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Assessment of Dynamical Parasitics in the EBS

C. James Elliott

**los alamos
scientific laboratory**

of the University of California

LOS ALAMOS, NEW MEXICO 87545

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ASSESSMENT OF DYNAMICAL PARASITICS IN THE EBS

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ABSTRACT

Significant improvements will accrue to the eight-beam system (EBS) by dynamical effects (shooting on the fly) depending on whether or not strong saturable absorbers are used in the system. When strong saturable absorbers are used, there is little reserve in peak gain and the gain rises slowly near extraction; thus, the static threshold is greatly improved, but the dynamical threshold is not. In this case the dynamical or conditional thresholds are at g_0 values 0.6 to 0.7 higher than static threshold. We have also determined that the method of measuring unconditionally stable values leads to values that are 0.5 to 0.3 above static threshold, giving a net improvement over measured values of 0.2 to 0.4. When saturable absorbers are not used, the dynamical threshold increments above static threshold are 1.7 to 1.4 for the four- and six-pass modes respectively. It thus appears that somewhere between 500J to 900J per beam may be put on target without saturable absorbers! And serious consideration should be given to postponement of saturable absorber installation. When using saturable absorbers, the $1/e$ rise time of the parasitic oscillation pulse at extraction is from 40 ns to 60 ns in the dynamical mode; and the full width at half maximum of the pulse is 390 ns to 415 ns when extraction (or damage) does not terminate its evolution. The values quoted here are based upon a few gain curves from one beam line and may not represent what the system could ultimately achieve. In this study we arrived at a single differential equation that adequately represents more detailed TARDAM calculations. The differential equation comes from both a point amplifier model and a model with gain and absorption uniformly spread between the two ends of the cavity. Using the differential equation, simple analytical expressions or results that are easily obtained on a HP-25 hand calculator compare within a per cent of TARDAM results for excess gain.

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I. Introduction

A major design problem of contemporary large laser-fusion CO_2 lasers is to successfully combat optical coupling between the target and an internal amplifier surface that generates stray light. The radiation starts as spontaneous emission that is emitted within the solid angle that will impinge on target. A fraction of the radiation is reflected by the target back onto the focusing mirror and back into the power amplifier. Some of this radiation is reflected as stray light from the power amplifier surface and back onto the target; thus, a feedback loop exists that is unstable for sufficiently high gain. Because the relatively low intensity in the power amplifier becomes concentrated when focused on the target, target damage which occurs at 0.4 J/cm^2 corresponds to radiation that has undergone small-signal (linear) gain and loss throughout its life. Previous calculations¹⁻⁵ have treated the Antares laser system, which is naturally isolated from target parasitics by long distances to target and fast rising gain. The EBS has smaller distances to target and a slower rising gain, but still derives some benefits from these factors. Indeed, oscillations involving the front end (which are not considered here) are similar to those in Antares.

The differences between the EBS and Antares lead to different approximations. In both of these systems, the radiation that arrives on target at a given time can be decomposed into contributions that were emitted as spontaneous emission at earlier times $\tau_b + n\tau_R$, $n=0, 1, 2, \dots$, where τ_R is the round-trip transit time in the cavity and τ_b is transit time from the target to the end of the amplifier. The $n=0$ term is direct amplified spontaneous emission that effectively comes from the last g_o^{-1} length of the amplifier, and n represents the number of additional round trips the radiation has taken before entering the laser cavity for the last time. In the EBS, the change β in the $n_p g_o \ell$ value is small (<2.5) during the round trip whereas in Antares it is large, where n_p is the number of passes in the amplifier and $g_o \ell$ is the product of the gain coefficient and length. This large change β that occurs in Antares leads to a single dominant term corresponding to a definite n value, whereas the small change in $g_o \ell$ in the EBS requires the contribution of many n values. In Antares only one additional round trip ($n=1$) occurred in the evaluation of the energy on target but in the EBS many round trips occur. The many-round-trip aspect of the dominant term in the EBS problem can be handled

approximately by an integral over the gain curve, and the many-term aspect of the problem can be handled by summing these terms approximately.

Three models of the gain region are considered and are shown in Fig. 1. Model A is that used in TARDAM which consists of two- or three-point amplifiers and several-point absorbers; the $\exp(-6)$ which appears represents two passes of the saturable absorber of $\exp(-3)$ each.

