Ionization dynamics in the laser plasma in gases and a possible way for optimization of the EUV source

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Introduction

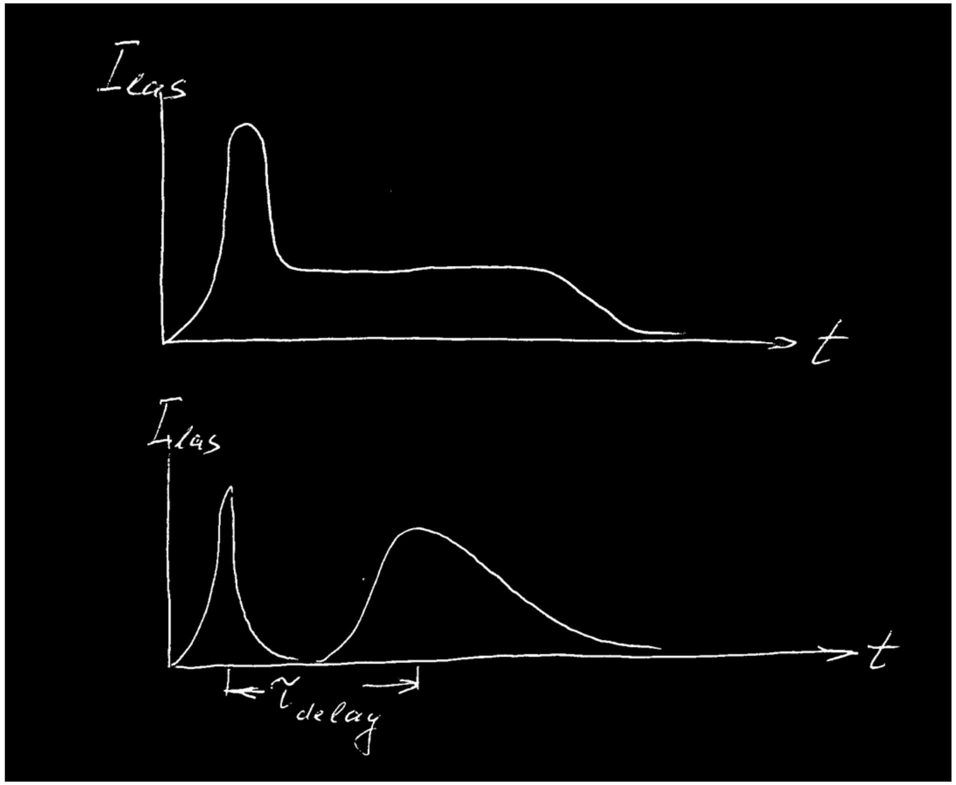
A program is carried out, in the Ioffe Institute, aimed at development and optimization of an EUV source based on the laser plasma with Xe gas jet target.

Objective of the optimization – enhancement of the conversion efficiency (CE)

