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TRANSPORT AND ACCELERATION OF HIGH CURRENT URANIUM ION BEAMS

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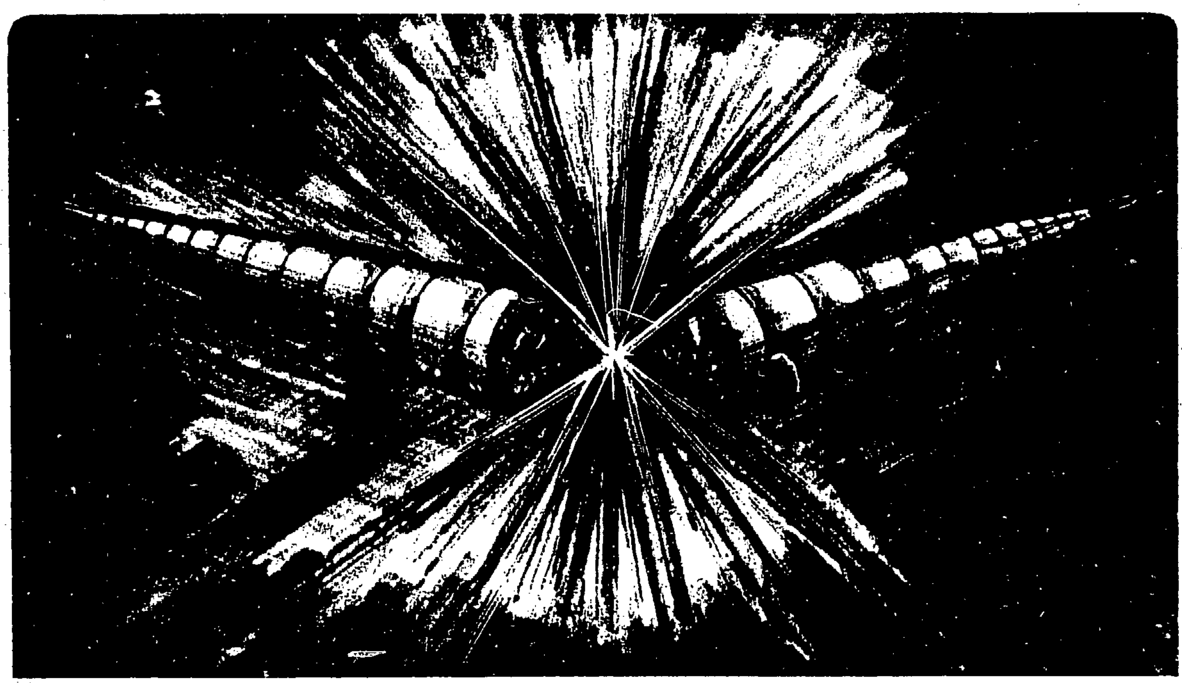

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ABSTRACT

Measurements have been made of the transport of beams produced by the high current ion source, MEVVA, and of the injection of these beams into the GSI heavy ion RFQ linac. This configuration has provided initial tests of the MEVVA ion source in an injector environment, and of the RFQ with uranium as the accelerated species. Beam currents of 78 mA of titanium and 19 mA of uranium, at an extraction voltage of 40 kV, have been transported through a 4.7 m long beam transport channel, and up to 40 mA of uranium has been transported through a single-gap accelerating column at a voltage of about 150 kV. A current of up to 5 mA of U^{3+} has been measured at the exit detector of the RFQ.

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1. INTRODUCTION

A new kind of ion source has been developed recently (1-3), with which high current beams of metal ions have been produced. This source, called the MEVVA ion source (MEtal Vapor Vacuum Arc), was developed at Lawrence Berkeley Laboratory as part of a continuing program to upgrade the heavy ion accelerator facilities at LBL. A beam current of over 1 Ampere has been extracted from this source. Simultaneously, a very heavy ion RFQ (Radio Frequency Quadrupole) accelerator (4-8) is being developed at GSI Darmstadt as an injector for the heavy ion synchrotron facility, SIS (9,10). A goal of this RFQ injector, called MAXILAC, is to provide accelerated high current beams of ions up to and including uranium.

We have operated the MEVVA ion source on the GSI facilities, including a high current beam line test-stand and the RFQ accelerator. Measurements have been made of the beam current, emittance and charge state spectrum. The source was used to provide a uranium beam for the RFQ, thus offering a test of the MEVVA source in an accelerator environment, and at the same time of the RFQ with a high current uranium ion beam. We report here on some initial results of this study.

2. EXPERIMENTAL SET UP

The MEVVA ion source (Figure 1) has been described elsewhere (1-3). Briefly, in this source an arc discharge between two electrodes in vacuum is used to create an intense plasma from the material of which the cathode is made. The plasma originates at the 'cathode spots' - minute regions of intense current concentration which form on the surface of the cathode. The quasi-neutral plasma plumes away from the cathode and toward the anode. A central hole in the anode allows a part of the plasma to stream through the hole and into the post-anode region toward a set of multi-aperture extractor grids. The source has been operated with a variety of cathode materials, including Li, Al, Si, Ti, Fe, Co, Ni, Nb, La, Ta, Au, Pb and U, among others. The maximum beam current measured to-date is 1.1 Amperes, at an extraction voltage of 25 kV. The normalized beam emittance lies in the range 0.02 to 0.07 π cm mrad, depending on the operating conditions. For the work reported on here, beam pulse lengths of about 250 microseconds and 1.1 milliseconds were used,

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with a repetition rate of one to several pulses per second. Two different sets of extraction grids were used: (a) 163 holes, each of 1 mm diameter, contained within a circular aperture of 2 cm diameter, and (b) 7 holes, each of 3 mm diameter, contained within a circular aperture of 1.1 cm diameter. Each extractor set consisted of three similar grids, arranged electrically in an accel-decel configuration - ie, the middle grid was biased negative with respect to ground so as to act as an electron suppressor. The extraction gap was 3.8 mm.

