BNL-23353

MASTER

CONF-770988--1

A SEPARATED FUNCTION FOCUSING MONOCHROMATOR SYSTEM FOR SYNCHROTRON RADIATION*

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ABSTRACT

The design and performance of a new general purpose focusing monochromator system is presented. Such a system is ideally suited to collect, focus, and monochromate the highly directional, broad band synchrotron radiation.

*Research supported by the U.S. Department of Energy under Contract No. EY-76-C-02-0016, and the National Science Foundation.

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Introduction

The synchrotron radiation source has regenerated interest in x-ray optics. It also demands new materials and new ideas to fully utilize the properties of the source as well as giving old ideas a new life with the use of new materials.

Recently several focusing monochromator systems[1-3] have been built using synchrotron radiation for diffraction. In the following discussion these systems will be reviewed and the details of a new focusing system constructed at the Stanford Synchrotron Radiation Project will be presented. These systems are just the beginning of what will be an ever increasing number of specialized x-ray optical systems that match the needs of experiment with the unique properties of the synchrotron as a source for x-ray photons.

The paper will begin with a discussion of the phase space optics and design criteria of the existing and newly constructed focusing systems in the next section. This will be followed by a detailed discussion of the new instrument, its components and performance. Lastly, possible improvements upon this design will be presented with an eye to the new dedicated synchrotron radiation sources presently under construction.

Optical Design

There are two general classes of experiments using photons in the x-ray regime. One is spectroscopy and the other is diffraction and scattering. Each experiment has specific requirements for the properties of the photon beam. In general diffraction experiments are concerned with the

angular resolution as well as the energy resolution while spectroscopy has requirements only on energy. In both experiments the monochromator system should deliver the maximum flux within the design constraints. To look at the design of these systems, the ideas of phase space optics,[4] common to the design of charged particle beam transport, will be employed.

Laboratory sources of x-radiation in general radiate into 4π sterad. solid angle. There is no space-angle correlation of these photons, a photon passing through a small aperature some distance from the source could have originated from any part of the source. The synchrotron on the other hand radiates into the plane of the electron beam with only small vertical divergence, and the photons arriving at an aperature far from the source may have come from a particular portion of the source. This property is most easily described by looking at the vertical phase space diagram for the SPEAR light source, shown in Fig. 1. Shown are two ellipses, the solid line in an equi intensity contour for the space-angle correlation of the electron beam itself. Each electron can emit a photon with opening angle $1/\gamma$. This emission angle is added to the angular width of the electron beam quadratically and the resulting vertical source is indicated by the dashed line in Fig. 1.

The horizontal phase space description of the source is shown in Fig. 2. It is a bit more complicated than the vertical because not only does one include the properties of the electron beam and photon emission angle at a single point but also the curvature of the orbit. In the figure, the phase-space ellipse of the electron beam, including the opening angle of the photon is superimposed on the effects due to

the curvature of the electron orbit described by the two parabolae $(X')^2 \pm X_o$, where the beam has width $2X_o$. The numbers correspond to the source point at SSRP with R = 1.27 m and $2X_o$ = 3.2 mm. These source descriptions can then be used as the inputs to the design of the x-ray optical system.

One can apply the techniques of phase-space optics to the small angle scattering system in operation at SSRP. Figures 3 and 4 are the phas space description of the beam delivered to the specimen. By the use of a focusing mirror monochromator scheme a 10:1 demagnification of the source is achieved with a sacrifice of angular resolution. To analyze the match between the monochromator and the source the emittance of the source (area in phase space) should be compared with the acceptance of the monochromator. The match of this monochromator with the source is improved because of the use of a logarithmic-spiral monochromator, first suggested by deBroglie and Lindemann,[5] that allows all photons of the proper wavelength to reflect at the Bragg angle. This design, however, is difficult to use if rapid tunability is required and therefore a new concept was applied to the system recently completed at SSRP.

The new instrument was designed as a general purpose monochromator system to do spectroscopy as well as diffraction. Because of its general purpose design, one to one focusing was used. The phase space description of the beam delivered to the sample is shown in Figs. 5 and 6, for the horizontal and vertical source, respectively. These figures are relevant to the source point at SSRP. With one to one focusing adequate energy resolution is provided to do spectroscopy,

in particular extended x-ray absorption fine structure, as well as good angular resolution that has been used in a number of diffraction experiments. To do the EXAFS measurements rapid tuneability is required and to provide this in the present system a separated function monochromator was developed.

In general, when crystals serve both a focusing and monochromating role in an x-ray optical system wither their position with respect to the source, or their curvature must be changed with a change in Bragg angle. Therefore we decided to use the separated function idea and do all the focusing, both vertical and horizontal, with a mirror, and monochromate the beam with a double crystal spectrometer in the parallel mode, using flat crystals. The mirror not only provides the focusing but also harmonic rejection because of its high energy cutoff. Also, when operating at low energies where the mirror passes the primary energy as well as harmonics, the double crystal monochromator can be slightly mistuned to reject harmonics[6]. These ideas were implemented in the hardware discussed in the next section.

