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2 Novembre 1982

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PRELIMINARY RESULTS OF THE ADONE STORAGE RING FEL EXPERIMENT, LELA

Presented to "Colloque International sur les Lasers a Electrons Libres", Bendor 1982

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PRELIMINARY RESULTS OF THE ADONE STORAGE RING FEL EXPERIMENT, LELA (*)

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Résumé - On donne une courte déscription de l'expériment LELA (Laser a électrons libres sur Adone). On discute aussi les résultats des mesures de distribution en angle et en énergie de la radiation spontanée et on donne des résultats préliminaires sur les mesures de gain optique.

Abstract - A short description of the LELA (Free Electron Laser on Adone) experiment is given. Results on the spontaneous radiation angle and energy spectra and preliminary results on optical gain measurements are also discussed.

I - INTRODUCTION

LELA (Laser ad Elettroni Liberi in Adone) is a FEL on a storage ring feasibility experiment and it has been described in some detail elsewhere1),2). The relevant parameters are:

Radiation wavelength	5145 Å
Electron energy	625 MeV
Undulator period	11.6 cm
Number of periods	20
Undulator strength (K_{RMS})	3.5

The undulator, a normal conducting electromagnet3), has been commissioned in June 1982; spontaneous radiation measurements were first performed in July. In this paper we report on the latter measurements and also on the preliminary measurements of gain on the first harmonic, carried out at the beginning of September. Evidence of gain on the third harmonic is also given.

II - THE SPONTANEOUS EMISSION

The spontaneous radiation produced in the undulator has been measured with the apparatus shown in Fig. 1. A more detailed discussion of the spontaneous radiation results will appear in a separate paper.

A Jobin Yvon H25 monochromator, 24 m downstream from the undulator center, and having a wavelength resolution of 10 Å (FWHM) and an angle acceptance of $\sim .17\ (\mu\text{rad})^2$, was mounted on a support equipped with computer controlled horizontal and vertical movements, and used to scan through the spontaneous radiation angular wavelength distributions. Fig. 2 shows the result of a radial scan through the typical4),5) annular radiation pattern, while the first harmonic wavelength distribution is plotted in Fig. 3.

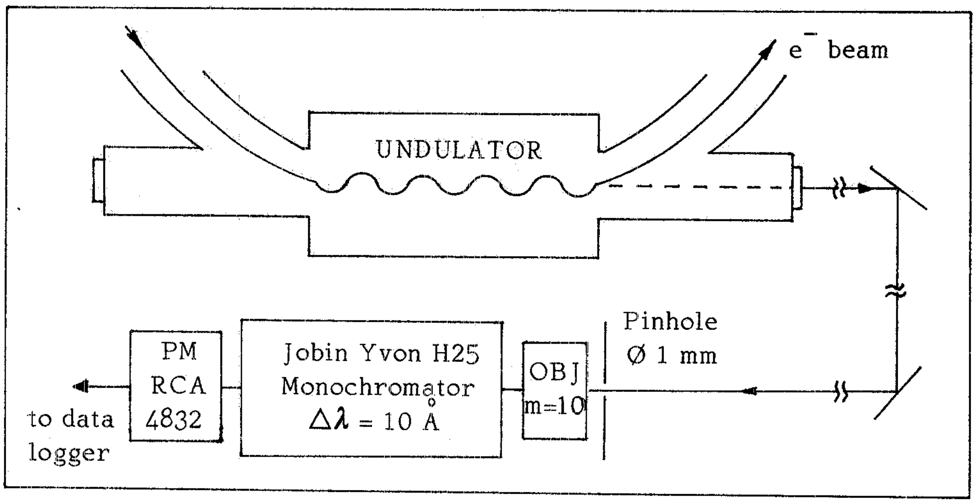

Fig. 1 – Optical setup for spontaneous radiation measurement.

