ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRO004

STUDY OF THE CLIO FEL IN THE FAR-INFRARED IN A PARTIALLY GUIDED MODE

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Abstract

The infrared free-electron laser offers a large tunability since the FEL gain remains high throughout the infrared spectral range, and the reflectivity of metal mirrors remains also close to unity. The main limitation comes from the diffraction of the optical beam due to the finite size of the vacuum chamber of the undulator. A solution is to use this chamber as a waveguide by adapting the radius of curvature of the cavity mirrors to this regime. Then, as has been shown before [1], a minimum appears in the spectrum that can be produced by the FEL. We discuss the physical mechanism of this particular regime and compare it to experiments using vacuum chambers of different transverse sizes. A good agreement is found with results of simulations and with a simple analytical formula.

INTRODUCTION

Infrared free-electron lasers (IRFELs) can operate in a very large spectral range [1]. However, diffraction losses increase with the wavelength. These happen mainly in the optical cavity. There, the size of the vacuum chamber is limited, in particular by the need to produce a sufficient magnetic field with the undulator. Therefore, most IRFELs use a waveguide in order to operate in far infrared and THz spectral regions. The configuration can be a waveguide extending all along the optical cavity and using cylindrical mirrors [2,3]. However, for practical reasons the waveguide may extend only along the undulator and use a combination of spherical and toroidal mirrors [1], for mid and far infrared respectively, or a combination of the 2 solutions [4]. At the CLIO FEL [5] we use such a partially guided mode, as illustrated in Fig. 1. The optical beam passes through a waveguide inside the undulator and in free space elsewhere (where it can be diffracted by the finite size of the dipole gaps).

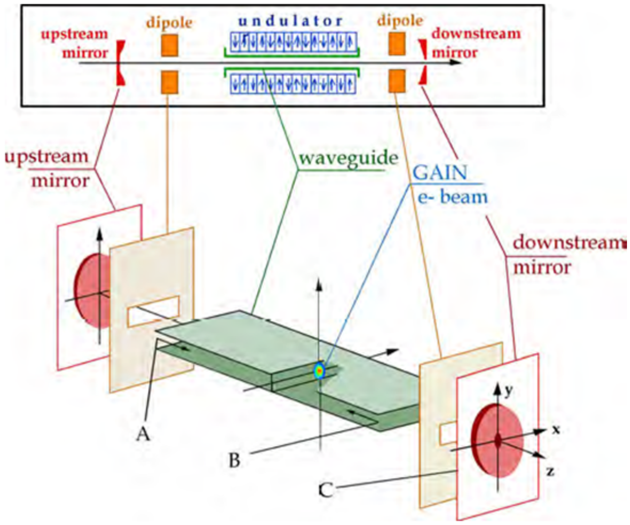


Figure 1: Scheme of the CLIO optical cavity.

We tested both spherical and toroidal mirrors. With both combinations, we found a gap in FEL power located at the same position, when sweeping its wavelength across the FIR region. This was correctly simulated with a numerical method taking into account all the propagation effects [6]. We suspected that this gap was due to an interference between the 1st and 3rd transverse guided mode at the exit of the undulator vacuum chamber (even modes cannot exist by symmetry in our case). However, we could not prove it, since at that time we used only one undulator vacuum chamber.

Recently, we have built an undulator with a stronger magnetic field in order to replace this vacuum chamber by a larger one while keeping the same wavelength tunability at a given accelerator energy[7]. We have then tested 2 new vacuum chambers with different (vertical) sizes, leading to different spectral gaps. We show in this paper that these new experimental results confirm our physical explanation of this phenomenon. Also we display some new simulation of the beam profile at various locations inside the optical cavity showing clearly its transverse behavior at different wavelegnths.

When the optical beam enters the vacuum chamber (points A and B on Fig. 1), its propagation remains nearly free in the horizontal plan, due to the large dimension of the chamber. Along the narrow vertical plane (direction of the undulator magnetic field), where the chamber is much narrower, the optical field becomes distributed between various transverse modes, mainly #1 and #3[1]. For a chamber of length L and height b, the phase difference between theses modes after passing along the waveguide can be calculated easily to be:

$$\Phi_{31} = 2\pi\lambda L/b^2 = \pi \quad \text{for } \lambda_1 = b^2/2L \qquad (1)$$

and :

$$\Phi_{31} = (2n + 1)\,\pi \quad \text{for } \lambda_n = (2n + 1)b^2/2L \qquad (2)$$

When this phase difference is equal to π, or an odd multiple, the central peak of the mode #3 will tend to subtract from each other, so that the side wings of the mode will dominate the profile. This is expected to produce more diffraction at the exit of the waveguide.

