PERFORMANCE OPTIMIZATION OF A CUSP-FIELD ION SOURCE
AND HIGH-PERVEANCE EXTRACTOR*

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Summary

The injector for the Fusion Materials Irradiation
Test (FMIT) Facility must deliver a 110-mA dc beam of
deuterons or H_2^+ ions to the radio-frequency quad-
rupole (RFQ) accelerator at 75-keV energy. Operational
parameters of a hydrogen-fed cusp-field ion source and
a high-perveance extractor have been evaluated on a
test stand and on the recently completed first stage
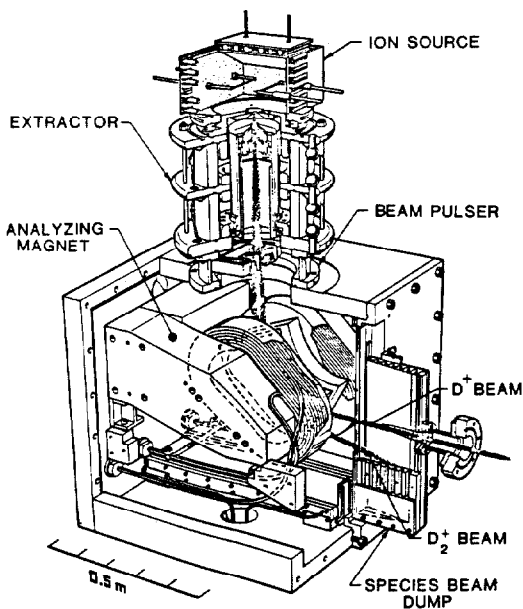of the prototype injector (Fig. 1).

Fig. 1. First stage of the prototype injector.

Introduction

The injection-energy requirement for the RFQ
accelerator was reduced from 100 keV to 75 keV to sub-
stantially reduce its length. Because the beam-current
requirement was not changed, this reduced voltage re-
quired an extractor of even higher perveance.
Electron-equivalent perveance is defined here as:

$$P = \sqrt{\frac{M_e}{e}} \frac{I}{V^{3/2}}$$ where M_e = effective ion mass
relative to electron mass

e = number of electron charges/beam particle

I = current in amperes

V = particle energy in electron volts

The perveance of a 75-keV, 250-mA deuterium beam with a
typical effective ion mass of 3 x 1836 is 0.90 x 10^{-6}
amp/volt$^{3/2}$. This new requirement, as well as the poor
beam quality obtained when scaling up the current
achieved with an earlier version, necessitated a
change in design.

All our previous extractor designs were based on
a planar-Pierce geometry, with a 60% empirical correc-
tion factor applied to the Child-Langmuir space-charge
limit.[1,2] Electrodes designed by this technique[2]
worked very well at 100 kV for apertures of 1 cm² and
current densities of 100 mA/cm². However, poor
quality beam resulted when we tried to double the
current, either by doubling the current density or
doubling the area. The limiting factor seemed to be
the severe aberration in the highly divergent exit
lens of the ground electrode.

Several designs were considered including an
accel-decel system and multiaperture electrodes with
subsequent convergence of the individual beamlets.
The simplest method considered and subsequently
adopted was a single-aperture, single-gap design that
produced a spherically convergent beam. The larger
area at the ion source plasma surface allows for low-
emission current density. Beam convergence permits
use of a small aperture at the ground electrode and
provides compensation for normal beam divergence. The
decision to switch to a spherically convergent Pierce
geometry was strengthened by Brewer's[3] report of
success on high-perveance electron guns.

We made a series of computations to determine
suitable electrode shapes to extract 240 mA of real
current at 75 keV. Details of the spherical extrac-
tion design process will be described in a subsequent
paper. Very simply, the method is that of determin-
ing the proper potential distribution along the beam
edge and solving for the equipotential (electrode)
shapes that can support the proper beam-edge potential
distribution. A series expansion solving Laplace's
equation using the spherical coordinates r and θ and
Legendre polynomials given by

$$V(r,\theta) = \sum_{n=1}^{\infty} \left[A_n r^n + B_n r^{-(n+1)} \right] P_n(\cos\theta) ,$$

is used to fit the beam-edge potential. A similar
technique was suggested by Mueller.[4]

Ion Source

The cusp-field ion source (Fig. 1) is a nearly
cubical chamber (18 cm per side) with room for five
rows of magnets along the sides and two square rings
of magnets on the top plate. The source is cooled by
water lines between the magnets and in the axial
region on top. Two ac-heated filaments are used made
of tightly wrapped 0.1-mm nickel gauze over a 1.0-mm
tantatum wire and coated with a barium-strontium
oxide.