A high current, very heavy ion, RFQ accelerator, MAXILAC, is being constructed at GSI. This device will serve as an injector for the UNILAC accelerator and the GSI heavy ion synchrotron SIS-18, and as a prototype for a heavy ion fusion driver accelerator. A complete description has been given previously (4-7). It is of a split-coaxial resonator design, operates at 13.5 MHz, and is to accelerate ions of mass-to-charge ratio A/Q up to 130. The first module, which is 1.5 m long and contains radial matching, bunch shaping and the first part of the gentle buncher, has already been tested using Ar^+, Kr^+ and Xe^+ beams (8). The input energy of 2.3 keV/amu was taken to an output energy of 4.3 keV/amu, and maximum transmitted beam currents of up to 10 mA Ar^+, 22mA Kr^+ and 10 mA Xe^+ were measured. A further two modules have since been added (of a final total of 12), and it is this combination of three RFQ modules that has been used in the work described here.

In the present work, the MEVVA ion source was installed firstly on a test beam line (11), for measurements of beam quality and charge-state distribution, and then in the high voltage terminal injecting into the RFQ. A schematic of the test beam line is shown in Figure 2. The line is 4.7 m in length and contains a quadrupole triplet and dipole analysis magnet, with current transformers and magnetically-suppressed Faraday cups to monitor the beam transport, and an emittance measuring device of the 'pepper-pot' variety (12).

In the RFQ configuration, shown in Figure 3, the ion source was housed within a $\leq$300 kV high voltage terminal. The beam was accelerated from the terminal through a single-gap accelerating column (13) and transported to the RFQ entrance through an 8 cm diameter beam line which contained a quadrupole singlet and quadrupole triplet; the quadrupole focusing thus provides a small degree of charge state selection. A negatively biased, electron suppressing ring electrode was located on the ground side of the column. We tried gap spacings of 15, 20 and 30 mm, and best results were obtained with the 15 mm gap; these are the results reported here. The source was positioned about 50 cm from the accelerating gap within the terminal, and the RFQ entrance was about 220 cm from the gap on the ground side.

3. *RESULTS*

A. High Current Test Bench.

On the test beam line, we ran the MEVVA ion source with cathodes of titanium and uranium (depleted uranium, >99.9% U238). For the case of titanium, and using the 163-hole extractor grids, we measured a beam current of approximately 200 mA into a 4.5 cm diameter Faraday cup located 40 cm from the source, at an extraction voltage of 40 kV. A current of 90 mA was measured at the second Faraday cup, of 3.0 cm diameter and located between the triplet and analysis magnets at a distance of z = 230 cm from the source. At the final Faraday cup, 4.5 cm diameter and located after the analysis magnet at a distance of 470 cm from the source, a total (charge-state integrated) beam current of 78 mA was measured, with currents of 18, 30, 12, 8 and 10 mA being in charge states Q = 1, 2, 3, 4 and 2/1 (charge exchanged 2 → 1), respectively. The current measured at the second cup appears to be anomalously low, but this is simply an artifact of the charge-state-sensitive focusing of the triplet; thus the beam current measured by the second cup is less than the total beam current in all charge states at this z location. It is important to note that quite apart from this impressively high current of transported metal ion beam, the charge state analysis recorded here provides general confirmation of the charge state spectra previously measured using a time-of-flight method (3), within the range of variation expected when operating the source under different conditions.

For uranium on the test beam line, up to 120 mA was measured at the first Faraday cup. The best transmission through the entire beam line, however, was obtained when we changed the ion source extractor grids from the 163-hole version to the 7-hole version, so as to provide a lower current output but better emittance from the source. At an extraction voltage of 38 kV we then measured a beam current of 50 mA at the first Faraday cup, 12 mA at the second Faraday cup, and a charge-state integrated beam current of 19 mA at the final, post-analysis cup; the charge-state distribution measured currents of 1.5, 5.5, 11, 1 mA in charge states Q = 2, 3, 4, 5, respectively. As for the titanium measurements above, the second cup current is artificially low because of the charge-state-sensitive focusing of the triplet. For these measurements, the ion source arc current was run at a low level so as to match the plasma density to the extractor geometry, thus providing a high quality (low emittance) beam; additional effects of the low arc current are (i) low beam current, and (ii) low average charge state.

The desirability of high ion source extractor voltage for efficient beam transport was clear. As an example, at 25 kV extraction voltage a charge-state-integrated current of 7 mA (3.5 mA of Q = 4+) was measured at the third Faraday cup, which increased to 19 mA (11 mA of Q = 4+) for 38 kV. At least two phenomena must play a part in this effect; at higher extraction voltage the MEVVA arc current must be increased so as to match the higher extraction field, thus increasing the density of the plasma from which the ions are to be extracted and the ion beam density; also, the higher beam velocity results in less beam blow-up due to imperfect space-charge neutralization and other defocusing causes.

The emittance of the beam, for several different operating conditions of the source, was measured using the pepper-pot diagnostic. For uranium the normalized emittance was determined to be from 0.015 to 0.03 π cm mrad. The emittance diagram obtained from such a measurement is shown in Figure 4.

B. Test Injector.

The ion source was installed within the injector, as described in Section 2, so as to provide a uranium ion beam input to the RFQ. For optimal transport of the beam through the accelerating column, it is important that the extractor voltage and terminal voltage be properly matched to the beam current, for that particular accelerating column geometry and gradient. Figure 5 shows data demonstrating this effect. Note that these data again underscore the importance of high extractor voltage to obtaining high usable beam current through the column. The emittance of the accelerated beam at the ground end of the column was measured, and an emittance diagram constructed from these data is shown in Figure 6. A distortion of the emittance ellipse due to aberrations in the column is evident. The normalized emittance corresponding to the outermost border, within which about 95% of the beam current resides, is 0.036 π cm mrad; however, the inner ellipse contains about 80% of the beam current, and the normalized emittance corresponding to this area is 0.015 π cm mrad. In the latter case the beam brightness is 1.4 A/(mm mrad)^2. These measurements were taken using the 7-hole extractor and the 1.1 millisecond long pulse line. An oscillogram of the uranium beam pulse measured by a Faraday cup at the ground side of the column is shown in Figure 7. The maximum uranium beam current that we measured at this point was 40 mA.

