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BEAM LINE DESIGN FOR SYNCHROTRON SPECTROSCOPY IN THE VUV *

by M. R. Howells

Brookhaven National Laboratory
Department of Physics
National Synchrotron Light Source
Upton, New York 11973

Abstract

The character of the radiation source provided by an electron storage ring is briefly reviewed from the point of view of utilization for VUV spectroscopy. The design of beam line components is then considered with special reference to the problems of contamination of optical surfaces and vacuum protection. The issues involved in designing mirrors for use with storage rings are considered with emphasis on the questions of power dissipation, image quality and materials selection.

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INTRODUCTION

It is now well established that the radiation emitted by electrons circulating in synchrotrons and storage rings is ideal for certain kinds of spectroscopy. In particular, its intensity, spectral continuity, wide wavelength range, high degree of collimation, strong polarization and good vacuum properties make it the best single source for many VUV applications.

The specialized nature of particle accelerators and the radiation hazards associated with them generally imply that they must be operated as major facilties shared by a number of users. The instruments which are required for spectroscopy are also quite special, and in recent years the design and operation of the beam lines, UHV systems, mirrors, monochromators, etc., which are needed for optimum exploitation of synchrotron radiation have developed into an important sub-branch of spectroscopic technology. Here we review the usual beam line structures which are used, with special reference to their limitations and their applicability to the new generation of storage rings which have been designed and built especially for use as light sources. We also examine the effect of some new techniques and design strategies which promise greatly improved experimental capability.

THE SOURCE

Synchrotron sources can deliver radiation from the X-ray region right through to the infra red and, indeed, they are actually used over most of this range. However, we confine our attention here to the VUV range (say 20-2000Å), although the presence of hard X-rays containing a large amount of power may have to be allowed for. Broadly speaking, the higher the energy of a storage ring, the higher the energy of the emitted photons and the higher the cost. Consequently, the most cost-effective storage ring for VUV work alone would have a fairly low energy, perhaps about 0.5-1.0GeV. Storage rings are always preferable to synchrotrons which suffer from temporal and spatial instabilities and radiation safety problems.

The synchrotron radiation spectrum consists of a single wide band whose low wavelength cut-off depends on the so-called critical wavelength of the storage ring given by:

$$\lambda_c = \frac{5.59R}{E^3} (\text{Å})$$

where R is the bending radius in m and E the energy in GeV. By plotting against the dimensionless parameter λ/λ_c one can have a universal curve for the synchrotron radiation spectrum[1]. This is shown in Fig. 1. Some examples of λ_c values for existing and planned synchrotron radiation sources are given in Table 1.

From an instrumentation point of view, the most important characteristic of the source is its geometry. The most naive definition of this is an extended source of spatial extent about 0.1-0.5mm vertically and 1-5mm horizontally and angular extent 1-10mr in the vertical direction and 1-50mr in the horizontal direction. These figures are typical of storage rings, not synchrotrons. The height, width and vertical angle are not sharply cut off, but are 2σ values of Gaussian distributions. In the VUV region, this naive picture is suprisingly adequate.

The physical origin of the height and width of the source is the geometry of the electron beam which is determined by the characteristics of the storage ring. The horizontal angle is limited by the size of the pipework used to take the radiation out of the machine and the vertical angle is determined by the physics of the emission process. The standard deviation σ_r of the angular distribution of the emitted radiation is given by:[2]

$$\sigma_r = \frac{570}{\gamma} \left(\frac{\lambda}{\lambda_c} \right)^{0.43}$$

where γ is the ratio of the electron's energy to its rest energy. The differences in the direction of electrons in different parts of the beam turn out to be small compared to σ_r in the VUV, although this is not normally true for X-rays. The only important complication is that there is some broadening of the source size in both the horizontal and vertical directions if a large horizontal angle ($\gtrsim$20mr) is accepted[3]. This arises because the source is now a long curved sausage of emitting points. The radiation originating at the back will have opened up to a certain width by the time it reaches the front. If this is larger than the electron beam width, then some vertical broadening will be seen. There is also a second effect which arises in an obvious way from the horizontal curvature of the sausage. This causes horizontal broadening.

Using these ideas, it is usually a simple matter to establish the spatial and angular extent of the source for a particular application, and this is the starting point for the design of a beam line to exploit the synchrotron radiation. We notice that the radiation is projected forward from a small source into a fairly small solid angle. Therefore, we have a source with high brightness and this is important because it is the parameter which determines the possible performance of optical instruments.

GENERAL LAYOUT OF EXPERIMENTAL BEAM LINES

In order to deliver monochromatic light on to a sample, which is by far the most common requirement, we need to construct beam lines with the following general features:

1. A 'front end'[4]. (See Fig. 2) This includes the components closest to the storage ring which are normally common to all beam lines.
2. A 'separation chamber'. This will contain one or more mirrors and will separate the light into several distinct beam lines.
3. Connecting sections.
4. A monochromator which delivers light from an exit slit.
5. A mirror to transfer light from the exit slit onto the sample.
6. The 'experiment'. We will not consider this aspect.

The 'front end' should consist of:

(i) A bellows to mechanically decouple from the storage ring vacuum vessel.

(ii) A UHV gate valve, preferably an all metal one.

(iii) A heat shield to prevent the synchrotron radiation from heating up the gate valve.

(iv) A fast valve with a closing time of about 10-15ms.

(v) A heavy shutter which can stop whatever hazardous radiation would come down the beam pipe in the event of the worst credible accident.

None of these items is particularly straightforward.

The separation chamber should be a UHV chamber to maintain cleanliness of the mirror surfaces. Its design is a problem in geometry, the idea being to find ways to reflect light down each beam line with appropriate small deflection angles without the chamber becoming unmanageably large. Once the geometry of the beam lines has been resolved, then the general character of the mirrors required can be determined. Both the science and technology of the mirrors are matters of considerable current interest and will be discussed later.

