THE ELFA PROJECT

R. Bonifacio, E. Acerbi, C. De Martinis,
F. Casagrande, G. Cerchioni, L. De Salvo Souza,
B. Mc Neil, P. Pierini, N. Sterpi
Dipartimento di Fisica dell' Universitá di Milano and
LASA (INFN) Via Fratelli Cervi 201, 20090 Segrate (Milano), Italy

T. Scharlemann
Lawrence Livermore National Laboratory

ABSTRACT

ELFA is a Superconducting Electron Laser Facility planned to operate in the high gain single pass FEL amplifier Compton regime in the range 30-300 GHz with peak power in excess of 100 MW. The peak power and frequency range, not accessible to normal Klystrons, have been chosen to test the feasibility of an FEL with short pulses as an RF source for high gradient accelerating structures. The fundamental goal of ELFA is to prove the existence of the Superradiant Regime of an FEL. A 10 MeV electron beam with peak current of 400 A and short bunches (200 ps) will be produced by a photocathode injector (3 MeV) followed by a superconducting Linac (a single module of the 352 MHz LEP-II cavities). A two section wiggler (hybrid and electromagnetic) is necessary to provide the high extraction efficiency. By properly tuning the e.m. section of the wiggler, the recently proposed superradiant emission of higher order harmonic radiation could be demonstrated. The project is supported by INFN and the final design of the photocathode, injector and wiggler is expected to be completed by the end of this year.

1. Introduction and General Outline

ELFA [1] is a project which intends to exploit the capabilities and the flexibility of the FEL as a source of tunable, coherent, high peak-power radiation centered on 100 GHz (3 mm) with the possibility of tuning from 30 to 3000 GHz. This project has both fundamental and technological novel goals. From the FEL physics viewpoint, ELFA will test the existence of three different high-gain regimes with short electron pulses, namely Steady-State, Weak and Strong Superradiance, the two latter regimes never observed and the first one only with very long pulses[2]. A beautiful and unique feature of the ELFA project is the possibility to test all these high-gain regimes with essentially the same experimental set-up, simply by varying the height b (the vertical transverse dimension) in a rectangular waveguide and correspondingly tuning the electron beam energy. From the technological viewpoint, ELFA will explore the matching of the advanced technologies of high-gain FEL's with the short bunch RF acceleration and photocathode injection with very high peak current and the composite wiggler. Sessler et al[3] have recently revaluated the FEL compared with the relativistic Klystron. Hence it is necessary to study experimentally what can be obtained from the European technology of S.C. cavities in this field. ELFA intends to start this activity. First of all, it is necessary to prove that the short pulse high gain FEL regime works. Once this first basic experimental step is demonstrated, then the pulse energy eventually can be increased, on the line of Amaldi–Pellegrini proposal[4]. A general layout of the experimental apparatus is shown in Fig.1, and a set of basic parameters for ELFA is reported in Table 1. The ELFA accelerator will provide a 400 A–10 MeV electron beam. Its basic components will be a photocathode injector and one superconducting 4–cell LEP II module operating at 352 MHz. The acceleration system is discussed in detail in a separate contribution to these proceedings [5]. The wiggler will be composed joining up two sections : a hybrid wiggler and an electromagnetic (e.m.) one. The e.m. wiggler will allow for tapering. The analysis of the wiggler for ELFA is the object of another contribution to these Proceedings [6]. From the feasibility study we recently obtained a relevant upgrading in the electron beam emittance so that ELFA could amplificate radiation not only in the microwave range, but also well into the IR. Actually, with a normalized emittance, $\epsilon_N \simeq 4 \times 10^{-4}$ mrad, from the inequality $\epsilon_N \leq \gamma\lambda/2\pi$ one gets as a limit on attainable wavelength, $\lambda \simeq 0.1$ mm. Moreover, by lowering the electron pulse current, the emittance and thus the radiation wavelength could be further lowered. IR operation should require a change of the gap of the wiggler, with minor modification of the whole accelerating structure. This result can greatly extend the application range planned for ELFA, e.g. in the direction of condensed matter physics.

