time dependence of this plasma is ruled by two processes, one enhancing its expansion and the other its shrinkage. The process enhancing its expansion is the heating by Coulomb scattering taking place between the electrons and positrons colliding head on. The other process, enhancing its shrinkage, is the cooling by emission of radiation from transverse oscillations of the particles confined in the magnetic field of the plasma current. If the radiation losses exceed the transverse energy gain by Coulomb collisions the plasma will shrink.

The energy gain by Coulomb collisions is most easily calculated in a local reference frame in which either the moving electrons or positrons are at rest. If the particle number density, either for electrons or positrons, in a laboratory system is n , then in a co-moving system the number density of that particle species colliding head on is equal to $n' = \gamma n$. Furthermore, if the time element in the laboratory system is dt , it is in a co-moving system equal to $dt' = dt/\gamma$. The transverse energy gain of one electron or positron in a co-moving system, assuming the relative drift velocity is $v \approx c$, is then given by [7],

$$\frac{dE}{dt'} = 4\pi n' \frac{e^4}{mc} \ln \Lambda' \quad (1)$$

and hence in a laboratory frame

$$\frac{dE}{dt} = 4\pi n \frac{e^4}{mc} \ln \Lambda \quad (2)$$

Here $\ln \Lambda'$ is the Coulomb logarithm with $\Lambda' = b_{max}/b_{min}$. One has to put $b_{max} = r_b$, where r_b is the plasma radius and furthermore $b_{min} = e^2/\gamma mc^2 = r_0/\gamma$ ($r_0 = e^2/mc^2$ is the classical electron radius). In going to a laboratory system the value of b_{min} has to be multiplied by γ and one has $\Lambda = r_b/r_0$. The total current in the plasma (using electrostatic cgs units) is $I \approx 2nec\pi r_b^2$. One then finds that

$$\frac{dE}{dt} = \frac{2ce^2}{r_b^2} \frac{I}{I_A} \ln \Lambda, \quad I_A = \frac{mc^3}{e} = 1.7 \times 10^4 \text{ A} \quad (3)$$

The azimuthal magnetic field inside the plasma column $r < r_b$ is given by

$$H_\phi = (2I/r_b c)(r/r_b) \quad (4)$$

and the radial restoring force acting on an electron or positron therefore given by

$$F = -e\beta H_\phi = -\frac{2e\beta I}{cr_b^2} \approx -\frac{2eI}{cr_b^2} r \quad (5)$$

This restoring force in conjunction with the excitation by the Coulomb collisions leads to the transverse radial oscillations determined by the equation of motion

$$\gamma m \ddot{r} = F \quad (6)$$

or

$$\ddot{r} + \omega^2 r = 0 \quad (7)$$

with $\omega^2 = 2eI/\gamma m c r_b^2 = (2/\gamma)(c/r_b)^2(I/I_A)$. Note that the relativistic transverse mass γm enters into Eq. (6). These transverse oscillations result in intense emission of radiation. The energy loss for one particle due to this radiation is given by [7]

$$P_e = (2/3) \left(e^2 \overline{\dot{v}_\perp^2} / c^3 \right) \gamma^4 \quad (8)$$

where v_\perp is the perpendicular velocity component, in our case $\dot{v}_\perp = \ddot{r}$. One thus finds that

$\overline{\dot{v}_\perp^2} = \overline{\ddot{r}^2} = \frac{1}{3} \omega^4 r_b^2$, and obtains

$$P_e = \frac{8}{9} \frac{e^2 c}{r_b^2} \left(\frac{I}{I_A} \right)^2 \gamma^2 \quad (9)$$

Since $\omega^2 = (2/\gamma)(c/r_b)^2(I/I_A) = \gamma m / 4\pi n e^2$, it follows that the plasma remains optically transparent for all frequencies of the emitted radiation, regardless of its radius r_b or particle number density n , and for this reason the emitted radiation cannot be reabsorbed by it. Therefore, if $P_e > dE/dt$, the plasma will ultimately shrink down to a radius r_{min} determined by Heisenberg's uncertainty principle:

$$\gamma m c r_{min} \approx \hbar \quad (10)$$

The condition $P_e > dE/dt$ implies that

$$\gamma^2 I / I_A > (9/4) \ln \Lambda \quad (11)$$

The condition against the plasma to pinch itself off by action of its own magnetic field is given by