With the terminal parameters, beam line tuning and RFQ tuning adjusted for best overall transmission, we measured a beam current of 33 mA at the ground side of the terminal accelerating gap, a current of 12 mA at the RFQ entrance, and 5 mA at the RFQ exit. An oscillogram showing typical beam pulses measured by the beam current transformers at the RFQ entrance and exit is shown in Figure 8; for these RFQ measurements we used the 250 microsecond arc pulse line length. The tuning was such that the Q = 3 charge state was accelerated within the RFQ; the output energy is 20 keV/amu, for a total of 4.76 MeV per uranium ion. A graphic confirmation of the exit beam pulse energy was provided by a thin (0.05 mm) tantalum foil positioned on the inside of a vacuum window at the beam exit. The foil was seen to pulse, or throb, at the source repetition rate, due to both the thermal expansion of the foil by the beam energy and the momentum of the beam particles also. A calorimeter located at the RFQ exit provided a further quantitative confirmation of the beam pulse power. In these RFQ measurements, no charge state separation was provided by the input beam line, except that introduced by the focusing quadrupoles. Furthermore, the beam current was near the current limit of the column, and the ion source extraction parameters had not been adjusted for minimum emittance. That is, the input optics to the RFQ were less than optimum for these measurements. We thus expect that considerable improvement in performance will be seen when this work is resumed. (At the present time, an additional two modules are being added to the RFQ line).

C. General Beam Qualities.

The values quoted above have been measured many times each or, in the case of emittances, averaged over periods of about 10 minutes. The pulse-to-pulse repeatability of the source, however, is not yet completely satisfactory. Typically, the difference in total transported beam current between adjacent pulses amounts to about 20%, but sometimes an entire pulse may be missing, or a pulse attains its full value for a part of its length only. The time structures of pulses of different charge states are different also; a U^{5+} pulse, for example, starts with a pronounced peak and then settles down to a constant value, whereas U^{4+} (and lower charge state) pulses tend to rise slowly during the first quarter of their length up to a saturation value. Also, these features vary from pulse to pulse. Such difficulties may be due to variations in the microstructure of the source cathode, leading to different conditions for each arc discharge pulse.

4. CONCLUSION

The MEVVA ion source has been tested on a beam line whose characteristics are well known from previous work, thus providing a good check on the MEVVA beam. Currents of 200 mA of titanium and 120 mA of uranium were measured near the entrance to the beam line, and transport through a focusing quadrupole triplet and a dipole analysis magnet was effected. Charge integrated beam currents of 78 mA for titanium and 19 mA for uranium were measured for that configuration for which a lower emittance was also measured. Higher transported current was measured for higher beam extraction voltage.

The ion source was also located within a high voltage terminal and the beam accelerated through a single-gap column. Up to 40 mA of uranium beam was measured at the ground (exit) side of the column. The uranium beam was transported to and accelerated through the RFQ. The beam current at the exit of the 3-section RFQ structure was measured to be 5 mA. This consititutes the first observation of an RFQ-accelerated uranium ion beam.

The experiments reported here demonstrate that the MEVVA ion source is able to deliver high current, high brightness, metal ion beams with low duty factor to an RF accelerator. Further development is needed to achieve a repeatability standard similar to that of other established accelerator ion sources.

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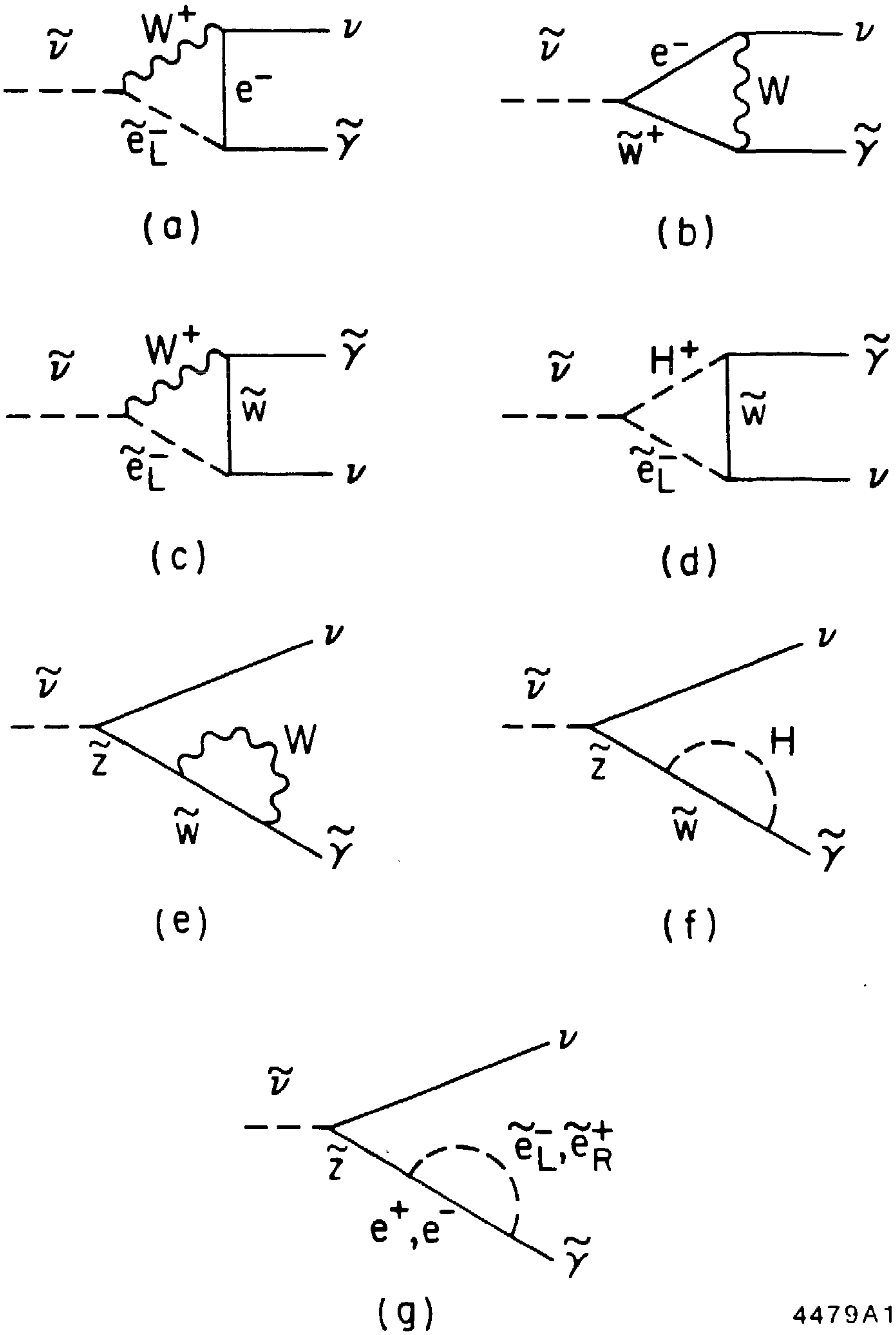

