Quality Factor of Radiation and Dose Equivalent behind the Shielding of the 70GeV Proton Synchrotron

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A great number of papers/1-4/ has been devoted to the problem of direct measurement of dose equivalent and quality factor of radiation at high energy accelerators. However the problem remains important and actual even up to the present day. At the Serpukhov proton synchrotron direct measurements of dose equivalent (DE) and quality factor (QF) pursued two aims: one of them was to receive a more trustworthy information on the values of the DE and QF and the other one was to compare a widely applied at the accelerators method of measuring over the components. For this purpose a section behind a comparatively thin (up to 2.2 m of concrete) schielding of the ring accelerator hall has been chosen.

1. LET-Spectrometer

For the LET analysis of radiation a spherical proportional counter with tissue-equivalent walls, similar to the one described in/5,6/ was taken. The constructional details and manufacturing technique for tissue-equivalent plastic are given in papers/7,8/, and papers/1,10/ present the methods of handling the apparatus spectra.

In combination with the pulse amplifier and multichannel pulse-height analyzer such a counter represents a LET spectrometer, that allows to measure dose absorbed or DE distribution over LET.

The counter was filled with propan/methane up to the pressure of 10-40mm of mercury column. The potentials of collecting and correcting electrodes were equal to 800 and 500 v respectively. Such an operational mode provided reliable registration of particles with LET $\geq$ 3.5 kev/μ of tissue. After evacuation and filling in, the counter was isolated from the vacuum system and operated independently without any pumping through of the working gas. The

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constancy of the operational mode of the counter after filling in was controled by the position of the peak in the apparatus spectrum from α-source. A calibrated α-source Pu^{239} built in the counter /10/ was used for the counter calibration. The resolution of the spectrometer comprised 10-13 %. When measuring QF, calibration was made before and after each measurement procedure.

LET analysis was performed separately in the LET range from 3.5 up to 53 and from 53 up to 200÷400 kev/μ of tissue. In all the cases the upper limit for the LET range was not lower than 200 kev/μ of tissue. It was assumed that the contribution of radiation with large values of LET is negligibly small. A typical LET spectrum, measured in the area of geodetic axis 14 is given in fig. 1a,b.

Simultaneously with the proportional counter there operated an ionization chamber, similar to the counter in its shape, with tissue-equivalent walls, filled with air at atmospheric pressure. The chamber was to take into account the contribution of radiation with LET less than 3.5 kev/μ of tissue.

As it was shown by preliminary measurements the chamber filled with air under real conditions reproduced the readings of a fully tissue--equivalent chamber with RMS deviation of $\pm$12%. The ratio of the chamber readings in separate measurement points is constant with RMS deviation less than $\pm$2%. The values of calibration constants over γ-radiation Co^{60} appeared to be equal to $5.4 \cdot 10^6$ and $6.6 \cdot 10^6$ rad /coul with an accuracy $\pm$10% for the chambers with a tissue-equivalent and air fillament respectively.

When analyzing the errors of measuring QFof radiation by the method of LET-analysis we took into account the following possible sources of errors:

a)preservation of theoretical prerequisites in the experiment.

b)linearity of the LET-spectrometer.

c)loading of the LET-spectrometer in a certain pulse of the accelerator radiation.

d)LET-spectrometer resolution.

e)errors in measuring the dose absorbed with a tissue-equivalent chamber.

f)errors in calibrating the LET-spectrometer (drift of -peak,etc.)

g)statistic errors in the apparatus spectrum.

When measuring QF of a mixed radiation Po-α-Be of a neutron source the obatined value of QF is equal to 5.9 ± 0.9. Assuming that the contribution of γ-radiation to the dose absorbed is 25% [12], it corresponds to QF of neutron component 7.5 ± 1.1.