BEAM LINE VACUUM SYSTEM

The connecting sections are rather straightfoward but two issues arise. The overall vacuum in the whole beam line should be in the UHV range unless some compelling reason, like the use of gaseous samples, prevents it. Even then, the base vacuum with the sample absent should be UHV. The levels of contaminants (hyro-carbons) should ideally be monitored and offending beam lines isolated from the rest of the system. The nature of the contamination layers which are so fatal to the efficiency of mirror and grating surfaces is not altogether clear. It is known to contain mainly carbon and it has been suggested[5] that the structure might resemble graphite. It is also established that the incident radiation, even if it be of low energy, plays a role in creating the deposits. There are some encouraging reports that indicate that meticulous attention to vacuum cleanliness pays off handsomely. Workers at Tantalus I, SURF II and ACO have all reported that for total pressures $<10^{-9}$ torr reflectors have shown undiminished efficiency after a year or so of use. At SURF II, the criterion for vacuum acceptability is that the largest hydro-carbon peak be 10^3 times smaller than the largest low mass peak. Experience with this condition has shown that freedom from the effects of contamination can be achieved even for unbaked systems working in the 10^{-8} torr range. The experience at ACO is even more encouraging since, unlike SURF II, ACO has substantial flux above the carbon K edge.

Another aspect of the contamination issue is the possibility of cleaning off the carbon layer. This has been investigated experimentally by space vehicle designers[6,7,8]. Beverly and co-workers deliberately contaminated various mirror surfaces with butadiene in the presence of VUV radiation or protons and measured the reflectance in the range 1000-3000Å to monitor the situation. The surface reflectances were reduced, typically, by more than an order of magnitude after contamination. (See Fig. 3) The surfaces were then exposed to atomic oxygen from an electrodeless r.f. discharge for about half an hour. In all cases, the reflectance was restored to its original value. Similar experiments were conducted with Al/MgF_2 and platinum coated replica gratings. In both cases, the first order diffraction efficiency was reduced below 2500Å, but increased at longer wavelengths. In the case of the platinum coated grating, the efficiency at 1000Å decreased by a factor of 30. For all these cases the cleaning process restored the original efficiency. Similar tests on uncontaminated gratings and mirrors showed that the cleaning process produced no significant harmful effects.

These results are so encouraging that some similar work is clearly indicated for optics contaminated by synchrotron radiation.. One can imagine that if the process works in the desired manner, then one would try to install in situ cleaning arrangements.

Another aspect of general beam line design is the impedance offered to the incoming shockwave of atmospheric air following a sudden rupture of the vacuum envelope. Considerable work has been done[9,10] to evaluate the effect of various 'delay line' structures in slowing down the shock wave, the idea being to give more time for the fast valve to close. The delay lines consist of a series of baffles placed concentrically in a widened section of the beam pipe. The experiments indicate that these devices do effectively reduce the speed of propogation of the shock wave and, in view of the low cost involved, it is obviously a good idea to incorporate delay lines in cases where a suitable space is available. However, since their role is to reduce the speed of the shock wave, they should be placed near the likely position of the accident and as far as possible from the storage ring. Some further experiments[11] have indicated that normal beam line components, especially slits and large vacuum vessels, are extremely effective as informal 'delay lines', so it is probably not necessary to make any real sacrifices in order to find space for a purpose-built delay line.

MIRRORS

The Power Problem

For both X-ray and VUV work it is usual to collect as much synchrotron radiation as possible with a mirror which directs the radiation into an optical instrument. In both cases, this mirror must receive the full synchrotron radiation power output of the storage ring on its surface and this presents a serious technical problem. Half the radiated power is contained in wavelengths below λ_c and so for X-ray experimenters the needed radiation contains a great deal of power which must be allowed for until after monochromatization. For VUV work the problem is not quite so serious. With high energy storage rings, the first mirror must function as an X-ray filter and, therefore, must still operate with a high power loading. However, this mirror is normally a 'transfer' mirror so that imperfections cause only a loss of flux, not resolution. Furthermore, it is often possible[12] to arrange for this mirror to be a rather simple shape such as a flat so that one does not have to simultaneously solve the problems of power dissipation and complex optical figuring. A better solution still is to do VUV experiments on a low energy storage ring, although suprisingly, the power problems do not scale with the power output. This is because of the use of larger acceptance angles, shorter working distances and less grazing reflectors compared to the X-ray case. To get an idea of the magnitudes involved, the maximum power output in watts per milliradian of the Brookhaven X-ray source, the SPEAR storage ring and the Brookhaven VUV source are respectively 34, 20 and 1.8. A normal incidence mirror collecting 50mr at 2.5m on the Brookhaven VUV source would receive a total power of 88W with a power density on the center strip of about $20W/cm^2$. These figures are not far different from those quoted for the SPEAR 4° beam line mirror[12] (125W and $5W/cm^2$), so we see that even for purpose built VUV sources we must still give serious consideration to the power problem. We notice, however, that in this example the mirror would only be 125mm long, suggesting that the problem is manageable.

It is clear that the general problem of designing and fabricating mirrors for synchrotron radiation is a very challenging one. It is fortunate that at the same time as the first generation of a dedicated synchrotron radiation sources are being developed, there are several other optics-based fields which are also going through periods of rapid development. These include high power lasers, laser fusion, X-ray astronomy and various defense-related technologies. The motivation provided by these interests has caused a surge of progress in optical fabrication methods and design techniques. The awareness within the synchrotron radiation community of the general nature of the mirror problem, and the evolving solutions to it, owes much to the work of Rehn[12,13,14,15]. Here we give a general review of the state of the art and add one or two new ingredients and speculations.

