Soft x-ray generation by a tabletop Nd:YAG/glass laser system

2006 J. Phys.: Condens. Matter 18 S2039

(http://iopscience.iop.org/0953-8984/18/33/S19)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **18** (2006) S2039–S2044 doi:10.1088/0953-8984/18/33/S19

Soft x-ray generation by a tabletop Nd:YAG/glass laser system

S Martellucci[1], **C Bellecci**[1], **M Francucci**[1], **P Gaudio**[1], **M Richetta**[1], **D Toscano**[1], **A Rydzy**[1], **M Gelfusa**[1] **and P Ciuffa**[2]

[1] Department of 'Ingegneria dell'Impresa', Engineering Faculty, University of Rome 'Tor Vergata', Via del Politecnico 1, 00133 Roma, Italy

[2] Elettronica s.p.a., Technology and Processing Department, 00131 Roma, Italy

E-mail: richetta@uniroma2.it

Received 31 January 2006, in final form 6 April 2006

Published 4 August 2006

Online at stacks.iop.org/JPhysCM/18/S2039

Abstract

The advent and development of ultra-intense tabletop laser systems has played a significant role in recent decades thanks to the wide number of applications and studies in which these systems were demonstrated to be appropriate. Among these, one of the main applications of ultra-intense radiation is generation of plasma by solid, liquid or gaseous targets. The by-product of x-radiation found many different applications such as spectroscopy, imaging, microlithography, microscopy, radiographies (in particular of biological samples), radiation–matter interaction, fundamental plasma parameter determination, astrophysics, inertial confinement fusion, high energy physics, quantum electrodynamics, and many others.

In the following a brief description of our tabletop Nd:YAG/glass apparatus (facility of the Quantum Electronic and Plasma Laboratory of the University of Rome 'Tor Vergata'), together with x-ray conversion efficiency studies for different targets, are reported.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Laser–plasma interaction is currently a subject of large and growing interest [1] for many concomitant reasons: (a) availability of laser systems with unique properties [2, 3]; (b) powerful computing means; (c) inertial confinement [4, 5]; (d) perspectives of several new possible applications [5, 6]. The laser–plasma field is now dividing into many branches concerning astrophysics [6–9], inertial confinement, quantum electrodynamics and high energy physics [10–12], atomic [13] and solid state physics [14], x-ray spectroscopy [15–20], radiographies [21] and imaging [22, 23].

As is well known, high temperature plasma can be generated by focusing intense laser pulses over different targets. Pulse intensity should reach or exceed the threshold for plasma formation, typically about 10^7 W cm^{-2}. Intense laser light is initially absorbed in a thin material layer (of the order of the skin depth), which is heated, melted and vaporized; then, an expanding plasma cloud is generated in the target vicinity. Working with pulse width longer than 10 ps, the plasma expansion timescale is shortened, then pulse duration and hydrodynamic effects become important. So a gradient in the plasma density develops and laser energy can be absorbed by the plasma as it propagates towards the target until it reaches the critical surface, where plasma frequency equals laser frequency and characterizes local charge oscillations in the plasma, proportional to the square root of the electron density.

Laser induced plasma is a good radiator and visible, UV and x-radiation can be emitted by such hot plasma due to line transitions, radiative recombinations and bremsstrahlung radiation [24–29]. Radiative properties represent a classical example of non-interfering probe. Much important information can be obtained directly from plasma by observing its emission spectrum as ionization balance, density, temperature and chemical composition. Radiative properties are therefore a powerful diagnostic of the plasma state. Such consideration can explain the increasing interest addressed to radiative properties of hot and dense matter. X-ray spectroscopy of multicharged ions appears as one of the most powerful techniques available for high temperature plasma investigation. For example, the x-ray emission spectrum from He-like ions has been used as a diagnostic for several types of hot plasmas [30–33]. These plasmas can be also laser induced and then exploited for several applications.

In the following we report a brief description of our experimental set-up, based on a Nd:YAG/glass laser source (section 2). In section 3, some results relevant to conversion efficiency for different solid targets are reported. Finally, section 4 contains the main conclusions we drew during this part of the experimental activities.

