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TITLE GRAZING INCIDENCE BEAM EXPANDER

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Grazing incidence beam expander*

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Abstract

A Grazing Incidence Beam Expander (GIBE) telescope is being designed and fabricated to be used as an equivalent end mirror in a long laser resonator cavity. The design requirements for this GIBE flow down from a generic Free Electron Laser (FEL) resonator. The nature of the FEL gain volume (a thin, pencil-like, on-axis region) dictates that the output beam be very small. Such a thin beam with the high power levels characteristic of FELs would have to travel perhaps hundreds of meters or more before expanding enough to allow reflection from cooled mirrors. A GIBE, on the other hand, would allow placing these optics closer to the gain region and thus reduces the cavity lengths substantially.

Results are presented relating to optical and mechanical design, alignment sensitivity analysis, radius of curvature analysis, laser cavity stability analysis of a linear stable concentric laser cavity with a GIBE. Fabrication details of the GIBE are also given.

Introduction

As the laser technology matures, more and more emphasis is being placed on optimum gain extraction, tunability considerations, etc. Optimal gain extraction places unique challenges on the optical design of these cavities. The tunability considerations pose challenges in coating technology. The optical systems design for such lasers is ultimately constrained by the damage of optical surfaces due to the laser fluence. Recently, Peter Mumola and David Jordan[1] have proposed the use of grazing incidence elements for these laser systems to increase the damage thresholds. Subsequently, several organizations[2,3] have proposed the use of grazing incidence elements for Free Electron Laser cavities.

Free Electron Lasers (FELs) offer the possibility of high extraction efficiencies with tunability. However, the nature of the gain volume (a thin, pencil-like, on-axis region where photons can interact with a stream of high velocity electrons) dictates that the output beam be very small. Such a thin beam with the power levels characteristic of FELs would have to travel perhaps a hundred meters or more before expanding enough to allow reflection from cooled mirrors. At shorter distances, the flux will be so large due to the small beam size that the thermal deformations of the mirror would ruin the beam quality.

In order to understand the mode-optic interaction of a FEL cavity with grazing incidence elements, we have designed and are in the process of fabricating a "Grazing Incidence Beam Expander (GIBE)". A GIBE consists of a long, narrow, Grazing Incidence Optic (GIO), followed by a larger, more conventional optic (in this case a retro-sphere). The GIO serves to diverge the beam and thus greatly reduce the total path length to the spherical retroreflectors at the end of the resonator.

This GIBE will be placed in a breadboard demonstration at Los Alamos National Laboratory to gain insights into these state-of-the-art cavities containing grazing incidence elements.

In this paper, we will provide a systems overview into the analysis, design, fabrication and test of the GIBE. Optical design details are provided in another paper (Ref. 4) which is also being presented at this conference.

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System requirements

The primary requirement in designing and building an FEL is to produce a system which is simultaneously capable of giving the required output power and high wavefront quality. This imposes tight requirements on the overall optical design, on the fabrication of the optical components, and on the assembly and alignment of the system. In this section, we consider the flowdown of these subsystem requirements. Although we do not present any specific numerical values for the requirements, we indicate the critical areas, which are then developed further under the heading of System Analysis and Design.

Optical design and system analysis

The general purpose of the optical design activity is to achieve a design which assures the required power and high wavefront quality, by setting balanced requirements on the fabrication, assembly, and alignment. Although it is relatively straightforward to come up with a theoretically acceptable design, it is more difficult to achieve an acceptable balance between the various fabrication areas, assembly, and alignment. Thus, the optical design phase is really the system analysis phase. The specific requirements placed on the optical design are (1) wavefront quality, which describes the root-mean-square (rms) wavefront error of the steady state mode of the resonator; (2) power loss per pass, which is the amount of power that would be lost during one round trip (pass) through the resonator, assuming there were no gain medium; and (3) the location of the beam waist and the orientation of the optical axis.

Again, it is relatively straightforward to come up with a design which theoretically meets all of the above requirements. However, the consideration of actual tolerances in the fabrication, assembly, and alignment areas leads to the development of subsystem requirements in these areas. This is done by way of error budgets, combined with overall requirements on major system characteristics such as resonator cavity length, beam waist size, and total output power.

The most important error budget is the one for wavefront quality. In most optical systems, this error budget relates to a wavefront which propagates only once through the system and which therefore never interacts with itself. The situation is more difficult for a resonator, where the important criterion is the wavefront quality of the steady state mode. There is no simple way to relate the steady state wavefront quality to the quality of a wavefront which propagates through the system only once. Nevertheless, the most reasonable way to approach this error budget as a first cut is to assign (budget) a single pass wavefront quality requirement to the system, and to Root Sum Square (RSS) the contributions to this budget from all the elements of the system. (For an FEL, where a relatively large percentage of the circulating power is extracted on each pass, implying that photons make only a small number of passes through the resonator, this is a more reasonable procedure than for a stable laser resonator where the percentage of extracted power is very small. The contributions to this error budget include the figure quality of all mirrors, the thermally induced mirror surface deviations, the system alignment, and vibration or jitter caused by both the environment and by the action of the cooling system.

