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[54] **MULTI-AMPERE DUOPIGATRON ION SOURCE**

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[73] Assignee: **The United States of America, as represented by the United States Atomic Energy Commission.**

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[52] **U.S. Cl.** .... **250/41.9 SE**, 313/63
[51] **Int. Cl.** **H01j 37/08**
[58] **Field of Search** .... 250/41.9 SE, 41.9 SA, 250/41.9 SB; 313/63

[56] **References Cited**

UNITED STATES PATENTS

3,238,414 3/1966 Kelley .... 250/49.5 R

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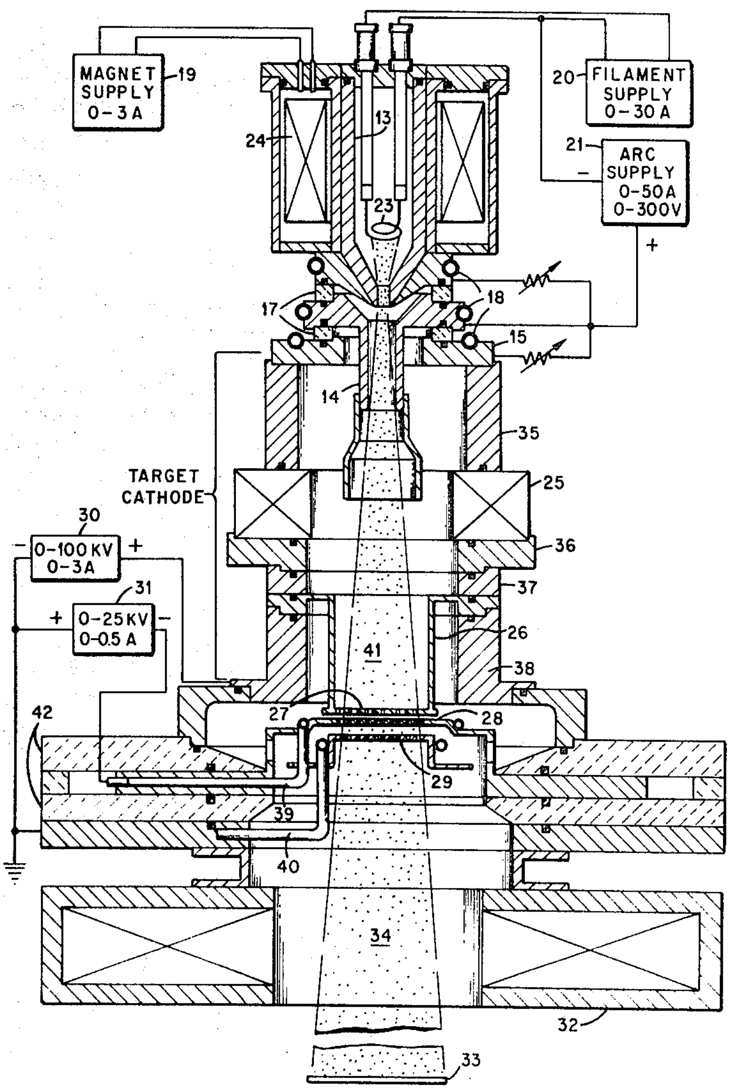
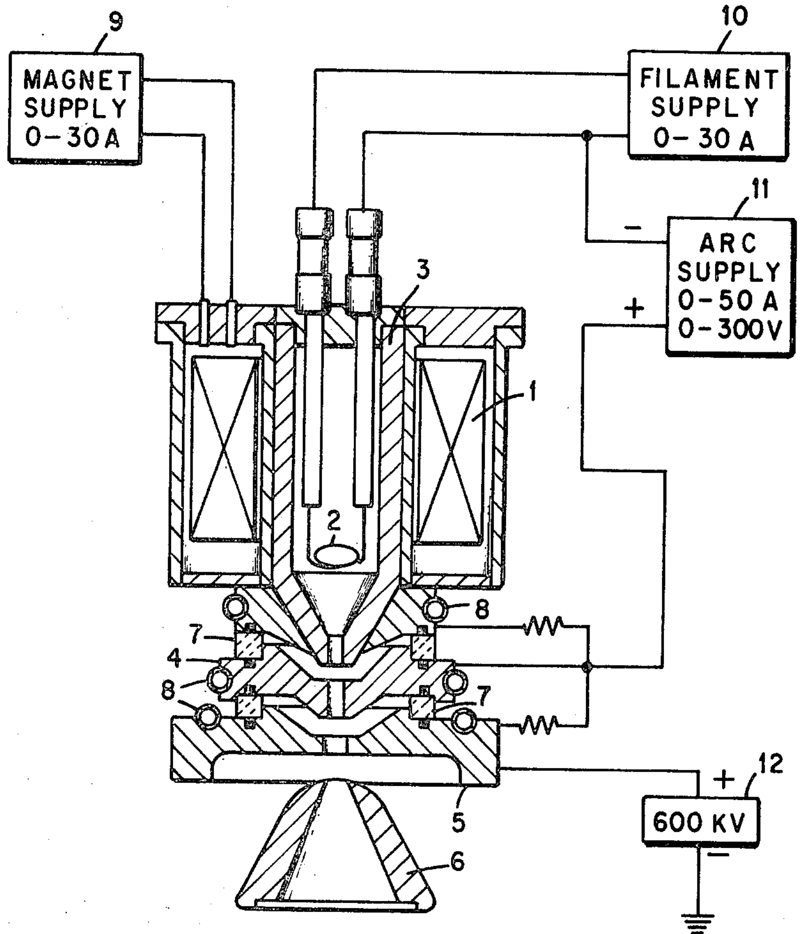
[57] **ABSTRACT**

