DEVELOPMENT AND STUDY OF THE UNK SUPERCONDUCTING DIPOLE MODELS

N.I.Andreyev, V.I.Balbekov, E.A.Bulatov, Yu.P.Dmitrevskiy, V.I.Dolzhenkov, K.F.Gertsev, V.I.Gridasov, K.P.Myznikov, V.V.Sytnik, N.M.Tarakanov, L.M.Vasiliev, V.A.Vasiliev, V.V.Yelistratov
Institute for High Energy Physics, Serpukhov, USSR

Two full-scale dipole models, 6 m long each, have been manufactured in the scope of the programme on development of superconducting dipoles for the UNK. Results of their tests in a bath cryostat are reported. A number of short models have been manufactured and tested with view to improve the integral characteristics of the magnetic field. The results of magnetic measurements of the central and edge field are prezented. Also reported are the results of study of training and dynamic characteristics of dipoles.

IHEP continues work on simulation of superconducting dipole magnets for the 3 TeV UNK/1/. Proceeding from the construction of the previous series of short models/2/, designed to obtain a 5 T bore field induction, there have been manufactured a few models of a new series from a superconducting cable with improved current density and a diameter of filaments of 10 μm. These models made it possible to obtain the UNK working field in the bore without training and to have a reserve in the critical current necessary in case of increased heat releases in the coil due to irradiation. Based on the experience in working out short models/3/, two 6-m full-scale models have been manufactured. Tests of the first long models showed reproducibility of the results obtained for short models.

FULL-SCALE MODELS

IHEP dipoles as those of FNAL/4/ have a two-shell coil with some distinct design features allowing an increase in the bore field up to 5 T. Due to a high field intensity of a proton beam accelerated in the UNK they should have a reserve in the critical current which could provide a stable operation of magnets with possible particle losses.

The cross-sectional view of the dipoles is given in fig. 1 and their basic characteristics are presented in Table 1.

Table 1
The Basic Characteristics of a Dipole

Inner radius of the 1st shell, mm	45.16
Angle of the 1st shell, deg	72.425
Angle of the 2nd shell, deg	36.532
Number of turns in the 1st shell	2 x 39
Number of turns in the 2nd shell	2 x 24
Total length of shells, mm	5925
Ratio B/I with iron, T/kA	0.880
Ratio B/I without iron, T/kA	0.753

For these models, the cable has been manufactured from 0.85 mm in diameter strands. Each strand contains 2970 Ni-Ti filaments, 10 μm in diameter, embedded into a copper matrix with a packing factor of 42%. The cable was transposed from 23 strands, 12 of which were coated by Sn - 5 wt % Ag with a 75 mm transposition pitch. The keystoned cable was 10.55 mm in height, the outer width was 1.68 mm and the inner one was 1.34 mm(without insulation). The cable was insulated by two layers of a 20 μm lavsan tape and 100 μm thick epoxy-impregnated fiber-glass tape with a 4 mm gap between the adjacent turns.

The models have been tested without an iron yoke in a bath cryostat with pool-boiling helium. The training curves for the two models are shown in Fig.2. For the first model, the maximum field was attained after the 3d quench. It exceeded by only 3% the field attained at the 1st quench. The maximum value of the attained current coincides with that of a short sample to an accuracy of 2.5%. The magnet has repeatedly been tested within every two months after warming up to the ambient temperature. Each time, the current attained its maximum value already at the 1st quench and its value was reproduced to an accuracy of 10 A. A second magnet model has been manufactured from a superconducting material with an improved current density. During just the 1st quench its current was 6 kA. At higher currents, there was a long-term training observed. After 26 quenches the attainable current was 6.6 kA, corresponding to a bore field of 5 T without an iron shield.

