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MEASUREMENT OF THE FREQUENCIES OF BETATRON OSCILLATIONS AT THE IHEP ACCELERATOR AT MEDIUM AND HIGH ENERGIES

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The programme for studying the characteristics of a beam accelerated to high energies included measuring the frequencies of the betatron oscillations. These measurements are important because their results serve as the basis for selecting the parameters of the systems for correcting the gradient and the non-linear components of the accelerator's magnetic field, in order to ensure the most favourable conditions for particle ejection.

The frequencies of the betatron oscillations were measured by two different methods in medium and high fields. The first method used the dependence of the relative displacement of the closed orbit, when there is local perturbation of the magnetic field, on the frequency of the betatron oscillations. A pulsed magnet, designed for fast beam spill on to the target(1) was used for radial perturbation of the closed orbit. Switching pulsed current into the magnet created artificial distortion of the closed orbit which increased with time. The amplitude of the distortion in relation to the unperturbed orbit was measured by pick-up electrodes and the apparatus described in(2). In order to increase the accuracy of measurement, the azimuthal position of the electrodes was chosen as the point where the dependence of the amplitude of the distortion on the frequency of the betatron oscillations has the steepest slope. The dependence of the relative displacement of the orbit on the frequency of the betatron oscillations at the points where the pick-up electrodes were located was calculated by computer, taking into account the real characteristics of the accelerator's magnetic field according to the method described in (3).

One of these dependences, corresponding to a pulsed magnet strength of 1.5 k. oe./m with an accelerator field strength $H = 12$ k.oe., is shown in Fig. 1. The frequencies of the betatron oscillations were determined by comparing the measured values of the relative deviations of the orbit at the given azimuth from a calculated curve similar to that shown in Fig. 1 *.

* A similar method of measuring the frequencies of betatron oscillations was described in 4).

Measurements were made in the horizontal plane only. For a selected radial position of the beam a series of measurements were made, which served to determine the mean frequency of the betatron oscillations and the root-mean-square error in the mean value. The accuracy of measurement of the relative deviation of the orbit in these experiments was ± 1 mm, which brought the root-mean-square error in determining the frequency of the betatron oscillations to 0.01 - 0.02. The frequencies of the betatron oscillations were thus determined for various radial positions of the beam. The beam was shifted radially by changing the frequency of the accelerating voltage. The radial position was determined from the value of the r.f. at the moment of measurement. The frequency corresponding to the closed orbit close to the axis of the vaccuum chamber was determined by the value:

$$f_p = \frac{q\, p_s\, c^2}{L\sqrt{m_o^2 c^4 + p_s^2 c^2}} ,$$

where q is the harmonic number of the acceleration, L = 1483,699 m the length of the axis of the vacuum chamber, c the velocity of light, $m_o c^2$ the rest energy of the proton, p_s the equilibrium momentum of the particles passing near to the axis of the vacuum chamber. The value p_s for each value of the field H was calculated by computer taking into account the real values of the effective lengths of the magnet units $^{3)}$. When the variation of the r.f. in relation to f_p was Δf_p , the variation of the mean radius was:

$$< \Delta R > = \frac{\Delta f_p}{f_p} \left[\left(\frac{E_o}{E} \right)^2 - \alpha \right]^{-1} \cdot < \psi > ,$$

where $\langle\psi\rangle$ is the value of the ψ function averaged per super-period, E_o is the energy of the rest proton, E is the total energy of the accelerated particles, α = 0.01112 is the space compaction coefficient of the orbits. The error in determining the mean radius did not exceed ± 1 mm. The results of the measurements of the frequencies of the betatron oscillations according to the method described above for H = 12 k.oe. are given in Fig. 2.

The other method was based on the resonant excitation of coherent betatron oscillations[5]. In this case the measuring apparatus included an r.f. system for exciting coherent betatron oscillations and a system for measuring the frequencies of the betatron oscillations. A block diagram of the exciting and measuring apparatus is given in Fig. 3. Excitation of coherent oscillations was carried out at a frequency $\Delta Q/f_o$, where ΔQ is the difference between the quantity Q and the nearest whole number, f_o is the frequency of revolution of the particles. Tuning of the exciting and measuring apparatus was carried out in the following order. At the moment of the accelerating cycle exactly synchronised with the given value of the magnetic field of the accelerator, r.f. voltage was fed into the electrostatic exciting plates from the device for resonant excitation of the oscillations. The duration of the r.f. signal did not exceed 1 msec, and its amplitude was determined according to the energy of the accelerated particles. The r.f. voltage in the plates was modulated by the exciting signal coming from the audio-frequency oscillator or the special frequency divider, in which the frequency of the accelerator $30f_o$ was divided into any whole number from 60 to 300. Next the frequency of the exciting signal and the depth of modulation were chosen so that the amplitude of the signal with a frequency of ΔQf_o, induced in the pick-up electrodes, was at a maximum. The signal from the electrodes was observed by means of an oscillograph. A filter was used before the oscillograph, selecting a signal with a frequency of ΔQF_o. Fig. 4 shows the characteristic oscillograms of the tuning of the exciting and measuring regime. The top trace in each oscillogram shows the r.f. signal, and the bottom trace the signal induced in the pick-up electrodes. Fig. 4a corresponds to the case when the modulation frequency is far from ΔQF_o. When it approaches a frequency of ΔQF_o wobbling occurs (Fig. 4b) and then an increase in the amplitude of the betatron oscillations (Fig. 4c). Accurate measurement of the frequency of the betatron oscillations was made after switching off the r.f. voltage (Fig. 4g). For these purposes a device was used which made it possible to select from one to seven periods of free oscillations and by means of a counter to count the number of pulses following each other with a frequency of $30\ f_o$ and filling them with interval selected. Errors in the measurements occurred owing to noise from the apparatus and counter errors.

