May 23, 1967 J. A. PHILLIPS ETAL 3,321,664

PLASMA ACCELERATOR HAVING RAPIDLY PULSED COIL FOR EXPELLING PLASMA

Filed Aug. 10, 1964 5 Sheets-Sheet 1

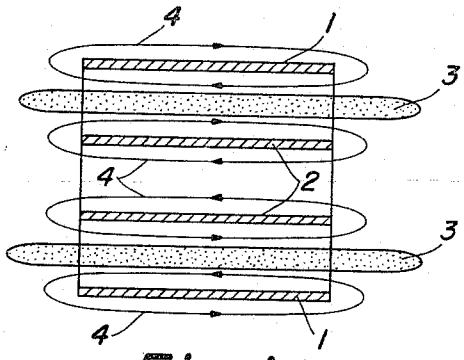


Fig. 1

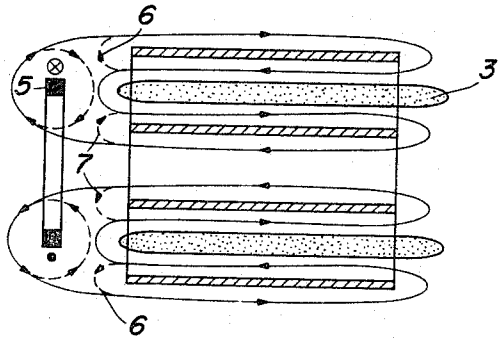


Fig. 2

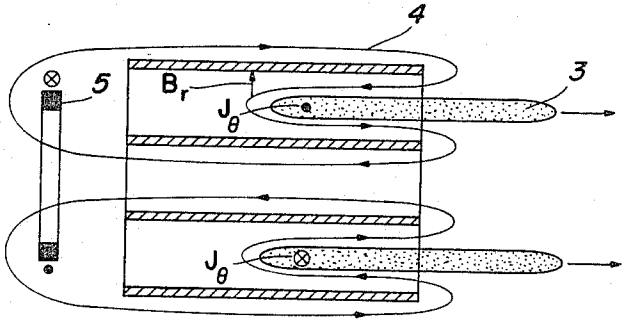


Fig. 3

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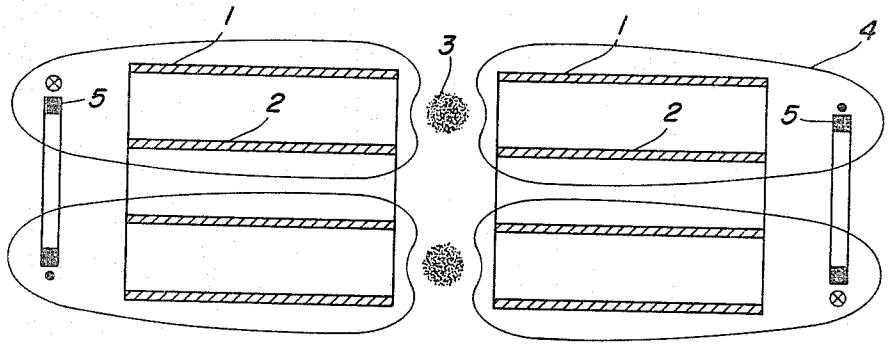