The other important error budget is the one for power loss per pass. The contributions to this error budget include the reflectivity of all mirrors, the mirror sizes (relative to the beam size), the system alignment, and to some extent, the surface quality, especially in terms of roughness, which contributes to scatter, which in turn results in power loss.

To summarize so far, we have discussed the general and specific requirements placed on the optical design (system analysis) task. Meeting these requirements requires the development of two major error budgets, and the recognition of overall requirements on major system characteristics such as resonator cavity length, beam waist size, and total output power. To meet the error budgets while falling within the constraints on the overall system, one must take a detailed look at the interplay between the various fabrication, assembly, and alignment issues. In this paper, we do not discuss the development of real error budgets. However, we have listed above the contributors to each error budget. Below, we summarize some of the various issues to be kept in mind in the areas of fabrication, assembly, and alignment while developing the real error budgets. We then discuss these topics in more detail under the heading of System Analysis and Design.

Impact on fabrication, assembly, and alignment

In the fabrication area, we must consider the size of the optics, their longitudinal and lateral radii of curvature, their coating, their surface quality, and their cooling systems. These parameters are all related in terms of their requirements. For example, one of the requirements on the cooling system for a mirror is to give acceptably small surface deformations due to the thermal effects of absorbed flux. This requirement on the surface deformations must be balanced directly against the requirement on residual figure errors on the mirror surface, since both errors affect the system performance in the same way, by degrading the wavefront quality. As another example, one of the purposes of the coating, obviously, is to minimize the power loss. However, in doing this, the coating also minimizes the power absorbed by the mirror, which minimizes the thermally induced surface deformations, which maximizes the wavefront quality. Thus, the coating affects the development of both error budgets. In short, all of the fabrication issues (size of the optics, radii of curvature, coating, figure quality, and cooling systems) must be examined not only in terms of practicality, but also in terms of their inter-relationships, and their impact on the system error budgets.

In the assembly and alignment area, we must consider the mounting and size of the optics, as well as their alignment. For very large systems, it is conceivable that the self weight deflection of the mounted optics could account for a considerable portion of the wavefront quality error budget, although this is usually not the case for smaller, demonstration systems. In addition, care must be taken in the mounting and assembly process not to clamp in any undue deformations into the surface. This can be accomplished by building mounts that are kinematic or nearly so. Finally, alignment methods must be provided in the mounts which have the sensitivities dictated by the wavefront quality and power loss error budgets. Providing highly sensitive alignment methods could affect the vibration levels allowed in the optics, which would then affect the wavefront quality error budget.

To summarize, we have discussed some of the issues involved in setting requirements on the fabrication, assembly, and alignment. These requirements are derived from the top level system requirements accounted for in the optical design/system analysis phase.

System analysis and design

In this section, we discuss in detail some additional issues involved in the optical design and the analysis of the resonator cavity. We also elaborate on the opto-mechanical design, and the fabrication/metrology/test effort.

Optical design

In this and the following section, we elaborate on some optical design considerations in an FEL system with a GIBE. In particular, we summarize in this section the considerations which govern the optical prescription of the GIO. Then, in the following section, we summarize some modelling efforts that have gone into studying and tolerancing a particular FEL design. These efforts include modelling the change in intensity distribution caused by the GIO, as well as modelling the alignment effects peculiar to an FEL resonator with a GIBE. (Both of these topics are covered in more detail in Ref. 4.)

In a conventional optical system, when a mirror is required to change the divergence angle of a spherical beam, a conic section (such as a hyperboloid or ellipsoid) is used. Since Gaussian-spherical beams of the type found in stable laser resonators have locally spherical wavefronts, it is natural to assume that a conic section, in particular a convex hyperboloid, should be used for the GIO in an FEL resonator. However, a given on-axis section of a Gaussian-spherical beam has an apparent center of curvature whose axial location depends on the axial location of the section being considered. This changes the whole geometry, and rules out the use of a conic section. (See Figure 1.) In other words, the section of the GIO closest to the wiggler sees a different apparent center of curvature of the beam than does the section farthest away from the wiggler. Therefore, a hyperboloid is not the required surface for maintaining the Gaussian-spherical beam character while changing the divergence angle. The definition of the optimum prescription for the GIO surface is that it is the surface in space for which, at each point, the optical path from the real beam waist is equal to the optical path from the virtual beam waist as imaged by the GIO.

