# EXPERIMENTAL STUDIES OF VOLUME FELS WITH A PHOTONIC CRYSTAL MADE OF FOILS

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*Abstract*

Operation of a Volume Free Electron Laser with a photonic crystal built up from brass foils strained inside a cylindrical waveguide is discussed. Dependence of the radiation yield on the crystal length is studied in the range up to 8 GHz. Experimental results are compared with those obtained for a photonic crystal formed by threads.

## INTRODUCTION

A Volume Free Electron Laser (VFEL) is a specific kind of radiation generators, which use volume multi-wave distributed feedback [1, 2, 3, 4, 5].

A particular type of VFELs exploits a "grid" photonic crystal formed by periodically strained threads (either dielectric [6] or metallic ones [7, 8, 9, 10]) as a volume resonator.

Wave propagation through photonic crystals is the subject of numerous studies, both theoretical and experimental [11, 12, 13, 14].

The "grid" photonic crystal made of metal threads has been thoroughly examined theoretically [7, 8] and tested experimentally [9, 10]. It is shown to be almost transparent to electromagnetic waves within the frequency range from gigahertz to terahertz and stable to heating by the electron beam.

Different designs of the photonic crystal made of tungsten threads are analyzed and applied for VFEL lasing: "grid" photonic crystals with a constant period [7, 8, 9, 10] in a cylindrical waveguide, grid" photonic crystals with a constant period in a waveguide with a rectangular cross-section and photonic crystals with a spatially variable period [16, 17, 18, 19]. It is shown that the resonators of rectangular cross-section cause additional perturbations of the axially-symmetrical electron beam and may bring about spike oscillation in the radiation process, which is crucial for lasing within the millimeter wavelength range. The cylindrical waveguide with fine surface treatment is a perfect solution to this problem.

In the present paper operation of a Volume Free Electron Laser with a photonic crystal built up from brass foils strained inside a cylindrical waveguide is discussed. Dependence of the radiation yield on the crystal length is studied in the range up to 8 GHz. Experimental results are compared with those obtained for the photonic crystal formed by threads.

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## DESIGN OF THE PHOTONIC CRYSTAL

The foil photonic crystal is designed (Fig.1,Fig.2) to provide lasing in the range 6.5 - 7.5 GHz. Brass foils of 100 $\mu$m thickness and 10 mm width are assembled in a 5-foil layers with 18 mm period inside the drift tunnel. Foil tapes are fixed in slots on the plexiglas rings tightened together by dielectric studs. Bent ends of a foil tape ensure a steady electric contact with the drift tube. A pencil-like electron beam has a diameter of about 40 mm. To reflect the backward wave to the output window, a combined resonance reflector composed of a stub of corrugated waveguide (4 periods) and a metal screen grid is used. Corrugated waveguide diameters are 50 mm and 20 mm, the period is 29 mm and the width of the membrane is 8 mm. It effectively reflects in the ranges 0 - 4.7 GHz and 6.3 - 7.5 GHz. The metal screen grid covers a wider range of frequencies.

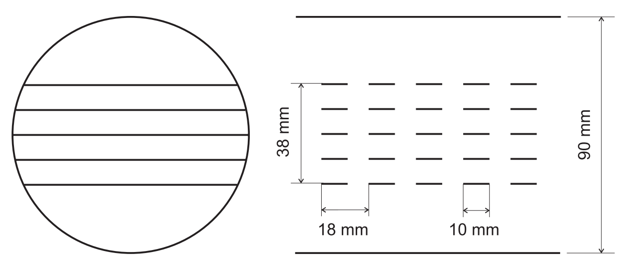


Figure 1: Foil photonic crystal design.

