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A FRONT END DESIGN FOR THE ADVANCED PHOTON SOURCE

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1. INTRODUCTION

X-ray sources on next generation low emittance/high brilliance synchrotrons such as the 7-GeV Advanced Photon Source (APS)(1) have unique properties which directly affect the design of the front end of the beam line. The most striking of these are the large peak photon power densities expected for the insertion device (ID) x-ray sources. Undulators, for example, can have highly peaked photon power distributions with central densities approaching 300 kW/mrad^2. Large power distributions can also be expected for some of the high critical energy wigglers. Front end components which intercept the photon beam produced by IDs must be able to absorb and safety dissipate the heat loads associated with their power distributions.

In addition, detection of the position of the photon beam in some cases requires a precision in the range of a few microns. The information from such photon beam monitors is used primarily in the particle beam control loop in order to maintain the position and take-off angle of the particle beam within some fraction of the beam size and angular divergence dictated by the emittance of the lattice. In most cases, these photon beam detectors must function in the high flux environment of the x-ray beam.

The conceptual design of the front ends for the undulator, wiggler, and bending magnet (BM) sources on the APS take these unique characteristics into account. In addition, they perform four basic functions which are related to their role as the interface between the x-ray source on the storage ring and the downstream components on the experimental floor. These functions are:

- to trigger protective measures against vacuum failures which could propagate along the front end to the storage ring.

- to provide the proper collimation which limits the maximum angular excursions of the x-ray beam in order to prevent it from striking any surface along the beam line which is not cooled even in the event of a steering error of the particle beam.

- to provide shutters and stops capable of absorbing the full intensity of the x-ray beam from an ID or bending magnet and/or Bremsstrahlung radiation originating from scattering of the 7-GeV particle beam during injection or vacuum failure.

- to monitor the position and average take-off angle of the photon beam with the precision necessary to control the phase-space parameters of the particle beam as well as devices downstream in the users' experimental station.

2. CHARACTERISTICS OF APS X-RAY SOURCES

The photon beam power distribution of an ID or BM directly determines the several design features of the front end. The relevant characteristics of the BM and typical APS wigglers and undulators are given in Table 1 for the APS operating at 7-GeV. Details of the power distributions for specific cases have been determined using single particle relation derived in[2,3]. Calculations which include emittance are in progress.

The unique feature of the high brilliance source is the very large peak power densities expected for the IDs in several cases. (The total powers for

Table 1. Parameters of x-ray sources for the APS operating at 7 GeV and 100 mA. E is either the critical energy (wiggler or bending magnet) or the undulator first harmonic energy at the magnet gaps indicated. P_K is the peak angular power density; P_A, the lineal peak angular power density integrated over the vertical opening angle; P_N, the peak normal power density at 15 m from the source point and P_T, the total power emitted by the device.

X-ray Source	Period (cm)	Length (m)	E (keV)	B_0 (T)	K	P_K (kW/mrad^2)	P_A (kW/mradθ)	P_N (W/mm^2)	P_T (kW)
BM	---	---	19.5	0.599	—	0.78	0.086	3.5	0.52
Wiggler A	15	1.5	32.6	1.0	14	26	2.90	116	4.6
Wiggler B	25	5	9.8	0.30	7	15.6	1.74	70	1.4
Undulator A:									
(Gap= 2.8 cm)	3.3	5.2	13.5	0.21	0.4	36	4.0	160	0.27
(Gap= 1.0 cm)	3.3	5.2	3.5	0.78	2.5	320	35.6	1400	9.8
Undulator B:									
(Gap= 1.9 cm)	2.3	5.2	19.3	0.13	0.3	48	5.3	212	0.3
(Gap= 1.0 cm)	2.3	5.2	13.0	0.47	1.0	250	28.3	1130	3.6

the devices considered up until now are similar to those at existing synchrotrons.) For example, for the undulators shown, the power is contained within an angular area of approximately 150 μrad vertical (ψ) by 110 μrad horizontal (θ) for K<1 and 150 μrad vertical by 300 μrad horizontal for the case where K>1. This wiggler powers are contained within 150 μrad vertical and K*150 μrad horizontal. The intense concentration of power requires careful state of the art engineering of front end components from the standpoint of heat removal and thermal stresses. The present design utilizes grazing incidence geometry to spread the power load over the absorbing surface and water cooling to remove the heat.

