Photoresonant Anode Plasma: Simulation of Interaction of Resonant KrF Laser Radiation with Fe- and Ta-Containing Gas Clouds, and Experimental Results

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Metal vapor ionization by dye laser radiation is an effective way to produce plasma clouds of elemets that have resonant transitions in optical region. Authors propose an universal technique of photoresonant plasma production of nearly any element of interest. Eximer laser radiation is absorbed by the element with a resonant transition overlapping with the laser spectrum doped to main plasma cloud. There are more than 20 transitions that overlap with eximer lasers spectra. Ion temperature of photoresonant plasma is low therefore this technique can be used to produce anode plasma of ion accelerators and ion beams with low divergence and desired elemental composition.

This work presents results of kinetics modeling and some experiments with single- and multicomponent targets in the field of KrF and N_2 laser radiation containing Ta, Fe, or Ti. Fe and Ti atoms have resonant transitions overlapping with KrF and N_2 laser spectra respectively. Ta atom and singly ionized ion have resonant transition within KrF laser generation spectrum. This leads to significant differences in plasma kinetics of clouds containing these metals. In particular, one can obtain Ta-doped doubly ionized clouds with a low ion temperature.

1. Introduction

A dense sodium vapor ionization by resonance laser radiation was first observed [1] at a surprisingly low laser power density. Mechanism of this "classic" Laser Ionization Based On Resonance Saturation (LIBORS) was explained by Measures et al. [2] and later specified by Kasyanov and Starostin [3] The LIBORS mechanism is a sequence of four stages. In the first stage laser radiation populates to saturation the resonance transition (see Fig.1). In the second stage the number of free electrons grows due to collisional and multiphoton ionization of the atoms. Free electrons rapidly gain energy in the atoms-radiation-electron system through super-elastic collisions and induced inverse bremsstrahlung. In the next stage upper atomic levels are populated by electron-atom collisions. Finally, when electron and highly-excited atom densities grow to critical values, runaway collisional ionization of the intermediate levels results in almost complete ionization of the vapor.

The advantages of LIBORS essential number of applications are a low temperature of the resultant plasma, and a possibility to produce plasma with no light contaminants. However, this technique can not be applied to production of arbitrary ions, because the resonance transitions of many elements lie in the UV range where there are no adequate tunable lasers.

UV-LIBORS

Fortunately, resonance lines of about twenty elements are within or close to the spectrum of one of the excimer lasers [4]. The advantages of LIBORS technique in UV region are

- excimer lasers are powerful, robust, have a high repetition rate and a long service life
- a single-photon ionization of resonant atom excited state is possible that can drastically increase production of seed electrons, specially in vapors with low initial temperature
- there are three elements whose resonance transitions of both atom and ion have almost identical wavelengths at reasonable oscillator forces, coinciding with the generation band of one of the excimer lasers: Ta (λ_a=248.50 nm and λ_i=248.47 nm) and Sn (λ_a=248.34 nm and λ_i=248.35 nm) for KrF laser, and U (λ_a=351.16.50 nm and λ_i=351.15 nm) for XeCl laser.

CATRION

UV LIBORS may be applied to produce a plasma of almost any elemental composition in many cases when a fraction of admixed resonant atoms is acceptable in the plasma, for example, in the ion sources with ion separation or in magnetically insulated light-ion diodes. To obtain desirable plasma composition, one needs to admix in the gas mixture one of the elements whose resonance transitions are resonant to an excimer laser wavelength. This element ("element-catalysts") is a relatively small fraction in the gas, but initiates the LIBORS process and drives ionization of the medium. The ionization of multi-component gas clouds containing resonant component is called CATRION (CATalythic Resonance IONization).

The process is the most effective if the mentioned elements (Ta, Sn or U) that have resonant transitions with the same wavelength for atom and ion are used as the admixture. In this case the laser energy will be transferred to plasma even after complete ionization of the catalyst atoms in the gas mixture (see Ta in Fig. 1).

