Generating the ionisation for Ni-like X-ray lasers in the wavelength range 50-100Å

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Introduction

Collisionally pumped soft X-ray lasers have been markedly improved in recent years by the introduction of short pulse CPA and grazing incidence pumping (GRIP). The underlying concept of these systems is the separation of a relatively long plasma preparation phase from short intense localized heating[1]. In this manner, the population inversion and gain are generated at near the optimum pumping density and in a region of small refractive index gradient. GRIP systems have proved remarkably successful with laser action at wavelengths as short as 100Å being generated with energies of less than 1J in each pulse[2,3].

It is of interest to see if these ideas can be taken to shorter wavelengths with a concomitant reduction in pump energy from that used in the past. The prospects, however, are not very promising. An experiment along these lines was carried out at RAL some years ago, using samarium. Analysis by the author indicated that the conditions were probably reasonably well optimized.

There are two major difficulties in moving to shorter wavelengths. Firstly ionisation becomes progressively more difficult to achieve and secondly the optimum pumping density increases beyond the critical density of Nd-glass laser radiation. In this note we shall concentrate on the first, and most difficult, of these problems.

Ionisation

In order to achieve laser action below about 80Å it is necessary to use Ni-like ions of atomic number greater than about 60. Since ionisation is a slow process, we use a relatively long pre-pulse to generate the plasma state and the ionisation increases towards an equilibrium state in which upward ionisation balances downward recombination. Knowing the appropriate rates it is a relatively simple matter to calculate the equilibrium temperature for a given ionisation. Using a set of four screened hydrogenic states to represent each ion stage we obtain the data shown in fig.1. We note the strong scaling of the temperature required to reach the Ni- or Cu-like ion stages,

$$T_e \approx A_{ion} Z^{5.5} \tag{1}$$

where Z is the atomic number, and A_{ion} an appropriate constant, determined empirically. This approximation is valid for Z>55.

Deflagration model

There are two models of laser-plasma heating relating to different laser conditions, namely the deflagration and self-regulating models. The simplest is the deflagration model which assumes that the laser radiation is absorbed in the plasma only at the critical density, ρ_c. Heat is dispersed upstream and downstream by thermal conduction in a manner similar to a classical deflagration. The downstream flow is an isothermal rarefaction, which ensures a Chapman-Jouget flow about the isothermal sonic point. The upstream flow is determined by the thermal conduction zone, described later.

The model scales the electron temperature as

$$T_e \approx 0.397 \frac{1}{\alpha \bar{Z} R_g} \rho_c^{-2/3} \Phi'^{2/3} \tag{2}$$

where $\bar{Z}$ the ionization of the requisite stage, R_g= k/M the gas constant, and Φ' the thermal flux, not including ionisation.

Combining this relation with the ionisation temperature dependence (1), and adding the ionisation energy we obtain the scaling for the total deflagration flux

$$\Phi = A_d Z^{8.25} \tag{3}$$

where A_d is a constant to be determined empirically. This relation is valid for Z>60.

Laser heating – Self-regulating flow

We shall show that the flows under our conditions can be described by the self-regulating model, in which the laser radiation is absorbed by inverse bremsstrahlung in an expanding plasma plume. Provided the transverse dimension is sufficiently large, the flow is one dimensional and time dependent. Within this regime the plasma temperature is given approximately by

$$T_e \approx 0.423 \frac{1}{\alpha \bar{Z} R_g} b^{1/4} \Phi'^{1/2} \tau^{1/4} \tag{3}$$

where b is the inverse bremsstrahlung coefficient given elsewhere[1] and τ the pulse length. Including the ionisation

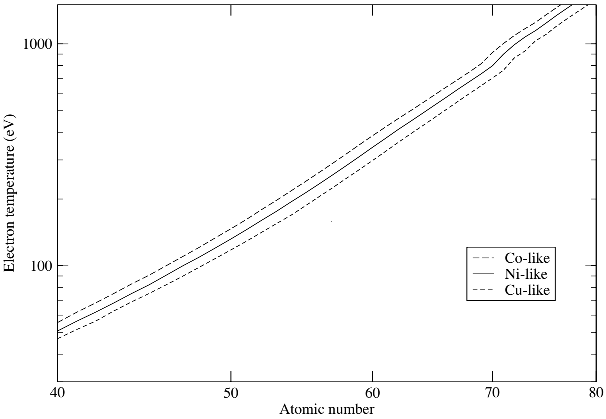

Figure 1. Plot of the steady state electron temperature necessary to achieve ionisation to the Cu-, Ni- and Co-like ionisation stages at electron density 10^{21} cm^{-3}.

