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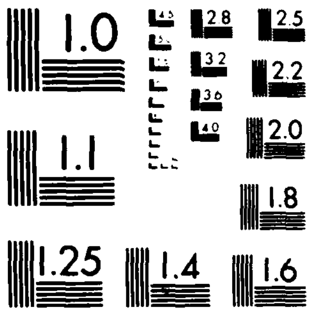

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ABSTRACT

To improve the gain in the Orsay storage ring free electron laser experiment, the seventeen periods permanent magnet undulator was modified into an optical klystron. We report the laser induced bunch lenghtening and the gain measurement on the optical klystron and compare them to the undulator case.

INTRODUCTION

This work is a part of the results of the LURE STANFORD collaboration undertaken in 1979 to examine the faisability of a free electron laser (FEL) using the storage ring ACO at Orsay.

In a first step a superconducting undulator was built and installed on the storage ring, several studies were conducted. The spontaneous emission of the system was observed [1], the optical gain as a function of the electron energy [2,3] and the laser induced bunch lengthening of the electron bunch were also measured, these results have already been reported [4].

The second step consisted in the contruction of a permanent magnet Halbach type undulator - optical klystron [7-8-11] optimized at 240 MeV, the injection energy of A.C.O., this work has already been reported [5].

Here we shall compare the bunch lengthening and the gain measurements made with the undulator and the optical klystron. For a planar undulator, the gain reads :

$$G = \rho\, r_0\, \lambda_0^2 \frac{8\pi^2 n K^2 N^3}{\gamma^3} [JJ]^2 \left[\frac{1 - \cos x - \frac{x}{2}\sin x}{x^3}\right] \quad (1)$$

λ_0 : undulator period
N : period number of the undulator
ρ : electron density
K : wiggler parameter ($e B_0 \lambda_0 / 2\pi mc$) B_0 magnetic field
n : harmonic number
r_0 : classical radius of the electron (e^2/mc^2)

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γ : electron total energy divided by the electron rest energy
x : resonance parameter = $4\pi n\, N d\gamma/\gamma$

$[JJ]^2$: bessel function $[J_{n-1/2}(\xi) - J_{n+1/2}(\xi)]^2$ with $\xi = n\, K^2/(4 + 2K^2)$
where J_n stands for the n^{th} order bessel function.

Note that the charge density ρ the square of the undulator period λ_0^2 and wiggler parameter K^2 and the cube of the period number N^3 give a good idea of the magnitude of the gain. Therefore the gain is proportional to the charge density and of course the gain is inversly proportional to the bunch lengthening.

The first order effect of the FEL interaction is to induce an energy modulation in the electron beam, the electron being accelerated or decelerated according to the sign of their initial phase with respect to the laser. This effect is very important on a storage ring free electron laser (SRFEL) where this energy modulation increases the energy spread which accumulates from pass to pass. Energy spreading naturally leads to bunch lengthening [6] and contributes to saturate the gain by reduction of the electron density. In case of low gain such as in the ACO experiment it is expected to be the main saturation mecanism.

To improve the gain we have modified the undulator into an optical klystron [7-8]. The optical klystron consists (Fig. 1) in an undulator with the central section replaced