In model B all of the gain and absorption are collapsed into a point, and in model C, the gain and absorption are distributed uniformly, filling out the entire cavity. In both models B and C the effective gain coefficient length product gL is the small-signal $g_0 l$ diminished by absorption and is given for

Fig. 1

Three models of the EBS. Each of the rectangular regions represents an amplifier or absorber, and in models A and B, these have no thickness.

the four- and six-pass modes by

$$\exp(2gL) = .861 \times .793 \times 2.48 \times 10^{-3} \times .891 \exp(2g_o \ell), \text{ four pass} \quad (1)$$

$$\exp(3gL) = .861 \times .793 \times 2.48 \times 10^{-3} \times .805 \exp(3g_o \ell), \text{ six pass,}$$

where ℓ is the length of the original laser cavity. The quantity L that represents the modeled amplifier length only appears with the quantity g so that in the point amplifier where $L \rightarrow 0$ and $g \rightarrow \infty$, the product gL remains finite. The parameters of the modes are summarized in Table I.

TABLE I

<u>Symbol</u>	<u>Four-Pass</u>	<u>Six-Pass</u>	<u>Definition</u>
n_p	2	3	Number of passes of amplifier
RF_t	0.1	0.1	Target return fraction
RF_p	6×10^{-7}	1.9×10^{-11}	Stray return fraction
τ_1	34.5 ns	47.8 ns	Model B, see Fig. 1b
δ	44.2 ns	69.6 ns	Model B, see Fig. 1b
τ_L	25.4 ns	25.4 ns	See Model A, Fig. 1a
τ_R	113 ns	165 ns	Round-trip time
K_o	3.63×10^6	1.385×10^4	Eq. (36)
$g_{oth} \ell$	7.41	6.76	Gross threshold
$g_o \ell - gL$	3.25	2.26	Eq. (1)
$g_{th} L$	4.16	4.50	Net threshold

The values of τ_1 and δ shown in Table I are based upon placing the point amplifier halfway between the front and back of the actual amplifying region. Other ways of defining τ_1 and δ will lead to different results and the usefulness of the models is established by our predictions being relatively independent of the choice of the location of the point amplifier.

II. The Point Amplifier Model

The point amplifier, model B of Fig. 1, has the characteristic that any pulse that goes through it at time t undergoes a gain of $\exp[n_p g(t)L]$, where $g(t)$ is proportional to the small signal gain coefficient g_o and the number of passes n_p but is diminished by the cold CO_2 (absorption coefficient $\approx 0.0167/\text{m}$) and the saturable absorber. The transit time from the point amplifier to target is τ_1 , whereupon a fraction of the pulse RF_t is returned

in the opposite direction. After traveling through the amplifier away from the target, the pulse is reflected as stray light off the troublesome surface in the power amplifier and returned through the amplifier a time δ later and weakened by the factor RF_p , the return fraction of the power amplifier surface. The static threshold condition is defined by the condition where the net gain is equal to the cavity loss by

$$RF_p RF_t \exp(n_p L g_{th}) = 1. \quad (2)$$

This condition can be translated into a threshold condition on g_0 as

$$g_{oth} = \frac{L g_{th}}{\ell} + \begin{cases} 1.63 \text{ four-pass} \\ 1.13 \text{ six-pass} \end{cases}, \quad (3)$$

where $g_{th} L$ is determined by Eq. (2) and is different for the four- and six-pass modes as shown in Table I.

A simple manipulation of previous results⁴ shows that we may write the intensity on target at time t due to a point amplifier as

$$I(t) = \sum_0^{\infty} I_N(t), \quad (4)$$

where

$$I_N(t) = S_F (RF_p RF_t)^N \exp n_p L \left\{ g(t - \tau_1) + \sum_{n=1}^N \left\{ [g(t - \tau_1 - n\tau_R) + g(t + \tau_1 - n\tau_R)] \right\} \right\}. \quad (5)$$

The parameter S_F in the EBS for a single beam may be evaluated^{1,2} (with $N_u/g_0 = 1.5 \times 10^{18} \text{ cm}^{-2}$, $S_2 = 1000 \text{ cm}^2$, and $f_t = 86 \text{ cm}$) to be $6 \times 10^{-5} \text{ W/cm}^2$. Before simplifying Eqs. (4) and (5) for a quadratic gain curve, we will address a subtle question of timing.

