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(71) Applicants *(for all designated States except US)*: **ALTA S.P.A.** [IT/IT]; Via A. Gherardesca, 5, I-56121 Ospedaletto, Pisa (IT). **CONSORZIO RFX** [IT/IT]; Corso Stati Uniti, 4, I-35127 Padova (IT).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **ANDRENUCCI, Mariano** [IT/IT]; Via dei Mille, 7, I-54036 Marina di Carrara (Massa Carrara) (IT). **PAGANUCCI, Fabrizio** [IT/IT]; Via Colombo, 31, I-58100 Grosseto (IT). **ROSSETTI, Paola** [IT/IT]; Via F.Palasciano, 9, I-56026 San Frediano a Settimo, Cascina (Pisa) (IT). **SIGNORI, Massimiliano** [IT/IT]; Via del Gallo, 136, I-51016 Montecatini Terme, Pistoia (Pisa) (IT). **ANTONI, Vanni** [IT/IT]; Via Eugenio Fuá, 5, I-35133 Padova (IT). **CAVAZZANA, Roberto** [IT/IT]; Via Zambon de 'Dauli, 10, I-35137 Padova (IT). **MARTINEZ, Emilio** [IT/IT]; Via Martiri della Libertà, 21, I-35137 Padova (IT). **SERIANNI, Gianluigi** [IT/IT]; Via E.Ferrari, 18, I-35020 Maserà di Padova (IT). **ZUIN, Matteo** [IT/IT]; Via Umberto I, 36, I-35123 Padova (IT).

(74) Agents: **BARDINI, Marco Luigi** et al.; Società Italiana Brevetti S.p.A., Corso dei Tintori, 25, I-50122 Firenze (IT).

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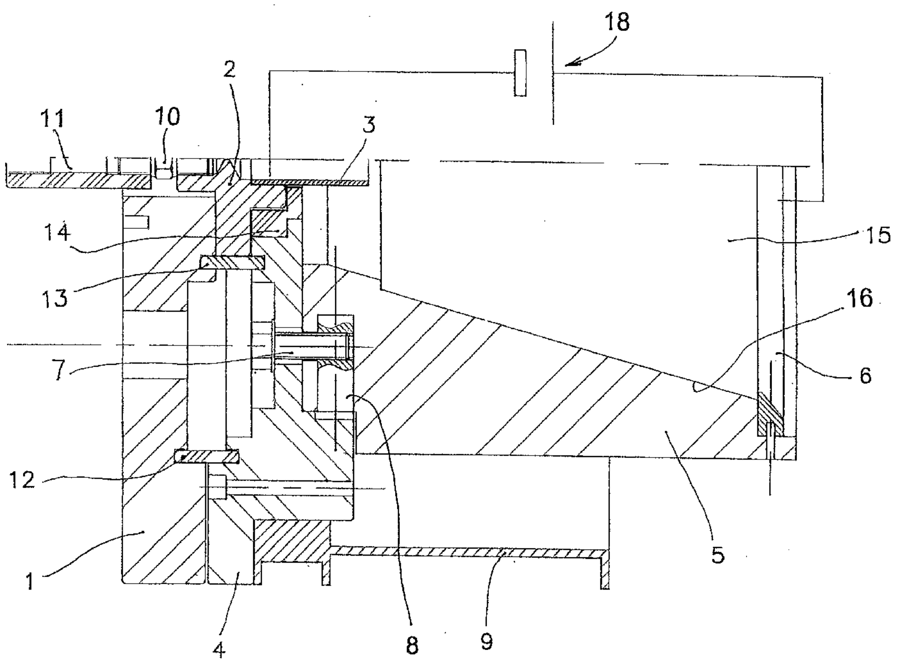
(54) Title: INSTABILITY CONTROL SYSTEM FOR MAGNETO-PLASMA-DYNAMIC THRUSTERS (MPDT)



(57) Abstract: A magneto-plasma-dynamic thruster (MPDT) modified by adding a non-conductive wall (15) dividing longitudinally the plasma volume generated by the thruster itself in order to avoid the onset of a critical regime characterized by an instability known as "kink mode", the main effect of which is the creation of helicoidal currents inside the plasma, leading to a consistent power dissipation.

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SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

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TITLE

INSTABILITY CONTROL SYSTEM FOR MAGNETO-PLASMA-DYNAMIC THRUSTERS (MPDT)

DESCRIPTION

Field of the Invention

This invention generally relates to electric propulsion for use in space, i.e. a type of propulsion in which electric energy supplied by a power generator is exploited instead of chemical energy stored in molecular bonds. Thrust is obtained either through gasdynamic expansion of a gaseous propellant heated by an electric resistance or by an electric arc discharge, or using the interaction of electrostatic or electromagnetic forces with a highly ionized gas (plasma). In particular, the invention is concerned with magneto-plasma-dynamic thrusters (MPDT), which use an electromagnetic acceleration and, more precisely, relates to a system for controlling the instability of such thrusters.

