INCREASING THE SPECTRAL RANGE OF THE CLIO INFRARED FEL USER FACILITY BY REDUCING DIFFRACTION LOSSES

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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 1. The main limitation comes from the diffraction of the optical beam due to the finite size of the vacuum chamber of the undulator. At CLIO, we had obtained previously[1] an FEL tunable from 3 to 150 µm by operating the accelerator between 50 and 14 MeV. However, we found that a phenomenon of "power gaps" is observed in far-infrared: the laser power falls down to zero at some particular wavelengths, whatever the beam adjustments are. We showed that this effect is related to to the waveguiding effect of the vacuum chamber leading to different losses and power outcoupling at different wavelengths[2]. To alleviate this effect we have designed a new undulator allowing to use a larger vacuum chamber without reducing the spectral tunability and agility of the FEL. From simulations, a large increase of available power is expected in far-infrared. The new undulator has been installed and its performances and first FEL measurement in far-infrared are presented.

INTRODUCTION

Infrared free electron lasers can potentially cover the whole electomagnetic spectrum, thanks to the metal mirrors that have reflectivities > 98 % from the near infrared to the millimeter waves. The FEL wavelength is approximately equal to the undulator first harmonic given by:

$$\lambda = \frac{\lambda_0}{2\gamma^2}(1+\frac{K^2}{2})$$

where λ_o is the undulator period and K the undulator parameter. Its maximum value is, for practical reasons, of the order of 2, allowing a wavelength variation by about the same factor. Therefore, variation of the wavelength throughout the infrared spectrum, i.e. by more than 2 orders of magnitude, requires an energy variation by, typically, 1 order of magnitude. The energy variation can be made only in step, so that fast and continuous variations of wavelength by varying the K (magnetic gap) are extremely important for the FEL users.

When the electron beam travels through the undulator it amplifies the intracavity stored synchrotron radiation by a factor (1 + G), where G is called the optical gain. In order to obtain laser oscillation G has to be larger than the losses of the optical cavity. As the energy decreases the gain is influenced firstly by an $1/\gamma^3$ term, and therefore tends to grow. Meanwhile, because of diffraction and slippage, the volume of the optical mode, growing like $\lambda^2 \sim 1/\gamma^4$, becomes progressively greater than the volume of the electron bunch and decrease the gain, but only at very long wavelength. The gain value depends in practice on the many parameters of the accelerator.

At CLIO[1] facility (38 periods of 5 cm) we found a gain growing from about 1 at λ = 5 µm to 10 at 100 µm (in this last case the gain is further enhanced by its exponential dependence along the undulator). At the same time the cavity losses grows even more drastically, due to the diffraction of the beam on the vacuum chamber apertures and finite transverse size of the cavity mirrors. Therefore, it becomes increasingly difficult to obtain laser oscillation and the extracted power is weaker, since most of the FEL power is dissipated at apertures.

In order to reduce losses our undulator vacuum chamber is wider perpendicularly to the (horizontal) magnetic field and smaller in the parallel direction since we chose a parameter K ≥ 2 in order to get sufficient wavelength tunability at each electron energy. Then the optical mode is freely propagating in the horizontal direction and partially guided vertically, i.e. inside the undulator vacuum chamber. The cavity mirrors are also elliptical, the horizontal and vertical radius of curvature being matched to the vacuum chamber. Numerical calculations determine these radiuses of curvature. These include propagation in free space and in the guide [2].

In any case, a larger chamber reduces the losses, provided that the magnetic field can be kept to a sufficient value, which is the purpose of this study.

UNDULATOR DESIGN

Numerical simulation [2] shows that the FEL spectral range can be substantially increased by choosing a vacuum chamber height of 18 mm instead of 14 mm (Fig. 1). A peculiarity of this partial guiding configuration is that "power gaps" appear at particular wavelengths that are unavoidable. In our case the first gap is at 50 µm with the old chamber and about 80 µm with the new one.

