REPRINTED FROM THE PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON LASERS '91, DECEMBER 9-13, 1991

X-RAY AMPLIFIER ENERGY DEPOSITION SCALING WITH CHANNELED PROPAGATION

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Abstract

The spatial control of the energy deposited for excitation of an x-ray amplifier plays an important role in the fundamental scaling relationship between the required energy, the gain and the wavelength. New results concerning the ability to establish confined modes of propagation of short pulse radiation of sufficiently high intensity in plasmas lead to a sharply reduced need for the total energy deposited, since the concentration of deposited power can be very efficiently organized.

I. Discussion of Research

Recent theoretical[1,2] and experimental[3] studies have led to a fundamental development concerning the generation of high-brightness x-ray sources. These results affect our ability to controllably apply very high power densities in materials, the basic issue for the creation of bright and efficient sources of radiation in the x-ray range. The main significance of this work is the establishment of the scaling law concerning the energy requirements for x-ray amplification in the kilovolt range shown in Fig. 1. Importantly, the parameters represented in Fig. 1, and which define the relationship presented, are based on both theoretical and experimental information.

The critical governing issue, which determines the scaling relationship between the required excitation energy (E) and the amplifier gain (G) of x-ray lasers, is the spatial control of the deposited energy. The information presented in Fig. 2 shows that optimizing the gain (G) per unit energy (E) calls for the guided mode of propagation in order to optimally control the deposition of the energy.[4] Overall, in comparison to traditional forms of excitation, for a fixed x-ray energy output (E_x) and wavelength (λ_x), a reduction of several orders of magnitude in the necessary energy (E) results, as shown in Fig. 1, if this form of confined (channeled) propagation can be achieved. Therefore, if this scaling holds, a relatively small and useful laboratory-scale technology becomes feasible.

Recent experiments,[3] which are supported by carefully developed theoretical analysis,[1–2] have demonstrated the basic physics of a new form propagation exactly of the type necessary for the implementation of x-ray lasers of a fundamentally new regime of electromagnetic propagation is expected to arise in plasmas for short-pulse radiation at sufficiently high intensity. Dynamical calculations of the propagation in plasmas, incorporating both relativistic[1,5] and charge-displacement mechanisms,[2,6–9] indicate that the combined action of these processes can lead to a new stable form of spatially channeled propagation. Specifically, these experimental studies which have examined a new relativistic regime of high-intensity short-pulse propagation in plasmas, present evidence for the information of such a stable mode of spatially confined (channeled) propagation. For an electron density of ~ 1.35×10^{21} cm^{-3} and a power of ~ 3×10^{11} W, the results indicate a channel radius < 1 μm and a peak intensity ~ 10^{19} W/cm^2. Comparison of these findings with