3. FRONT END COMPONENTS

A typical front end for both the IDs and bending magnet consists of several basic components which are described below in the order they appear along the beam line beginning at the upstream point closest to the source point. The conceptual design of a typical layout for an undulator front end is shown in Fig. 1.

Fixed Mask Assembly. This is the first component which interacts with the photon beam. This mask, along with a second mask downstream, defines the maximum vertical and horizontal angular excursions of the beam from some predefined center line. The masks are water cooled copper metal plates and are arranged so that downstream non-cooled components never intercept any part of the photon beam. In the present design, which is similar to the NSLS X-17 fixed mask assembly(4,5), the horizontal mask consists of two water cooled copper bars in an open "v" arrangement (see Fig. 2). The vertical mask is made up of two set of bars in a closed "v" arrangements above and below the beam. In both cases, the absorbers are at horizontal grazing incidence to the photon beam. The second set of cooled fixed masks downstream in the front end is similar to design to the first set. In the case of the APS, the masks are designed to contain the beam rather than define it and must be able to absorb large power densities from part of all of the photon beam.

Photon Beam Position Monitor. The photon beam position monitor measures the average position of the x-ray beam. It consists of identical tungsten blade monitors on each side of the beam. The design is similar to that for the one used on the PEP beam lines(6) (see Fig. 3). The photoelectric current produced in each blade is processed and compared to give the beam position. For wiggler and bending magnet beam lines, a set of two photon beam position monitors is used to measure the vertical position of the x-ray beam at two places. The first monitor is located just after the fixed mask assembly, and the second monitor approximately 10 to 15 m downstream. For undulator beam lines, both the horizontal and vertical positions are measured and two sets of monitors are required.

If the position of the photon beam is known at two places along the beam line, then the average position and angle of the particle beam in the x-ray source can be determined. As is shown in Appendix A, a precision of ±1 μm in photon beam position monitors located in 18 and 28 m from source point results in ±3.3 μm precision in the particle beam position determination and ±0.14 μrad in the angle.

Photon Shutter or Movable Mask. The purpose of this component is to completely intercept the x-ray photon beam in the closed position. It must be able to absorb the full power of the photon beam so as to isolate downstream component from the x-ray source. The time necessary to close this shutter is on the order of seconds.

Personnel Safety Shutter. The purpose of the safety shutter is to absorb Bremsstrahlung radiation from scattering of 7-GeV particle beam which could occur during injection of the particle beam into the storage ring. The absorber consists of either 20 cm of steel clad lead or a tungsten-based alloy. The radiation path length through the absorber is long enough to absorb stray radiation in the beam line path. The shutter is not cooled and cannot handle the photon beam power loading. Therefore, the upstream photon shutter must be closed before the safety shutter can be closed. A fail-safe system and interlocks are necessary in order to insure the correct sequence during a fill of the storage ring and when either shutter is activated.

Collimators. These components are required to define the line of sight to the source point. They absorb both scattered x-rays and Bremsstrahlung radiation which are outside the predetermined cone around the forward direction along the beam line.

Isolation Vacuum Valves. These are remotely actuated UHV metal seal gate valves which isolate the upstream storage ring vacuum from the downstream one. They require seconds in order to completely close. They cannot accept the heat load from the x-ray beam and are interlocked to close only when no beam is present or when the photon shutter is closed.