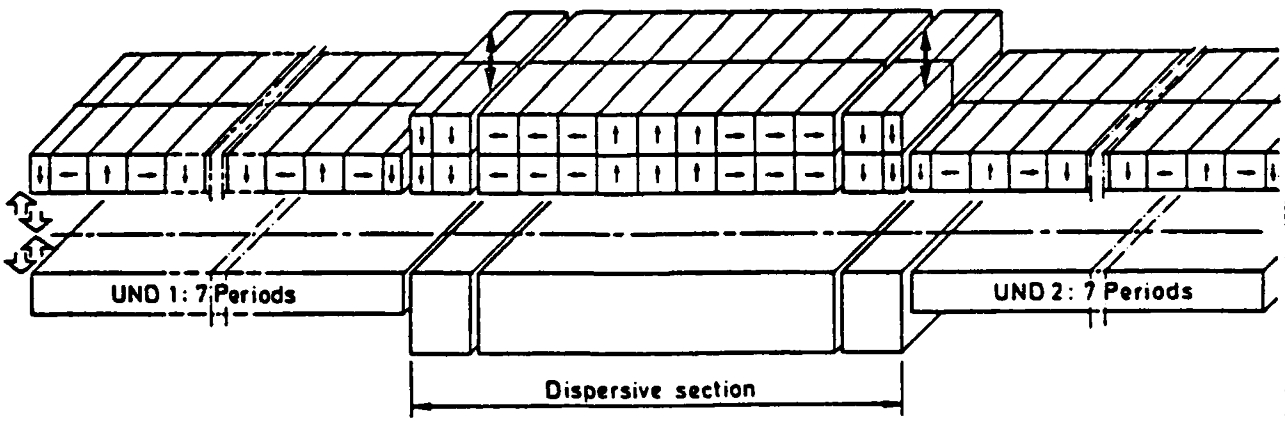

Figure 1 - Optical klystron magnet configuration.

by a dispersive element in which high energy electrons travel a shorter distance than the low energy ones. The dispersive section greatly increases the micro bunching of the relativistic electrons and as a consequence increases the gain.

Essentially the first undulator section modulates the electron energy, the dispersive section transforms the energy modulation into a spatial bunching, and the third section gives a high gain with the modulated beam.

Figure 2 presents calculated spontaneous emission and gain curves for an undulator and an optical klystron having the same total number of periods. The sinusoïdal like fine structure is due to the interference of the synchrotron radiation emitted by the same electron in the two undulator sections.

To investigate the SRFEL saturation mechanism namely the bunch lengthening we have developped a sensitive method [9] to measure the laser induced change in the electron bunch length.

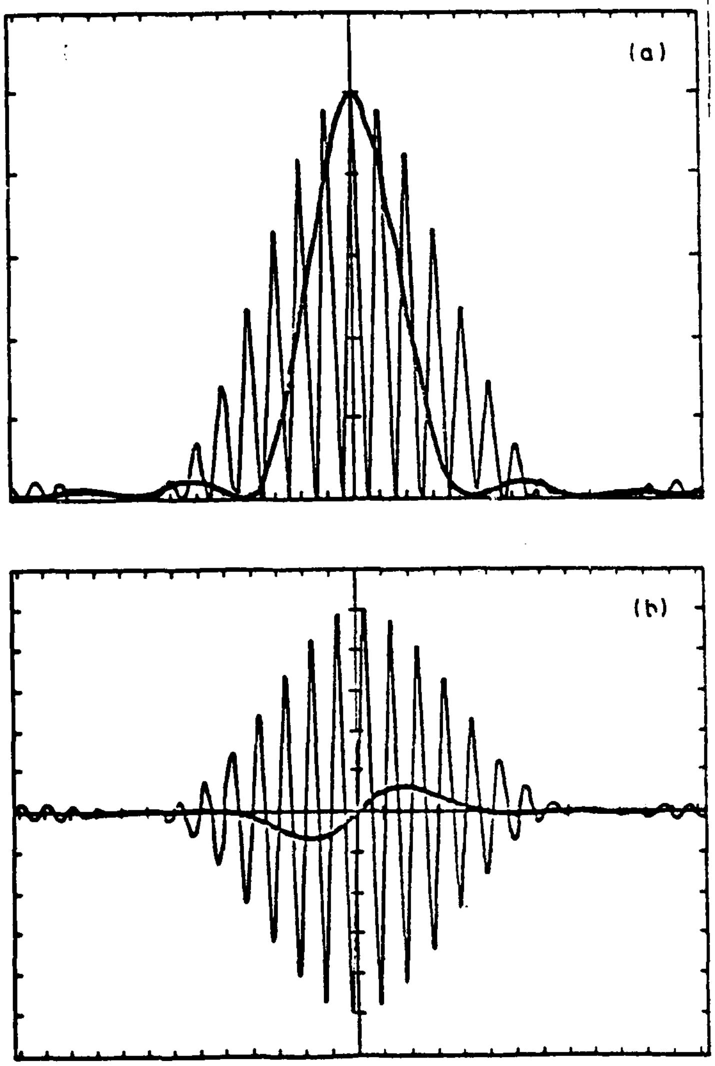

Figure 2 -

a) Spontaneous emission :

- oscillating curve with the dispersive section
- smooth curve without dispersive section

b) Gain :

- oscillating curve with the dispersive section
- smooth curve without dispersive section.

