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The Development of an X-Ray Lasing Oscillator

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Abstract. An X-ray lasing oscillator is being developed which uses visible laser irradiation of solid targets in multipulse, multipass, operation to produce dramatic, rather than incremental, improvement in almost any X-ray lasing scheme. Hydrodynamic code simulations indicate reproducible plasma conditions are possible with multiple pulses, while ray trace simulations define mirror cavity configurations in a refracting carbon plasma under multipass operation.

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The development of X-ray lasers of sufficient brightness to be useful in research applications has been the activity of several laboratories over the past 7 to 8 eight years [1]. Every year new lasing schemes are proposed and a few are tested. The most successful X-ray lasing scheme reported to date has been obtained using neon-like selenium [2], yielding a spectral brightness in excess of 10^{29} photons/cm^{2}s/sr, in a line focus length of 3.5 cm and a gain coefficient of 4.5 to 5.0 cm^{-1}. Attempts to increase its output by increasing the line focus length beyond 3.5 cm have been unsuccessful because refraction effects divert the X-ray beam outside the gain volume [3].

Moderate success has been achieved in increasing the output by reflecting the output beam back through the gain region using X-ray mirrors during the interval the irradiating pulse is on. Using a cavity consisting of a concave mirror of 12 cm radius, 20% reflectivity, spaced 8.5 cm from a plane beam splitter of 5% transmission and 15% reflectivity, Ceglio et al. were able to demonstrate increasing gain for two passes, for a Ne-like selenium gain medium lasting about 500 ps. By the time of the third pass the beam either no longer intersects the gain region or the gain conditions no longer exist, and the output is reduced by mirror losses [4]. What is needed is a way either to sustain the gain conditions or to reproduce them at a later time.

1. Cavity Design

Taking advantage of the way high power mode-locked oscillators operate we have come up with a way to increase the output from X-ray lasing media, utilizing the functional aspects of X-ray mirror cavities. By irradiating the lasing material in multiple pulses in a mirror cavity whose transit time is equal to the interpulse interval, each pulse is amplified as it passes again and again, by mirror reflection, through the gain medium reproduced by each succeeding target irradiation. We propose to do this by developing an X-ray regenerative amplifier – in reality, an X-ray lasing oscillator. Figure 1 is a conceptual design of such an oscillator [5].

In contrast to the earlier multi-pass efforts [4] in which only one pulse was used, we propose to take advantage of the multi-pulse character of a high power mode-locked oscillator. Its output usually is a series of pulses whose inter-pulse interval is determined by the

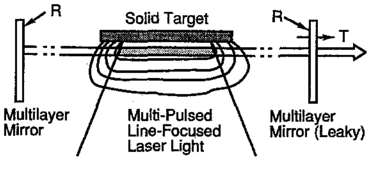

Fig. 1. Conceptual design of a multi-pulsed, multi-passed regenerative amplifier – an X-ray lasing oscillator

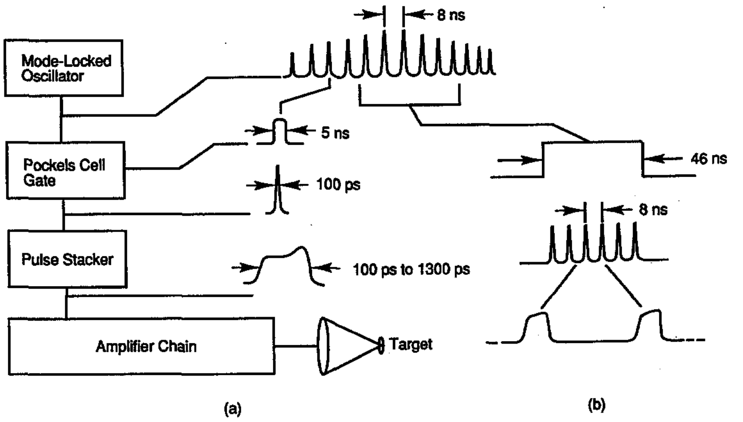

Fig. 2. **a** Conventional operation of a mode-locked oscillator system. **b** Proposed modification to provide more than one pulse out of the mode-locked train

