UCRL - 74959
PREPRINT

CONF-731009--12

31963

LAWRENCE LIVERMORE LABORATORY
University of California/Livermore, California

X-RAY LASERS: NECESSARY CONDITIONS*

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October 26, 1973

This paper was prepared for presentation at the 1973 Annual Meeting of the American Physical Society Division of Plasma Physics, Philadelphia, PA, 31 October - 3 November 1973.

*Research performed under the auspices of the USAEC.
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Introduction

There has been a great deal of recent interest in the possibility of achieving x-ray laser (XRL) action, including several suggestions as to how this might be realized,[1-5] and even claims of attaining XRL operation.[6,7]

We wish to give here some of the more readily apparent necessary conditions on the attainment of x-ray laser action, primarily for use by those attempting to design, conduct and analyze x-ray laser experiments. We believe these conditions to be of essentially self evident necessity for the restricted set of circumstances we will treat: cylinders of potentially x-ray lasing media of large aspect ratio without an external optical cavity. We treat only lasers operating on bound-bound transitions, whose practical feasibility are great relative to those coupling free-free or free-bound transitions,[8] whose gain widths are effectively very broad and whose peak gains are relatively very small. We will discuss sufficient conditions on XRL action only briefly.

Superfluorescence and Superradiance. X-rays are considered to cover the electromagnetic spectrum from 100 Å to ∿ 0.1 Å. At these frequencies,

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excited state radiative (allowed) lifetimes τ_{spon} range from 10^{-11} to 10^{-17} secs, so 3×10^{-7} cm < $c\tau_{spon}$ < .3 cm; a resonant cavity-enclosed XRL would therefore require essentially CW pumping. (We will note below that metastable upper level XRLs do not appear to be physically accessible.) Furthermore, the specific energies absorbed by the most ideal x-ray reflectors at XRL operating fluxes appear sufficient to immediately destroy such reflectors, as will be noted below. Therefore, we consider axial superfluorescence to be a necessary condition on XRLs. Also, we admit the possibility of travelling wave-type XRLs in the sequel, to minimize the stringency of the necessary conditions we will derive.

Axially superfluorescent lasers generally have small signal gains of the order of 100 dB[9] and, to avoid marginal designs, we will require system gains of several hundred dB. Therefore, we require that the net medium gain α be such that

$$\alpha \, \ell \gtrsim 10^2 \quad , \tag{1}$$

where ℓ is the length of the lasing medium ($\alpha \, \ell = 10$ would clearly be submarginal). To avoid radial superfluorescence we require

$$\alpha \, d \lesssim 5 \tag{2}$$

where d is the diameter of the lasing medium. In order to avoid severe diffraction losses we require

$$d^2 \gtrsim \lambda \, \ell \tag{3}$$

where λ is the wavelength of the radiation being produced by the laser.

<u>Coherence</u>. In order for stimulated emission effects to be important, there must be many photons per unit quantized volume of phase space. Therefore,

if $\mathcal{F}$ is the flux of photons in the XRL beam, we must necessarily have (assuming many phase states contribute)

$$\mathcal{F} \gg \frac{\Delta\nu}{\lambda^2} \Delta\Omega \quad , \tag{4}$$

where $\Delta\nu$ is the spectral width of the beam and $\Delta\Omega$ is the solid angle filled by the beam.

Inversion Densities. The density of photons from spontaneous decays into the solid angle associated with the laser mode is $\sim N^*\Delta\Omega/8\pi$, where N^* is the net inversion density and $\Delta\Omega$ is the solid angle of the laser mode; we assume here that the length of the laser medium is large compared to $c\tau_{spon}$, i.e. we have a travelling wave laser. In order to satisfy the condition for stimulated emission effects to be important, N^* must satisfy

$$N^* > \frac{8\pi}{\lambda^3} \frac{\Delta\nu}{\nu} \quad . \tag{5}$$

In cold matter the Auger effect width ($\approx$ 1 ev) fixes a lower bound on the inversion density $\sim 10^{19}$ cm^{-3}. In a plasma the lower bound on the inversion density will be determined by the Stark width. Because the Stark width $\Delta\nu$ increases with density it will in general be impossible to satisfy Eq. (5) for small values of N^*/N. In fact, estimates of the line width indicate that if N^*/N is smaller than about .01 Eq. (5) cannot be satisfied for x-ray wavelengths.

