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Thermal velocities in the plasma of a MOA Device

A Brief Summary to an Adiabatic Plasma Heating Process

Brief Summary

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Abstract

Although a privately funded technology is in need for some discretion it also should be scientific discussed. Therefore the topic of this brief summary is to introduce some results in a little bit more detail rather than technical details of the MOA thruster. In some settings a MOA device can be adjusted to reach exhaust velocities in the range analog to the targeted temperatures of nuclear fusion devices. These results are documented by the method of measuring the kinetic impact energy of ions. Although MOA has the ability to generate fusion temperatures in the ion gas of a plasma but the system is not designed to generate reaction rates necessary to realize a positive energy balance. If the principle of its heating mechanism has the capability of a fusion device it may be recognized in future developments and this idea is not affecting the current development yet. At the moment the technique should be optimized for applications which to perform it is able now. But some results are worthy to be discussed in the view of extended applications in possible later developments.

Introduction

As noted in some other publications the magnetic field oscillation amplified thruster MOA [1, 6] originally was designed as flexible low thruster with the ability reaching also a high ISp for deep space missions and also in NSSK applications capable to use any fuel that can be transformed in a gas [2, 9].

A main component of a MOA device is a coil system to generate an altering magnetic confinement and a magnetic nozzle. Hereby the shape of a primary magnetic field will be periodically altered by the interaction with a secondary magnetic field. Therefore the primary coil is permanently DC supported while the also DC supported secondary coil is periodically modulated [3, 4, 7]. At the moment the system was tested with several devices in frequencies between 1 Hz and 3 MHz at field strengths between 130 mT to 1 T.

The pre-ionized fuel will be heated in a way that is similar to effects in the magnetosphere of our sun and also other stars. In the plasma densities of a usual mass flow of a low thruster [10, 11] with a nearly full degree of ionization the ion gas temperatures is reaching up to 10.000° K. In less plasma densities the energy fed into the system by the heating mechanism will be distributed to a much less number of ions increasing their kinetic energy and so their temperature. Hereby also the plasma sonic velocity inside the magnetic confinement will be altered affecting the exhaust velocity of a thruster. Some of these settings also could be in interest for a thruster running in a high ISp mode with low thrust density [5, 8].

Dynamic Lorentz Forces

Usually the interaction of a quasi-stationary charges particle in defined by the Lorentz force sometimes also noted as classic J x B force.

$$F = e \,.\, v \,.\, B \,.\, \sin(\beta)$$

where v represents the velocity of the particle which moves in a spiral like trajectory with the mean gyration radius

$$r = m \,.\, v \,/\, (e \,.\, B)$$

while v as a thermal velocity depends on the temperature. These classic J x B force is less significant in the heating mechanism of a MOA device rather than in a MPD device for example.

In an environment dominated by altering magnetic field strengths

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v must be replaced by vA based on a magneto acoustic phase velocity oversimplified described by

$$v_A = B_0/\sqrt{\mu_0 m n_0}$$

while v as an average radial velocity of the ions spiral trajectories with the radius r averaged towards and away from the gradient equals zero relative to the vector of the magneto acoustic wave in the z axis of their movement

$$r_z = r - r$$
$$v_z = v - v$$

Therefore the charged particles in the plasma remain quasi static in relation to any wave phenomena along the z axis in a magnetic field. Of course they tend to spiral towards the fields gradient because r is smaller in the direction towards the gradient where the local field strength is a little bit stronger. Due to this slow accumulation the density of charged particles usually is slightly increasing along the gradient in a static magnetic field. But this movement is not significant against a high value of v_A.

Looking at the definition of the Lorentz force so v is to replace by vA in case of an interaction with a magneto acoustic wave along the z axis.

$$F = e . v_A . B . sin(ß)$$

It does not matter which inertial system is moving, the consequence remains the same. The transfer of energy therefore depends on the values of v_A and dB where

$$dB = B0 - B(x, y, z)$$

in respect to the local value of B at the particles location before interacting with the wave phenomenon.

Therefore is to differentiate between a classic Lorentz force and a dynamic Lorentz force in the environment of altering magnetic fields.

Signal Modulation and Field Strengths

In a classic AC modulated coil the strength of the magnetic field is increasing between zero and maximum depending to a sinus function. Therefore the velocity v_A of any magneto acoustic wave depending on B_0 is increasing in the same manner and reaches its maximum value only for a short asymptotic small time. Hereby the energy transfer via a dynamic Lorentz force depending on v_A and d_B is not really significant.

Thus this effect becomes more significant in the magnetic field of DC supported coil which periodically changes its shape due to interaction with the magnetic field of secondary dynamic modulated coil. This is the principle of the MOA device claimed in an earlier patent AT502984 (A1) by the author [13].

