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INTRODUCTION

A new axial injection beam transport line has been designed for the 88-inch cyclotron. The old line[1] used electrostatic quadrupole doublet lenses with a 3.0 cm aperture. The new line uses electrostatic quadrupole triplet lenses with a 7.3 cm aperture and has been designed with more emphasis on efficient beam optics.

We plan to use several external ion sources with this new line. The most important, initially, will be a polarized proton and deuteron source now under construction. Also a duoplasmatron source has been built and tested. It will provide proton beams to study the beam optics of the line and the cyclotron acceptance.

I. DESIGN CRITERIA

The new axial injection line for the 88" cyclotron has been designed to satisfy the following requirements. The line should have:

a) A good overall transmission efficiency, within the unavoidable geometrical constraints, of the beams delivered by the polarized ion source.

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b) A reasonable range of matching between the phase space characteristics of the external sources and the supposed cyclotron acceptance. A high degree of flexibility is desirable because of the many beams eventually available for injection and the lack of precise information about the real cyclotron acceptance.
c) Acceptance of beams of small emittance, delivered by conventional sources, but with high d.c. intensities, in excess of several hundred microamps. This calls for compensating the related space charge effects and extra aperture for the lenses.
d) Enough space between the lenses in order to accomodate: deflecting plates for pulsed beam operation; various monitoring equipment, in order to control the beam behavior along the line; a suitable buncher,[2] in order to match the narrow R.F. phase acceptance of the cyclotron. These requirements will be discussed in a quantitative way in connection with the beam optics.

II. DESCRIPTION OF THE LINE

The total distance, Fig. 1, between the cyclotron median plane and the upper starting point of the line is 4.4 meters. Beams delivered by the polarized ion source and the duoplasmatron test source (or any other source available in the future) are supposed to be focused at the starting point. That is, suitable optical systems have to be provided with each source in order to meet this initial requirement.

The duoplasmatron ion source is positioned at 90° with respect to the injection line and the beam transfer is thus obtained by means of a 90° bending magnet, with uniform field. Wedge vertical focusing is obtained at the magnet entrance and exit edges, which are 26° from normal to the beam line. The polarized ion source is placed directly in line with the injection line.

The optical elements of the injection line are three electrostatic quadrupole triplets, positioned as indicated in Fig. 1. The component quadrupoles of each triplet have 7.3 cm aperture, a length of 18 cm, and are separated by 3 cm (Fig. 2). The poles are machined to a curvature radius of 4.15 cm with centers 7.8 cm off axis, which is the best approximation[3] to the ideal hyperbolic surface. The aperture chosen is almost the largest one compatible with the dimensions of the hole in the magnet yoke in agreement with point (c) of page 2. Triplets have been selected, instead of doublets, because of the great flexibility of the system with respect to the matching requirements, as will be apparent later, and their easy use as astigmatic optical elements.

Sets of collimators are provided within every triplet, as indicated in detail in Fig. 2, in order to avoid beam losses on the quadrupoles themselves. The sets at the entrance and exit of every triplet have an aperture of 50 mm, while those in between the quadrupoles have apertures of 60 mm. The beam currents possibly dumped on each collimator can be read independently.

Two deflecting plates, at 90° to each other, are provided for beam steering. The upstream one, D_0 in Fig. 1, is supposed to be used in the future for beam pulsing. For that reason a collimator of variable aperture is set at the waist position determined by the first triplet, in order to dump on it the swept away beam. The deflecting plates are 15 cm long, with a gap of 6 cm, and are 9.5 cm wide.

The buncher, as referred to in a previous report,[2] will be placed between the two last triplets as close to the median plane as possible.

Three sets of monitoring equipment are provided, positioned at: a) the starting point of the line, b) the downstream waist produced by the first triplet, c) at a distance of 30 cm downstream from the second triplet. This position does not correspond necessarily to a waist because of the varying focal position required by the different matching combinations.

Each set comprises: motor driven X-Y double scanning wires for precise measurement and recording of the beam shape on a storage oscilloscope; an aluminum oxide plate for visual beam spot control, and a Faraday cup for total beam intensity measurements and transmission efficiency tests. Both the aluminum oxide and the Faraday cup are remotely controlled for operating convenience.

III. BEAM OPTICS

Notations and Definitions

In treating not only simple beam transfer, but also the problem of matching the 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. In what follows, and in the line geometrical arrangement, the x-z plane is defined parallel to the Dee edge in the center of the cyclotron. Also the polarities of the quadrupoles are so 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. The waist positions for the two phase spaces do not necessarily coincide along the line. However, when this happens, the beam there has the minimum size.

For the purpose of discussing the matching requirements we shall describe the beam, at a waist, through the characteristic length of the phase space ellipses, defined as $X_r = x_0/x'_0$ and $X_v = y_0/y'_0$ where the subscripts (0) refer to the corresponding semiaxis of the ellipses, taken at the waist. The advantage of describing the beam in this way comes from two arguments: 1) The strengths of the lenses, for a given energy beam and a fixed type of beam transfer and matching depend only upon the initial X's. 2) The treatment of the optics is done independently of the value of the beam emittance, which enters thus only in transmission efficiency considerations.

Matching Requirements

Many possible solutions have been developed for the line and a substantial computing effort has been aimed toward predicting the quadrupole strengths, studying the flexibility of the line and evaluating the transmission efficiencies.

A rather 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 are expected to have cylindrical symmetry around the z-axis, so that the initial characteristic lengths $X_{r,in}$ and $X_{v,in}$ are supposed to be equal.

The range of values X_{in} for which optics 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 might be 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 real large excursion in what can be accepted by the line, and easing somewhat the requirements on the optical system of each individual source.

From the point of view of matching the cyclotron acceptance, only fairly broad limits can be stated at present. Consequently we look for a high degree of flexibility both on the waists to be obtained and their position with respect to the median plane. Previous calculations of the trajectories through the hole lens[4] have indicated that a distance around 10 - 15 cm from the median plane and an $X_{fin} = 0.2$ or so could be adequate. For the present study two extreme positions, namely 5 cm and 15 cm away from the median plane have been selected, and optics solution developed accordingly. As far as the range of X_{fin} is concerned solutions are available for the following values: 0.1, 0.2, 0.3. Of course any intermediate or even lower value can be easily obtained and will probably be tried during the early tests of the line, when an empirical optimization will be done.