XRL Dimensions. The minimum possible length of an XRL with inversion density N^* can be found by substituting the lossless gain $N^*(\lambda^2/8\pi)(\Delta\nu\tau_{spon})^{-1}$, into Eq. (1). In the case where the inversion density is the minimum inversion density, Eq. (6), we have

$$\ell(N^*_{min}) \gtrsim 100(c\tau_{spon}) \quad . \tag{6}$$

The actual length of an XRL system can, of course, be made smaller than 100 $c\tau_{spon}$ if $N^* >> N^*_{min}$.

The maximum diameter d_{max} for an XRL will be given by

$$d_{max} \approx 5(c\tau_{spon}) \quad . \tag{7}$$

The minimum diameter d_{min} and maximum length ℓ_{max} will be fixed by the diffraction condition, Eq. (2). The ranges of densities and lengths possible for an XRL system are shown in Figure 2 for three x-ray wavelengths. The upper limit of density results from electron impact broadening causing too large a line width to satisfy Eq. (5). For a 1 kev system $N^* \gtrsim$ 1% solid density.

Pumping Energy and Power Requirements. The required pumping energy E_{pump} must be supplied in a time, τ_{pump} on the order of 100 τ_{spon}; τ_{pump} is characteristically 10^{-11} seconds for 1 kev transitions and scales as λ^2. The pumping efficiency, ε, is upper-bounded by $(.1Z^{-1/3})N^*/N$, from Thomas-Fermi theory, due to the necessity of stripping higher level electrons from the ions to avoid overwhelming photoelectric absorption and Auger effect losses (discussed below). Pumping powers, assuming $\varepsilon = 10^{-3}$, are shown in Figure 2. Although the powers required are quite large, the total energies required are modest--of the order of 0.1 to 10 joules--because the required pumping times are so short.

Losses. It should be remembered that the pumping source must so excite the lasing medium that all energy loss mechanisms are overwhelmed. The main pumping power losses are hydrodynamic and electron thermal conduction power drains. At multi-kev temperatures and small diameters hydrodynamic losses may become quite large. For XRL media surrounded by relatively large masses, thermal conduction losses may be fatally large. The most important propagation loss is photoelectric absorption. Photoelectric absorption (bound-free opacity) may be a significant, even limiting, loss mechanism for marginally inverted XRL systems. The photoelectric absorption cross section per electron is less than that of the peak (Stark-broadened) stimulated emission cross section by a factor of the order $\nu/\Delta\nu$. If $\tilde{Z}$ is the number of electrons bound with less energy than that of the XRL transition, we see that the ratio of net photoelectric absorption to that of stimulated emission, per atom, is $\sim \frac{\tilde{Z}\Delta\nu}{\nu}$. An XRL design thus becomes marginal when $N^*/N \lesssim \tilde{Z}\,\Delta\nu/\nu$. For this reason, sustained high electron temperatures must be used to collisionally strip the ions of outer electrons so that $\tilde{Z}$ is small, for the existence of marginal population inversions in cold matter will not produce net positive XRL gain of the medium, due to photoelectric absorption.

Available Transitions; Metastable States. It has been suggested that metastable states (associated with dipole forbidden transitions) could be used to obtain XRL action.[3] However, metastable states of ions will very rapidly mix with configurations corresponding to allowed transitions, and decay on time scales comparable to the lifetimes of these latter transitions due to the high plasma densities needed for XRL action. An upper limit to the lifetime of metastable S states is provided by the Stark mixing of S and P states due to ion electric fields. For example, for a 1 kev $3 \to 2$ transition, we find that $\tau_s \gtrsim 200\,\tau_p \gtrsim 2.10^{-11}$ sec. There may also be appreciable mixing due to electronic Stark mixing.

If population inversions are to be developed in inner shells of only weakly ionized configurations, inversion destruction via the Auger effect must be overcome. The characteristic Auger lifetime of K or L shell vacancy is $\sim 10^{-15}$ sec in cold matter;[14] these Auger lifetimes are essentially Z-independent, and are comparable to the natural lifetime of a 10 kev dipole-allowed transition. Such Auger lifetimes of course increase as more electrons are stripped from the ion core, especially from the shell constituting the upper levle of the inversion; indeed, the Auger effect operates to do just this. Thus, it is clearly essentially impossible to operate an XRL with any significant number of bound electrons in or above the upper lasing state level, because the specific pumping energies needed to overcome Auger losses would automatically strip the atoms.

Finally, it should be noted that population inversions will be quenched rapidly if the lower lasing state is the ground state, primarily through radiative and collisional recombination into this state from both positive and negative energy levels other than that in which one hopes to build up excess state density. Therefore, XRL schemes should have their lasing transition terminate in the L shell, or higher.