Instrument:

The whole instrument is shown schematically in Fig. 7. The mirror is located midway between the source and the focal spot, for a total distance of 20 m. The mirror surface is a bent cylinder, which approximates an ellipsoidal mirror. The mirror, made of fused quartz (SiO_2), was obtained from P. Horowitz who first used it as a condensing element for x-ray microscopy at the Cambridge Electron Accelerator[7] and in a paper with J. Howell the effectiveness of the bent cylinder and its performance as an approximation for an ellipsoidal surface are-

discussed in detail. In the present application the mirror is too short. Although it is wide enough to intercept 10 mrad. of horizontal divergence because of its length at a 10 mrad grazing angle it effectively collects only about 6 mrad.

One important aspect of the mirror was the question of plating the surface. There are tradeoffs between low Z and high Z surfaces. Low Z materials have a much sharper cutoff at this critical energy than high Z materials as can be seen in Fig. 8. However, the critical angle for a fixed energy goes as the square root of the density of the surface. For 8 KeV photons the critical angle for SiO_2 is 3.8 mrad while for Pt it would be roughly 10.6 mrad. In the balance, and because the mirror is only 60 cm long, a platinum surface was chosen. The platinum surface was applied in a UHV system that was ion pumped and therefore required no Cr under layer to insure good adhesion. The resulting surface has survived approximately 9 months of operation with no measurable degradiation in performance.

The monochromator consists of a double crystal spectrometer that rotates as unit about the first crystal. As such it acts like a "channel cut" crystal once aligned. Because the crystals are separate, however, one can detune the primary wavelength and reduce the harmonics as discussed earlier. Another possibility is to use assymetric cut crystals. This allows an increase in the angular acceptance of the monochromator, at the expense of beam size, to better match the admittance of the monochromator system to the source emittance. Mechanically, the second crystal of the two crystal system is provided with two orthogonal motions that are remotely controlled that permit the tuning of the monochromator system.

Performance:

The performance of the system has been measured with respect to beam size, mirror reflectivity and cutoff, the flux has been measured and the harmonic rejection at the low energy side of the spectrum has been determined. The 1σ beam size that was calculated with the phase-space optics gives a beam size of 1.6 mm x 3.2 mm and should be roughly elliptical. These dimensions, measured photographically give a beam size of approximately 2 mm x 4 mm in good agreement with design.

The reflectivity of the mirror was measured in a relative fashion. Using a solid state detector and looking at the scattering from the gas at atmospheric pressure the spectrum with and without the mirror were measured. By taking the ratios, and scaling to unit reflectivity, the curve of figure 9 was obtained. The solid curve corresponds to the reflectivity calculated for a Pt surface and a critical angle of 10 mrad and agrees well with the measured reflectivity.

The total flux was measured with SPEAR operating at 3.7 GeV electron energy and 20 mA of current gave 1×10^{12} photons/sec. in a five eV bandwidth at 7.1 KeV photon energy. This number compares favorably with the factor of 50 increase expected over the other EXAFS instruments at SSRP[8] where values of 2×10^{10} photons/sec. in a 1 eV bandwidth at 7.1 KeV have been measured at similar operating conditions. This flux increase corresponds to a factor of 150 in photons/sec/mm^2.

Harmonic rejection proved very successful in the energy range of 3 KeV to about 4.5 KeV. The monochromator consisted of two Ge(111) crystals so that the λ/2 combination from the (222) forbidden (222) reflection was small. At 3 KeV however, 9 KeV photons from the (333)

reflection do contribute to the main beam. By detuning, with a loss of twenty five percent of the 3 KeV flux, no detectable 9 KeV photons were present in the incident beam.

Conclusions:

Based on the measured performance, the separated function monochromator system at SSRP, provides the proposed photon beam characteristics. Improvements in the present instrument could be made by installing a longer mirror or multiple mirrors which would intercept the full 10 mrad of horizontal divergence. Also, the use of assymetric cut crystals would better match the source emittance. For specific experiments the one to one focusing may not be ideal but this system clearly demonstrates the advantages of spearated function design.

Acknowledgements:

The authors would like to thank the SSRP staff for its assistance in the construction of this system. The authors would also like to acknowledge the contributions of G. K. Green to our understanding of phase space optics.

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Figure Captions:

FIG. 1 Vertical phase space diagram for SPEAR light source.

FIG. 2 Horizontal phase space diagram for SPEAR light source.

FIG. 3 Horizontal phase space diagram showing 10:1 demagnification.

FIG. 4 Vertical phase space diagram showing 10:1 demagnification.

FIG. 5 Horizontal phase space diagram showing 1:1 focusing.

FIG. 6 Vertical phase space diagram showing 1:1 focusing.

FIG. 7 Schematic of separated function monochromator system.

FIG. 8 Reflectivity of platinum and fused quartz (SiO_2) as a function of $(\sigma-\sigma_c)/\sigma_c$.

FIG. 9 Relative reflectivity of Pt coated fused quartz mirror as a function of photon energy. The solid line is a calculation for Pt with a critical angle of 10 mrad.

