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Results of the free electron laser oscillation experiments on the ACO storage ring

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Résumé. — On a fait fonctionner un laser à électrons libres sur anneau de stockage à 6 500 Å de longueur d'onde. L'effet laser a été obtenu avec des électrons de 166 MeV circulant dans l'anneau de stockage ACO. La lumière émise par les électrons lorsqu'ils passent à travers un klystron optique (une version modifiée de l'onduleur) est stockée dans une cavité optique à faibles pertes. On analyse tout d'abord les phénomènes sous le seuil. La seconde partie décrit les caractéristiques spectrales et macrotemporelles du laser. On montre que la puissance moyenne est en accord avec la limite imposée par le chauffage du paquet d'électrons (limite de Renieri). Finalement une augmentation d'un facteur 100 de la puissance crête, a été obtenue en asservissant le laser à un générateur extérieur de signaux basse fréquence.

Abstract. — A storage ring free-electron laser oscillator has been operated above threshold at a visible wavelength $\lambda \simeq 6\,500$ Å. This laser was obtained with electrons of 166 MeV circulating in the storage ring ACO. The light emitted by the electrons passing through an optical klystron (a modified version of an undulator) is stored in a high-Q optical cavity. First some below laser threshold phenomena are reported. Then the spectral and macro-temporal structure of the laser are described. The average power is shown to be consistent with the limit imposed by the heating of the electron beam (Renieri's limit). Finally a factor of 100 enhancement in the peak power, over the Renieri's limit, has been obtained by driving the laser with an external low frequency generator.

In recent years, much attention has been given to radiation emitted by relativistic electrons. This is principally synchrotron radiation in a dipole field [1], in an undulator [1] or from a free electron laser. The free electron laser (F.E.L.) is a very promising source of coherent radiation in the spectral range from the far I.R. to the V.U.V.; the earliest proposals for such a device were made by Ginzburg [2] and Motz [3].

There are basically two classes of F.E.L. One type

operates in the « collective » regime where the electronic density and Coulomb interaction are very strong, the electron energy is rather low (a few MeV) and the radiation is emitted in the far I.R. [4]. The order class operates in the low density or « Compton » regime, where Coulomb interactions are negligible, the energy is high ($10\text{-}10^3$ MeV) and the emission comes at short wavelengths (I.R., Visible, U.V.). Our experiment belongs to the second category. This type of F.E.L. has been studied by Madey [5] and his group at Stanford where the first laser action was achieved in 1977 in I.R. [5]. Since that time many theoretical and experimental studies have been done on this subject [6].

Most F.E.L. experiments involve either linear accelerators and microtrons [7] or electron storage rings [8]. One expects the storage ring D.E.L. to reach much shorter wavelengths, particularly in the U.V.

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and V.U.V. spectral range. Our experiment is the first example of an F.E.L. working on a storage ring. We have recently reported the first operation of the laser [9]. In this paper we described in more detail the operation of the F.E.L., its behaviour as a driven pulsed laser and the interpretation of its macro-temporal structure. We have used the Orsay storage ring ACO, an « old » machine, first operated in 1965. Its characteristics for this experiment are given in table I.

Table I.

ACO characteristics in the F.E.L. experiment	
Energy	160-166 MeV
Circumference	22 m
Bunch to bunch distance	11 m
Electron beam current for oscillation	16 to 100 mA
R.M.S. bunch length σ_1	0.5 to 1 ns
R.M.S. bunch transverse dimensions σ_x, σ_y	0.3 to 0.5 mm
R.M.S. angular spread σ'_x, σ'_y	0.1 to 0.2 mrad
R.M.S. relative energy spread	0.9 to 1.3×10^{-3}
Electron beam life time	60 to 90 min
R.F. frequency	27.2361 MHz

The core of an F.E.L. is an undulator (periodic transverse magnetic field) on passage through which high energy electrons radiate a series of harmonics of a fundamental line of wavelength, λ , given by :

$$\lambda = \frac{\lambda_0}{2\gamma^2} \left[1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right] \quad (1)$$

where γ is the electron energy normalized to their energy at rest, λ_0 the undulator period and θ the angle of observation with respect to the electron trajectory axis. K is the deflection parameter of the undulator given by :

$$K = \frac{eB_0 \lambda_0}{2\pi m_0 c} = 93.4 B_0 \lambda_0 \text{ in S.I. units} \quad (2)$$

where B_0 is the peak undulator magnetic field, e and m_0 the electron charge and mass. The characteristics of our undulator/optical klystron are listed in table II.

