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TITLE THERMAL ANALYSIS OF MULTIFACET-MIRROR RING
RESONATOR FOR XUV FREE-ELECTRON LASERS

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Thermal Analysis of Multifacet-Mirror Ring Resonator for XUV Free-Electron Lasers*

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ABSTRACT

XUV ($10 \text{ nm} \leq \lambda \leq 100 \text{ nm}$) free-electron lasers (FELs) are potentially important light sources for advanced lithography and materials applications. The average power of an XUV FEL oscillator may be limited by thermal loading of the resonator mirrors. We analyze the requirements for the thermal performance of the mirrors of a metal, multifacet-mirror ring resonator for use at 12 nm. We use analytical methods and numerical approaches which include simulations with the 3-D FEL code FELEX. Thermal distortion of mirror surfaces leads to optical wavefront aberrations which reduce the focusability of the light beam in the gain medium (wiggler/electron beam) and limit the laser performance.

1.0 Introduction

Our previous extensive theoretical studies of the requirements and performance of an XUV FEL oscillator [1], [2], [3], with an optical ring resonator composed of metal, multifacet mirrors [4] have demonstrated the feasibility of such devices if modest advances can be achieved in the technology of wiggler magnets and very bright relativistic electron beams. Although metal, multifacet mirrors [4] appear to provide sufficiently high reflectivity at various optical wavelengths in the XUV, individual mirror facets may each absorb up to several percent of the incident optical power. Since transverse optical spot sizes for an XUV resonator are very small, the optical power densities on each mirror element can be quite large. These combined effects can lead to thermal deformation of the mirror surfaces. Newer synchrotron radiation facilities which use undulators rather than bending magnets as radiation sources face similar mirror thermal distortion problems in the optical transport system from the synchrotron to experimental stations [5]. In an XUV FEL oscillator, the light generation process itself requires a well-focused optical mode in the interaction region of the laser. Thermal mirror distortions lead to aberrations of the optical mode and generally reduce the laser gain by reducing the focusability of the light in the wiggler. Hence, the steady-state power of the laser may be substantially reduced if the mirrors distort too much.

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In this paper we present results of a first approach to the problem of thermal distortion of the mirrors of an XUV FEL resonator. In Section 2 we review the configuration and properties of a 12 nm oscillator as previously determined by 3-D numerical simulations. In Section 3 we discuss the results of numerical calculations of the heating and distortion of mirror elements. These calculations were done for models of actively cooled mirrors. The results of the calculations are summarized by an analytical fit to the numerical data for the distortion of the mirror's surface. In Section 4 we use an analytical theory to study the effects of aberrations of the optical beam, induced by reflections from thermally distorted mirror surfaces, upon laser performance to obtain approximate limits on allowable aberration magnitudes. In Section 5 we use numerical simulations to study the dependence of the steady-state circulating optical power on the magnitude of the mirror thermal distortion coefficient. These results yield limits for the allowable aberration per round trip added by mirror thermal distortion. In Section 6 we study the scaling of resonator dimensions and power handling capacity with variations of the number of facets of each multifacet retroreflector. Finally, we summarize our conclusions from this work in Section 7.

2.0 XUV FEL Configuration and Performance

The geometry of the optical resonator for an XUV FEL oscillator is shown in Figure 1. The resonator is a unidirectional ring. In the forward-going leg, the light beam is tightly focused as it passes through the wiggler magnet and interacts with the electron beam. The light in the backward-going leg is collimated and expanded to a large transverse size. The mode size changes are accomplished with two telescopes, at either end of the resonator, each of which consists of a grazing angle-of-incidence hyperbolic mirror located along the wiggler/electron beam axis, and an off-axis parabolic mirror which is the last element of a multifacet retroreflector. Typical parameter values for the optical components, electron beam, and wiggler magnet are shown in Table 1.

