Evidence for competition modes in a partially guided far-infrared free-electron laser

J.-M. Ortega,[*] J.-P. Berthet, F. Glotin, and R. Prazeres
CLIO/LCP, Batiment 201 Porte 2, Université Paris-Sud, 91405 Orsay Cedex, France

(Received 4 July 2014; published 13 October 2014)

The infrared free-electron laser (FEL) 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, 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.

DOI: 10.1103/PhysRevSTAB.17.100701 PACS numbers: 41.60.Cr, 42.55.-f, 42.60.-v, 42.79.Gn

I. INTRODUCTION

Infrared free-electron lasers (IRFELs) can operate in a very large spectral range. This is due to the combination of wideband optical gain and metallic mirrors. Infrared FELs like the CLIO user facility [1] can lase (Fig. 1) over more than one decade of wavelength (4 to 150 μm).

The limitation in the far infrared occurs because the diffraction losses increase with the wavelength. Indeed, the amplifying medium of the FEL is a high energy electron beam, which has to circulate in a magnetic periodic structure ("undulator") and in a vacuum chamber. For practical purposes, in most cases the undulator is located outside the vacuum chamber. Therefore, the size of the vacuum chamber (or the space between the undulator poles if the chamber is outside) is limited by the need to produce a sufficient magnetic field within the undulator.

This produces diffraction losses at the entry of the undulator. Therefore, most IRFELs use a waveguide in order to operate in the far infrared and the THz spectral regions. The configuration can be a waveguide extending all along the optical cavity and using cylindrical mirrors [2,3]. However, if one wants to produce an FEL with a large tunability, extending from near to far infrared, one is led to use an intermediate case where the beam propagation is "free space" propagating in the near infrared and becoming progressively guided in the waveguide/vacuum chamber as the wavelength increases. Then, the waveguide may extend only along the undulator and one often uses a combination of spherical and toroidal mirrors [4], for mid-infrared and far-infrared respectively, or a combination of the two solutions [5]. At the CLIO FEL [6] we use such a partially guided mode, as illustrated in Fig. 2. 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).

We tested both spherical and toroidal mirrors. With both combinations, we always observe a gap in FEL power located at the same position, when sweeping its wavelength across the far-infrared region. This was correctly simulated with a numerical method taking into account the propagation effects [7]. We suspected that this gap was due to an interference between the first and third transverse guided mode at the exit of the undulator vacuum chamber (even modes cannot exist by symmetry in our case). However, we

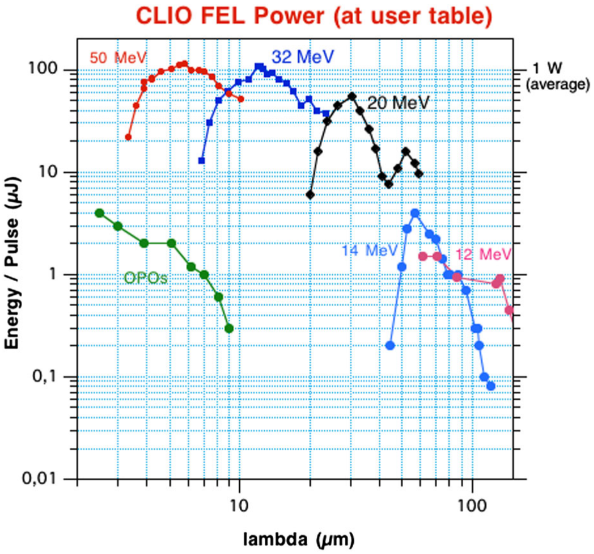

FIG. 1. Spectral range of CLIO and associated optical parametric oscillators (OPOs).

---

[*] jean-michel.ortega@u-psud.fr

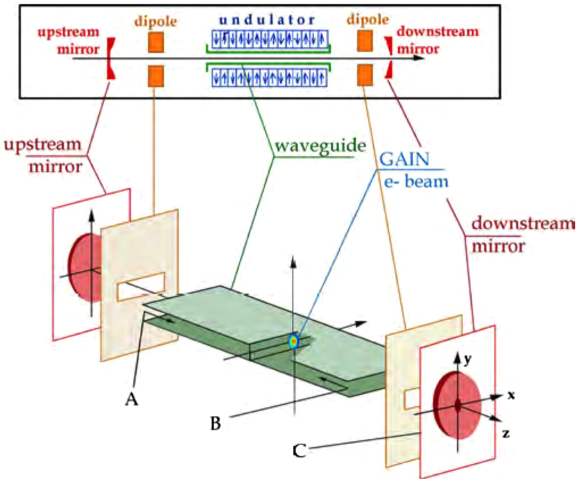

FIG. 2. Scheme of the CLIO optical cavity.

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 [8]. We have then tested two 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 wavelengths.

When the optical beam enters the vacuum chamber (points A and B in Fig. 2), 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 [4]. 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

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

and

$$\Phi_{31} = (2n-1)\pi \quad \text{for } \lambda_n = (2n-1)b^2/2L. \tag{2}$$

When this phase difference is equal to π, or an odd multiple, the central peaks of 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.