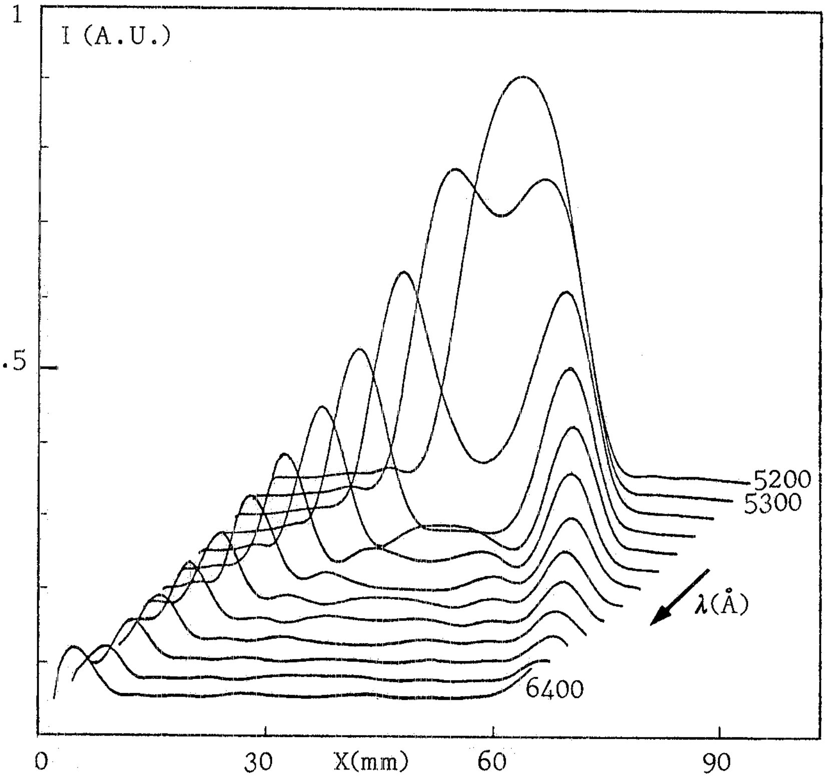

Fig. 2 – First harmonic measured spectral distribution vs. wavelength λ and pinhole position, X, in the radial plane.

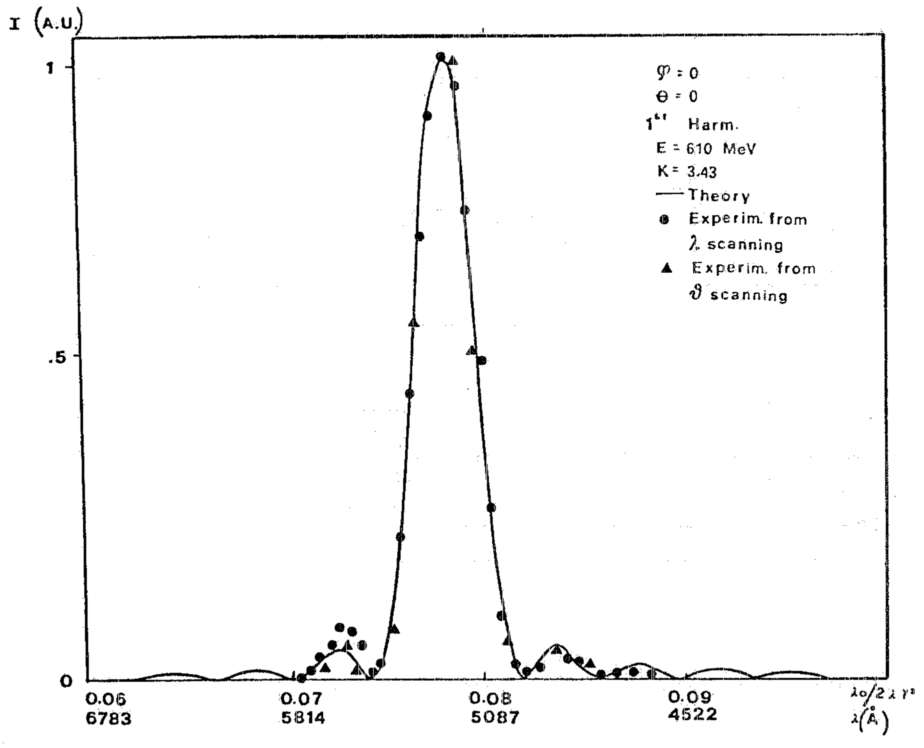

Fig. 3 - First harmonic intensity distribution on the undulator axis, vs. wavelength λ.

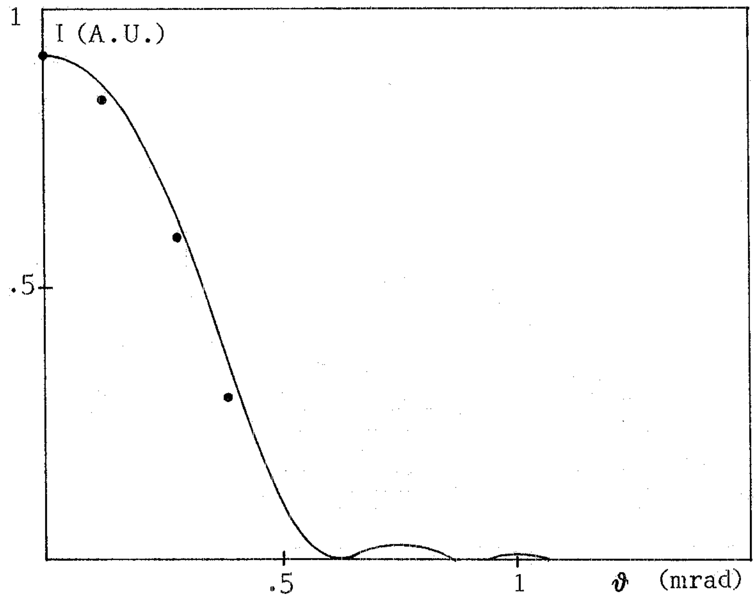

Fig. 4 - First harmonic intensity distribution vs. angle ϑ in the radial plane at $\lambda = 5145$ Å.