A duoplasmatron ion source is modified to provide a large plasma surface with a uniform density at a target cathode. The target cathode and the acceleration and deceleration electrodes are gridded or multi-apertured and are spaced in close proximity each to the others with the apertures being in alignment. With such an arrangement, it is possible to extract multi-ampere bright ion beams at energies of tens of KeV. Conversion of the ion beam to a neutral particle beam can be readily accomplished by addition of a gas cell.

6 Claims, 2 Drawing Figures





PRIOR ART

Fig. 1

2 Sheets-Sheet 2

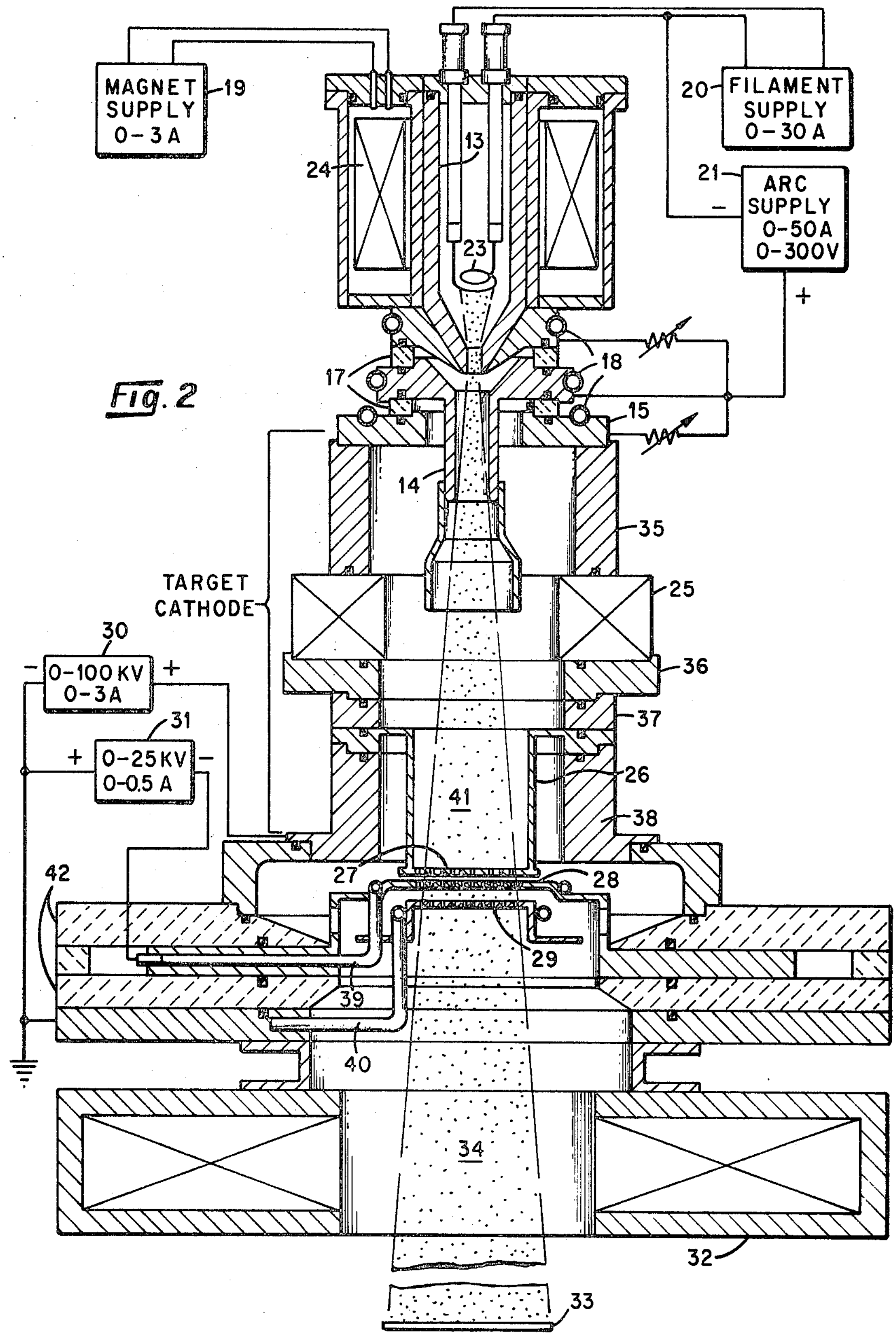


Fig. 2

MULTI-AMPERE DUOPIGATRON ION SOURCE

BACKGROUND OF THE INVENTION

This invention was made in the course of, or under, a contract with the United States Atomic Energy Commission.

In the past ten years there has been a continued increase in the desired or required ion current from ion sources. This has resulted in a continued redefinition of the term "intense" ion beam to refer to beams from milli-amperes (mA) to hundreds of mA to A's at the present time.

The plasma required for the extraction of an ampere ion beam can be obtained from any of several types of electron oscillating or arc type ion sources. Some of the most obvious of these are the calutron, Penning discharge (PIG), Lamb-lofgren, radio-frequency, and duoplasmatron. There have been many developments in all of these sources that indicate that they are capable of producing intense ion beams. However, most applications are small when compared to various modifications of the duoplasmatron. Some of the various modifications to the duoplasmatron that have been developed at the Oak Ridge National Laboratory (ORNL) are described in an article published in The Review of Scientific Instruments, Vol. 38, No. 4, pp. 467–480, April 1967, titled "Technology of Intense DC Ion Beams" by Ora B. Morgan et al.