EXPERIMENTAL PROCEDURE

The experimental set up is shown in figure 3. An argon ion laser is coupled to the electron beam in the magnetic structure through a mode matching telescope system and an optical transport system. Synchrotron light from a bending magnet on the ACO storage ring is detected by a fast photodiode and the signal is sent to a spectrum analyser, lock in amplifier or averaging oscilloscope, chart recorder and computer.

The synchrotron light emitted by the electron, consists in a serie of periodic pulses whose period is fixed by the orbit frequency, and which shape is the electron bunch shape. The spectrum of the signal from the photodiode will be a comb spectrum which envelope is the fourier transform of the electron bunch shape convoluted with the photodiode's response.

Under idealized conditions the electron bunch shape should be a gaussian and the fourier transform of the synchrotron light should have a gaussian envelope.

The power spectrum $F(\omega)$ of the photodiode output will have the form :

$$F(\omega) = P(\omega) \exp - 1/2\ \omega^2\sigma^2$$

where $P(\omega)$: response of the measuring system
σ : the temporal bunch length
ω : the detection frequency.

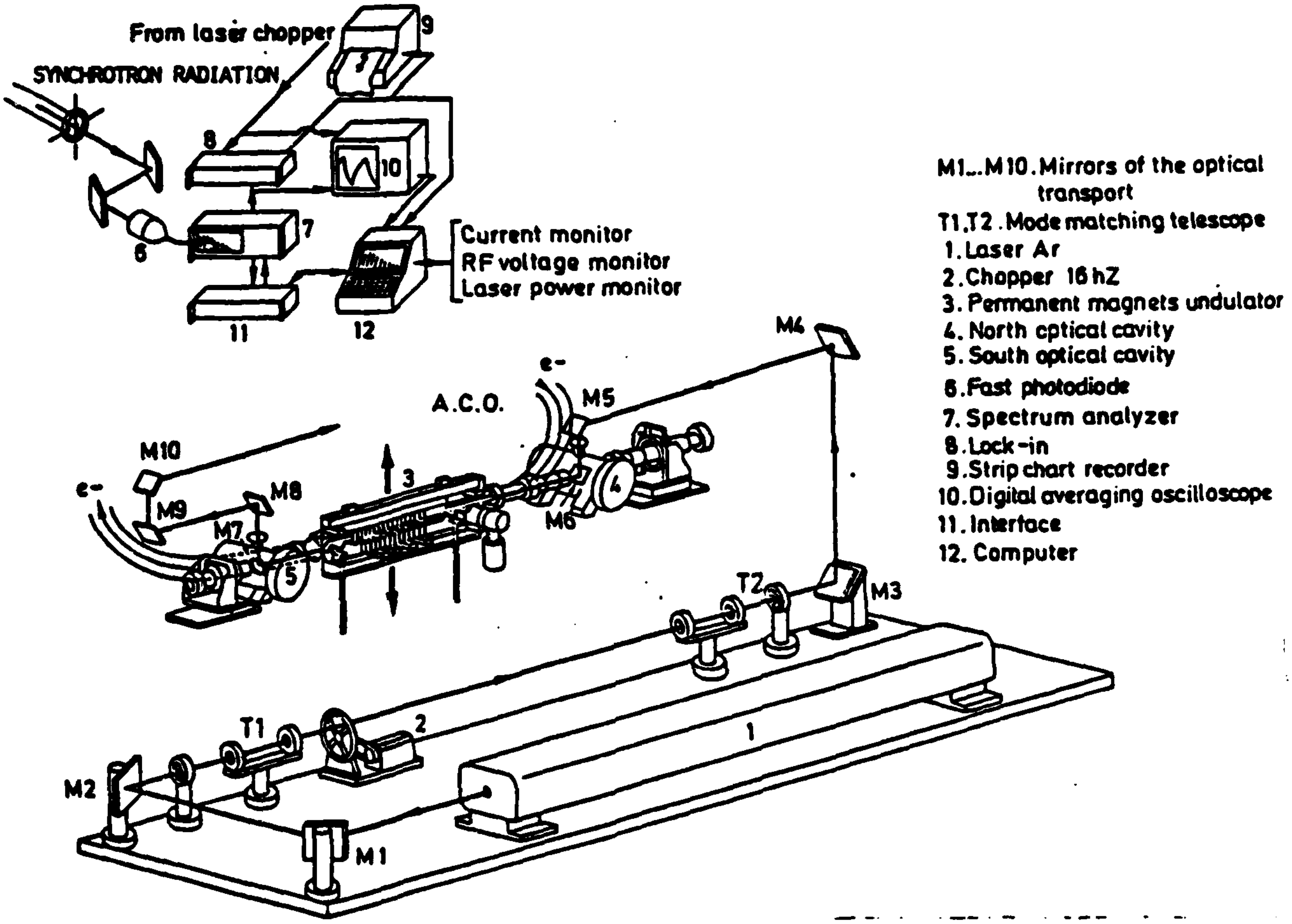

Figure 3 - Schematic of the bunch lengthening experiment.

If the detection frequency is fixed and the temporal bunch length change from σ_i to σ_f (Figure 4) the fractional signal change as :

$$\text{Log}\,\frac{F_f(\omega)}{F_i(\omega)} = -\frac{1}{2}\,\omega^2(\sigma_f^2 - \sigma_i^2) \qquad (2)$$

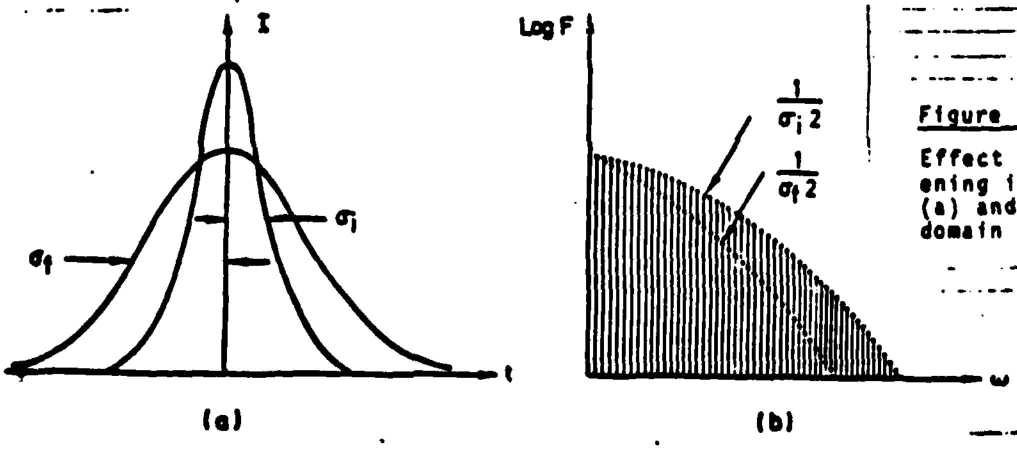

Figure 4 - Effect of the bunch lengthening in the time domain (a) and the frequency domain (b).

The fractional change in signal amplitude is determined by the absolute change in the bunch length and scales as the square of the detection frequency. Note also that the fractional change in the detected signal is unaffected by the response of the photodiode, because $P(\omega)$ is absent of the final formula.

EXPERIMENTAL RESULTS

1/ Bunch lengthening measurement :

Figure 5 shows the time averaged response of the electron bunch length to the chopped external laser in the low current region (less than 1 mA total average current). Note that a fall in $F(\omega)$ in Figure 5 signifies an increase in the bunch length. This response is the same for the undulator and the optical klystron.

