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ANALYSIS OF THE FUSION-EFFECTIVENESS OF ACTIVE AND PASSIVE PULSE-STACKERS*

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ABSTRACT

The laser fusion effectiveness of various active and passive pulse-stacking schemes is investigated. Factors considered include efficiency, achievable rise-times, variety in output pulse shapes, simplicity of construction and operation, and compatibility with existing and proposed fusion laser systems. During the research phase of laser-fusion development a particular class of active pulse-stackers should be superior, although a passive system, such as the KMSF pulse-stacker, should be superior for use in a fusion reactor system.

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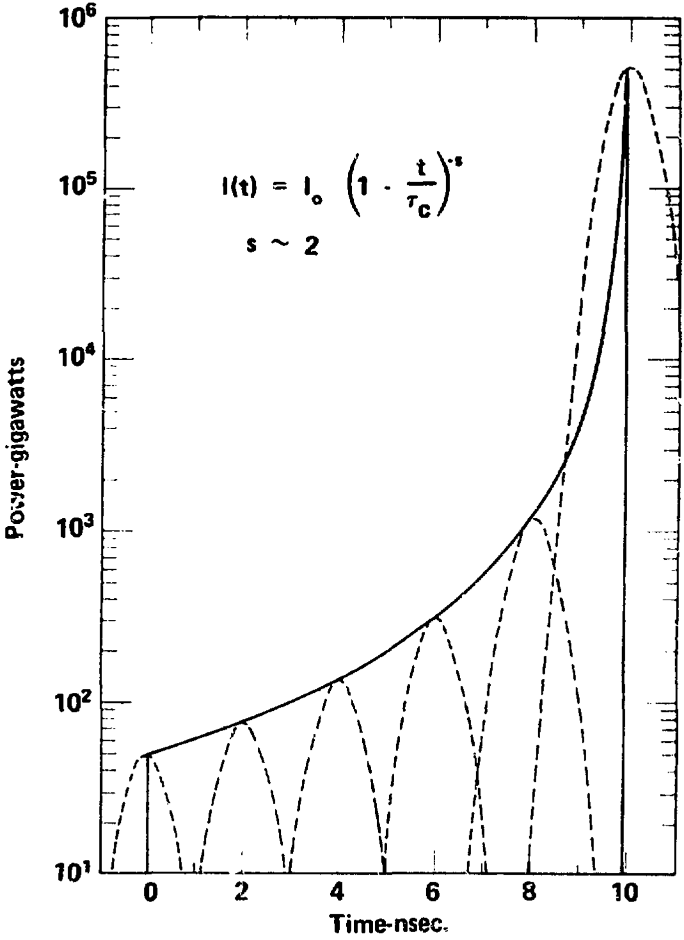
Isentropic compression of homogeneous thermonuclear fuel pellets in laser fusion systems requires a laser pulse with a faster-than-exponential rise in intensity.[1] The theoretically-predicted pulse shape[2-4]

$$I(t) = I_0 \left(1 - \frac{t}{\tau_c}\right)^{-s} \qquad s \sim 2$$

is shown as the solid curve in SLIDE 1 for a compression time τ_c = 10ns and a total pulse energy of 50kJ. As pulses of this general shape cannot be generated directly by existing lasers, methods of external pulse-shaping must be utilized. One such method, known as pulse-stacking, consists of generating a sequence of pulses with appropriate amplitudes and recombining these pulses with appropriate time delays to form an approximation to the required pulse shape. The dotted curves represent six gaussian laser pulses of 1 ns FWHM duration separated by 2 ns from each other, with peak amplitudes chosen to match the theoretical curve. Although the envelope of these pulses gives a fair approximation to the theoretical curve, severe deviations are apparent at the beginning and shortly before the peak of the pulse envelope. The requirement of isentropic compression demands a good match to the initial portion of the pulse envelope while the criterion of thermonuclear ignition requires a good match near the peak of the pulse envelope.