Experimental data are well fitted by the theoretical Liénard Wiechert radiation formula$^{5)}$, and the resulting FWHM is consistent with a pure homogeneously broadened line. From this type of data we can deduce that neither the undulator vertical field gradient nor any electron beam trajectory distortion, nor the e-beam emittance and energy spread affect the spontaneous radiation first harmonic linewidth appreciably.

A first harmonic angular distribution in the radial plane is shown in Fig. 4; a good agreement between theory and experimental points is again apparent. We remark here that the FWHM of spontaneous radiation is very close to that of the laser used to perform the gain measurements (see below); in our case therefore to try to discriminate between the two by means of irises is rather ineffective.

III - THE GAIN MEASUREMENTS

The stimulated radiation produced in the interaction between an external laser beam and the electron bunch stored in Adone has been measured as a function of electron beam energy at $\lambda = 5145$ Å, $K_{RMS} = 3.5$, with a double demodulation system similar to the one in use at ACO$^{6),7)}$. We recall briefly its main characteristics.

A CR-12 laser beam, chopped at a frequency $f_o \sim 900$ Hz, is focussed to a waist $w_o = .35$ mm at the undulator mid point by means of a mode matching telescope (Fig. 5). The overall radiation emerging from the undulator is then collected and brought back onto the optical table; it is then spatially and frequency filtered by means of an iris giving a rejection factor of ~ 1.5, and a high resolution monochromator giving a rejection factor of 250. The optical signal detected by a photodiode is then processed by the electronics sketched in Fig. 6. The current from a fast photodiode (either solid-state or vacuum) is converted into voltage in a resonant active load, tuned to the revolution frequency of the e$^-$ bunch ($f_R = 2.856$ MHz), then narrow band amplified and mixed to a L.O. signal with proper phase relationship with the RF accelerating voltage in order to shift the sidebands at the chopping frequency f_o around f_R (which contain

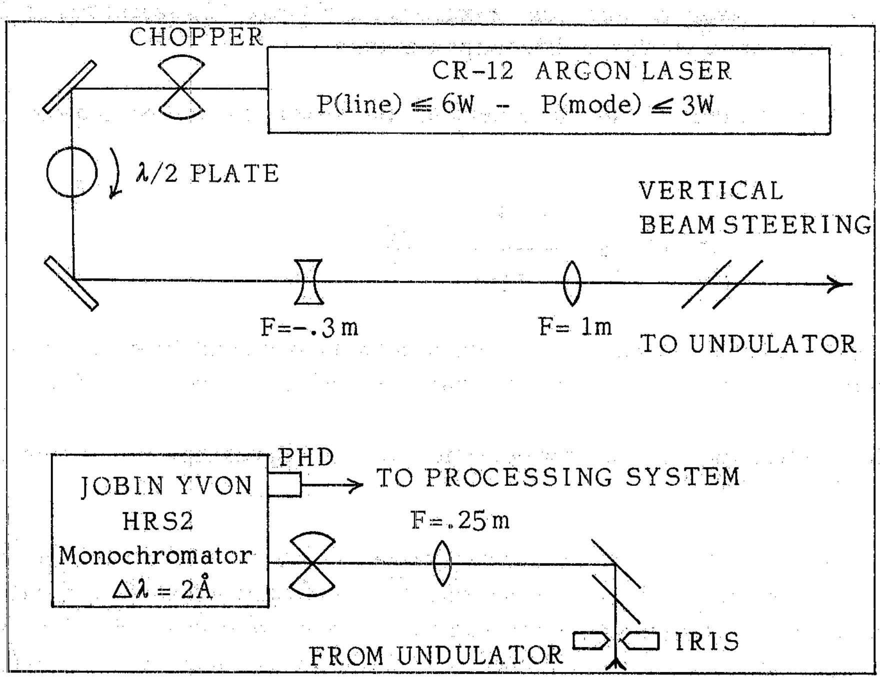

Fig. 5 - Layout of the optics for the gain measurements.

