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Ion Sources for Heavy Ion Fusion

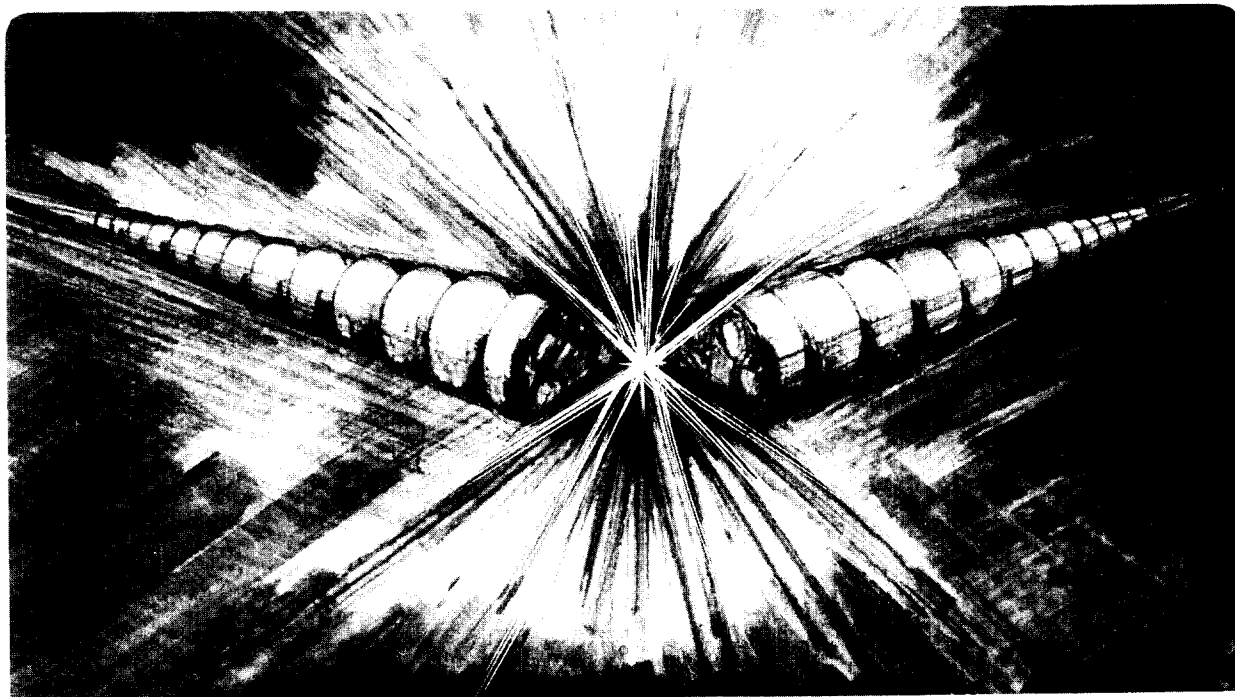
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ION SOURCES FOR HEAVY ION FUSION

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Abstract

The development of ion sources for heavy ion fusion will be reported with particular emphasis on a recently built 2 MV injector. The new injector is based on an electrostatic quadrupole configuration, and has produced pulsed K^+ ions of 950 mA peak from a 6.7" curved alumino silicate source. The ion beam has reached 2.3 MV with an energy flatness of $\pm 0.2\%$ over $1 \mu s$. The measured normalized edge emittance of less than 1π mm-mr is close to the source temperature limit. The design, construction, performance, and comparisons with three-dimensional particle-in-cell simulations will be described.

I. Introduction

The goal of inertial confinement fusion with heavy ion drivers is to deliver several megajoules of heavy ions at 5 to 10 GeV onto a target several mm in spot-size to initiate thermal implosion. The induction linac approach to the heavy ion accelerator, pursued over the past two decades in the U.S. is based on a multiple-beam scenario, where a number of high current ion beams, several tens of microseconds in length, are produced, accelerated, longitudinally compressed, and possibly combined, and eventually focused onto the target at a pulse length of the order of ten nanoseconds. The ILSE (Induction Linac Scaled Experiments) project [1]

has been proposed as a 10 MeV 4-beam prototype that will test all key physics and engineering issues in a fusion driver, and Elise, the first 5 MeV of ILSE has been approved. Physics and engineering designs are progressing in earnest. The front-end of Elise is a one-beam injector which has been built and operated for nearly two years [2]. The present paper covers the development of ion sources within the context of ILSE/Elise, with emphasis on the 2 MeV injector.