$\tilde{\nu}$
W^+
e^-
ν
$\tilde{e}_L^-$
$\tilde{\gamma}$
(a)
$\tilde{\nu}$
e^-
W
ν
$\tilde{w}^+$
$\tilde{\gamma}$
(b)
$\tilde{\nu}$
W^+
$\tilde{w}$
$\tilde{\gamma}$
$\tilde{e}_L^-$
ν
(c)
$\tilde{\nu}$
H^+
$\tilde{w}$
$\tilde{\gamma}$
$\tilde{e}_L^-$
ν
(d)
$\tilde{\nu}$
ν
$\tilde{z}$
W
$\tilde{w}$
$\tilde{\gamma}$
(e)
$\tilde{\nu}$
ν
$\tilde{z}$
H
$\tilde{w}$
$\tilde{\gamma}$
(f)
$\tilde{\nu}$
ν
$\tilde{z}$
$\tilde{e}_L^-, \tilde{e}_R^+$
e^+, e^-
$\tilde{\gamma}$
(g)
4479A1

FIG 14

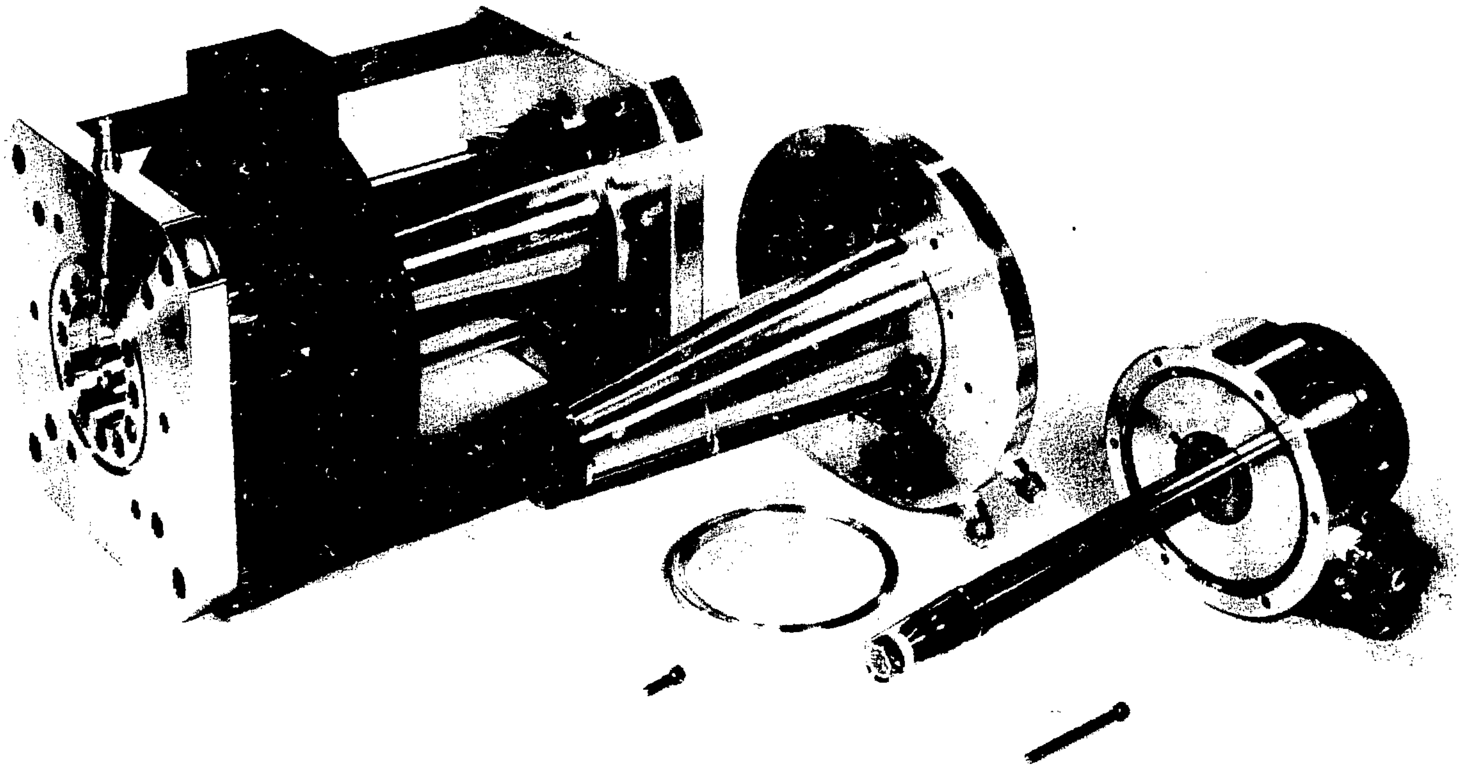

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Fig. 1 Photograph of the MEVVA IIb ion source.