$$H_\phi^2 / 4\pi < 2\gamma n m c^2 \quad (12)$$

which results in

$$I < \gamma I_A \quad (13)$$

This can be combined with the inequality (11) to give

$$\gamma > I / I_A > (9/4) \ln \Lambda / \gamma^2 \quad (14)$$

The maximum current is thus given by

$$I_{max} = \gamma I_A = 1.7 \times 10^4 \gamma \text{ A} \quad (15)$$

To satisfy inequality (14) requires that

$$\gamma^3 > (9/4) \ln \Lambda \quad (16)$$

setting a minimum γ value which is $\gamma_{min} = \left(\frac{9}{4} \ln \Lambda\right)^{1/3}$. The minimum current I_{min} required to lead to collapse is thus given by

$$I_{min} = \frac{9}{4} \frac{\ln \Lambda}{\gamma^2} I_A = \frac{\gamma_{min}^3}{\gamma^2} I_A = \left(\frac{\gamma_{min}}{\gamma}\right)^3 I_{max} \quad (17)$$

Assuming that $\frac{9}{4} \ln \Lambda \approx 10^2$, which is valid for $r_b \approx 1$ cm, one has $\gamma_{min} \approx 4.5$ and $I_{min} \approx 1.7 \times 10^6 \gamma^{-2}$ A.

If, for example, $\gamma = 10^2$, corresponding to beams with a particle energy of ≈ 50 MeV, one has $I_{min} = 170$ A. For $\gamma \approx 3 \times 10^3$, which is typical for electron intersecting storage rings, one has $I_{min} = 0.17$ A. Electron beams of this magnitude can be easily produced and also seem to be principally attainable for positrons with the state of the art in storage-ring technology.

After its collapse to the radius r_{min} given by Eq. (10), the number of particles per unit beam length, counting both electrons and positrons, is equal to $(1/r_0)(I/I_A)$. The particle number density in the plasma is therefore calculated to be

$$n_{max} = (\gamma^2 / \pi r_0 \lambda_e^2) (I / I_A) = \frac{\alpha^2 \gamma^2}{\pi r_0^3} \left(\frac{I}{I_A}\right) \quad (18)$$

with $\lambda_e = \hbar / mc$ and $\alpha = e^2 / \hbar c$, hence $n_{max} = 7.5 \times 10^{32} (I / I_A) \gamma^2$. The maximum density in the collapsed plasma is given by $\rho_{max} = \gamma m n_{max} \approx 6.8 \times 10^5 (I / I_A) \gamma^3$. Assume for example that $I = I_A = 17$ kA and $\gamma \approx 10^2$, it follows that $\rho_{max} \approx 6.8 \times 10^{11}$ g/cm³. With $I = 170$ kA, $\gamma = 2 \times 10^3$, which seems at the limit of technical feasibility, $\rho_{max} \approx 5.3 \times 10^{16}$ g/cm³, the range of nuclear densities.

The collapse time is given by $\tau_c = E_{\perp} / P_e$, with the perpendicular kinetic particle energy $E_{\perp} \approx \frac{1}{2} \gamma m v_{\perp}^2 \approx \frac{1}{2} \gamma m \omega^2 r_b^2 = mc^2 (I / I_A)$, hence

$$\tau_c = (9/8) (r_b^2 / r_0 c \gamma^2) (I_A / I) \quad (19)$$

Assume that initially $r_b \approx 1$ cm and that $I = I_A$, $\gamma = 10^2$, it follows $\tau_c \approx 10^{-2}$ sec.

In the last stage of the collapse the maximum photon energy, estimated from the lowest harmonic of the emitted radiation, is

$$\hbar \omega_{max} = E_{\perp} = mc^2 (I / I_A) \quad (20)$$

For example, if $I = I_A$, one has $\hbar \omega_{max} = mc^2$. Because of a small plasma diameter this presents a highly coherent γ radiation. Furthermore, since the collapse time τ_c depends on the plasma radius r_b according to $\tau_c \propto r_b^2$, most of the dissipated beam energy is released in the last moment of the collapse, resulting in

a burst of very intense γ radiation. The maximum power of this final burst can be computed by putting $r_b = r_{min}$ into Eq. (9) with the result

$$\begin{aligned} P_e^{max} &= (8/9)(c/r_b)(I/I_A)^2 \gamma^4 mc^2 \\ &\approx 2.1 \times 10^8 (I/I_A)^2 \gamma^4 \text{ erg/sec} \end{aligned} \quad (21)$$

where $r_b = \hbar^2 / me^2$ is the Bohr radius. If, for example, $I = I_A$, $\gamma = 10^2$, one finds

