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X-Ray Emission From Plasmas Produced by Nd-Laser on Fe Targets.

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Summary. — We studied the X-ray emission from laser plasmas produced by irradiating thick solid Fe targets with 1.064 μm Nd-laser light at intensity up to $1.2 \cdot 10^{13}\,W/cm^2$ with 3 and 20 ns pulses. Measurements include X-ray signal dependence on energy and focusing of laser light; X-ray pin-hole pictures of the plasma; time duration of X-ray emission.

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1. – Introduction.

Laser-produced plasmas are high-brigthness soft–X-ray sources, as already evidenced in the early '80s [1], useful for applications such as microscopy [2], microlithography [3], radiobiology [4], EXAFS [5]. In these fields they are potentially competitive with synchrotrons. Up to now, the most used laser systems have been Nd and KrF, in the near IR and near UV, respectively. The duration of the X-ray pulse is generally comparable to the laser pulse: $t_X \approx t_L$. We consider here only laser pulses in the nanosecond and sub-nanosecond range, which is presently the most interesting for applications. However, a new class of very interesting experiments is now progressing in the picosecond and sub-picosecond range of laser pulses. In these cases of course $t_X > t_L$ due to the time needed by the plasma to cool down.

An important parameter to compare the effectiveness of different laser drivers is conversion efficiency, which is defined as $\eta = E_X/E_L$, where E_L is the laser pulse energy and E_X the energy emitted by the plasma in the soft X-ray region of the electromagnetic spectrum. It is generally believed that KrF lasers can give a better laser-plasma coupling, due to their shorter wavelength, and hence a better X-ray conversion efficiency. However it has been experimentally shown that with long pulses (a few nanoseconds or more) KrF lasers give $t_X < t_L$ and this negatively affects conversion efficiency. This has been called the «pulse shortening problem» and it is discussed, for instance, in [6]. As a consequence, the question of what are the best laser drivers for X-ray sources remains still open.

The aim of the experimental work we present here was to measure the soft X-ray signal from Nd-laser–generated plasmas and to investigate its dependence on pulse duration, laser energy and beam focusing. Pin-hole images of the X-ray source and spectra in the region around 1 keV were also obtained.

2. – Plasma production and diagnostics.

The experimental set-up is shown in fig. 1. The beam from a Nd laser ($\lambda = 1.064\,\mu m$, $t_L = 3$ or 20 ns FWHM), was focused on a metallic target by an $f/8$ lens into a vacuum chamber. We are reporting data obtained with Fe targets, however Cu targets were also used in the same experiment [7] with similar results. Focal-spot diameter was $\approx 60\,\mu m$. The 3 ns pulse was obtained by «cutting» the 20 ns pulse with a Pockels cell outside the laser cavity. We believe that our system is particularly suitable to investigate the conversion efficiency behaviour since our pulse cutting does not operate in the laser cavity and hence leaves all beam characteristics practically unchanged, in particular in our system $E_L \approx I_L t_L$ with I_L practically the same at 3 and 20 ns.

X-ray emission was detected with a silicon PIN diode (025-PIN-125 produced by Quantrad Corporation) filtered with aluminium filters (typical thickness was 26 μm). This detector was placed 20 cm away from the plasma, in the horizontal plane and at 45° from the laser beam axis. The laser pulse energy E_L was monitored shot by shot with calorimetric measurements.

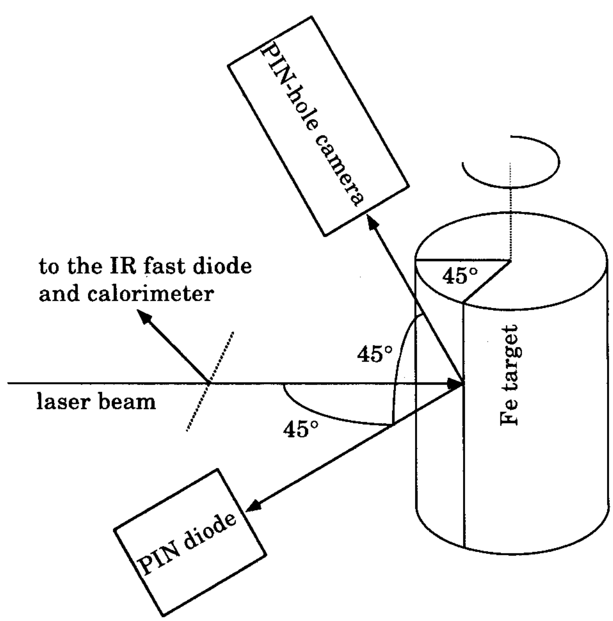

Fig. 1. – Sketch of the experimental set-up.

