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Abstract

We report on ongoing experiments and simulations which model the performance of hole-coupled resonators. We have previously studied a hole-coupled resonator which was well inside the stable region (stability parameter $g = -0.8$). In the far field, good agreement between experiment and simulation was obtained for both the intra-cavity and outcoupled mode-profile. The present study involves a resonator with a stability parameter of -0.987, identical to the stability parameter of the proposed Infrared Free Electron Laser (IRFEL) at Lawrence Berkeley Laboratory. The experiments were carried out with a frequency stabilized CW-HeNe laser beam at a wavelength of 632.8 nm. Both intra-cavity and outcoupled mode profiles and power levels were measured. The simulations were done using the code HOLD, which is based on the Fresnel approximation for the Huygens kernel. Within the experimental uncertainties, magnified due to the $1/(1+g)$ dependence of the mode characteristics on errors in measured resonator parameters, we have obtained fair agreement between experiment and simulation.

1. Introduction

Although the concept of hole-coupling has been studied more than two decades ago, it has regained attention for its usefulness in high power, broadband tunable Free Electron Lasers and is presently used in the FELIX project.[1] The main considerations for the use of hole-coupling for FEL's are: 1) reasonable coupling efficiency (50%), defined as the ratio of loss through the hole over total loss; 2) the mode profile inside the wiggler should have good overlap with the electron beam (e.g. have a smooth, Gaussian-like shape) ; 3) mode degeneracy should be avoided through transverse mode control with intra-cavity apertures; and 4) the outcoupled mode must be transported efficiently to the user.

A hole-outcoupling scheme, satisfying the previous considerations, is being considered for the proposed IRFEL at Lawrence Berkeley Laboratory.[2] This high power IRFEL for the Chemical Dynamics Research Laboratory will operate from 3 - 50 μm and requires all metal optics for both power handling and frequency tunability requirements. The FEL resonator will have a length L of 24.6 m, a Rayleigh range z_R of 1 m (hence a radius of curvature for the mirrors of 12.38 m) resulting in a stability parameter, g, of

-0.987. A detailed study of resonator modes in this cavity utilizing a hole-outcoupling scheme and using such mirrors has been made using the code HOLD.[3]

To bench mark the code we carried out a scaled resonator experiment with a visible CW HeNe laser. Aside from the absence of gain in this experiment another key difference with an actual FEL is the injection of an external mode into the resonator. The main emphasis of the experiment was to compare measured mode profiles and power levels, both intra-cavity and outcoupled, with computed profiles and power levels. In the first phase of the experiment a resonator with $g = -0.8$ was studied.[4] This g-value was chosen so that the pointing accuracy of the resonator mirrors (10 μrad) was 1/10 of the mode rms-angle. Due to the particular choice of hole size of the outcoupling mirror, the intra-cavity transverse-mode-controlling aperture size, and the g-value, mode degeneracy was observed as evidenced by an intra-cavity mode profile which alternated between two higher order modes. Periodic and aperiodic power spikes also occurred, typically lasting 5 ms, due to uncontrolled longitudinal phase shifting caused by mirror vibrations and frequency changes of the injected laser beam.

Here we report on the results of our study of a resonator with $g = -0.987$, i.e. identical to the design value for the proposed IRFEL for the CDRL.[2] This case became accessible in the experiment through improvement of the pointing accuracy of the cavity mirrors.

2. Experiment

2.1 Equipment

The lay-out of the experiment is shown in Fig. 1.

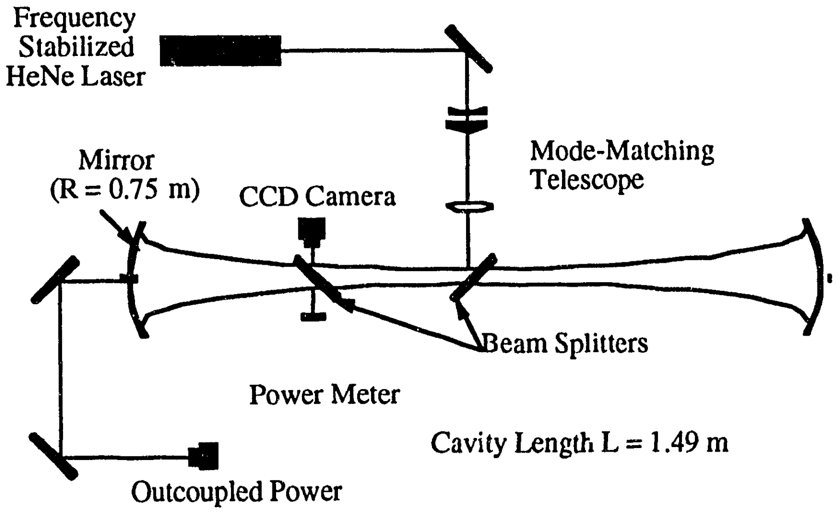

Figure 1: Set-up of the scaled cavity experiment.