The intensity appearing in Eq. (4) is that upon the target, and it differs from that leaving the amplifier. The timing convention¹ is that the gain coefficient g_0 is that corresponding to the time the pulse leaves the power amplifier on the third pass. The intensity leaving the amplifier is then $I(t + \tau_L)$ since τ_L is defined as the time the pulse takes to travel to the target after leaving the amplifier. The use of this delay τ_L (see Fig. 1a) rather than the delay to the location of the point amplifier in Model B, τ_1 ,

may be shown to be appropriate either by analytical examination of two-point amplifiers with a linear gain or by comparison to TARDAM calculations. When we use $I(t + \tau_L)$ as the intensity leaving the amplifier, the choice of the location of the point amplifier then makes very little difference in the calculation.

In the EBS, the increment achievable in gain above the static threshold is expected to be small, and this suggests that we expand the gain curve about threshold retaining the first two or three terms

$$g(t) = g_{th} + \dot{g}t + \frac{1}{2}\ddot{g}t^2, \quad (6a)$$

or equivalently

$$g_o(t) = g_{oth} + \dot{g}_o t + \frac{1}{2}\ddot{g}_o t^2, \quad (6b)$$

where we have taken time zero to be at threshold. The sums which appear in Eq. (5) involve summing an expression which is quadratic in n and this leads to an expression which is cubic in N . Since the most important radiation in the cavity starts near threshold, the dominant terms in the summation occur in the vicinity of $N = t/\tau_R - 1/2$, and we expand the summed cubic expression in N about this point to terms which are quadratic in ϵ_N where

$$\epsilon_N = N - t/\tau_R + 1/2. \quad (7)$$

Equation (5) now becomes

$$I_N = S_F \exp(n_p L g_{th}) \exp(U_o + U_1 \epsilon_N - \beta \epsilon_N^2), \quad (8)$$

where

$$U_o = \beta \left[2 \left(\frac{t}{\tau_R} \right)^2 + \frac{1}{4} - \frac{\tau_1}{\tau_R} \right] - \gamma \left\{ \frac{1}{3} \left(\frac{t}{\tau_R} \right)^3 + \frac{t}{\tau_R} \left[\left(\frac{\tau_1}{\tau_R} \right)^2 - \left(\frac{\tau_1}{\tau_R} \right) + \frac{1}{6} \right] \right\}$$

$$U_1 = -\gamma \left[\left(\frac{\tau_1}{\tau_R} \right)^2 - \frac{1}{12} \right] \quad (9)$$

$$\beta = n_p L \dot{g} \tau_R, \quad \gamma = -n_p L \ddot{g} \tau_R^2.$$

The parameter β is approximately the increase in $n_p gL$ over a round trip ending a time $\tau_R/2$ after threshold and starting at $-\tau_R/2$, before threshold. Although Eqs. (8) and (9) are not very informative per se, they are quite tedious to derive and are the basis of further simplification.

We may now presume that enough round trips have occurred, such that the contribution of I_o , direct amplified spontaneous emission, may be ignored, in which case we may sum Eq. (8) over N to give

$$I \approx S_F \exp(n_p L g_{th}) \exp(U_o + U_1^2/4\beta) T(\beta, \hat{n}) , \quad (10)$$

where

$$n' = t/\tau_R - U_1/2\beta - 1/2, \quad (11)$$

and

$$T(\beta, n') \equiv \sum_{-\infty}^{\infty} \exp[-\beta(n-n')^2] . \quad (12)$$

The approximation here was in replacing the zero lower bound for n by $-\infty$. (If this were not justified, Eqs. (10) - (12) would overestimate energy on target.) The number T is the effective number of terms (were they all unity) that contribute in the sum for I . The actual number of terms Δn required in Eq. (12) is few if we start near $n \approx n'$, and may be estimated in the case of integral n' by dropping all the terms less than 0.1 as given by

