# Laboratori Nazionali di Frascati

**LNF-88/04(R)**
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# AN INFRARED FREE ELECTRON LASER ON THE SUPERCONDUCTING LINAC LISA

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## Abstract

The main parameters of a Free Electron Laser covering the infrared wavelength region and using the high quality electron beam produced by the Superconducting Linac LISA in development at the Frascati National Laboratories are breafly reviewed. Some considerations of the effects of the FEL interaction on a possible electron beam energy recovery are also presented.

## 1 - Introduction

A program to construct a test superconducting electron linac (LISA) is in progress at the Accelerator Division of the Laboratori Nazionali di Frascati[1].

The main parameters of the linac are summarized in Table I.

**TABLE I**

| | |
|---|---|
| Beam energy | 25÷50 MeV |
| Normalized emittance | $< 10^{-5}$ m rad |
| Energy spread (@25 MeV) | $2\ 10^{-3}$ |
| Macropulse | ≥1 ms (10 Hz) |
| average current on macropulse | 13 mA |
| Peak current | 6 A |
| Microbunch length(full width) | 1.3 mm |
| Microbunch frequency | 500 MHz |

A superconducting RF linac can easily work in a continous way. The choosing of a 1% duty cycle is only due to the necessity of reducing the radioprotecting shieldings mantaining a high average current during the macropulse.

The good beam quality is well suited for a high efficiency Free Electron Laser covering the infrared wavelength region. In fact, using an undulator of **5 cm** period and field parameter **.5≤K≤1.5**, values easily obtainable both with electromagnetic and hybrid undulators[2], the radiation wavelengths of the $1^{st}$ harmonic emission are shown in Fig. 1.

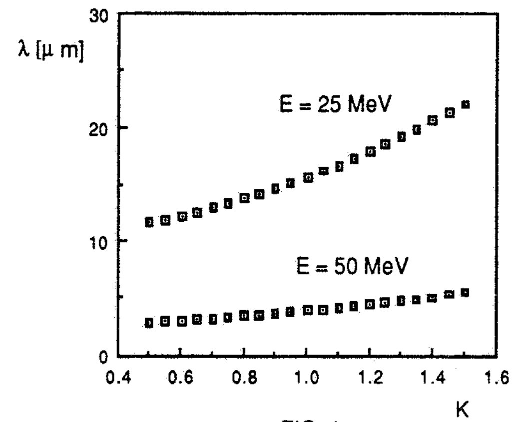


FIG. 1

Using the $3^{rd}$ harmonic emission, it is also possible to reach the visible region. Longer wavelengths can be obtained reducing the electron beam energy.

The given energy spread and transverse emittance are such that the inhomogeneous broadening of the emitted radiation is negligible for an undulator length up to more than 100 periods.

In this paper we will make a preliminary analysis of the FEL main parameters and of the electron beam interaction with the radiation inside the optical cavity.

In Fig. 2 a schematic layout of the complex Linac-FEL is shown.

The electron beam, after its extraction from the 25 MeV linac, can follow two alternative paths: either through the undulator or directly at the beginning of the linac going through it a second time and increasing its energy to 50 MeV. In this latter case the beam will then pass through the undulator to generate short wavelength radiation.

In the former case, the 25 MeV beam, after the interaction with the FEL radiation, will be guided again through the linac, but half a period out of phase, in order to be decelerated and to give back energy to the superconducting cavities.

