ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

E.N.Dementiev, E.Ya.Dovga,
E.I.Zagorodnikov, G.N.Kulipanov,
A.S.Medvedko, N.A.Mesentsev,
V.F.Pindyurin, A.S.Sokolov,
V.A.Ushakov, M.A.Sheromov

THE FAST RESPONSE SCINTILLATION ONE-COORDINATE X-RAY DETECTOR FOR MEDICAL DIAGNOSTICS USING SYNCHROTRON RADIATION

PREPRINT 84-19

НОВОСИБИРСК

THE FAST RESPONSE SCINTILLATION ONE-COORDINATE X-RAY DETECTOR FOR MEDICAL DIAGNOSTICS USING SYNCHROTRON RADIATION

E.N.Dementiev, E.Ya.Dovga, E.I.Zagorodnikov,
G.N.Kulipanov, A.S.Medvedko, N.A.Mesentsev,
V.F.Pindyurin, A.S.Sokolov, V.A.Ushakov,
M.A.Sheromov

Institute of Nuclear Physics,
630090, Novosibirsk, U S S R

Abstract

In the work presented here the fast response, one-coordinate X-ray detector being built for operation with synchrotron radiation is described. The detector consists of 128 channels, each is the scintillation counter. The spatial resolution of the detector is 1.5 mm, its count rate is 128x1 MHz. The results of the study of the unit consisting of three detector channels on the SR beam are given. The detector operational features with the NaI (Tl) scintillators near the iodine absorption K-edge (33.2 keV) are discussed. The main purpose of the detector is to study the man's circulation system with the differential angiography method at a quantum energy corresponding to the iodine absorption K-edge.

I. INTRODUCTION

In recent years, the growing interest is noticed to the problem of using the synchrotron radiation (SR) for the purposes of medical diagnostic of various diseases of a man. The digital differential angiography method (DDA) is being actively developed which employs the survey of two X-ray pictures at the quantum energy close to the iodine absorption K-edge /1,2/. The development of this method required to design an appropriate X-ray detector with a spatial resolution of the coordinates of detected quanta. As shown in Ref. 2, such a detector should have sensitivity area of $\geqslant 100$ mm, the spatial resolution $\leqslant 1$ mm, high detection efficiency (close to 100%) for the photons of energies up to 100 keV, an acceptable counting rate.

The one- and two-coordinate detectors available do not satisfy the main requirements of the DDA method. Typically, for the quanta with energies of 30-100 keV the conventional detectors have the too low detection efficiency ($\sim 1 \div 10\%$); in the quantum counting mode - too low total (for the whole detector) counting rate ($\leqslant 1$ MHz), in the current mode - too low sensitivity for small fluxes of quanta.

The work presented here is devoted to the scintillation detector which is being built in the Institute of Nuclear Physics of the Siberian Division of the USSR Academy of Sciences, Novosibirsk. The detector having the spatial resolution of 1.5 mm consists of 128 independent scintillation counters with a counting rate ~ 1 MHz for each channel, an average detection efficiency for the quanta of energies 33.2 keV is 75%.

2. THE DETECTOR DESIGN

The detector is designed for operation with synchrotron radiation reaching the detector after the monochromator in short pulses. One pulse can have one or more X-ray quanta and in the storage ring operation in a single bunch mode the pulse repetition rate is equal to the electron revolution frequency. The introducing into the detector scheme of the elements for the signal amplitude analysis and thus for counting the X-ray quanta reaching the detector for one pass of an electron beam enables one to increase the detector count rate which in the opposite case is limited by the revolution frequency.

The detector consists of 128 independent and identical channels. The sensitive elements of the detector are the crystals of the NaI(Tl) scintillator where the X-ray quantum energy is converted into the light flashes. The design of the light guide with a scintillator is shown in Fig. 1.

The light guide is made of organic glass, it consists of the flat and cylindrical light guides bonded to each other with an adhesive. The scintillator disks of 4.5 mm in diameter and 1 mm thick are polished and sealed in the head part of the flat light guide. The total thickness of a single light guide is 1.5 mm with the sensitive area of 1 mm. The cylindrical part of the light guide is glued directly to the input window of the photomultiplier. The light guide design provides 12-15 electrons from the photocathode of the multiplier per single quantum of X-ray radiation at an energy of 30 keV. The FEU-60 with a SbCs photocathode of 10 mm in diameter is selected as an operational photomultiplier in the detector channel. The PM output signal in the form of a succession of signals synchronised with the beam revolution in the storage ring comes to the amplifier-discriminator (AD). The determined time structure of the signals analysed enabled one to introduce an external triggering of some AD units. This permitted to increase substantially the system count rate, its noise protection and to avoid the use of the complicated and inertial circuits for the reset of the discriminator zero, which are usually used in operation with large fluxes of the statistically distributed quanta. The integration time of the amplifier signal is selected equal to 500 ns that practically corresponds to the total PM charge collection.

The AD enables one to perform the minimal amplitude analysis of the signal. The circuit has two discrimination thresholds, of the lower and the higher levels. The lower level discriminator serves the traditional function of removing the noises from the PM signals of small amplitude; the upper level discriminator is tuned to detection of two and more quanta of the incident monochromatic SR beam.

