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TITLE: ANALYSIS OF FEL OPTICAL SYSTEMS WITH GRAZING INCIDENCE MIRRORS

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Analysis of FEL optical systems with grazing incidence mirrors

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Abstract

The use of grazing incidence optics in resonators alleviates the problem of damage to the optical elements and permits higher powers in cavities of reasonable dimensions for a free electron laser (FEL). The design and manufacture of a grazing incidence beam expander for the Los Alamos FEL mock up has been completed. In this paper, we describe the analysis of a bare cavity, grazing incidence optical beam expander for an FEL system. Since the existing geometrical and physical optics codes were inadequate for such an analysis, the GLAD code was modified to include global coordinates, exact conic representation, raytracing, and exact aberration features to determine the alignment sensitivities of laser resonators. A resonator cavity has been manufactured and experimentally setup in the Optical Evaluation Laboratory at Los Alamos. Calculated performance is compared with the laboratory measurements obtained so far.

Introduction

The free electron laser (FEL) offers the possibility of high extraction efficiency combined with with tunability. However, the thin, pencil-like nature of the gain volume (where photons interact with a stream of relativistic electrons) dictates that the output beam be very small in diameter. The various problems associated with realizing a practical resonator design for these types of systems and the possible solutions are discussed in detail in reference 1. The particular grazing incidence beam expander that was designed and manufactured is described in detail in reference 2. While grazing incidence optics have been previously used in X-ray and EUV astronomy,³⁻⁵ and have been suggested for application in free electron lasers by various authors,^{1,6,7} to our knowledge this is the first that anyone has set up such a resonator system in the laboratory. (This system lased for the first time on December 6, 1985.) In this paper, we discuss our efforts in modeling such systems and compare calculated performance with the experimental results obtained to date.

The basic approach we have taken is to benchmark the code results with experimental results as often as possible. This is because the existing codes were not adequate for the task. The design of the resonator involved heavy usage of both geometric optics techniques, using codes like ACCOS V^{8,9}, and tolerance analyses involving diffraction codes. Neither of which were adequate to the task. Consequently, the GLAD¹⁰ diffraction propagation code has been expanded to include global coordinates, exact conic representation, raytracing, and exact aberration calculations.¹⁰ It now allows components to be positioned and rotated arbitrarily. Aberrations are calculated for components in aligned or misaligned configurations by using ray tracing to compute optical path differences, prior to diffraction propagation. Optical path lengths and beam rotations between components in complex mirror systems are now calculated accurately, so that coherent interactions in phased arrays and coupled devices may be treated correctly. This is a significant advance from the existing diffraction codes, which are restricted to geometrically linear (paraxial) systems.

The subsequent section of this paper deal with: 1) The standard resonator case, modeling and experiments; 2) The grazing incidence beam expander resonator case, modeling and experiments to date; 3) Conclusions; and 4) Future plans.

The standard case¹¹ consisted of a long (64 and 65 meters) laser cavity with a spherical mirror at either end, which was set up at the Optical Evaluation Laboratory at Los Alamos. Comparison of code results with the experiment showed excellent agreement for both beam shape on the mirror and mirror-tilt versus beam-displacement for various internal aperture sizes.

The second resonator setup consists of the grazing incidence beam expander within the long cavity. Comparisons are currently being conducted between code and experiment, and the results to date will be reported in this paper.

Standard case resonator

The standard case resonator was designed to study the problems involved with long cavities. The resonator was a simple near-concentric cavity. The data presented here is for two different length cavities about 64 and 65 meters long. The parameters of the setup are given in Fig. 1. A variable aperture was located 30 cm in front of mirror 1, and was set to the diameters 0.86 cm, 1.2 cm, 1.5 cm, 2.5 cm and "wide open." In the laboratory setup, an argon-ion plasma tube was used to simulate the gain medium of an FEL. In the code, the plasma tube was represented as an aperture of diameter 0.25 cm.

In comparing the experiment to the code, two features were examined. The first was the beam profile. Under nominal conditions, measured data showed the beam profile to be gaussian (see Fig. 2), and the code predicted a gaussian beam of the same beam width. Shown in Fig. 2 are the measured data, and a best-fit gaussian.

The second feature was the displacement of the beam and alignment sensitivity with mirror tilt for various aperture sizes (i.e., the variable aperture described above.) With the aperture "wide open" (Fig. 3) the beam displacement behaved geometrically for both code and experiment. The remaining values for the variable aperture produced decreasing alignment sensitivity with decreasing aperture size. The data in Fig. 3 are all for one tilt angle, 10 mrad of tilt in mirror 2, and the displacement is measured at mirror 2.