TABLE 1. FEL Oscillator Parameter Values

Optical	
wavelength	12 nm
resonator end mirror separation	42 m
hyperboloid-paraboloid separation	6.3 m
wiggler center to grazer distance	14.7 m
number of facets (rhodium)	9
peak power output	10 MW
average power output	~100 W
Electron Beam	
energy	535 MeV
charge per bunch	3 nC
peak current	300 A
fractional energy spread	0.1 %

normalized transverse emittance 20π mm-mr

Undulator

length	12 m
period	1.60 cm
full gap	0.47 cm
peak magnetic field	0.75 T

Other resonator geometries have been studied [6] for properties advantageous to an XUV FEL, but in the present work we shall assume the general layout shown in Figure 1. Not shown explicitly in the figure is the method of output coupling: the numerical studies have considered both scraping with an annular mirror located along the back leg of the resonator, and hole coupling with a hole in the first facet of the downstream retroreflector. For the purposes of the present work, the details of the outcoupling will be ignored. We however note that typically the optimum magnitude of the outcoupling is about 20 % so that the required internal power is about five times the output power. In particular, for applications to production of microcircuits by lithography, sources with average powers in the range of tens of watts to one hundred watts are needed [7].

3.0 Mirror Thermal Distortion Calculations

The design of the optical resonator is dependent upon the required laser output power. The amount of power absorbed by each mirror facet depends upon the magnitude of the incident optical power density (intensity). For a given incident power, the intensity on the mirror surface is proportional to the cosine of the angle of incidence; thus, it is advantageous to use many facets in the multifacet retroreflectors since the angle of incidence is approximately given by $\theta_i = (\pi / 2) (1 - 1/N)$ for a reflector with N facets. For laser operation at 12 nm, rhodium mirrors are needed. The absorption of such mirrors can be obtained from the known material constants [4] and the geometry.

The temporal structure of the light generated in a free-electron laser has several time scales. Individual optical micropulses may be as short as several picoseconds; a macropulse may be several hundred microseconds long during which a micropulse appears every one hundred nanoseconds; finally, macropulses may be repeated at a rate of tens of hertz. Lithographic applications require that the laser remain on for hours or even days at a time. Hence, although the energy absorbed by individual mirror elements has a complicated time structure, the steady-state performance of the mirrors is of primary interest.

The magnitude of the absorption of individual mirror facets (~ percent) together with the requirement of an average internal circulating optical power of several hundred watts forces us to consider actively cooled mirrors. Numerical calculations of the deformation of the surface of a mirror which consists of a silicon faceplate (with a very thin rhodium coating for 12 nm operation; the rhodium has a negligible thermal mass) coupled to a fixed temperature thermal reservoir by coolant flowing at a given rate have been performed [8]. Various mirror dimensions, faceplate thicknesses, and reservoir temperatures were

considered. The incident illumination levels were obtained from the performance figures obtained in [2] in which perfect mirrors were assumed.

Although the thermal calculations show temporal variations associated with the time structure of the incident radiation, we shall ignore such small variations and summarize the average steady-state results. It was found that the shape of the surface deformation could be described as the sum of two terms: an "irradiance mapping" term which is proportional to the intensity I (W/cm^2) through a thermal deformation coefficient D (Angstroms per W/cm^2), and a thermal bowing term. The thermal bowing produces a curvature change of the phase front of the incident light; in what follows, we have assumed that the effects of this term can be compensated for by refocusing the resonator. It therefore will not be explicitly discussed. Since the intensity distribution of a resonator mode is typically Gaussian in profile, the irradiance mapping term adds a Gaussian-shaped distortion to the phase front of the incident optical beam. Such a term corresponds to a complicated aberration which can drastically change the mode overlap with the electron beam within the wiggler. The magnitude of D was found to vary with the specific mirror configuration (faceplate thickness) but was generally in the range of 0.3 to 4.0 Angstroms per W/cm^2 . Note that increasing the number of facets of the multifacet retroreflectors not only reduces the absorbed intensity but also reduces the magnitude of the added phase error since another factor of $\cos \theta_i$ modifies the irradiance mapping term in order to account for the non-normal illumination of the distorted surface.

