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ALTERNATING PINCH PLASMA DRIVE

Filed March 4, 1965

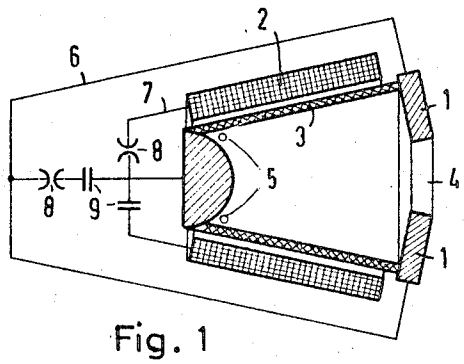


Fig. 1

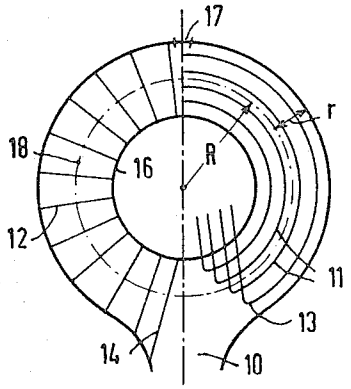


Fig. 2

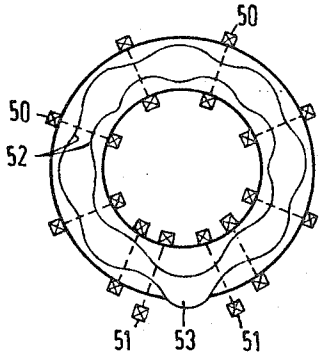


Fig. 4

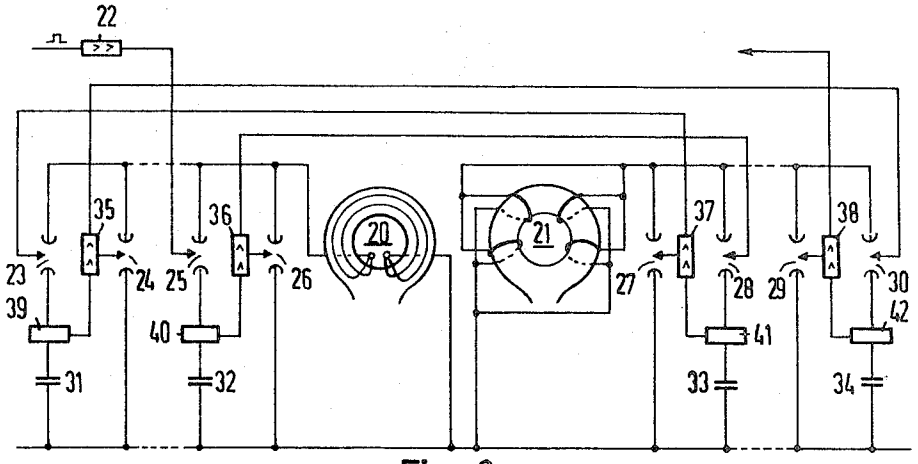


Fig. 3

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ALTERNATING PINCH PLASMA DRIVE

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7 Claims. (Cl. 60—202)

My invention relates to a plasma accelerator for producing a flow of compressed plasma for various purposes such as for propulsion or attitude control of satellites and other space vehicles.

When an electric current is caused to flow through a plasma on a filamentary path, the current filament is subjected to compression due to the Lorentz force resulting from its own magnetic field circularly surrounding the filamentary path. If by means of external current a temporally variable magnetic field in the longitudinal direction is produced in a cylindrical plasma, this field induces in the plasma an electric current which is circularly closed upon itself. If under such conditions the vectors of the magnetic field strength and its variation have the same direction, the plasma, in this case too, is compressed. These two phenomena are called "pinch effect," the former being designated as "Z pinch" and the latter as "theta pinch."

Plasma accelerators utilizing the Z pinch and accelerators operating with the theta pinch within vessels of cylindrical or conical shape are known. Such devices are described, for example, in the copending application Ser. No. 374,617, filed June 12, 1964, as well as in the references mentioned therein. Plasma accelerating devices of this kind afford attaining thrusts in the order of magnitude of 10 kp. for short intervals of time, namely for a few microseconds as compared with the approximately 10^4 times greater thrust obtainable with chemical rockets. In the pertinent literature, this plasma thrust is indicated as being characteristic of electromagnetic space propulsion drives.

