X-ray plasma-source for biological applications

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INTRODUCTION

This article presents the plasma-source layout at the PLASMA-X laboratory and the results of the measurements of soft X-ray emission due to laser plasma source which uses different materials as target (mylar and yttrium).
Plasma is obtained by focalizing Nd: YAG/Glass laser beam on target at λ = 532 nm. The pulse duration is tL = 6 nsec and the laser shot energy EL ranges from about 300 mJ and 4 J.
The spectral X-ray emission is measured with a laser intensity of I ≈ 1012 - 1013 W/cm2. The conversion efficiencies of soft X-ray emission were measured in different energy ranges. One from 300 to 510 eV (almost coincident with the Water Window) and the other from 450 to 850 eV.
The experimental data of conversion efficiencies are important in the realization of an intense monochromatic X-ray beam. In particular, the aim is to achieve a monochromatic microbeam to be used in radiobiological topics and in transmission X-ray microscopy.

The X-ray source

Figure 1 provides a vision of the said X-ray source located in the PLASMA-X laboratory of the Physics Department at the University of L'Aquila.
The X-ray source consists in a Nd:Yag/Glass laser and two interaction chambers into which the laser beam is sent alternatively, with a system of mirrors (red and blue lines). To cover the entire range the source can assumes two configurations: the first for X -ray emission from 70 eV to 1 keV (the interaction chamber, Soft X-rays, in the middle of figure 1), the second for X-rays from 1 keV to 30 keV (the interaction chamber HT, Hard X-rays, at the left top in figure 1) with the control sistem of the high voltage circuit.
In both configurations, the mechanism of X-ray production is based on the generation of plasma obtained by focusing a NdYag laser beam (5J per pulse max value, 6 ns duration, 0.3 mrad divergence, 532 nm wavelength) on a metal target or otherwise.

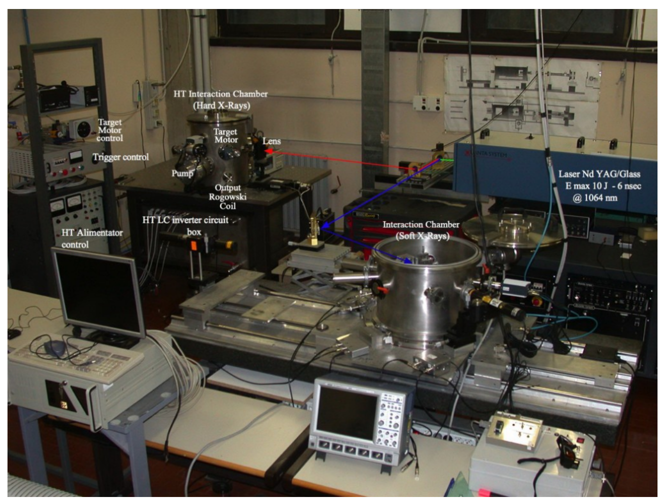

Fig.1 The X ray plasma sources, located in the PLASMA-X Laboratory of the Physics Department at the University of L'Aquila.

The two interaction chambers are shown in figure 2 and 4.

Soft X-ray source and conversion efficiency

Figure 2 shows the interaction chamber, where X-rays are produced directly from the hydrodynamic expansion of plasma, with energy from 70 eV to 1 - 1.5 keV. Plasma is obtained by focusing the laser beam on the target (copper in the figure) with a power density of I ~ 10^{11} to 10^{13} (W/cm^2) produced by an aspheric lens (triplet) of 132 mm focal length (f

3). The plane copper mirror is placed at 5 degrees grazing angle to obtain an X ray beam in the sub-keV region.

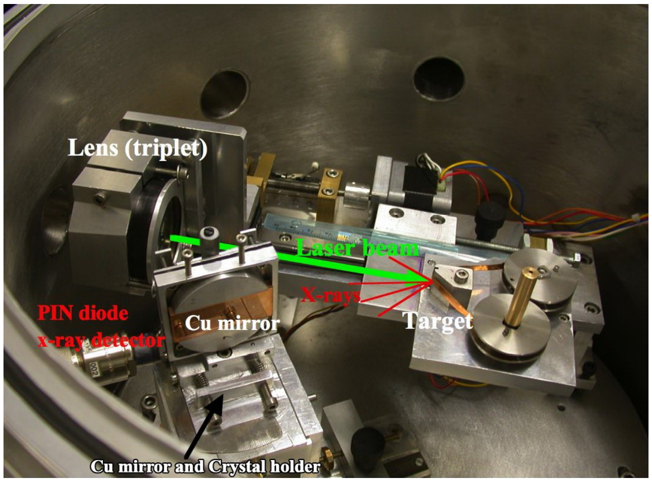

Fig. 2 Interaction chamber (Soft X-rays) for soft X-ray production.

