MODE STABILITY AND OUT-COUPLED POWER IN FREE-ELECTRON LASER OSCILLATORS

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Abstract

We study, using two- and three-dimensional multi-particle codes, the stability of FEL oscillators, for both, concentric as well as confocal configurations, as a function of wavelength as well as size of the out-coupling hole. We find that the dominant mode and out-coupled power are influenced by these parameters. We also study mode stability as a consequence of misalignment of the out-coupling mirror. We find that here the effect is stronger, and can induce non-axisymmetric modes.

INTRODUCTION

For conventional lasers, the preferred cavity configuration is generally the confocal one and is well studied in standard texts using an empty-cavity analysis. In the case of free-electron lasers (FELs), the presence of an undulator within the resonator introduces a strong, nonlinear, interaction, that must necessarily affect the stability of the system. Stability of modes for symmetric FEL resonators (i.e. g_1 = g_2) has been studied in Ref.[1]. It was found that the FEL interaction changes the resonator stability, so that the exactly concentric and exactly confocal configurations are now stable. However, the concentric is preferred because the mode in this case is close to Gaussian, and hence gives more out-coupled power, whereas in the confocal case substantially non-Gaussian modes can develop. Subsequently [2] the study was extended to asymmetric resonators (i.e. $g_1 \neq g_2$), both analytically (using a simple thin lens model), and with the simulation code TDAOSC [1,3].

Here we restrict our study to symmetric resonators, in the concentric and confocal configurations. In the next Section we show results from two-dimensiona simulations, looking at the out-coupled power as a function of both, wavelength as well as hole-size. In Section III we validate these results with three-dimensional simulations, again varying wavelength as well as hole-size. In Section IV we use the three-dimensional simulations to study the effect of tilting the outcoupling mirror.

TWO DIMENSIONAL SIMULATIONS

We first performed simulations using the axisymmetric code TDAOSC, varying both, the wavelength of the radiation, as well as the size of the out-coupling hole.

We chose an undulator parameter $a_w = 0.637$, undulator length $L = 2$ m, and undulator period $\lambda_U = 5$ cm. We chose a standard Fabry-Perot resonator, with concave mirrors. One of the mirrors had a hole to outcouple the cavity power. The electron (micropulse) current was 100 A, and the normalized emittance was 20e-6 mm-mrad in both the transverse directions. The electron beam energy was 30.3, 19 and 13.4 MeV, for FEL wavelengths of 10, 25 and 50 μm, respectively. In all cases the simulation was run until the FEL saturated, typically in less than 100 passes, and the optical mode was stable.

Wavelength Dependence

We explored the stability of the FEL resonator as a function of wavelength, by performing TDAOSC simulations for both, a concentric cavity (D = 12.3 m and R_1 = R_2 = 6.15 m) as well as a confocal cavity (D = 6.15 m and R_1 = R_2 = 6.15 m), at various wavelengths. All other parameters, including the hole size (4 mm), were fixed. Figure 1 shows the peak out-coupled power as a function of wavelength, for both concentric and confocal cases. It can be seen that at long wavelengths, there isn't much difference between the confocal and the concentric resonators, because the optical beam is large. However, at shorter wavelengths, the concentric resonator delivers higher power, and is therefore clearly preferable. The reason for this is evident from Fig. 2, which shows the optical beam profile (mode) on the out-coupling mirror, for both cases, at a wavelength of 25 μm. The concentric resonator supports a near-Gaussian mode, and so the out-coupled power is high. For the confocal resonator, however, the dominant mode has a minimum at the centre, and therefore the outcoupled power is lower.

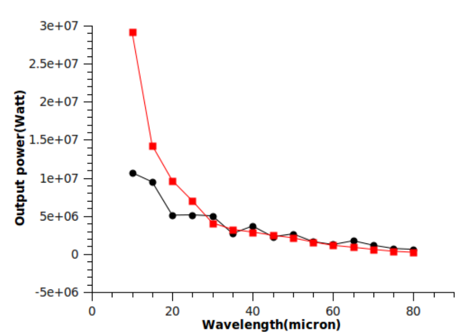

Figure 1: Peak out-coupled power as a function of wavelength for the confocal (red squares) and concentric (black circles) configurations.

