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Laboratori Nazionali di Frascati

LNF-79/42(R)
16 Luglio 1979

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MODE LOCKING ON COUPLED AND LONG LASER CAVITIES. THE NEW EXPERIMENTAL SET-UP FOR THE LADON BEAM.

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MODE LOCKING ON COUPLED AND LONG LASER CAVITIES. THE NEW EXPERIMENTAL SET-UP FOR THE LADON BEAM.

1. - INTRODUCTION.

The Ladon photon beam, which has recently come into operation at Frascati(1, 2) does not use the long laser cavity as it was proposed in the original design of the project(3). This arrangement was supposed to provide an intracavity light power up to 250 Watts, but its realization would have encountered the following difficulties :

a) This long cavity should have been internally modulated, but there was no experience at all about the possibility of obtaining mode-locking with a cavity length that comes out to be 17.55 m.
b) The synchrotron radiation impinging on the end mirror forced to use either a metallic mirror with a consequent high loss or a dielectric one but protected against the radiation damage by a window made of a suitable material.
c) The alignement of such a long cavity on the electron beam line appeared very hard to be performed with the required high accuracy ($\sim 10^{-5}$ rad).

Due to these difficulties, we choose to temporarily abandon this original design and in the present operation mode, a laser cavity-dumper, extensively described elsewhere(4), has been used. This technique produces light pulses 15 nsec long at the Adone RF frequency of ~ 8.5 MHz. The maximum peak power does not exceed ~ 25 W and consequently the average power is ~ 3 W.

Now, since the practical feasibility of the Ladon project has been experimentally proved, we have to go toward a definitive set-up of the experiment able to produce the foreseen laser power and then the expected gamma rays yield.

The long cavity remains the best solution of the problem and we will later discuss its practical feasibility. However, most of this paper is devoted to present another possible configuration, consisting in two coupled cavities, that, even if the obtainable power is lower than in the long cavity case, presents the advantage that it can be surely realized at present and it is able to produce a power larger than with the cavity-dumping technique.

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In effects, as we will discuss more extensively in next chapters, the coupled cavities technique will produce about the same CW power than a long cavity, but in the mode locking operation there is a decrease in the useful light power.

Let us see briefly how the difficulties that the long cavity encountered could be overcome by the coupled cavities configuration. In this set-up the active cavity is only ~3.5 m long and should be easily mode-locked in accordance with the standard results widely experienced elsewhere(5). Moreover the alignement procedure would be the same we usually follow in the present arrangament without any further complications. Finally this method can tolerate highly lossy elements in the passive cavity without the collapse in the internal power that one would have with the same losses inserted in the active cavity.

It will be easily shown that the power one can store in the passive cavity is at least the power coming out from the active divided by the total losses of the passive. In order to evaluate more precisely the performances one could expect, we will present in Section 2, a detailed discussion on the power inside a laser cavity extending the argument to the case of two coupled cavities in Section 3.

Numerical estimates of the power obtainable with the coupled cavities technique using a SP 166 or a SP 171 Argon Ion Lasers, will be reported in Section 4.

Finally, in Section 5 we will discuss briefly the problem to mode lock a long cavity, and in Section 6 we will present some experimental results together with the description of a possible practical realization of the mode-locked long cavity in Adone.

2. - INTERNAL POWER IN A LASER CAVITY.

As it is very well known, any gas-laser line is broadened with respect to its natural width by the two following effects :

a) The first is caused by the interaction between the atoms which enlarges the natural linewidth. As a consequence the frequency distribution that each atom can emit has a Lorentz-like shape and the broadening effect caused by this process is known as homogeneous.
b) The second is caused by the Doppler effect due to the atom thermal motion. Each atom emittes within its natural linewidth but the center of the frequency distribution is shifted proportionally to its velocity. The consequent total spread of the emitted frequencies has a gaussian-like distribution and this broadening effect is called inhomogeneous.

The difference between the two cases stands not only in the different shape of the frequency distributions but mainly in the fact that in the homogeneous case a photon of any frequency lying in the broadened line can induce stimulated emission in any of the excited atoms of the active medium, whereas, in the inhomogeneous case, stimulated emission can only occur between atoms having the same velocity.

This difference has a great influence on the gain behaviour of a laser tube as a function of the light power. Since the number of photons oscillating in a laser cavity can become not negligible in comparison with the number of excited atoms, the stimulated de-excitation rate is not much less than the sum of the optical pumping and spontaneous emission rates. This causes a decrease of the active medium gain with increasing light power. For this reason the laser gain curve, that is proportional to the frequency distribution, is defined as the gain per unit length experienced by a light beam with "zero" power.

Furthermore, in the homogeneous case the presence of light at any frequency lowers the whole curve and thereby the gain at a given frequency is strongly influenced by the presence of other oscillating frequencies. On the contrary in the inhomogeneous case, the gain of any frequency behaves independently and the gain curve presents a hole in correspondence to any oscillating frequency, remaining unchanged at all the other frequencies (Fig. 1).

In a real active medium both the homogeneous and inhomogeneous broadening are present so that the gain behaviour is intermediate between the two(6).

