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Proposal for a IR Waveguide SASE FEL at the PEGASUS Injector*

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Abstract

Free Electron Lasers up to the visible regime are dominated by diffraction effects, resulting in a radiation size much larger than the electron beam. Thus the effective field amplitude at the location of the electron beam, driving the FEL process, is reduced. By using a waveguide, the radiation field is confined within a smaller aperture and an enhancement of the FEL performance can be expected. The PEGASUS injector at UCLA will be capable to provide the brilliance needed for an IR SASE FEL. The experiment PERSEUS (Power Enhanced Radiation Source Experiment Using Structures) is proposed to study the physics of a waveguide SASE FEL in a quasi 1D environment, where diffraction effects are strongly reduced as it is the case only for future FELs operating in the VUV and X-ray regime. The expected FEL performance is given by this presentation.

1 INTRODUCTION

Todays electron beam sources for SASE FELs, operating in the 500 nm or longer wavelength regime, provide a sufficient beam quality so that a beam size below the millimeter level is achieved within the undulator. The resulting diffraction of the emitted radiation field degrades the FEL. Even for a high gain (gain $> 10^5$) SASE FEL experiment at 12 μm [1] the ratio between the electron beam and radiation field size is 1:3 at its equilibrium state in the linear regime of the FEL amplification.

Diffraction is eliminated if the radiation field is enclosed by a waveguide. Waveguides reduces the diffraction effects and have successfully been used in FEL experiments in the millimeter wavelength region [2]. Based on the current research on IR waveguides the enhancement of the FEL efficiency can be extended to shorter wavelengths such as the FEL of the PEGASUS injector [3].

2 THE PERSEUS EXPERIMENT

PERSEUS (Power Enhanced Radiation Source Experiment Using Structures) is an extension of the FEL at the PEGASUS injector. The undulator itself has already been used for an IR SASE FEL experiment with a gain larger than 10^5 [1]. Tab. 1 lists all important parameters of the PERSEUS experiment.

electron beam	
energy	17.9 MeV
energy spread (rms)	0.15 %
normalized emittance	2 π mm·mrad
charge	1 nC
bunch length (rms)	0.9 mm
undulator (planar)	
period length	2.05 cm
undulator parameter K	1.04
undulator length	2 m
β-function	22 cm
waveguide size	1 mm $\times$ 1 mm
radiation	
resonant wavelength	12.85 μm
fundamental waveguide mode	TE$_{01}$
ρ-parameter (1D)	2.04·10^{-2}
diffraction parameter B	0.061

Table 1: Parameters of the PERSEUS waveguide FEL

The IR-waveguide is a Hollow Glass Waveguide (HGW) with a thin metal and dielectric layer deposit on the inside of the waveguide. Losses less than 0.2 dB/m at 10.3 μm have been measured for a waveguide radius of 500 μm and a layer thickness of 600 nm [4]. The same type of waveguide has been used to transport the radiation at the Vanderbilt FEL without any need for cooling [5]. The average power level of the PERSEUS experiment is 300 mW and thus lower than that for the Vanderbilt FEL. Therefore no FEL performance limitations are expected caused by the waveguide.

3 WAVEGUIDE MODES

The resonance condition for a waveguide mode is

$$\beta_z = \frac{\omega_{mn}/c}{k + k_U} \quad , \tag{1}$$

where β_z is the longitudinal velocity of the electrons, normalized to c, k_U is the undulator wavenumber, k the wavenumber of the waveguide mode and ω_{mn} the frequency of the TE$_{mn}$ or TM$_{mn}$ mode.

Further we assume that the waveguide size is much larger than the radiation wavelength and, thus, the waveguide is overmoded. The frequency can be approximated as

$$\omega_{mn} = ck + \frac{c}{2k}\left[\left(\frac{m\pi}{l_x}\right)^2 + \left(\frac{n\pi}{l_y}\right)^2\right] \tag{2}$$

where l_x and l_y define the size of the waveguide in the x- and y-direction, respectively. A detail description of the physics of waveguide FELs can be found at [7] or [6].