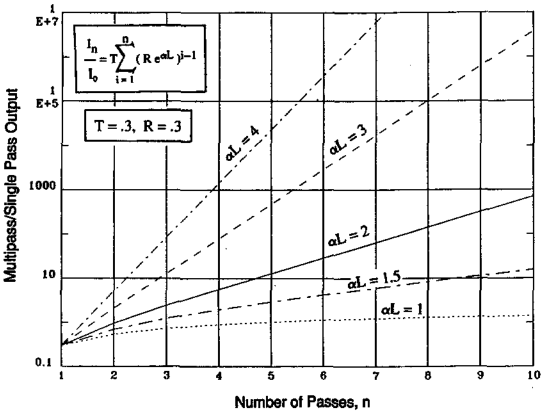

Fig. 3. Multipass/single pass out vs number of passes for a mirror reflectivity $R=30\%$, a transmission $T=30\%$, and gain-length products $\alpha L=1$, 1.5, 2, 3, and 4

cavity length of the oscillator, as indicated in Fig. 2a. Conventionally, a Pockels cell gate is employed to extract one of these pulses, which then is amplified and focused on to a target. We propose to modify the Pockels cell open time to allow more than one pulse to be extracted from the mode locked train, as shown in Fig. 2b. When amplified these pulses are incident on a solid target situated in the center of an X-ray mirror cavity whose length is exactly equal to the inter-pulse interval, so that the X-ray lasing emission generated during each target irradiating pulse is synchronized to get boosted every time it passes through the gain medium.

The evolution of the increasing output due to the multi-passing of the multi-pulses within the cavity of the amplified spontaneous emission is straight forward. Each pulse contributes as a single pulse as well as being amplified after each pass, as shown in (2), (3), and (4), where the gain-length product, αL, is assumed to be reproduced at the target for every irradiating laser pulse.

Single Pass:

$$I_1=J\left(\frac{e^{\alpha L}-1}{\alpha L}\right)T=I_0T \tag{1}$$

Double Pass:

$$I_2=I_1+I_1Re^{\alpha L}=I_1(1+Re^{\alpha L}) \tag{2}$$

Triple Pass:

$$I_3=I_2+I_1(Re^{\alpha L})^2=I_1[1+Re^{\alpha L}+(Re^{\alpha L})^2] \tag{3}$$

N-Passes:

$$I_N=I_{N-1}+I_1(Re^{\alpha L})^{N-1}$$

$$I_N=I_1[1+Re^{\alpha L}+(Re^{\alpha L})^2+\ldots+(Re^{\alpha L})^{N-1}]$$

$$I_N=I_0T\sum_{i=1}^{N}(Re^{\alpha L})^{i-1}\,. \tag{4}$$

As indicated in Fig. 3, for a mirror reflectivity $R=30\%$, a transmission $T=30\%$, and a gain-length product $\alpha L=2$, the intensity increase for $n=10$ is 1000; for $\alpha L=3$ the intensity increase for $n=10$ is over 10^6. Actually, for large number of passes and/or for gain-length products greater than one, saturation effects would eventually limit the X-ray output; instead of increasing exponentially with n, it would level off.

One of the advantages of multi-pulse, multi-pass cavity operation over single pulse operation is that it reduces the threshold mirror parameter requirements. Defining threshold of the cavity output as $I_n/I_1=1$ then, for example, in a 4-pass shot, with a gain-length product, $\alpha L=2.0$, the mirror reflectivity and transmission, could be as low as 20% and still yield output equivalent to a single pass shot. For a larger gain-length product, the mirror parameter requirements are even less stringent. Said another way, the larger the number of passes, the smaller the gain-length product that would need to be measured above background.

Output from the cavity is not a single amplified pulse, but a series of pulses of increasing and decreas-

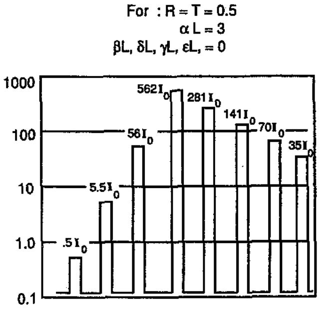

Fig. 4. Output from the cavity is a series of pulses of increasing intensity for four target irradiation pulses, then of decreasing intensity due to mirror losses

