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PROGRESS IN THE FEL PROJECT AT THE C.N.E.N. FRASCATI CENTER

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Abstract

We present the essential features of the 20 ÷ 30 MeV microtron single pass FEL (oscillator) project developed at the C.N.E.N. Frascati Center for high average power infrared radiation generation (λ = 10 ÷ 30 μm).

1. Introduction and Theoretical Remarks

It has been undertaken at the C.N.E.N. Frascati Center an experimental activity to realize a FEL operating with a microtron as electron beam (e.b.) source.[1]

In recently developed theoretical analyses[2-4] of the single pass machine FEL operation, it has been shown that the small signal gain per pass, relevant to the r-th Supermode (SM)[2], is

$$G^r = g_o \ \mathrm{Re}\, q_\gamma^r(\Theta;\ \mu_c;\ \mu_\varepsilon,\ \mu_a) \tag{1}$$

where

$g_o = 2\sqrt{3}\ \pi(2\lambda_o/\lambda_q)^{1/2}(I_p/I_o)K^2/(1+K^2)^{3/2}(\Delta\omega/\omega)_o^{-2}$,
$(\Delta\omega/\omega)_o = \lambda_q/2L_w$,

λ_q ≡ Wiggler pass, L_w ≡ Wiggler length, I_p ≡ peak current, $I_o = ec/r_o$

$\Theta = -2/\pi(\Delta\omega/\omega)_o(\omega_o\delta t/g_o)$, $\lambda_o = \lambda_q/2\gamma^2(1+K^2)$,
$\omega_o = 2\pi c/\lambda_o$,

$\delta T = T_c - T_e$, T_c ≡ cavity round trip period, T_e ≡ bunch-bunch time distance,

$\gamma = E/mc^2$, E ≡ e.b.energy, $K = eB_o\lambda_q/2\sqrt{2}\pi m_o c^2$ (linear polarized wiggler)

B_o ≡ peak magnetic field

$\mu_c = (\lambda_o/2\sigma_z)\cdot(\Delta\omega/\omega)_o^{-1}$ ≡ Coupling parameter, σ_z ≡ r.m.s. e.b. length

$\mu_\varepsilon = (\Delta\omega/\omega)_\varepsilon\cdot(\Delta\omega/\omega)_o^{-1}$, $(\Delta\omega/\omega)_\varepsilon = 2\sigma_\varepsilon$ ≡ Inhomogeneous broadening due to the energy spread, σ_ε ≡ r.m.s. relative energy spread

$\mu_a = (\Delta\omega/\omega)_a\cdot(\Delta\omega/\omega)_o^{-1}$, $(\Delta\omega/\omega)_a = (\sqrt{2}\ K/\sqrt{1+K^2})\sigma_a/\sqrt{\lambda_o\ \lambda_q}$ ≡

≡ Inhomogeneous broadening due to the emittance, σ_a = r.m.s. emittance. (For comments see[1-4]). (2)

Without entering the details of $\mathrm{Re}\, q_\gamma^r$ we recall that it is a function depending on Θ and on the parameters μ_c, μ_ε, μ_a. Its typical behaviour is displayed in Fig. 1 where we have plotted $\mathrm{Re}\, q_\gamma^r$ vs Θ for the first seven SMs in the following cases

(a) $\mu_c = .5$, $\mu_\varepsilon = \mu_a = 0$ ("homogeneous broadening")

(b) $\mu_c = .5$, $\mu_\varepsilon = .18$, $\mu_a = .26$ ("Inhomogeneous broadening" typical for the FEL-microtron operation at 20 MeV).

By comparing Fig. 1a and Fig. 1b it appears that the presence of the energy spread and emittance, as elsewhere noticed[4], reduces both the maxima of $\mathrm{Re}\, q_\gamma^r$ (and thus the gain) and the maximum Θ variations (and thus the maximum cavity length variations). In the present case the reduction lies within 10%.