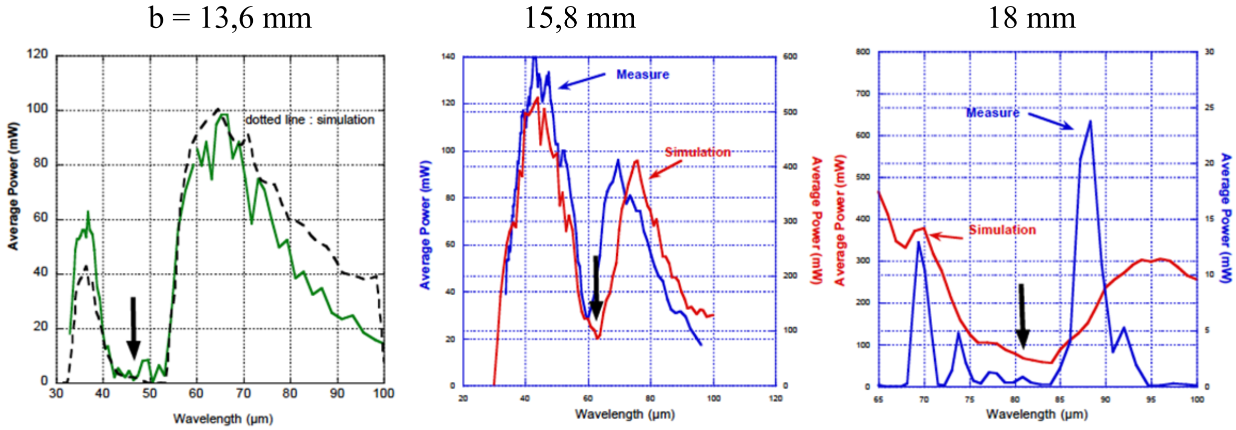
RESULTS

The Fig.2 displays the FEL power (measurements and simulations) for 3 different chambers. The values of the first minimum, from eq.(1), are indicated by an arrow. The agreement between the simple considerations leading to the theoretical value of the minimum and its value in the experiments and simulations appears to be very good. Further gaps (n>1) are located too far in infrared to be observed.

Furthermore, the small difference between the value for b =15,8 mm seems to be due to the compression, of 0,2 mm, by the air pressure of the chamber, this one being made in Cu (the other in Al). For the 18 mm chamber the simulation and experiments have quite different profile. Indeed, this last chamber was slightly elliptical, having been made by Al extrusion. This shape couples the horizontal and vertical polarizations of the light, which reduces the gain and the FEL power. This is not taken into account by our simulations (designed for rectangular shapes).

The following figures, extracted from the simulations, compare the optical intensity distribution at 2 different wavelengths for the 15,8 mm chamber. The 1^{st} wavelength (64 µm) is the one at which the power gap occurs. The2^{nd} wavelength is a wavelength about 30% larger, well apart from the gap.

The results are shown in the steady state regime, i.e. after sufficient number of passes inside optical cavity, so that the modes are stabilized. The transverse shapes are shown at the waveguide output and entry after having propagated in free space and be reflected by the cavity focusing mirror. This is displayed (Fig. 3 & 4) for both ends of the vacuum chamber.



b = 13,6 mm

15,8 mm

18 mm

Figure 2 : FEL power for 3 heights of the vacuum chamber, the horizontal dimension (35 mm) being held constant.