The computer BESM6 using the programs PATMOD and LAPA, was used for handling the apparatus spectra. The programs are worked out on the basis of the known relation:

$$D(L)dL = \frac{1.6 \cdot 10^{-1}}{2\pi r^2}\left(\frac{L}{h}\right)\left[-h^3 \frac{d}{dh}\frac{Q(h)}{h}\right]dh, \quad L = kh$$

taking into account the ratio K, obtained in calibration with source. The first program forsees the calculation of an average QF of a mixed radiation in the full LET range from 0 up to L_{max}, in the LET range 3.5 kev/μ of tissue and the definition of the statistic errors of these values. The readings of the tissue-equivalent chamber and weight of each exposure in the spectrum.

The program LAPA was constructed to calculate the distribution of DE and dose absorbed over LET. There was applied a parabolic approximation of a section of the apparatus spectrum with 7 points by the method of the smallest squares and the calculation of a derivative value for an average point. In this we used a partial-linear approximation of the dependence of QF of radiation upon LET, recomended by IAEA [9].

2. Recombination Chamber

Direct determination of QF and DE of a mixed radiation was performed with the help of the Rossi counter as well as applying a well-known [14-22] method, based on measuring column recombination in the ionization chamber, filled with a tissue-equivalent gas at a high pressure. The device, involving this principle was worked out by the Union Scientific Institute for Instrument Making. It consists of a two-channel electrometer and double ionization chamber "Sukhona", whose one section operated in a suturated mode, the second one operated in the mode of column recombination. The device allows to perform a simultaneous measurementof the dose absorbed and and average QF of a mixed radiation per one cycle of the accelerator operation as well as of average values obatined during the exposure.

The main characteristics of the double chamber: the system of electrodes is a plane parallel one, the electrodes themselves are disks 5mm thick, made of organic glass with a conductive Al layer that is evaporated in the vacuum;

the gap between the electrodes is 5mm. Each chamber has 5 working sections produced by one central collecting electrode and HV onesthe working sections of one chamber altarnating with the sections of the other one; the total working volume of 5 sections of each chamber is 770cm^3. The supply voltage of the saturated and recombination chambers is 1000 and 110 respectively, the pressure in the chamber is 4 atm. The measuring accuracy with the electrometer in the mode of charge storage is $\pm 1.5\%$ The chamber sensitivity operating in saturated mode with respect to a unit pressure is $2.7 \cdot 10^{-7}$ coul/ rad. atm $\pm 6\%$ and coincides within the limits of the above indicated accuracy for γ-radiation of Co^{60} and neutrons Po-α-Be source

Calibration of the device over QF, fig.2, was performed with γ-radiation of Co^{60} by neutrons of Po-α-Be source and α-radiation of Pu^{239}, as well as in the fields of mixed n,γ-radiation from the source of Co^{60} and Po-α-Be with different average QF. The calibration showed a satisfactory correspondence of the experimental points of linear dependence:

$$K = M \ln \frac{I_o}{I}$$

where I_o is the current of a saturated chamber
and I is the current of a recombination chamber
M=24.2 is a calibration constant valid through the whole range of QF from 1 up to 20 with the accuracy $\pm$ 25%.

The Appendix to the calibration scheme (fig.2) presents a satisfactory correspondence of calibrating points of the device with the regions of QF, recomended by IAEA /9/.

A comparison of the readings of a saturated chamber with the readings of the tissue-equivalent chamber, applied for LET analysis was made. Both chambers were located on the shielding in the area of geodetic axis 13-14 as close to each other as possible. The charges of the both chambers were measured simultaneously with the help of a two-channel electrometer with the mode of charge storage during an exposure.

The relative error in defining absorbed dose rate for each chamber includes the error of the calibration constant when measuring the sensitivity ($\pm 6\%$ for both chambers) and the error in measuring the charges ($\pm 1.5\%$ and $\pm 2\%$ for a tissue equivalent and saturated chambers respectively). In this the data from the saturated chamber is averagely by 4.7% higher than those from the tissue equivalent chamber.