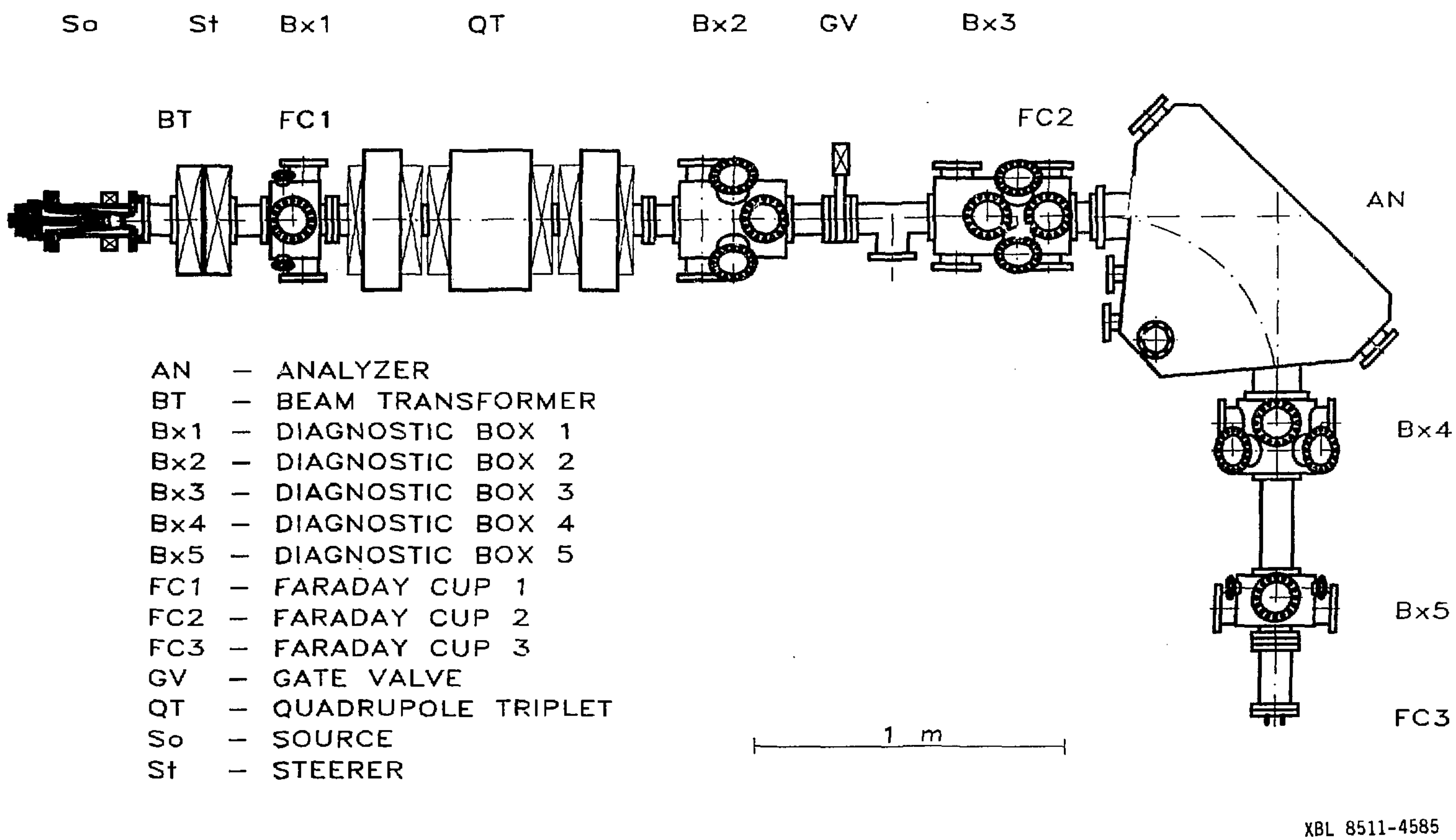

Fig. 2 Schematic of the high current beam line test-stand.

