J. Phys. IV France 11 (2001)

Computational modelling of a Ne-like-Ar collisionally pumped O.F.I. X-ray laser

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Abstract. Schemes in which a hot plasma is formed through optical field ionisation (OFI) of a noble gas lasing in the X-UV and pumped by collisional excitation have been proposed for some time [1]. However experimental evidence has been published only once [2] to date and only recently been reproduced [3]. We have performed detailed computational simulations for OFI produced neon like argon (Ar^{8+}) which is predicted to lase at 46.9 nm on the $2p^53p\ ^1S_0 \rightarrow 2p^53s\ ^1P_1$ transition. Simulations of the atomic and hydrodynamic process within the plasma are used to calculate the temporal evolution of the gain and saturation intensities. A separate code is used to examine the propagation of the driving laser into the plasma and calculates the dispersion of the beam and the resulting degree of ionisation. We find that although high gains are predicted, the saturated output is relatively low at $10^7 - 10^8$ W/cm^2. Furthermore we find that propagating the driving laser into the gas is difficult due to severe diffraction effects and will be a limiting factor in the usefulness of such schemes.

1. INTRODUCTION

1.1 OFI Schemes

Following the work of Delone and Krainov [4] who obtained analytic expressions for the energy and angular distributions of electrons released by a strong low frequency electromagnetic field, Lemoff *et al* [1] proposed three X-UV laser schemes; Ne like Ar lasing at 46.9 nm, Ni like Kr lasing at 31.9 nm and Pd like Xe lasing at 41.8 nm. The essence of these systems is that a high intensity (~10^{17} W/cm^2) femtosecond laser is used to strip a noble gas target to a closed shell configuration, the nature of the OFI process allowing for precise control of the ion species created. By using a driving laser of long wavelength (800 nm) with circular polarisation the released electrons are hot enough to allow for efficient collisional excitation from the ground state to the upper lasant level.

The results of Lemoff *et al* [1] using a simplified level scheme which considers only the rates into and out of the lasant levels, suggest that modest gains of around 34 cm^{-1} are achievable at ion densities of 2×10^{17} cm^{-3} for the Ar system. As important as the gain is, an equally significant factor, the saturation intensity was not considered and neither was the feasibility of propagating the driving laser through the gas.

The only published experimental results for such a system are those by Lemoff *et al* [2] for Pd like Xe who reported an estimated gain of 13 cm^{-1} at an ion density of around 4×10^{17} cm^{-3} although there were no measurements of the saturation intensity. It is only recently that the scheme was shown to be readily reproducible by Balcou *et al* [4].

1.2 Simulation Codes

The one dimensional code BREAKDOWN models the hydrodynamic and atomic processes in the plasma after its creation by the driving pulse. For the duration of the pulse both OFI and inverse bremsstrahlung (IB) effects are considered. Following the pulse a complete collisional / radiative treatment of the ions and electrons is performed. Using supplied level data (which consists of collisional and radiative rates between atomic levels in *LSJ* notation) for the species of interest allows for the level populations to be modelled over time thus giving gain and saturation intensity profiles.

A second code PROPAGATE solves the paraxial wave equation for a gaussian pulse as it propagates through the initially neutral gas. As the beam travels through the gas it is subject to diffraction and refraction effects. The evaluation of the electric field intensity allows for the ionisation of the gas by OFI to be determined.

2. RESULTS

Initial investigations using BREAKDOWN were performed for an incident laser pulse of FWHM 30 fs, a focal spot size of 30 μm, a wavelength of 800 nm and a peak intensity of 10^{17} W/cm^2 giving a beam energy of 90 mJ. This produces electrons with an initial temperature of 1.4 keV significantly above the 280 eV needed to pump the monopole transition from the ground state to the upper lasant level. The laser intensity needed to produce the Ar^{8+} species is ~10^{17} W/cm^2 while that needed to over ionise to Ar^{9+} is around 48 times this value, thus we expect to obtain a useable volume of Ar^{8+}. Thermal conduction effects were included thus allowing the plasma to cool. Figure 1 illustrates the gains and saturated output intensity for this system for a range of ion densities.

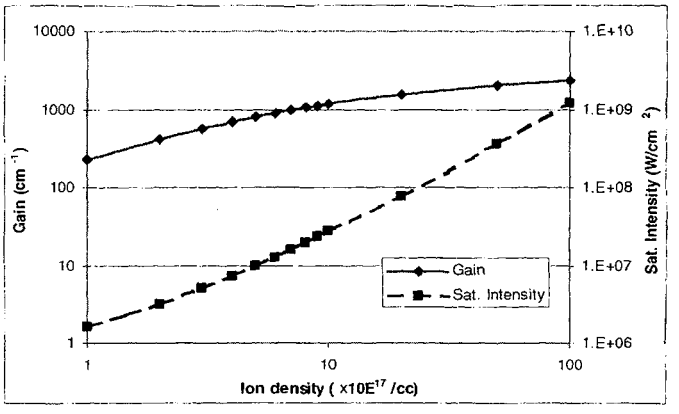

Figure 1. Peak gains and saturation intensities (at time of peak gain) for a range of ion densities.