2. Apparatus description

The experimental facility applied for the generation of soft-X rays is schematically reported in figure 1. Its main constituents are a Nd:YAG/glass laser source in MOPA configuration, a lens system focusing the beam on the target, a double stage vacuum chamber where plasma is generated, a vacuum pump system linked to the chamber, some detectors, a spherical crystal based spectrometer for radiation analysis, an oscilloscope outside the vacuum chamber, a fast photodiode put right next to the oscillator, and others.

The source is a non-commercial one. It is composed by a Nd:YAG oscillator, based on the Q-switched technique, followed by four amplification stages. The first two are also Nd:YAG, while the last are Nd:glass. The radiation emerging at the end of the whole chain has the following main features:

(1) $\lambda = 1064$ nm;
(2) $\tau = 15$ ns;
(3) $E_p = 36$ mJ (pulse energy);
(4) TEM_{00};
(5) P-polarized;
(6) pulse repetition rate (PRR) = 10 Hz.

The radiation enters the chamber through a glass flange. Here it is focused over the target (a thin strip a few microns thick), which is mounted on a rotating support with an incidence angle of 45°, to minimize debris projection near the target.

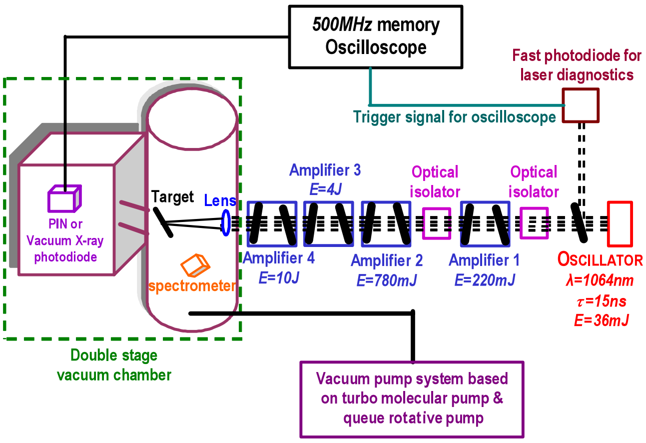

Figure 1. 'Tor Vergata' ultra-intense Nd:YAG/glass laser facility for soft x-ray generation by laser induced plasma.

Figure 2. Photograph of the first stage of the vacuum chamber.

To analyse soft x-rays, inside the chamber a spherical mica crystal spectrometer is located (see figure 2). This spectrometer, achieved at the *Multicharged Ions Spectra Data Center* of VNIIFTRI Institute of Moscow thanks to Drs A Ya Faenov and T A Pikuz, can cover a spectral region ranging from 632 eV to 10 keV and combines the focusing properties typical of a spherical mirror with Bragg diffraction typical of a crystal.

3. IR–soft x-ray conversion efficiency

In this section a study of the x-signal (V_x) detected by a pin diode is reported. In particular, we evaluated (a) the x-energy (E_x) emitted on the half solid angle, namely

$$E_x(in J) \cong 3.93 \frac{V_x}{R_L} \frac{\tau_x}{S_{\mathrm{XRD}}} \frac{d^2}{A_{\mathrm{esposta}}^{\mathrm{XRD}}} \frac{1}{T_f} \Rightarrow E_x \propto V_x$$

and (b) the conversion efficiency (η) from infrared laser to soft x-radiation, namely

$$\eta\ (\text{laser} \to \text{x-rays}) = \frac{E_x}{E_{\text{laser}}} \Rightarrow \eta(\text{IR} \to \text{x-rays}) = \frac{E_x}{E_{\text{IR}}}.$$

The analysed spectral region ranges between 1.3 and 1.55 keV (i.e. λ between 8 and 9.56 Å) and it was selected by an aluminium filter 40 μm thick. Its transmission coefficient is about 0.8%.