The 3D time-dependent code GENESIS 1.3 [8] has been modified to study the expected performance of the

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PERSEUS FEL. The radiation field is expanded into a series of empty waveguide modes for a rectangular waveguide.

The performance of the PERSEUS FEL for different sizes of the waveguide is shown in Fig. 1. Beyond 5 mm the FEL amplification is almost independent of the waveguide size and converges towards the results of the free-space FEL excluding waveguides.

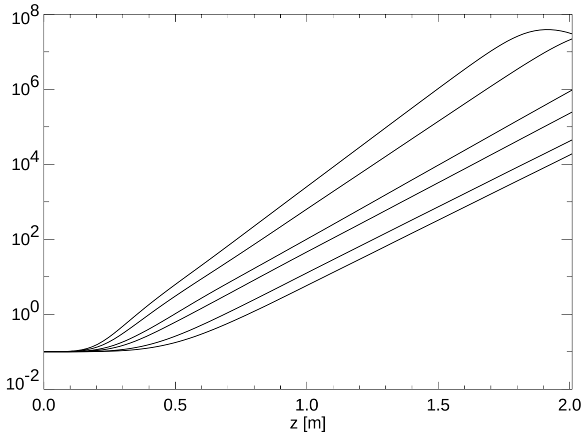

Figure 1: Radiation power along the undulator for different waveguide sizes (Graphs from top to bottom correspond 0.8, 1, 1.5, 2, 2.5 and 5mm waveguide size).

Unfortunately the radiation power does not saturates for the design waveguide size of 1 mm × 1 mm. As discussed in the next section the FEL performance is rather insensitive on variation in the beam size or emittance. This would allow to runs the PEGASUS injector with a higher bunch charge, where the benefit of a higher peak current exceeds the degradation by a larger emittance.

As mentioned above the fundamental mode is the TE_{01} mode (Fig. 2). The next higher modes are the TM_{21} and the TE_{21} mode. The TE mode couples only half as strong as the corresponding TM mode [9].

All modes have the same growth rate and belong to the decomposition of the fundamental eigenmode of the FEL amplification into the eigenmode of the empty waveguide. The second largest mode (TE_{21}) is of the percent level compared to the dominant fundamental TE_{01} mode. Therefore the TE_{01} mode can be regarded as a good approximation of the fundamental FEL eigenmode.

4 BEAM TOLERANCES AND DIAGNOSTICS

For the PERSEUS experiment the tolerance of only two parameters are of particular interest: the emittance and the beam alignment.

The dependence on the emittance is shown in Fig. 3. Below 5 π mm·mrad the dependence is rather weak, which yields a relaxed tolerance on the emittance. The degradation above 5 π mm·mrad arises mainly from particle losses because the electron beam cannot be matched to the focusing of the undulator with the given aperture of the waveguide.

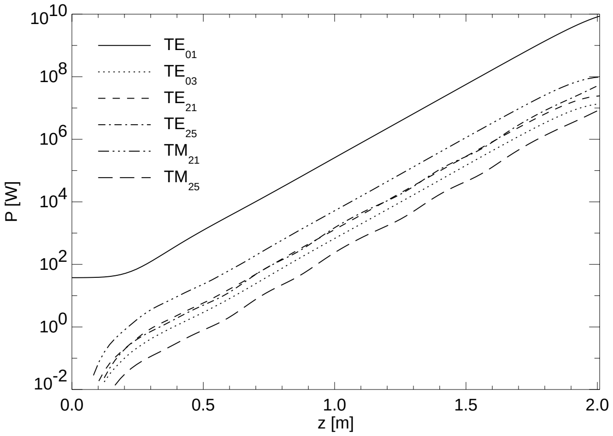

Figure 2: Radiation power along the undulator of individual empty waveguide modes.