4.0 FEL Performance with Aberrations and Thermal Distortion

The performance of an FEL oscillator is dependent upon the ability to focus an optical beam down to a transverse size comparable to that of the electron beam. For an unaberrated Gaussian beam, the spot size transport is given by the well known formula

$$w^2(z) = w_0^2 [1 + (z - z_f)^2 / z_r^2] \quad (\text{EQ } 1)$$

where $\pi w_0^2 = \lambda z_r$, z_r is the Rayleigh range, and z_f is the focal position. The minimum focal spot size and the expansion length are both dependent upon the Rayleigh range. For a given wiggler length, the Rayleigh range is chosen to maximize the FEL gain. For the case considered here: $L_w = \text{wiggler length} = 12 \text{ m}$, $z_r = 3 \text{ m}$, and $z_f = 0$ (the center of the wiggler).

For an optical beam with an arbitrary intensity and (aberrated) phase profile, the rms spot size transport is given by the following equations [9]:

$$w^2(z) = C z^2 + B z + A \quad (\text{EQ } 2)$$

$$C = (1 / (k_0^2 w_1)) \int dx dy [(\nabla E_0)^2 + E_0^2 (\nabla \phi)^2] \quad (\text{EQ } 3)$$

$$B = (2 / (k_0 w_1)) \int dx dy E_0^2 (\mathbf{r} \cdot \nabla \phi) \quad (\text{EQ } 4)$$

$$A = (1 / w_1) \int dx dy r^2 E_0^2 \quad (\text{EQ } 5)$$

$$w_1 = \int dx dy E_0^2 \quad (\text{EQ 6})$$

where the optical field is of the form:

$$E^* = E_0 e^{i\varphi} \quad (\text{EQ 7})$$

and k_0 is the wavenumber in free space. Equations (2) - (6) are derived by taking appropriate moments of the paraxial wave equation. Similarly, a linear equation can be derived for the centroid transport.

The effects of thermal distortion of the mirror surfaces of the resonator are investigated by assuming an optical amplitude and phase profile of the form:

$$E_0 = I^{1/2} \exp(-(r/w)^2) \quad (\text{EQ 8})$$

$$\varphi = -k_0 D I \exp-2(r/w)^2 + (k_0 r^2)/(2 R_c) \quad (\text{EQ 9})$$

where I is the intensity, w is the Gaussian spot size, D is the thermal distortion coefficient, and R_c is a focus correction. We have assumed a Gaussian intensity profile and a phase profile that is dependent upon the intensity. This is the irradiance mapping term in the deformation of a mirror surface. As noted above, in this paper we assume that other thermal distortion effects, such as thermal bowing, can be corrected by displacement of the resonator mirrors relative to the nominal focus. Substituting Equations (8) and (9) into (3) - (5), the coefficients can be evaluated:

$$C = (2/(k_0 w)^2) + 0.5 (w/R)^2 + (DI)/R + (8/9) (DI/w)^2 \quad (\text{EQ 10})$$

$$B = (w^2/R) + DI \quad (\text{EQ 11})$$

$$A = w^2/2 \quad (\text{EQ 12})$$

Further, Equation (2) can be cast into the form of Equation (1), and expressions for the focal spot size, Rayleigh range, and focal position can be obtained:

$$w_0 = 0.5 (\sqrt{S}/\sqrt{C}) \quad (\text{EQ 13})$$

$$z_r = 0.5 (\sqrt{S}/C) \quad (\text{EQ 14})$$

$$z_f = -0.5 (B/C) \quad (\text{EQ 15})$$

where

$$S = 4CA - B^2 = (4/k_0^2) + (7/9) (DI)^2 \quad (\text{EQ 16})$$

Equations (13) - (16) provide a simple model to estimate the effect of thermal distortion on the mirror surfaces in ring resonators of the geometry of Figure 1. First, the optical propagation in the back leg is geometrical. This is a consequence of the optical beam Rayleigh range being ~ 1 cm after reflection from the hyperboloid, and the beam is collimated after reflection from the paraboloid. The accumulation of aberrations due to thermal distortion of the mirror surfaces will add coherently. The total wavefront aberration can then be applied to the optical beam after reflection from the upstream hyperboloid (the mirror prior