Source efficiency tests were conducted varying
the number of magnets on the sides, with and without
flux return plates, and with single or double magnets.
A two-dimensional analysis of the magnetic field in a
cusp-field ion source, and the effect of this field
on the ion motion in the plasma was developed. The
analysis is based on an approach suggested by
K. Halbach.[5] The resultant equation relates the
loss area for the ions and electrons to all the
geometrical parameters that need to be considered in
designing a cusp-field source. A few geometries have
been calculated and compared to measurements of the
performance of the ion source. The results can be

summarized as follows. A source designed to have a long confinement time for the primary electrons that do most of the ionizing is characterized by high gas efficiency but has a rather poor H$^+$ species ratio. The poor species ratio is attributed to the fact that under these conditions, the thermal electrons that do most of the dissociation of the gas are confined to less than one-half the source volume; thus, the abundance of molecular gas increases the production of triatomic ions as was observed. Reducing the confinement time for the primary electrons and increasing the active volume for the thermal electrons by increasing the spacing between fewer magnets yielded a modest increase in the species ratio for the monoatomic and diatomic ions and reduced the gas efficiency as calculated. These tests proved that changing the magnet configuration can significantly alter the gas efficiency, power efficiency, and species ratio. This program of ion source optimization is continuing.

75-kV Extractor

The 75-kV single-gap extractor (Fig. 1) was originally designed for 100-kV operation and is described in a previous paper.[2] Only the electrode gap and electrode contours shown in Fig. 2 were changed when the requirement for injection into the RFQ was reduced to 75 keV. Voltage grading is provided by an adjacent water-resistive divider using the 4 megohm-cm deionized water that also is used to cool the ion source.
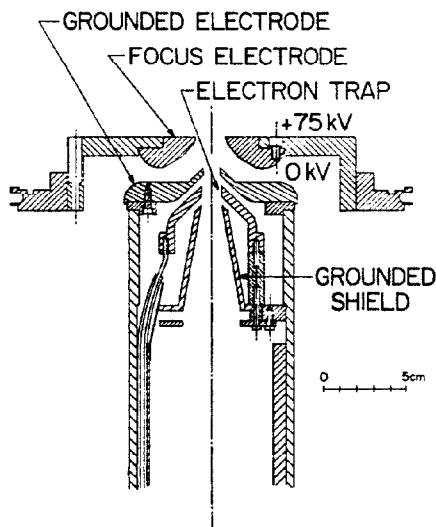

Fig. 2. Electrode geometry of the high perveance 75-kV extractor with spherically convergent beam.

The focus electrode at +75 kV is made of OFHC copper with a 1.95-cm-diam aperture, and the grounded molybdenum electrode has a 1.0-cm-diam aperture. There is a 1.84-cm spacing between apertures. The stainless steel electron trap, normally biased at -2 kV, is spaced 0.20 cm from both the grounded molybdenum electrode and the grounded stainless steel shield that is used to minimize electrical field penetration into the region below. The electron trap lead, insulated by a pyrex tube, passes between the ground electrode support tube and a heavy walled copper sleeve. The latter shields the lead from beam

impingement and the beam from the electric field of the lead that would reduce space-charge neutralization in this region. It is imperative that the electron trap be suitably biased at all times to prevent serious damage to the ion source or focus electrode. On one occasion when the electron trap lead shorted to ground, back-streaming electrons quickly melted a hole through the top of the copper ion source.

Vacuum System

Nearly all of the 0.1 torr ℓ/s hydrogen gas load from the ion source is pumped by a 10 000 ℓ/s oil diffusion pump backed by a 47-ℓ/s two-stage Roots blower and mechanical pump. No oil-contamination problems have been observed on any of the high-voltage insulators in 27 months of operation. Precautions against contamination from the diffusion pump include use of a Freon-refrigerated trap, low vapor pressure polyphenyl ether pumping fluid, and a fast-acting pressure-actuated valve on the foreline. The entire vacuum system, including automatic sequencing, is controlled by an industrial programmable controller.

Test Results

Species-ratio measurements are made by bending the beam with a double-focusing analyzing magnet and calorimetrically measuring the beam current at various locations. A pepper-pot device is available for measuring beam emittance after species separation. However, beam-quality measurements made at that point were dominated by aberrations from the bending magnet. A new bending magnet is now in use and improved pole faces are being designed. An overall hydrogen gas efficiency of 20% to 25% is typical.

One of the requirements for the FMIT ion source was that of having a source that could effectively produce both the monoatomic and diatomic species of a hydrogen isotope. The cusp source has proven to be reasonably adept at this, capable of optimizing on either H$^+$ or H$_2^+$ ions with less than 10% H$_3^+$ production.

The cusp-field source was operated briefly with deuterium rather than hydrogen as the feed gas. This test was run to verify that the source would run stably with deterium and to quantify the neutron production rate. Neutrons (2.4 MeV) are produced by the D-D fusion between incident ions and deuterium atoms embedded in the copper beam dumps. The source operation was quite stable, with an observed species ratio of 54%, 31%, and 15% of D$^+$, D$_2^+$ and D$_3^+$ respectively. The observed neutron production rate agreed within 15% with the formula reported by Kim, et al.[6]

$$F = 640 \ IV^{2.32}$$

with I in mA
V in keV
F in neutrons/second .

The results of operation with the new spherical extractor have been extremely satisfying. More than 240 mA of beam current can be extracted at 75 keV. After a 110-cm drift length (no focusing), the visible beam diverged to only 2.3 cm in diameter. The calorimetrically measured current at this position represents about 92% of the total drain from the high-voltage power supply. This small degree of divergence would indicate an effective space-charge neutralization of greater than 99.5% and a normalized emittance no greater than 0.03 π mrad-cm.

References

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