Results on Testing Pilot Industrial Batch of SC Magnets for the UNK

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Abstract

IHEP has developed and studied the superconducting dipoles and quadrupoles of the regular part of the UNK main ring which satisfy the requirements imposed on them. The pilot-industrial batch of the UNK SC magnets is produced now. The reproducibility of the magnet characteristics is studied and the mass production technology is optimised with this batch. The paper presents the results on the cryogenic tests and the magnetic field measurements for the UNK SC dipoles of the pilot-industrial batch.

1 INTRODUCTION

The superconducting ring of the UNK consists of 2192 dipoles and 474 quadrupoles [1]. To satisfy the operational conditions in the accelerator and colliding beam modes, the SC magnets should withstand heavy demands imposed on the field quality, heat load on the cryogenic system, temperature reserve. The nominal bore field in dipoles was chosen to be 5 T and the nominal gradient in quadrupoles of the regular part is 97 T/m.

The SC dipoles and quadrupoles of the regular part of the UNK main ring which satisfy the requirements imposed on them have been developed and studied in IHEP [2]. The pilot-industrial batch of the UNK SC magnets is produced now. The reproducibility of the magnet characteristics is studied and the mass production technology is optimised. The paper presents the results on the cryogenic tests and the magnetic measurements for the UNK SC dipoles of the pilot-industrial batch.

2 DESIGN OF THE UNK SC DIPOLES

The design of a SC dipole has been considered in papers [2]-[4]. The major element of the design is a two-layer shell-type cold-iron coil having 80 mm inner diameter. The dipole design is tailored to use superconductors having a critical current density of $2.3\cdot10^5$ A/cm^2 at 5 T and 4.2 K.

The cable for the SC dipoles is manufactured from multifilament composite wires 0.85 mm in diameter, containing 8910 Nb-Ti filaments, each 6 μm in diameter, embedded into a copper matrix. The packing factor is 0.42, the filaments twist pitch is 10 mm. The cable consists of 19 strands, 9 of which are coated with an Sn+5%Ag alloy. The cable has a keystoned cross-section with the bases 1.30 mm and 1.62 mm and height 8.5 mm for the inner layer and 1.33 mm, 1.59 mm and 8.5 mm for the outer one. The cable is insulated with two layers of 20 μm thick kapton tape and a layer of epoxy-impregnated fiberglass tape 100 μm thick and 10 mm wide [5].

The collars are made from 2 mm thick stainless steel sheets of quality 05X20H15AΓ6. The beam pipe is made from an stainless steel of quality 03X20H16AΓ6. The magnetic susceptibility of these steels at 4.2 K and in fields from 0 to 5 T is $6.5\cdot10^{-3}$.

The magnetic shield for SC dipoles is manufactured from 3 mm sheet electric steel of quality 2081. The coercive force and saturation magnetization of this steel at 4.2 K is 2.1 Oe and 2.19 T, respectively.

The cryostat consists of a vacuum vessel, thermal shield and helium vessel with the coil assembly and magnetic shield placed inside it. The helium vessel is fixed to the vacuum vessel by the Ti vertical suspensions and horizontal extension rods placed in two cross sections along the magnet. The longitudinal motions of the helium vessel are prevented by the anchor extension rods fixing the central cross section and allowing a free motion of the magnet ends in thermal cycles. The helium part of the cryostat is covered by 10 layers of superinsulation. The thermal shield is cooled by an 80 K liquid nitrogen flow. It is covered by 40 layers of superinsulation.

The SC magnets are cooled by a 4.4–4.6 K single-phase helium flow. A part of this flow goes through the circular channel formed by the coil and beam pipe and between the coil layers, while another one is by-passed into channels going in the magnetic shield. There is a heat exchange between the single-phase helium and a two-phase helium counterflow going inside the pipes of the by-pass channels.

3 TEST RESULTS

23 SC dipoles of the pilot-industrial batch have been manufactured and tested. The tests were made in the force-circulating cooling mode at 4.4 K.