The discriminator threshold levels ratio is 3:1, being the same for each channel. The general value for the threshold levels is established with a computer during the detector adjustment. The use of two thresholds in the discriminator instead of one makes the detector count rate more than twice higher in operation with a monochromatic synchrotron radiation.

The detector is designed in the unit-and-module version. The channel modules of the detector are groupped in the sectorial units which are mounted in the detector body. The channel module comprises the elements given in Fig. 2 by dashed lines. All the parts of the module are installed on the special guide having the fine fit in the sector.

Each sectorial unit of the detector is designed for 16 channel modules and has a form of a circle sector with apex angle of 140° (see Fig. 3). The sector has the dovetail slots for each guide of the channel modules which are laterally spaced along a helix forming a fan with a step of 1.5 mm being equal to the total thickness of the light guide. Such a design leads to that the flat light guides of the channel modules conveging in the center of the sector form the fan 24 mm thick.

The channel-module and the sector guides are made of the all-milled aluminium details produced with the computer controlled machines. The detector design allows the superposition of any number of sectors. In our case, the detector is designed for 8 sectors (128 channels). In the place of the flat light guide convergence the area in the form of the rule of 192 mm long sensitive to the X-ray radiation is formed. On the front wall of the detector body before the light guide rule the X-ray radiation input window is cut and covered with a removable berillium foil 300 μm thick. The lower part of the body is used for the detector cable braids and connectors. General view of the detector with one sector installed is shown in Fig. 4.

The functional diagram of the detector is shown in Fig. 5. All the electronics beyond the detector body is located in one rack. The measurement and control units are produced in the CAMAC standard; they take two crates.

Eight of the 16 channel units of the high voltage sources (VVI-16), which are monitored with a computer by eight of the 16 channel digit-to-analog converters (DAC-16), are used for the PM power supply. The output voltage and load currents of VVI-16 channels are controlled with a 12-bit analog-to-digital converter (ADC). Two of the 128-channel commutators of analog signals (CAS-128) are used for applying the controlled voltages to the ADC input.

The discriminator threshold level is established with DAC-integrator. The timing pulse generation for the amplifier-discriminators of the detector channels is provided by the synchronisation unit from the first harmonic signal of electron revolution frequency f_0 in the storage ring. The timing pulse position is tuned by 50 ns steps within the beam revolution period. The beam revolution frequency for the storage ring VEPP-4 is 816 kHz.

For counting the detector channel output signals sixteen of the 8-channel, 24-bit counters are used (C-8) with maximum counting rate of 10 MHz for each channel. The pulse counting rate is established with a timer.

3. EXPERIMENTAL TEST OF DETECTOR CHANNEL WITH SYNCHROTRON RADIATION

In order to check the detector operability and to study its parameters, the main characteristics of a single channel has been studied with the SR beam from the storage ring VEPP-4 in the following operation mode: electron energy - 5 GeV, electron current-5-10 mA, magnetic field in the radiation point - - 0.65 T, a distance from the radiation point - 25 m. The measurements have been carried out in the single bunch mode of the storage ring operation.

The Ge (III) "butterfly" was used as an X-ray monochromator tuned to the iodine absorption K-edge (33.2 keV). The dimensions of the monochromatic X-ray beam reaching the channel scintillator were formed with two X-ray slits having the adjustable gaps. The flux of the X-ray quanta in a scintillator was measured with the flight ionization chamber installed in front

of the detector channel. The detector channel-module was placed on the two-coordinate scanner table being movable both in the vertical and horizontal directions.

Prior to operation with the detector channel the SR beam spectrum was measured after monochromator with the NaI(Tl) (Ø 20 mm, h = 20 mm) spectrometric scintillator mounted on the input window of FEU-130 with a large coefficient of a secondary emission on the first dynode. The spectrum analysis has shown that the intensities of the crystal higher order reflection lines are negligibly small compared to the main line intensity (relative contribution is $4\cdot10^{-3}$ and $2\cdot10^{-3}$ for the second and the third orders respectively).

The differential amplitude spectra of the channel amplifier output signal were taken by the PM high voltage scanning with a constant discrimination level and also be varying the discrimination threshold at a given high voltage. In both cases, the quantum absorption photopeaks are well separated from the noises.

The study of the detector channel load characteristics (the count rate dependence on the quantum flux F absorbed in the scintillator) has been performed for the one- and two--threshold amplifier discriminators.

The X-ray quantum flux was adjusted with the horizontal size of the slit and controlled by the ionization chamber signal. The absolute calibration of the ionization chamber signal for the quantum flux was performed at small loads (10-20 kHz).

The experimental dependencies of the counting rate in the channel on the load during operation with the one- and two--threshold AD are given in Fig. 6. The calculated dependencies, obtained in the approximation of the full separation of the single quantum peak from the two-quanta peak and from the noises, are also given in Fig. 6. From the diagrams given it is seen that at large loads the counting rate curves are approaching to their asymptotic values being equal to f_0 for the single threshold AD and to $2f_0$ for the two-threshold AD. An agreement between the experimental and calculated dependencies for the two-threshold AD one can consider as a good one, especially within the load range of ~1 MHz. A decrease in the load curve bending coefficient by 30% from the unity occurs at the load of F = 340 kHz for the single-threshold AD, and at F=950 kHz for the two-threshold AD.