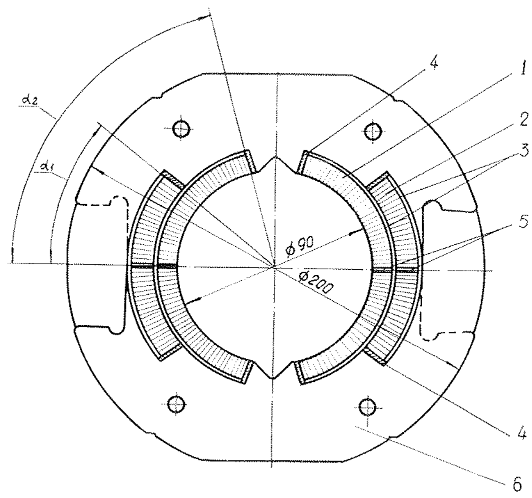

Fig. 1. Magnet cross-section: inner coil shell (1), outer shell (2), helium flow channels (3), spacers (4), insulating spacers (5), bandage (6).

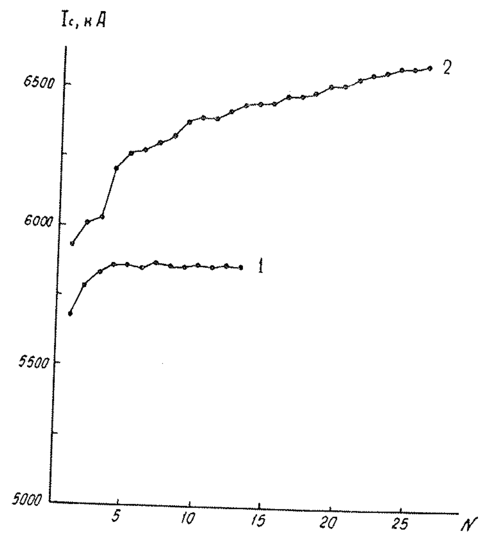

Fig. 2. The training curves for full-scale models: I - model DD-1, 2 - model DD-2.

A detailed study of harmonics of central field nonlinearity has been made for both magnets. Inacuracy of measuring the relative value of field harmonics did not exceed $5\cdot10^{-5}$ for nonlinearities lower than the 5th order and 10^{-4} for higher-order nonlinearities/5/. Fig. 3 and 4 show even and odd nonlinearities*), respectively, at a distance of 35 mm from the centre versus the magnet current. The analysis shows that within the 70 mm bore diameter the field nonlinearities are close to those calculated for both full-scale magnets and keep their values unchanged within tolerances in a working field range from 0.67 T to 5 T.

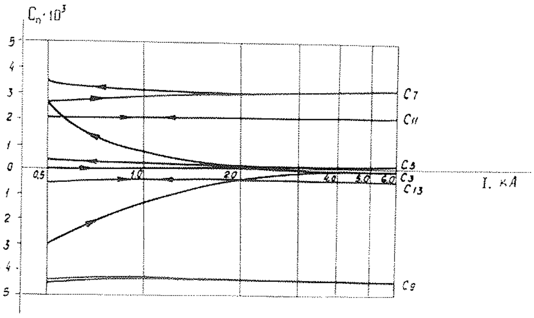

Fig. 3. Normal even nonlinearities versus magnet current.

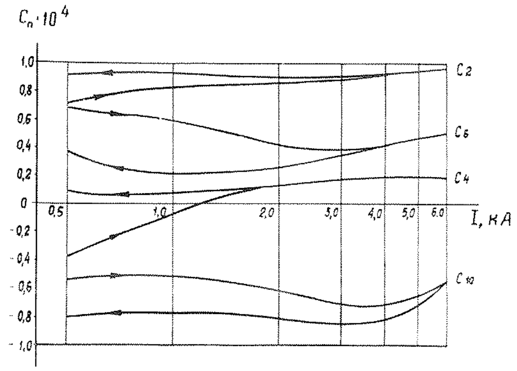

Fig. 4. Normal odd nonlinearities versus magnet current.

The dynamic losses measured in the trapezoidal cycles of current changes for the 100A/sec ramp rate and 6 kA amplitude (the real cycle of the UNK) were 750 J, 550 J being hysteresis losses.