The theoretical description of a real active medium can become quite complex, expecially when there are many longitudinal modes. Therefore, in order to avoid too involved calculations, we will limit ourselves to single-line lasers purely homogeneous or inhomogeneous.

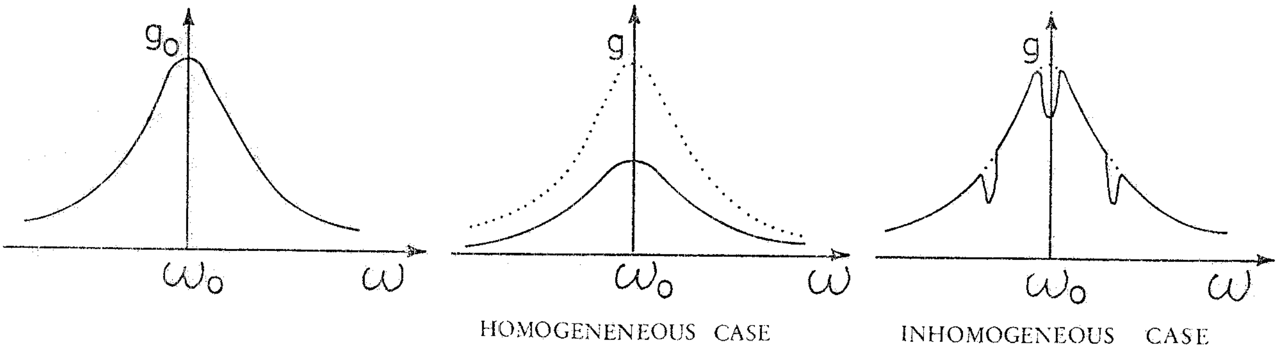


FIG. 1 - Gain curve both in the homogeneous and inhomogeneous case.

The expression of the laser gain as a function of the light power comes out to be[(7)]:

$$g(P) = \frac{g_o}{1 + \frac{P}{P_m}} \qquad \text{homogeneous} \qquad (1)$$

$$g(P) = \frac{g_o}{(1 + \frac{P}{P_m})^{1/2}} \qquad \text{inhomogeneous} \qquad (2)$$

where :

g_o = gain at "zero" power ;
P_m = saturation parameter ;
P = light power.

Let us now consider the cavity shown in Fig. 2, where :

T = transmittivity of the mirror M_1 ;
gL, a = gain and loss in the laser tube LT (L = tube length) ;
T' = transmittivity of the mirror M_2.

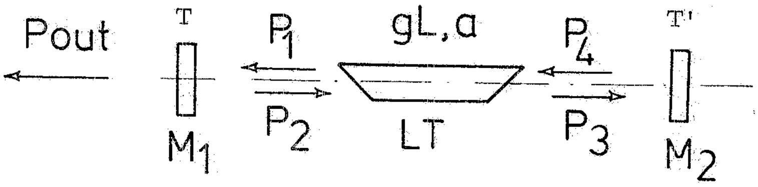


FIG. 2 - Schematic of a laser cavity.

For semplicity we assume T' = 0 (only one semireflecting mirror as generally used) and the gain to be the same in both directions. Furthermore we assume the integrated gain over the tube length to be simply gL. With these assumptions one has (see Fig. 2):

$$\begin{aligned} P_1 &= (1 + gL - a) P_4 , \qquad & P_3 &= (1 + gL - a) P_2 , \\ P_2 &= (1 - T) P_1 , & P_4 &= P_3 , \end{aligned} \qquad (3)$$

and from these, the equilibrium condition:

$$1 + gL - a = \frac{1}{\sqrt{1 - T}} \quad . \tag{4}$$

By inserting (1) or (2) in this equation, one obtains the following expressions for the internal power at the equilibrium:

$$P^{*}_{hom} = P_m \left[\frac{g_o L \sqrt{1-T}}{1 - (1-a)\sqrt{1-T}} - 1 \right] \quad , \tag{5}$$

$$P^{*}_{inh} = P_m \left[\left(\frac{g_o L \sqrt{1-T}}{1 - (1-a)\sqrt{1-T}} \right)^2 - 1 \right] \quad , \tag{6}$$

where, with a good approximation:

$$P^{*}_{hom} = P_1 + P_2 \; , \qquad\qquad P^{*}_{inh} = (P_1 + P_2)/2 \quad . \tag{7}$$

The difference lies in the fact that in the inhomogeneous case the forward and backward light power saturates independently.

Substitution of eqs. (3) and (7) in (5) and (6), gives:

$$P_1 = \frac{1}{1 - T/2} \, \frac{P_m}{2} \left[\frac{g_o L \sqrt{1-T}}{1 - (1-a)\sqrt{1-T}} - 1 \right] \qquad \text{homogeneous} \tag{8}$$

$$P_1 = \frac{1}{1 - T/2} \, P_m \left[\left(\frac{g_o L \sqrt{1-T}}{1 - (1-a)\sqrt{1-T}} \right)^2 - 1 \right] \qquad \text{inhomogeneous} \tag{9}$$

It is easy to verify that for $a \ll 1$ and $T \ll 1$, (8) and (9) become:

$$P_1 \cong \frac{P_m}{2} \left(\frac{g_o L}{a + T/2} - 1 \right) \qquad \text{homogeneous} \tag{10}$$

$$P_1 \cong P_m \left[\left(\frac{g_o L}{a + T/2} \right)^2 - 1 \right] \qquad \text{inhomogeneous} \tag{11}$$

that are the most widely used expressions.

