CS8920014

INSTITUTE OF PLASMA PHYSICS

CZECHOSLOVAK ACADEMY OF SCIENCES

ULTRASOFT X–RAY DIAGNOSTICS OF SHORT LIVING PLASMAS

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RESEARCH REPORT

IPPCZ 278

September 1987

POD VODÁRENSKOU VĚŽÍ 4, 18069 PRAGUE 8

CZECHOSLOVAKIA

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ABSTRACT

Ultrasoft X-ray plasma diagnostics in IPP is realized by using X-ray diodes with Al photocathodes and submicrometer nitrocellulose filters. Construction, calibration and characteristic properties of apparatus are described. Main results of diagnostics of REB-heated plasma are presented as an example of use of this apparatus.

INTRODUCTION

The spectral analysis of electromagnetic radiation is one of the principal methods of plasma diagnostics. In a great many of plasma experiments electron temperatures of tens or hundreds of eV and short plasma lifetimes are achieved. Therefore, measurements in ultrasoft X-ray region (10 - 1000) eV with a high temporal resolution (e.g. 10 ps for laser-heated target plasmas) are necessary. The basic type of detector for such measurements is a vacuum X-ray diode with metal photocathode (XRD) [1, 2]. Spectral analysis of radiation is made by filters, which have to be of submicrometer thicknesses for this spectral region. The whole apparatus must be vacuum-connected to the radiation source.

This methodics is useful for determination of total radiation intensity in particular spectral intervals, or electron temperature measurements from the shape of continuum spectra of plasma radiation. Recently, also time resolving ultrasoft X-ray spectrographs were developed, which can be used for more complete measurements [3]. However, these apparatus are relatively complicated and expensive and at present they are used only in large laboratories, especially for plasma sources with high radiation intensities. The method employing XRD's and filters is still generally used because of the possibility to obtain relatively much information by a low-cost apparatus simple in construction and without material accessibility problems.

In the Institute of Plasma Physics in Prague, this apparatus was developed with respect to special conditions of experiments with a plasma heated by high-power relativistic electron beam (REB). Calibration measurements were made, such as calibration of amplifying scintillator-photomultiplier system (which is used in the case of low radiation intensity) by using a special X-ray tube or optical calibration of filters.

The diagnostics of a plasma heated by REB is the main use of this apparatus in IPP (experiment REBEX). Results of such measurements are also presented in this paper. Recently, measurements at an gas puff Z-pinch were made, which can be mentioned as an example of further use of this apparatus.

DETECTORS

The scheme of a simple XRD used in our laboratory is shown in fig. 1. The photocathode views the X-ray source through a wire mesh anode. Incident photons cause emission of electrons (photoelectric, Auger, secondary) from the photocathode, which are accelerated across the cathode-anode gap. The necessary voltage is determined from the requirement of the saturated current regime:

$$(1) \qquad U[V] = 6.67\times10^{3}\left(\frac{d}{D}\right)^{4/3} I^{2/3}[A] \quad ,$$

where d is the cathode-anode distance and D the diode diameter. In the case of REB-heated plasma diagnostics in the REBEX experiment, the XRD is placed in transverse magnetic field. The voltagenecessary for reaching the anode by emitted electrons (ExB drift) is:

$$(2) \qquad U = \frac{e}{m} B^2 d^2 \quad ,$$

where e/m is the specific charge of electron. For the saturated current regime in this case the double of the voltage given by eq. (1) is sufficient. Sustaining of a proper working regime during the measured radiation pulse is guaranteed by a sufficient supply capacity. The detector with parameters shown in fig. 1 is constructed for currents up to 1 A at the pulse duration of 10 µs in conditions of REBEX experiment. Temporal response of the detector is determined by its geometry and measuring electric circuit. In our case the time constant is less than 1 ns.

The spectral dependence of Al photocathode sensitivity, as reprinted from ref. [1], is shown in fig. 2. In this reference, the most useful calibrations for photocathodes of practical interest are made. The sensitivity shows a threshold at 4.25 eV (detectors are not sensitive to a visible light), a maximum between 10 and 20 eV and a relatively rapid drop for higher energies (low sensitivity to hard X-rays). For plasma diagnostic measurements, secondary electron emission by particle impact must be taken into account. Charged particles can be deflected by magnetic field. The signal caused by neutral particles can be separated from that caused by X-rays by utilizing a sufficient detector-plasma distance and a time of flight of these particles.

