2

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Conditions for X-ray Laser Action

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MASTER

Abstract: For X-ray Laser Action

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Abstract

Abstract: On sufficient conditions for using atomic transi-
tions to produce x-ray laser action in review 1. It is shown
that it will be very difficult to produce laser action for photon
energies above a few kilovolts.

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.¹⁻⁷ We set down here some of the more readily apparent necessary conditions on the attainment of x-ray laser action, primarily for use in those attempting to design, conduct and analyze x-ray laser experiments. We believe these conditions to be of essentially self-evident necessity in 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 will discuss primarily XRL systems operating in bound-bound transitions, where large gains per unit length should be more easily achieved due to the greater concentration of oscillator strength.

Axial Inversion Requirement. X-rays are considered to cover the electromagnetic spectrum from 100 Å to ~ 0.1 Å. It will be shown below that at these wavelengths readily attainable inversion densities are such that the length of the medium needed to produce laser action will exceed τ_{spont} , where τ_{spont} is the spontaneous radiative lifetime of the x-ray transition. Thus, in general, it will be necessary to use a "traveling wave" or "free-running" type of the XRL medium. In the case of a cavity-mounted device, a traveling wave excitation will have to be swept back and forth between the mirrors. It should be noted, however, except possibly in the soft x-ray region, operation of an XRL with mirrors does not appear to be possible because of the low reflectance of materials for $\lambda < 100$ Å. Furthermore, the operating fluxes in an XRL may be sufficiently high to immediately destroy any reflectors. Therefore, we consider operation without reflectors to be a necessary condition of XRLs. One may picture the XRL operating as an isthmus of the wave

of a pumping excitation along a suitable medium at the speed of light, a growing x-ray photon would be conviving with the pumping excitation.

To compensate for the absence of reflectors, the gain along the length of the laser must be large--on the order of a hundred db (based on experience with large laser systems). Thus to avoid marginal operation we will require that the length, L , of the laser medium satisfy

$$aL \geq 10 \quad (1)$$

where a is the net signal gain per unit length. Correspondingly, the initial gain on either side of the laser cannot be too large. Therefore, we will require that the diameter, d , of the lasing medium be much smaller than its length;

$$d \ll L \quad (2)$$

i.e., the lasing medium must have the form of a thin cylinder. The diameter of the lasing medium cannot be too small, however, because diffraction losses become important at very small diameters. To avoid serious losses due to diffraction losses, we require

$$d^2 \gg \lambda L \quad (3)$$

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

Threshold Condition. In order for stimulated emission effects to be important, there must be many photons per unit quantized volume of phase space. Therefore, if F is the flux of photons in the XRL beam, we must necessarily have (assuming many modes contribute)

$$F \gg \frac{h\nu}{\lambda^2} \quad (5)$$

where λ is the wavelength of the beam and F is the flux of photons by the beam. If the flux of photons from spontaneous emission in the angle associated with the laser beam is to satisfy this condition, the inversion density N^* must satisfy the condition

$$N^* \gg \frac{4\pi}{\lambda^2} \left(\frac{c\tau_{\text{spont}}}{2} \right) \quad (6)$$

The expression $(c\tau_{\text{spont}}/2)$ can be thought of as the effective emission cross-section. Therefore, if losses are negligible the minimum threshold inversion density needed to satisfy Eq. (1) is:

$$N_{\text{thr}}^* \approx \frac{2}{\lambda^2} \frac{h\nu}{c} \frac{c\tau_{\text{spont}}}{2} \quad (7)$$

In the absence of losses, this will be the threshold condition for the coherent x-ray laser. It should be noted that for allowed transitions

($\tau_{\text{spont}} = 10^{-15}$ - 10^{-10} sec) the minimum N^* depends only on the photon energy, $h\nu$, independent of the photon energy:

$$N_{\text{thr}}^* \approx 10^{19} h\nu / \lambda^2 (\text{cm}) \text{ cm}^{-3} \quad (8)$$

Inversion Densities. In solid matter, the laser effect with $\lambda = 0.1$ nm gives a lower bound on the inversion density. According to (7) the minimum inversion density in solid matter with $\lambda = 0.1$ nm is $N^* \approx 10^{20} \text{ cm}^{-3}$. This is a very high density for solid matter. In experiments with x-ray lasers the highest laser power densities were obtained in the case of a low inversion density. It must certainly exist a high threshold of the medium.

two-thirds power is inserted in Eq. (4). Thus Eq. (9) will not hold and Eq. (8) will have no solution when the plasma density implied by Eq. (4) is much larger than the critical density.