The match between the approximated pulse envelope and theory can be improved by using pulses of variable duration or variable separation or by using more pulses of shorter (fixed) duration and interpulse separation. No convenient method exists for producing subnanosecond pulsewidths which are variable on nanosecond time scales. Pulse-stacking schemes do exist which can produce

PULSE SHAPE FOR ISENTROPIC COMPRESSION



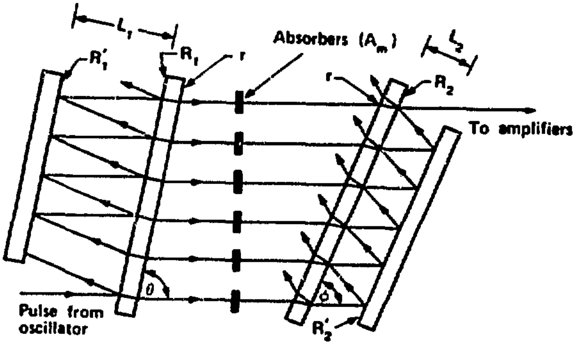
SLIDE 1

variable pulse separations, the Rochester multiple beamsplitter system being a notable example.[5] However, these systems all require a large number of components, each of which must be properly aligned. This complicates fabrication and makes changing the output pulse shape extremely difficult. In the remainder of this talk we will consider only those devices which have a constant interpulse separation, as these devices require relatively few components.

Numerous active and passive pulse-stacking schemes have been proposed which fall into this last category, but little documentation has appeared in the literature. We report herein an analysis of four classes of pulse-stacking devices, two of which are new. The four classes of device are: 1) the Thomas-KMSF passive pulse stacker (now well known)[6]; 2) an active pulse stacker utilizing an electro-optical modulator[7]; 3) a passive pulse stacker conceived by Emmett at LLL; and 4) a class of passive devices using sectored reflectors.

The Thomas-KMSF pulse-stacker,[6] shown schematically in SLIDE 2, consists of two tilted etalons and a set of attenuators A_m. A single laser pulse incident on the first tilted etalon generates N separate pulse images displaced in time and space. After each pulse image is attenuated by an appropriate amount the images are recombined spatially by the second etalon. Due to the geometry of the device, each pulse image is separated in time from its neighbors by a constant amount. The intensities of the different output pulse images and the interpulse separations are given by the relations in SLIDE 3, where θ and ϕ are the tilt angles of the etalons; r, R_1', R_2, and R_2' are the reflectivities of the indicated surfaces; and L_1 and L_2 are the etalon spacings.

THOMAS-KMSF PULSE-STACKER



SLIDE 2

CHARACTERISTICS OF THE THOMAS PULSE-STACKER

Pulse Intensity (m^{th} output pulse)

$$I_m = I_0 (1 - R_1)(1 - R_2)(1 - r)^2 (R_1 R_1')^{m-1} (R_2 R_2')^{N-m} A_m$$

Pulse Delay (of m^{th} output pulse with respect to first output pulse)

$$D_m = [2(m-1)/c] [L_1 \csc\theta - L_2 \csc\phi + L_1 \sin(\theta - \phi) \cot\theta \csc\phi]$$

