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F. Tazzioli and G. Cavalieri: HIGH POWER LIGHT PULSES
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1. - INTRODUCTION. -

The nuclear physics experiment called LADON, which is being prepared at the Frascati National Laboratories⁽¹⁾, for the generation of monochromatic rays from the interaction of a laser beam with the electrons circulating in a storage ring, requires high peak power light pulses (some hundreds of watts) of some nanosecond length (< 10 nsec) and a repetition period of 117 nsec.

One of the methods to obtain such pulses is to lock the phases of the modes of oscillation of the electro-magnetic field in a laser cavity by the insertion of a periodic perturbation, of frequency $\nu = c/2L$ (where c is the velocity of light and L the length of the cavity) on the beam trajectory⁽²⁾. Once locking has occurred the light circulating in the cavity is concentrated in a pulse that bounces between the end mirrors. The half maximum width of the pulse is about $(N\nu)^{-1}$, where N is the number of modes above threshold. The optical spectrum of such an oscillation is a set of lines of steady amplitude, whose frequency separation is $c/2L$.

To obtain a period of 117 nsec between two consecutive transits of the pulse at a given point on the trajectory the length of the cavity must be 17.55 m. The problem is therefore to obtain high peak power pulses in a long laser cavity. Besides the problems of mechanical stability, that will not be discussed here because they have been already treated⁽³⁾, we have to solve the problems of the choice of the perturbing device (or modulator) and of maximization of the peak power of the light pulses as a function of the parameters of the modulator itself. In the following pages we shall describe the type of modulator that has been implemented and we shall discuss the results obtained.

2. - THE MODULATOR. -

It is known that the mode-locking frequency range is very narrow ($\Delta\nu/\nu \approx 5 \times 10^{-5}$) (see Fig. 1 where the locking threshold is shown as a function of frequency) and the intensity of the perturbation must be such as to bring the laser operation near to extinction (i. e. the loss introduced by the modulator on the beam must be of the order of the single pass gain in the laser medium which is of the order of 30%)⁽⁴⁾.

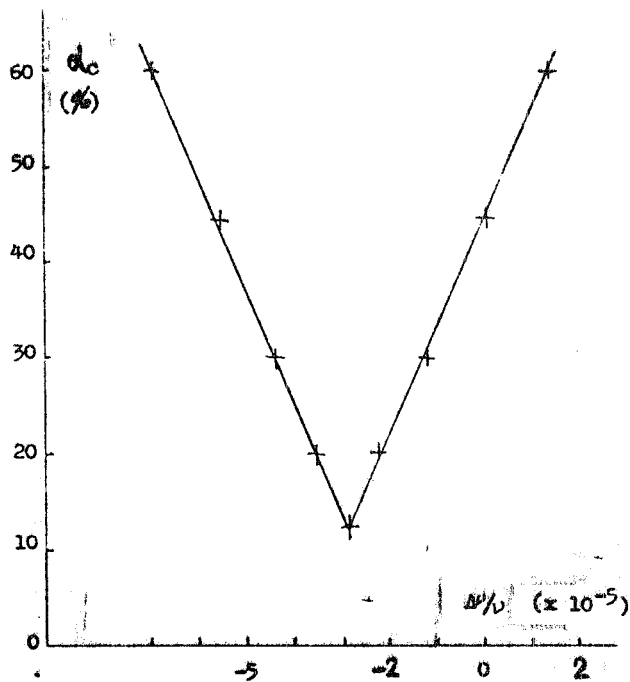


FIG. 1 - Locking threshold as a function of frequency.

The perturbation may be a phase or a intensity modulation; both may be obtained by exploiting the electro-optic effect in crystals of special materials or by exciting acoustic waves in some transparent amorphous substances by piezo-electric transducers.

