Short Soft X-Ray Sources

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Abstract

We report on the characterization of pulsed soft X-rays emitted from laser-produced plasma. The plasma was generated by 40, 80 and 120 mJ laser energies provided by a pulsed KrF excimer laser focused on pure Si, Cu and Ta targets. The utilized detector was a very sensitive Faraday cup which opportunely biased was able to record time resolved signals of X-rays and to estimate their energy. The found X-rays energy values were compared with the ion temperature of the plasma obtained by fitting the time resolved ion current signals with a shifted Maxwell-Boltzmann velocity distribution. The results showed that the laser produced Ta plasma induced bunch of X-rays having in average the highest energy values and it was also characterized by ion temperature higher than the ones of the laser produced Si and Cu plasmas.

INTRODUCTION

Conventional pulsed X-rays sources are easily realizable in vacuum chambers by high voltage breakdown using fast capacitors as energy storage. Instead, the production of soft X-rays, having energy in the range of few hundreds of eV, is very difficult to obtain by conventional methods. Such X-rays are suitable for ultra-short exposure and to improve the contrast and the spatial resolution of the images [1]. Beside, an important biological application of soft X-rays consists to improve the potentiality on studying of the sequencing of DNA [2-4].

Laser-produced plasmas induced by pulsed laser ablation (PLA) of solid targets offers the possibility to generate easily soft X-rays [5-8]. The efficiency on the production of X-rays bunches and their emission spectrum depends on many factors such as the laser incident energy, the characteristic of the focused beam, the laser wavelength, the laser pulse duration and the atomic number of the target. In particular, the short wavelength of excimer lasers is useful on the production of plasmas characterized by high density and high temperature values which makes the laser induced plasma an innovative media for the production of X-rays bunches [9, 10].

In this work, we report on the results concerning the emission of soft X-rays induced by laser plasmas from three metal targets of different atomic weight. The diagnostic device was a very sensitivity Faraday cup which, working as X-rays diode, was able to catch on X-ray signals and to estimate the energy in the range from near extreme ultraviolet (EUV) to soft X-rays.

EXPERIMENTAL APPARATUS

The interaction chamber

All the measurements were performed in a vacuum stainless-steel chamber pumped up to 10^{-7} mbar pressure. Fig. 1 shows a sketch of the interaction chamber (IC) equipped by a drift tube (DT). In this experiment the used laser was an excimer KrF of 248 nm laser wavelength, operating with laser pulses of 23 ns FWHM and energies of 40, 80 and 120 mJ. The laser beam was focused on the target by a 15 cm focal length forming a spot dimension of about 0.01 cm^2, with a resulting irradiance of

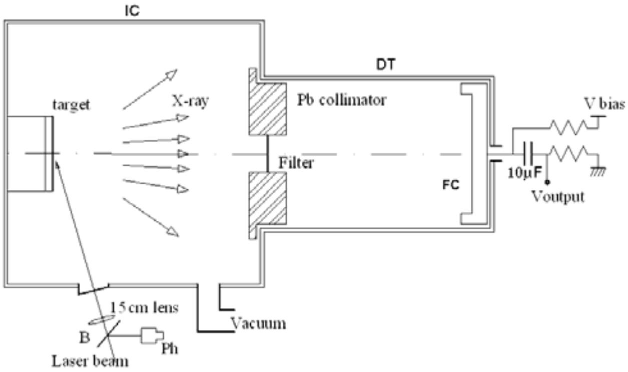

Fig. 1. Experimental set-up. IC: interaction chamber; DT: drift tube; B: beam splitter; Ph: photodiode; FC: Faraday cup.

1.7, 3.5 and 5.2x 10^8 Wcm^{-2}. The incident angle of the laser beam respect to the normal of the target surface was 70° in order to limit the interaction of laser beam with the plasma. A beam splitter (B), located outside the apparatus, sent about the 5% of the laser beam energy to a fast Hamamatsu R1328U-02 photodiode (Ph) connected to a digitizing oscilloscope LeCroy 422, 2 GS/s. In this way it was possible to record the laser waveform which was also used as trigger to measure the signals of the diagnostic device.
Three different targets were utilised, Si (14), Cu (29) and Ta (73) having a purity of 99.99%.

