PROTECTION MEASURES FOR SUPERCONDUCTING MAGNET UNITS OF THE UNK AGAINST RADIATION

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Further progress in high-energy physics is closely connected with the creation of accelerators incorporating superconducting magnets (SM).[1] Even the very first experiments and calculations devoted to the estimates of the effects of high-energy radiation on the operation of the SM[3-8] made it clear that radiation-heating effects on the superconducting windings caused by beam losses might turn out to be a decisive factor that would impose limitations to the beam intensity. In the present work possible protection measures have been treated by the example of the accelerating-storage complex of IHEP.

The UNK project foresees the construction of a two-stage proton accelerator. The first stage is a 400-GeV accelerator with conventional magnets. Acceleration up to the ultimate 3 TeV energy is realized in the second stage with superconducting magnet units. The U-70 accelerator, whose intensity will be raised up to 5×10^{13} ppc, will be used as an injector for the first stage. During injection, 10-12 proton pulses from the U-70 are stacked in the first stage so that the UNK intensity should be $(5\text{-}6)\,10^{14}$ ppc.

If we take into account the SM cooling dynamics,[7] beam losses on the UNK elements during injection, stacking, acceleration, and extraction may conditionally be classified as instantaneous ($\tau \lesssim 1$ msec) and continuous ones ($\tau \gtrsim 100$ msec). Instantaneous losses may occur during injection, the first revolution, and fast extraction as well as during the development of fast instabilities in the beam during acceleration. As for the continuous losses, they may take place during scattering on the residual gas, gradual hitting of the vacuum chamber walls by the fraction of protons not captured into the acceleration mode, and at slow beam extraction. Beam losses may also be classified as distributed ones when protons hit the vacuum chamber walls (at angles from 0.1 to 1 mrad) along $\ell > 10$ m and concentrated ones for which ℓ is less than 3 m.

Particles interacting with the matter initiate internuclear cascades in the elements of the system. Energy emission during the cascade development provokes heating of the superconducting winding which may thus undergo a quench. A Monte-Carlo method was used to calculate the internuclear cascade in the UNK magnets with the help of the MARS-4 program.[9] In this we used a model[7] presented in Fig. 1.

For distributed losses, a divergent proton beam strikes the walls of a circular vacuum chamber with uniform intensity along the length of the chamber and at a fixed angle of incidence in the transverse plane; i. e., each element of surface area receives the same flux at the same angle of incidence. To simulate a concentrated loss, the divergent beam strikes the vacuum chamber at a single position along its length but still with a uniform distribution transversely. Figure 2 illustrates radial distributions at the cascade maximum for concentrated losses. Here, the effect of the magnetic field on the internuclear cascade development was not taken into account, and the results were averaged azimuthally over the magnet cross section. According to our estimates the effect of the magnetic field may increase several-fold the maximum energy density. In contrast to Ref. 7, the results were extrapolated to the inner radius of the coil winding.

Transformation from the calculated values for energy density to the admissible values for beam losses depends on the choice of the value for admissible heating of the superconducting winding as a function of the current density in it. The temperature increment ΔT due to radiation heating should be lower than the maximum increment, determined by that permitted by the critical temperature.[8] There are no reliable data for the quantity ΔT. In the calculations quoted below the following values for the quantity ΔT due to radiation heating are assumed: $\Delta T = 2.0^{\circ}$ at the injection energy and at the beginning of the acceleration cycle and $\Delta T = 0.2^{\circ}$ at the maximum beam energy. Knowing ΔT and the maximum energy density (Fig. 2) allows us to estimate the value for the admissible instantaneous losses of the beam ΔI. This value depends on the radiation conditions, initial temperature of the winding T_0 and the state of the SM at the instant of time considered, characterized by the beam energy E_0 and ΔT. The dependence of the admissible instantaneous distributed beam losses on proton energy at fixed ΔT and T_0 is given in Fig. 3. The longer the duration of the losses, the higher values for ΔI are needed for the SM to quench, i. e., the value for the admissible losses increases as compared with those in the figure. As follows from Fig. 3, for homogeneously distributed instantaneous losses at $\theta \simeq 1$ mrad and $T_0 = 4.55^{\circ}$ K the value for the admissible beam losses will be

$$\Delta I = 2.6 \times 10^{8}\ \mathrm{p\,m^{-1}} \tag{1a}$$

during injection and the beginning of acceleration (E_0 = 400 GeV), and

$$\Delta I = 5.7 \times 10^6 \, p \, m^{-1} \quad (1b)$$

at the end of acceleration (E_0 = 3000 GeV).

From comparison of these values with the design beam intensity it becomes clear that the admissible level of SM irradiation may be achieved only if we take special measures as considered below.

While tracking the beam around the first turn in initial operation, the beam may be lost practically anywhere. Assuming that the minimal length of the section where losses occur will comprise six magnet units azimuthally, then the admissible value is 10^{10} protons. Thus this value is the maximum intensity of the injected beam while tuning up.