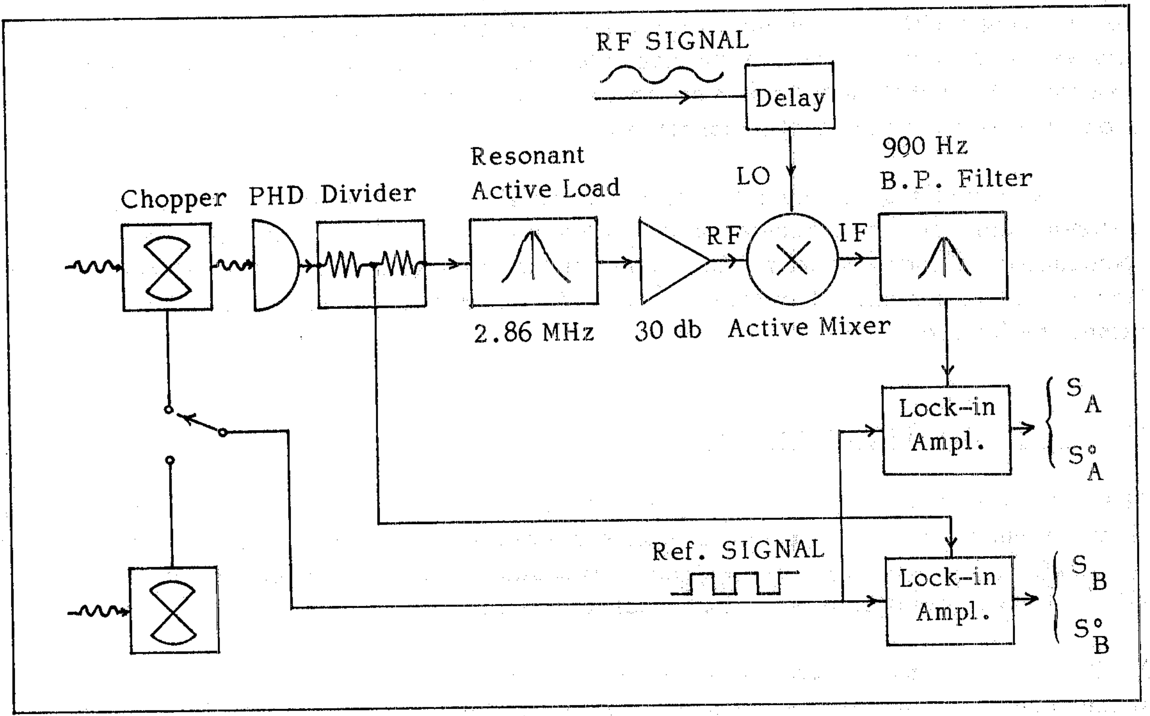

Fig. 6 - Block diagram of the signal processing system.

the stimulated emission information) down to around DC. After further band pass filtering at f_0 the signal is fed to a lock-in amplifier, giving a DC signal, S_A, proportional to the average power of stimulated radiation.

A second signal, derived from a voltage divider in the diode supply circuit is directly fed to a second lock-in amplifier and provides the signal S_B proportional to the incoming laser power. The two channels can be intercalibrated by moving the chopper downstream from the undulator, switching the laser off and measuring signals S_A° and S_B° analogous to S_A and S_B but proportional to the spontaneous radiation power only.

The average gain, defined as the ratio between the stimulated power and the laser beam power is given by:

$$\langle G(E) \rangle \simeq \frac{S_A(E)}{S_B} \cdot \frac{S_B^\circ}{S_A^\circ} \tag{1}$$

The ratio S_B°/S_A° and the signal S_B are practically independent from energy and depend only on the electronics. In our measurements the ratio S_B°/S_A° has a value of $\sim 5\ 10^{-5}$.

The equivalent noise level in our demodulation system corresponds to an average gain in the range from $5\ 10^{-9}$ to 10^{-8}.

During the first set of measurements, reported here, the ratio of stimulated to spontaneous radiation was rather small and the feedthrough$^{6)}$ of spontaneous radiation into the demodulated channel, due to the modulation of the photodiode transfer characteristics by the high power laser beam, produced an important background to the experiment. The unwanted signal ΔW_{sp} produced by the combined action of the laser radiation and the spontaneous radiation has in fact the same time structure as the stimulated radiation. In the frequency domain this background signal appears in the sidebands around f_R, which should, in principle, contain solely

