Time Resolved XUV and X-ray Spectra from a 200-ns X-Pinch Plasma

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Abstract - A series of seven *XRD* and four *p-i-n* detectors with *K*- and *L*-filters was employed to measure absolute time resolved spectra of 200-ns 200-kA molybdenum *X*-pinch plasma.

1. Experimental set-up

X-pinch plasmas are point-like x-ray sources with potential application for backlighting diagnostic in the keV range. A very compact *LC* generator [1, 2] (40kV, 200 kA) has been used for driving *X*-pinches made of 18-25 µm diameter wires with a current rise ~ 1kA/ns.

A series of XRD and silicon *p-i-n* detectors with various filters was employed to study UVX and X-ray spectra in the range 10 eV - 10 keV [3]. The detectors and the filters were developed and fabricated at the Research Institute of Pulse Technique in Moscow. Spectral selection has been achieved by an optimal combination of detectors and filters. Below 1 keV, we have used small-size vacuum diodes with aluminium and gold cathodes. Their time resolution (FWHM) is not worse than 200 ps and the maximum linear current is 1.5-2 A. The metallic XRD filters thickness can be varied from 0.15 up to 0.4 µm with precision not worse than ± 50 E. The main XRD characteristics are presented in Tab. 1.

Small-size silicon photodiodes operate with output current greater than 1.5 A with time resolution not more than 1.5 ns. They were employed with Cu_1µm, Al_3µm, Be_10µm, Mylar_29µm together with XRDs. These kinds of filter combination allow realizing the spectral measurements essentially in the region 0.65<E<2-3 keV. Another set of filters was employed during a second campaign of measurements in the range 800-7000 eV when Si diodes were used only: Al_5µm, Ti_4µm, Mylar_29 µm, Cl and P containing polymer films (Fig.1) [4].

The XRD16 detector together with 25-µm Be filter allows us to follow *x*-ray radiation above 900 eV with temporal resolution of 150ps.

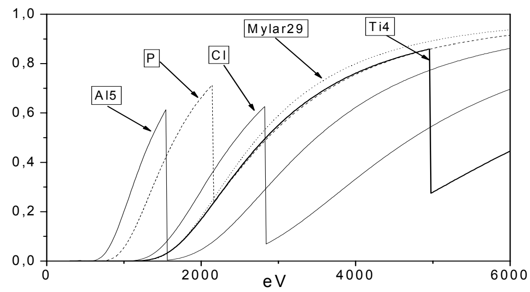

Fig. 1. Si detectors spectral responses

A numerical procedure was used to acquire a rather detailed time resolved energy spectrum from the *x*-ray detectors. The output current of the *i*-th detector with ideal time resolution in the case of an isotropic flux distribution is defined by:

$$I_i(t) = (4\pi r_i^2)^{-1} * \int S_i(E) * F_i(E) * f(E,t)dE \qquad (1)$$

where r_i is the source-detector distance, *S(E)* the detector spectral response (A.cm^2/W), *F(E)* the filter spectral transmission and *f(E,t)* the unknown source power spectrum in W/eV. The method was implemented using a gradient-type Monte-Carlo program. Taking into account the spectral responses of the used detectors, the energy range 10/20-3000 eV was divided into a specific number *N* of large intervals for defining a multi-steps function $f_N(E)$ solution of Eq. 1. Typically, N=12 was used with the boundary points E_i= 10/20, 60, 120, 200, 280, 375, 480, 640,

Table 1

Cathode/diam., mm	Al / ш6	Al / ш6	Au / ш6	Au / ш6	Au / ш6	Au / ш6	Au / ш16
Filter/thickness, µm	Al/0.4	Zr/0.2	Ag/0.15	PP/4	Ti/0.25	Cu/0.15	Be/25
designation	N6	N5	N4	N3	N2	N1	XRD16
Sensitivity range, eV	20-60	60-200	115-405	205-290	220-465	325-935	> 950
Max. sensitivity, 10^{-4}*A*cm^2/W	3.5	0.5	0.2	0.3	0.26	0.16	0.6

770, 935 eV for XRDs and 640, 935, 1550, 2150, 3000 eV for *p-i-n* detectors. But others intervals have been chosen during the second campaign of measurement, when using only Si detectors to study spectra in the region 800 - 7000 eV more carefully.

The 10-m signal cables plus the bias units have a high cutoff frequency at -3 dB f=2.8 GHz, which corresponds to 125 ps risetime. The experiments with seven XRD and four *p-i-n* detectors together were carried using three LeCroy oscilloscopes with bandwidth from 1 up to 6 GHz and 2-20 GHz sampling frequency.