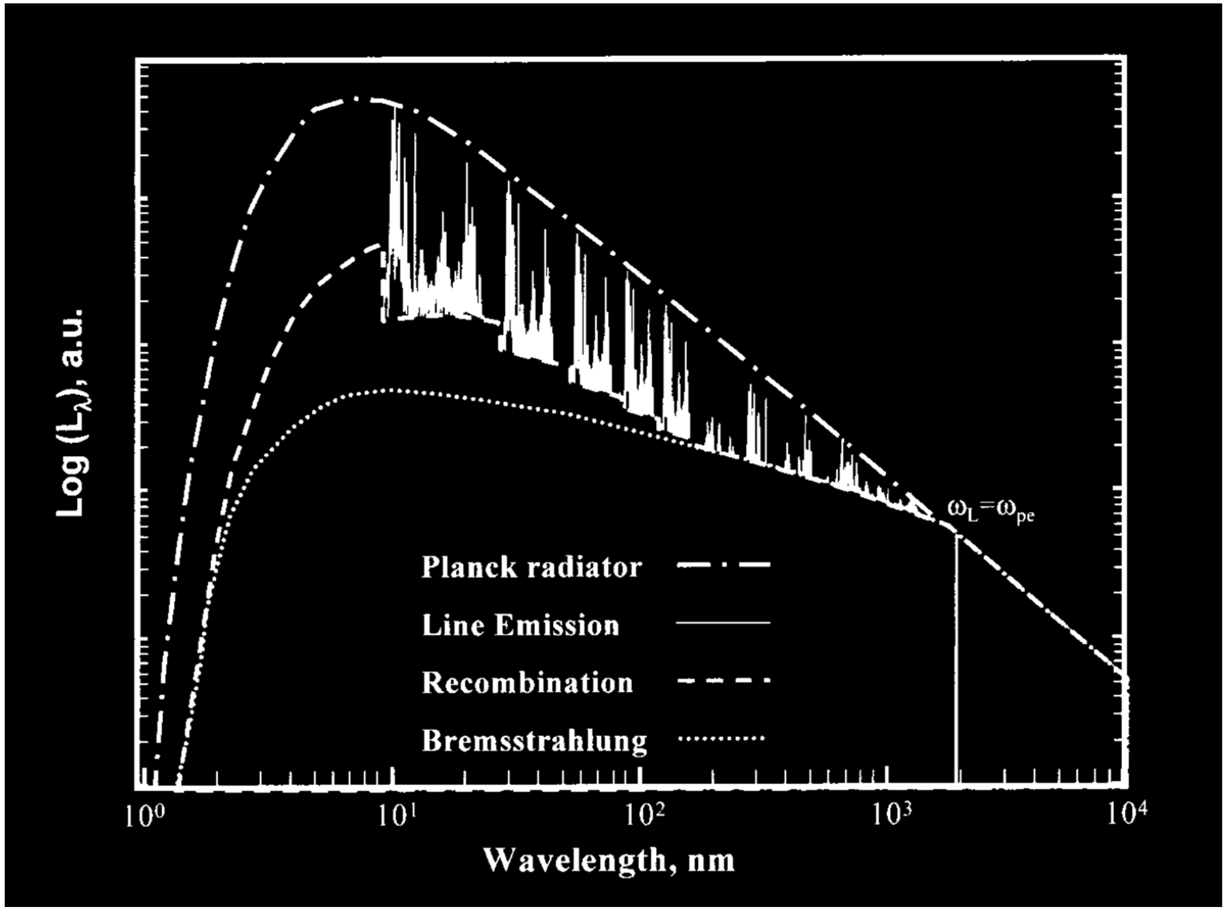
- The world practice demonstrates a wide scattering of experimental data: from CE = 0.03% to CE = 0.6-0.8%.
- In the Ioffe, tentative experiments with this type of the source had yielded CE = 0.05-0.1%.
- Theoretical limit for the equilibrium plasma (Plank's radiator) – 1.5%.

Several different approaches to the problem can be considered:

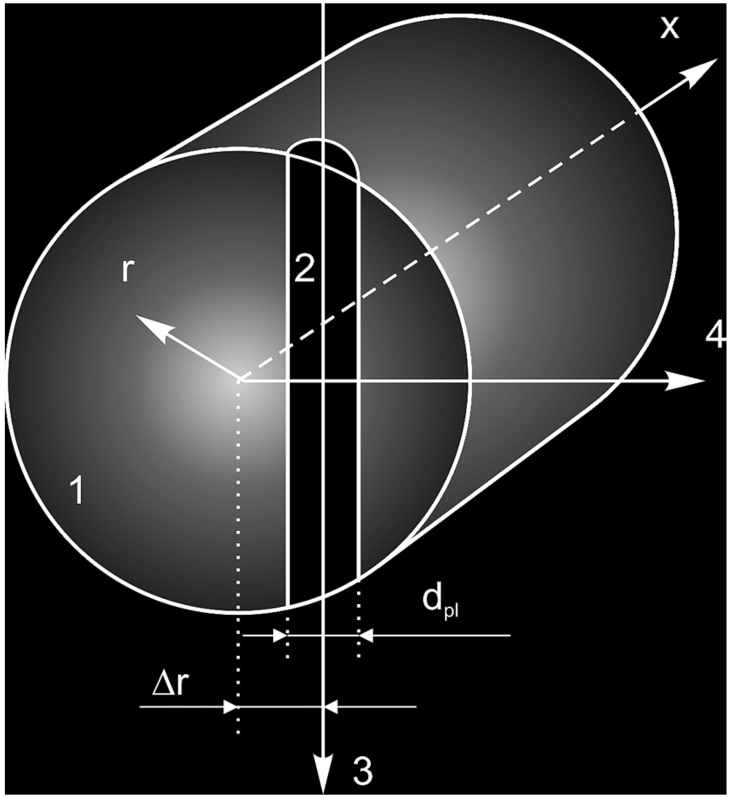
1. Control of the laser radiation intensity in time using various time scenarios.