$P_e^{max} \approx 2.1 \times 10^{16}$ erg/sec. The energy of this pulse is delivered in the time τ_c^{min} obtained from putting $r_b = r_{min}$ into (19) and one finds

$$\tau_c^{min} = (9/8)(r_b / c\gamma^4)(I_A / I) \quad (22)$$

During the time the plasma collapses down to the radius r_{min} , it decays by electron-positron annihilation with a cross section equal to $\sigma \approx (\pi r_0^2 / 2\gamma^2) \ln(2\gamma^2)$ [8]. The decay time for annihilation is therefore given by

$$\tau_d \approx (\sigma n c)^{-1} = \frac{2\gamma^2 r_b^2}{r_0 c \ln(2\gamma^2)} \frac{I_A}{I} \quad (23)$$

From Eq. (19) and (23) we find that

$$\tau_d / \tau_c = (16/9) \gamma^4 / \ln(2\gamma^2) \quad (24)$$

Because the collapse must occur prior to the electron-positron annihilation time, it requires that $\tau_d \gg \tau_c$. This condition means that $(16/9) \gamma^4 \gg \ln(2\gamma^2)$, which for $\gamma \gg 1$ is well satisfied. For the collapsed state to form a quasistatic electron-positron “linear atom,” τ_d must be large in comparison to the orbital time scale of this atom, which is $\tau_0 = r_{min} / c = \hbar / \gamma mc^2$, where $r_{min} = \hbar / \gamma mc$ is the electron (positron) Compton wave length. Setting in Eq. (23) $r_b = r_{min} = \hbar / \gamma mc$ and $r_0 = e^2 / mc^2$, one finds that

$$\frac{\tau_d}{\tau_0} = \frac{2\gamma}{\ln(2\gamma^2)} \frac{\hbar c}{e^2} \frac{I_A}{I} \quad (25)$$

For $I = \gamma I_A$ one has for $\tau_d > \tau_0$

$$\frac{\tau_d}{\tau_0} = \frac{2\gamma}{\ln(2\gamma^2)} \frac{\hbar c}{e^2} \gg 1 \quad (26)$$

This result means that the annihilation time for the linear electron-positron atom is long enough to be viewed as the upper laser level for the decay into MeV gamma rays by the annihilation of the electrons with the positrons [9]. This finding suggests to search for a GeV gamma ray laser by the annihilation of protons with antiprotons.

3. Magnetic Implosion of a Hydrogen-Antihydrogen Ambiplasma

A magnetically imploded electron-positron plasma can be made by the coalescence of two intense multi-MeV electron and positron beams. A likewise magnetically imploded proton-antiproton plasma could be made by two multi-GeV proton and antiproton beams. But this would be a very inefficient way to make a proton-antiproton annihilation laser, because it would require to accelerate the protons and the antiprotons to the same γ -value as for the electrons and positrons to achieve the same kind of radiative collapse to high energies. For the example $\gamma \approx 100$, it would require the protons and antiprotons to an energy by two orders of magnitude larger than their rest energy, which would be to accelerate the energy of the gamma ray photons released by such a laser.

Fortunately, there exists a better way: It is through the magnetic implosion of hydrogen-antihydrogen ambiplasma. There only the electrons and positrons have to be accelerated to a large γ -value, with the hydrogen-antihydrogen plasma there formed by the coalescence of a hydrogen with an antihydrogen pinch discharge. For the induced coalescence into an ambiplasma pinch discharge the currents of the pinch discharges must be in the same directions, with the electrons and positrons moving in the opposite direction as the protons and antiprotons. As for a pinch discharge in an ordinary plasma, an externally applied axial magnetic field can stabilize the pinch discharge in the ambiplasma.

