# Dynamag Ion Source with Open Cylindrical Extractor

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## Summary

A description is given of a duoplasmatron type ion source which features a novel, open cylindrical extractor electrode, a visible arc chamber and a short-path magnetic circuit. The glass spacer in the arc chamber permits observation of the plasma and filaments. The short magnetic circuit gives high plasma density at low magnet and arc currents. The open extraction geometry provides high pumping speed to the source and reasonable tolerances for anode alignment. Above a critical value of extraction voltage the ion emission is independent of voltage. At 16 kV, a 5 mA beam of mixed hydrogen ions can be obtained through an 0.008 in. anode aperture. Gas consumption is about 5 atm.-cc/hr. with a conversion efficiency of about 70%. Proton yield is usually better than 50% of the total beam current under these conditions. The emittance (phase space area) is about 3 mrad.-cm. MeV$^{1/2}$ at 1.0 mA.

## Introduction

The Dynamag ion source is a duoplasmatron of the Von Ardenne[1-2] type with a number of distinguishing features. The present model has evolved during a five year development program which has produced numerous changes and modifications in the original design of Eklund[3]. The Dynamag is designed primarily for use in the Dynamitron line of high voltage accelerators, but is also applicable to low voltage atomic research programs. The reliability and repeatibility in performance of this latest model has been shown on the 3.0 MeV Dynamitron at the University of Tokyo, at the Joint Research Center of Ottawa-Carleton Universities and on the new 4.0 MeV machine presently being tested in Westbury for the University of Stuttgart.

## Construction

The complete ion source assembly (Fig. 1) is comprised of two sections: the plasma gun and the extractor-lens section which are held together with fiberglass-reinforced cinch rods. This arrangement holds all seals in compression and also provides convenient access to the anode plate for inspection or replacement of the aperture button.

## Plasma Gun

The plasma gun is composed of the following main items: cathode plate with filaments, top plate, glass spacer, arc focus plate, X-ray shield, magnet coil, anode plate with aperture button and retaining cone. These parts are held together by four stainless steel cinch rods with springs.

The cathode plate is fabricated of copper with four silver-brazed ceramic feed thrus. Four filaments, each 2½ in. by ½ in., are formed from #80 mesh platinum-rhodium wire and inserted into the feed thru chucks in a square array. This arrangement gives increased filament surface area as well as protection against damage to the filaments by high energy backstreaming electrons seen through the anode aperture. The filaments are coated with a standard barium-strontium oxide emission mixture.[4]

The Freon-cooled aluminum top plate serves as the cooling flange for the cathode plate as well as the supporting flange for the cinch rod springs. A channel drilled through the side of this plate allows gas to be fed into the arc chamber. To this same channel is fitted a thermocouple tube to measure the vacuum within the arc chamber.

Visibility into the arc chamber is provided by a 0.65 in. Pyrex glass spacer between the top plate and the arc focus plate. The primary purpose of the spacer is to serve as the electrical insulator for the cathode, however, it has the secondary advantage of enabling one to observe the plasma, cathode dark space and filament condition.

The arc focus plate holds the arc focusing cone which acts as part of the magnetic circuit to constrain the plasma formed by the arc discharge. The structure of the arc focus plate is basically a flat steel flange. The outer edge has a short, thick cylindrical extension which provides a low reluctance return path through the anode. A small air gap prevents electrical contact with the anode. The arc focusing cone can be readily removed from the main plate to accommodate geometry changes or adjustment of the cone to anode spacing. Freon is circulated through the flat flange section to cool the plate.

Available space between the arc focusing cone and the anode is filled with an X-ray shield. This high density, nonmagnetic insert[5] absorbs damaging X-rays produced by high energy backstreaming electrons that bombard the anode insert.

A short-path magnetic circuit is achieved by designing the magnet coil as a flat, multi-layered pancake winding enclosed in an aluminum housing. The location of the coil between the arc focus plate and anode minimizes stray fields and loss of field strength due to parallel elements in the magnetic path. One side of the coil housing is coated with an epoxy layer to insulate the housing from the anode. The other side is in electrical contact with the grid. The coil housing forms the vacuum seal between the anode and arc focus plates.