The electro-optic effect, by modifying the refraction properties of crystals, allows implementation of both phase and intensity modulators⁽⁵⁾, but its magnitude is remarkable only in crystals of special materials (KDP, etc.) which are difficult to work to the required surface finishing, and it is evidenced only by very high electric fields (of the order of kilovolts/mm). We

have therefore deemed it advantageous to employ, for laboratory tests, the acousto-optic effect in a synthetic quartz crystal. The acoustic waves that interact with the light beam have been generated by the piezo-electric effect in the crystal body. This technique is much simpler than the usual one of surface transducers; it only requires the application of an R. F. voltage across the body of the crystal itself by simple electrodes.

The crystal is X-cut, 3.5 mm thick along the some axis, it has a dimension of 35 mm along the Y axis and 15 mm along the Z axis. The acoustic waves are excited by an R. F. field along the X axis. The light beam propagates along the Y axis with its electric vector polarized along the X axis. The incidence faces are cut at the Brewster angle. It is known that il these conditions the crystal can vibrate extensionally along the X axis with a standing elastic wave pattern to which is associated a similar variation of the refractive index of the medium. A diffraction grating is thus formed that deflects periodically the light beam in the direction of propagation of the elastic waves.

The fundamental vibration frequency of the crystal is $f_0 = v/2s$, where s is the thickness and v is the sound velocity along the X axis ($v \cong 6 \times 10^3$ m/sec). It is known that, if the light beam has a characteristic incidence angle θ_B (Bragg angle) with the sound wave direction, the beam is partially deflected through an angle $2\theta_B$. There subsists the following relation:

$$\text{sen } \theta_B = \frac{\lambda}{2\Lambda} \quad , \quad (1)$$

where λ is the wavelength of light and Λ the acoustic wavelength. The intensity of the deflected beam, referred to the incident one, is⁽⁶⁾:

$$\frac{I_1}{I_0}(t) = \text{sen}^2 \sigma l \quad , \quad (2)$$

where:

$$\sigma = \sqrt{2} \left(\frac{\Delta n}{n} \right) \frac{\pi}{\lambda \cos \theta_B} (1 - \cos 2\Omega t)^{1/2} \quad ,$$

l = length of interaction ,

n = refractive index ,

Ω \cong acoustic angular frequency.

Note that the beam intensity is modulated at a frequency which is double of that of the acoustic wave. To obtain a high deflection efficiency with an interaction length of some centimeters, variations of the refractive index of the order of $\Delta n/n \cong 10^{-6}$ are needed. Very high electric fields would be needed to obtain such variations in a non-resonant regime. On the contrary, to excite a mechanical resonance of the crystal much lower fields are sufficient. As the thickness s has a lower limit due to machining difficulties, the crystal is made to oscillate on a harmonic. In Fig. 2 is shown the deflection efficiency

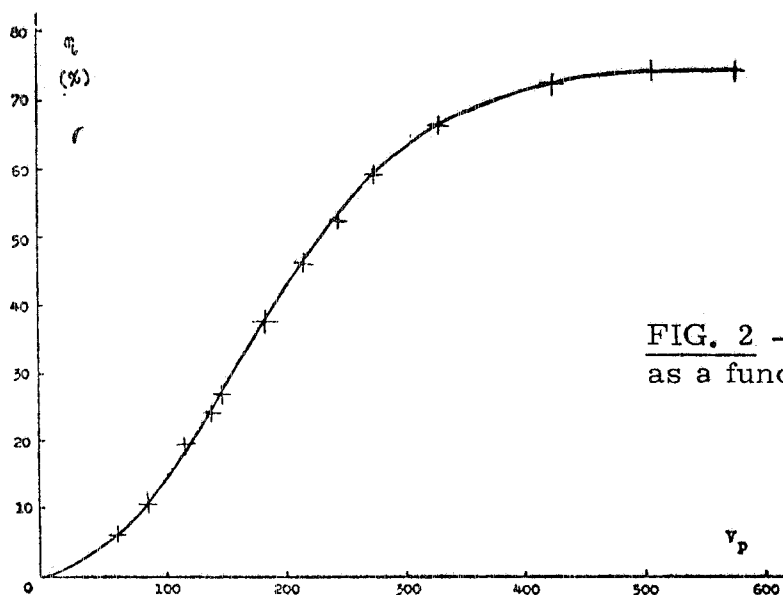


FIG. 2 - Deflection efficiency as a function of applied voltage.