To reduce possible dangerous reflections of laser light from the solid target, the laser beam was incident on it at 45° from the normal to the target surface; residual backscattered light was stopped by a Faraday isolator. The PIN diode looked normally at the target surface.

A Bragg crystal spectrometer was placed inside the vacuum chamber to record the X-ray spectrum from the plasma source. It was filtered with a 13 μm beryllium foil. We used Kodak DEF films and KAP crystals ($2d = 26.632$ Å) to record X-ray spectra. A second 5.3 μm magnesium filter was placed on half slit to give a wavelength fiducial: indeed, it is characterized by a K-edge absorption at 1.3 keV and by a cut-off frequency (e^{-1} transmission) at 0.9 keV [8]. Some of the spectra we obtained were already reported in [7].

We obtained images of our X-ray source with a pin-hole camera so that the plasma could be seen «in front» with a 45° angle in the vertical plane. Images were taken with 20 μm pin-hole diameter. A 13 μm thick Be filter made the pin-hole camera spectral window to be the same as the spectrometer one. The pin-hole camera magnification was 5. The size of the X-ray source was measured to be comparable to the laser spot diameter. The expansion of the plasma plume in direction normal to the target surface gave typically a $(400 \div 500)$ μm longitudinal size.

3. – X-ray emission data.

We measured the X-ray energy *vs.* target position at both sides with respect to the best focus. These measurements were performed at different laser intensities with both the PIN diode and the pin-hole camera.

At lower laser intensities displacements from the best focus produced a decrease in X-ray emission. This behaviour is shown in fig. 2 where data from a focal scan obtained at $I_L = 10^{11}\,W/cm^2$ are reported (open circles). The FWHM of the curve is about 500 μm, slightly larger than the focal depth of our focusing system.

A different behaviour was evidenced by the focal scans performed at higher laser intensities. At $I_L = 5 \cdot 10^{12}\,W/cm^2$, *e.g.*, two maxima for the X-ray signal were found symmetrically at 1.15 mm away from the best focus for X-ray signal, as reported in

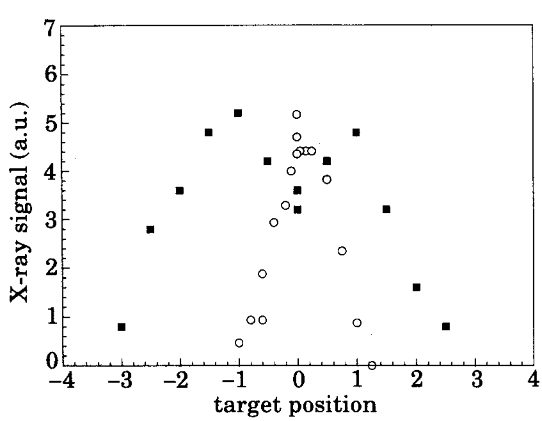

Fig. 2. – X-ray signal *vs.* position of target with respect to lens focus, for high laser intensity (■), $I_L \approx 5 \cdot 10^{12}\,W/cm^2$ and for low laser intensity (○), $I_L \approx 10^{11}\,W/cm^2$. The two sets of signals were recorded with different Al filters in front of the PIN diode.