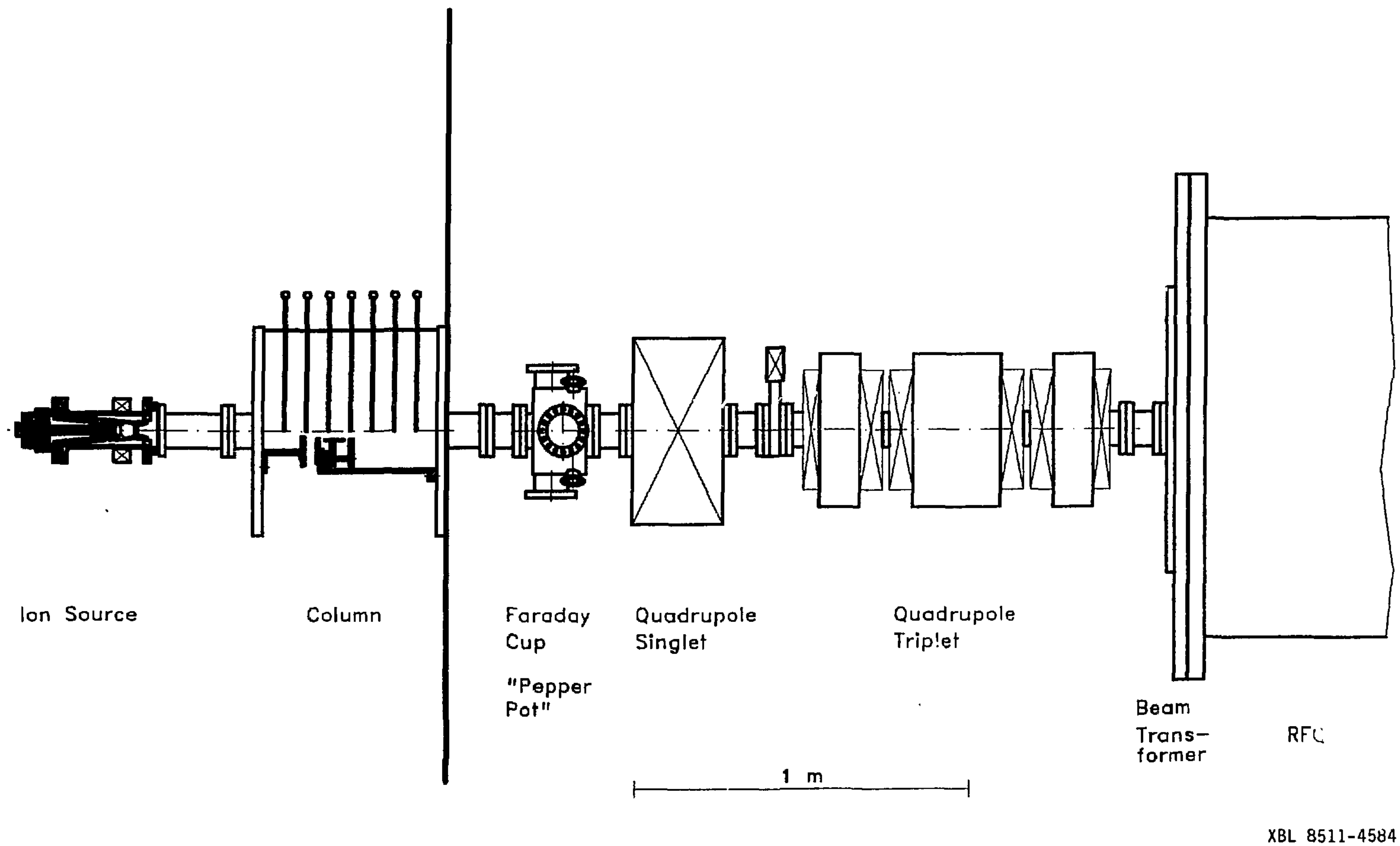

Fig. 3 Schematic of the high voltage terminal, beam line and RFQ.

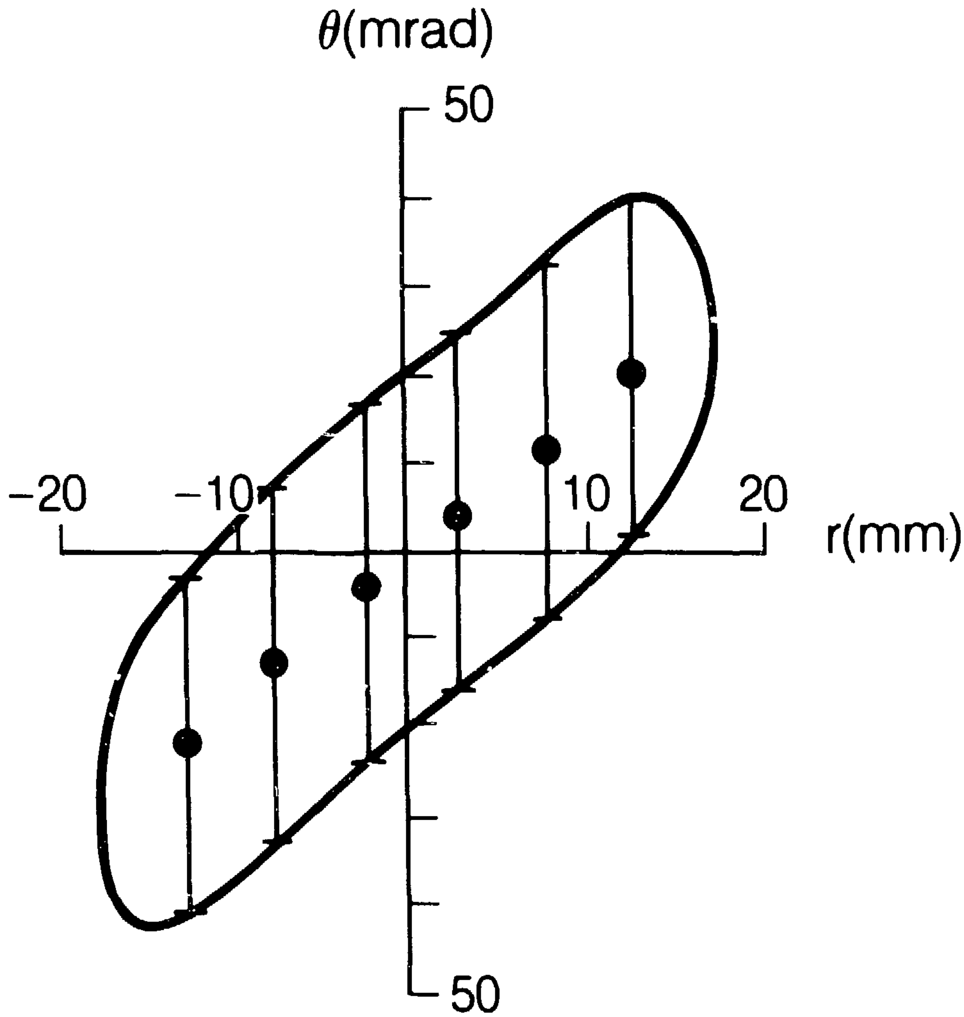

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Fig. 4. Emittance diagram for a uranium beam, as measured using the 'pepper-pot' diagnostic on the high current beam line test stand at a location z = 40 cm. from the extractor. The emittance is 200 π mm mrad, or a normalized emittance of 0.028 π cm mrad. Extraction voltage 25 kV; 163-hole extractor grids; beam current 80 mA.