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(defined as the time average of the total diffracted light) of the said modulator as function of the applied voltage, with the crystal being driven at a high harmonic. The mechanical resonance has the drawback of a narrow bandwidth as shown in Fig. 3 where the deflection

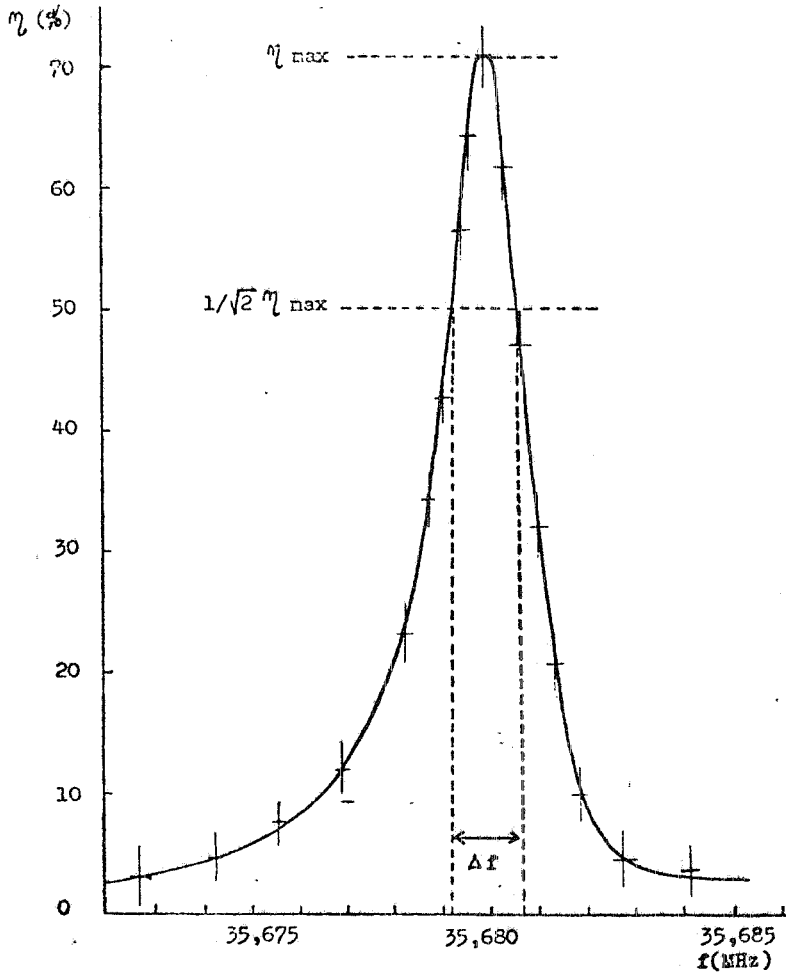


FIG. 3 - Deflection efficiency as a function of frequency.

efficiency (for an applied voltage of 400 volts) is plotted as a function of frequency. This entails some difficulties in the tuning of the crystal to the wanted center frequency. However for the long cavity, where the center frequency is 4.28 MHz, the mechanical working precision is of the order of 10^{-3} , which is not excessive. It must moreover be kept in mind that the tune can be controlled over a few kilocycles by temperature variations.