In this detector design the channel modules are located in the form of a fan and the angle between the quantum incidence direction and the extreme channel light guide axis in the sector reaches the value of ± 70°. A decrease in the light collection factor as a function of the incidence angle of X-ray quanta was also studied.

The dependency obtained has the form of the function falling down slowly to the angles 90°. A decrease in the light collection coefficients for the extreme light guides (an angle ±70°) with respect to the central light guides (an angle ± 4.7°) is within the acceptable value of 36%.

The feature of the use of the NaI(Tl) crystals as scintillators is that at the quantum energies higher than the iodine absorption K-edge the intense radiation of fluorescent quanta of the iodine K-series is occured in scintillator. A part of these quanta escapes the scintillator and can reach the detector neighbouring channel scintillators. With a quantum energy lower than the iodine absorption K-edge the fluorescence in a crystal occurs from the low energy L,M, etc. shells of the iodine atom and nearly totally absorbed in the crystal. This leads to changes in the absolute efficiency of detection and in influence of the neighbouring channels to each other.

For the detector absolute efficiency estimates the NaJ(Tl) (D106-2) X-ray scintillator and PM FEU-130 were used which guaranteed the full separation of the quantum absorption photopeak from the noises in an amplitude spectrum. The correspondence was found of the counting rate for PM quanta to the signal from the ionization chamber at a quantum energy higher and lower than the iodine absorption K-edge. An absolute efficiency of the commercially available scintillator was calculated taking into account the NaI(Tl) crystal and the escape of the fluorescent and scattered quanta from the scintillator. By the measurements of counting rate with an industrial scintillator and in the detector channel at a given signal from the ionization chamber the estimates are obtained for an absolute detector efficiency. It is 84% at a quantum energy lower than the iodine absorption K-edge and 57% at the energy higher than the K-edge.

For the study of the detector channels influence to each other the flat light guides (without cylindrical components) with scintillators were mounted on the flat light guide from its both sides.

Such a sandwich made of three flat light guides was scanned vertically with respect to the X-ray beam of $65 \mu m$ in vertical size. The counting rate in operation channel was measured in each scanning point. The sandwich profiles obtained at quantum energies both lower and higher than the iodine absorption K-edge are shown in Fig. 7.

The operation light guide profile at a quantum energy lower than the iodine absorption K-edge is similar to the orthogonal profile. At a quantum energy upper than the iodine absorption K-edge the profile goes down rapidly from the center to the edges that can be explained by the escape of iodine K-series fluorescent quanta through the lateral facet of the scintillation disk. The profile side lobes (dashed in the pictures) correspond to the detection of the X-ray quanta which came to the operation scintillator from the side light guides.

An influence of the detector channels to each other can be given by the ratio between the integral under the profile side lobes and the integral value of the main peak. For the cases a and b in Fig. 7 the ratio is 3.7% and 14.1% respectively. The interchannel influence became equal to 0.5% and 1.2% respectively after putting a $50 \mu m$ W foil between the flat light guides in the places of the crystal location. The total foil thickness of $100 \mu m$ between the light guides envisaged in the detector design should decrease the detector interchannel influence down to 0.1%.

The well known effect of the slow post luminescence of NaI(Tl) caused some uncertainties for the detector operability at higher counting rates ($F \gtrsim 1$ MHz). The experimental tests of a single detector channel with SR beams have shown that for the standard modes of operation the postluminescence pulses are not observed in practice in the PM amplitude spectra.

In the spectra obtained at low counting rate after intense irradiation of the crystal ($F \gg 1$ MHz) the post-luminescence phenomenon was observed as single peak corresponding to the PM signal small amplitudes (in the noise area). During the analysis of such spectra it was noticed that the post-luminescence maximum peak moves to the area of the signal smaller amplitudes and it disappears for the time interval of about 15 minutes.

4. CONCLUSION

The tests of the parameters of the detector single channel with SR at a quantum energy of 33.2 keV have shown that the detector described should have a high count rate (~ 1 MHz/chan), high detection efficiency (60-90%), weak inter channel influence (~ 0.1%). The full operation of 128 channels is planned to the end of 1983.

It seems promising and attractive to change the NaI crystals to the YAl - garnet scintillators. Such a replacement would simplify considerably the light guide production technology, eliminate the dead zones in the detector sensitive zone and would also enable one to avoid the specific difficulties in operation at a quantum energy near the iodine K-edge. In addition, the shorter time of luminescence required for YAl-garnet (130 ns) would permit the detector operation in the multi-bunch mode of the storage ring operation.

The main purpose of the detector is its use for DDA. Though, the detector can also be used in other studies which do not require a very high spatial resolution, for example, for the studies of dynamics of diffraction pictures for various materials with a high time resolution (~1 ms). The operation energy range of the detector corresponds to 15-150 keV. From the low energy part this energy range is limited by the scintillator light yield and from the high energy part it is limited by the decrease in the quantum detection efficiency.

In conclusion, the authors wish to acknowledge A.V.Pavlenok and L.V.Ankudinov for preparation of the light guides and for the help in current work and to thank G.M.Kolachev for the useful discussions of the detector design.

REFERENCES

1. E.B.Hughes, H.D.Zeman et al., "The application of synchrotron radiation to non-invasive angiography", Nuclear Instruments and Methods, 208, 665, 1983.

