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Dense plasma focus for space technology

Abstract

In this paper, we investigate the possibility of using a plasma focus system as a nuclear fusion reactor for two applications: source of antimatter positron (e^+) and a thrust producer. The nuclear fuel (propellant) utilizes gas mixture of deuterium-triggered ^{20}Ne to produce ^{18}F short-lived radioisotope (SLR) through nuclear reaction $^{20}Ne(d, ^4He)$ ^{18}F. The SLR ^{18}F is a positron emitter with the maximal kinetic energy of 0.635 MeV and a half-life of 109.8 min. The induced activity of ^{18}F with the repetition rate of 10 H_Z, positron annihilation rate, I_{sp}, and the total thrust are approximately calculated.

Keywords

Plasma focus; Plasma sheath; Positron; Antimatter; Propulsion; Thrust.

INTRODUCTION

A plasma focus (PF) machine, which consists of two coaxial electrodes that is opened at one end and closed with insulator at the other end, is a discharge machine Figure 1. Excitation of bank energy creates hot and dense short-lived magnetized plasma that is so called "pinch". The pinch itself goes through magnetic compression (thermonuclear phase) and then the expansion process (non-thermonuclear phase) occurs. Both phases are involved in the neutrons production and electromagnetic radiations if the filling gas is deuterium. The energetic beam of charged particles such as ions and electron are also produced in the PF that is characteristic of non-thermonuclear or the beam target phase[1-4].

A DPF machine works in a pulse mode manner in which the frequency of operation depends on the system capacitor bank energy. Consequently, the relationship between stored energy and the outcome of medium size DPF can be characterized by $N_i \propto W^2$, $Y_p \propto W^2$, $Y_t \propto W^2$, where N_i is the deuteron ions, W is the stored bank energy, Y_p is the nuclear reaction yield and Y_t is the reaction yield on the external targets[5].

In recent years, it has been shown that DPF machines with sufficient threshold energy is capable to produce short-lived radioisotopes (SLRs), ^{18}F, ^{15}O, ^{13}N, and ^{11}C, which have a half-lives of 109.8, 2.4, 10, 20 minutes, respectively, either through exogenous or endogenous targets[6,7].

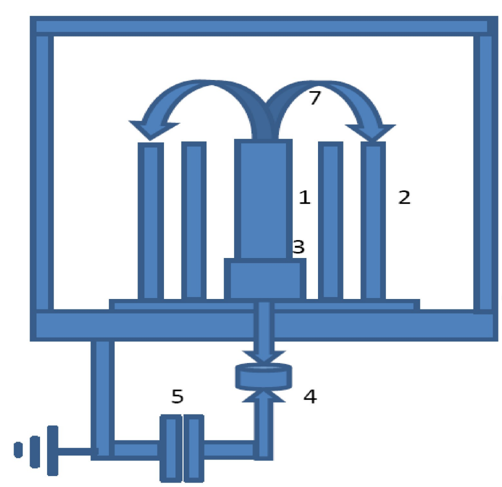

Figure 1 : The numbers are; 1- the anode electrode, 2- the cathode electrodes, 3- the insulator, 4- the spark gap, 5- Capacitor bank, 6- the vacuum chamber, and 7- the plasma sheath, the pumping system and gas inlet are not shown.

Positrons, antiparticle, are easily produced and isolated. Positrons are now routinely used in medicine, such as positron emission tomography[8], physics, surface analysis, and atomic physics[9,10]. Fluorine 18 decays positron by 97% energy of 0.635 MeV and 3% captures electron with energy of 1.655 MeV. After decays, fluorine 18 becomes stable ^{18}O.

The produced positrons could rapidly interact with surrounding gas, liquid or solid and annihilate with electron to produce 511 MeV gamma rays that lead to an increase some temperatures in the surrounding medium. For example, for all nuclear reactions, a decrease in the positron energy in the below sub-threshold, which causes to heat gas molecules in the spacecraft propellant, will not contaminate the atmosphere and can be one of the cleanness methods of exciting the working gas[11-14].

In this article, we study a DPF machine that can produce antimatter e^+ through $^{20}Ne(d, {}^4He)\,{}^{18}F$ reaction. The level of activity, total thrust and I_{sp} of DPF machine are calculated and presented.