The relative error of the counter was $\varepsilon_c = \frac{\Delta Q}{30 \cdot n}$, and the relative error due to the noise of the apparatus was $\varepsilon_a = \frac{\Delta Q \cdot U_{\text{ш}}}{\pi U_n \cdot n}$, where n is the number of periods selected by the counting device, U_n, $U_{\text{ш}}$ are respectively the voltage of the useful and noise signals of doubled amplitude. The total error of the measurements reached the highest value at maximum energy. This is explained by the fact that in the apparatus used the amplitude of the exciting r.f. voltage was limited, and therefore as the energy increased to the maximum value the signal/noise ratio decreased from 4 to 5. On the other hand, as the energy increased the damping decrement of the coherent oscillations increased after the exciting signal had been switched off. Therefore the number of oscillation periods selected by the measuring circuit did not exceed three.

For the most unfavourable value of ΔQ close to 0.5, the measuring error in maximum fields was about 0.015. With later improvements in the apparatus it should be possible to reduce the measuring error.

Measurements of the frequencies of the betatron oscillations were made by this method at values of H equal to 4000, 9000, 10,000, 11,000, 11,500 and 12,000 oersted. For given fields the dependence of the frequencies of the betatron oscillations were plotted in both planes from the radial position of the beam. The beam was shifted in the radial direction by changing the frequency of the accelerating voltage. Its position in the chamber was determined according to the frequency of the accelerating voltage by the method described above. The frequency of the r.f. voltage was measured at the moment when the device for measuring the frequency of the betatron oscillations was switched on. The relative error in measuring the frequency of the accelerating r.f. voltage was $2 - 3 \times 10^{-6}$.

The results of the measurements of the frequencies of the betatron oscillations at various levels of the magnetic field of the accelerator are given in Figs. 5-10 as a function of the value $\langle \Delta R \rangle$ or Δf_p. Since when the beam shifts within limits of -20 +20 mm, the influence of non-linearities of the magnetic field higher than second order on the frequencies of the betatron oscillations is small 3), the given dependences were approximated to linear functions. The linear function coefficients were selected by the least squares method.

In conclusion the writers wish to express their gratitude to V.E. Pisarevskij for his co-operation in carrying out the measurements, A.P. Gudkov, A.A. Rukin and V.N. Chepegin for their participation in the work and L.I. Nikitaeva for her assistance in formulating the results of the measurements.

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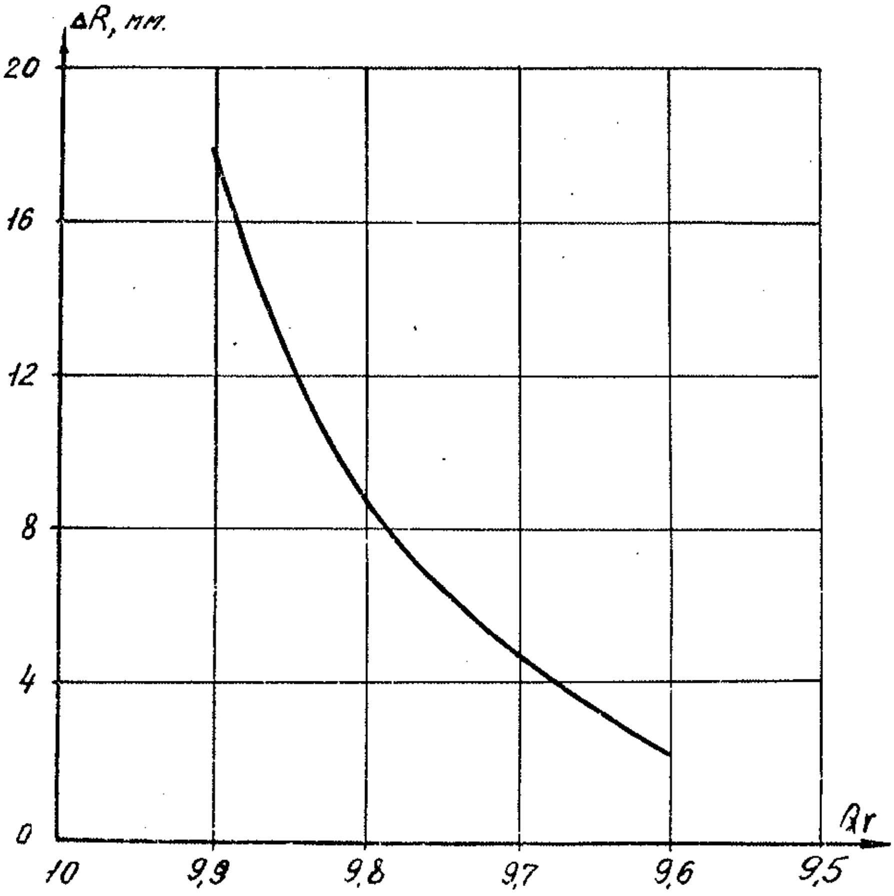


Fig. 1. Dependence of the value of the relative orbit displacement on the frequencies of the betatron oscillations when H.L∂ = 1.5 k oe/m and H = 12 k oe in the middle of straight section number 20.