The original duoplasmatron is a very efficient, compact source of ions, and a description thereof was published in Tabellen Der Elektronen Ionenphysik and Ubergikroskopie by M. Von Ardenne, (VEB Deutscher Verlag der Wissenschaften, Berlin, 1956). Also this ion source is described in U. S. Pat. No. 2,975,277, issued Mar. 14, 1961, to M. Von Ardenne. It can be operated with high gas efficiency and a plasma density at the anode of approximately 10^{14} ions/cm^3. The ions can have an outward directed velocity greater than 10 eV which can result in a plasma flow equivalent to a current density of about 100A/ cm^2. This density exceeds that from which ions can be extracted and, therefore, the plasma must expand as it leaves the anode aperture. A second problem appears when trying to operate with the high DC arc current required for intense DC beams. The electrodes tend to overheat and result in damage to the anode. Improved cooling is also needed for the intermediate electrode. Solutions to this heating problem were found at the ORNL by incorporating a copper anode and a heavily cooled intermediate electrode in a manner as desribed in the above-mentioned article in The Review of Scientific Instruments.

Adding a fourth electrode to the duoplasmatron ion source resulted in a system that can be operated stably at low pressure. Such an ion source is illustrated in FIG. 1 of the present disclosure which will be described hereinbelow. In this prior art source, the added electrode is termed the target cathode and is seen to be distinguished from the existing electrodes, namely, the intermediate electrode, anode, and extraction electrode. This prior art ion source as well as other modifications to the original duoplasmatron ion source are described in the above-mentioned article. Most of these prior ion sources have been utilized in various experimental fusion research devices at ORNL. However, the ion beams that can be extracted from these prior devices are, in most instances, less than 1 ampere since the plasma density over a relatively large cross section is not as uniform or intense as desired in each of these devices thus limiting the output therefrom.