The emittances taken into account for the evaluation of transmission efficiencies vary between 200 and 1000 mm mrad.

Computing Methods

The problem of finding the conditions under which waist-to-waist transfer can be obtained with a set of triplets, or doublets, and determining the strengths of the lenses is not entirely trivial, due to the typical multiplicity of the solutions. A graphical method, described in another connection,[5] has been used with remarkable success, providing quadrupole strength estimates generally closer than ± 2% to the true values.

The program "TRANSPORT"[6] which essentially performs the transfer matrix calculations and tracks the beam envelope along the line has then been used in order to refine the graphical estimates and get the magnifications with high accuracy. Direct use of "TRANSPORT" for the study of waist-to-waist transfer with one or two triplets and without the availability of close guesses has proved generally unsuccessful, or extremely time consuming.

The results of the calculations presented here are exact, under the assumption of an ideal quadrupole field. No attempt has been made so far to take into account the possible aberrations of the system, which should, however, be small for most beams, due to the quadrupole geometry chosen. Also, the actual system performance, when considered in its entirety from the injection into the cyclotron to the beam extraction is so much affected by other hard-to-control factors that an aberration study would not be very realistic at the present time.

Optical Solutions

From the point of view of beam optics the operation of the system is so devised that the desired flexibility is obtained by varying the parameters of the minimum number of lenses. As will be shown later, two triplets, if properly positioned, can spot the required waists over the previously mentioned range of downstream distances (5 - 15 cm from the median plane). Consequently the first upstream triplet, T_0 in Fig. 1, will be used only to perform a symmetric transfer of the beam, operating with a magnification equal to unity in both the x-z and y-z planes.

The distance between the upstream (downstream) waist and the physical edge of the first (3rd) quadrupole of triplet T_0 is 40 cm. Since the total length of the triplet is 60 cm, this unit provides a convenient transfer over a total length of 1.40 meters. As in all other triplets, the two outer quadrupoles are equally excited, because it has been found that independent excitation does not improve significantly the flexibility of the system.

The required voltages for the quadrupoles are given in Fig. 3, as a function of X_{in}, for a proton energy of 10 keV, the scaling law being obviously linear with energy for electrostatic quadrupoles. The total potential difference between the elements of a quadrupole is plotted, rather than the more conventional (+,-) voltage of each element with respect to ground, because in our system each quadrupole singlet will be excited with a single power supply. T_0^+ is the center element and T_0^- represents the two outer elements connected in parallel.

It is apparent from Fig. 3 that the variation in voltages for different X_{in} is quite large. These settings are the same for any optical solution discussed here, because only the triplets T_1 and T_2 are used for matching purposes.

It is seen in Fig. 1 that T_1 and T_2 are 110 cm apart. The upstream waist, produced by T_0, is at 40 cm from T_1, while the ultimate downstream waist is between 40 and 30 cm from T_2. The last two values correspond to a distance respectively of 5 and 15 cm from the cyclotron median plane. The corresponding solutions to the beam optics are labeled 1 and 2. Any intermediate waist position can easily be determined from the knowledge of these solutions.

Recalling the matching requirements stated at page 5 each one of the solutions 1 and 2 contains three subcases: A, B, C, corresponding respectively to X_{fin} = 0.3, 0.2, 0.1 and calculated for a range $0.05 \leq X_{in} \leq 0.5$.

When these solutions are represented on a (X_{in}, X_{fin}) plane we have a diagram like the one in Fig. 4. There each case A, B, C, forms a straight line, both for the radial and the axial planes.

The polarities of the quadrupoles of T_1 and T_2 are inverted to one another. That is, the sequence for the x-z plane motion is DFD in T_1 and FDF in T_2, and the opposite for the y-z motion. For the purpose of matching alone, the available range of transformations would be as wide in an equal polarities set-up (i.e., the DGD-DFD and FDF-FDF sequences) but the arrangement above provides generally better overall transmission efficiencies and has thus been adopted.

The strengths of the quadrupoles needed for solution 1 and 2 are represented in Figs. 5 and 6, with self-explanatory notation for the subcases A, B, and C. Solutions with intermediate X_{fin} values, for any X_{in} in the range here considered, can be determined interpolating between the given graphs. It might be worthwhile to note that only a small (typically between 2% and 4%) variation in the quadrupole voltages is needed to shift from one solution to another, as far as a given X_{fin} or a given downstream position is concerned. That calls in turn for a good stabilization of the power supplies down to say 0.1%.

The intermediate waist positions between T_1 and T_2 for the x-x' and y-y' phase spaces do not necessarily coincide, nor do they have the same characteristics. The waists are, however, equal and at the same position downstream from T_1. For the sake of example typical beam envelopes are plotted in Fig. 7 for the X_{in} and X_{fin} values shown. The last remark which should be made is that while the present solutions are developed for

$X_{r,fin} = X_{v,fin}$, it is completely possible to vary, for a given initial beam, the X_{fin} in one plane, say the radial, while keeping the other one constant. This feature, for which appropriate solutions can be easily worked out, could be important in the process of empirical optimization of the line.

Transmission Efficiencies

The overall transmission efficiencies for the line have been evaluated, using the program "TRANSPORT" for determining the beam envelopes in the various solutions. The results are plotted in Fig. 8, for the solutions 1A, 1B, 1C, and beam emittances between 200 and 1000 mm mrad, as a function of X_{in}. It can be seen that even for quite large emittance beams, like 600 - 800 mm mrad, the transmission is generally satisfactory, ranging between 50 and 100%. The corresponding values for the set of solutions 2 are significantly close to the one presented here and would add nothing to the description of the line performance.

The results of Fig. 8 point out that the initial beam shaping is important in determining the transmission, if the beam emittance is appreciably higher than 400 mm mrad, and if this is the case it is quite desirable to have X_{in} values higher than 0.15 or so.

IV. FINAL REMARKS

From the complex of results presented here 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 hole do not influence dramatically the overall transmission, for reasonable injected beams.

The performance of the line with high intensity beams where space charge forces are important is being investigated with further calculations.

Preliminary results indicate that currents in excess of 800 micro-amp for 10 KeV protons can be transmitted and focused with the desired phase space characteristics. The full results will be available soon.

ACKNOWLEDGMENTS

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REFERENCES

1. R. Burger, D. J. Clark, E. Close, and H. Kim, Machine Development at the Berkeley 88-Inch Cyclotron, IEE Trans. Nucl. Sci. NS-13, 366 (1966).