Of course also in this two coil configuration the signal response time also depends on the electro-technical parameters of the secondary coil but the field strength B0 at the gradient of the primary field and therefore also vA is always is at its maximum during the full cycle.

Despite this dB depends on the shape of the magnetic field and therefore on the construction of the coils as a topic in the development of MOA. Hereby the design of the new MOA P5-type-coils and their modulation is to note but not to discuss in detail at the moment.

Thermal Velocities and Plasma Density

As seen in the simplified formula defining the velocity vA of a magneto acoustic wave, its value also is depending on the plasma density.

$$v_A = B_0/\sqrt{\mu_0 m n_0}$$

Although there are several variations of this formula at least it depends on the relation between the mass of charged matter and the number of charges in a defined volume. So in a low dense plasma the energy will be distributed only to less particles via a stronger dynamic Lorentz force due to a higher v_A resulting in increased thermal velocities. Similar conditions can also be found in a partial ionized gas with very low density. Because the charges particles are coupled by their charge a plasma behaves like a fluid even if the mean free path is greater than the diameter of the confinement. In this condition the neutral gas will not be disturbed by the plasma even if the pressure of the plasma is increased due to its temperature.

In several measurements MOA has generated a kinetic ion energy of 11 keV. Hereby this result was measured the first time with a mass flow of 50 sccm aka 1 mg/s Nitrogen with a degree of ionization of 2% at a gas pressure of 10-4 mbar in the vacuum chamber with a free mean path of 6,2 m in the gas. This result was reproduced with different mass flows and therefore gas pressures but with the same power in the pre-ionization device. Finally with an improved pre-ionization device with an increased degree of ionization to generate more thrust also the kinetic ion energy decreased.

The energy transferred by the dynamic Lorentz force onto the Nitrogen ions has a value of 1,06 . 10^{-14} J per particle resulting in a thermal velocity of 9,56 . 10^5 m/s according to an ion sonic velocity vi of 2,76 . 10^5 m/s according the definition of the Bohm velocity

$$v_i^2 = k . T / m$$

Using the Langmuir approximation to respect the electron gas temperature

$$v_S^2 = v_i^2 . [1 + (T_e / T_i)]$$

the resulting plasma sonic velocity v_S has a value of 3,9 . 10^5 m/s. So the kinetic energy of the ion has the value of 1,77 . 10^{-15} J according to 11 keV.

Thus in this example the ions are singl ionized therefore T_e and T_i have the same value if the electron gas is not disturbed by external excitation [15-17].

Measurement Examples

In the low dense environment there are no laminar effects and the plasma does not interact with the remaining neutral gas in the confinement because of its free mean path. So the exhaust velocity of the plasma plume guided by the magnetic nozzle only depends on the plasma sonic velocity v_S. By impacting into a defined target the kinetic energy of the ions can be calculated by measuring their impact depth. A useful tool for the calculation of these stopping range tables for example the SRIM tool by James Ziegler [14] applying the well known Bethe-Bloch equation.

$$-\frac{dE}{dx} = \frac{4\pi n z^2}{m_e c^2 \beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

In the measurement examples discussed hereby copper samples were used as targets analyzed at the University of Augsburg [12].

Hereby the maximum of counts of N-signals was detected in a depth of 13 nm according to a kinetic energy of 11 keV.

Comparing measurements were performed by the use of Silicon targets proceeded with Argon ions. Hereby the maximum of implanted Argon was detected in a depth of 6 nm also according to a kinetic energy of 11 keV. The kinetic energy in the value of 1,06. 10^{-14} J per particle transferred by the dynamic Lorentz force onto the Argon ions corresponds to a resulting thermal velocity of 5,66 . 10^5 m/s of the Argon ions according to an ion sonic velocity vi of 1,63 . 10^5 m/s and a plasma sonic velocity of 2,31. 10^5 m/s according to a kinetic impact energy of the plasma plume in the value of 11 keV.

Similar measurements were performed by implanting Nitrogen into Aluminum samples in other test series analyzed for example by Fraunhofer IGB in Stuttgart. So the 11 keV mark became a calibration point for several settings on MOA devices. This also was done as an additional measurement of the exhaust velocities by performing thrust measurements with low plasma densities.

Increased Plasma Densities

In an environment of increased gas pressure the plasma begins to interact with the neutral gas distributing the thermal energy into the neutral gas affecting v according to

$$v < v_A \,.\, (m_i \,.\, n \,/\, m \,.\, n)$$

in an advantage to generate thrust. Hereby *m* describes the mass of neutral gas particles.

Therefore a low pressure environment with a low plasma density is necessary to generate high temperature ions which are topic in this discussion [11].

Partly and Fully Ionized Ions

In these examples noted above the ions in the plasma were single ionized with only one electron left the orbit. In respect to the mass of the power source of a spacecraft the ion gas in a plasma should only be single ionized. Not only the pre-ionization device but also the beam power of a thruster must be supported by onboard systems [10, 11]. But also the different conditions in a plasma depending on multiple or fully ionized ions should be noted in the further discussion.