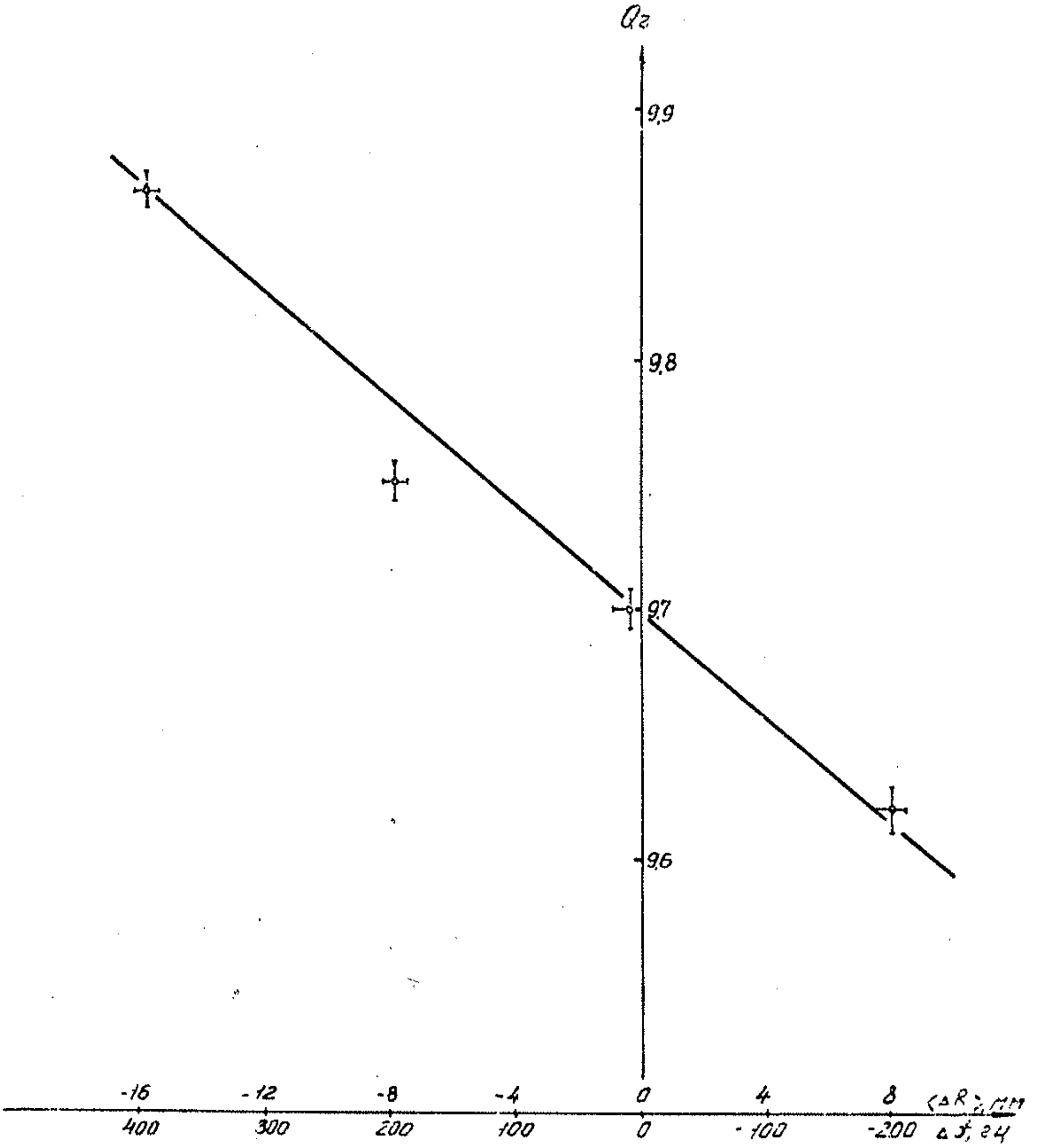


Fig. 2. Dependence of the frequencies of the radial betatron oscillations when H = 12 k oe on the value of the mean displacement of the beam orbit in relation to the axis of the vacuum chamber of the accelerator.