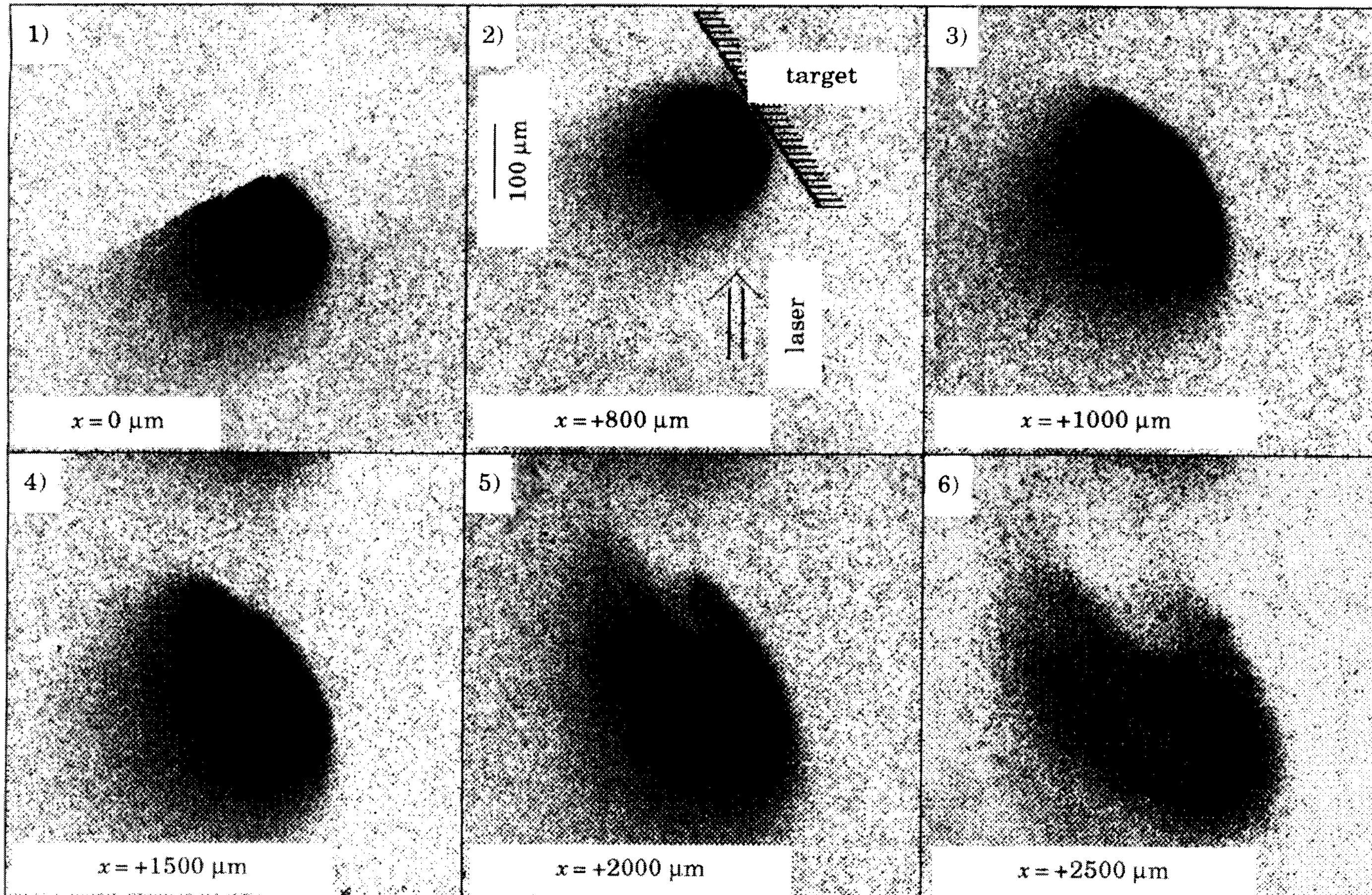

Fig. 3. – Pin-hole camera pictures taken at different target positions with respect to the best focus. The variation of X-ray source size during a focal scan can be pointed out. The target displacement ahead the focus is reported in each image. The first picture was marginally shadowed by an edge of the pin-hole support.

fig. 2 (full squares). The local minimum of X-ray signal at the best focus is to be related to the smaller plasma volume involved in the emission, due to the smaller spot, as can be seen from the pin-hole camera pictures shown in fig. 3-1). A more quantitative theoretical explanation of this behaviour was given by Tallents *et al.* [5]. Displacing the target away from the focus, the increase of the plasma volume causes an increase in X-ray emission as far as the laser intensity keeps high enough to heat the plasma above the temperature needed to excite deep L-shell transitions in Fe-ions (see also O'Neill [6]). At larger defocusing this «threshold» laser intensity is no longer reached, so that the X-ray luminance drops dramatically and the loss of X-ray emission is no more balanced by the increase in the plasma volume. This is particularly evident in pin-hole camera pictures obtained at target displacements larger than 2 mm (see fig. 3-6)).

We also notice the presence of some structures in the last images of fig. 3. Their origin is not yet explained but could be related to some hot spots in the laser beam.