II. Ion Source Requirement for HIF

Although ILSE and Elise are low energy machines, to provide meaningful tests for the full driver, it was determined from the outset that the energy, current, and emittance of the injector should be the same as the full-scale machine. Thus, the energy required was set at 2 MeV, the line charge density at $0.25 \mu\text{C}/\text{m}$ (which translates to 790 mA of singly charged potassium ions), and a normalized edge emittance of less than $1 \pi \text{ mm}\cdot\text{mr}$. The ILSE injector was to have a pulse length of about $1 \mu\text{sec}$, which is much shorter than the full-scale driver, and was a compromise reached for cost reasons. Nevertheless, as a driver demonstration, it is essential to show that the desired parameters can be attained over the entire microsecond pulse, and that the head-to-tail variation be minimal. Furthermore, the source must have long lifetime as required for a fusion power plant.

When the source development for ILSE started several years ago, several approaches, including plasma and vapor sources, were pursued in parallel. Hot plate alkali ion sources were found to satisfy the ILSE requirements [3] and potassium and cesium alumino-silicate sources have been fabricated and deployed in the 2 MeV injector as well as several other smaller machines at LBNL and LLNL.

From the point of view of minimizing emittance, it would be advantages to have small, high-density sources. However, the simultaneous requirements of high

energy and high current make the high voltage engineering a technical challenge, and a conservative approach would be to start with relatively low accelerating gradients. This in turn implies low current density and therefore, large sources. Earlier tests with 1" sources have demonstrated current densities of nearly 20 mA/cm², good emission uniformity and long life. The fabrication of large current sources was an additional effort which we undertook in conjunction with the injector development.

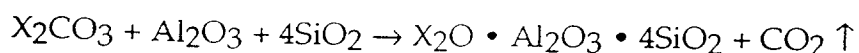
III. Fabrication of Large Thermonic Ion Emitters

We describe a procedure for producing high quality alkali atom ion emitters for use in space charge limited ion guns - the emitter consisting of a sintered tungsten disk coated with an alkali-atom aluminosilicate.

As a first step, sintered tungsten (~80% density) is machined to a specified size and shape as prescribed by the ion gun diode geometry and ion optics. After machining, the surface is restored to its original porosity (~20%) by chemical or electrolytic etching. This is followed by a chemical neutralizing procedure and prolonged rinsing in distilled water.

Prior to coating, the emitter plate is then thoroughly vacuum de-gassed in a vacuum furnace, gradually raising the temperature to 1200°C to 1500°C and holding until the pressure is stabilized. After cooling and removal from the furnace the emitter plate is kept clean and dry until coated.

The aluminosilicate emitter material is prepared by following a procedure utilized by R.K. Feeney et al. [4] Utilizing the highest purity chemical compounds readily available, we mix stoichiometric quantities of the constituent compounds according to the assumed reaction,



where X is the desired alkali atom (Potassium is the relevant atom in this present case.) After thorough mechanical mixing, the material is placed in a high alumina crucible and fired at 1200°C - 1500°C in a resistance heated air-atmosphere furnace. After the evolution of carbon dioxide generated during the reaction ceases, the crucible is slowly cooled. The aluminosilicate is most easily removed by breaking the crucible and chipping away the aluminosilicate. This material is then ground in a mortar until it will pass through a 200 mesh sieve. (A small portion is further ground to pass through a 400 mesh sieve.)

The coating is carried out by making a slurry of the powder and deionized water and building up the surface to the desired thickness by repeated brushing. The <400 mesh material is applied first in order to provide better surface penetration. An adequate amount must be applied to allow for a final surfacing.

After a partial drying period the emitter plate is mounted in a lathe chuck and scraped to a final surface contour (either spherically concave or flat), as required of uniform thickness. The initial drying phase is then completed at low temperature (40°C - 100°C) for approximately 24 hours. (A rapid drying cycle will generate surface cracks.)

The final step in the process is to install the emitter plate in a vacuum furnace with a reference thermocouple in contact with the outer edge of the emitter plate. The temperature is gradually raised to 1550°C - 1575°C and held for a one hour period. It is then cooled to ambient temperature.

IV. Beam Extraction

The 2 MeV injector consists of two parts, an axisymmetric diode front-end that extracts and accelerates the ion beam to 750 keV and an electrostatic quadrupole (ESQ) section which consists of four quadrupoles arranged to provide strong focusing and at the same time accelerate the ion beam to 2 MeV. (See Figure 1.)

