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# PHOTORESONANCE ANODE PLASMA SOURCE: NUMERICAL SIMULATION

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# Photoresonance anode plasma source: numerical simulation

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## Abstract

Numerical simulations of UV photoresonance ionisation of vapour layers containing atoms of the elements whose resonance lines coincide with KrF laser spectrum are presented. A simple model, which describes the interaction of a two-level atom with an intense resonant radiation and subsequent chain of elementary processes leading to the vapour ionisation, has been developed. Time dependence of component densities for iron, tantalum, and multi-component clouds containing “non-resonant” boron was calculated. Experiments on the excitation of Fe, Ta and Sn vapour clouds by resonant laser radiation using a new modification of KrF laser are in progress.

# Фоторезонансный источник анодной плазмы: численное моделирование

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## Аннотация

Представлены результаты численных расчетов УФ фоторезонансной ионизации слоев пара, содержащих атомы элементов, резонансные линии которых перекрываются со спектрами генерации KrF лазера. В расчетах использовалась простая модель двухуровнего атома. При взаимодействии атомов с резонансным излучением в режиме насыщения энергия, получаемая атомами, передается электронам за счет столкновений второго рода, что приводит в результате цепи элементарных процессов к практически полной ионизации пара. Приведены временные зависимости плотностей нейтральных и заряженных компонентов облака для железа, тантала и их смесей с “нерезонансным” бором. Используя новую модификацию KrF лазера начаты эксперименты по возбуждению резонансным излучением облаков Fe, Ta и Sn.

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## Introduction

Ion source is one of the critical elements for ion driven inertial fusion.[1,2] If a light ion driver is used (Light Ion Fusion, — LIF), anode plasma must provide uniform emission of singly ionised atoms with a density of $10^{15}$ ions/cm$^2$ during 50 ns at a repetition rate of about 1 Hz [1]. For a heavy ion driver (Heavy Ion Fusion — HIF) a pulse of 1–20 $\mu$s at a repetition rate of 1–20 Hz is required, whereas ion density and composition depends on specific scheme.

For a full-scale reactor and intermediate experiments surface, gas, and arc ion sources [2, 3], as well as laser ion sources [4, 5] are considered. Photoresonance technique (UV photoresonance ionisation, — UVPRI) — when expanding vapour is affected by intense resonant excimer laser radiation — can produce relatively cold singly ionised clouds [6, 7, 8]. The ions of Fe, Sn, Ta (KrF laser), U (XeF laser), and Al, V and Co (XeCl laser), which are of interest to HIF, can be obtained with the photoresonance sources. Tantalum and tin have a remarkable feature because both their ions and atoms have the resonance transitions overlapping with KrF laser spectrum, therefore $Sn^{++}$ and $Ta^{++}$ containing plasma can be obtained by UVPRI. Experiments on the photoresonance ionisation of Ta and Fe with 100 ns KrF laser have been performed recently [6, 7]. Here we present the results of numerical simulations of the ionisation by KrF laser of Ta, Fe and their two-component mixtures with boron. Experiments on spectroscopic study of UVPRI of tin vapours with a new 24 ns, 200 mJ KrF laser ($\lambda$=248.5 nm) are in progress.

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## Numerical simulations of UV photoresonance ionisation

A number of photoresonance ionisation (PRI) models for alkali metals were developed earlier [9, 10, 11]. Our model is similar to the model of R.M. Measures [9], but there are three essential differences: (*i*) excited atoms can be directly ionised by UV laser; (*ii*) ionisation potential of the heavy metal ions is, as a rule, substantially lower than for the alkali ions; (*iii*) since some ions are resonant to the laser radiation, one can obtain plasma consisting mostly of the doubly-ionised atoms.