Aberration studies were conducted on the computer, but have not yet been verified with experiments. The results will be briefly presented here. Astigmatism was added to the cavity in two different locations, 200 cm in front of mirror 1 and 75 cm from the center of the resonator. The change in loss per pass was observed after the resonator had reached stability. This was done to simulate a possible beam splitter being inserted into the cavity for a real-time alignment system or for diagnostic purposes. The results are given in Table I.

The second aberration study involved the addition of linear ripple to the surface of mirror 2. It was found that in adding integer numbers of periods at .1 λ amplitude caused the loss per pass to degrade from the nominal case of 6.2% loss per pass to 23.4% for all integer values, except for multiples of about 15. At multiples of 15 periods across the 5.68 cm aperture, the loss per pass returned to near that of the nominal case. The ripple was put in as an odd function about the center of the mirror. This study has not been pursued any further, as this phenomena is not well understood.

Grazing incidence beam expander resonator

System description

The grazing incidence beam expander resonator consisted of a hyperbolic grazer and two spherical mirrors positioned to form a laser resonator approximately 64 m long (Fig. 4). The grazing incidence optic is an off-axis section of a hyperboloid which is rotationally symmetric about the z axis. For different cavity lengths, the angle of incidence of the chief ray on the grazer ($\approx 84^\circ$) is held constant. Hence, the distance from the point of incidence on the grazer to the focal point A is constant (25 m). The right-hand sphere, mirror 3, is positioned so that its center of curvature is approximately coincident with focus B of the hyperboloid. The left-hand sphere, mirror 1, is placed to the left of focus A. The optical distance between the two spherical mirrors is then varied, to model four different cases, with four different $g_1 g_2$ products (stability parameter). In the laboratory, the active lasing medium was placed symmetrically about focus A.

The waist of the resonator is at the position w_0 as indicated in fig. 4. Ideally, w_0 should coincide with focus A to minimize aberrations due to an extended source. However, because of hardware considerations when changing the cavity length, the coincidence was allowed to vary from 4 mm to 0.5 m.

Each of the four cases is based on a simpler, two mirror, near concentric system, in which the mirror on the right (referred to as mirror 4 in Fig. 4) is replaced by the grazing incidence beam expander and the spherical retro-mirror 3. It is placed at a fixed distance in front of the grazer, and thus determines the position of mirror 1 for a given $g_1 g_2$ value. This mirror is used in both the calculations and the laboratory setup. Parameters for the system are given in Fig. 4.

Four variations on the above setup were considered, each based on a different $g_1 g_2$ product. The stability criterion, $0 \leq g_1 g_2 \leq 1$, is discussed in Chapter 8 of Siegman.¹² As this value approaches 1.0, the beam size on the normal-incidence mirror increases, and the energy density is reduced. On the other hand, approaching this limit of the stability condition makes the system more difficult to align. The details of the

four cases are specified in Table II. They have been modeled in GLAD and for ideal conditions have excellent agreement with hand calculations using gaussian propagation and ray tracing techniques.

After 100 passes through the resonator, under ideal conditions, the code indicates that a stable gaussian-like beam is established for the first three cases. Case #4 was somewhat unstable in 100 passes, but was found to be stable if the diameter of the right-hand sphere was doubled. The laboratory setup has successfully produced a stable gaussian-like mode with beam sizes at the mirrors roughly in agreement with the code predictions. This experimental setup represents a case between #2 and #3.

Experimental Setup

The grazing incidence resonator is physically located in the same laboratory where the previous 65-m cavity experiment was conducted. This laboratory environment has been described elsewhere;¹¹ however, several equipment modifications have been implemented since the last experiment. The most important of these modifications include the use of a grazing incidence optic, a ten-inch clear aperture retrosphere, integration of an alignment interferometer, and implementation of a closed-loop stabilization system.

As shown in Figure 4, the grazing incidence optic and retrosphere replace one end of the normal incidence cavity. The grazer is fabricated of Zerodur and overcoated with aluminum and SiO_2 . Pertinent parameters for the grazer and retrosphere are delineated in Table 3. In the nominal design of the hyperbola, the waist of the laser is 25 m from the grazer and a virtual image is formed by the surface at the grazer's focus 3.238 m behind the optic. Mounting of both grazer and retrosphere permits control of all translational and rotational degrees of freedom. The mounted grazer is illustrated in Figure 5.

Initial alignment of the grazing incidence beam expander was accomplished through the use of conventional optical tooling and an interferometer. The interferometer setup is shown schematically in Figure 6. Insertion of the auxiliary spherical mirror (mirror 4) in Figures 4 and 6 permits alignment of mirror 1 and establishes a reference for the interferometer. Use of the diverger (Fig. 6) allows the wavefront emerging from the interferometer to match that established by the auxiliary sphere when the normal incidence cavity is lasing. Subsequent to optical tooling alignment of the grazer and retrosphere, the interferometer is used for final alignment and best wavefront quality. In addition to providing an alignment device, the interferometer also establishes a means for evaluating the wavefront's susceptibility to alignment errors. This in turn provides a benchmark for the design codes and specifications.