In the case of low radiation intensity another detector is used (fig. 3), in which photoelectrons are accelerated up to (10 - 20) keV and detected by a scintillator-photomultiplier system [4]. In fig. 4 amplification of such system is shown, depending on its parameters (calibrations made by X-ray tube). The threshold value of accelerating voltage is determined by Al light-tight shield of scintillator. Linearity of such system is limited by photomultiplier working in current mode; in our detectors (using photomultipliers TESLA) it is conserved for signals up to 5 mA at the pulse duration of 10 µs. The time resolution of this type of detector, determined by the scintillator decay constant and risetime of the photomultiplier, is about

10 ns. These systems have to be carefully shielded from magnetic field and hard X-rays (for example caused by REB).

FILTERS

The submicrometer nitrocelulose layers for filter production are made by spreading a drop of zapon-lack (solution of nitrocelulose in organic solvents) on a water surface. In the spectral range above 60 eV, the same absorption characteristics as in the Kurchatow Institute of Atomic Energy in Moscow are used [2]. Calibration in the spectral range below 60 eV was made by means of synchrotron radiation in the Institute of Nuclear Physics in Novosibirsk. The resulting sensitivities of XRD's using filters of different thicknesses are shown in fig. 2 simultaneously with the sensitivity of bare photodiode. At present we plan to make filters also from other materials to obtain more advantageous properties of detection system [1].

The filter thickness is measured by a laser interferometer (λ_{HeNe}= 0.633 µm) with a double transit of light beam through the messured object. The essential refractive index was determined from the position change of interference minimum of reflected light at different incident angles (30°, 60°) of white light. It is 1.46 ± 3% for $\lambda \sim \lambda_{HeNe}$. In the first order of interference, thicknesses up to 0.344 µm can be measured, with the maximum accuracy in the range of (0.15 - 0.20) µm. From the interference measurements also inhomogenities of filter thickness can be determined (usually ± 5%).

The relative filter thicknesses are also measured by means of absorption of infrared light at absorption peaks at the wavelengths about 6 µm and 8 µm. The resulting inaccuracy of filter thickness determination is about 15%.

RESULTING PROPERTIES OF APPARATUS

The specral sensitivities of aluminum measured or calculated by other authors and the accuracy of filter absorption characteristics were studied. By taking into account the possible inaccuracy of sensitivities shown in fig. 2, the inaccuracy of absolute intensity measurements in the spectral range (10 - 1000) eV can be estimated to be of factor 2.

For the electron temperature determination from the shape of continuum spectra of plasma radiation, only relative measurements are necessary. With respect to all facts mentioned above, T_e in the region of tens eV can be determined by filter-method [5] with accuracy between 30% and 40%, which is comparable with that of other diagnostic methods used at REBEX experiment.

The utilization of such apparatus for T_e measurements below 10 eV and above 100 eV is not suitable.

X-RAY TUBE

The "Henke-type" X-ray tube [6] was used as a radiation source for calibration measurements (e.g. the calibration of amplifying system mentioned above). The concrete geometrical arrangement was designed by using the electroplating vat. In fig. 5 equipotential lines and traces of electrons and emitted photons are shown. The right shape of electric field with the effect of space charge taken into account was adjusted by little changes of the anode and holder widths. The cathode is a directly -heated W coil. The electron beam is electrostatically focused on the area of 20 mm (~ cathode length) x 3 mm on both sides of the anode. The anode, heating voltage supply and cylindrical shielding are water-cooled.

Main advantages of such arrangement of low voltage tube are the following:

a) tungsten from cathode cannot be deposited on the anode and influence the spectrum of radiation, which is generated only in a thin surface layer of the anode;

b) the construction is simpler than that of linear electron guns, especially in connection with possible modifications of the arrangement for other measurements.