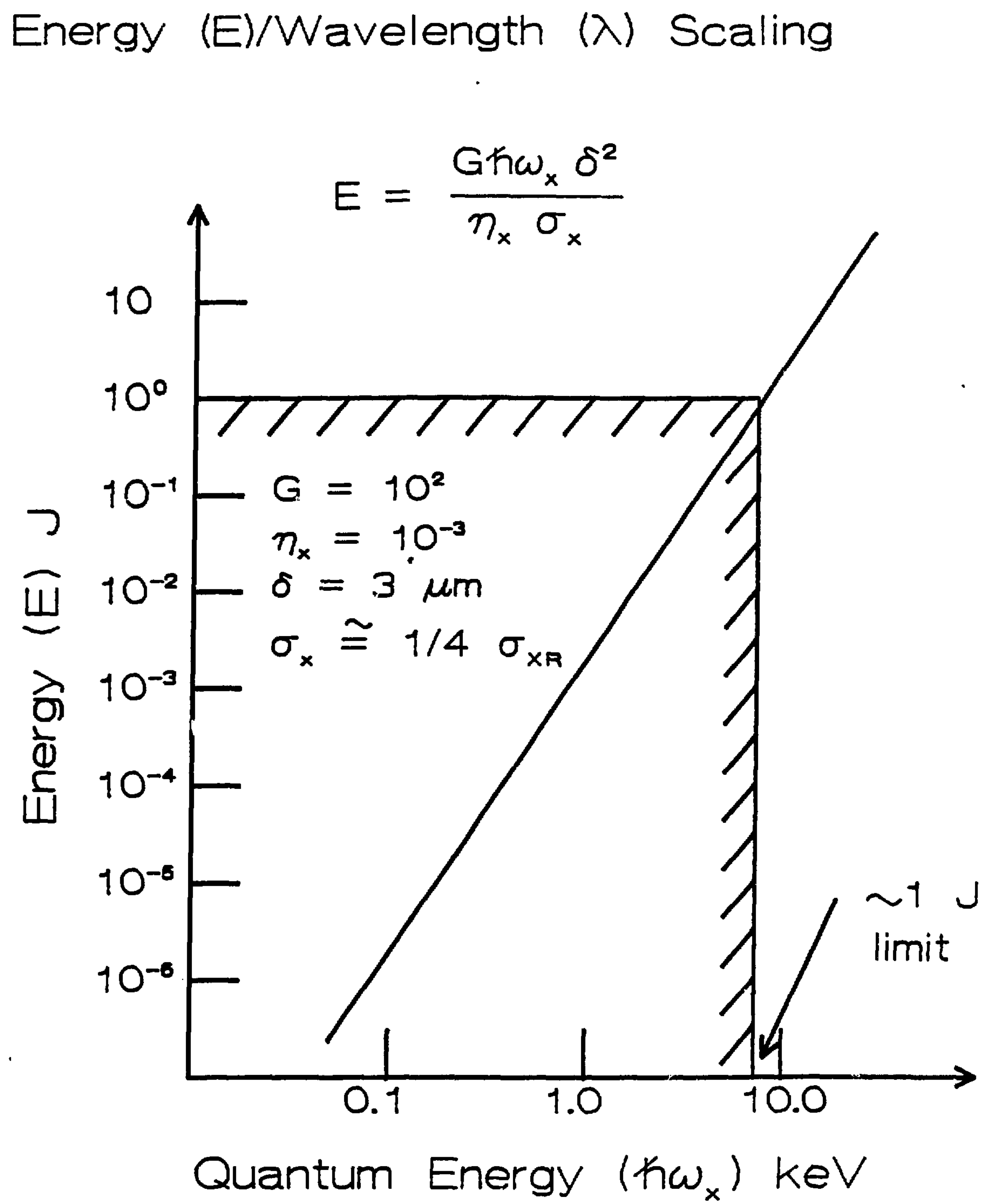
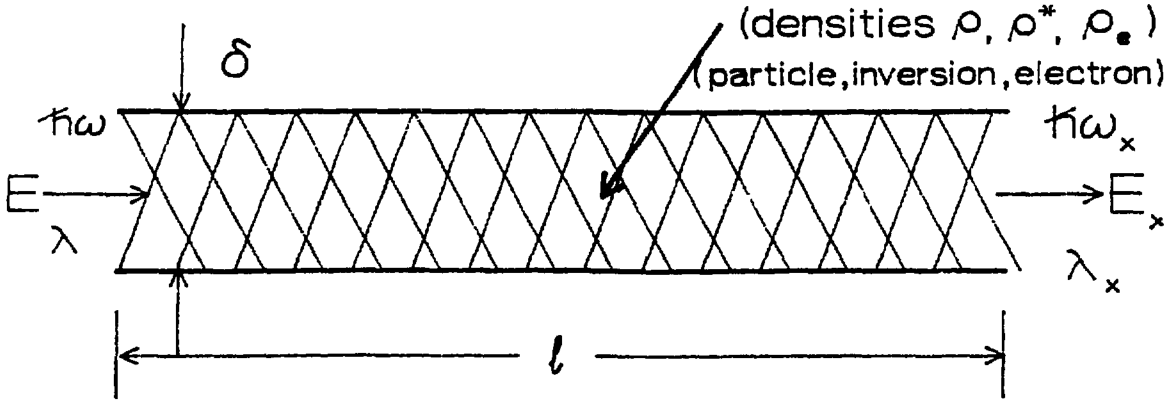