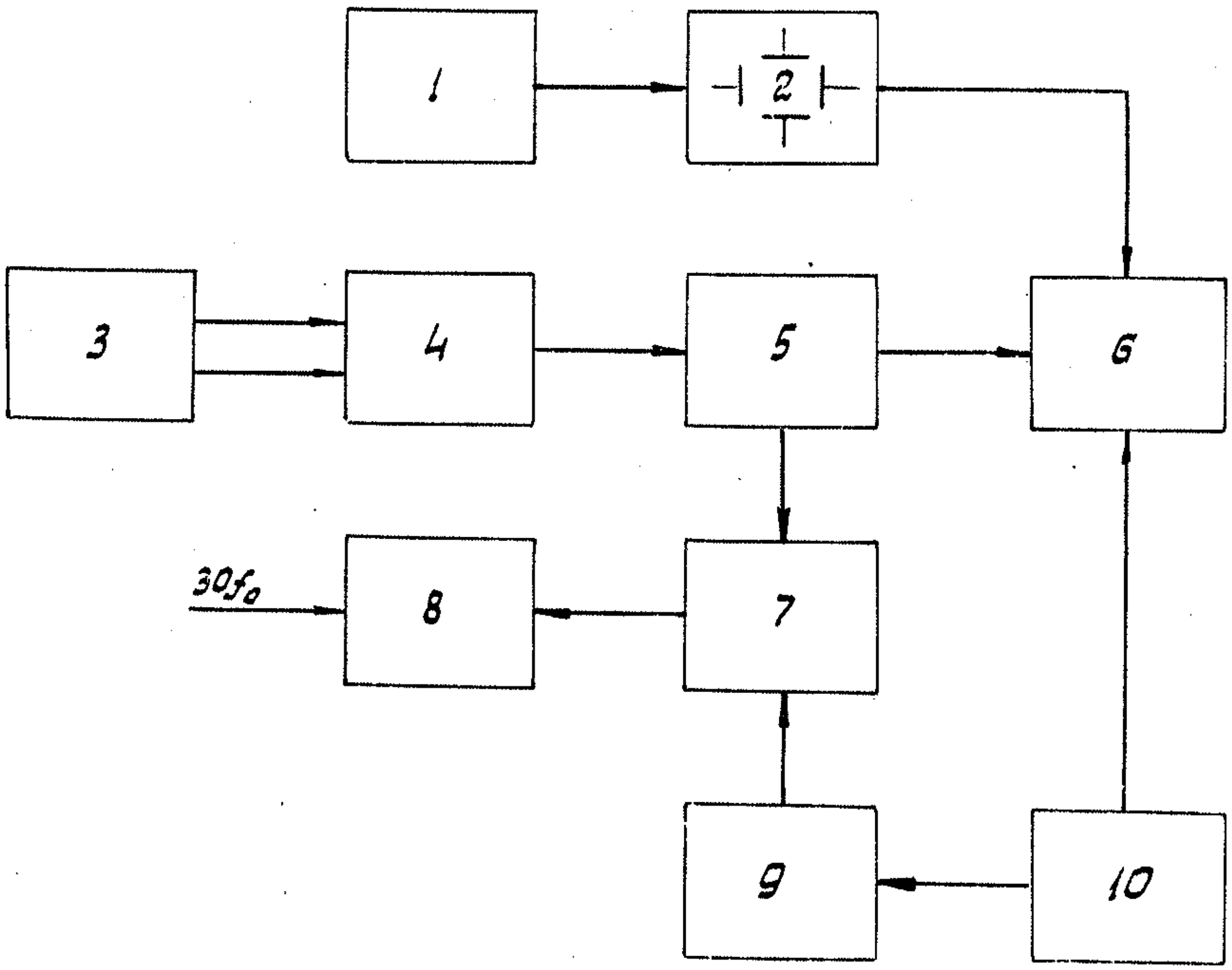
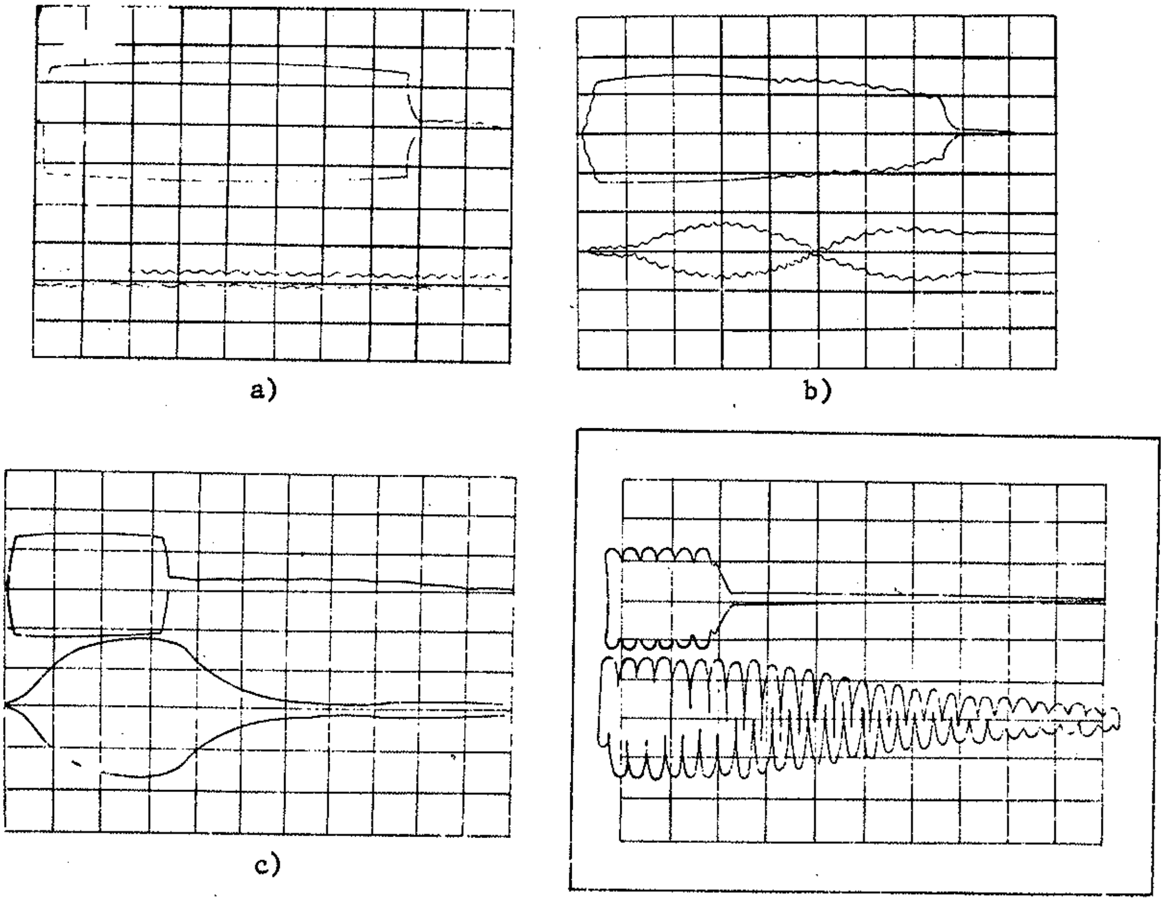


Fig. 3. Block diagram of the apparatus for exciting and measuring the frequencies of the betatron oscillations.

1. Resonance build-up system.
2. Exciting plates.
3. Pick-up electrodes.
4. Differential amplifier.
5. Low frequency filters.
6. Oscillograph.
7. Device for selecting 1, 3, 5, 7 periods of free oscillations.
8. Counter.
9. Controlled delay device.
10. Timer



a) b) c) d)

Fig. 4. Oscillograms of the tuning of the exciting and measuring regime. Top trace - exciting signal; Bottom trace - signal response; a) exciting frequency far from the resonance frequency, Time scale 100 m.sec/sq. b) exciting frequency near to resonance. Time scale 100 m.sec/sq. c) accurate resonance. Time scale 250 m.sec/sq. d) end of excitation. Time scale 50 m.sec/sq.