A light beam of convenient wavelength in coincidence with an electron beam is amplified when passing through an undulator. The magnitude of the optical gain was first calculated by Madey [5]. We have measured the gain of the Orsay undulator made with 17 periods of 7.8 cm [10] placed on the ACO storage ring working at 240 MeV. The stimulating light was an argon laser at 5 145 Å. The measured gain value was near 2×10^{-4} [11]. This gain is too small to achieve laser oscillation; therefore, we have transformed our undulator into an optical klystron [12](O.K.). This is done by replacing the 3 central

Table II.

Optical klystron characteristics

Overall length	1.3 m
Type	SmCo5 permanent magnets

Undulators

Number of periods	2×7
Period	78 mm
Transverse pole width	100 mm
Minimum magnetic gap	33 mm
Maximum field	$0.31 \frac{1}{2}$ T
K	0 to 2.3

K in the F.E.L. experiments	1.1 to 1.2
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Dispersive section

Length	240 mm
Maximum field	0.58 T
N_d (see text)	70 to 100
N_d in the F.E.L. experiments	95

periods of the undulator by a longer period, analogous to a 3-pole wiggler, called the dispersive section. The rôle of this section is to « bunch » the electronic density faster than a regular undulator [12]. Therefore, the optical klystron gain, $G_{o.k.}$ is larger than the gain $G_{und.}$ of the undulator of same length by a maximum factor of :

$$\frac{G_{o.k.}}{G_{und.}} \approx \frac{3.6 \times 10^{-3}}{\sigma_E/E} \quad (3)$$

where σ_E/E is the R.M.S. relative energy spread of the electrons circulating in the ring.

The synchrotron light emitted by the O.K. exhibits a characteristic modulation [13] which is shown on figure 1a. The optical gain (Fig. 1b) which by virtue of the Madey's theorem [14] is the derivative of the spontaneous emission with respect to energy, also appears modulated. For a given fundamental wavelength $G_{o.k.}/G_{und.}$ depends on the magnetic gap and on the energy spread. The measured value confirms a predicted factor of 4 gain enhancement at 240 MeV and 1×10^{-3} energy spread.

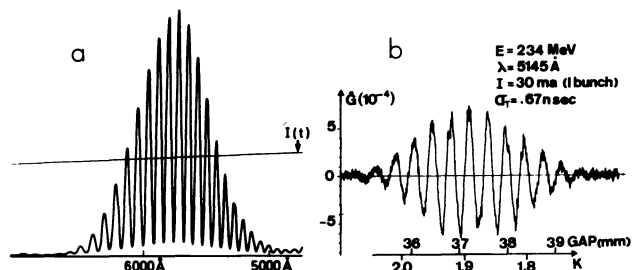


Fig. 1. — (a) On axis spectral distribution of the optical klystron spontaneous emission measured using 240 MeV electrons and a magnetic gap of 34.4 mm. (b) The corresponding gain curve versus magnetic gap measured with an external laser.

In this paper we present results obtained with our optical klystron working at a low electron energy (166 MeV). This energy range was chosen in order to minimize the cavity mirror degradation due to V.U.V. emissions [11] from the undulator and dispersive section.

The light emitted by the O.K. was stored in the highest-Q optical cavity that we could obtain (Table III). The measured average round trip losses

Table III.