It is immediately seen that the peak gains predicted are large even at fairly low densities. This result is encouraging since it means that plasma lengths of only a few mm would be required to generate saturated output. The disappointing prediction is that the saturation intensity is low (<10^8 W/cm^2) for realistic densities of less than 10^{18} cm^{-3}. This is primarily due to the fact that the ions are cold since they do not gain appreciable energy from electron collisions during the simulation. For an ion density of 5×10^{17} cm^{-3} the ions have only heated to around 0.06 eV by the time of peak gain (around 6 ps after the end of the driving pulse).

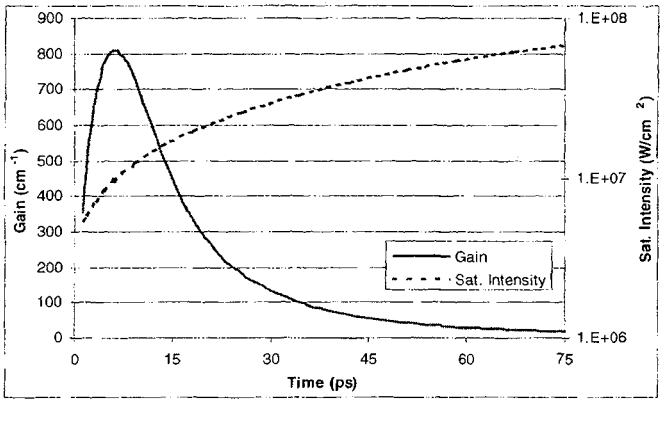

Figure 2. Temporal evolution of the gain and saturation intensity profiles for an ion density of 5×10^{17} cm^{-3}.

In addition to high peak gains, the gain period is also fairly long lived and lasts for several 10's of picoseconds at densities of less than about 10^{18} cm^{-3}. Above this density collisional ionisation over ionises the system to Ar^{9+} limiting the total significant lasing period to less than 10 ps. Gain and saturation intensity profiles are shown in figure 2 for an ion density of 5×10^{17} cm^{-3}. It is seen that after a rapid rise in gain as the population inversion is established, significant gain is still being produced at times greater than 30ps. More importantly the saturation intensity has risen to around 5 times the value at the time of peak gain. The electron temperature by this point is around 330 eV.

The effect of changing the degree of polarisation in the driving beam was also investigated. Moving from circular ($\phi = 0.5$) to elliptical ($0.0 < \phi < 0.5$) has two major effects on the collisional OFI scheme. The first is to reduce the electron temperature and hence how strongly the upper lasant level is pumped. This will decrease both the peak gain and the gain duration. The second effect is to increase the volume of the lasant ion species. This is due to the fact that although the laser intensity has not changed the amplitude of the electric field in one of the two transverse directions in the plane of polarisation is larger and thus increases the tunnelling rate of electrons in the OFI process. Both effects can be seen in figure 3 by the gain profile.

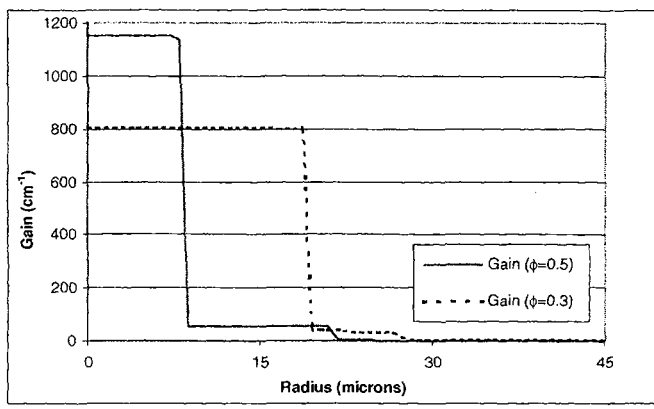

Figure 3. Gain profiles at the time of peak gain (around 3.6ps for both cases) for a driving beam of circular ($\phi = 0.5$) and for elliptical ($\phi = 0.3$) polarisation. The ion density is 10^{18} cm^{-3}. The stepwise nature of the OFI process is clearly illustrated. The primary lasant regions are due to the Ar^{8+} ion. A small amount of lasing occurs in the adjacent regions of predominantly Ar^{7+} from collisional ionisation.

The reduction in the already large gains may be an acceptable penalty at the price of total lasing time in an attempt to increase the output power from these schemes. As seen from figure 3 for a reduction in the peak gain of a factor $^1/_3$, the lasant volume is approximately doubled by using an elliptical pulse with $\phi = 0.3$. The saturation intensity will also increase modestly since it is inversely proportional to the gain coefficient.

Results from PROPAGATE illustrate the main difficulty that these schemes suffer from. Two contour plots showing the degree of ionisation in the plasma following propagation of the driving beam through the gas are shown in figure 4. Both are for an ion density of 5×10^{17} cm^{-3} . Figure 4(a) uses identical pulse parameters as for the BREAKDOWN simulations and it can clearly be seen that no volume of the Ar^{8+} species is created. The reason for this is due to the long wavelength of 800 nm of the laser which is strongly scattered thus reducing the peak intensity below the threshold for creation of the Ar^{8+} ion. A further consequence of the long wavelength is that the Rayleigh length for a beam of FWHM 30 μm is around 3.5 mm meaning that focusing the beam is a major problem.