$$\beta \frac{\Delta n + 1}{2} \approx 2.3, \quad (13)$$

Equation (13) suggests that there are two regimes in the evaluation of T (and hence I) corresponding to high and low values of β . The value of β for just one term ($\Delta n = 1$) is 2.3 and hence for β this large or larger, only one term in the sum of I_N contributes to I when n' is integral. If n' is half integral, each of two terms contribute equally in the transition region where the largest term in the sum yields to the next. Thus, in the large β limit, only one, or at most two, terms are required, and as is shown below, 10% accuracy results for the intensity with $\beta \geq 2.5$. This was the approach for Antares where β is 3.5

to 7.0. In the low- β limit (≤ 2.5) the effective number of terms T is expected to go like Δn of Eq. (13) and be inversely proportional to the square root of β . These statements are verified by the approximation

$$T(\beta, n') \approx \begin{cases} \sqrt{\frac{\pi}{\beta}} & \beta \leq 2.5 \\ \exp(-\beta n'^2) + \exp[-\beta(n'-1)^2] & \beta \geq 2.5 \text{ and } \frac{1}{2} > n' > -\frac{1}{2} \end{cases} \quad (14a)$$

which is good to 10% of the value of T . When n' does not fall into the required range, we use

$$T(\beta, n' + 1) = T(\beta, n') \quad (14b)$$

to bring it into range.

The value of β in the EBS ranges from 0 to 0.83 and, thus, this system lies in the low- β limit. Four gain curves were obtained from E. Jolly (shot numbers 1010, 1011, 1013, and 1034) and these raw data were reduced to gain coefficient, g_0 , curves shown in Fig. 2 as determined by the equation

$$\exp[(g_0 + \alpha_0)2/1.2] = G_R \quad (15)$$

Fig. 2

Small-signal gain coefficient curves for the EBS. Curves labeled by 1034, 1013, 1011, 1010 represent smoothed raw data which have been reduced. The two dashed curves are calculations by Kirsher. The four circles represent 90% of peak gain where tangents were drawn.

where G_R is the raw gain and where the factor of 1.2 is estimated to translate the measured gain path to an average path. The curves with data points represent the reduced Jolly data. The dashed curves near 1034 and 1013 are calculations by M. Kirsher for these same conditions. The straight lines shown in Fig. 2, in four cases, intersect the Jolly data at 90% of peak value which is shown by an oversized data point. At the 90% of peak value point, the slopes are shown to range from $0.70/\mu\text{s}\cdot\text{m}$ to $0.84 \mu\text{s}\cdot\text{m}$, and these correspond to β of 0.32 to 0.39 for the four-pass mode and 0.69 to 0.83 for the six-pass mode. Consequently for the EBS we may write

$$I(t) \approx \sqrt{\frac{\pi}{\beta}} S_F \exp(n_p L g_{th}) \exp[U_o + U_1^2/4\beta]. \quad (16)$$

We will now manipulate Eq. (16) to be in integral form by simply noting that we may write

$$U_o + U_1^2/4\beta = \frac{2n_p L}{\tau_R} \int_0^t dt [g(t) - g_{th}] + C_1 t + C_o, \quad (17)$$

where

$$C_o = \beta \left[\frac{1}{4} - \frac{\tau_1}{\tau_R} \right] + \frac{\alpha^2}{4\beta} \left[\left(\frac{\tau_1}{\tau_R} \right)^2 - \frac{1}{12} \right]^2 \quad (18)$$

$$C_1 t = \alpha \frac{t}{\tau_R} \left[\frac{\tau_1}{\tau_R} - \frac{1}{6} \left(\frac{\tau_1}{\tau_R} \right) \right].$$

For the EBS, we have for the six-pass mode $|C_o| < .08$ and $|C_1 t| < .04$, thus, these corrections are negligible, and the following approximation is justified:

$$I(t) = \left[\sqrt{\frac{\pi}{\beta}} S_F \exp(n_p L g_{th}) \right] \exp \left\{ \frac{2n_p L}{\tau_R} \int_0^t dt [g(t) - g_{th}] \right\}. \quad (19)$$

The first term in brackets can be interpreted as the effective amount of spontaneous emission at threshold time, and the second term is the gain due to multiple passes through the gain medium.