When the complex was designed as a whole we considered the necessity of reducing the losses and protecting the elements of the UNK. In the approved two-stage acceleration version the losses are mainly concentrated in the iron circular magnet of the first stage. The beam is recaptured at the accelerating frequency of 200 MHz in the U-70 accelerator. Here, before injection into the first stage of the UNK, sharp edges of the beam are formed so that less than 0.1% of intensity occurs outside of the emittance of 2 mm mrad. High intensity is stacked at 70 GeV in the first stage. In the first stage we foresee forming sharp edges to the beam before its transfer to the second stage. There are gaps in the longitudinal beam distribution during the stacking process to allow for the rise time of the current pulses of the kickers in the transfer and extraction systems. The aperture of the transfer channel is chosen equal to that of the first stage. All these measures allow a transfer efficiency better than 99%. Strict tolerances are imposed on the stability of the magnet currents in the transfer system, so that the coherent oscillations caused by instabilities in the injection would not result in beam losses. Straight sections (485 m long) in the UNK permit the installation of a beam scraper in both stages to localize the losses. The beam scraper consists of a scatterer and an absorber after it. The local orbit is distorted near the absorber in such a way that protons with large oscillations hit the scatterer. Due to the multiple coulomb scattering in it the particles then come to the absorber. With our choice of the target thickness, the density distribution of the scattered protons at the edges of the absorber is shown in Fig. 4. Here at 400 GeV up to 2% of particles inelastically interact with the scatterer. As for the particles that hit the absorber, they initiate an internuclear cascade in it. A fraction of the particles produced in the cascade goes through the vacuum-chamber aperture and irradiates the SM elements installed behind the absorber. The beam scraper efficiency is defined as the fraction of the beam energy striking the scatterer that is absorbed in the absorber itself. When the steel absorber is 6 m long the value for the efficiency obtained from the calculation is 97% at 200-400 GeV taking into account the radial density distribution of the incident beam (Fig. 4) and inelastic interactions on the scatterer.

In the acceleration mode in the second stage the most dangerous moment from the standpoint of heating is injection into the second stage and beginning of acceleration. The admissible value for the losses localized in the beam scraper during injection will be defined from the conditions of admissible radiation heating of the superconducting winding in the nearest lens, located at a distance of 150 m from the beam scraper. Secondary hadrons generated in the absorber produce an almost homogeneous (along the lens length) distribution with the density per meter 10^{-4} hadrons/m, normalized for one proton incident on the absorber. Taking into account relations (1) this corresponds to the capturing during injection of a few per cent from the design intensity. When it is necessary to capture the largest fraction of the beam during injection we plan to solve the problem of protecting the SM in the straight section in the same way as it is done in the case of beam extraction.

Three extraction modes have been planned for the UNK, i.e., one turn fast extraction, slow resonance extraction (38 sec) and fast resonance extraction of 1 msec duration almost 10 times per accelerator cycle, i.e., 6×10^{13} protons per burst in 3 seconds at the magnetic field flattop. Figure 5 presents the scheme of the matched straight section of the UNK where the ejection system units are located. A kicker magnet (KM 1) guides the beam into the septum magnet during fast extraction. In resonance fast and slow extraction the beam is steered into the ES septum through resonance excitation of betatron oscillations. Since we do not plan to extract the whole intensity during one-turn fast extraction, the most dangerous from the standpoint of SM irradiation would be the mode of fast resonance extraction. The fraction of beam hitting the 0.1 mm septum is one per cent of the extracted intensity. At 3 TeV 10-15% of the particles will leave the septum avoiding nuclear interactions due to the multiple coulomb scattering. The remaining part of the beam (5×10^{11}) experiences inelastic nuclear interactions with the septum matter.

Secondaries produced in inelastic interactions in the ES septum irradiate the superconducting elements installed downstream. Hadrons initiate internuclear cascades; γ-quanta from pion decay generate electron-photon showers. Figure 6 illustrates the dependence of energy emission density in the lens superconducting winding installed at a distance of 170 m from the ES (lens Q_5 in Fig. 5) on the thickness of the iron shielding layer covering the vacuum chamber. As is seen the shielding layer of some mm reduces energy emission in the winding due to a reduction of the contribution from the electron-photon shower from photons produced in the ES. When the thickness of the shielding is more than 3 mm this contribution is almost completely suppressed. In practice this can be achieved by a proper chamber thickness. A steel shielding ~ 1 cm thick surrounding the vacuum chamber inside the SM may protect quite reliably the superconducting windings. This measure also allows one to reduce 2-3 times the value for energy emission density from any hadrons hitting the chamber at the angle $\theta \lesssim 1$ mrad in the windings.

Figure 7 gives the value for the coefficient K_0 that characterizes over-irradiation of the SM, depending on the distance between the SM and ES when the number of interactions on it is 5×10^{11}. At $K_0 = 1$, energy emission density is equal to the adopted admissible value at which the overheating does not exceed $\Delta T = 0.2°$. The calculated dependence of the coefficient K_0 on the distance L for different energies of protons on the ES and aperture of the irradiated SM are presented. The angle between the beam hitting the septum and the vacuum chamber axis in the straight section is taken as a parameter.