Table 1

Element	Wave-length	Pulse length	Self-reg. density	Self-reg. flux	Defln flux	Burn flux	Total flux	Simulation flux	Inv brems abs	Crit dens abs
	μm	ps	W cm^{-2}	W cm^{-2}	W cm^{-2}	W cm^{-2}	W cm^{-2}	W cm^{-2}		
Ag	1.06	600	1.5×10^{20}	4.6×10^{10}	3.6×10^{11}	4.3×10^{10}	8.9×10^{10}	8.3×10^{10}	0.63	0.22
Sm	1.06	290	3.0×10^{20}	6.6×10^{11}	2.8×10^{12}	2.0×10^{12}	2.7×10^{12}	2.4×10^{22}	0.60	0.24
Gd	1.06	290	3.2×10^{20}	8.8×10^{11}	3.6×10^{12}	2.9×10^{12}	3.8×10^{12}	4.3×10^{12}	0.56	0.18
	0.53	290	6.5×10^{20}	1.8×10^{12}	1.4×10^{13}	2.9×10^{12}	4.7×10^{12}	4.3×10^{12}	0.82	0.13
Dy	0.53	100	1.2×10^{21}	4.0×10^{12}	1.8×10^{13}	1.2×10^{13}	1.6×10^{13}	1.8×10^{13}	0.57	0.25
		200	8.2×10^{20}	2.8×10^{12}	1.8×10^{13}	6.2×10^{12}	9.0×10^{12}	1.2×10^{13}	0.68	0.19
Yb	0.53/1.06	100	8.2×10^{20}	6.8×10^{12}	2.9×10^{13}	2.6×10^{13}	3.3×10^{13}	3.5×10^{13}	0.22	0.30
		200	9.1×10^{20}	4.8×10^{12}	2.9×10^{13}	1.3×10^{13}	1.8×10^{13}	3.1×10^{13}	0.57	0.25
		300	7.4×10^{20}	3.9×10^{12}	2.9×10^{13}	8.7×10^{12}	1.3×10^{13}	2.2×10^{13}	0.65	0.23
		400	6.4×10^{20}	3.4×10^{12}	2.9×10^{13}	6.5×10^{12}	9.9×10^{12}	1.6×10^{13}	0.67	0.20

flux and making use of the relation for the ionisation temperature we obtain the empirical scaling for Z>60

$$\Phi = A_{sr} Z^{10} \tag{4}$$

where A_{sr} is determining by fitting to numerical values.

Self-regulating flow occurs if the absorption density

$$\rho_a \approx 0.784 b^{-3/8} \Phi'^{1/4} \tau^{-3/8} \tag{5}$$

is less than the critical density.

Laser heating – thermal conduction zone

At these high temperatures thermal conduction is strong in the upstream plasma, generating a zone of plasma from the absorption density back to the solid and terminating in a sharp heat front. The dimensions of this heat front depend on the flux limitation coefficient, and the conditions at the isothermal sonic point in the expanding flow. In particular we may calculate the energy held in this region in terms of thermal, ionisation and kinetic energy, which again may be scaled for the ionisation condition. We find the approximate scalings for Z>60

$$\begin{aligned} M &\approx 6.25\times10^{-22} Z^{13/4} \quad J/cm^2 \\ E &\approx 2.55\times10^{-15} Z^{9} \quad \mu g/cm^2 \end{aligned} \tag{6}$$

for the mass and energy respectively.

We may compare the mass and energy stored in this zone with that released into the corona, fig.2. As can be seen this term dominates the mass and the energy at quite low values of Z.

Ionisation time

Ionisation is a relatively slow process, whose duration determines the necessary pulse duration of the ionizing pump pulse. We have calculated the time taken to reach the Cu-like ion at the Ni-like steady state temperature at electron densities 10^{21} cm^{-3} and 4×10^{21} cm^{-3}. The results are shown in fig.3. We note that the time taken is roughly inversely proportional to the density as would be expected. More serious is the rapidly increasing time in the ns.

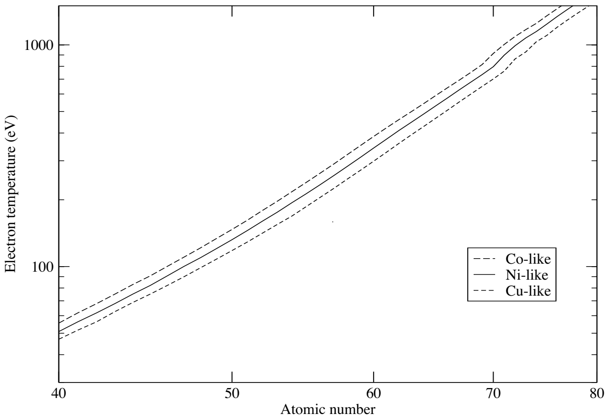

Figure 2. Comparison of the mass and energy stored in the ablation zone with that in the corona at the ionisation temperature of an electron density of 10^{21} cm^{-3} for Cu-like ions and time 200ps.