We may write Eq. (19) as a differential equation with an initial condition near threshold:

$$I(t) = \frac{2n_p L}{\tau_R} \left[g(t) - g_{th} \right] I(t) , \quad (20)$$

$$I(0) = \sqrt{\frac{\pi}{\beta}} S_F \exp(n_p L g_{th}) .$$

This equation differs from similar differential equations written previously⁶ in three respects: (1) there is no source term in our differential equation, (2) our initial condition is near threshold ($t=0$), rather than at gain turn-on, and (3) the effective number of passes $\sqrt{\pi/\beta}$ appears. An important feature of this is that the location measured by τ_1 of the point amplifier does not enter, except through the negligible correction $C_0 + C_1 t$.

III. The Uniform Model

Model C of Fig. 1 gives rise to a similar differential equation. The quantity I_n at time t involves spontaneous emission which has made n round trips in the cavity and an additional half round trip. The expression for the intensity on target is, thus, approximately

$$I_n(t) = S_F (R_F R_t)^n \exp \left[c \int_{t-n\tau_R - \tau_R/2}^t g(t) dt \right] . \quad (21)$$

The integral is expanded near $n \approx n_0 = t/\tau_R - \frac{1}{2}$ to terms which are quadratic in $n - n_0$ and the resultant expression is summed over n to give an expression which can be written in differential form as

$$\dot{I}(t) = c(g(t) - g_{th}) I(t) \quad (22)$$

$$I(0) = T(\beta, n') S_F \exp(n_p g_{th} L) ,$$

where T is defined in Eq. (14) and is $\approx \sqrt{\pi/\beta}$ for the EBS. Here $n' = t/\tau_R - \frac{1}{2}$ and β is $c\dot{g}(0)$. There is no difference between Eq. (22) applied to Model C and Eq. (20) applied to Model B.

An alternate way of deriving Eq. (22) exists which is based upon combining of point amplifiers, but this applies to the case of linear gain only. This method shows that a continuous amplifier is equivalent to a point amplifier

located halfway between either end of the cavity with $\tau_1 = \tau_R/4$. Evaluation of $C_0 + C_1 t$ in Eq. (18) with $\alpha = 0$ and $\tau_1 = \tau_R/4$ gives identically 0, and hence, Eq. (22) follows.

IV. Application of the Models

There are two types of computation to which we can apply our models. The first concerns the relationship between the static threshold g_{oth} and the threshold value which is measured on the EBS. The second tells us how much higher than the static threshold we may go without target damage by shooting "on the fly."

A. Unconditionally Stable Operation

When a measurement of the parasitic threshold is made on the EBS, it is established by finding the peak gain on the gain curve during a shot which produces no visible target damage. This value is referred to as the unconditionally stable value as opposed to the conditionally stable value, which would suppose that the gain is dumped at extraction time. The unconditionally stable value is not the same as the static threshold which lies below it. In Fig. 3 we see the gain curve,

Fig. 3

Gain curve for unconditionally stable operation. The static threshold g_{th} is exceeded for time $2\Delta t$ by an amount Δg .

and we note [see Eq. (20)] that roughly from the time the threshold value is exceeded to the time threshold is crossed again an increase in the intensity within the cavity occurs. If the gain is just above the unconditionally stable

value, damage will occur near the time the threshold is crossed the second time and only slightly later for an energy-per-unit-area criterion.

In applying our models [Eq. (20) and/or Eq. (22)] in computing unconditional-ly stable values, an additional complication occurs beyond that encountered in the Antares calculations. There the intensity was rapidly exponentiating at extraction time, but here the intensity is at its peak as we cross threshold the second time and decreases beyond. The pulse width is determined by approximating the gain near the second crossing $t \approx t_{th2}$ by a linear curve so that Eq. (20) reads

$$\dot{I}(t) = -\frac{2n_p L}{\tau_R} |\dot{g}_{th2}| (t - t_{th2}) I(t) , \quad (23)$$

and solving gives

$$I(t) \approx I(t_{th2}) \exp \left[-\frac{n_p L}{\tau_R} |\dot{g}_{th2}| (t - t_{th2})^2 \right] . \quad (24)$$

This is a Gaussian pulse of FWHM of

$$\Delta t_{1/2} = 2\tau_R \sqrt{\frac{\ln 2}{n_p L |\dot{g}_{th2}| \tau_R}} , \quad (25)$$

where we note that

$$n_p L |\dot{g}_{th2}| \tau_R \approx \beta , \quad (26)$$

this being exact for a quadratic gain pulse. The ratio of the total illuminance to the intensity is the quantity we need in order to compute the illuminance (J/cm^2), and for the Gaussian this time is given by

$$\Delta t_g = \sqrt{\frac{\pi}{\beta}} \tau_R = 0.94 \Delta t_{1/2} . \quad (27)$$

This equation has a simple interpretation: $\sqrt{\pi/\beta}$ is the effective number of passes (or terms contributing to T) and τ_R is the time required per pass or round-trip time; Δt_g is just the time all of these passes are rattling around.