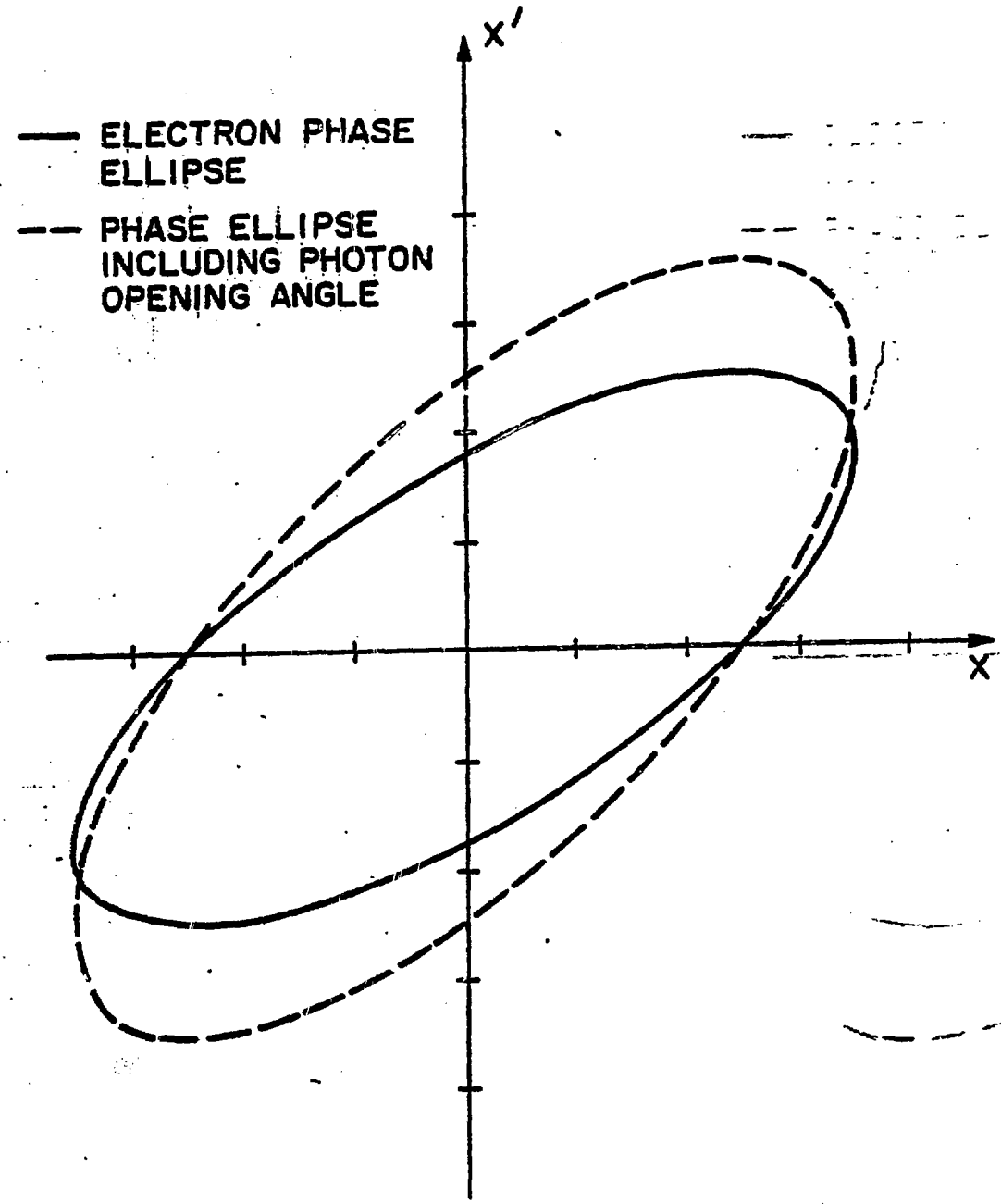
