Title
SPACE CHARGE EFFECTS IN THE AXIAL INJECTION LINE FOR THE 88-INCH CYCLOTRON

Permalink
https://escholarship.org/uc/item/0q3488fv

Authors
Resmini, F.
Clark, D.J.

Publication Date
1969-05-01

For 1969 Particle Accelerator Conference,
Washington, D. C., March 5-7, 1969

UCRL-18596
Preprint

cy. 2

SPACE CHARGE EFFECTS IN THE AXIAL INJECTION LINE FOR THE 88-INCH CYCLOTRON

F. Resmini and D. J. Clark

May 1969

AEC Contract No. W-7405-eng-48

LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

cy 2

SPACE CHARGE EFFECTS IN THE AXIAL INJECTION LINE FOR THE 88-INCH CYCLOTRON*†

F. Resmini†† and D. J. Clark

Lawrence Radiation Laboratory
University of California
Berkeley, California 94720

May 1969

INTRODUCTION

A new axial injection beam transport line has been designed for the 88-inch cyclotron (Fig. 1). A description of the line beam optics[1] and construction[2] have been given previously. In this report we give the results of space charge calculations at higher beam intensities in this line.

I. BEAM OPTICS—NOTATIONS AND MATCHING

In treating the problem of matching external sources to the cyclotron acceptance, it is convenient to refer to the phase space representation. The two phase spaces (x,x') and (y,y'), are associated with the beam, travelling along the z-axis. The units used here for position (x and y) and divergence (x' and y') are mm and mrad. The x-z plane is defined parallel to the Dee edge in the center of the cyclotron and the polarities of the quadrupoles are so

---

[*] This work performed under the auspices of the U. S. Atomic Energy Commission.

[†] Revised version of paper presented at the 1969 Particle Accelerator Conference, Washington, D. C., March 5-7, 1969.

[††] On leave of absence from University of Milan, Milano, Italy.

chosen that the motion in the x-z plane generally corresponds in a triplet to the sequence DFD (defocusing-focusing-defocusing), and FDF for the y-z plane.

The beam is at a waist, along a drift length, when the representative ellipses in phase space are upright, i.e., their axes coincide with x,x' (y,y') axes. However, the waist positions for the two phase spaces do not necessarily coincide along the line.

In discussing the matching requirements we shall describe the beam, at a waist, through the characteristic length of the phase space ellipses, defined as $X_x = x_0/x'_0$ and $X_y = y_0/y'_0$ where the subscripts (0) refer to the semiaxes of the ellipses at the waist.

A wide range of matching requirements to be satisfied has been chosen. The beams delivered both by the polarized ion source and the duoplasmatron test source should have cylindrical symmetry around the z-axis, so that the initial characteristic lengths $X_{x,in}$ and $X_{y,in}$ are supposed to be equal.

The range of values X_{in} for which calculations have been performed is between 0.05 and 0.5, thus including a typical value measured for the duoplasmatron source (0.3), and what is expected for the polarized ion source (0.1 - 0.25). It is appropriate to note, at this point, that a variation of 10 in the X_{in}, like the one considered here, means for a fixed emittance beam a variation of $\sqrt{10} = 3.16$ in the spot size, thus allowing a large excursion in what can be accepted by the line.

II. SPACE CHARGE EFFECTS

Interest in studying in some detail the optics of the line taking into account also space charge effects arises because of the advantages of injecting very intense (non polarized) beams. In some cases, e.g., alpha particles or heavy ions, this possibility would allow for overcoming the intensity limits of conventional cyclotron sources and eventually lead to more intense accelerated beams. While the feasibility of such a scheme has not yet been proved, it is nevertheless worthwhile to get some insight into the problem. The aim of the present calculations is therefore to: a) evaluate the desirable characteristics, such as emittance and initial phase space shaping of such beams. b) Determine the range of currents which can be transmitted through the line, still satisfying, however, some reasonable requirements on phase space matching.

The program "Beamcal" developed at Los Alamos,[3] was used to perform the Runge-Kutta integration of the Vladimirskiy-Kapchinskiy[4] equations. As in the zero current calculations[1] convergence problems are encountered for waist to waist transfer if the initial guesses are not close enough to the solutions. The values of the quadrupole voltages, previously found in the zero current approximation, were then used as starting guesses and the solutions obtained for each current are the starting point for the next higher intensity. In this way solutions for a number of currents can be found with few iterations.