The development of the optimum prescription for the GIO is covered in detail in a separate paper[4]. It is worthwhile to note, however, that in the end, the difference between the optimum prescription and a simple hyperboloid which relays the real beam waist to the virtual beam waist, was essentially negligible in the particular case we studied. This was true because, in our case, the GIO was many Rayleigh lengths away from the beam waist, and because the GIO was relatively short. When, the GIO is either fewer Rayleigh lengths away from the beam waist, or else longer, the deviation from a hyperboloid would be more substantial.

Cavity analysis

In this section, we summarize some modelling efforts that have gone into studying and establishing tolerances for a particular FEL design. These efforts include modelling the change in intensity distribution caused by the GIO, as well as modelling the alignment effects peculiar to an FEL resonator with a GIBE.

We first examine the change in intensity distribution. The GIO is designed to change the local spherical curvature of the wavefront while still maintaining the beam's Gaussian-spherical characteristics. In other words, the GIO changes the effective beam focus (or waist) location. The question that arises is how this optic affects the Gaussian intensity profile. To answer this question, we traced rays from the wavefront incident on the GIO to the reflected wavefront, keeping track of each ray's relative position in the pupil. From the ray trace, we determined how each ray shifts its relative location within the pupil. The maximum shift in the case studied was determined to be only 2.25% of the pupil diameter, in a region where the intensity is only 5% of the peak. Consequently, the pupil shifting has a negligible effect on intensity. (For details of this analysis, see Ref. 4.)

We now turn to the analysis of misalignment effects. From the optical description, we have expressions defining the phase of both the incoming and outgoing beams at any point in space. We have also computed a set of points defining the GIO surface. Next we can apply a misalignment by tilting or displacing the GIO in any direction and computing a new set of points defining the surface coordinates of the misaligned GIO. Substituting these values into the expressions for phase of the two wavefronts, we can calculate the OPD applied to the wavefront and account for the pupil shifting that occurs. Because the pupil shifting is different for the two directions in which the light is travelling, depending on the misalignment, the wavefront distortions may be different in the two directions. We have looked at six possible types of misalignment of the GIO, displacements in x, y, and z, and rotations about the x, y, and z axes (Figure 2). In order to characterize the phase aberrations due to each misalignment, we have decomposed the distortions on each wavefront into Zernike polynomials. Each misalignment translates onto the wavefront primarily as some combination of piston, tilt, focus, and astigmatism.

In the modelling, we ignored the piston, tilt, and focus components of the wavefront error. This was justified by a two stage argument. First, the presence of small amounts of these aberrations does not influence the amount of astigmatism added by the GIO either on the first pass or on the return trip. Second, the tilt and focus components of the wavefront error simply imply that the waist location of the stable mode will be shifted slightly. (Piston errors are entirely irrelevant.) In this sense, the situation is the same as for a conventional stable resonator: small misalignments of one of the end mirrors do not affect the shape of the stable mode but only the waist location. Tolerances on the waist location were met, but this is beyond the scope of this paper. Thus, only the astigmatism components were relevant to this analysis.

Table 1 relates each misalignment to which astigmatism (0 degrees or 45 degrees) is created, and also shows the relative magnitudes of the aberrations seen by the incoming and outgoing wave. For the rotations, the magnitudes of the aberration are equal for the incoming and outgoing wave. For displacements, the relative magnitudes are design dependent. For our design, the outgoing wave showed aberrations about an order of magnitude greater than the incoming wave. The incoming wave is defined as that coming from the wiggler and the outgoing as that coming from the retrosphere and directed toward the wiggler.

To summarize the modelling effort and results, we used a physical optics propagation computer code to simulate FEL resonator with a GIBE. The most important aspects examined were the redistribution of intensity and the effects of misalignments. The redistribution of intensity caused by the GIO was found to be negligible. The effects of misalignments were modelled in terms of Zernike polynomial coefficients. It was found that the most critical misalignments (those of the GIO) caused various amounts of tilt, focus, and astigmatism errors in the wavefront. The tilt and focus errors were interpreted in terms of displacement of the beam waist. The astigmatism errors, however, contributed directly to a degradation in both the mode shape and the beam power. In fact, we found that both the mode shape and power loss could be modelled quite accurately in terms of just the misalignment-induced astigmatism. This made the derivation of a misalignment error budget, in terms of system requirements on mode shape and power loss, a relatively straightforward procedure.

GIBE opto-mechanical design and fabrication

The grazing incidence beam expander (GIBE) consists of two mirror elements: a long narrow grazing incidence optics (hyperboloid) operating at an 86 degree angle of incidence which diverges a pencil-like beam on to a larger conventional spherical retroreflector 17 meters away at the end of the resonator cavity. Because of the large separation between the two mirrors, it is impractical to mount the mirrors as a set in one structure; therefore, each mirror assembly has been designed to have its own respective mount with each element on its own optical bench. Stability of each optical bench relative to the other benches will be maintained in the laboratory environment.