Performance Limitations

Ideally, we would like the mirror to make a perfect image of the source without any loss of radiation. We list here the various limitations that, in practice, will prevent that happening and then consider them individually:

1. Aberrations: It is well known that a perfect imaging system for an extended source cannot be designed[16], even in principle, so some aberrations are always present. The use of single bounce grazing incidence reflectors, which is common in synchrotron radiation practice, gives rise to large aberrations. These would occur even for a perfectly figured surface.
2. Inefficient Reflection: This is primarily a matter of the choice of coating and its level of carbonaceous contamination.

3. Scattering [17,18]: The microscopic roughness of real surfaces causes small errors in the direction of reflected rays. The result is that the reflected angular distribution has 'wings' either side of the specular direction. For the shorter wavelengths, these contain a significant amount of flux. The only cure is to use extremely smooth reflecting surfaces.

4. Inaccuracy of Figuring.

5. Thermal Distortion : The concentration of most of the power load into the center strip causes thermal gradients and, hence, differential thermal expansion.

6. Mechanical Instability.

7. Irreversible Surface Damage by Heat or Radiation.

The question of aberrations is readily amenable to calculation and one can determine by means of ray tracing whether or not a mirror of a given shape will give an acceptable image of the source for a particular application. However, generally speaking, one is constrained in the choice of figure, and figuring accuracy, by considerations of cost and these are affected by the method of fabrication and the choice of materials. Similarly, the surface smoothness which is achievable is best for simple shapes (spheres and flats) and depends on the choice of material and and the money available. Thermal and mechanical stability and resistance to surface damage are all materials issues, but the possible choices are also constrained by cost.

We see that the choices facing the designer are all inter-linked and there is really no simple prescription for finding an optimum. The starting point is the performance required by the user of the beam line and one can derive from this an estimate of the aberrations that can be tolerated. It is then necessary to understand the aberration properties of the various possible reflecting systems and determine which ones can meet the requirements. One must then try to choose a material and a realistic method of fabrication which can satisfy all of the constraints, including cost. This is often very difficult at the present time, but to achieve the best trade-offs, one must obviously have a good understanding of aberrations and optical materials and their fabricability, performance and cost. We now consider the questions of aberrations and materials in more detail.

Aberrations in Grazing Incidence Reflectors

It is well known that single grazing incidence mirrors give very poor images. They are useless, for example, as X-ray microscopes. The reason the images are so bad is usually coma, which arises because the sine condition is violated severely by all single grazing reflectors. One way to approximately satisfy the sine condition and get vastly better images is to use two reflections. The principles underlying this were discussed originally by Wolter[19] in 1952 and many others since[20,21,22]. They form the basis of modern X-ray telescopes and have been applied successfully to X-ray microscopy.[23]

To understand in a simple way how bad the single reflector is and why the double reflector is so much better, we proceed as follows: consider the simple paraboloid of revolution shown in Fig. 4 and consider the image produced by the thin ring of reflecting surface $P_1\ P_2\ P_3$. For the rays (shown as continuous lines) that enter parallel to the axis the image is perfect and the rays unite at F. In other words, there is no spherical aberration. For the rays (shown dashed) that enter at a small angle δ below the axis-parallel rays, the reflected rays from P_1 and P_3 will both be deflected downwards by δ and will meet the focal plane at F_1 and F_3, which are both below F. In the projection in which we are looking at the dashed ray through P_2, it will appear undeflected and will arrive at F_2, which is above F. From the geometry of the figure we can see that:

$$FF_1 = \frac{-r'\sin\delta}{\cos(\alpha+\delta)}$$

$$FF_3 = \frac{-r'\sin\delta}{\cos(\alpha-\delta)}$$

$$FF_2 = r'\tan\delta$$

where $r' = P_1F$ and $2\alpha = P_1\hat{F}P_3$.

If we now take $\delta \ll \alpha$ we get that F_1 and F_3 become the same and both have :

$$y = \frac{-r'\delta}{\cos\alpha} \qquad (1)$$

F_2 has

$$y = r'\delta \qquad (2)$$

Thus, if F_1 and F_2 are to be the extremities of a circle then it must have radius R given by:

$$R = \tfrac{1}{2}\, r'\delta \left(\frac{1+\cos\alpha}{\cos\alpha}\right) \qquad (3)$$

We can guess from the symmetry of the situation that the image must indeed be a circle. If we look up the textbook version of this, we find that the circle has:

$$R = \tfrac{1}{2}\, r' \tan\delta \left(\frac{1+\cos\alpha}{\cos\alpha}\right)$$

and that its center is shifted off axis by s where

$$s = -\tfrac{1}{2}\, r' \tan\delta \left(\frac{1-\cos\alpha}{\cos\alpha}\right)$$

If we consider an extended object distant r from the reflector and a point on the object distant Δ from the axis, then for the grazing incidence case δ is Δ/r and α is small so $\left(\frac{1+\cos\alpha}{\cos\alpha}\right) \sim 2$ giving that $R \sim \frac{r'}{r}.\Delta$ or $R \simeq \Delta$ x magnification.

In addition, $\left(\frac{1-\cos\alpha}{\cos\alpha}\right) \simeq 0$ so the image of an off-axis point is a circle centered on the axis and the circle passes through the point where the object point should have been imaged.

This striking conclusion allows us the following insights:

1. The effect of using a ring of reflector with a finite width would be to create several concentric circles with different R values but for practical synchrotron radiation cases, the differences would not be very large.
2. These conclusions are valid for any surface of revolution for which spherical aberration can be neglected. This may sometimes include the toroid.
3. We see why in near normal incidence the paraboloid gives good images. For this case $\alpha \simeq 180°$ and $\left(\frac{1+\cos\alpha}{\cos\alpha}\right)$ is close to zero.
4. As the point P runs once around the ring of reflector $P_1 P_2 P_3$, the ray traces out the image circle <u>twice</u>. This is typical of coma.