We may now write an expression for the total illuminance on target during a gain pulse that is not truncated due to extraction.

$$\epsilon = (\tau_R S_F \pi / \beta) \exp \left\{ \int_0^{\tau_{th}^2} \frac{2n_p L}{\tau_R} [g(t) - g_{th}] dt + n_p g_{th} L \right\}, \quad (28)$$

specializing to a quadratic gain curve we have

$$\epsilon = \frac{\pi}{\beta} S_F \tau_R \exp \left[n_p g_{th} L + \frac{4}{3} \beta (\Delta t / \tau_R)^2 \right]. \quad (29)$$

Thus for a given β and a given $g_{th} L$ we can solve for Δt and the corresponding Δg which produces a given $\epsilon = \epsilon_{\max}$:

$$\Delta t = \left\{ \frac{3\tau_R^2}{4\beta} \ln \left[\frac{\epsilon_{\max} \beta}{\pi S_F \exp(n_p g_{th} L) \tau_R} \right] \right\}^{1/2} \quad (30)$$

$$\Delta g = \beta \Delta t / 2n_p \tau_R, \quad (31)$$

which for the six-pass and four-pass modes can be written for $\epsilon_{\max} = 0.1 \text{ J/cm}^2$ as

$$\left. \begin{aligned} \Delta t &= \sqrt{\frac{\ln 4430\beta}{49\beta}} \text{ } \mu\text{s} \\ \Delta g_0 &= 1.01 \beta \Delta t \end{aligned} \right\} \text{ six-pass} \quad (32a)$$

$$\left. \begin{aligned} \Delta t &= \left[\frac{\ln 1.16 \times 10^6 \beta}{104\beta} \right]^{1/2} \\ \Delta g_0 &= 2.21 \beta \Delta t \end{aligned} \right\} \text{ four-pass} \quad (32b)$$

Calculations using TARDAM are shown in Fig. 4 as solid lines for the four-pass and six-pass modes. The curves labeled by $\ddot{g}_0$ are curves on which $\ddot{g}_0$ is the indicated value. The typical value of $\ddot{g}_0$ on the four gain curves near peak gain is $-1(\mu\text{s})^2 - \text{m}$, and this curve intersects the four-pass mode curve at $\Delta g_0 l = 0.4$ and the six-pass at $\Delta g_0 l = 0.3$. The triangles shown are generated by Eq. (32b) and the circles by Eq. (32a) and the agreement is seen to be excellent.

Fig. 4

Excess of gain-length product above static threshold for unconditionally stable operation as a function of time to peak gain or of $\ddot{g}_0$.

B. Conditionally Stable Operation

It is planned to operate the EBS in a manner so that the laser pulse arrives near the peak of the gain curve or possibly slightly earlier. The stored energy is dumped at extraction time and what occurs later is immaterial as regards target performance. In the unconditionally stable mode of operation, the entire time $2\Delta t$ (see Fig. 3) that the gain is above threshold contributes to the damage of the target. In the conditional or dynamical mode (actual operating circumstances) only half that time or less is available. Consequently the measured unconditionally stable value of the gain underestimates how high we may pump the system and still not have target damage due to parasitics; the conditionally stable value of the threshold is a better measure of system performance. To be sure, there are questions of jitter control in coordinating all eight beams, but even if the system were operated just at

peak gain, benefits do occur in pushing the system beyond the unconditionally stable point of operation.

The harder the system is pumped for a given extraction $g_o l$, the higher the conditionally stable threshold. This means that the more the excess gain is, the earlier extraction can be and the higher in gain we can go. These effects are evaluated below.