2. F. Resmini and D. J. Clark, A Proposed Sawtooth Buncher for the 88-Inch Cyclotron Axial Injection System, University of California, Lawrence Radiation Laboratory, Berkeley, UCRL-18125 (1968).

3. P. Grivet and A. Septier, Les Lentilles Quadrupolaires Magnetiques (1), Nucl. Instr. Methods 6, 126 (1960).

4. A. U. Luccio, Axial Injection Studies on the 88-Inch Cyclotron Hole Lens, University of California, Lawrence Radiation Laboratory, Berkeley, UCRL-18016 (1968).

5. F. Resmini, A Method for Determining Waist-to-Waist Transfer Properties in Quadrupole Doublets and Triplets (Manuscript in Preparation).

6. S. K. Howry, C. H. Moore, Jr., and H. S. Butler, "TRANSPORT": A Computer Program for Designing Beam Transport Systems, SLAC Internal Report, Stanford University, Stanford, California (October 1963).

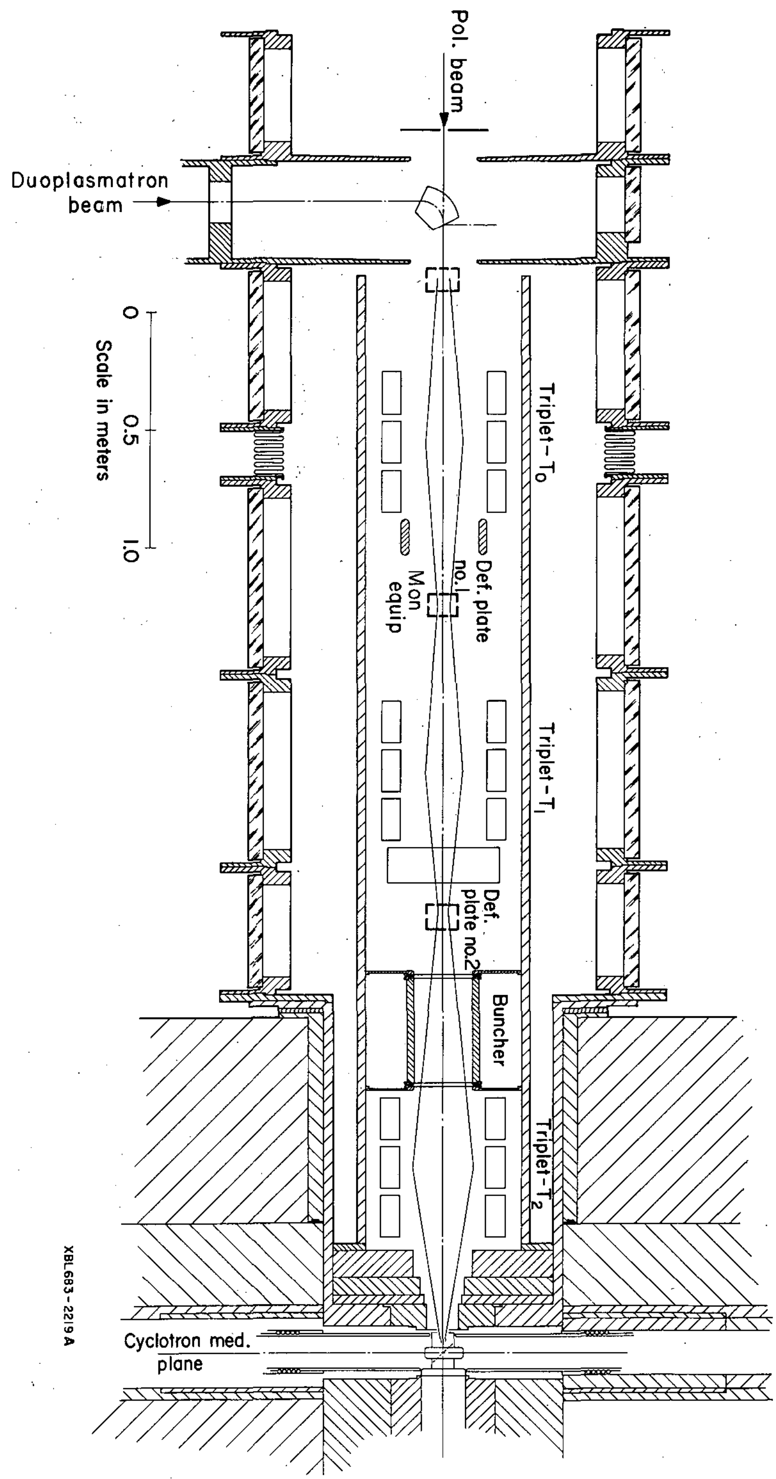

Fig. 1 Layout of the axial injection line. Only schematic beam envelope is shown.