As is clear from Fig. 7 at 3 TeV and $\theta = 0$ the value for the coefficient K_0 may be almost 40. The increase of the diameter of the SM aperture does not result in any significant reduction of the coefficient K_0. At energies above 1 TeV an effective measure would be an increase of the angle θ. For the geometry of the considered straight section at 1.5-3 TeV and the angle $\theta = 2$ mrad one manages to reduce the irradiation of the superconducting elements located in the straight section almost down to the admissible value. As follows from Fig. 7 irradiation of the SM in the ring magnet becomes considerably lower as well. The angle needed in practice may be created if the beam is deflected before hitting the septum with the help of bending magnet (BM3). Magnets BM3, BM2, and BM1 may compensate for the disturbances of the circulating beam.

It should be noted that the influence of the magnetic elements, located downstream from the ES, would re-distribute the particle flux, which would result in the change of the value for the coefficient K_0. This effect should be taken into account when choosing the construction of the straight sections and installing the equipment in them.

Application of special collimators is another protection measure for the SM. The aperture sizes of separate collimators are determined proceeding from a condition of complete shielding of the vacuum chamber surface of the protected element against secondaries generated in the ES. The coefficient when protection is realized with a collimator whose length is 6 m is practically constant and equal ~ 4 at hadron energy 0.2-3 TeV. In order to increase the coefficient we may propose to use several collimators at a certain distance from each other. Under proper shielding conditions for a sequence of collimators the value for the coefficient may be 100. However, the fulfillment of this condition results in a noticeable decrease of the accelerator acceptance. This fact puts quite considerable limitations on application of this type of protection.

To avoid destruction and overheating of the SM, in emergency cases a beam-abort system with an efficiency better than 99% is foreseen in both stages of the UNK.

The results quoted in the report are quite preliminary. This important problem is still being studied. However, the results obtained give us hope that the measures on minimizing the losses and protecting the SM worked out in the frame of the UNK project would provide possibilities for operating the complex at the design beam intensity.

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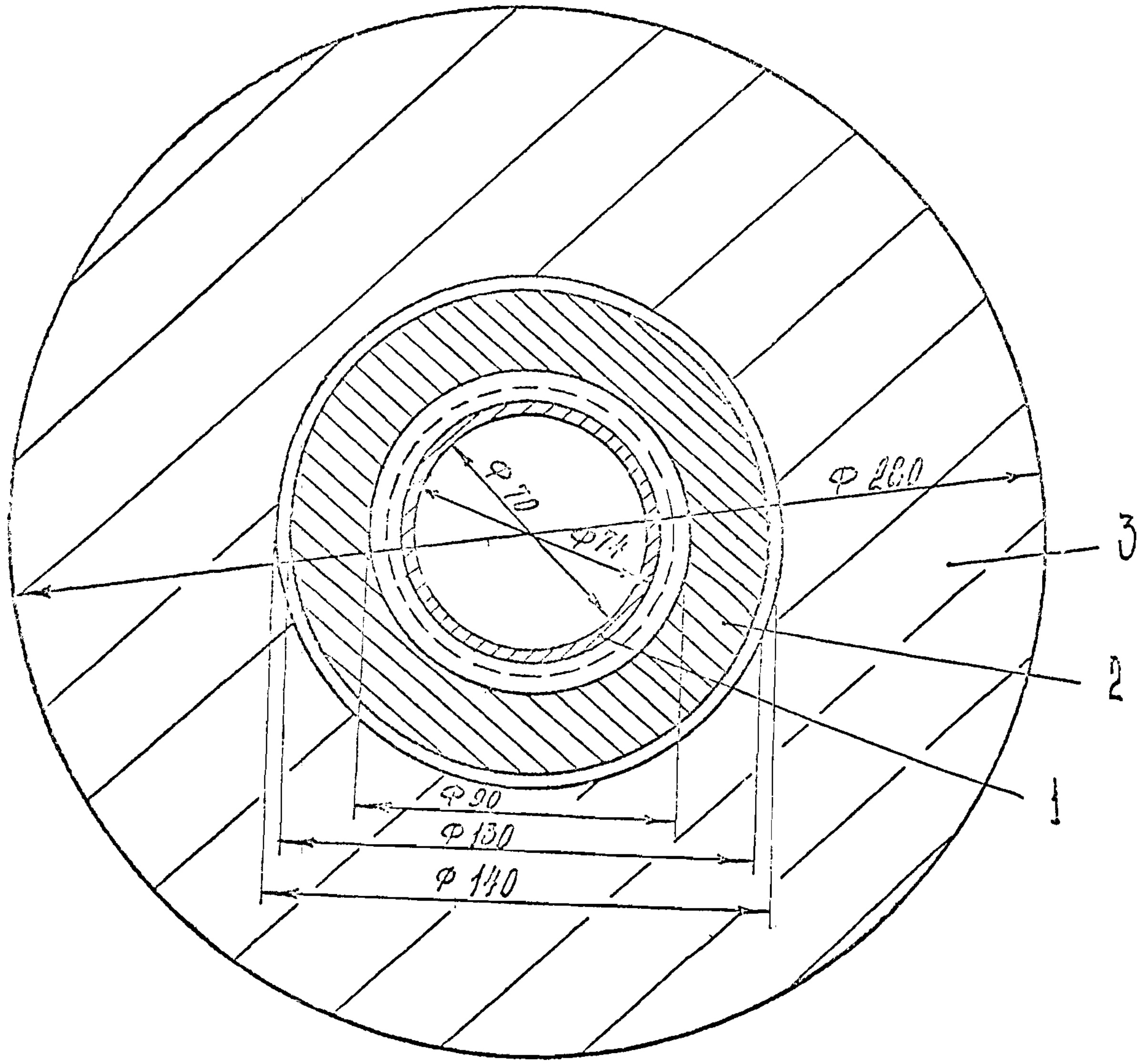