3. Measurement Results

The measurements were performed at a standard operational mode of the accelerator, i.e. the energy of protons was 70GeV average intensity $(5-9)\cdot 10^{11}$ protons/cycle. In the ejection system there operated two internal targets at partial consumption of the intensity $50\pm 20\%$. Fig.3 shows the location of the targets and the points of measurements.

Fig.4 presents the results of measuring the dose absorbed and QF of radiation on the shielding of the ring hall. QF was measured with the help of the Rossi counter on the upper shielding between axes 5-14 and between axes 13-14 we use the recombination chamber "Sukhona". The measurement error of the dose absorbed and QF of the mixed radiation comprised 13,27 and 25% respectively.

As is seemed from fig. 4 we have a quite satisfactory correspondence of the results in the three schemes for the Rossi counter as well as for the double chamber. Here also we presnt the results of the component measurements, that were made at the same points of the shielding with the help of the apparatus usually applied for routine dosimetry purposes at the accelerators. The list of the apparatus is given in Table 1. The Table indicates the values of the calculated factors used to determine DE. As is seen the component method provides the results higher 1÷4 times (in average 1.8) for the dose absorbed, and 1.6÷7 times (in average 2.7 times) for DE as compared with a tissue-equivalent chamber.

QF of radiation according to the measurements made by the Rossi counter mainly are in the range 1.3÷3.0. Estimations, performed over the results of the component measurements using the coefficient in Table 1 provide higher values:from 2.6 up to 4.5.

Table 2 presents the measurement results on DE with a recombination chamber and on the component method, and are compared with those made with the Rossi counter (the last ones taken to be 1).

Apparatus for Component Measurements and Factors used in Measurements

	Components of a Mixed Radiation				
	NEUTRONS				
	termal	slow, intermed	fast	hadrons	radiation relativistic charged part.
Energy Range of the Components	0.1	0.1 ÷100kev	100kev÷2oMeV	$E_n \geq 20MeV$ $E_\pi \geq 50MeV$	$E_\gamma > 50$ KeV $E_{ch.p} >$ sev. MeVs
Average in Range QF	3	4.3 b)	7÷10 (a	5.2 (b	1
Average in Range Conversion Factor rad $neutr^{-1}cm^2$	$0.33 \cdot 10^{-9}$	$0.50 \cdot 10^{-9}$	(4÷6) (a $.10^{-9}$	$1.2 \cdot 10^{-8}$	--------
Apparatus and Methods(detectors)	1. BF_3 counter (in Cd and without) 2. In-detector (in Cd and without)	1. BF_3-counter with moderators with walls 20, 40 120 mm thick(24)	1. BF_3 -counter in moderators with walls 20.40 and 12omm thick(24) 2. In'detector in the same moderators	$C^{12}(x,nx)C^{11}$	1. Air chamber with Al walls 2. Air-equivalent chamber

a) depending on the effective energy of neutrons
b) average over spectrum, assuming that the spectrum is $A.E^{-1}$ /23/
c) average over spectrum, the spectrum form is taken from

Number of axis	Recombination chamber	Component Method	
		5 components	2 components
14	0.81	2.7	2.7
13	0.95	2.9	2.7
12		5.3	4.8
11		4.4	3.6
10		3.5	3.0
9		7.0	6.3
8		1.6	1.9
7		4.1	3.4
6		2.3	1.9
5		2.3	2.0

R E F E R E N C E S

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C A P T I O N S

Fig. 1a,b. Typical distributions over LET of the dose absorbed DE, measured on axes 14 of the experimental hall.

Fig. 2. Calibrated diagram of the chamber 'Sukhona'.

Fig. 3. Layout of the experimental hall.

* internal targets,

● measuring points on the shielding of the ring hall.

Fig. 4. Distribution of the radiation field on the upper shielding of the accelerator.

o component method,

● Rossi counter,

■ recombination chamber.