3. - COUPLED CAVITIES.

Let us now consider the internal powers in the coupled cavities of Fig. 3, where:

C_1, C_2 = active and passive cavities;
T = transmittivity of the coupling mirror M_2;
L = lens;
LT = laser tube with gain gL and loss a;
α_1, α_2 = fixed losses for C_1 and C_2.

We assume that the geometries of the two cavities are perfectly matched together, i.e., that on M_2 the beam has the same dimension and curvature radius in C_1 and C_2.

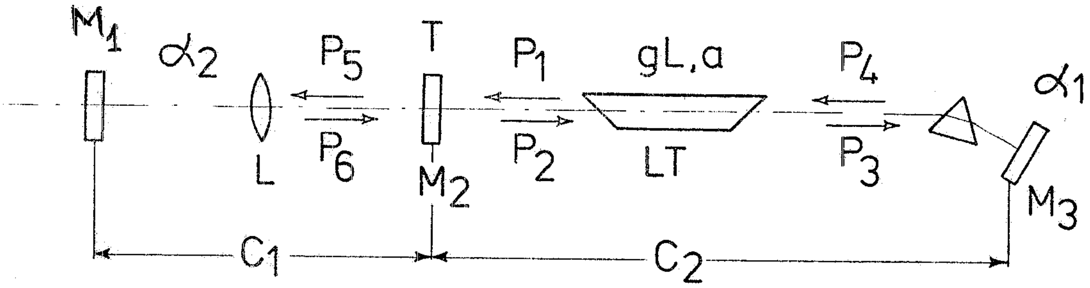


FIG. 3 - Schematic of two coupled cavities.

To find the ratio between the power levels that establish at equilibrium in the two cavities, let us write down the following relations :

$$P_2 = (1-T)\,P_1 + TP_6 \,, \qquad P_5 = (1-T)\,P_6 + TP_1 \,, \qquad P_6 = (1-\alpha_2)\,P_5 \,, \tag{12}$$

and from these :

$$P_5/P_1 = \frac{T}{\alpha_2 + T(1-\alpha_2)} \quad . \tag{13}$$

Therefore the power inside the passive cavity C_2 is at least $1/(\alpha_2 + T)$ times the output power TP_1 of the active in absence of the passive.

Besides, for the active cavity the presence of the passive is equivalent to a change of the transmittivity from T to a new value T' that we find from (12) and (13). In fact from these we can write :

$$P_2 = (1 - T')\,P_1 \,, \tag{14}$$

where :

$$T' = \frac{T}{1 + T\left(\frac{1}{\alpha_2} - 1\right)} \quad . \tag{15}$$

In this sense the active cavity C_1 behaves as shown in Fig. 4, with the usual relations :

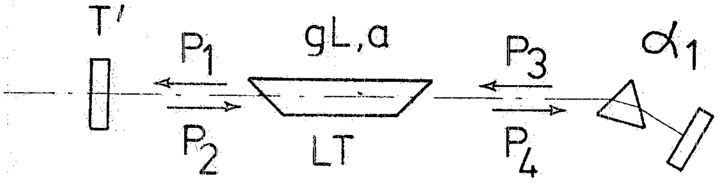


FIG. 4 - Active cavity representation in the two coupled cavities arrangement.

$$\begin{aligned} P_2 &= (1-T')\,P_1 \,, \\ P_1 &= (1+gL-a)\,P_3 \,, \\ P_4 &= (1-\alpha_1)\,P_3 \,, \\ P_3 &= (1+gL-a)\,P_2 \,. \end{aligned} \tag{16}$$

and the equilibrium condition :

$$1 + gL - a = \frac{1}{\sqrt{(1-T')(1-\alpha_1)}} \quad . \tag{17}$$

According to eqs. (1), (2) and (7) we can write::

$$g(P) = \frac{g_o}{(1 + P^{*}/P_m)^{\nu}} \tag{18}$$

where :

$\nu = 1, \quad P^* = 2(1 - T'/2)P_2$ in the homogeneous case ,

$\nu = 1/2, \quad P^* = (1 - T'/2)P_2$ in the inhomogeneous case .

By combining (17) and (18) we obtain :

$$P^* = P_m \left[\left(\frac{g_o L \sqrt{(1 - T')(1 - \alpha_1)}}{1 - (1 - a) \sqrt{(1 - T')(1 - \alpha_1)}} \right)^{1/\nu} - 1 \right] , \qquad (19)$$

and then :

$$P_1 = \frac{P_m}{2\nu(1 - T'/2)} \left[\left(\frac{g_o L \sqrt{(1 - T')(1 - \alpha_1)}}{1 - (1 - a) \sqrt{(1 - T')(1 - \alpha_1)}} \right)^{1/\nu} - 1 \right] . \qquad (20)$$