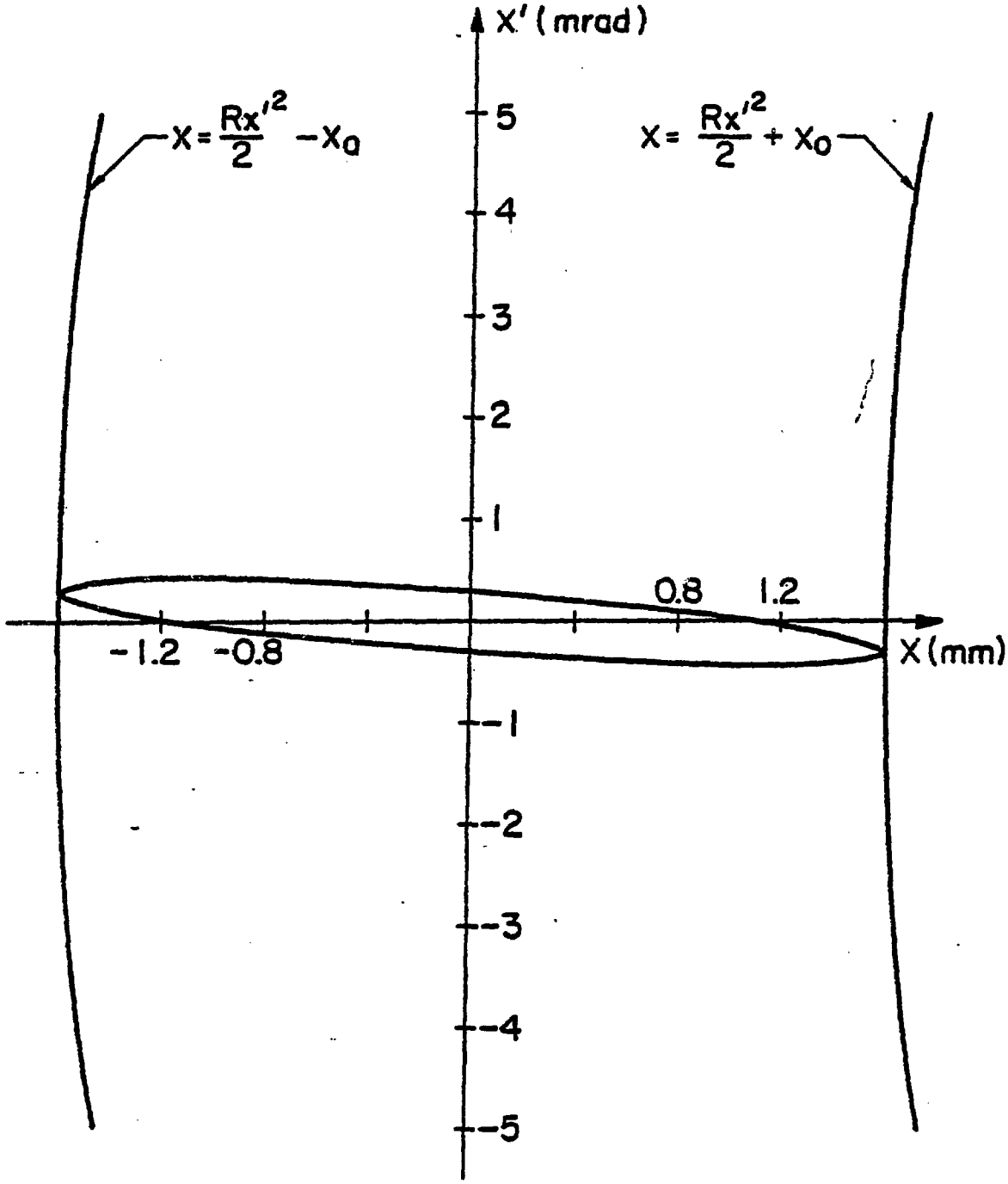
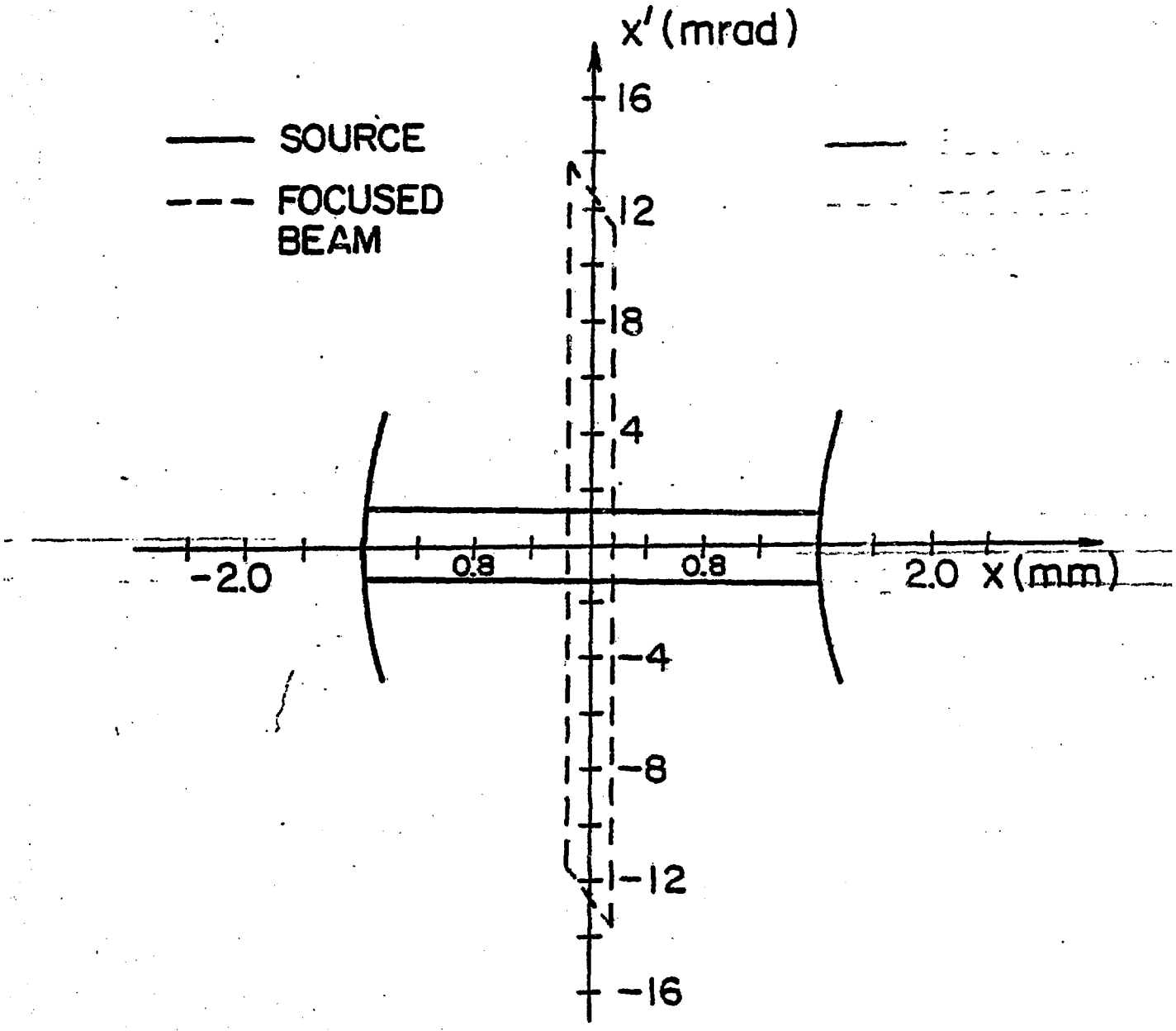