Optical cavity characteristics	
Length	5.5 m
Mirror radius of curvature	3 m
Rayleigh range	1 m
Wavelength of maximum Q	620 to 680 nm
Average mirror reflectivity at 6 328 Å	99.965 %
Round trip cavity losses at 6 328 Å	7×10^{-4}
Mirror transmission	3×10^{-5}

for the mirrors that we used were near 2×10^{-4} at 6 328 Å when the mirrors were in the air. However when placed in the ultra-vacuum of the cavity and irradiated with the light produced by the undulator or optical klystron the losses grow rapidly [11]. At 240 MeV the degradation drives the losses almost instantaneously above 1 or 2×10^{-3} . However it is possible to operate the O.K. at lower electron energy by increasing the magnet gap (thereby decreasing K) in order to keep the emitted wavelength near 6 500 Å, wavelength of maximum reflectivity for the mirrors used in these experiments. A lower K decreases the harmonics content of the undulator emission and therefore the U.V. flux received by the mirrors. The O.K. was finally operated at $K = 1.1$ to 1.2 with a dispersive section characterized by [13] $N_d \simeq 95$ where N_d is the number of laser optical wavelengths passing over an electron in the dispersive section.

At a low energy of 150 MeV, after an initial degradation the losses were stabilized near $(7 \pm 1) \cdot 10^{-4}$. At this energy the optical gain is only slightly smaller than the losses and very interesting « below threshold » phenomena may be observed (§ 1). At higher energy (160-166 MeV) an intense amplification of the stored emission is observed (laser effect). The various characteristics of the laser are detailed in § 2 and discussed in § 3.

1. Below threshold phenomena (150 MeV).

When the optical cavity mirrors are set parallel to each other, the spontaneous emission of the O.K. is stored in the cavity. The resulting optical spectrum (Fig. 2, lower curve) is the spontaneous emission spectrum modified by the phase shifts of the various cavity transverse modes in which it is stored [15] and by the output mirror transmission. When the cavity length is exactly matched with the electron round-trip time

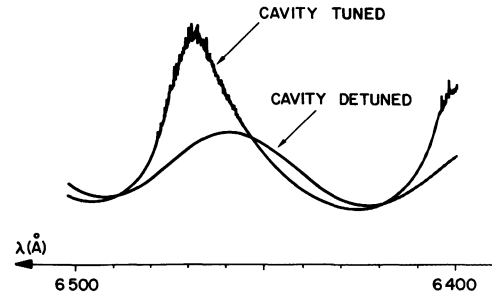


Fig. 2. — Fine structure spectrum of the stored spontaneous emission from the optical klystron. The « cavity tuned » curve is obtained for a perfect time synchronism between light and electron pulses in the cavity. The « cavity detuned » curve is obtained for complete desynchronization. Gain and absorption appear on the higher and lower wavelength side of the maximum.

in the ring the cavity is considered to be « tuned ». Then amplification of the stored spontaneous emission occurs through the gain mechanism mentioned above. One clearly sees in figure 2 an amplification at $\lambda \simeq 6 470$ Å by a factor close to 2 and an absorption at $\lambda \simeq 6 440$ Å by a factor 0.8. This amplification occurs at several wavelengths along the spontaneous emission curve with a maximum depending mostly on the mirrors reflectivity curve. The spectral distribution of the amplified beam is no longer proportional to the derivative of the stored spontaneous emission because of the non-linearity of the multipass amplification when the gain value is close to the cavity losses. Also the noise that can be seen at the top of the amplified curve is clearly related to the fact that we are very near the laser threshold. A small gain variation produces a large amplification variation. By aligning the optical cavity axis and the electron beam trajectory within 0.1 mm, a maximum amplification ratio of 3 has been observed for a 50 mA ring current. Figure 3 shows horizontal and vertical transverse profiles of the stored spontaneous emission recorded at $\lambda \simeq 6 470$ Å, corresponding to the most amplified wavelength. The net amplification (obtained by subtracting the cavity detuned curve from the cavity tuned one) has a profile very close to the fundamental cavity TEM_{00} profile.