For a given optical transformation between X_{in} and X_{fin}, the calculations need to be done only at one energy, as a function of the beam current. In fact, under the assumptions of the Vladimirskiy-Kapchinskiy theory, if the parameters above are held constant, the space-charge effect depends upon the ratio $I/(E^{3/2})$. Consequently, if for example, the beam amplitude A, at any point along the line, is known at an energy E_0, as a function of the current I_0, the same amplitude at an energy E_1 and current I_1 will be given:

$$A_{(E_1,I_1)} = A_{(E_0,I_0)} \quad \text{if} \quad I_1 = I_0\left(\frac{E_1}{E_0}\right)^{3/2}$$

and the quadrupole voltages, if the same relation between the currents holds, are given by $V_1/V_0 = E_1/E_0$.

In the injection of intense beams it is intended to use the first triplet, T_0, in the $M_x = M_y = 1$ magnification mode, performing a symmetric beam transfer over the length of 1.4 meters. It has been found that this mode of operation is generally possible, if the quadrupole voltages are properly corrected. The main results can be summarized as follows:

1) The initial shaping in phase space for a given emittance is far more critical than in the zero current approximation, from the point of view of transmission efficiency. The effect is illustrated in Fig. 2, where beam envelopes are plotted for 10 keV protons and a 200 mm mrad emittance, for different beam currents. For example, two extreme X_{in} values have been chosen, $X_{in} = 1$ and 0.14. It is clear that while 800 μA can be transmitted in the first case, 400 μA already exceeds the available aperture in the second. This of course reflects the fact that space charges effects are less pronounced for a large diameter, nearly parallel, beam.

2) The increase in quadrupole strengths needed in order to correct for space charge effects and still get the desired focusing is rather sensitive to

current and to beam emittance. As an example, Fig. 3 presents the quadrupole voltages as a function of I for $X_{in} = X_{fin} = 1.0$. Curves are plotted for emittances of 200 mm mrad and 50 mm mrad. As one notices from the graphs, one should design for a margin of about a factor of 2, or more, in the voltages, with respect to the I = 0 solutions, if high intensity beams have to be injected.

3) The transmission efficiencies through the triplet T_0 are presented in Fig. 4, again for 200 and for 50 mm mrad beams, 10 keV protons, and the X_{in} values shown. The result that a beam of smaller emittance is less efficiently transmitted (for the same X_{in} and I values), which is the opposite of what happens in the I = 0 case, is explained again by the fact that what really affects the space charge limit, for very high currents, is the beam size. One might observe, for example, that the transmission efficiencies for $X_{in} = 1$ (50 mm mrad) and $X_{in} = 0.36$ (200 mm mrad) are nearly the same. These two cases in fact, correspond to nearly equal beam radii of 4.0 and 4.8 mm respectively. It is thus desirable to shape the beams, in phase space, to say $X_{in} \geqslant 0.5$, before injection into the line. If at all possible even higher X_{in} values, like 1 or 2 should be obtained, the higher values being better for smaller beam emittance.

On the basis of these results we have further investigated the problem of the transmission through the entire line, subject to some matching requirements. It is not possible, at present, to formulate an exact hypothesis on the phase space shaping of beams at the injection in the cyclotron. That would require a complete study of the beam behavior, taking into account space charge forces, through the hole lens and the mirror.

In the absence of precise information it seems safe to assume that phase space matching should be available within some reasonable limits which, in analogy to the I = 0 case, we set tentatively to $0.1 \leqslant X_{fin} \leqslant 0.3$. The results of beam envelope tracking presented here (10 keV protons, 200 mm mrad), Fig. 5, refer to a beam with $X_{in} = 0.5$, matched to $X_{fin} = 0.3$ and 0.1 at 5 cm from the median plane. It can be seen from Fig. 5 that a current of 600 μA can be transmitted and properly matched to an $X_{fin} = 0.3$, while the limit is much smaller, $I \approx 300$ μA, for $X_{fin} = 0.1$. Somewhat better results can be obtained with a different X_{in}. However, the pattern presented here is fairly representative of what one should expect.