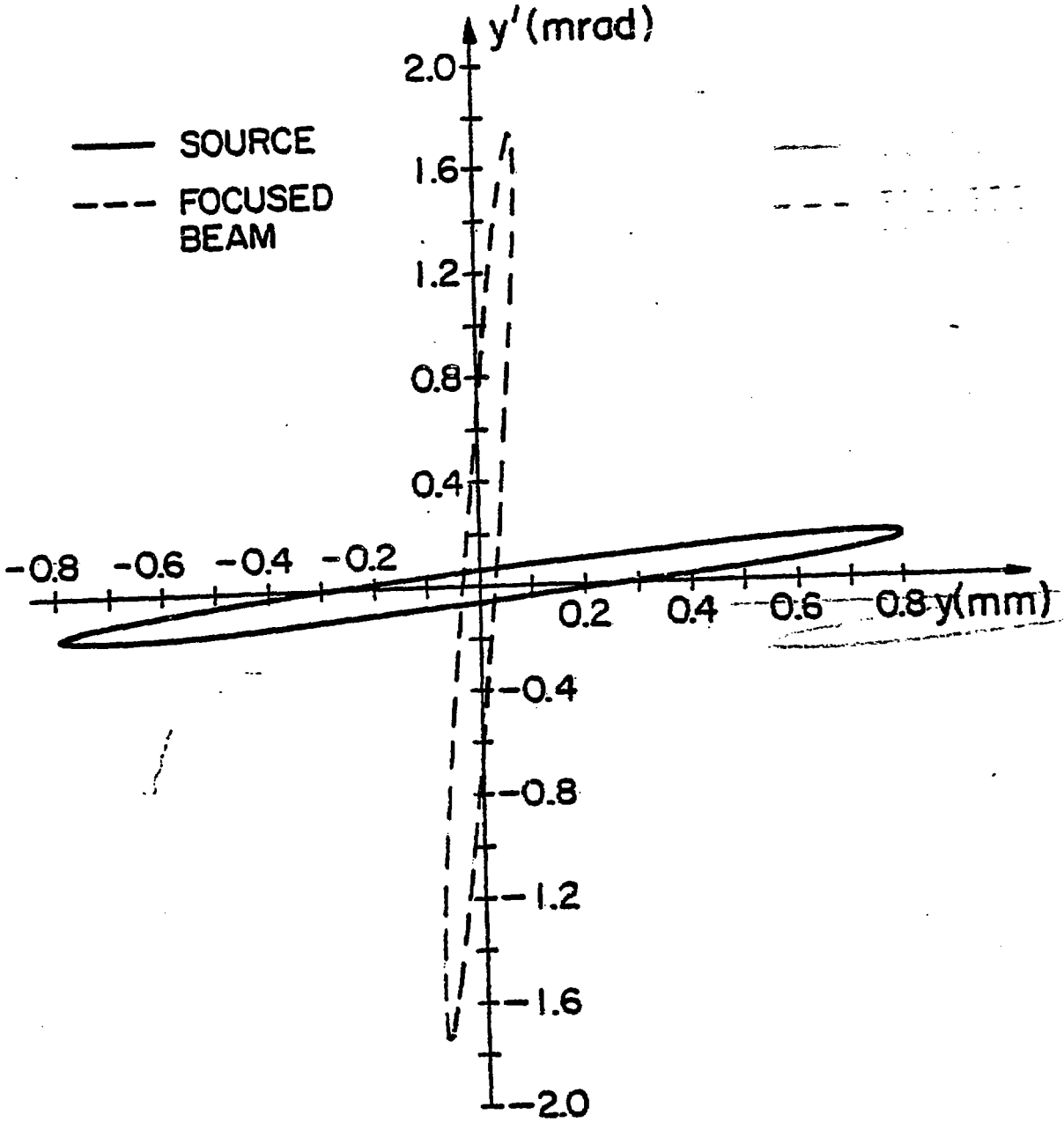