Figure 1 presents the distribution of the first quench current for the SC dipoles of the pilot-industrial batch. The first quench current of the 5 magnets was in the interval from 4770 to 5055 A. This is a little bit lower than the maximum current in the UNK cycle, 5100 A. The fluctuations of the value of the first quench current from magnet to magnet can be explained by two factors: 1) the coil temperature fluctuations during the magnet tests, caused by the "anticryostat" heat leaks; 2) changes of the mechanical characteristics of the magnet, connected with the development of the coil production technology, the assembling and collaring process. After training, the maximum critical current of the magnets determined by that of the short

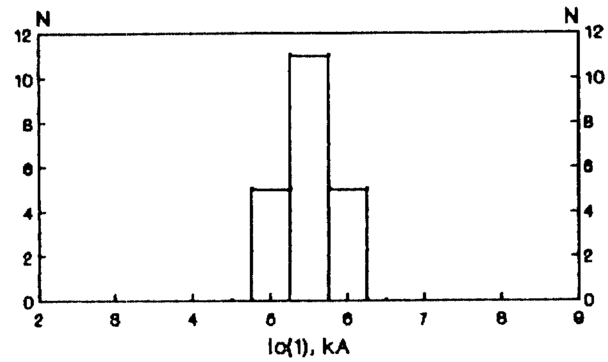

Figure 1: Distribution of the first quench current.

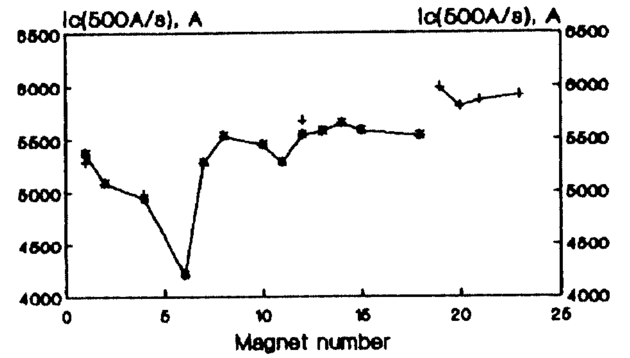

Figure 3: Critical current at 500 A/s ramp rate with (*) and without (+) "anticryostat".

sample with account of the temperature and magnetic field in the coil was attained. The studies performed show that the magnets do remember the training after the cooldown and warm-up cycle when the critical current of the magnet achieved during the training is less than 6200 A. But if the current is higher than that, training starts at 100-200 A less than the one attained in the previous test.

Figure 2 shows the temperature dependence of the critical current for the SC dipoles of the pilot-industrial batch. As is seen, the temperature reserve of the SC dipoles is at least 0.8 K at the helium temperature 4.4–4.6 K and the maximum operating current 5100 A in the UNK cycle.

Figure 3 presents the change from magnet to magnet of the dipole critical current at 500 A/s ramp rate corresponding to the maximum current variation rate in the UNK magnets during emergency energy removal. The low critical currents at 500 A/s ramp rate for the first magnets were explained by the high temperature during the coil curing that increased AC losses in the cable. When the coil curing temperature was decreased to 150 C all quenches of the magnets at 500 A/s ramp rate were over the maximum operating current in the UNK cycle.

Figure 4 presents the change from magnet to magnet of AC losses in the cycles with the current change in the interval 600–5250 A and current ramp rates 100 and 300 A/s. The increase of the AC losses in the first magnets was caused by the same reasons as above. After the coil curing modes were stabilized, the AC losses in the acceleration cycle of the UNK for the 100 A/s ramp rate reached the level of 700–800 J, corresponding to the mean power of 6–7 W per magnet. The static heat leaks to the helium vessel were about 5 W, and those to the nitrogen shield were 20–30 W.

Figures 5 and 6 present the results on measuring of the field-current ratio, B/I, and of the effective length L for the SC dipoles of the pilot-industrial batch versus the coil current. The relative RMS spread of B/I in the operating current range does not exceed $6 \cdot 10^{-4}$, while that of the effective lengths in the operating current range does not exceed $4 \cdot 10^{-4}$. The measured values and spread in B/I and L yield the relative value of the RMS spread of the field integral less than $5 \cdot 10^{-4}$, which is twice as little as the established tolerance.