2. Results

Our earlier publications [1, 2] were pointed to the main peak emission which occurs, normally, with a delay more than 170 ns after the current onset, when the driving current reaches the level 130-140 kA for Mo 25-μm wire *X*-pinch. We have measured the *x*-ray source size to be about 40 μm for the range >1.8 keV. With help of the penumbral image taken on the edge of a 200-μm pinhole covered by 8-μm thick Ti (hν>2.4 keV) the source size was found to be about 10μm. Thus, our *X*-pinch allows to realize point-projection radiography of dense plasmas and other small objects using a detector film placed at more than 2.5 m from the source working with the optical density D~0.6. The FWHM of the peak, varying in the range 0.4-0.7 ns, was measured with the rapid XRD filtered by 25-μm Be (hν> 900 eV).

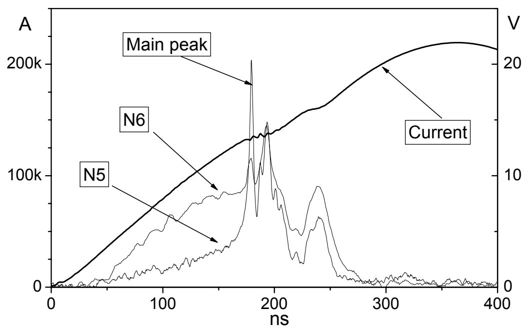

Fig. 2. Current and XRD N5 and N6 signals

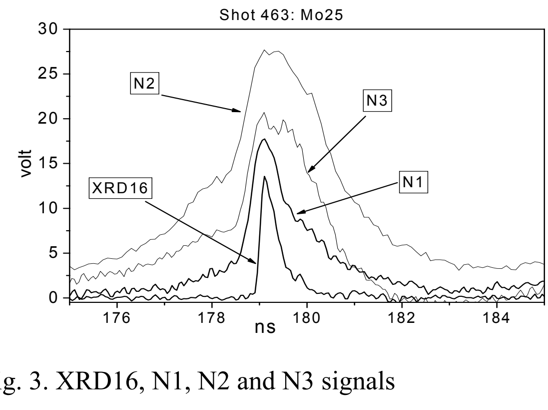

Fig. 3. XRD16, N1, N2 and N3 signals

The paper describes the spectral features in the case of two Mo 25-μm wires for *X*-pinch discharge. Figures 2 and 3 show experimental signals of a typical shot #463 of this series intended to present a usual scenario and typical values.

The UVX and *X*-signals allow us to distinguish the different phases of X-pinch process. The first stage deals with plasma load preparation, while XUV radiation is presented mainly by N5 and N6 XRDs (Fig.2). It starts with a delay ~ 35 ns after the current onset and it's rising slowly during about 130 ns. This phase will be naturally referred as "preliminary". The total radiation power at this moment (9ns before the main peak) is $8.5*10^7$ W with about 90% in *h*ν < 200 eV region. It yields a total energy ~ 5.5 J.

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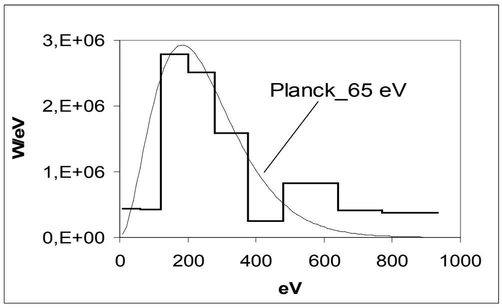

Fig. 4. Power spectrum of the main burst

In the interval between 9 and 0.6 ns before the main peak, the spectrum is moving into the region 120-375 eV and the total radiation power rapidly increases up to $4.7*10^8$ W. So energy about 2 J is emitted during the last 9 ns just before the peak.

The main coupling of the energy with the load appears with a delay ~ 175 ns, when all the detectors are peaking. Assuming a pinching process as the main cause of the *x*-ray burst, we can say that the final stage of this one starts 0.5-0.6 ns before the peak at the moment when a rapid kink is observed on the N1 detector (Fig. 3). Silicon photodiodes signals appear at this moment as well. Their spectral analysis gives about 285 mJ in the range 640-3000 eV with about 65% being in the range higher 935 eV. To transform the energy spectrum from Si detectors into the power one, we used the FWHM= 1ns provided by the N1 detector for the region 640-935 eV and 0.4 ns taken from XRD16 for the interval 935-3000 eV. Finally, a quite good agreement between XRDs and *p-i-n* diodes is obtained in the common region 640-935 eV.

