Nuclear Instruments and Methods in Physics Research B xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Development of a compact laser-produced plasma soft X-ray source for radiobiology experiments

Daniel Adjei [a,f,*], Mesfin Getachew Ayele [a], Przemyslaw Wachulak [a], Andrzej Bartnik [a], Łukasz Wegrzynski [a], Henryk Fiedorowicz [a], Luděk Vyšín [b,c], Anna Wiechec [d], Janusz Lekki [d], Wojciech M. Kwiatek [d], Ladislav Pina [c], Marie Davídková [e], Libor Juha [b]

[a] Institute of Optoelectronics, Military University of Technology, 2, Kaliskiego Str., 00-908 Warsaw, Poland
[b] Institute of Physics, Czech Academy of Sciences, Na Slovance 2, 182 21 Prague 8, Czech Republic
[c] Faculty of Nuclear Sciences and Engineering Physics, Czech Technical University in Prague, Břehová 7, 115 19 Prague 1, Czech Republic
[d] Institute of Nuclear Physics, Polish Academy of Sciences, 152, Radzikowskiego Str., 31-342 Cracow, Poland
[e] Institute of Nuclear Physics, Czech Academy of Sciences, Řež, Czech Republic
[f] Radiation Protection Institute, Ghana Atomic Energy Commission, P.O. Box LG 80, Legon, Accra, Ghana

ARTICLE INFO

Article history:
Received 20 September 2014
Received in revised form 20 August 2015
Accepted 21 August 2015
Available online xxxx

Keywords:
Laser-produced plasma
Soft X-rays
Radiobiology
Gas puff target
Water window

ABSTRACT

A desk-top laser-produced plasma (LPP) source of soft X-rays (SXR) has been developed for radiobiology research. The source is based on a double-stream gas puff target, irradiated with the focused beam of a commercial Nd:YAG laser. The source has been optimized to get a maximum photon emission from LPP in the X-ray "water window" spectral wavelength range from 2.3 nm (i.e., an absorption edge of oxygen) to 4.4 nm (i.e., an absorption edge of carbon) (280–540 eV in photon energy units) by using argon gas-puff target and spectral filtering by free-standing thin foils. The present source delivers nanosecond pulses of soft X-rays at a fluence of about 4.2×10^3 photons/μm^2/pulse on a sample placed inside the vacuum chamber. In this paper, the source design, radiation output characterization measurements and initial irradiation experiments are described. The source can be useful in addressing observations related to biomolecular, cellular and organisms' sensitivity to pulsed radiation in the "water window", where carbon atoms absorb X-rays more strongly than the oxygen, mostly present in water. The combination of the SXR source and the radiobiology irradiation layout, reported in this article, make possible a systematic investigation of relationships between direct and indirect action of ionizing radiation, an increase of a local dose in carbon-rich compartments of the cell (e.g., lipid membranes), an experimental estimation of a particular role of the Auger effect (in particular in carbon atoms) in the damage to biological systems, and the study of ionization/excitation-density (LET – Linear Energy Transfer) and dose-rate effects in radiobiology.

1. Introduction

Ionizing radiation of various kind, e.g., gamma rays, X-rays, neutrons, energetic electrons, protons and atomic ions, is routinely used to understand the effects of ionizing radiation on organisms, biological cells and tissues, subcellular structures (organelles) and particular biomolecules for more than one century (see for example [1–3]). Those extensive studies revealed a dependence of an efficiency of producing biological damage on the radiation quality. It seems that, among all the kinds of ionizing radiation utilized in radiobiology, Soft X-rays (SXR) (0.3–30 nm) play a unique role (see for example [4–6]). It has been demonstrated by the use of characteristic X-rays of carbon-K (280 eV) and aluminium-K (1.5 keV) to induce DNA double strand breaks in yeast and Chinese hamster V79-4 cells [7–9]. Also, copper L-shell edge (0.9 keV) X-rays were used to investigate the radiation effects on mammalian cells. The biological damage produced by SXR radiation was found very often (but not always) more effective as compared with much harder X-rays and gamma rays (for a review see [4]). There are numerous important reasons for the systematic use of the SXR for radiobiology research at biomolecular and cellular level. Radiation of this kind interacts with matter mainly by photoelectric effect providing a photoelectron, initiating formation of secondary electrons by collisional ionizations, and a hole in an

* Corresponding author at: Institute of Optoelectronics, Military University of Technology, 2, Kaliskiego Str., 00-908 Warsaw, Poland.
E-mail address: nana.adjeidan@gmail.com (D. Adjei).

http://dx.doi.org/10.1016/j.nimb.2015.08.065
0168-583X/

electron shell of the atom providing low-energy electrons and highly charged ion by Auger processes. Typically, the range of the low-energy electrons generated in the above-mentioned processes is of the order of ~10 nm. Thus, a large portion of the SXR photon energy is deposited in the target area. So, the action of SXR photons is localized to target atoms. By tuning the wavelength of the radiation, we may enhance energy deposition in a certain element, e.g., in carbon when choosing wavelengths in the water window. This makes the use of SXR a useful method for investigating the mechanisms of radiation damage.