THEORY AND CALCULATIONS

A typical Mather type DPF and conceptual design for producing SLRs have been discussed in this article[15]. The first step in designing a DPF machine is to choose the proper capacitor bank energy and to calculate others parameters as shown in TABLE 1. When the DPF machine is operated, a plasma layer creates; Lorentz magnetic force compresses that and finally, a pinch at the middle of central electrode (the anode) builds up. At this situation, two currents are formed: the ion is moving away from the top of anode due to the change in the plasma inductance and the electron is moving in the opposite direction. The time varying of plasma inductance is given by the following

$$\left(\frac{dL_p}{dt}\right) = \frac{\mu_0}{2\pi}\left[\ln\left(\frac{b}{r_p}\right)V_a + \left(\frac{Z}{r_p}\right)V_r\right]$$

Here, b is the cathode radius, r_p is the pinch plasma radius, V_a is the radial plasma speed, Z is the pinch length, and V_r is the radial speed of the current sheath. As we are interested in the numbers of ions produced in the pinch region, a diode model similar to the current density formula of Langmuir is used[16]. If we put $\varnothing$ as a induced voltage into plasma column $\varnothing = I_{max}\left(\frac{dL_p}{dt}\right)$ and

$$J_i = 1.86 \times \left(\frac{4}{9}\right)\varepsilon_0\sqrt{\frac{2\times e}{m_i}} \times \frac{\varnothing^{\frac{3}{2}}}{w^2} \qquad (1)$$

where $I_{max} \approx \frac{V_0}{\sqrt{\frac{L_{0ext}}{C_0}}}\left(\frac{dL_p}{dt}\right)$, L_{0ext} is the external circuit, C_0 is the capacitor charged, ε_0 is the permittivity of free space, e is the electric charge, m_i is the mass of deuterium, and w is the width of the low conductivity plasma diode layer.

Tranformation of the magnetic field to the electrical field through instability mainly m = 0 mode, induces a high voltage in which ions are accelerted away from the anod tip. The number of ejected and accelerated deutron ions can be written as;

$$N_i = \pi\frac{r_p^2}{e}J_i\tau_p \qquad (2)$$

where τ_p is the pinch life time. Equation 1 in Eq. 2, gives the number of ejected deuteron, TABLE 1.

TABLE 1 : Physical constants with operational and geometrical parameters of the PF

Specific heat ratio of the deuterium γ	$\frac{5}{3}$
Deuterium ion mass m_1	3.34×10^{-27} kg
Density of deuterium ρ_d	$1.32 \times 10^{-3}\ \frac{kg}{m^3}$
Permittivity of free space ε_0	$8.854 \times 10^{-12}\ \frac{F}{m}$
Electric charge e	1.602×10^{-19} C
Pressure of neon gas	15% of deurrium pressure
Impedance $Z_0 = \sqrt{\frac{L_0}{C_0}}$	Z_0 = 173.2 mΩ
Peak circuit current $I_0 = \frac{V_0}{Z_0}$	I_0 = 46 kA,
Maximum charging voltage V_0	V_0 = 8 kV
Capacitor bank C_0	$C_0 = 1\ \mu F$
Stored bank energy E	32 J
Inductance of the circuit L_0	30×10^{-9} H
Period of circuit trace t_0	$t_0 = \sqrt{L_0 C_0} = 1.73 \times 10^{-7} s$
Anode radius a	0.5 cm
Anode length Z	6 cm
Cathode radius b	1.75 cm
Speed for the axial V_2	$1.78 \times 10^4\ \frac{m}{s}$
Speed for the radial	$5 \times 10^4\ \frac{m}{s}$
Pinch radius r_p	0.6 mm
Pinch life time τ_p	10 ns
Pinch length d	4 mm
Operating gas pressure P	6 torr
Operating gas admixture	$P_{Ne} = 15\% P_d$
Current loss factor	0.6
Mass-sweep factor f_m	0.2
Induced voltage ϕ	3.7×10^3 V