FIGURE 1

The diode as well as the ESQ section are powered by a 2 MeV Marx designed and constructed to provide a 4 μ s flat-top. This relatively long flat-top guarantees that the ion energy is constant during the 1 μ s pulse extraction time as well as the subsequent 2 μ s when the ion beam traverses the long ESQ column.

Extraction is provided by a separate pulser. (See Figure 2.) Our design was motivated by the desire to have an energy and current flat-top without the introduction of a grid (with its associated reliability and emittance spoilage issues). Prior to beam extraction, the source assembly is set to -80 kV relative to an extraction electrode which is at Marx voltage. The negative surface field from the DC bias inhibits ion emission even while the positive Marx voltage is being turned on. Beam extraction is initiated by a +160 kV pulser which floats on top of the negative DC bias at the source assembly. This new pulser consists of a 5:1 voltage step-up transformer with a tunable inductance to generate a 1 μ s flat-top. The pulser was a compact design made to fit into the limited space of a high-voltage "dome." The primary function of the extraction electrode is to provide a "gridless grid," but is also carefully shaped to optimize the beam optics.

FIGURE 2

V. Beam Optics Design

Our design goal for normalized beam edge emittance was 1π mm-mr. The emittance at source (0.1 eV) is 0.3π mm-mr. Very little emittance growth can be allowed as the beam traverses the diode and ESQ column. Thus, careful design with EGUN was performed to ensure minimal emittance growth in the diode ($< 0.5 \pi$ mm-mr), and a 3-D particle-in-cell code, WARP3D, was used to optimize beam optics through the ESQ column [5]. The final emittance at exit is somewhat current dependent, but is as low as 0.6π mm-mr, and is less than 1π mm-mr over a broad parameter range around the design point.

VI. High Voltage Engineering

Reliable injector performance requires great care in the engineering of all components within as well as around the ceramic column. The alumina column consists of brazed structures with 1 1/2" rings separated by thin niobium rings in the diode section, and 3" rings in the (lower gradient) ESQ sections. Thick stainless steel and copper shields on the vacuum side of the column were carefully shaped to block unwanted X-rays and secondary electrons. The shields together with all the electrodes were computer-designed to have no more than 60 kV/cm surface fields (with the exception of the extraction electrode tips in the diode where the field is as high as 80 kV/cm). Outside the column, we have 80 psi of SF₆ and the column is protected with guard rings and metal-oxide-varistors.

VII. Injector Performance

The injector produced 800 mA at 2.15 MeV on the first day of operation. It has subsequently been tested at 950 mA and 2.3 MeV with no signs of having reached its ultimate limit of performance. The normalized edge emittance has been measured to be less than 1π mm-mr over a broad range of voltages and currents. The energy flatness can be tuned to $\pm 0.15\%$ over a 1 μ s flat-top and the current, beam envelope,

and centroid displacement are very uniform over the beam body. (See figures 3, 4, & 5.)

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

VIII. High Charge-State Ion Source Development

All the HIF ion source development up to this point has been focused on singly charged ions. Multiply charged ion sources (+2, +3) may have long-term economic advantages for a fusion-driver power plant. A high charge state injector system proposed by one of the authors (Eylon) [6] consists of a neutral gas "beam stripper" followed by a high charge state beam separator. (Figure 7) Preliminary experiments indicate that a substantial fraction of the singly charged ions are converted to +2 and +3 species by passing the ion beam through a 2 cm thick beam stripper with 100 mT of He. 3-D particle-in-cell simulations show that a full-current beam with mixed ionic species can be passed through an electrostatic dipole separator consisting of two parallel plates along the beam line, beyond the stripper, and the resultant +2 and +3 beams can be totally separated from the +1 ions, each experiencing negligible emittance growth.