The diagnostic system

The characterization of the X-rays radiation emitted by laser-produced plasma was performed utilising a home made Faraday cup (FC) which worked as X-rays diode. The FC was composed by an aluminium collector of 80 mm in diameter and it was placed inside the DT at a distance of 50 cm from the plasma source (target). To decoupling the FC circuit from the bias voltage a separating 10 μF capacitor was applied, Fig. 1. The cup signal was terminated on a 50 Ω load resistor connected to the oscilloscope.

The advantage to use this device consists to the possibility to diagnostic the X-rays radiation emitted from the plasma and the corresponding ion temperature.

The X-rays, emitted from the laser plasma, strikes the FC collector and the internal walls of the chamber inducing photoelectron production. Without any bias, the FC signal results to be positive in amplitude. This behaviour points out that, in this case, the photo-peak, ascribed to the photoelectron emission from the FC, is predominant with respect to the signal of the electron arriving from the chamber walls. If we apply a positive bias, the FC signal is modified. In this case the photo-peak diminishes, while the chamber wall electrons are attracted inducing a negative signal just after a few nanoseconds. Fig. 2 shows the typical waveforms of the laser pulse and the FC signal. This last is provided by a bias voltage of +25 V. We can observe that the

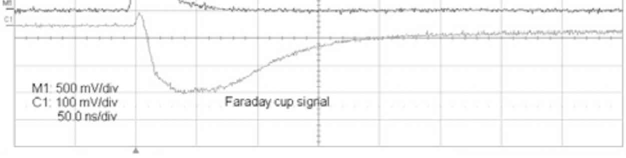

Fig. 2. Typical waveforms of the laser pulse and FC signal obtained from laser induced Ta plasma with 40 mJ laser energy. The FC signal was obtained by a bias voltage of +25 V.

FC positive signal is delayed of about 10 ns with respect to the beginning of the laser pulse. This time is necessary during the plasma formation for improving the plasma density and to induce the X-rays emission.

For the characterization of the photo-peak induced by X-rays, we have applied different positive bias voltage to the collector. Nevertheless, the signal of the electrons deriving from the chamber wall affects these measurements and in order to overcome this problem, we utilized a bored Pb collimator placed in front the FC. In this way, the most part of the electrons generated from the chamber walls was stopped and the discrepancy between the photo-peak signal and the signal of the electrons of the chamber walls was improved.

RESULTS AND DISCUSSION

Fig. 3 shows the behaviour, on the FC bias voltage, of the maximum amplitude values of the photo-peak signal ascribed to the electrons that backward the FC (out-electron) and the maximum amplitude values of the negative signals corresponding to the electrons that forward the FC (in-electrons) utilizing three different Pb collimators of 15, 10, and 5 mm in diameter. The results are obtained for negative and positive bias voltage up to 900 V, with the laser induced Cu plasma with a laser energy of 80 mJ. It is possible to observe that the discrepancy on the ratio of out/in-electrons signals increases as the collimator diameter decreases.

To characterize and compare the photo-peak signal induced by X-rays of the three different plasmas, we utilised the collimator of 10 mm in diameter in order to not reduce too much the fraction of X-ray radiation which arrived to the collector. Fig. 4 reports the data plot of the maximum value of the photo-peak amplitude on positive bias voltage which results as a trapping voltage for the electrons extracted from the FC. Increasing the trapping voltage, the photo-peak amplitude decreases and the resulting electron current is characterized by a minimum value attending at a bias voltage of +800 V. Nevertheless, just at about +200 V the electron current corresponds to about 1% with respect to the current obtained without any trapping voltage. This result evidences that the most part of electrons has got an energy up to about 200 eV.