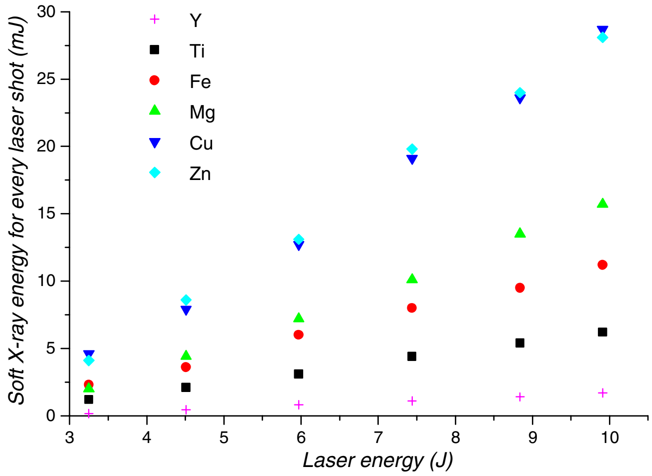

Figure 3. Soft x-ray energies versus laser energy (detected by PIN photodiode) for different targets.

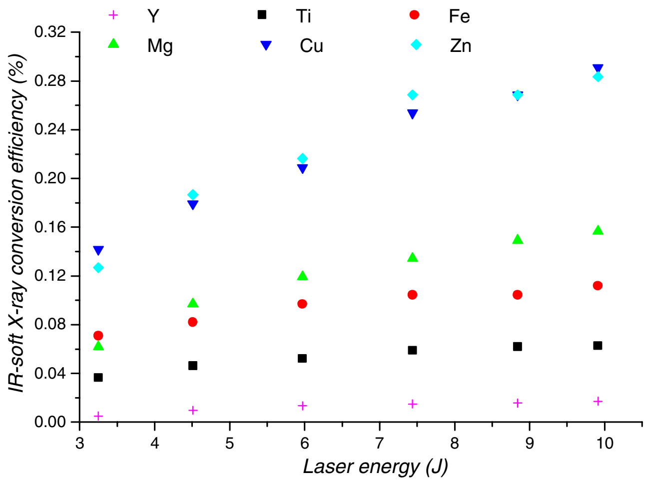

Figure 4. IR $\rightarrow$ soft x-ray conversion efficiency versus laser energy, for different solid targets.

The adopted solid targets were Mg, Ti, Fe, Cu, Zn, and Y.

For each measurement, the laser beam energy ranged between 3.25 and 9.91 J, corresponding to an intensity within the range 2.76×10^{12}–8.41×10^{12} W cm^{-2}. The obtained results are reported in figures 3–5.

4. Conclusion

In this paper, we discussed the IR x-ray conversion efficiency for six different solid targets interacting with the radiation emitted by our tabletop solid state laser source.

By the information that one can deduce from the results of the previous section, together with the help of the literature, it can be asserted that conversion efficiency

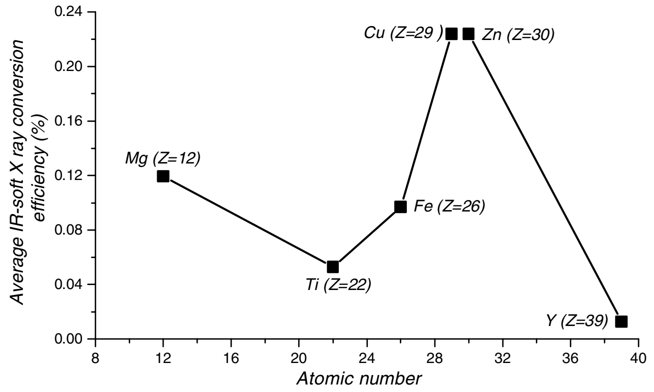

Figure 5. Average conversion efficiency versus atomic number for different solid targets (1.3 and 1.55 keV).

- depends on the type of target, since it is connected to the transition probability between levels involved in the x-ray emission,
- increases/decreases increasing/decreasing laser intensity over the target,
- depends on the soft x-ray spectral region and
- assumes the highest values for copper ($Z = 29$) and zinc ($Z = 30$), with almost the same mean value equal to $\eta \cong 0.22\%$.