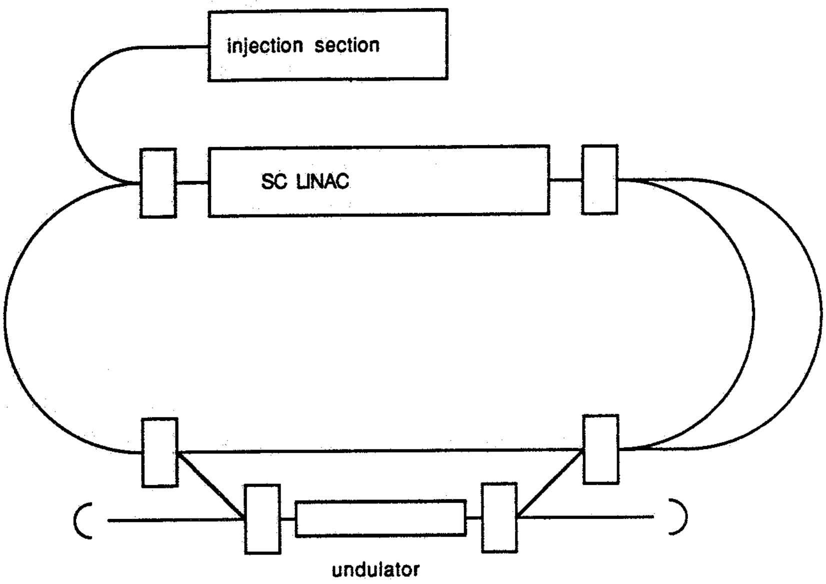


FIG. 2

## 2 - Fel Power and Efficiency

The best overall efficiency in tranfering energy from plug power to FEL radiation is obtained using a constant period undulator followed by a high efficiency energy recovery in the linac.

In a constant period undulator the maximum power which can be extracted from the electron beam is given by[3]

$$P_l \cong \frac{P_e}{2n} = \frac{IE}{2N}$$

in which I is the average current, E the electron energy and N the number of undulator periods.

Defining as $G_T$ the output coupling of the optical cavity and as $G_M$ the total passive losses, the extracted power results

$$P_{ex} \cong \frac{G_T}{G_T+G_M}\,\frac{IE}{2N}$$

and the total FEL efficiency is

$$\eta \cong \frac{G_T}{G_T+G_M}\,\frac{1}{2N}$$

The largest efficiency is obtained for the lowest N value for which the peak single pass gain g is greater than the total cavity losses $G_P = G_T + G_M$.

It must also be noted that the laser pulse rise time is given by

$$\tau_r\,[\mu s] = .14\,\frac{L\,[m]}{g - G_P}$$

in which L is the optical cavity length.

The laser linewidth is determined by the electron bunch length, and is given by

$$\frac{d\lambda}{\lambda} \cong \frac{\lambda}{L_B}$$

in which $L_B$ is the bunch length.

With the mentioned parameters, we have a linewidth of the order of 1% for the wavelengths obtainable with a 25 MeV beam, and of the order of 2-3 ‰ with 50 MeV.

The peak gain for a monochromatic unidimensional electron beam, in the small gain and plane wave approximation, is given by

$$g_0 = 32\sqrt{2}\,\pi^2\lambda^{\frac{3}{2}}\lambda_w^{\frac{1}{2}}\frac{\frac{K^2}{2}}{\left(1+\frac{K^2}{2}\right)^{\frac{3}{2}}}\,\frac{I_p}{I_a}\,\frac{N^3}{<\Sigma_L>}\,f(x)\;F(K)$$

in which

$\lambda$ is the radiation wavelength

$\lambda_w$ is the undulator period

N is the number of undulator periods

$I_P$ is the peak current

$I_a = ec/r_e = 17000$ A

$$x = 4\pi N\,\frac{\gamma - \gamma_r}{\gamma_r}$$

$\gamma_r$ is the resonance energy

$$f(x) = \frac{1}{x^3}\left[\cos x - 1 + \frac{1}{2}x \sin x\right]$$

$F(K) = [\,J_0(\xi) - J_1(\xi)\,]^2$

$J_n$ is the Bessel function of order n

$$\xi = \frac{\frac{K^2}{2}}{2\left(1+\frac{K^2}{2}\right)}$$

$<\Sigma_L>$ is the mean transverse area of the optical mode and its optimum value is

$$<\Sigma_L> = \frac{L_w \lambda}{\sqrt{3}}$$

in which $L_w$ is the undulator length.

Taking into account that

$f_{max}(x) = .0675$ for $x = 2.6$

we have

$$g_0 = 1.54 \cdot 10^{-3} \left(\frac{\lambda}{\lambda_w}\right)^{\frac{1}{2}} N^2 I_p \frac{K^2}{\left(1+\frac{K^2}{2}\right)^{\frac{3}{2}}} F(K)$$

For a real beam many factors contribute to decrease the gain value. Energy spread and transverse emittance give rise to the inhomogeneous broadening of the spontaneous radiation and affect the gain which is proportional to the linewidth derivative. The "slippage" of the radiation pulse over the electron bunch due to the different longitudinal velocities decrease the overlap between them and thus the gain.

Following reference [3], we can define

$$\mu_\varepsilon = 4\,\sigma_\varepsilon N$$

$$\mu_y = \frac{8}{\sqrt{2}} \frac{K}{2+K^2} \frac{\gamma \varepsilon_y}{\lambda_w} N$$

$$\mu_c = \frac{\lambda N}{\sigma_z}$$

by neglecting for the moment the sextupolar terms of the undulator, we do not have any contribution from the radial emittance.