After this, we placed an aluminium filter of 0.2 μm thickness, deposited on 1 μm of C_3H_6, in front of the hole of Pb collimator. The resulting filter is sensitive to the transmission of X-ray radiation of energy up to about 1.2 keV. Fig. 5 shows an example of X-rays signal with the use of the filter, obtained with a laser beam of 40 mJ of energy with

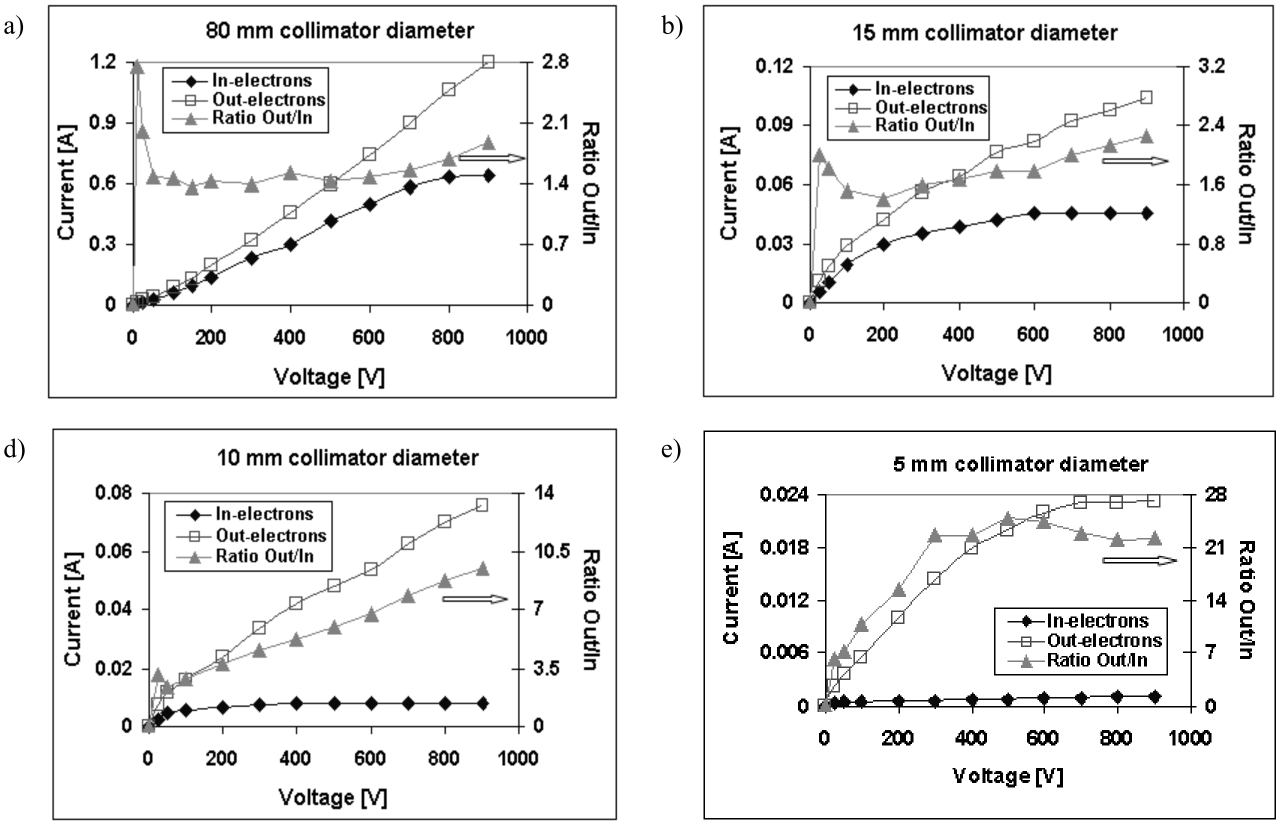

Fig. 3. Data of the maximum amplitude values of the photo-peak signal ascribed to the electrons that backward the FC (out-electron) and the maximum amplitude values of the negative signals corresponding to the electrons that forward the FC (in-electrons), obtained from the laser-induced Cu plasma, with a laser energy of 80mJ. The data are reported for the following cases: a) without any collimator; b) for Pb collimator of 15 mm in diameter; c) for Pb collimator of 10 mm in diameter; d) for Pb collimator of 5 mm in diameter.

the Cu target.