2. G.N.Kulipanov, N.A.Mesentsev et al. "Application of synchrotron radiation to the study of man's circulatory system", Nuclear Instruments and Methods, 208, 677, 1983.

FIGURE CAPTIONS

Fig. 1.	The design of the light guide with a scintillator.
Fig. 2.	Functional scheme of the detector channel.
Fig. 3.	Detector sector with channel-modules.
Fig. 4.	Detector with one sector installed.
Fig. 5.	Functional scheme of detector electronics. DB-distribution plate; CAS-128 channel analog commutator; ADC - analog-digital converter, HVSS-16 - 16-channel high voltage source; DAC-16 - 16-channel digital-to-analog converter; S-8 - 8-channel counters ; f_o - beam revolution frequency.
Fig. 6.	Experimental dependencies of the counting rate f in the channel on the load F during operation: 1 - one-threshold discriminator, 2- two-threshold discriminator, 3- theoretical curves.
Fig. 7.	The sandwich profiles obtained at quantum energies both lower (a) and higher (b) the iodine absorption K-edge.

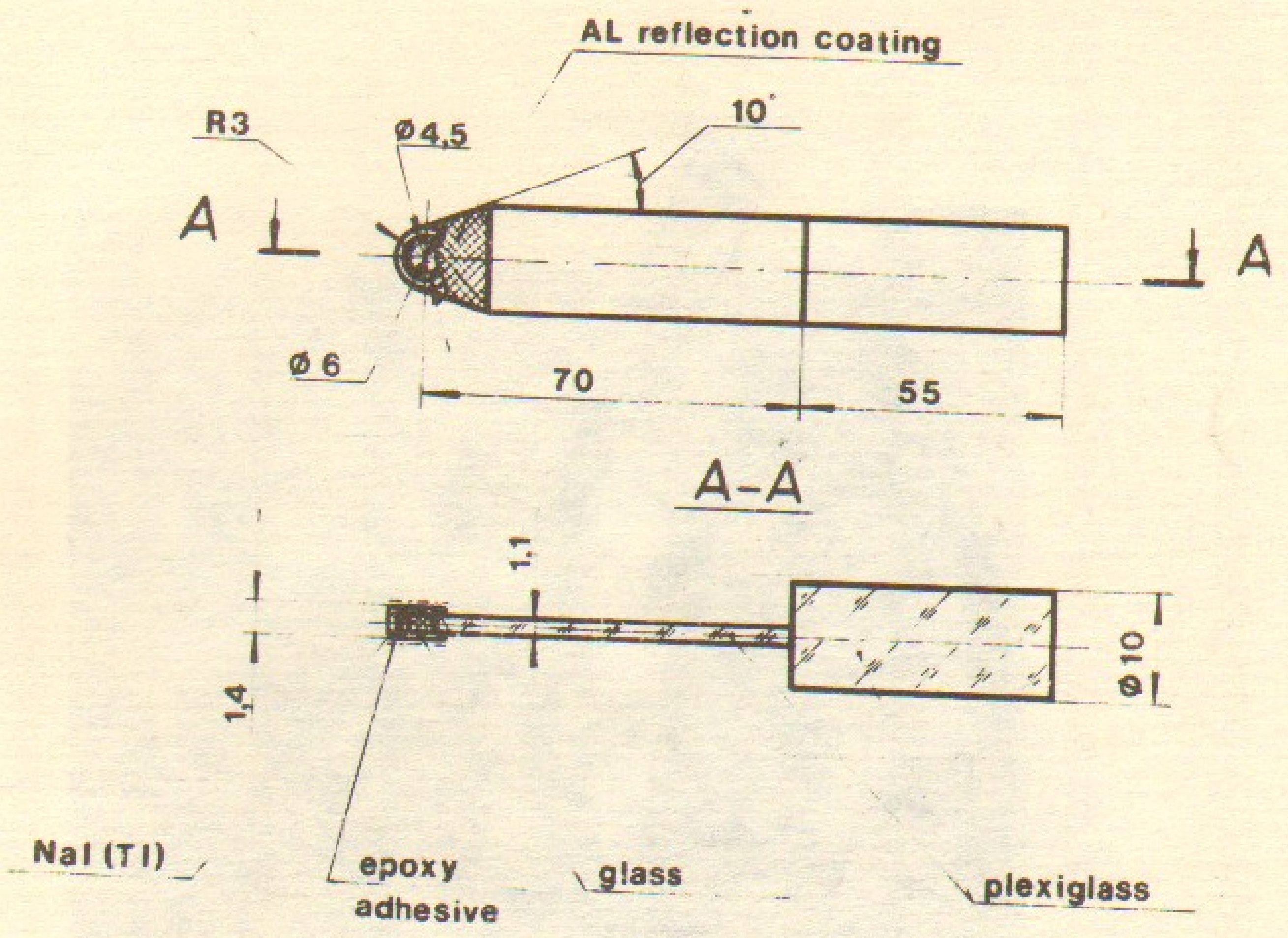

Fig. 1.

