OPTIMIZATION OF THE CLIO INFRARED FEL GAIN WITH THE ELECTRON BEAM TRANSPORT LINE

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Abstract

The CLIO infrared free-electron laser (FEL) electron transport system is studied and optimized for FEL operation between 50 and 20 MeV. This study is made by comparing theoretical simulations with experimental results obtained by maximizing the FEL power. Two quadrupoles pairs are used to make the beam line achromatic and nearly isochronous. These two pairs lead to a continuum of solutions. By comparing these solutions to the experimental points, we show that a pulse magnetic compression effect is used below 32 MeV to increase the peak current and so the optical gain and power. Two others quadrupoles pairs are used to match the beam in the undulator, the experimental matching exhibit discrepancies which are discussed.

1 INTRODUCTION

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

CLIO was initially designed to operate from 2 to 16 µm (50 to 32 MeV) [4]. A larger sized vacuum chamber within the optical cavity, to minimize diffraction effects, and a new longer undulator period has enabled us to lase up to 60 µm at 19 MeV [5].

The FEL is operated at a 62.5 MHz micropulse repetition rate, and 25 Hz macropulse rate. Recently, the power has been enhanced by one order of magnitude at long wavelengths by using a new gun pulser which delivers higher bunch charges [6].

The optical power, P_{opt}, is optimized when the small signal gain at the start of the amplification process is maximum. A simplified small gain formula (1) shows the electron beam parameters that can be varied to optimize P_{opt}:

$$G \propto \frac{\hat{I}}{\Sigma_e + \Sigma_O} Finh\ (\sigma_\gamma, \sigma_x, \sigma_y, \sigma_{\theta x}, \sigma_{\theta y}) \qquad (1)$$

where $\sigma\gamma$ is the energy spread, σ_x, σ_y are the beam transverse dimensions and $\sigma_{\theta x}$ and $\sigma_{\theta y}$ its angular divergence, Î the peak current and Σ_e and Σ_o respectively the electron and the optical beam cross-sectioned areas, assuming Gaussian beams.

The average power up to 20 µm at 32 MeV is about 3 W and decreases strongly between 24 and 21 MeV. This is due to :

- smaller efficiency of electron bunching in the injector at low energies (< 32 MeV) leading to a smaller peak current Î since our buncher and accelerating section are fed by the same klystron.

- increase of the diffraction losses in the optical cavity at great wavelength [6].

The P_{opt} enhancement at great wavelength is in great part achieved by optimizing Î, F_{inh} and Σe [7] and corresponds to the following defined beam transports characteristics [8]:

1. First-order achromaticity in the horizontal plane at the undulator entrance (position and angle dispersion functions respectively η and η' made zero), which leads to quasi-isochronicity (when no magnetic pulse compression is desired to increase the peak current).
2. In the vertical plane, the betatron motion is adjusted so as to give rms beam radius Y and Y', $Y = (\varepsilon/\sqrt{K_y})^{1/2}$, $Y'/Y = K_y$ (2) which minimize the inhomogeneous broadening F_{inh} and Σe (where $K_y = 1/2(e\ B_0/\gamma mc^2)$, B_0 is the vertical magnetic field of the undulator),
3. In the horizontal plane the waist at the undulator middle point L/2 minimizes the 'z-averaged' beam radius Σe:

$$\frac{d}{dx}\left(\frac{1}{L}\int_0^L \sqrt{X^2 + z^2 X'^2}\, dz\right) = 0 \qquad (3)$$

2 THE CLIO BEAM TRANSPORT LINE SYSTEM

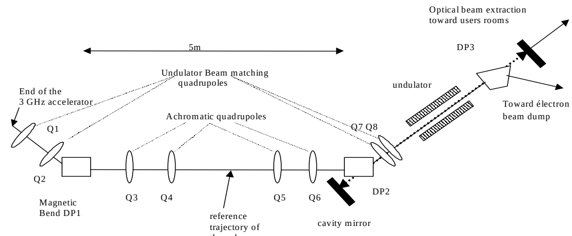

Figure 1: CLIO transport line, undulator and optical cavity synopsis.

It consists in a serie of focussing quadrupoles either horizontal (QF), or vertical (QD), vertical focussing rectangular magnet (MD). The (MD-QD-QF-QF-QD-MD) arrangement constitue an achromatic system (see figure 1). Two rectangular bending magnets DP1 and DP2 deflect the beam by 30°. To make this system achromatic, the quadrupoles Q3 and Q6 (vertical focussing), and Q4 and Q5 (horizontal focussing for the dispersed beam) are configured symmetrically about the bend center and have the same field strengths. The beam matching in the two transverse planes of the CLIO undulator is achieved with Q1, Q2, Q7 and Q8. This “FEL” adjustement of Q1 and Q2 do not provide the best energy resolution at the analysing slit (0.4% instead of 0.2%) but sufficient for the desired energy selection (1 to 2 %).

3 FEL GAIN OPTIMIZATION

During the beam transport system design, a procedure to fit the quadrupoles fields at first order have been used in order to verify the required electron beam characteristics (1), (2) and (3).

It was divided in two steps:

1/ (Q3-Q6) and (Q4-Q5) field strength parameters are fitted to make the angle dispersion function (η’) null at the bend center.

2/ the field parameters obtained from the first step are fixed, then Q1, Q2, Q7 and Q8 are fitted so as to horizontally and vertically make the beam waists at the undulator center.

3.a. Achromaticity

Linear beam transport optics may be reduced to a process of matrix multiplication. At first order, the matrix equation is represented by:

$$x_i(t) = \sum_{j=1}^{6} R_{ij} . x_j(0) \qquad (4)$$

where x1 = x, x2 = θ, x3 = y, x4 = φ, x5 = l and x6 = δp/p are the phase-space coordinates of a particle [9, 10]. Global achromaticity at the undulator entrance is obtained when R16 (η) and R26 (η’) are both null thus leading to a nearly isochronous bend. As R51, R52 and R56 are governing isochronicity, they are linearly bound to R16 and R26 which means that when the latter are null the former are also null, providing the required isochronicity.