FINAL REMARKS

From this complex of results the transfer line for the 88" cyclotron appears to meet the design specifications and to allow a very good degree of flexibility in its performance. The aperture limits imposed by the size of the magnet yoke do not influence dramatically the overall transmission, for reasonable injected beams. Currents in excess of 500-600 μA, for 10 keV protons, can be injected. The efficiency can be lower if matching to small X_{fin} values is required like the 0.1 case discussed previously. In order to appreciably increase the transmitted intensity for these cases the only way out would be to inject at much higher energies, like 20 keV or so, which would in turn call for off-center injection.

Experimental investigation of the line optics is under way at the time of writing this paper.

REFERENCES

1. F. Resmini, Optics of the Axial Injection Line for the 88-Inch Cyclotron, University of California Lawrence Radiation Laboratory Report UCRL-18442, (unpublished).
2. D. J. Clark et al., Design and Construction of the Axial Injection System for the 88-Inch Cyclotron, University of California Lawrence Radiation Laboratory Report UCRL-18608.
3. P. W. Allison, private communication.
4. I. M. Kapchinskiy and V. V. Vladimirskiy, Limitations of Proton Beam Current in a Strong Focusing Linear Accelerator Associated with the Beam Space Charge, Proceedings of the Int. Conf. on High Energy Accel. CERN, 1959, p. 274.

FIGURE CAPTIONS

Fig. 1. Layout of the axial injection line. Only schematic beam envelope is shown.

Fig. 2. Beam envelopes through triplet T_0 for 10 keV protons and different beam currents.

Fig. 3. Quadrupole voltages for triplet T_0, for 10 keV protons, as a function of the beam intensity.

Fig. 4. Transmitted currents through triplet T_0, for 10 keV protons, as a function of the injected beam intensity.

Fig. 5. Typical beam envelopes through triplets T_1 and T_2, for several beam intensities, 10 keV protons, 200 mm mrad, and waist position at 5 cm from the cyclotron median plane.

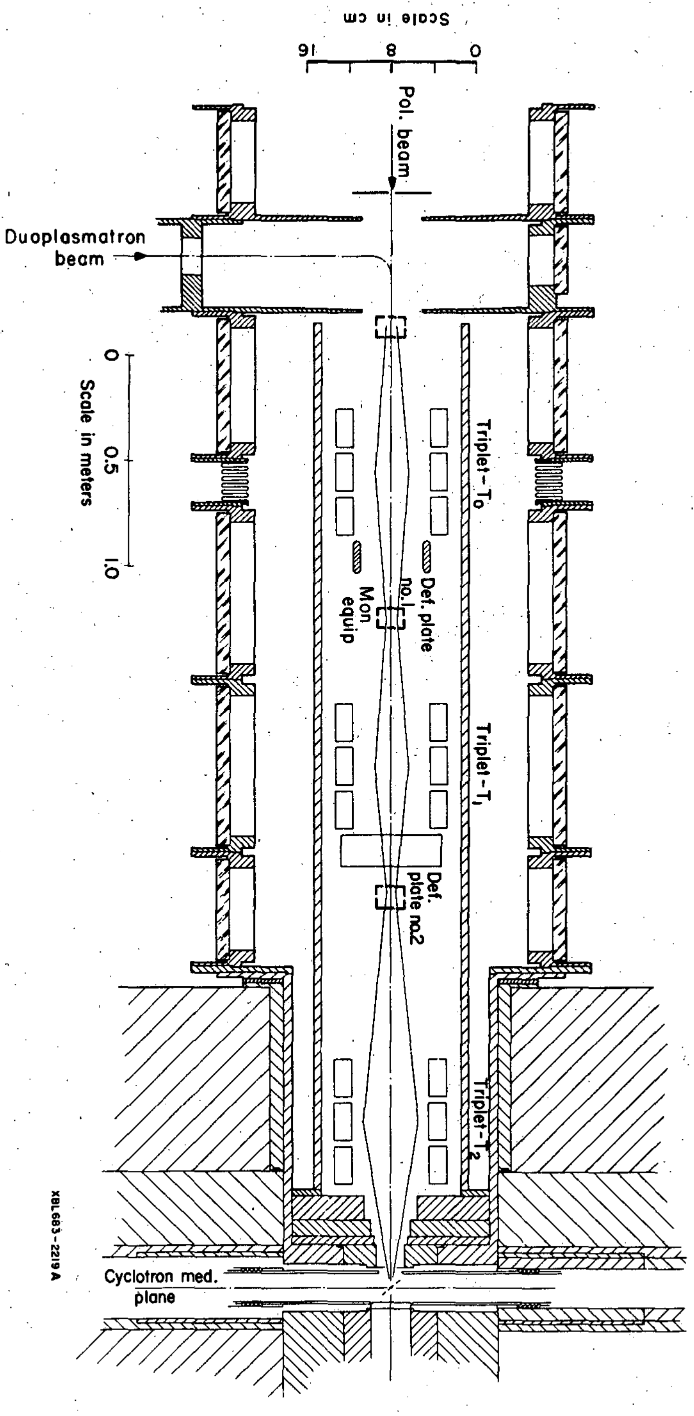
Scale in cm
0
8
16
Pol. beam
Duoplasmatron beam
Scale in meters
0
0.5
1.0
Triplet-T_0
Def. plate no.1
Mon. equip
Triplet-T_1
Def. plate no.2
Triplet-T_2
Cyclotron med. plane
XBL683-2219A