3. - THE APPARATUS. -

Figure 4 shows the experimental apparatus that has been set up to study mode-locking by the acousto-optic modulator. The laser employed is Coherent Radiation model 53 Argon ion laser that may reach 50 w of power stored in the cavity on some ten lines between

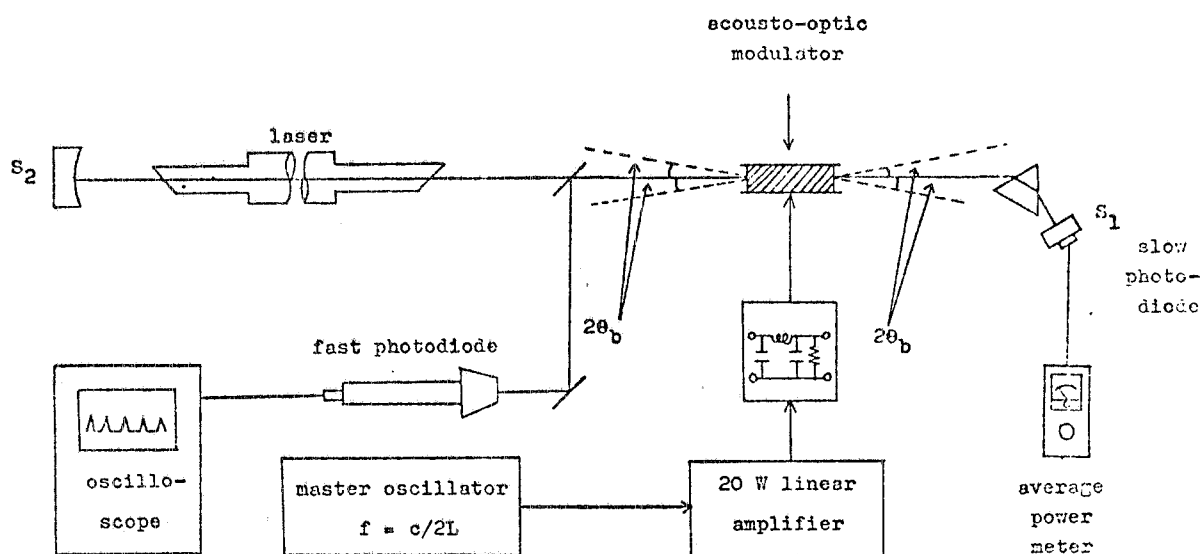


FIG. 4 - Experimental apparatus.

4545 and 5287 Å. The modulator is placed near to an end mirror, which has a slight transmittance ($\approx 10^{-4}$) to allow the measurement of the average power stored in the cavity by means of a slow photodiode (Spectra Physics mod. 404). The light pulses are monitored by a fast photodiode (Spectra Physics mod. 403) and sent to a 500 MHz plug in of a Tektronix series 7000 oscilloscope. The line chosen for all the measurements has 5145 Å wavelength. Mode-locking experiments have been made on cavities of varying length between 3 and 17 meters. In Fig. 5 are shown the pulses obtained in a cavity 3.75 m long. They have about 2 nsec width and 500 mW peak power. Figure 6 shows the beat spectrum of the modes above threshold. In Figs. 7 and 8 are shown some graphs of pulse duration τ/T , of average power P_{ml}/P_{cw} and peak power P_p/P_{cw} in mode-locking regime,