X'
X
ELECTRON PHASE ELLIPSE
PHASE ELLIPSE INCLUDING PHOTON OPENING ANGLE

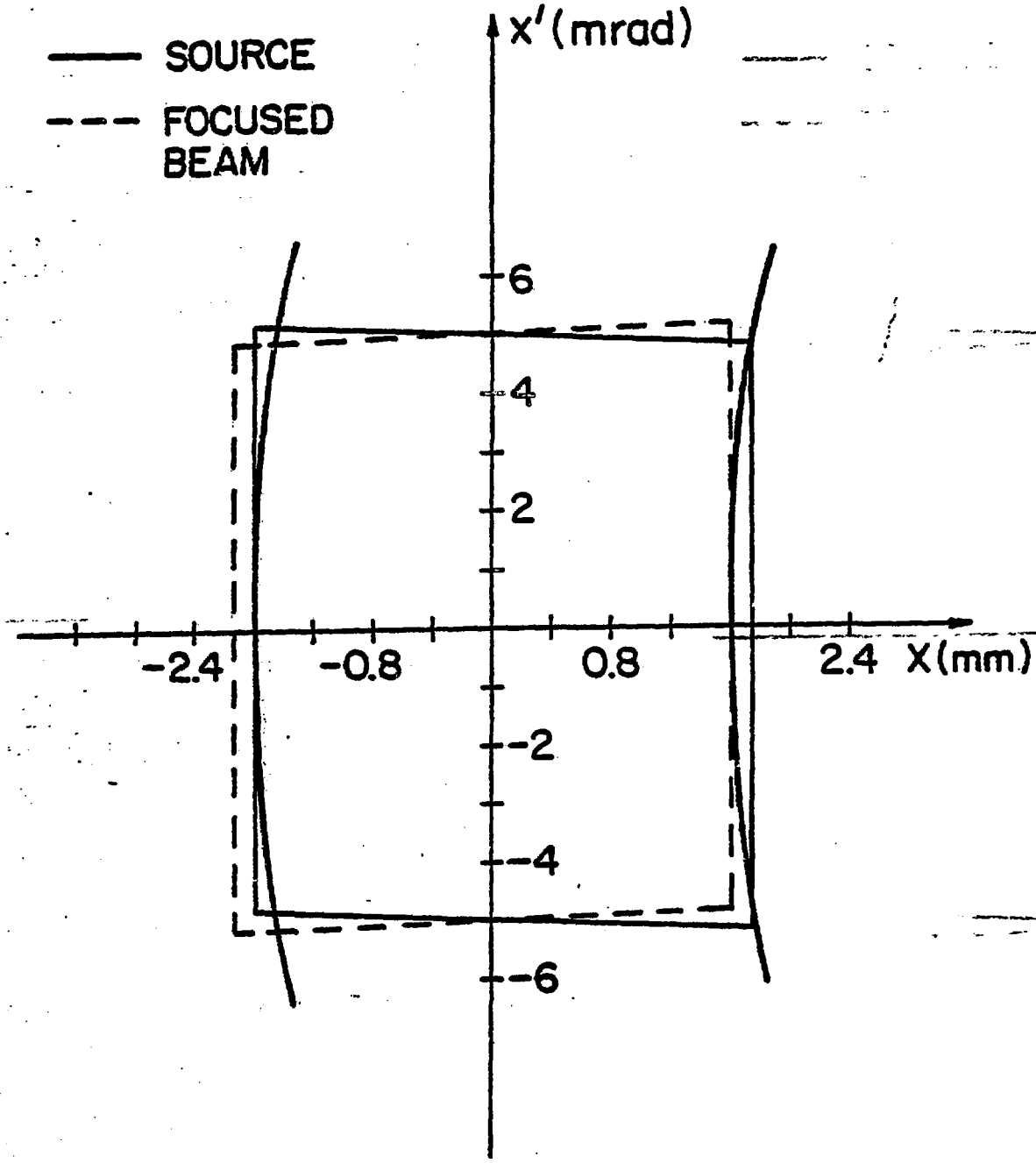
Fig. 1

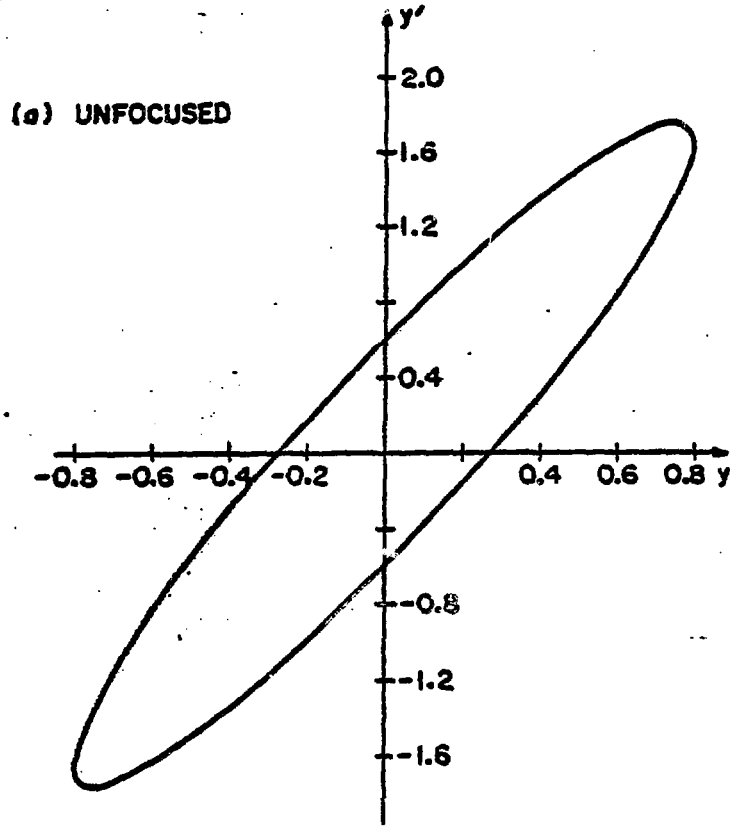