There exists a need for an ion source that produces a very intense ion beam output that can be used as an injector for experimental thermonuclear fusion devices, such as the ORMAK device at ORNL, where the energy of ion beam is utilized in the technique of neutral injection heating. The desired goal of such an injector is to produce several amperes (equivalent) of highly collimated neutral particles in an energy range of about 5 to 60 KeV, and a very important requirement is that the ion source produce a plasma with a uniform density over a large cross section. Another requirement is to incorporate an electrode structure that is highly transparent to the beam and which prevents self-caused electric field distortions. The present invention was conceived to meet the above need for an improved ion source in a manner to be described hereinbelow.

SUMMARY OF THE INVENTION

It is the object of the present invention to provide an improved ion source for use as a means of neutral injection heating in a thermonuclear fusion device, wherein amperes (equivalent) of highly collimated neutral particles are produced by the ion source and an associated gas cell.

The above object has been accomplished in the present invention by modifications of the four-electrode duoplasmatron ion source, illustrated in FIG. 1 of the present disclosure, for producing a large plasma surface. These modifications include a new shaping of the ion source in the area where the intense discharge of arc takes place (that is, the target cathode area), and in the area where the ions are accelerated. The anode is also reshaped, the target cathode is provided with a plurality of apertures and is positioned in close proximity to the acceleration and deceleration electrodes which are also provided with a plurality of apertures, and a field shaping auxiliary coil is positioned between the apertured target cathode and the intermediate electrode. The reshaped anode, target cathode, and the auxiliary coil provide a long mean free path for the electrons and the combined effect is to shape the electric and magnetic fields to produce a large uniform density plasma surface at the target cathode grid. From this modified ion source, 1-ampere beams can be extracted in steady state operation with ion energies of from 1.5 to 5 KeV. When this ion source is operated in the pulsed mode with 0.1 to 0.2 second pulses and 10% duty cycle at ion energies of 20 to 40 KeV, 4-ampere beams can be extracted from the source. At 30 to 40 KeV, about 60 percent of the ion beam is within a half angular divergence of 1.2° with no magnetic lens. Using a hydrogen gas cell coupled to the outputs of the ion source, this system produces 2.6 amperes (equivalent) of 17.5 and 35 KeV H° particles within a half angular divergence of 1.2°

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a cross-sectional view of a four-electrode douplasmatron ion source of the prior art; and

FIG. 2 shows a cross-sectional view of the improved ion source of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The prior art, four-electrode douplasmatron ion source illustrated in FIG. 1 includes a source coil **1** connected to a magnet supply **9**, an intermediate electrode **3** provided with a copper jacket at its lower tapered end which is cooled by means of a cooling line **8**, a filament cathode **2** connected to a fillament supply **10**, a copper anode **4** separated from the jacket of the electrode **3** by means of an insulator **7**, a target cathode **5** separated from the anode **4** by means of another insulator **7**, and a nickel extractor electrode **6**. The anode **4** and the target cathode **5** are also cooled by means of additional cooling lines **8**. An arc supply **11** is connected between the anode **4** and the filament cathode **2**. Feed gas is fed into the interior of the intermediate electrode **3** in a conventional manner, not shown, such as shown in the above-mentioned Von Ardenne patent. The device of FIG. **1** is used with a suitable vacuum chamber, not shown, and a magnetic lens, not shown, is mounted below the extractor electrode **6** in a conventional manner for focusing the output beam from this ion source. It should be noted that in the operation of this ion source, only about 100 mA of the output beam is available as H_2^+ ions through 4-cm diameter apertures located at 178 and 250 cm from the magnetic lens.

The ion source of the present invention, illustrated in FIG. 2 of the drawings, was conceived to provide a substantially greater extractable ion beam than is possible with the above prior art source in a manner to be described hereinbelow.