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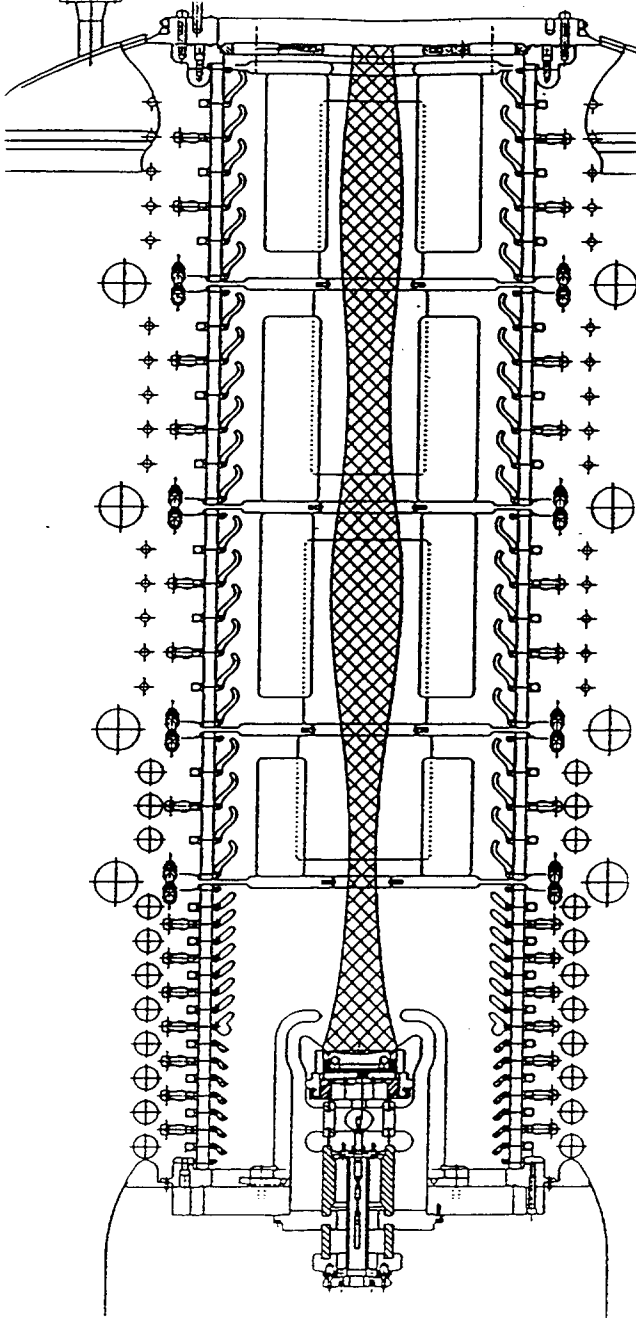


Figure 1. ESQ Injector

Author: Yu
Figure 2

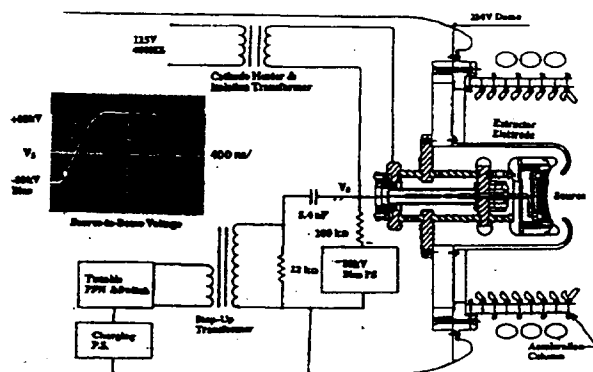
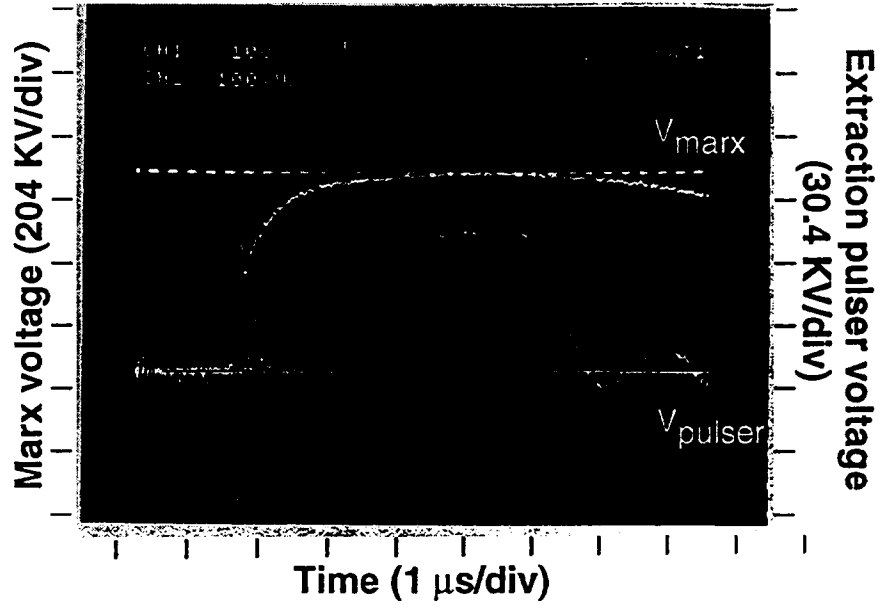