Figure 4(b) illustrates that a much more energetic beam is required before a useable volume of Ar^{8+} is created. Here a channel of around 30 μm radius and 5 mm in length is created but only just reaches the focal position with sufficient intensity. The energy of the beam in this case is now 750 mJ. The results in

4(b) are qualitatively very similar to those experimental conditions and results of Balcou *et al* [3] for Xe. In their experiments beam energies of 500 – 700 mJ were used and they estimated a lasant channel of around 40 μm radius by 4 mm in length.

Recent PROPAGATE simulations for Xe have also provided good confirmation of these results and we believe they also illustrated why the Xe scheme has been successfully demonstrated while the Ar scheme has not. For a peak intensity of 10^{17} W/cm^2 the strong scattering means that the intensity quickly falls below the threshold for Ar^{8+}. However the first 8 ionisation energies of Xe are much less than those of Ar and with a threshold intensity of ~4×10^{16} W/cm^2 the required ion species can more easily be created.

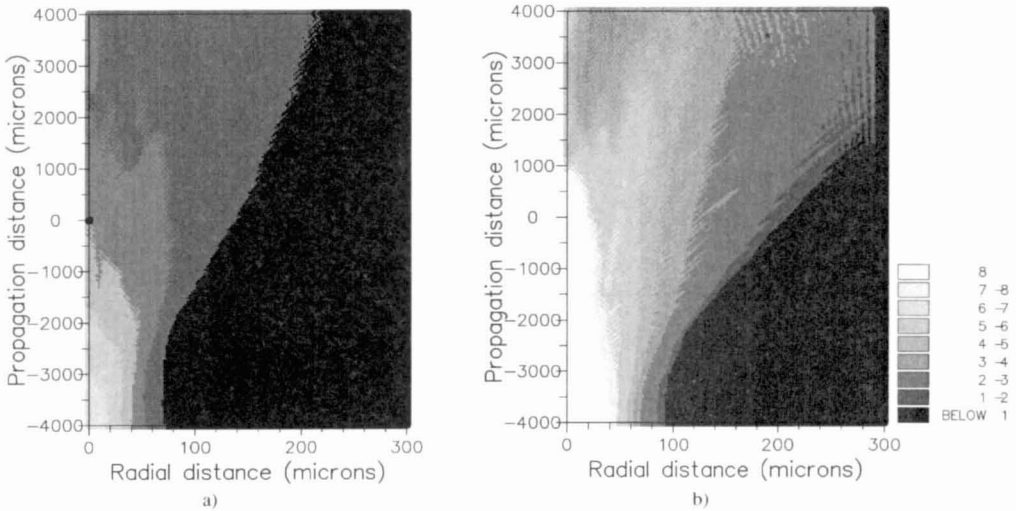

Figure 4. Contour plots showing the ionisation state of the Ar plasma as the driving beam propagates to the ideal focus (zero on the vertical axis) In both cases the ion density is 5×10^{17} cm^{-3} and the contour shading is equal for both plots. a) is using a peak intensity of 10^{17} W/cm^2 and a focal spot size of 30 μm. b) uses a higher intensity of 5×10^{17} W/cm^2 with a spot size of 50 μm. The structure seen on the upper right hand corner of b) is a consequence of the electric field reflecting from the simulation mesh.

CONCLUSIONS

It is seen that although large gains are predicted, the saturated output of the Ar system is low (a few 10^7 W/cm^2) for ion densities as low as 5×10^{17} cm^{-3}. The lasant volume and saturation intensity can be increased modestly at the expense of the total lasing time by using a degree of ellipticity in the driving pulse and thus the output efficiency can be increased. However even at these low densities producing the required plasma is difficult due to the necessity of the driving laser having a long wavelength to generate the hot electrons needed to pump the system. Only by using a large focal spot size and increasing the peak intensity of the driving pulse significantly above the threshold for OFI can a useable plasma channel of the required ionic species be created.

The deleterious effect of the long wavelength is less important for the Xe scheme than for the Ar since the lower ionisation energies mean a lower intensity is required to generate the plasma.

References

[1] Lemoff B. E., Barty C. P. and Harris S. E., *Optics Letters*, **8** (1994) 569

[2] Lemoff B. E., Yin G. Y., Gordon C. L, Barty C. P. and Harris S. E. *Phys. Rev. Lett.* **74** (1995) 1574

[3] Balcou Ph., Sebban S., Haroutunian R., Rousse A., Grillon G., Rousseau J-Ph., Notebaert L., Pittman M., Chambaret J-P., Hulin D., Klisnick A., Ros D., Jaegle P., Carillon A., Jamelot G., "Femtosecond laser driven XUV sources, High harmonic and OFI X-Ray laser studies", 7th International Conference on X-Ray Lasers, St. Malo, France 18-23 July 2000.

[4] Delone N. B., Krainov V. P. *J. Opt. Soc. Am. B* **8** (1991) 1207