

A TAPERED UNDULATOR EXPERIMENT AT THE ELBE FIR OSCILLATOR FEL*

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Abstract

A tapered undulator experiment was carried out at the Forschungszentrum Dresden-Rossendorf (ELBE) far-infrared FEL. The main motivation was to see whether the presence of a dispersive medium in the form of a waveguide in the resonator has any effect on the outcome. The FEL saturated power and the wavelength shifts have been measured as a function of both positive as well as negative undulator field amplitude tapering. In contrast to the typical high-gain FELs where positive tapering (i.e. a decrease of undulator field amplitude over the beam path) proves beneficial for the output power we observe an improvement of performance at negative taper. During the same experiments we studied the characteristics of the detuning curves. The width of the curves indicates a maximum small-signal gain for zero taper while the output peak power is highest for negative taper. Whereas the saturated power output and the detuning curve characteristics agree with the known theoretical predictions, the wavelength shifts showed deviations from the expected values. Details of the experiment are presented.

INTRODUCTION

The concept of tapering the undulator parameters to increase the electron energy extraction efficiency and thereby to extend the operating limit of the free electron laser to higher powers was first suggested by Kroll et al. [1]. The FEL amplifier experiments with tapered undulator did show the expected improvement in the performance [2]. However the gain of the tapered undulator at low power levels at which oscillations must start was low and hence the tapered undulator FEL oscillators had a start up problem [3]. Later on, in a detailed theoretical analysis, Saldin et al [4] have shown that the position of the maximum of the FEL gain curve shifts with the tapering depth of the undulator and this shift plays a crucial role in any tapered undulator FEL

oscillator design. The idea of inverse(negative) tapering, where the undulator field strength increases along the undulator length, was explored and was found to have better performance characteristics as compared to the conventional(positive) tapering [4, 5-7]. In order to reduce the diffraction losses the FELs operating in the submillimetre wavelength range make use of hybrid optical cavities. In such cavities a waveguide is installed in a part of the cavity and the remaining part is a free space. The theoretical analysis of Saldin et al does not take into consideration the hybrid optical resonator FELs. An experiment was performed to study whether the presence of a waveguide in the optical resonator will have any effect on the conclusions of the paper by Saldin et al. In this paper we present the results of an experiment carried out on a short pulse tapered undulator free electron laser with an hybrid optical resonator. A brief description of the FEL set up is followed by the experimental results and comparison with the predictions of theoretical and numerical analyses [4,8].

DESCRIPTION OF THE FEL SET-UP

In the tapered undulator free electron laser oscillator experiment the electron beam was supplied by a superconducting rf linear accelerator ELBE (Electron Linac with high Brilliance and low Emittance). Initially microbunches of r.m.s. bunch length of ~500 picoseconds are generated by an electronically pulsed thermionic electron source with subsequent electrostatic acceleration to an energy of 250 keV. These electron bunches are compressed first by a subharmonic buncher and then by a fundamental frequency buncher. The beam is then accelerated to the full energy in the main accelerator which consists of two 20 MeV superconducting linear accelerator modules. The electron beam parameters associated with this experiment are – micro pulse duration of 2 ps (FWHM), peak current of 10.8 A, pulse repetition frequency of 13 MHz and kinetic energy of 32 MeV.

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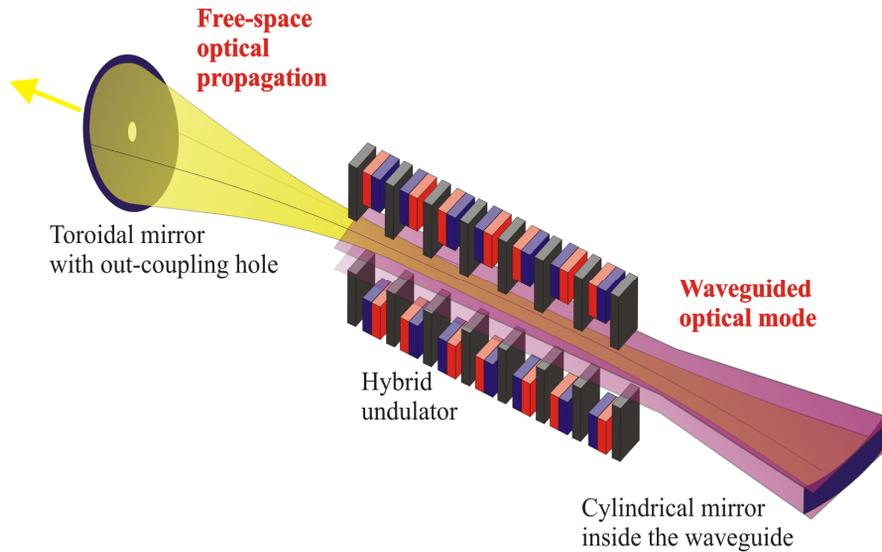


Figure 1: Scheme of a partial waveguide resonator with a bifocal mirror (M1) and a cylindrical mirror (M2).

not lase for the range of values beyond those shown in the table 1.

RESULTS AND DISCUSSION

In the untapered FEL configuration lasing was achieved and optimized to obtain maximum output power by adjusting the electron beam parameters. Power was measured using fast pyroelectric detector. The operating wavelength is 68 microns corresponding to an undulator gap of 32 mm. With about 5200 cavity round trips during the macropulse the laser had enough time to reach saturation power level.