To achieve laser action one must optimize the fundamental parameters of the apparatus to have enough gain per pass to reach the saturation in a time small with respect to the e.b. pulse duration. Including the losses the net gain for each SM is

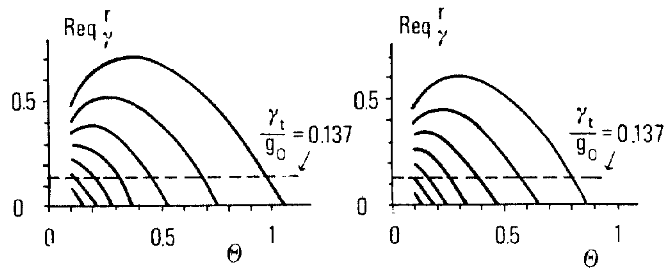

Fig. 1 - Plot vs Θ of the first seven SMs ($\mathrm{Re}\, q_\gamma^{r+1} < \mathrm{Re}\, q_\gamma^r$)
(a) $\mu_c = 0.5$, $\mu_\varepsilon = 0$, $\mu_a = 0$
(b) $\mu_c = 0.5$, $\mu_\varepsilon = .18$, $\mu_a = .26$

$$\begin{cases} \alpha^r = (1-\gamma_T)G^r - \gamma_T \\ \gamma_T \equiv \text{total cavity losses} \end{cases} \tag{3}$$

In this connection SMs with $\alpha^r > 0$ saturate (see Fig. 1) and the maximum Θ variations for the laser action are reduced. To account for the saturation effects we need the strong signal analysis developed in[3], where the numerical dependence on Θ of the laser pulse energy has been studied, and it has been found a behaviour similar to the experimental one[5] (for further comments see[3] and references therein). The laser pulse energy or better the adimensional laser pulse energy χ[3], has been useful in defining the single pass FEL efficiency which, in this connection, reads

$$\eta \cong \chi(\Delta\omega/\omega)_o. \tag{4}$$

2. Experimental Characteristics

(a) Microtron

The first step towards the realization of the experimental program has been the modification of the 12 MeV, 60 mA Frascati microtron[6], to increase the energy by substituting the Wernholm-type injection with the Kapitza one.[7] Such an improvement has allowed to reach an energy around 20 MeV to the 22-th orbit, with a maximum pulse current of about 35 mA, an emittance of 3 mm. mrad and an energy spread of 0.12% :

Such performances have been obtained with the microtron operating with a 2MW, 2 ÷ 4 μsec S-band magnetron. The power lost in the resonator was about 600 kW and the e.b. power about 700 kW.[7]

The electron beam parameters, to have laser action, are summarized in Table I and will be achieved by substituting the actual magnetron with a CSF-Thomson 12 μsec-3 GHz high power (15 MW/30 kW) klystron, with a maximum e.b. energy available of 20 MeV; and, successively, by substituting the actual 80 cm diameter magnet with a new 150 cm one (whose realization is in progress) to reach an energy up to 35 MeV.

(b) Wiggler Magnet and Transport Channel

The Wiggler magnet designed for the Frascati FEL-microtron operation is a permanent magnet ($SmCo_5$)[8], with the following project parameters[9]

λ_q = 5 cm, L_w = 2.25 m $(\Delta\omega/\omega)_o \sim 1.1\times10^{-2}$

h ≡ (magnet gap) = 2.4 cm, $B_o \sim 3$ kG, $K \sim 1$.

The transport channel has been designed to match the optical e.b. characteristics at the microtron output with the suited ones to minimize the inhomogeneous

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spread in the wiggler magnet. To this aim two pairs of independent quadrupole magnets (D-F) have been inserted and the bending structure is provided by the magnets B. The general layout is sketched in Fig. 2 while in Fig. 3 we have plotted the optical functions (β_x, β_y).[10]

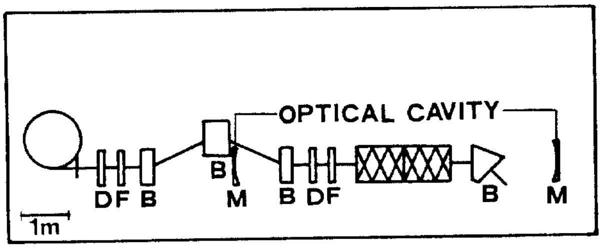

Fig. 2 - FEL microtron experimental layout
D-F ≡ vertical and radial focusing quadrupole magnets
B ≡ bending magnet
W ≡ wiggler magnet
M ≡ optical cavity mirror

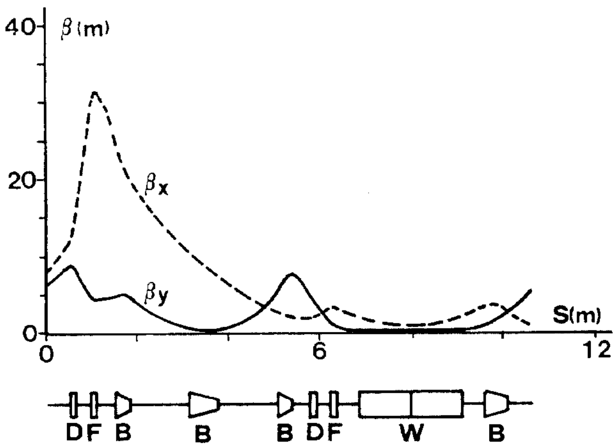

Fig. 3 - Transport channel optical functions
β_x, β_y ≡ radial and vertical beta functions