The radiation intensity is measured by using a solid state detector (125PIN100, Quantrad System). To carry our measures of X-ray conversion efficiency of mylar and yttrium, the PIN diode is placed at 84.5 cm from plasma. The radiation is filtered through a vanadium microfoil 1 μm thick or a nickel microfoil 1 μm thick or an aluminium microfoil 7.5 μm thick placed in front of the detector entrance window.

To measure the conversion efficiencies in the range of about 300 eV - 510 eV and in the range of about 450 eV - 800 eV the vanadium microfoil and the nickel microfoil are placed respectively. For the measurement of the radiation component of more than 800 eV, it is used an aluminium microfoil 7.5 μm thick. Figure 3 shows the transmission curves (calculated from [1]) for the three used microfoils. The vanadium microfoil 1 μm thick has a transmission range from 300 to 510 eV with a tail at energy higher then 800 eV. The nickel microfoil 1 μm thick has a transmission between 500 and 800 eV with a tail at energy higher then 800 eV, but less relevant than the vanadium one. Instead, the aluminium microfoil 7.5 microns thick has a significant transmission for energies higher than 800 eV.

From the experimental data, to obtain the conversion efficiency in the intervals from 300 to 510 eV (V) and from 450 to 850 eV (Ni) the contribution of photons with energy higher than 800 eV is subtracted from the total signal of the detector filtered with V and Ni. The photon contribution was derived from the detector signals filtered with 7.5 μm aluminium which, as shown in Figure 3, has a transmission (> 10-4) with photon energy higher than 800 eV.

Yttrium and mylar data analyses, regarding the three laser energy configurations, are shown in Table 1 and Table 2. The laser beam energy is shown in each table. For each material used as a target, these tables also show the power density on the target, the X-ray energy produced by plasma and the conversion efficiencies in the three energy intervals.

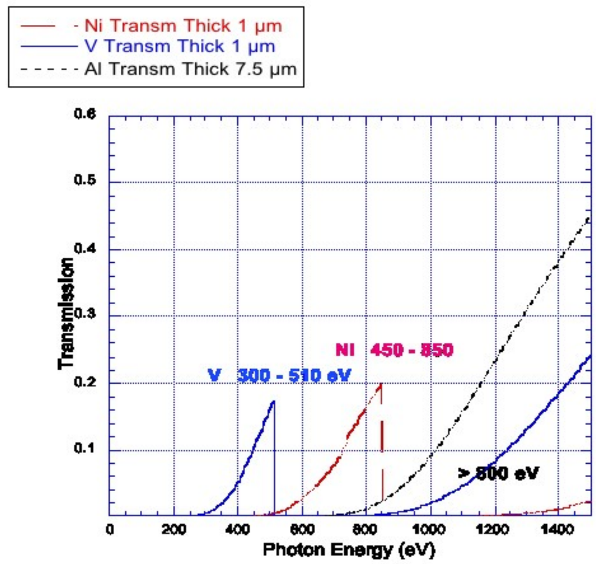

Fig. 3 The transmission curves for the three microfoils used. The vanadium microfoil,1 μm thick, has an average transmission ≈ 10% from 300 to 510 eV and a tail a higher energy than 800 eV. The nickel microfoil, 1 μm thick, has an average transmission ≈ 12 % from 500 to 800 eV and a small tail at higher energy than 800 eV. The aluminium microfoil, 7.5 μm thick, has a significant transmission for energies higher than 800 eV. [1]

Hard X-ray source and High-voltage circuit

Figure 4 shows the interaction chamber in which the X-ray emission in the range 1keV to 30keV takes place.

As in the case of a normal X-ray tube, X-rays are obtained by the bremmstrhalung effect on the anode of plasma accelerated electrons in an electric field. In this case, the focusing lens, with its area of handling, is placed outside the interaction chamber and the laser beam is focused onto a target (cathode) in continuous rotation. These measures were taken in order to move the high voltage discharge points out of the area of handling and eliminate unwanted high voltage. The current is measured with a Rogowski coil.