Minimum XRL Intensities. The minimum XRL fluences, $\ell N^*\hbar\omega$, are shown in Table 1. It should be noted that the minimum fluxes and fluences which may be attained in an XRL are quite high, as indicated in Table 1, and, as they derive immediately from fundamental quantum statistics considerations, apparently cannot be avoided. These fluxes and fluences point to an obvious, indeed, unavoidable method for detection of true XRL action--one listens for a distinct report as a plasma plume jets out of the nearest surface irradiated by the XRL beam; if a hole is not blown in the surface in even the shortest possible time in which the XRL may be operated, no XRL beam was generated. Furthermore, even if cavity mirrors which might possibly be employed in an XRL system[15] can be made to absorb $\lesssim$ 5% of the incident flux, specific energy depositions in such materials would be $\gtrsim 10^5$ joules/gm for 1 kev XRLs, with the minimum fluences just noted. The amount of energy actually deposited would impinge on the mirror for many inversion lifetimes, if the cavity were to be of any utility. However, the specific x-ray energy deposition associated with the minimum (axially superfluorescent) fluence over even one inversion lifetime would be much more than sufficient to vaporize the reflector surface. Even when the lower fluxes permitted by mirror usage are taken into account, this conclusion appears qualitatively valid over the XRL photon energy range 0.3-100 kev, for virtually all reflector materials, due to the variations with XRL photon energy of material opacities and the minimum XRL beam fluences of Table 1. Soft XRLs (k << 1 kev) may, however, be an exception to this general statement, in that minimum fluences, upperstate lifetimes and use of diamond Bragg reflectors might be combined to produce a feasible cavity-bounded quasi-CW XRL in the $0.15 \lesssim k \lesssim 0.3$ range.

Conclusion

Taken together with beam monochromaticity and phase coherence, the minimum brightness and fluence conditions stated above are sufficient to prove XRL action. Conversely, any system that does not meet all of these four necessary conditions is not an XRL, whatever else it may be.

For bound-bound XRL systems, optimal operating conditions apparently lie in the region of relatively high density of the XRL medium and high temperature (to avoid propagation losses by various opacity-generating mechanisms). We believe that the most practical scheme for obtaining XRL action consists of flash-heating a small, isolated, basically cylindrical geometry of medium Z material to kev temperatures, via use of a suitable multi-terawatt source, and lasing on a bound-bound transition which is population-inverted by collisional recombination into upper bound states outpacing radiative recombination into lower states.[5] This approach is the only one known to us to meet all of the conditions stated above, and one which morever meets the test of detailed simulation code evaluation.[16]

Acknowledgment

We wish to thank Edward Teller and John Nuckolls for several most helpful and seminal discussions.

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Fig. 1 Conditions for X-ray Laser Action

$$\alpha l \gtrsim 100 \qquad (1)$$

$$\alpha d \lesssim 5 \qquad (2)$$

$$d^2 \gtrsim \lambda l \qquad (3)$$

$$\mathcal{F} \gg \frac{\Delta\nu}{\lambda^2}\Delta\Omega \qquad (4)$$

$$\mathcal{F}_{spon} \approx cN^* \frac{\Delta\Omega}{8\pi}, \quad c\tau_{spon} \ll l$$