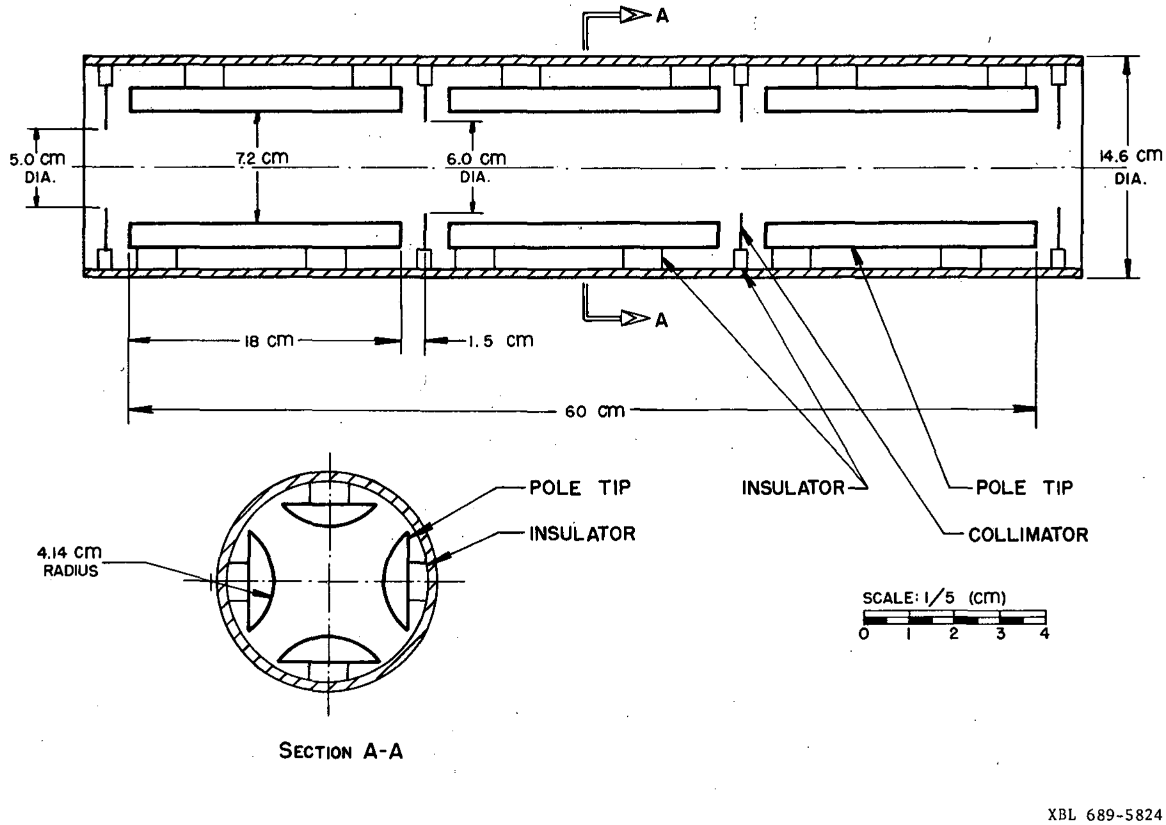

Fig. 2 Detail of a triplet and section view.

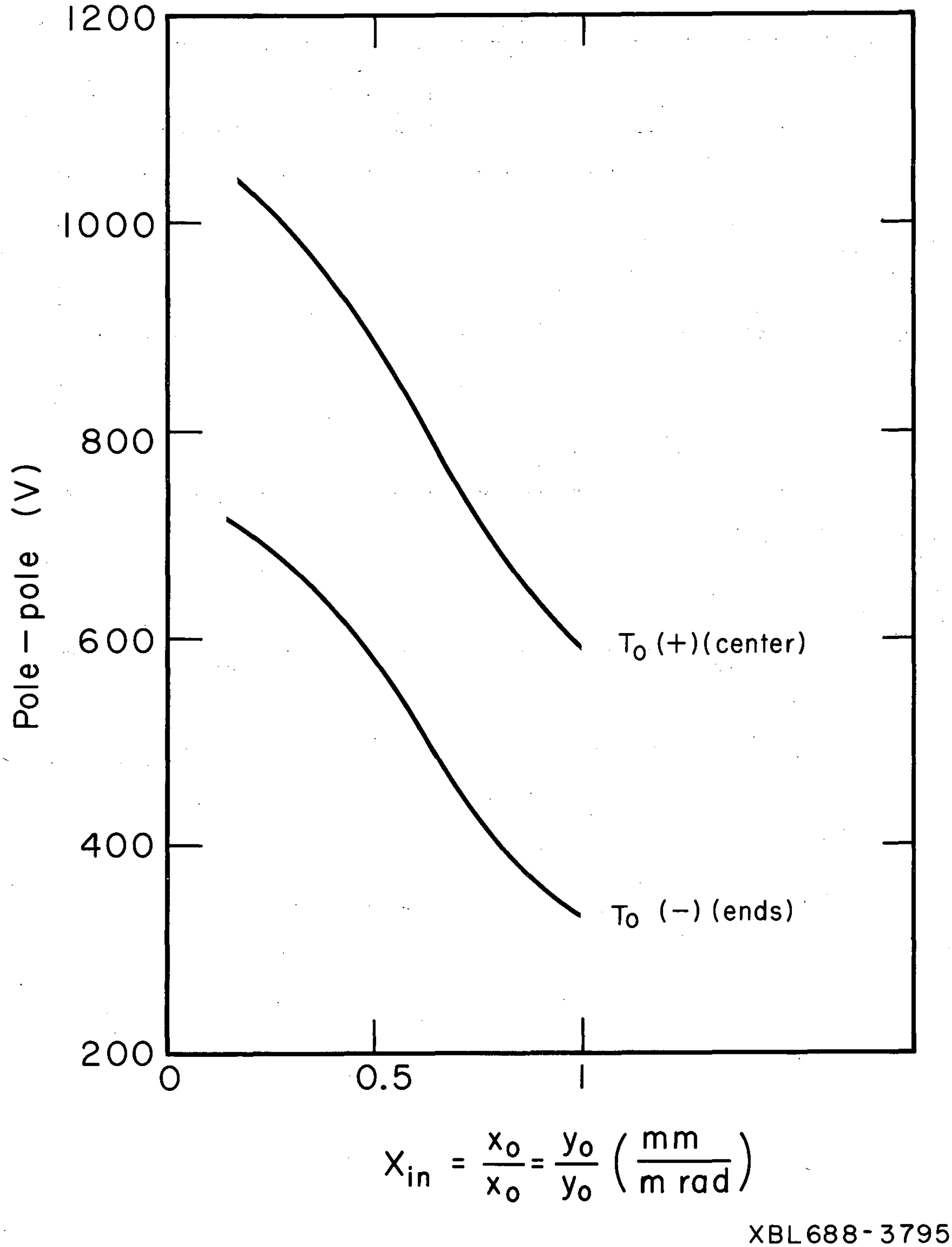

Fig. 3 Quadrupole voltages for triplet T_0 as a function of X_{in}, for 10 keV proton beam.