Fast Closing Vacuum Valve. This valve occurs immediately downstream from the isolation valve and has the function of protecting the ring vacuum from the initial shock wave of gas resulting from a vacuum failure downstream from it. It requires approximately 10 ms to close. The valve seal is not vacuum tight but does delay the leak propagation long enough for the isolation valve to close. The fast valve cannot accept the heat load from the x-ray beam and is interlocked to the photon shutter during normal operation. In the event of a vacuum failure, the stored particle beam must be dumped before the fast valve can be closed since activation time for the photon shutter is too slow to shut off the photon beam. The time required for a beam dump is less than 10 μs.

Vacuum Delay Tank. The delay tank contains a baffle arrangement to further delay the shock wave propagating toward the storage ring from a vacuum failure downstream. It is estimated that the shock wave from a vacuum failure occurring at 30 m downstream from the source point takes approximately 20 ms to reach the fast valve. The delay tank can be considered as an optional safety measure to further increase the propagation time.

Photon Power Absorber. This component consists of a set of pyrolytic graphite absorbers which absorb the unwanted power from the low energy component of the x-ray beam. This reduces the heat load on downstream optical components and vacuum windows.

Beryllium Window. This window is the last component in the present design of the front end. Its purpose is to isolate the front end/storage ring vacuum from the downstream vacuum. The assembly is composed of two 0.01 in. water cooled beryllium windows. The majority of the power is absorbed by the first window. Consequently, the space between the windows is filled with dry helium gas in order to minimize surface contamination and induced chemical reactions which could cause weakening of the window. The entire assembly is positioned outside the main shield wall in order to facilitate maintenance and inspection.

4. POWER HANDLING CONSIDERATIONS

The approximate location of the first mask in both the BM and ID beam lines is 15 m from the source point. The peak normal power density at the distance is given in Table 1. As is the case of previous designs of front ends for high power x-ray sources(3,4,5), metal surfaces will need to intercept the photon beam at near grazing incidence and must be efficiently cooled in order to withstand the unprecedented peak power loads expected for APS sources.

Finite element modeling of the photon flux thermal loading is currently underway for specific front end elements, discussed further on. In addition, stress analysis and thermal cycling effects are also being investigated. However, it is instructive to compare the present 7-GeV APS design with other high power sources such as the proposed superconducting wiggler for the X-17 beam line(4) at NSLS - Brookhaven National Laboratory and the X-IV beam line 54-pole wiggler(3) at SSRL. In both cases, extensive finite element analysis of the power loading has been done for the front end components and the results serve as a preliminary guide for similar APS front end components.

The normal peak power density for the superconducting wiggler at 10 m from the source at 3.88 kW/cm^2. The total power emitted within the horizontal acceptance angle is approximately 35 kW. For the 54 pole wiggler, the peak density is 20.5 kW/cm^2 at 6.5 m and the total power is 6.85 kW. The front ends of both IDs use grazing incidence-water cooled masks in which the power density on the metal surface is reduced by spreading the beam in the horizontal direction (see Fig. 2). The actual peak power density at a distance D(m) from the source point is given approximately by the relation,

$$P_N = P_K * \sin \theta / D^2$$

where θ is the angle of incidence of the photon beam measured from surface of the absorber.

As is obvious, very different peak angular power densities from different x-ray sources can have similar <u>peak</u> power densities on a given surface depending on the relative distances from the source point and the incidence angle. Of course, the total power deposited could be very different.

For the NSLS superconducting wiggler, the first mask assembly uses hollow OFHC copper stock bus conduit(4,5) which intercepts the beam horizontally (see Fig. 2). The vertical mask consists of an upper and lower set of two bars in a "v" configuration intercepting the beam at an angle of 6°. The horizontal mask consists of two bars in an open "v" configuration at 6° to the beam. In addition, the mask assembly contains a set of beam splitters which intercept the photon beam vertically at an angle of 2°. The peak power loadings on the copper bus bars are 4 W/mm^2 for the 6° set and approximately 11.6 W/mm^2 for the 2° beam splitter. The latter case requires a slight overpressure of cooling water in order to avoid the possibility of boiling of the cooling water.