2. Proper choice of the gas target density (increase of $n_e n_i$-product, approach to in-band black body conditions).



3. Proper positioning of the laser beam axis with respect to that of the target jet to decrease EUV re-absorption in the peripherical neutral gas.



One more optimization possibility exists. It originates from the fact that too long time is expended on the 1st ionization of the neutral target gas when IR lasers are used for the plasma ignition.

A numerical estimation of time expended on the 1st ionization of the target gas

Let us consider a very simplified model:

- Target gas is Xe at $n_a = 10^{18}$ cm^{-3} (typical for the jets);
- Nd:YAG laser, $\lambda = 1.06$ µm, $I_{las} = const = 10^{12}$ W/cm^2 at the focus, $\tau_{las} = 30$ ns;
- no loss mechanisms for electron/ion population nor for electron energy are taken into consideration.

Multiphoton ionization phase

In the neutral gas, at the very beginning of the ionization phase, there are no ionization mechanisms but the nonlinear multiphoton effect:

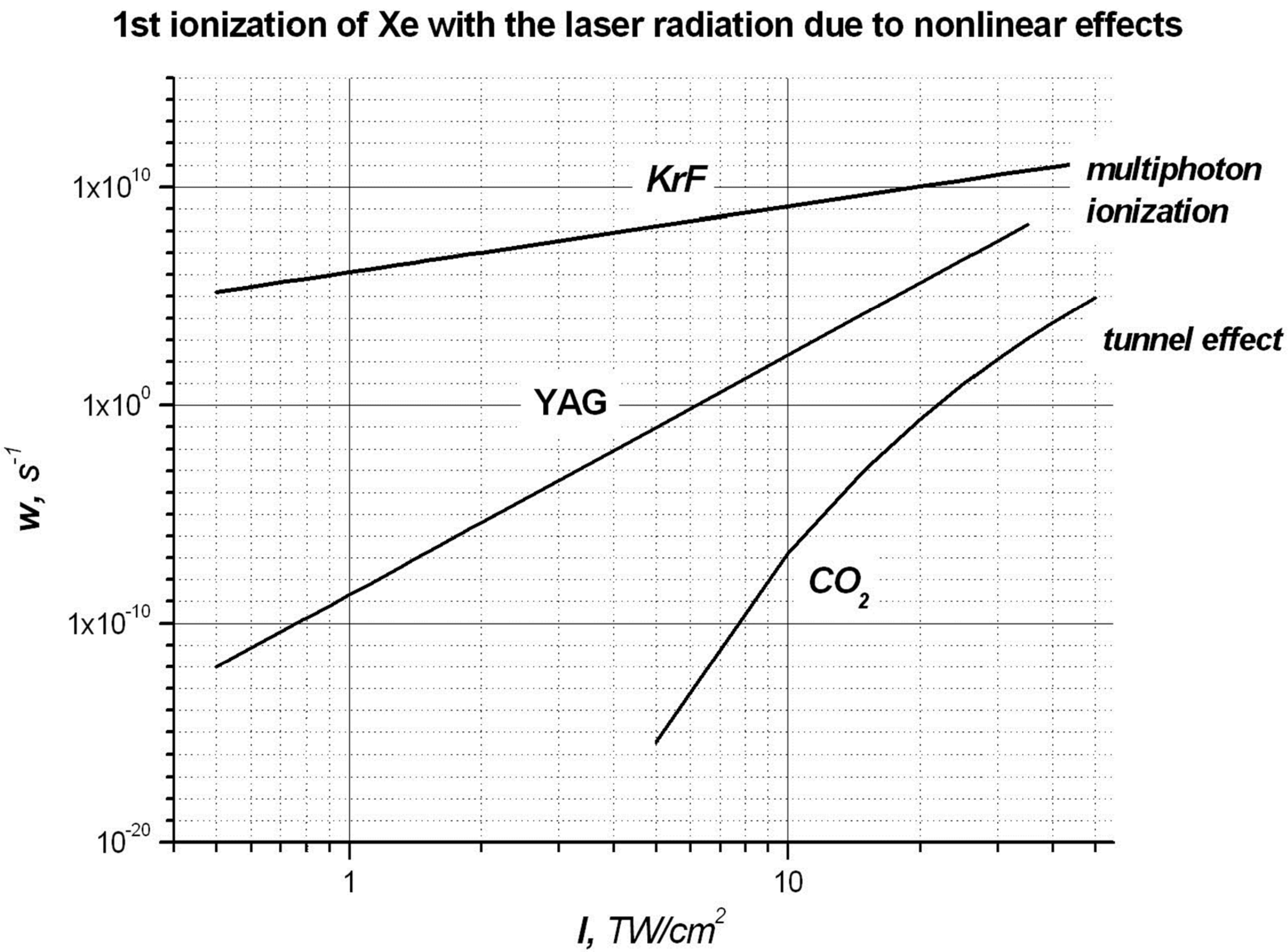
$$w_{mph} = \left(\frac{4\pi\hbar}{U_i}\right)^{k-1} \left(\frac{I_{las}}{\hbar\omega}\sigma_{ph,1}\right)^{k}$$, where