The full-scale dipole models are taken as the basis for further development. One of the models is assembled now in a force-circulating cryostat with a magnet shield (fig. 5) and is ready to be tested at a force-circulating cryogenic test facility.

STUDY OF SHORT MODELS

Study of short models is going on. A few models with an improved current density of the cable have been manufactured. Being tested in a bath cryostat at a temperature of 4.25 K these models with an iron shield provide bore field of about 5.5T after the 1st quench. Fig. 6 shows the training curves for three magnets of this series. As seen, after some training the maximum field attained was 6.2 T. With a temperature of the helium bath down first to 3.9 K and then to 3.65 K the maximum field attained was 6.55 T and 6.7 T, respectively, after a short-term training at each level (3÷4 quenches). The harmonic analysis has been done for each field level. Besides, with the help of resistor-type strain gauges the dependence of radial bandage movement due to ponderomotive forces has been measured. As shown by these measurements, the relative values of harmonics deviate from those tolerable by $1\cdot10^{-4}$ at a field exceeding 6 T, which is accompanied by a bandage deformation by above 100 μm. So, the developed construction has a good mechanical stability at the UNK working field and also a necessary reserve in the critical current.

*)The coefficient C_n corresponds to the nonlinearity of the order of n-1.

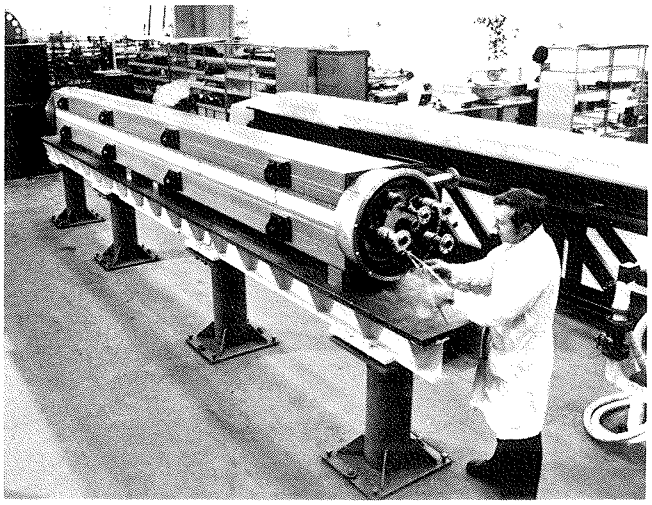

Fig. 5. A full-scale dipole model in a force-circulating cryostat.

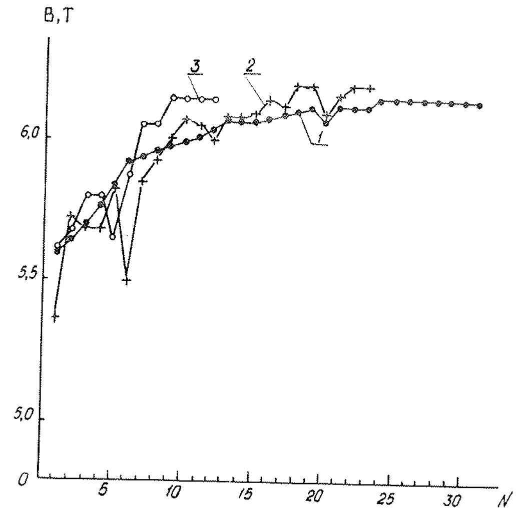

Fig. 6. The training curves for new short dipole models.