The anode is a flat, Freon-cooled, steel flange. The projecting lip on the plasma side shields the epoxy layer of the coil assembly from the radiant heat of the arc. The projecting lip on the beam side provides accurate alignment with the extractor-lens section. The central region of the anode is machined to accept a tungsten alloy[5] aperture button drilled to an orifice size of 0.008 in.. The button is held in place by a conical retaining ring. The channel of the arc focusing cone and the anode orifice are aligned accurately by a centering jig inserted in the anode in place of the aperture button. After the inner set of stainless steel cinch rods are tightened down the jig is removed and the aperture button and retaining cone are replaced.

## Extractor-Lens Section

The extractor is designed as a simple cylindrical electrode with a 1.9 in. internal diameter. The end facing the anode is rounded to inhibit sparking. The electrode is easily removed for modifications.

The lens electrode is also cylindrical with a 2.6 in. internal diameter.

The extractor-lens assembly is equipped with heavy cylindrical shields of a tungsten alloy[5] which fits outside the extractor and lens electrode. These shields perform two necessary functions: (1) absorption of X-rays caused by backstreaming electrons and, (2) shielding of the glass spacers against bombardment by scattered electrons and ions. Without these shields, the glass would become electrostatically charged, leading to beam instabilities or glass fractures. Without the X-ray absorption feature the performance of the accelerator would be limited because of the effects of ionization of the insulating gas and radiation damage to components in the high voltage terminal. X-ray absorption is also important in exposed low voltage apparatus to reduce radiation hazards to personnel.

The complete assembly is cemented together using a soft, low resistivity epoxy resin. The coaxial alignment of the various parts is guaranteed by means of an accurate assembly jig. Alignment lips or grooves are provided on the end flanges to give automatic alignment of the extractor-lens assembly with the source and with the acceleration tube. Cooling tubes are soldered to the outside edges of the flanges to extract the heat generated by ion and electron bombardment.

## Open Cylindrical Extractor Design

The traditional Pierce[6] extraction design consists of a conical anode and a narrow-nosed extractor. The extractor orifice is typically about 0.125 in. in diameter and the spacing between the extractor tip and the ion source anode is also about 0.125 in.. This configuration establishes a strong extraction field but has undesirable practical limitations: (1) In a high voltage accelerator with high intensity ion beams the narrow extractor tip is subject to overheating and burnout by backstreaming electrons. (2) The coaxial alignment between the extractor tip and the source anode is extremely critical. A small lateral displacement off axis produces a large angular displacement of the extracted ion beam, which is intolerable in a long, high voltage accelerator. (3) The small extractor orifice impedes the flow of neutral gas from the ion source to the high vacuum pump. The low energy ions in the extraction region are easily scattered by the residual neutral gas causing an undesirable increase in the beam emittance. These scattered particles bombard the extractor and cause secondary electron loading of the extractor power supply. Poor vacuum in this region can also lead to uncontrolled discharges from the extractor tip to the anode.

The above limitations can be overcome by use of an open cylindrical extractor without adverse effects on the beam characteristics of emittance, emission, proton yield, or injection optics. This can be understood by considering the mechanism of beam extraction.

The separation of the positive ions from the plasma occurs at a well-defined boundary located between the extractor and the anode. This boundary is determined by a balance between the external electrostatic field and the internal plasma forces and is affected by the shapes of the anode surface and the extraction electrode. The location of the boundary is also dependent on the extraction voltage and the ion beam current. An increase in ion emission from the source (controlled by plasma parameters) will cause the boundary to expand toward the extractor electrode, whereas, an increase in extraction voltage will cause the boundary to recede. With the open extractor the extraction field is weak and the plasma boundary may expand up to 1/2 in. in diameter depending on the current and voltage. If the anode surface is irregular in the central region, the beam divergence will be variable and the beam emittance will be large. To achieve a low emittance beam the anode button and retaining cone are machined to form a continuous conical surface of large diameter, free from sharp corners.

In order to produce either a parallel or a focused beam at the target of an accelerator, it is necessary to inject a divergent beam into the accelerating tube. Then convergence is produced by the entrance lens effect of the tube. A properly divergent beam is provided by the large angle of the anode surface in combination with the open cylindrical extractor.

The new extraction geometry provides a simple and practical solution to the problems of ion beam extraction, focal adjustment and acceleration.

## Ion Emission

In Fig. 2, a plot of emission current as a function of extractor voltage for various plasma gun parameters is presented. The total current from the ion source was collected in a biased Faraday cage arrangement. It can be seen from these curves that for a given set of ion gun parameters the emission of the source attains a maximum value above a given extractor voltage. The rising portion of these curves is determined by space charge effects. To extract a mixed hydrogen ion current of 5 mA the extractor voltage must be at least 16 kV.