Precise tilt angles may be deliberately induced in the end mirrors with the aid of the stabilization system. This system consists of dual-axis Hewlett Packard interferometers, control computers, and computer-driven piezoelectric activators. This system is capable of driving the mirrors to any desired angle within the range of the piezo stroke (10 μm). This position is then held to within 100-200 nanoradians, the bandwidth of the system being on the order of 100 Hz. Use of the stabilization system with the interferometer is the fundamental tool for a systematic evaluation of alignment sensitivities.

Results of Modeling

Aberrations in the form of random phase have been studied in the modeling, but no measurements have been made on the optical setup. Adding random phase to the spherical mirrors is fairly straight forward. One needs to specify an autocorrelation radius (or smoothing function) and a wavefront error. They are equal in both transverse directions since the beam is normal to the mirrors. The grazer, however, requires some careful considerations. Since the angle of incidence is about 84° in one transverse axis and not the other, the autocorrelation radius for the tilted axis is given by the normal value times a cosine of the incident angle. The other axis being normal is unaffected. The wavefront error is greatly improved by the tilt since it is multiplied by the cosine of the incident angle and, furthermore, the error is uniform across the surface so it is not axially dependent.

The aim of this study was to determine the effect of random phase error on the strehl ratio, and in particular how much could be tolerated in mirror 3. The random phase was applied to the grazer with a surface error of $\lambda/20$ rms. Two different values were applied to mirror 3, $\lambda/100$ rms and $\lambda/45$ rms. An autocorrelation radius of $1/3$ the mirror diameter was chosen to model a random figure error for mirror 3. For the grazer it was chosen to be $1/3$ of the small dimension and $\cos 84^\circ$ times that for the long dimension. Mirror 1 was not aberrated.

A half pass was run, starting at the waist and coming back to the waist. The strehl ratio was estimated by comparing the peak intensities at the waist, before and after, regardless of where the peak was located. The results are indicated in Table IV, and are for runs with various combinations of the above mentioned values. The last entry, the one with the most aberration, has a strehl ratio of .9382, which was felt to be acceptable. A multi-pass study is currently underway, but at this time the results are incomplete.

The ability to tilt a mirror about any arbitrary point on its surface has recently been added to GLAD. A coordinate system is defined at that point with the z axis normal to the surface, the y axis in the incident plane, and the x axis perpendicular to the plane of incidence. Rotations about all three axes are possible. A tilt study of the grazer is currently in progress, and the results to date are as follows. Since the z axis is the normal to the surface, tilts about it leave the chief ray unaffected. A 20- μ rad tilt about this axis causes a normally gaussian beam to become elongated diagonally into a "fin" (Fig. 7). The peak is still on-axis and at the waist it is somewhat gaussian-like (Fig. 8). For a tilt of 30 μ rad the "fin" develops lobes on either side, and at the waist the beam breaks up into three peaks with diagonal symmetry (Figs. 9 and 10).

Tilting about the y axis causes the chief ray to shift. A new stable mode is generated off the optic axis, for small tilts. To date, only a few tentative results have been obtained (see Figs. 11 and 12).

A tilt about the x axis appears to cause the chief ray to "walk" off the grazer in a few passes. It behaves like an unstable resonator. This causes problems because when the chief ray "walks" off the mirror, the program stops. What one would like to do is follow only the energy that stays within the cavity for many passes. This might be solved by merely judiciously choosing a new chief ray. This problem is currently being studied.

Conclusion

In conclusion, it has been demonstrated that a resonator with grazing incidence optics will actually lase. Secondly, a code now exists that is capable of physical optics modeling for any case from simple paraxial systems to complicated off-axis systems involving even grazing incidence optics. The code has been carefully compared to hand calculations, in ideal cases, and to experiments having two different resonator configurations, in more complicated cases. The standard case was designed to analyze the problems associated with long cavities. The second configuration was implemented to test the concept of grazing incidence beam expanders within the cavity. A number of variations on both configurations have been analyzed including mirror tilt, mirror aberrations, change in cavity length, and variation of aperture size. The code agrees well with experiment in those cases tested to date.

Future Plans

An effort is currently underway to add to the code the capability to model the gain volume of an FEL. It is presently being debugged and will soon be on-line. It will then be possible to model the complete optical system, including the effects of the gain medium on the optical beam, which may have some impact on the mirror design.

In addition, it is planned to continue the current effort to compare the code with experiment. The current studies of mirror tilt and aberrations will be completed, so that a more definitive tolerancing can be placed on the components of the optical system for an FEL. The code will become a major tool for the design and analysis of the total optical system of future FELs.