Description of the prior art

In the field of electric propulsion, magneto-plasma-dynamic thrusters (MPDT), either with or without an externally applied magnetic field, are seen as a promising option for high power space applications (starting from 50-100kW), ranging from orbit raising of large satellites to interplanetary missions, like Earth to Mars transfer of a cargo vehicle or manned missions to Mars [Leifer, S., Noca, M. "*Negative C3 Launch for Solar System Exploration*", 34th Joint Propulsion Conference, Cleveland, OH, USA, 1998, AIAA-98-3925; Frisbee, R.H., Hoffman, N.J., "*SP-100 Nuclear Electric Propulsion for Mars Cargo Missions*", 32nd Joint Propulsion Conference, Lake Buena Vista, FL, USA, 1996, AIAA-96-3173].

The main features of MPDT are the high specific impulse (more than 5000 s), high thrust (up to about 100 N) and high thrust density (one order of magnitude higher than for other high specific impulse engines), robustness (no moving parts), compactness (a 5 MW MPDT has a diameter of about 25 cm and a weight in the order of 15 kg), relative simplicity in the geometrical and mechanical configuration, and capability of using a large variety of gaseous and solid propellants. Advanced MPDTs have a coaxial geometry, which is convenient both in terms of manufacturing aspects and as regards the physical phenomena involved.

A typical MPDT generally comprises a cathode and a cylindrical or annular coaxial anode. Propellant is injected between cathode and anode and ionized by the electric discharge established by applying a potential difference between said electrodes. The cathode may be also of the multichannel type as disclosed for example in FR 1541788.

In self-induced field MPDTs the main acceleration mechanism [Choueiri, E.Y., "*Scaling of Thrust in Self-Field Magnetoplasmadynamic Thrusters*", Journal of Propulsion and Power, 14(5):744-753, 1998] is represented by the interaction between the discharge current and the self-induced, azymuthal magnetic field (magnetic acceleration by Lorentz force): high thrust level can be obtained only for high discharge currents (5-100kA) and, consequently, for high powers (0.5-10MW). On the contrary, the application of an external magnetic field introduces an additional acceleration mechanism that does not directly depend on the discharge current and thus can allow the thruster to effectively operate at lower powers

(50-100kW) [Paganucci, F., et al., "*Performance of an Applied Field MPD Thruster*", 27th International Electric Propulsion Conference, Pasadena, CA, USA, 2001, IEPC-01-132; Krulle, G., Auweter-Kurtz, M., Sasoh, A., "*Technology and Application Aspects of Applied Field Magnetoplasmadynamic Propulsion*", Journal of Propulsion and Power, 14(5):754-763, 1998; Sasoh, A., Arakawa, Y., "*Electromagnetic Effects in an Applied-Field Magnetoplasmadynamic Thruster*", Journal of Propulsion and Power, 8:98-102, 1992]. Because of the power level involved, these thrusters are tested in stationary mode only for lower power levels, and in quasi-stationary mode for the higher ones (1-2 MW) with shot durations of a few milliseconds.

Up to now, MPDT operation is limited by the onset of plasma instability phenomena which limit the system efficiency to values in the order of 0.35-0.45 (compared to 0.55-0.65 in other thruster types) and also have an impact on the attainable thrust density. Beyond a threshold current level (onset value), there is a consistent increase of the electrodes potential drop, with oscillations of increased amplitude of the voltage signal and an increased electrodes erosion rate, especially at the anode. Consequently, thrust efficiency is substantially reduced because of the power dissipation inside the engine.

These instability phenomena have been object of studies and many explanations have been proposed.

Tikhonov gave a semi-empirical relation that predicts quite well the threshold current at which instabilities occur [Tikhonov, V. B., et al., "*Research of Plasma Acceleration Processes in Self-Field and Applied*

Magnetic Field Thrusters", 23rd International Electric Propulsion Conference, Seattle, WA, USA, 1993, IEPC-93-76]. He explains the growth of plasma resistivity in the critical regime with a propellant rarefaction at the anodic zone caused by a radial component of the Lorentz force that pushes the plasma toward the thruster axis at high currents. A way proposed by Tikhonov to solve the problem [Tikhonov, V.B., Antropov, N.N., Dyakonov, G.A., Paganucci, F., Rossetti, P., Andrenucci, M., "*Development and Testing of a New Type of MPD Thruster"*, 27th International Electric Propulsion Conference, Pasadena, CA, USA, 2001, IEPC-01-123; Paganucci, F., Rossetti, P., Andrenucci, M., Tikhonov, V.B., Obukhov, V., "*Performance of an Applied Field MPD Thruster with a Pre-Ionization Chamber"*, 33rd Plasmadynamics and Lasers Conference, Maui, Hawaii, USA, 2002, AIAA-2002-2103] is the introduction of a second discharge chamber that shares the anode with the primary one, with the objective of introducing ionized propellant in the anodic region to counteract the rarefaction effect thought to be the primary cause of the problem. Nevertheless a large experimental campaign conducted on this thruster type did not reveal substantial beneficial effects of the new design with rwspect to the "onset" problem.

