Self-Photopumped X-Ray Lasers from Elements in the Ne-like and Ni-like Ionization State

Michael Siegrist, Fei Jia and Jürg Balmer

Abstract Self-photopumped x-ray lasers in laser-produced plasma have been previously proposed as an alternative scheme to electron collisional excitation. While, in general, self-photopumped lasers suffer from somewhat lower gain, their higher saturation intensity could in principle lead to higher peak irradiace. We have performed experiments on the 3d $^1P_1 \rightarrow$ 3p $^1P_1$ and 4f $^1P_1 \rightarrow$ 4d $^1P_1$ transitions for Ne-like and Ni-like ions, respectively. Lasing on the self-photopumped laser line has been observed for the first time for several elements including Ne-like V, Cr, Fe, and Co as well as Ni-like Ru, Pd, and Ag. We have investigated the lasing process by varying the prepulse delay, which shows a shift of the optimum main pulse to second prepulse delays towards lower values with higher atomic number Z. Experiments have been performed with the Bern Advanced Glass Laser (BeAGLE) laser using three pulses with total energy up to 15 J at a wavelength of 1054 nm.

1 Introduction

The Ne-like and Ni-like ionization states offer very similar energy level diagrams. Both ionization states have a monopole and a dipole transition leading to a "collisional" and a "self-photopumped" lasing line (see Fig. 1). The collisional laser line is preferentially pumped by electron collisions and is denoted as 3p $^1S_0 \rightarrow$ 3s $^1P_1$ and 4d $^1S_0 \rightarrow$ 4p $^1P_1$ for Ne-like and Ni-like ions, respectively. The self-photopumped line, which is the main focus of this work, is pumped by a hybrid pumping process [1]. Firstly, the population inversion is achieved by electron collisions. Secondly, the population inversion is preserved by radiation trapping, as the plasma is optically thick for this line. The self-photopumped laser lines are denoted as 3d $^1P_1 \rightarrow$ 3p $^1P_1$ and 4f $^1P_1 \rightarrow$ 4d $^1P_1$ for Ne-like and Ni-like ions, respectively. While the self-photopumped laser line suffers from somewhat lower gain compared to the monopole-pumped line, its higher saturation intensity gives rise to the potential of becoming the dominant lasing line [1]. Self-photopumped x-ray lasers have been shown before for Ne-like Ti as well as for Ni-like Zr, Nb and Mo [1, 2]. Using the BeAGLE system we were able to demonstrate several new elements to lase on

M. Siegrist (✉) · F. Jia · J. Balmer
Institute of Applied Physics, University of Bern, Sidlerstrasse 5, Bern, Switzerland
e-mail: michael.siegrist@iap.unibe.ch

© Springer International Publishing Switzerland 2016

J. Rocca et al. (eds.), *X-Ray Lasers 2014*, Springer Proceedings in Physics 169,
DOI 10.1007/978-3-319-19521-6_11

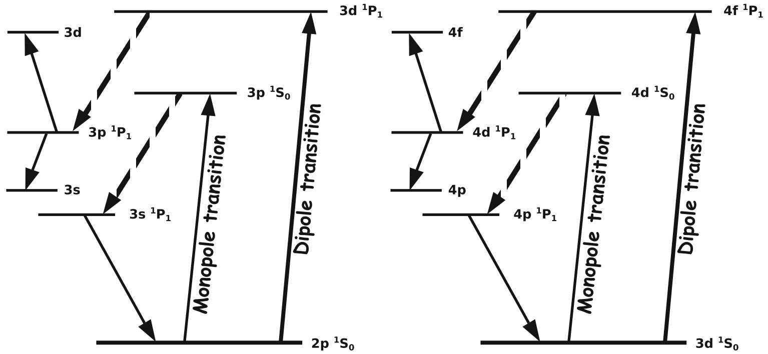

Fig. 1 Level diagram for the Ne-like (*left*) and Ni-like (*right*) ionization state respectively. The *dashed lines* mark the corresponding laser transitions, where the self-photopumped and the collisional transitions are pumped by the dipole and the monopole transition, respectively

this line, namely self-photopumped x-ray lasers for Ne-like V, Cr, Fe and Co as well as Ni-like Ru, Pd and Ag.