The SSRL 54 pole wiggler uses a grazing incidence mask with horizontal walls at an angle of 1.65° to the photon beam. The movable shutter or mask is at 3.28° to the beam. In the first case, the peak power density is approximately 5.7 W/mm^2. For a movable mask, the power density of 11.7 W/mm^2. The total power contained in the beam is approximately 6.9 kW.

The maximum peak heat loads for both X-17 and beam line VI are similar (11.7 W/mm^2). This value was taken as the largest allowable load in the design of APS front end components. In addition to the peak power density, the total power contained in the photon beam must be considered in order to completely specify the design of a given component. As mentioned, finite element analysis which includes both the <u>total power</u> and its <u>distribution</u> from an x-ray source are underway for the critical components of the APS beam lines.

A preliminary analysis of the first fixed mask in the wiggler front end shows that a conceptual design similar to that used for the X-17 superconducting wiggler is adequate if the horizontal incidence angle of the photon beam is 6°. Finite element analysis of the heat load shows that the temperatures on the surface of the copper bus and of the cooling water are below 100°C at full power load from the ID. The total length of the mask unit is approximately 1.6 m.

The results for Undulator A at the smallest gap and maximum power load show that the largest angle for which boiling of the cooling water occurs is approximately 1°. If overpressure of the cooling water is to be avoided, then a more efficient design of the absorbers intercepting the photon beam is necessary. Instead of using available copper bus conduit, with a standard cooling channel, other more efficient shapes of absorbers made of aluminum and copper are being investigated. If adopted, these absorbers would require custom extrusions which in principle should not present technical difficulties. In addition, other geometries for intercepting the photon beam are being studied. It is estimated that a factor of two to three reduction in the peak power load would be adequate for safe operation of the mask (and movable shutter) without the need to pressurize the cooling water.

For the beryllium window at approximately 30 m from the source point, the worst case power loading is again from the undulators at closed gap. In this case, the first window absorbs approximately 2% of the incident power. The majority of the heat load is from photons with energies less than 4 keV. The peak power load is approximately 5 times that estimated for the 54 pole wiggler. These preliminary results indicate that it may be necessary to insert the vitreous carbon foil absorbers from undulators working in the closed gap configuration. Further estimates of the beryllium window power loading are underway.