5. We can now see the effect of using an incomplete surface of revolution. Suppose our reflecting surface subtends an azimuth ϕ at the axis. Then the image will be an arc of the image circle of angle 2ϕ. The location of the arc will be determined by the direction of the off axis displacement Δ.

We are now in a position to calculate the image shape for a more or less practical case. Consider an ellipsoidal mirror imaging a rectangular source 0.2mm high and 1.0mm wide with a vertical deflection. Suppose the angle of incidence is 85° and the object and image distances are 2.5m and 1.5m, respectively. Now if the horizontal angle collected is 30mr, the mirror width comes out as 62.5mm and ϕ is 16.5°. The resulting image can be constructed as shown in Fig. 5. We recognize the expected 'bow tie' shape. Furthermore, we have the important conclusion that the primary determinant of image quality for this case, is the angle ϕ. We see that by using rather small ϕ values we can get 'images' that may be tolerable for spectroscopy even if microscopy is out of the question. The consequence of using a large ϕ value would be a circular image.

We can use the same approach to understand the double reflection Wolter telescope[19]. The layout of this is shown in Fig. 6. Following Wolter, let us suppose that the ring of reflecting surface P_1 P_2 P_3 contains the 'joint' between the two reflectors. Consider the same three rays through P_1, P_2 and P_3.

The difference now is that because of the double bounce, the dashed rays from P_1 and P_3 will be deflected upward by δ instead of downwards. Now, FF_1' has:

$$y \approx +\frac{r'\delta}{\cos\alpha}$$

and FF_2 still has

$$y \simeq + r' \delta$$

so that for F_1 and F_2 now to be extremities of a circle, the radius must be R_w where

$$R_w \simeq \tfrac{1}{2} r' \delta \left(\frac{1-\cos\alpha}{\cos\alpha}\right) \qquad (4)$$

which agrees with Wolter's result. We see from (3) and (4) that the double reflection brings about an improvement in imaging by a factor of $\frac{1+\cos\alpha}{1-\cos\alpha}$. For small α this is a huge factor and gives us image quality comparable to a normal incidence paraboloid. It also allows large ϕ values to be used if desired and has the added benefit of doubling the angular separation between neighboring beams.

Materials Questions

The material which is traditionally used for optical quality mirrors is fused silica. A highly refined technology exists for producing extremely smooth accurate figures in fused silica and similar materials such as zerodur. These materials are thus the materials of choice for cases where they can be used. Unfortunately, for applications where high power loadings and hard X-rays are present, these materials fail, often catastrophically[24]. In addition, for very large mirrors of highly complex figure the conventional fabrication methods may be prohibitively expensive. In this case, a good alternative is the new technique of diamond turning[25,26,27]. This offers extreme flexibility in figure but is limited generally to certain metals.

Most of the items listed above as performance limitations are issues which bear on the materials question and Table II collects a range of information about a number of candidate materials to allow an overview. Based on the considerations there one can make the following general statements:

1. Zerodur is best if the levels of power and hard radiation are low and fabrication problems are not too complicated.
2. For the most hostile environments, SiC is by far the best material if it can be obtained and figured in the required size and shape.
3. A good alternative to SiC is Copper/Electrodeless Nickel or Aluminium/Electrodeless Nickel.

The use of copper or aluminium is a close choice. For the largest heat loads, copper is certainly better[24], but aluminium/electrodeless nickel has been very widely used for X-ray telescopes[18,28] because of its weight advantage. Consequently there is a large body of experience in the use of aluminium and there are established proceedures[29] for overcoming the long term mechanical stability problem. Both copper and aluminium are well suit. for diamond turning and for water cooling arrangements. Aluminium alloy 6061-T6 has a possibly non-trivial cost advantage over almost anything. A sensible division based on present technology may be that for smaller sizes and simpler figures, SiC is best. Otherwise copper or aluminium plated with electrodeless nickel are probably more realistic.

All of the above materials are substrate materials and apart from SiC in the range 10-22eV they are generally not suitable for reflecting surfaces. It is normal to use a thin coating of heavy metal to obtain the best reflectance, the most popular being gold and platinum. Nickel[30] has also found some use as a reflector in X-ray and soft X-ray telescopes. There is a case[5] for thinking that platinum and nickel may catalyze the reaction that leads to the formation of contaminant layers so perhaps gold may be the safest alternative. Hunter, et al[31,32], have pointed out that not all metal/metal layers are stable. Some show a slow diffusion which leads to dissintegration of the top layer and a drastic worsening of its reflectance. The diffusion process is naturally much more rapid at higher temperatures. Gold on aluminium and gold on chromium have been observed to fail in this way. Platinum on copper is proven[12] to be stable. It may be that some experimental work, or at least further scrutiny of past experience, is required here.

CONCLUSION

Following the hardware discussed above, one normally has the exit slit of a monochromator which delivers monochromatic photons into the experiment. The design of monochromators which are compatible with the UHV environment, high intensity and wide spectral coverage of the storage ring sources now becoming available is a highly challenging problem which has been reviewed elsewhere.[33,34]

One can see that to achieve the optimal exploitation of the properties of synchrotron radiation, one has to make use of a number of advanced design techniques and fabrication methods. To some extent, these developments have been stimulated by the needs of the science, but we may hope that as the various dedicated synchrotron radiation sources grow toward maturity, the reverse will occur and the range of scientific questions that can be addressed will be an ever-widening one.