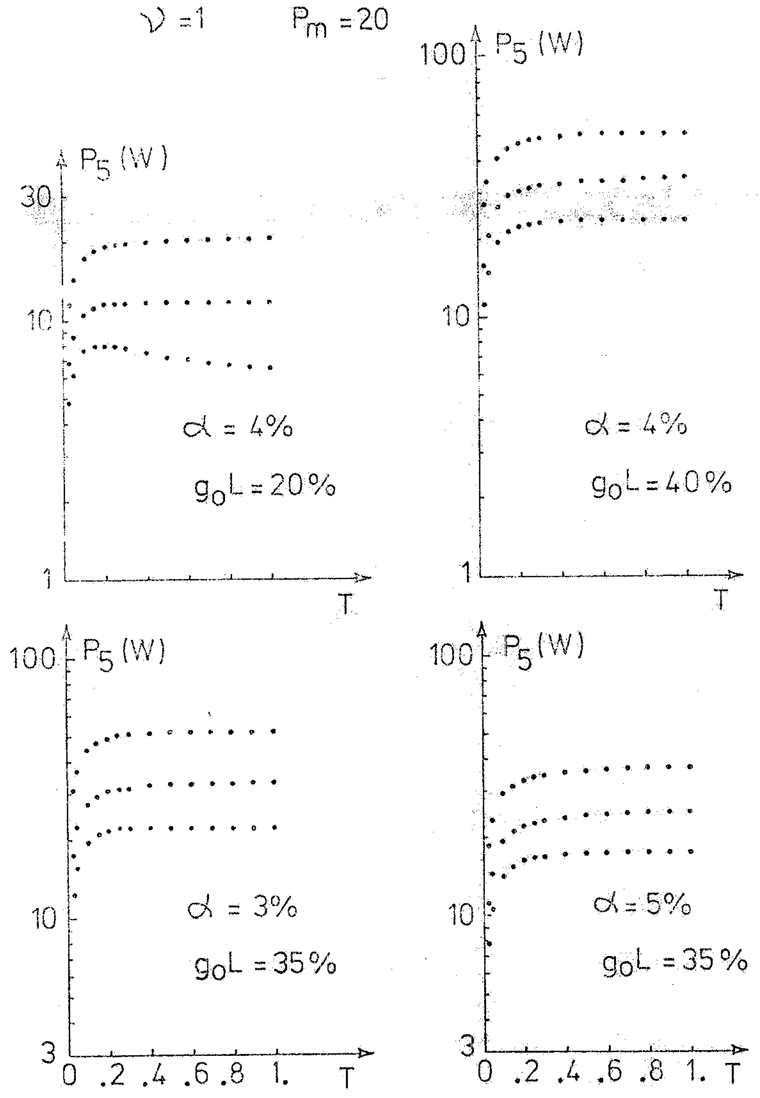


FIG. 5 - Stored power in the passive cavity;homogeneous case.

The power stored in C_2 can be writen from (13) and (15) as:

$$P_5 = T' P_1/\alpha_2 \ , \qquad (21)$$

and finally:

$$P_5 = \frac{T}{\alpha_2} \frac{P_m}{2\nu(1 - T'/2)} \left[\left(\frac{g_o L \sqrt{(1 - T')(1 - \alpha_1)}}{1 - (1 - a) \sqrt{(1 - T')(1 - \alpha_1)}} \right)^{1/\nu} - 1 \right] . \qquad (22)$$

The power inside C_2 depends on the characteristic parameters of the laser tube like $g_o L$, a, P_m, on the losses α_1, α_2 and on the coupling T.

In order to maximize P_5, while it is obvious to make α_1, α_2 as small as possible, it is not evident what T value would be the best. Figs. 5 and 6 show the dependence of P_5 on T for different values of the parameters g_oL, a and α_2 (for sake of simplicity we set $\alpha_1 = 0$). When T = 1 the two cavities become only one long cavity and from the graphs it can be seen that for high values of α_2 it is more convenient the coupled cavities configuration (with a suitable value of T) with respect to the long cavity. In any case the coupled cavities technique can be at least performed with a negligible decrease in power.