X-ray spectra were centred around $\lambda \approx 14$ Å. They are composed of lines from Na-like (Fe XVI) to O-like (Fe XIX) ions. Since the conversion efficiency is rather high, and the film sensitivity is about 1 photon/μm^2 [9], only one laser shot is enough to record an X-ray spectrum or a pin-hole camera picture. Our spectra are not very different from those recorded with UV lasers (see [10]); there is only a slightly higher abundance of Fe XVIII and Fe XIX as compared to Fe XVII: this could be due to the higher plasma temperature as expected with lasers of longer wavelength.

Since the KAP crystal cuts away the high-energy region of the X-ray spectrum, we could not measure the electron temperature of our plasmas by the slope of the bremsstrahlung continuum, but only by comparison of the average ionization states resulting from X-ray spectra, with the predictions of Colombant and Tonon [11]. We could also get an indication of the electron temperature T_e of the plasma region emitting X-ray radiation from theoretical models (see for example [12]), which give $T_e \approx 400$ eV in our experimental conditions.

4. – X-ray signal dependence on laser pulse.

We recorded (see fig. 4) the variation of the X-ray signal as a function of laser intensity for 20 ns laser pulses on Fe targets. We can distinguish different regimes. From the lowest intensities we used ($I_L \approx 5 \cdot 10^{10}$ W/cm^2) up to $I_L \approx 2 \cdot 10^{12}$ W/cm^2, the X-ray emission is slowly increasing with laser intensity, while above this value a fast increase of X-rays is observable. This «thresholdlike» behaviour is to be related to the L-shell nature of X-ray emission in Fe targets [6]. For $I_L > 5 \cdot 10^{12}$ W/cm^2 the X-ray signal shows a slower increasing trend. In this range the X-ray–to–laser-energy ratio (proportional to conversion efficiency) is decreasing.

If we assume that all the X-ray energy is emitted around $h\nu \approx 1$ keV from fig. 4 we can estimate a maximum conversion efficiency of a few percent ($\approx 5\%$). This is smaller than that ($\approx 13\%$) measured in [13] with 600 ps UV pulses but definitely higher than the one ($\approx 0.35\%$) measured in [4] with excimer laser pulses of comparable length (25 ns).

The X-ray–to–laser-energy ratio is half its maximum value at $I_T \approx 2 \cdot 10^{12}$ W/cm^2; this «threshold intensity» is very close to those already observed even at different

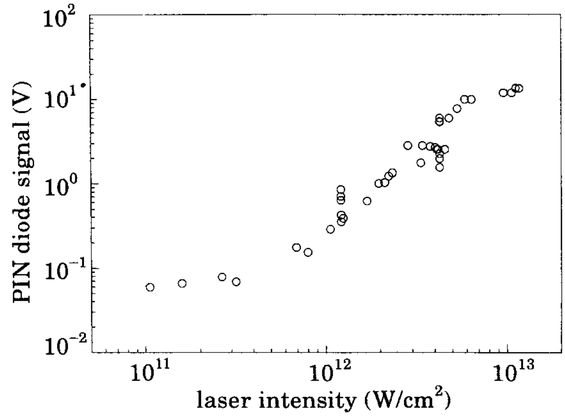

Fig. 4. – X-ray signal *vs.* laser intensity for laser pulse duration of 20 ns.

wavelengths [13]. Also the value at which conversion efficiency starts to decrease, $I_L \approx 5 \cdot 10^{12}$ W/cm^2, is similar to that reported in [13].

In the pin-hole camera picture of fig. 5 we see the variation of the plasma size as a function of laser pulse energy between 0.2 J and 2 J. We notice that $E_L \approx 2$ J corresponds approximately to the I_T value.

To study the effect of laser pulse duration we detected X-ray pulses with 3 and 20 ns laser pulses. In fig. 6 PIN diode signals are reported at $t_L = 3$ ns and $t_L = 20$ ns, respectively. The temporal resolution of our PIN-oscilloscope system is about 2.5 ns. From these scope traces it is evident that in our case there is no pulse shortening. This seems to be a general feature of IR lasers, consistently with the observations of O'Neill *et al.* [14] who used a 20 ns, 12 J Nd-laser pulse. We also measured (at $I_L \approx$ $\approx 5 \cdot 10^{12}$ W/cm^2) the X-ray–to–laser-energy ratio at the two different t_L and we found that at 20 ns it is about six times larger than at 3 ns. An increase in conversion efficiency with laser pulse length was also observed (but in a different regime) by Soom *et al.* [15] with 250 and 750 ps Nd-laser pulses at $I_L \approx (10^{12} \div 10^{13})$ W/cm^2.