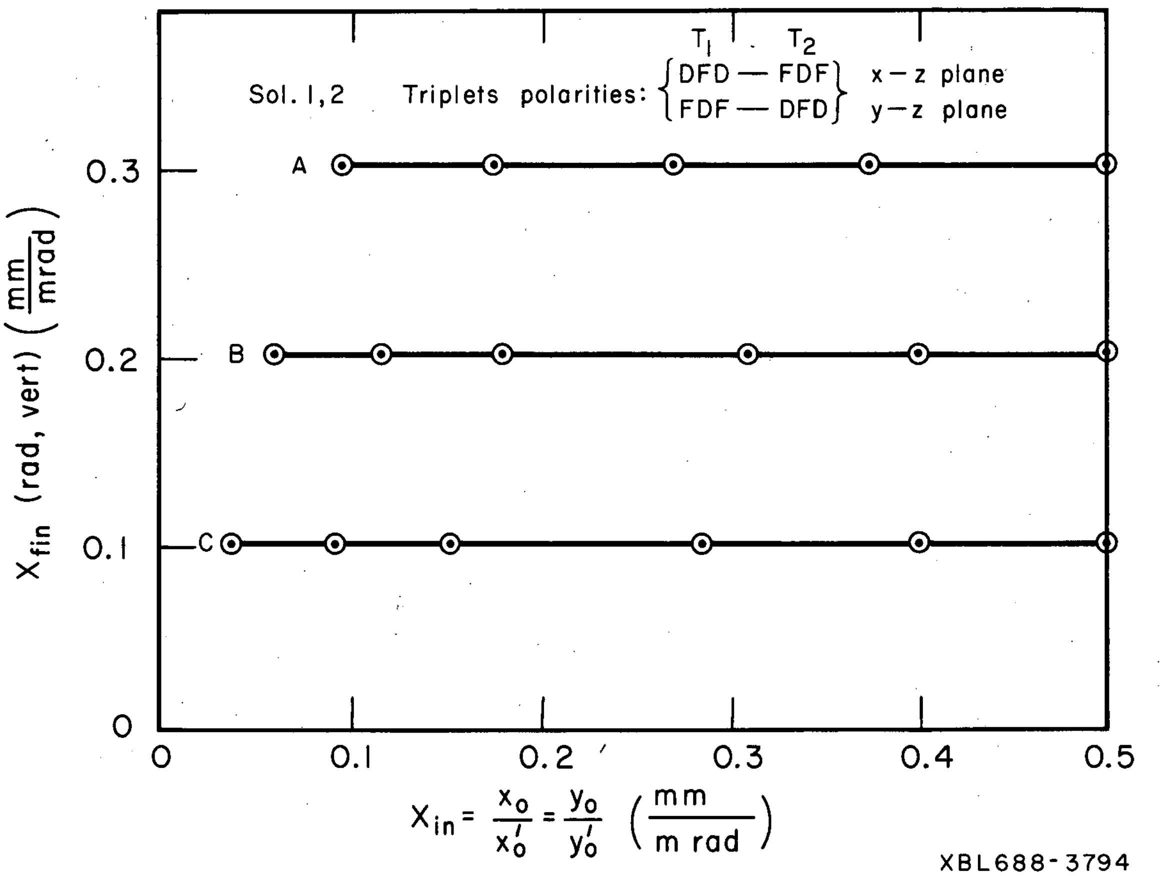

Fig. 4 Diagram $X_{fin} = X_{fin}(X_{in})$ for the available matching solutions. Circles indicate computed points.

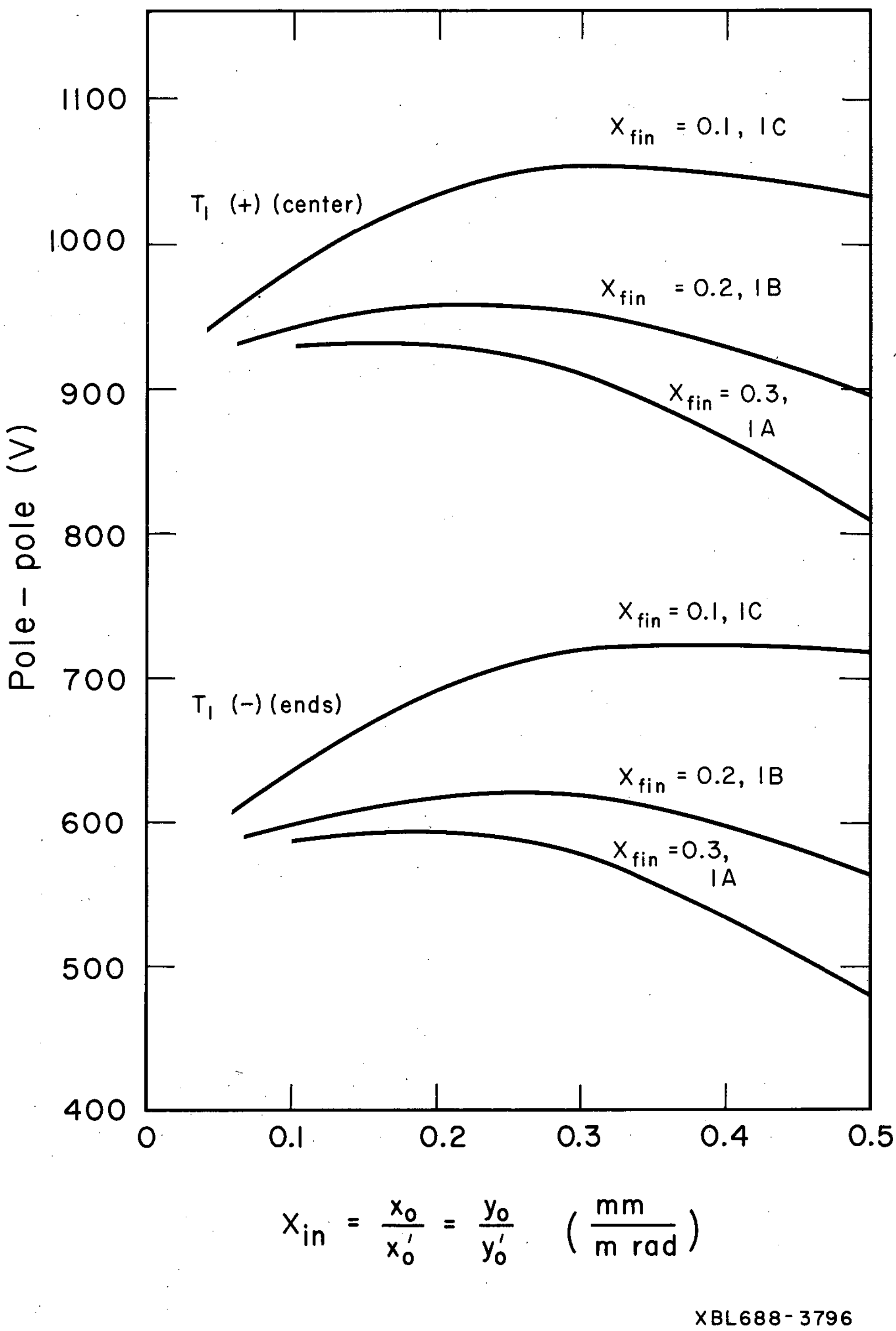

Fig. 5a Quadrupole voltages for triplet T_1 as a function of X_{in}, for X_{fin} = 0.3 (1A), 0.2 (1B), 0.1 (1C) and final waist position at 5 cm from the cyclotron median plane (Solution 1, 10 keV protons).