2 Experimental Setup—The BeAGLE System

The **Be**rn **A**dvanced **G**lass **L**aser **E**xperiment (**BeAGLE**) is a high-power laboratory-scale Nd:glass laser system that provides energies up to 25 J with 1.5 ps pulse duration at 1054 nm. In order to maximize the x-ray output, we use **g**razing-**i**ncidence **p**umping (**GRIP**) at an angle of $\sim 50°$ and traveling-wave speeds ranging from 0.8 to 1 c. For the self-photopumping experiments we generated two pre-pulse by inserting beamsplitters with reflectivities of 0.5, 2.8, 4.5, 8 or 16 % (see Fig. 2) [3]. The BeAGLE system has two x-ray diagnostics to measure the plasma x-ray generation. Firstly, a pinhole camera pointing at a 45 angle to the target surface in order to measure the spontaneous emission from the plasma. Secondly, we measure the x-ray laser beam by using a CCD camera aligned with the beam axis. In the horizontal plane we measure the beam divergence and intensity distribution, whereas in the vertical plane, a flat field grating spectrally resolves the beam with a precision of ± 0.2 nm. Figure 3 shows a measurement of a Ne-like Ti shot. By using known laser lines to calibrate the spectrometer, the self-photopumped laser transition of the Ne-like Ti has been estimated to be at 30.1 ± 0.2 nm, which is in good agreement with literature data [2].

3 Experimental Results—Variation of the Prepulse Delays

Besides the energy, the prepulse configuration of the laser system is of high importance. In experiments we observed that the timing of the first prepulse (3–5 ns) has only a minor effect on the x-ray output. In contrast to this, the main pulse to second

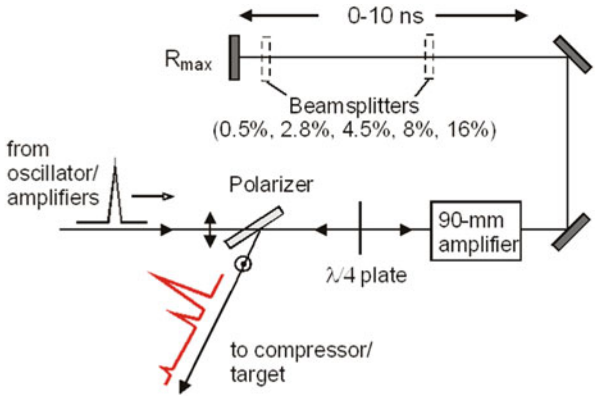

Fig. 2 Schematic of the prepulse setup

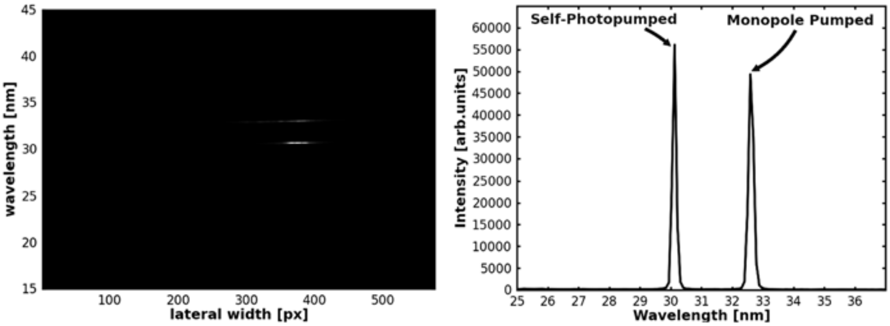

Fig. 3 Raw image (*left*) and the corresponding lineout spectrum (*right*) clearly showing the two distinct lines for the monopole and the self-photopumped lasing lines for Ne-like Ti

prepulse delay has been found to be the critical parameter on self-photopumped lasing. In Fig. 4, we show the dependence of the laser output on the second prepulse delay of Ne-like Ti and V and Ni-like Mo and Pd. Experiments have been performed with a 0.5 % first prepulse, which precedes the main pulse by 5 ns. For the second prepulse the 16 % beamsplitter was used. The total energy of the three pulses has been ∼3 J.

We have investigated the time delay between the main pulse and the second prepulse for Ne-like Ti, V, Cr, Fe and Co as well as for Ni-like Mo, Ru, Pd and Ag. The parameters mentioned before have been used for all measurements, except for Ne-like Fe and Co, where we used a 2.8 % first prepulse, which preceded the main pulse by 4 ns with a total energy of 11 and 15 J, respectively. By plotting the delay for the highest output for each element against the atomic number Z, one observes a shift towards smaller delays with increasing atomic number Z for both the Ne-like and the Ni-like ionization scheme (see Fig. 5). The optimum delay seems to converge to a value around 100 ps for both the Ne-like and Ni-like lasing scheme. In addition, lasing has never been observed for a delay smaller than 100 ps, which could give rise to a explanation of the converging curve towards a value around 100 ps.