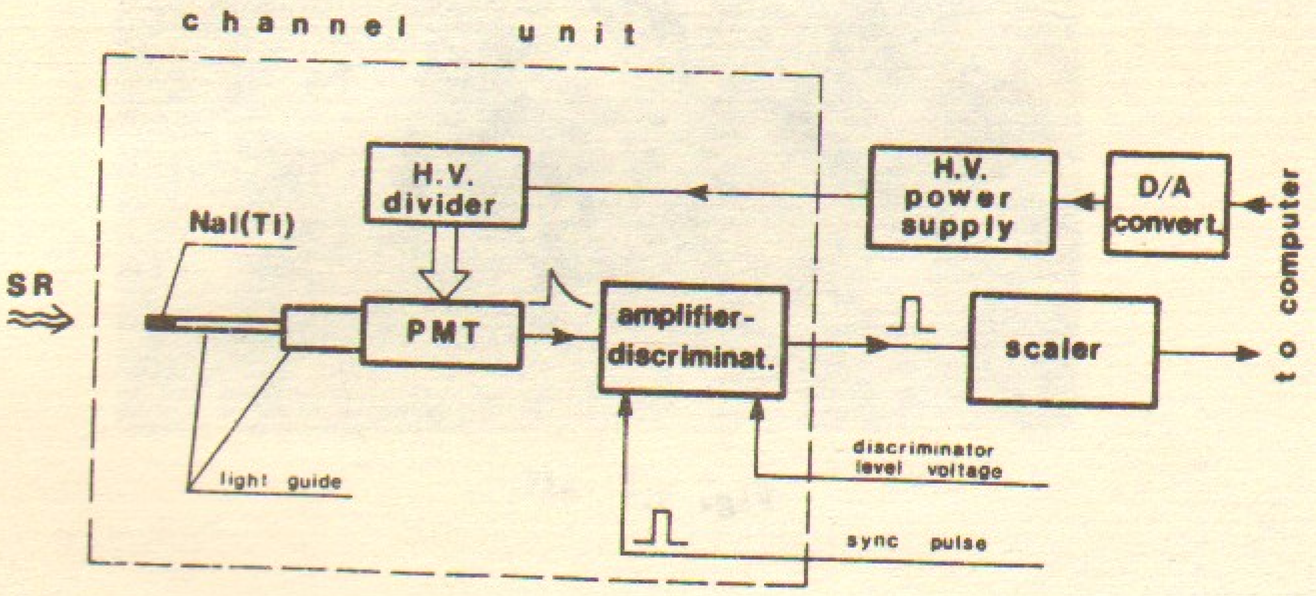

Fig. 2.