As is seen in Figure 3, the unusual geometry of the hyperboloid mirror (a thin, long, narrow element of varying radius of curvature) required that novel design techniques be employed for fabrication and mounting. Two candidate materials were investigated in the fabrication of this element: aluminum that was diamond-turned and post polished, and glass that was ground and polished. Aluminum, even though it is not a very stable material, is a viable choice because of the optical surface figure requirement of only 0.126 micrometer rms and the controlled laboratory temperature environment of 70°F ± 5°F. A cost tradeoff study comparing aluminum to glass on a one piece quantity basis shows glass to be approximately one-half the cost of aluminum. The primary reason for the high cost of diamond machining is due to the elaborate fixturing required. However, for quantities of two or more, diamond machining should be considered since the cost of the second diamond machined element would only be several thousand dollars. Also, diamond machining offers easier metrology inspection using electronic sensors of the finished optical surface as opposed to interferometric methods. For lowest program cost glass was chosen for the grazing incidence optic baseline design. Figure 4 shows the grazing incidence optics in the stage of fine grinding. Both fused silica and Zerodur are viable options for the glass material. Zerodur was chosen because least cost and best delivery were assured.

To accommodate the GIBE FEL pencil beam, the hyperboloid mirror was configured into a thin rectangle 635 mm long x 76 mm wide x 50.8 mm thick. The thickness of the mirror element was based on achieving adequate structural stiffness when supported on edge through its center of gravity as a triple span beam with outer ends free with supports spaced such that self deflection at the ends is equal to center deflection (about 1 microinch for high f_n). In order to maintain the alignment tolerances of the grazing incidence as specified by the optical design (Figure 2), a three-point kinematic support scheme insensitive to loading and temperature as shown in Figure 5 was implemented. Basically, the mirror attachments consist of one fixed reference point and two floating points which are free to move orthogonally with respect to the fixed point in response to temperature changes without inducing undesirable strain in the mirror. Ball joint type flexures are used at the mirror attachment ends to avoid moment or mirror bending distortion. At the base attachment ends of the two floating supports, directional flexure blades are used for controlled softness in one direction and high stiffness normal to that direction. Super-invar material which matches the near zero thermal coefficient of expansion of Zerodur is used for the three mounting pads which are epoxy bonded to the mirror. The three mounting posts which extend down from the invar pads attach to a plate which ties the mirror assembly to the mount backing plate. A standard, commercially available mount (DSM-12) from John Unertl Optical Company was selected for both the hyperboloid and spherical mirrors. The mount is a rugged design (cast iron base) and provides two axes of fine tilt adjustment and three axes of translation adjustment. Fine pitch screws on the tilt axes provide the required alignment precision as dictated by the optical tolerances. Locking nuts are included on all adjustments to maintain stability after alignment. The DSM-12 mount also provides the correct height of 12.0 ± 0.25 inches from the optical axis of each element to the table surface.

The spherical Zerodur mirror, having a 28 cm outside diameter and 25 cm clear aperture, is a straightforward design; it is kinematically mounted in a conventional aluminum cell at three points and held in place by flexure blades as shown in Figure 6. The cell is attached to the Unertl mount (DSM-12) backing plate at three points.

For checking day to day optical alignment, three alignment reference flats (K&E P/N 716250) have been provided: two on hyperboloid and one on spherical retro-reflector. The mirror flats include targets so that you can check position as well as angle with respect to the line of sight.

Metrology and test

In this section, we summarize the critical issues involved in measuring both the GIO during its fabrication, and the system during its alignment.

In order to measure the surfaces of all the mirrors in an FEL cavity except the GIO, conventional interferometric techniques can be used, and will not be discussed here. However, different techniques must be used for the GIO. The choice of technique can depend very heavily on the fabrication method chosen.

In particular, if the GIO is fabricated with diamond turning techniques, then it could be quite feasible to use the diamond turning machine itself as the measuring instrument. Although it is better in theory not to use any device to measure its own performance, this objection can be overcome and indeed has been overcome in some other diamond turning applications. For instance, the diamond turning machine can be used to measure a cylinder or a sphere which was previously certified by a different instrument. If the diamond turning machine agrees with the previous certification, then it is a safe assumption that it will be able to go back and reliably measure the surface of the GIO.

In our case, the GIO was fabricated with conventional optical grinding and polishing techniques. This called for the use of more conventional means of optical metrology during fabrication. However, since the optic was gradually brought into its final figure from a much coarser figure, the usual problems of making the transition between coarse mechanical metrology and fine optical metrology had to be considered.

To measure the final figure and to solve the transitioning problems, two generic types of optical metrology were considered. First, there was the possibility of normal incidence metrology, using a previously certified toroid as a reference surface. And second, there was the possibility of grazing incidence metrology, using a sphere as a reference surface. The two generic approaches are shown in Figure 7. The pro's and con's of each approach are summarized below.