Fig. 1. The cross section of the magnet model used in calculations of internuclear cascades for distributed and concentrated losses. 1: vacuum chamber; 2: superconducting winding; 3: iron yoke.

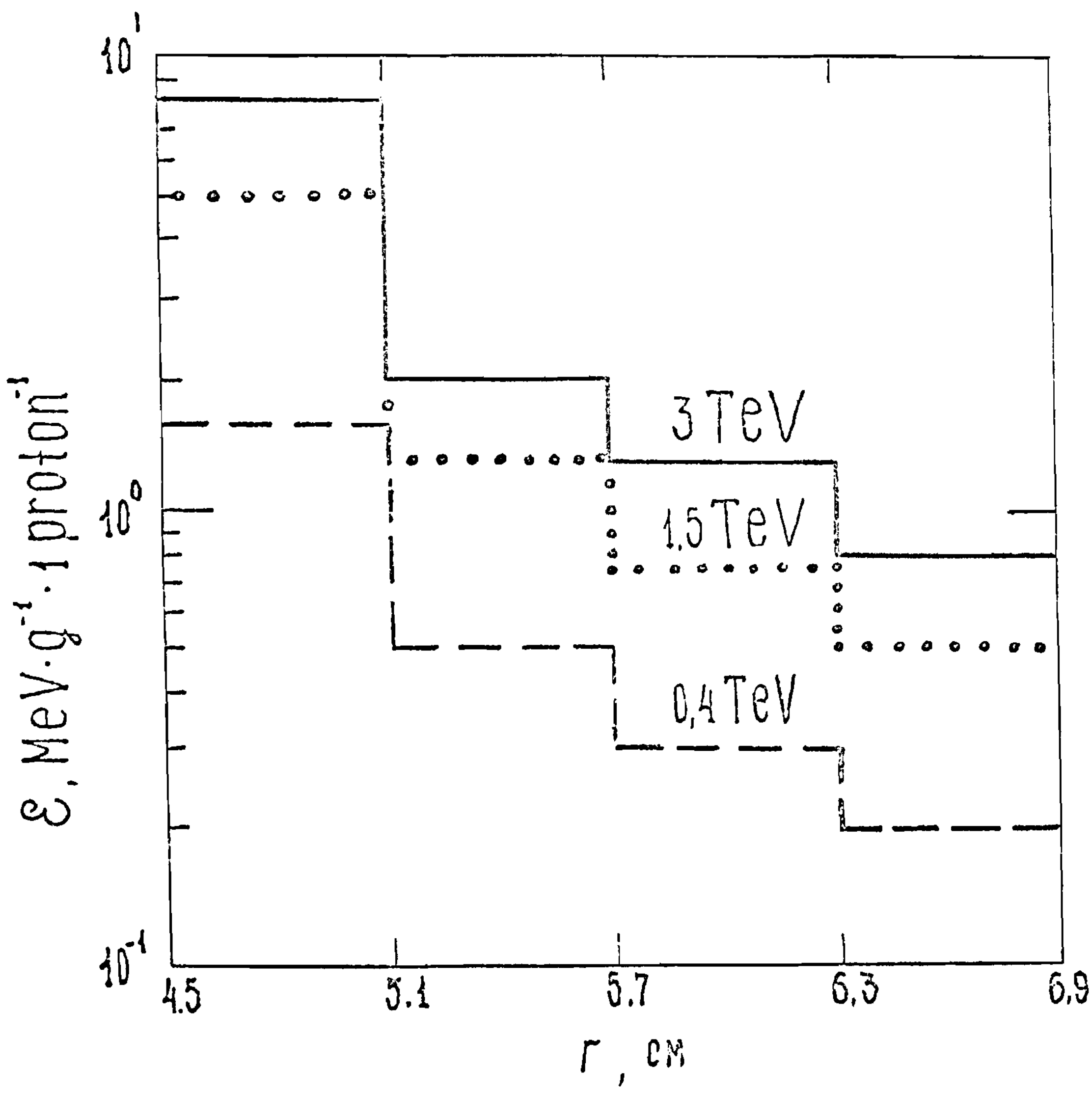

Fig. 2. Radial distributions of energy emission density in the magnet windings at the maximum of the cascade for concentrated losses of protons with different energies. The vacuum chamber wall thickness is 0.5 mm.