$k = \frac{U_i}{\hbar\omega} + 1$ – number of photons necessary to produce the ionization

For Xe (U_i = 12.1 eV):

at IR ionization ($h\nu$ = 1.17 eV), k = 11;

at UV ionization ($h\nu$ = 5 eV), k = 3 (even 2 if the resonance ionization is taken into account).


1st ionization of Xe with the laser radiation due to nonlinear effects
1x10^10
1x10^0
1x10^-10
10^-20
w, s^-1
1
10
I, TW/cm^2
KrF
YAG
CO2
multiphoton ionization
tunnel effect

For the conditions accepted, multiphoton ionization rate is $w_{mph} \sim 3\times10^{-9}$ s^{-1}.

At n_a = 10^{18} cm^{-3}, for an initial period, say 5 ns, only single photoelectrons can be born inside volume of the laser focus.

Collisional phase

Since free electrons have emerged, subsequent ionization will be realized by means of electron impact.

Each ionization interaction, $e + a \Rightarrow i + 2e$, doubles the electron population. About $\log_2 (10^{17}\text{-}10^{18}) \approx$ 55-60 duplications must happen for the 1st ionization to be completed.

A time period should pass between two ionization acts for the electron to accumulate the ionization energy. This time is:

$$\tau_i = \frac{U_i}{E_{e,osc}} \tau_{ea}$$

$$\tau_i = \frac{U_i m_e c \omega^2}{4e^2 I_{las}} \times \frac{1}{n_a \sigma_{ea} < V_e >}$$

At U_i = 12.1 eV, $n_a = 10^{18}$ cm^{-3} and I_{las} = 1 TW/cm^2,

$\tau_i \approx 0.2$ ns.

Thus, the 1st ionization takes about 10-15 ns – approximately a half of the 30ns pulse!

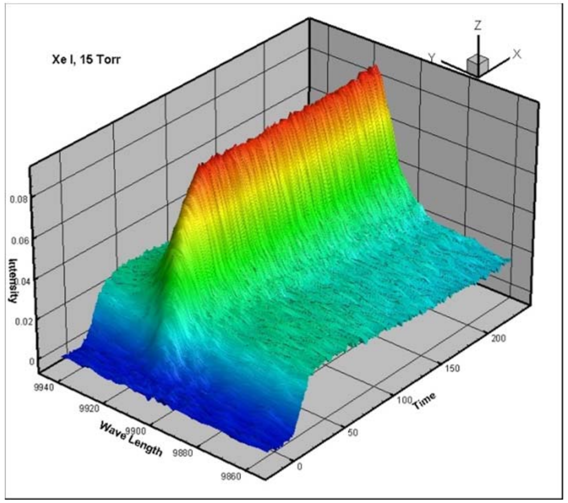
During this period, the laser beam absorption is very weak, so the beam energy is expended in vain.