Fig. 1

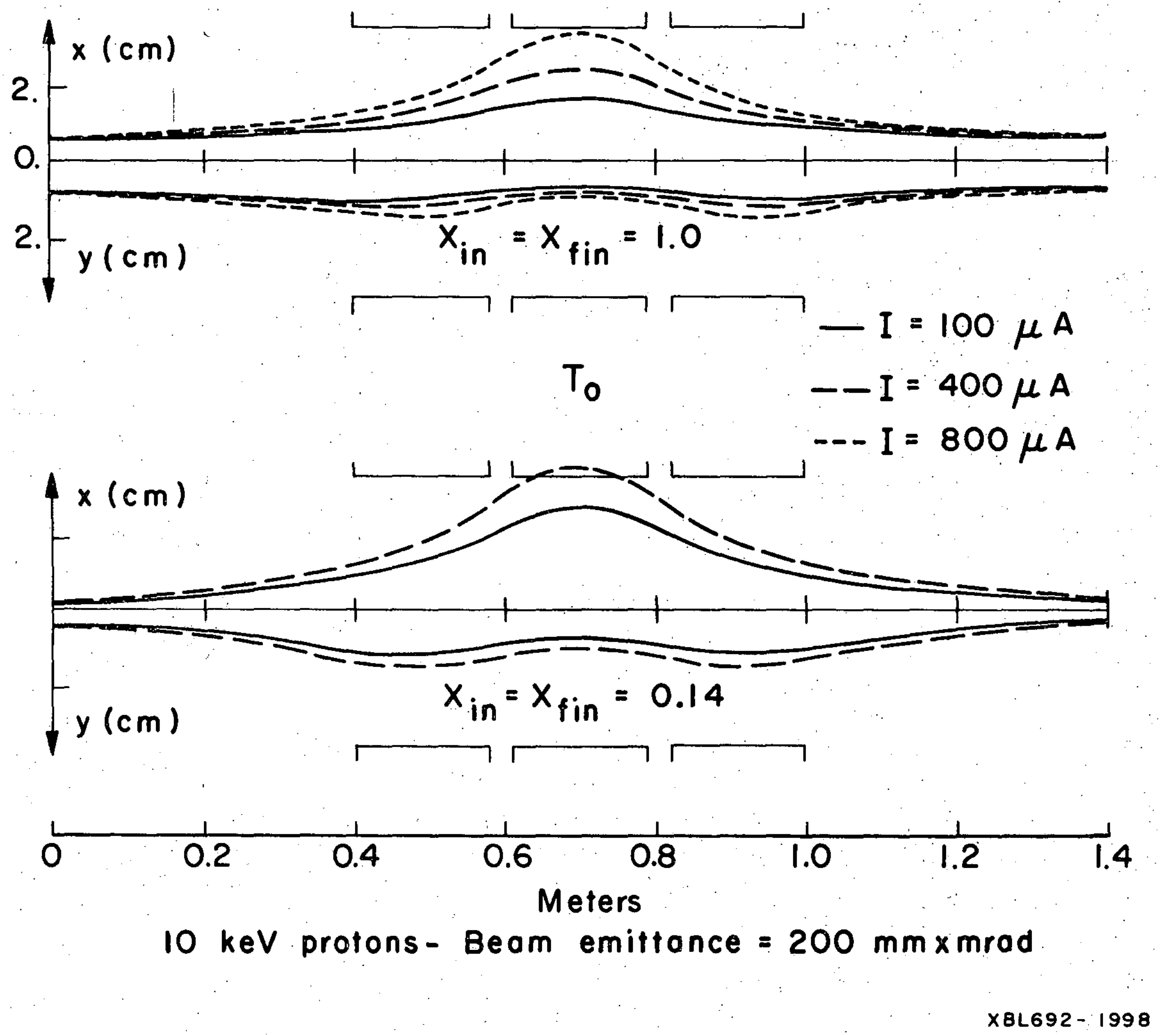
x (cm)
2.
0.
2.
y (cm)
$X_{in} = X_{fin} = 1.0$
— I = 100 μA
– – I = 400 μA
--- I = 800 μA
T_0
x (cm)
y (cm)
$X_{in} = X_{fin} = 0.14$
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Meters
10 keV protons - Beam emittance = 200 mm x mrad
XBL692-1998