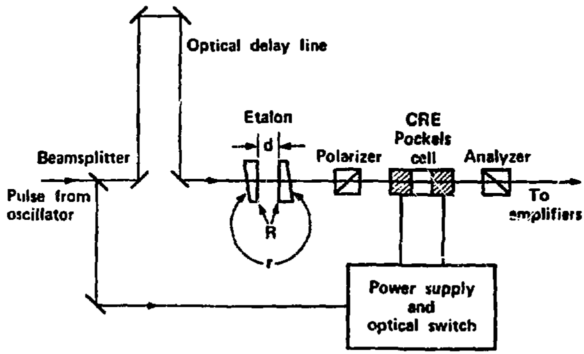
$$= (m - 1)\, \tau_K$$

SLIDE 3

The Pockels cell pulse-stacker,[7] shown schematically in SLIDE 4, consists of an etalon and a Pockels cell (with its power supply) placed between crossed polarizers. A single laser pulse incident on the etalon generates a train of pulse images of ever-decreasing amplitude. This pulse train is linearly polarized by the first polarizer; and, as it passes through the Pockels cell, the train is converted to elliptically polarized light, the degree of ellipticity being linearly dependent on the instantaneous voltage across the Pockels cell. The second polarizer transmits only that component polarized perpendicularly to the initial polarization. The convolution of the decreasing etalon output with the voltage-dependent transmission of the polarizer-Pockels cell combination determines the output pulse shape. SLIDE 5 gives the relations governing pulse intensity and pulse separation for the Pockels cell pulse-stacker. A_0 is the intrinsic loss in the polarizers and Pockels cell, r and R are the reflectivities of the indicated surfaces, d is the etalon spacing, λ is the laser wavelength, n_o and r_{63} are the refractive index and electrooptic coefficient of the Pockels cell, and V(t) is the applied voltage.

The passive pulse-stacker developed by Emmett[8] at LLL is shown schematically in SLIDE 6. A single laser pulse passes through a beam splitter and into a solid etalon tilted at an angle α to the propagation direction. The etalon generates N pulse images displaced in space and time which are then attenuated by the absorbers A_m. A mirror, normal to the propagation direction, reverses the beams causing them to be further attenuated and then recombined spatially by the tilted etalon. A portion of the pulse train exiting from the etalon is deflected towards the amplifier chain by the beamsplitter. The pulse intensities and pulse separations

POCKELS CELL PULSE-STACKER



SLIDE 4

CHARACTERISTICS OF THE POCKELS CELL PULSE-STACKER

Pulse Intensity (m^{th} output pulse)

$$I_m = I_0 A_0 \ (1 - r)^2 \ (1 - R)^2 \ R^{2(m-1)} \ \sin^2(\Phi/2)$$

$$\Phi(t) = 2\pi n_0^3 \ r_{63} \ \lambda^{-1} \ V(t)$$

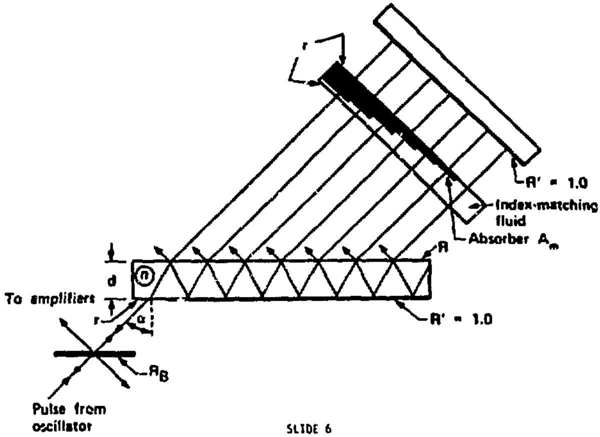
Pulse Delay (of m^{th} output pulse with respect to first output pulse)

$$D_m = 2(m - 1) \ d/c$$

$$= (m - 1) \ \tau_p$$

SLIDE 5

EMMETT-LLL PASSIVE PULSE-STACKER



SLIDE 6

CHARACTERISTICS OF THE EMMETT PULSE-STACKER

Pulse Intensity (m^{th} output pulse)

$$I_m = I_0 R_B (1 - R_B) (1 - r)^6 (1 - R)^2 R^{2(m-1)} A_m^2$$

Pulse Delay (of m^{th} output pulse with respect to first output pulse)

$$D_m = [4(m - 1)d/c] (n^2 - \sin^2 \alpha]^{1/2}$$

$$= (m - 1) \tau_L$$

SLIDE 7

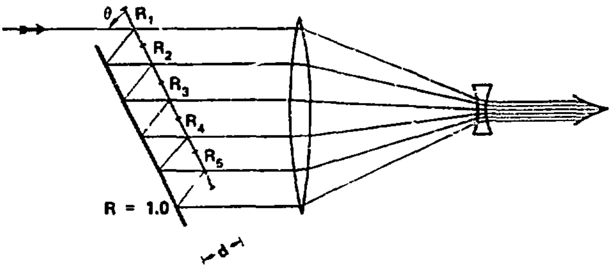
for the Emmett-LLL pulse stacker are given in SLIDE 7. R, R_B, and r are the reflectivities of the indicated surfaces, d is the etalon spacing, and n is the etalon refractive index.