(c) Laser Beam Performances

We now briefly discuss the main laser beam (l.b.) expected characteristics. We recall that at the saturation the l.b. power is linked to the e.b. one by the relationship[3,11] (see Eq. (4) and recall that $\chi \sim 1$)

$$P_L \cong (\Delta\omega/\omega)_o P_E \quad (5)$$

where $P_{L,E}$ are the l.b. and e.b. power respectively. In Table I we summarize typical l.b. characteristics for the operating regions $\lambda \sim 25 \div 35$ μm (Table IIa, e.b. characteristics from Table Ia) and $\lambda \sim 10 \div 20$ μm (Table IIb, e.b. characteristics from Table Ib).

As to the maximum cavity length admissible variations, it has been already noticed, that they are reduced if the losses are taken into account. As example let us consider the case of Fig. 1b relevant to the FEL operation at 32.6 μm, from the figure it appears that fixing the losses around 5% we obtain a maximum cavity length variation $\delta L_c \sim 280$ μm. For a further example we have plotted in Fig. 4 $\mathrm{Re}\, q_\gamma^1$ vs Θ (at $\mu_c \sim 0.3$; $\mu_\varepsilon \cong .125$, $\mu_a \sim .18$) for the FEL operation at $\lambda \sim 16$ μm; taking into account the losses, which are of the order of 3%, we find $\delta L_c \sim 75$ μm. We have planned to measure

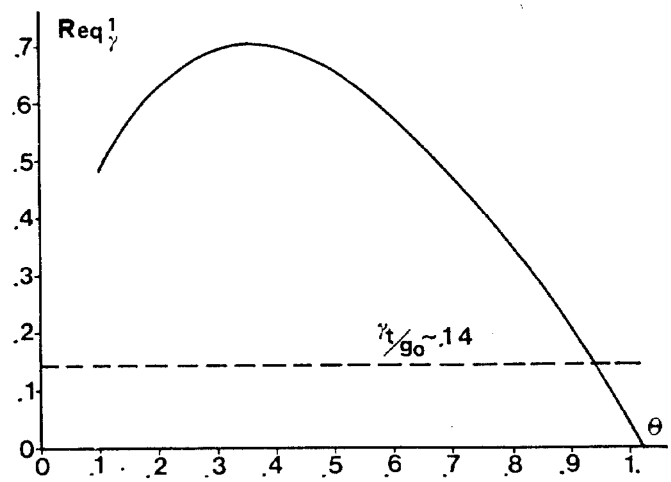

Fig. 4 - $\mathrm{Re}\, q_\gamma^1$ vs Θ (μ_c = 0.3, μ_ε = .125, μ_a = .18)

TABLE I

		(a)	(b)
e.b. Energy E	(MeV)	20	⩾ 30
Average Current (Pulse)	(mA)	∿ 350	∿ 250
Peak Current (Bunch)	(A)	∿ 6.5	∿ 4.5
Pulse Duration τ_M	(μsec)	12	12
Energy spread σ_ε	(%)	∿ .12	∿ .08
Emittance (vertical) σ_a	(mm•mrad)	∿ 3	∿ 2
Klystron Peak Power P_P	(MW)	15	15
Klystron Average Power P_M	(kW)	30	30
Magnet Diameter	(cm)	80	150
Injection		Kapitza	Kapitza
Bunch Length	(mm)	∿ 7	∿ 7
Repetition Frequency	(Hz)	∿ 1	∿ 150

TABLE II

		(a)	(b)
Wavelength λ	(μm)	32.6	16
e.b. Energy E	(MeV)	20	28.5
Gain G	(%)	27	15
Cavity losses γ_T	(%)	5	3
Net gain α	(%)	22	12
Pulse rise time τ_R	(μsec)	∿ 3.5	∿ 6.5
Energy per pulse $\mathcal{E}$	(J)	∿ 0.7	∿ 0.45
Average power P_L (at 150 Hz)	(W)	∿ 100	∿ 70
Wiggler magnet		permanent magnet	

the variation of the cavity length by means of an interferometric system and to control the tune between the round trip cavity period and the electron bunch-bunch time distance by using an active computer controlled feedback.

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