EXPERIMENTAL DESIGN OF A SINGLE BEAM PHOTONIC FREE-ELECTRON LASER

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Abstract

The photonic free-electron laser (pFEL) aims to realize compact microwave sources with the potential to generate multi-Watt level teraHertz radiation. For this purpose it uses a photonic crystal to coherently couple the Cerenkov radiation from a set of individual electron beams streaming through this structure. The resulting transverse coherence of the radiation allows a power scaling of the device by extending its cross-section and the number of electron beams. To study the fundamental physics of such devices, and to compare single beam with multi-beam performance, we first designed a single electron beam pFEL operating at a frequency of around 22 GHz. The general design of this single beam pFEL will be presented.

INTRODUCTION

Although various, well developed, microwave sources exist to date, they all show a reduction in output power when the operating frequency is increased. Therefore, the interesting frequency range spanning from about 100 GHz to a few THz is still lacking compact and powerful sources [1]. Having a compact, robust Watt-level source available would enable numerous industrial applications [2] as the radiation penetrates dielectric materials, like ceramics, paper, wood or clothes, which are opaque for IR or visible light. Additionally, sharp and molecular-specific resonances exist in this frequency range, which can be used for highly material-specific imaging. Examples are control of chemical reactions, quality control in manufacturing, security-surveillance, and imaging of goods, mail or people. However, the central problem for industry to apply existing THz sources is that they are not compact, do not provide Watt-level output power, and, foremost, are not economical.

Recently, we presented the concept of a photonic free-electron laser (pFEL) to provide such a 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. This power scaling is one of the most important features of the pFEL concept. It allows to keep the total beam current streaming through the device constant while the PHC's lattice constants are scaled down to increase the operation frequency of the laser. Further-

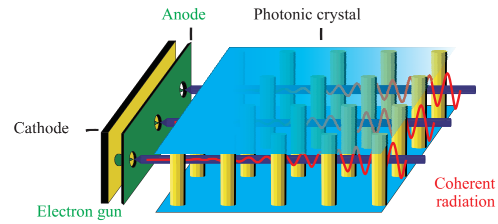

Figure 1: Schematic overview of a pFEL, Not shown: solenoid for electron beam guiding.

more, PHCs strongly slow down the light's phase velocity [4], which allows the use of slow electrons ($\beta < 0.3$, where $\beta = v/c$ is the electron velocity v normalised to the speed of light c). Therefore, a compact electron gun can be used keeping the whole device small. To investigate the physics of this type of devices and to allow comparison with future multi-beam devices we have designed a single electron beam pFEL. In this paper we present details of its design. We first will give an overview of the complete setup and then describe several main components in more detail in the remainder part.

SCHEMATIC OVERVIEW

A schematic overview of the complete device is shown in Fig. 2. It consists of a standard thermionic electron gun used in commercial traveling wave tubes [5]. It provides an electron beam of high current ($I_{b,max} = 2.8\,\text{A}$), which is guided through the PHC by a solenoid. The interaction structure consists of a PHC in a rectangular waveguide. In 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 resonator 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 waveguide loaded with 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 (Fig. 2).

The guiding magnetic field reduces sharply in magnitude shortly after the electron beam leaves the PHC to allow the electron beam to expand and be collected in a cooled section of the waveguide wall. The radiation continues and enters a mode converter that transforms the TM-mode to