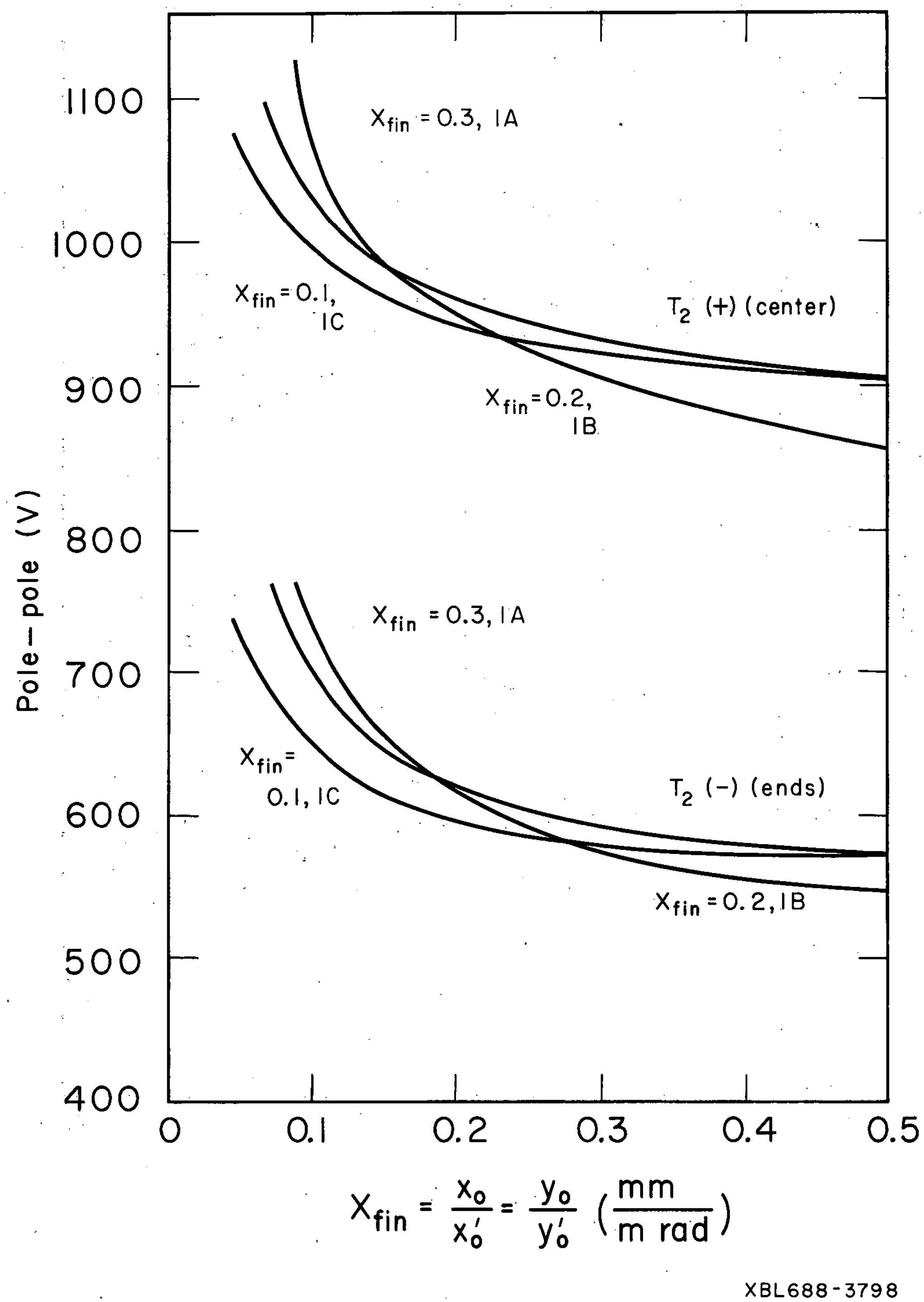

Fig. 5b Quadrupole voltages for triplet T_2 as a function of X_{in}, for X_{fin} = 0.3 (1A), 0.2 (1B), 0.1 (1C) and final waist position at 5 cm from the cyclotron median plane (Solution 1, 10 keV protons).