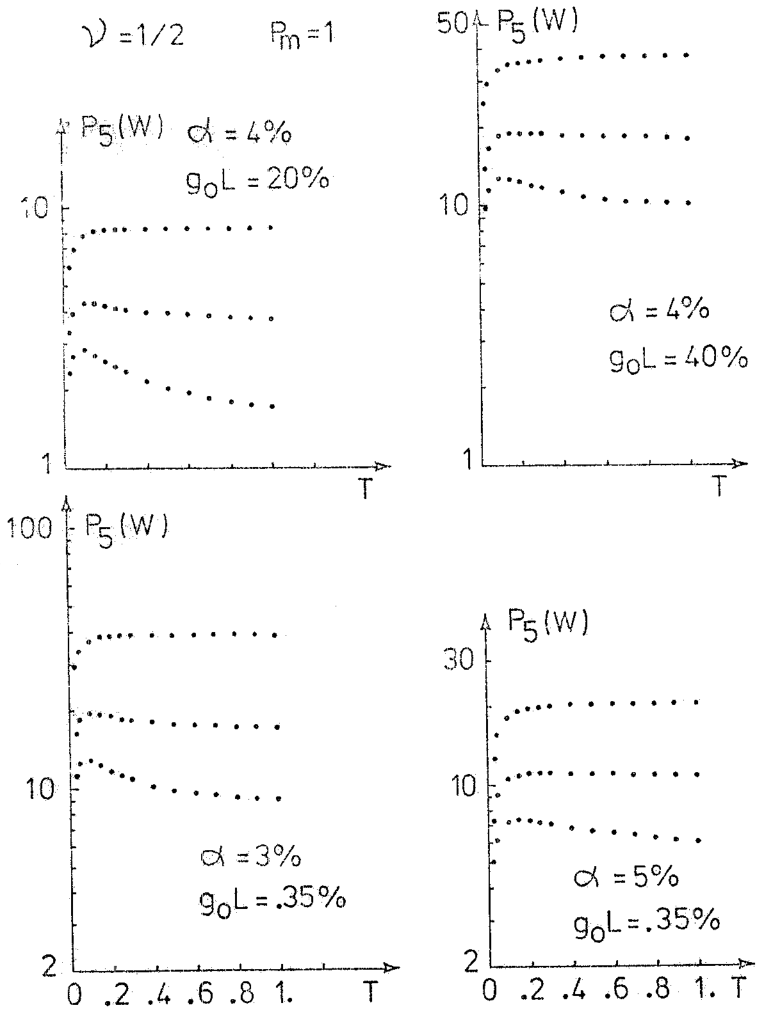


FIG. 6 - Stored power in the passive cavity, inhomogeneous case.

4. - APPLICATIONS OF THE COUPLED CAVITIES METHOD.

Let us discuss how these considerations would apply to some practical realizations using a SP 166 or a SP 171 Argon Ion lasers.

Experimental measurements of the SP 166 intracavity power indicate to be reproducible assuming an inhomogeneous broadening and the following set of parameters :

$$g_0L = 0.4 , \qquad a = 3.5\% , \qquad \alpha_1 = 2\% , \qquad P_m = 1\ \mathrm{W} .$$

With this numbers, P_{pass} (= P_5, the internal power in the passive cavity) behaves as shown in Fig. 7 and for high values of α_2 presents a maximum for T = 10%.

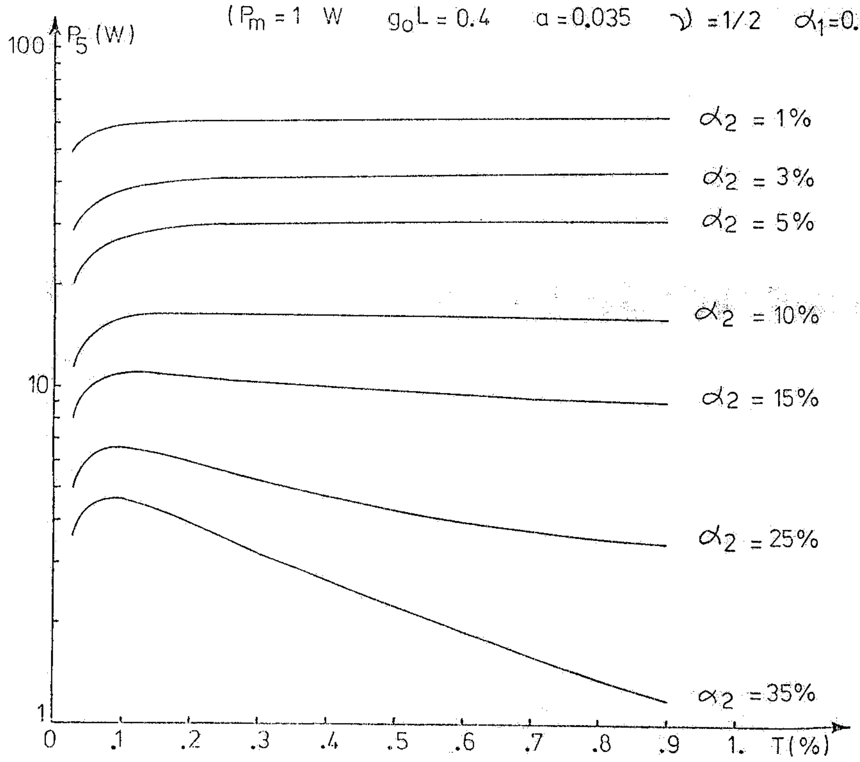


FIG. 7 - Stored power for the SP 166.

We have no estimate of the characteristic parameters of the SP 171 which is the laser at this moment installed in Adone, and therefore it is impossible to find the optimum value for T, but the comparison with the SP 166 can help us in evaluating P_{pass}. In fact in any case one has :

$$P_{pass} = \frac{T'}{\alpha_2} P_1(T') > \frac{1}{\alpha_2 + T} TP_1(T') > \frac{1}{\alpha_2 + T} TP_1(T) \qquad (23)$$

(where $TP_1(T)$ = output power with coupling T) and therefore, being :

for the SP 166	TP_1 = 2 W	T = 4% ,
for the SP 171	TP_1 = 8 W	T = 12% ,

one has, assuming a reasonable α_2 = 5% :

$$P_{pass}(166) \simeq 20\ W\,, \qquad P_{pass}(171) \simeq 48\ W\,.$$

Moreover, in this conditions T' for the SP 171 comes out to be :

$$T' = \frac{T}{1 + T\left(\frac{1}{\alpha_2} - 1\right)} \simeq 4\%$$

and we know that in this case $P_1 \simeq 150$ W. Consequently we expect P_{pass} to become :

$$P_{pass} = \frac{T'}{\alpha_2} P_1(T_1) \simeq 100\ W \qquad (24)$$

that has to be considered already quite a good number.