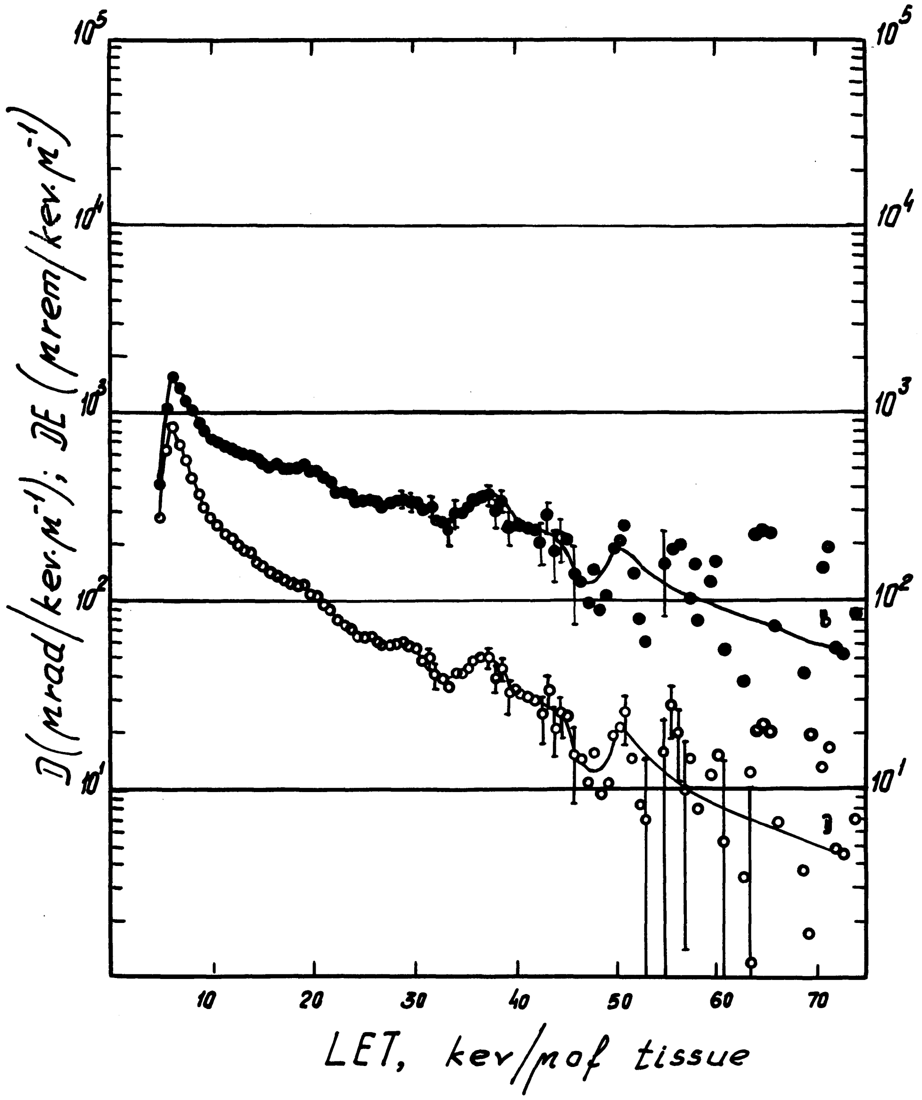
D(mrad/kev·μ⁻¹); DE (mrem/kev·μ⁻¹)
10⁵
10⁴
10³
10²
10¹
10
20
30
40
50
60
70
b
a
LET, kev/μ of tissue

