HOLE-COUPLING IN IR FELS: AN EXPERIMENTAL STUDY

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Abstract

Even though hole-coupling has been used for many years at several IR FEL facilities, its usefulness as out-coupling scheme has recently been questioned[1]. Also, it has been suggested that the output beam profile will inevitably show strong asymmetries at the short-wavelength end of the tuning curve[2]. In this contribution, experimental results for the dependence of cavity loss, energy extraction from the electron beam, output power and optical beam profile on the size of the hole in relation to the wavelength are presented.

INTRODUCTION

In IR FELs, on-axis hole-coupling is a common method for coupling out part of the circulating optical power in the resonator, primarily for lack of transparent materials that could be used as substrate for the mirrors. Many years ago, when this scheme was proposed in the context of FELs, it was already mentioned that in an empty cavity that supports a large number of transverse modes, an optical mode with a null at the position of the hole will naturally develop as this would be the mode having the lowest roundtrip loss. Recently, this point was raised again as a serious problem of hole-coupling[1]. Moreover, significant distortions of measured beam profiles of the out-coupled radiation at the CLIO facility were reported and it was argued that this was an inevitable effect at the short-wavelength end of the tuning curve of a mirror with a hole[2]. As hole-coupling has been used at the FELIX facility for over 20 years now without apparent problems, it seemed appropriate to investigate its performance in greater detail.

EXPERIMENT

In particular, we measured the out-coupled macropulse energy, the decay of the output after turn-off of the electron beam, the profile of the out-coupled radiation and the energy extracted from the electron beam for a number of hole sizes and wavelengths. All these measurements were done for the short-wavelength free-electron laser (FELIX FEL2) at a fixed beam energy of 44 MeV. Undulator gap-tuning was used to vary the wavelength. The parameters of the resonator of FEL2 are given in table 1.

Table 1: Resonator Parameters

Tuning range:	fundamental	5 - 45 μm
	3rd harmonic	2.7 - 5.0 μm
Resonator length:		6 m
OFHC copper mirrors:		
	diameter	50 mm
	ROC upstream	4 m
	ROC downstream	2.75 m
Rayleigh range:		1.03 m
Out-coupling via on-axis hole in upstream mirror		
Hole sizes: 0.9, 1.4, 2.2 or 3.0 mm diameter		

EFFICIENCY

After reflection from the mirror with the hole, the optical mode will have zero intensity at the position of the hole. This 'hole' in the intensity profile will lead to enhanced diffraction and hence the development of radial 'tails' that are likely to be clipped by apertures such as the vacuum chamber inside the undulator. When the hole size becomes smaller, the extent of the tails grows and therefore the likelihood of clipping these. As the reflected beam can be thought of as the interference of two beams, an undisturbed reflected beam and the reflection of the out-coupled beam shifted in phase by π, the potential diffraction loss equals the energy coupled out through the hole. This means that the intrinsic efficiency of small holes is only 50%. In fig. 1, the measured ring-down of the power coupled out through the hole after the electron beam is turned off (α = decay per roundtrip) is compared to the computed out-coupling fraction for the lowest-order resonator mode (α_0). For each of the hole sizes we find an almost linear relationship between α and α_0 for the wavelengths used (7, 9, 12, 15 and 19 μm). However, the slope increases with decreasing hole size, and therefore the intrinsic efficiency seems to drop to only 25% for the 0.9 mm case. A disturbing finding that even led us to re-measure the hole sizes. Shortly after this measurement campaign was finished, the machine was being dismantled for the relocation to the university of Nijmegen and the downstream mirror was found to be

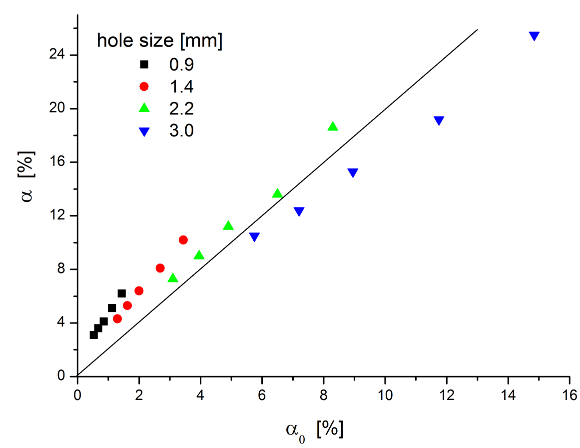

Figure 1: Roundtrip loss versus computed out-coupling. The drawn line has a slope of 2.