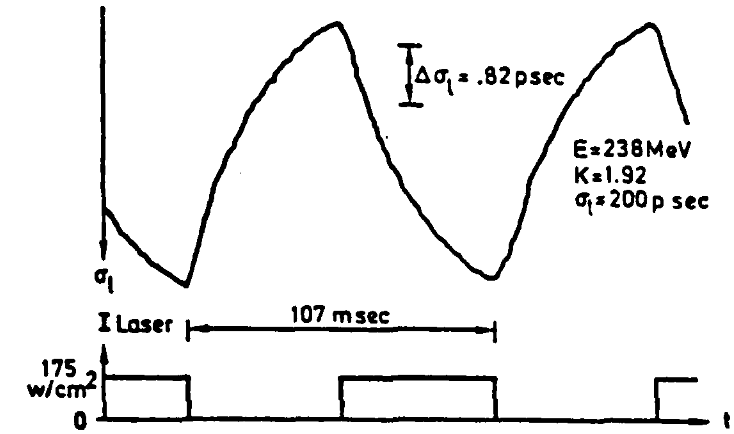

Figure 5 - Time averaged response of the electron bunch length at low current. The upper trace shows the time dependence of Log $F(\omega)$, the power output of the photodiode detector at 1062,2 MHz harmonic of the orbit frequency. As described in the text, an increase in the bunch length reduces the amplitude of Log $F(\omega)$. The lower trace records the laser intensity incident on the electron beam.

The exponential response of the bunch lengthening is due to the storage ring damping time. The DC lengthening under this conditions was 5 % which is in good agreement with the theoretical prediction. However at high current there are important deviations from the simple stochastic theory which require the inclusion of more complicated behaviour in the storage ring with the free electron laser interaction.

Figures 6 and 7 show the experimental spontaneous emission and bunch lengthening at the external laser wavelength as a function of the gap between the pole faces of the permanent magnet undulator and optical klystron. The results are in good agreement with the theorem demonstrated by Madey [10] that the mean squared energy spread is proportional to the spontaneous power spectrum.

2/ Gain measurement :

We have measured the gain with an external laser, the experimental method has already been described [2-3-4]. A typical gain profiles versus the gap on the undulator K parameter is shown in Figure 8 : (a) is a gain with the seventeen periods undulator and (b) with the optical klystron. As expected from Madey's theorem [10] the gain is roughly the derivative of the spontaneous emission curve (Figures 6(a) and (b)). The absolute gain is in very good agreement with the predicted one. The optical klystron gives a gain enhancement by a factor up to 7 [12] (according to the energy and ring current) compared to the original 17 periods undulator. Moreover the maximum DC bunch lengthening measured as function of the magnetic gap is about the same for the undulator and the optical klystron. The optical klystron gives a higher gain than the undulator for the same bunch lengthening, confirming the prediction that the SRFEL should have more power with the optical klystron than with the undulator [8] since bunch lengthening is expected to be the main saturation process.

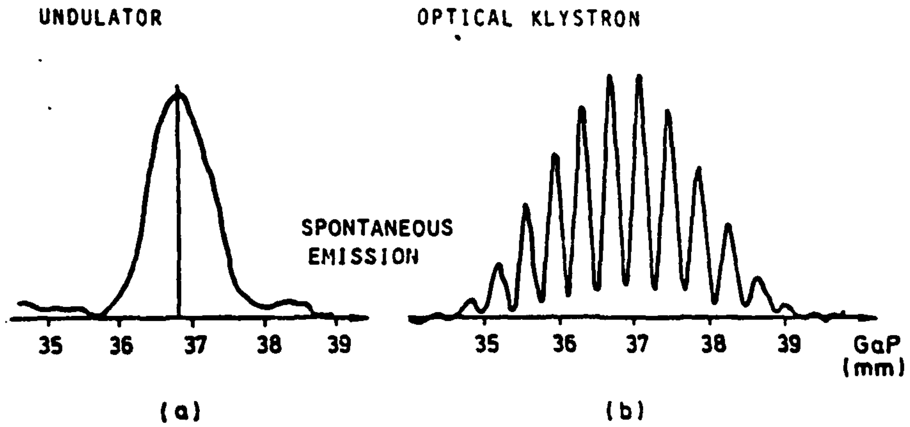

Figure 6 -

Spontaneous emission as function of the gap in mm for the seventeen periods undulator (a) and the optical klystron (b).