Fig. 1a

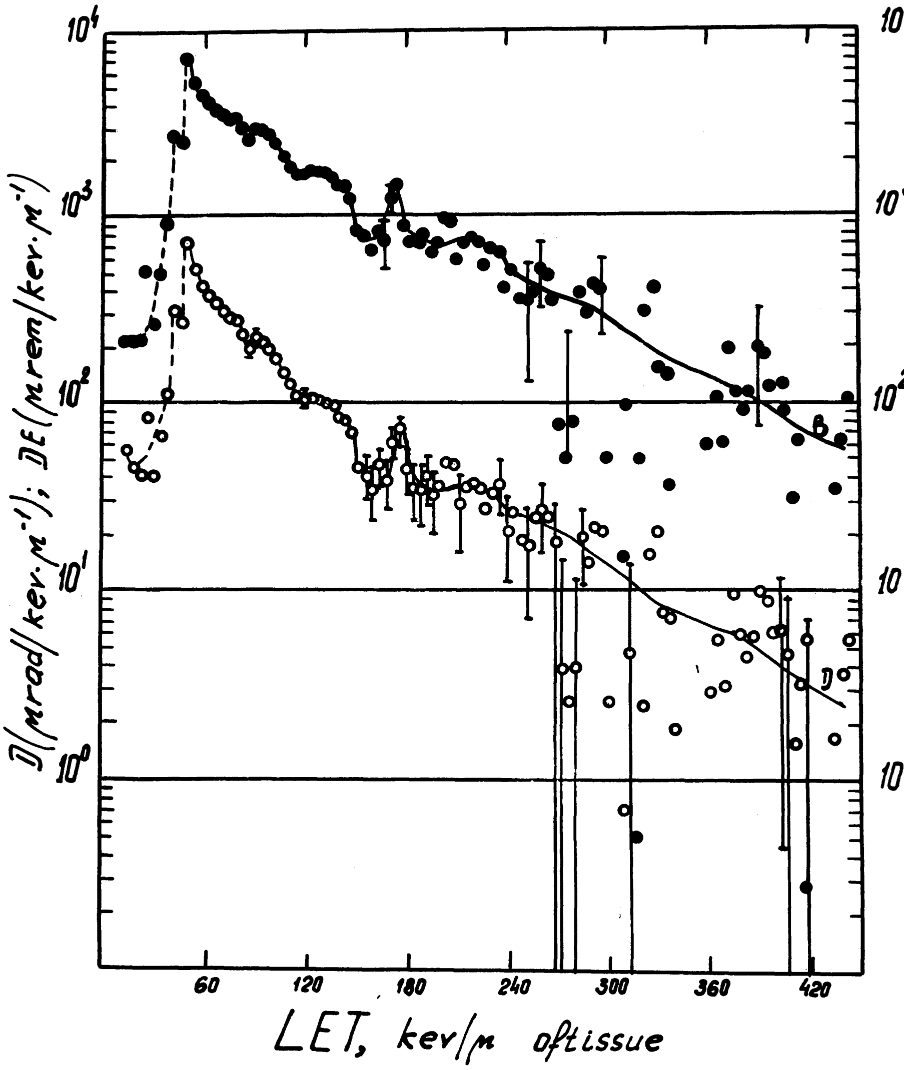
10^4
10^3
10^2
10^1
10^0
D(μrad/kev·μ⁻¹); DE(μrem/kev·μ⁻¹)
60
120
180
240
300
360
420
LET, kev/μ of tissue
DE
D