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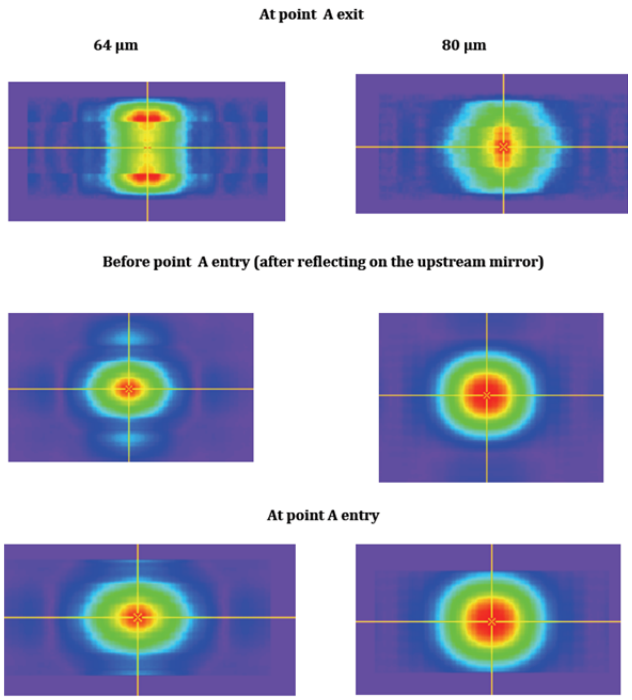

Figure 3 : beam profile at the upstream side of the optical cavity.

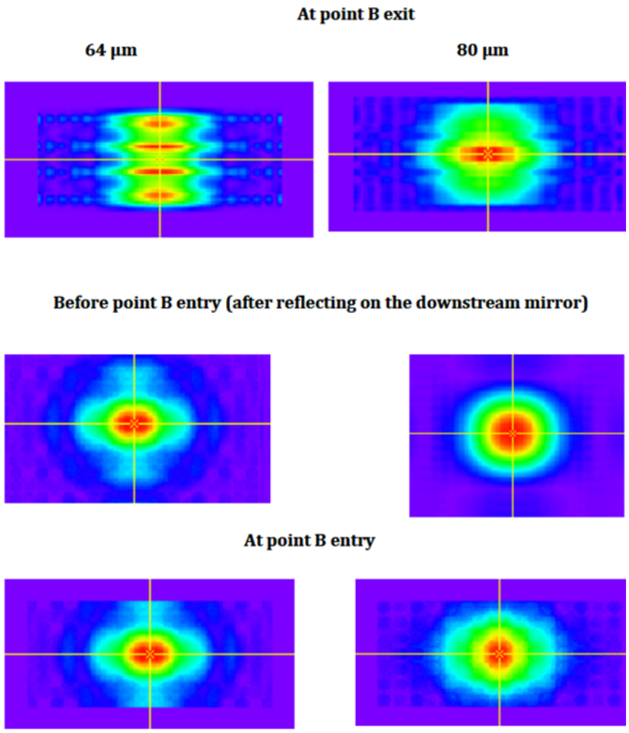

Figure 4 : beam profile at the downstream side of the optical cavity.

One can see that, at 64 µm, the transverse profile exhibit strong wings at the output of the waveguide, as expected.

These wings results in “satellites” after propagation and reflection. These satellites are lost at the entrance of the waveguide, leading to high intensity losses. These losses are not predominant compared to the total intensity but are high when compared to the outcoupling (provided by a hole in the mirror). Then, the extracted power is low and can even be zero if the total losses overcome the optical gain (depending on the chosen output coupling value). At 80 µm, it appears that the profile remains peaking at the center, leading to practically no losses after propagation.

At point B exit, one sees that the mode profile is more complicated, showing the influence of higher order modes. Indeed there exist some, at a low level as displayed in ref. [1], but they do not modify the overall conclusion

CONCLUSION

The unexpected spectral gaps in the infrared FEL power have been shown to come from the mode competition and phasing in a part of the optical cavity vacuum chamber acting as a waveguide. They obey to a very simple analytical formula. This effect depends only on the waveguide geometry. There is no mean to get rid of these gaps. A way to recover power at a gap location would be to replace the vacuum chamber by another one with different characteristics, which only changes the location of the spectral gap and constitutes a very time consuming operation. Installing a chamber with a poor reflectivity, i.e. not guiding, would only increase drastically the losses and prevent lasing at long wavelengths. A solution could be to use a undulator under vacuum, taking care of the flatness of the overall surface of the magnets so as to guide (reflect) the light. Then, various combinations of electron energy and magnet gap would circumvent the problem.

Finally, the “all waveguide” set-up could be a solution. But this does not seem compatible with mid-infrared lasing, which requires free propagation and spherical mirrors. Even in far-infrared, preliminary results indicate that similar power gaps do also appear.

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