

Fast pulsed X-ray sources tightly coupled with small targets for isomer triggering studies

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Final report: Characterization of the fast pulsed X-ray source prototype tightly coupled with small targets for isomer triggering studies

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Introduction

In this report we characterize a fast pulsed X-ray source designed to operate with different kinds of targets (metallic or dielectric), in order to obtain the strongest possible coupling with the irradiated sample for future isomer triggering studies. The source operates based on dielectric hollow cathode transient discharges [1-3], as we have already suggested in the previous reports. In order to achieve these purposes, we took into account the latest results on the induced gamma emission [4], which suggest that the most probable triggering of Hf isomers is realized with X-ray radiation corresponding to the L3 edge of Hf (9.56 keV).

X-ray source design

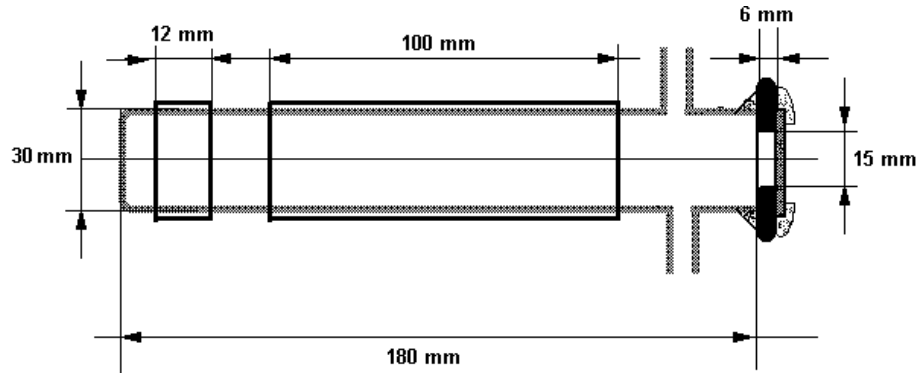
a. Discharge tube

The discharge tube is shown in Fig.1. It is made of pyrex. The anode, placed at the upper end of the tube, consists of an aluminium plate with a 15 mm diameter hole pierced on the tube axis. Different kinds of targets such as aluminium foils, micas and mylar foils were attached to the external anode surface. The cathode is the inner surface of the discharge tube, capacitively coupled with a metallic external electrode. Thus hot spots formation is eliminated and discharge evolution to superglow is prevented. Preionization is also assured by capacitive coupling through an additional external electrode located at the lower end of the tube. The working gas is argon in the pressure ranging between $4 - 5 \cdot 10^{-2}$ torr, in a steady low flow regime assured in the anode

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region.



a)



b)

Fig. 1 Sketch (a) and picture (b) of the discharge tube

As we have already presented in the second interim report, we can ascertain that the maximum value of the X-ray pulse corresponds at the beginning of a pseudo-spark regime, when discharge filamentation does not occur yet. The voltage on the inner dielectric side of the cathode is almost the voltage measured on the external electrode, because an equivalent 200 pF capacity of the pyrex tube in the cathode zone leads to a voltage shift of maximum 1000 V for the total measured current. We estimate that the energy of the beam electrons is approximately equal to the applied voltage for the peak of the X-ray signal. The evolution of the space charge within the hollow cathode region results in a decrease of the acceleration voltage on the discharge tube axis, corresponding to a passage from the high impedance to the low impedance mode of operation [7], thus accounting for the presence of lower energy X-ray photons in the trailing edge of the measured global X-ray signal. The presence of pre-ionization acts as a plasma lens for the fast electrons in the initial phase of the discharge, as described in [1,2] and also assures a low jitter between the high voltage pulse rising edge applied on the cathode and X-ray pulse.

b. High voltage pulse generator

We tested two kinds of pulse generators. The first one is similar with those presented in the previous reports and is operating on a wide voltage range, from 10 to 40 kV. The second pulse generator used, presented in Fig. 2 was designed for pulsed output voltages ranging from 10 to 20 kV, with an output impedance of $450\ \Omega$. Its operating parameters would allow replacement of the rotary spark gap with a BEHLKE fast high voltage transistor switch HTS 80-20-UF Option 04 (8 kV, 200 A, 2.2 ns rise time and $1\ \mu\text{s}$ on time). In both cases, capacitively coupled preionization uses the same switch (rotary spark gap or HTS device) by means of an adapted circuit made of L_2 , R_4 and R_5 .