Fig. 1b

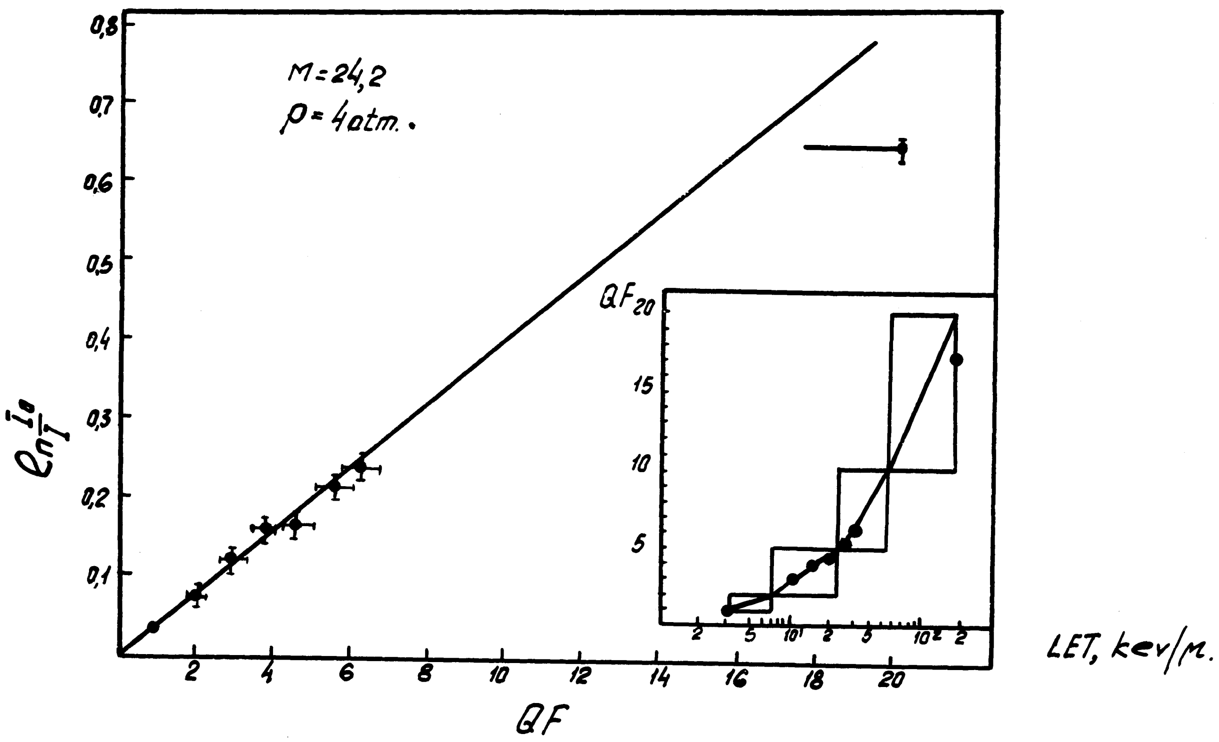
M=24,2
ρ=4atm.
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
2
4
6
8
10
12
14
16
18
20
QF
QF20
15
10
5
2
5
10¹
2
5
10²
2
LET, kev/μ.