TABLE I

Effect of astigmatism on loss

Location of Astigmatism	Percent loss per pass	
	-0.5 λ of Astig	-1.1 λ of Astig
75 cm from center	76.5	20.3
200 cm from mirror 1	77.2	34.5

TABLE II

Specification of Four Configurations

Case #	$g_1 g_2$	d^* (cm)	$l_1 + d$ (cm)	l_3 (cm)	w_0 (cm)
1	0.90	56.59864	2136.599	1688.228	.0756119
2	0.95	27.40097	2169.401	1687.723	.0632626
3	0.997	1.41925	2198.419	1687.283	.0302607
4	0.9996	0.23656	2199.737	1687.264	.0193375

	Mirror 1 w_1 (cm)	Grazer w_2 (cm)	Mirror 3 w_3 (cm)	Temporary w_4 (cm)
1	.4454023	.5076289	3.172350	.4974740
2	.5364193	.6104103	3.813257	.5982007
3	1.128907	1.282938	8.012311	1.257280
4	1.767124	2.008119	12.54122	1.967956

* Please see Figure 4 for the definition of d , l_1 , l_3 , and w_0 .
NOTE: All beam radii are measured at the $1/e^2$ point.

Table III

Specifications for grazing incidence beam expander

	<u>Hyperboloid</u>	<u>Retrosphere</u>
Surface Finish	20 Å rms	20 Å rms
Surface Figure	$\lambda/5$ rms	$\lambda/45$ rms
Clear Aperture	60.5 cm x 4.0 cm elliptical	25 cm diam circular
Eccentricity	1.00149	----
Radius	3.2458 cm (vertex) 109 m (long) 49.1 cm (short)	20.18 m
Reflectivity at 4880 Å	$\geq 99\%$ at 86°	$\geq 98\%$

TABLE IV

Aberrations on the Grazer and Mirror 3

Run	Description	Strehl Ratio
1	No aberration, no apertures	1.00
2	No aberration, apertures (4 x beam size)	1.00
3	Random phase on grazer only, $\lambda/20$	0.9966
4	Random phase on mirror 3 only, $\lambda/100$	0.9887
5	Random phase on mirror 3 only, $\lambda/45$	0.9446
6	On both mirror #3 $\lambda/100$ and grazer $\lambda/20$	0.9639
7	On both mirror #3 $\lambda/45$ and grazer $\lambda/20$	0.9382

NOTE: 1. The apertures for runs 3-7 are the same as for run 2.
2. All λ values are in rms and indicate surface error.

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STANDARD CASE

DIFFRACTION EFFECTS ARE STUDIED IN THE RESONATOR
BY INTRODUCTION OF A VARIABLE APERTURE

Figure 1

BEAM PROFILE AT MIRROR 2 FOR STANDARD CASE

Figure 2

DATA INDICATE THAT DIFFRACTING APERTURES DECREASE ALIGNMENT SENSITIVITY

Figure 3

GRAZING INCIDENCE BEAM EXPANDER RESONATOR SCHEMATIC OF OPTICAL LAYOUT

Figure 4

Mirror 1 (sphere)

R_1 = radius of curvature = 2200. cm
 aperture (circular diam.) = 5.08 cm

Mirror 2 (grazing incidence hyperboloid)

e = eccentricity = 1.00149
 distance between foci = 2179.44 cm
 mirror center to focus A = 2500. cm
 aperture (elliptical) = 63.6 cm x 7.62 cm

Mirror 3 (sphere)

R_3 = radius of curvature = 2011. cm
 aperture (circular diam.) = 25.0 cm

Mirror 4 (sphere)

R_4 = radius of curvature = 2450. cm
 aperture (circular diam.) = 5.08

Figure 5

ALIGNMENT INTERFEROMETER FOR GRAZER PROVIDES FOR LASER OPERATION AND EVALUATION OF ALIGNMENT SENSITIVITY

Figure 6

BEAM INTENSITY AT MIRROR 3 WITH GRAZER TILTED $20 \mu\text{rad}$ ABOUT THE Z AXIS

Figure 7

BEAM INTENSITY NEAR WAIST WITH GRAZER TILTED $20 \mu\text{rad}$ ABOUT THE Z AXIS

Figure 8

BEAM INTENSITY AT MIRROR 3 WITH GRAZER TILTED $30 \mu\text{rad}$ ABOUT THE Z AXIS

Figure 9

BEAM INTENSITY NEAR WAIST WITH GRAZER TILTED ABOUT $30 \mu\text{rad}$ ABOUT THE Z AXIS

Figure 10

BEAM INTENSITY AT MIRROR 3 WITH GRAZER TILTED $8 \mu\text{rad}$ ABOUT THE Y AXIS

Figure 11

BEAM INTENSITY NEAR WAIST WITH GRAZER TILTED $8 \mu\text{rad}$ ABOUT THE Y AXIS

Figure 12