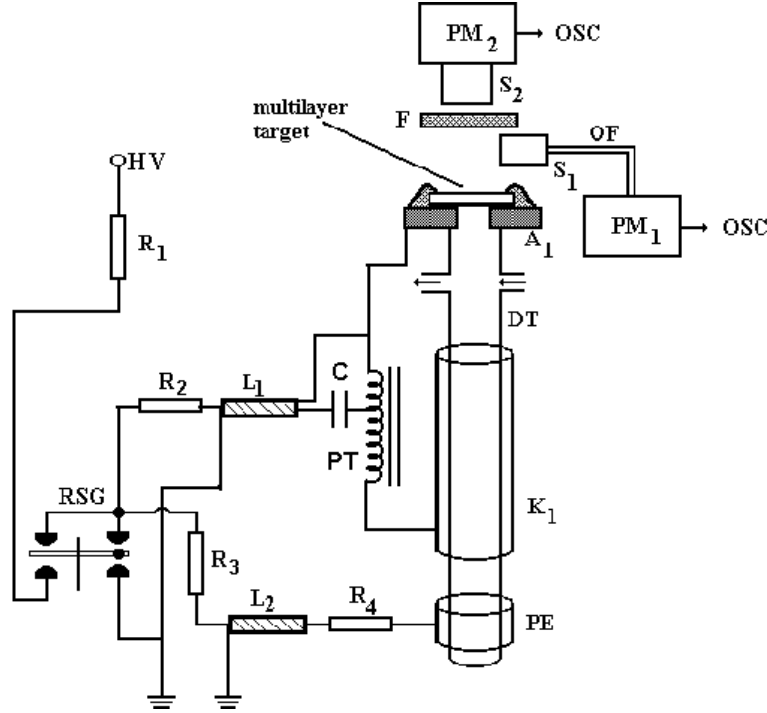


Fig.2 Scheme of the experimental setup for X-ray source characterization: RSG-rotary spark-gap; DT-discharge tube; PM_1 and PM_2 -photomultipliers; OF-optical fiber; S_1 and S_2 -scintillators; F-filter; K_1 and A_1 - cathode and anode for pulsed discharge; PE preionization electrode; $R_1 = 10\ \text{k}\Omega$, $R_2 = 50\ \Omega$, $R_3 = 10\ \text{M}\Omega$, $R_4 = 1\ \text{M}\Omega$, $C = 3.3\ \text{nF}$; PT- pulse transformer 1:3; L_1 = coaxial cable ($l = 1\ \text{m}$) $Z = 50\ \Omega$, L_2 = coaxial cable ($l = 1\ \text{m}$) $Z = 50\ \Omega$,

A set of oscillograms presenting the electrical pulse shape at the cathode, both with and without breakdown, together with the associated X-ray emission are shown in Fig.3. Due to internal photomultiplier delay and measure cable length, the electric signal from the photomultiplier lags 90 ns compared with respect to X-ray pulse.

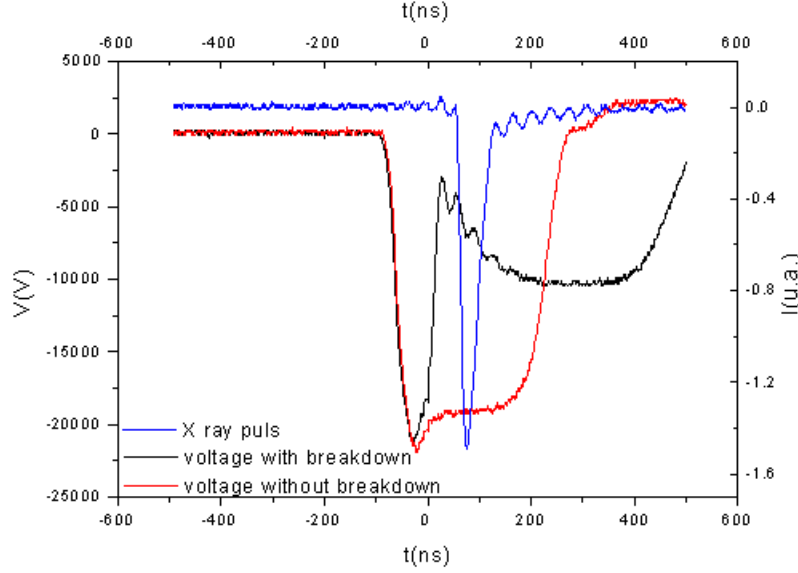


Fig. 3 Electrical pulse shape at the cathode, both with and without breakdown, together with the photomultiplier electric signal associated of X-ray emission