The improved ion source of FIG. 2 includes a source coil **24** connected to a power supply **19**, a filament cathode **23** connected to a power supply **20**, an intermediate electrode **13**, an anode **14**, and a target cathode assembly including an annular hollow electrode member **15**, annular hollow members **35** and **36** which has mounted therebetween an auxiliary field shaping coil **25**, annular hollow members **37** and **38** which has mounted therebetween a cylindrical target cathode support member **26** which supports an annular gridded target cathode **27**. Member **35** is affixed to member **15**, member **37** is affixed to member **36**, and member **38** is supported by a portion of the ion source housing as shown. The spacing between the tip of the intermediate electrode **13** and the gridded target cathode **27** is about **9** inches, for example, to provide for a relatively long electron oscillation space in the source plasma region, **41**. The ion source of FIG. **2** further includes an arc supply **21** connected between the cathode filament **23** and the anode **14**, a gridded acceleration electrode **28** connected to the negative side of a power supply **31** and being cooled by means of a cooling line **39**, a gridded deceleration electrode **29** connected to ground and being cooled by means of a cooling line **40**, and an ion beam acceleration power supply **30** connected to the gridded target cathode **27**, and to the deceleration electrode **29**. The electrodes **13**, **14**, and **15** are separated by means of ceramic insulators **17**, as shown, and these electrodes are cooled by means of cooling line **18**. The electrodes **27**, **28**, and **29** are separated by means of the epoxy insulators **47**.

Hydrogen feed gas, for example, is fed by means, not shown, into the interior of the intermediate electrode **13** in the same manner as disclosed in the above-mentioned patented Von Ardenne ion source. A power supply, not shown, connected to the auxiliary coil **25**, is of the same polarity as the source coil **24**. If the ion source is used with a lens coil **32** the auxiliary coil opposes the fringe field of the lens coil **32** to provide a near zero field at the surface of the gridded target cathode **27**. The ion beam **34** which is extractable through the gridded electrodes **27**, **28**, and **29** from the ion source may be directed upon a target **33** for measuring the ion output of the ion source. When the output beam **34** is utilized for injection heating in a thermonuclear reactor such as the ORNL experimental fusion device ORMAK, the output beam **34** may be directed through a hydrogen gas cell for converting the molecular ions in the beam **34** to energetic neutral particles. These neutral particles are then injected into the interior of the ORMAK device in a manner as described in the AEC Report ORNL-TM-3472, issued July 30, 1971. A description of the ORMAK facility without the ion source of the present invention has been published in IEEE Trans. Nuclear Science NS-18, No. 4.

The gridded electrodes **27**, **28**, and **29** are 5 -cm in diameter and each electrode is provided with **109** apertures of 3.75 mm diameter, for example, with the electrodes being about 50 percent transparent. The extraction gaps between the respective electrodes **27**, **28**, and **29**, may be from 3 to 6 mm, for example. The reshaped anode **14**, target cathode **27**, and the auxiliary coil **25** shape the electric and magnetic fields to provide a large uniform density plasma surface at the grid of the target cathode **27**. The other two grids, referred to in FIG. **2** as the acceleration (reverse biased) electrode **28** and the deceleration (grounded) electrode **29**, replace what would be the extractor electrode in FIG. **1**. The radius of the apertures, r, of the electrodes **27**, **28**, and **29** and the spacings of the electrodes, Z, are chosen for the desired ion energy. The minimum spacing is dictated by the maximum stable electric field gradient. The electrode apertures are assumed to act as a diverging lens. Therefore, the system is designed with an aspect ratio, $R = 2r/Z$, that should yield a beam with a small divergence.

The system of FIG. **2** can be operated in steady state (continuous) operation and 1-ampere beams can be extracted with ion energies of from 1.5 to 5 KeV. However, for 0.1 to 0.2 second pulses and 10 percent duty cycle, 4-ampere beams can be extracted at ion energies of 20 to 40 KeV. At 30 to 40 KeV, about 60 percent of the ion beam is within a half angular divergence of 1.2° with no magnetic lens. Using a hydrogen gas cell connected to the output of the ion source of FIG. **2**, such a system produces 2.6 amperes (equivalent) of 17.5 and 35 KeV H° particles within a half angular divergence of 1.2° without the magnetic lens **32**. The device of FIG. **2** can be operated with or without the magnetic lens **32**. Eliminating the magnetic lens makes the system simpler and makes it possible to utilize all of the ion species. The device of FIG. **2** will be used for injecting through a gas cell into the ORMAK without a magnetic lens as illustrated in FIG. **4** of the above-mentioned AEC Report, ORNL-TM-3472, issued July 30, 1971. The gas cell is a simple conductance limited conical tube with the 1.2° angle divergence acceptable for ORMAK.

The improved and enlarged plasma surface obtained from the operation of the ion source of the present invention has provided so superior an ion beam, as compared to prior ion sources, that the new term "duopigatron" has been given to it. Among its advantages are that it is simple, compact, efficient, and operates stably over a large variation in source pressure. Many essential features of the present ion source such as space-charge neutralization throughout the beam drift region, high electric fields, elimination of regions where electric and magnetic fields will cause PIG discharges, and use of either no lens or a magnetic lens are indicative that the ion source incorporates many of the outstanding ion source advances of recent years.