In this way, the estimated total peak power is 1.4 GW, with about 65% being in the range below 900 eV. The main part of the low energy spectrum in the range 120-375 eV as shown in Fig. 4 can be fitted by a 65 eV Planck distribution. It's difficult to clarify the energy in the main burst. As the size of the *X*-pinch *x*-ray source depends on spectral registration range, the peak energy depends on spectral region as well. For example, XRD_N2 is the most sensitive in 200-470 eV region, so its signal let one to say that the flux duration in this spectral region at the peak moment is 2.2 ns with power about $3.8*10^8$ W. But XRD16 gives us 0.4 ns. With the energy measured by Si diodes the power yield is $4.6*10^8$ W for the region $h\nu > 935$ eV.

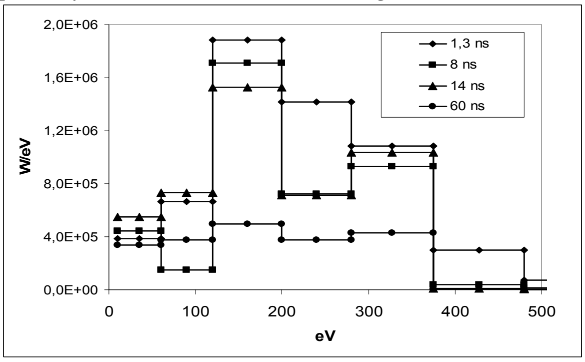

Fig. 5. Power spectra of the tail bursts

The interesting feature of the main burst spectrum is a presence of the bump in the region 480-640 eV. It appeases only if Mo wires are employed. But because of poor precision of spectral value here it does not seem reasonable to draw any definite conclusion.

The last phase is the emission tail followed after the main peak. As well seen in Fig. 2, it composed of a few bursts fairly pronounced under some background radiation. The bursts are accompanying by the drops on the current derivative signals. The spectra of a few burst are shown in Fig.5. Basically, more than 75% of its radiation is concentrated in 120-375 eV range with total maximal power $(3\text{-}5)*10^8$ W. The burst duration is varied between 2 and 20 ns. We estimate the total energy in the tail to be greater than 6 J.

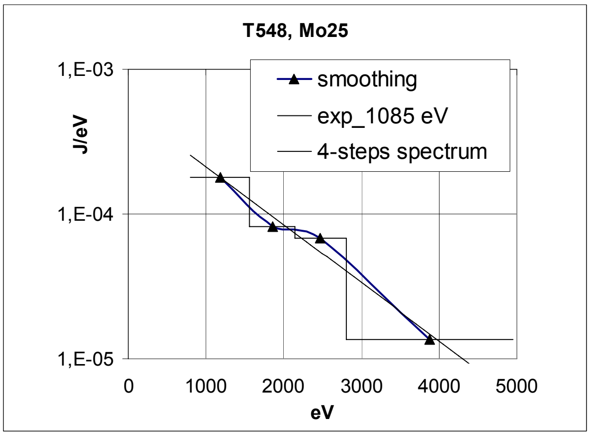

Fig. 6. Energy spectrum of the main burst in the range 800-5000 eV

More detail spectral measurements in the range >800eV have been carried out with Si diodes only. The energy spectrum in the shot #548 with Mo wires is plotted in Fig.6. It can be fitted with exponential function with a temperature T=1085 eV. One can see a small bump in the interval 2145-2800 eV which seems to be attributed to Ne- and F-like ionization stage (Mo XXXIII and Mo XXXIV) already presented in [5]. Available statistics gives rather good approach of the spectra to an exponential one with the temperature 900-1150 eV. The total emitted energy was measured to be in the interval 240-365 mJ. No more than 1% might be emitted in the range $h\nu > 5000$ eV.

In summary, an *X*-pinch installed on a 200-kA, 40-kV, 200-ns *LC* generator is capable to produce one 10-μm size, 0.4-0.7 ns *x*-ray source emitting above 0.9 keV with a radiation power about $5*10^8$ W, while the total power may reach 1.5 TW. The four steps energy radiation spectral distribution of Mo *X*-pinch in the range 800-5000 eV is fairly closed to an exponential one with temperature near 1 keV. The preliminary stage lasts more than 100 ns reaching about 10^8 W close to the main *x*-ray burst. Its spectrum lays essentially in <200 eV region. Following the main peak, radiation is composed of a few bursts with the spectra essentially inside 100-400 eV, having the peak power $>3*10^8$ W. This phase lasts up to 80 ns. Total UVX and X-ray yield varies in the interval 10-30 J.

3. Acknowledgments

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