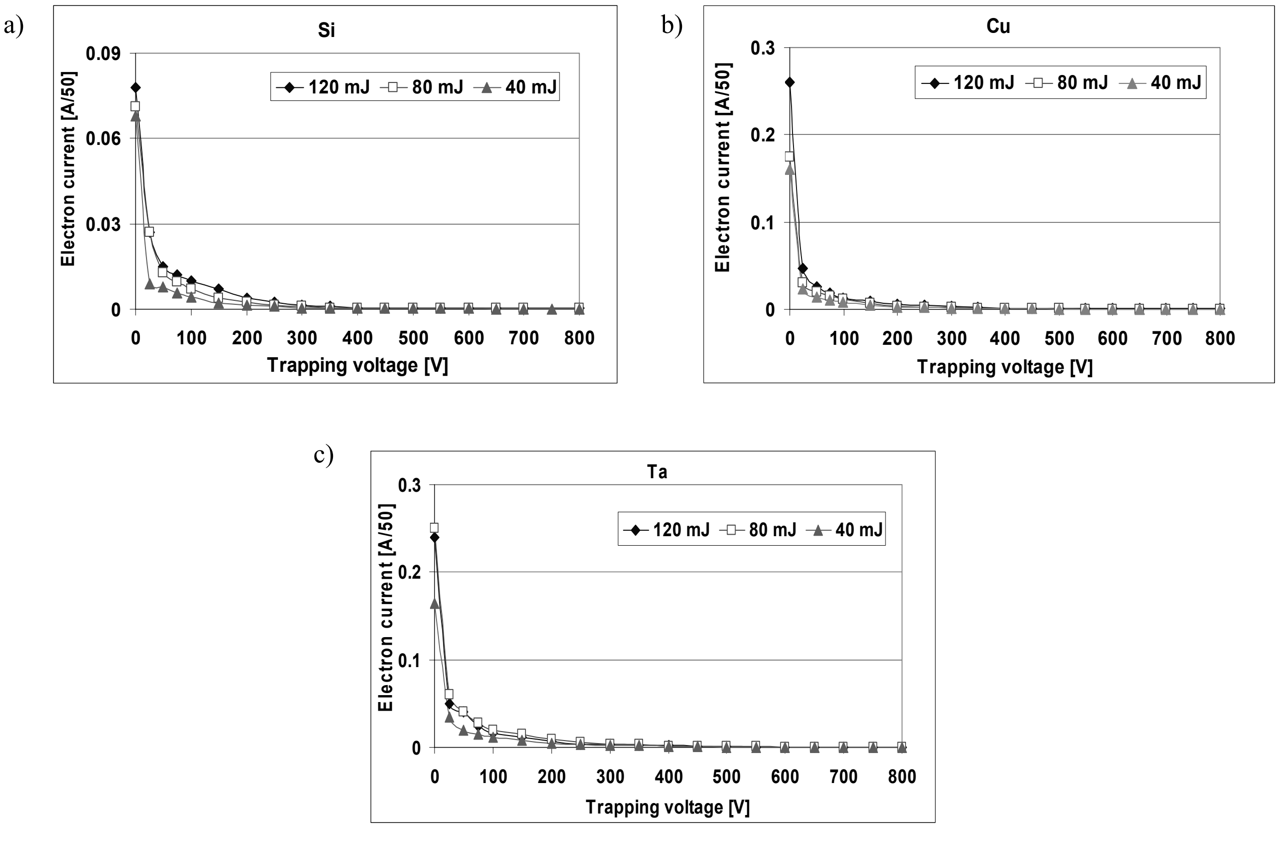

Fig. 4. Extracted electron current on trapping voltage obtained for the different plasmas.