## Mass Analysis

With hydrogen gas in the source the ion beam consists primarily of three species: protons, diatomic and triatomic hydrogen molecules. The beam composition is analyzed magnetically with good resolution using small entrance and exit apertures. The data is presented in Fig. 3. The mass spectrum is primarily effected by arc and pressure parameters. Increasing the arc current results in a higher proton yield, and with a total beam of 5 mA, the proton yield is usually better than 50%. With a pulsed arc the proton yield rises to 80% at 10 mA peak beam current.

## Gas Conversion Efficiency

The conversion efficiency is usually defined[7] as the ratio of charged particles per second in the extracted beam to neutral gas input in particles per second. With the monatomic gases this definition is clear, but with more complex gases it can be ambiguous. We prefer to use the concept of mass flow rather than number of particles. The gas efficiency is then given by the formula:

$$E = \sum_{i=1}^{n} N_i M_i / N_o M_o$$

where $N_o$ and $M_o$ are respectively the number of molecules per second and molecular weight of the neutral gas and $N_i$ and $M_i$ are, respectively, the number of ions per second and the molecular weight of each species of ion in the beam.

For hydrogen gas this formula reduces to:

$$E = (1N_1 + 2N_2 + 3N_3)/2N_o$$

Using typical operating parameters of 5.0 mA beam, 1.8 A arc current, 1.3 A magnet current, 325 microns indicated source pressure, 5.0 atm-cc/hr. flow rate (from Fig. 4), 50% protons, 30% diatomic ions and 20% triatomic ions, the gas (mass) efficiency is computed to be 70%.

## Emittance Measurements

Emittance measurements were performed on the beam from a 3.0 MV Dynamitron accelerator using a copper plate machined with a line of ten 0.1 cm. holes drilled on the horizontal and vertical axes. This plate was placed in a position normal to the direction of the accelerated beam. The beams of ions passing through this plate produced burn spots on a copper flange positioned 91 cm. from the plate.

With an optical comparator the dimensions of the burn marks were compared with the dimensions of the drilled holes. The phase space diagram resulting from these measurements is shown in Fig. 5.

The area of the ellipse gives an emittance of approximately 3.0 mrad.-cm. for a beam energy of 1.0 MeV and a total beam current of 0.9 mA composed of mixed hydrogen ions.

## References

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(4) R.C.A. #33-C-118 Cathode spraying solution, R.C.A. Tube Division, New York, New York.

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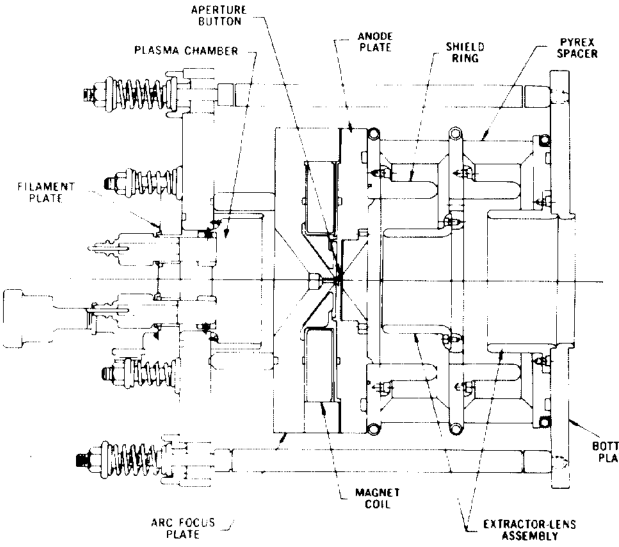

Fig. 1. Dynamag Ion Source.

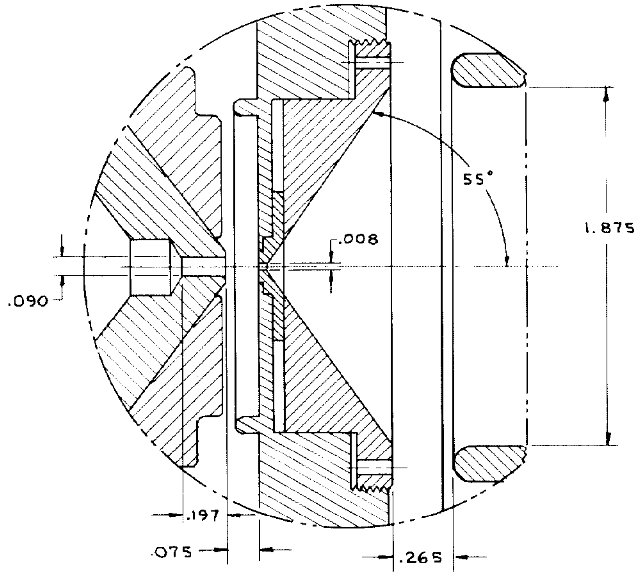

Fig. 1a. Exploded View of Dynamag Extraction Geometry.