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damaged (fig. 2). A central, dark spot with a diameter of about 0.5 mm was clearly visible. Realizing that a dark spot like this one will have a similar effect as an outcoupling hole, it is possible to correct the x-axis of figure 1 for the damaged mirror. The result is shown in

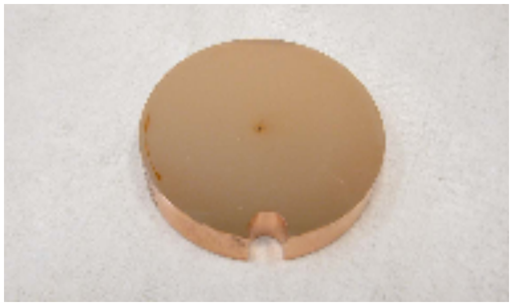

Figure 2: Damaged downstream mirror.

fig. 3. Now all the points of the smallest mirrors fall close to the line given by $\alpha = 2\ \alpha_{0,c} + 0.012$, where the 'c' means corrected. The offset of 1.2% can be interpreted as the loss associated with the finite reflection coefficient of

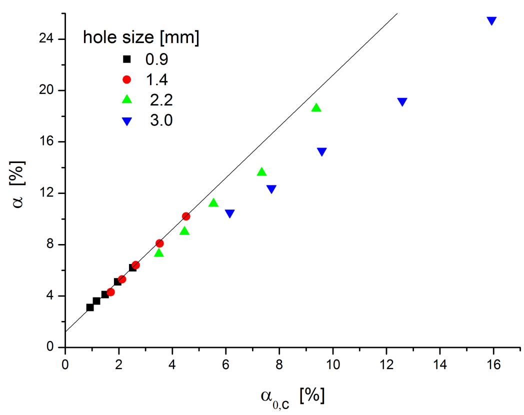

Figure 3: Roundtrip loss versus computed out-coupling, corrected for the damaged mirror. The drawn line has a slope of 2 and an offset of 1.2[%].

the copper that the mirrors are made of, for which a value of 99.4% is quite reasonable.

For judging the efficiency of hole coupling, the intrinsic efficiency only provides a first estimate though, as most of the optical energy might be off-axis and never show up in a measurement of the power coupled out through the hole. What is more important to know is how much energy is extracted from the electron beam and how much of this is actually coupled out through the hole. To measure the energy extracted from the beam, an OTR based, 48-channel spectrometer, situated directly behind the magnet used to dump the electron beam, was used. An example of an energy spectrum recorded during lasing and one when lasing was suppressed by increasing the resonator length to well beyond its synchronous value, is shown in fig. 4. By taking the difference of these, the energy extracted from the beam, δE_b, can be computed.

For each of the outcoupling mirrors, δE_b was

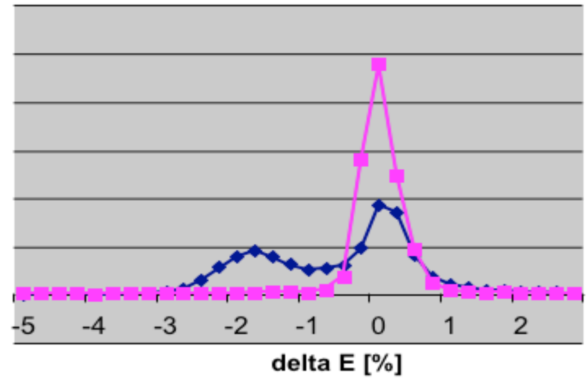

Figure 4: Electron beam energy spectrum, with (blue) and without (magenta) lasing.

determined at 7, 9 12, 15 and 19 μm respectively. The result is shown in fig. 5. Two direct observations can be made: δE_b increases with decreasing hole size and the dependence on wavelength is similar for each mirror. In fact, this dependence on wavelength strongly resembles that of a typical computed small-signal gain curve for the FEL2 parameters (see fig. 6).