Activity determination

The time-average spectral distribution of ions accelerated out of pinched plasma can be written as:

$$\mathbf{f(E)} = \frac{\mathbf{dN_i}}{\mathbf{dE}} = \mathbf{CE^{-m}}$$

where f(E) is the deuteron ion's distribution function, N_i is the number of deuteron ions, C is the normalization coefficient, and $2 < m < 3.5$. The integral form of f(E) is determined as;

$$\mathbf{N_i} = \int_0^{\mathbf{N_i}} \mathbf{dN} = \int_{\mathbf{E_{min}}}^{\mathbf{E_{max}}} \mathbf{CE^{-m}}$$

or

$$\mathbf{N_i} = [\mathbf{C}\frac{\mathbf{E^{1-m}}}{\mathbf{1-m}}]_{\mathbf{E_{min}}}^{\mathbf{E_{max}}}$$

So, the deuteron ion's energy spectral distribution becomes:

$$\mathbf{f(E)} = \mathbf{N_i}[\frac{\mathbf{1-m}}{\mathbf{E_{max}^{1-m} - E_{min}^{1-m}}}]\ \mathbf{E^{-m}} \qquad (3)$$

Here, $\mathbf{E_{max}^{1-m}}$ **and** $\mathbf{E_{min}^{1-m}}$ are the maximum and minimum energy of deuteron ions burst pinched plasma, respectively. The reaction yield for the ^{18}F can be done using Eq. 3 and 2 as;

$$< \boldsymbol{y} > = \mathbf{n_t N_i t_{emission}} \int_{\mathbf{m=2}}^{\mathbf{m=3.5}} \mathbf{dm}$$

$$\int_{\mathbf{E_{min}}}^{\mathbf{E_{max}}} \left[\frac{\mathbf{1-m}}{\mathbf{E_{max}^{1-m} - E_{min}^{1-m}}}\right] \mathbf{E^{-m}}\ \ \boldsymbol{\sigma}\mathbf{(E)dE} \qquad (4)$$

where n_t is the number of target particles and $t_{emission}$ is the emission time after pinch explosion. For the nuclear reaction ^{20}Ne(d, ^{4}He) ^{18}F, the cross-section σ(E) has been fitted with a polynominal function corresponding to the experimental curve[17];

$\sigma(E) = -195.595 + 170.265 - 24.213E^2 + 1.237E^3 + 0.021E^4$

The yield integral has been calculated using the fallowing parameters and Eq. 4: $E_{min} = 0.065$ MeV, $E_{max} = 4.3$ MeV, $n_t = 2.95 \times 10^{25}$ m^{-3} and $t_{emission} = 19.83$ ns.

In our calculations, the lower integral limit has been fixed to 0.065 MeV for taking account some thermonuclear participation in the yield product. If we take the repetition rate as f = 10 H_Z, then, the induced activity of ^{18}F at the time $\boldsymbol{T_{\frac{1}{2}}}$ of the DPF machine will be:

$$\mathbf{A} =< \mathbf{y_{^{18}F}} > f(1 - \mathbf{e^{-\lambda t}})$$

where $\boldsymbol{\lambda} = \frac{\mathbf{ln2}}{\mathbf{T_{\frac{1}{2}}}}$ and $\mathbf{T_{\frac{1}{2}}}$ is the half-life time of ^{18}F. Finally we have found the induced activity as;

$$\mathbf{A = 9.78 \times 10^7} \quad \frac{\mathbf{particle}}{\mathbf{second}}$$

Positron annihilation

Plasma focus machine is capable to produce deuteron beam with sufficient energy in comparison to threshold energy of antiparticle (positron) nuclear reaction that is performed through aneutronic reactions. Antimatters, such as positron and antiproton are known for their deposition of energy in the environment by interacting and annihilating with matter. The manner they depose energy in the medium depends on the density of the interacting medium and the annihilation cross-sections[13]. In the case of positron, the annihilation cross section can be written as[12]:

$$\boldsymbol{\sigma} = \frac{\boldsymbol{\Gamma}}{\mathbf{nv}} = \frac{\boldsymbol{\pi}\mathbf{r_0^2 cZ_{eff}}}{\mathbf{v}} \qquad (5)$$

where Γ is the annihilation rate, n is the number density of molecules, v is the velocity of the incident positrons, r_0 is the classical electron radius, c is the speed of light, and Z_{eff} is the structure of the atomic or molecular electron wave function and positron-electron correlation. A positron emitted from ^{18}F has a maximum energy of 0.635 MeV with the relativistic velocity of $\mathbf{2.68 \times 10^8}\ \ \frac{\mathbf{m}}{\mathbf{s}}$. The values of Z_{eff} for Ne and deuterium gases are 5.5.99 and 14.7, respectively[12]. So, the corresponding annihilation cross-sections (5) will be:

$\sigma_{Ne} = 1.67 \times 10^{-24}$ cm^2

and

$\sigma_d = 4.1 \times 10^{-24}$ cm^2

respectively. With this annihilation cross-section, the number density of neon and deuterium are $n_{Ne} = 0.15 \times 10^{23}$ m^{-3} and $n_d = 0.85\ \ 10^{23}$ m^{-3}, respectively, the average value of positron annihilation rate in the mixed fusion fuels (Ne and deuterium gases) has been found as:

$$\boldsymbol{\Gamma}_{\mathbf{total}} = \frac{\boldsymbol{\Gamma_{Ne} + \Gamma_d}}{\mathbf{2}} = \frac{\mathbf{1}}{\mathbf{2}}(\mathbf{0.67 \times 10^3 + 9.33 \times 10^3})$$
$$= \mathbf{0.5 \times 10^4}\ \ \mathbf{s^{-1}}$$

and the approximate annihilation time is:

$$\boldsymbol{\tau} = \frac{\mathbf{1}}{\boldsymbol{\Gamma}_{\mathbf{total}}} = \mathbf{2 \times 10^{-4}}\ \ \ \mathbf{s}$$

Without excluding the values of Z_{eff}. However, it has been shown that electron-positron annihilation time depends on the gas density[18]. The positron annihilation rate is more efficient in a blanket when positron annihilation creates at the center[14]. It is demonstrated that the dependence of annihilation rates of positron on Ne gas temperature has a slow change of annihilation rates with respect to the temperature[19].

The behavior of positron is just like an electron[20]. When an energetic positron enters working gas meidum (a blanket), it will lose its energy through interactions with gas molecules, resulted in ionization and excitation until the positron comes to rest. The positron at this moment will annihilate with an electron which is always exist. This annihilation will produce two gamma rays in the gas, traveling in opposite directions and each of those has 511 keV energy. The gamma ray could have the following ranges: 10 mm in tungsten, 20 cm in light-weight carbon, 10 cm in water and 90 m in air[10]. However, the positron will lose energy at a rate approximated by Bethe-Bloch equation;

$$\frac{\mathbf{dE}}{\mathbf{dx}} \approx \boldsymbol{\rho} \times \mathbf{2}(\mathbf{MeV}\frac{\mathbf{cm^2}}{\mathbf{g}})\ \frac{\mathbf{Z^2}}{\boldsymbol{\beta}^2}$$

where ρ is density, Z is the charge of the incident positron, and β is the relativistic parameters. We have only used the averge density of Ne and deutrium for the calculations of the target density. At 800 Pa chamber pressure and β = 0.893, the Coulomb's interactions of positron with the target electrons the energy loss will be given as:

$$\frac{\mathbf{dE}}{\mathbf{dx}} \approx \mathbf{2.588 \times 10^{-6}}\ \frac{\mathbf{MeV}}{\mathbf{cm}}.$$

So, for given dimensions of the chamber, we expect that the gamma rays of annihilation will not much spend its energy in the DPF ambiance. If suffecient stoping power of gamma rays is provided the 2 × 511 keV enrgy, the energy could be better used.

ANALYSIS

Determination of thrust

While the working fusion fuels reacte with DPF ambiance, whish are resultant from The mechanisam of thermonuclear, the resultant charged particles leave the pinch during the non-thermonuclear mechanism. The energies of the product charged particles are fuction of the fusion fuel used in the DPF machine and that have very high velocities[21]; the reaction ^{20}Ne(d, ^{4}He) ^{18}F produces 0.507 MeV fluorine-18 and 2.28 MeV alpha particles and the velocities of the order of $\mathbf{10^7}\ \frac{\mathbf{m}}{\mathbf{s}}$. These high velocities lead to specific impulse as following:

$\mathbf{I_{sp}} \cong \mathbf{0.23 \times 10^6}\ \frac{\mathbf{m}}{\mathbf{s}}$ and $\mathbf{I_{sp}} \cong \mathbf{1 \times 10^6}\ \frac{\mathbf{m}}{\mathbf{s}}$, respectively. High specific impulse will result in a lower thrust for the propulsion.