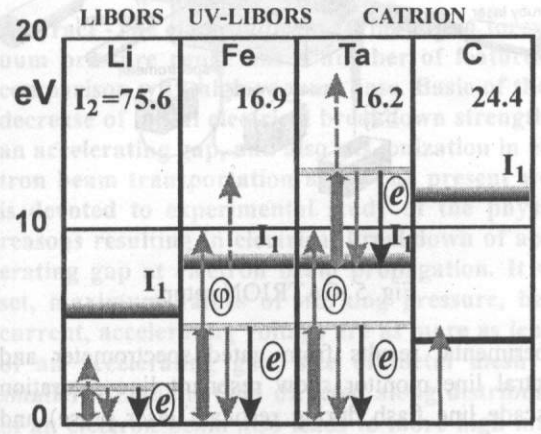

Fig.1. Schematic diagram of atomic levels for LIBORS, UV-LIBORS and CATRION processes.

2. Model

In our simulations we considered a simplified model of the photoresonant ionization. Atoms and ions are assumed to have only two energy levels (ground and excited states), electrons are maxwellian with a temperature T_e. The processes taken into account are photoexcitation, stimulated and spontaneous radiation, electron impact excitation and ionization, three-body recombination. All the processes involve atoms and ions. Additionally, single-photon ionization of the atomic excited state is taken into account. For the atoms of admixture the electron impact ionization and three-body recombination of the ground state is considered.

A system of nine differential equations have been solved to find the time dependence of particle densities. As an initial electron temperature we took the evaporation temperature of the target. Initial electron and excited atom densities are calculated using Saha and Boltzman equations. Approximate formula for reaction rates (recommended by Drawin) were used.

Time dependence of the component densities and temperature for TaTi cloud in the field of resonant radiation of N_2 laser is shown in fig. 2 for the following initial conditions: electron temperature is 0.1 eV, resonant (Ti) atom density is $3 \cdot 10^{17}$, non-resonant (Ta) atom density is $3 \cdot 10^{17}$, resonant radiation intensity is equal to tenfold saturation intensity, single-photon ionization cross-section of resonant atom excited state is 10^{-21} cm^2. Laser pulse is assumed to be a step function turning on at zero time.

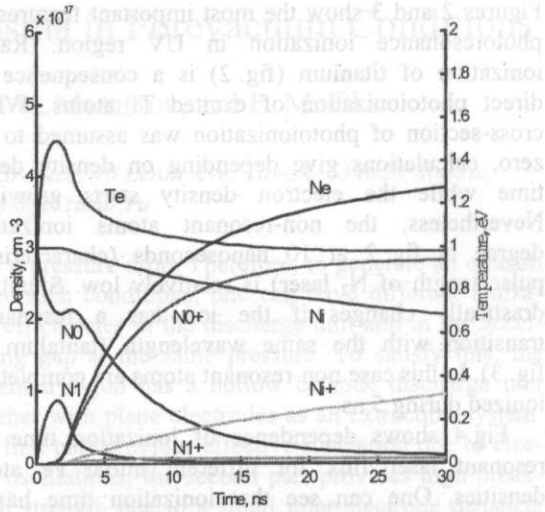

Fig.2. Time dependence of component densities and electron temperature. N0, N1 - ground and excited states of Ti (resonant) atom, N0+, N1+ - ground and excited states of Ti (non-resonant) ion, Ni, Ni+ - Ta atom and ion, Ne - electron density.

The same dependences for TaB cloud in the field of KrF laser radiation are shown in fig. 3. Initial conditions: electron temperature is 0.3 eV, resonant (Ta) atom density is $3 \cdot 10^{17}$, non-resonant (B) atom density is $3 \cdot 10^{17}$, resonant radiation intensity is equal to tenfold saturation intensity, single-photon ionization cross-section of resonant atom excited state is 10^{-21} cm^2.

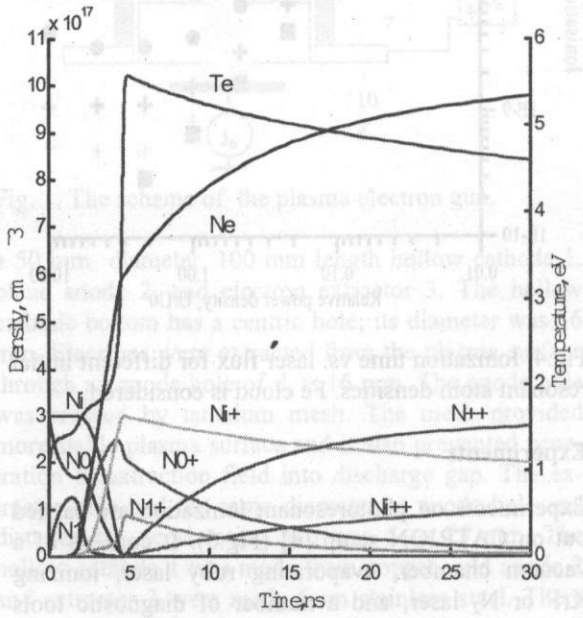

Fig.3. Time dependence of component densities and electron temperature. N0, N1 - ground and excited states of Ta (resonant) atom, N0+, N1+ - ground and excited states of Ta (resonant) ion, N++ - doubly ionized Ta atom, Ni, Ni+, Ni++ - Ta atom, singly and doubly ionized atom, Ne - electron density

