BEAM ADAPTATION AT THE INFRARED FEL CLIO

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Abstract

The infrared free-electron laser CLIO is tunable from 3 to 150 µm by operating its driver RF linear accelerator between 50 and 12 MeV. This is the largest spectral range ever obtained with a single optical cavity. We have studied the electron beam transverse adaptation in the FEL undulator throughout the spectral and energy range. Each beam dimension is measured by a moving wire whose temperature dependant resistivity is monitored. The results are compared with simulations computed with the TRANSPORT code.

INTRODUCTION

The CLIO mid-infrared free electron laser (FEL) is a user facility since 1992. It is based on a 3 GHz RF LINAC with a thermo-ionic gun [1]. It has given rise to many FEL developments and applications [2].

CLIO was initially designed to operate from 2 to 16 µm (50 to 32 MeV) [4]. A programm was then developped to increase this spectral range: larger undulator vacuum chamber in order to minimize diffraction effects together with a new longer undulator period, modification of the RF circuit to obtain a larger current at low energy and use of toroidal mirrors in the optical cavity. This has enabled us to lase at 150 µm at 12 MeV [3]. Fig.1 displays the typical average power emitted from the FEL operating at a 62.5 MHz micro pulse repetition rate, and 25 Hz macro pulse rate. The average power up to 20 µm at 32MeV is about 1 W. It decreases strongly at longer wavelengths due to a lower transmitted current and diffraction losses both in the optical cavity and transport beam line[4]

The optimised optical power, P_{opt}, depends on the small signal gain at the start of the amplification process. A simplified small gain formula (1) shows the electron beam parameters that can be varied to optimise $P_{opt:}$

$$G_{laser} \approx \frac{I_{pp}}{\Sigma_e + \Sigma_o} F_{inh}(\sigma_\gamma \sigma_x \sigma_y \sigma_{\theta x} \sigma_{\theta y}) \quad (1)$$

where F_{inh} is a function depending on the energy spread, σ_γ are the beam transverse dimension, σ_x, σ_y and angular divergence, σ_x and σ_y. I_{pp} is the peak current and Σ_e and Σ_o are respectively the electron and the optical beam cross- section areas, assuming Gaussian beams.

The optimisation of the gain at short wavelengths is achieved by minimizing the surface (Σ_e) of the electron beam along the undulator (the surface of the optical beam being determined by the cavity mirrors). At long wavelengths, it is expected that a thin beam may increase diffraction losses in the optical cavity and that the optimized size can be different. In order to adress this problem, we have measured the electron beam profiles at different energies and compared with analytical values and TRANSPORT numerical optimisations.

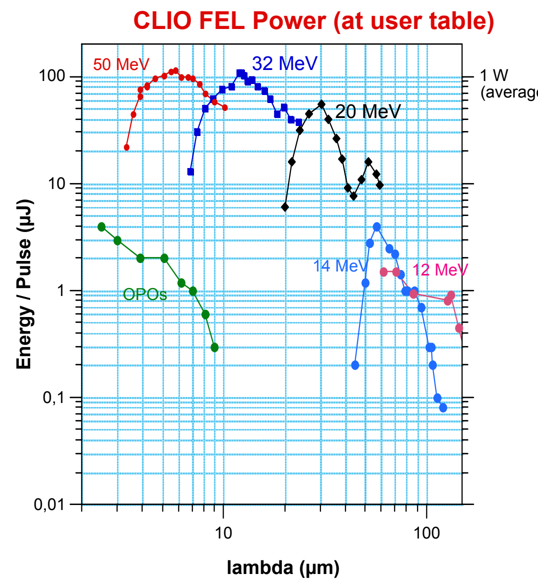

Fig:1 Spectral range of CLIO

WIRE SCANNER PRINCIPLE

A set of two orthogonal movable wires has been installed at each end of the 2m undulator. During displacement, the wires intercept part of the beam, and produce a signal that can be either a current of secondary electrons or a variation of the wire resistance. Due to noise, we used only the second signal.

The following table shows the parameters of the wires.

Table 1: Wire Parameters

Parameters	Symbol	Unit	Value
Wire diameter	d	m	2.10^{-5}
e^-/macropulse	N		3.10^{12}
Energy loss	dE/dx	$J.m^2/kg$	$2.2\ 10^{-14}$
Specific heat capacity	Cp	$J\ kg^{-1}\ K^{-1}$	130
Melting temp.	T	°C	3410
density	ρ	$kg.m^{-3}$	19 300

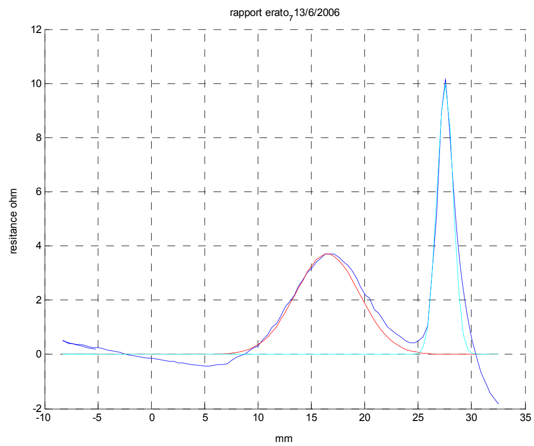

Fig 2 : typical resistance variations in vertical (left) and horizontal (right) wires. Gaussian fit is also displayed. The 2 wires being mounted on the same fork, there is an overlapp between the 2 signals.

The traces obtained with the horizontal and vertical displacement are fitted with a Gaussian curve (fig. 2). From their width one can deduce the beam transverse dimensions. We assume that the resistivity increase linearly with temperature and that the wire cooling is dominated by black body radiation.