Fig. 1: Scaling relationship between required excitation energy (E) and quantum energy ($\hbar\omega_X$) characteristic of the amplifier. Parameters: total gain exponent G = 100, energy efficiency $\eta_X = 10^{-3}$, channel diameter δ = 3 μm, x-ray ($\hbar\omega_X$) cross section for stimulated emission σ_X, x-ray cross section for stimulated emission for radiatively-broadened transition σ_{XR}.

X–Ray Laser Scaling

Spatial Distribution/Amplifying Volume



$$E = \frac{\hbar\omega_x \rho^* \delta^2 \ell}{\eta_x}$$

$$G = \rho^* \sigma_x \ell$$

Laboratory Scale Technology––

$$\frac{G}{E} = \frac{\eta_x \sigma_x}{\hbar\omega_x \delta^2} \Rightarrow \text{small } \delta$$

$\therefore$ Large ℓ/δ, but $\delta \geq \sqrt{\lambda \ell}$ free space propagation

Really want to set––

$\ell >>$ Rayleigh range $\ell_R \sim \delta^2/\lambda$

$\ell \sim$ loss length

δ small

ρ^* large as possible

$\therefore$ **Guided Mode of Propagation**

Fig. 2: Spatial distribution of energy of excitation (E) for an x–ray ($\hbar\omega_X$) amplifier. Parameters are the same as in Fig. 1 with λ the wavelength of the excitation energy, assumed longitudinally delivered, and with ρ, ρ^*, and ρ_e representing the particle, inversion and electron densities, respectively. The analysis shows that optimization of G/E requires a guided mode of propagation so that high concentrations of power can be organized into high–aspect–ratio spatial volumes.

a dynamical theory[2] yield close agreement for both the longitudinal structure and the radial extent of the propagation observed. These results represent a profound change in the field of x-ray laser research because they alter drastically the fundamental scaling relationships among the relevant physical variables.

The implications of this development for general applications to x-ray imaging and the micro-characterization of condensed matter are extremely important and propitious. In terms of the x-ray source, they are (1) that a properly controlled energy deposition rate, sufficient for the production of stimulated x-ray sources up to a few kilovolts in quantum energy, can now be achieved with an excitation energy of ~ 1 J, (2) that an x-ray output energy of ~ 1 mJ per pulse is achievable with laboratory-scale technology, and (3) that an x-ray beam diameter (~ 2 – 3 μm) arises as a natural consequence of the physics. These parameters represent an exceptionally high peak brightness figure that permits a new and completely unexplored range of physical measurements to be made. Indeed, a high-brightness source of this nature is ideal for the microimaging of condensed matter. In particular, an x-ray source with these parameters is perfectly matched to the requirements for holographic imaging of biological materials[10–14] in terms of all its relevant properties, specifically, wavelength (10 – 40 Å), pulse energy (~ 1 mJ), pulse length (~ 10^{-13} s), beam diameter (~ 2 – 3 μm), and divergence (~ 1 mrad).

II. Conclusion

Recent experimental and theoretical results on electromagnetic propagation at high intensities in plasmas lead to very favorable scaling relationships for high-brightness x-ray amplifiers. Such x-ray sources will have important applications in the holographic imaging of biological materials.

III. Acknowledgements

The authors acknowledge the expert technical assistance of J. Wright and P. Noel in addition to fruitful conversations with A. R. Hinds, R. R. Goldstein, and B. Bouma. Support for this research was partially provided under contracts AFOSR-89-0159, (ONR) N00014-91-J-1106, (SDI/NRL) N00014-91-K-2013, (ARO) DAAL 3-91-G-0174, (DoE) DE-FG02-91ER1208, and (NSF) PHY-9021265.

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