Figure Captions

Fig. 1 - Universal Synchrotron Radiation Spectrum.

Fig. 2 - Typical 'front end' components for a VUV storage ring light source.

Fig. 3 - Measurements of Beverly, et al, on a MgF_2/Al-coated mirror.

(a) Uncontaminated mirror

(b) After contamination with butadiene.

(c) After 5 minutes exposure to oxygen plasma.

(d) After a further 5 minutes.

(e) After a further 15 minutes.

(f) After a further 17 minutes.

Fig. 4 - Aberrations of a simple paraboloid of revolution. Two incoming beams of light are considered: an axis-parallel one and another making angle δ to the axis. One can see from the drawing that the angle $yF_1'P_1 = \pi/2 - (\alpha-\delta)$ and $yF_1P_1 = \pi/2 - (\alpha+\delta)$.

Fig. 5 - Simple geometrical construction of an 'image' formed by the single grazing incidence reflector described in the text. The object is rectangular and the circular arcs in the image plane due to the points marked 'x' are shown. The explanation of the well known 'bow tie' image is easily seen.

Fig. 6 - Layout of Wolter telescope. The parabolic primary and hyperbolic secondary have a common focus. For a microscope the parabola would need to become an ellipse.

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*Stanford Synchrotron Radiation Laboratory.

TABLE I

STORAGE RING RADIATION SOURCES

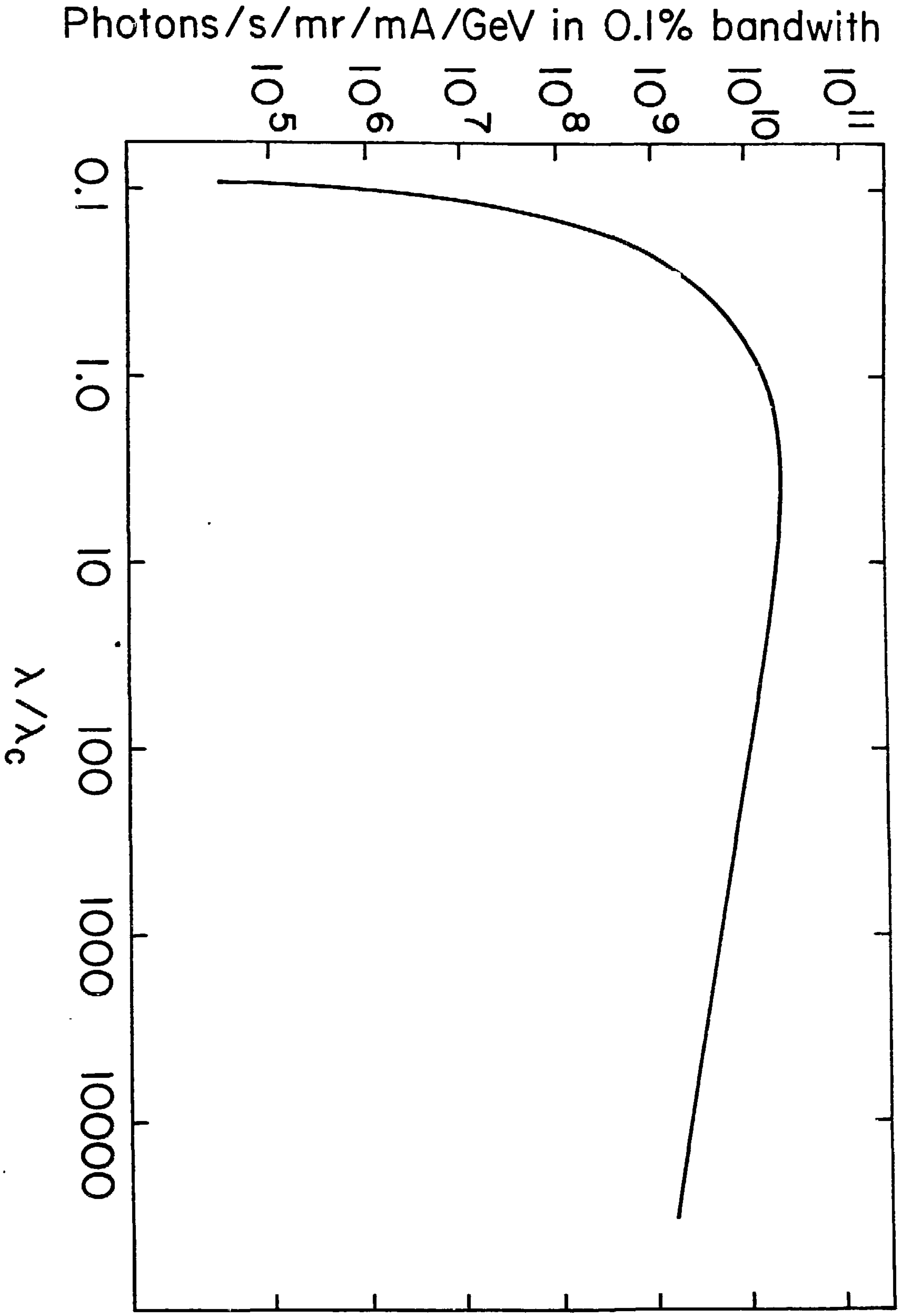
Name & Location	Energy (GeV)	λ_c (Å)
ACO (Paris)	0.54	39
DORIS (Hamburg)	5.0	.54
PHOTON FACTORY* (Tsukuba)	2.5	3.0
VEPP-2M (Novosibirsk)	0.67	23
SPEAR (Stanford)	4.0	1.1
VUV SOURCE* (Brookhaven)	0.70	31
TANTALUS I (Stoughton)	0.24	260

* - Under Construction.