For the normal incidence metrology approach, it would be necessary to fabricate and certify a long, concave, toroidal test plate. This is not unthinkable, but would be a major effort. Nonetheless, it is possible that the test plate could be used as an integral part of the generation process of the real optic. Another drawback to the normal incidence approach is that there would be several fringes of interference between the test plate and the optic, even when the real optic achieved its final figure and all relative tilt was removed from the optics. Finally, in favor of this method, normal incidence metrology offers the highest sensitivity in terms of number of interferogram fringes per unit surface deformation. However, because of this high sensitivity, while the optic was in between a coarse state and its final figure, this method would be very difficult to use, since the high sensitivity itself would imply an impractically large number of fringes. Therefore, a separate metrology method would have to be devised for this transition period.

For the grazing incidence metrology approach, the reference surface could be a simple sphere, and there would be no interference fringes between the test plate and the optic when the optic achieved its final figure. In this approach, the sensitivity is reduced by the cosine of the incidence angle, which can mean a sensitivity decrease by a factor of ten or more. This apparent drawback, however, offers the possibility of using this same approach during the transition period between coarse figure and final figure.

It was decided to use the grazing incidence metrology approach because of the ease of making a reference surface, because of the lack of interference fringes at the achievement of final figure, and because the approach could be used to make the transition period easier. Because we had a relatively loose tolerance on the absolute surface error on the GIO, we did not feel that the loss of sensitivity was critical, especially given the advantage of easing the transition period.

Finally, the use of the grazing incidence approach allowed us to gain experience in the alignment procedure. Specifically, we designed an interferometer for performing system alignment which shared many common features with the metrology interferometer. We also specified an alignment monitoring system using flats whose purpose was to verify that alignment was maintained during laser operation, without having to turn the laser off and re-install the alignment interferometer.

Conclusions

In conclusion, we have designed and fabricated a Grazing Incidence Beam Expander. This GIBE will be used in a breadboard demonstration to understand the systems issues associated with a Free Electron Laser system. This experimental demonstration is a key milestone in the FEL technology.

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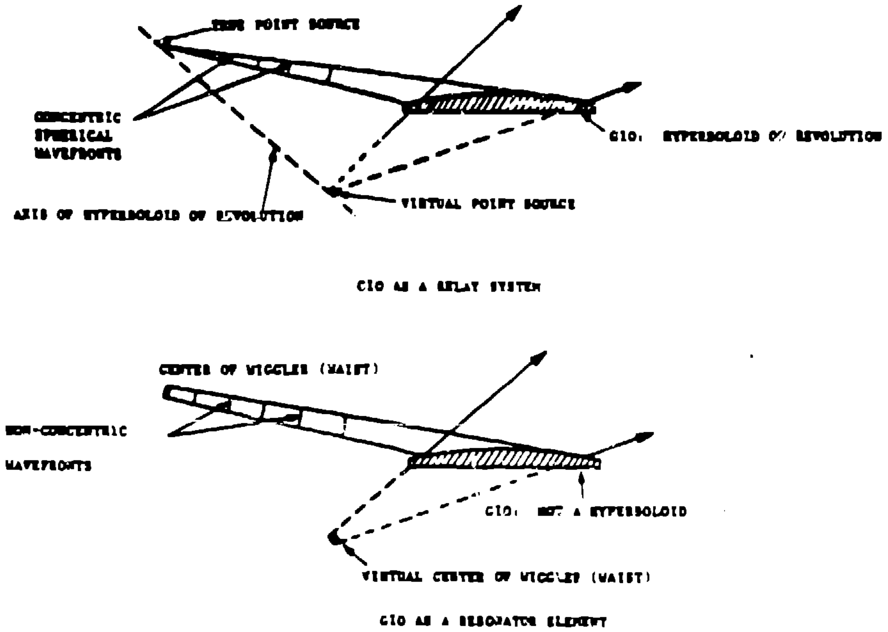
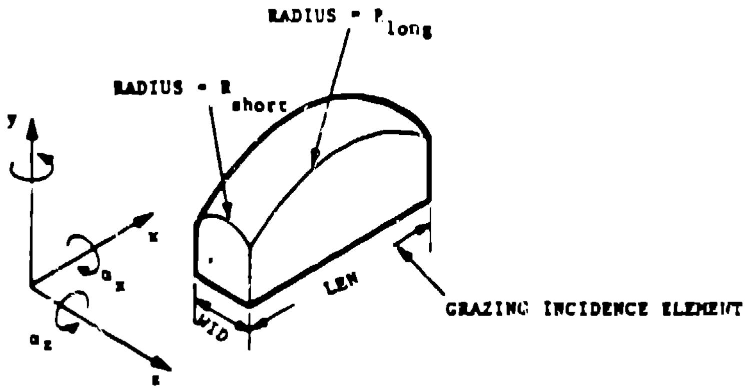


Fig. 1. The actual figure of the GIO depends upon the wavefront emanating from the wiggler waist being concentric or non-concentric. This figure illustrates this point.