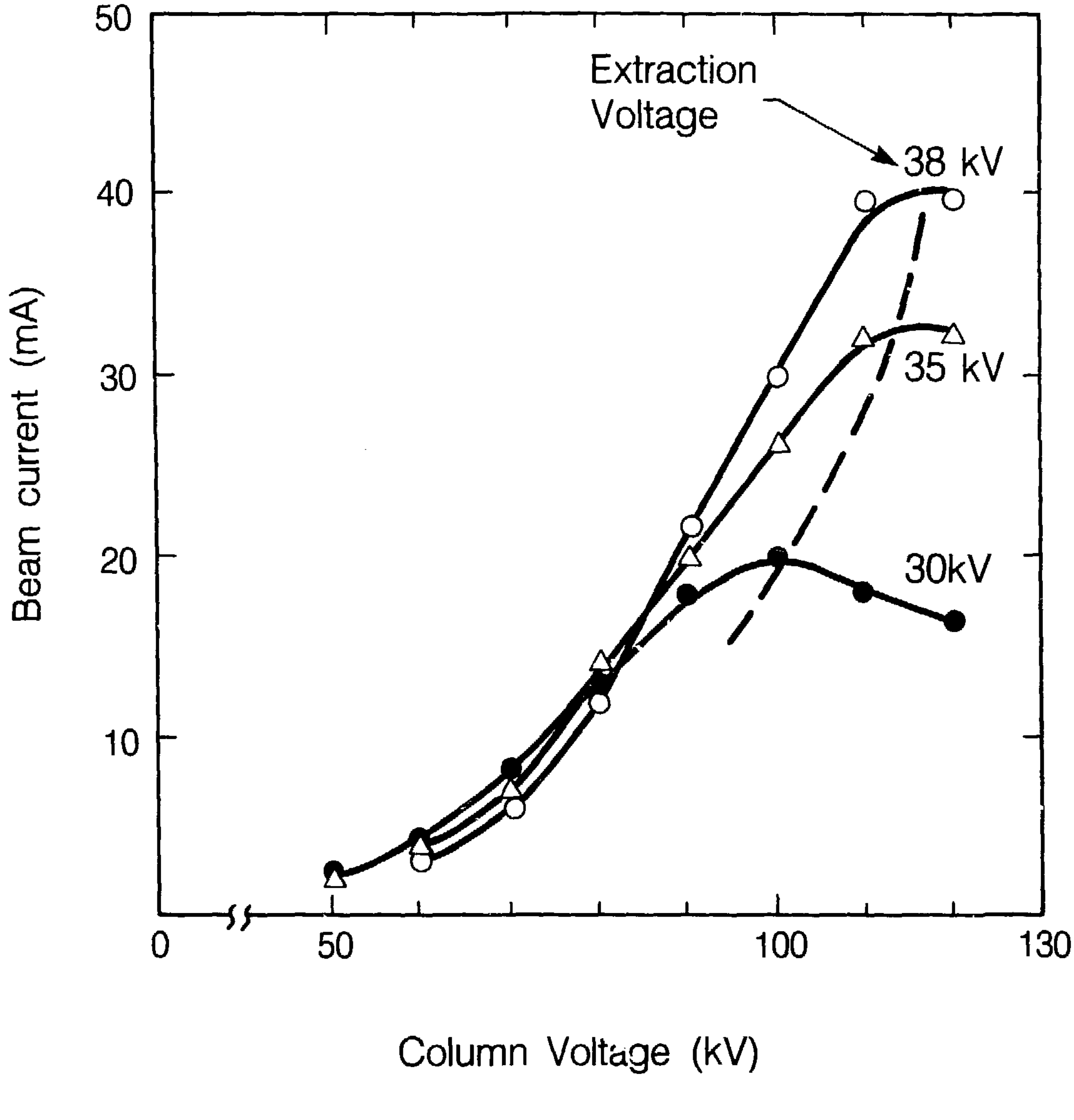

Fig. 5 Current measured at the ground side of the high voltage column vs. column voltage, for several different extractor voltages. The importance of high extractor voltage and of proper matching of extractor voltage to column voltage, for maximum transported beam current, is evident; the operating line is indicated.