Immediately following their coalescence into an ambiplasma pinch discharge, a powerful gigavolt pulse is applied to the discharge, accelerating the electrons and positrons to high energies by the run-away mechanism. The resulting high electron-positron current magnetically insulates the protons and antiprotons against the development of a significant current. This can be seen as follows: In the first moment when the high voltage pulse is applied, the motion of the electrons and the positrons, but also of the protons and antiprotons can be described non-relativistically, with the result that the velocity of the electrons (positrons) v_e , and the protons (antiprotons) v_i , are given by

$$\left. \begin{aligned} v_e &= \frac{e\mathcal{E}}{m} t \\ v_i &= \frac{e\mathcal{E}}{M} t \end{aligned} \right\} \quad (27)$$

where \mathcal{E} is the applied electric field, v_e , v_i are the electron (positron), and proton (antiproton) velocities at the time t . The electron (positrons) approach the velocity of light at the time $t_0 = mc / e\mathcal{E}$. Up to the time t_0 one has

$$v_i / v_e = v_i / c = m / M \quad (28)$$

To magnetically insulate a proton-antiproton current from developing requires that

$$r_L < r \quad (29)$$

where

$$r_L = \frac{Mvc}{eH_\phi} \quad (30)$$

for the magnetic field H_ϕ given by the Alfvén current, the maximum current possible. For this current one has

$$H_\phi = \frac{2\gamma I_A}{rc} \quad (31)$$

Inserting (31) into (30), one finds that (29) is satisfied if

$$v_i / c < 2\gamma m / M \quad (32)$$

Because of (28) this is well satisfied, this means that the protons and antiprotons do not acquire a large axial velocity.

It still has to be checked if the protons and antiprotons cannot significantly be heated by their collisions with the energetic electrons and positrons. This heating is determined by the equation describing the heating of cold ions by hot electrons [10]:

$$\frac{dE}{dt} = n_e \sigma_d v_{th} \left(\frac{3kT}{2} \right) \left(\frac{m}{M} \right) \quad (33)$$

where for relativistic electron energies $v_{th} \rightarrow c$, $(3/2)kT \rightarrow \gamma mc^2$, $m \rightarrow \gamma m$ and the collision cross section

$$\sigma_d \approx \frac{e^4 \ln \Lambda}{(\gamma mc^2)^2} \quad (34)$$

Setting $n_e \approx n$ one finds that

$$\frac{dE}{dt} = \frac{ne^4}{Mc} \ln\Lambda \quad (35)$$

as in Eq. (2), but smaller by the factor m/M . Eq. (3) is multiplied by m/M . For $I = \gamma I_A$ one obtains

$$\frac{dE}{dt} \approx \frac{2ce^2}{r_b^2} \left(\frac{m}{M} \right) \gamma \ln\Lambda \quad (36)$$

With the collapse time given by (19), $\tau_c \approx r_b^2 r / r_0 c \gamma^3$, the gain in energy in the collapse time τ_c is

$$\Delta E \approx \frac{2mc^2}{\gamma^2} \left(\frac{m}{M} \right) \gamma \ln\Lambda \quad (37)$$

which for large γ -values is insignificant.

For the establishment of an electron-positron run-away current it is required that

$$e\mathcal{E}c > \frac{dE}{dt} = \frac{4\pi ne^4}{mc} \ln\Lambda \quad (38)$$

where \mathcal{E} is the electric field in electrostatic cgs units applied to the ambiplasma. With Eq. (3) for $I = \gamma I_A$, one has

$$\mathcal{E} > \frac{2e\gamma}{r_b^2} \ln\Lambda \quad (39)$$

with $\ln\Lambda \approx 10$, one finds that

$$\mathcal{E} > \frac{10^{-8} \gamma}{r_b^2} [\text{esu}] \approx \frac{3 \times 10^{-6}}{r_b^2} [\text{V/cm}] \quad (40)$$

As we have done for the electron-positron plasma, we have here also to determine if the collapse time is short in comparison to the annihilation time for the protons and antiprotons. This annihilation time is given by

$$T_d = \frac{1}{n\sigma_D v_i} \quad (41)$$

where $\sigma_D \approx \pi r_0^2$ is the annihilation cross section, n the number density of the protons and antiprotons in the collapsing pinch, and v_i the proton and antiproton velocity. For n we have $n = N / \pi r_b^2$ where $N = (1 / r_0)(I / I_A)$ is the number per length of the pinch channel. With $I = \gamma I_A$, we find that $N = r / r_0$ and