The real gain can be parametrized as

$$g = g_0 \frac{1}{\left(1+\frac{\mu_c}{3}\right)\left(1+\mu_y^2\right)\left(1+1.7\,\mu_\varepsilon^2\right)}$$

With this gain, a 25 MeV electron beam, an undulator period of 5 cm, a 5% output coupling and 2% passive cavity losses, the minimum number of undulator periods and the external power which can be obtained are shown in Fig. 3 as functions of the radiation wavelength. In Fig. 4 the corresponding extraction efficiency and power inside the optical cavity are also illustrated.

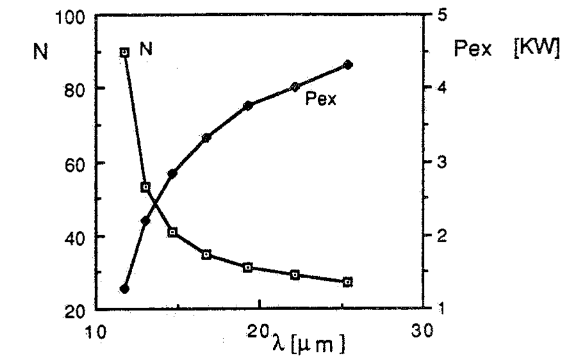


Fig. 3

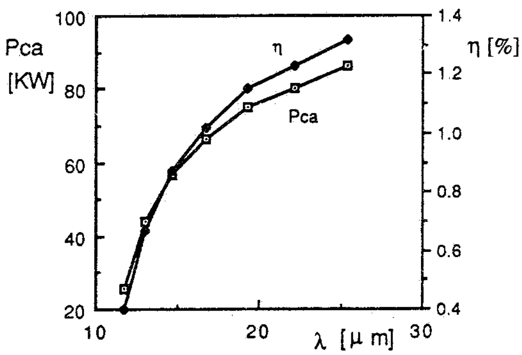


Fig. 4

It is evident that a large power can be obtained with efficiency of the order of 1%. A careful analysis of all parameters is necessary in order to realize a final project, taking also into account the very high peak power of the radiation. Optimization of undulator parameters will depend on the spectral range and power requested by final users.

If the electron beam, after the interaction with the FEL radiation, is carried again at the beginning of the Linac and injected into it with a half period phase shift, it will be decelerated by the Linac field and will give back its energy to the superconducting cavities.

If $\eta_R$ is the efficiency of this energy recovery, the overall FEL efficiency is

$$\eta = \frac{\eta_{FEL}}{1 - \eta_R + \eta_{FEL}}$$

Due to the small value of $\eta_{FEL}$, $\eta$ is very sensitive to the energy recovery and any effort to increase this parameter may pay with a high total FEL efficiency.

## 3 - Optical Cavity and Electron Beam Dimensions

To synchronize the optical pulses inside the cavity with the 500 MHz electron bunches, the cavity length must be a multiple of 30 cm. The lower limit is given by the length of the undulator and of the magnets for electron injection and extraction which must be contained inside the cavity. With a maximum undulator length of 2.5 m, the distance between the mirrors has to be greater than 5 m.

The possibility of having a larger spotsize on the mirrors, reducing the thermal problem due to the high peak power of the radiation, would require a greater length. On the contrary mechanical stability and alignment tolerances get worse with cavity length.

We consider a symmetrical cavity with spherical mirrors of curvature radii R at a distance $L_C$, an undulator with a period $\lambda_W$ and length $L_W = N\,\lambda_W$. The Rayleigh length of the fundamental mode is

$$Z_R^2 = \frac{L_c\,(2R - L_c)}{4}$$

and the waist of the fundamental mode is

$$w_0 = \left[\frac{\lambda^2}{\pi^2}\,\frac{L_c\,(2R - L_c)}{4}\right]^{\frac{1}{4}}$$

in which $\lambda$ is the radiation wavelength.

In order to derive the best values for these parameters, we have to leave the simple plane wave approximation and to consider the interaction of the electron beam with a gaussian radiation beam.