The tube was operated in the regime with beryllium anode by the voltage of 1 kV and the anode current of 30 mA. By the use of our XRD's and filters, the radiation intensity of the order of 10^{-4} W/ster. with comparable parts of Be_K(109 eV) spectral line and bremsstrahlung spectra was found. For further calibration measurements (calibrations of semiconductor X-ray detectors in low energy region, for example) we plan to generate the Be_K and C_K lines by suppression of bremsstrahlung spectra at utilizing the radiation in backward direction compared with electron beam incidence on the anode [7]. The accurate intensity measurements will be made by gas proportional counter.

REB-HEATED PLASMA DIAGNOSTICS

On the REBEX experiment the REB-plasma interaction is investigated in connection with the research of magnetic confinement linear thermonuclear reactors [8]. One of the main tasks of this experiment is to solve the problem of energy balance, i.e. the determination of total energy content (by measuring plasma diamagnetism) and its distribution between various plasma components (plasma bulk, overthermal electrons) and contingent macroscopic motion of plasma column (configuration oscillations). For this reason the above mentioned measurements of electron temperature of plasma bulk by filter-method in the ultrasoft X-ray region were made.

In this paper results of such measurements are presented in the case of a dense plasma $(10^{20} - 10^{22})\ m^{-3}$ generated by two cooperating plasma guns (fig. 6 - scheme of experiment and axial profile of plasma density). At the plasma-vacuum boundary fixed by a terminating foil, the injected beam (350 kV, 30 kA, 120 ns) is reflected back into the plasma (the reflection regime corresponding to the higher heating efficiency [8]). As shown in fig. 6, the X-ray measurements were made in two regions with different plasma density levels, simultaneously with the diamagnetic ones.

The XRD signals shown in fig. 7 exceed by three to four orders of magnitude those given by the hypothesis of pure hydrogen plasma radiation. Nitrogen, oxygen, carbon and aluminum are the probable impurities which can cause this observed increase of radiation intensity. In some regimes, macroscopic particles are presented in the plasma, arising from an Al-coated mylar anode foil of the beam-injecting diode (the principal component is carbon). Radiation of electrons interacting with these particles was taken into account as that of solid targets in a plasma. It cannot influence the plasma bulk electron radiation, but the excitation of C_K line may be one of the radiation mechanisms caused by overthermal electrons.

In the dense plasma region $(10^{21} - 10^{22})\ m^{-3}$, the light impurities mentioned above are almost in the corona equilibrium [9]. In this case, theoretical curves of decrease of XRD signal by filters for pure hydrogen plasma and plasma with several per cent of such impurities are nearly the same for $kT_e = 12$ eV. In the peak of XRD signal (beam injection time - fig. 7a), the results of measurements with filters of thicknesses $d < 0.1$ μm correspond to this temperature (fig. 8a). The small decrease of signal measured by thicker filters can be explained, at this temperature, only by the radiation of overthermal electrons. The rapid drop of XRD signal (fig. 7a) corresponds to the decrease of intensity of impurity line emission by increasing electron temperature (after beam injection it can be caused by relaxation of overthermal electrons and/or dissipation of energy of plasma column oscillations [8]). The electron temperature of about 20 eV, determined from DIA signal at the corresponding moment, can produce this decrease of intensity only for carbon [10]. Therefore, it has to be the dominant impurity (~2% of total plasma density), in agreement with the presence of target particles mentioned above.

In the low-density region of REBEX experiment (10^{20} m^{-3}), the characteristic ionization times of impurities are comparable with the plasma lifetime [9]. During the measured X-ray pulse, the ionization state of plasma corresponds to the energies of spectral lines and recombination thresholds of tens of eV [10]. For our T_e measurements they can be suppressed by using filters with thicknesses $d > 0.3$ μm. The resulting electron temperature is near to 60 eV (the slope of measured curve - fig. 8b). At the time of beam injection and closely after it, the influence of overthermal electron radiation is observed by using filters of such thicknesses (similarly as in the dense plasma region). The correlation of XRD- and DIA- signals is very good in this case (fig. 7b). The HF component of both signals corresponds to the configuration oscillations of plasma column. The first large peak of DIA signal can be explained by overthermal electrons.

ACKNOWLEDGEMENTS

We would like to acknowledge Ing. P. Šunka, CSc. for many helpful discussions and Ing. J. Ullschmied, CSc. for cooperation in REB-heated plasma diagnostics, especially in diamagnetic measurements interpretation.