The amplification is a sharp function of the adjustment of the cavity length. The dependence of its value *versus* the detuning of this length is shown on figure 4. The amplification as a function of the mirror displacement from the tuned position, δ , can be computed by summing the contributions over the electron positions (characterized by δ_0) inside the electron bunch and over a quasi-infinite number of pass, n , in the optical cavity. Let $F(\delta)$ be that sum, then :

$$F(\delta) = (1 - \bar{R}^2) \int \sum_{n=0}^{\infty} \bar{R}^{2n} \times \\ \times \prod_{p=0}^n [1 + g_p f(\delta_0 + 2p\delta)] f(\delta_0) d\delta_0 \quad (4)$$

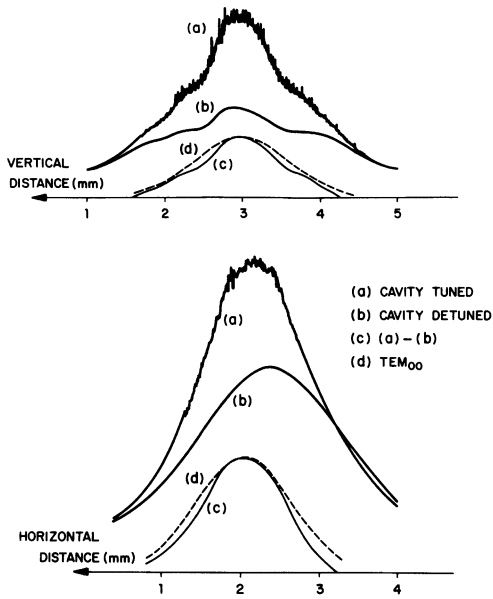


Fig. 3. — Horizontal and vertical profiles of the stored spontaneous emission at the wavelength of maximum gain. The difference between the « cavity tuned » and « cavity detuned » curves show a good agreement with the cavity TEM₀₀ profile.

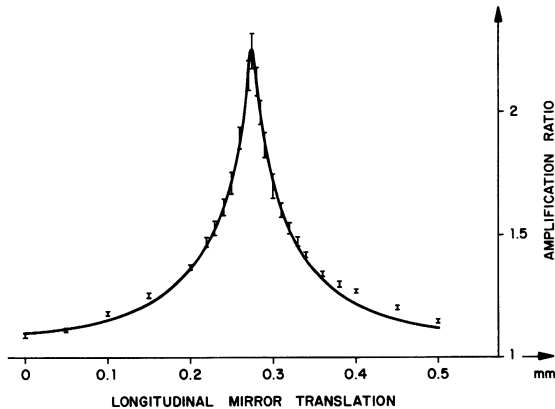


Fig. 4. — Maximum on axis amplification ratio versus cavity length. The dark curve shows the theoretical prediction for 0.23 m R.M.S. bunch length, 3.6×10^{-4} average loss per mirror and 5.1×10^{-4} peak gain per pass.

where \bar{R} is the average reflectivity per mirror, $f(\delta_0)$ is the normalized shape function of the electron bunch and g_p the peak gain at the wavelength considered. From (4) one deduces :

$$F(\delta = \infty) = 1 \quad \text{and} \quad F(\delta = 0) = \int \frac{f(\delta_0) d\delta_0}{1 - \frac{g_p f(\delta_0)}{1 - \bar{R}^2}} \quad (5)$$

valid for $g_p < 1 - \bar{R}^2 = P$.

For a uniform distribution of the electrons inside the bunch (5) reduces to :

$$F(\delta = 0) = [1 - g_p/P]^{-1}.$$

This would yield $g_p/P = 0.60$ in the case of figure 4 (amplification by 2.5). In our case (Gaussian electronic distribution) the integral has been computed numerically using the measured R.M.S. bunch length of 0.23 m. The best fit to the experimental results shown in figure 4 was obtained for $P = 7.2 \times 10^{-4}$ (close to the measured value of 7.0×10^{-4}) and $g_p/P = 0.71$.