The measurement results showed that the statistical characteristics of normal C_n and skew S_n integral field nonlinearities of the SC dipoles are actually independent of the level of the coil current, except for the sextupole nonlinearity C_3. Its variation is caused by the effect of filament magnetization at low currents and iron saturation at high currents. Table 1 presents the mean values and RMS spread of normal and skew integral field nonlinearities of the SC dipoles of the pilot-industrial batch at 3.5 kA on the bore radius 3.5 cm. The mean value, $\overline{C}_3$, and RMS spread, $< C_3 >$, of sextupole nonlinearity at 0.5 kA are $-10.3 \cdot 10^{-4}$ and $3.0 \cdot 10^{-4}$, whereas at 5 kA

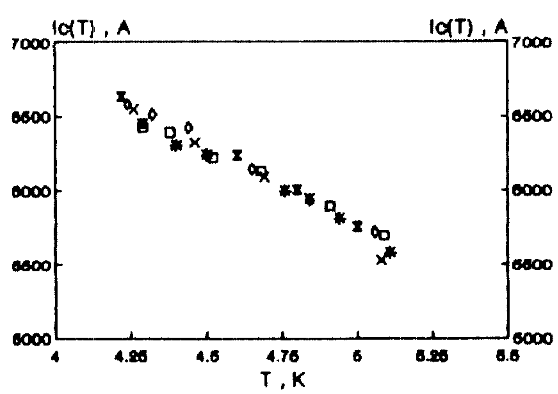

Figure 2: Temperature dependence of the critical current.

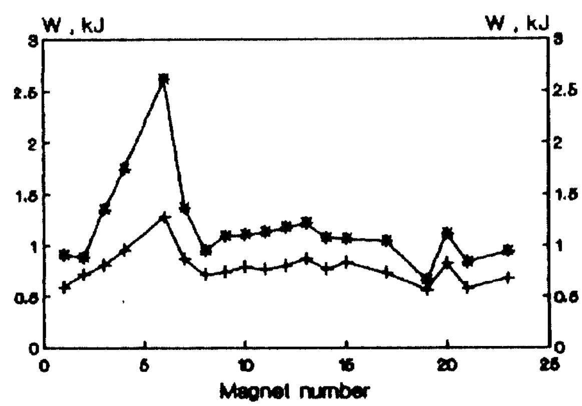

Figure 4: AC losses in the cycle 600-5250-600 A: + - 100 A/s; * - 300 A/s.

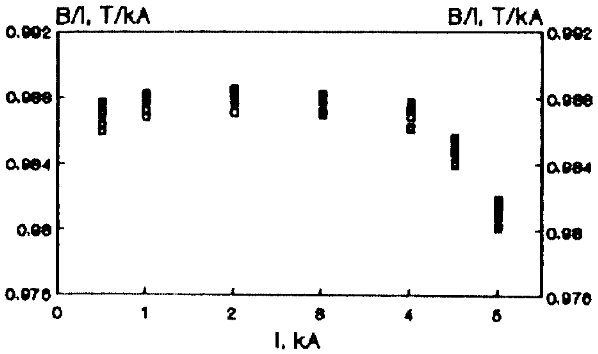

Figure 5: The transfer function of the SC dipoles versus the coil current.

they are $-2.4 \cdot 10^{-4}$ and $3.2 \cdot 10^{-4}$.