## ANALYSIS OF THE PHOTONIC CRYSTAL DISPERSION PROPERTIES

In obtaining the dispersion properties of a photonic crystal made of brass foils strained inside a cylindrical waveguide it is assumed to have an infinite length (see Fig.3). The considered structure is not axially symmetric. Therefore, one cannot establish a strict correspondence between the types of electromagnetic waves, which are excited inside it, and the eigenmodes of the cylindrical waveguide. Moreover, the analytical solution for such geometry does not exist, and the calculation is made using the finite-difference

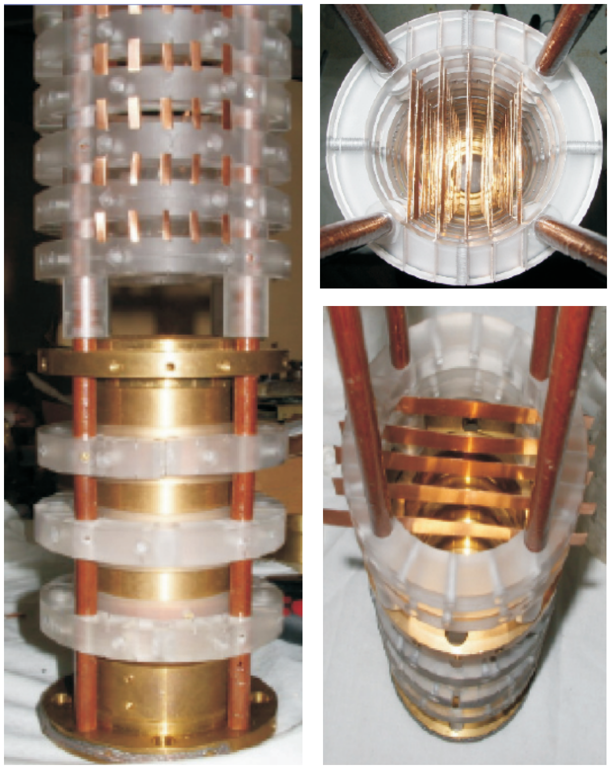

Figure 2: The foil photonic crystal.

method.

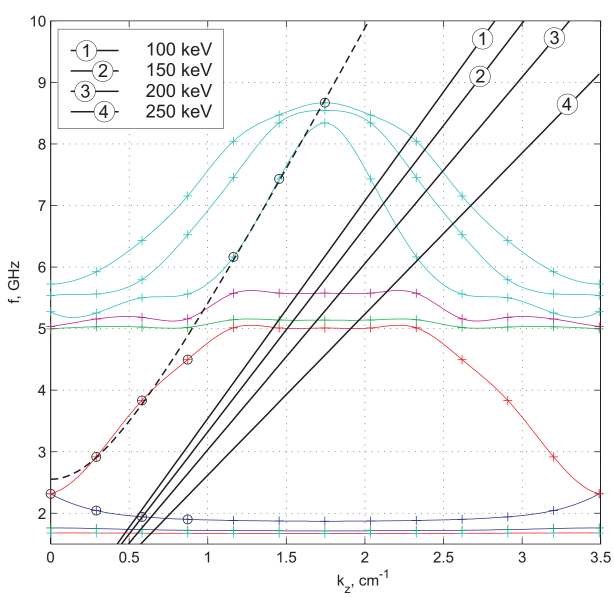


Figure 3: Dispersion properties of the foil photonic crystal.

Dashed hyperbola in Fig.3 shows the dispersion curve for the unloaded cylindrical waveguide of 90 mm diameter. Encircled marks in the dispersion curves indicate the points, in which the field structure approaches the structure of $E_{01}$ mode of the unloaded cylindrical waveguide. Lines for the electron beam with the energy of 100-250 keV are also shown. Points of intersection of the beam lines and the dispersion curves define the lasing frequencies (see Table.1). The accuracy of values in Table.1 is evidently excessive just to emphasize the tendency. The rows in bold mark the high-symmetry waves (similar to $E_{01}$).