$$n = \frac{\gamma}{r_0} \frac{1}{\pi r_b^2} \quad (42)$$

For v_i we set in accordance with (32)

$$v_i = 2c\gamma(m / M) \quad (43)$$

We thus obtain

$$T_d = \frac{r_b^2}{2\gamma^2 r_0 c} \left(\frac{M}{m} \right) \quad (44)$$

With τ_c which for $I = \gamma I_A$ is given by

$$\tau_c = \left(\frac{9}{8} \right) \frac{r_b^2}{\gamma^3 r_0 c} \quad (45)$$

one finds that

$$\frac{T_d}{\tau_c} = \left(\frac{4}{9} \right) \gamma \frac{M}{m} \quad (46)$$

For $T_d / \tau_c \gg 1$, one has $10^3 \gamma \gg 1$. This is well satisfied.

This chapter can be summarized as follows: If a current equal to $I = \gamma I_A$, and for a large value of γ , passes through a hydrogen-antihydrogen ambiplasma, it is going to collapse down to extremely high densities with the protons and antiprotons together with electrons and positrons compressed by the confining azimuthal magnetic field.

4. The Collapsed Hydrogen-Antihydrogen Ambiplasma as the Upper Level of a GeV Gamma Ray Laser

It is now proposed, to employ the collapsed hydrogen-antihydrogen ambiplasma as the upper laser level of the linear atom made up from a large number of hydrogen-antihydrogen atoms, held together by the ultrastrong magnetic field of the pinch discharge. The annihilation of hydrogen with the antihydrogen goes over the production of π^0 , π^+ , and π^- pions for the proton-antiproton reaction, and into two γ photons for the electrons and positrons. The π^0 decays further into 4γ photons, with the π^+ and π^- pions decaying into μ^+ , μ^- leptons and their associated μ neutrinos and antineutrinos. But with the high intensity of

stimulated γ -ray cascade, it is likely that there is a reaction channel where all the energy of the proton-antiproton annihilation reaction goes into two γ -ray photons, with the photons of the gamma ray cascade overwhelming all the other reaction channel. This is the mechanism for the electron-positron annihilation laser, and we will here assume that it also occurs for the proton-antiproton laser.

If this transformation takes place as a gamma ray laser avalanche, and if the recoil of this avalanche is transmitted by the strong azimuthal magnetic field of the pinch discharge, then with the return current conductor fastened to the spacecraft, all the momentum of the annihilation reaction goes into the spacecraft.

The idea is explained in Fig. 1, where the laser avalanche is launched from the left end of the pinch discharge, moving to the right with a velocity close to the velocity of light. As in the Mössbauer effect [11], the gamma ray photons transmit their recoil momentum to the linear atom of the ultradense pinch discharge. For this idea to work requires that the recoil energy

$$R = (1/2)Mc^2 \quad (47)$$

must be smaller than $\hbar\omega_{max}$ given by (20), therefore

$$\hbar\omega_{max} = mc^2 (I / I_A) > (1/2)Mc^2 \quad (48)$$

or that for $I = \gamma I_A$,

$$\gamma \geq (1/2)M / m \approx 10^3 \quad (49)$$

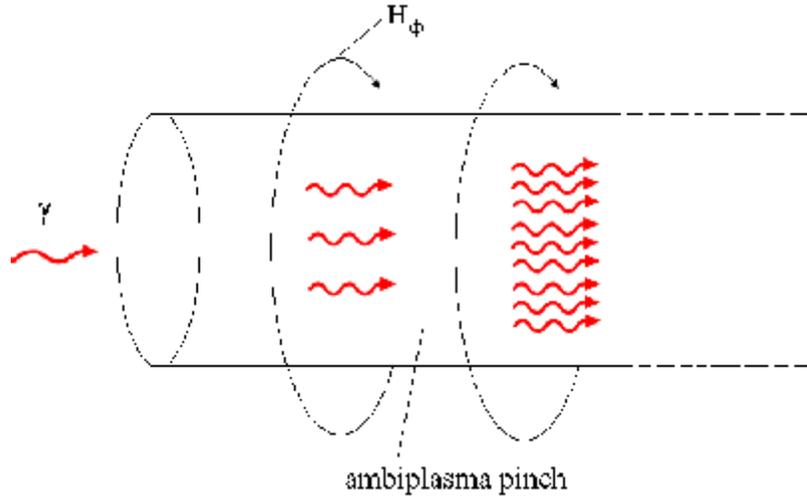


Figure 1: Ambiplasma pinch with laser avalanche

Because of the Mössbauer effect, the recoil momentum is transmitted to the entire pinch discharge channel, with the recoil energy delivered to the pinch discharge is reduced by the factor Nl , where $N = \gamma/r_0$ is the number of particles in the channel per length, and l the length of the channel. For the