Fig. 7

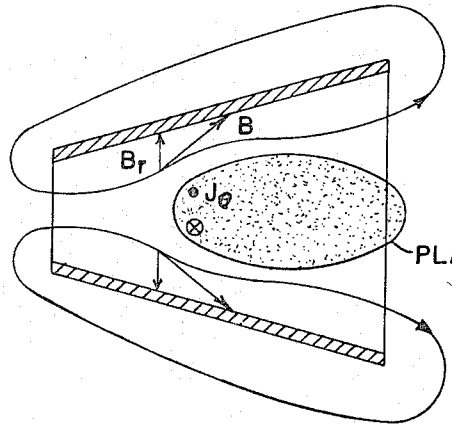


Fig. 4

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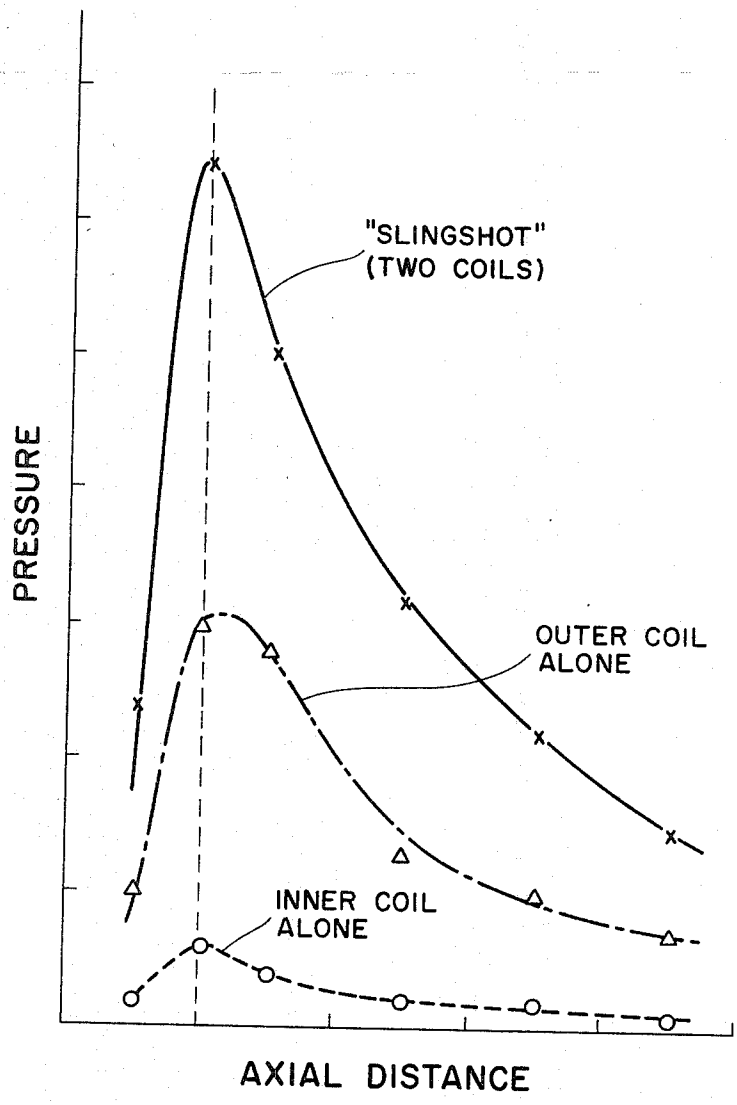


Fig. 5

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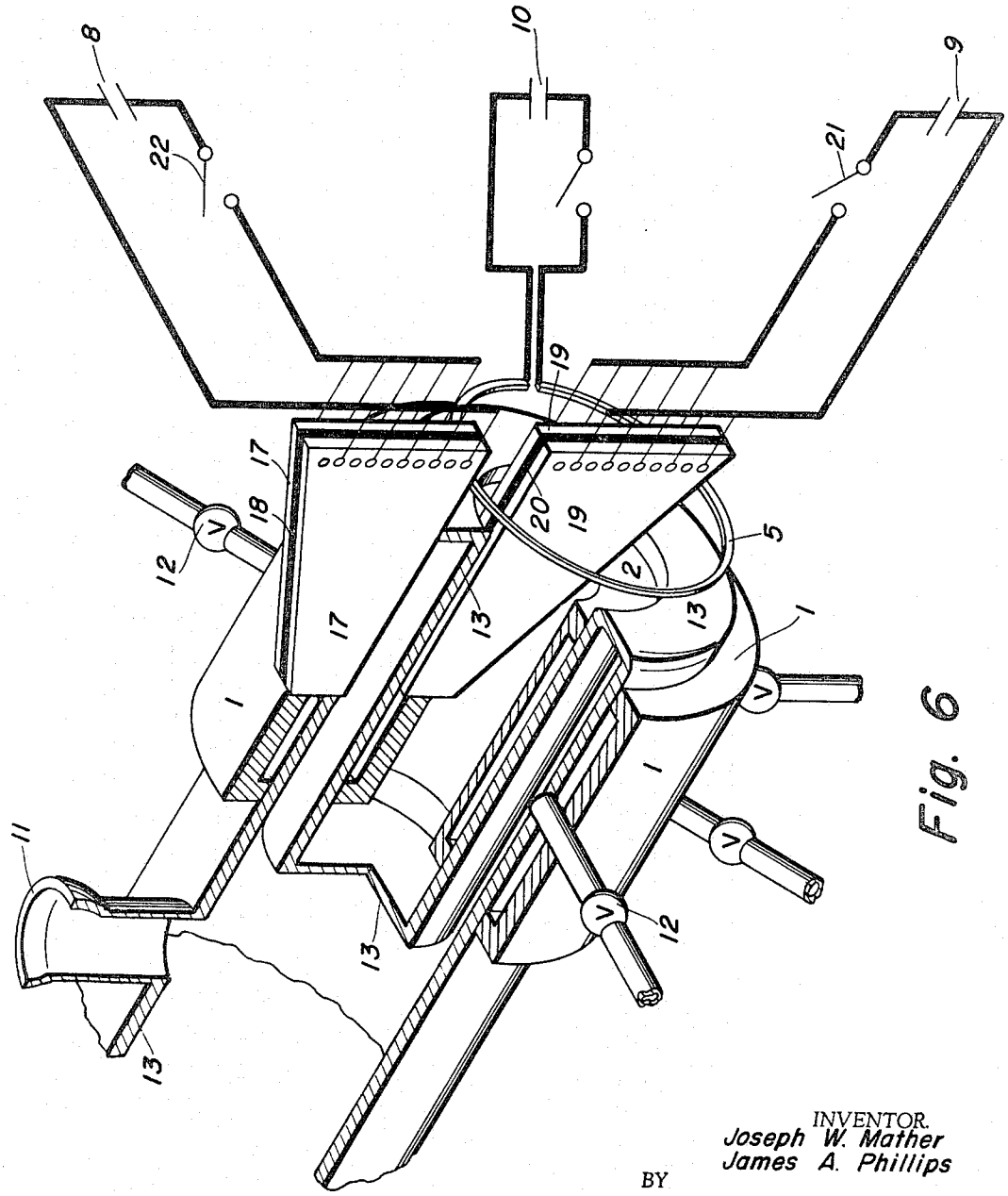