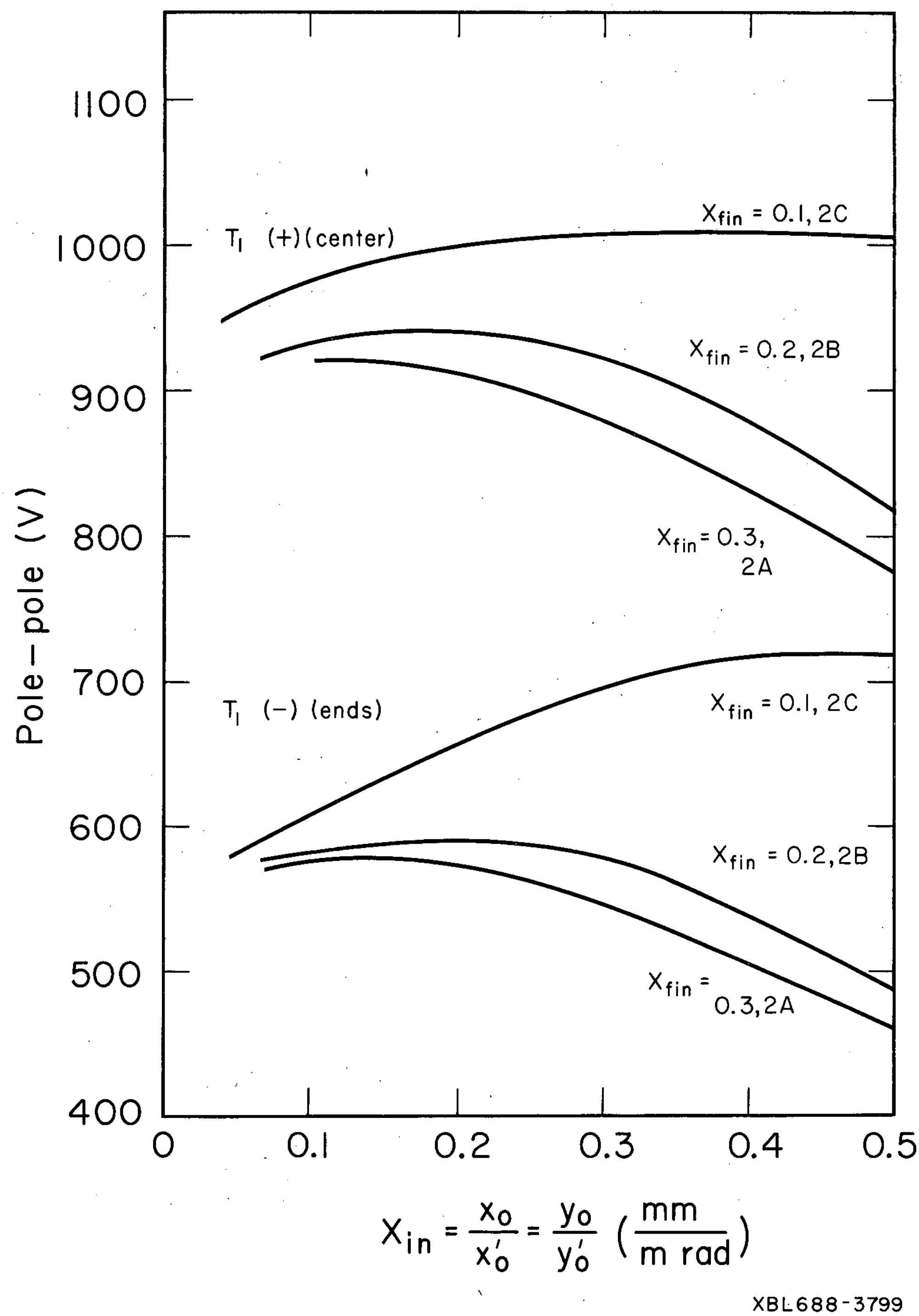

Fig. 6a Quadrupole voltages for triplet T_1 as a function of X_{in}, for X_{fin} = 0.3 (2A), 0.2 (2B), 0.1 (2C), and final waist position at 15 cm from the cyclotron median plane (Solution 2, 10 keV protons).

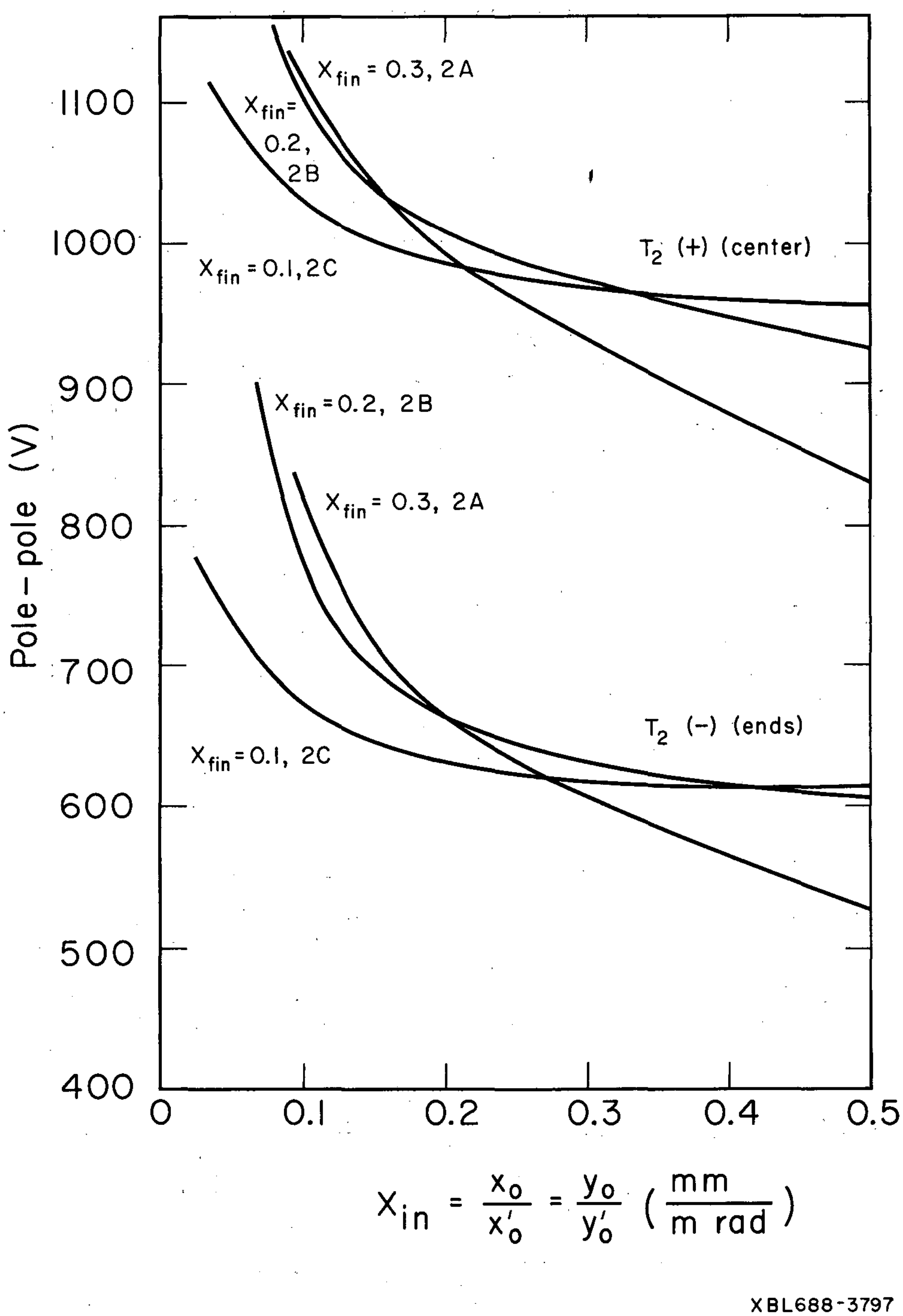

Fig. 6b Quadrupole voltages for triplet T_2 as a function of X_{in}, for X_{fin} = 0.3 (2A), 0.2 (2B), 0.1 (2C) and final waist position at 15 cm from the cyclotron median plane (Solution 2, 10 keV protons).