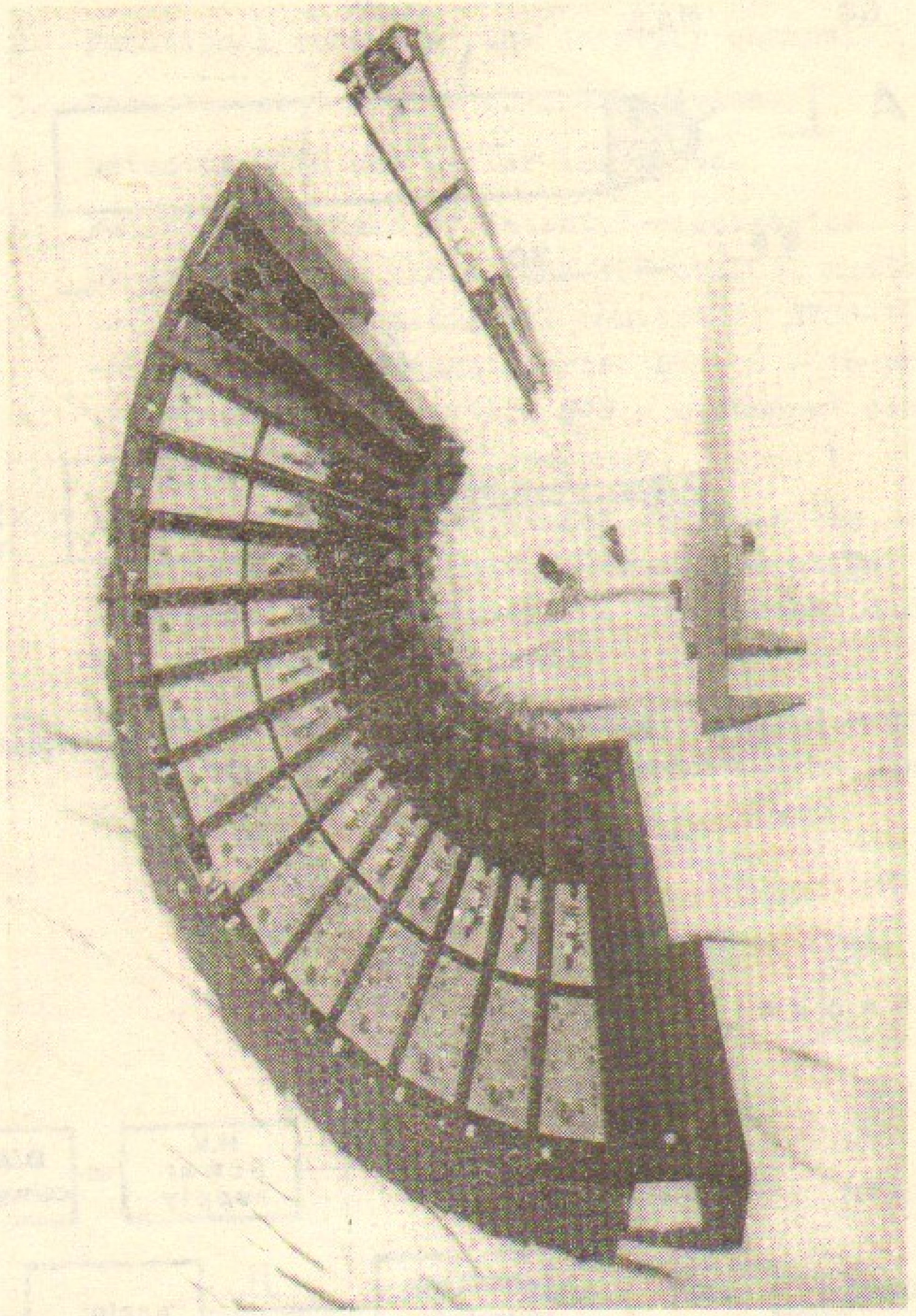

Fig. 3.

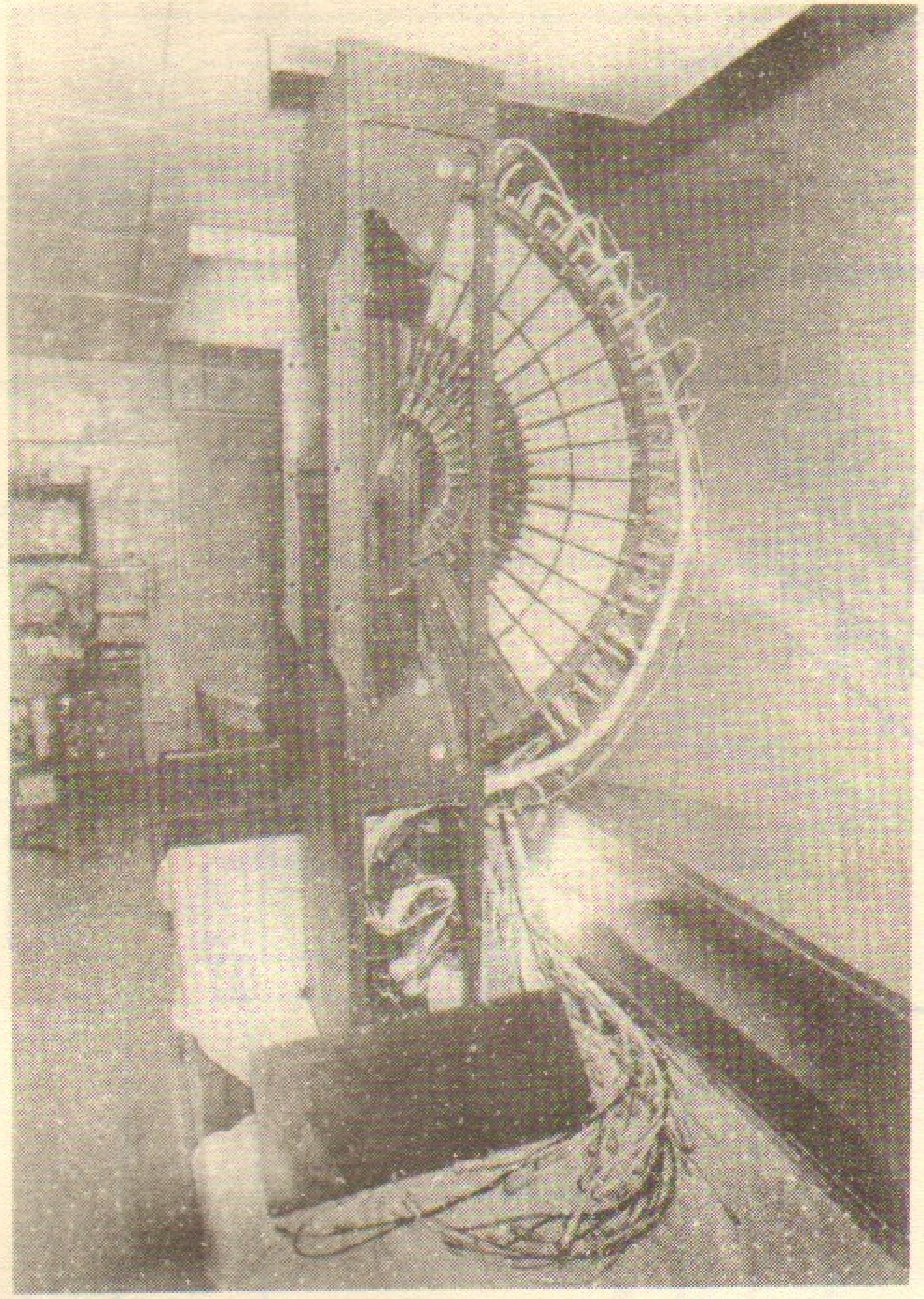

Fig. 4.