ACKNOWLEDGEMENTS

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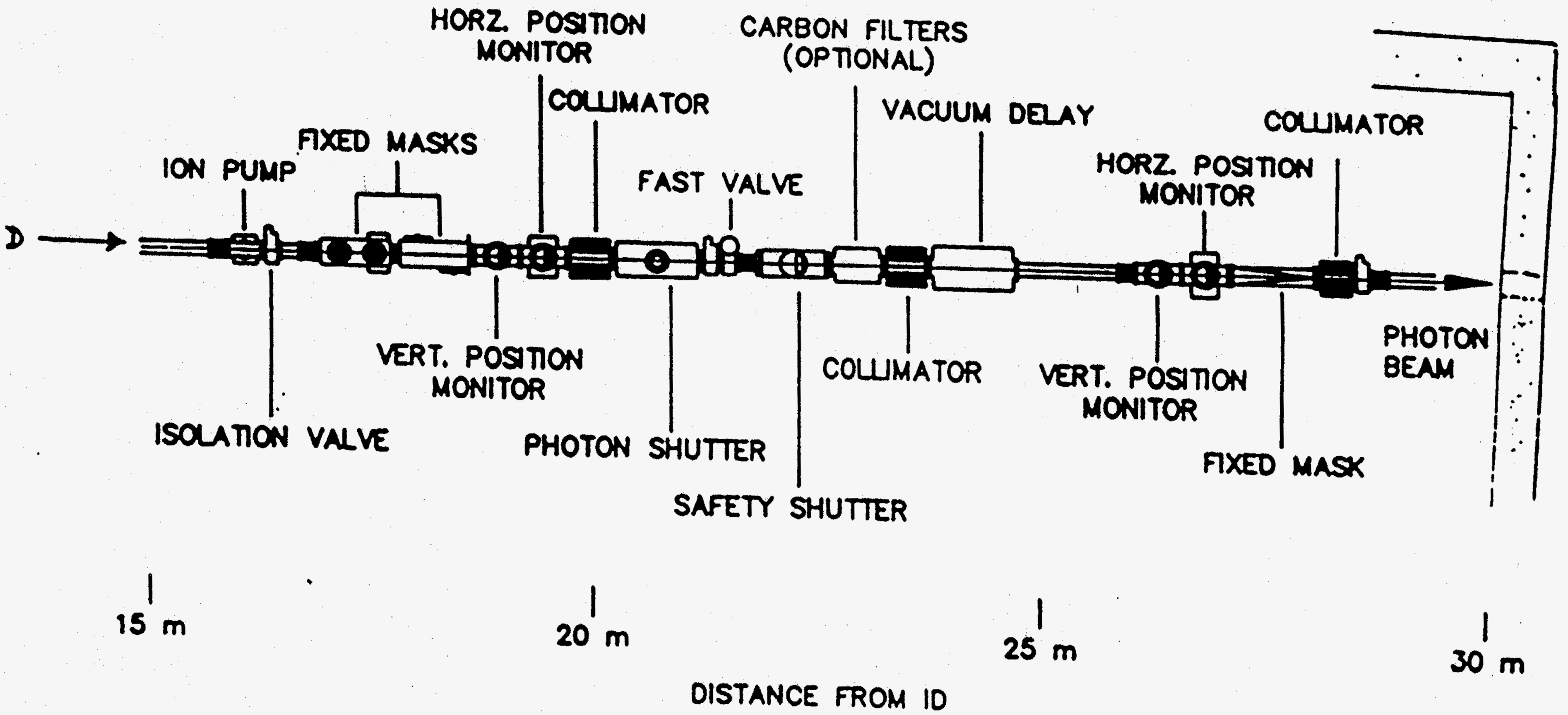


Fig. 1. Typical layout of an undulator front end. The beryllium window is located to the right of the shield wall at approximately 31 m.