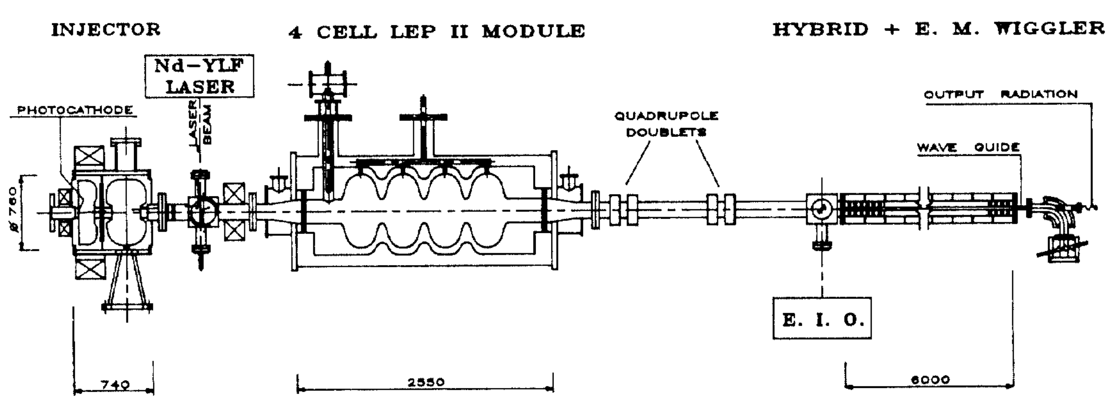

Fig.1 ELFA layout.

Table1: Basic Parameters for ELFA

Beam Parameters	$I = 400$ A $E = 7\text{–}10$ MeV $\epsilon_n = 5 \times 10^{-4}$ m rad $\Delta\gamma/\gamma \simeq 1\%$ $L_b \simeq 6$ cm
Wiggler Parameters	$\lambda_w = 12$ cm $B_w = 3.6$ KG $L_w = 6$ m $gap = 3.6$ cm
Radiation Parameters	$\lambda_r = 3$ mm $P_0 = 20$ W
Waveguide	$a = 5$ cm $b = 1; 1.5; 3$ cm

2. Basic FEL Physics with the ELFA Project

In ELFA the FEL is configured as a single-pass amplifier operating in the high-gain Compton regime using short electron bunches (6 cm) provided by a Superconducting Linac. With short bunches we can exploit the slippage effects, since the difference between the electron velocity and the radiation group velocity becomes relevant: according to the theory developed by R. Bonifacio and coworkers[7], three dynamical regimes can occur in an FEL depending on the values of the unsaturated gain parameter G, slippage parameter S, and superradiant parameter K, defined as

$$G = 4\pi\rho N_w(1 - X/2) > 1$$

$$S = \frac{N_w \lambda_r}{L_b}(1 - X)$$

$$K = \frac{S}{G} = \frac{L_c}{L_b}$$

where N_w is the wiggler period number, λ_r is the radiation wavelength, L_b the bunch length $L_c = \lambda_r(1 - X)/4\pi\rho(1 - X/2)$ is the cooperation length, X is the waveguide parameter defined in the interval $0 \leq X \leq 1$ [8] ; in a rectangular waveguide with height b for operation in the TE_{01} mode $X = \lambda_r \lambda_w / 4b^2$ and ρ is the fundamental FEL parameter[9]

$$\rho = \frac{1}{\gamma_r}\left(\frac{a_w \omega_p}{4ck_w}\right)^{2/3}(1 - X/2)^{-1/6}$$

$$\gamma_r{}^2 = \frac{(1 + a_w{}^2)\lambda_w}{2\lambda_r(1 - X/2)}$$

This expression fixes the resonance energy in the range 7–10 MeV depending on the value of b. In the definitions above, k_w is the wiggler wavenumber, a_w is the wiggler parameter, ω_p the effective plasma frequency and γ_r the electron resonant energy. The three dynamical regimes are the well known Steady-State (SS) regime, and the two novel regimes of Strong and Weak Superradiance with peak intensities proportional to the square of the electron density[7,10]. The conditions for the observation of the three regimes are shown in Table 2. The experimental parameters of Table 1 have been fixed according to Table 2. The SS regime has been already