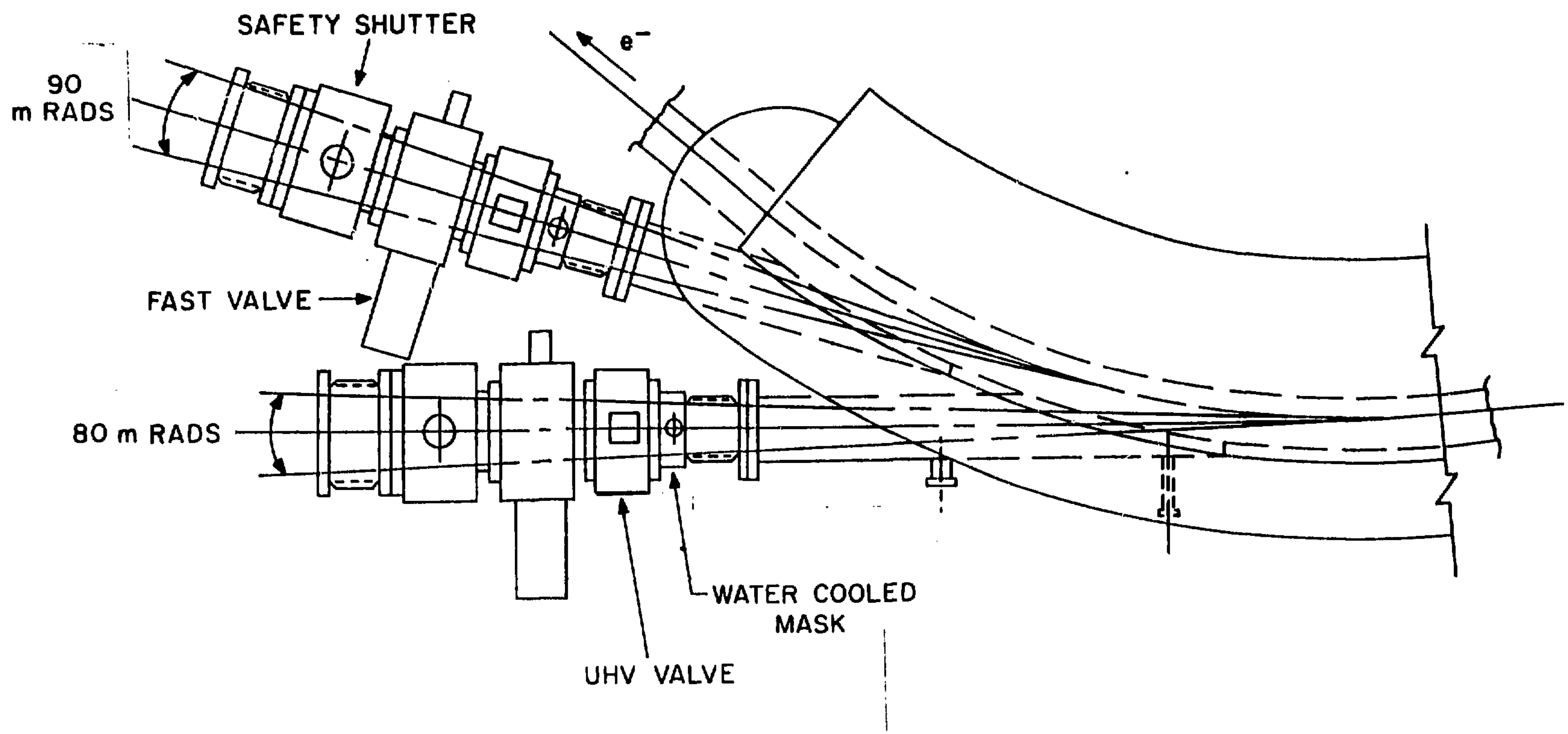
TABLE II

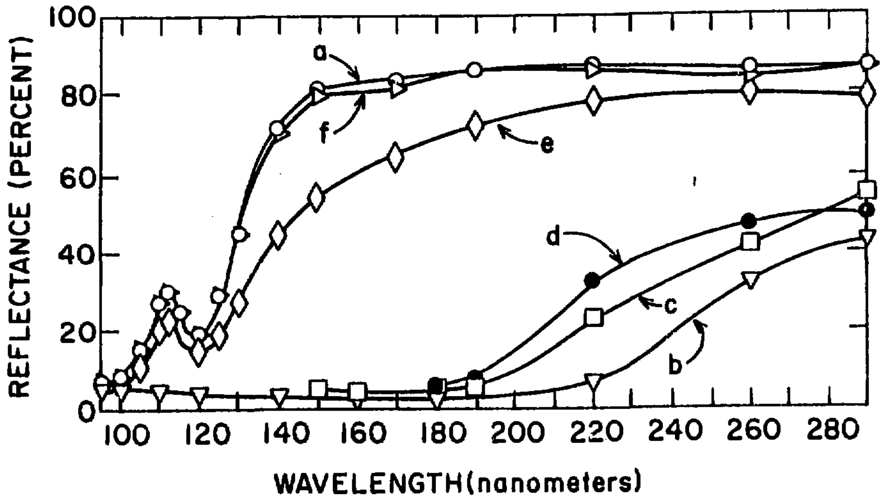
	Fused Silica	Zerodur	CVD-SiC	Si/Ge	Cu	Al	Electrode-less Ni	Be	Mo	Stainless Steel
Thermal Distortion Figure of Merit K/α (10^{-5}w/cm)	0.25[14]	3.2[14]	6.7[14]	Si:2.5[14]	2.5[14]	1.0[14]		1.7[14]	2.7[14]	.15
Polishability: rms Roughness (Å) Reported	<2.5[18] Normally* 13	<2.5[18]	Normally 10		30[35,36] Normally 50		<10[18] Normally 18		40[35] 20[36] Normally 50	Normally 40
UHV Properties	Good	Good	Good but Possible Substrate Problems.	Good	Good	Good	Good	Good	Good	Good
Availability in Large Sizes	Fair	Good[18]	Poor	Poor	Good	Good	--	Good	Fair	Good
Thermal/Radiation Damage Resistance	Poor[24]	Poor[24]	Out-Standing[24]	Poor[24]	Good[24]	Fair[24]	Good[24]	--	Good	Good
Diamond Turnable	No	No	No	Yes	Yes	Yes	Yes	No	No	No
Long Term Mechanical Stability of Large Pieces	Good	Out-Standing[37]	Probably Good	Probably Good	--	Some Problems	--	Good	--	--