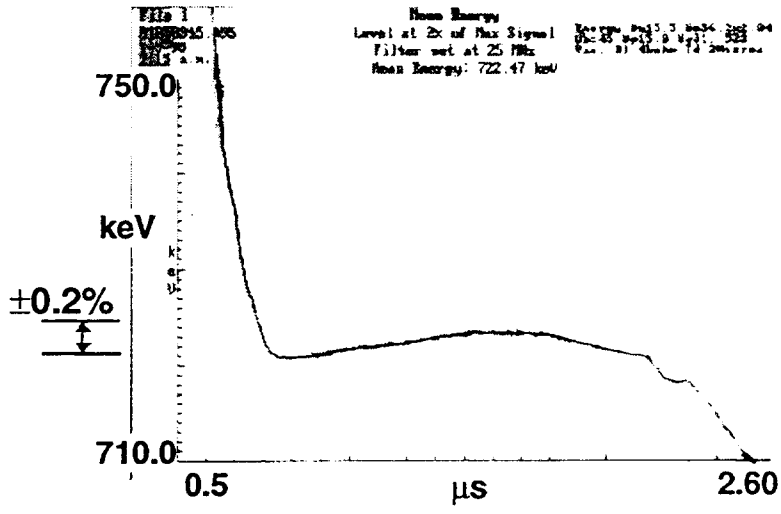
Figure 2. Ion source and beam extraction pulser

Marx & gate voltage



Author: Yu
Figure 4

average beam energy



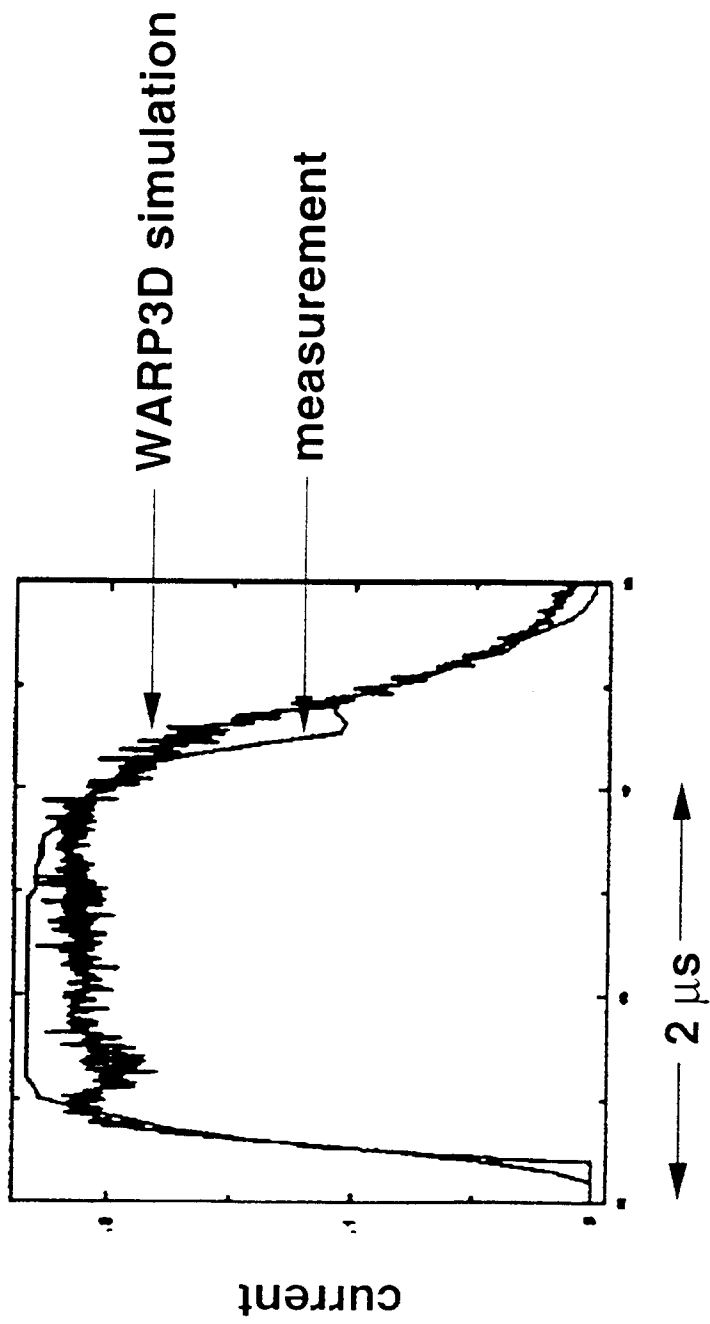


Figure 5. Beam current (measured & simulated)