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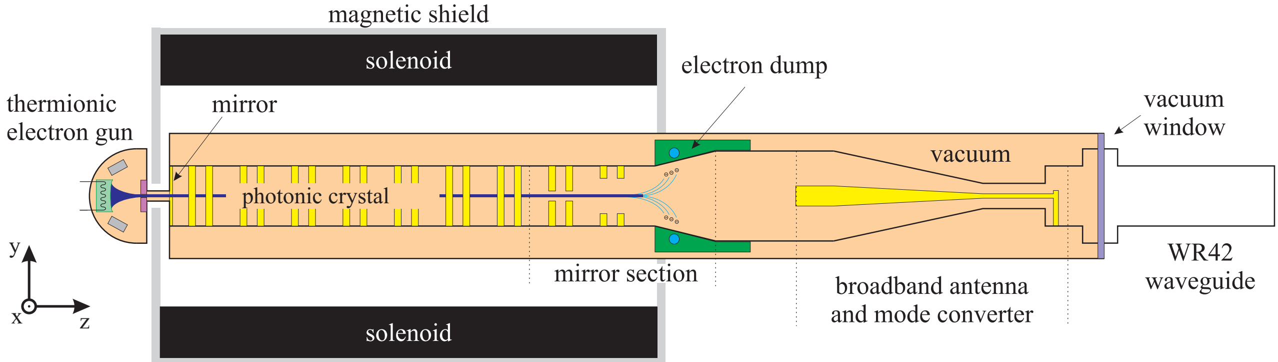

Figure 2: Schematic setup of the single beam pFEL.

the fundamental TE_{10} mode. This not only allows the use of standard microwave components, but it also allows for a simple design of a broadband vacuum window [6].

In the remainder of this paper we will present some of these components in more detail. First, we describe the electron gun with guiding magnet. Then the PHC and the partial reflected mirror design will be discussed. Finally, the broadband antenna, mode converter and vacuum window are presented.

ELECTRON GUN AND BEAM GUIDING

Thermionic electron guns have been used in microwave sources for over 60 years and they are are well developed. Therefore, for the single beam pFEL, a thermionic, double gridded electron gun used in traveling wave tubes was chosen [5]. It has a perveance of $1.65 \cdot 10^{-6}\,\mathrm{AV}^{-3/2}$ and was designed to operate at a voltage of $V_b = 14.2\,\mathrm{kV}$. However, the operating voltage can be varied between 7 and $15\,\mathrm{kV}$. The gun produces a beam radius of approximately 1 mm and Brillouin flow guiding is used to transport the beam through the PHC.

For Brillouin flow, the required magnetic flux density B to guide the beam can be estimated by [7]:

$$B = 0.83 \times 10^{-3} \left[\frac{\mathrm{TmV}^{1/4}}{\mathrm{A}^{1/2}}\right] \frac{I^{1/2}}{aV_b^{1/4}}, \tag{1}$$

where a is the beam radius at the anode aperture of the gun. With $a \approx 0.8\,\mathrm{mm}$, Brillouin flow requires a flux density of approximately $B = 0.16\,\mathrm{T}$. Additionally, Brioullin flow also requires the flux density to be zero at the cathode. Therefore, the solenoid has iron end caps of $1.5\,\mathrm{mm}$ thickness to shorten the flux outside the solenoid. The added advantage is a more homogeneous flux density inside the solenoid, as is shown in fig. 3. The cathode position is approximately at $-11.5\,\mathrm{mm}$ and the magnetic field at the cathode position is reduced to about a few tenth of a mT when the end caps are used.

To investigate the electron beam properties of this combination using the Opera-3D software [8], a magnetic model of this solenoid is combined with the 3D-electron

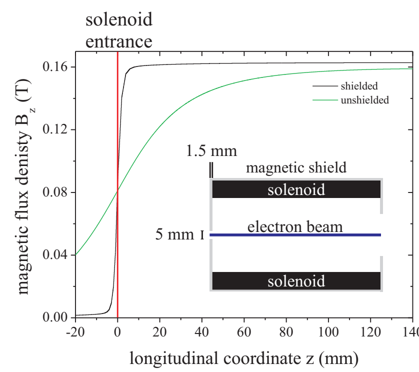

Figure 3: Magnetic flux density produced by the solenoid with (shielded) and with-out (unshielded) end caps. The current density in the solenoid windings is $6.5\,\mathrm{A/mm}^2$.

gun model that has been provided by the gun manufacturer. The calculated electron beam trajectories are shown in fig. 4 for the design beam voltage of $14.2\,\mathrm{kV}$. This 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. 4. From this figure we derive that the electron beam radius r_b is approximately $1\,\mathrm{mm}$. We also estimate that the longitudinal velocity spread $\delta v_z/v_z$ is less than $1\,\%$ for this configuration.

