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Application of Soft X-Ray Laser in Nano Scale Region

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Abstract. We have studied the dynamics of argon discharge Z-pinch plasma in a capillary and the optimum condition for amplification of a soft x-ray laser. The gain coefficients for lasing obtained were 0.428 cm^{-1} with trapping effect and 6.195 cm^{-1} without trapping effect for 3s-3p transition of wavelength 46.9 nm in Ne-like Ar plasma.

The theoretical study of the energy loss rate of an incident laser beam through the target matter has been made in order to obtain the quantitative effect of interaction with matter. The most fundamental problem in the study of interaction of an intense x-ray laser with condensed or gas phase exists in collisional process of photons. The choice of an optimal wavelength for a soft x-ray depends on kinds of application.
"Key words:" soft x-ray laser, capillary discharge, Z-pinch plasma,

1. INTRODUCTION

There are two different pumping schemes to achieve population inversion due to collisional excitation and recombination mechanism in plasma, namely laser-produced plasma and discharge plasma.

In the recent ten years since the first demonstration of stimulated emission of soft x-ray lasing, a major concern has been large and compact optical laser pumping requirement to produce population inversion resulting in substantial x-ray output. On the other hands, the significant progress has recently made in the area of capillary discharge soft x-ray lasing using the imploding Z-pinch[1-5]. This direct plasma heating approach has obvious advantages in the compact efficient and simpler pumping scheme for soft x-ray lasers or soft x-ray sources.

Concerning application of soft x-ray laser, the short wavelength x-ray lasers pay attention to achieve pump conditions operating at high irradiance. Biological imaging will benefit greatly from <100 fsec duration x-ray laser at wavelengths from 2.2 to 4.4 nm. The choice of an optimal wavelength for soft x-ray holography of biological samples would be best in the water window region between 2.32 nm and 4.37 nm[6,7]. Even shorter wavelengths could be useful for semiconductor device imaging studies of non-linear phenomena, as well as applications to solid state physics and atomic physics such as lithography and microscopy.

The Z-pinch plasma has attracted researchers due to its copious x-ray radiation. Attenuation length and energy loss of an incident soft x-ray on the target material (solid or gas phase, and biological structure) are evaluated by reduction of photon intensity.

We have investigated the spatial and temporal behavior of the Z-pinch discharge plasma in a capillary filled with an initially pre-ionized argon gas. To study the dynamics of the discharge plasma based on the computer simulation, one-dimensional magneto- hydrodynamics (1-D MHD) equations in the cylindrical coordinate are adopted and are solved by the Lagrangian method.

The rate equation describing the various atomic processes occurring in the plasma are coupled with the MHD equations. The coupled equations include the each ionization stage of the plasma. The power losses due to plasma atomic processes are also included along with the calculation of populations. The calculation of the gain of the soft x-ray laser amplification of the lasing line 3p-3s is carried out considering the effect of the radiative trapping due to the photon escape probability.

Moreover, the effects of pressure[8] on gains in imploding Z-pinch Ne like Ar plasma lasing are also discussed.

Soft x-ray lasers produced by capillary discharge pump irradiate target materials. These targets are consisted of solid state or gas phase, and biological structure. The damping rate of laser depends on the distribution function of its field through interaction with electrons and ions in matter. The rate of energy loss from the incident electromagnetic wave must balance the rate at which the oscillatory energy of electron is randomized by the electron scattering [9]. We made this formulation in the theory of absorption of energy.

2. MODEL AND CALCULATION

The present model is illustratively explained in Fig.1.

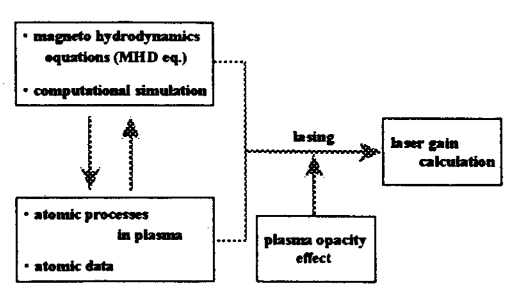

Fig.1 The relation of Z-pinch discharge plasma dynamics considering these plasma atomic processes and application advance of x-ray lasers and soft x-ray source.

The relation between the Z-pinch discharge plasma dynamics and the plasma atomic processes are major treatment to find the optimum conditions of soft x-ray lasing.