Choueiri gave an explanation of these malfunction phenomena in terms of turbulence related to current driven plasma micro-instabilities [Tilley, D.L., Choueiry, E.Y., Kelly, A.J., Jahn, R.G., "*Microinstabilities in a 10-Kilowatt Self-Field Magnetoplasmadynamic Thruster"*, Journal of Propulsion and Power, 12(2):381-389, 1996], without giving a way to solve the problem.

Diamant [Diamant, K.D., Choueiri, E.Y., Jahn, R.G., "*Spot Mode Transition and the Anode Fall of Pulsed Magnetoplasmadynamic Thrusters*", Journal of Propulsion and Power, 14(6):1036-1042, 1998] gave an explanation based on measures carried out in the anodic region. According to this research, when a critical current is reached, a transition occurs from a regime of diffused arc attack on the anode to a regime of localized attack (spot attack) with a consequent increase of the potential drop at the anodic region. In this case too, an effective system to overcome the problem is not suggested.

Many experiments have been conducted using lithium as propellant [Tikhonov, V.B., Semenikhin, S., Brophy, J.R., Polk, J.E., "*The Experimental Performance of the 100kW Lithium MPD Thruster With External Magnetic Field*", 24th International Electric Propulsion Conference, Moscow, Russia, 1995, IEPC-95-105; Emsellem, G., Kodys, A.D., Choueiry, E.Y., "*Thermal Analysis of a Lorentz Force Accelerator with an Open Lithium Heat Pipe*", 26th International Electric Propulsion Conference, Kitakyushu, JAPAN, 1999, IEPC-99-166] trying to improve low power performances, thus avoiding the critical regime. This solution allowed to achieving thrust efficiencies up to 50%, but with a low specific impulse. Unfortunately, to have a higher specific impulse we must go to higher current levels and thus we find again the onset of the critical regime [Tikhonov, V.B., Semenikhin S.A., Polk, J.E., "*Own Magnetic Field Impact on MPD Thrusters Performance with External Magnetic Field*", 26th International Electric Propulsion Conference, Kitakyushu, JAPAN, 1999, IEPC-99-176].

A recent research [Zuin, M., Antoni, V., Bagatin, M., Cavazzana, R., Martines, E., Serianni, G., Andrenucci, M., Paganucci, F., Rossetti, P., "*Kink Instabilities in a Magneto-Plasma-Dynamic Thruster With and Without External Magnetic Field*", 40th Joint Propulsion Conference, Fort Lauderdale, FL, USA, 2004, AIAA-2004-3473] confirmed that performances of MPDTs are related to the plasma turbulence. In particular, it has been put in evidence the presence of a magneto-hydro-dynamic instability, with a prevalently helicoidal structure, known in the field of plasma physics as "kink mode". The intensity of the instability and thus the energy dissipated grows quickly beyond a threshold value of the discharge current, which is the same predicted by the semi-empirical relation proposed by Tikhonov.

Objects and summary of the Invention

The main object of the invention is to provide a MPD thruster having a simple control device to prevent this plasma instability from originating, thus increasing the thruster efficiency up to values useful for application in space missions requiring high thrust level and very low fuel consumption.

Another object of the invention is to provide a MPD thruster of the above mentioned type wherein the electrode erosion be significantly reduced.

According to the invention, the suppression of the instability mode can be achieved with the installation of a non conductive wall to divide longitudinally the plasma volume generated by the thruster.

The wall is a physical constraint which prevents this kind of instabilities from rising, thus consistently reducing the power dissipation inside the plasma due to the formation of helicoidal currents therein typical of the kink type instability.

Brief description of the drawings

Further features and advantages of the MPD thruster with instability control system according to the present invention will be apparent from the description set forth below of a non-limiting, exemplifying embodiment thereof, the description making reference to the attached drawings, in which

Figure 1 is a prespective sectional view of the thruster according to the invention;

Figure 2 is a middle axial section of the thruster of figure 1;

Figure 3 is a schematical side view of a first alternative configuration of the axial wall used in the thruster of the invention;

Figures 4 and 5 are schematical side and front views of a second alternative configuration of the axial wall used in the thruster of the invention;

Figures 6 and 7 show the voltage and the current as a function of the time in a thruster with and without wall.