5. - MODE-LOCKING ON A LONG CAVITY.

As it has been extensively discussed elsewhere[(8)] the laser beam must be bunched in order to avoid the Adone quadrupole regions. Owing to this, the dumping technique has been used but better results may be obtained with the mode locking method which can be applied to coupled cavities as well as long cavities.

Briefly speaking, when the longitudinal cavity modes of the laser are forced to maintain a fixed phase relationship with one another, the laser is said to be mode locked. In this condition the amplitudes of modes add constructively at a particular point. This has the effect of converting the continuous beam circulating within the laser to a small intense spike of light which bounches back and forth between the mirrors. A wider discussion on the subject will be presented in a forthcoming paper but now let us limit the discussion to the average power.

It is widely believed that theoretically the average power does not decrease apprecciably in the course of mode-locking, expecially when there are only few modes locked together. This has been experimentally confirmed by several authors but only on some types of lasers (expecially He-Ne) and with short cavities.

Other authors[(5)] have found for the Argon-Ion laser a discrepancy between theory and practice attributed probably to a more complex mode structure present in this type of laser. Moreover when the cavity become very long, another effect arises in connection with the upper state lifetime of the lasing transition, leading to a decrease in the average power. As discussed in ref. (9), the upper level population $n_2(t)$ in pulsed operation behaves as shown in Fig. 8.

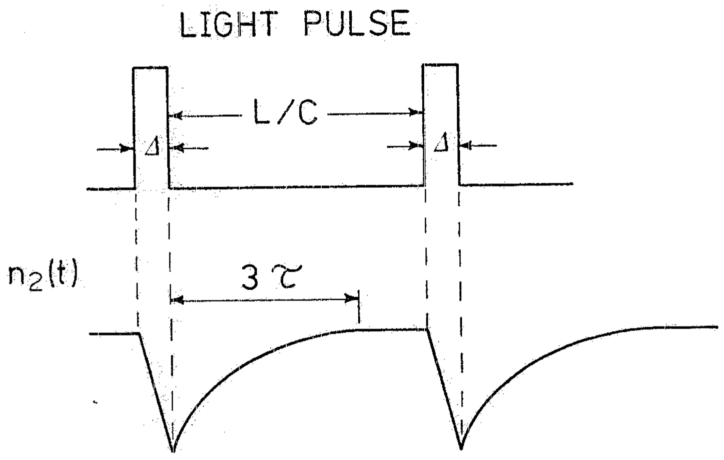


FIG. 8 - Behaviour of the upper level population $n_2(t)$ in pulsed operation mode.

The initial decrease is due to the light pulse whereas the following rising goes as $\exp(-(\beta+\frac{1}{\tau})t)$ where: β = pumping rate; τ = upper state lifetime (τ = 7.5 nsec for the 5145 Å line). We can say that $n_2(t)$ returns to its equilibrium value after $\simeq 3\tau$ ($\simeq$ 20 nsec in our case). The absence of light in a generic point of the active medium lasts $T_a = (L/c - \Delta)$, Δ being the light pulse width.

Then one has to expect that the pulse peak power does not increase any more when T_a goes over 3τ and consequently the average intracavity power decreases, with respect to its CW value, of the factor:

$$\frac{P_{ML}}{P_{CW}} \approx \frac{\Delta + 3\tau}{L/C} \tag{25}$$

for $T_a > 3\tau$.

6. - FIRST EXPERIMENTAL RESULTS AND FUTURE PLANNING.

6.1. - Coupled cavities.

Let us examine the arrangement with two coupled cavities we would suggest for a new Ladon set-up in Adone. Fig. 9 shows a ~ 3.5 m long active cavity (C_1), the coupling mirror T and a ~ 14 m long passive cavity (C_2) including the Adone straight section and the connected vacuum channels leading to the lens L and to the end mirror M_2.

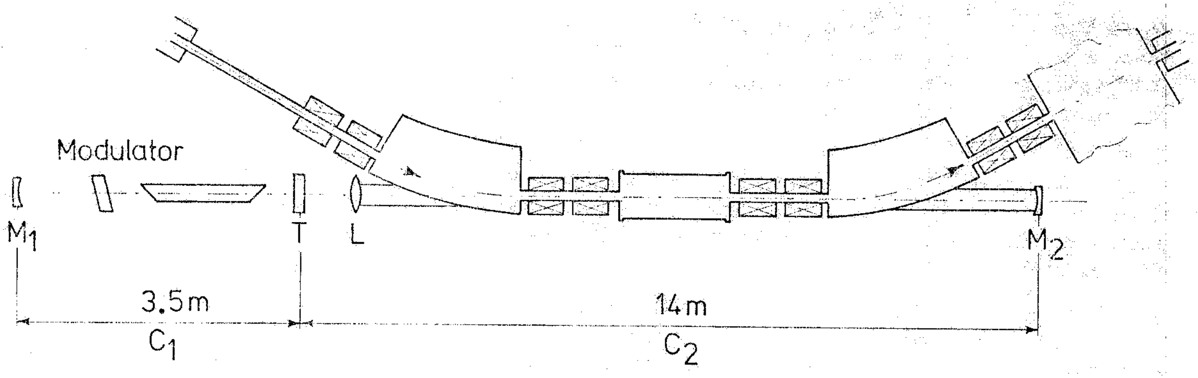


FIG. 9 - Set-up with two coupled cavities on Adone.