II. RESULTS

Figure 3 displays the FEL power (measurements and simulations) for three 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 simulations and experiments have quite different profiles. 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).

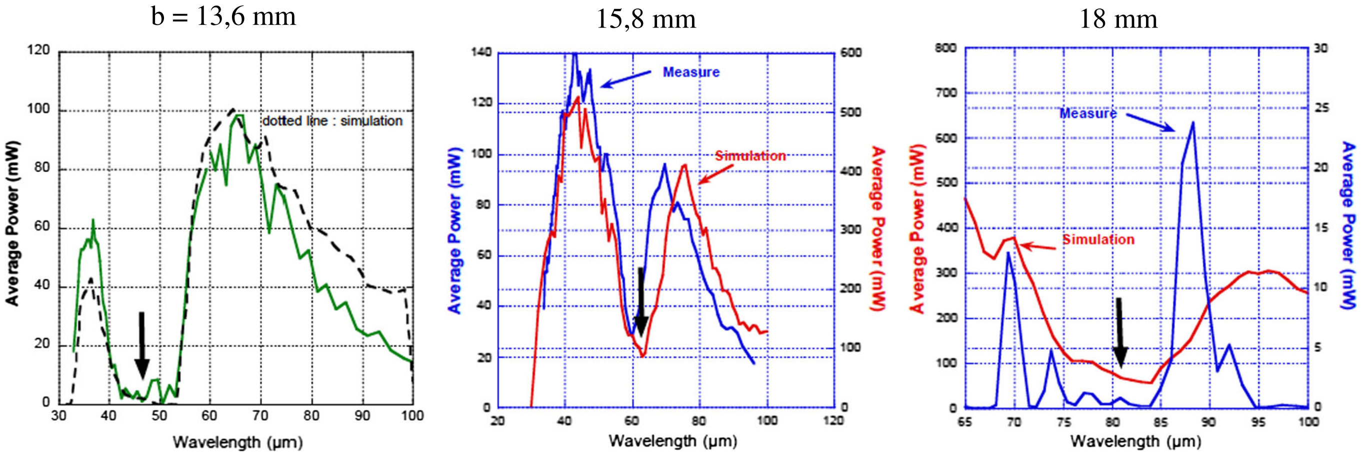

FIG. 3. FEL power for three heights of the vacuum chamber, the horizontal dimension (35 mm) being held constant.

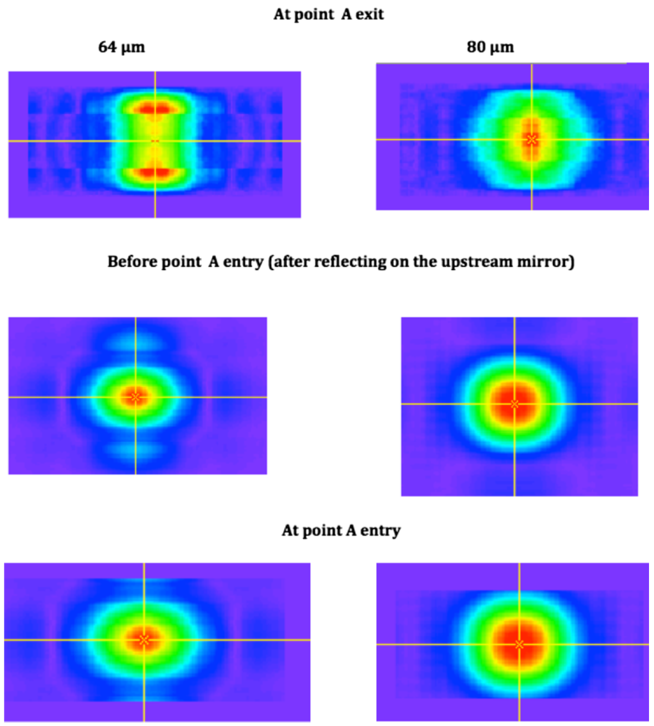

FIG. 4. Beam profile at the upstream side of the optical cavity.

The following figures, extracted from the simulations, compare the optical intensity distribution at two different wavelengths for the 15,8 mm chamber. The first wavelength (64 μm) is the one at which the power gap occurs. The second wavelength is a wavelength about 30% larger, well apart from the gap.