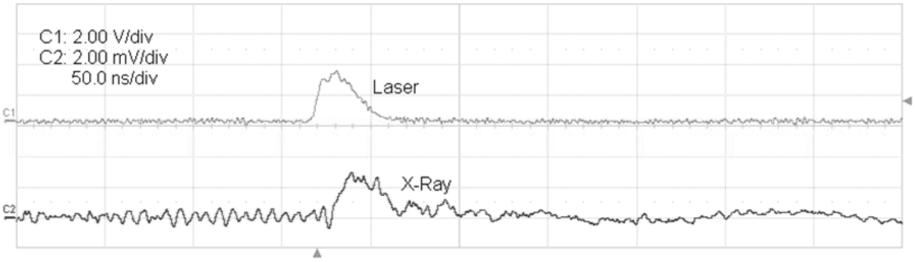

Fig. 5. X-ray waveform with the application of the filter for the laser energy of 40 mJ and Cu plasma.

By recording the photo-peak signal with and without the filter and along to the characteristic of the filter transmission [11], we have determined the upper average energy of the X-rays bunch. The results for the different targets and the laser energies are reported in the Table 1. As it is possible to observe, the laser-induced Ta plasma generated X-rays radiation with energy having an upper average value higher than the X-rays radiation obtained from Si and Cu plasmas.

In the same table, we also report the extracted electron charge calculated by the photo-peak area with the FC biased at -900 V and 80 mJ laser energy. The laser produced Ta plasma is responsible of an extracted charge of 7 nC against to 2 nC for the Si plasma and 5 nC for Cu plasma. This means that the Ta plasma induced soft X-rays of a more energetic and intense bunch than the other two plasmas.

The results was compared with the ones concerning to the ion temperature of the plasmas. For this goal we recorded the time-resolved ion current by setting the oscilloscope at long time of flight, i.e. 10 µs, with the FC biased at -500 V. Due to the collisions between ions during the initial phase of the plasma expansion, a shifted Maxwell–Boltzmann distribution (MBD) characterizes the velocity distribution of ions far from the target, where the ion charge-states are frozen and ions freely drift into the vacuum [12]. The time-resolved ion current signals are well described by the following rearranged MBD:

$$j_{IC}(L,t) \propto t^{-5} \exp[-\beta^2 (L/t - u)^2]$$

where, L is the target-cup distance, u is the centre-of-mass velocity and

$$\beta^2 = \frac{m}{2kT}$$

where m is the mass of ion, k is the Boltzmann constant and T is related to the ion temperature. The fit of the experimental data by the Eq. (1) gives information about the temperature and the centre of mass velocity of ions at the different irradiation conditions.

The data reported in the Table 1, confirm that the laser-induced Ta plasma is characterized by an ion temperature higher than the other two plasmas.

The obtained results can be ascribed exclusively to the different processes involved during the interaction of the laser pulse with the target and plasma plume which induce the production of soft X-rays bunches of different energy range. Beside, inverse bremsstrahlung, photoionization mechanisms as well as the presence of tree body recombi-

	Laser Energy (mJ)	**Extracted charge at -900 V (nC)**	**Soft X-ray energy (eV) (everage energy up to)**	**Ion Temperature (eV)**
Si	**120**		**175**	**22**
	80	**2**	**170**	**17**
	40		**160**	**16**
Cu	**120**		**178**	**50**
	80	**5**	**172**	**44**
	40		**166**	**36**
Ta	**120**		**194**	**82**
	80	**7**	**188**	**74**
	40		**182**	**62**

Table I: Characteristics of the laser-induced plasmas and soft X-rays for the different targets and the laser energies.

nation processes are also responsible of plasma characterized by ions of different temperatures and of different charge state abundance [13].

CONCLUSIONS

In this work, we have characterized the X-ray radiation obtained from laser-produced plasma by utilising laser beam of moderate intensities ($<10^9$ Wcm^{-2}). A fast FC, appropriately biased, was a suitable device for the characterization of photo-peak induced by soft X-rays as well as for the diagnostic of the ion component of the plasma. By utilizing a dedicated X-ray filter we have further estimated the average upper value of X-rays energy which resulted to be higher for the Ta plasma. The time resolved current of the ion component of the plasma showed that Ta plasma is also characterized by a high temperature than the Cu and Si plasma.

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