PHOTONIC CRYSTAL AND MIRROR DESIGN

The purpose of the PHC in a pFEL is to couple the set of electron beams to the radiation field and to each other. The first is done by slowing done the phase velocity of the radiation field and amplification takes place through the normal Cerenkov FEL gain mechanism [3, 9]. The second is realised through the transverse scattering that takes place in the PHC and this allows the various electron beams to build up a transversely coherent radiation field. Gain calculations are under way, and it is expected that, for a compact device,

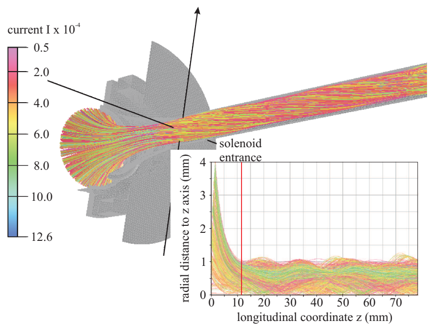

Figure 4: 3D view of electron beam propagation and its projection on the r-z plane. The colour of the trajectory is a measure of the current it carries.

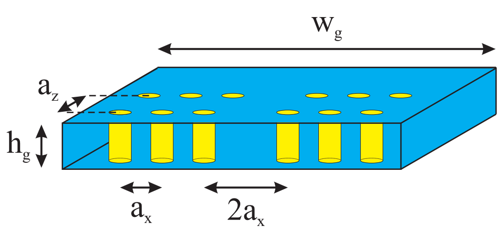

Figure 5: Unit cell of the PHC for the single beam pFEL, consisting of a rectangular waveguide and metal posts of radius $r = 0.75\,\mathrm{mm}$, $a_x = 2.7\,\mathrm{mm}$, $a_z = 3\,\mathrm{mm}$, $w_g = 18.9\,\mathrm{mm}$, $h_g = 8\,\mathrm{mm}$.

the single pass gain is not sufficient to saturate the laser in a single pass. 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. A short tube will connect this mirror to the anode of the electron gun in order to extend the endcap of the solenoid to close to the beam axis (see fig. 2). The hole diameter is about $3\,\mathrm{mm}$. This hole forms together with the short tube a cylindrical waveguide for which all all modes are well below cut-off for 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 the rectangular waveguide (fig. 5) with the center line of posts removed. 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 and creates almost a bandgap between the two lowest order modes (fig. 6) [10]. A large mode spacing will simplify the analysis of experimental results. Fig. 6 also shows that the electron gun allows operation in the frequency range between 20.5 and 24 GHz, assuming an interaction at a higher spatial mode. For the current design we have chosen a length of the PHC of 30 unit cells, however this number may be

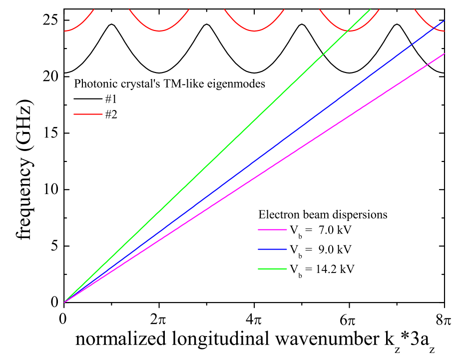

Figure 6: Dispersion of the first two TM-like eigenmodes and electron beam dispersion for several beam voltages.

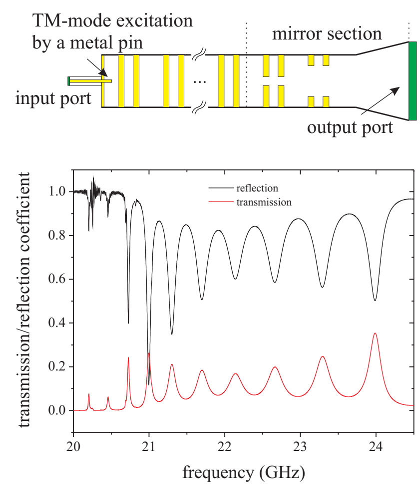

Figure 7: Numerical model of the mirror section and its calculated transmission and reflection coefficient.

optimised depending on the gain of the device.