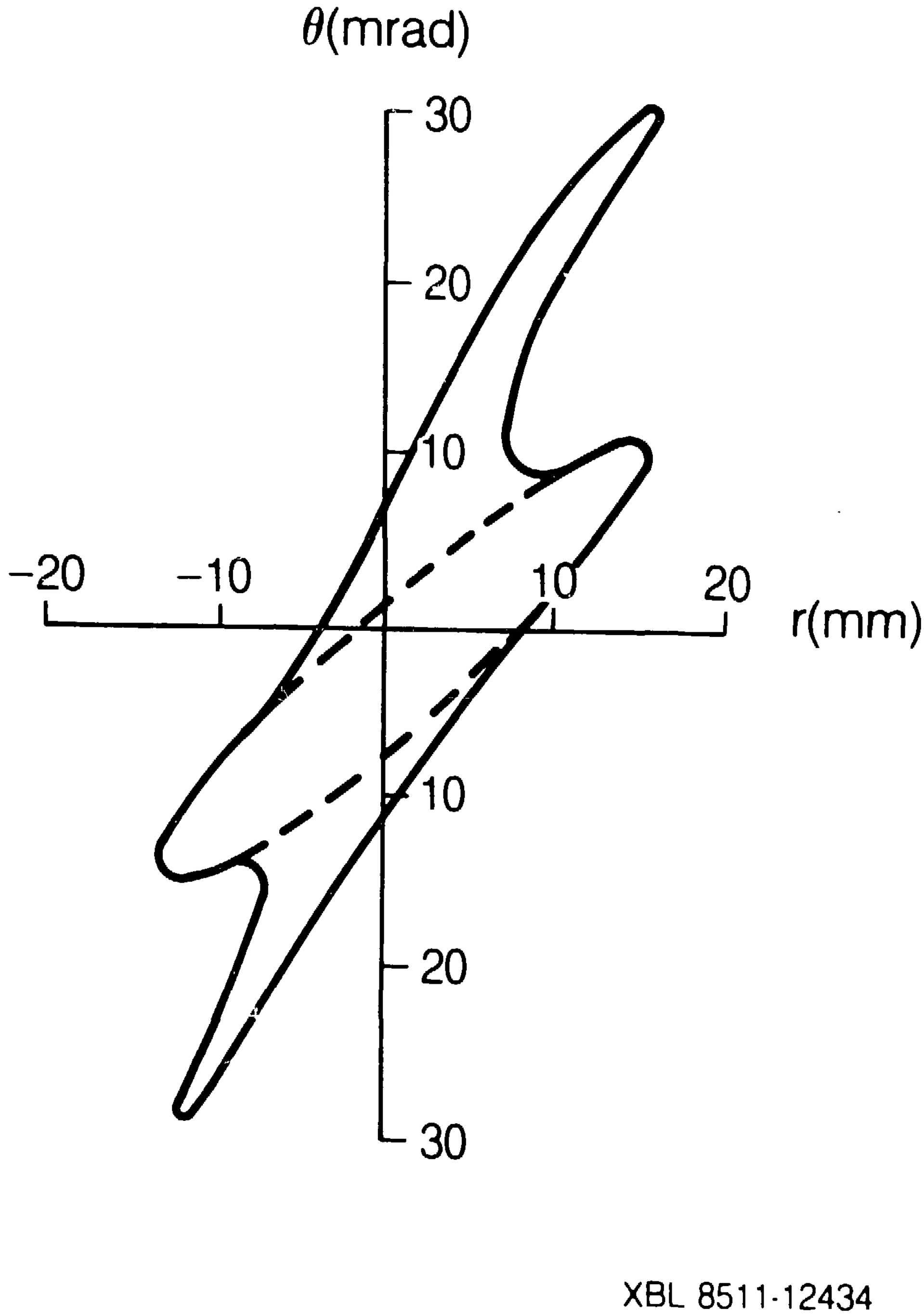

Fig. 6 Emittance diagram for a uranium beam, as measured using the 'pepper-pot' diagnostic. Measured at the ground side of the high voltage column. Extraction voltage 38 kV; 7-hole extractor grids; column voltage 120 kV; beam current 40 mA. About 95% of the beam current lies within the outermost border, and about 80% lies within the inner (dotted) border.

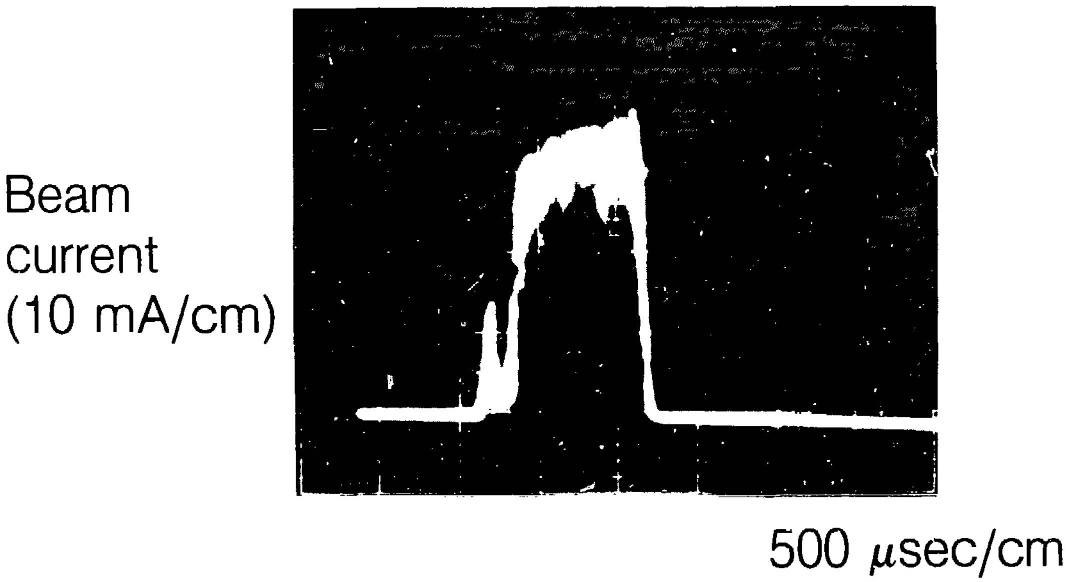

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Fig. 7 Oscillogram of the beam pulse measured by a Faraday cup at the ground side of the high voltage column, for the 1.1 millisecond long beam pulse. Uranium; vertical scale 10 mA/cm; sweep speed 500 microseconds/cm. Extractor voltage 40 kV, column voltage 120 kV.

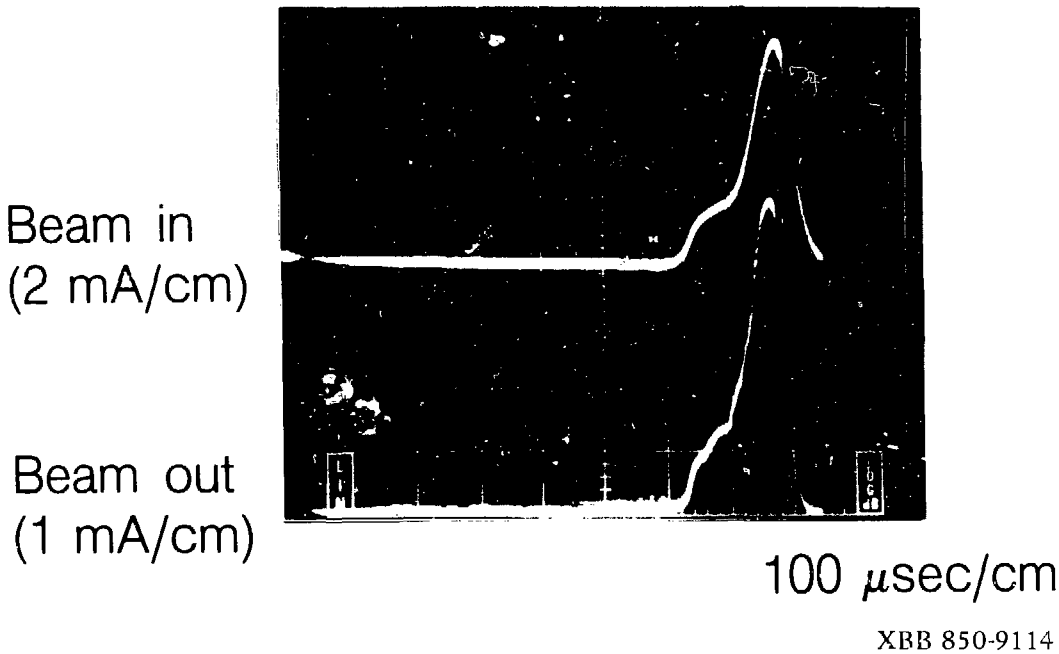

Fig. 8 Oscillogram of beam current pulses measured at the input to and the output from the RFQ. Upper trace: input beam current transformer, 2 mA/cm. Lower trace: output beam current transformer, 1 mA/cm. Sweep speed: 100 microsecond/cm.