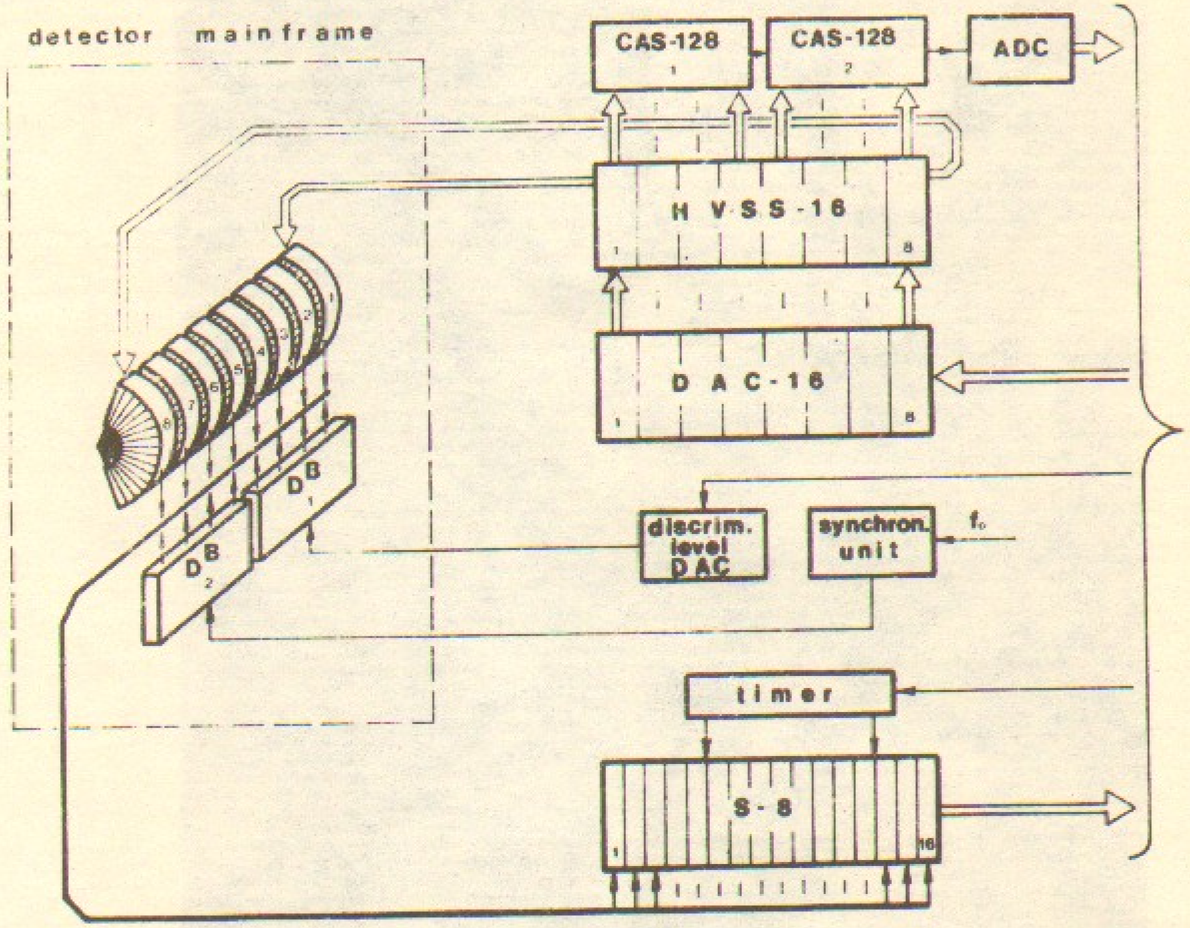

Fig. 5.

