THRESHOLD OF A MIRROR-LESS PHOTONIC FREE-ELECTRON LASER OSCILLATOR PUMPED BY ONE OR MORE ELECTRON BEAMS

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Abstract

Transmitting electrons through a photonic crystal can result in stimulated emission and the generation of coherent Cerenkov radiation. Here we consider a photonic-crystal slab consisting of a two-dimensional, periodic array of bars inside a rectangular waveguide. By appropriately tapering the bars at both ends of the slab, we numerically show that an electromagnetic wave can be transmitted through the photonic-crystal slab with close to zero reflection. Furthermore, the photonic-crystal slab allows transmission of electrons in the form of one or more beams. We design the tapered photonic-crystal slab to have a backward wave interaction at low electron-beam energy of around 15 kV, that results in distributed feedback of the radiation on the electrons without any external mirrors being present. Here we discuss the dynamics of the laser oscillator near threshold and numerically show that the threshold current can be distributed over multiple electron beams, resulting in a lower current per beam.

INTRODUCTION

Electron beams have been used to generate incoherent and coherent radiation over a large spectral range. Among the huge range of sources are microwave devices [1, 2], gyrotrons [1, 3], synchrotrons [4] and free-electron lasers (FELs) [5–8]. These sources can be divided in two classes, the so-called fast-wave (e.g., gyrotrons, synchrotrons and FELs) and slow-wave or Cerenkov devices (e.g., traveling wave tubes, Smith-Purcell and Cerenkov free-electron lasers). Here we focus on the slow-wave devices that use an interaction structure to slow down the phase velocity of the wave to make the electron move synchronous with the wave. This phase matching results in bunching of the electrons on the scale of the radiation wavelength and is responsible for the generation of coherent radiation [1, 2, 9]. The slow-wave devices are very efficient and powerful sources of radiation at microwave frequencies, however, when scaled to higher frequencies the output power drops. The reason for this is that the characteristic size of the interaction structure reduces when the operating frequency increases. The maximum current that can be transported through the interaction structure is also reduced and, hence, the output power. However, in a photonic free-electron laser (pFEL) a photonic crystal is used as interaction structure to slow down the wave. Electrons streaming through a photonic crystal can move synchronous with a co-propagating wave and emit coherent Cerenkov radiations [9, 10]. A photonic crystal typically has many parallel channels through which the electrons can propagate. For example, the photonic crystal shown in Fig. 1 allows up to seven beams to propagate in parallel through the photonic structure. Therefore, when the photonic crystal shrinks in size to support higher operating frequencies, one can increase the transverse extend of the crystal to create more parallel channels for the electrons and keep the total current streaming through the crystal constant. As the current per individual electron beam will decrease, it is of interest to investigate the behavior of a photonic free-electron laser near threshold when pumped by one or multiple electron beams.

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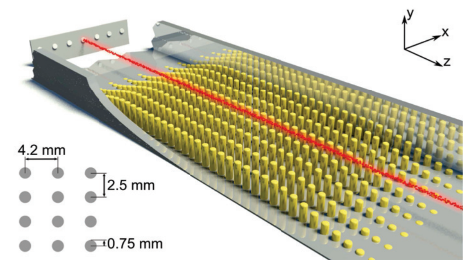

Figure 1: Schematic view of the photonic free-electron laser with a single electron beam. The red dots represent the electrons. The inset shows the orientation of the coordinate system.

The remainder of this paper is organized as follows. We first present the photonic crystal considered in this paper and then we use a particle-in-cell code (CST particle studio 2014) to investigate the performance near threshold of the backward-wave pFEL oscillator when pumped by a single electron beam in the center of the photonic crystal. This is followed by investigating the performance when the same oscillator is pumped by several electron beams and the paper concludes with a discussion and outlook.