The cavity length in this experiment was nominally 1.49 m. The radius of curvature of both cavity mirrors was 0.75 m resulting in a g-value of -0.987. A P-polarized CW HeNe beam was injected into the cavity using the uncoated side of a plane parallel beamsplitter (BS1). The other side of the beam splitter was anti-reflection (AR) coated to minimize cavity losses. Both the right and left going wavefronts encounter 4 beam splitter surfaces while propagating in the resonator, resulting in a measured total reflective loss of 9.8 %.

The first mirror (from hereon referred to as the RH mirror) had a hole drilled through the center of the quartz substrate with a diameter, 2 a, of 300 μm. Although the length of the hole through the mirror was 4 mm this did not cause any loss to the outcoupled power as discussed next. The reflectivity of the RH mirror was measured as follows: the mirror was illuminated with the HeNe laser using BS1. The incident power and spot size, w, on the mirror surface were measured. The ratio of power transmitted through the hole over incident power was in excellent agreement with the theoretical value given by

$$\frac{P_{hole}}{P_{inc}} = 1 - e^{-\frac{2a^2}{w^2}} \qquad (1),$$

which is the fraction of the area of a Gaussian beam with spot size w transmitted through a hole with radius a. This implies that no loss occurred to the outcoupled beam while propagating through the 4 mm long hole in the RH mirror. The reflected power was measured 1 m away from the mirror (looking through BS1) and resulted in an overall mirror reflectivity of 95.1 %. This far field measurement assures that diffraction losses are taken into account in the overall power balance. The second mirror (from hereon referred to as the LH mirror) was a solid mirror. The LH mirror had a reflectivity of 99.8%.

The measured surface reflectivity of the different mirrors and intra-cavity beamsplitters, cavity dimensions and properties of the injected beam were used as input parameters in the code HOLD. A 4 mm diameter iris was placed 8 cm in front of the RH mirror for transverse mode profile control.

The injected power from the HeNe laser was 380 μW. The laser was feedback stabilized against frequency drifts to within 100kHz of the center-frequency. Since the free spectral range was about 100 MHz such small frequency changes should not give rise to a substantial mismatch between the phase of the injected wavefront and the wavefront circulating inside the resonator. The main source of phase mismatch is then due to mirror vibrations which causes a cavity length change, i.e. path length change. The transverse properties of the injected mode were controlled through the use of a three-lens mode matching telescope, allowing for good flexibility in adjusting spot size and radius of curvature of the phase-fronts at the injection point and hence waist size and location of the injected beam.

The cavity performance was monitored using a second intra-cavity beamsplitter (BS2) with the AR-coated side sampling the intra-cavity mode and the uncoated side sampling the intra-cavity power. The optical power was measured by monitoring the output of a calibrated silicon diode on a 250 MSample/s digital oscilloscope. Both the intra-cavity and out-coupled mode-profile were measured using a CCD camera with 19 μm/pixel spatial resolution, connected to an 8 bit framegrabber board with a system dynamic range of about 100.

2.2 Experimental results

The injected mode properties were carefully determined by Gauss-fitting profiles taken at different locations along the beam path. Both the waist size and location were obtained by fitting the obtained spot size as a function of distance to M^2 model:[5]

$$w(z) = w_o\sqrt{1+\left(\frac{M^2(z-z_o)}{z_R}\right)^2} \qquad (2).$$

Here w_o is the waist size, and z_R is the usual Rayleigh range given by

$$z_R = \frac{\pi w_o^2}{\lambda} \qquad (3),$$

λ is the wavelength (i.e. 632.8 nm) and z_o is the location of the origin. This model takes higher order transverse modes into account by allowing the mode size and divergence angle to increase faster than a TEM_{00} beam by a factor M^2. The χ^2 fitting procedure also gives an estimate of the error. An example of this procedure is shown in Fig. 2. For this particular case z_o was 0.012 m ± 0.007 m, w_o = 206μm ± 8 μm, and $M^2 = 1.135$ indicating that the injected mode is nearly a pure TEM_{00} mode.