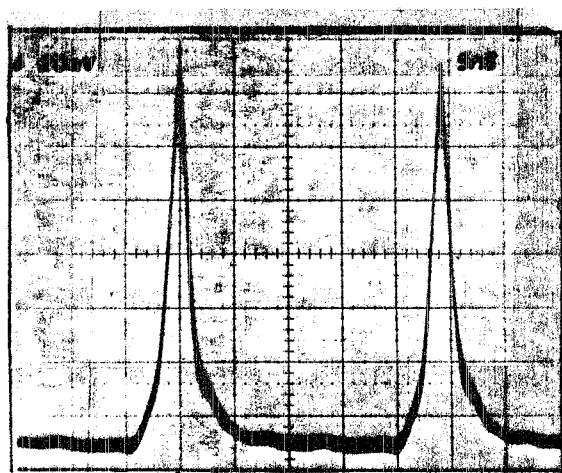


FIG. 5

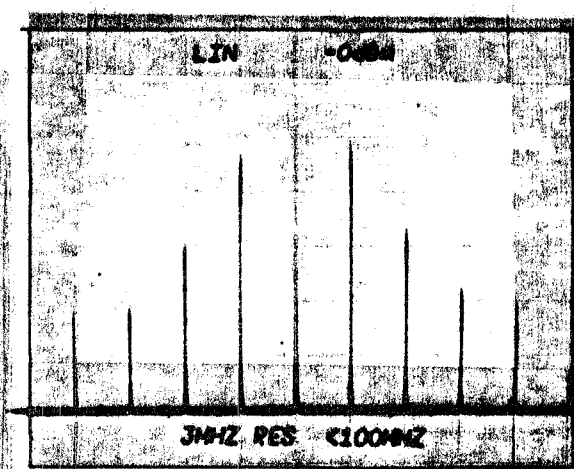


FIG. 6

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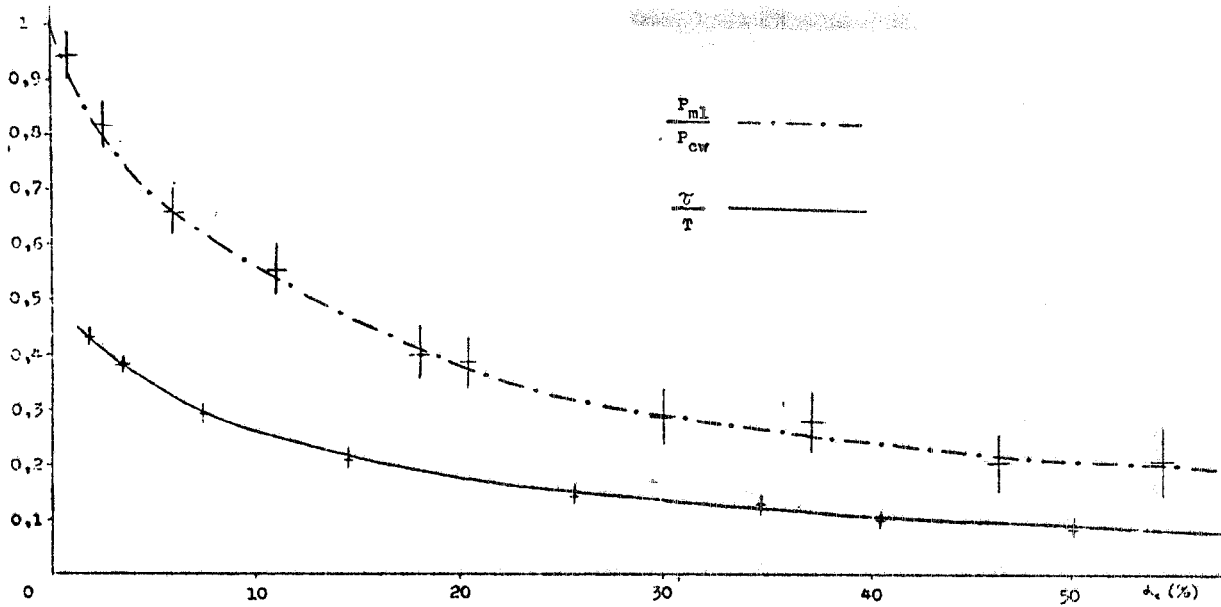


FIG. 7 - Normalized pulse duration and average power as a function of modulation depth.