example $\gamma = 10^3$, $l = 10^2$ cm, $Nl = 10^{18}$, it follows that $R \approx Mc^2 \approx 1$ GeV is reduced to 10^{-9} eV. This means the heating of the channel and the line broadening of the γ -ray emission by the absorbed recoil energy is insignificant, ensuring a large stimulated emission cross section.

For electrons the value $\gamma \sim 10^3$, implies a voltage of $\sim (1/2)$ GeV, and a maximum current $I = I_A \sim 1.7 \times 10^7$ Ampere, with a beam power of 10^{16} Watt. If the voltage pulse lasts 10^{-8} sec, the energy delivered is 340 MJ. Such an enormous beam power can be reached with a super Marx generator [12].

From the pinch discharge the recoil momentum is transmitted to the return current conductor by the azimuthal magnetic field H_ϕ . For the current I (in Ampere), this field is given by $H_\phi = 0.9I / r$, or for $I = 1.7 \times 10^7$ Ampere and $r = 10$ cm, equal to $H_\phi = 340,000$ Gauss, with $H_\phi^2 / 8\pi \approx 6 \times 10^9$ dyn/cm², below the tensile strength of steel, of which the return conductor can be made.

For a pinch discharge of length l , and the magnetic field \mathbf{H} , the time $t \sim l/c$ for the destruction by proton-antiproton annihilation, an electric field \mathbf{E} is induced in the return current conductor. Its magnitude is determined by Maxwell's equation

$$-\frac{1}{c} \frac{\partial \mathbf{H}}{\partial t} = \text{curl} \mathbf{E} \quad (50)$$

resulting in

$$E \approx H_\phi \quad (51)$$

for $H_\phi \sim 10^5$ G, one has $E \sim 10^5$ esu $\sim 10^7$ V/cm, just large enough to implode a follow-up GeV pinch discharge in a $l = 10^2$ cm long hydrogen-antihydrogen ambiplasma column.

5. Conclusion

Regarding the idea of a relativistic matter-antimatter annihilation photon rocket, the author was privileged to learn first-hand the opinion of Edward Teller. He did not think that this idea was impossible. He raised the question what Columbus might have thought if and when man can travel to the moon, and he had concluded that this will never be possible. Teller then told me that "never" means 500 years, and that a photon rocket will be possible in about that time.

Could it be possible in less than 500 years? The study presented in this paper is an attempt to answer this question in the positive, on the basis of the known laws of physics. The three basic technical problems are: the rocket engine itself, the production of the large needed quantities of antimatter, and lastly, how to store the antimatter.

The production of antimatter, even in the huge quantities needed, can be done on the earth, or another planetary body, with all the resources such a body has. And the same can be said about the storage of the

antimatter, preferably suspended in strong magnetic fields. To store large amounts of antimatter in a spacecraft, even in a very large spacecraft, is much more difficult, unless the spacecraft has a dimension of a planet, even of a small planet, something which belongs in the realm of scientific fiction. But storing large amounts of antimatter in a spacecraft not as large as a small planet, would become possible if there exists a state of matter a million times more dense than liquid hydrogen. There is experimental evidence that such a state might exist for deuterium [13], with a possible explanation of such a state that it is made up by a lattice of deuterium linear vortex atom molecules [14]. Such a state, of course, would by itself be of great interest for nuclear rocket propulsion by deuterium thermonuclear micro-explosions which at these densities could be easily ignited with lasers of modest energy. But because a million-fold increase in the density, would also imply, a 10^4 times increase for the maximum field of a superconductor, and a 100 times increase in the critical magnetic field and melting point. Such a substance, if it exists, could be used for normal temperature superconductors with a critical field of 10^9 Gauss, ideally suited for the storage of antihydrogen.

Therefore, if nature is kind of us, the goal for a relativistic photon rocket might be closer than the 500 years prophesized by Teller.

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