A single beam photonic free-electron laser

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The photonic free-electron laser (pFEL) aims to realize a scalable, compact microwave source with the potential to operate well into the THz range with Watt-level output. Radiation is produced by a set of electron beams propagating through a photonic crystal. The transverse coherence of this radiation allows a unique power scaling by extending its cross-section and the number of electron beams. We designed a single electron beam pFEL operating between 20-24 GHz to study the fundamental physics of such devices. We will present the experimental design of this single beam pFEL.

Introduction

Microwave sources are today well developed, compact and provide high output power. However, all these sources decrease in output power when their operating frequency is scaled into the THz range (0.1 GHz – 10 THz). Therefore, no compact THz source with Watt-level output power currently exists [1] that allow the development of numerous new industrial applications [2]. Examples are security-surveillance and imaging of goods, mail or people as THz radiation penetrates many optically opaque materials, like plastics, paper or clothes.

Recently, we presented the concept of a photonic free-electron laser (pFEL) to develop a compact and Watt-level THz source [3]. The pFEL uses a set of individual electron beams, which stream through a photonic crystal (PHC, fig. 1). The PHC coherently couples the Cerenkov radiation of these electron beams due to its transverse scattering. This allows a unique power scaling of the pFEL by increasing its transverse size and number of electron beams. Thereby, the total beam current streaming through the device can be kept constant when the PHC's lattice constant is scaled down to operate the pFEL in the THz range. Furthermore, PHCs strongly slow down the light's phase velocity [4] allowing the use of low electron velocities $v_{el} < 0.3c$. Therefore, a compact electron gun can be used to keep the device small.

In this paper we present the design of a pFEL operating between frequencies of 20-24 GHz. This single beam pFEL will be used to study the physics of this device. We begin with an overview of the pFEL setup and then describe its main components in more detail.

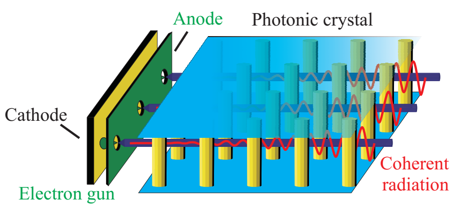

Figure 1: Schematic overview of a pFEL

Schematic overview

A schematic overview of the complete device is shown in fig. 2. It consists of a thermionic electron gun used in traveling wave tubes. It provides an electron beam which is guided through the PHC by a solenoid. Inside the PHC the electrons interact with the PHC-eigenmodes and emit radiation due to the Cerenkov effect. Interaction with TM-like eigenmodes ($E_z \neq 0$) results in longitudinal bunching and hence coherent amplification of the radiation. In order to keep the device compact, the single pass gain will be limited and a cavity is required to reach saturation. The upstream mirror is formed by a copper plate with a hole to allow the electron beam to enter the PHC. The downstream mirror is partial reflecting and is formed by a tapered PHC section followed by an empty but tapered section of rectangular waveguide.

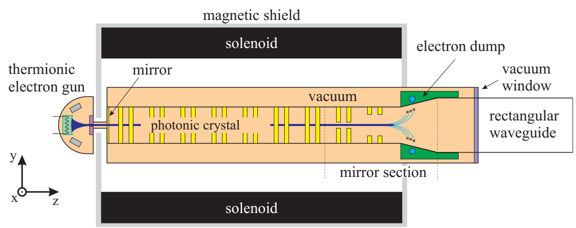

Figure 2: Schematic setup of the single beam pFEL

The guiding magnetic field reduces sharply after the electron beam leaves the PHC, and, consequently, the beam expands and is collected in a cooled section of the waveguide wall. Finally, the radiation is extracted from the vacuum by a waveguide window. In the remainder of this paper we will describe the electron beam guiding, the cavity and the vacuum window in more detail.

Electron gun and beam guiding

For the single beam pFEL, a thermionic, double gridded electron gun is chosen. It has a perveance of $1.18 \cdot 10^{-6}\,\mathrm{AV}^{-3/2}$ and is designed to operate at a voltage of $V_b = 14.2\,\mathrm{kV}$. However, the operating voltage can be varied between 7 and 15 kV. At the anode the beam radius is approximately $a = 0.8\,\mathrm{mm}$ and a magnetic field produced by a solenoid is used for Brillouin flow guiding through the PHC.
This requires a maximum magnetic flux density of approximately $B_z = 0.16\,\mathrm{T}$ for this gun and the flux density must be zero at the cathode [5]. Therefore, iron end caps with a thickness of 1.5 mm are used to shorten the flux outside the solenoid (fig. 2). Fig. 3 a) shows that this reduces the magnetic flux at the cathode position $z = 0$ to a few mT. A further advantage by using end caps is a more homogeneous flux density inside the solenoid.
The electron beam propagation is modeled using the Opera-3D software (Cobham Technical Service). First the magnetic field of the solenoid is calculated and it is then combined with the 3D-electron gun model. The calculated electron trajectories are shown in fig. 3 b) for a beam voltage of 14.2 kV. The figure shows that the electrons rotate around the z-axis, as is to be expected for Brillouin flow. A projection on the r-z plane (cylindrical coordinates) is also shown in fig. 3 b). From this figure the guided electron beam radius is read to be approximately 1 mm. We also estimate that the longitudinal velocity spread $\delta v_z / v_z$ is less than 1 % for this configuration.

a) b)