Experimental set-up for X-ray source characterization and results

Measurement of the X-ray radiation with temporal resolution was accomplished by means of an ensemble consisting of a scintillator (NE 102A), optically coupled to a photomultiplier (RCA 7265) and a Tektronix TDS 320 oscilloscope, with a total characteristic rise time of about 6 ns. An additional X-ray detection channel made up of a scintillator (NE 102A), optical fiber and EMI 9656 photomultiplier was used to monitor the overall X-ray emission. To optimize the maximum bremsstrahlung X-ray emission in the 9 - 11 keV range (corresponding to the L edge of Hf), the target used for the electron beam is a 1 μ m thick gold layer, deposited on an aluminium foil of 100 μ m thickness. The gold layer thickness is chosen such as to completely stop the electrons, while maintaining a convenient transmission for the useful X-ray photons. The 100 μ m aluminium substrate coupled with the bremsstrahlung X-ray emission for around 18 keV electron energy, results in an energy distribution of emitted photons towards the irradiated sample, with a maximum around 10 keV. The chromium layer of tens of nanometers thick, located at the gold-aluminium interface, has a negligible effect on the X-ray absorption within the range of interest.

A small scintillator plate (2 mm thick x 10 mm width x 20 mm length) can be placed in contact with the aluminium layer. Thus a sample with dimensions similar to those reported in [4], can be simulated.

Under these specific conditions, we reached the optimum regime in which a maximum dose of X-ray emission through the multilayer target was achieved. The shape of the X-ray pulse is presented in Fig.4. An estimation of the mean energy of the X-ray emitted photons was performed using the filters method. Two detection systems based on the NE 102A scintillator

have been used. The first one ($S_1 + PM_1 + OF$) provided a monitoring signal for the overall X-ray emission. The second ($S_2 + PM_2$) was used with different aluminium filters placed in front of the scintillator (2.5 cm thickness and a 5 cm diameter). The signals obtained for different used filters are also presented in Fig 4. The signals were selected to correspond to reproducible discharge conditions defined by the monitoring (PM_1) detection channel. For the peak of the X-ray signal, measured with the scintillator-photomultiplier ensemble, a mean energy of 9.8 keV is estimated for a gas pressure of $4.3 \cdot 10^{-2}$ torr.

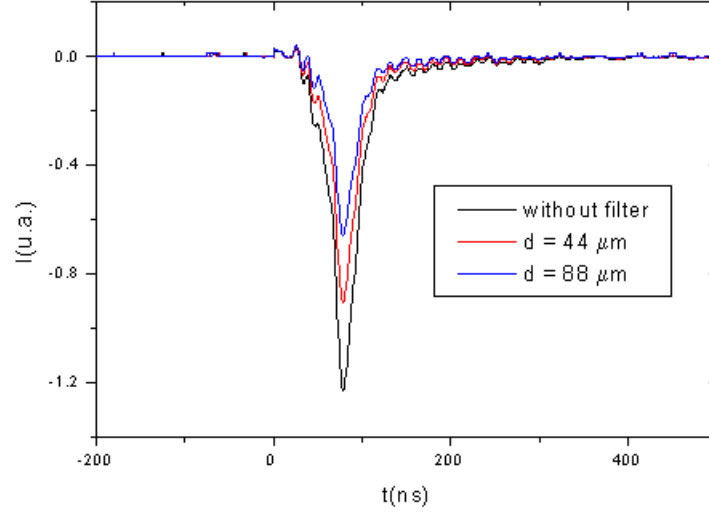


Fig. 4: Signals of X-ray emission for different thickness aluminium filters for a target made of a sandwich consisting in a gold sheet (1 μ m thick) and an aluminium foil (100. μ m thick).

By changing the gas pressure ($4.1 \cdot 10^{-2}$ torr), the mean energy of the emitted X-ray radiation was estimated to be around 11.5 keV.

X-ray signal fluctuations from one discharge to another did not exceed 10% for a repetition frequency of 100 Hz.

For the same parameters of the high voltage pulse and gas pressure, we tested two kinds of dielectric targets: mica and mylar.

The X ray signals obtained with aluminium filters for target made of a mica and mylar sandwich, mica being in contact with discharge electron beam are presented in Fig.5. In this case we estimate a mean energy of about 9 keV.