Detailed description of the Invention

Figures 1 and 2 show a magneto-plasma-dynamic thruster (MPDT) according to the invention comprising a base plate 1, of generally circular shape, with a centre where a support 2 for a cathode 3 of generally tubular shape is mounted. A main plate 4, made of non-conductive material, is mounted on base plate 1 and a tubular support 5, made of non-conductive material, extends from main plate 4 coaxially to cathode 3. An annular anode 6 is secured to the free end of tubular support 5. The tubular support 5 of anode 6, in the present embodiment of the invention, has a diverging, frusto-conical shape and is fixed to main plate 4 through a connection device of the conventional type, indicated at 7 and 8 in figure 2, and defines a plasma acceleration chamber 17 on the inside. It is worth noting that in the present specification the terms "insulating" and "non-conductive" has to be meant as "electrically non-conductive".

Cathode 3 and anode 6 are electrically connected to means for generating a potential difference generally indicated at 18 in figure 2 and not described in detail as of the type commonly used for these applications and well known to the person skilled in the art.

A tubular casing 9 for supporting a solenoid, not shown, for the generation of the applied magnetic field extends coaxially to, and externally of, tubular support 5 of anode 6 from main plate 4.

The gaseous propellant is supplied through a nipple 10 and an insulating sleeve 11, coaxially aligned to cathode 3. Two insulating spacers 12, 13 are also provided having an annular shape and being coaxial to cathode 3. Spacers 12 and 13 are respectively arranged between plates 1 and 4 and the innermost one close to support 2 of cathode 3. Support 2 also comprises an adapter 14, made of non-conductive material, that allows the use of different cathode diameters.

A wall 15, made of non-conductive material, axially sharing the acceleration chamber 17 in two parts, is mounted in the tubular support 5. Wall 15 is engaged within diametrically opposed, longitudinal grooves 16 formed in tubular support 5 and is kept in place by anode 6 as shown in figure 2.

Two alternative configurations of wall 15 are shown in figures 3, 4 and 5. The common feature of these configurations is the presence of coplanar fins 15a outwardly projecting from the acceleration chamber 17, with the only difference in the two cases that, in the case of the wall of figures 4 and 5, it has a cross configuration. It must be said that the two variations resulted in a less efficient performance, mostly because of the two fins protruding from the thruster outlet that interfere with one of the main plasma acceleration mechanisms.

An MPD thruster, modified according to the invention, affords various advantages. Figures 5 and 6 show the voltage between the electrodes of a quasi-stationary MPDT (shot duration 5 ms) and, respectively, the current flowing through them as a function of the time, in both cases with and without the wall 15, in full critical regime. As can be seen, while the current substantially does not change, the voltage is reduced when the wall is present, thus the total electric power required is reduced. The difference in the electric power can be explained observing that the plasma has a rotational component due to the kink mode, the onset of which is prevented by inserting the wall. This rotational motion absorbs a consistent amount of power that is not used for thrust generation, thus resulting in power dissipation.

According to a theoretical relation largely confirmed by experimental data, thrust is directly proportional to current (without changing the other parameters). Thus it can be stated that it remains the same with and without the use of the wall. To summarize, with the use of the wall, thrust does not change while the power introduced decreases, that is the efficiency (thrust power over electric power) is increased.

In figure 6 it can be noted the disappearance of the oscillations in the voltage signal, this meaning a more regular behaviour. Finally, the reduction of dissipation in the plasma reduces the thermal stress at the electrodes, thus reducing the erosion phenomena that affect their operative lifetime.

The simplicity of the solution is advantageous from the point of view of construction and costs, because there are no moving parts or electronic systems involved. This implies great advantages in terms of weight, which is a very important factor when dealing with space applications.

Even if in the present description of the invention reference has been made to a MPD thruster with an annular anode, it is to be understood that it can be applied likewise to a MPD thruster with cylindrical anode. In this case it is the anode that defines the plasma acceleration chamber and supports the diametrical wall dividing the chamber. The anode may have a variable cross-section, for example enlarging toward the outlet section or a nozzle-shaped section. Finally, it must be noted that the invention also applies to MPD thruster with multichannel hollow cathode.

The invention is not to be considered as being limited by the embodiment described herein and it is understood that it comprises any form of variation or modification which falls within the scope and spirit of the claims appended hereto.

CLAIMS

1. Magneto-plasma-dynamic thruster (MPDT) comprising a cathode (3) and an anode (6) coaxially arranged with respect to said cathode and electrically connected to means (18) for applying a potential difference therebetween, a plasma acceleration chamber (17) extending between said cathode (3) and said anode (6), means (10,11) for feeding a propellant within said acceleration chamber (17), characterized in that a diametrical wall (15), made of non-conductive material, is mounted axially within said acceleration chamber (17).