PHOTON POSITION MONITOR

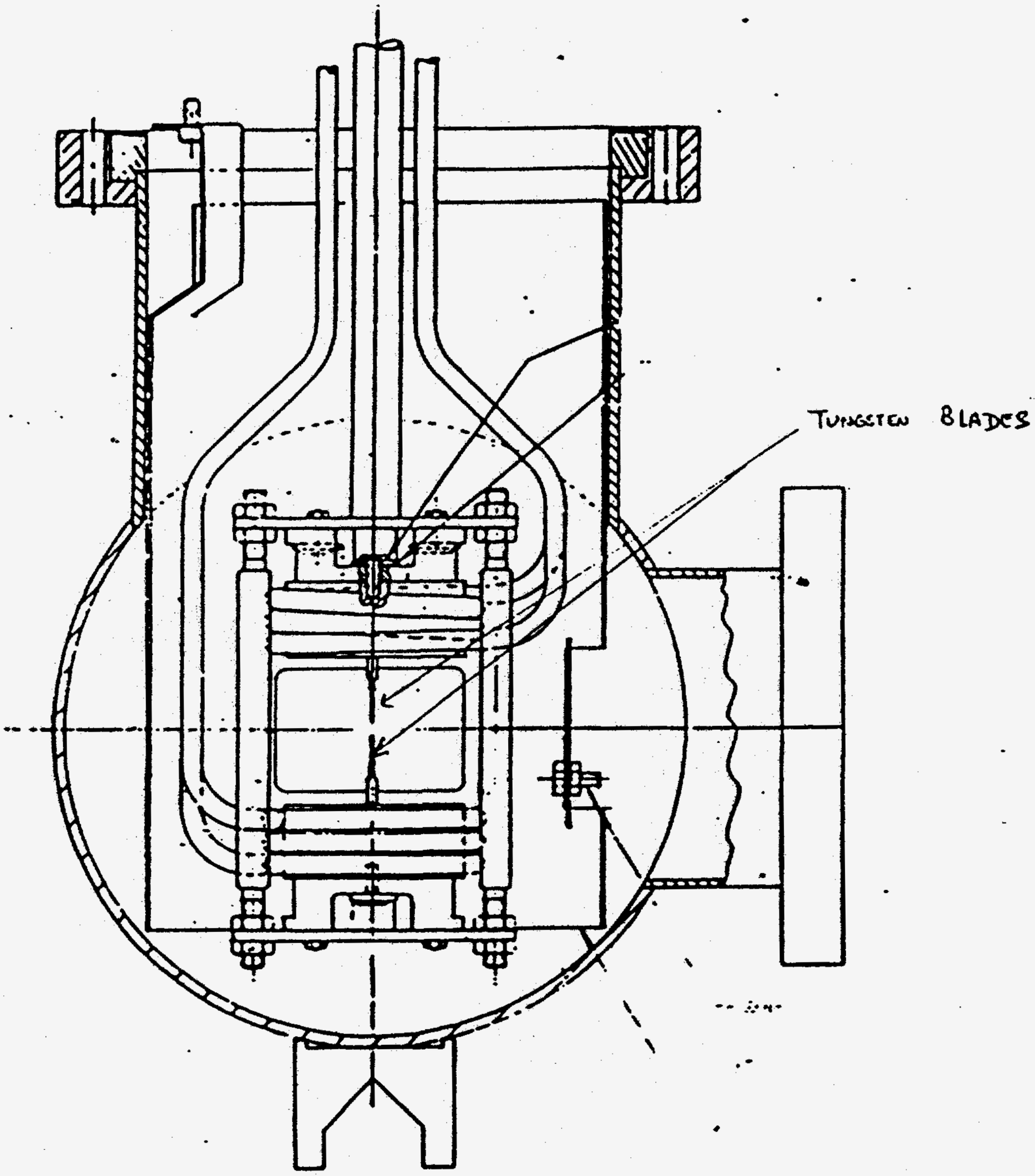
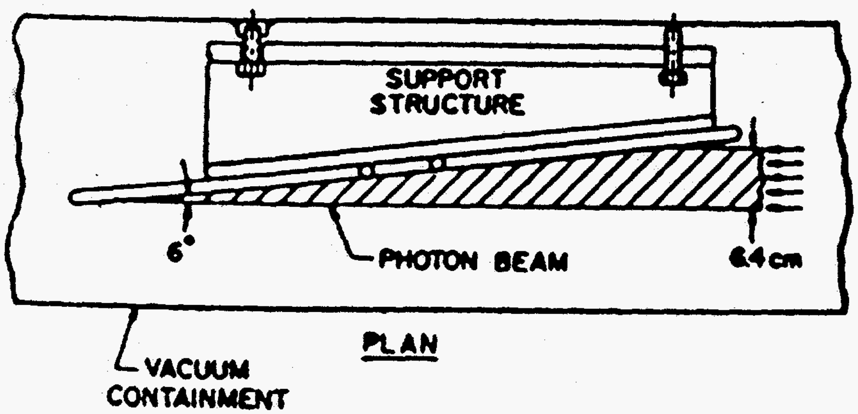


Fig. 2 Cross section view perpendicular to the particle beam direction of a typical tungsten blade photon position monitor.