MISALIGNMENTS:

- Δ_x - DISPLACEMENT ALONG X-AXIS
- Δ_y - DISPLACEMENT ALONG Y-AXIS
- Δ_z - DISPLACEMENT ALONG Z-AXIS
- α_x - ROTATION ABOUT X-AXIS
- α_y - ROTATION ABOUT Y-AXIS
- α_z - ROTATION ABOUT Z-AXIS

Fig. 2. Co-ordinate systems to calculate the GIO misalignments.

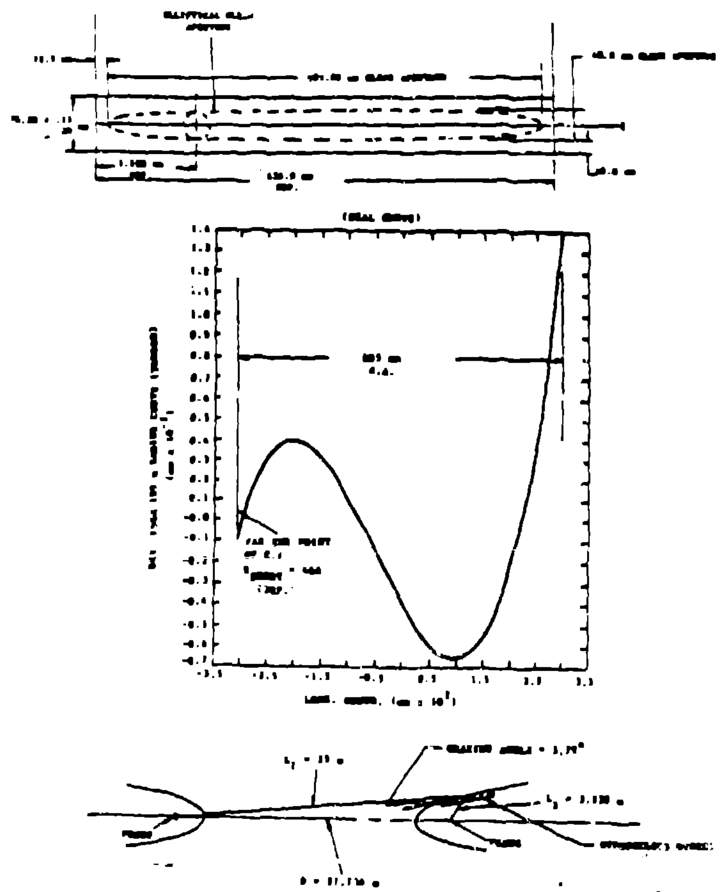


Fig. 3. Design of the GIO showing the figure deviation from a ~~true hyperboloid~~ toroid.

MISALIGNMENT	ASTIGMATISM ORIENTATION	RELATIVE MAGNITUDES INCOMING	OUTGOING
X-AXIS ROTATION	45 DEGREES	1	-1
Y-AXIS ROTATION	45 DEGREES	1	1
Z-AXIS ROTATION	0 DEGREES	1	-1
X-DISPLACEMENT	0 DEGREES	1	A*
Y-DISPLACEMENT	0 DEGREES	1	B*
Z-DISPLACEMENT	45 DEGREES	1	C*

*CONSTANTS A, B, AND C DEPEND ON THE DETAILS OF THE GIBE DESIGN, BUT TEND TO BE LARGER THAN UNITY.

Table 1: Misalignment tolerances of the GIO calculated from the POP code.