A pulse-stacking device utilizing an etalon with a sectored reflector[9] is shown schematically in SLIDE 8. A single pulse incident on the tilted etalon generates N pulse images separated in space and time. The pulse images are then concentrated spatially by a telescope system. The intensity of each pulse image is determined by the reflectivities of the different sectors of the reflector. SLIDE 9 gives the relations governing the pulse intensities and pulse separation for the sectored reflector pulse stacker. The R_n are the reflectivities of the indicated surfaces, d is the etalon spacing, and θ is the tilt angle. If a given set of pulse intensities is desired, the requisite R_m may be determined from the given relation

A number of factors influence the utility of a pulse-stacker in fusion applications. Foremost of these is the ability of the system to generate a good approximation to the required pulse shape. Corrections to the output pulse shape required by conditions of saturated gain in the amplifier chain and possible modifications of the pulse envelope caused by interpulse interference effects[10] notwithstanding, all of the previously-mentioned devices should be capable of generating reasonable approximations to the desired pulse shape.

The Pockels cell pulse-stacker is restricted to generating pulses of total duration greater than one nanosecond due to the characteristics of presently-available electrooptic modulators. This is not a great problem as multi-nanosecond pulses will be required in the later stages of laser fusion research and in laser-fusion reactors. Further improvements in Pockels cell design may reduce this

SECTORED REFLECTOR PULSE-STACKER



SLIDE 8

CHARACTERISTICS OF THE SECTORED REFLECTOR PULSE-STACKER

Pulse Intensity (m^{th} output pulse)

$$I_m = I_o(1 - R_m) \prod_{n=1}^{m-1} R_n$$

$$R_m = \frac{1 - \sum_{n=1}^{m} I_n/I_o}{1 - \sum_{n=1}^{m-1} I_n/I_o}$$

Pulse Delay (of m^{th} output pulse with respect to first output pulse)

$$D_m = 2(m - 1)d \sin\theta/c$$

$$= (m - 1)\tau_S$$

SLIDE 9

restriction. The passive pulse-stackers are limited to pulse durations and rise-times greater than 100ps by size (speed of light) considerations, the requirement of many output pulse images, and probable input pulse durations (10-100ps). The shorter pulse durations make the passive pulse-stackers necessary during the initial phases of fusion research.

During the research phase of laser fusion efforts flexibility in the shape of the pulse envelopes which a single pulse-stacker may generate is a great asset. This is because agreement between the predicted and actual pulse shape requirements is not assured. When using a passive pulse-stacker, changing the output pulse shape may require fabrication of an entirely new unit or replacement of one or more components and subsequent realignment. Without replacing at least one component, only one pulse envelope may be obtained from the Emmett-LLL pulse-stacker. In both the Thomas-KMSF and sectored reflector pulse-stackers the inter-pulse image separation and therefore the pulse duration may be varied over a small range by changing the etalon spacings and the angles of incidence. However, the pulse image-to-pulse image intensity variation may not be altered without component replacement. In the Pockels cell pulse-stacker, on the other hand, the etalon spacing, voltage risetime, voltage magnitude, bias voltage, and the delay between initiation of the voltage transient and the arrival of the pulse images, may all be varied independently without component replacement or realignment. Thus a wide variety of pulse shapes may be obtained from a single active device. However, in a laser fusion reactor system simiplicity and reliability in producing a single pulse shape are of prime importance, and a passive system is obviously superior to an active one.