In order to study the dynamics of the Z-pinch plasma in a capillary discharge, the 1-D single-fluid, dual temperature MHD equations are adopted in the Lagrangian cylindrical geometry. The Lagrangian methods are well suited to 1-D fluid problem. These equations include Joule heating, shock-wave heating, bremsstrahlung radiation, heat conduction and magnetic field diffusion.

The power losses due to various atomic processes are treated as the coupled rate equations of each ionization stage of ion.

We consider the evolution process of Ar pre-ionized plasma with an initial electron temperature Te = 2eV, which implodes on axis. All dynamical values in the equations evolve as the position r from the capillary axis at a time t.

The radiative MHD equations deal with the system in a 35-zone Lagrangian reference frame. The number of particle is conserved in each zone. The position of each cell and the velocity on cell boundary is determined as (d/dt) $r = v$. The relevant MHD equations in the cylindrical coordinate have the following forms in cgs-Gauss unit and in eV for temperature.

The mass conservation reads

$$\frac{\partial \rho}{\partial t} + \frac{\rho}{r}\frac{\partial}{\partial r}(rv) = 0 \quad , \tag{1}$$

where ρ is the mass density and v the plasma fluid velocity.

The momentum equation is given by

$$\rho\left(\frac{\partial}{\partial t} + v\frac{\partial v}{\partial r}\right)v = -\frac{\partial}{\partial r}\left(P_e + P_i + Q\right) - \frac{B\partial}{4\pi r}\frac{\partial}{\partial r}(rB) \quad , \tag{2}$$

where B is the magnetic field strength induced by the axial driving current, and P_e and P_i are the thermal pressure due to electron and ion, respectively; Q the artificial viscosity term due to the strong shock waves[11]:

$$Q = \begin{cases} l^2 \rho \left(\dfrac{\partial v}{\partial r}\right)^2 & \text{if } \dfrac{\partial v}{\partial r} < 0 , \\ 0 & \text{if } \dfrac{\partial v}{\partial r} > 0 , \end{cases}$$

According to various calculations for the artificial viscosity, Q, we chose a constant parameter $l^2 = 10^{-4}$ cm in such a way that no numerical instabilities take place because of the propagation of a shock wave.

The energy conservation for electrons and ions are represented by

$$\frac{\partial T_e}{\partial t} + v\frac{\partial T_e}{\partial r} = -\frac{2}{3}T_e\frac{1}{r}\frac{\partial}{\partial r}(rv) + \frac{2}{3}\frac{1}{n_e r}\frac{\partial}{\partial r}\left(k_e r\frac{\partial T_e}{\partial r}\right) - \frac{T_e - T_i}{\tau_{eq}} + \frac{2}{3}\frac{1}{n_e}\left(P_J - P_{brem} - P_{atom}\right) \quad , \tag{3}$$

$$\frac{\partial T_i}{\partial t} + v\frac{\partial T_i}{\partial r} = -\frac{2}{3}\left(T_i + \frac{Q}{n_i}\right)\frac{1}{r}\frac{\partial}{\partial r}(rv) + \frac{2}{3}\frac{1}{n_i r}\frac{\partial}{\partial r}\left(k_i r\frac{\partial T_i}{\partial r}\right) + \frac{T_e - T_i}{Z_{eq}} \quad , \tag{4}$$

where T_e and T_i are the electron and ion temperature, n_e and n_i the electron and ion density, respectively. The first term in eq.(3) is the energy loss due to the volume expansion, the second is the heat conduction; k_e and k_i the electron and ion heat conductivity, P_J Joule heating and P_{brem} the power loss due to bremsstrahlung radiation; the energy losses due to atomic processes in plasma;

$P_{atom} = P_{rad} + P_{ionaiz} - P_{recomb}$, τ is the electron-ion equilibration time.

The magnetic field transport and diffusion equation is

$$\frac{\partial B}{\partial t} = \frac{\partial}{\partial r}\left\{\frac{\eta c^2}{4\pi r}\frac{\partial}{\partial r}(rB)\right\} - B\frac{\partial v}{\partial r} \quad , \tag{5}$$

where η is the plasma resistivity.