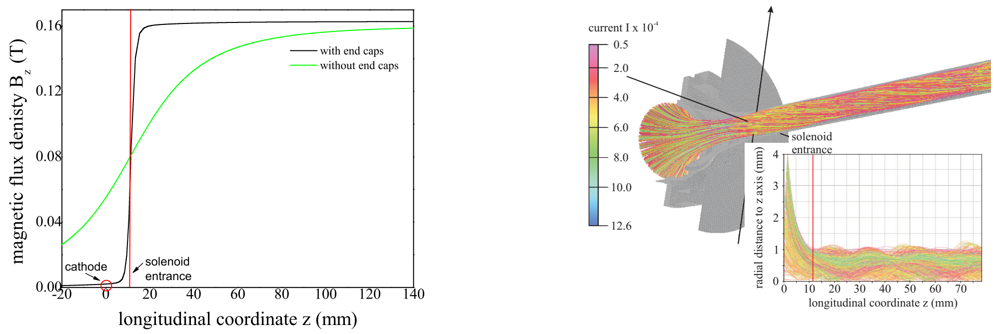

Figure 3:
a) Magnetic flux density B_z of solenoids with and with-out end caps at a current density of $6.5\,\mathrm{A/mm^2}$ in the solenoid windings.
b) 3D view of electron beam propagation and its projection on the *r*-*z* plane. The trajectory's color is a measure of the current it carries.

Cavity design and vacuum window

The PHC in a pFEL is used to couple the set of electron beams to the radiation field and to each other. For the first the radiation field's phase velocity is slowed down by the PHC and amplification behaves similar to Cerenkov FELs [3, 6]. The second is realized due to the transverse scattering of the radiation field in the PHC. Gain calculations are under way, but it is not expected, that a single pass saturates the laser. Hence, a cavity is required with ideally a total reflecting upstream mirror and a partial reflecting downstream mirror. The upstream mirror consists of a copper plate with a hole for the electron beam and a short tube connects this mirror to the anode of the electron gun. This hole has a diameter of about 3 mm and forms together with the short tube a cylindrical waveguide. In this waveguide all modes are well below cut-off at the frequency range of interest. Thus, this mirror is expected to be a nearly perfect reflector.
The PHC is placed against the upstream mirror and consists of a double periodic array of metal posts, embedded in a rectangular waveguide with the center line of posts removed (fig. 4 a)). Removing the center line of posts creates a large channel ($4.9\,\mathrm{x}\,8\,\mathrm{mm}^2$) that provides ample space for the electron beam. The advantage of a double periodic unit cell is that the mode spacing between the lowest order TM-like modes is larger than in a regular lattice (fig. 4b)). A large mode spacing simplifies the analysis of experimental results. Fig. 4 b) also shows that the electron gun allows operation in the frequency range between 20-24 GHz, assuming an interaction at a higher spatial mode. For the current design the length of the PHC is 30 unit cells; however this number may be optimized depending on the gain of the device.
When the PHC is abruptly terminated into the empty waveguide an impedance jump arises and hence (partial) reflection of the radiation occurs. The PHC termination itself therefore acts as the downstream mirror. The amount of reflection is controlled by tapering both the PHC and waveguide height (fig. 2). The taper of the PHC consists of 2 unit cells with reduced height of the posts, followed by a taper of the height of the empty rectangular waveguide. Its calculated transmission is approximately 20 %.

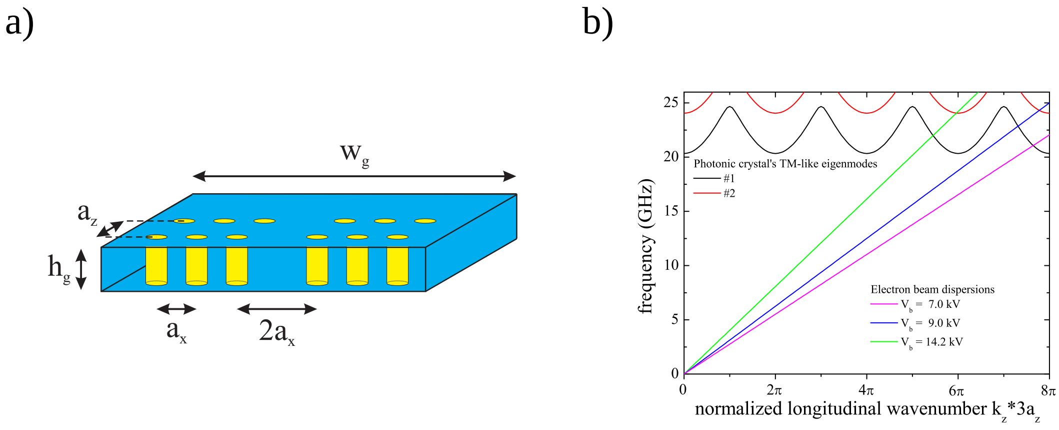

Figure 4:
a) Unit cell of the pFEL's PHC, consisting of a rectangular waveguide and metal posts of radius $r = 0.75\,\mathrm{mm}$, $a_x = 2.7\,\mathrm{mm}$, $a_z = 3\,\mathrm{mm}$, $w_g = 18.9\,\mathrm{mm}$, $h_g = 8\,\mathrm{mm}$
b) Dispersion of the first two TM-like eigenmodes and electron beam dispersion for several beam voltages.

Finally, the produced radiation is coupled out from the vacuum section by a window. It consists of a dielectric having a half wavelength thickness. This compensates the reflection from the boundary surfaces and, e.g., with a fused silica window the reflection is less than five percent over the pFEL's operating range.

Conclusion

We presented the design for a single beam pFEL operating within a frequency range of 20-24 GHz. Due to the use of a PHC slow electrons can produce microwave radiation in a compact design. This pFEL oscillator can be used to investigate the fundamental physics of pFELs, which are a promising source for a compact and Watt-level THz source.

Acknowledgement

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