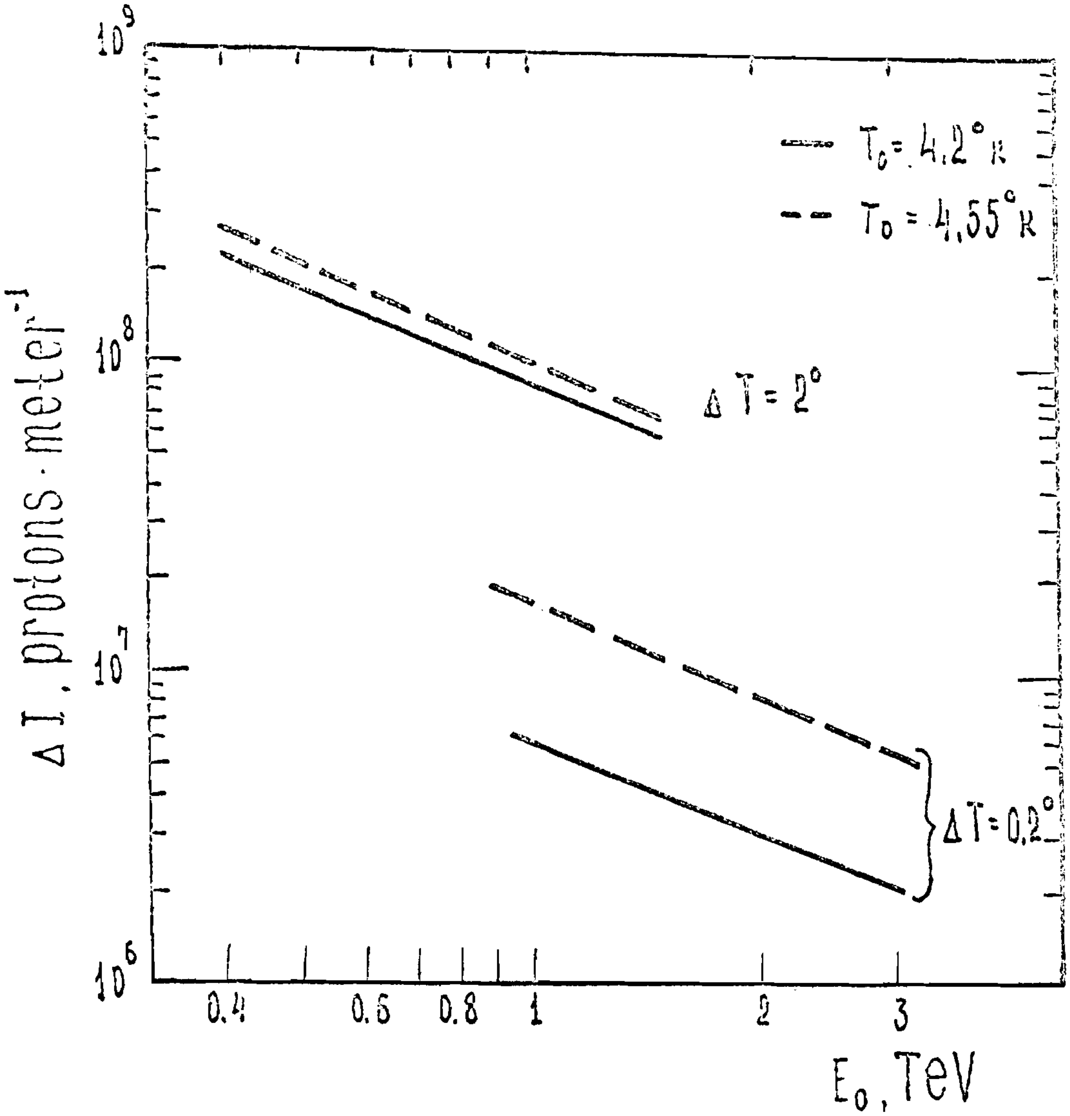

Fig. 3. Dependence of admissible values for instantaneous distributed losses of protons on their energy. T is the initial temperature of the winding before irradiation.