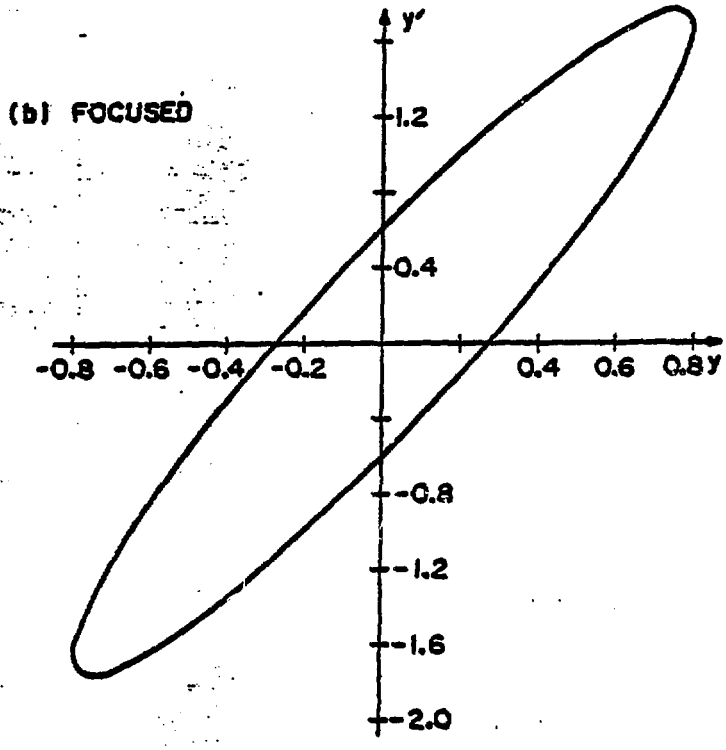
2

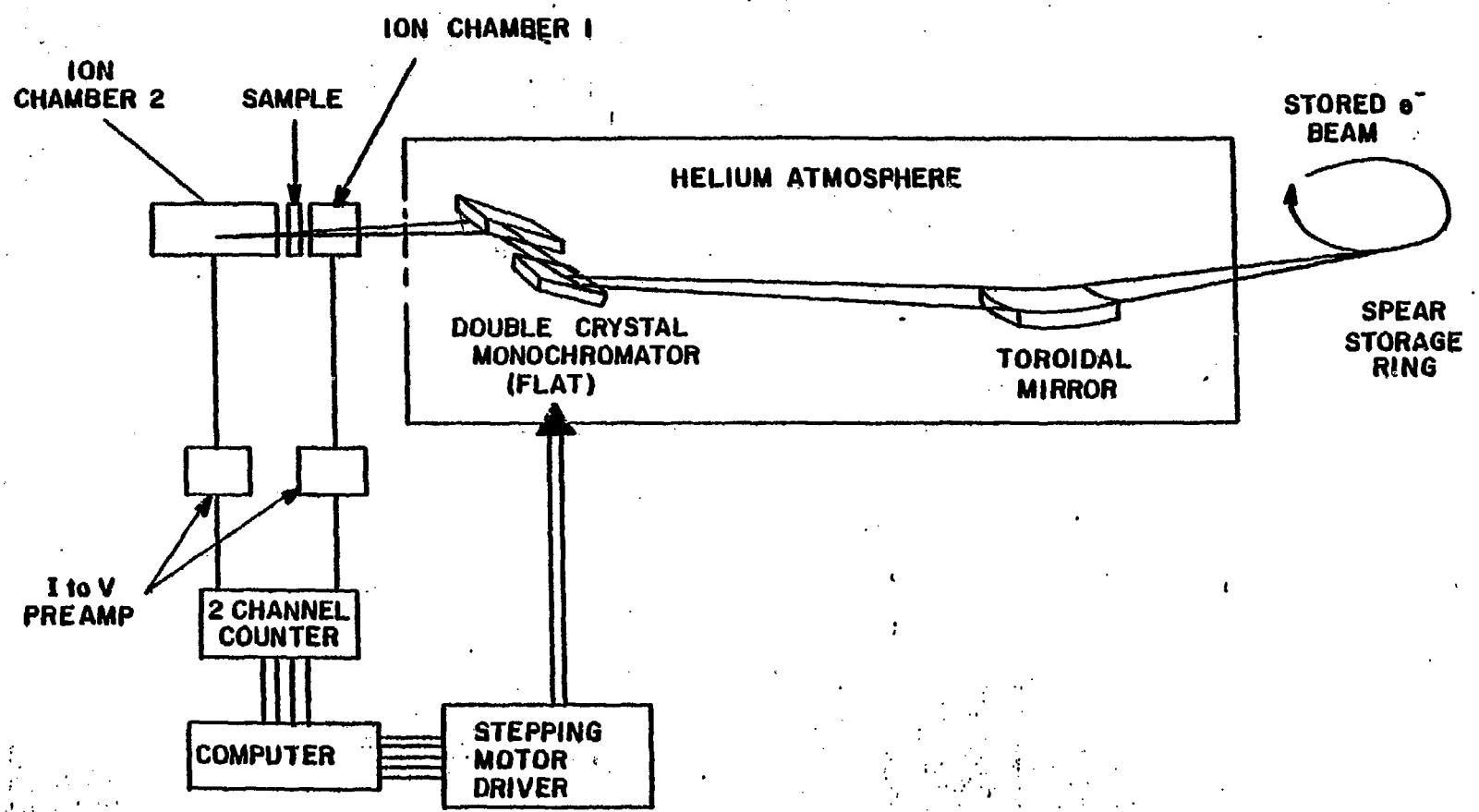

x' (mrad)
16
12
8
4
-4
-8
-12
-16
SOURCE
FOCUSED BEAM
-2.0
0.8
0.8
2.0
x (mm)