Very good agreement has also been found in the tail of this detuning curve showing a significant amplification of 1.02 for a detuning as high as 0.8 mm.

2. Above threshold phenomena.

At 166 MeV laser oscillation is obtained by a careful alignment of the electron beam on the cavity axis (within 0.1 mm and 0.1 mrad) and maximization of emission as a function of the storage ring R.F. cavity voltage and the optical cavity length. Laser operation requires very precise synchronism between the light pulse round trip frequency and the bunch revolution frequency. To avoid backlash and mirror misalignment, fine tuning was performed by slightly changing the R.F. frequency instead of translating the mirrors. Laser oscillation lasted typically 1 h after each electron injection.

Due to the weak gain/loss ratio the cavity length (or R.F. frequency) is a very crucial parameter. Figure 5 shows two « detuning curves » of laser power (normalized to the maximum) versus R.F. frequency variation and equivalent mirror displacement. Curve (a) has a 3.4 μm F.W.H.M. of equivalent mirror displacement; curve (b), recorded much closer to laser threshold, has only a 1.6 μm F.W.H.M. The shift in displacement between curves (a) and (b) is probably

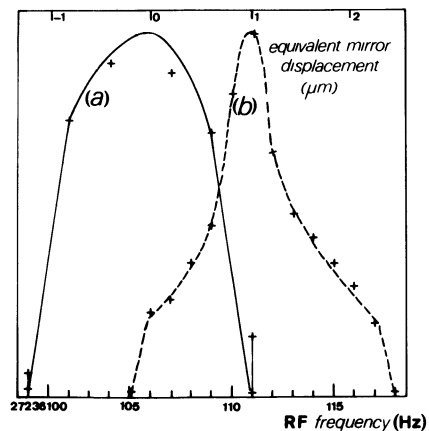


Fig. 5. — Normalized laser power as a function of R.F. frequency and equivalent mirror displacement. Curve (a) is recorded close to the maximum gain/loss ratio and curve (b) close to the laser threshold. The shift between the two curves is probably due to some slight cavity length drift. The upper scale has to be multiplied by a factor 2.

due to a slow cavity length drift (a temperature drift of 0.02 °C in 30 min would be sufficient). However the length of the cavity was stable enough to allow laser operation without adjustments during typically more than half an hour.

The horizontal and vertical transverse profiles of the laser mode are very close to the cavity TEM₀₀ mode (Fig. 6) as expected from the below threshold measurement. The small observed discrepancies may arise from some residual instability of the laser too close to threshold or from non uniform mirror reflectivity.

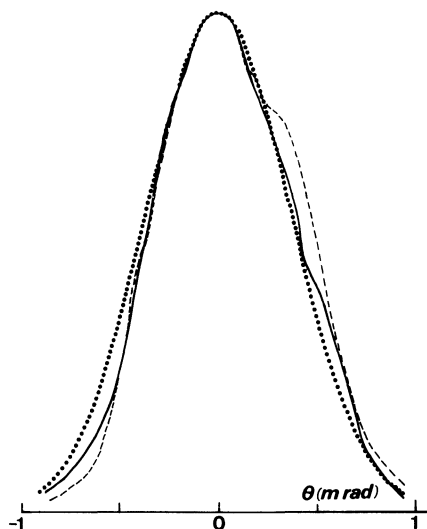


Fig. 6. — Experimental laser horizontal (—) and vertical (- - -) transverse profiles and the calculated (...) cavity TEM₀₀ profile

The laser exhibits a particular time structure : (i) it is pulsed at the ACO storage ring frequency (27.2 MHz with two bunches in the ring), (ii) its structure on a long time scale (of the order of 1 s) is quite irregular as shown by the photograph in figure 7a, (iii) the laser may be triggered by an external low-frequency generator (Fig. 7b). This will be discussed in section 3.