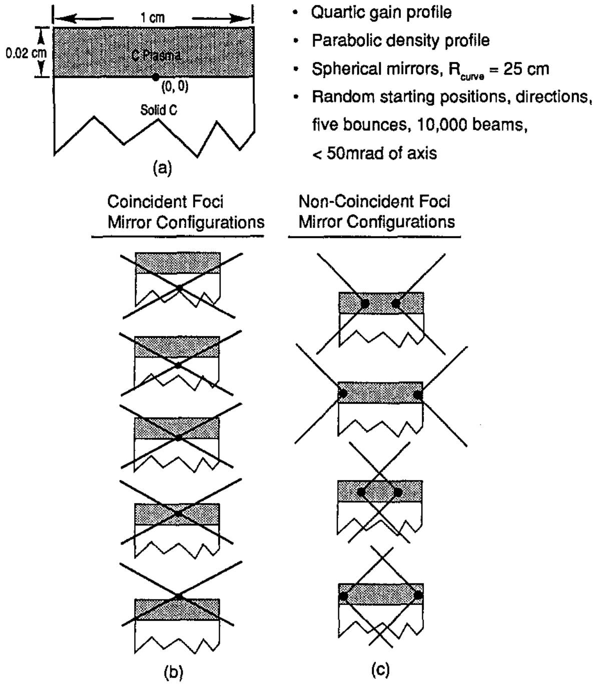

Fig. 5a–c. Ray trace simulations for a carbon plasma of dimensions and conditions indicated in **a**, and mirror configurations for coincident foci **b**, and non-coincident foci **c**

ing intensity. As shown in Fig. 4 for a 4-pulse, multipass shot, successive output pulses would increase in intensity by an order of magnitude after each irradiating pulse until the end of the 4th pulse. Thereafter, due to mirror losses, the gain-generating pulses are multipassed within the cavity and transmitted out in a reducing intensity train of pulses.

Moreover, the gain-length product can be monitored, on an average basis, from the increasing intensity train of output pulses via the following relations:

$$\frac{(I_{N+1}/I_N)-1}{1-(I_{N-1}/I_N)}=Re^{\alpha L};\quad (I_N-I_{N-1}/I_1)=(Re^{\alpha L})^{N-1}. \tag{5}$$

2. Simulations and Discussion

Since the gain medium in the plasma invariably will reside within plasma density gradients the stimulated X-ray beam will be refracted laterally. To assure that the reflected beams return to the gain medium the cavity mirrors should be spherical instead of planar, with their center of curvature residing in the gain region. For a gain volume length small compared to the mirror radius of curvature, the centers of curvature for the two mirrors should coincide. As the gain volume length is increased, the relative placement of the centers of curvature becomes less obvious, since refraction also may change the effective focusing position of the mirrors.

In order to quantify the effects of refraction in the gain medium, we have performed ray trace simulations of a 1 cm long by 200 μm diameter half cylinder of plasma generated from a solid target, as shown in Fig. 5a. The expression [6]

$$\mu=(1-n_e/n_c)^{1/2} \tag{6}$$

was used to determine the index of refraction, μ. Here n_c is the critical electron density. The ray equation of geometrical optics was used to calculate ray trajectories. A parabolic electron density of the form

$$n_e=n_0[1-(y/Y)^2] \tag{7}$$

where n_0 is density on axis, and quartic gain profile of the form,

$$G=G_0[-(y/Y)^4+(y/Y)^3-(y/Y)^2+(y/Y)] \tag{8}$$

were assumed, in agreement with recent experimental evidence [3]. Here Y is the plasma radius and G_0 is a maximum gain. The effects on X-ray laser performance of changes in plasma density, mirror radius of curvature and mirror foci location were examined using a Monte Carlo technique. For each configuration, ten thousand rays were started in random directions within 50 mrad of the axis at random locations within the plasma, and were followed until they had undergone four bounces from the spherical mirrors. The resultant aggregate intensity of the emergent beam was calculated.