2. The thruster according to claim 1, wherein said wall (15) divides said chamber in two equal parts.

3. The thruster according to claim 1, wherein said wall (15) has a cross configuration.

4. The thruster according to any one of the previous claims, wherein said anode (6) has an annular shape and is placed at the free end of a non-conductive tubular support (5) coaxially connected, at the other one of its ends, to support means (1,2,4) for said cathode (3), said tubular support (5) defining said plasma acceleration chamber (17).

5. The thruster according to claim 4, wherein said wall (15) is engaged within longitudinal grooves (16) formed on said non-conductive tubular support (5) and abuts against said anode (6).

6. The thruster according to claim 4, wherein said wall (15) is engaged within longitudinal grooves (16) formed on said non-conductive tubular support (5) and is provided with coplanar fins protruding from said anode (6).

7. The thruster according to any one of the previous claims, wherein said cathode (3) is tubular and said propellant feeding means (10,11) are coaxial thereto.

8. The thruster according to any one of the claims 1 to 6, wherein said cathode (3) is a multichannel hollow cathode.

9. The thruster according to any one of the preceding claims, wherein means for the generation of a magnetic field are provided externally of, and coaxially to, said plasma acceleration chamber (17).

10. The thruster according to any one of the claims 1 to 3, wherein said anode (6) has a cylindrical shape and is non-contuctively connected to support means (1,2,4) of said cathode (3) at one of its ends, said anode (6) defining said plasma acceleration chamber (17).