It should be understood that the 5-cm diameter size electrodes, for the electrodes **27, 28,** and **29,** are not limited to this size or to a 50 percent transparency, but may be scaled to even larger sizes when higher current exaction power supplies become available resulting in a corresponding increase in output currents from the ion source. Also, the number of apertures in the electrodes **27, 28,** and **29** may range from tens to hundreds with the apertures having diameters from 2 to 5 mm. The number of apertures and their sizes depend upon the use and current output desired of the ion source.

It should be understood that other types of extraction geometries can be utilized with the ion source of the present invention. For example, multi-slits instead of multi-apertures can be used in the electrodes **27, 28,** and **29.** Such a system would have the possibility of better thermal conductivity with the same transparency and this could make it possible to increase the duty cycle.

The above-described ion source is readily applicable for use as the plasma source in the technique of neutral injection not only for toroidal fusion devices, such as ORMAK, but also for mirror-type fusion devices. Neutral injection is probably the most powerful and universally applicable technique for producing plasmas in any magnetic configuration at the high ion temperatures and densities necessary for abundant fusion reactions to take place. The present ion source provides larger ion current at high ion temperatures than were previously available.

This invention has been described by way of illustration rather than limitation and it should be apparent that it is equally applicable in fields other than those described.

What is claimed is:

1. A high current duopigatron ion source comprising a heated filament cathode; an intermediate electrode provided with an apertured, tapered lower end portion, said intermediate electrode enclosing said filament cathode and adapted to receive a feed gas thereinto; a source coil encompassing the upper portion of said intermediate electrode; a source magnet supply connected to said coil; a copper anode insulatingly spaced from said intermediate electrode, said anode being provided with a centrally disposed aperture and a hollow elongated tail portion contingent with said aperture and extending longitudinally away from said intermediate electrode; a target cathode assembly defining an elongated ion beam drift space and including a first, centrally apertured electrode insulatingly spaced from said anode and encompassing a portion of said anode tail portion, a first tubular elongated member affixed to said first electrode, an annular auxiliary, field shaping coil affixed to said first member, a second tubular member affixed to said auxiliary coil, a third tubular member affixed to said second tubular member, a cylindrical target cathode support member affixed to said third tubular member, a fourth elongated tubular member affixed to said cathode support member and to the housing of said ion source, and a multi-apertured target cathode supported by said cathode support member; means for cooling said intermediate electrode, anode, and first electrode, a source of arc supply connected between said filament cathode and said anode; a multi-apertured acceleration electrode mounted beyond and closely spaced from said apertured target cathode; a source of negative acceleration voltage connected to said acceleration electrode; a source of high voltage connected to said target cathode; means for cooling said acceleration electrode; a multi-apertured deceleration electrode connected to ground and mounted beyond and in close proximity to said apertured acceleration electrode; and means for cooling said deceleration electrode, said anode and target cathode assembly providing a long mean free path for the electrons produced by the ion source discharge with the combined effect of shaping the electric and magnetic fields to produce a large uniform density plasma surface at the surface of said apertured target cathode thereby permitting the extraction of a high density and high temperature ion beam through said apertured electrodes.

2. The ion source set forth in claim **1,** and further including an annular lens coil mounted beyond said apertured deceleration electrode and encompassing said extracted ion beam for focusing thereof.

3. The ion source set forth in claim **1,** wherein said multi-apertured target cathode, acceleration electrode and deceleration electrode are each 5-cm in diameter and each is provided with 109 apertures of 3.75 mm diameter, the respective spacing between said apertured electrodes being from **3** to **6** mm.

4. The ion source set forth in claim **2,** wherein said ion source is operated in the continuous mode to produce an output ion beam of at least **1** ampere with ion energies from 1.5 to 5 KeV.

5. The ion source set forth in claim **3,** wherein said ion source is operated in the pulsed mode with 0.1 to 0.2 pulses and 10 percent duty cycle to produce an output ion beam of at least **4** amperes at ion energies of 20 to 40 KeV.

6. The ion source set forth in claim **5,** and further including a hydrogen gas cell connected to the output of said ion source to thereby produce 2.6 amperes (equivalent) of 17.5 and 35 KeV H° particles within a half angular divergence of 1.2°.

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