In Fig. 5b we show various mirror configurations in which the two foci are coincident but displaced above and below the target surface. Figure 6 shows the variation in beam intensity as the foci are moved down through the plasma and, finally into the carbon target. As this occurs, more and more of the rays are stopped as they hit the solid carbon surface. At the same time, however, rays which do make it through four bounces tend to follow more optimum trajectories, so the

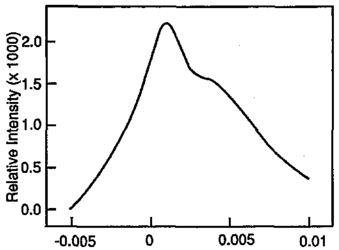

Fig. 6. Relative X-ray intensity for four pulse, four pass output as the coincident mirror foci are varied from 5 μm below the carbon target surface to 10 μm above it

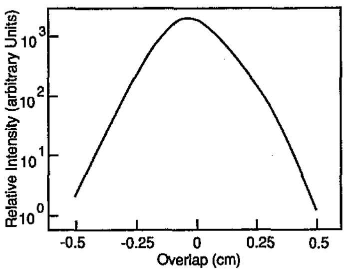

Fig. 7. Relative X-ray intensity for four pulse, four pass output as non-coincident foci are varied from an underlap of −0.5 cm to an overlap of +0.5 cm from the center of the target

aggregate beam intensity remains fairly stable. The point at which the loss of rays outweighs this effect depends on the plasma density. At densities near those predicted for the laser plasma by the HYRAD 2D hydrocode, the ray tracing package indicates that the mirror foci should be positioned just above the solid target surface.

Our simulations also show that non-coincident foci have a deleterious effect on X-ray lasing performance. Computer runs were made for overlapping and non-overlapping foci, examples of which are depicted in Fig. 5c. As shown in Fig. 7, laser performance deteriorated in both cases as the distance between foci was increased. Moving the foci apart had the effect of directing ray trajectories into the target surface.

For fixed and coincident mirror foci it was found that increasing plasma density had a negative effect on laser performance assuming a constant (quartic) gain profile. This is as one might expect, since the refraction effects become more severe when one increases the density and, with it, the slope of the density gradient.

Decreasing mirror radius of curvature might be expected to impair performance, as it would result in an increased angle between the out going and reflected, incoming beam. The refraction code predicted that this would, indeed, happen. However, the degree of impairment with significant changes in radius of curvature was found to be small. It is likely that other factors will outweigh this small effect in selecting a radius of curvature for the two mirrors.

No attempt was made to model the detailed atomic physics of the X-ray lasing process, so no quantitative predictions can be made regarding actual beam intensities. However, assuming density and gain profiles approximately as given in the examples above, the code predicts that saturation will typically occur after a few bounces. Thus, intensities much higher than those achieved to date in the regime of amplified stimulated emission appear to be possible.

The reproducibility of the plasma in space from pulse to pulse is important; without it the multipass, multipulse concept is not possible. The first pulse serves to preheat the surface and create the blowoff plasma. Subsequent pulses must then penetrate the remnants of the ionized gas and deposit their energy near the critical surface. If the time interval between the pulses is large enough so that the blowoff plasma expands to extinction, then each pulse will encounter the same conditions coming in and the temperature and density profile of the created plasma should be quite similar pulse after pulse. For intermediate inter-pulse intervals reproducible plasma conditions probably would be established only after one or more laser pulse irradiations. To investigate this question we ran our 2-D hydrodynamic code HYRAD [7] in multi-pulse mode. Here the two dimensional expansion is a critical feature since it allows for a more efficient dissapation of the blowoff material by the end of each inter-pulse interval. For the 2-D simulation we chose 4 pulses of 5×10^{12} W/cm^2 intensity impinging on a carbon disk of 3 μm thickness. This thickness permits no laser breakthrough, so it is a good representation of a solid carbon surface, yet it was thin enough to do fine zoning of the hydrodynamic flow, necessary to identify the regions being heated. Each of the four pulses was 100 ps in duration. The inter-pulse duration was 4 ns. We looked for spatial repeatability (within 50–75 μm) of the electron density, temperature and the average number of stripped electrons.

These simulations indicate that for the inter-pulse interval we have chosen, the plasma conditions are repeatable directly following the second, third, and fourth pulses, but not after the first. As seen in Fig. 8a the bare carbon nucleus, necessary for a recombination X-ray laser, occurs around 200 μm above the target surface in all shots except the first (which is not plotted). Similarly, in Fig. 8b the electron density at 10^{21} cm^{-3}, and the electron temperature, in Fig. 8c, at 100–150 eV, are also repeatable at the same distance above the target surface for the second, third, and fourth pulses, and presumably for subsequent pulses. We are, therefore, confident that plasma conditions conducive to