Equation (4) suggests that it may be difficult to produce ionization using ion beams as has been proposed in several XBL schemes.^{1,7} Because of space-charge limitations ion beam densities cannot be made larger than about 10^{17} cm⁻³ even for $Z = 1$. Thus the fractional inversion in such beams must be fairly large, viz. ≥ 1 , if XBL action is to be achieved. It may be possible to produce high fractional inversions in ion beams using resonant charge exchange,^{8,9} but the attainment of sufficiently high beam densities for $Z = 1$ or 2 may be quite difficult. It is possible, however, that resonant charge exchange might be useful in a charge-neutralized environment such as a neutral plasma.¹⁰

Required Ion Beam Parameters. The required pumping energy E_{pump} must be supplied in a time of the order of $1/\omega$. The pumping power $P_{pump} = dE_{pump}/dt$ must satisfy

$$P_{pump} = \frac{2\pi\hbar\omega}{\epsilon} \quad (1)$$

where ϵ is pump efficiency. If we assume $\epsilon = 0.1$, i.e. $d = 0.1\lambda_{min}$, then

$$P_{pump} = 2\pi\hbar\omega \cdot 25(3\pi)(A\sigma_{open})n_{0.1} \quad (2)$$

where $\epsilon = 0.1$ is pump efficiency. Epsilon (ϵ) is upper-bounded by $(10^{-2}/\lambda)^2 \hbar\omega/m$, from Raman-Brillouin theory, due to the necessity of stripping higher level electrons from the ions. As in overcoming the photoionization and Auger effect (see Appendix A below). Assuming $\lambda = 10^{-5}$ we obtain a minimum pumping power of

about 10^{15} watts. This pumping power assumes that an optimal traveling wave excitation is used to pump the XEL medium. If one cannot produce an optimal traveling wave excitation, e.g. because the pumping energy is not focused to a spot that is small along the XEL medium, then corresponding higher powers would be needed. As a practical matter pulsed laser light cannot be focused to a pump spot with a diameter smaller than about 10^{-4} m. It will be desirable to use laser light with as short a wavelength as possible for XEL pumping. An XEL operating on transitions exceeding a few eVolts will probably require ultraviolet lasers for pumping.

Metastable states. If population inversion is to be developed in excitation lines of low-lying excited configurations, ionization autoionization via the Auger effect must be overcome. The characteristic Auger lifetime of a low-lying shell would be $\sim 10^{-15}$ sec in solid matter; i.e. comparable to the natural lifetime of a keV dipole-allowed transition. Such Auger lifetimes increase if more electrons are excited from low-lying states, especially from shells constituting the upper level of the inversion. Thus, it is already practically impossible to operate an XEL with any significant number of excited electrons in near the upper lying state level. Even the specific pumping energies needed to overcome Auger losses would be enormous.

Because of the very short radiative lifetimes of all low-energy transitions ($< 10^{-15}$ sec for 10^4 eV transition) one might think that autoionization would be a problem to be overcome or forbidden to achieve a metastable state of the excited electron ions with lifetimes on the order of 10^{-9} sec or more. In fact it has been observed in low density ion beams.¹² However, such metastable states are not likely to be very longlived at the high densities required for an XEL.

medium because of the mixing or triplet-triplet annihilation, provided, of course, that metastable states of many electron ions observed in beam foil excitation experiments²² may be considered metastable two electron ions plus excited electrons in high principal quantum number states. Here again these metastable states would probably be lost at high densities. It should be noted, however, that metastable states in ion beams might be collected in sufficient numbers to permit their use in a very soft XRL.²³

Finally, it should be noted that population inversion will be maintained only if the lowest lying state is the ionic ground state, provided that the radiative and collisional recombination into this state is not too positive and not too energy levels other than that in which one might be looking for a population inversion. Therefore, XRLs should be designed so that their exciting sources terminate in the L-shell, or higher.