However, if it is taken into account that with the experimenting installations presently available, only about one plasma push per minute can be issued, then the continued thrust attainable is reduced approximately by the factor 10^{-7}. This suffices for attitude control of communication satellites, such as a trajectory correction. To achieve greater amounts of thrust, plasma discharges of highest possible frequency must follow each other. A high frequency of discharging pulses can be reached if a relatively large number of capacitors are successively discharged through the same equipment. The number of capacitors is limited by the requirement for minimum mass in the space vehicle.

Many of the plasma drives heretofore proposed for space vehicles involve extreme difficulties with respect to cooling and burning off at the electrodes. The required plasma burner must maintain an arc between two electrodes. The plasma temperatures, therefore, remain at 10^4 to $2 \cdot 10^{4\circ}$ K., and the expulsion speeds of the plasma are limited to approximately 10 km./sec.

Pulse-wise operated plasma accelerators with electrodes achieve higher temperatures and higher expulsion speeds, and the heating of the electrodes can be kept low. These advantages, however, can be obtained only on account of considerably reducing the thrust because the heating of the electrodes can be prevented only if the expulsion frequency is kept low.

With the inductively operated plasma accelerators, the electrode problems are avoided. However, the limitation imposed upon the thrust by a maximal discharging frequency remains, because another capacitor can be discharged only after the spark gaps of the previously discharging capacitors are extinguished.

It is an object of my invention to improve plasma accelerators by minimizing or eliminating the above-mentioned limitations and achieving an increased plasma output or increased thrust under otherwise comparable conditions.

Another object of the invention is to provide a plasma accelerator which is particularly well suitable for the propulsion of space vehicles (or attitude control).

According to the invention, I provide an alternating pinch plasma accelerator with an acceleration vessel which has an outlet opening through which the plasma, compressed by the pinch effect, is ejected and I provide the vessel with pinch effect means, namely theta pinch windings and Z pinch windings or electrodes, and connect these pinch-field producing means with a periodic electric energizing circuit for alternately producing a Z pinch and a theta pinch.

It has become known to exert electromagnetic forces upon a plasma by causing a Z pinch and a theta pinch to alternately act upon the plasma periodically; but these methods have heretofore been used only in conjunction with devices for generating and confining a plasma. For example, a method for producing and confining a plasma of high energy is described and explained in the above-mentioned copending application Ser. No. 374,617. According to this method, an inertia phase free of a magnetic field is produced in the discharge vessel between each two sequential Z pinch and theta pinch phases. The inertia phase prevents the super-position or other unfavorable interaction of the two magnetic fields caused by the Z pinch and the theta pinch; and such an inertia phase may also be employed in devices according to the present invention for improving the reliability of operation.

In contrast with the known plasma accelerators utilizing only one of the two pinch effects, an alternating pinch plasma accelerator according to the invention having a cylindrical or conical plasma vessel affords doubling the discharging and consequently the plasma expulsion frequency. The theta pinch may commence even while the last active spark gap of the Z pinch is still ignited, and vice versa. Since the plasma is ejected from the compression chamber immediately upon electromagnetic compression and hence does not return to the vessel wall, but escapes axially, the interposition of an inertia phase free of a magnetic field between the Z pinch phase and the theta pinch phase is not absolutely necessary. However the discharging frequency can be somewhat increased with the aid of such an interposed inertia phase.

In contrast to the known plasma confinement devices, care must be taken to provide a plasma drive according to the invention with a continuous replenishment of driving gas, preferably pre-ionized gas. For this purpose, the accelerator vessel is preferably provided with one or more gas inlet openings.

If the alternating pinch plasma accelerator is provided with a cylindrical or conical accelerator vessel, the theta pinch is produced with windings on the vessel, whereas the Z pinch is produced by means of electrodes mounted on the vessel. Consequently, with such accelerators there also occurs the problem of excessive electrode heating under continuous operation. This can be avoided by giving the alternating pinch accelerator vessel a toroidal shape.