W (W/cm^2)	Filter	Energy Interval (eV)	EX (mJ in 2 π sr)	Conversion Efficiency % (in 2 π sr)
1.4 x 10^{12}	V 1 µm thick	300 - 510	3,93	1,2
1.4 x 10^{12}	Ni 1 µm thick	450 - 850	1,34	0,4
1.4 x 10^{12}	Al 7.5 µm thick	> 800 eV	2 µJ in 2 π sr	6 x 10^{-4}

Target **MYLAR** - E laser = 321 mJ +- 7 mJ

W (W/cm^2)	Filter	Energy Interval (eV)	EX (mJ in 2 π sr)	Conversion Efficiency % (in 2 π sr)
6.6 x 10^{12}	V 1 µm thick	300 - 510	59,1	3,7
6.6 x 10^{12}	Ni 1 µm thick	450 - 850	22,9	1,4
6.6 x 10^{12}	Al 7.5 µm thick	> 800 eV	0,3	2 x 10^{-2}

Target **MYLAR** - E laser = 1.6 J +- 0.1 J

Target **MYLAR** - E laser = 3.7 J +- 0.2 J

W (W/cm^2)	Filter	Energy Interval (eV)	EX (mJ in 2 π sr)	Conversion Efficiency % (in 2 π sr)
1.6 x 10^{13}	V 1 µm thick	300 - 510	144,6	4
1.6 x 10^{13}	Ni 1 µm thick	450 - 850	83,6	2,3
1.6 x 10^{13}	Al 7.5 µm thick	> 800 eV	1,2	3 x 10^{-2}

Table 1 – Analysis of X-ray intensity measurements and mylar conversion efficiencies (on 2π sr) in the three energy intervals indicated at laser beam different irradiances.

W (W/cm^2)	Filter	Energy Interval (eV)	EX (mJ in 2 π sr)	Conversion Efficiency % (in 2 π sr)
1.3 x 10^{12}	V 1 µm thick	300 - 510	10,1	3,3
1.3 x 10^{12}	Ni 1 µm thick	450 - 850	1,4	0,5
1.3 x 10^{12}	Al 7.5 µm thick	> 800 eV	9.8 µJ in 2 π sr	3 x 10^{-3}

Target **Y** - E laser = 308 mJ +- 9 mJ

W (W/cm^2)	Filter	Energy Interval (eV)	EX (mJ in 2 π sr)	Conversion Efficiency % (in 2 π sr)
7 x 10^{12}	V 1 µm thick	300 - 510	136,8	8,4
7 x 10^{12}	Ni 1 µm thick	450 - 850	22,4	1,4
7 x 10^{12}	Al 7.5 µm thick	> 800 eV	0,35	2 x 10^{-2}

Target **Y** - E laser = 1.63 J +- 0.06 J

Target **Y** - E laser = 3.7 J +- 0.2 J

W (W/cm^2)	Filter	Energy Interval (eV)	EX (mJ in 2 π sr)	Conversion Efficiency % (in 2 π sr)
1.6 x 10^{13}	V 1 µm thick	300 - 510	413,4	11,2
1.6 x 10^{13}	Ni 1 µm thick	450 - 850	67,2	1,8
1.6 x 10^{13}	Al 7.5 µm thick	> 800 eV	1,6	4 x 10^{-2}

Table 2 – Analysis of X-ray intensity measurements and yttrium conversion efficiencies (on 2π sr) in the three energy intervals indicated at laser beam different irradiances

The orange tube, that surrounds the X-ray production, supports the safety shield against the X-ray radiation. This shield is in lead and 3 mm thick.

The circuit is based on a power supply providing a 40 kV maximum voltage and an LC-inverter circuit whose scheme is shown in figure 5. The latter shows the values of the most important circuit elements. Its stucture is indicated in figure 6.

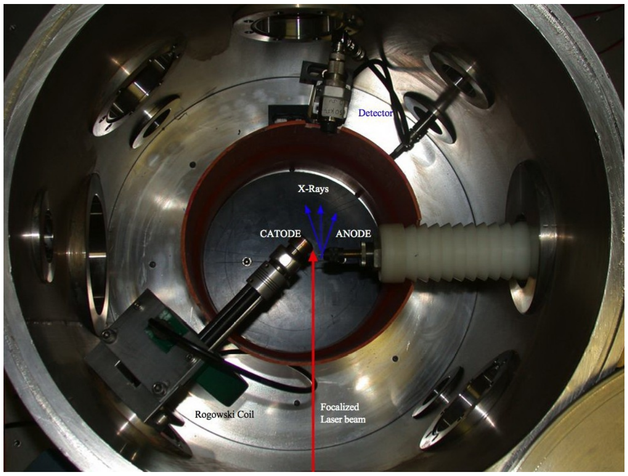

Fig. 4 HT interaction chamber (Hard X-rays)