To exemplify the first point, δE_b is plotted versus α (fig. 7): at each wavelength there is an almost linear relationship between δE_b and α! (it should be noted that as a result of the resonator detuning of -2λ, the threshold for the side-band instability was not reached even for the 0.9 mm hole size case.) Because α is a characteristic of

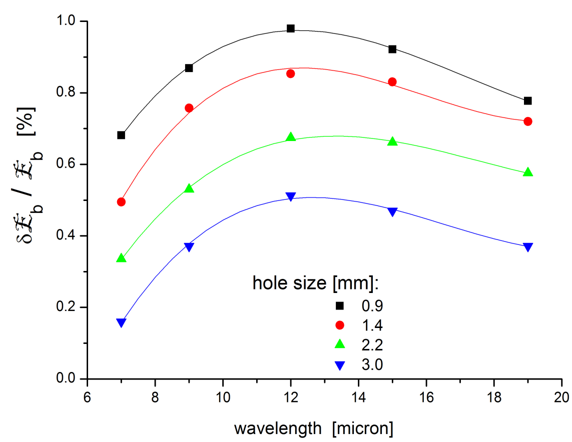

Figure 5: Relative energy extracted from the electron beam as a function of wavelength for three hole sizes.

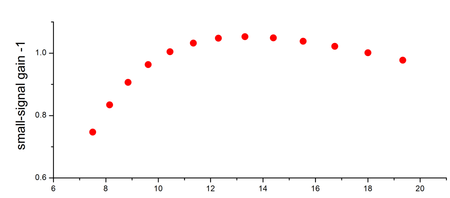

Figure 6: Typical computed small-signal gain.

the optical power that is coupled out through the hole, and α correlates very well with α_0, this strongly indicates that the fundamental resonator mode is the dominant optical mode.

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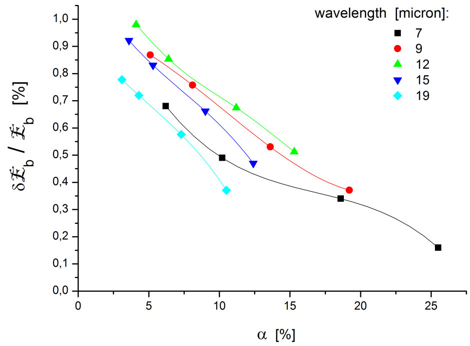

Figure 7: Extracted energy versus α.

In the case that the fundamental resonator mode is the only mode present, there is a simple relationship between the out-coupled energy, $\mathcal{E}_m$, and the energy extracted from the beam: $\mathcal{E}_m = \delta\mathcal{E}_b \cdot \alpha_0/\alpha$. For the measurement of $\mathcal{E}_m$ a pyro-electric detector in the diagnostic station was used. The ratio between $\delta\mathcal{E}_b \cdot \alpha_0/\alpha$ and $\mathcal{E}_m$ is shown in fig. 8, corrected for an estimate of the transmission loss, 50%, of the optical transport system in between the out-coupling hole and the detector, consisting of a vacuum window, 17 mirrors and a 25% beam splitter used for diagnostic purposes. As can be seen, this ratio is close to unity for the 3.0 mm hole size and generally lies in between 1 and 1.5, except for the smallest hole size for which it increases with wavelength to about 2.5. The latter may be partly due to enhanced losses in the transport sytem due to the diffraction loss of the higher order transverse modes associated with the 'top-hat' profile of the out-coupled beam right after the hole, which is most severe at small hole sizes and long wavelengths. This means that 60-100% of the extracted energy can be accounted for by losses of the fundamental resonator mode. This includes the outcoupling and diffraction loss of the hole, the absorption and diffraction loss of the damaged spot and the reflection loss from the mirror surfaces. Moreover, if mode rearrangement were to occur, it would do so in particular for the larger hole sizes. So the discrepancy at smaller hole sizes, would rather point towards the excitation of higher order modes due to gain guiding. For convenience, the measured values of $\mathcal{E}_m$, multiplied by 1.75, 1.31, 1.13 and 1.07 for the hole sizes 0.9, 1.4, 2.2 and 3.0 mm respectively, to compensate for the 'out-coupling' loss (= absorption loss) due to the

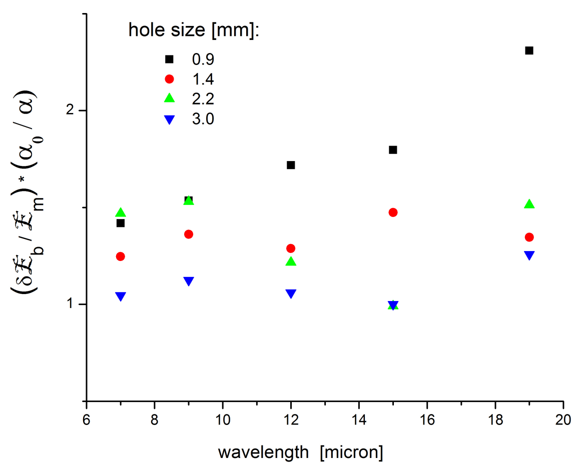

Figure 8: Ratio between extracted and optical energy at diagnostic station, corrected for transport loss.