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Figures 2 and 3 show the most important features of photoresonance ionization in UV region. Rapid ionization of titanium (fig. 2) is a consequence of direct photoionization of excited Ti atoms. When cross-section of photoionization was assumed to be zero, calculations give depending on density delay time while the electron density starts growing. Nevertheless, the non-resonant atoms ionization degree in fig. 2 at 10 nanoseconds (characteristic pulse length of N_2 laser) is relatively low. Situation drastically changes if the ion has a resonance transition with the same wavelength (tantalum in fig. 3). In this case non-resonant atoms are completely ionized during 5 ns.

Fig.4 shows dependence of ionization time on resonant laser flux for different initial Fe atom densities. One can see that ionization time has a minimum at approximately saturation intensity (about 150 kWt/cm^2·nm) and further intensity increase is inefficient.

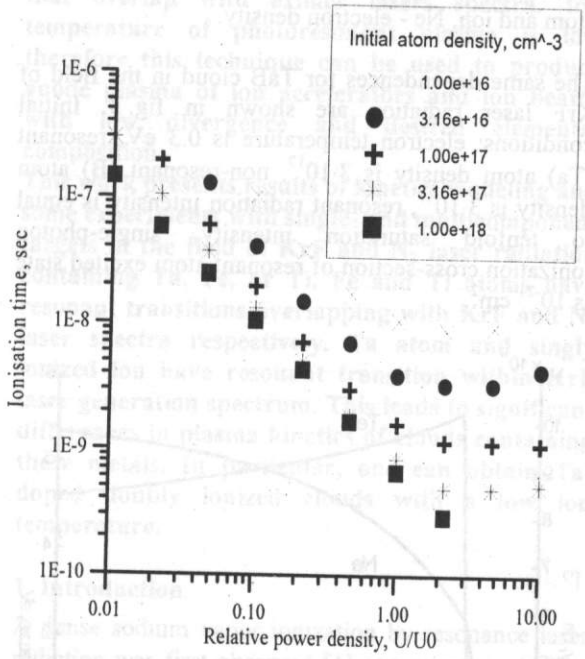

Fig.4. Ionization time vs. laser flux for different initial resonant atom densities. Fe cloud is considered.

Experiments

Experiments on photoresonant ionization are carried out on CATRION setup [4] (Fig.5). It consists of a vacuum chamber, evaporating ruby laser, ionizing KrF or N_2 laser, and a number of diagnostic tools (Lengmuir probes, Faraday cups, gated spectrometer, spectral line monitor, deflectometry diagnostic, schlieren diagnostic, electron image converter). Experiments are carried out with Ta- or Fe-contained clouds and KrF laser or Ti-contained clouds and N_2 laser.

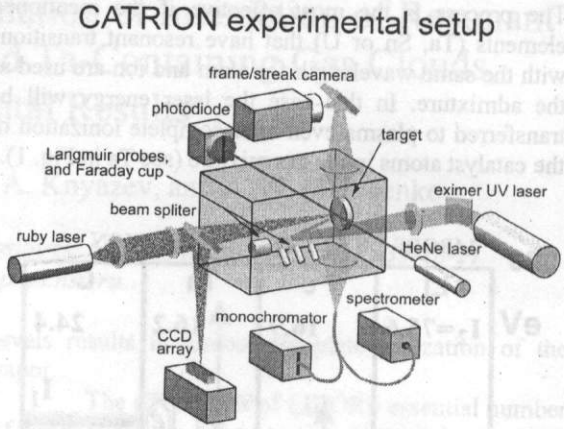

Fig. 5. CATRION setup

Experimental results from gated spectrometer and spectral line monitor show resonant line saturation (cascade line flash during resonant laser pulse) and intense light irradiation in continuum after the laser pulse.

Experiments carried out gave qualitative agreement with the simulations.

Acknowledgements

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