From the above considerations, we can deduce that, within the spectral range taken into account, the IR–soft x-ray conversion efficiency is less than 1%. The remaining portion of laser energy is converted partially into VIS and UV radiation and mainly transformed into the heat necessary to warm up the target to plasma temperature, which for our source is around 10^6 °C.

References

[1] Kruer W L 1988 *Physics of Laser Plasma Interaction* (Redwood City, CA: Addison-Wesley)
[2] Perry M D and Morou G 1994 *Science* **264** 917
[3] Morou G, Barty J and Perry M D 1998 *Phys. Today* **51**
[4] Lindl J D 1995 *Phys. Plasmas* **2** 3933
[5] Hogan W *et al* 1994 *Energy from Inertial Fusion* (Vienna: IAEA)
[6] Turcu I C E and Dance J B 1998 *X ray From Laser Plasma: Generation and Applications* (London: Wiley)
[7] Remington A, Arnett D, Drake R P and Takabe H 1998 *Science* **284** 1488
[8] Remington A, Arnett D, Drake R P and Takabe H 2000 *Phys. Plasmas* **7** 1641
[9] Liang E P, Wilks S C and Tabak M 1998 *Phys. Rev. Lett.* **81** 4887
[10] Ledingham K W D and Norreys P A 1999 *Contemp. Phys.* **40** 367
[11] Tajima T and Dawson J M 1979 *Phys. Rev. Lett.* **43** 267
[12] Pukhov A, Sheng Z M and Meyer-ter-Vehn J 1999 *Phys. Fluids* **6** 2847
[13] Gavrila M 1992 *Adv. At. Mol. Opt. Phys. Suppl.* **1** 435
[14] Celliers P *et al* 2000 *Phys. Rev. Lett.* **84** 5564
[15] Fournier K B *et al* 2002 *J. Phys. B: At. Mol. Phys.* **35** 3347
[16] Skobelev I Yu *et al* 2002 *J. Exp. Theor. Phys.* **95** 421
[17] Fournier K B *et al* 2003 *J. Quant. Spectrosc. Radiat. Transfer* **81** 167
[18] Fournier K B *et al* 2003 *J. Phys. B: At. Mol. Opt. Phys.* **36** 3787
[19] Fournier K B *et al* 2004 *Phys. Rev.* E **70** 016406
[20] Faenov A Ya *et al* 2004 *JETP Lett.* **80** 730
[21] Reale L *et al* 2004 *Microsc. Res. Techn.* **64** 21
[22] Pikuz T *et al* 2004 *Proc. SPIE* **5196** 362
[23] Pikuz T *et al* 2004 *Laser Particle Beams* **22** 289

[24] Falkone R and Murname M 1986 *AIP Conf. Proc.* **147** 81

[25] Murname M, Kapteyn H C, Rosen M D and Falkone R 1991 *Science* **251** 531

[26] Giulietti D and Gizzi L A 1998 *La Rivista Nuovo Cimento* **21** 1

[27] Gizzi L A, Giulietti A, Willi O and Riley D 2000 *Phys. Rev.* E **62** 2721

[28] Gizzi L A, Cecchetti C A, Galimberti M, Giulietti A, Giulietti D, Labate L, Laville S and Tomassini P 2003 *Phys. Plasmas* **10** 4601

[29] Labate L, Cecchetti C A, Galimberti M, Giulietti A, Giulietti D and Gizzi L A 2005 *Phys. Plasmas* **12** 083101

[30] Kallne E, Kallne J and Pradhane AK 1983 *Phys. Rev.* A **28** 467

[31] Phillips K J, Keenan F P, Harra L K, McCann S M, Rachlew-Kallne E, Rice J E and Wilson M 1994 *J. Phys.* B **27** 1939

[32] Gabriel A H 1972 *Mon. Not. R. Astron. Soc.* **160** 99

[33] Kato T, Fujiwara T and Hanaoka Y 1998 *Astrophys. J.* **492** 822