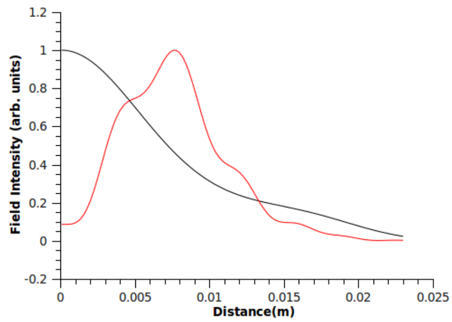

Figure 2: Mode profile on outcoupling mirror for concentric (black) and confocal (red) configurations at 25 μm wavelength.

Dependence on Hole-Size

We next varied the hole size, at wavelengths of 10 μm, 25 μm, 50 μm, for the confocal as well as the concentric case. Figure 3 show the variation of out-coupled power with hole size, in the two cases. It can be seen that in general the concentric configuration gives slightly higher power, especially at shorter wavelengths.

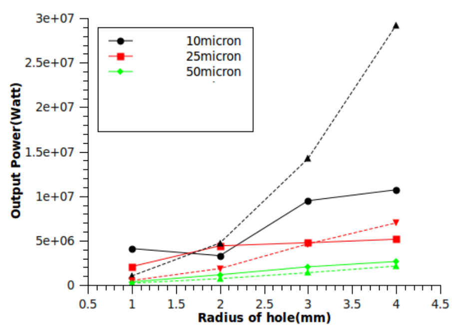

Figure 3: Peak out-coupled power as a function of hole size for concentric (dashed lines) and confocal (solid lines) configuratons.

THREE DIMENSIONAL SIMULATIONS

TDAOSC is a two-dimensional code, that has the limitation that it cannot model non-axisymmetric effects. We therefore performed fully three-dimensional simulations using GENESIS [4] along with the code OPC [5] that together simulate an FEL osciallator. The aim was to see if non-axisymmetic modes could be excited at large hole sizes, or by tilting the out-coupling mirror.

Wavelength Dependence

We first repeated the earlier simulations of wavelength dependence, using the three-dimensional code, results of which are shown in Fig. 4. It can be seen that for both, the concentric and confocal cases, the power drops with increasing wavelength - which is expected as a consequence of greater diffraction. Comparison with Fig. 1 shows that the 2D and 3D simulations agree quite well, except at the shortest wavelength, where in the 2D simlations the power in the concentric case is much higher than in the confocal case, whereas in the 3D simulations the powers are comparable.

Figure 5 & 6 show the intensity plot on the outcoupling mirror, at a wavelength of 25 μm. It can be seen that in the concentric case, the intensity is maximum at the centre of the out-coupling hole and has a secondary maximum, before decaying away. For the confocal case, however, the intensity is lower at the centre, and there are several secondary maxima. This agrees reasonably well with the intensity plot from the 2D simulations (Fig. 2).

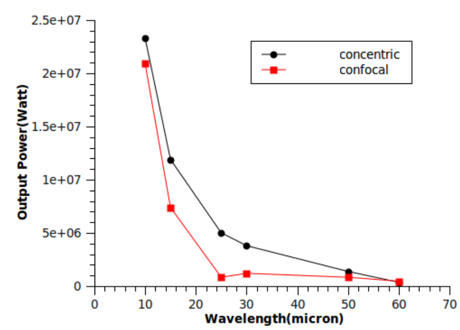

Figure 4: Peak out-coupled power as a function of wavelength for the concentric (black circles) and confocal (red squares) configurations.

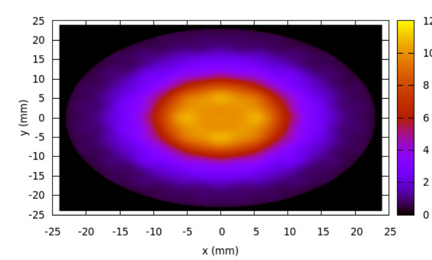

Figure 5: Contour of field intensity on outcoupling mirror for concentric case for 25 μm

Dependence on Hole-Size

Next we studied the dependence of the out-coupled power as a function of the hole-size. Figures 7 show these results for the concentric and confocal cases . Again, there is broad agreement with the corresponding figures (Fig. 3), for the 2D simulations. In addition, the intensity plots (not shown here) show good azimuthal symmetry, indicating the absence of non-axisymmetric modes.