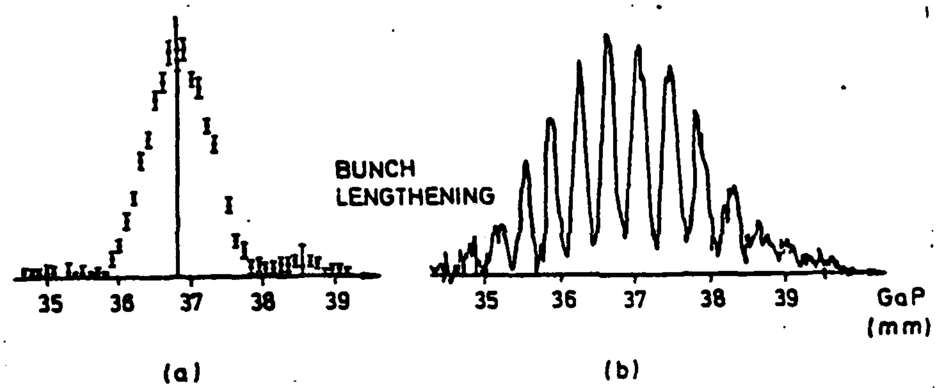

Figure 7 -

Laser induced bunch lengthening as a function of the gap in mm. As predicted from first Madey's theorem, bunch lengthening is proportional to the spontaneous spectrum.

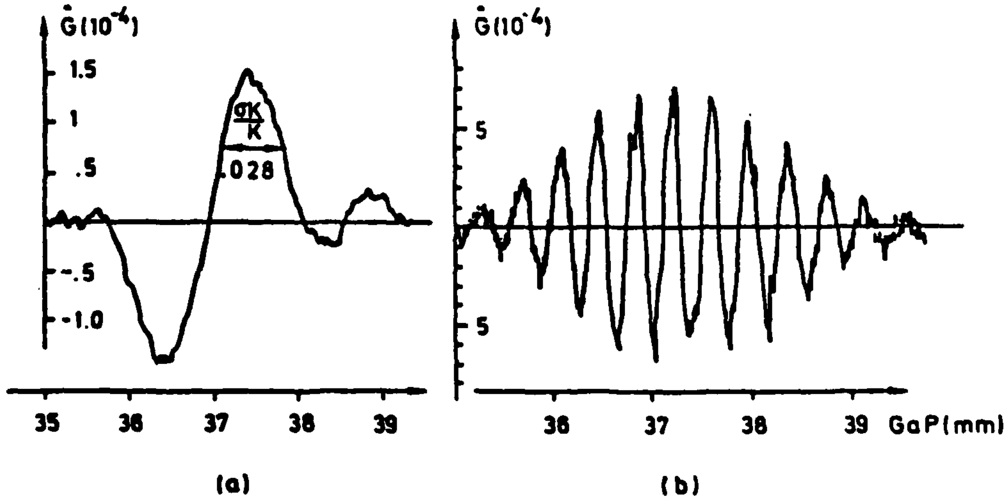

Figure 8 -

Gain profiles versus magnetic gap measured on an argon laser. As predicted from a second Madey's theorem, these curves are roughly the derivative of the spontaneous emission ones.
(a) λ = 4880 Å
(b) λ = 5145 Å
with electron bunch
(a) I = 30 mA (2 bunches)
(b) I = 30 mA (1 bunch)
with the energy
(a) E = 243 Mev
(b) E = 234 Mev
with the bunch length
(a) σ = .52 ns
(b) σ = .67 ns

CONCLUSION

We have measured bunch lengthening with the seventeen periods undulator and the optical klystron. The results have shown, at low current a good agreement between theory and experiment as far as the spectral shape and amplitude of the curve are concerned. However at high current regimes are dominated by anomalous bunch lengthening effects.

The magnitude of the gain and its dependence on the magnetic gap are also in a very good agreement with the classical theory.

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