Another factor affecting the effectiveness of a pulse-stacker is its efficiency, defined as the ratio of useful energy in the output pulse to energy in the input pulse. Comparing the efficiencies of different pulse-stackers is difficult because of the complexity of the relations governing the pulse intensity. However it is possible to separate each expression into two factors: one, called the intrinsic efficiency, which is independent of the pulse image number m; and one which is dependent on the pulse image number. This separation is indicated in SLIDE 10, where for simplicity we have set $r = 0$, $R_B = 1/2$, and $R_1' = R_2' = A_o = 1$. The pulse image-dependent factor determines the shape of the output pulse envelope. If these factors are made identical for each class of pulse-stacker, equivalent to having each device generate the same relative pulse shape, the pulse image-independent factors determine the relative efficiencies. For typical values $R \simeq R_1 \simeq R_2 \simeq .85$ we obtain intrinsic efficiency values of .011 for the Thomas-KMSF device, .031 for the Pockels cell system, .008 for the Emmett-LLL device, and 1.00 for the sectored reflector pulse-stacker.

On the basis of efficiency alone the sectored reflector is clearly the superior system with the Pockels cell pulse-stacker being a poor second choice. However, the importance of pulse-stacker efficiency on the performance of a laser fusion system is difficult to ascertain. A small decrease in pulse-stacker efficiency can be compensated for by adjusting the gain in one or more amplifiers, while a large decrease in efficiency requires the addition of extra preamplifier stages, thereby increasing the cost and complexity of the laser system. Other factors, however, may outweigh the disadvantage of added preamplifiers. For example, the simplicity advantage of a passive system such as the Thomas-KMSF device may be more

INTRINSIC EFFICIENCIES OF PULSE-STACKERS

Thomas $I_m = I_o \left[(1 - R_1)(1 - R_2)R_2^N/R_1\right] \left[(R_1/R_2)^m A_m\right]$

Pockels Cell $I_m = I_o \left[(1 - R)^2/R^2\right] \left[R^{2m} \sin^2 \phi_m\right]$

Emmett $I_m = I_o \left[(1 - R)^2/4R^2\right] \left[R^{2m} A_m^2\right]$

Sectored Reflector $I_m = I_o \left[1\right] \left[(1 - R_m) \prod_{n=1}^{m-1} R_n\right]$

SLIDE 10

COMPARISON OF PULSE-STACKING SCHEMES

Scheme	Type	Intrinsic efficiency	Risetime	Flexibility	Comments
Thomas	Passive	.011	$\gtrsim$100 ps	Slightly flexible	–
Pockels Cell	Active	.031	$\gtrsim$1 ns	Highly flexible	Must be isolated from oscillator
Emmett	Passive	.008	$\gtrsim$100 ps	Inflexible	Must be isolated frcm oscillator
Sectored Reflector	Passive	1	$\gtrsim$100 ps	Slightly flexible	Output beam may not propagate properly

SLIDE 11

valuable in terms of reliability than is the factor-of-three efficiency advantage of the Pockels cell system.

The preceding results are summarized in SLIDE 11. Two additional noteworthy facts are included in the chart. First, both the Pockels cell and the Emmett-LLL pulse-stackers require isolation from the oscillator as they reflect a substantial portion of the beam back along the beam line. This is not difficult to do and may in fact be automatically accomplished by the single pulse switchout apparatus of the mode-locked oscillator. Second, due to the initial spatial displacement of the different pulse images, the output pulse from the sectored reflector pulse-stacker will not propagate properly in amplifier chains utilizing apodized apertures and spatial filters. Thus the sectored reflector pulse-stacker may have no utility in current laser systems unless it is placed after the last amplifier (a definite possibility because the device is 100% efficient).

Based on the preceding arguments we conclude that during the research phase of the laser fusion effort the Pockels cell pulse-stacker is superior to all others considered because of its extreme versatility and high efficiency. Because the reliability of the Thomas-KMSF system plus an added preamplifier is believed to be slightly greater than that of the Pockels cell pulse-stacker in producing repeatable output pulses, the Thomas-KMSF pulse-stacker may be the ultimate choice for a fusion reactor system among the devices considered here.

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