The active cavity C_1 will be mode-locked, through an acoustooptical modulator, placed as close as possible to the mirror M_1, at a frequency $c/2L \simeq 42.85$ MHz exactly equal to five times the Adone RF frequency of $\simeq 8.57$ MHz. The passive cavity length will be four times the active one in such a way to synchronize the pulses inside the two cavities.

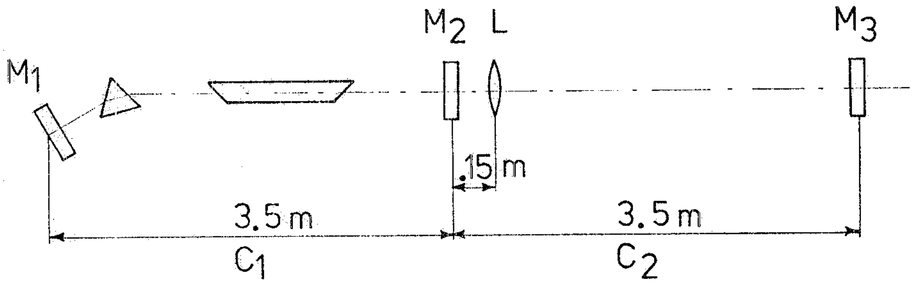
The only drawback of this idea lies in the fact that only one pulse out of five would interact with the electrons stored in Adone and at present nothing can be done to overcome this difficulty. For this reason only a fraction 1/5, then about 20 W, of the estimated average power given in (24) is useful for the interaction.

However, it is foreseen a change in the Adone RF frequency with a consequent doubling of the electron bunches number (from 3 to 6). So if the time distance between two electron bunches goes from $\simeq 117$ nsec to $\simeq 58.5$ nsec, we can have the following, more convenient, possibilities (others are excluded because the minimum distance between the lens and the mirror M_2, i.e. the minimum passive cavity length, is ≈ 12 m):

Time distance between light pulses (nsec)	:	58.5	29.25	19.5	14.6
Length of the active cavity (m)	:	8.78	4.39	2.93	2.19
Length of the passive cavity (m)	:	17.55	13.17	14.65	13.16
Useful fraction of power	:	1	1/2	1/3	1/4
Useful average power (Watts)	:	100	50	33	25

One of the most significant measurements has been obtained with the configuration illustrated in Fig. 10. In those conditions we measured through the leakage from the HR mirror M_3, an internal power in C_2 equal to ~34 W and ~25 W in mode-locking; it means we had a ratio:

$$\frac{P_{ml}}{P_{CW}} = 74\% \; .$$



M_1 :	HR ,	$R = \infty$
M_2 :	$T = 12\%$,	$R = 6$ m
M_3 :	HR ,	$R = 5$ m
L :	AR ,	$F = 2.65$ m.

FIG. 10 - Sketch of the two coupled cavities arrangement used in the experimental measurement.

The modulation depth was kept just a bit over the locking threshold; in this condition the pulse width was ~6 nsec. Of course, an increase in the modulation depth resulted in a further decrease in average power and in a shorter pulsewidth. However we have to stress that we are interested in having the maximum energy per pulse, whatever being the pulsewidth as long as less than ~18 nsec.

Since the back surface of the coupling mirror M_2 was uncoated, its loss was quite high ~10%.

Considering also the losses introduced by the other elements, we may conclude the measured CW of 34 W to be substantially in agreement with the previsions made in Section 4.

6.2. - Long cavity.

Let us discuss now on the actual possibilities of making only one cavity 17.55 m long, overcoming the difficulties presented in the introduction. The alignement could be performed in this way: we could make first two coupled cavities using as coupling mirror a plane one with perfectly parallel faces (parallelism $\leq 10^{-5}$ rad) so that, once we have aligned the beam in this situation, we will remove the coupling mirror and the long cavity would oscillate with the beam on the same line it was before.

Confident to reduce under 10% the losses in the part of the cavity including the lens and the end mirror M_2 (see later for the practical design of the cavity), we estimate the internal power of the long cavity to approach 100 W. As we have discussed in Section 5, the average power decrease in mode locking operation on a long cavity depends on three factors: the upper state lifetime τ, the pulsewidth Δ and the cavity length L. In our case, being $3\tau \simeq 20$ nsec, and keeping Δ equal to the maximum acceptable value of ~20 nsec, the average power should not decrease for $L/c \leq 40$ nsec ($L \leq 12$ m). With $L = 17.55$ m the decrease factor due to this effect should be $\simeq 0.68$ (see eq. (25)).

Some significant experimental results, we have so far obtained, are reported in Table I.