The expression for the ratio of the energy on target to the intensity is based on the same method used in simple calculations for Antares. On a log plot, the intensity is assumed to follow the instantaneous tangent over its past history, hence, the ratio of the energy to intensity is the time Δt_e given by

$$\Delta t_e = \tau_R \left\{ 2n_p L [g(t) - g_{th}] \right\}^{-1} \quad (33)$$

in both models B and C. This expression should be good, as before, several round trips away from threshold time. Consequently we may write the energy on target as

$$\epsilon = \Delta t_e \sqrt{\frac{\pi}{\beta}} S_F \exp(n_p L g_{th}) \exp[G(t)] , \quad (34)$$

where G is the integral of the excess gain above threshold given by

$$G(t) = \int_0^t \frac{2n_p L}{\tau_R} [g(t) - g_{th}] dt . \quad (35)$$

Assuming a quadratic gain curve, we may write Eqs. (33) to (35) as

$$\exp[T_R^2 (\beta - \gamma T_R / 3)] = K_o (\beta / \pi)^{1/2} T_R (2\beta - \gamma T_R) \quad (a)$$

$$K_o = \epsilon_{\max} [\tau_R S_F \exp(n_p L g_{th})]^{-1} \quad (b)$$

$$T_R = t / \tau_R \quad (c) \quad (36)$$

$$\beta = n_p l \ddot{g}_o \tau_R \quad (d)$$

$$\gamma = - n_p l \ddot{\ddot{g}}_o \tau_R \quad (e)$$

This equation (Eq. 36a) can be solved by iteration for T_R from which we find the increase in $g_0 l$ as the pulse is coming the amplifier by using

$$t_g/\tau_R = T_R - \tau_L/\tau_R \quad (37)$$

$$\Delta g_0 l = n_p^{-1} [\beta(t_g/\tau_R) - \frac{1}{2}\gamma(t_g/\tau_R)^2] ,$$

and the e-folding time of the pulse Δt_e is

$$\Delta t_e = \tau_R / (2n_p \Delta g_0 l). \quad (38)$$

Equations (36) and (37) may be programmed on an HP-25 by iteration where we store an initial guess for T_R such as 1 in 0, β in 2, γ in 3, τ_L/τ_R in 4, K_0 in 6, and n_p in 7; the program is

RCL2	2	x	RCL3	RCL0	x	-	RCL0	x	RCL6
x	RCL2	π	$\div$	$\sqrt{}$	x	$\ln$	RCL2	RCL3	RCL0
x	3	$\div$	-	$\div$	$\sqrt{}$	ST00	RCL4	-	ST05
RCL2	RCL3	RCL5	x	2	$\div$	-	RCL5	x	RCL7
$\div$	ST01	PAUSE	GT001						

The program pauses after the calculation of $\Delta g_0 l$ and may be stopped when it converges by passing R/S.

The TARDAM calculations, which are shown in Figs. 5a and b, require some explanation. The upper curve is for a linear gain curve that is entirely characterized by $\dot{g}_0(0)$ or β , and the increase $\Delta g_0 l$ achievable before damage occurs, is plotted versus β or $\dot{g}_0$. The other curves are for $\ddot{g} < 0$, which means the gain curves go through a maximum at a positive time $-\dot{g}_0/\ddot{g}_0$. When β is large, the maximum is far away and never reached; however, as β gets small enough, there comes a point at which $\Delta g_0 l$ occurs at the peak of the gain curve and these points are shown as solid circles in Fig. 5. As β drops below this value, damage occurs after peak gain and the peak gain values are as the parabolic curve which goes through the origin.

Fig. 5

Excess of gain-length product above static threshold as a function of β for various $\dot{g}_0$.

Calculations using the hand calculator program above are compared to the TARDAM (Model A) calculations in Fig. 5a and b. For all the curves, we used the values in Table I, and for the four-pass curves, $\alpha = 0, 0.051$, or 0.102 , and for the six-pass, $\alpha = 0, 0.163$, or 0.327 . All of these calculations are based upon $\epsilon_{\max} = 0.1 \text{ J/cm}^2$. The agreement is seen to be excellent, and slightly better for the six-pass curves than for the four-pass. In the four-pass case, Model B retains spontaneous emission from the point amplifier of Model A farthest away from the target. Normally this would be adequate, but between this amplifier and the other lies the saturable absorber, which diminishes almost all of the amplification the spontaneous emission receives; consequently, the contribution from the amplifier nearest the target (i.e., the last pass) is non-negligible and may be shown to be an additional $\exp(-g_{\text{oth}}\ell)/0.793 \exp(-6)$ or 31% of that which we assumed. In the six-pass case this situation is not as important because there are two passes of gain before the saturable absorber.