Fig. 6

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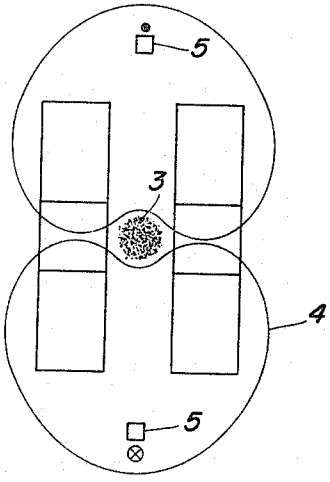


Fig. 8

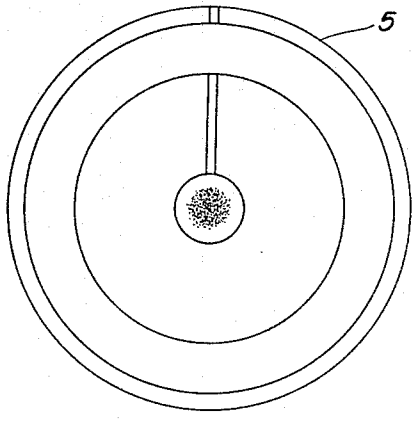


Fig. 8A

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United States Patent Office

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PLASMA ACCELERATOR HAVING RAPIDLY PULSED COIL FOR EXPELLING PLASMA

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Filed Aug. 10, 1964, Ser. No. 388,735
6 Claims. (Cl. 315—111)

The present invention is directed to methods and means for accelerating plasma jets to very high energies and is particularly concerned with thus accelerating a plasma of hydrogen isotopes. Such jets are useful as detonating waves, in accelerating ions against fixed targets to obtain nuclear reactions, in rocket propulsion, studies of highly energetic air streams on airframes, and studies of blast effects. They are also useful in neutron sources operating by means of fusion reactions, and may be particularly useful with controlled thermonuclear reactors.

Plasma accelerators of somewhat different structures and methods of operation have been developed in the past, but such accelerators were unable to produce plasma jets of the high energies and lack of contamination produced by embodiments of the present invention.

It seems that if higher efficiencies of energy transfer are to be achieved in plasma accelerators, the inherent slowness of practical energy sources must somehow be circumvented. The normal problem for those engaged in plasma physics is to transfer a maximum amount of energy from a capacitor bank to a load through an electrical circuit. The peak current at the load is proportional to the voltage on the condenser divided by the square root of the inductance in the circuit. Since making order of magnitude changes in voltage or inductance presents considerable engineering problems, it is difficult to increase the peak current substantially.

The means by which the present inventors have circumvented the above problems is to first convert energy into magnetic energy in the plasma accelerator itself at a relatively slow rate. When this is completed, the system is triggered by an auxiliary coil which produces an imbalance in the magnetic field so that the magnetic energy may be converted into thermal or translational energy of the plasma considerably faster than can be handled by an entire energy source consisting of switches, capacitors, and cable.