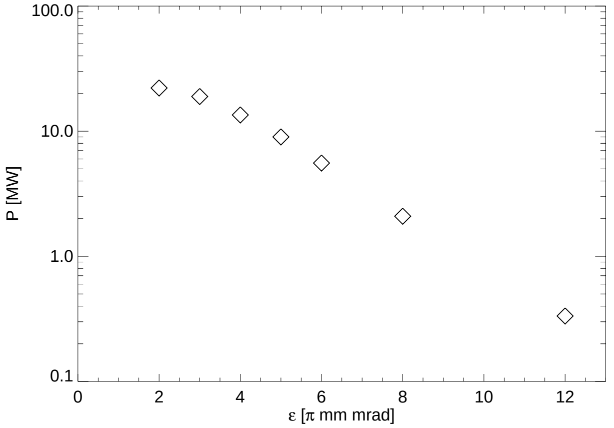

Figure 3: Output power for different emittances of the electron beam.

Fig. 4 shows the output power for different initial beam offsets. The power drops for offsets in y because any offset within the undulator reduces the coupling between the electron beam and the fundamental TE_{01} mode. The reduction is 70% for an offset of 250 μm.

The coupling of the beam to the fundamental TE_{01} mode is independent on the x-position. The enhancement for an offset in x arises from the excitation of the next higher modes, namely the TE_{11} and TM_{11} modes. The coupling strength is identical for both modes and increases with increasing offset. If the electron beam is aligned to the waveguide center the coupling to these modes is zero. The excitation of these modes adds up coherently with the fundamental mode, increasing the bunching process and, thus, the FEL amplification. The phase advance of the TE_{11} and TM_{11} with respect to the electron beam is comparable to

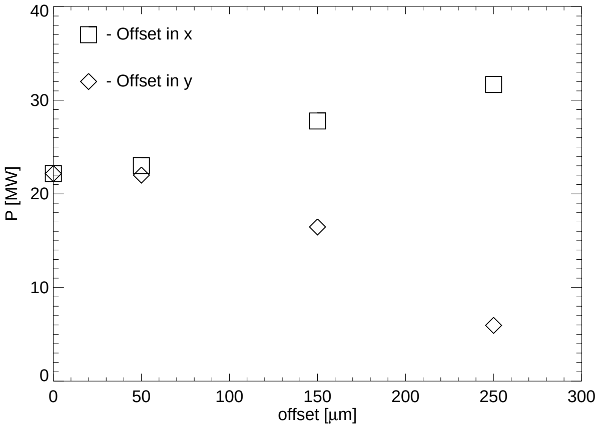

Figure 4: Output power for different initial offsets of the electron beam.

the betatron motion. Therefore the direction of the electric field of these modes remains almost constant at the position of the electron beam over the entire undulator.

The FEL performance might also be affected by the need for beam diagnostic within the undulator. The diagnostics consist mainly of insertable screens for OTR measurements. The waveguide is cut into smaller pieces, which are separated by cavities to provide the required space for the screens. This causes two effects: increased wake fields and coupling losses of the fundamental TE_{01} mode into the next waveguide segment.

The wake fields due to the resistance of the vacuum chamber and the dielectric layer are negligible compared to those caused by the change in the waveguide aperture. The resulting energy modulation has its maximum close to the beam center with an amplitude of 90 keV/m [10]. The reduction of the FEL output power is less than 1% and can be considered as negligible.

More stringent is the requirement for good coupling of the radiation field into the next segment of the waveguide. For a cavity length of 12 mm the loss per single cavity is 11% adding up to 30% power reduction for three cavities in total.

5 CONCLUSION

The usage of a waveguide for the FEL at the PEGASUS injector improves the FEL performance by reducing the saturation length of about 50%. Another improvement is the tolerance on the beam alignment, which is more relaxed compared to the free-space case. Therefore commercially available waveguides of sub-millimeter sizes can either reduces the saturation length of IR-SASE FELs or allows to operate the FEL with a reduced brilliance of the electron beam source.

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