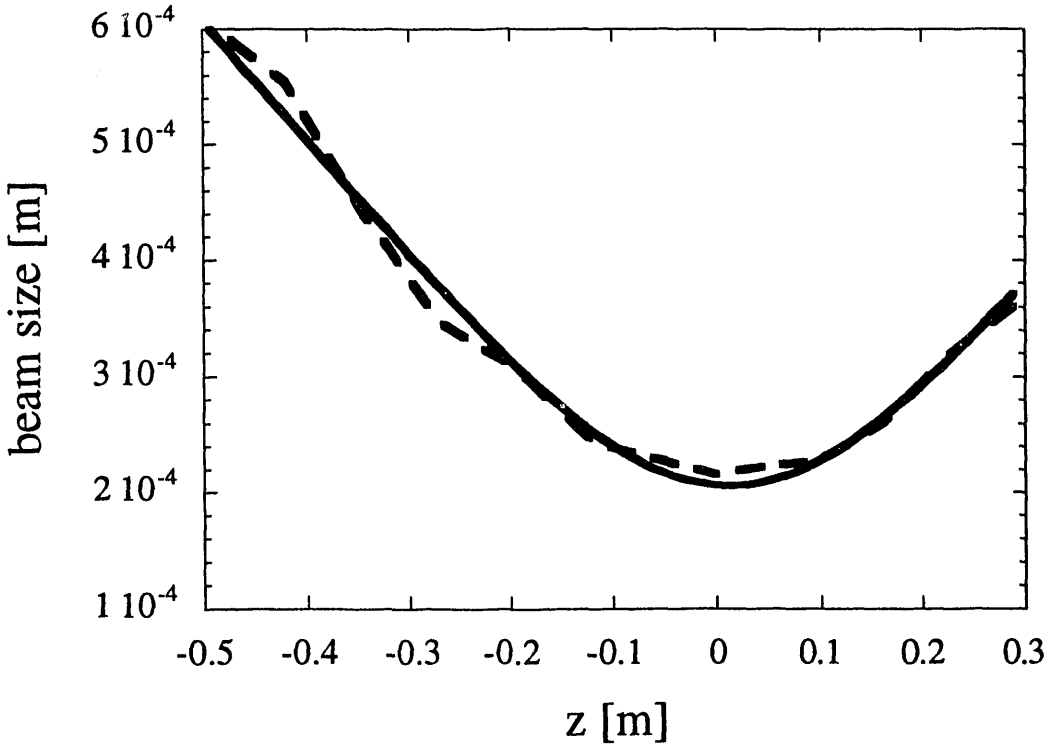

Figure 2: Measured (dashed line) and fitted (solid line) injected spot size vs. distance. The fitting procedure uses the M^2 model . The waist size and location for this case are w_o = 206 μm ± 8μm and z_o = 0.09 m ± 0.01 m respectively. The M^2 value is 1.135 indicating that the injected mode is almost purely TEM_{00}.

The cavity alignment was found to be very critical: changing the pointing angle by 1 μrad typically reduced the intra-cavity power by 10 - 20 %. The cavity resonances typically lasted 20 - 30 ms. The frequency locker on the stabilized HeNe laser did not show substantial frequency pulling due to optical feedback. We therefore believe that vibrations are the main cause of spiking.[6] Of course, if the resonator operates in a mode-degenerate regime, mode-hopping also gives rise to substantial power spiking. In fact, by opening the iris in front of the RH mirror, radially degenerate modes as well as higher order azimuthal ($m = 2, 3$) Hermite - Gaussian like modes were observed, giving rise to large power fluctuations.

By closing the iris to a diameter of 4 mm, the azimuthal mode degeneracy was suppressed. The obtained mode profiles of the right (towards mirror with hole) and left (towards solid mirror) propagating wavefronts are shown in Fig. 3. The peak intra-cavity and outcoupled power were measured to be 51 μW and 1.96 μW respectively. Scanning the mode matching telescope increased the intra-cavity power by a factor two and the outcoupled power by about a factor 5. At the same time, the mode-profile changed only in a minor way.