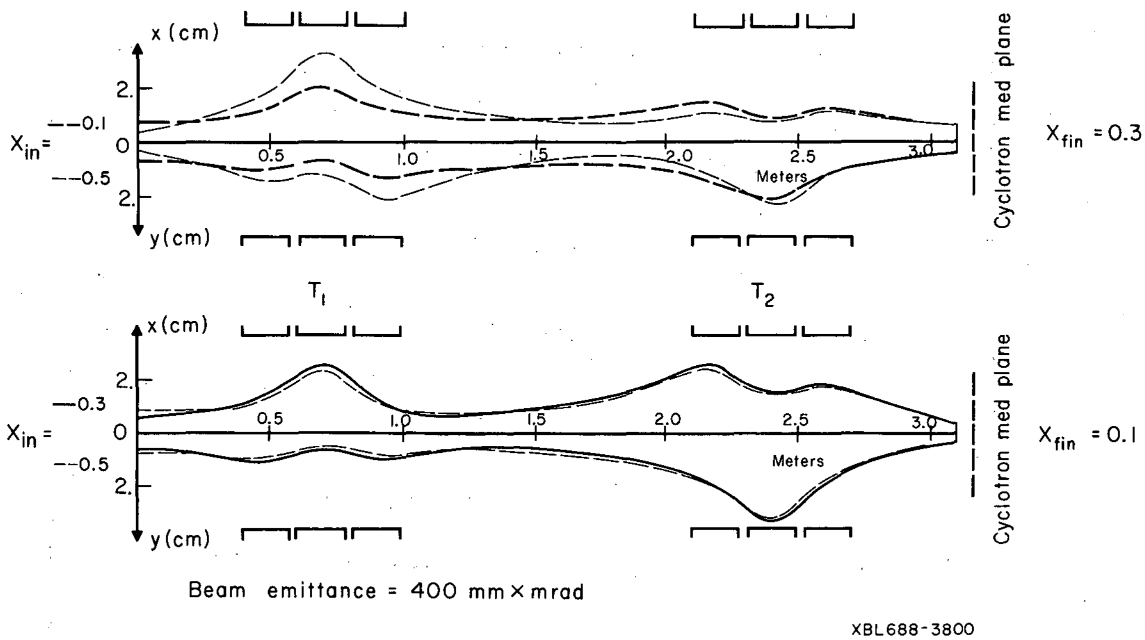

Fig. 7 Typical beam envelopes through triplets T_1 and T_2, for several X_{in} and X_{fin}, and waist position at 5 from the cyclotron median plane.

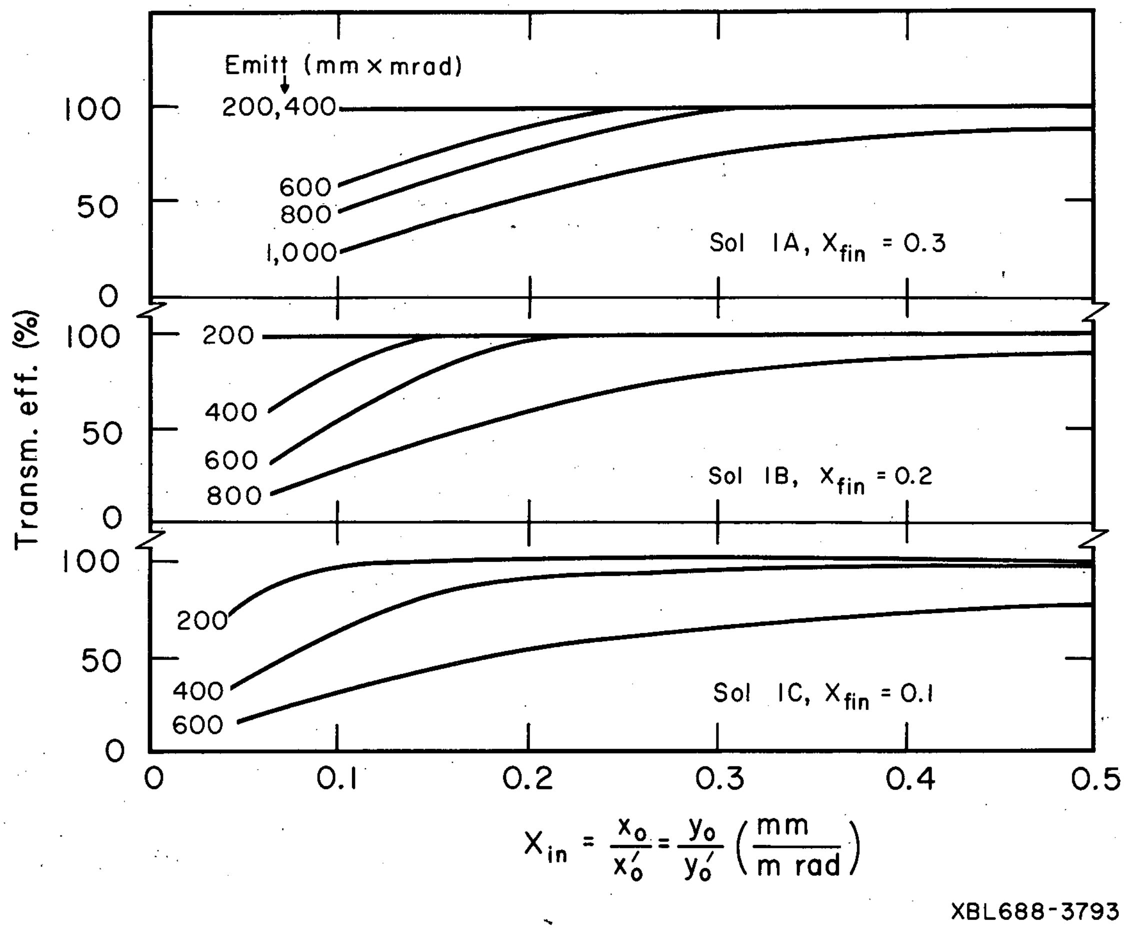

Fig. 8 Transmission efficiencies for beam emittances of 200, 400, 600, 800 and 1000 mm mrad over a range of X_{in} and X_{fin} values. Final waist position at 5 cm from the cyclotron median plane (Solution 1).