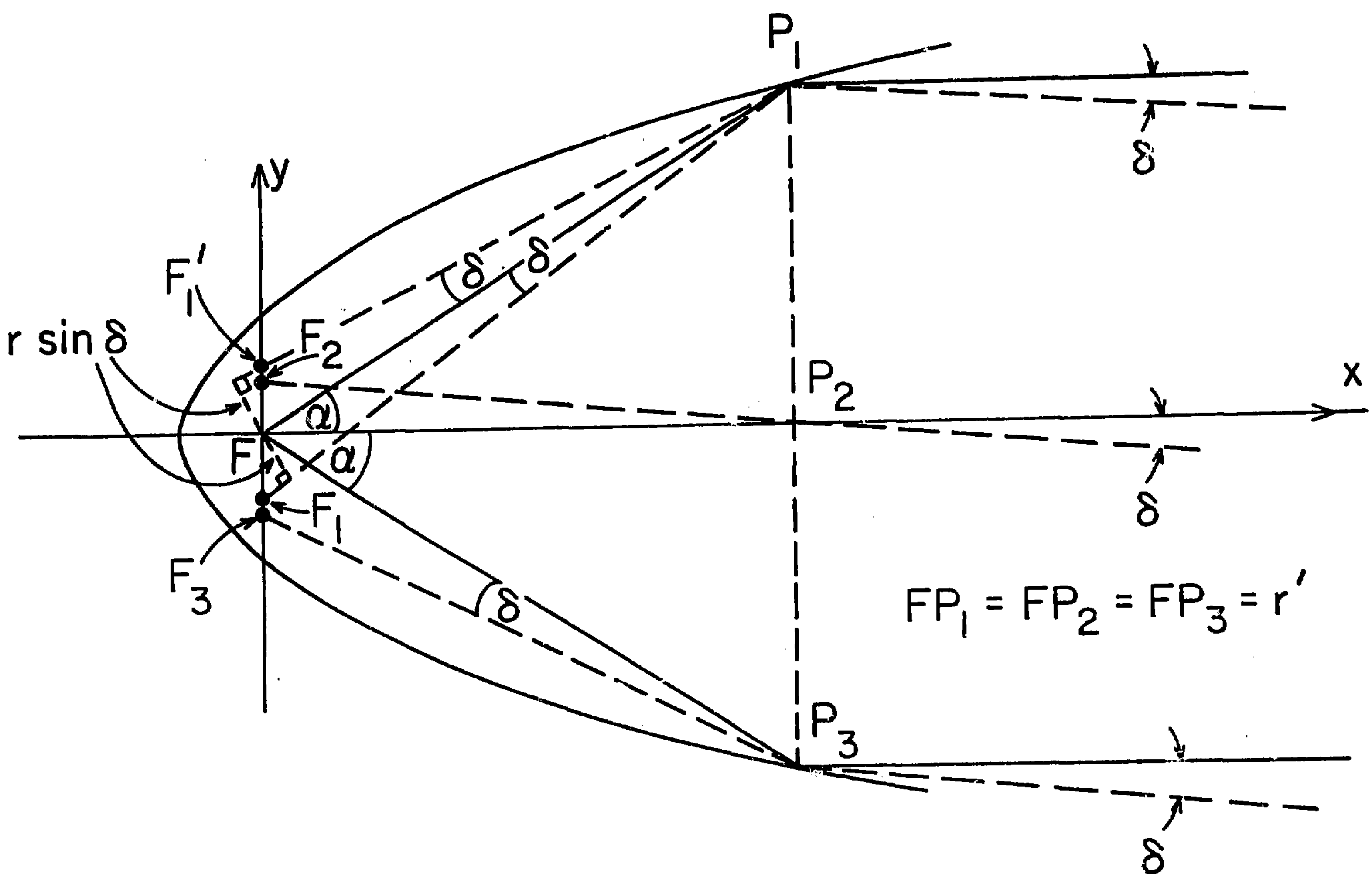
* "Normally" means the average value of a number of 'best effort' pieces from various firms, measured by Bennett[17].