The undulator gap taper was varied in steps of 0.5 mm and for every taper value the gap at the undulator entrance was maintained at the value 32 mm. The reliability of encoder readings for a gap setting was confirmed using a precision dial gauge. Knowing the variation of undulator field with the gap the field taper can be calculated from the gap taper. For each gap taper the optical resonator length was changed from the synchronous value and stabilized using interferometers to detect the mirror positions. The average macropulse power was measured as a function of cavity length. The radiation spectra were recorded at the peak of the detuning curves. The results of the measurements are displayed in Table I. As explained in Ref [4], the FEL efficiency is maximum only for a certain optimal value for the cavity loss. The experiments described here are carried out at a fixed value of cavity losses.

Gap taper indicates the change in the undulator gap over the length of the undulator. The parameter $\hat{\alpha}$ is the taper depth parameter as defined in Ref [4]. Negative and positive gap tapers correspond to decrease and increase in the undulator gap by the indicated figure. Though it was possible to change the gap taper by ± 2 mm the laser did

Table 1: Variation of power with taper

Gap taper (mm)	$\hat{\alpha}$	Power (mW)
-1.0	-14.56	305
-0.5	-07.06	250
0.0	00.00	158
+0.5	06.83	151
+1.0	13.54	152

The reason for this could be the decrease in the small signal gain for the large of $\hat{\alpha}$. The total cavity loss, including the outcoupling through the mirror hole, is around 10 %.

As can be seen from Table 1, for negative tapers, the power output increases with the taper depth, whereas, for positive tapers, it remains more or less at the same level, as compared to the value for zero taper. In fact there is a slight dip in output power level before there is a sudden decrease in it's value at $\hat{\alpha}$ value of 17.56. These observed variations with taper are on the expected lines as shown in [Figs.11 & 12 in [4]]. We would like to emphasize here that it is very important to maintain the undulator entrance gap at the same value, as that of untapered undulator, for all the gap tapers [4]. We had observed that, if this condition is not fulfilled, there is no

noticeable variation in the output power level with the field taper.

Fig. 2 shows the measurement of saturated optical power as a function of cavity length. The vertical axis represents the total power measured with a fast pyroelectric detector. The detuning curves for positive and negative tapering are shown separately so that the features can be seen clearly. The characteristics of the detuning curves such as the width for zero taper case is maximum, the width decreases with the taper depth and is independent of the sign of taper agree with the known results [8].

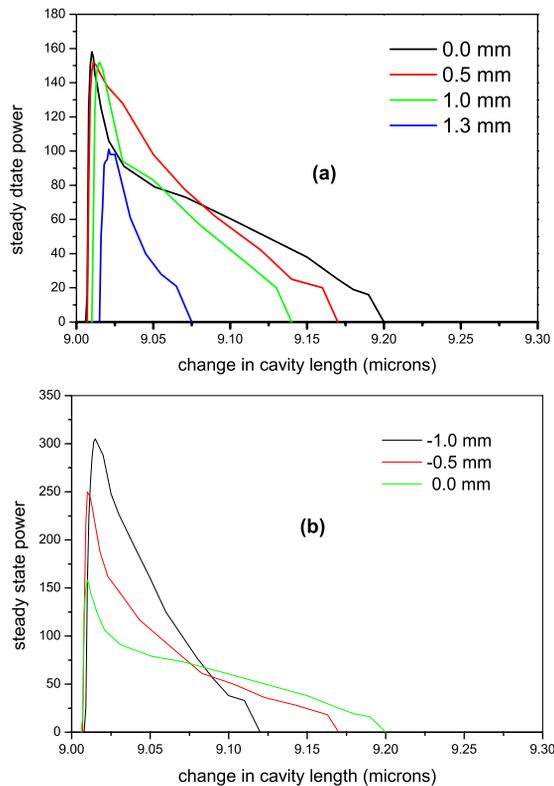


Figure 2: Desynchronism curves for (a) positive taper and (b) negative taper

FEL radiation spectrum was recorded at the peak of each detuning curve. The shift in the wavelengths, as compared to that of an uniform gap undulator, for different field tapers is shown in Fig 3. The range of taper depth is the one over which the lasing was observed. Though the measured values of the wavelength shift do not exactly match with the theoretical values the trend of variation is identical.

CONCLUSIONS

In the tapered undulator FEL oscillator experiment with a hybrid optical resonator the variation of the output power with the undulator field taper depth agrees well with the theoretical analysis. This shows that the presence of a waveguide in the resonator has no effect on

this aspect of FEL dynamics. Also, the nature of the desynchronisation curves agrees with the linear dependence of the width of the curves and the FEL gain.

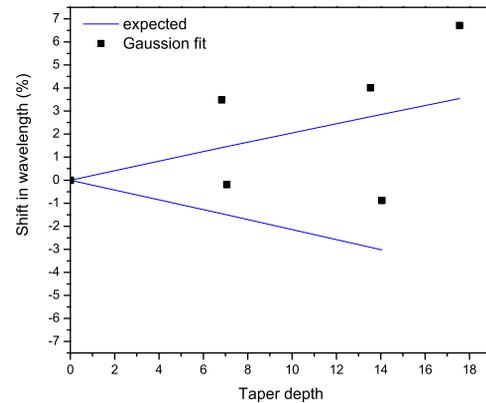


Figure 3: Shift in wavelength with taper

However, as far as the shift in the wavelength with the taper is concerned, though the trend of variation is on the expected lines, all the values show a deviation in the same direction and by approximately the same factor. Further work is required to understand the reasons for these deviations, especially whether they are due to the presence of a dispersive element in the form of a waveguide in the resonator.

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