Table 2

Three Dynamical Regimes For A High-Gain FEL $G \gg 1$		
$K \gtrsim 1$ $L_b \lesssim L_c$	Short Pulse Limit **Weak Superradiance**	$\|E\|^2 \propto I^2$
$K \ll 1$ $L_b \gg L_c$	Long Pulse Limit $S \ll 1$ Small Slippage **Steady State Regime** $S \gtrsim 1$ Strong Slippage **Strong Superradiance**	$\|E\|^2 \propto I^{4/3}$ $\|E\|^2 \propto I^2$

observed with long electron pulses from an induction linac[2]. In that case the propagation effects were negligible; in ELFA the slippage is controlled with the waveguide, so that the SS regime is observable with short pulses. Numerical results showing the emitted power versus the longitudinal coordinate z are reported in Fig.2 (Steady State), Fig.3 (Strong Superradiance on resonance), Fig.4 (Strong Superradiance with detuning) and Fig.5 (Weak Superradiance). Since Superradiance is a phenomenon of collective spontaneous emission, and not stimulated emission (as SS), it does not depend on resonance; on the contrary, it is more efficient out of resonance where the steady-state instability does not degrade the electron energy distribution, as shown by comparison of Figs. 3 and 4.

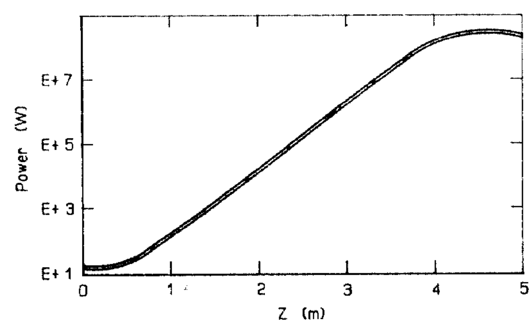

Fig.2 Steady State regime: output power vs the longitudinal coordinate z ($b = 1$ cm, $\gamma_r = 18.4$).

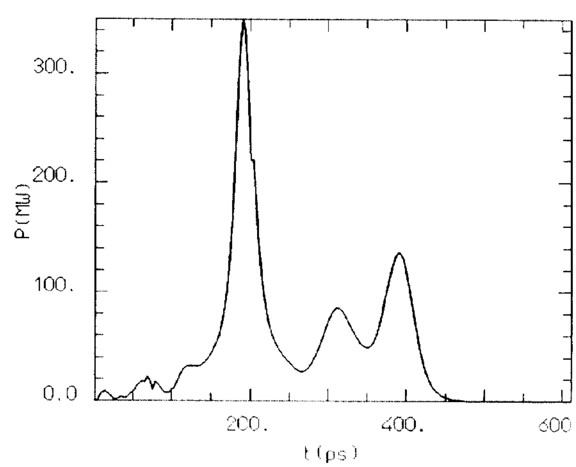

Fig.3 Strong Superradiance on resonance: output power vs time ($b = 1.5$ cm, $\gamma_r = 15.2$).

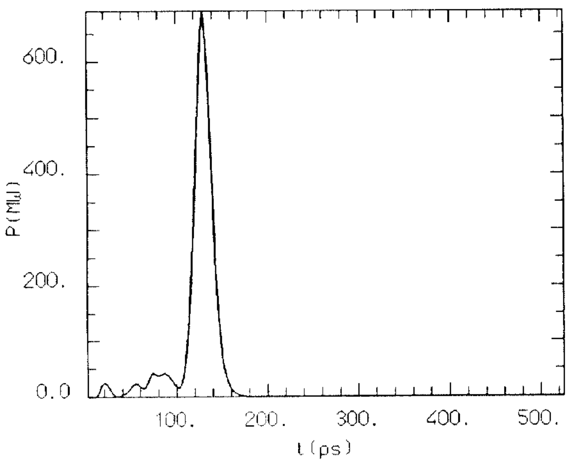

Fig.4 Strong Superradiance with detuning: output power vs time ($b = 1.5$ cm, $\gamma_r = 15.2$, $\gamma_0 = 17$).

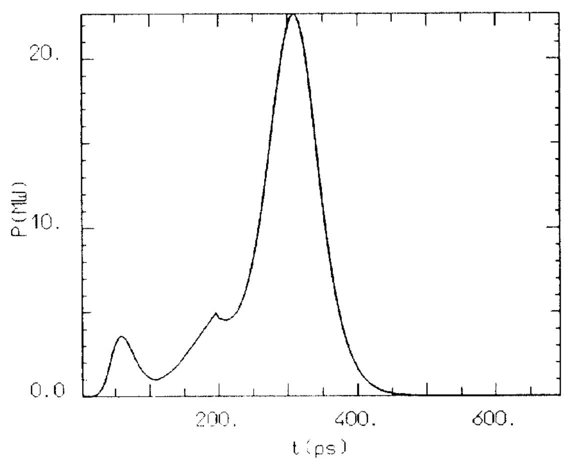

Fig.5 Weak Superradiance: output power vs time ($b = 3$ cm, $\gamma_r = 13.9$).