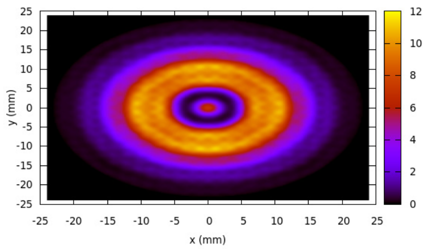

Figure 6: Contour of field intensity on outcoupling mirror for confocal case for 25 μm

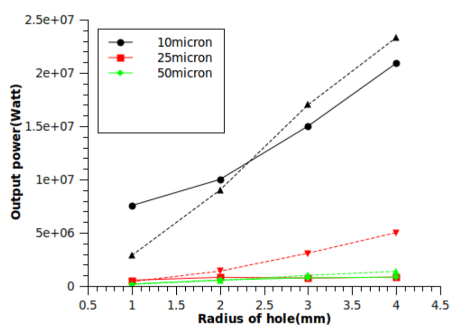

Figure 7: Peak out-coupled power as a function of hole size for concentric (dashed lines) and confocal (solid lines) configuratons.

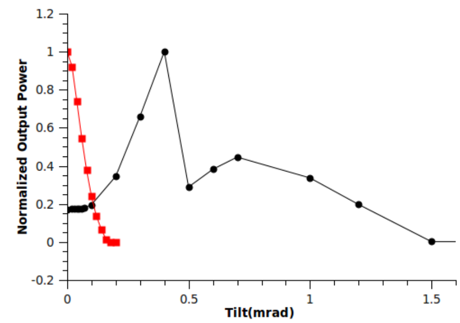

Figure 8: Peak out-coupled power as a function of mirror tilt for concentric (red) and confocal (black) configurations for 25 μm.

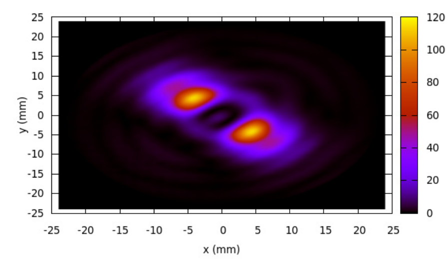

Figure 9: Contour of field intensity on outcoupling mirror for confocal case for 25 μm with 0.4 mrad tilt.

TILTING THE OUT-COUPLING MIRROR

We next decided to deliberately introduce a tilt in the outcoupling mirror, in order to introduce azimuthal asymmetry in the resonator. Clearly, this cannot be modeled by an axi-symmtric code such as TDAOSC, so all results of this section are using GENESIS and OPC. We studied consequences of tilting the mirror only at the wavelength of 25 μm, but for both, the confocal as well as the concentric configuration. The mirror was tilted equally in x and y.

We found that for the confocal case, the output power is maximum at a tilt of 0.4 mrad , whereas for the concentric case the power decreases monotonically with the tilt angle (Fig. 8). Figure 9 shows the intensity contour for the 0.4 mrad case for confocal configuration. It can be seen that the plot is hightly asymmetric. The beam itself is centred, but the distribution is not axisymmetric, indicating the influence of a non-axisymmetric mode. Further, it is clear that the mode is non-Gaussian, with a minimum at the centre. Thus, while the out-coupled power may be high, the mode is poor.

CONCLUSION

We have performed, using TDAOSC and GENESIS+OPC, two- and three-dimensional simulations of an FEL resonator, at different wavelengths, which show that the concentric configuration is generally preferable compared to the confocal, especially at shorter wavelengths. We have also explored the variation of the output power as a function of hole size, and find that the outcoupled power increases fairly substantially at shorter wavelengths, but at longer wavelengths the increase is modest.

With the 3D code we have also performed simulations of the effect of a tilt in the mirror. We find that tilting the mirror produces a substantial asymmetry in the mode. For the concentric configuration the power decreases monotonically with increase in hole size, but for the confocal case, there is an optimal tilt, corresponding to maximum outcoupled power; however the mode is highly asymmetric and non-Gaussian in this case. This corresponds well with some measurements done at the CLIO FEL (albeit at a different wavelength), and we plan to pursue this in future work.

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