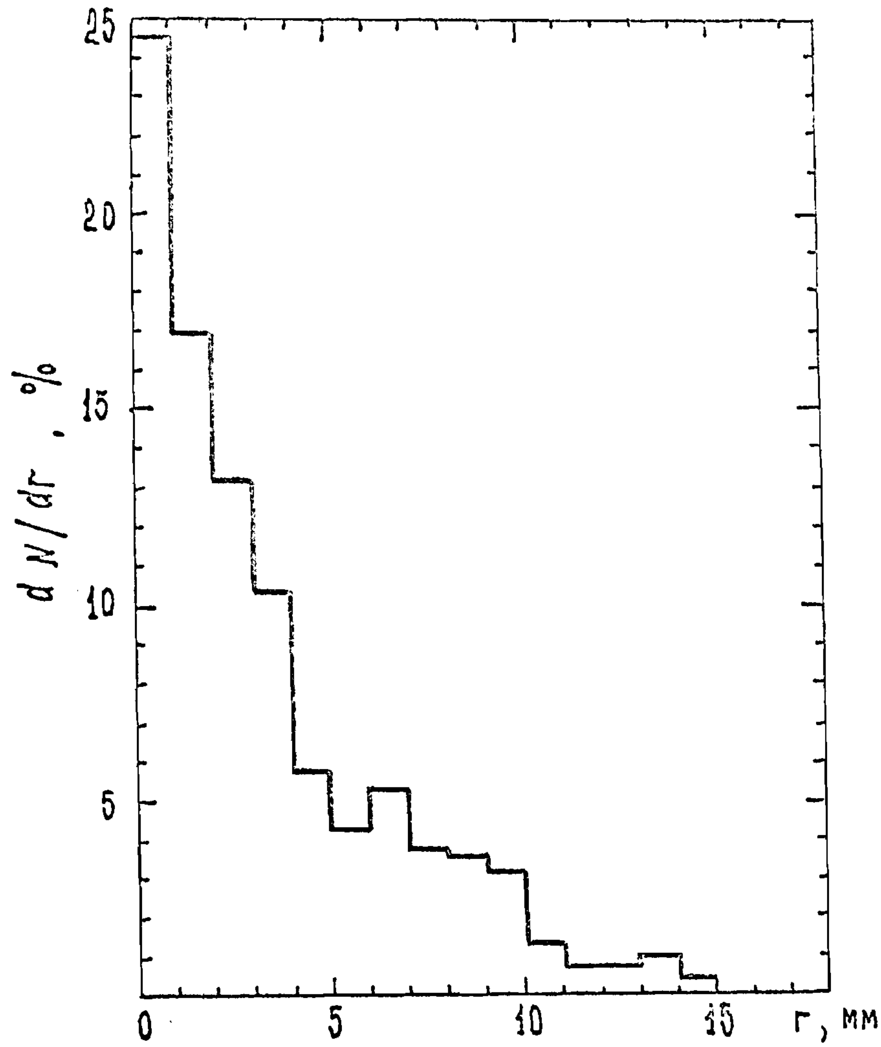

Fig. 4. Radial distribution of proton beam density at the edge of the aperture of the absorber in the scraper during injection.