Fig. 2

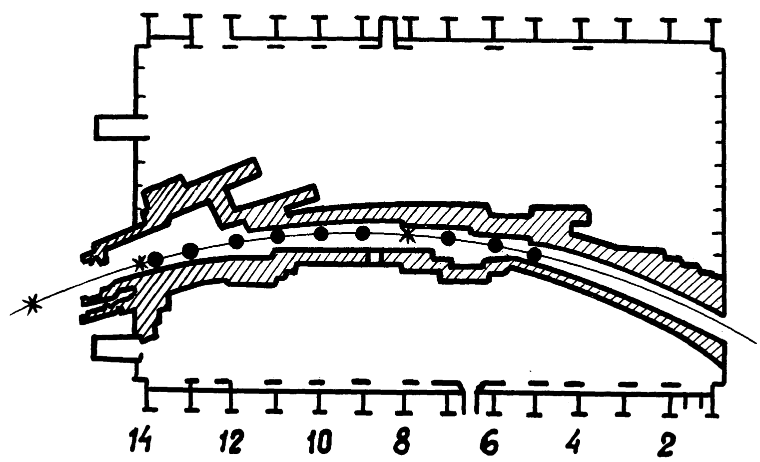
14
12
10
8
6
4
2

Fig. 3

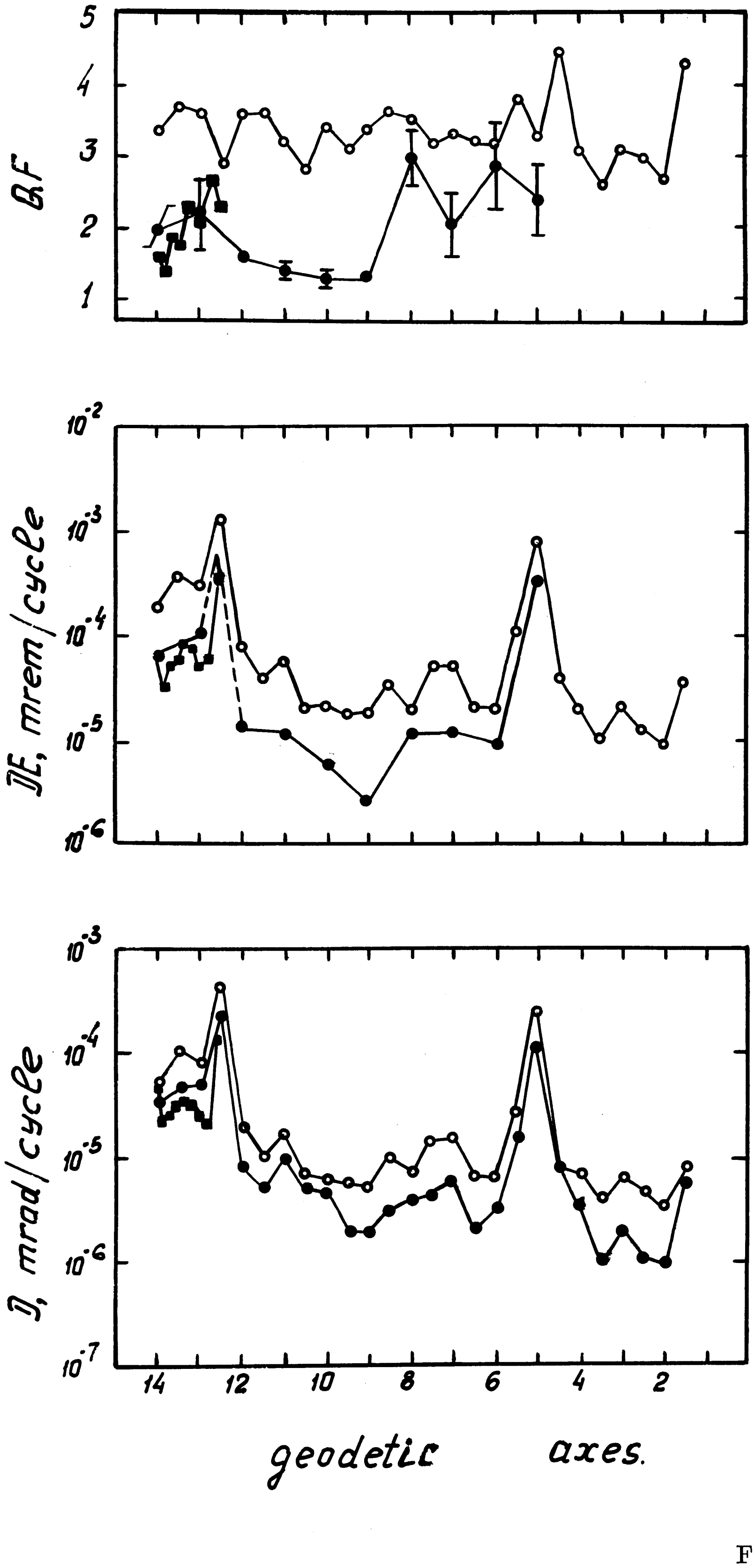
5
4
3
2
1
Q.F
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
E, mrem/cycle
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
D, mrad/cycle
14
12
10
8
6
4
2
geodetic axes.

Fig. 4