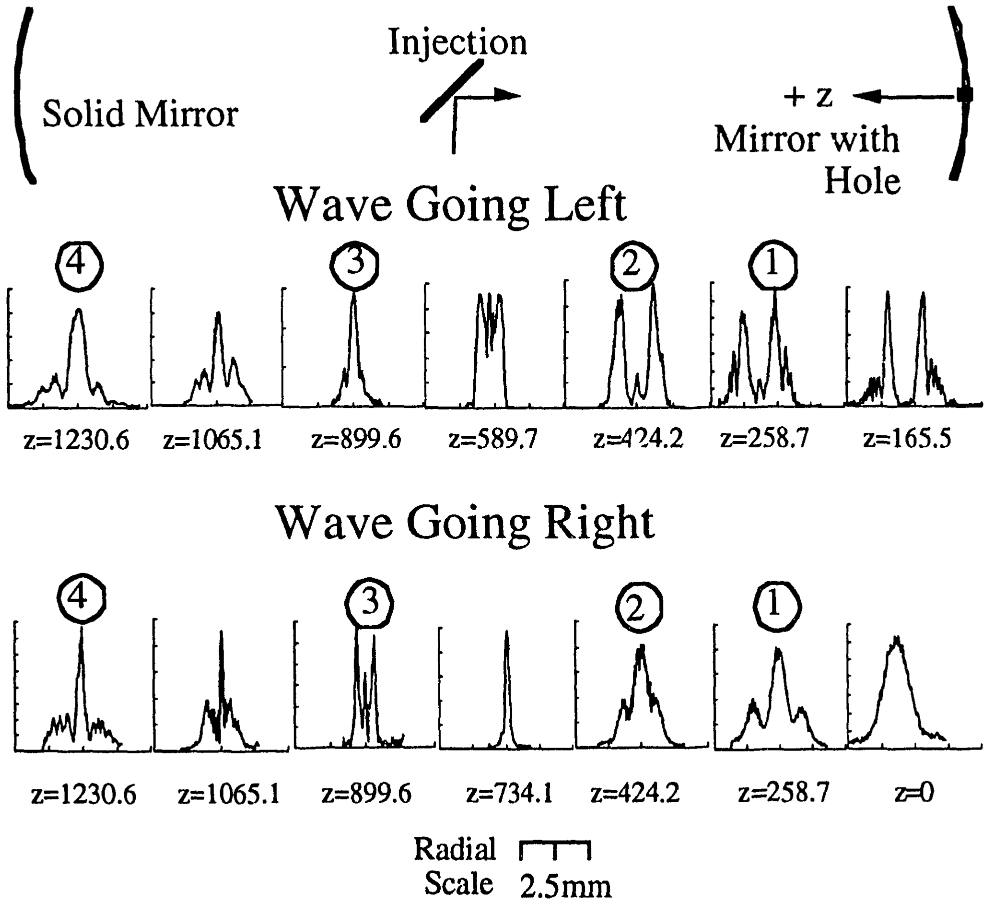

Figure 3: Measured intra-cavity mode profiles for the left and right propagating wavefronts. The cavity lay-out shows the location at which the measurement was made.

3. Theory

3.1 Simulation results

The simulations were carried out with the code HOLD which has been modified to allow for external continuous injection of wave fronts into the cavity. The modification was made necessary by the use of a CW HeNe laser in the experiment. The code first calculates the properties of a self-consistent mode-profile after injecting a single wave front into a specified cavity. It then determines the necessary waist size, waist location and radius of curvature of the injected mode for an optimum matching to the lowest order cavity mode. This is called the transverse mode matching[7] and is analogous to the experimental procedure. After the user has specified the injected mode properties, the code calculates the mode profiles and the optical power at the beamsplitter locations and both mirrors. For a given complex injected electric field, E_{in}, the complex intra-cavity field amplitude, E_c, can be obtained from

$$E_c = \frac{E_{in}}{1 - e^{j2kL(L+\delta L)}M} \qquad (4).$$

Here k is the usual wave number, M is the complex roundtrip transfer matrix, and δL is a cavity length adjustment. Adjusting the phase advance $k\delta L$ for maximum power is called longitudinal mode matching. The code can optimize both the transverse and longitudinal mode matching through iteration.

The intra-cavity mode profiles (right and left going wavefront) from simulation calculation for the case g = -0.987 are shown in Fig. 4. The outcoupled mode profile was very similar to the previously measured profiles.[4] Also, note that the mode profile at z = 743.1 mm in Fig. 3 (about center of the wiggler in the FEL version of this resonator) is fairly smooth which would assure good coupling between the electron beam and the optical field inside the wiggler.