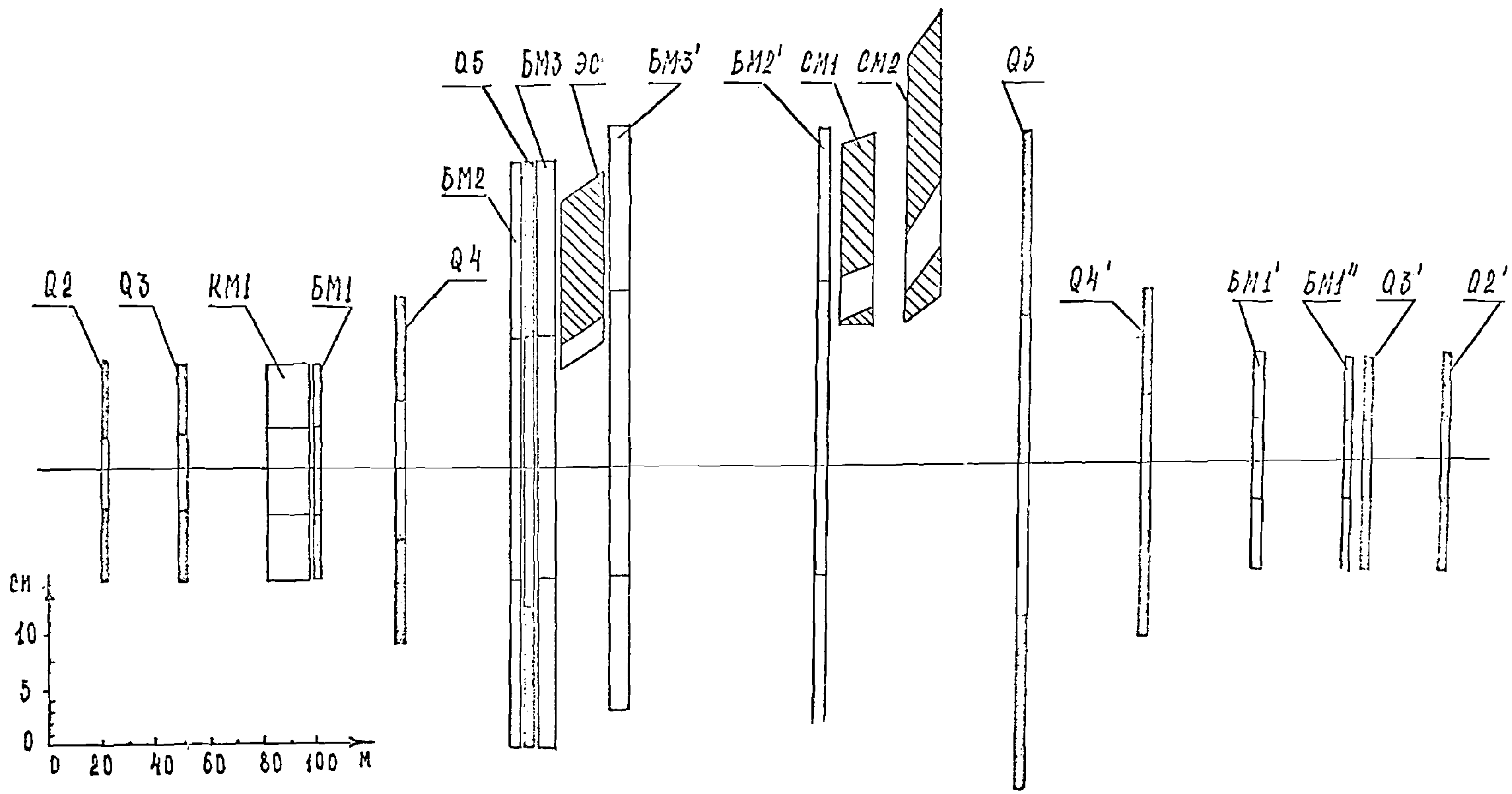

Fig. 5. The layout of the extraction straight section of the UNK. Q2-Q4: quadrupole matching lenses; KM1: kicker magnet of fast extraction system; ES: electrostatic septum; SM1-SM2: extraction magnets with a current septum; BM1-BM3: auxiliary bending magnets.