Excitation Mechanisms. It should be remembered that the population must be excited in a medium that all energy loss mechanisms are well understood. Perhaps among such mechanisms are hydrodynamic and electron thermal conduction power drains. The hydrodynamic loss rate per ion may be estimated as

$$P_{\text{hyd}} = \frac{1}{2} m_e (u/c_s)^2 = (e^2/2/c) \cdot 10^{-11} \text{ kcal/ion-sec}^{-1},$$

where c_s is the electron temperature in eV, c is the speed of light 3×10^{10} cm/sec and 10^{-11} is the ion speed. At multi-eV temperatures and high densities these losses may become quite large. Considerably more important in some circumstances, however, is the electron thermal conduction power loss:

$$P_{\text{cond}} \approx 3.2 \times 10^{12} A_{\text{He}}^{1/2} / Z^2 \text{ watts}$$

where A_0 is the area of the area A of the lasing medium in contact with front laser and A_0 is the screened charge of the ions. For XRL media characterized by relatively large masses, thermal conduction losses may be large.

For gas-like population, free-bound transitions are generally sitting within the of pumping. These include both collisional and radiative processes; however, collisional transitions do not remove energy directly from the plasma, as the radiative ones do. The power loss due to this effect is

$$P_{\text{free}} = 1.1 \times 10^{-10} Z^2 n_e^{1/2} n_i \text{ keV/ion-sec}$$

where n_i is the ion density in units of $5 \times 10^{22} \text{ cm}^{-3}$. Furthermore, there are free-bound transitions losses, given by

$$P_{\text{free}} = 1.5 \times 10^{-14} Z^2 n_e^{3/2} \text{ keV/ion-sec}$$

the power loss due to this process will dominate only at high temperatures.

Population Inversion. The attainment of a population inversion is a necessary, but not sufficient, condition for producing net gain in the XRL medium. The losses mechanisms which must be considered include Compton scattering, photoelectric absorption, and inverse bremsstrahlung. The Compton (Thomson) scattering mean free path, $30/Z \text{ cm}$, is larger than λ for $10^{21} \text{ g cm}^{-3}$, and Compton scattering is therefore unimportant in essentially all cases of practical interest. Inverse bremsstrahlung absorption of XRL photons will be available in virtually any type of XRL supporting photons of $h\nu > 1.5 \text{ keV}$ due to the steep decline in absorption opacity $\kappa = .026 Z^2 \nu_e^{-1} \text{ cm}^{-1}$ with photon frequency. Photoelectric absorption (bound-free opacity)

may be a significant (even limiting, loss mechanism for marginal designs) for XRL systems. The photoelectric absorption cross section per electron is less than that of a peak (Stark-broadened) stimulated emission transition by a factor of the order $\nu/\Delta\nu$. If $\bar{n}$ is the number of electrons per unit loss energy than that of the XRL transition, we see that the ratio of the photoelectric absorption to that of stimulated emission per atom is $\frac{\bar{n}}{1-\bar{n}}$. An XRL design thus becomes marginal when $\bar{n}^2/\bar{\nu} \geq \bar{h}\nu/\Delta\nu$. For this reason, sustained high electron temperatures must be used to utilize the energy in ions of water or other media that $\bar{h}$ is small, i.e., the existence of a small population inversion in relatively cold matter will not produce net positive XRL gain of the medium due to photoelectric absorption.

Minimum XRL energies. The minimum x-ray output of an XRL will be $\bar{n}^2 \Delta\nu_{\text{XRL}}^2$. From eq. (3) we find that this will be on the order of

$$E_{\text{out}} \approx 1/2 (h/\bar{h})^2 (c/v)^2 \text{ joules} \quad (11)$$

where h is photon energy in eV.

Equation (11) implies that the x-ray flux will increase with the square of $h/\bar{h}$ which will be produced by an XRL and a plasma. Therefore, $h/\bar{h} = 10^4$ the fluxes would be on the order of 10^4 J/cm^2 . These large fluxes and the high point-to-point gain, indeed, unavoidable method for detection of the XRL action-time 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 window in even the shortest possible time in which the XRL may be operated, no XRL beam will appear. Furthermore, even if only minimal values that can be employed in an XRL system can be made to absorb $\geq 5\%$ of the incident flux, specific energy depositions in such materials would be $> 10^5 \text{ J/gm}$ for 1 μm XRLs

mixture to raise its temperature via use of a terawatt laser beam.¹⁷ The heating laser pulse would be focussed to a small spot which would be swept along the cylinder at the speed of light. Under suitable circumstances population inversion could be produced in the relaxing plasma.¹⁸

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