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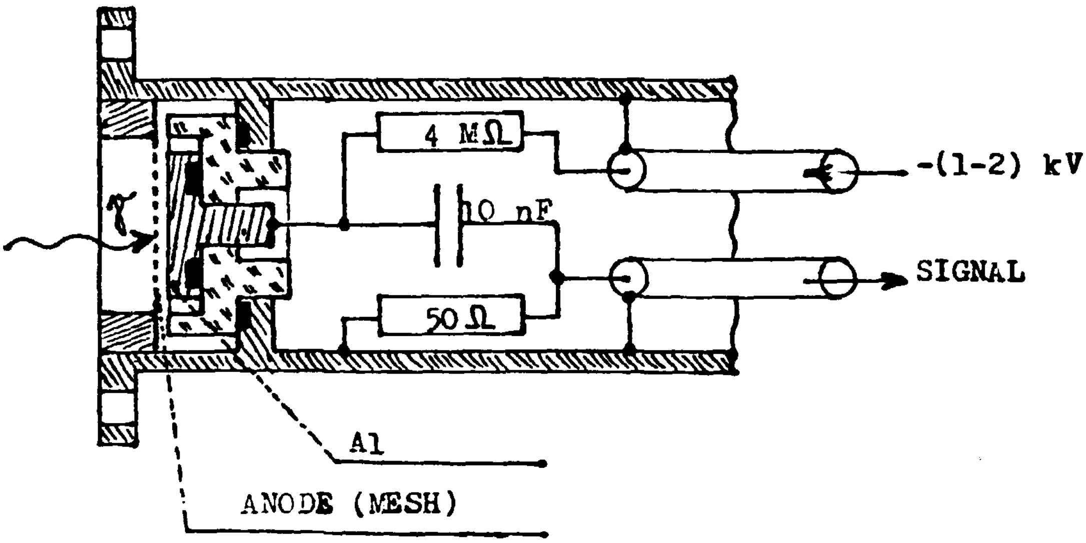


Fig. 1: Scheme of X-ray diode

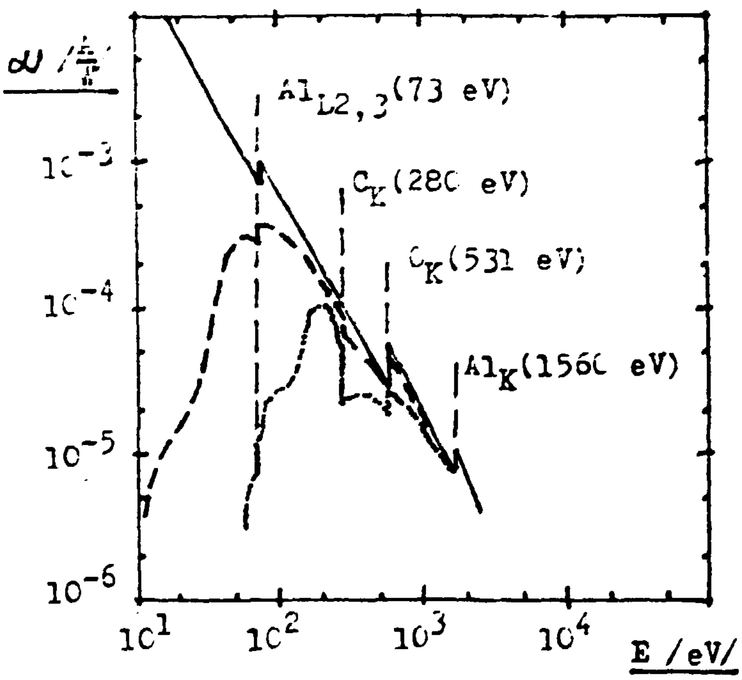


Fig. 2: Spectral sensitivity of XRD;