In the single particle and small gain approximation of Colson and Elleaume [4], the gain becomes a function of the ratio

$$q = \frac{L_w}{Z_R} = \frac{2\,L_w}{[L_c\,(2R - L_c)]^{\frac{1}{2}}}$$

and for a unidimensional electron beam the maximum gain is obtained for $q = 4$. For a beam with finite transverse dimensions the maximum is somewhat smoothed, but if the electron are fully contained in the optical mode no substantial difference is found.

In Fig. 5 the mirrors curvature radius R is shown as function of the cavity length $L_C$, together with the quantity

$$f = \frac{R}{2R - L_c}$$

which is an amplification factor of the angular deviation of the cavity optical axis due to mirrors tilting and can be considered as a quality factor for the cavity mechanical stability.

The arrow indicates the point which seems the best compromise. For this point we have

$L_c = 5.7$ m $\qquad$ $R = 2.99$ m

The waist dimension is given by

$$w_0 = \left[\frac{Z_R \lambda}{\pi}\right]^{\frac{1}{2}} = \left[\frac{L_w \lambda}{4\pi}\right]^{\frac{1}{2}}$$

For an undulator length of 2.5 m, we have

$$w_0 = .446\, \lambda^{\frac{1}{2}}$$

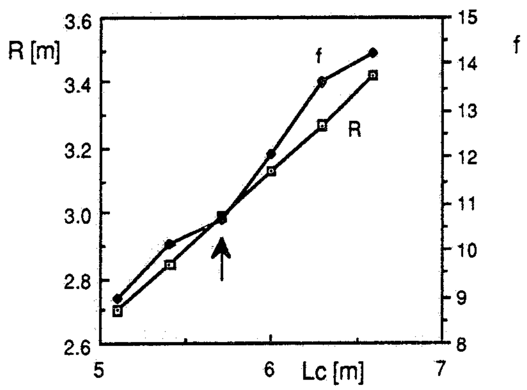


Fig. 5

The optical spot size on the mirrors in the same conditions is given by

$$w = w_0 \left[1 + \frac{16\,(L_c/2)^2}{L_w^2}\right]^{\frac{1}{2}} = 2.08\, \lambda^{\frac{1}{2}}$$

With a 15 mm radiation we have

$w_0 = 1.7$ mm $\qquad\qquad w = 8.1$ mm

At 25 μm, the longest wavelength we can obtain with a 25 Mev beam,

$w_0 = 2.2$ mm $\qquad\qquad w = 10.4$ mm

The spotsizes can result not large enough to reduce the power density on the mirrors to a tolerable level. A more complete analysis of the optical cavity, taking into account also the mirror construction technology, is needed.

If the output coupling is a diffractive one, through a hole in one mirror, the coupling factor is a function of the spotsize, which means of the radiation wavelength, and decreases with increasing wavelength. The gain, on the contrary, is an increasing function of the wavelength, so that a high efficiency becomes incompatible with a wide spectral tunability. A special optimization is then needed for each application.

The electrons must be fully contained inside the optical mode, so that for the 15 μm case and for a round gaussian beam, its standard deviation in the waist must be

$$\sigma_0 < \frac{w_0}{2} = .85 \text{ mm}$$

For the given normalized emittance this corrisponds to a β function

$$\beta^* < \frac{\sigma^2 \gamma}{\varepsilon_n} = 3.5 \text{ m}$$

For a 50 MeV energy, 3 μm radiation wavelength and the same optical cavity structure

$$\beta^* < 1.5 \text{ m}$$

These values must be considered as upper limits, because in these situations the gain would be greatly decreased. The real value will be given by the optimized design of the transport channel optics. The undulator periods number and the optical cavity structure will be also affected by these final values.

## 4 - Energy Recovery and Electron Transport Channel

We have already seen that the energy recovery efficiency is a fundamental parameter for a high total FEL efficiency. The energy recovery is performed bringing the electron beam, after its interaction with the Fel radiation, again at the beginning of the linac, but with a phase shift of half a period with respect to the accelerating field. In this way the beam is decelerated and gives back its energy to the superconducting cavity. It is highly desirable that all the electrons reach the end of the linac with a residual small amount of kinetic energy, avoiding in this way the problems which can derive by electron trapping in the last cavities. It is perhaps a good choice to ask for a residual energy of at least 1 MeV, the energy supplied to the beam by the injection system.

In this framework, to evaluate the maximum theoretical recovery efficiency it is necessary to know the beam parameters after the FEL interaction.

In a constant period undulator the mean energy loss of the electron beam which give rise to the optical gain is a second order effect, the first order being a large energy spread.