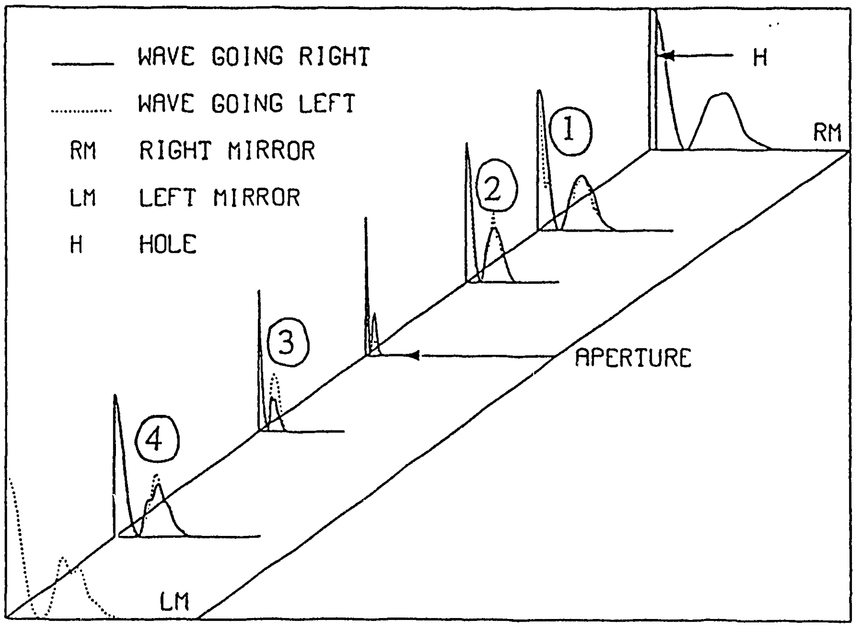

Figure 4: Calculated intra-cavity mode profile for the left and right propagating wavefronts. The number next to some of the profiles denotes the corresponding experimental profile at that location shown in Fig. 3.

The agreement of the calculated profiles in Fig. 4 with the experimentally measured profiles in Fig. 3 is not apparent. The measured and calculated outcoupled and intra-cavity power levels also differed. The measured and calculated *outcoupled* power were 1.5 μW and 1.96 μW respectively. The measured and calculated *intra-cavity* power levels were 51 μW and 165 μW respectively. These discrepanies may be due to experimental uncertainties in the resonator parameters and the extreme sensitivity of the resonator performance on the precise values of the resonator values when g is very close to -1. This point is discussed further in section 3.2.

3.2 Error sensitivity of resonators close to the unstable region

The main reason for the discrepancy in measured and calculated resonator performance is the high sensitivity of resonators close to the unstable region to errors. Since the nominal cavity length of 1.49 m puts g at -0.987 for mirrors with a radius of 0.75 m, small errors in radius of curvature can put the resonator in the unstable region. To ascertain that the cavity was stable, we gradually changed the cavity length from 1.57 m (unstable) to 1.40 m (stable) while monitoring the resonator power. The power level was found not to increase for cavity lengths below 1.5 m which confirms that the radius of curvature of the mirror must be indeed close 0.75 m. The manufacturer specified the radius of curvature to be 0.75 m ± 0.5 %, but we have not verified this. The change in optimal waist size $\delta w_o/w_o$ for a Gaussian resonator as a function of uncertainty in the radius of curvature $\delta R/R$ can be calculated using

$$\frac{\delta w_o}{w_o} = -\frac{L}{2R}\,\frac{\delta R/R}{(1-g)(1+g)} \qquad (5).$$

which, for our experimental parameters, results in $\delta w_o/w_o = 2.5\ \delta R/R$ for case 1 ($L = 1.35$ m, $g = -0.8$) and $\delta w_o/w_o = 38.5\ \delta R/R$ for case 2 ($L = 1.49$ m, $g = -0.987$). Hence, for $\delta R/R = 0.5$ %, we find $\delta w_o/w_o$ = 1.25 % and 20 % respectively for case 1 and 2. We believe that this large uncertainty in optimal waist size (and hence beam size on the cavity mirrors) for a resonator close to the unstable region is the reason of the discrepancy between experiment and modeling of such resonators. To illustrate the sensitivity of the resonator performance to small changes of the cavity parameters we changed the mirror size in the code from 2.65 mm to 2.70 mm, a 1.85 % mirror size change. This changed the mode profile from having no rings to having two rings.

4. Conclusion

We have reported on the continuation of an experimental study of hole-coupled resonators. The main purpose of the experiment was to benchmark the code HOLD, which was used extensively for the design of the proposed Infrared Free Electron Laser (IRFEL) at Lawrence Berkeley Laboratory. Previously we had studied a resonator with a g-value of -0.8 and obtained good agreement with simulations Improvement of the pointing accuracy of the cavity mirrors to better than 1 μrad allowed us to study the properties of a resonator with a g-value of -0.987, identical to the proposed IRFEL. Both intra-cavity and outcoupled mode profiles and power levels were measured. It was found that matching the experimental and simulation results was less successful due to the extreme sensitivity of the mode characteristics on uncertainties in measured resonator parameters. The measured outcoupled (intra-cavity) power level was a factor 0.77 (3) lower than the calculated value. Fair qualitative agreement (appearance and number of rings) was obtained between the measured and calculated far field mode profiles (i.e. at locations "far" removed from the hole).

5. Acknowledgments

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