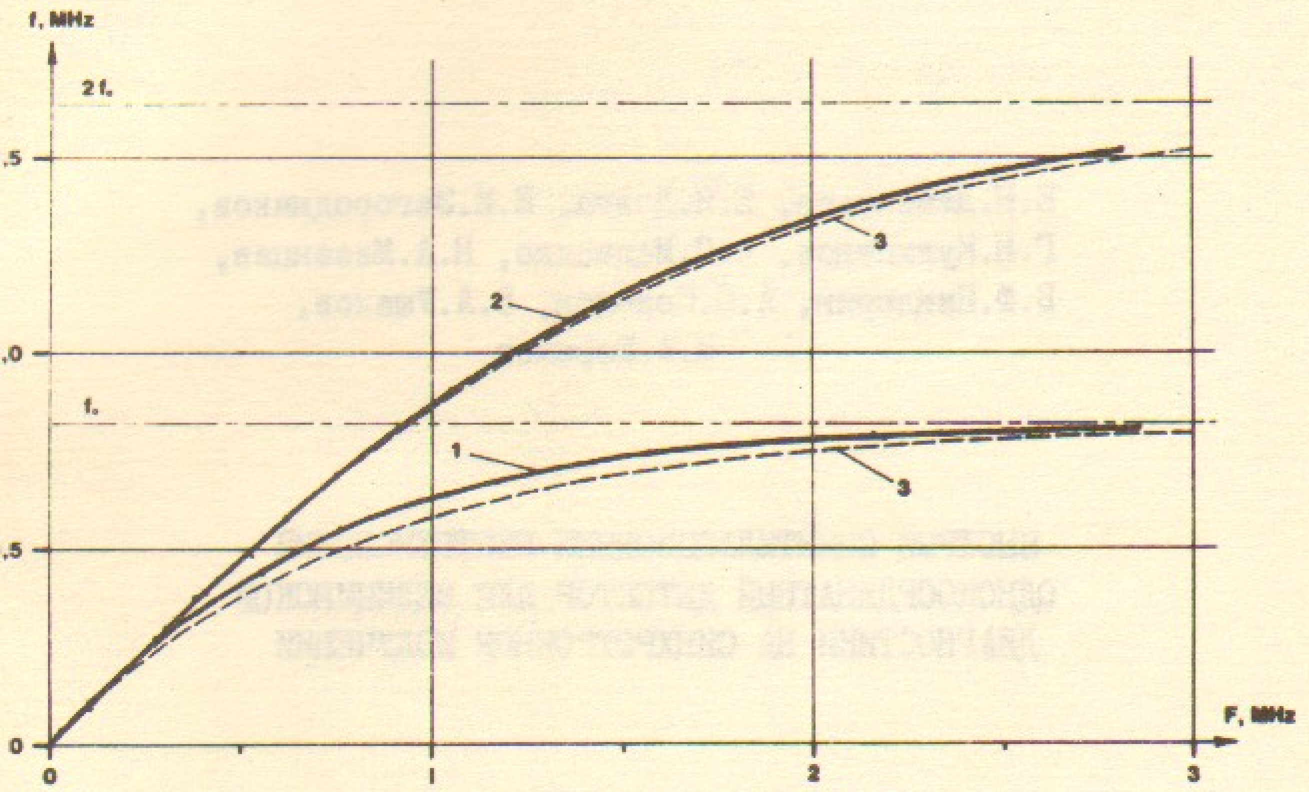

Fig. 6.

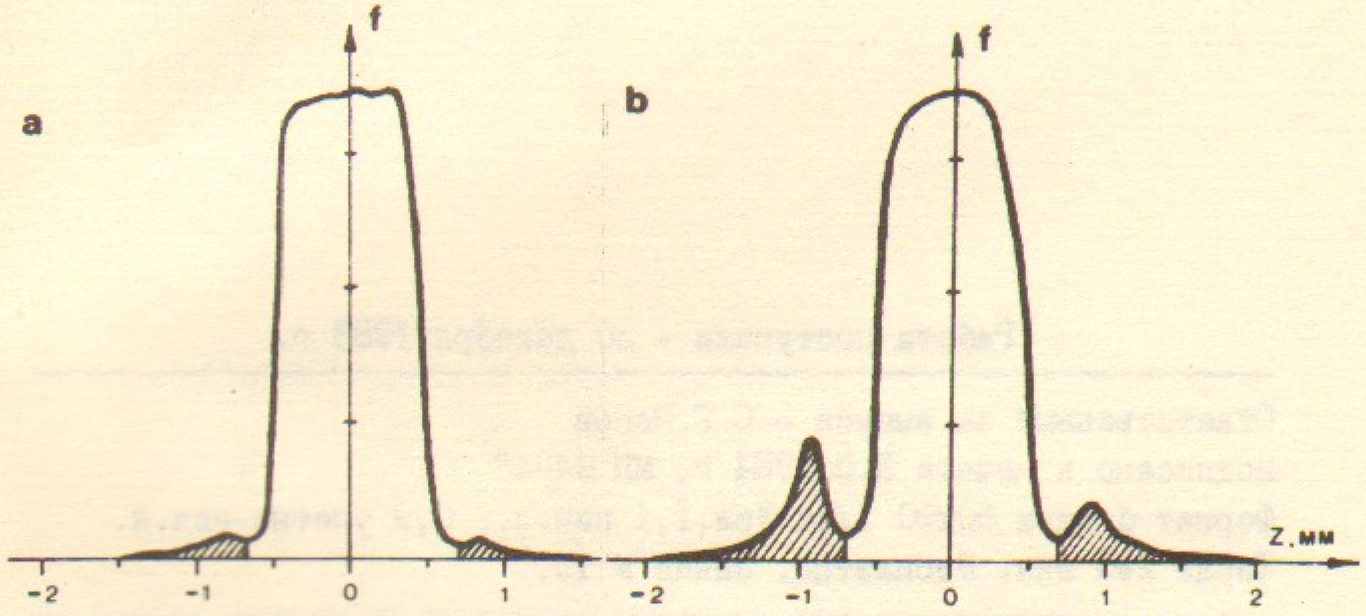

Fig. 7.

Е.Н.Дементьев, Е.Я.Довга, Е.И.Загородников,
Г.Н.Кулипанов, А.С.Медведко, Н.А.Мезенцев,
В.Ф.Пиндюрин, А.С.Соколов, В.А.Ушаков,
М.А.Шеромов

БЫСТРЫЙ СЦИНТИЛЛЯЦИОННЫЙ РЕНТГЕНОВСКИЙ ОДНОКООРДИНАТНЫЙ ДЕТЕКТОР ДЛЯ МЕДИЦИНСКОЙ ДИАГНОСТИКИ НА СИНХРОТРОННОМ ИЗЛУЧЕНИИ

Препринт
№ 84-I9

Работа поступила - 30 декабря I983 г.

Ответственный за выпуск - С.Г.Попов
Подписано к печати 3.П-I984 г. МН 04048
Формат бумаги 60x90 I/I6 Усл.I,I печ.л., 0,9 учетно-изд.л.
Тираж 290 экз. Бесплатно. Заказ № I9.

Ротапринт ИЯФ СО АН СССР, г.Новосибирск, 90