Briefly stated, the method of the present invention is practised by forming a hard vacuum between two concentric coils, introducing an ionizable gas in the space under hard vacuum between said two concentric coils, energizing said coils by passing current in the same direction through each of said coils, the current in each of said coils being supplied by an independent power supply, each of said power supplies having identical ringing frequencies, and triggering the resulting magnetic field into an unbalanced configuration by passing a current through a third coil placed between the concentric coils at one end thereof. The apparatus in which this method is practised may be described as comprising two concentric coils, said concentric coils being driven by two independent power supplies and so connected to said power supplies that the currents in the two coils are flowing in the same direction, means for introducing an ionizable gas in the space between said coils, a third coil located between the said concentric coils at one end thereof, and said third coil being connected to a third independent power supply so that current flows in the same direction in the third coil as in the two concentric coils.

An object of the invention is to provide methods and means for producing plasma jets having energies approaching thermonuclear temperatures.

It is a further object of the present invention to provide methods and means for producing plasma jets wherein the plasma is not contaminated by electrode materials.

The present invention can be easily comprehended by reference to the accompanying drawings in which:

FIGURE 1 is a schematic drawing illustrating the operation of the accelerator when the two concentric coils are energized.

FIGURE 2 is a schematic drawing illustrating the operation of the device when the third coil has been energized.

FIGURE 3 is a schematic drawing illustrating the operation of the plasma gun a short time after the third coil has been activated.

FIGURE 4 is a schematic drawing of a conventional conical orthogonal (or θ) pinch.

FIGURE 5 is a graph demonstrating the relative impulse as a function of length along the coil given by a θ-pinch and by a "Slingshot" accelerator.

FIGURE 6 is a partially cutaway isometric view of the plasma accelerator and associated auxiliary equipment.

FIGURES 7 and 8 are schematic drawings of interesting experimental arrangements utilizing the plasma gun of the present invention.

FIGURE 8A is an end view of FIGURE 8.

In FIGURE 1, the two concentric coils **1** and **2** are driven by two independent power supplies (shown schematically in FIGURE 6) having identical ringing frequencies with the currents in the two coils flowing in the same direction. If a good conductor (the plasma **3**) is located in the annular space between the two coils, the magnetic field lines **4** on each side of the conductor will be in opposite directions. If the plasma-magnetic field interfaces are stable, the plasma will be radially compressed by the magnetic fields. At peak currents when the energy is in the magnetic fields between the coils and plasma, a third coil **5** (shown in FIGURE 2) between the coils and plasma is energized by passing through it a current in the same direction as that flowing in coils **1** and **2**. The power supply used to build up current in coil **5** should permit a very fast rise time. When this is done the magnetic fields in the regions **6** and **7** (FIGURE 2) are to first order cancelled, with the field lines on each side of the plasma joining together around the end of the plasma. At this point the pressures on the plasma are no longer balanced and the plasma is accelerated to the right (as shown in FIGURE 3).

Three very important advantages will be seen from a consideration of the described device. One important advantage is that acceleration may be initiated at maximum current. A second advantage lies in the fact that the plasma is not in contact with the vacuum walls and is, therefore, not contaminated with high Z-number material. The third advantage may be illustrated by a comparison of the conventional conical orthogonal or θ-pinch as shown in FIGURE 4 with the plasma accelerator of the present invention. In the conventional conical θ-pinch geometry, axial acceleration is by the $\vec{J}_\theta \times \vec{B}_r$ force where $\vec{J}_\theta$ is the azimuthal current density in the plasma and $\vec{B}_r$ is the radial component of the magnetic field. In the proposed geometry, axial acceleration is also given by $\vec{J}_\theta \times \vec{B}_r$, but here $\vec{B}_r$ is the full magnitude of B. These three advantages are illustrated by the comparative results shown in FIGURE 5.

FIGURE 5 plots pressure versus axial distance along the coil for three situations. The curve labeled "Slingshot" illustrates the results obtained by utilizing the pres-

ent invention. If only one of the concentric coils are energized (which is analogous to a θ-pinch) it can be seen that the resulting curves give greatly inferior results.

FIGURE 6 is an isometric schematic drawing illustrating the plasma accelerator and its associated auxiliary equipment. Independent power supplies **8** and **9** having identical ringing frequencies drive current in the same direction through coils **1** and **2**. As may be noted, coils **1** and **2** are built up at the ends to form a magnetic mirror. This optional feature should tend to confine the plasma longer since charged particles, moving from a region of lower to higher field strength will be reflected back to the former region. A third power supply **10** energies coil **5** with current flowing in the same direction as that in coils **1** and **2**. It may be preferable to use conductive plates (as illustrated) in place of cables in linking the power supplies to the concentric coils in order to lower the inductance. Each power supply is normally a capacitor bank but, for purposes of illustration, has been represented by a single capacitor. The power supplies **8**, **9** may be electrically connected to plates **17**, **19** and coils **1** and **2** by switches **21**, **22**.