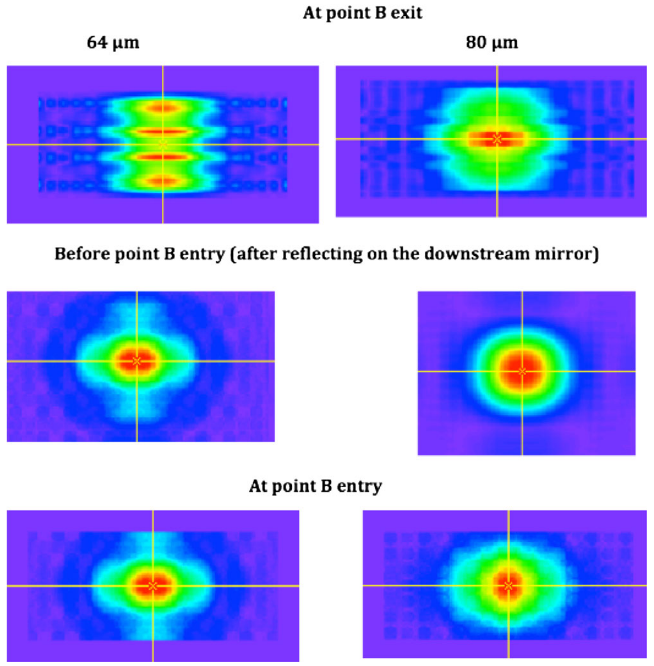

FIG. 5. Beam profile at the downstream side of the optical cavity.

The results are shown in the steady state regime, i.e. after a sufficient number of passes inside the 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 been reflected by the cavity focusing mirror. This is displayed (Figs. 4 and 5) for both ends of the vacuum chamber.

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

These wings result 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 the point B exit, one sees that the mode profile is more complicated, showing the influence of higher order modes. Indeed there exists some, at a low level as displayed in Ref. [4], but they do not modify the overall conclusion.

III. DISCUSSION

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. At CLIO they obey a very simple analytical formula. However, the process is not as simple as this formula could lead to think. Schematically, due to the resonant wavelength shifts with the mode orders, only the fundamental mode is resonant, i.e. amplified. The higher modes are created when the optical beam enters the waveguide: if they interfere negatively with the first one, this favors the wings of the distribution. These wings are then lost when entering the waveguide again. Also, the gain imprinted to the beam in the undulator is not matched to the first one. However, its transverse profile is much smaller than the waveguide and, being emitted at the end of the guide, it will propagates almost freely and its divergence will rather match the first mode. In free space propagation the modes are mixed together in a manner that can be evaluated only numerically. The simulations show that is has little influence on the result.

At others IRFELs such as FELIX [9] and FELBE [10] spectral gaps have been observed as well. However, their characteristics are such that the first minimum should occur at short wavelengths (<10 μm) at which waveguiding does not occur. The gaps, observed at much longer wavelengths, correspond to multiple odd π shifts and may involve many modes. They are well reproduced by our simulations [9], but are not related to a simple formula.

The spectral gaps depend 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" setup could be thought of as a solution. But this is not compatible with midinfrared lasing, which requires free propagation and spherical mirrors. Moreover in this configuration, recent results show that many power gaps do also appear in the far infrared [11]. As shown recently [12], this effect is different and comes from the competition between the high and low frequency branches of the resonant FEL condition that exist in a planar waveguide [13]. As in our case, it seems that the presence of these gaps cannot be overcome.

[1] J. M. Ortega, Nucl. Instr. Meth. **507**, 8 (2003).

[2] L. R. Elias and J. C. Gallardo, Appl. Phys. B **31**, 229 (1983).

[3] Th. Rasing, J. C. Maan, A. P. M. Kentgens, and F. J. M. Harren, http://accelconf.web.cern.ch/AccelConf/f06/PAPERS/TUCAU01.PDF.

[4] R. Prazeres, F. Glotin, and J.-M. Ortega, Phys. Rev. ST Accel. Beams **12**, 010701 (2009).

[5] L. Y. Lin and A. F. G. van der Meer, Rev. Sci. Instrum. **68**, 4342 (1997).

[6] J.-M. Ortega, F. Glotin, and R. Prazeres, Infrared Phys. Technol. **49**, 133 (2006).

[7] R. Prazeres, Eur. Phys. J. Appl. Phys. **29**, 223 (2005).

[8] J.-M. Ortega, J.-P. Berthet, F. Glotin, G. Perilhous, R. Prazeres, F. Marteau, H. Abualrob, T. El Ajjouri, Ph. Berteaud, L. Chapuis, J. Veteran, and M.-E. Couprie, http://accelconf.web.cern.ch/AccelConf/IPAC2012/papers/tuppp048.pdf.

[9] D. Oepts and A. F. G. van der Meer, https://accelconf.web.cern.ch/accelconf/FEL2010/papers/tuoc4.pdf.

[10] U. Lehnert, V. Asgekar, P. Michel, G. Staats, J. Teichert, and R. Wünsch, https://accelconf.web.cern.ch/accelconf/FEL2008/papers/mopph016.pdf.

[11] R. Chulkov, V. Goryashko, D. D. Arslanov, R. T. Jongma, W. J. van der Zande, and V. Zhaunerchyk, Phys. Rev. ST Accel. Beams **17**, 050703 (2014).

[12] R. Chulkov *et al.*, *Phys. Rev. ST Accel. Beams (to be published).*

[13] S. K. Ride, R. H. Pantell, and J. Feinstein, Appl. Phys. Lett. **57**, 1283 (1990).