Global achromaticity downstream a symmetric bend occurs when the angle dispersion function R26 (η’) is null at its center point. Since two quadrupoles Q3 and Q4 are placed before this point, a relation Q4 = f(Q3) leads to condition (1). An analytical calculation was carried out using the transfer matrix formalism. It appears that a continuum of solutions does exist at each energy distributed on a smooth curve (fig.2).

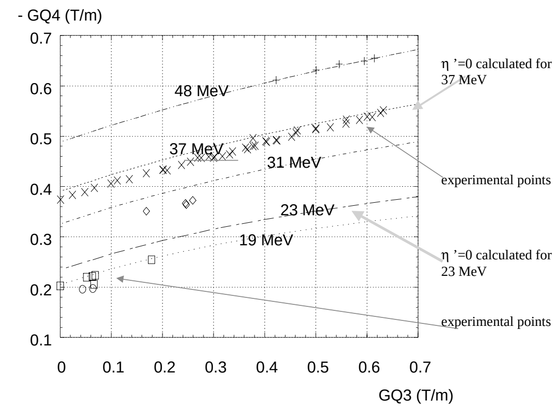

Figure 2: Comparison of the experimental points to the achromatic Q4 = f(Q3) analytical curves.

A large number of different quadrupole values to obtain best laser operation is indeed observed experimentally. Experimental points recorded over the past few years at various electron beam energies are partially displayed figure 2. It appears that all the points are located closely along the calculated curve. The numerous points at 37 MeV were taken recently to verify that the whole Q4= f(Q3) curve could be swept entirely. As (Q3, Q4) is varied the other quadrupoles are reajusted until the maximum FEL power is found. This shows the validity of the calculation and explain the previously observed dispersion of the points.

Even in a MD-QF-QF-QF-QF-MD configuration, the smoothness of the transport line optics enables us to operate despite a beam envelope divergence in the vertical plane which is balanced by the focussing effect of DP2. A greater transverse admittance of the line in this area leads to an observed enhancement of the average current of 5%. The increase of the laser power is of 15 % around a region where GQ4/GQ3 ≈ 1.15.

3.b. Magnetic pulse compression effect.

We observed on the figure 2 that as the energy decreases the experimental points are deviating from the Q4 = f(Q3) curves. This corresponds to a variation of the non-isochronicity value R56. This variation could correspond to a magnetic pulse compression effect if an energy-phase correlation in the electron bunch is introduced in the accelerating section, it can be used in the bend to maximize the peak current by adjusting R56. Provided that the center bunch dephasage angle ϕ_0 has to be rather small (≤ 20°) in order to avoid a too large energy spread (<3 %).

This effect is assumed to compensate the decreasing of the RF voltage in the buncher linearly with beam energy below 40 MeV, thus leading to a lower peak current.

We have obtained from experimental points with trace3d relevant values of -R56/c. An increase of 30 to 50 % of the peak current, assuming a R56/c of -4 ps/% and a ϕ_0 of – 10° is obtained as the bunch length is assumed to be around 15 ps. The electron bunch energy spread is increased from about 0.5% to 1 % FWHM at the peak of the bunch which is compatible with our 38 periods undulator. Our results show that a pulse compression effect probably takes place. At the moment, the energy analyzing slit resolution is of 2.5% preventing us from verifying accurately the dephasage of the bunch in regard of the RF wave, and the phase is adjusted experimentally by optimizing the FEL power.

3.c. Undulator beam matching.

A satisfactory laser power is obtained by optimizing manually the quadrupoles values. However the final value of Q_1, Q_2 and Q_7, Q_8 are always somewhat different from the calculated ones. This is particularly observed for Q_1 which cannot be set to a theoretical value without a loss of beam current in the bend. Indeed, the theoretical values are calculated by assuming a waist of the electron beam at the exit of the accelerating section corresponding to a (β_y = 1.12 m, α=0). In that case, it appears that the size of the beam after Q_1 (horizontally focussing) in addition with the effect of its centroïd trajectory (which is likely far from the reference axis at the DP_1 entrance in the vertical plane) doesn't match the size of the vacuum chamber in DP_1 (22 mm).

Therefore, we have to change the beam at the accelerating section (β_y = 3 m, α= 0.5) output together with reducing the strength of Q1. However, the phase space distribution is not sufficiently well known so as to allow an accurate theoretical calculation of the transport line optics. Therefore, the final adjustments of Q_1, Q_2, Q_7 and Q_8 steel relies on optical measurement : the stored spontaneous undulator emition is optimized with the steers and once the system is lasing the FEL power is maximized with the quadrupoles settings.

The electron beam envelop profiles calculated with Trace 3D from experimental files are quite different from one experimental point to the other along a Q4 = f (Q3) curve at given energy and initial conditions. FEL gain calculation should be performed in the near future on these profiles [11].

CONCLUSIONS

The analysis of the FEL bend has been compared with experimental points by maximizing the FEL power. This comparison shows that the FEL power is maximized when :

- Achromaticity is realized at the undulator entrance. An average laser power maximum has been found along the Q4= f(Q3) curve.

- At low energy, a deviation from isochronicity is explained by a magnetic compression effect. This compression increases the peak current and is made necessary that due to our particular RF circuit. This decrease of the RF power will be corrected in the near future by the implementation of new RF components.

- The beam matching quadrupoles Q1, Q2, Q7 and Q8 are adjusted roughly by the theoretical fit and then with optical measurements.

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