Fig. 2

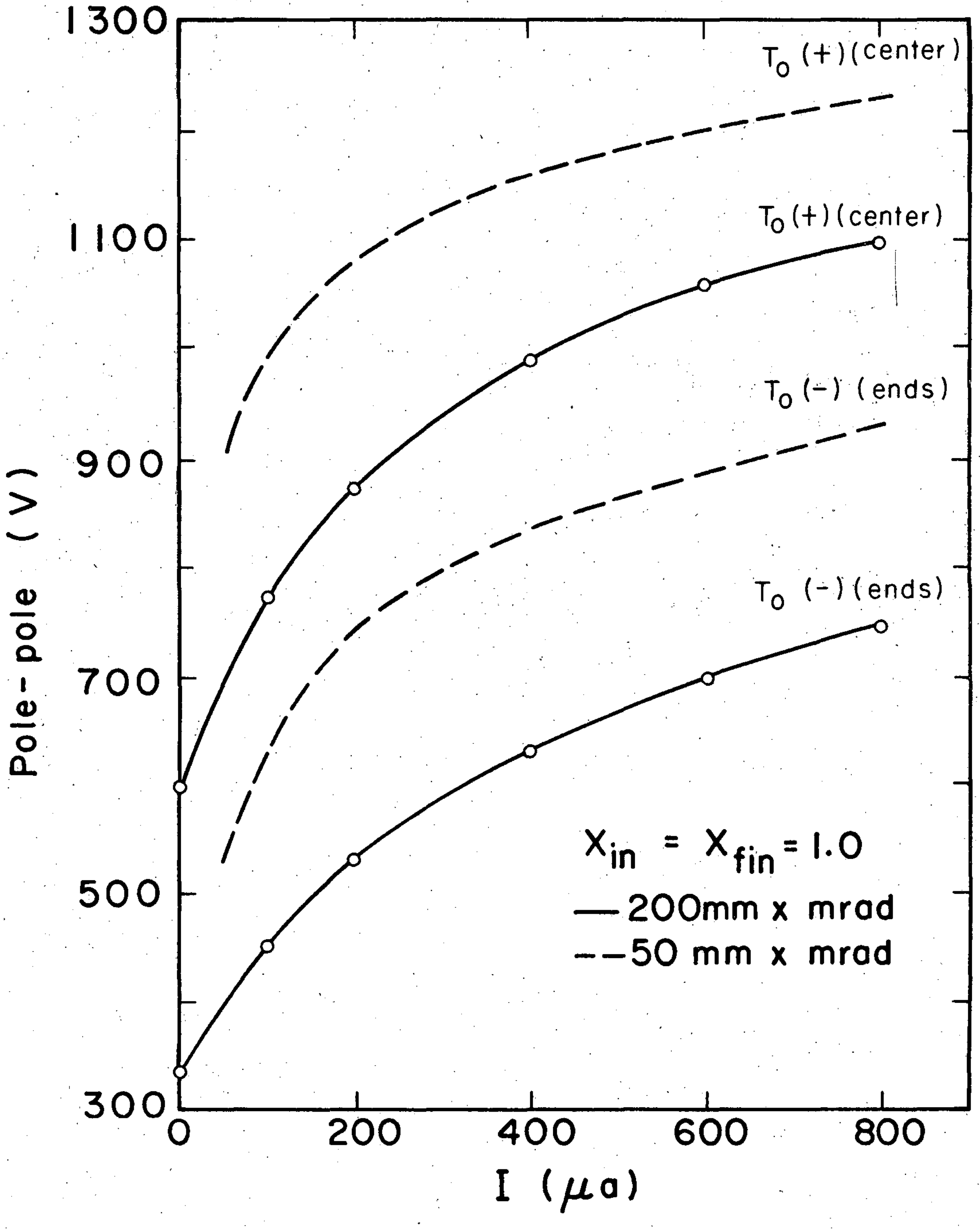

Fig. 3

XBL692-1996

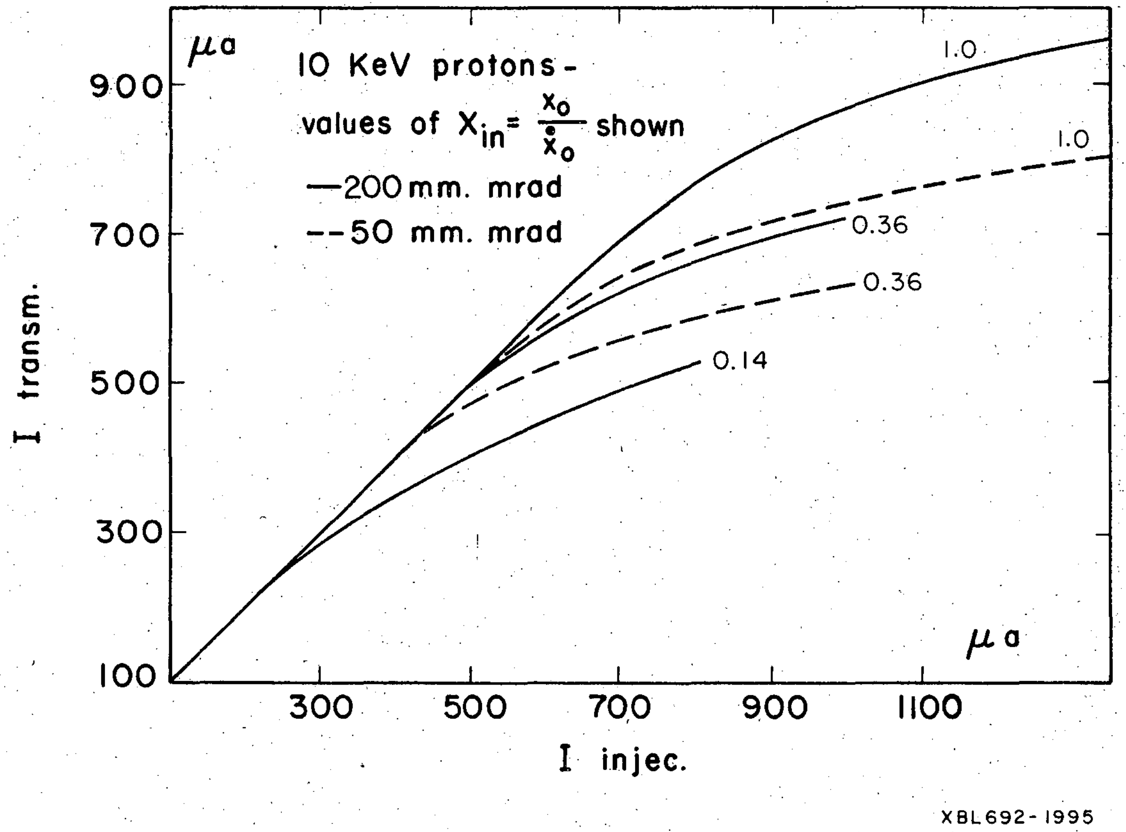
μa
10 KeV protons -
values of $X_{in} = \frac{x_o}{\dot{x}_o}$ shown
—200 mm. mrad
--50 mm. mrad
900
700
500
300
100
I transm.
1.0
1.0
0.36
0.36
0.14
μa
300
500
700
900
1100
I injec.
XBL692-1995