$$\boxed{N^* > \frac{8\pi}{\lambda^3}\frac{\Delta\nu}{\nu}} \qquad (5)$$

$$(1) \Rightarrow l(N^*_{min}) \approx 100\, c\,\tau_{spon} \qquad (6)$$

$$(2) \Rightarrow d_{max} \simeq 5c\,\tau_{spon} \qquad (7)$$

$$(3) \Rightarrow d_{min}(N^*_{min}) \approx 10^3 \lambda / k \qquad (8)$$

Figure 1

PARAMETER SPACE

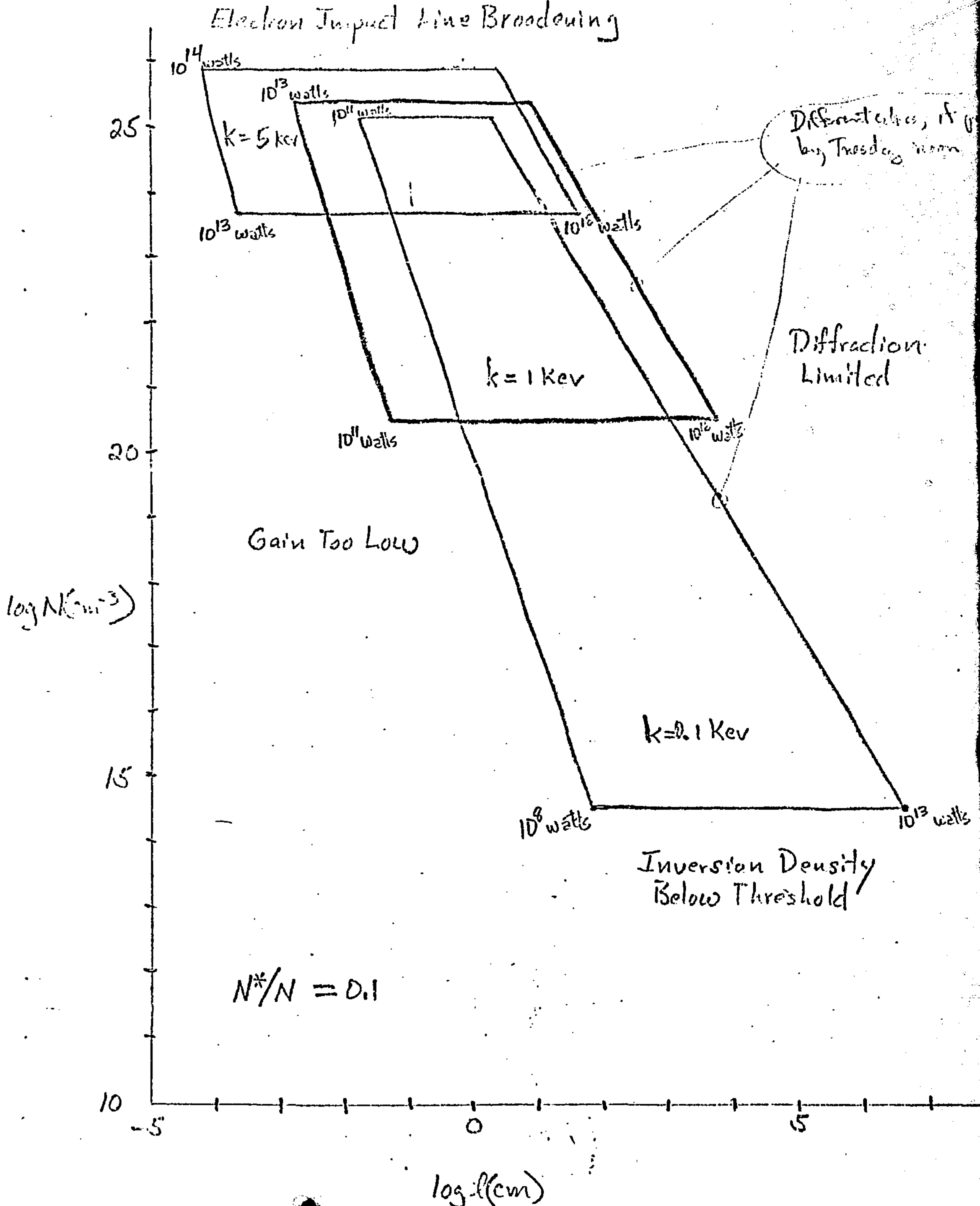

Figure 7

B. OPERATING PARAMETER SPACE

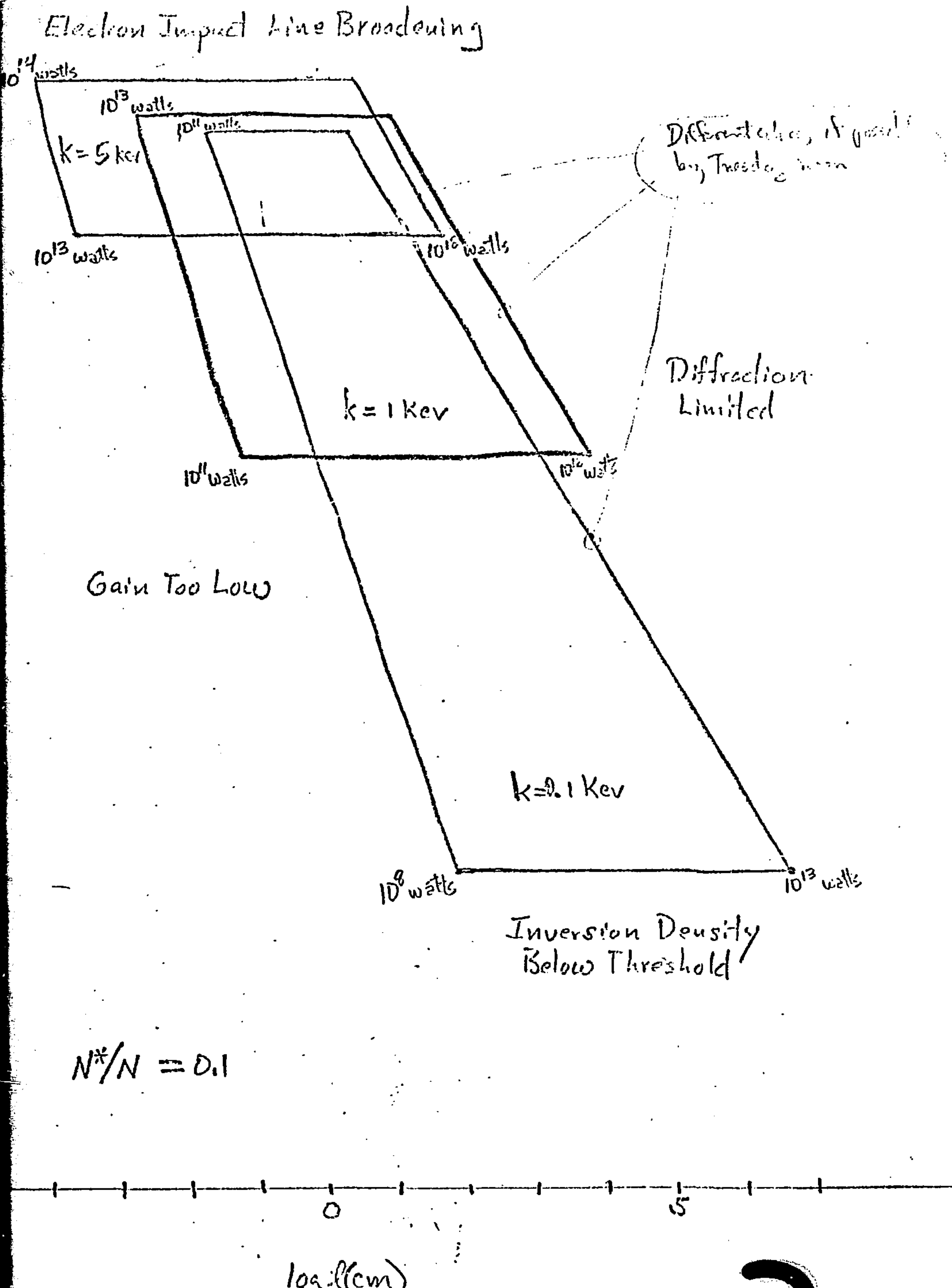

Figure 7

TABLE I										
λ	k	τ_{spon}	$\Delta\nu/\nu$	N^*_{min}	ℓ^*_{min}	d_{min}	d_{max}	P_{min}	$\int F dt$	θ_B
(Å)	(kev)	(sec)		(cm^{-3})	(cm)	(cm)	(cm)	(watts)	($ergs/cm^2$)	(kev)
10^2	.12	10^{-11}	$4\cdot10^{-6}$	10^{14}	30	.05	~~2~~ 1.5	10^8	10^5	0.90 ~~1.16~~
10	1.2	10^{-13}	$4\cdot10^{-3}$	10^{20}	.3	$5\cdot10^{-4}$	.015 ~~.02~~	10^{11}	10^{10}	25 ~~20.7~~
1	12	10^{-15}	~ 1	10^{26}	.003	$5\cdot10^{-6}$	.0015 ~~.002~~	10^{14}	10^{15}	[illegible] ~~116.5~~

<u>Table I.</u> Shown as functions of the photon wavelength λ of an XRL are the spontaneous decay time τ_{spon}, the relative Stark width, $\Delta\nu/\nu$, at a total XRL medium density of $10N^*$, the threshold population inversion density N^*_{min}, the ~~minimum~~ length ℓ^*_{min} of inverted medium of minimum inversion density N^*_{min}, corresponding to Eq. (1), the minimum diameter d_{min} of the medium with minimum inversion density corresponding to Eq. (3), the minimum medium pumping power P_{min} corresponding to an inversion density N^*_{min}, the minimum fluence of an XRL beam $\int F dt$ and the temperature θ_B of the blackbody of equivalent bolometric brightness of the minimum intensity XRL beam.

7l

P-l