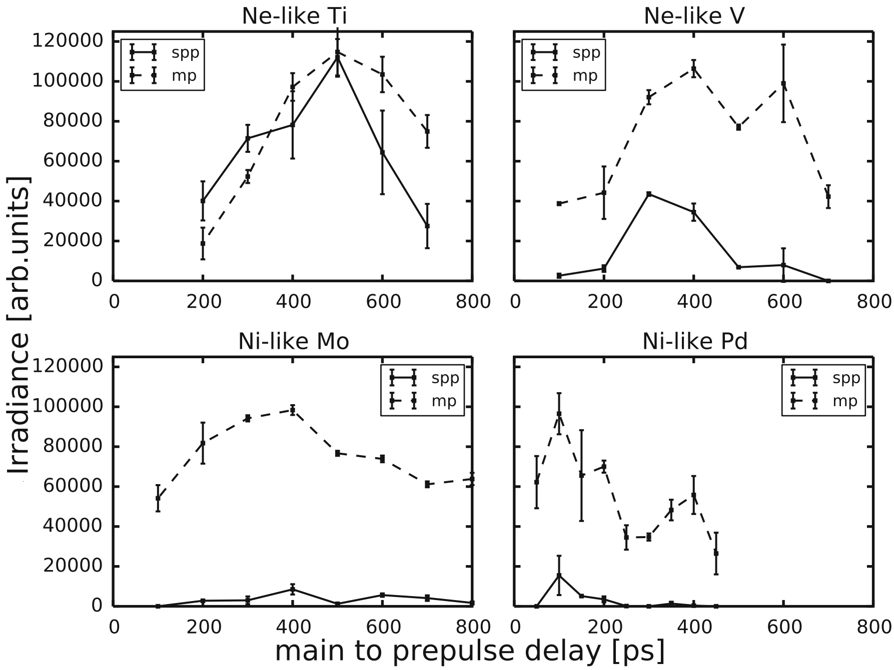

Fig. 4 Dependence of the self-photopumped (*spp*) and the monopole pumped (*mp*) on the main to second prepulse delay

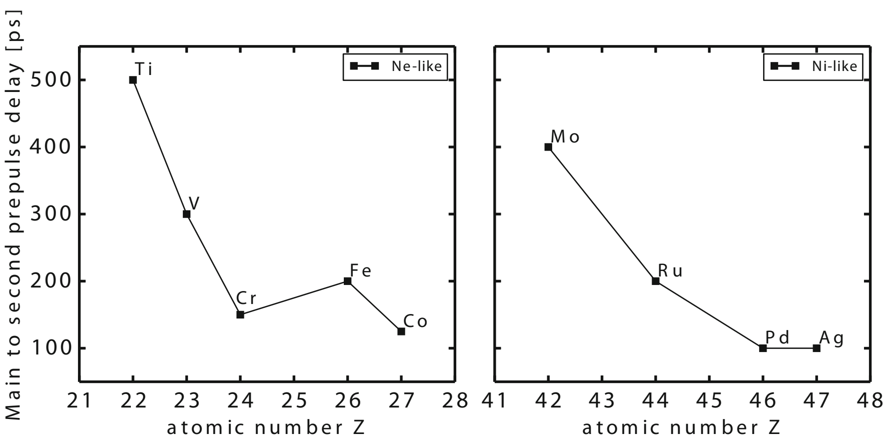

Fig. 5 Dependence of the optimum main to second prepulse delay on the atomic number Z

4 Conclusion and Outlook

The experiments on the self-photopumped transition demonstrate that the list of elements that lase on the self-photopumped transition can be extended much further than originally known. Namely, this includes lasing on the Ne-like 3p $^1S_0 \rightarrow$ 3s $^1P_1$ laser line for the first time for V, Cr, Fe and Co as well as on the Ni-like 4d $^1S_0 \rightarrow$ 4p $^1P_1$ line for Ru, Pd, and Ag. The desired characteristic of the self-photopumped lasing line to be the stronger has been only encountered so far in some shots in Ne-like Ti (see Fig. 3). Additionally, we found a strong dependence on the main to second prepulse delay. The optimum delay shifts towards smaller delays with increasing atomic number Z.

In order to get more insight into the self-photopumped lasing mechanism we plan to measure existing lasing elements more in detail and moreover try to expand the number of lasing elements even further. Besides that, time-resolved measurements comparing the collisional and the self-photopumped lasing lines are under way to provide more information on the time domain in which this lasing mechanism occurs.

Acknowledgements This work was supported in part by the Swiss National Science Foundation.

References

1. Nilsen, J., Dunn, J., Osterheld, A.L., Li, Y.: Lasing on the self-photopumped nickel-like $4f^1P_1$->$4d^1P_1$ x-ray transition. Phys. Rev. A. **4** R2677–2680 (1999)
2. Nilsen, J., Li, Y., Dunn, J.: Modeling picosecond-laser-driven neonlike titanium x-ray laser experiments. J. Opt. Soc. Am. **6** 1084–1092 (2000)
3. Balmer, J.E., Staub, F., Jia, F.: X-Ray Lasers 2012. Springer Proceedings in Physics, vol. 147, Chap. 5. Paris (2014)