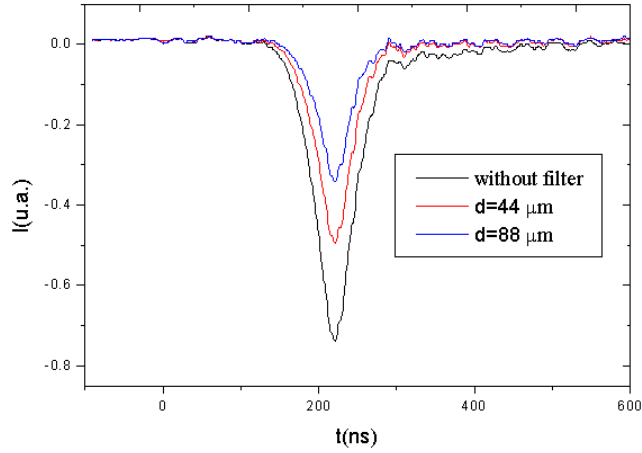


Fig. 5: Signals of X-ray emission for different thickness aluminium filters for target made of a sandwich made of mica ($10\ \mu\text{m}$ thick) and mylar ($20\ \mu\text{m}$ thick)

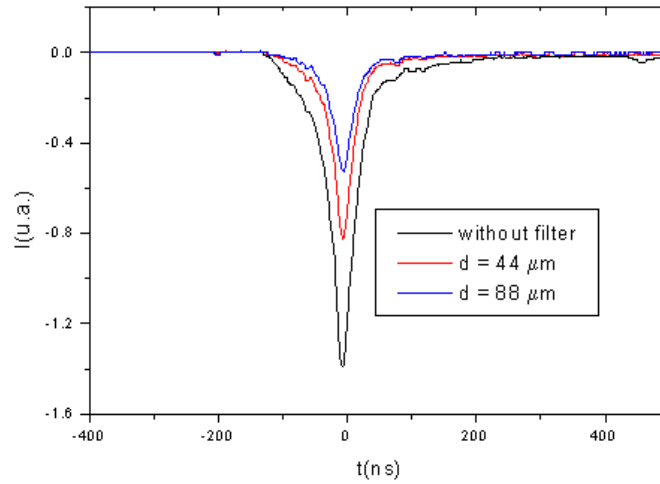


Fig. 6: Signals of X-ray emission for different thickness aluminium filters for target made of a two mylar foils sandwich (each one $20\ \mu\text{m}$ thick)

For a target made of a sandwich of two $20\ \mu\text{m}$ thick mylar foils the X ray signals obtained by using different filters are presented in Fig. 6. The estimated mean X-ray energy is about $8.3\ \text{keV}$. Under these experimental conditions we succeeded in decreasing the mean energy measured up to $3\ \text{keV}$. Due the fact that with this detection system the X ray zero signal is measured with a $8.5\ \mu\text{m}$ aluminium foil placed in front of the scintillator we are not able to detect X-rays with energy smaller than $3\ \text{keV}$

Discussions and conclusions

The described X-ray source based on dielectric hollow cathode transient discharges was designed for isomer triggering studies, for different irradiating configurations in order to obtain the strongest possible coupling with the irradiated sample [8]

The system can be carried very easily, due to its compactness and small dimensions. Because an absolute measurement has not been yet performed, estimation of the X-ray doses was achieved by considering the mean current of the fast electron beam. The mean current value of 2 A over 50 ns is larger than the maximum current in a X-ray source intended for medical purposes.

Synchronization for synchronous detection is achieved by the falling edge pulse of the high voltage measured at the cathode, which assures a jitter of less than 2 ns with respect to the X-ray pulse. If the pulse rising edge is considered as reference, the jitter becomes less than 10 ns. In this case, it is possible to obtain a total jitter value around 10 ns if the rotary spark gap is replaced by a HTS switch and synchronization is realized using external triggering pulses.

The advantages of synchronous detection would result in an improvement of the ratio between the induced gamma emission and the spontaneous emission for the Hf target. This improvement is roughly given by the ratio of the electron currents on the target obtained in different cases for the same acceleration voltage and irradiation geometry.

X-ray source coupling with the probe can be achieved through direct contact, thus leading to an important increase of the irradiation dose.

The X-ray source can use both a metallic and a dielectric target for the discharge electron beam. For a metallic target formed by a 1 μm thick gold layer, deposited on an aluminium foil of 100 μm thickness, for the peak of the X-ray signal, a mean energy of 9.8 keV was estimated (Ar gas pressure of $4.3 \cdot 10^{-2}$ torr and maximum applied high voltage pulse on the cathode of 18kV). In the case of a dielectric target, the negative electric charging of the target is prevented by an ionization state of gas near the target, which is in connection with discharge current growth. In comparison with metallic target we observed that in the case of dielectric target the mean energy of X-ray radiation is lower at the beginning of X-ray pulse. This is due to the fact that accumulated negative electric charge on the dielectric target is not fully compensated from the beginning and a decelerating field appears. As the electron beam current raises the ionized state enhances and surface neutralization is achieved, thus accounting for the increase of the X-ray mean energy.