—— Al; ---- Al+0.1 um filter; -........ Al+0.5 um filter

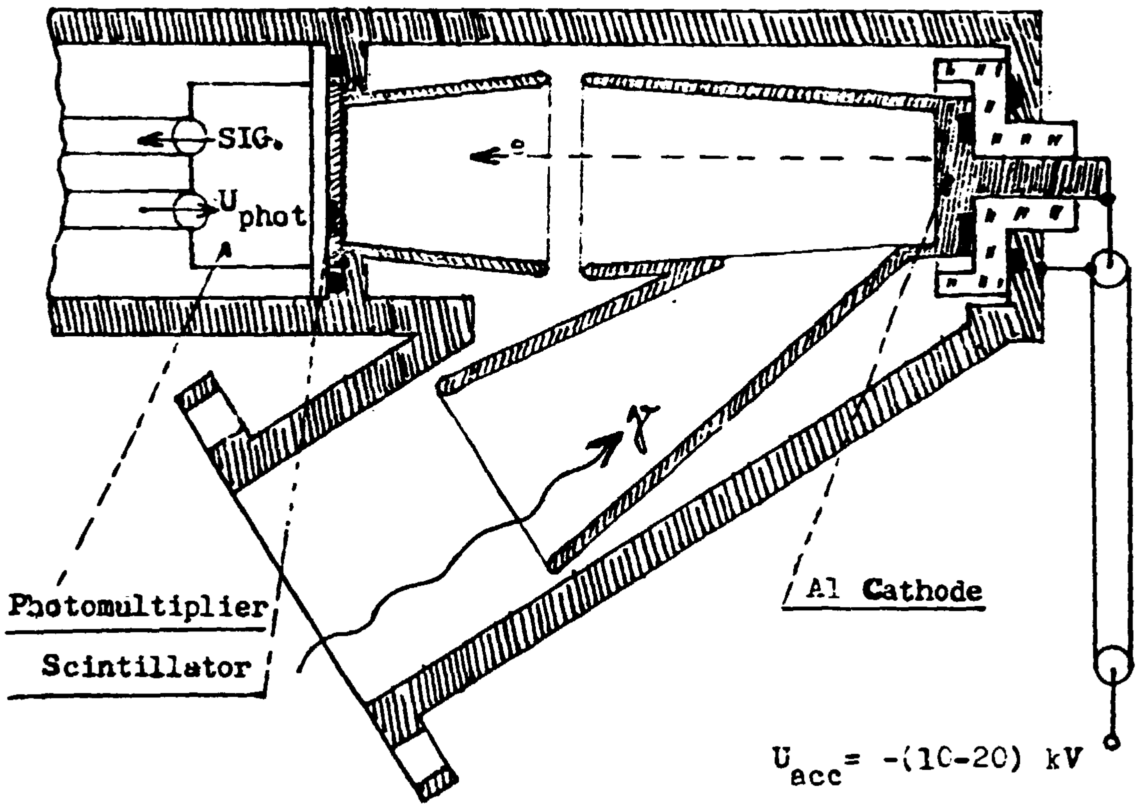


Fig. 3: Low intensity detector