Regarding the trend of conversion efficiency with laser pulse length there is no definitive answer in the literature. While it is well established that η decreases with t_L for UV laser pulses, also because of the pulse shortening problem, it is not so clear for visible and IR laser light.

In table I we report some results which may somehow be compared to ours and were obtained by changing the laser pulse duration. We just report relative η since experimental conditions were very different, so that a direct comparison of absolute values could be misleading.

It is evident that the different results are only partially in agreement. We note in particular that our results are in contradiction with those of ref. [16]. In general, X-ray–emitted energy will be proportional to

$$E_X \propto \int_0^{t_L} \int_V n_e^2 (T_e)^{1/2} \, dV \, dt,$$

where n_e is the electron density.

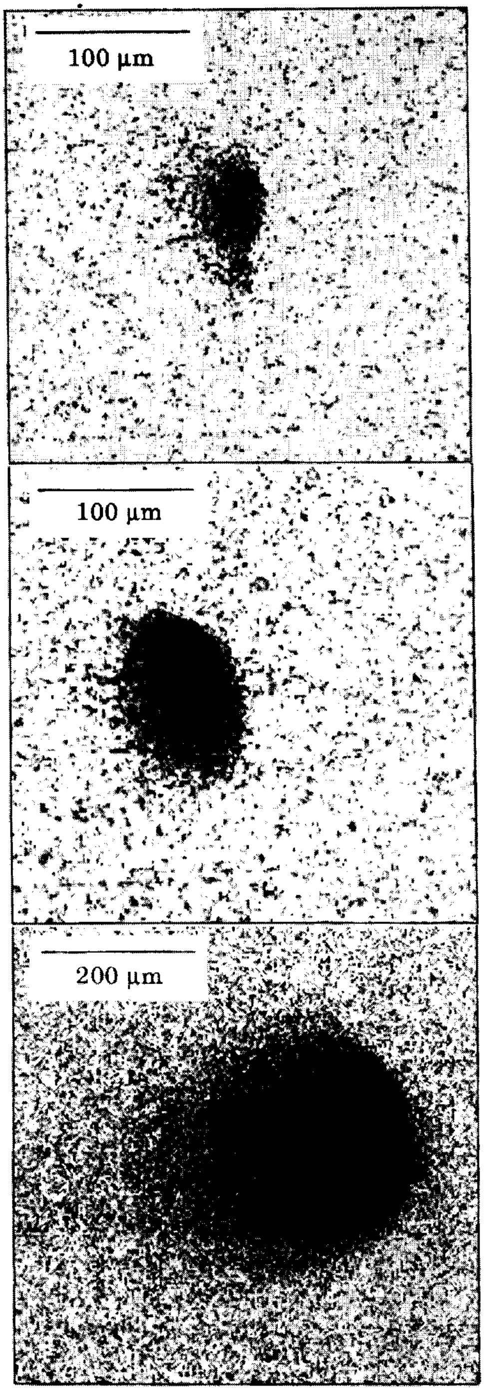

Fig. 5. – Pin-hole camera pictures showing the variation of the X-ray source size as a function of laser pulse energy E_L. The laser pulse energies were 0.2 J, 0.4 J, and 2 J, respectively.

TABLE I. – *Conversion efficiencies at different laser pulse durations obtained in experiments using* Nd ω *and* 2ω *laser illumination.*

Paper	Year	Laser	Observed X-ray
this work and [7]	1992	$1.06\,\mu m$ $\leqslant 10^{13}\ W/cm^2$	$\approx 1\,keV$
Tallents *et al.* [5]	1986	$1.05\,\mu m$ $\leqslant 10^{17}\ W/cm^2$	$(1.5 \div 4)\,keV$
Soom *et al.* [15]	1990	$1.06\,\mu m$ $(6\cdot 10^{12} \div 10^{14})\,W/cm^2$	$(0.8 \div 5.5)\,keV$
Thoubans *et al.* [16]	1989	$1.06\,\mu m$ $(10^{12} \div 10^{14})\,W/cm^2$	$(0.1 \div 2)\,keV$
Brug *et al.* [17]	1989	$0.53\,\mu m$ $(6\cdot 10^{12} \div 10^{14})\,W/cm^2$	$(0.1 \div 2)\,keV$
Eidmann *et al.* [18]	1991	$0.53\,\mu m$ $(10^{13} \div 10^{14})\,W/cm^2$	$50\,eV \div 4\,keV$
Kodama *et al.* [19]	1987	$0.53\,\mu m$ $10^{14}\ W/cm^2$	$(1 \div 5)\,keV$