The comments we can make are:

a) The differences in the power absolute values are due to the different practical situations, and in particular the very low values in the third case were due to the use of a modulator not cut at the Brewster angle. In any case, it is surely possible to obtain higher power working in better conditions.

b) The ratio P_{ML}/P_{CW} does not change up to $L = 10$ m, and decreases at 17.5 m of a further factor $0.45/0.68 = 0.66$ that is very near to the predicted 0.68.

TABLE I

Cavity length	(m)	3.5	10	17.5
L/c	(nsec)	12	34	58
Δ	(nsec)	~6	~18	~20
P_{CW}	(W)	50	75	36.2
P_{ML} (average)	(W)	35	51	16.3
P_{ML} (peak)	(W)	70	190	98
P_{ML}/P_{CW}		0.7	0.68	0.45

In conclusion, the long cavity can be foreseen to provide ~100 W CW and ~45 W in mode-locking with pulses of ~20 nsec duration and ~270 W peak power.

6.3. - Future plannings.

Actually the laser is mounted on a base, set on an optical bench, moveable by four position encoded engines to align the output beam onto two crosses set before the lens and a third one set after the end mirror. In the new set-up (see Fig. 11) we will adopt the system of having the laser fixed on the bench and to align the beam by moving the two mirrors M_3 and M_4.

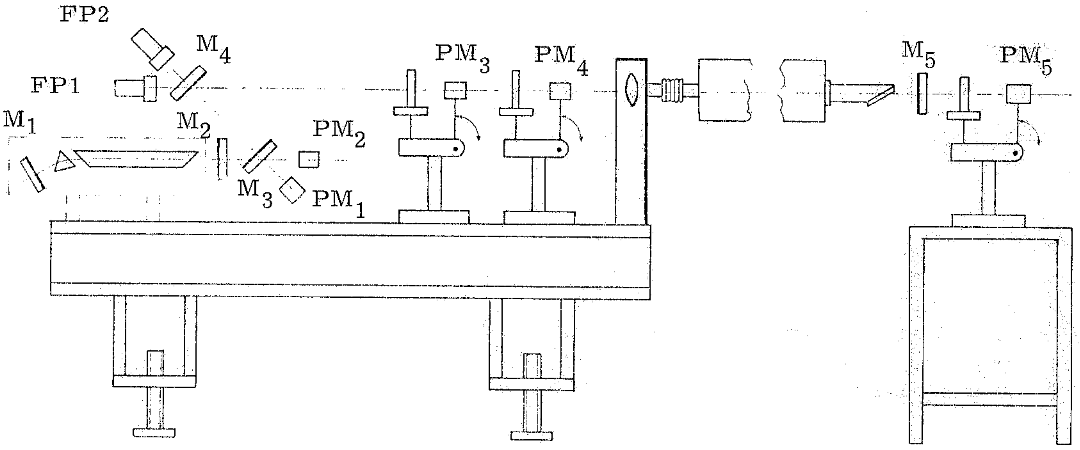


FIG. 11 - Sketch of the long cavity arrangement suggested for the new experimental set-up.

The beams transmitted by these mirrors (~0.5% transmittivity) will serve for the detection of the forward and backward average power and of the pulse shape by means of the slow photodiodes PM_1 and PM_2 and the fast photodiodes FP_1 and FP_2 respectively.

For an automatic alignement procedure, we have suggested a system with two engined slides cutting the beam and a slow photodiode behind them, whose exit will be sampled and computer analized giving both the transverse dimension of the beam and its center position(10).

Just near the laser tube, there is the partially reflecting mirror M_2 used for the alignement with the coupled cavities.

The end mirror M_3 will be no longer included in the vacuum channel that ends with a large quartz window at the Brewster angle. If this window should be damaged by the synchrotron radiation, this arrangement will be changed as shown in Fig. 12, with a metallic mirror (M_6) set at a

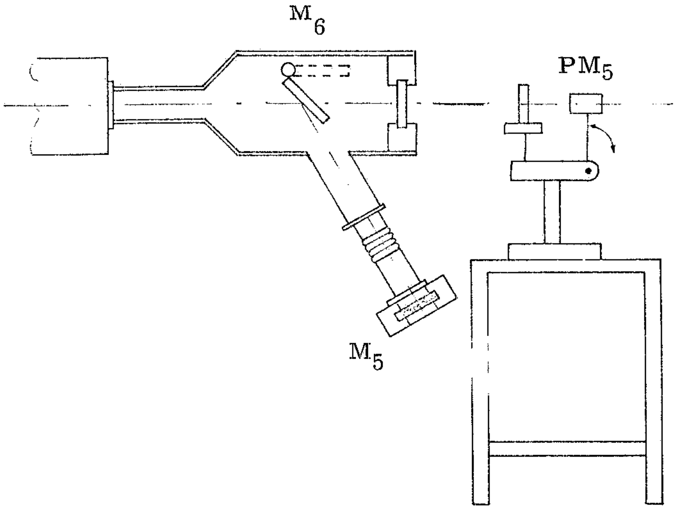


FIG. 12 - Design of the metallic mirror positioning.

great angle with respect to the beam axis in such a way to get a very high reflectivity and to have the end dielectric mirror (M_5) out of the synchrotron radiation influence.

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