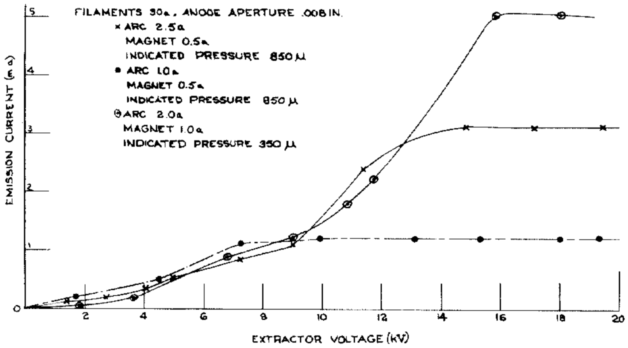

Fig. 2. Emission Current as a Function of Extractor Voltage.

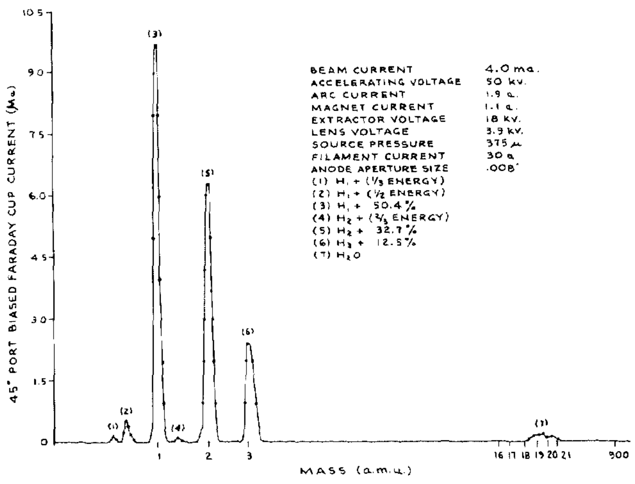

Fig. 3. Hydrogen Mass Analysis.

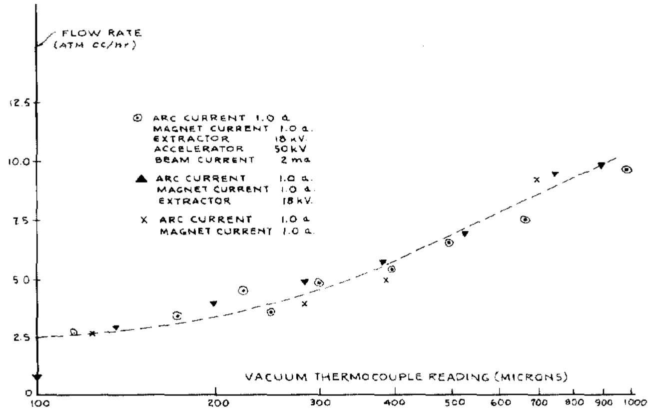

Fig. 4. Hydrogen Gas Flow Rate Through .008 in. Aperture As A Function of Indicated Source Pressure.

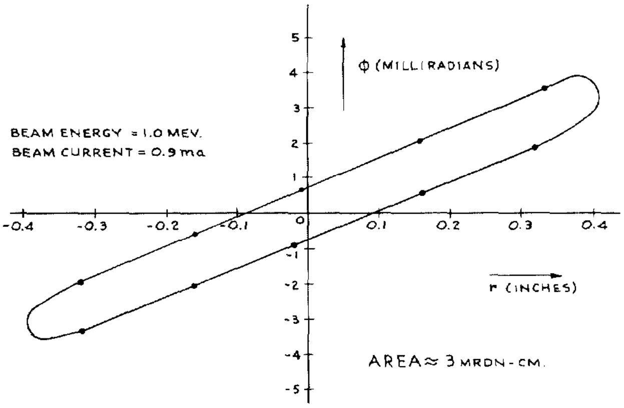

Fig. 5. 3.0 MV Dynamitron Phase Space Diagram.