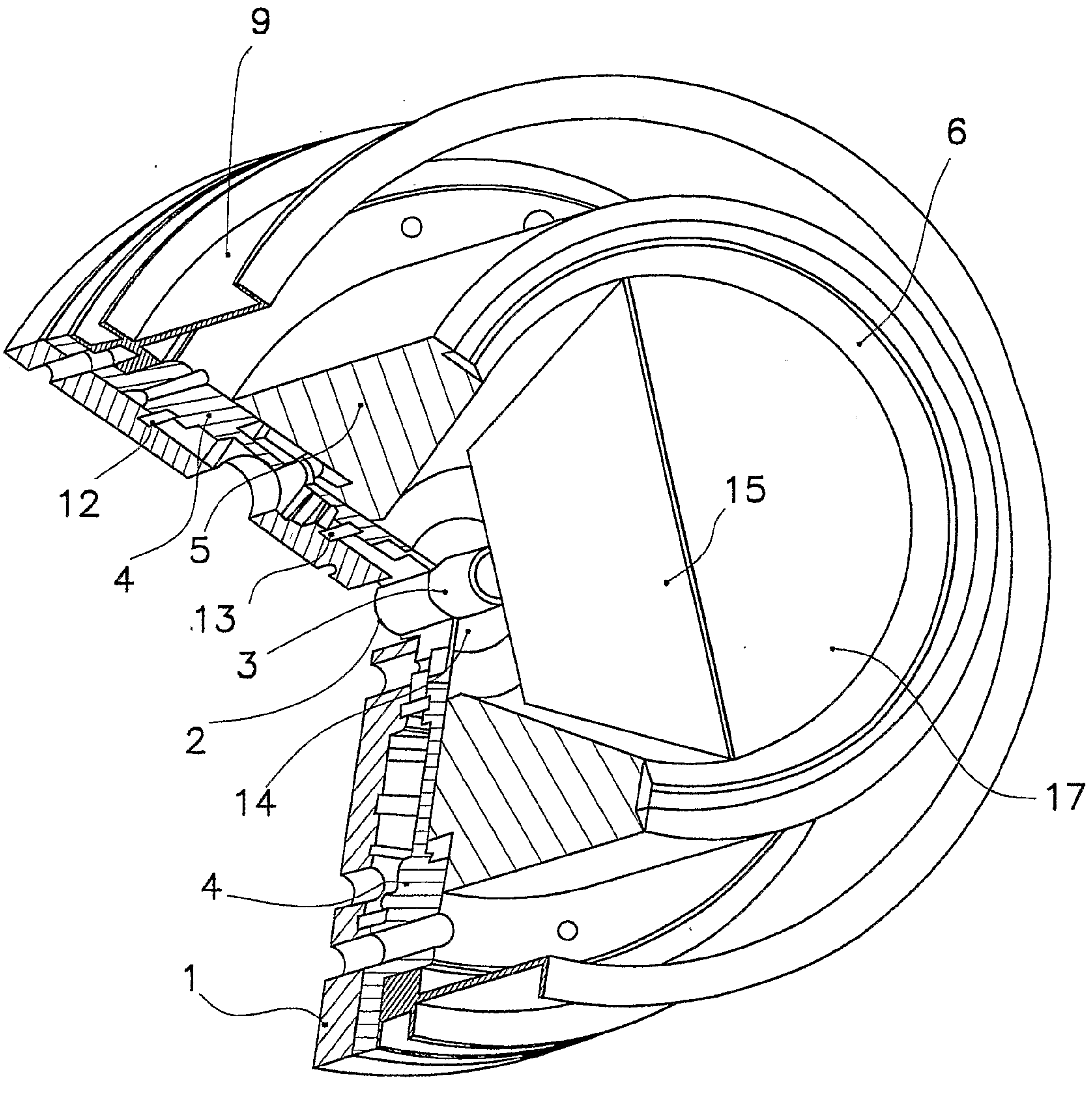


Fig. 1

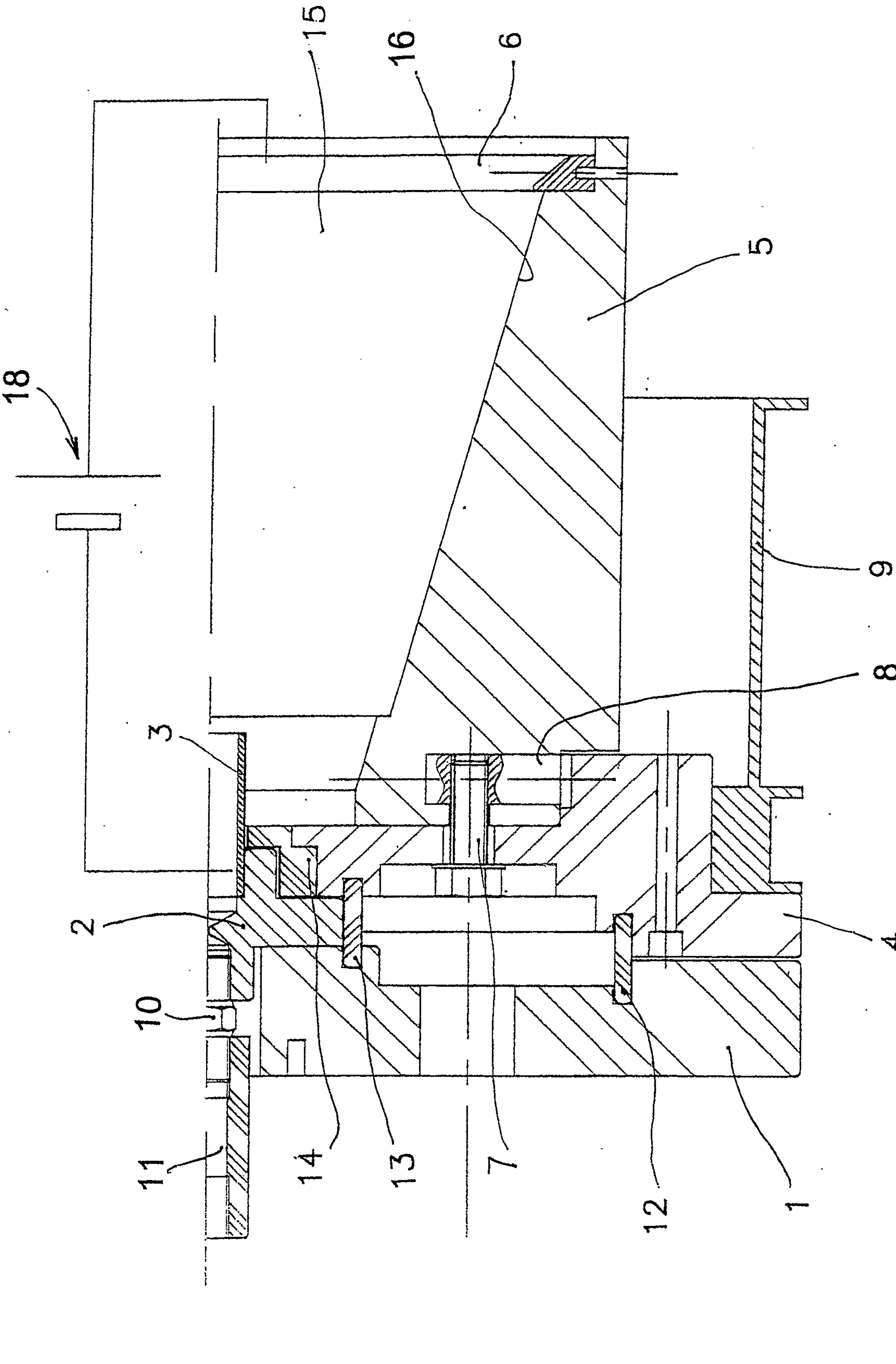


Fig. 2

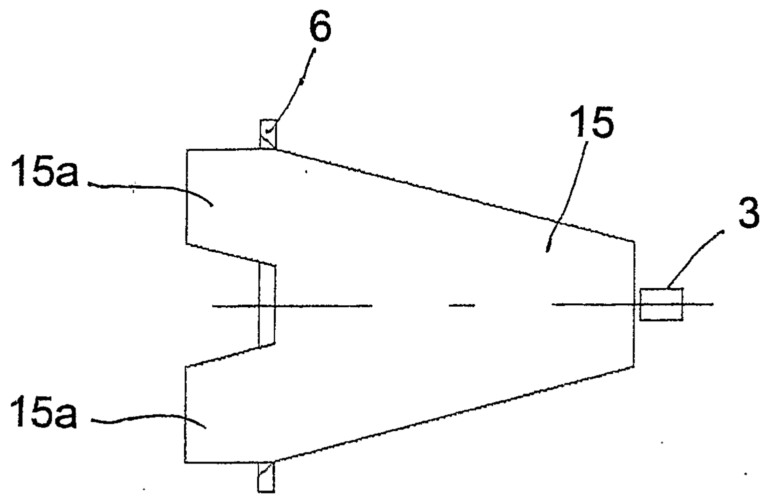
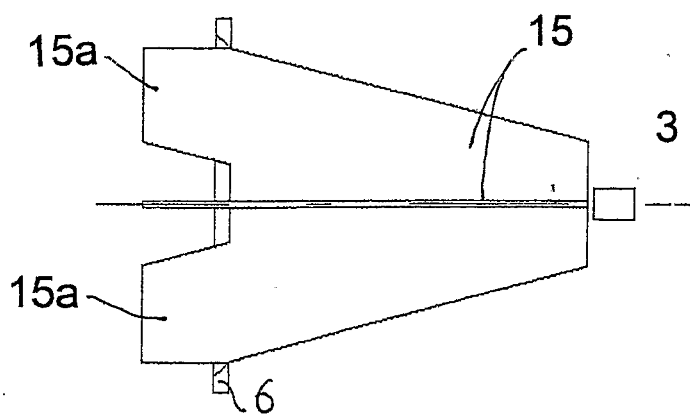