Table 1: Calculated lasing frequencies

| electron energy, keV | 100 | 150 | 200 | 250 |
|---|---|---|---|---|
| | 1.68 | 1.68 | 1.68 | 1.68 |
| | 1.73 | 1.73 | 1.73 | 1.73 |
| frequency, | **1.92** | **1.93** | **1.94** | **1.94** |
| | 4.99 | 5.00 | 5.00 | 5.03 |
| GHz | 5.13 | 5.13 | 5.13 | 5.13 |
| | 5.61 | 5.57 | 5.57 | 5.57 |
| | **6.12** | **6.66** | **7.03** | **7.29** |
| | 6.70 | 7.24 | 7.60 | 7.83 |
| | 6.99 | 7.55 | 7.90 | 8.11 |

## EXPERIMENT LAYOUT

A pencil-like electron beam with maximum electron energy of 250 keV is guided through the resonator by the magnetic field $\sim 1.6$ tesla. The total diode current is about 2 kA. Either a plexiglass or quartz output window is used in the experiments. Electron gun voltage and current are detected by a TDS5 digital oscilloscope along with the signal from two microwave detectors of 3.8-10.0 GHz range connected to two antennas placed at a distance of 1 m from the output window in vertical and horizontal polarizations. Horn-lens antennas for the ranges 0.8-18 GHz, 8-12 GHz and 4-8 GHz are placed 1.5 m from the output window and a TDS7 digital oscilloscope records high resolution signals from them. The number of periods in the photonic crystal is varied in different experiments up to 15.

## EXPERIMENT RESULTS

A typical view of current and voltage oscillograms and microwave signals is shown in Figs.4, 5. Comparison of the radiation yield for plexiglass and quartz output windows shows that absorbtion in quartz window is higher. Therefore, further analysis concerns the experiments with a plexiglass output window. Measured dependance of the radiation output on the photonic crystal length agrees with the results obtained for a photonic crystal made of threads [10]: saturation is reached for a crystal with more than 15 periods.

The obtained radiation spectra have peaks near 2, 5, 6.7 and 8 GHz, which correspond to different radiation modes in compliance with preliminary simulation (see Fig.3 and Table.1). Note that the lowest frequency obtained in the experiments is smaller than the cutoff frequency of the cylindrical waveguide of 90 mm diameter (as it is expected according to Fig.3). The most of the intensity is concentrated in the line close to 5 GHz. The electric field strength at a distance of 1.5 m from the output window is 10 kV/m for 10 periods and 15 kV/m for 15 periods of a photonic crystal. These values are 1.5 times higher than those for a crystal made of threads [10].

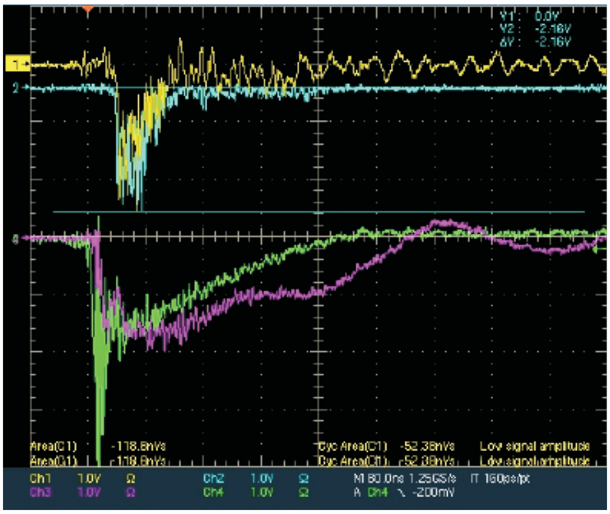

Figure 4: A typical signal from a TDS5 oscilloscope: diode voltage - green curve, diode current - magenta curve, blue and yellow - microwave signals.