Only at the second half of the laser pulse, after completion of remaining 9 ionizations (up to Xe^{+10}), one can expect appearance of the EUV-emission.

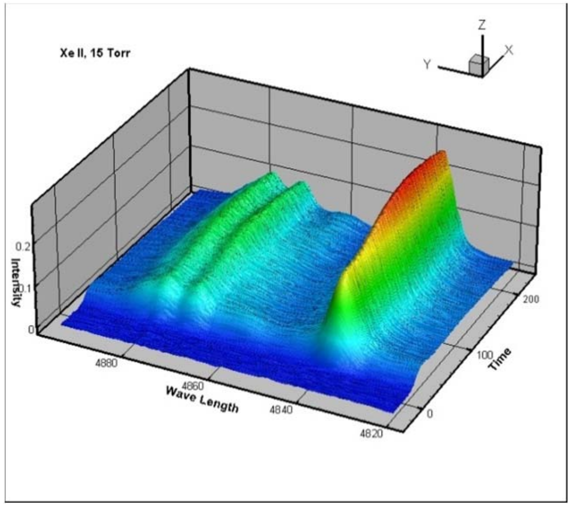
Probably, this is an essential explanation of low CE values and their wide scattering from one experiment to another?

Spectroscopical measurements

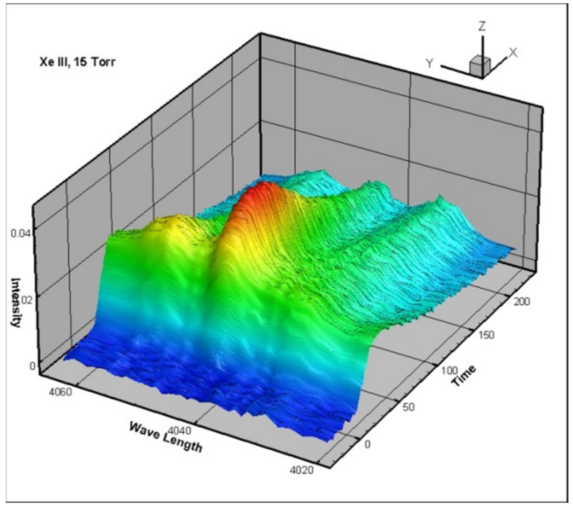
Results obtained from such a simplified model must be confirmed experimentally.



