LASER GAIN AND INTRA-CAVITY LOSSES OF THE ELBE MID-IR FEL

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Abstract

The U27-FEL of the ELBE radiation source allows to choose between five mirrors with different outcoupling holes. This allows to adapt the optical resonator to the required wavelength range to ensure the needed laser gain and to optimize the outcoupled laser power.

Another parameter which influences the achievable laser gain and output power is the detuning length of the optical cavity. While for CW operation often the minimum detuning point is choosen which maximizes the outcoupled power, for pulsed-mode operation about one wavelength of cavity detuning maximizes the laser gain and yields best stability of the laser.

To gain some insight into the behavior of the optical resonator we have measured the round-trip losses and the net laser gain and compared both to calulations. We have used a fast-readout MCT detector to measure the decay and rise-time of the outcoupled infrared beam caused by a 10 μs break in the electron beam micro-pulse train. We show gain and loss for 5, 10 and 20 μm wavelength with the typical detuning curves of an FEL.

INTRODUCTION

The U27 mid-IR FEL of the ELBE radiation source was designed to cover a wavelength range from 3 to 20 μm. The optical resonator is equipped with two spherical mirrors with a free propagating optical mode of fixed Rayleigh length. Therefore, the optical mode size at the mirrors shows a big variation over the whole wavelength range. To achieve a suitable outcoupling different sizes of the outcoupling hole are required. The mirror chamber containing the outcoupling mirror was designed with a mirror wheel which allows to choose between 5 different mirrors. At present outcoupling holes from 1.5 to 4 mm are available. Now, the fraction of outcoupling can be adjusted to ensure the needed laser gain and to optimize the outcoupled laser power.

GAIN AND LOSS MEASUREMENTS

For measurements of the laser gain and round-trip losses of the optical cavity we switch off the electron beam for a 10 μs period. An MCT detector with a fast readout electronics is used to measure the decay and rise of the optical power (see Fig. 1). The decay can easily be fitted by a single exponential giving the optical losses per round-trip.

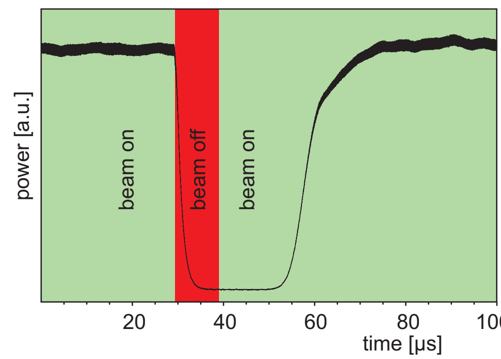

Figure 1: Decay and rise of the optical power caused by a 10 μs break of the electron beam.

ROUND-TRIP LOSSES

Round-trip losses inside the optical cavity were computed using the GLAD [1] code (see Fig. 2). The computation (totals shown with red triangles) includes the outcoupling of optical power (blue circles) as well as diffraction losses due to the aperture limits of the optical beam path in

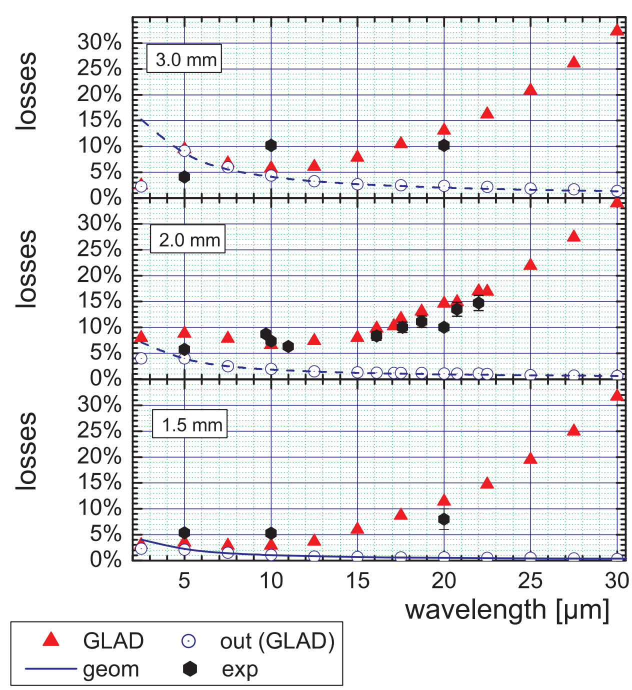

Figure 2: Comparison of measured and computed values of the round-trip losses inside the FEL resonator.