Because of their rest mass the thermal velocity of the ions in a plasma is lower than those of the free electrons at the same temperature. In the condition of a plasma containing multiple or fully ionized ions these balance is shifted [11].

Regarding again the definition of the Lorentz force so is to note that e as the elementary charge is to multiply with the number of charges in the nucleus of an ion which are not compensated by remaining electrons it its shell

$$F = Z_i \,.\, e \,.\, v_A \,.\, B \,.\, sin(ß)$$

where Z_i is the difference between the Atomic number and the remaining electrons in the shell of the ion.

Therefore the energy transferred to a multiple or fully ionized ion accordingly has a higher value than which is transferred to an electron with only a single charge. So the ion gas temperature becomes greater than the electron gas temperature. Although because of the mass of the ions the thermal velocity of the ions remains less than that of the electrons. But this fact should be respected in the intension to heat up ions in a plasma. This finally also results in an increased plasma sonic velocity and so in an increased ISp in the application for a thruster. Because of the need to support the beam power by the mass of an integrated power supply this option should be well calculated but in other applications it could be an advance in any case.

Due to the strength of the coupling forces between the nucleus and the ions remaining electron shell and because the accelerated nucleus distributes the energy to a number of remaining electrons it must not lead to a multiple ionization in a plasma heating by Lorentz forces by itself. Therefore scattering processes are still

Figure 1. The SRIM analysis of a copper sample with Nitrogen implanted by a MOA plasma plume.

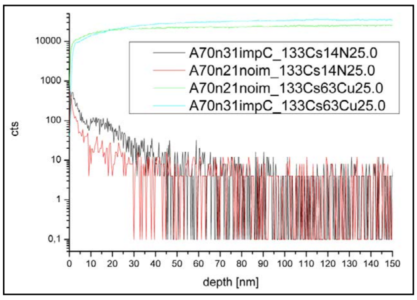
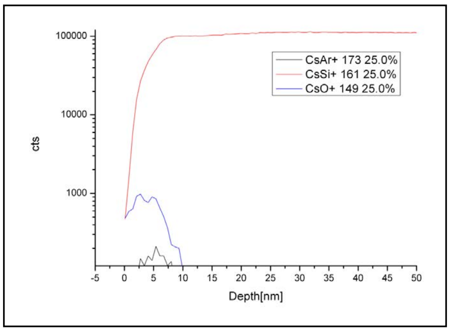


Figure 2. The SRIM analysis of a silicon sample with Argon implanted by a MOA plasma plume.



the dominant factor for multiple ionization of ions in a heated plasma. So in a low dense plasma with a long free mean path inside a small confinement also the degree of multiple ionization remains low. This also is consistent with the conditions of the measurement examples noted before. Of course a higher degree of pre-ionization leads to increasing secondary ionization processes. Finally a multiple or fully ionization of the ions in a plasma depends on the distribution of temperature the whole confined mass also including the originally not pre-ionized gas. Hereby is to refer on the brief note above respecting increased plasma densities.

Fusion Temperatures

Kinetic energies above 10 keV are applied in some fusion devices in mainly homogenous confinements. Beside the long term stability of magnetic confinement hereby the reaction rate is the main issue to reach a positive energ balance. Maybe a contracting confinement generating dynamic Lorentz forces could be an idea for further discussion because the stability of the confinement would not be an issue hereby. Up-scaling a MOA-like device possibly adapting on a larger and maybe torodial confinement to enable sufficient reaction rates therefore would be the challenge.

Additionally is to note that a real clean and possible economic feasible fusion technique could use aneutronic reactions like 11B + p or 7Li + p with the final product of 4He. The efforts to generate 3H or 3He had to become more economic than the production of isotopes used in fission processes. In example the necessary ion temperatures to use the resonance of the 11B nucleus at 660 keV would be a challenge for itself especially to adapt a thruster device.Although it is a logical step for any technique to realize fusion processes using De with 3H or 3He with least necessary energies at first the 10 keV value is to discuss [18, 19].

Maybe the principle of MOA could be an idea for the efficiency of plasma heating it is not a solution for the issue to generate sufficient reaction rates in the existing design at least at the moment.

Conclusion

Because of the relevant kinetic energy of the ions in some settings it was frequently asked if MOA could be used as a fusion device. The answer is simply that it is not designed to generate a reaction rate to enable a positive energy balance as seen in this brief overview.

The fact that its mechanism enabling the use of dynamic Lorentz force is in need to lesser energy input to generate relevant temperatures than some other techniques could possibly offer some discussion on thinkable options to use its principle in this view in the future. At the moment the development is focused on other applications that can use this technology generating high plasma temperatures and of course also in its origin application as an effective electrically supported thruster.

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