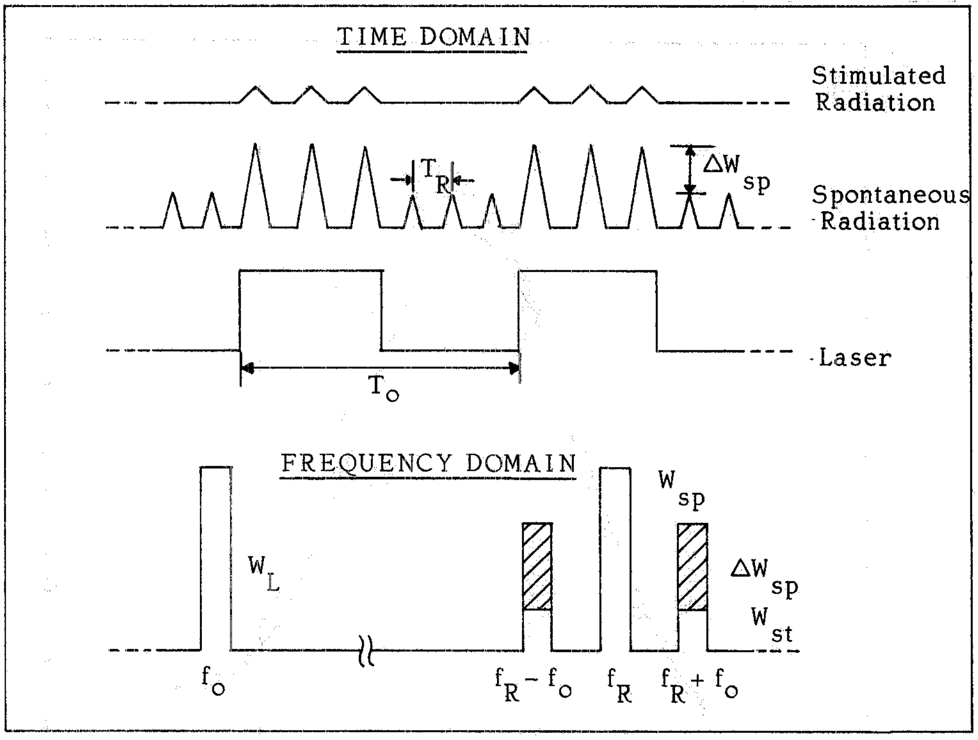

Fig. 7 - Signal behaviour in the time and the frequency domains.

the information from the stimulated power (see Fig. 7). However, the different symmetry of spontaneous and stimulated power with respect to the resonance energy allows the gain to be extracted as a difference between the two curves $S_A(E)$ and $\overset{\circ}{S}_A(E)$. The gain formula (1) must be modified as follows:

$$\langle\!\langle G(E)\rangle\!\rangle \simeq \frac{S_A(E) - \overset{\circ}{S}_A(E)\left[S_A(E_r)/\overset{\circ}{S}_A(E_r)\right]_{\max}}{S_B}\cdot\frac{\overset{\circ}{S}_B}{\overset{\circ}{S}_A} \qquad (2)$$

where the ratio $\alpha = \left[S_A(E_r)/\overset{\circ}{S}_A(E_r)\right]_{\max}$ is evaluated at the resonance energy corresponding to the maximum of the spontaneous radiation curve.

The measured signals, S_A and $\overset{\circ}{S}_A$ are plotted vs. beam energy in Fig. 8, and the result of formula (2), corresponding to the same data is shown in Fig. 9. The solid curve in Fig. 9 is a fit to the data using the energy derivative of the spontaneous radiation curve $\overset{\circ}{S}_A$. The peak gain per pass in this run is:

$$G_{peak} = (.7 \pm .1) \times 10^{-5}$$

having used the measured bunch length.

A number of gain measurements has been performed at various beam currents, as shown in Fig.10. The upper curve is the theoretical small signal gain one would obtain in the hypothesis of maximum filling factor and taking into account the anomalous bunch lengthening in the storage ring and the consequent increase in the beam horizontal dimension due to the fact that, in the lattice configuration so far used, a 2 m dispersion exists in the undulator straight section.

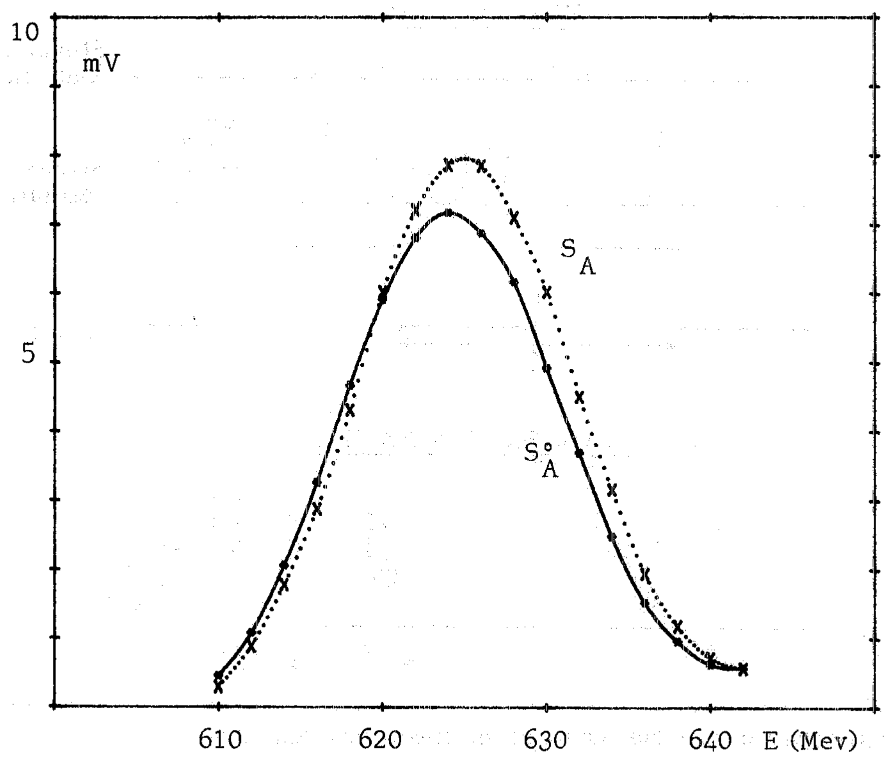

Fig. 8 - Experimental values S_A (laser on) and $\overset{\circ}{S}_A$ (laser off). Electron beam current i = 18 mA in one bunch. The statistical error is not visible on this scale.