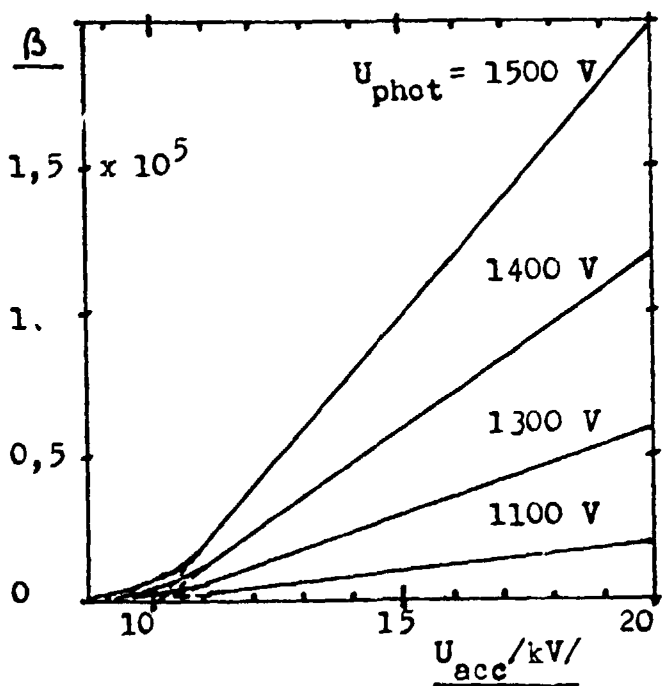


Fig. 4: Amplification of a scintillator-photomultiplier system

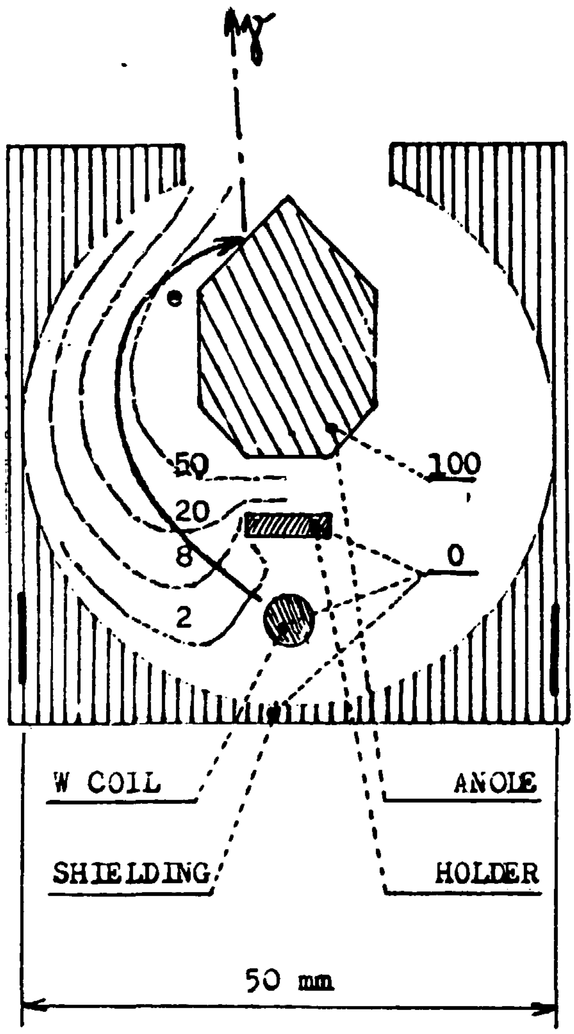


Fig. 5: X-ray tube