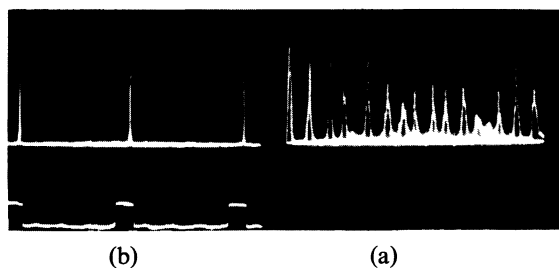


Fig. 7. — Laser time structure over a 200 ms total interval, (a) « natural » time structure ; (b) time structure when the electron beam transverse position is modulated (upper trace). The vertical scale is 1/4 the scale on (a) (see text).

Figure 8 presents two spectra : (a) is recorded without amplification (optical cavity completely detuned), (b) is recorded at laser operation (cavity tuned).

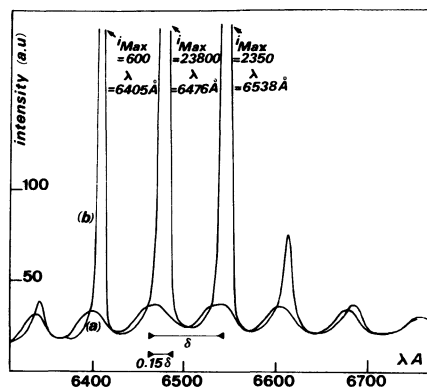


Fig. 8. — Spectra of the cavity output radiation under two conditions : (a) cavity detuned (no amplification), (b) cavity tuned (laser on).

For case (b), the laser oscillates at three wavelengths, with a strongly dominant one at $\lambda = 6\,476\text{ \AA}$; each wavelength is located at a maximum of the gain versus wavelength curve [5]. Typical laser lines are Gaussian if averaged over a long time scale of $\geq 1\text{ s}$ with 2 to 4 Å F.W.H.M.

The central wavelength of any line is always equal to the wavelength of maximum emission of spontaneous emission with the cavity completely detuned (no amplification) plus 0.15 of the wavelength interfringe distance (see Fig. 8) instead of 0.25 as predicted from Madey's theorem [14]. This discrepancy is probably due to the transverse multimode content of the spontaneous emission stored in the cavity; laser operation is only achieved on the TEM₀₀ mode. Laser tunability was obtained between 640 nm to 655 nm by changing the magnetic gap (equivalent to a change of K in Eq. (1)). The range of tunability is limited for the moment by the mirror reflectivity bandwidth.

The laser spectrum has also been recorded on a Reticon diode array. The laser was driven by the Reticon « start » signal in order to synchronize the laser pulses with the Reticon read out. For a driving frequency of $\sim 800\text{ Hz}$, as discussed in section 3, the laser pulse intensities were unstable and it was observed that the higher the pulse the narrower its spectral line. For the higher pulses the observed spectral width is less than 1 Å (Fig. 9) well below the above mentioned spectral width.

In the experiments the gain is not directly proportional to the electron current, mainly due to the anomalous bunch lengthening and energy spreading at high current. These effects make that the gain versus ring current reaches a broad maximum near 50 mA and then decreases. However despite this effect and despite the irregular pulsed time structure described above the laser average power is very stable and depends almost linearly on the ring current as shown by the recording of figure 10. This fact shows clearly that the free electron laser has saturated and reached its equilibrium average power.

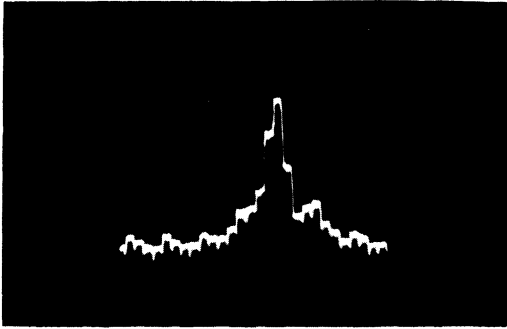


Fig. 9. — Recording of the spectral distribution of a laser pulse on a reticon diode array. The laser was driven at a frequency of 8.8 kHz (see text). Each diode corresponds to 0.3 Å in wavelength which is also the spectral resolution of the monochromator used.