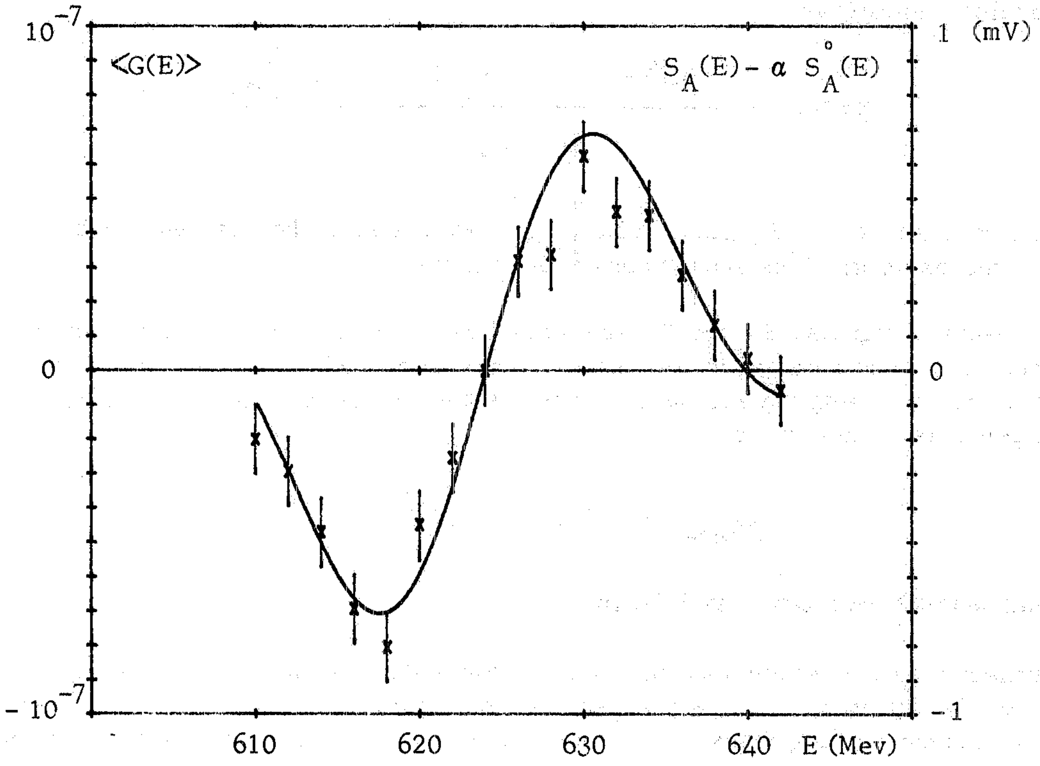

Fig. 9 - Gain signal as obtained from (2), using signals S_A and $\overset{\circ}{S}_A$ of Fig. 8. The solid curve is a fit to the energy derivative of the spontaneous radiation curve $\overset{\circ}{S}_A$. Errors on the experimental points are purely statistical.

The first data points, shown in Fig. 10, are actually rather scattered and considerably lower than the theoretical curve. A possible explanation, consistent with the accuracy with which it was possible during the present experimental runs to align the laser beam on the circulating electron beam, is that a vertical misalignment between the laser and the e-beam centerlines, of the order of 0.5 to 1 mm, existed. This hypothesis will have to be further investigated. The measurements were performed with a single-mode laser power of .5 ÷ 1 W.

A few runs have been carried out on the third harmonic, $\lambda = 5145\ \mathring{A}$ and $K_{RMS} = 3.5$, by lowering the electron resonance energy down to 360 MeV. These data points are also plotted in Fig. 10.