Fig. 3



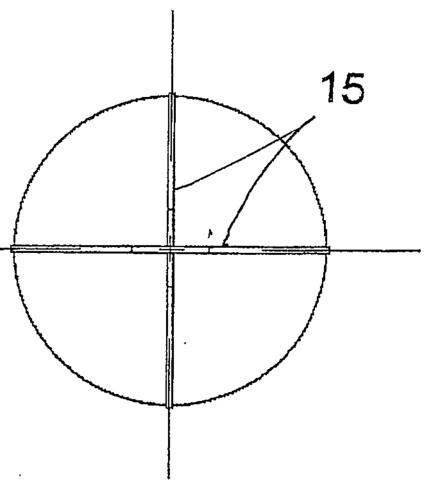


Fig. 4

Fig. 5

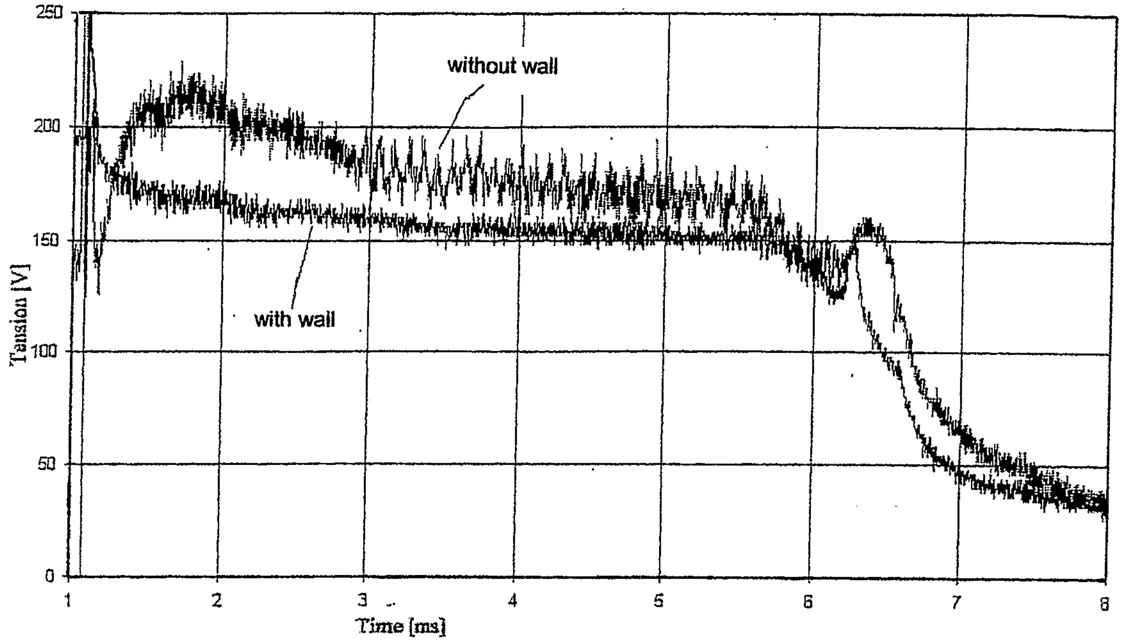

250
200
150
100
50
0
Tension [V]
without wall
with wall
1
2
3
4
5
6
7
8
Time [ms]