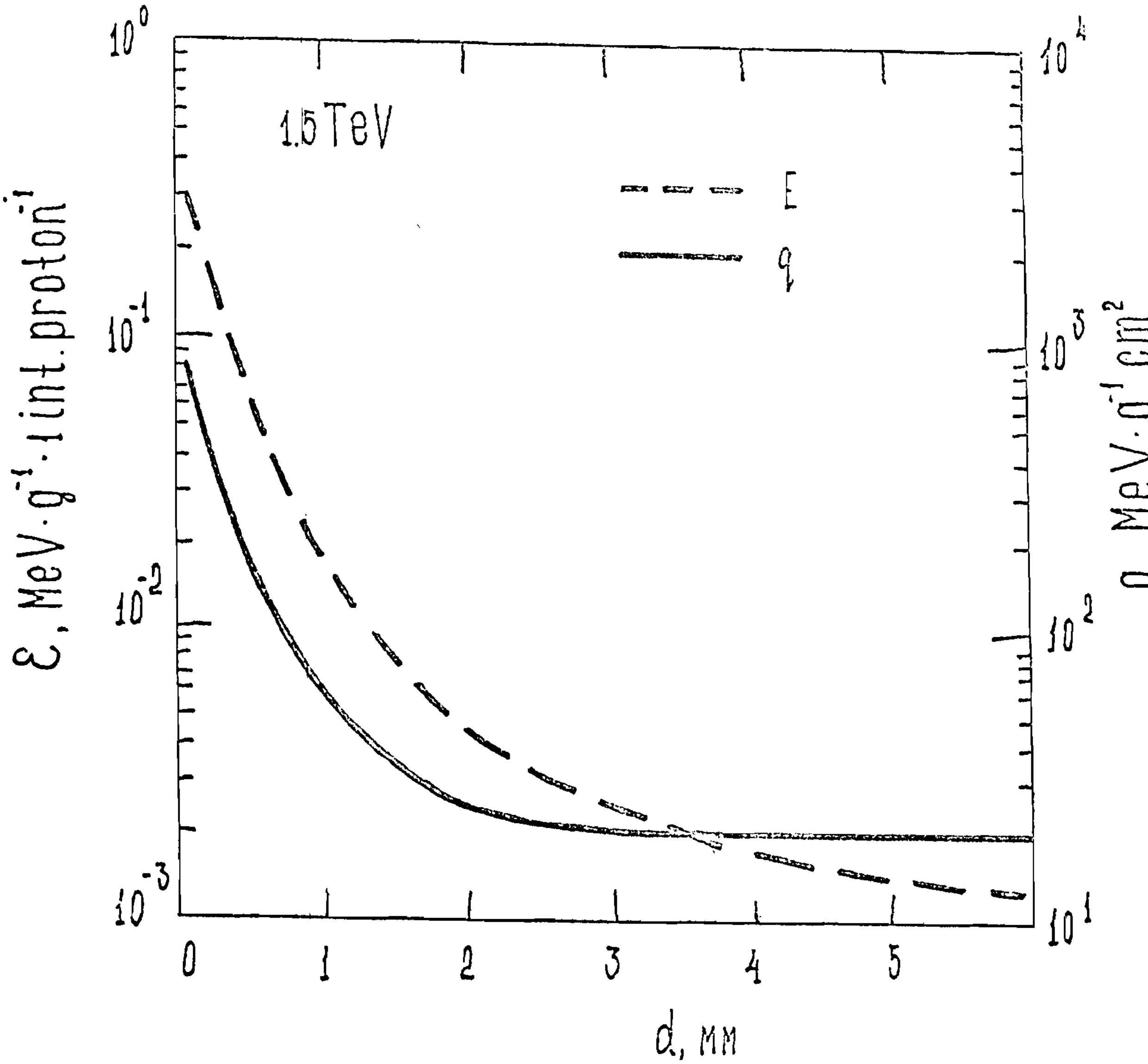

Fig. 6. Typical dependence of the maximum density of energy emission ϵ in the superconducting winding on the thickness of the vacuum chamber when irradiated by secondaries from the ES septum; q: transformation coefficient of hadronic fluence in the winding to the energy emission density.

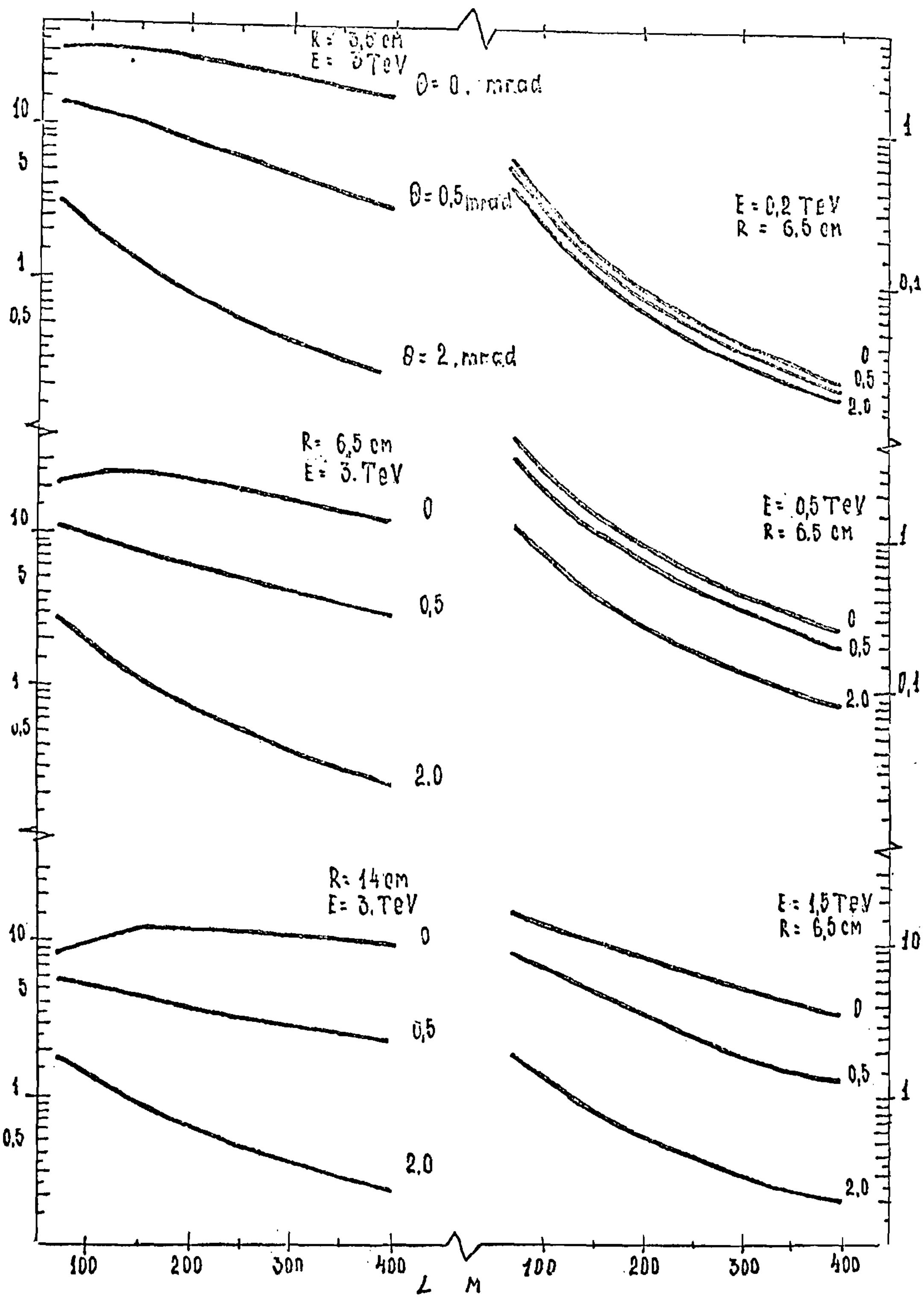

Fig. 7. The dependence of the coefficient K_0 on the distance L between the E_S septum and irradiated superconducting element. R: element aperture radius; E: beam energy, TeV; θ: the angle between beam direction on the septum and the vacuum chamber axis in the straight section.