Fig. 4

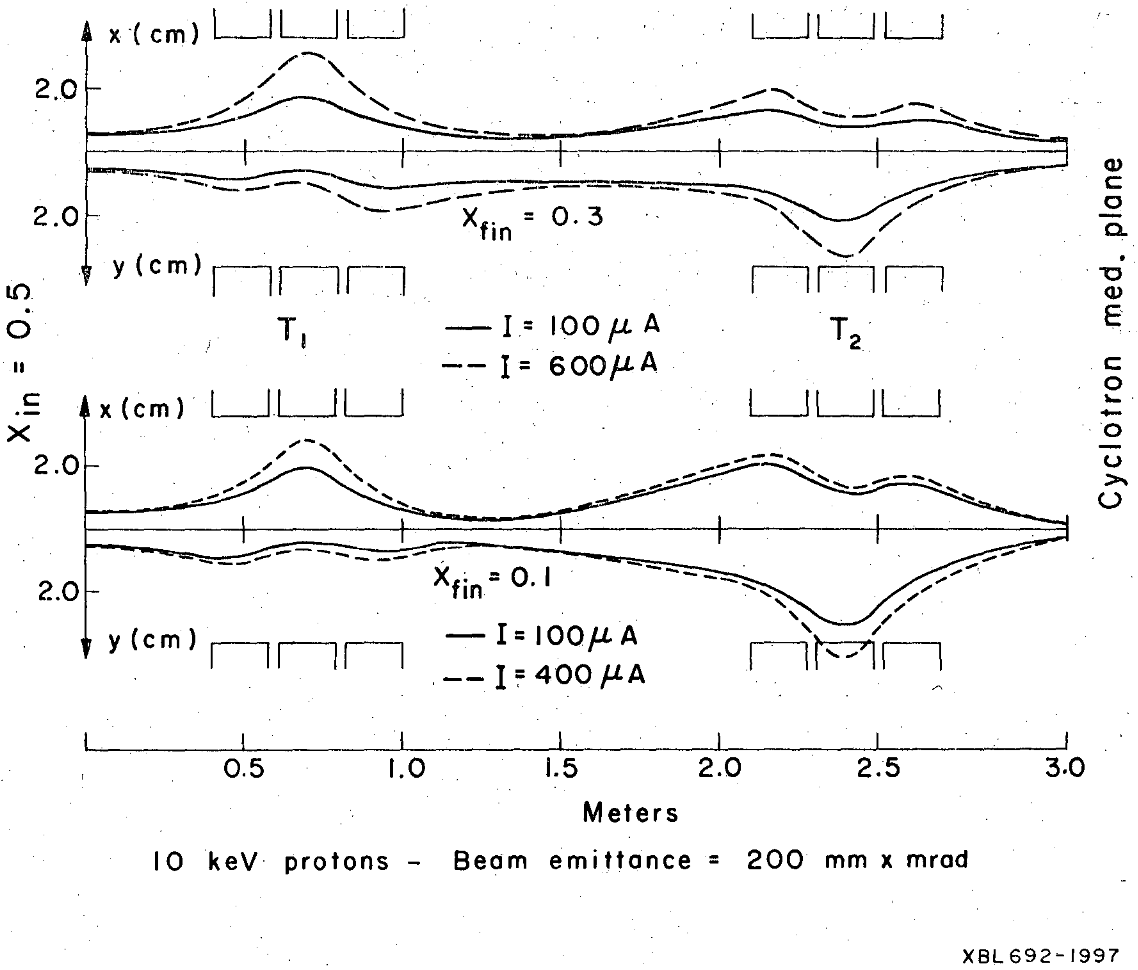
x (cm)
2.0
2.0
X_{fin} = 0.3
y (cm)
T_1
— I = 100 μA
-- I = 600 μA
T_2
X_{in} = 0.5
Cyclotron med. plane
x (cm)
2.0
2.0
X_{fin} = 0.1
y (cm)
— I = 100 μA
-- I = 400 μA
0.5
1.0
1.5
2.0
2.5
3.0
Meters
10 keV protons - Beam emittance = 200 mm x mrad
XBL 692-1997

Fig. 5

TECHNICAL INFORMATION DIVISION
LAWRENCE RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720