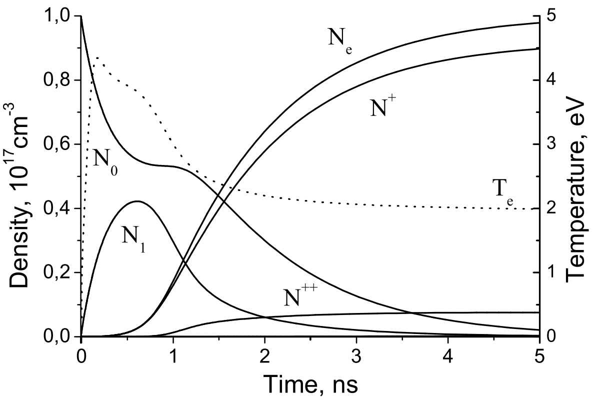

Fig. 1. Component densities and electron temperature vs time in the iron cloud irradiating by a stepwise KrF laser pulse at the saturation parameter $S = 5$. Here $T_e$ is electron temperature; $N_e$ – electron density; $N_0$ and $N_1$ – densities of atoms in the ground and excited states; $N^+$ and $N^{++}$ – corresponding ion densities.

Since we aimed to compare PRI with UVPRI and to estimate the cloud and laser parameters necessary for the experiments, a simple two-level model of atom and ion was assumed. This assumption can be justified by the results of R.M. Measures [9], who reported 20-level and 5-level models to give similar to 20% results. We took into account photoexcitation, stimulated and spontaneous radiation, electron impact excitation and ionisation, three-body recombination, photoionisation of the exited state, and the other essential for the task processes. A uniform cloud with independent of space coordinates density and laser radiation parameters was assumed. More detailed model specification and reaction rates will be published elsewhere.

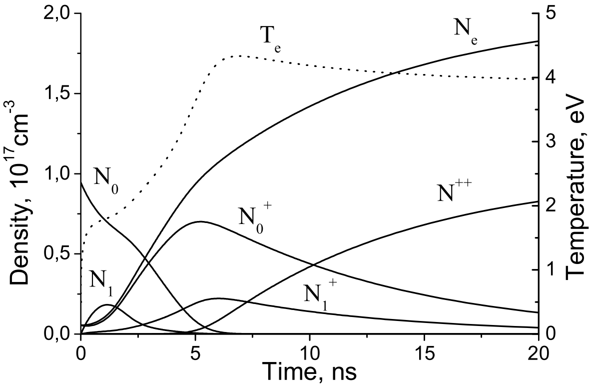

Fig. 2. Component densities and electron temperature vs time in the tantalum cloud (KrF laser, $S = 5$); $N_0^+$ and $N_1^+$ – densities of ions in the ground and excited states; the other notations are as in Fig. 1.

The calculations were carried out for the initial cloud density of $10^{17} - 10^{18}\,\mathrm{cm}^{-3}$ and the saturation parameter $S = I_{\mathrm{KrF}}/I_\lambda^S$ from 1 to 100, where $I_\lambda^S = 1.4 \cdot 10^{14}/\lambda^5[\mathrm{nm}] = 150\ \mathrm{kW}/(\mathrm{cm}^2 \cdot \mathrm{nm})$ for KrF laser wavelength. Figures 1 and 2 show the time dependence of component densities and electron temperature for pure Fe and Ta clouds for the laser spectral power density $I = 5I_\lambda^S$. One can see that the singly ionised (90%) iron plasma with the electron temperature of about 2 eV is produced after 5 ns from the laser pulse beginning. Tantalum cloud, due to the resonance transition of Ta$^+$ ion, continues to absorb laser radiation even after complete ionisation of the atoms. As a result, it is heated up to 4 eV and converts to plasma containing mostly doubly charged ions. When the laser power density rise from $I_\lambda^S$ to $70I_\lambda^S$, ionisation time for cloud densities of $10^{17} - 10^{18}\,\mathrm{cm}^{-3}$ decreases from $30 - 100$ ns to a fraction of nanosecond.

Figures 3 and 4 show ionisation processes in the two-component plasmas, where the second component (boron) has no transition resonant to KrF laser radiation. The differences between Ta–B and Fe–B clouds are, obviously, due to resonant transition of Ta$^+$. Estimations show that the electrons does not transfer their kinetic energy to the ions during a pulse and the ions keep their initial temperature close to the element evaporation temperature.