A big advantage of a dielectric target is the preventing of sputtering on reverse pulses, which are inherent in case of capacitive coupling. This situation results in a good stability of the target characteristics and it was verified by analysis of a 20 μm thick mylar target, after 10 operating hours at a repetition rate of 50 Hz. This proves the possibility of using even a Hf target (Hf in hafnium oxide state) for a thickness of about 0.5 μm , deposited on a dielectric substrate. The 0.5 μm thickness ensures complete absorption of electrons at energies around 10 keV. The Hf target can eventually be protected by means of a 0.1 μm sheet, made of another dielectric such as SiO_2 . Thus Hf is in the same time both electron target and X-ray target. This kind of

target was simulated by using a micas foil as a target for electrons. Henceforth, a dielectric target could be prepared by controlled ionic implantation of Hf atoms in a proper dielectric target, ensuring that implantation is to be achieved in a thickness around hundreds of nm, corresponding to the stopping length of electrons. This situation also allows direct excitation of the L and M electron shells. The use of an Al_2O_3 substrate of 500 μm thickness allows both a convenient thermal dissipation as well as a sufficiently high transmission in order to monitorize the X-ray pulses with energies around 10 keV ($\approx 10\%$). For a repetition rate around 200 Hz, an electron current around 2 A/cm² at 50 ns duration time and a 15 kV pulse voltage value, we obtained a deposited power of around 300 mW/cm², which does not raise difficult problems regarding target heating.

For a mylar target we succeeded in decreasing the mean energy measured down to 3 keV. In case of a 20 μm thick mylar window, also used as target, we estimate that transmitted X-ray radiation (10% transmission) occurs even at energies as low as 1.6 keV, corresponding to the M5 edge of Hf. Under these circumstances, it would be of interest to investigate a possible coupling between the atomic shells and the nucleus, by using as target a mylar foil in which Hf atoms were implanted.

In the case of a possible direct coupling of the bremsstrahlung X-ray radiation with the Hf nuclei we estimate that this coupling would be more effective by employing Hf nuclei themselves as target for the electron beam in order to produce the X-ray radiation.

Moreover, in this case we also expect a direct electron-nucleus coupling through "virtual photons" to occur (simultaneously with the generation of the bremsstrahlung photon able to excite the nucleus), which would entail a more efficient rate of Hf nuclei excitation. If using fast electrons, a synchronous magnetic perturbation with photonic absorption at the nucleus is likely to occur. This perturbation can be induced by the electron propagating in the vicinity of the nucleus and may alter some selection rules. A detailed, quantitative analysis of the theoretical aspects of this problem could represent a matter of further investigation.

A preliminary analysis led us to conclude that employing Hf nuclei as target for the electron beams producing the bremsstrahlung X-rays needed to initiate the excitation process would increase the nuclear cross-section of the X-ray capture. The emission and nuclear absorption process of bremsstrahlung X-rays proceed in this case via virtual photons, and the computation of the corresponding cross-section could be done by standard perturbation methods of quantum electrodynamics, making use of a model interaction hamiltonian that couples directly the electrons to the nuclear states. The latter are taken, to the first approximation, as input model parameters. Preliminary algorithms for targets with given geometry are already sketched, which would enable one to predict quantitatively the variations in the cross-section of such process measured experimentally. At this level of calculations these results would depend of course on the details of the Hf multiplet structure.

Realization of an experimental set-up employing Hf nuclei as electron target and measurements of the cross-section of the excitation process, would give the opportunity to check the theoretical calculations described above, based on the the virtual-photon mechanism and to choose between various models of nuclear structure. In particular, after completing the steps discussed above, one may approach the problem of Hf de-excitation from an excited state toward

states lower in energy, which may imply different types of nuclear bands, of various symmetry and origins, which usually are governed by various selection rules. Possible mechanisms of removing such selection rules, especially by a direct coupling to an external perturbation during the excitation-de-excitation process, also deserve a particular attention. Such complex mechanisms might involve deformed-assisted or symmetry-breaking transition processes, which usually alter the transition rate.

A suitable experimental setup for employing Hf nuclei as target nuclei for the pulsed electron beam could be realized by using the "cruise effect" [9-12] in a configuration for which the energy of the cruising electrons can be modulated in the 10 keV to 1 MeV range. For the 10 keV – 20 keV range, the actual experimental configuration can be optimized. For energies ranging up to 1 MeV, it is necessary to develop special experimental configurations comprising a fast Marx switch and a compact pulsed linear electron accelerator driven by a short laser pulse. The preparation of the target requires the deposition of a thin layer of hafnium oxide on a ceramic support. For reasons of protection, the hafnium oxide layer will be covered with a thin dielectric layer (whose thickness depends of the electron energy range intended to be used).

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