UNK full-scale dipoles to be manufactured are supposed to be rectilinear. In this case stringent requirements are imposed on the edge field quality. The relative values of harmonics C_3 and C_5 should satisfy the conditions

$$\left|\int_{\Delta s} C_3 ds\right| < 3,5\cdot10^{-3}\ \text{m} \quad \text{and} \quad \left|\int_{\Delta s} C_5 ds\right| < 4\cdot10^{-4}\text{m},$$

where Δs is the end length. To meet these requirements, the turns at the edges were laid in such a way that the integral values of harmonics C_3 and C_5 in the edge field be close to zero/6/. Fig. 7 shows the picture of these coils. The end part of the coil of the inner shell has a 11.2mm wide fiber-glass spacer after the 4th turn and a 47.2 mm wide one after the 30-th turn. The outer layer has no such spacers. Fig. 8 shows the design and measured dependences of dipole and sextupole components of the edge field on the longitudinal coordinate measured from the middle of the dipole. The calculated and experimental data are in a satisfactoty agreement. The way of laying out turns at the coil edges made it also possible to improve the integral characteristics of the dipole field. The contributions from the edge field into lower-order nonlinearities are within tolerances for the case of a full-scale dipole.

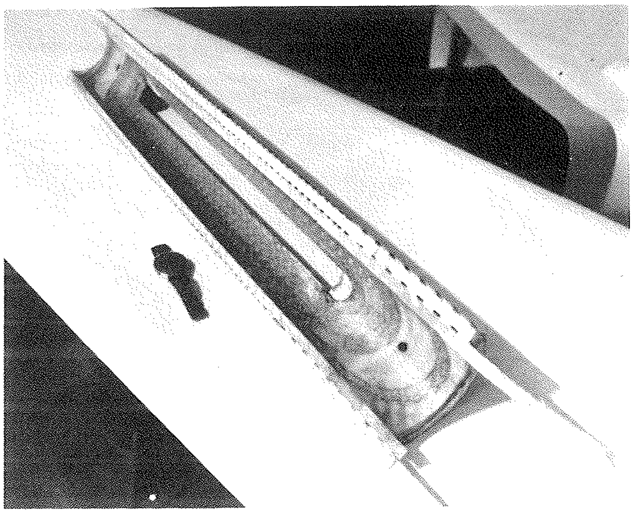

Fig. 7. A half-coil of a short model; the layout of turns on the edges is seen.

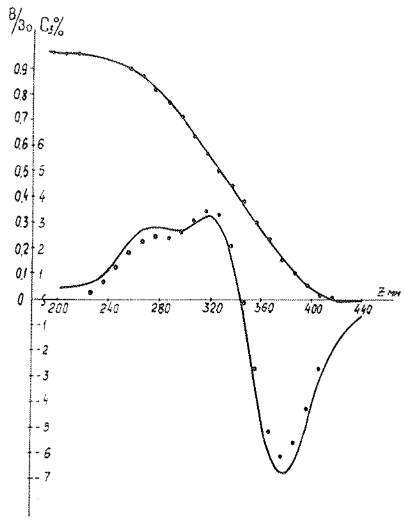

Fig. 8. The dipole and sextupole components of the edge magnetic field. The solid lines are for the calculation, the points are for the experimental values.

Dynamic characteristics of dipoles have been measured. Fig. 9 shows a dependence of the critical current on the ramp rate, typical for the dipoles of this series. As seen, in the whole range of rates up to 250 A/sec the quench current remains unchanged.

Presently the work on dipole study contines. As a next step, a study will be made of their operational peculiarities in force-circulating cooling mode.

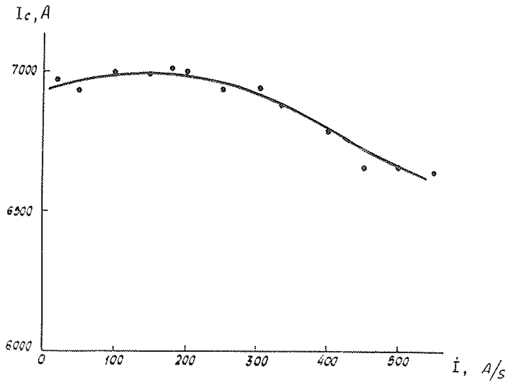

Fig. 9. The critical current of a short model versus ramp rate.

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