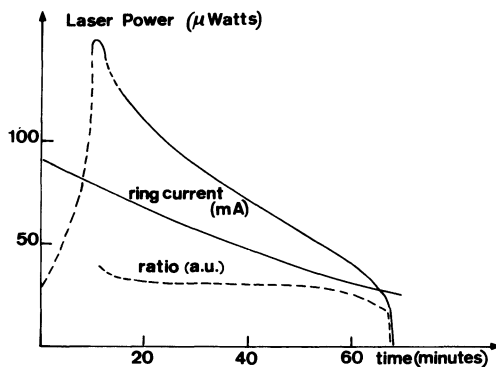


Fig. 10. — Recording of the laser average output power together with the ring current. The ratio of the two quantities is a constant on most of the laser operation range.

3. Laser saturation and peak power enhancement

It has been shown that storage ring F.E.L. would saturate by laser induced electron energy spread which would decrease the gain by inhomogeneous broadening [16]. The energy spreading is also expected to lengthen the electron bunch and decrease the peak density and therefore the peak gain [17]. Renieri [16] has shown that the average power (P_a) is a fraction η of the total synchrotron radiation (P_s) emitted by a single bunch in the whole storage ring. η represents the laser efficiency since it is the ratio between the laser power and the Radio Frequency (R.F.) power given by the R.F. cavity to the electron beam to compensate for the power lost by electrons by synchrotron radiation emission. η has been calculated for a weakly saturated optical klystron to be (18) :

$$\eta = \eta_c \frac{f}{2\pi(N + N_d)} \text{Ln}(g_0/P)$$

where

$$\eta_c = \frac{\text{output mirror transmission}}{\text{round trip cavity losses}} \quad (7)$$

η_c is the cavity efficiency, f is the optical klystron

modulation rate [13], N is the number of periods of one of the two identical undulators constituting the optical klystron, g_0/P is the ratio between the start-up peak-gain and the round trip cavity losses.

The laser output power always decreases with the electron beam current and, except in regions too close to threshold, is usually proportional to the current (see Fig. 10). Such a result is in good agreement with the theory since P_s is proportional to the current but η is only weakly dependent. A typical 75 μW average output power has been recorded at 50 mA current of 166 MeV electrons; this corresponds to an efficiency $\eta = 4.8 \times 10^{-5}$ with respect to the 1.55 W of single bunch total synchrotron radiation. Taking the following measured quantities, $\eta_c = 0.047$ (due to the high absorption losses in the dielectric layers of the mirrors compared to the transmission), $f = 0.7$, $N + N_d \simeq 100$ and assuming $g_0/P = 3$, one calculates $\eta = 5.7 \times 10^{-5}$.

Considering the errors in the calibration of ring current and power meter and the uncertainty in the determination of g_0/P , one concludes in the good agreement of the measured average power with the one predicted by theory [18]. This theory does not consider the anomalous bunch lengthening and energy spreading as observed on ACO and on almost every storage ring. The most striking example of this anomalous behaviour was the observed bunch shortening and electron energy spread reduction at the initial laser start-up. Although, as we shall see later, the bunch lengthens when the laser saturates as predicted by the theory.

The rather low average output power is therefore the result of the weak total synchrotron radiation power at 166 MeV, the low cavity efficiency and the high sensitivity of the optical klystron to the energy spread.

Figure 7a shows the observed F.E.L. time structure over a 200 ms time interval. The irregular time structure of the laser is the result of the large difference in magnitude between the fast laser rise time, τ_m , of the order of 50 to 100 μs , and the slow response time τ_s of the electron beam, which is 200 ms at 166 MeV. It has long been anticipated that at the instant of laser turn-on in a storage ring laser, the power would dramatically overshoot the equilibrium value and perhaps oscillate until the electron beam had a chance to stabilize at a level which saturates the gain. Our results show that such an equilibrium may be very difficult to obtain due to fluctuations in the gain. Elleaume [19] has recently studied the stability of the laser, and found that although the equilibrium situation is stable, it is only weakly damped. The laser operation is resonant at a period T_r of the order of $2\pi\sqrt{\tau_s\tau_m/2}$ (15-25 ms for these experiments as shown in Fig. 7a), and even a very small fluctuation of the electron energy spread, the bunch length, or the electron beam position with this period will cause the laser to pulse on and off.