In interpreting these results, the difficulty of establishing a value for $\epsilon_{\max}$ per beam should be kept in mind. The criterion we use here is that four beams in concert produce 0.4 J/cm^2 , which will damage glass microballoons and give $\epsilon_{\max} = 0.1 \text{ J/cm}^2$. This is believed to be a conservative criterion because the line shape effects⁵ lower the illuminance by about a factor of 3 in Antares and perhaps more here; also, the long rise times tend to damage targets with more difficulty than ns pulses.

It is now a simple matter to apply our calculations to the Jolly gain curves of Fig. 2. We simply translate the indicated slope into a β value using Eq. (36c) with $\ell = 2\text{m}$. At the 90% of peak gain point we have $\beta = 0.69$ to 0.82 for the six-pass mode and $\beta = 0.32$ to 0.38 for the four-pass. We also estimate that $\ddot{g}_0 = -1/(\mu\text{s})^2\text{-m}$ for most of these cases. Consequently, Fig. 5 gives $\Delta g_0 \ell \approx 0.5$ to 0.6 for the six-pass mode and $\Delta g_0 \ell \approx 0.5$ to 0.7 for the four-pass mode. The corresponding rise times as given by Eq. (38) are 45ns to 55ns in the six-pass case and 40ns to 57ns in the four-pass case.

We will now estimate what would happen if we dropped the saturable absorber pressure to zero. The gain curve of shot #1034 as shown in Fig. 2 is used. With no saturable absorber we have $g_0 \ell = 4.41$ ($g_0 = 2.21/\text{m}$) at the static threshold of the four-pass mode rather than 7.71 ($g_0 = 3.70/\text{m}$) with the saturable absorber. For the six-pass mode these values are $g_0 \ell = 4.76$ ($g_0 = 2.38/\text{m}$) with, and $g_0 \ell = 6.76$ ($g_0 = 3.38/\text{m}$) without the saturable absorber. The operating point on shot #1034 without SF_6 thus occurs near $\dot{g}_0 = 2.1/\mu\text{s}\cdot\text{m}$ and $\ddot{g}_0 \approx -1$; the corresponding values of β are 0.95, 2.08 for the four-pass and six-pass modes, respectively. Examination of Fig. 5 shows that $\Delta g_0 \ell$ achievable above threshold is 1.7 ($\Delta t_e = 17\text{ns}$) in the four-pass mode and 1.4 ($\Delta t_e = 20\text{ns}$) in the six-pass mode, giving conditionally stable values of 6.1 and 6.2 for the four- and six-pass modes. Examination of calculations⁷ by Montgomery et al. show that $\approx 900\text{J}$ may be extracted at this point!*

Before dispatching the saturable absorber cells on their way, the two following points should be considered: (1) jitter is present in initiation of the eight separate discharges and this problem may require some R and D to improve to acceptable levels on the EBS, and (2) a misfiring of the oscillator may lead to a strong parasitic oscillation and damage internal surfaces.

*Note added in proof: We assumed a threshold $g_0 \ell$ of 4.4. Experiments that are not unambiguous give $g_0 \ell$ of 3.5 and would lower this number to 500-600J.

At one time Schappert argued that even without the benefits of a fast-rising gain curve, it makes sense to pull out the saturable absorber cell to make the system more reliable, even if at a lower output. Furthermore, his suggestion of a different gain mix in conjunction with the fast-rising gain effects reported here might lead to 1 kJ/beam without saturable absorbers.

V. Conclusion

The increase above static threshold due to dynamical effects has been well estimated in simple models for unconditionally stable operation, Eq. (32), and for conditionally stable operation, Eq. (36). When the system is operated with saturable absorbers and extraction is at 90% of peak gain, conditional improvements in $g_0 l$ are up to 0.6 to 0.7 above static threshold. When the saturable absorbers are removed, the dynamic improvement can be greater at 1.7 to 1.4 (however with no static improvement) with theoretical estimates of conditionally stable operation at $g_0 l \sim 6$. Thus, the possibility of postponement of installation of saturable absorbers should be seriously entertained if the benefits from saturable absorbers do not justify their costs and delay to the program.

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