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The magnetic field of the undulator can be increased, in order to keep the same K value at minimum gap by increasing the volume of magnets in our Halbach[3] configuration using "pure permanent magnets". The on-axis peak field is given by:

$$B_{\max} \propto B_r(1-e^{2\pi h/\lambda_0})e^{-\pi g/\lambda_0}$$

where B_r is the remnant field, h the magnet height and g the magnetic gap. By using $h = \lambda_o/2$ instead of $\lambda_o/4$ and choosing a remnant field close to 1.1 T (about 5% higher than previously) we are able to produce a K parameter slightly higher than before (close to 2.1 instead of 2), thus preserving the wavelength tunability.

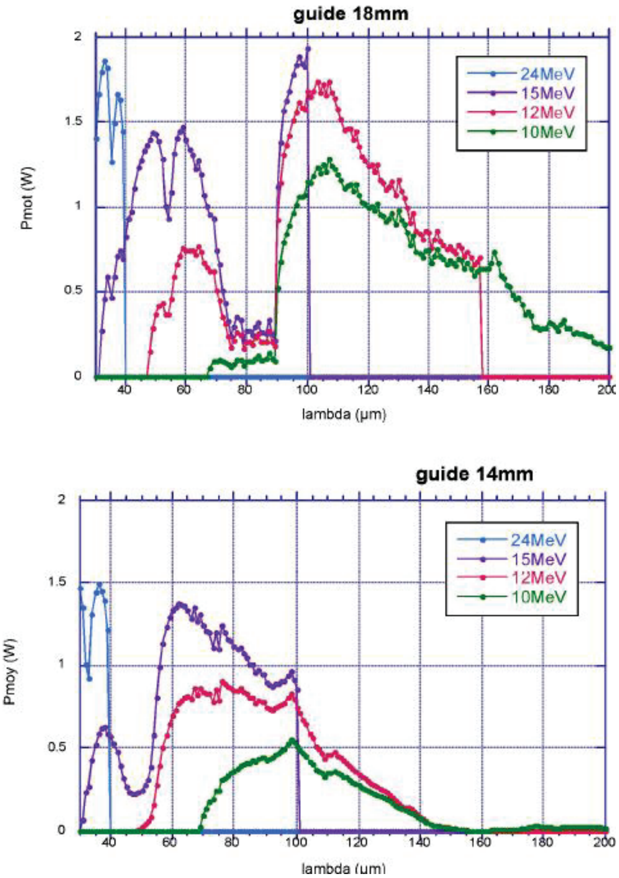

Figure 1: Simulation of laser power with 2 different heights of the undulator vacuum chamber.

UNDULATOR MEASUREMENTS

Magnetic measurements have been performed at the magnetic lab of the SOLEIL synchrotron in several steps [4]:

- Pairing of the individual magnets from the measurements made by the manufacturer (VAC).
- Measurements of the of the 3 and 5 magnet units with a rotating coil.
- Assembly of these units, measuring the field at each step by rotating coil and Hall probe.
- Final optimization by "shimming", in this case by slightly varying the vertical position of selected magnets.

A final measurement with a Hall probe has been made in-situ on the CLIO machine (Fig. 2 & 3)).

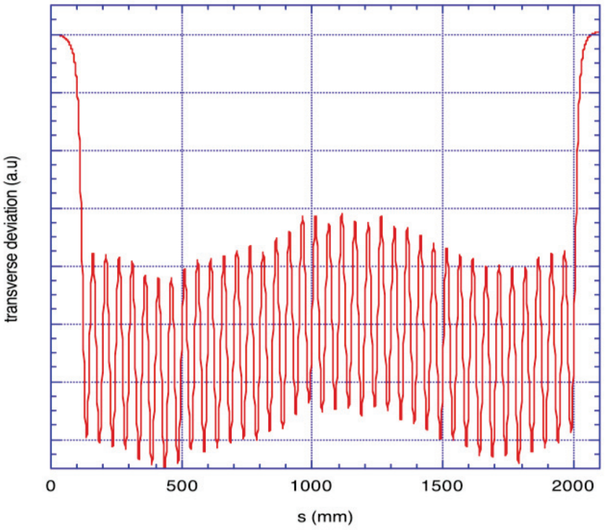

Figure 2: Trajectory calculated from measurements on-site.

