WIDEBAND INFRARED FEL

J.-M. Ortega, F. Glotin, R. Prazeres, LURE, 209d, Université de Paris Sud BP 34, 91898 ORSAY cedex, FRANCE

Abstract

We review the issues and problems related to the obtention of the largest possible spectral domain by infrared free electron lasers. At Orsay, the CLIO FEL[1] spans from 3 to 120 μm. This is the largest spectral range ever obtained with a single optical cavity. We plan to extend this spectral range inside the THz region.

INTRODUCTION

Infrared free electron lasers can potentially cover the whole electromagnetic spectrum, thanks to the metal mirrors that have reflectivity > 95 % from the near infrared to the millimeter waves. The FEL wavelength is approximately equal to the undulator first harmonic given by :

$$\lambda = \frac{\lambda_o}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \qquad (1)$$

Where λ_o is the undulator period and K the undulator parameter. Its maximum value is, for practical reasons, of the order of 2 to 3, 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. 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, 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 into the chamber walls (fig. 1). Let us now analyze the different components that can modified for improved lasing.

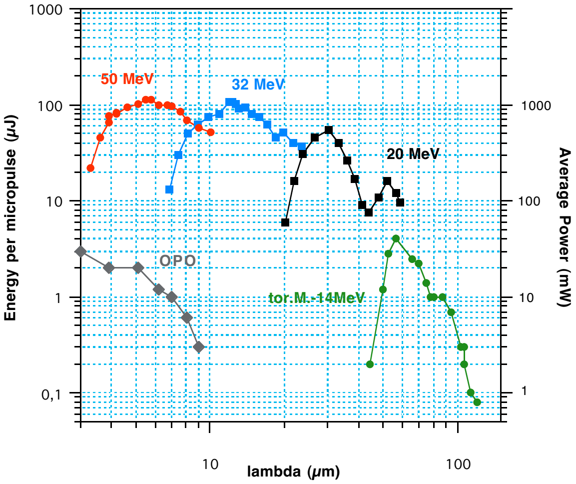


Figure 1: FEL power "at user table" obtained at various electron energy. Data of a classical near infrared laser ("OPO") are also displayed for comparison.

THE ACCELERATOR

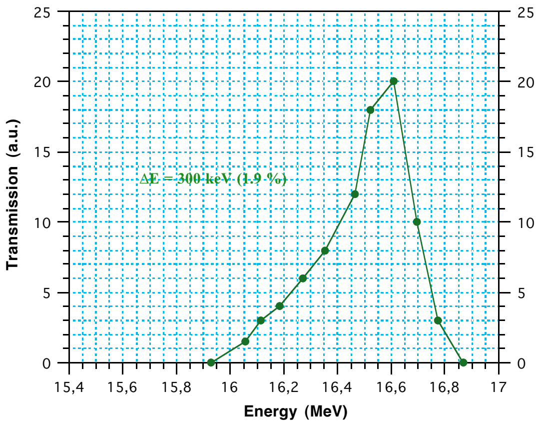
Like most machine used for FELs, CLIO is based on an 3 GHz RF accelerator[2]. It includes the following elements:

- A 90 kV gridded planar cathode gun delivering 10 μs long trains of pulses at 25 Hz. Each pulse is 1 ns long and pulse separation is 16 or 32 ns.
- A 500 MHz sub-harmonic buncher reducing pulse length to 200 ps.
- A 5 MeV fundamental buncher further reducing pulse length to about 10 ps.
- A 4.5 m accelerating section bringing the energy up to 50 MeV.

Although the buncher and accelerating section are powered by the same klystron the RF fields can be adjusted independently by RF attenuators and phase shifters. When reducing the energy, the RF field is maintained constant in the buncher in order to keep the pulses at the same length.

After acceleration the relative energy spread is larger at low energy since a fixed spread of about 200 keV is experienced by the beam in the buncher (see Fig. 2). The magnetic bend acceptance being 3 %, we measured a transmitted current almost unchanged when lowering the energy to 14 MeV

This is expected to remain true down to 8-10 MeV. The current was found to be unstable at the beginning of experiments when lowering the energy and stabilizing after a few hours; this is probably due to temporary multipactoring appearing when the field is lowered in the accelerating cavities. The field in the last cells becomes close to zero for a final energy of about 18 MeV. At lower energies, the accelerator cells experience successively a near zero electric field.



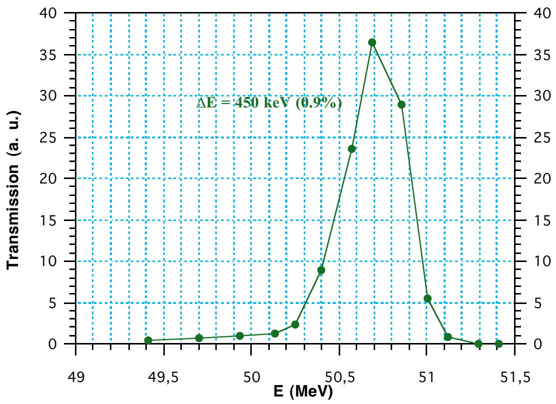


Figure 2: Energy distribution at 2 different energies showing an increase in relative energy spread..