Toroidal devices according to the invention do not require any electrodes. In the toroidal acceleration chamber, the theta pinch as well as the Z pinch are generated without electrodes, that is, purely inductively. The Z pinch and the theta pinch are produced by respective coils whose windings extend perpendicularly to each other.

Such toroidal plasma accelerators according to the invention attain very high expulsion frequencies in comparison with the known plasma accelerators. These frequencies may have an order of magnitude between 10^4 and 10^5 per second and they are essentially limited only by the dimensioning of the appertaining charging and ignition device.

To reliably prevent an unfavorable interaction between the respective magnetic fields produced in the toroidal chamber by the Z pinch and the theta pinch, the above-mentioned inertia phase free of a magnetic field may be interposed between each two successive Z pinch and theta pinch phases.

The toroidal plasma accelerators according to the invention are provided with one or more inlet openings for driving gas, preferably pre-ionized gas, which are located at the periphery of the vessel and they are provided with one or more outlet openings through which the compressed plasma is ejected. For the ejection of the plasma from the outlet openings, use is made of the fact that during the Z pinch as well as the theta pinch the plasma is driven toward the outer periphery of the accelerating chamber. This phenomenon is due to the fact that when the Z pinch is effective, there occurs a ring-shaped current flow closed upon itself which under the effect of its own magnetic forces expands against the outer periphery. During the theta pinch the driving force is caused by the fact that the inhomogeneous toroidal magnetic field produces a drift toward the outer periphery of the toroidal vessel. This is because the toroidal magnetic field is stronger near the inner periphery than at the outer periphery. While these effects have a disturbing and undesired influence in the known investigations relating to controlled nuclear fusion, they are desired and advantageously utilized at the plasma outlet localities in a device according to the invention.

The desired effects of the phenomena just described can be augmented according to the invention by giving the theta pinch windings at the outlet openings a larger diameter than at the remaining portion of the accelerator vessel. As a result, the theta pinch at the outlet opening assumes a conical shape which promotes the expulsion of the plasma gases by the resulting course of the field lines.

According to still another feature of the invention, the Z pinch windings are placed closer together at the inner periphery of the toroidal vessel in the vicinity of the outlet openings, than at the outer periphery. The resulting field configuration at these windings also promotes an increased expulsion effect upon the plasma through the outlet opening.

The invention will be further described with reference to embodiments of alternating pinch plasma accelerators according to the invention illustrated by way of example on the accompanying drawings.

FIG. 1 shows schematically and in section a plasma accelerator equipped with a conical plasma vessel.

FIG. 2 shows schematically a plan view of a toroidal plasma accelerator, the theta pinch coil being removed from the right-hand portion of the vessel in order to expose the Z pinch windings.

FIG. 3 is a schematic circuit diagram for operating the plasma accelerator according to FIG. 2; and

FIG. 4 shows schemtaically a plan view of a plasma accelerator with $M+S$ configuration.

The conical plasma accelerator shown in FIG. 1 is equipped with Z pinch electrodes **1** and a theta pinch coil **2**, mounted on a conical vessel **3** which has an axial outlet opening **4** for the rejection of the compressed plasma and is provided with inlet openings **5** for gas supplied preferably in pre-ionized constitution such as from a plasma burner. The wall of the conical vessel **3** may consist of quartz glass. The electrodes **1** and the theta coil **2** are connected by respective leads **6**, **7** with spark gaps **8** and a bank of capacitors **9** schematically represented by a single capacitor. The capacitors are charged from a current source (not illustrated). The spark gaps **8** are ignited by a firing circuit, for example similar to the one shown in FIG. 3 and described below. The ignition circuit operates to displace the respective currents of each two successive pinches by 90° geometrically with respect to each other.

The alternating pinch plasma accelerator shown in FIG. 2 comprises a toroidal vessel which at one place of its outer periphery forms an outlet opening **10** for the compressed plasma. In the right-hand portion of the illustration there are shown the windings **11** of the Z pinch coil, and in the left-hand portion, the windings **12** of the theta pinch coil. In reality, each coil extends over the entire toroidal vessel, with the theta pinch coil on top of the Z pinch coil. The individual turns of the Z pinch and theta pinch coils extend perpendicularly to each other. The coils **11** and **12** are energized, for example, by voltages of 20 to 40 kilovolts and currents in the order of 100 kiloamps. The individual turns **11** and **12** of the Z pinch and theta pinch coils are preferably connected in parallel in order to obtain a low coil inductivity and thus a high rate of coil-current increase. The turns are preferably formed of band- or tape-shaped conductors. The current supply leads to the coils preferably consist of coaxial cables for reducing the inductivity.