Proposed high charge state beam schematics

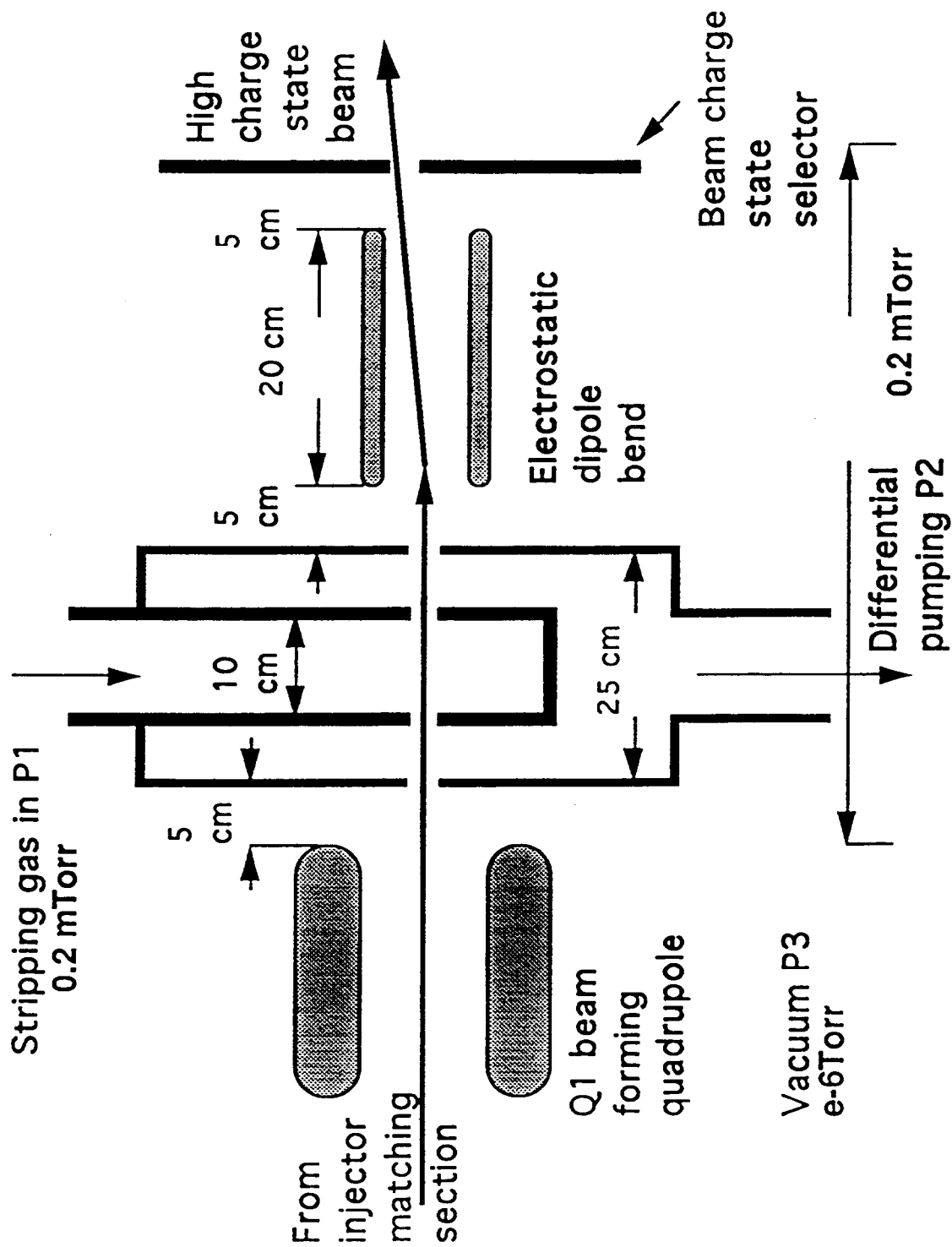


Figure 7