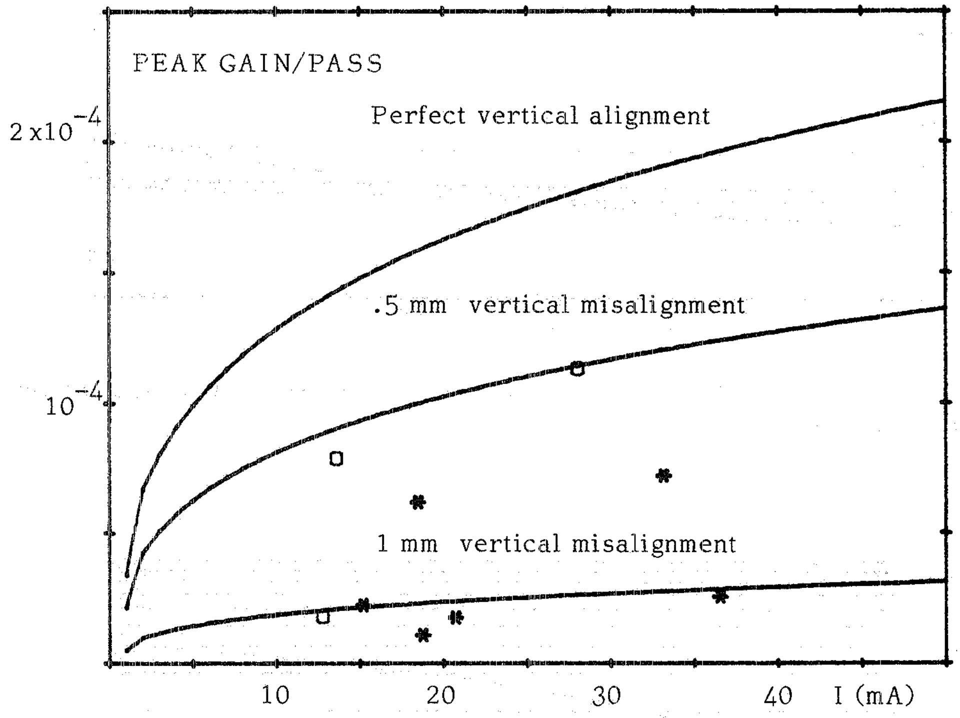

Fig. 10 - Solid curves: Theoretical small signal peak gain/pass for various e-beam and laser beam alignments, on the first harmonic. Stars are experimental points on the first harmonic ($K_{RMS} = 3.5$, resonance energy $E_r = 624$ MeV); squares are experimental points on the third harmonic ($K_{RMS} = 3.5$, $E_r = 360$ MeV).

The uncertainty in the overlap between the electron and the laser beams, prevents us, at the present stage, from drawing quantitative conclusions on the expected 2),8) gain increase relative to the first harmonic.

IV - FURTHER DEVELOPMENTS

A number of improvements are foreseen in order to overcome the experimental difficulties encountered in this set of runs; namely:

- To increase the stimulated-to-spontaneous power ratio at the detector input by adding a Fabry-Perot interferometer having a narrow passband around the stimulated frequency.

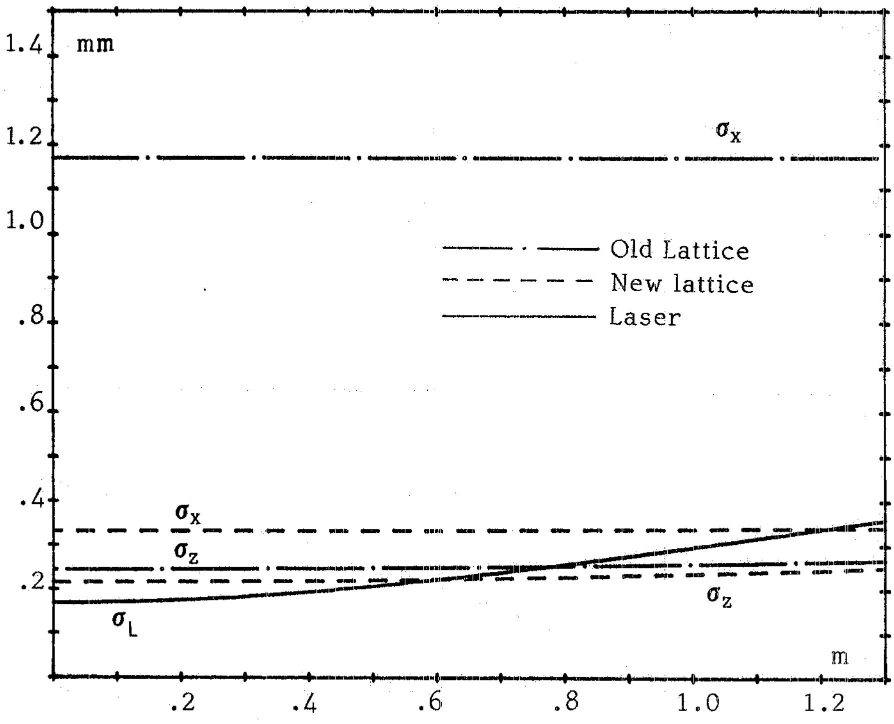

Fig. 11 – Laser beam and electron beam envelopes in the old and the new machine lattice starting from the undulator center.