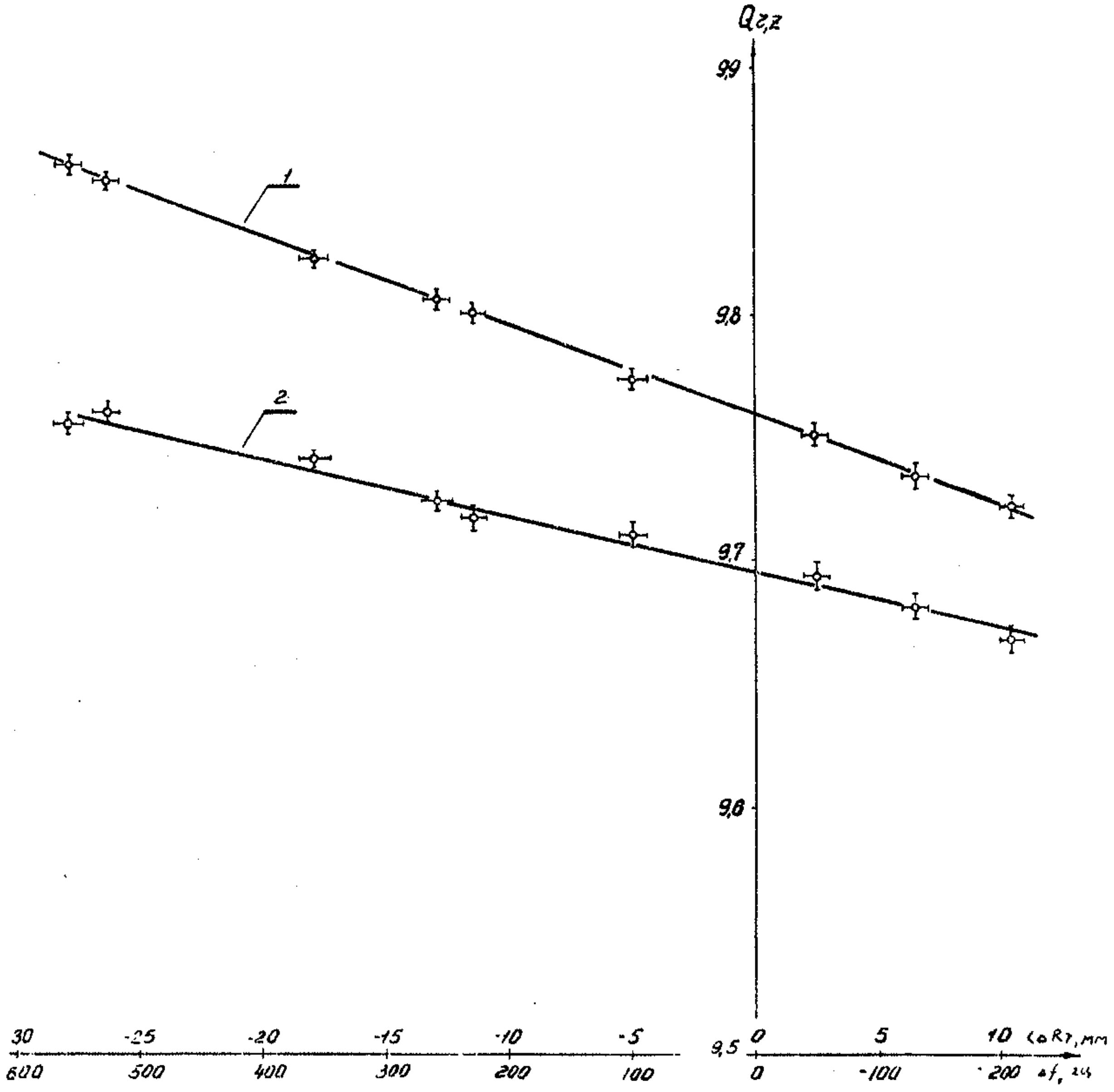


Fig. 5. Dependence of Q_r (Curve 1) and Q_z (Curve 2) on the position of the mean radius of the beam **$\langle \Delta R \rangle$** in relation to the central orbit or on the corresponding frequency shift of the accelerating voltage **Δf_p** when H_o = 4000 oersted.