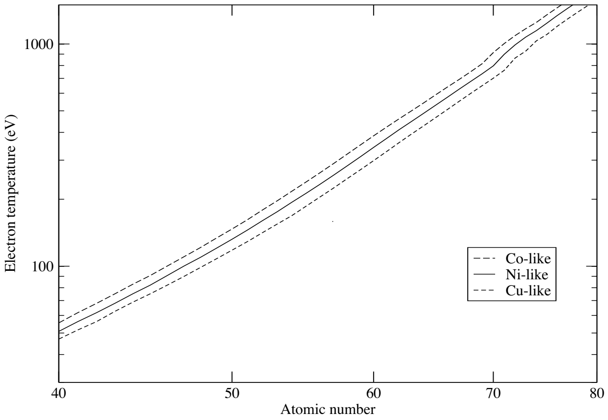

Figure 3. Plot of the time taken to reach the Cu-like ion stage for plasma at the steady state electron temperature necessary to achieve ionisation to the Ni-like stage at electron density 10^{21} cm^{-3}.

domain for Z>70. Although Cu-like ionisation is satisfactory for Ni-like lasing, this implies that we must use higher temperatures than given in fig.1 for Z>70 to achieve the necessary initial state.

Comparisons with simulation

We compare the results from our model with values generated by simulation using EHYBRID and a number of different elements. In these tests we calculate the irradiance needed to generate the Cu-like ionisation stage using various combinations of element, wavelength and pulse duration.

The results are shown in Table 1. The last two columns show the fractional absorption due to inverse bremsstrahlung and to absorption at the critical density. It can be seen that in every case the self-regulating model is appropriate. The fractional absorption due to inverse bremsstrahlung in the plasma can be seen in nearly every case to be significantly larger than that at the critical density, where a reflectivity of 0.7, in accord with experimental data has been assumed.

Ytterbium (Z=70) demonstrates the limitations of this analysis. To improve the efficiency of the pumping we have used a 1::1 mixture of the fundamental and harmonic of Nd glass, yet at short pulses the beam is poorly absorbed. The absorption increases as we increase the pulse length and the scale length of the plasma grows. Unfortunately so does the required energy as the irradiance remains nearly constant. In fact the best compromise appears to be 200ps, which requires only slightly more energy than 100ps and provides a more gentle refractive index, in which the laser is formed.

Unlike gadolinium and dysprosium, the irradiance required to ionise ytterbium to the Cu-like stage is significantly greater than that predicted by our model. This is due to the increasing time required for ionisation, shown in fig.2. Extending the pulse length to 400ps. allows the ionization to develop, but as noted above, the increased energy required by the longer pulse is not compensated by a lower temperature required for ionisation.

Conclusions

Simple modeling allows us to examine the development of ionisation is plasmas suitable for generating laser action in the soft X-ray range. At wavelengths above about 100Å, the necessary ionisation is easily obtained with relatively small lasers. Grazing incidence pumping (GRIP) is extremely efficient in the region. At shorter wavelengths higher atomic number elements are required, and ionisation requires progressively higher temperatures, which scale very adversely with temperature. As a result of the relatively weak scalings of electron temperature with laser irradiance, the necessary irradiance increases very rapidly as we move to larger atomic numbers. To further complicate the issue the time taken for ionization to the lasing stage also starts to increase rapidly as we move to these elements.

At the temperatures required for ionisation in atoms of atomic number greater than about the 50, the upstream plasma is dominated by a large zone heated by thermal conduction. The mass and energy contained in this region exceed that in the corona, becoming a major heat loss, which must be supplied by the pump. However as a consequence, gain can be generated upstream of the relatively low absorption density associated with inverse bremsstrahlung. Since gain depends approximately linearly on density (up to the LTE limit), and since the thermal conduction zone has only a weak density gradient, this allows the gain to develop and be effective at higher density than might otherwise be expected.

Ytterbium, lasing at 50Å, represents a limit to this approach. We have already seen the problems with generating the ionisation. However at this value of Z the mass of the thermal conduction zone becomes approximately 100μg. At larger Z, we can limit the plasma mass by using exploding foils as in early work. This has the additional advantage that we generate the gain at high density in a flat density profile. We will investigate these systems later.

References

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