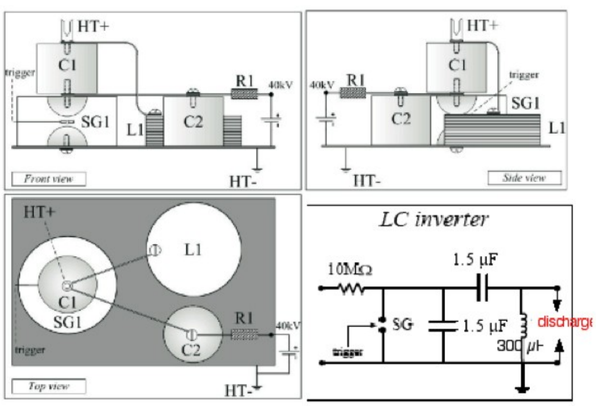

Fig. 5 Schematic layout of the LC-inverter circuit. SG indicates the spark gap.

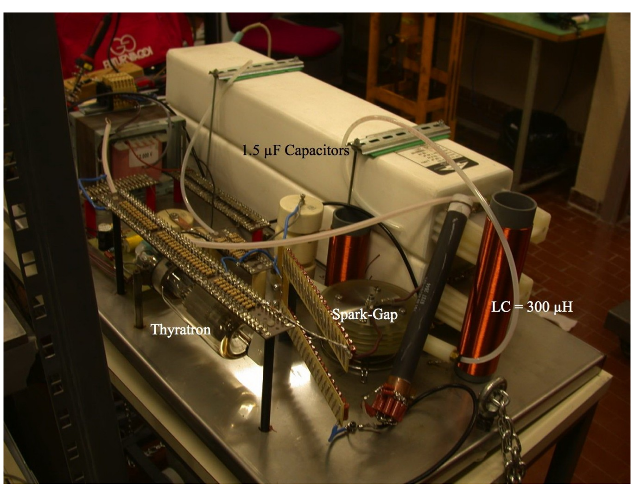

Fig. 6 Implementation of the LC-inverter circuit with its major components.

The first measures were performed in air and the results are shown in Figure 7a and 7b where the voltage applied to the discharge and its current are plotted. The signal characteristics of current and voltage are consistent with the circuit characteristics, as the oscillation period and the signal damping.

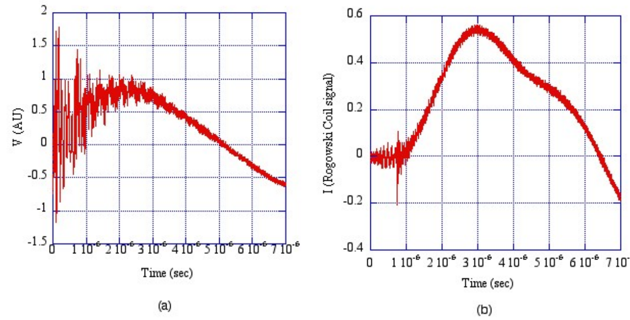

Fig. 7 Evolution of voltage and current for a discharge in air with a 20kV voltage supply.

The system is designed to make the charging circuit equivalent to the one released during a 18 keV mammogram exposure.

Conclusions and discussion

The yttrium conversion efficiency in the vanadium energy window, which almost coincides with the water window, is systematically 2 or 3 times larger than the mylar conversion efficiency. In the nickel energy window the two materials offer conversion efficiencies essentially identical. This happens with every power density.

In the vanadium energy window, the different performance is due to the type of spectrum emitted by the two materials. Yttrium shows a quasi-continuous emission due to the threshold M that is excited and then a uniform spectrum around 400 eV. Instead, mylar generates a line spectrum of the carbon K threshold (280 eV). However, the conversion efficiencies are similar for the two materials in the energy region of the nickel window, because they mainly emit bremsstrahlung radiation. In the Water Window, yttrium is a good X-ray emitter and can be possibly emploied in X-ray microscopy where an image of a biological sample with a single X-ray shot has to be obtained.

According to the test in the air above shown in figure 7, the analysis of current and voltage curves indicates that the useful discharge takes about 4 microseconds. This time interval corresponds to the period in which the spark-gap is closed. Further measures are needed to understand the dynamics of the discharge in vacuum, in conditions in which it is triggered by plasma produced in the laser beam focusing onto the target.

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[1] Calculated from X-Ray Data Booklet – Center for X-ray Optics and Advanced Light Source – Lawrence Berkeley National Laboratory. http://henke.lbl.gov/optical_constants/