Apart from the product charge particles from the pinch, there are some other particles which do not participate in the fusion reactions, but, they can take part in the propulsion impulse. A number of fusion reactions, in general, is not high so that the contribute of the mass flow rate to the thrust is not high. However, the fusion fuels and the pinched charged particles in the plasma directly participate in the thrust. For the calculations of the thrust, $\mathbf{T = m_F \times \frac{J}{e} \times \upsilon_F}$, we can take V(V), therefore, the induced accelerated voltage obtains from the pinch and $\boldsymbol{\upsilon}_\mathbf{F} = \sqrt{\frac{\mathbf{2eV}}{\mathbf{m_F}}}$, where m_F is the mass of ^{18}F, υ_F is velocity of ^{18}F, n is the number of fluorine, and J is current density. For the fluorine ^{18}F the thrust is:

$\mathbf{T_F = 5.14 \times 10^{-7}\ N}$

And the same for ^{4}He thrust;

$\mathbf{T_{He} = 2.425 \times 10^{-7}\ N}$

The neutral particle's thrusts is given by $T_d = m_d \times \chi_d \times \upsilon_{thd}$ e.g. deuterium where m_d is the mass of deuterium, the product of $m_d \times \chi_d$ is the mass flow rate with $\boldsymbol{\chi}_\mathbf{d} = \frac{\mathbf{n_d \times \upsilon_{thd} \times A\ \times \boldsymbol{\varphi}}}{\mathbf{4}}$, where υ_{th} is the thermal velocity $\boldsymbol{\upsilon}_\mathbf{th} = \sqrt{\frac{\mathbf{8kT}}{\boldsymbol{\pi}\mathbf{m_d}}}$, n_d is number density of deuterium, A is the cross section of the pinch, φ is a transparency constant which we have taken as 0.5, and T is ambient temperature. Here, it has been assumed that those neutral deuterium and neon particles are coming from pinched plasma region and do not participated in the fusion reactions. So, the calculated thrust for neutral deuterium T_d = 0.879 N, and for the neutral neon Ne is $T_{Ne} = m_{Ne} \times \chi_{Ne} \times \upsilon_{th}$ = 0.125 N, where m_{Ne} is the mass of neutral neon, n_{Ne} is the number density of neon, υ_{th} is thermal velocity of neon. So, the total thrust will be the sum of all thrusts, charged and neutral particles: $T_d = T_F + T_d + T_{Ne}$ = 1 N.

DISCUSSION AND CONCLUSION

What we have shown here is a direct thrust with the produced ions and neturals. However, if the incident positrons and the others productions (charged and netural particles) interacte with the approprite blanket, the enrgy loss would be more than some thermal excitations of the gas targets. For example, if the same positrons interacte with ^{131}Xe target then, the rate of energy loss would be $\frac{\mathbf{dE}}{\mathbf{dx}} \approx \mathbf{14.8 \times 10^{-3}}\ \frac{\mathbf{MeV}}{\mathbf{cm}}$, or even further, if they interact with the soild hydrogen target, the energy loss rate would be $\frac{\mathbf{dE}}{\mathbf{dx}} \approx \mathbf{0.216}\ \ \frac{\mathbf{MeV}}{\mathbf{cm}}$, the later aproximetly is 10^5 higher than the first positron interactions in the DPF. It should be notice that the production of positron in DPF depends highly on the capacitor bank energy. The aim of presented DPF here with low bank energy is to show its potential application in the space technology either as a source of antimatter (positron) and/or as an accelerator of charge particle for thrust. While the ion beam produced in a plasma focus is interacting with a gas, liquid or solid targets, the accelerated charge particle and the system lose a high rate of energy in the target. Therefore, the system heats up to a high temperature and produces high Newton thrust. Consequently, the low DPF system introduced here could be employed as a satellite keeping on an orbit. Thereby, the higher energetic repetition rates DPF systems are used, so the more thrust is produces. Finally, for a long-lived DPF pulse power thrusters, special capacitor banks and the problem of erosion must be solved. Accordingly, this type of thruster can be the most useful for all the type interactions between gas and solid, gas and gas, and gas and liquid targets.

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