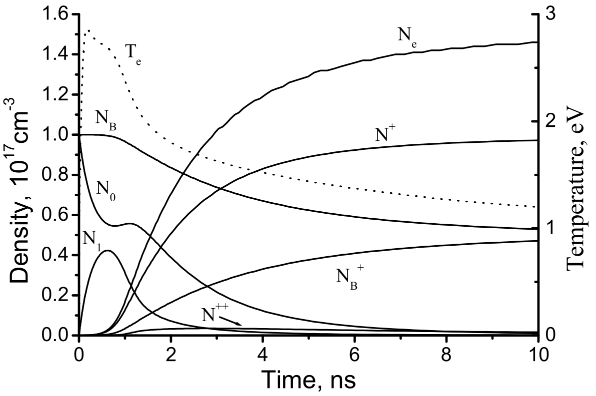

Fig. 3. Component densities and electron temperature vs time in the iron-boron (50% – 50%) cloud (KrF laser, $S = 5$); $N_B$ and $N_B^+$ – densities of boron atoms and ions.

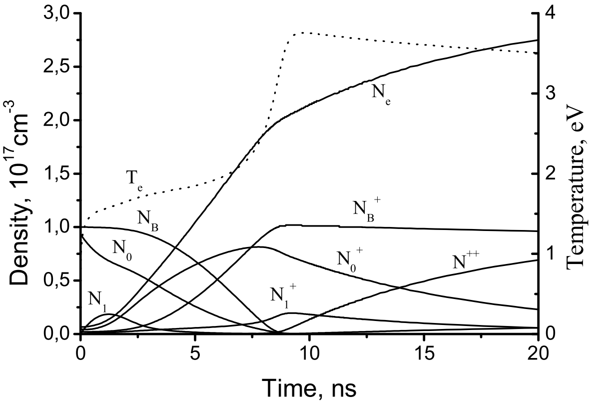

Fig. 4. Component densities and electron temperature vs time in the tantalum-boron (50% – 50%) cloud (KrF laser, $S = 5$).

## Experiments on Sn vapor excitation by KrF laser radiation

The previous experiments on the photoresonance ionisation of Ta and Fe clouds have been performed on CATRION setup with a 100 ns KrF laser. The clouds are produced by a ruby laser pulse and, with some delay, are irradiated by the KrF laser. The experimental setup was described in detail in the paper [12]. The experiments have evidence of the effect of UVPRI, but the complexity of Ta and Fe spectra did not allow us to clearly identify the energy migration pattern over atomic levels. At present we have started an experiment with Sn clouds, because tin atom has much more simple level system. The lower state of the transition that is resonant to KrF laser has energy of 3500 $\mathrm{cm}^{-1}$. This feature is also a subject of special interest for both future simulation and experiments.

A compact high-efficient discharge-pumped KrF (248 nm) excimer laser with active gas media based on He as a buffer gas was used in the experiments. For pumping of an 80 cm3 active volume the construction and parameters of the high voltage excitation circuit of the L-C inverter type based on standard spark-gap switch RU-65 with automatic preionisation were optimized. The circuit developed allows obtaining the specific pump power up to 2.5 MW/cm3. In the active gas media of $\mathrm{He} : \mathrm{Kr} : \mathrm{F}_2 - 89.8 : 10 : 0.2$ at the total pressure of 2.9 atm the maximum output radiation energy of 400 mJ with overall efficiency of 1.2% have been obtained. The pulse duration (FWHM) was $24 \pm 1$ ns and the pulse power was of 16 MW.

A gatable intensified optical multichannel analyser is used for the record of the fluorescence spectra of Sn and In clouds. Simultaneously, ion current to Lengmuir probes and time dependence of a Sn or In spectral line intensity were measured. First experiments have shown that effective energy transfer at least to the levels close to the resonant level take place in Sn cloud. Relative fluorescence intensities from the resonant level and nearby levels are nearly the same that evidence the appearance of additional electrons after KrF laser pulse.

## Discussion

The numerical simulations and the experiments [6, 12, 7] have demonstrated feasibility of UVPRI for the formation of Fe, Sn, and Ta anode plasmas as well as two-component plasmas of interest to LIF and HIF. An important feature is that the ion temperature can remain low in a course of the laser photoionisation that is essential for the low-emittance beam formation. It should be mentioned, however, that the calculation results should be treated as qualitative only, since the assumptions of LTE and stationarity are not fulfilled completely in reality. These considerations call for a model taking account of parameters' spatial distribution, which is currently being developed.

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