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Matter–antimatter gigaelectron volt 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 Sänger, 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 gigaelectron volt 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 by the Moessbauer effect to the spacecraft. The gamma ray laser beam is launched as a photon avalanche from one end of the pinch discharge channel. Because of the enormous technical problems to produce and store large amounts of anti-matter, such a propulsion concept may find its first realization in small unmanned space probes to explore nearby solar systems. The laboratory demonstration of a gigaelectron volt gamma ray laser by comparison requiring small amounts of anti-matter may be much closer.

1. Introduction

The idea of the photon rocket was first proposed by Sänger [1], but at that time considered to be utopian. Sänger showed that if matter could be completely converted into photons, and 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 gigaelectron volt gamma ray laser beam, with the entire recoil of this beam pulse was 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

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

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[3]. Because these densities can be of the order 10^{15} g/cm^3, comparable to the density of a neutron star, has led the Russian physicist 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 conducted by Frisbee [5]. It was relying on "off 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.

2. 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.

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 much 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 a co-moving system equal to $dt' = dt/\gamma$. The transverse energy gain of an electron or a positron in a co-moving system, assuming the relative drift velocity is $v \approx c$, is then given by [7],

$$\frac{dE}{dt'} = 4\pi n' \frac{e^4}{\mathrm{mc}} \ln \Lambda' \tag{1}$$

and hence in a laboratory frame

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

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 centimeter gram second units) is $I \approx 2nec\pi r_b^2$. One then finds that

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

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

$$H_\phi = (2I/r_b c)(r/r_b) \tag{4}$$

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

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

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

$$\gamma m \ddot{r} = F \tag{6}$$

or

$$\ddot{r} + \omega^2 r = 0 \tag{7}$$

with $\omega^2 = 2eI/\gamma mcr_b^2 = (2/\gamma)(c/r_b)^2(I/I_A)$. 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]

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

where $v_\perp$ is the perpendicular velocity component, in our case $\dot{v}_\perp = \ddot{r}$. One thus finds that $\overline{\dot{v}_\perp^2} = \overline{\ddot{r}^2} = (1/3)\omega^4 r_b^2$, and obtains

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

Since $\omega^2 = (2/\gamma)(c/r_b)^2(I/I_A) = \gamma m/4\pi ne^2$, 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:

$$\gamma mc r_{\min} \approx \hbar \tag{10}$$

The condition $P_e > dE/dt$ implies that

$$\gamma^2 I/I_A > \left(\frac{9}{4}\right) \ln\Lambda \tag{11}$$

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

$$\frac{H_\phi^2}{4\pi} < 2\gamma nmc^2 \tag{12}$$