Table 1: Mean values and RMS spread (10^{-4}).

n	2	3	4	5	6	7	8	9
$\overline{C}_n$	-0.2	-0.2	0.0	1.2	0.2	-0.8	-0.1	-0.2
$< C_n >$	0.6	3.2	0.5	2.5	0.3	1.3	0.3	1.1
$\overline{S}_n$	1.5	-0.2	0.6	0.0	0.1	-0.2	0.3	0.1
$< S_n >$	3.8	0.4	3.1	0.5	1.1	0.4	0.9	0.3

The magnetic measurement results show that the mean values of nonlinearities remain within the tolerances, except for a skew gradient. Its systematic value is 1.5 times as large as the tolerance and cannot be compensated by a correction system of the difference coupling resonance, whose maximum strength is tailored to suppress the effect of $|\overline{S}_2| < 1 \cdot 10^4$. It should be noted that the value of $\overline{S}_2$ reduced by more than a factor of 2 when the statistics increased from 10 to 20 magnets [4]. At 0.7 kA the value of $\overline{C}_3$ is within the tolerance, $-10 \cdot 10^{-4}$. 20% oversising the tolerance for $\overline{C}_3$ at 5 kA is not dangerous for the stability of particle motion and the negative sign of this value will decrease the load on the correction system for the machine chromaticity.

The RMS spread of the majority of nonlinearities is within the tolerances, except for that of $< S_2 >$, whose value is now about twice as large as desired. But still it was brought down with the latest magnets of the pilot-industrial batch. The value of $< C_3 >$ at a low current level, when the beam sise is relatively large and effect of betatron resonances most noticeable, is within the tolerances. At high currents, when the beam sise is not large, $\sim$ 20% oversising the tolerance is acceptable.

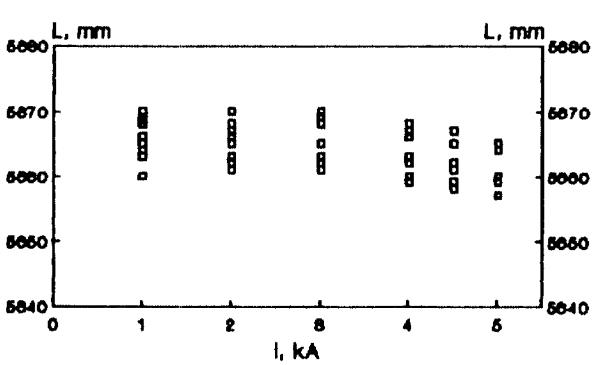

Figure 6: The effective length of the SC dipoles versus the coil current.

During the tests of the first SC dipoles turn-to-turn shorts were observed, making three magnets go faulty. In all cases that happened after 4–10 quenches at the currents exceeding essentially the operating current of the UNK cycle. As it turned out, the reason for that were sharp edges of the SC cable which damaged the insulation under a high stress caused by ponderomotive forces. After that the production technology for the SC cable was modified and its quality control became more stringent. This made it possible to avoid turn-to-turn shorts in magnets.

One of the SC dipoles was tested during prolonged operation in the cyclic mode when the coil current varied from 0.6 to 5.25 kA at a ramp rate of 300 A/s. Preliminary the magnet was quenched 25 times at current exceeding essentially the maximum current of the UNK cycle. During the tests the magnet was cooled down and warmed up in the temperature range 4.4–300 K. The field components in the bore were also measured. No variations in the field nonlinearities were recorded after 10^5 current cycles and 8 thermal ones. The magnet showed a stable operation in the cyclic mode without spontaneous quenches when the mean power of energy releases was $\sim$ 30 W.

4 CONCLUSIONS

The study of the first 23 SC dipoles of the pilot-industrial batch show that actually all major parameters of the SC dipoles for the UNK satisfying the requirements imposed can be obtained during mass production. The quenches induced by mechanical distortions (training), AC losses in the coil (ramp rate dependence), coil temperature variation (temperature dependence) occur at currents exceeding the operating ones of the UNK. AC losses in the coil and static heat leaks to the cryostat satisfy the requirements imposed with the feasibilities of the UNK cryogenic system. The magnetic measurement data show that they have satisfactory characteristics of the bore field. An exception is the systematic value and RMS spread of the skew gradient that should be decreased by 1.5–2 times. This has to be accomplished by upgrading the production technology for the collared coils and their quality control done proceeding from the results on warm magnetic measurements.

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