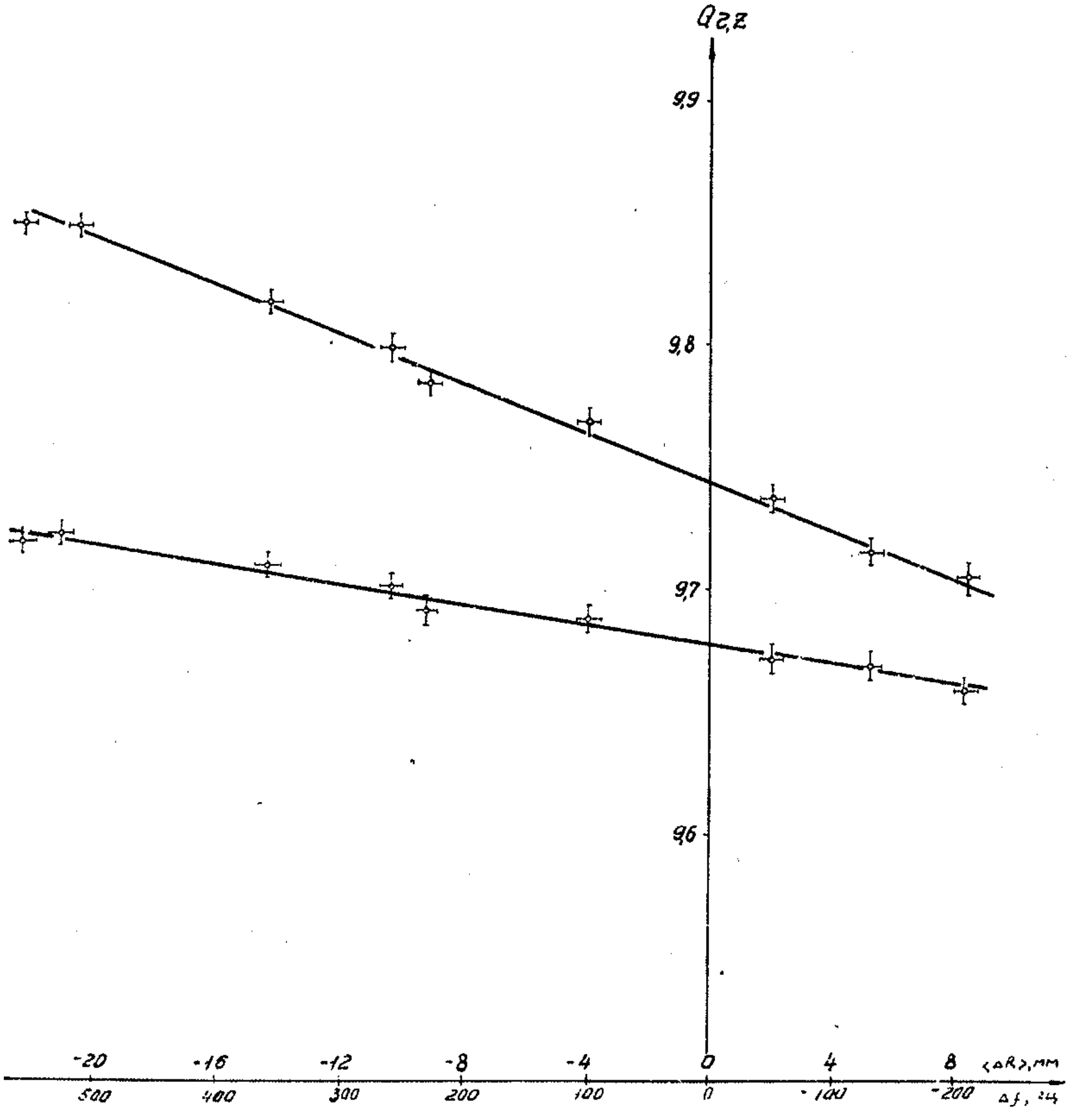


Fig. 6. Dependence of Q_r (Curve 1) and Q_z (Curve 2) on the value $\langle\Delta R\rangle$ or ΔF_p. H_o = 9000 oersted.

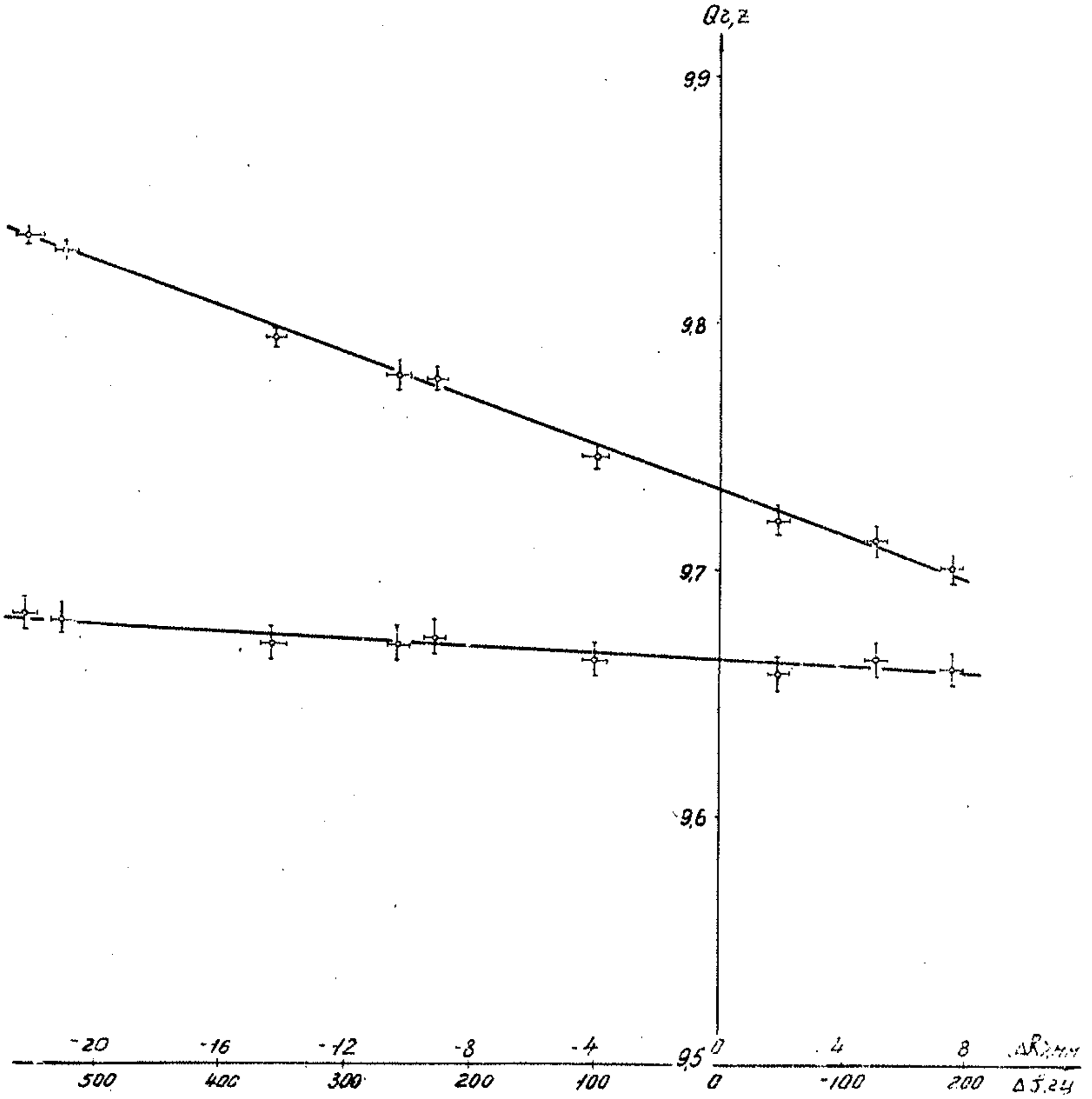


Fig. 7. Dependence of Q_r (Curve 1) and Q_z (Curve 2) on the value **<ΔR>** or **Δ**F_p. H_o = 10000 oersted.