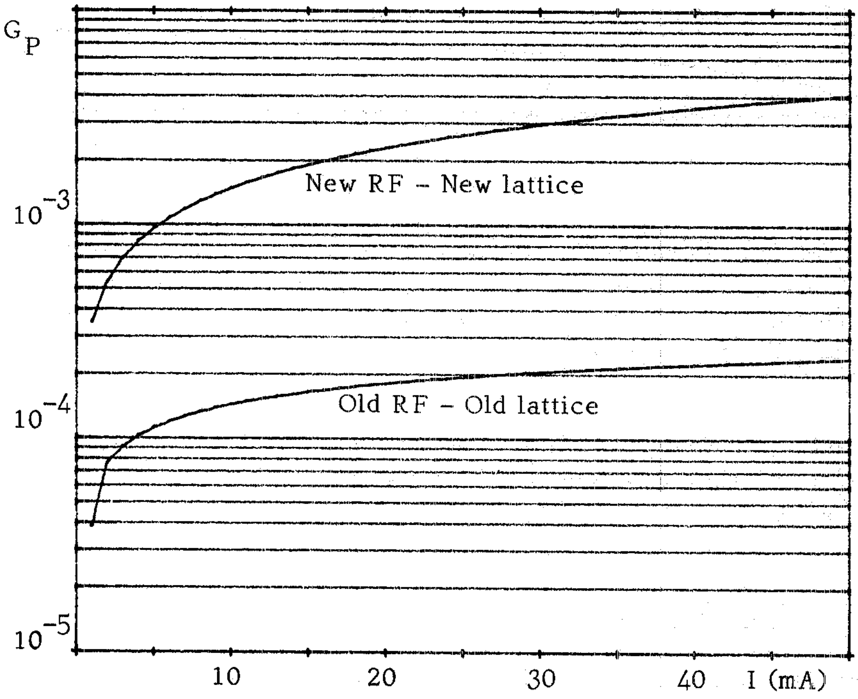

Fig. 12 – Expected peak gain/pass vs. average current on the first harmonic at E_r = 625 MeV, λ = 5145 Å.

We estimate that an additional factor of the order of 20 can be obtained in the spontaneous radiation rejection;

- Improved electron beam and laser beam steering and additional diagnostics are being installed to achieve a more precise alignment between the e-beam and the laser;
- To increase the laser power;
- A new machine lattice$^{1)}$ with vanishing dispersion in the undulator straight section is being commissioned. The laser and the e-beam envelopes are expected to become those shown in Fig. 11, and to yield a net increase in the filling factor and therefore in the gain figure of the order of a factor of five;
- A 51.4 MHz, 180 kV RF cavity already installed and operating in Adone, but temporarily unavailable during the one week shift in which the present work was carried out,is expected to improve the peak gain by a factor of the order of 2 ÷ 3 (see Fig. 12);
- Other minor improvements on windows giving access to the storage ring vacuum chamber, on the detector circuit, the optics and the accelerator controls for this experiment, are in the works.

In conclusion a gain of some units in 10^{-3}, hopefully sufficient for the operation of an oscillating optical cavity, is expected in the next stage of the experiment.

REFERENCES

1) R. Barbini and G. Vignola, LELA: A free electron laser experiment in Adone, Frascati internal report LNF-80/12 (1980).

2) R. Barbini and G. Vignola, Physics of Quantum Electronics, Vol. 8, p. 235, eds. S.F. Jacobs, G.T. Moore, M.S. Pilloff, M. Sargent III, M.O. Scully and R. Spitzer (Addison-Wesley), 1982.

3) R. Barbini, A. Cattoni, B. Dulach, C. Sanelli, M. Serio and G. Vignola, Nucl. Instr. & Meth. 190, 159 (1981).

4) C. Bazin, M. Billardon, D. Deacon, Y. Farge, J.M. Ortega, J. Pérot, Y. Petroff and M. Velghe, J. Physique-Lettres 41, (1980).

5) R. Barbini et al.: Rivista del Nuovo Cimento, Vol. 4, n. 8 (1981).

6) G. Bazin, M. Billardon, D.A.G. Deacon, P. Elleaume, Y. Farge, J.M.J. Madey, J.M. Ortega, Y. Petroff, K.E. Robinson, M. Velghe, Ref. 2, p. 89.

7) R. Barbini, M. Serio, F. Tazzioli and G. Vignola, Apparato sperimentale per la misura del guadagno ottico nell'esperimento LELA con tecniche di demodulazione sincrona, Frascati internal report LNF-81/70 (1981).

8) W.B. Colson, IEEE J.Q.E., QE-17, 1417 (1981).

POSTER SESSION

THE LELA UNDULATOR: MAIN FEATURES AND PERFORMANCE

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ABSTRACT

The LELA plane undulator installed on Adone is a 20 period normal conducting electromagnet; the wavelength is 11.6 cm and the magnetic field can be as high as 5.0 kG on axis. It is tunable over the entire field range.

The measured field has an almost ideal cosine-like behaviour longitudinally; the large transverse dimension of the poles (34.8 cm) ensures a large magnetic field flat top radially. The excellent field quality is confirmed by the measured spontaneous radiation spectral lines which exihit a purely homogeneous bradening.

An other important feature is the possibility of rearranging the field pattern to produce for instance an Optical Klystron configuration by simply reversing the current flow in some of the coils.

All the above advantages are obtained at the expense of a rather high power consumption at the normal operating point: 500 kW at B = 4.5 kG. The consequent thermal drift causes a drift in the field that has to be compensated by means of a feed-back system. The system utilizing a Hall plate has demonstrated to work satisfactory and allows the magnetic field setting to be accurately reproduced and kept constant to within the required precision.

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