TAPERED PHOTONIC CRYSTAL

The photonic free-electron laser considered here is shown schematically in Fig. 1. The photonic crystal consists of 8 rows of 40 posts placed in a rectangular waveguide, where the height of the nth post in a row is given by:

$$h_n = \begin{cases} h_0 \cos^2\left(\frac{\pi}{2}\left(\frac{n}{11} - 1\right)\right) & \text{if } 1 \leq n \leq 10 \\ h_0 & \text{if } 10 < n \leq 30 \\ h_0 \cos^2\left(\frac{\pi}{2}\frac{n-30}{11}\right) & \text{if } 30 < n \leq 40 \end{cases}, \quad (1)$$

where $h_0 = 4$ mm is the full post height. The other dimensions of the photonic crystal are a post radius of 0.75 mm, a distance between post centers of 2.5 mm along the z axis and 4.2 mm along the x axis. The waveguide has a cross-section of 33.6 by 8.0 mm. The taper at both ends of the crystal is

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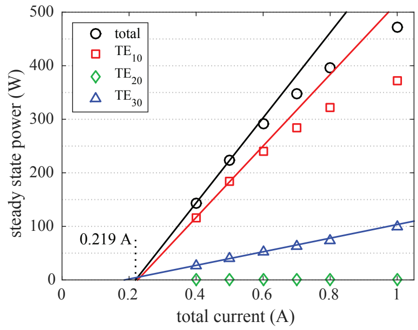

Figure 2: The output power of the pFEL as a function of electron beam current. The electron energy is 14 keV for all data points, and the pFEL is pumped by a single beam in the center of the photonic crystal.

used to suppress reflections at the transition between empty waveguide and waveguide loaded with the photonic crystal [10]. As a consequence, the pFEL has no external mirrors, as the waveguide is assumed to terminate in matched ports and therefore does not reflect any radiation. Still, due to the periodicity of the dispersion of the Bloch modes [11], the pFEL can be operated in the so-called backward-wave regime where the group velocity is directed opposite to the phase velocity. Because of this, light generated at the downstream side of the photonic crystal travels to the upstream side, where it bunches the electron beam. Consequently, the backward wave provides feedback for the electron bunching and thereby creates an oscillator configuration. For more details on the photonic-crystal slab and its dispersion, the reader is referred to Ref. [10].

SINGLE BEAM THRESHOLD CURRENT

First we consider the structure of Fig. 1 when pumped with a single electron beam in the center having a beam voltage $V_b = 14$ kV. Note that after the tapered section the empty waveguides continues for another 13.75 mm before it ends in a matched waveguide port where the radiation is analyzed in terms of waveguide modes. As the waveguide modes and photonic crystal Bloch eigenmodes couple one-to-one [10], the waveguide modes are representative for the Bloch eigenmodes inside the crystal. Figure 2 shows the output power of the backward-wave pFEL oscillator as a function of the electron beam current for the three lowest order modes, TE_{10} (squares), TE_{20} (diamonds), and TE_{30} (triangles), and the total power P_{tot} (circles). Because the electron beam and therefore the gain is purely in the center of the waveguide, only modes with a strong on-axis longitudinal field are expected to couple strongly to the electron beam. Indeed, Fig. 2 shows that 99.5 % of the total power is in modes one and three and that the even modes, with zero on-axis longitudinal field, contain negligible power. The power in higher order odd modes is also negligible.

Figure 2 shows that the output power behaves like any other laser oscillator. The pumping power, which is set by the accelerated electrons, has to overcome a minimum threshold that is defined by the roundtrip loss of the oscillator. Although 100 % of the wave is coupled out of the photonic crystal slab the backward-wave interaction still provides feedback between the wave and the electrons. In this case, the bunching induced by the wave, that grows in the direction towards the electron gun, must be sufficient to dominate the noise in the electron beam. Due to a threshold in the pumping current, the slope efficiency, η_{sl}, defined by [12, 13]

$$\eta_{sl} = \frac{dP_{out}}{dP_{in}} = \frac{1}{V_b}\frac{dP_{out}}{dI_b}. \tag{2}$$

is considered instead of the intrinsic efficiency η_{int} given by [14, 15]