to the wiggler entrance). At this position, Equations (13) - (16) are applicable in determining the focal properties of the aberrated Gaussian beam. For a hyperboloid position of 1470 cm from the wiggler center, $\lambda = 12$ nm, and $z_T = 300$ cm, Figure 2 plots the optical waist size as a function of waves of thermal distortion (DI product in Equation (9)). Curve a is the case where the curvature R_c is held fixed. Curves b and c are the cases where R_c is adjusted to obtain a focal correction where the focus position is at the center of the wiggler, or 3 m toward the wiggler's entrance, respectively. For curve a, it is observed that 0.5 waves of cumulative thermal distortion wavefront error increases the spot size by a factor of two. Further, from Equation (14), the Rayleigh range increases from 300 cm to 920 cm. Under these conditions, it is apparent that the FEL gain will decrease. This is verified in Table 2 where the single-pass FEL gain is tabulated as a function of the magnitude of the thermal distortion DI. The product DI determines the focal properties w_0 , z_T , and z_f which were assumed in the FEL calculations using the simulation code FELEX (which is briefly described below in Section 5).

TABLE 2. Focal Parameters and FEL Gain with an Aberrated Wavefront

$k_0 \text{DI} / (2\pi)$	w_0 (cm)	z_T (cm)	z_f (cm)	Gain
0.0	0.0107	300	0	3.1
0.2	0.0139	439	169	2.9
0.4	0.0203	723	293	2.7
0.6	0.0290	1133	290	2.5
0.8	0.0382	1573	72	2.3

As the thermal distortion increases, the single-pass gain decreases monotonically. In an oscillator configuration, this will result in a decrease of the saturated power. In Figure 2, it is observed that with focus correction a smaller spot size can be maintained as thermal distortion increases. In this case, better performance of the FEL oscillator is expected. Note that focal correction is readily obtained by displacing the upstream paraboloid - hyperboloid relative to each other. The formalism in this section provides a qualitative description of the effect of thermal distortion on mirror surfaces in the ring resonator. In the next section, full FEL oscillator simulations provide a quantitative performance prediction as a function of the number of waves of thermal distortion.

5.0 XUV FEL Oscillator Simulations

In this section, we summarize the results of FEL oscillator simulations which determine the allowable thermal distortion level for a typical multifacet mirror ring resonator geometry. The simulation code used is FELEX [10]. In essence, FELEX models the FEL oscillator as follows. The optical field is determined by a solution of the paraxial wave equation which has a source term in the wiggler / electron beam region. The source term is defined by the self-consistent interaction of the optical field - wiggler field and the electron mo-

tion. The 3 - D motion of discrete electrons (typically ~20,000) are followed to accurately simulate a finite sized electron beam. At the end of the wiggler, the optical field is propagated through the resonator. At each mirror surface, the optical field amplitude and phase are altered to model the reflectivity and curvature of the mirror. In addition, mirror aberrations such as thermal distortion are modeled by the appropriate phase addition. FELEX solves the paraxial wave equation numerically on a finite grid, typically 128 x 128.

FEL oscillator simulations were performed for the parameters summarized in Table 1. The electron beam and wiggler parameters are those required to have sufficient gain to overcome the surface absorption and outcoupling losses of the resonator. The effect of the mirror surface distortion coefficient in Angstroms per W / cm² on the average circulating power in the resonator is shown in Figure 3. The distortion coefficient was applied to each of the twenty mirrors in the resonator. For curve a in the figure, the mirror spacing was fixed at the nominal settings for the zero thermal distortion case. For zero mirror surface distortion, the circulating power is limited by a balance of FEL gain and resonator losses. For large mirror surface distortion, the circulating power asymptotes to a value where the product DI of Equation (9) is approximately constant. For this regime, the total wavefront error accumulated in one roundtrip through the resonator is estimated to be 0.25 waves. For curve b in Figure 3, a focal correction is made by adjusting the distance between the upstream paraboloid - hyperboloid mirrors. It is observed that, for a given mirror surface distortion level, ~60 % more circulating power is obtained. For this case, the cumulative thermal distortion through the resonator is 0.5 waves. This level of accumulated error will be used in the next section in evaluating various resonator designs.