The coupled rate equations describing the various atomic processes occurring in plasma are directly solved. Then the population N_q^l of excited state l in the q-th ionization stage is obtained by

$$\frac{dN_q^l}{dt} = n_e \sum_{m=l+1}^{\max}\left(N_q^m S_{ml}^{\mathrm{II}} - N_q^l S_{lm}^{\mathrm{I}}\right) + n_e \sum_{n=1}^{l-1}\left(N_q^i S_{il}^{\mathrm{I}} - N_q^l S_{li}^{\mathrm{II}}\right) - N_q^l \sum_{k=1}^{l-1} A_{li} + \sum_{m=l+1}^{k\max} N_q^m A_{ml} - n_e N_q^l S_{ql} + n_e N_{q+1}\left(R_{ql}^{rr} + n_e R_{ql}^{cr}\right) \quad , \tag{6}$$

where S_q^l is the collisional ionization stage, S_{ml}^{I} and S_{ml}^{II} are the collisional excitation and deexcitation rate between levels m and l, respectively , S_{ql}^{rr} and R_{ql}^{cr} express the radiative recombination and the collisional recombination rate, respectively.

The rate A_{ml} denotes the spontaneous emission. In the computer simulation, the capillary channel is initially filled with a pre-ionized argon gas of uniform electron density $n_e(0) = 10^{17}\text{cm}^{-3}$, and with the electron and ion temperature $T_e(0) = T_i(0) = 2.0$eV and the initial plasma fluid velocity $v(0) = 0$.

Fig.2 shows the illustration of capillary discharge Z-pinch argon plasma due to the induced magnetic field $\boldsymbol{B}$ through a driving electric current I(t).

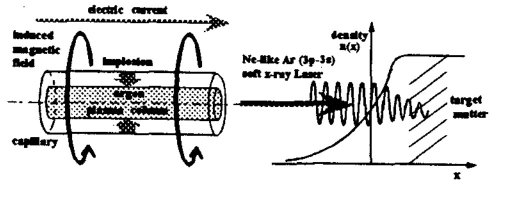

Fig.2 Soft x-ray laser for Ar 3p-3s transition incidents on target. The incident laser beam loses its energy in target matter, from surface density $n(0)$,colliding with electrons and ions.

Following a x-ray lasing, the x-ray laser beam irradiates a target matter.

The calculations have been carried out using an external discharge current $I(0)$, and then the induced magnetic field at the capillary wall $B(r_0)$

$$I(t) = I_0 \sin \omega t \quad [\text{kA}] \tag{7}$$

$$B(r_0) = \frac{2I}{c r_0} \quad [\text{kG}] \tag{8}$$

where I_0=50kA, $2\pi/\omega$=120ns and the capillary radius r_0=0.2cm. The dynamics of these plasmas are shown in Fig.3 as the spatial and temporal behavior.

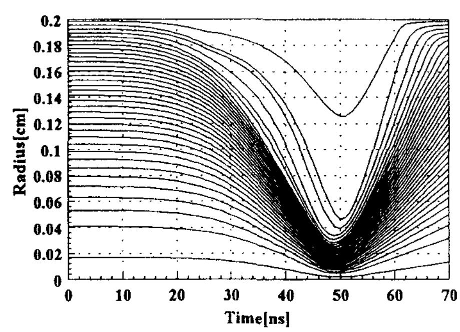

Fig.3 Time-space flow diagram of capillary discharge obtained by 1-D MHD simulation. Radius is represented as a distance from the capillary axis.

Figs.4 and 5 show the time-space distributions of electron temperature in eV (Fig.4) and electron density in cm^{-3} (Fig.5).

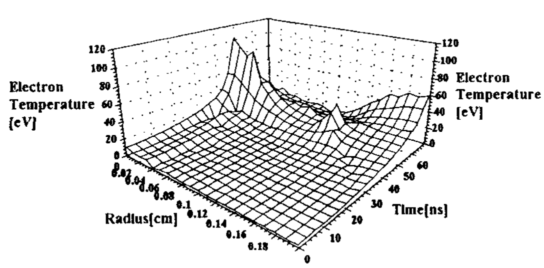

Fig.4 Electron temperature distributions *Te* of time-space variables in Z-pinch discharge Ar plasma: *Te* in unit of eV.

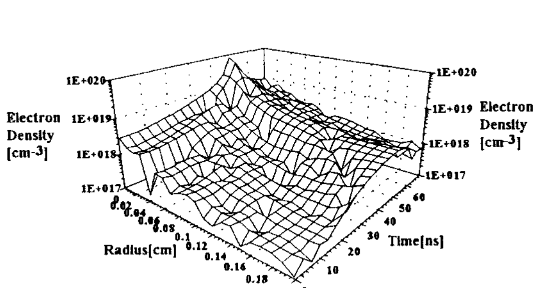

Fig.5 Electron density distributions n_e of time-space variables in Z-pinch discharge Ar plasma: n_e in unit of cm^{-3}.