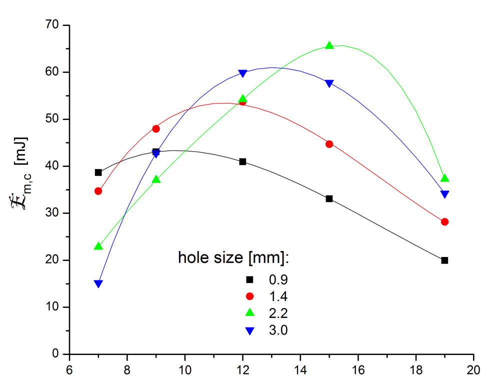

Figure 9: Optical energy corrected for loss at downstream mirror.

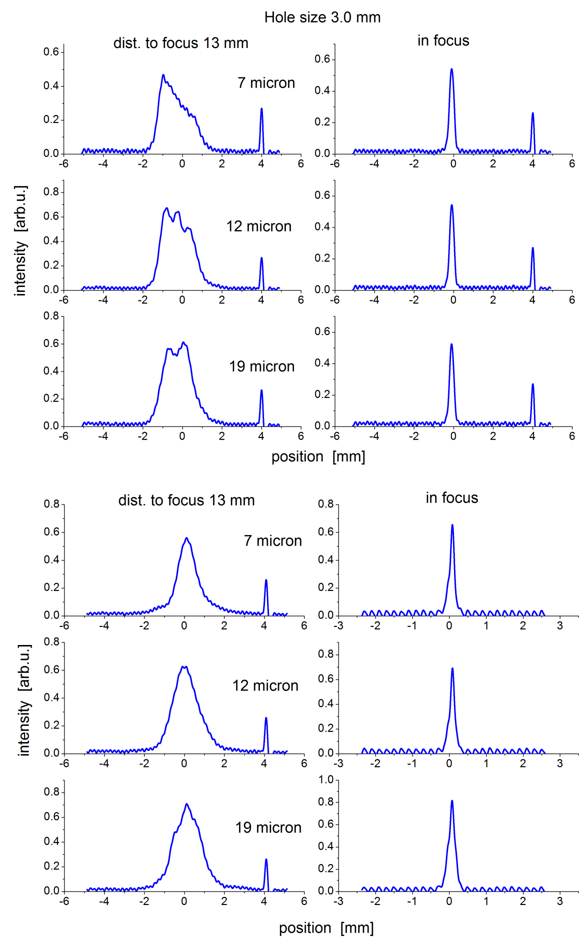

Figure 10: Spatial beam profiles measured in a user station, using a 150 mm parabolic mirror. Top 3 panels: hole size 3.0 mm, left: 13 mm from the focus, right: in the focus for 7 (top trace), 12 (middle) and 19 (bottom) μm respectively. Lower three panels: the same for the 1.4 mm hole size.

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damaged spot on the downstream mirror, are shown in fig. 9.

Finally, a not very extensive set of beam profile measurements has been performed in one of the user stations. Only for the largest hole size in combination with the shortest wavelengths, a significant distortion was observed (see fig. 10). But in this case the hole is by far larger than the optimal value. This result is not necessarily in disagreement with the observation reported in [2]. But this study shows that if possible, it is much better to reduce the size of the outcoupling hole rather than optimizing the power by using mirror steering to reduce the overlap of the optical beam with the hole, as was done in [2].

CONCLUSION

The use of an on-axis hole has been shown to be a viable method for out-coupling, with a typical wavelength tuning range of a factor of two to three. In particular, no evidence for mode rearrangement as a result of the presence of the hole used for out-coupling was found. In fact, the only drawback of hole coupling that was confirmed, is that the intrinsic efficiency is only 50% or slightly above, due to the diffraction losses caused by the hole.

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[2] R. Prazeres et al., Phys. Rev. S.T. A/B, 13 (2010) 090702.

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