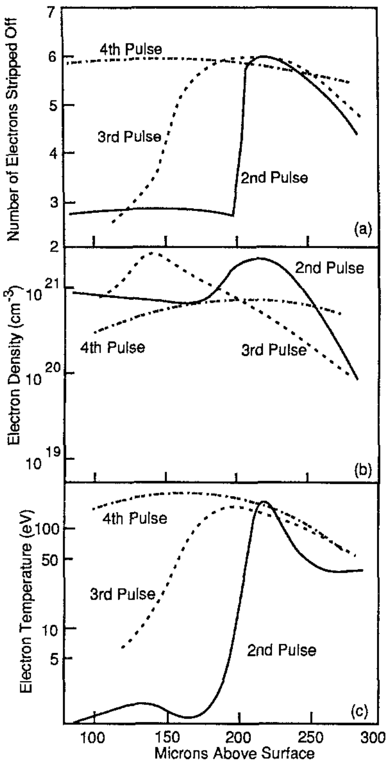

Fig. 8a–c. 2-D hydrodynamic simulations of **a** the number of electrons stripped-off of solid carbon and **b** the electron density and **c** the temperature profiles, 100 ps after each of the 2nd, 3rd, and 4th pulse irradiations

X-ray gain are possible in multipulse irradiations of solid targets.

In conventional visible laser oscillators the cavity mirrors are highly reflective, with one of the mirrors very weakly transmissive, and even with a small gain-length product, the oscillator output is substantial because of many passes within the gain medium. This is not the case for soft X-ray lasing cavities, where the mirror reflectivities are no larger than 60%, but typically less than 30%. The gain-length product must then be greater than one, the mirror transmissivity at least 30%, and the number of passes at least equal to seven for the output to be larger than an order of magnitude over that for a single pass.

Extracting the multi-passed beam from within the cavity using a thin multi-layer also means that the transmitting mirror reflectivity would be very small. Another way would be to make one of the (spherical) cavity mirrors into a reflective grating, whose zero order axis is collinear with the cavity axis, and a higher grating order is then used to extract a portion of the X-ray lasing energy. Yet another way would be to drill a large number of small holes in one of the cavity mirrors. The transmitted X-ray energy through the holes would then be focused on to a detector by another multi-layer off-axis mirror. Such a multi-pulsed, multi-passed regenerative (oscillator) amplifier system, as it would be irradiated by the KMS Chroma laser, is illustrated in Fig. 9.

3. Summary

An innovative program for the development of an X-ray lasing oscillator at KMS is presented which can produce dramatic, rather than incremental, improvement in almost any lasing scheme. It emphasizes the use of multipulses from a mode-locked oscillator synchronized with the round-trip interval of an X-ray mirror cavity to generate a series of amplified X-ray pulses which would eventually approach saturation. Ray trace code simulations indicate that high output intensities would be obtained using spherical cavity mirrors with coincident foci at or slightly above a solid target surface. Hydrodynamic code simulations also show that plasma conditions for reproducible gain is possible after more than one pulse irradiation of a target.

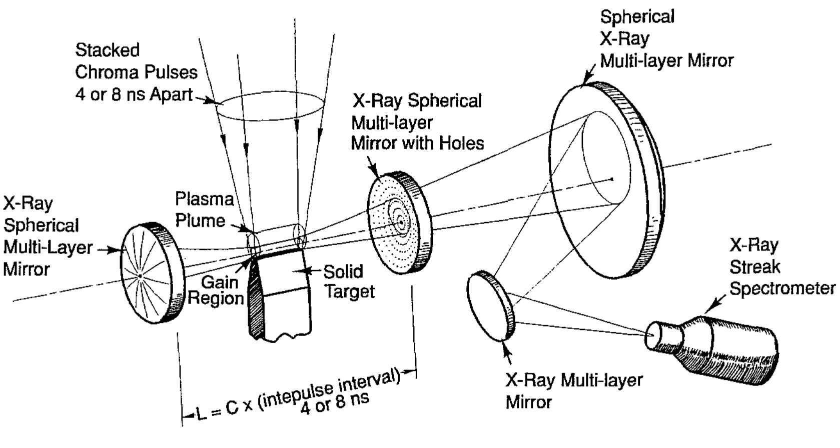

Fig. 9. A schematic of a multipulse, multipass regenerative X-ray oscillator system, including a large number of small holes in one of the mirrors for extracting the amplified beam out of the cavity

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