As plasmas are compressed, the electron temperature and density increase with increasing Joule and shock heating.

Radiation is coupled to the plasma through emission and absorption processes. For an optically thin plasma, this radiation escapes from the plasma with a significant amount of energy. If the plasma is optically thick, it reabsorbs the photons before they escape. These facts have dramatic effect on the inversion kinetics of the lasing transition in the x-ray laser scheme. This is estimated by a probabilistic transport scheme in which the angle and frequency averaged escape probabilities are calculated for each line[6]. Then, the original Sobolev escape probability is replaced with the more accurate angle-averaged Sobolev escape probability for an axially symmetric plasma[11]. This escape probability is essential for gain calculations because it allows the photon to escape in frequency spaces in the presence of large velocity gradients and the curvature effects in the plasma[12.13].

The gain for the soft x-ray lasing transition 3p-3s in Ne-like Ar plasma (469 Å) is calculated using the Doppler broading. In the presence of steep velocity gradients, reabsorption of photons occurs up to a distance of the transition line width. Photon escape probabilities are used for the simulation of the spectral line radiation reabsorption inside a plasma.

As a result, Fig.6 shows the time-space distributions of the gain with the opacity effects.

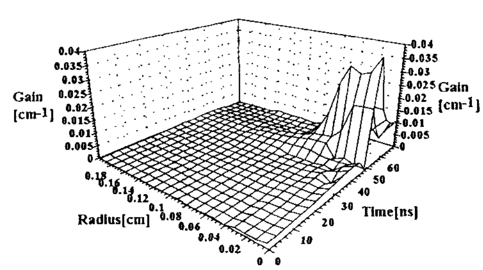

Fig.6 Gain counters and time-space distributions of the gain with trapping from 3p-3s transitions in Ne-like Ar plasma.

3. APPLICATION OF SOFT X-RAY LASER

It is usually believed that the x-ray laser can be developed to provides all of powerful, high brightness most coherent x-ray sources[6].

X-ray microscopy and x-ray imaging technology are currently developing [7,14,15] for studying biological structures for living microorganisms as well as for studying material science. X-ray sources are needed that operate in the so-called water window, 2.3 nm < λ < 4.4 nm, *i.e.* at wavelengths that maximize the visibility of carbonaceous material that is located in a water host. In order to study the objects *in vivo*, it is also necessary to produce intense bean of photons of very short duration.

We will assume that the soft x-ray laser is deposited in a sphere of initial radius *R*. After that its energy is transferred from the surface of a specimen to the internal surrounding material. It will change in the plasma phase creating a spherically expanding shock wave.

The incident x-ray laser beam passing though the specimen of an average mass m loses its energy due to collision with electrons or ions. The rate of energy loss from the laser light wave ($\nu E^2/8\pi$) must balance the rate at which the oscillatory energy of the electron-ion scattering with a frequency ν_{oi}.

The rate of energy loss in laser-plasma interactions is estimates by

$$\nu = \frac{\int \nu_{ei} \frac{1}{2} n_e m v_{os}^2 dt}{E^2/8\pi} \quad , \tag{9}$$

where v_{os} is the velocity of oscillation of an electron in the electric field E:

$$v_{os} = \frac{eE}{m\omega} \quad ,$$

$$\omega = \omega_{pe}^2 + k^2 c^2 \quad ,$$

where $\omega_{pe} = (4\pi n e^2/m_e)^{1/2}$ is the electron plasma frequency for a plasma with electron density $n_0 = Z\, n_{0i}$. If the density is expressed in unit of cm^{-3}, then $\omega_{pe} = 5.64 \times 10^4 n_e^{1/2}$.

4 . SUMMARY AND CONCLUSION

Many important application require short wavelength, high intensity and high coherence x-ray source. The current trend of developing shorter wave length output x-ray lasers is nm length ; recently, many of the applications are currently dependent on the development of x-ray lasers with wavelengths from 1 to 0.01 nm.

For biological investigations, we wish to generate an image of the specimen with so high a resolution as possible.

Modeling of the dynamics of the Z-pinch Ar discharge plasma is described using 1-D MHD equations and the coupled rate equations. The imploding plasma is assumed to remain in a cylindrically symmetric shell.

The output soft x-ray laser beam incident on target material and the laser energy in matter will be able to be analyzed on basis of the present model.

We described the energy loss rate of the x-ray laser using laser-plasma interactions based the electromagnetic field theory. The present fundamental model will be useful for x-ray microscopy, microholography and x-ray imaging technology.

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