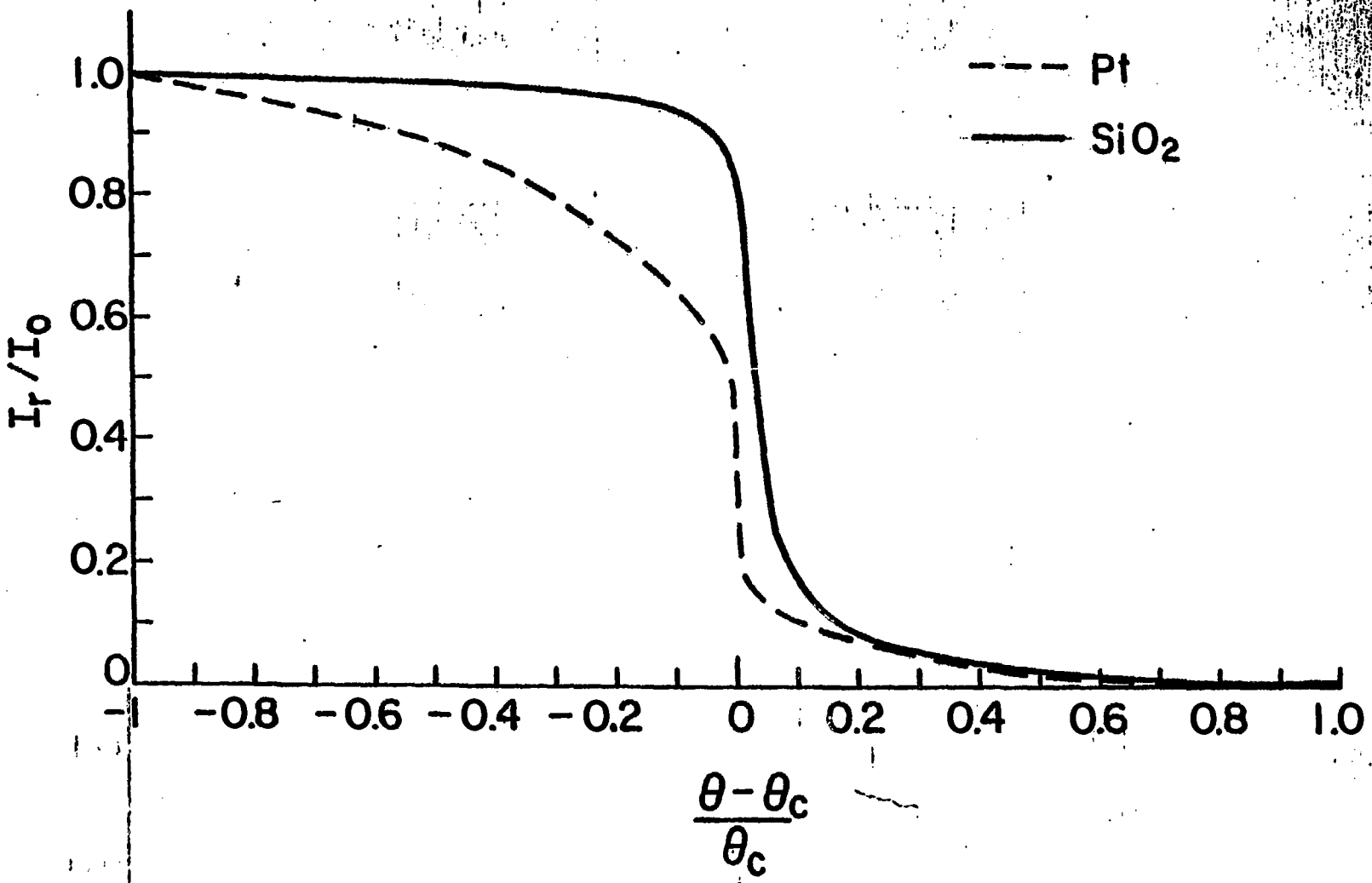

y'(mrad)
2.0
1.6
1.2
0.8
0.4
-0.4
-0.8
-1.2
-1.6
-2.0
SOURCE
FOCUSED BEAM
-0.8
-0.6
-0.4
-0.2
0.2
0.4
0.6
0.8
y(mm)


SOURCE
FOCUSED BEAM
x′(mrad)
6
4
2
-2
-4
-6
-2.4
-0.8
0.8
2.4
X(mm)


(a) UNFOCUSED
y'
2.0
1.6
1.2
0.4
-0.8
-1.2
-1.6
-0.8 -0.6 -0.4 -0.2
0.4 0.6 0.8 y


(b) FOCUSED
y'
1.2
0.4
-0.8
-1.2
-1.6
-2.0
-0.8 -0.6 -0.4 -0.2
0.4 0.6 0.8 y


ION CHAMBER 1
ION CHAMBER 2
SAMPLE
STORED e⁻ BEAM
HELIUM ATMOSPHERE
DOUBLE CRYSTAL MONOCHROMATOR (FLAT)
TOROIDAL MIRROR
SPEAR STORAGE RING
I to V PREAMP
2 CHANNEL COUNTER
COMPUTER
STEPPING MOTOR DRIVER


Pt
SiO2
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0.8
0.6
0.4
0.2
0
Ir / Io
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1.0
θ - θc / θc