Figure 3: Undulator on-site before mounting the vacuum chamber in order to perform the magnetic measurement. The Hall probe displacement is made by the motor temporarily mounted on the right of the last quadrupole.

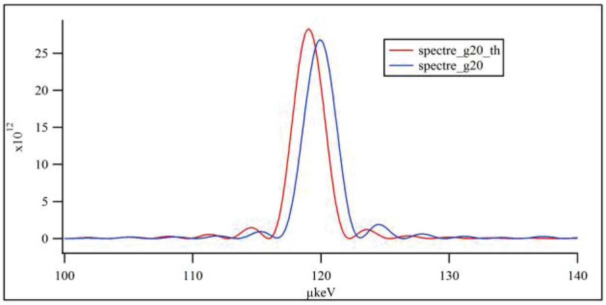

Figure 4: Comparison of spontaneous emission calculated from magnetic measurements and theory.

The final trajectory simulated from Hall probe measurements made on-site on the CLIO machine is shown on Fig. 2. The corresponding calculated spontaneous emission (Fig. 4) show that it is very close to theory for gaps ranging from 20 to 40 mm.

FIRST EXPERIMENTS

The characteristics of the old configuration are shown on Fig. 5 & 6 and the first experiments with the new configuration on Fig. 7. The spectral gap is displaced as expected. However, in both configurations, the optical power is anomalously low compared to the simulations at long wavelengths. We attributed these effects to the fact that we did not use a rectangular vacuum chamber, as in the simulation, for mechanical reasons. The present chamber has an elliptical transverse shape which couples the linear horizontal field of the undulator emission to waveguide modes having vertical components, since the field has to be perpendicular to the chamber walls. These components are not amplified inside the undulator and, therefore, introduce additional losses. Therefore, a new vacuum chamber of rectangular shape has been undertaken.

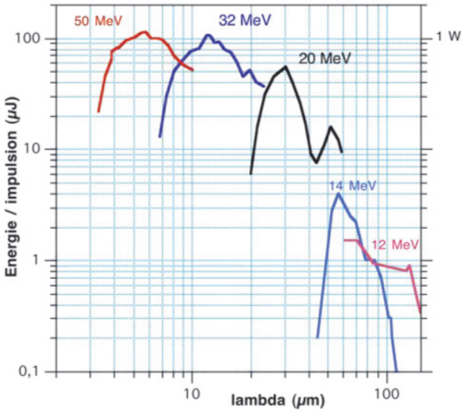

Figure 5: Optical power in the old configuration (log – log scale in order to display the spectral range).

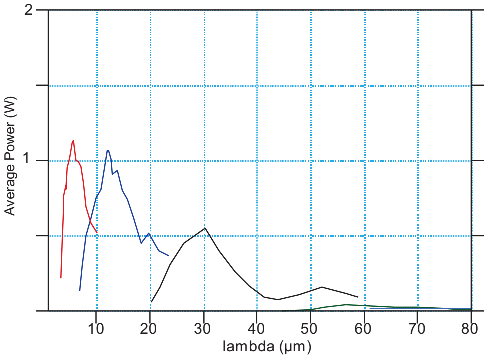

Figure 6: Optical power in the old configuration (Linear scale for comparison with simulations).

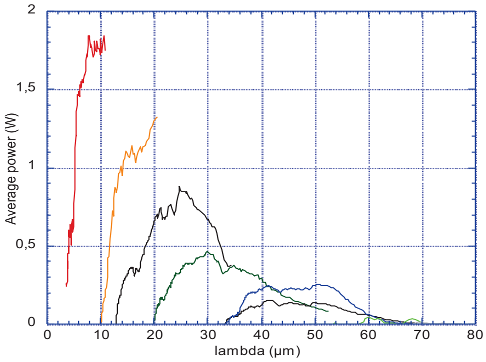

Figure 7: Optical power in the new configuration (New undulator – linear scale).

ACKNOWLEDGMENT

This work was supported by the CNRS (Centre National de la Recherche Scientifique), Université Paris-Sud and contract RTRA 2009 N°044T.

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