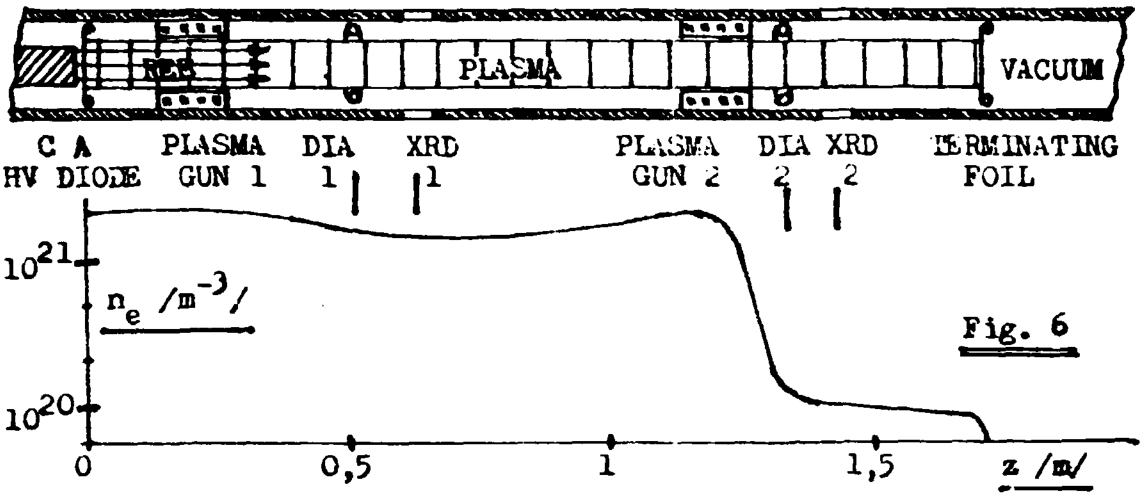
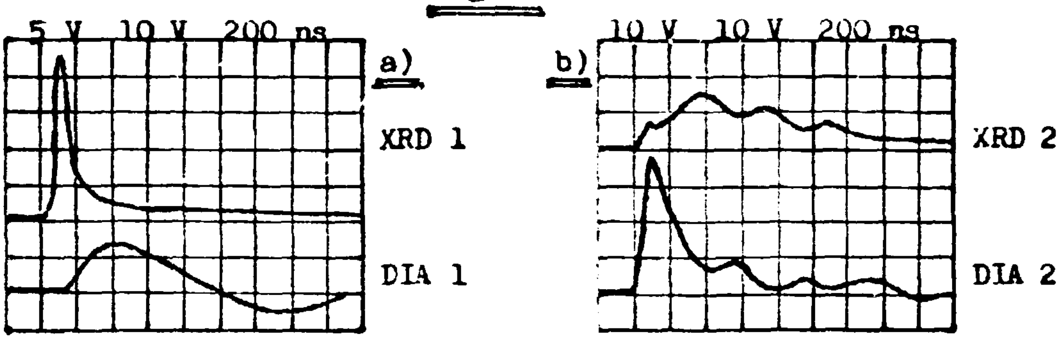
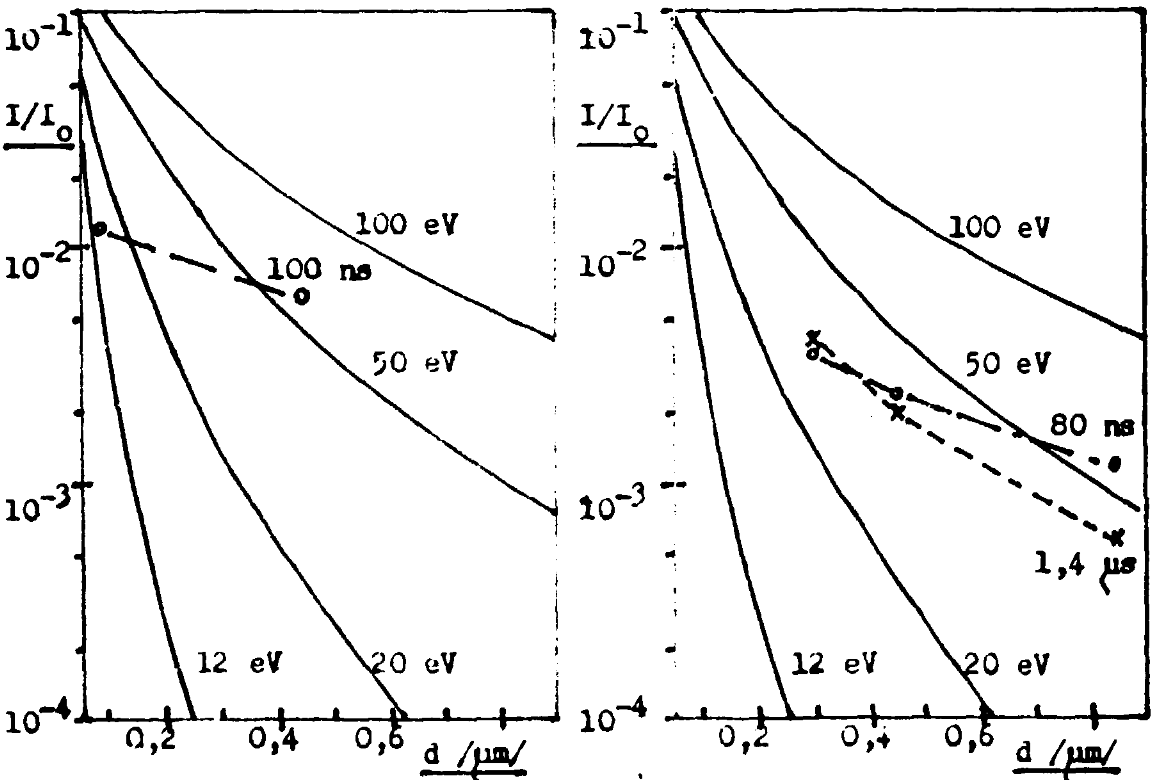


Fig. 6

Fig. 7





a) Fig. 8 b)