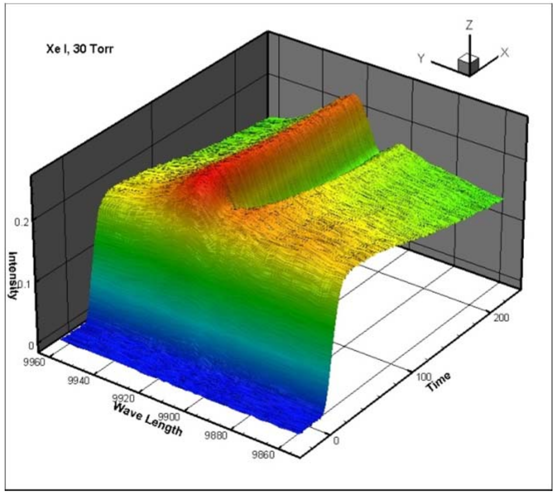
Xe I, 9912 Å, 5.3×10^{17} cm^{-3}



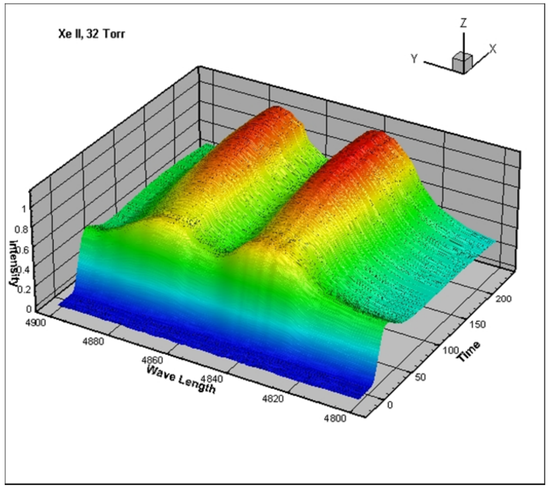
Xe II, 4838 Å, 5.3×10^{17} cm^{-3}



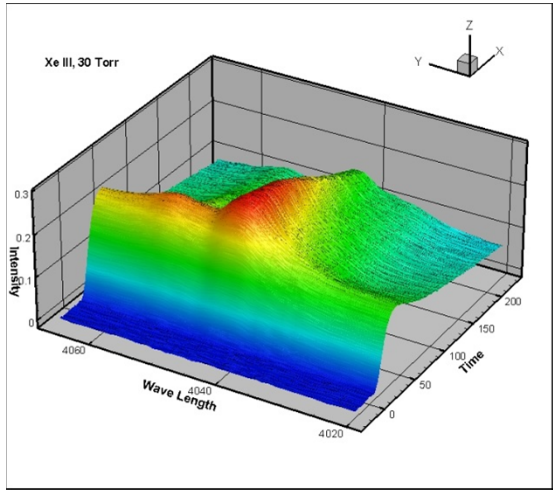
Xe III, 4044 Å, 5.3×10^{17} cm^{-3}



Xe I, 9912 Å, 1.1×10^{18} cm^{-3}

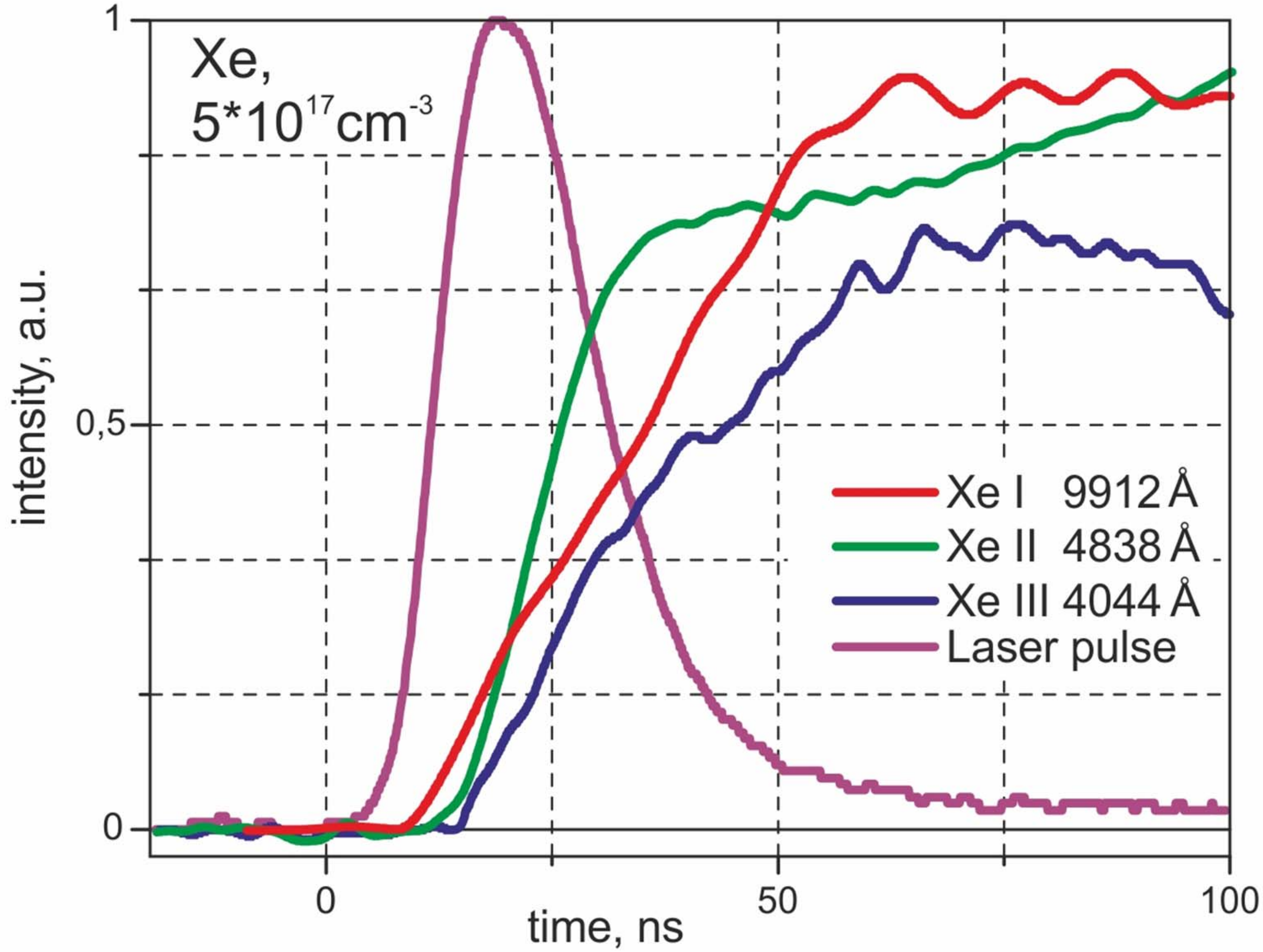


Xe II, 4838 Å, 1.1×10^{18} cm^{-3}



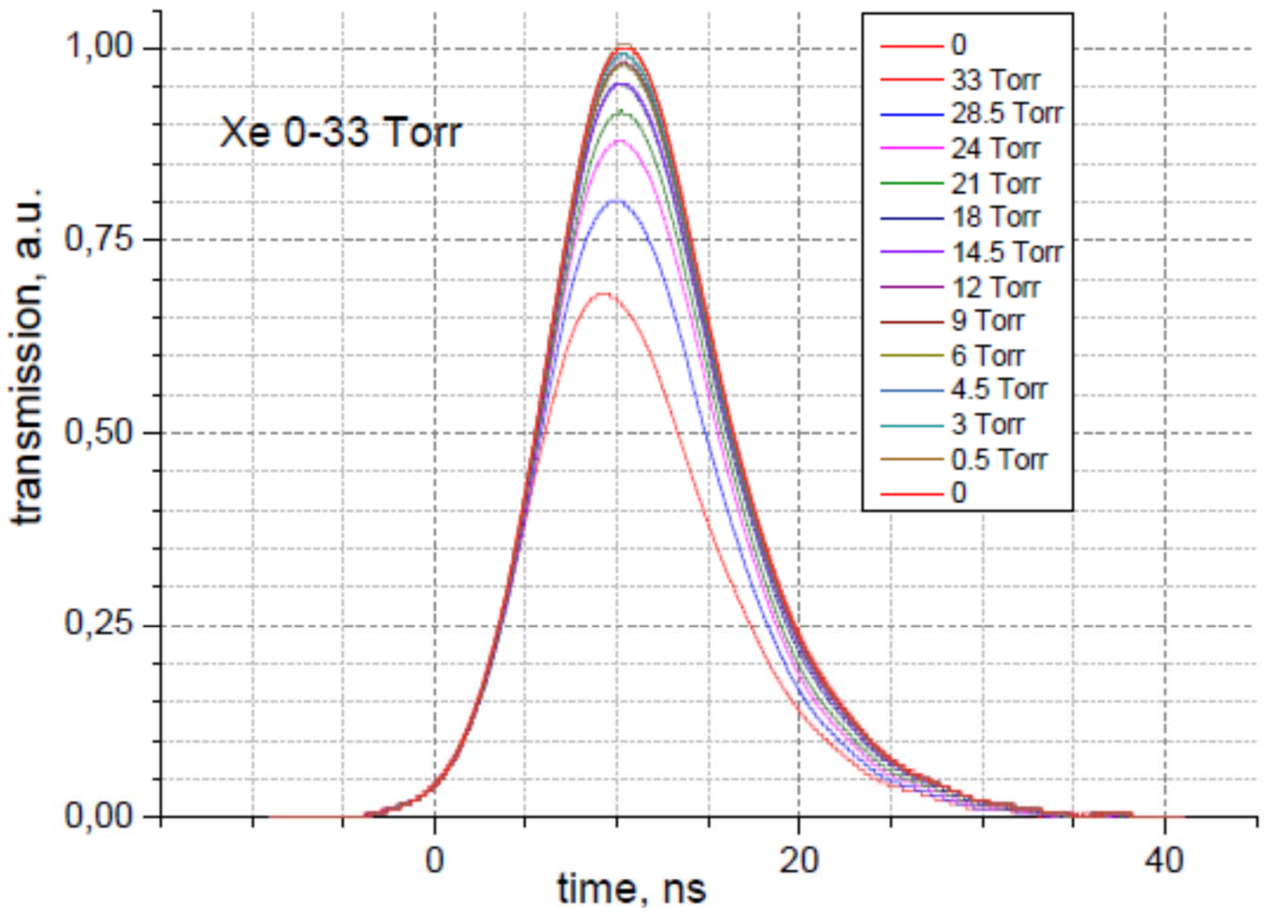
Xe III, 4044 Å, 1.1×10^{18} cm^{-3}

Interesting features: plasma opacity and self-absorption of Xe I spectral line at higher density.



Delay between the laser pulse front and that of XeI/XeII emission amounts to 7-16 ns that is in a reasonable agreement with the numerical estimate.

Absorption of the laser light by the plasma



Absorption coefficient, *μ*:

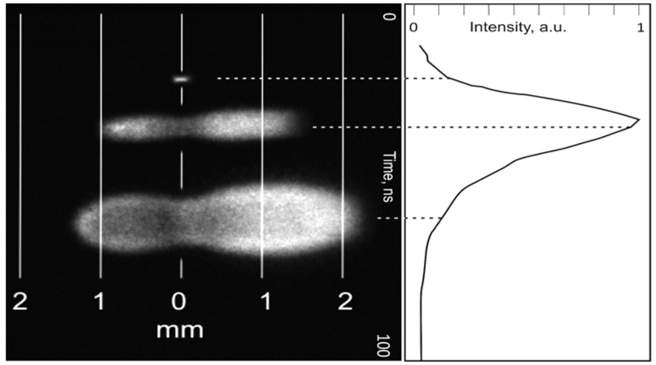
$$\mu = \frac{4\pi e^2}{m_e c}\frac{n_e \nu_{ei}}{\omega^2} = \frac{4\pi e^2}{m_e c}\frac{n_e n_i \langle \sigma_{ei} V_e \rangle}{\omega^2} =$$

$$\frac{16\pi^2 e^6}{(3m_e)^{3/2} c} L_C \frac{Z^3 n_i^2}{\omega^2 (k_B T_e)^{3/2}}$$

From the measured momentary values of the laser light transmission and the plasma length, a combination of Z and Te

$$\frac{Z}{\sqrt{T_{e,eV}}} = \sqrt[3]{\frac{\mu}{0.49 n^2_{i,10^{18}\,cm^{-3}}}}$$

is easily derived.



Plasma length measurement

At maximum of the laser pulse (14th nanosecond from the laser pulse start):

$n_i = 0.85\times10^{18}$ cm^{-3};

absorption – 12%;

measured laser plasma length – 2 mm;

$\mu = 0.53$;

at supposed T_e = 25-30 eV, Z_{eff} = 5-6.

This quantitative experimental result evidences the fact that ions Xe^{+10} and EUV emission should appear well after the middle of the pulse.

Proposed optimization method

Nd:YAG laser plasma needs a pre-ionization.

2-photon resonance ionization of Xe gas by KrF excimer laser radiation (λ = 248 nm) is a very effective mechanism. At 1 TW/cm^2, all Xe atoms of the target are expected to be ionized during several first nanoseconds of the pulse.

So, an idea emerges to combine favourable features of both the lasers – to realize fast pre-ionization of the Xe target by means of the KrF excimer laser and then to heat and maintain the plasma with the aid of the IR laser (because the latter is by 18 times more effective ($\sim \lambda^2$) for collisional mechanisms).