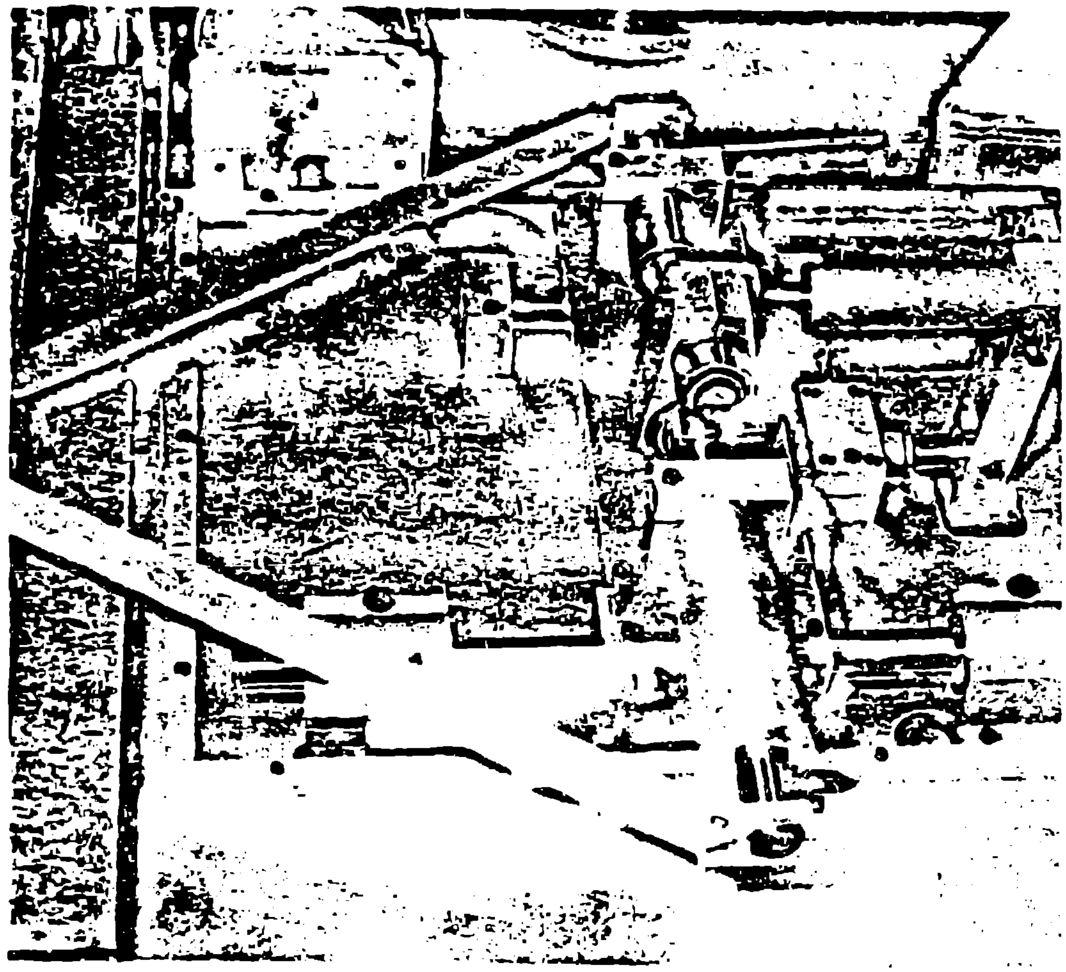


Fig. 4. GIO shown in fine grinding fixture.

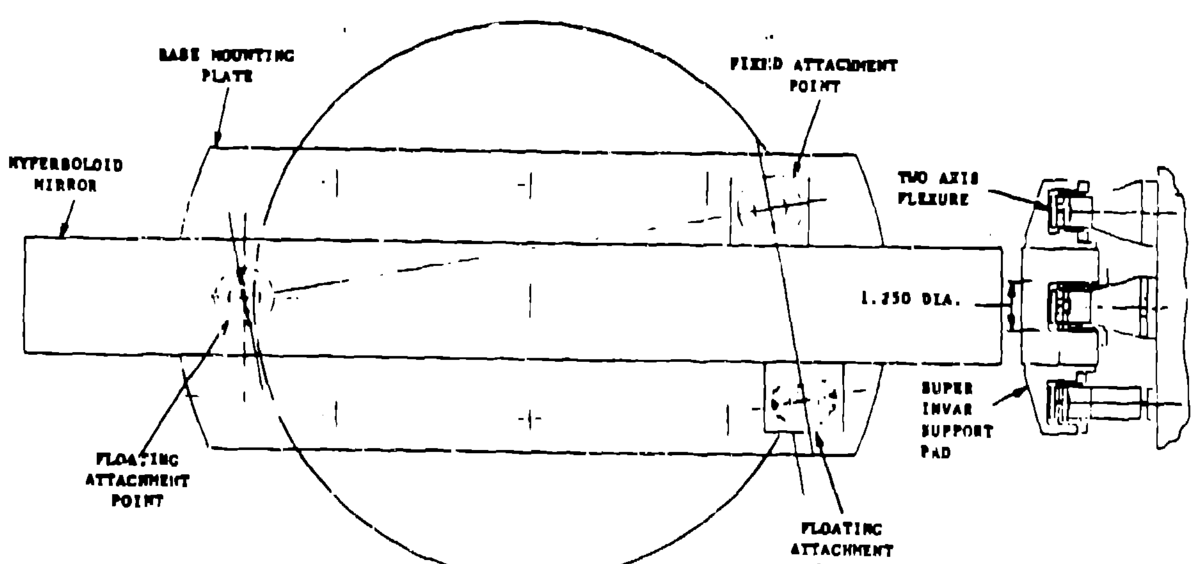


Fig. 5. Three point kinematic mount design to hold the GIO.