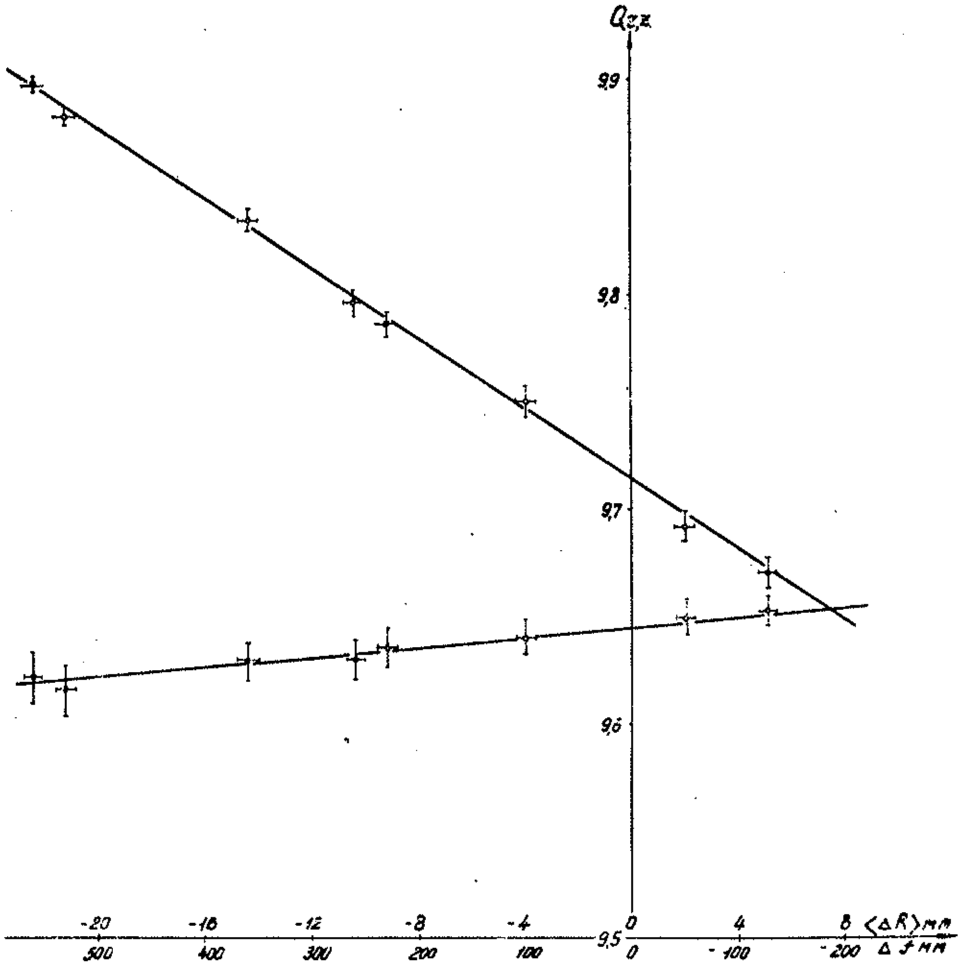


Fig. 8. Dependence of Q_r (Curve 1) and Q_z (Curve 2) on the value **<ΔR>** or **Δ**F_p.^{r} H_o = 11000 oersted.