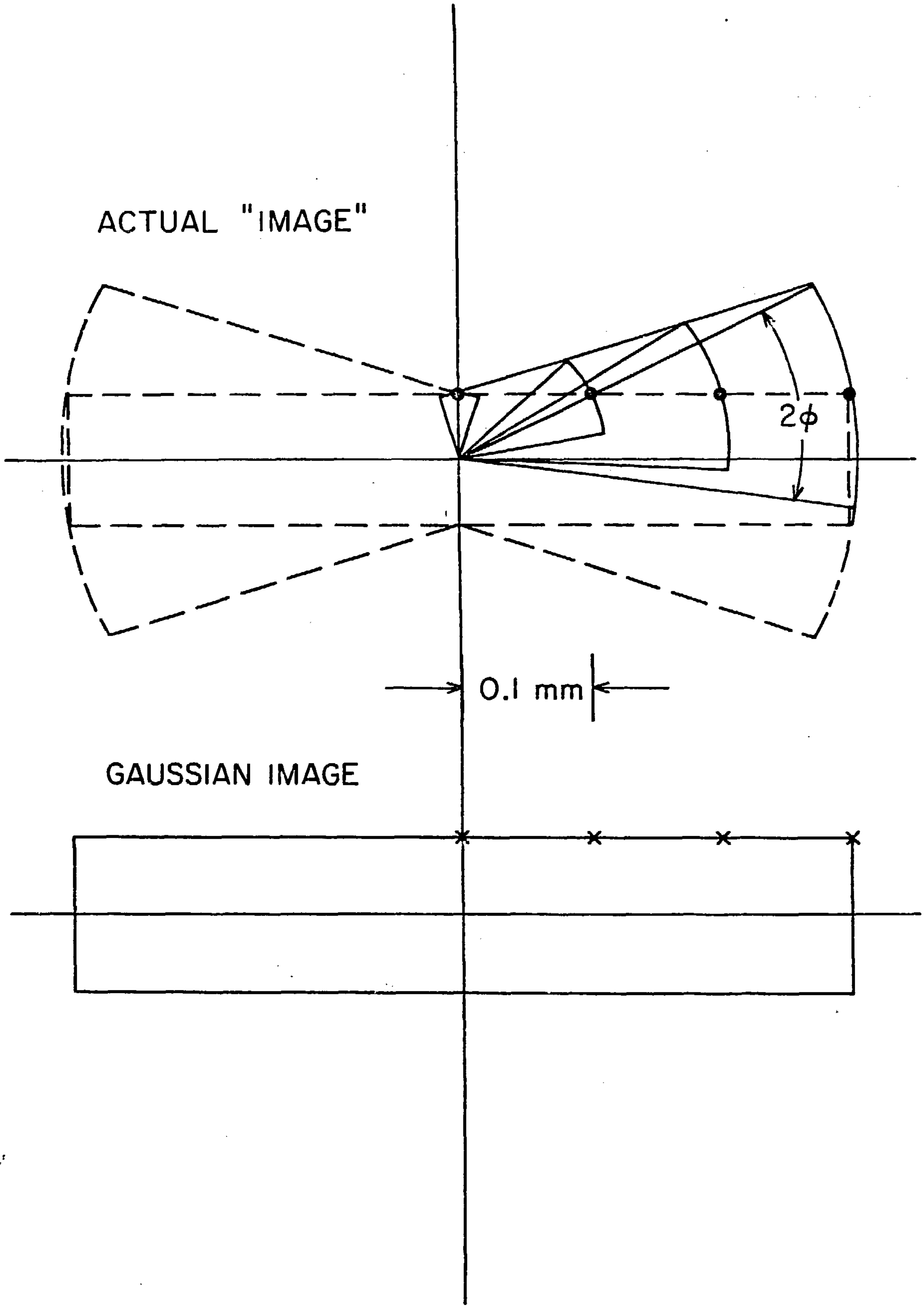


Photons/s/mr/mA/GeV in 0.1% bandwith
10^5
10^6
10^7
10^8
10^9
10^10
10^11
0.1
1.0
10
100
1000
10000
100000
λ/λc


SAFETY SHUTTER
e⁻
90
m RADS
FAST VALVE
80 m RADS
WATER COOLED
MASK
UHV VALVE


REFLECTANCE (PERCENT)
WAVELENGTH(nanometers)
a
b
c
d
e
f
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280


P1
P2
P3
x
y
F
F1'
F2
F1
F3
r sin δ
α
α
δ
δ
δ
δ
δ
δ
FP1 = FP2 = FP3 = r'



ACTUAL "IMAGE"
2φ
0.1 mm
GAUSSIAN IMAGE

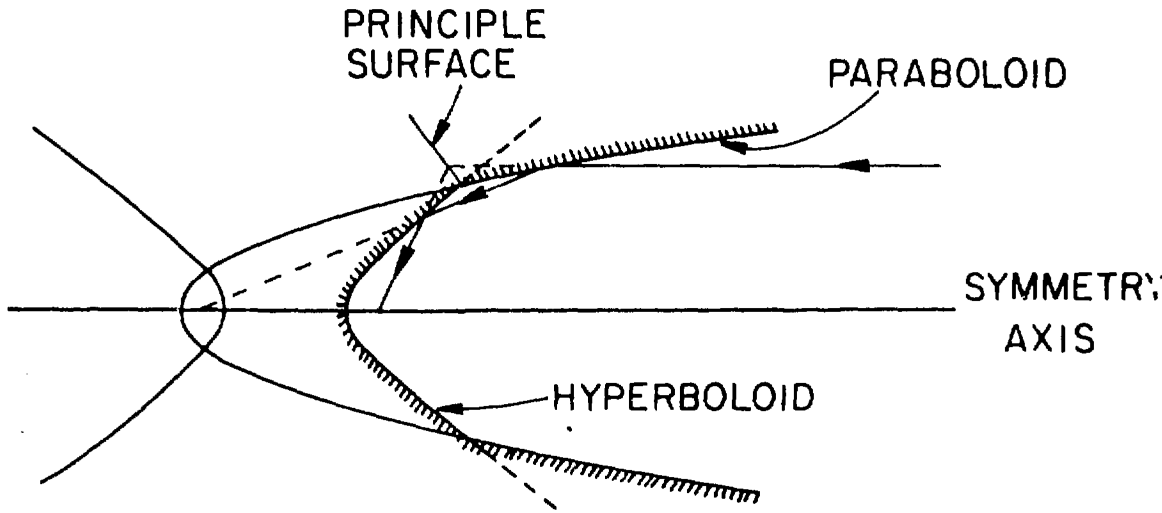


Fig. 6