Paper	Target	Conversion efficiency *vs.* t_L	Focal spot
this work and [7]	Fe, Cu	$\eta(20\,ns) \approx 6\,\eta(3\,ns)$	$60\,\mu m$
Tallents *et al.* [5]	Au, Mo, Pb	$\eta(200\,ps) \approx \eta(20\,ps)$	$2\,\mu m$
Soom *et al.* [15]	Cu	$\eta(670\,ps) \approx 3\,\eta(100\,ps)$	$100\,\mu m$
Thoubans *et al.* [16]	Cu	$\eta(3\,ns) \approx 0.5\,\eta(600\,ps)$ $\eta(30\,ns) \approx 0.5\,\eta(3\,ns)$	$100\,\mu m$
Brug *et al.* [17]	Au, Mo, Cu,Fe, etc.	$\eta(20\,ns) \approx \eta(30\,ps)$	$65\,\mu m$
Eidmann *et al.* [18]	Al, Cu, Au	$\eta(3\,ns) \gg \eta(30\,ns)$	$50\,\mu m$
Kodama *et al.* [19]	Cu	$\eta(400\,ps) \approx 2\,\eta(200\,ps)$ $\eta(1\,ns) \approx \eta(400\,ps)$	$270\,\mu m$

Hence results with short pulses in which X-ray conversion efficiency increases with laser pulse length were explained in terms of an increase both in plasma volume and in emission time. On the contrary, results (with longer pulses) where η saturates or decreases were explained on the basis of 2D expansion effects whose consequence is a reduction of plasma density.

Our results are in contradiction with this explanation because our focal-spot size is smaller than that of ref. [16]. Probably this approach does not take into consideration different factors, *i.e.* the real size of the supercritical region (which is the main source of X-rays), the change in the absorption with plasma scale length, etc.

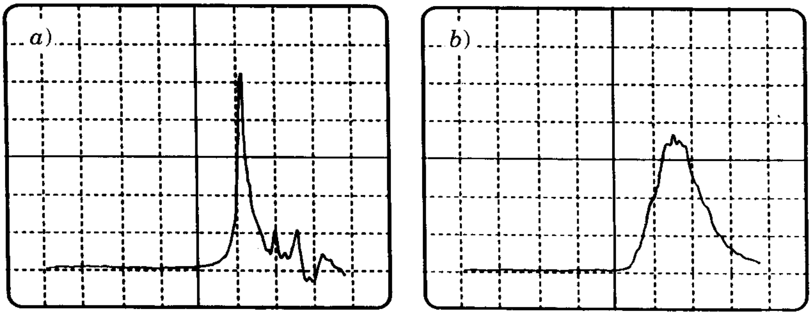

Fig. 6. – Typical time shape of an X-ray pulse with 3 ns (*a*)) and 20 ns (*b*)) laser pulses, from a PIN diode with 26 μm Al filter. The time scale is 10 ns/div.

A point which deserves particular attention is the effect that intensity modulation in multi-mode lasers has on X-ray conversion efficiency and X-ray pulse length, which has already proved to be very important with UV lasers [20].

6. – Conclusion.

We studied the X-ray emission from IR-laser plasmas produced on thick Fe targets. The main diagnostics were a PIN silicon diode for X-rays, filtered with thin Al foils, and an X-ray pin-hole camera. The X-ray signal was measured at different focusing conditions and at different laser intensities and pulse lengths. The last measure gave information on the conversion efficiency dependence on laser pulse properties. Our measurements seem to point out an increase of η with t_L. This suggests the use of Nd-lasers as sources of X-ray pulses of the order of 20 ns, where excimer lasers are affected by the pulse shortening problem ($t_X \ll t_L$), while UV lasers are optimum sources for short pulses or for trains of short pulses [20].

* * *

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