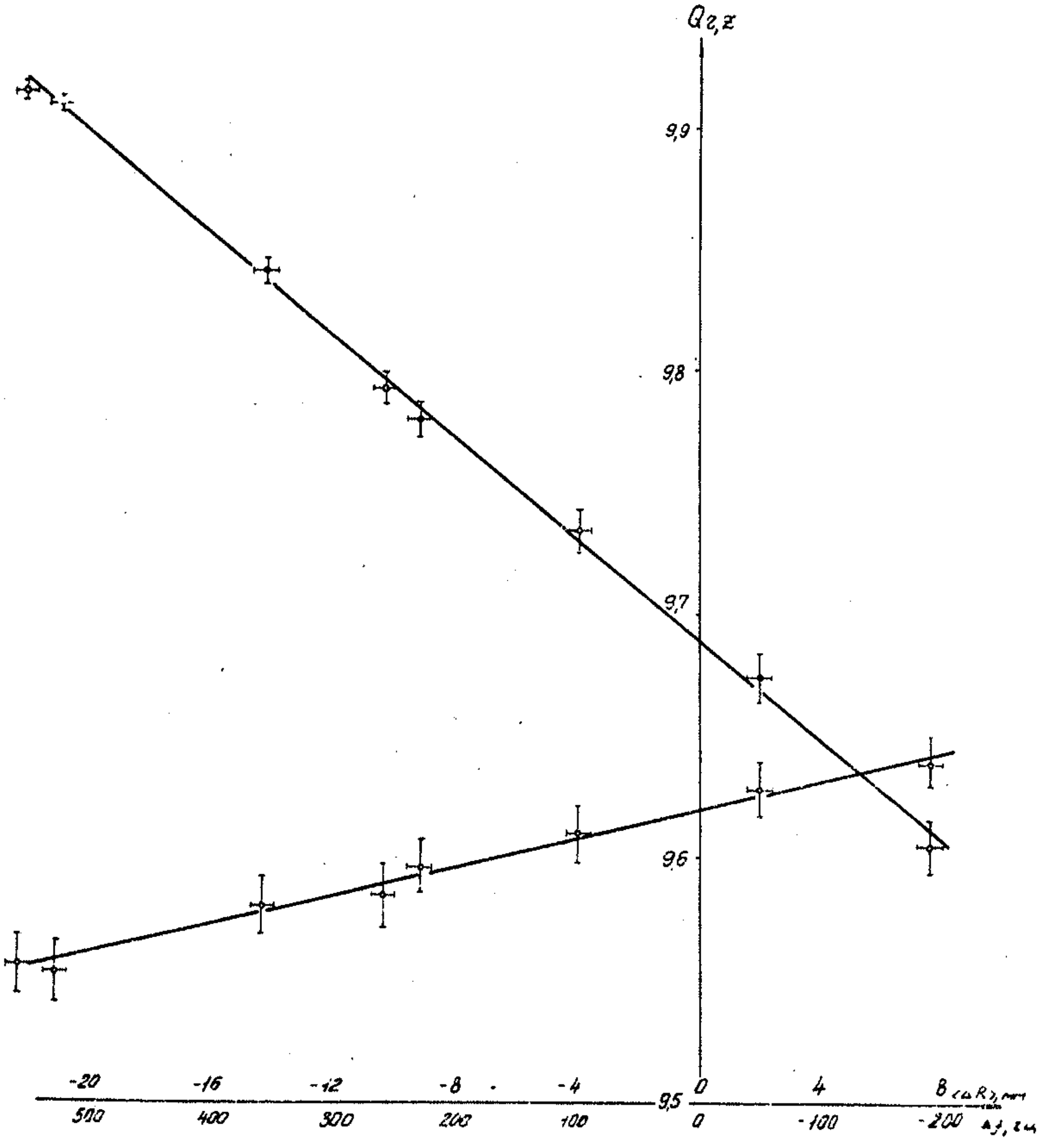


Fig. 9. Dependence of Q_r (Curve 1) and Q_z (Curve 2) on the value $\langle\Delta R\rangle$ or ΔF_p.^{r} $H_o = 11500$.

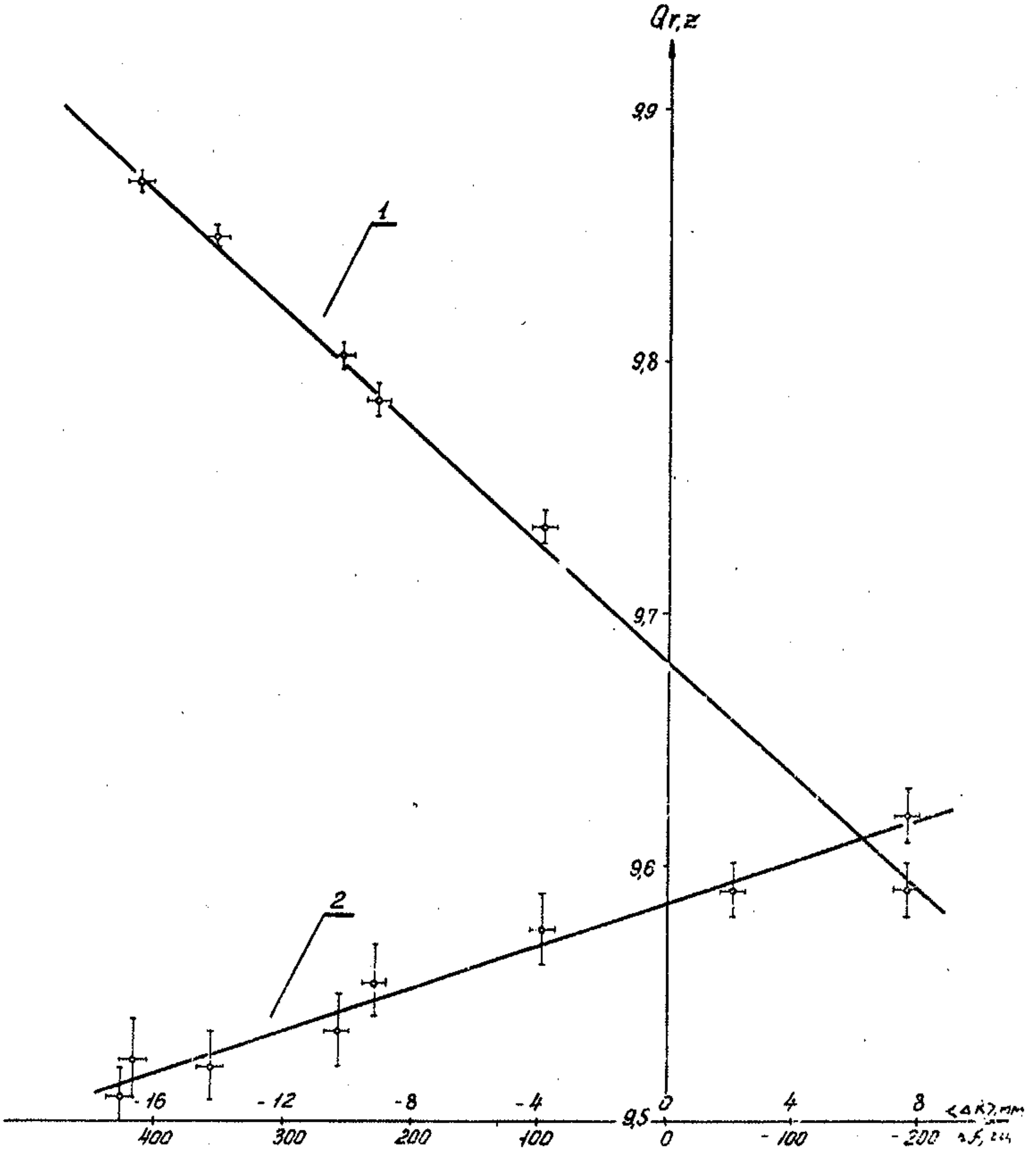


Fig. 10. Dependence of Q_r (Curve 1) and Q_z (Curve 2) on the value **<ΔR>** or $\Delta F_p.^{r}$ $H_o = 12000$.