$$P_{out} = \eta_{int} P_{in} = \eta_{int} I_b V_b, \tag{3}$$

where for a free-electron laser (including the pFEL) the input power P_{in} is the product of the total electron beam current, I_b, and the total accelerating voltage, V_b. As is known from many other laser oscillators [12, 13] the slope efficiency is more or less constant when pumped up to a few times the threshold pump power. From Figure 2 it is clear that the slope efficiency is not constant for the total power and the power in the fundamental mode, whereas the slope efficiency is approximately constant for the third order mode. Therefore, the lowest available current data are taken to determine the threshold beam current via linear extrapolation, giving a threshold current of 0.22 ± 0.03 A. This means that the highest beam current investigated is far above threshold (by nearly a factor of 5), and that for the total power the slope efficiency is nearly constant ($\eta_{sl} = 5.7$ %) up to a beam current that is about 3 times the threshold current. Analysis of the $P_{out}(I_b)$ relation, as shown in Fig. 2, shows that the slope efficiency does not follow a simple power relation, and, consequently, differs from the 4/3-power relationship found for η_{int} off an FEL [14, 15]. Furthermore, these results show that the feedback provided by the photonic crystal in combination with the gain provided by the electron beam is sufficient to obtain lasing as long as the electron beam current is above a threshold.

MULTI-BEAM THRESHOLD CURRENT

When pumping with multiple electron beams, it is of special interest to investigate if lasing is still obtained when the current per beam is dropped below the current threshold for single-beam pumping. This is a necessary condition to scale the pFEL to higher operating frequencies. To investigate this, we used the same structure, beam voltage and total current as in the previous section, while the number of electrons beams is increased from 1 to 5 in steps of 2 (i.e. by filling adjacent free channels). Figure 3 shows the total output power versus the current per electron beam for pumping with one electron beam (circles), three electron beams (triangles) and five electron beams (stars). The current thresholds have been obtained in the same way as described above. The threshold current per beam is found to be 0.219, 0.088 and 0.071 A

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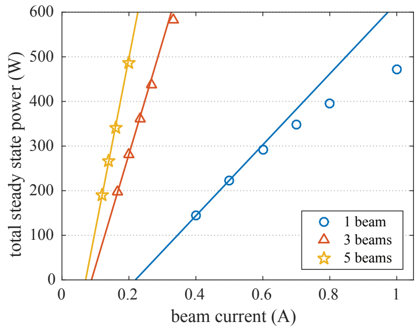

Figure 3: The output power of the pFEL for one (circle), three (triangle) and five (star) electron beams with varying current per beam. The electron energy is 14 keV for all data points.

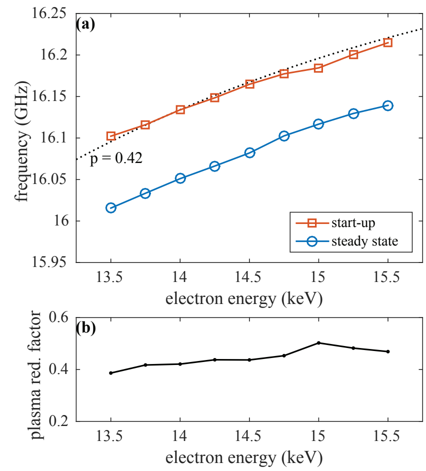

Figure 4: Spontaneous emission (squares) and steady-state (circles) frequency as a function of total electron energy as obtained from the PIC simulations (a). The dotted and dashed lines show the frequency expected from velocity-matching using $p = 0.42$. The plasma reduction factor as calculated from the spontaneous emission frequency (b).

when pumping with one, three and five beams, respectively. We observe that the total threshold current increases with the number of pump beams. This is caused by the lower field strength at the location of the additional beams [10], which results in a lower gain [16]. The most important conclusion that can be drawn from this data is that it is possible to distribute the current over multiple beams, such that the current in each beam is lower than the single-beam threshold and the laser oscillator still turns on if the total current is above a threshold.

Using Eq. 2 where I_b is now the total current, we find for the slope efficiency 5.7 %, 6.0 % and 5.4 % when pumping with one, two and three beams, respectively. In more detail, we observe that up to a total beam current of 0.7 A, the single-beam pFEL produces the highest output power. For higher total current, the three-beam pFEL produces the highest output power, more than 100 W more than the single-beam pFEL for a total current of 1 A. The five-beam pFEL only just surpasses the single-beam pFEL in output power at a total current of 1 A and remains below the output level of the three-beam pFEL for all total beam currents investigated. On the other hand, the mode purity increases when the number of pump beams increases [10].