6.0 Average Power Scaling of the Multifacet Mirror Ring Resonator

Given the criterion that ~0.5 waves of cumulative thermal distortion is allowable, a multifacet ring resonator can be designed without the need for detailed FEL simulations. The size of the ring resonator will be determined by the level of mirror surface distortion and by the level of circulating power desired. A small computer program was written to define the geometry of a grazing incidence multifacet ring resonator using the inputs given above, and the estimated reflectivity of rhodium - coated mirrors at non - normal incidence. Typical results from these calculations are shown in Figures 4 - 6. A mirror surface distortion coefficient of one Angstrom per W / cm² was assumed for each of the mirrors in the resonators. The hyperboloid was assumed to have an incident angle of 86° and a magnification of 0.088 for Figure 4 and 0.05 for Figure 5. The hyperboloid - multifacet mirror spacing was 6.3 m for Figure 4, and the hyperboloid - wiggler center spacing was 14.7 m for Figure 5. The results indicate the resonator size required for a given circulating power level as a function of the number of facets in each of the multifacet mirrors. It is observed that the power handling increases with an increasing number of facets. This is a result of the fact that the normal wavefront error due to thermal distortion at grazing incidence scales as $\cos^3\theta_i$. For a power output of 100 W, a circulating power of about 500 W is required. A resonator design with 9 facet retroreflectors and a hyperboloid - retroreflector spacing of 6.9 m (Figure 5) is needed to accommodate that power level. The overall resonator length would be 44 m. This is a rather large resonator which requires an accurate

alignment system. An alternative approach that would make the resonator much smaller is to decrease the mirror surface distortion coefficient below the one Angstrom per W / cm^2 assumption. This may be accomplished by cooling a silicon substrate to 110°K where the thermal expansion coefficient is near zero. In this case, a much smaller resonator could be designed for a given power level.

7.0 Summary and Conclusions

We have performed an initial study of the impact of thermal distortion of the mirrors of a multifacet mirror ring resonator designed for use in a free-electron laser oscillator operating at an optical wavelength of 12 nm. The basic requirements and laser performance without consideration of mirror distortion were obtained by numerical simulation in [2]. This information was used to do a series of mirror thermal distortion calculations for various configurations of cooled mirrors [8]. The results of those calculations can be summarized by stating that the displacement of the mirror surface due to heating can be represented as the sum of two terms: an irradiance mapping term which is proportional to the transverse profile of the incident optical intensity (which we assumed was Gaussian), and a thermal bowing term which results in a spherical curvature of the surface. We assumed that the effects of the thermal bowing, which will change the curvature of the incident light beam, can be compensated for by appropriately refocusing the resonator. The irradiance mapping term, for which the displacement of the surface of the mirror is represented by the product of a thermal distortion coefficient D (Angstroms per W / cm^2) and the optical intensity I , leads to a complex aberration of the optical phase. This aberration has the effect of increasing the size of the optical focal spot in the interaction region of an FEL (the wiggler / electron beam) and thus reducing the laser gain and saturated power. The magnitude of allowable phase error accumulated over one roundtrip through the resonator was first estimated by using an analytical theory of spot size transport. Then, full oscillator simulations were performed with the 3 - D FEL simulation code FELEX in order to determine quantitative limits on accumulated phase error due to thermal distortion. These calculations used a value of D equal to one Angstrom per W / cm^2 although the thermal deformation calculations produced values ranging from 0.3 to 4.0 depending upon the design of the cooled mirror. It was found that the maximum allowable accumulated phase error per round trip $k_0 D I / (2 \pi)$ was about 0.5 waves if the resonator was refocused and about 0.25 waves if no refocusing is done. These limits were then used to study the scaling of the size of a multifacet mirror ring resonator with circulating power and number of mirror facets. Future studies of this subject will include further characterization of thermal deformation of substrates and analysis of hole - coupled resonator designs.

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Figure Captions:

Figure 1: Typical geometry of a ring resonator with multifacet mirrors for an XUV FEL oscillator.

Figure 2: Focal spot sizes for an aberrated light beam from analytical theory.

Figure 3: Resonator average power handling capability from FELEX simulations vs. thermal distortion coefficient.

Figure 4: Resonator power handling vs. number of mirror facets for various wiggler center - hyperboloid spacings.

Figure 5: Resonator power handling vs. number of mirror facets for various hyperboloid - multifacet mirror spacings.

Figure 6: Definitions of spacings L and L_1 .

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