In more than 15 successive experimental runs, involving ring currents ranging from 80 to 15 mA, continuous operation has never been observed. The laser always pulses in an irregular, pseudo-periodic fashion with a period of 10 to 25 ms. Sometimes, the peaks are more or less modulated at the ring synchrotron frequency (~ 13 kHz).

As a consequence of this high sensitivity to gain fluctuations, the laser may be triggered by an external low-frequency signal. Stable pulsed operation has now been achieved by modulating either the transverse beam position or the R.F. frequency. Figure 7b shows a single trace of the laser output when the transverse position of the electron beam is periodically displaced. The peak power has been increased by a factor of 4 over that of figure 7a; the horizontal time scale is the same. This result was obtained by turning on the gain long enough for the pulse to develop, heat the beam, and decay, and turning it off again for a long time to allow the beam to cool down. A vertical displacement of $160 \mu\text{m}$ is enough to turn off the laser. The beam motion is adiabatic with respect to the betatron motion in the ring, so the transverse dimensions are not affected by the periodic orbit distortion. Stable driven pulses have also been obtained by modulating the R.F. frequency back and forth from the synchronism condition, but this procedure presents the disadvantage of inducing synchrotron oscillation of the electron bunch.

When driven by beam displacement as shown in figure 7b, pulse widths less than 1 ms are obtained with periods from 1 to 60 ms. No change in the average power is observed over this range, although the peak power can be adjusted by more than a factor of ten. A peak power 100 times larger than the average power has been obtained so far.

This pulsed operation of the laser allows another test of the saturation theory. Figure 11 presents the laser pulse structure together with a signal proportional to the bunch length. The bunch length measurement technics is described in [17]. A negative variation corresponds to a bunch lengthening. One clearly sees a fast bunch lengthening induced by the laser pulse followed by a slow relaxation time. The bunch length curve appears to be the integral of the laser pulse shape. These results were precisely predicted to occur with energy spread [18] and therefore

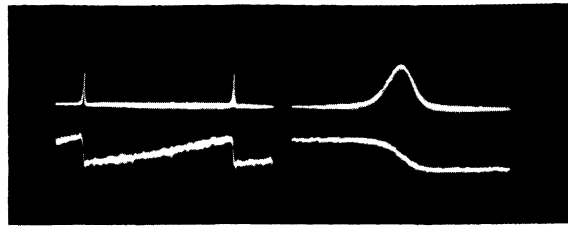


Fig. 11. — Time recording of the laser intensity (upper trace) together with the bunch length evolution (lower trace). A negative signal corresponds to a lengthening of the bunch. The total time interval is 100 ms for the left picture and 5 ms for the right one.

bunch length since energy spreading automatically induces a bunch lengthening in a time of the order of the synchrotron period (0.08 ms) which is much shorter than the pulse duration.

Therefore the laser time structure can be understood by a simple model [19] where the fast increase in energy spreading is responsible of the off-equilibrium behaviour of the system. The energy spread evolution has been verified experimentally through the time-resolved recording of the electron bunch length. Moreover we have shown that this off-equilibrium laser behaviour offers an opportunity to drive the laser intensity by an external trigger and to obtain a pulsed laser without any loss of average power.

The experiments will continue in the future to analyse the short time structure of the laser with a streak camera. Also higher gain/loss ratios are expected to be obtainable at higher energy and from the use of better mirrors, a second R.F. cavity and positrons instead of electrons. This should extend the range of tunability of the laser towards the U.V. region.

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