A beam of N particles, crossing the wire at coordinate x looses an energy :

$$w_d = \frac{N.d^2.\rho}{2\pi\sigma_x}.(\frac{dE}{dx}).\exp(-\frac{x^2}{2\sigma_x^2}) \qquad (2)$$

For one CLIO macropulse, the energy deposited increases the temperature of the wire by a maximum of :

$$\Delta T = \frac{w_d}{\rho d^3 C_p} \cong 160 \text{ K} \qquad (3)$$

The radiated power, from the Stephan-Bolzmann law, is proportional to (T^4- T_o^4). At normal repetition rate of macropulses (25 Hz), at equilibrium, the radiated power is equal to the deposited power and one finds a maximum temperature of about 2000 K, well below fusion. If one assumes $T_o << T$, it comes for the resistance variation:

$$\Delta R(x) \propto T \propto w_d^{1/4} \propto \exp(-\frac{x^2}{8\sigma_x^2}) \qquad (4)$$

Therefore, the experimental curve should be gaussian with RMS values equal to $2\sigma_{x,y}$. Despite the crude approximations, one expect this model to fail only on the wings of the curves, where the $\Delta T/T_o$ is weaker. Indeed the fits made on the measurements show that the center of them is correctly approximated by gaussian distibutions.

COMPARISON WITH OPTIMISATION

The measurements can be compared either to the analytical fit or to numerical simulation. The analytical well known minimized values are:

- In the undulator focusing (vertical) plane :

$$\sigma_y = \sqrt{\frac{\varepsilon_n \lambda_o}{\sqrt{2}\pi K}} \cong 0.5\text{mm} \qquad (5)$$

where ε_n (=$\gamma\varepsilon$) is the normalized emittance (40 µm at CLIO), λ_o = 50 mm and K is close to 1.5.

- In the horizontal plane the minimum average size result from minimization of :

$$\overline{\sigma_x} = \frac{2}{L}\int_0^{\frac{L}{2}} \sqrt{\sigma_{xo}^2 + \frac{z^2\varepsilon^2}{\sigma_{xo}^2}}dz \qquad (6)$$

$$\Rightarrow \sigma_x^{'}(mm) \cong 1.1\sqrt{\frac{50}{E(MeV)}} \quad (7) \text{ at wire position}$$

The figure 3 displays the beam measurements at energy ranging from 20 to 48 MeV. It can be seen that the measured value are closed to the ones predicted by analytical theory. The difference may be due to the fact that the beam emittance is smaller inside the undulator than the value measured in front of the bend [1] since the particle of undesirable energy (+/- 1%) are filtered by an energy analyzing slit.

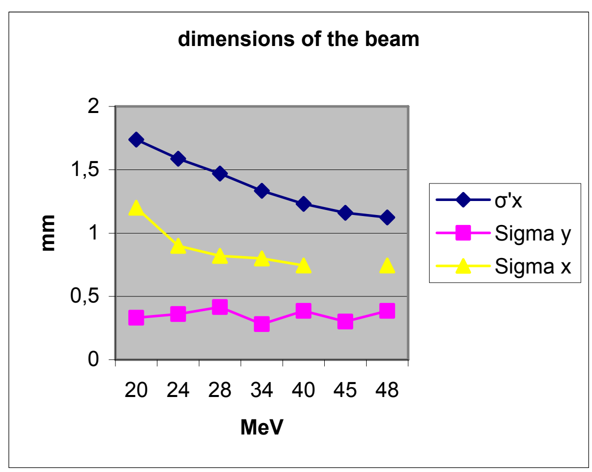

Fig. 3: Beam sizes at the undulator end estimated from the wire resistance variations. Analytical theory is displayed for comparison (blue lines)

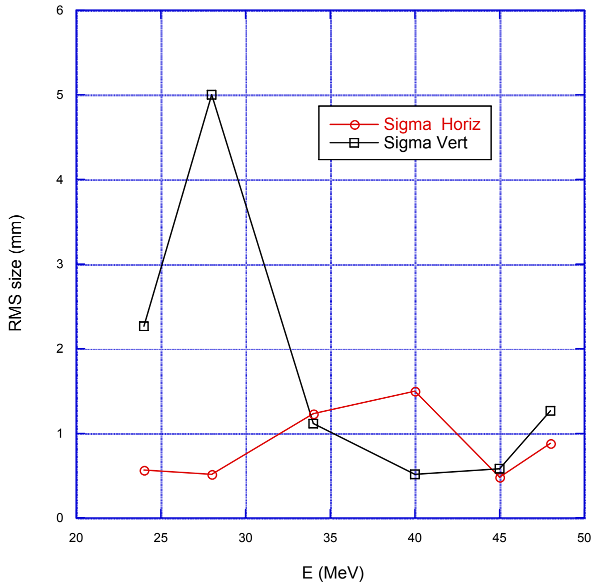

Fig. 4: Simulated values of the beam sizes at the undulator entry calculated using the experimental strengths values of the bend magnetic elements.

The experimental values can also be compared with the value obtained by TRANSPORT from the values of the quadrupoles adjusted experimentally to optimize the FEL power (Fig. 4). The bend is composed of 8 quadrupoles and 2 dipoles in order to adapt the beam inside the undulator and to ensure achromatism and approximate isochronism[5]. These simulated values are not in agreement with the measured ones and seem aberrant in most cases. This discrepancy is not yet fully understood. More simulations have been undertaken in order to understand the influence of the particle distribution at the bend entry and the possible effect of the magnetic elements hysteresis curve.

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