Plates **17** are separated by insulation **18**, this insulation also providing a discontinuity in coil **1** so that current may flow. In the same manner plates **19** are separated by insulation **20**. Containment vessel **13**, made, for example, of glass, serves to contain and separate the plasma from the conductive concentric coils. The plasma is admitted to container **13** between concentric coils **1** and **2** by valves **12** which each admit a "puff" of easily ionizable gas. The valves may be any quick acting type such as an electromagnetically operated valve. Prior to admission of the easily ionized gas, the plasma gun is pumped out to a hard vacuum through conduit **11**.

In operation a vacuum is formed in container **13** (e.g., 10^{-6} mm. Hg). The easily ionizable gas is then delivered to container **13** in the annular region between coils **1** and **2**. After this space is filled with the gas to density of 10^{14}–10^{15} particles/cc. (preferably about 1–10μ gas fill), coils **1** and **2** are activated. As previously stated, the condenser banks **8** and **9** are matched, each being capable of delivering a peak current of about one million amperes at a period of about 10μ sec. As the current is built up in coils **1** and **2** a magentic field is built up in the annular region. Some field intermixing occurs, thus heating the gas. This results in ionization of the gas to form a conductive plasma. In the preferred embodiment, a magnetic field of 50 kilogauss is generated resulting in a 100 atmosphere pressure on each side of the plasma. At peak current when the energy is in the magnetic fields between the coils and plasma, coil **5** is activated by power supply **10**.

In the preferred embodiment, this capacitor bank **10** is rated at about one-tenth that of banks **8** and **9** (i.e., about 100,000 ampere peak current and a period of about 1μ sec.) and is placed about the same distance from coils **1** and **2** as the distance between coils **1** and **2**. Coils **1** and **2** are about 8 inches long, the outside coil is of 12-inch diameter and there is a space of about 2 inches between the inner and outer coils. It should be stressed that the above dimensions are not critical. The only dimensional requirement is that coil **5** should be placed close enough to the concentric coils to permit coupling of the magnetic fields. It should, however, be noted that the peak current in coil **5** should be (within a factor of two or three) equal to the current per unit length in coils **1** and **2** multiplied by the distance between coil **5** and coils **1** and **2**. The new magnetic field causes imbalance of the

pressures on the plasma and consequent acceleration of the plasma. A plasma density in excess of 10^{16} particles/cc. before acceleration will, at a velocity of about 10^8 cm./sec., indicate a total energy of about ten kilojoules. Although not shown, a magnetic field may be applied downstream of the concentric coils to prevent contact of the emerging plasma with the container **13**.

FIGURE 7 represents an interesting experimental configuration embodying the "Slingshot" plasma gun. As shown, two plasma guns are mounted facing each other so that the accelerated plasma forms a plasma ring. Although the magnetic confinement is somewhat unstable, the very rapid increase in density would make this experiment interesting.

FIGURE 8 depits a device analogous to that of FIGURE 5 except that instead of concentric coils, cylindrical discs are used. Current is passed in the same direction around discs **14** and **15** and trigger coil **16**. This configuration may be even more interesting than that of FIGURE 7 since the plasma is accelerated radially to a center hot spot rather than to a ring-shaped hot spot as in FIGURE 7.

The methods and means described above are presented for the purpose of facilitating the explanation of this invention and not for limiting the scope thereof. Accordingly, the invention should be limited only by the following appended claims.

What is claimed is:

1. A plasma accelerator comprising:

(a) two concentric coils,

(b) said concentric coils being driven by two matched independent power supplies and so connected to said power supplies that the currents in the two coils are flowing the same direction,

(c) means for introducing an ionizable gas in the annular space between said concentric coils, and

(d) means for triggering the magnetic fields resulting from flowing currents in the two concentric coils into unstable configurations.

2. A plasma accelerator as in claim **1** wherein means are provided for pumping out the space between said concentric coils to a hard vacuum.

3. The plasma accelerator of claim **1** wherein the means for triggering the magnetic field into an unstable configuration comprises a third coil located between the said concentric coils at one end thereof.

4. The plasma accelerator of claim **3** wherein said third coil is about the same distance from the concentric coils as the distance between the two concentric coils.

5. The plasma accelerator of claim **3** wherein said third coil is connected to a third independent power supply so that current flows in the same direction in the third coil as in the two concentric coils.

6. The plasma accelerator of claim **5** wherein the ends of said two concentric coils are enlarged so that the resulting magnetic fields form a magnetic mirror.

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