THE OPTICAL CAVITY

The optical cavity contains the following elements, which have been recently adapted for long wavelength operation:

- Accelerator elements : beam position monitors, 2 focusing quadrupoles, 2 dipoles. The dipole gaps have been recently enlarged to avoid diffraction losses
- 2 mirror separated by a length of 4.8 m, matched with the repetition rates of the macropulses (multiples 32 MHz).
- A 2 m long undulator. The undulator vacuum chamber is the main limiting factor to obtain long wavelength. Its geometrical aperture is limited by the fact that one needs a sufficient number of periods to optimize the optical gain and a parameter K ≥ 2 in order to get wavelength tunability at each electron energy (in our case $K_{max} = 2.2$ for a gap = 17 mm)

At the output of the undulator, the diameter of a freely propagating optical mode matched with the electron beam (i.e. of minimum average surface) is :

$$2w = \sqrt{\frac{2\lambda L}{\pi\sqrt{3}}} \qquad (2)$$

When this diameter is of the same order of magnitude than the vacuum chamber aperture, the optical losses tend to become very large. In order to reduce losses our chamber is wider perpendicularly to the magnetic field, with a small aperture of 14 mm which gives, from eq. 2, a maximum wavelength of 70 µm. This is approximately the longest wavelength obtained with spherical mirrors (fig. 1).

Longer wavelengths can be produced by using a waveguide inside the undulator. Generally a rectangular waveguide, considered as a semi-infinite guide, is used [3]. In our case, there is no room to introduce a waveguide and we have used a mode guided only in the undulator vacuum chamber. We have replaced the old chamber by a new one of elliptical form and manufactured in aluminium in order to minimize losses on the wall. The cavity mirrors are also elliptical, the horizontal and vertical radius of curvature being matched to the vacuum chambers. Only numerical calculations can determine these radius of curvature. These include propagation in free space and in the guide [4].

The implementation of elliptical mirrors matched to the waveguide has allowed us to reach a maximum wavelength of 120 µm (figure 3). The numerical simulation reproduce quite well the experimental data. In particular, the measured power is proportional to the ratio of the transmission through the extracting hole in one mirror to the total losses. The diffraction losses increasing rapidly with the wavelength, this power is much weaker than in mid-infrared. Moreover, the calculation show that the intracavity optical mode intensity distribution tends to present a minimum at its center for $\lambda \cong 50$ µm. This minimum is therefore located at the position of the extracting hole. It follows that the extracted power is very weak around this wavelength, as displayed in fig.3,. Although the intracavity mode profile could not be measured directly, this result is an excellent test of the reliability of the numerical calculations.

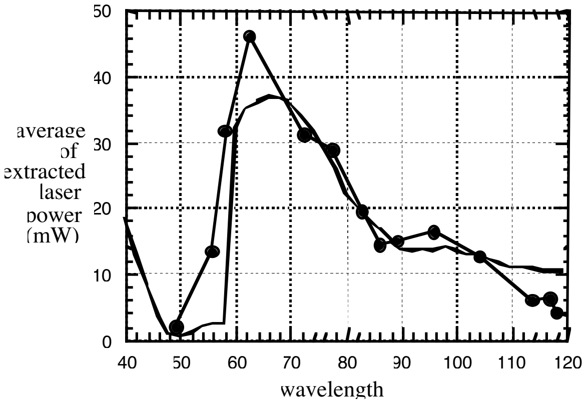


Figure 3: Extracted laser power at long wavelength. The simulations (full line) reproduces rather well the experimental points.

Of **great** interest is the spectral distribution of the laser power. Indeed, the FEL users are interested by a narrow line width as well as having short pulses in order to get high power and to measure ultra fast phenomena. In far infrared, the wavelength becomes so long that picosecond long optical pulses do not produce very small bandwidth. Then as the wavelength increases the line width becomes larger.

If one assumes that the spectral width is transform limited, the optical pulse length can be estimated, from fig. 4, to lie between 10 and 20 ps. This is substantially longer than the electron pulse and this is due to the fact that the optical cavity is a Fabry-Perot and can act as a monochromatizing element. This is achieved by lengthening the optical pulse when detuning the cavity length from perfect synchronism. As the overlap between the optical and electron pulse length diminishes, the optical gain decreases and tends to prevent lasing which limits achievable bandwidth. Also, at long wavelength, the increasing intracavity diffraction losses reduces the cavity quality factor down to a few units. Therefore, the bandwidth becomes dominated by the slippage effect and should tend towards the value of undulator spontaneous emission ≅ 0.9/N (2.4 % in our case).

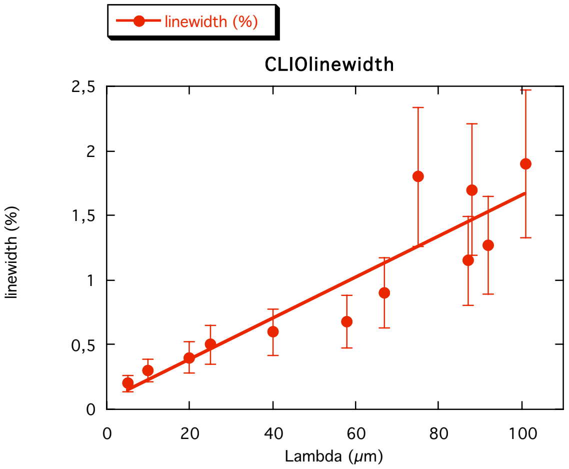


Figure 4 : Minimum spectral width of CLIO. The linear fit corresponds to the assumption of a constant length of the optical pulse. In practice this length is determined by many accelerator parameters varying with energy.

FUTURE PLANS

Numerical calculations show that full advantage of using a partially guided mode requires cavity mirrors of larger size than the present (38 mm). Therefore a new optical cavity is being made, that will also allow to commute mirrors for different spectral ranges without breaking vacuum. A maximum wavelength of 200 µm is expected. Furthermore coherent emission in the THz region will be explored by reducing the electron pulse length.

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