In the region of the outlet opening **10**, the Z pinch windings are denoted by **13** and the theta pinch windings by **14**. As shown, the windings **14** of the theta pinch coil have a larger diameter at the outlet opening **10** than at other localities of the toroidal vessel. Furthermore, the Z pinch windings **13** near the outlet opening **10** are closer to each other at the inner periphery than at the outer periphery. By virtue of these inhomogeneities of the winding turns at the ejection locality, an increased expulsion of the plasma is obtained, as explained in the foregoing. The toroidal vessel **16** is provided with an opening **17** through which a gas, preferably ionized, is replenished.

In FIG. 2, the radius of the circular torus axis **18** is denoted by R, and the radius of the toroidal tubular space by r. The plasma travels along the axial circle **18** a maximal distance of $\pi \cdot R$, whereas the corresponding travel distance with a linear pinch (maximal travel distance) amounts to r and hence is much shorter. Consequently in the toroidal plasma accelerator, one and the same plasma particle can be subjected several times to the pinch effect before it reaches the outlet opening **10**. In the cylindrical or conical theta pinch plasma accelerator, both travel distances are approximately equal.

In the circuit diagram of FIG. 3 the accelerator according to FIG. 2 is schematically illustrated twice in order to simplify the representation of the circuit connections. Shown at **20** is the Z pinch coil of the accelerator, and at **21** the theta pinch coil. The individual turns of the Z pinch coil and the theta pinch coil are connected in parallel. The circuitry comprises a commercially available pulse generator **22**, spark gaps **23** to **30**, capacitors **31** to **34**, commercially available time-delay components **35** to **38**, and inductive voltage transmitters **39** to **42** such as Rogowski coils. In principle, the illustrated ignition control network is similar to the one illustrated and described in the above-mentioned copending application Ser. No. 374,617.

A starting signal issuing from the pulse generator **22** causes ignition of the spark gap **25**. The capacitor **32** then discharges through the Z pinch coil **20** which then produces a Z pinch in the accelerator. The inductivities and resistances of the coil windings, capacitors, spark gaps and connecting leads are not illustrated.

The discharge of capacitor **32** furnishes an input signal for the delay chain **36**. This input signal is caused by the inductive voltage transmitter or Rogowski coil **40**. The delay component **36** produces two output pulses of which one is delayed relative to the other. The first delayed pulse triggers the short-circuiting spark gap **26** and

a second, more delayed pulse triggers the spark gap 28 and thus causes the capacitor 33 to discharge through the theta pinch coil 21 which then produces a theta pinch. Due to the fact that the spark gap 26, which short-circuits the Z pinch coil when triggered, enters into operation before the theta pinch circuit is released, an inertia phase during which no magnetic field is effective, is interposed between the Z pinch and the theta pinch.

The discharging current from capacitor 33 also produces in the inductive voltage transmitter 41 an input signal for the delay component 37. This delay component 37 again produces two output pulses which are delayed relative to the input signal as well as relative to each other. The first output pulse triggers the short-circuiting spark gap 27. The second, more delayed pulse triggers the next Z pinch circuit through the spark gap 23. Thus the condenser 31 now discharges through the Z pinch coil 20 and produces another Z pinch.

The discharge of the capacitor 31 furnishes an input signal through the inductive voltage transmitter 39 for the delay component 35. This again produces two output pulses. The first delayed pulse triggers the short-circuiting spark gap 24. The second, more delayed pulse triggers the spark gap 30 and thus causes the capacitor 34 to discharge through the theta pinch coil 21 which again produces a theta pinch.

The discharge current of capacitor 34 causes the inductive voltage transmitter 42 to pass an impulse to the delay component 38. Of the two output pulses from component 38, the first pulse triggers the short-circuiting spark gap 29 and the second pulse triggers a further, unillustrated Z pinch circuit, and so forth.