Table 1: Parameters of the optical resonator of the U27 FEL measured at 10 μm wavelength for different sizes of the outcoupling hole. The intra-cavity power is estimated using the computed fraction of outcoupling. To scale it to the saturation power a pulse length of 2 ps was assumed which was previously measured for a minimum-detuning setting of the optical resonator.

out-coupling hole size	1.5 mm	2.0 mm	3.0 mm
measured average power	16.8 W	24.8 W	13.9 W
measured round-trip losses	5.25 ± 0.25 %	7.25 ± 0.25 %	10.0 ± 0.6 %
computed round-trip losses	2.9 %	6.6 %	5.8 %
out-coupled fraction	1.1 %	2.0 %	4.4 %
average intra-cavity power	1600 W	1300 W	330 W
intra-cavity saturated power	62 MW	50 MW	13 MW

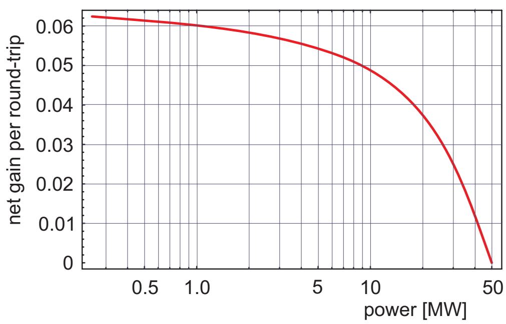

Figure 3: Analytical model of the gain drop at high laser powers approaching saturation.

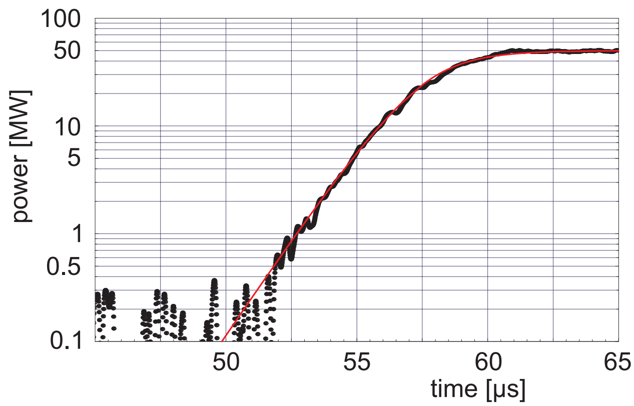

Figure 4: The rise of the optical power computed from the model in Fig. 3 very well fits the measured power data.

particular inside the undulator. The amount of outcoupling very well agrees with a simple geometrical model (blue line) except for very short wavelengths where the optical mode has a tendency to avoid the outcoupling hole. The latter effect was seen experimentally as well. At 5 μm wavelength the measured losses were significanly smaller when using the 3 mm outcoupling hole than with the 1.5 mm or 2 mm holes. In general, the measured round-trip losses show a quite reasonable agreement with the computation.

LASER GAIN AND POWER

The rise of the optical power is determined by the net laser gain. However, the rise curves shown in Fig. 1 need a more involved analysis as the gain itself depends on the optical power. We use a simple analytical model (see Fig. 3) to simulate the gain drop at high powers caused by overbunching and wave-breaking effects. This model very well fits the measured curves of the laser turn-on as shown in Fig. 4. In the example shown we have a 6% small-signal gain over 7% round-trip losses. The laser saturates at 50 MW optical power. At this point the gain has dropped to just match the losses.

THE OPTIMAL OUTCOUPLING

The measurements performed at 10 μm wavelength demonstrate that there exists an optimal outcoupling hole for a given cavity and beam setup. The data shown in Table 1 were measured with a 22 MeV electron beam with 50 pC bunch charge. The round-trip losses roughly correspond to the computed ones considering that the losses at the mirror surfaces are not included in the calculations. Going from 1.5 mm to 2 mm outcoupling hole size one sees the expected rise of the losses (approx. 2%) due to the outcoupling and the increased diffraction losses at the hole. At this power level the gain changes quite rapidly with the power. So the needed 2% higher gain translates only into a small drop of the intra-cavity power. The outcoupled power is increased. But when going further to 3 mm hole size the increased losses yield a much lower saturation power inside the cavity. Despite the higher outcoupling fraction the outcoupled power drops. The measured power levels again roughly confirm the gain model shown in Fig. 3.

REFERENCES

[1] GLAD, Applied Optics Research, Woodland, WA 98674, USA.