To give a rough estimate of the effect, we evaluate the energy distribution of the electron beam after the FEL interaction in one particular case, with the parameters given in Table II.

The beam is supposed unidimensional and monochromatic at the entrance into the undulator.

**TABLE II**

| | |
|---|---|
| E | 25 MeV |
| N | 50 |
| $l_w$ | .05 m |
| l | 15 mm |
| $G_M$ | 2 % |
| $G_T$ | 5 % |
| $P_{ca}$ | 60 KW |

The power inside the cavity corrisponds to a peak electric field on the axis at the waist of the optical mode

$$E_0 = 6{,}6\ 10^7\ \frac{V}{m}$$

supposing the cavity structure optimized for the maximum gain.

The energy spread of the electron beam is shown in Fig. 6.

The bunch length is not significatively affected by the FEL interaction.

If the transport channel from the undulator to the linac is achromatic and isochronous, as must be the channel for the energy doubling recirculation, and if we want all the electrons with at least 1MeV at the end of the linac, from the data of Fig. 6 it can be seen that the mean energy of the beam after the deceleration is of **.6 MeV.**

This corrisponds to a maximum energy recovery efficiency in the linac

$$\eta_R = 97.5\ \%$$

To increase this number we need a dispersive channel which brings electrons with different energy at the rigth phase value in the linac in order to have at least a residual 1 MeV energy for all electrons and minimizing the mean energy of the bunch.

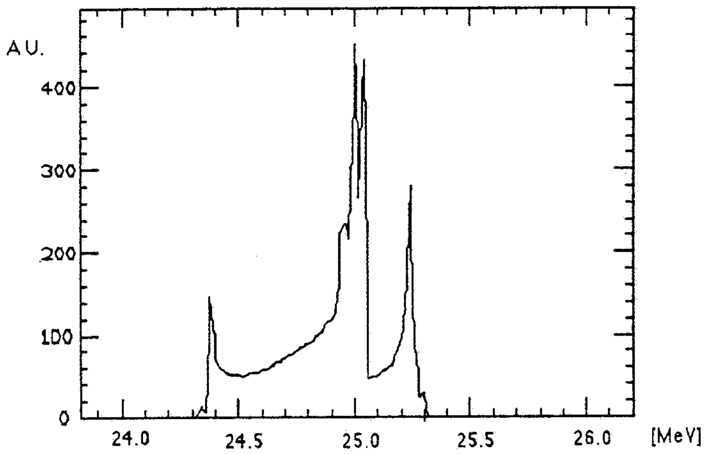


Fig. 6

If we suppose a linear correlation between energy and position at the entrance of the linac of the type

$$\phi = a\,\varepsilon + b$$

in which $\phi$ is the phase of the decelerating field and $\varepsilon$ the energy deviation from the nominal one, the energy distribution of Fig. 7 can be obtained at the end of the linac with the values

$$a = .28\ \frac{\text{rad}}{\text{MeV}} \qquad b = .07\ \text{rad}$$

The output mean energy is in this case .06 MeV, corresponding to a recovery efficiency in the linac

$$\eta_R = 99.7\ \%$$

This solution corrispond to a phase of 4° for electrons with unchanged energy, and to a dispersion of 2.6 cm/MeV.

This last value is not easy to obtain, and a special device is needed along the transport channel.

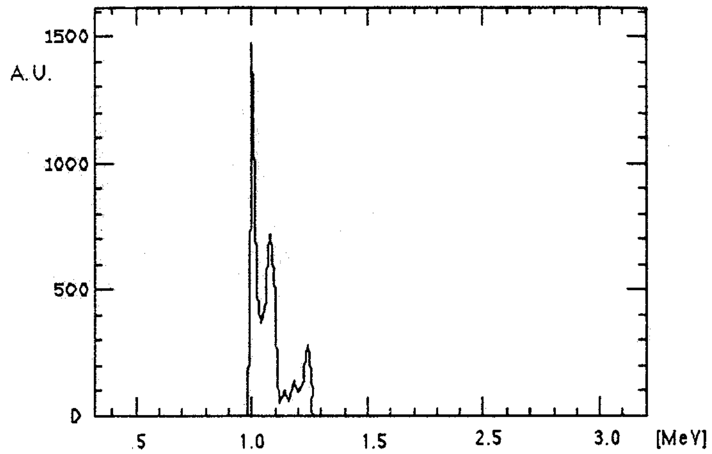


Fig. 7

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