There are numerous sources of SXR including X-ray tubes (electron beam interacting with a solid target), synchrotrons, free-electron lasers, hot plasmas, both discharge and laser-produced, among others. Currently, biological effects of low-energy X-rays are studied using, mainly, monochromatic synchrotron radiation [2,5,6]. The synchrotrons, although state of the art facilities for cutting-edge experiments, offer limited accessibility, have high running and maintenance costs and are not a compact sources for laboratory use. They are or have, therefore, become national and increasingly international facilities and as such are not suitable for the wide-scale development of radiobiology studies. Therefore, for widespread of applications, it has become important to have laboratory based facilities with almost similar characteristics. Experimental laboratory sources of SXR radiation based on micro-focus X-ray tubes, delivering broadband radiation at energies up to 15 keV, or quasi-monochromatic radiation at 284 eV, 1.5 keV, 4.5 keV or 5.4 keV, have been useful for radiobiology studies [4,8–10]. However, these sources deliver radiation to the sample at a low dose rate, and thus a relatively long irradiation time is needed to induce measurable biological effects. Higher dose rates can be achieved with laser-produced plasma sources emitting high-intensity pulses of X-ray radiation [11,12]. However, only a few laser-produced plasma soft X-ray sources have been used in radiobiology studies so far.

The use of a laser plasma X-ray source in radiobiology experiments has been demonstrated by Hill et al. [13]. In the study they used the source developed at the Rutherford Appleton Laboratory (RAL) that was described in the Annual Reports of RAL (1999/2000) [14] and in the book by Turcu [15]. The source was also presented in the article by Turcu et al. [16]. Similarly, Shinohara et al. also studied the cytotoxic effects on cultured mouse L5178Y cells and its radiosensitive, XRCC4-deficient mutant M10 cells irradiated with single pulses of X-ray at energies ranging from a few tens of keV to 1 MeV [17]. The effect was consistent with the data obtained by conventional approaches. The use of SXR in the range of approximately 1.13–4.77 keV photon energies in a single pulse from a laser-produced plasma source driven with a high-pulsed-power laser facility – PALS, Czech Republic, irradiating xenon gas puff target to induce DNA single strand breaks (SSB) in plasmid DNA, has been demonstrated [18]. The laser plasma X-ray source that was used in the experiments described by Davídková et al. has been presented in the article published in 2004 [19]. The X-ray source driven with a femtosecond laser has also been used for this purpose [20]. Laser-driven soft X-ray lasers have also been used in the radiobiology research [21–23].

Laser produced plasma based on solid targets typically produce debris which may cause degradation to the optical elements of the system and the irradiated sample. The debris-free gas puff targets have successfully been used to eliminate such effects. Besides, the X-ray and EUV emissions for such source targets are relatively high.

In this study, a laser plasma source of soft X-rays based on a gas puff target, developed for radiobiology research, is described. Opposite to the source described by Davídková et al. [18], that was a single-shot X-ray source driven by a high-power laser, the source described here represents a compact, handy device. The present article reports on the development, characterization and initial radiobiology application of the laboratory LPP-SXR source.

2. Material and methods

2.1. Laser plasma X-ray source development

The Laser–Matter Interaction group of the Institute of Optoelectronics MUT has developed a laser-plasma laboratory EUV and X-ray sources based on a gas puff-target for different applications. Among them, for examples, were production of efficient EUV [24] and X-ray [25] emissions for lithography [26], metrology [27,28], microscopy [29–31], radiography [32,33], tomography [34], micromachining [35,36], processing materials [37], etc. Similar techniques with modifications in the experimental setup have been used to develop a source dedicated for radiobiology experiments. The present source is modular in its design and compact enough to fit on a small optical table (about 1 m^2). This laboratory system is composed of a cylindrical vacuum chamber, 150 mm diameter and 210 mm in height, inside which all internal components were located. The chamber is clamped firmly onto the optical table such that no special measures were required to isolate against vibration during operation.

Inside the vacuum chamber, the electromagnetic valve system to form gas puff targets, bi-convex focusing lens, x-y-translational stages, sample irradiation stage and spectral thin film filters are mounted. Currently, the electromagnetic valve system is composed of a double nozzle used to inject small amount of two, high- and low-Z, gases under high pressure into the laser focus region, forming a gas puff target. The details and the operation of the valve system is described elsewhere [38,39].

The source chamber is composed of flanges designed with groves to engage metal gaskets and/or o-rings to provide a seal capable of ultra-high vacuum requirements. The chamber has four main ports to mount the flanges. Two of these ports were dedicated for flanges composed of fittings of different shapes (elbows, tees and crosses) for the installation of electrical feedthroughs, pumping systems, manipulation systems, etc. Third port was dedicated for window to load samples into the chamber while the remaining one served as a window for the X-rays for external irradiation. The chamber was firmly fitted onto an optical table with claw clamps. The robustness of the chamber together with its firm clamping to the optical table guarantees an absolute stability of conditions during running.

Presently, a custom-made sample mounting system is installed inside the vacuum chamber. The system is composed of L-shaped aluminium piece mounted with one arm 30 mm upstream of the source. The top of the L-shape piece has a U-shaped recess to accommodate two X-shaped spacers which serve as a sandwich for the filters whiles making it possible to avoid any damage which might be due to different pressure gradient on the filters. The use of the spacers was appropriate to allow vacuum throughout the vacuum chamber. The spacers are nailed together when the first and the second filters are mounted appropriately and placed in the U-shaped recess in the holder. This orientation also ensures the vertically upward direction of the beam. A rotary stage with a disc composed of 8 holes is installed above the filters to allow irradiation of about 8 samples before venting and opening of the chamber to take the samples. The schematic view of the internal arrangement of the source components is shown Fig. 1. Similarly, a second stage system, currently under design, will be installed in a He-environment. These stage systems will allow the irradiation of dry, wet or cryo-fixed samples.

The soft X-ray source is produced by focusing a commercial Nd:YAG laser (λ = 1064 nm; NL 303HT, from EKSPLA) onto the double

Please cite this article in press as: D. Adjei et al., Development of a compact laser-produced plasma soft X-ray source for radiobiology experiments, Nucl. Instr. Meth. B (2015), http://dx.doi.org/10.1016/j.nimb.2015.08.065