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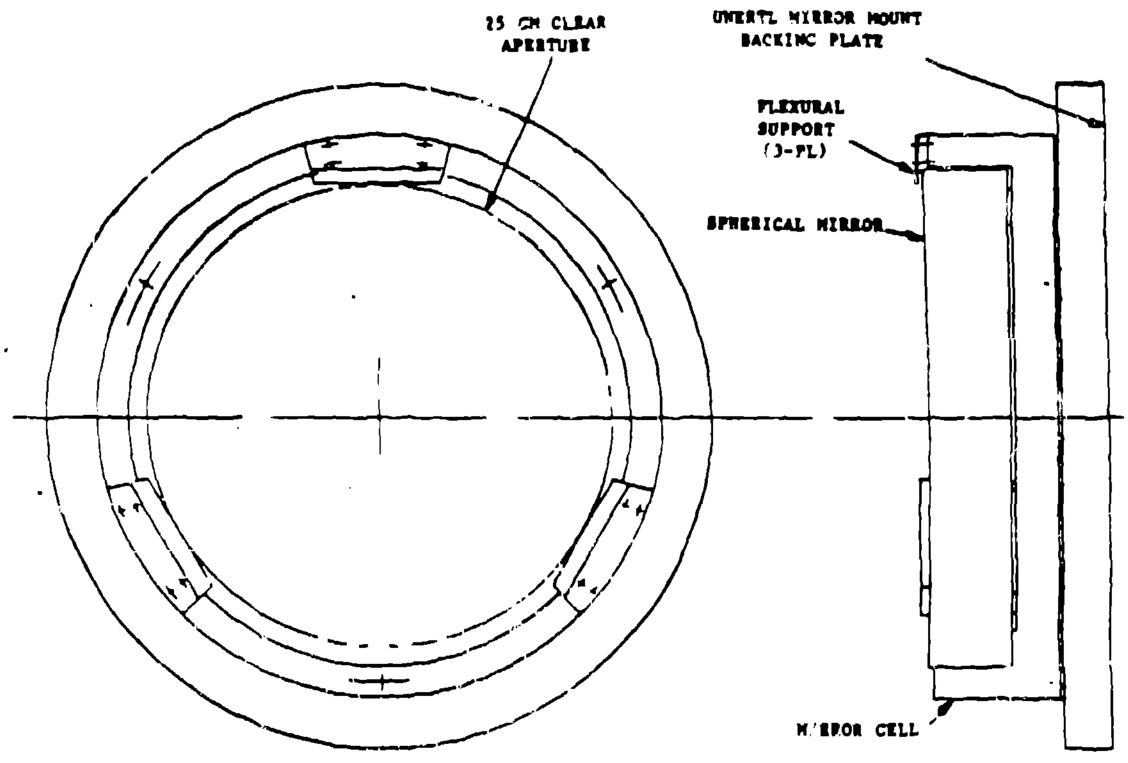

Fig. 6. Kinematic mount design for the spherical end mirror.

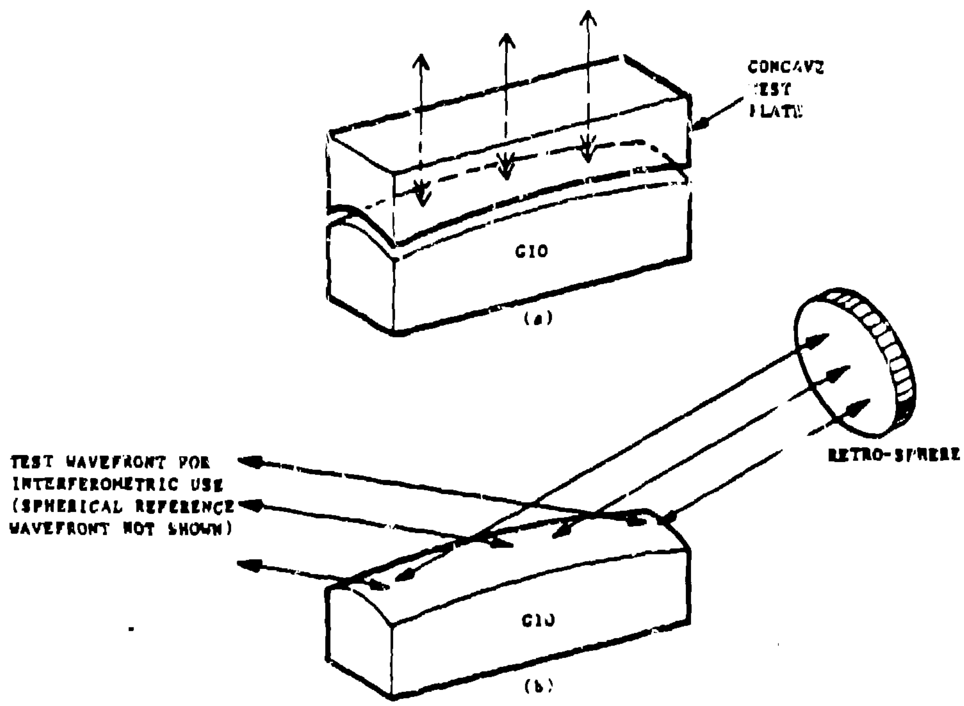

Fig. 7. Two generic approaches for optical metrology for the GIBE system.