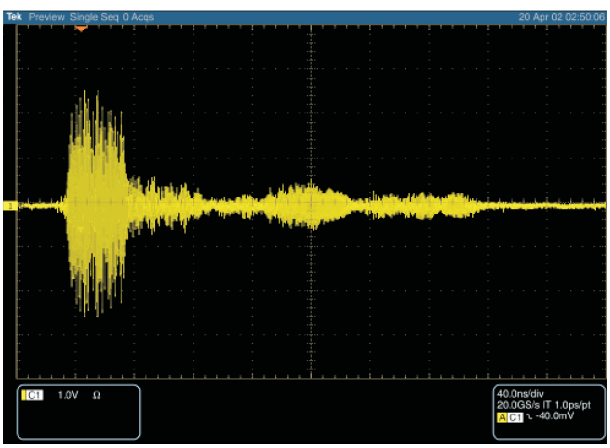

Figure 5: A typical microwave signal from a TDS7 oscilloscope.

## CONCLUSION

Operation of the Volume Free Electron Laser with a photonic crystal built up from brass foils strained inside a cylindrical waveguide is considered. The stability of the foil photonic crystal to the electron beam action is proved. Comparison of the experimental results with those obtained for a photonic crystal formed by threads demonstrates higher efficiency of a foil photonic crystal.

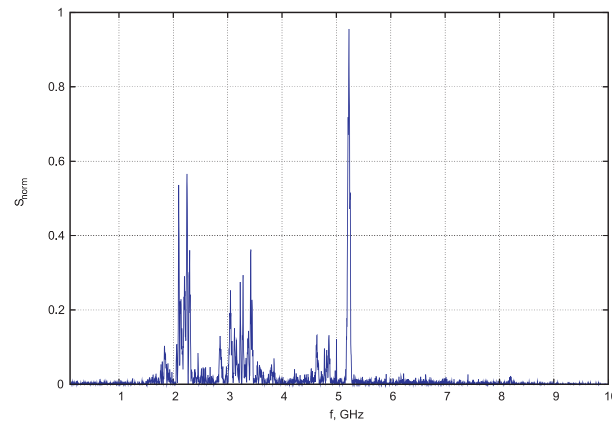


Figure 6: Radiation spectrum obtained by fast Fourier transform of the signal from the antenna for 0.8-18 GHz range.

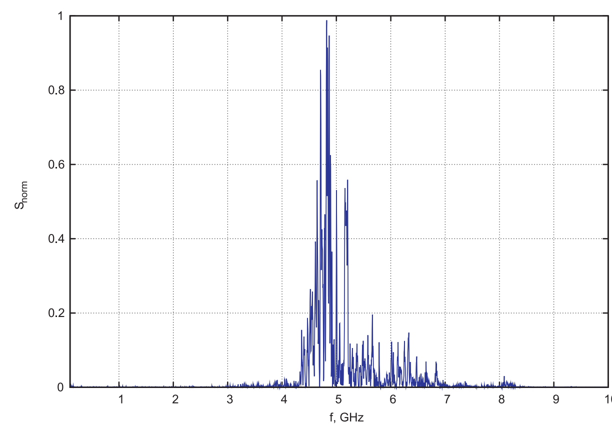


Figure 7: Radiation spectrum obtained by fast Fourier transform of the signal from the antenna for 4-8 GHz range.

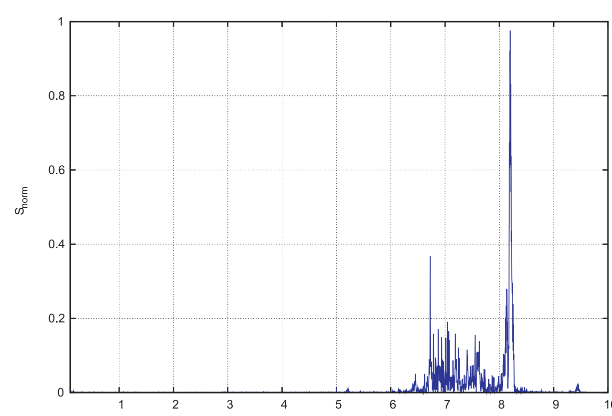


Figure 8: Radiation spectrum obtained by fast Fourier transform of the signal from the antenna for 8-12 GHz range.

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