An abrupt termination of the PHC into an empty waveguide results in an impedance jump and hence in (partial) reflection of the radiation. The PHC termination itself therefore acts as the downstream mirror. To control the amount of reflection we both taper the PHC and taper the height of the waveguide. The model used to predict the mirror performance is shown in fig. 7. 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. A TM-like mode is launched into the structure through a coaxial feed that ends in an antenna that exists this particular mode. At the output port a matched load is created to remove any reflections from this port. The transmission into the TM_{11} mode and reflection of this structure is calculated using the Concerto software [11] and the results are shown in fig. 7 as well. For computational efficiency the homogeneous part of the PHC is only 10 unit cells in the model. However, this only changes the number

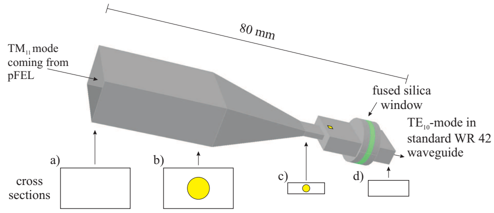

Figure 8: 3D view of the broadband antenna, mode converter and vacuum window

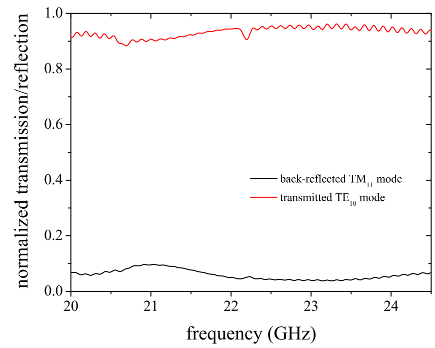

Figure 9: Calculation of transmission and reflection coefficients for the whole device of Fig. 8.

of transmission peaks and not the actual reflectivity [10]. The transmission is nearly constant at approximately 20 % for the TM_{11} mode once the frequency is sufficiently far above cut-off.

BROADBAND MODE CONVERTER AND VACUUM WINDOW

The TM-like radiation mode in the PHC is required by the FEL gain mechanism. However, propagating this mode through a waveguide system is far from ideal and it is better to convert it to the fundamental waveguide mode. This greatly simplifies the design and improves the performance of the vacuum window. Here we present one solution for a broadband mode converter and a vacuum window.

The broadband mode converter and vacuum window is shown in fig. 8. The design of the converter follows the design presented by Eisenhart for a cylindrical input waveguide [12]. We assume that only the TM_{11}-mode of a rectangular waveguide enters the mode converter (fig. 8a). Its E_z-field component excites a current on a coupling antenna, which is oriented along the z-axis (fig. 2). A broadband match is achieved by tapering this section ((b) to (c) in fig. 8). In the following coaxial section only a TEM mode can propagate (fig. 8c). This coaxial line is then terminated with an antenna in a standard WR42 waveguide (fig. 2). The antenna is optimized for exciting the fundamental TE_{10}-mode as other modes are well below cut-off. This waveguide is terminated by a standard vacuum window of the pillbox design. The performance of the mode converter and vacuum window has also been calculated. The calculated TM_{11} to TE_{10} transmission and back reflection is shown in fig. 9. The transmission is better than 90 % over the whole tuning range of the pFEL. Some improvement may be obtained when a newly available vacuum window, consisting of a quartz window brazed directly in a Kovar WR42 flange, is used [13].

CONCLUSION

We have presented a design for a single beam pFEL operating within a frequency range of 20.5 to 24 GHz. The PHC consists of a rectangular array of metal posts with the center line removed to provide space for the electron beam. A double periodic structure is used to almost create a bandgap between the two lowest order TM-like modes of the structure. The device is configured as an oscillator where a tapered transition from PHC to empty waveguide produces the required feedback. A design for a broadband mode-converter and vacuum window is presented to deliver the output radiation in the fundamental TE_{10} mode of a WR42 waveguide. This device will be used to study the fundamental physics of photonic FELs and will provide reference data for future multi-beam devices.

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