FIXED MASK ASSEMBLY
(BASED ON NSLS SUW DESIGN)



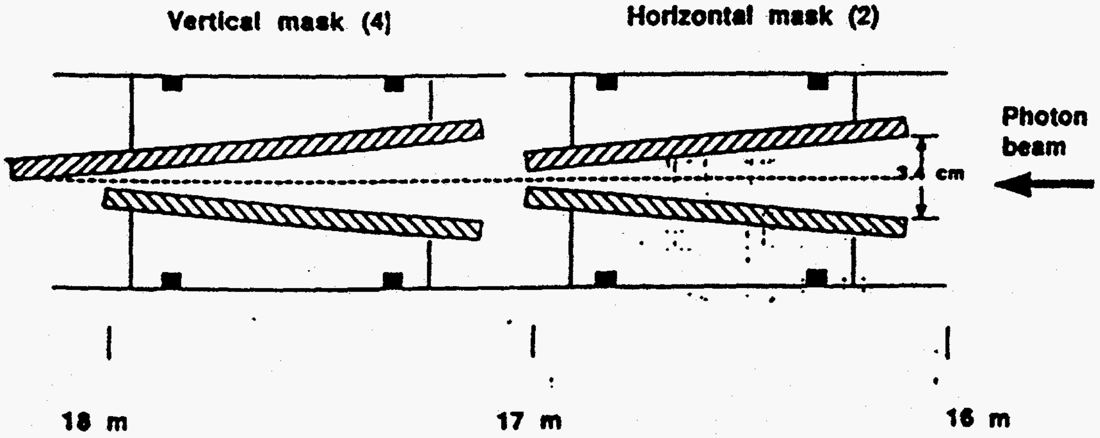


Fig. 3 Partial layout of a fixed vertical and horizontal fixed mask assembly.

APPENDIX A

Particle Beam Position Determined from Photon Beam Position Monitors

The deviation in a given direction of the particle beam's position and trajectory angle from the golden orbit of the storage ring can be determined by measuring the position of the photon beam from an x-ray source using photoelectric-based monitors at two positions along the beam line. The precision with which the particle beam parameters can be estimated depends on the precision of the photon beam position measurement.

For example, let y_0 be the vertical displacement of the particle beam and α, the angular deviation from the golden orbit. As is shown in Fig. 1, the resultant vertical displacements of the photon beam, y_1 and y_2, measured at the positions x_1 and x_2 along the beam line are given by:

$$y_1 = y_0 + \alpha * x_1$$

$$y_2 = y_0 + \alpha * x_2$$

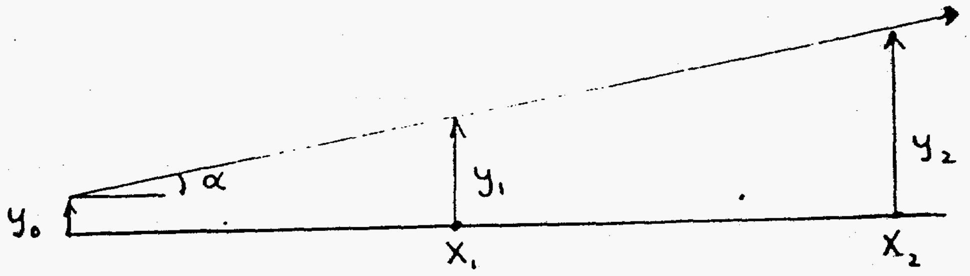


Fig. 1

If the precision associated with the photon measurement is δ for both photon beam position monitors and there is no error assumed in the positions x_1 and x_2, then it can be shown that the precision associated with α and y_0 is given by:

$$\delta_\alpha = \sqrt{2} * \delta/(x_2-x_1)$$

$$\delta_{y0} = \delta * \sqrt{(x_1^2 + x_2^2)}/(x_2-x_1)$$

As an example, if the photon beam position monitors are located at 18 and 28 m from the x-ray source point, and have precision of ±1 μm, then the associated particle beam parameters have the precisions:

$$\delta_\alpha = \pm 3.5 \quad \mu m$$

$$\delta_{y0} = \pm 0.14 \quad \mu rad$$