OUTPUT FREQUENCY

The pFEL oscillator of Fig. 1 has no external resonator and the oscillator can therefore be continuously tuned due to the absence of longitudinal modes. An estimate of the operating frequency can be obtained from the intersection of the dispersion of an appropriate Bloch eigenmode [10] with the dispersion of the slow space-charge wave given by [1]

$$\omega = k_z v_e - p\gamma^{-3/2}\omega_p, \tag{4}$$

where $\omega_p = \sqrt{\frac{e^2 n_e}{m_e \epsilon_0}}$ is the non-relativistic plasma frequency, v_e is the electron velocity, γ is the Lorentz factor, e, n_e and m_e are the electron charge, density and mass, respectively, ϵ_0 is the permittivity of free space and p is the so-called plasma reduction factor. Note, there also exists a fast space-charge wave, but only the slow space-charge wave can give up energy [1] and facilitate the pFEL interaction. The fast space-charge wave will be ignored in the remainder of this paper.

A more accurate prediction of the output frequency is obtained from the PIC simulations. To obtain the output frequency, we apply a Fourier transform to the electric field when the laser is in steady state. Figure 4a shows the steady-state output frequency (blue circles) as a function of the beam voltage for the pFEL oscillator of Fig. 1 pumped by a single, 1-A electron beam. Note, the same photonic crystal without tapered end sections would have reflections at the end facets, and the resulting resonator would have a free spectral range of about 0.15 GHz.

Calculating the operating frequency from the velocity matching requires knowledge about the plasma frequency reduction factor p. This parameter can not readily be calculated independently for this geometry. However, using the operating frequency obtained from the PIC simulations, it should be possible to calculate the plasma reduction factor as function of the electron beam energy. As in steady state the electrons will have on average a reduced longitudinal velocity with an increased spread and a non-uniform longitudinal distribution, the frequency during start-up of the laser, where the electron velocity distribution is still uniform with small spread, will be used. To obtain this frequency, the Fourier transform is applied to the electric field for the first 4.2 ns and zero-padding is used to increase the resolution of the Fourier transform. This is essentially the frequency of spontaneous emission of the pFEL oscillator. This spontaneous emission frequency is plotted as well in Fig. 4a (red squares). We observe that the steady-state frequency is slightly lower (< 100 MHz) than the spontaneous emission frequency that is emitted when the gain is below or just above threshold.

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This difference is under investigation and could be caused by an interaction induced change in the wave phase.

Using the average longitudinal electron velocity from the PIC simulations, which takes into account the buildup of potential energy in the metallic structure [17], and the frequency of the spontaneous emission, Eq. 4 is used to calculate the plasma frequency reduction factor p. This factor is plotted in Fig. 4b as a function of the initial total electron energy. From Fig. 4b it follows that p increases slightly with increasing electron energy, which agrees with the dependency found for other geometries [18]. For comparison, the operating frequency predicted from velocity matching using the average value $p = 0.42$ is also shown in Fig. 4a as dotted line.

CONCLUSION

A backward-wave photonic free-electron laser oscillator is numerically investigated using a particle-in-cell code. We have determined the threshold current for laser operation when pumped by a single and by multiple electron beams. We find that the threshold current per beam reduces with the number of beams, but the total threshold current increases. The latter is due to the reduced field strength of the Bloch eigenmodes of the crystal near the sidewalls of the waveguide. This reduces the overall gain and consequently raises the total threshold current. Still, when the number of electron beams is increased, the current per beam can be reduced while approximately maintaining the output power. Using multiple beams has the added advantage that a higher mode purity can be be obtained. We have observed that the frequency of spontaneous emission is slightly higher than the steady-state frequency of the oscillator. Due to absence of any external resonator, the output frequency can be continuously tuned by varying the accelerating voltage for the electrons.

The multi-beam performance of the pFEL oscillator suggests an interesting scaling route to increase the operating frequency to well into the THz domain, compared to the microwave frequencies investigated here. This requires the crystal to be scaled down in size by two orders of magnitude. Instead of increasing the current density in a single beam, the same total current can now be obtained by propagating many electron beams in parallel through the pFEL. Such a massively parallel set of electron beams may be produced by so-called field-emitter arrays [19]. Switching individuals beams on and off, or providing a chirp in the accelerating voltage, either in time or as a function of transverse position, may provide the source with interesting capabilities to manipulate the light produced.

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