In order to test the proposed superradiant emission on harmonics[11] it is enough to arrive close to saturation in the first wiggler and then, instead of tapering, tune the second wiggler of ELFA on the n-th harmonic. To do that it is enough to fix the wiggler strength in the second wiggler according to the formula

$$a_{w2} = \sqrt{\frac{1 + a_{w1}^2}{n} - 1}$$

provided that $n < (1 + a_{w1}^2)$ For example, with $a_{w1} = 2.85$ as in ELFA, one gets, for $n = 2$, $a_{w2} \simeq 2$,i.e., $B_w \simeq 2.5\ KG$ and, for $n = 3$, $a_{w2} \simeq 1.4$ and $B_w \simeq 1.8$ KG. If this experiment is successful, it will be a test in view of superradiant generation (Coherent Spontaneuos Emission) of harmonic radiation in the XUV, where the conditions on beam quality are much more restrictive.

3. Conclusions

In this paper we have outlined the experimental set-up and the basic FEL physics in the ELFA project. The main scientific goals of this project are: i) the test of the existence of the new superradiant regime of an FEL; ii) the test of C.S.E. on higher harmonics with a two-wiggler technique. Finally, the experimental study of the high gain FEL scaling laws, lethargy, fluctuation and spectral properties at long wavelength can be a preliminary step necessary before going to more difficult and expensive UV experiments. For its range of frequency, power and energy, ELFA looks particularly interesting for applications to study high gradient acceleration structures and condensed matter physics. A possible extension of the operation range from microwaves to IR has been also discussed.

The conceptual design of injector and accelerator has been completed in a collaboration with Los Alamos and the final definition of the main components of the accelerator will be ready by the end of the year. A preliminary design of the wiggler has been already done and the construction of few periods of a full scale prototype will be completed by the end of the year.

REFERENCES

[1] R. Bonifacio et al. *Nucl. Instr. and Meth. A*, **289**, 1 (1990).

[2] T.J. Orzechowski, R.B. Anderson, W.M. Fawley, D. Prosnitz, E.T. Scharlemann, S. Yarema, D. Hopkins, A.C. Paul, A.M. Sessler and J. Wurtele, *Phys. Rev. Lett.*, **54**, 889 (1985).

T.J. Orzechowski, R.B. Anderson, J.C. Clark, W.M. Fawley, A.C. Paul, D. Prosnitz, E.T. Scharlemann, S. Yarema, D. Hopkins, A.M. Sessler and J. Wurtele, *Phys. Rev. Lett.*, **57**, 2172 (1986).

[3] U. Amaldi and C. Pellegrini, *New Techniques for Future Accelerators*, ed. M.Puglisi, S.Stipcich and G.Torelli, Plenum, 139-162 (1987).

[4] C. De Martinis et al. Contribution to these proceedings

[5] E. Acerbi et al. Contribution to these proceedings

[6] A.M. Sessler, E. Sternbach, J.S. Wurtele, preprint.

[7] R. Bonifacio, C. Maroli and N. Piovella, *Opt. Comm.* **68**, 369 (1988).

R. Bonifacio, B.W.J. McNeil and P. Pierini, *Phys. Rev. A*, **40**, 4467, (1989)

[8] R. Bonifacio and L. De Salvo Souza, *Nucl. Instr. Meth.* A, **276**, 394 (1989).

[9] R. Bonifacio, C. Pellegrini and L. Narducci, *Opt. Comm.*, **50**, 373 (1984).

[10] R. Bonifacio, F. Casagrande, G. Cerchioni, L. De Salvo Souza and P. Pierini, *High-gain High-power Free Electron Laser* (North-Holland, Amsterdam, 1989). pp 35-94 , see also Rivista del Nuovo Cimento, in press.

[11] R. Bonifacio, L. De Salvo Souza, P. Pierini, T. Scharlemann *Nucl.Instr. and Meth. A*, in press