Fig. 6

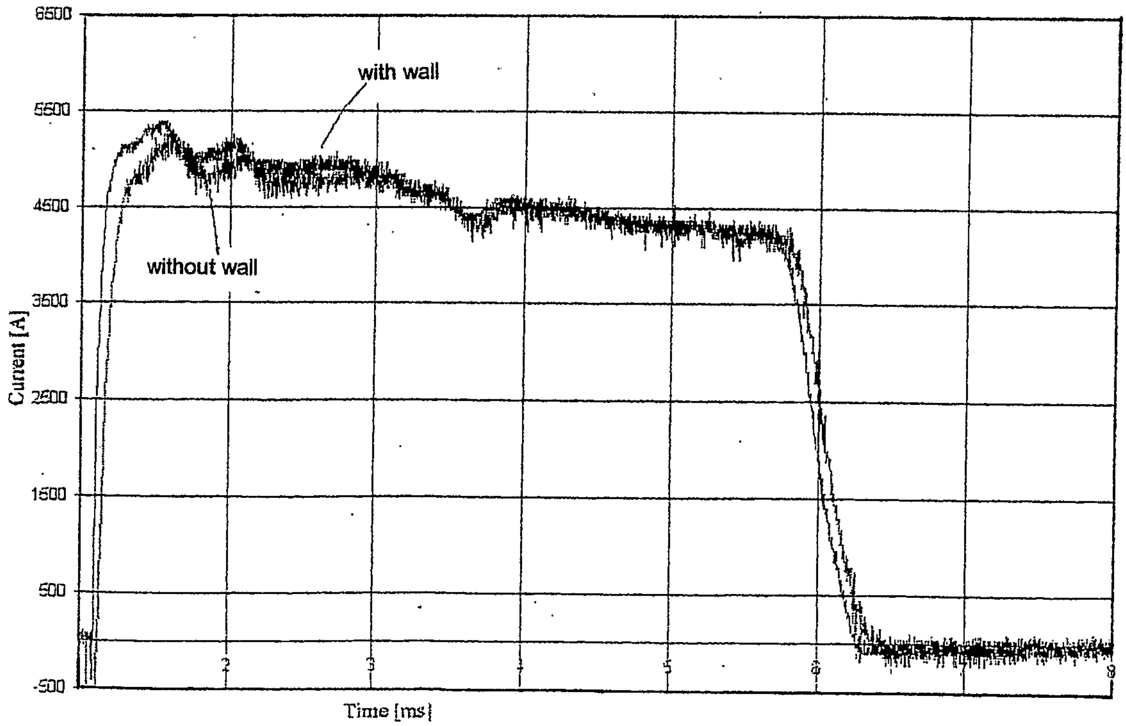

6500
5500
4500
3500
2500
1500
500
-500
Current [A]
with wall
without wall
2
3
4
5
6
8
Time [ms]

Fig. 7

INTERNATIONAL SEARCH REPORT

International Application No
PCT/IT2005/000015

A. CLASSIFICATION OF SUBJECT MATTER
F03H1/00 B64G1/40

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F03H B64G H05H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	ZUIN M ET AL: "Critical regimes and magnetohydrodynamic instabilities in a magneto-plasma-dynamic thruster" PHYSICS OF PLASMAS AIP USA, vol. 11, no. 10, October 2004 (2004-10), pages 4761-4770, XP008055136 ISSN: 1070-664X the whole document ----- -/--	1-10

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search	Date of mailing of the international search report
7 November 2005	25/11/2005

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Loiseleur, P

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	IMASAKI A ET AL: "A macroscopic instability and its suppression in a magneto-hydro-dynamically accelerated plasma" RECORD OF ELECTRICAL AND COMMUNICATION ENGINEERING CONVERSAZIONE TOHOKU UNIVERSITY TOHOKU UNIV JAPAN, vol. 71, no. 1, October 2002 (2002-10), pages 18-21, XP008055210 ISSN: 0385-7719 abstract -----	1-10
A	US 5 357 747 A (MYERS ET AL) 25 October 1994 (1994-10-25) the whole document -----	1-10

INTERNATIONAL SEARCH REPORT

Information on patent family members

tern[redacted]nal Application No

PCT/IT2005/000015

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 5357747	A	25-10-1994	NONE	