The embodiment schematically illustrated in FIG. 4 shows how at the closed localities of the torus a drift of the plasma in the outward direction can be suppressed by applying an $M+S$ configuration (Meyer and Schmidt, Zeitschrift für Naturforschung, vol. 13a, 1958, page 1005 ff). The turns of the Z pinch and theta pinch coils are not shown in FIG. 4 since they are mounted on the toroidal vessel in the same manner as explained above with reference to FIG. 2. In addition to the windings of the theta pinch coils according to FIG. 2, individual narrow coils 50 are placed about the toroidal tube in FIG. 4. The distance between the individual coils 50 is so chosen as to be in the order of magnitude of the tube diameter of the vessel. In the vicinity of the outlet opening 53 for the compressed plasma, the coils which form the $M+S$ configuration have a larger radius than elsewhere. These wider coils are denoted by 51. The coils 50 are traversed by a stronger electric current than the theta pinch coils 12 according to FIG. 2, it being understood that the coils 50 are connected to a suitable source of current. In this manner, a sequence of mirror fields is produced around the torus which in totality assume the mentioned $M+S$ configuration. Due to the more favorable confining properties of this configuration compared with a purely toroidal magnetic field, the plasma 52 is prevented from drifting against the torus wall at the closed localities of the torus.

Plasma accelerators according to the invention are not only useful for space vehicles but are applicable for other purposes in which an intensive current of compressed plasma is desired, for example as devices for supplying such a plasma current to magnetohydrodynamic generators where exothermic processes take place in the plasma. In this case, the kinetic energy of the plasma current issuing from the outlet opening of the plasma accelerator is converted into electrical energy.

The jets of plasma issuing from a plasma accelerator according to the invention are also applicable for a surface treatment. The advantage of the accelerator for such purposes resides in the fact that the quasi-continuous or intermittently ejected plasma jets can be given a very accurate dosage.

Plasma accelerators according to the invention may also be operated as toroidal Z pinch accelerators only, or as toroidal theta pinch accelerators only, utilizing only one type of pinch at a time.

To those skilled in the art it will be obvious upon a study of this disclosure that alternating pinch plasma accelerators according to the invention may be modified in various respects and may be given embodiments other than particularly illustrated and described herein, without departing from the essential features of my invention and within the scope of the claims annexed hereto.

I claim:

1. A plasma accelerator, comprising a plasma vessel having a plasma outlet opening and pinch effect means for ejecting compressed plasma through said opening, said pinch effect means comprising theta pinch field windings and Z pinch field means on said vessel, and periodic electric energizing means connected to said windings and field means for alternately producing a Z pinch and a theta pinch.

2. A plasma accelerator, comprising a substantially tubular vessel having a straight axis and having an axial outlet opening, pinch effect means on said vessel for causing compressed plasma to be ejected through said opening, said pinch effect means comprising Z pinch electrodes and theta pinch windings, and periodic electric energizing means connected to said electrodes and windings for alternately supplying them with respective currents of 90° displacement relative to each other to alternately produce a Z pinch and a theta pinch.

3. In a plasma accelerator according to claim 1, said electric means comprising time delay means for interposing a field-free phase between successive Z and theta pinches.

4. A plasma accelerator, comprising a toroidal vessel having a plasma outlet opening at its outer periphery, a Z pinch coil and a theta pinch coil on said vessel for causing compressed plasma to be ejected through said opening, each of said coils having its turns extending substantially perpendicular to those of said other coil, and periodic electric energizing means connected to said coils for alternately producing a Z pinch and a theta pinch.

5. A plasma accelerator, comprising a toroidal vessel having a plasma outlet opening at its outer periphery, a Z pinch coil and a theta pinch coil on said vessel for causing compressed plasma to be ejected through said opening, each of said coils having its turns extending substantially perpendicular to those of said other coil, and periodic electric energizing means connected to said coils for alternately producing a Z pinch and a theta pinch, said electric energizing means comprising time delay means for interposing a field-free phase between successive Z and theta pinches.

6. In a plasma accelerator according to claim 4, said turns of said theta pinch windings having a larger diameter at said outlet opening than elsewhere on said toroidal vessel.

7. A plasma accelerator according to claim 6, comprising an $M+S$ configuration at the closed localities of said vessel away from said outlet opening.

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