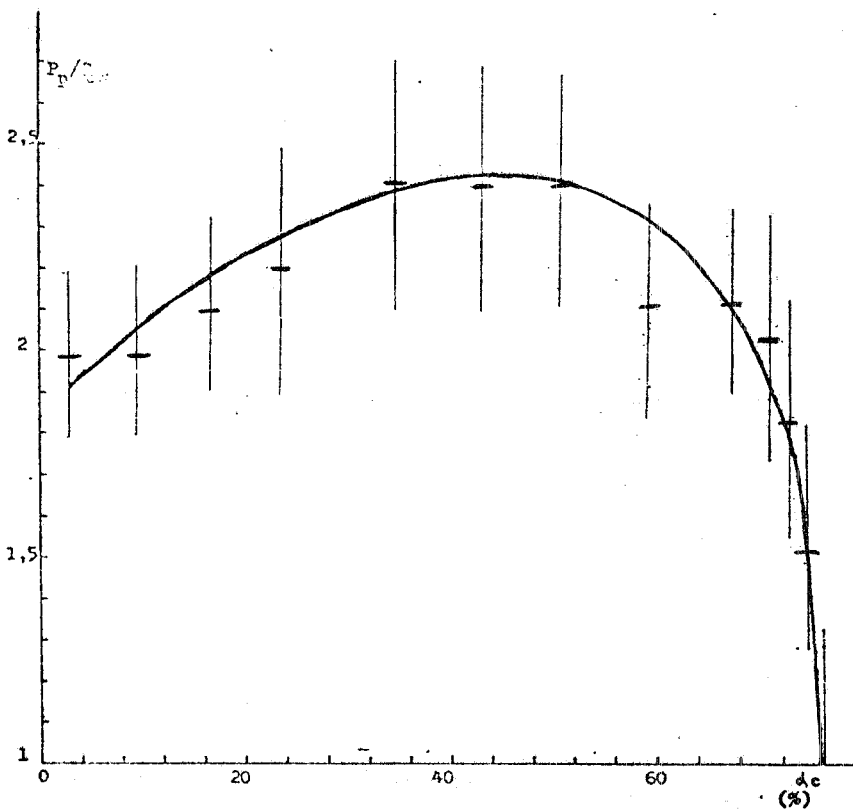


FIG. 8 - Normalized peak power as a function of modulation depth.

referred respectively to the period between pulses and to the average power in the absence of modulation, as a function of modulation depth α_c . It is to be noted that there is an optimum modulation interval, that is a compromise between high peak power and short pulse duration and that the best condition is obtained for a remarkable modulation depth, i. e. between 40 and 50 per cent.

4. - RESULTS. -

Laser operation in mode-locking regime differs from the normal one in that the active medium is stimulated by the light pulse only in short time intervals, while between one crossing of the pulse and the next one the energy stored in the upper levels is lost by spontaneous emission⁽⁷⁾. With constant pump power there is therefore a decrease of the average power stored in the cavity. If the length of the pulse τ is much less than the lifetime t_m of the upper levels, such a decrease is nearly equal to the ratio t_m/T between lifetime and pulse period. In practice the decrease depends also on the supplementary loss introduced by the modulator. In the Table I are shown some ratios P_{ml}/P_{cw} measured for various cavity lengths on our

TABLE I

T (nsec)	τ (nsec)	P_{ml}/P_{cw}
14.3	2	0.20
50	4	0.14
100	7	0.06

Argon laser in which $t_m \approx 4$ nsec: These values are to be compared with the ratios t_m/T when $\tau < t_m$ and τ/T when $\tau > t_m$. The discrepancies between measured and computed values are to be attributed to different working conditions for the various resonators and to τ not being negligible with respect to t_m . This latter fact is due to high residual losses in our experimental cavities, caused by imperfections in the optical components used in this first set of measurements. For the some reason we have obtained pulses of only about 4 W peak power, but the normalized results should be extendable to higher power levels.

From the above tests however it results that it is possible to obtain, in such a long cavity, a peak power greater than the average value in the unperturbed cavity. The effective value that can be reached depends on the entity of the residual losses in the cavity, including those on the modulator surfaces.

8.

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