Investigation of the String of UNK Superconducting Magnets

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Abstract
A string test facility of 4 UNK SC dipoles, interleaved by a quench stopper in the two protected cells, is described. The string is equipped with a sufficient number of temperature and pressure sensors and potential taps to measure electrical and cryogenic parameters. All the signals are monitored and recorded by a 128-channel quench analyzer. On a SC element transienting from a superconducting to normal state, studied are the quench onset localization, quench propagation along the string of elements, as well as the helium temperature and pressure behavior. Parameters of quench protection system elements — a quench stopper, safety leads, bypass switches, safety valves — are established.

I. INTRODUCTION

The quench protection system (QPS) for the UNK ring electromagnet is based on breaking the whole ring into cells (QPU), shunting them with thyristor switches placed at the exterior of the cryostats at the ambient temperature, and energy removal from the rest part of the ring into dump resistors [1]. QPUs, each consisting of 12 dipole and 2 quadrupole magnets, are separated by quench stoppers, containing a pair of safety leads. Each QPU is shunted with two quench bypass switches. The status of the SC circuit is monitored by the quench protection monitor system (QPM).

To investigate processes in QPU during the quench, the string containing 4 UNK-type SC dipoles is assembled at IHEP. The program of string investigation includes studies of quench onset in some of its SC elements, monitoring energy dissipation, temperature and pressure distribution during the quench, as well as tests of QPM prototype and QPS elements (a quench stopper, safety leads, quench bypass switches).

Below, a brief description of the string and its first test results are presented.

II. DESCRIPTION OF THE STRING FACILITY

The string facility consists of 4 SC dipoles, cryogenic system, power supply, cryogenic control system, quench detection system and diagnostics. Cryogenic system contains liquefier, satellite refrigerator and cold box. The magnets are connected to the cryogenic system through the head, intermediate and return boxes. The intermediate box contains the quench stopper (QS) and safety leads (SL). The QS serves to prevent the quench propagation from one QPU to another and is a helium-cooled massive copper radiator. The helium venting system consists of 5 fast response quench valves [2], quench gas header and 140 m^3 gas tank. The cryogenic control system permits an automatic execution of the string cool-down and warm-up, normal string cooling operation by both 1Ø and 2Ø helium, and recovery of cooling conditions after a quench.

The UNK SC dipole magnets [3] additionally equipped with voltage taps and spot heaters are used in the string. Magnets have been previously tested at the magnet test facility, and they have the critical current above 6000A. Electrically, the magnets are connected in a series circuit as shown in Fig.1. There are two QPUs: one of them includes magnets M1 and M2, another one — M3 and M4. In the first QPU the coil of M1 and return bus of M2 are shunted with QBS1, while the coil of M2 and return bus of M1 are shunted with QBS2. In the second QPU both dipoles and their return buses are shunted with a single QBS3.

The SC circuit is monitored with 4-channel quench detector (QD) based on extracting the coil resistive voltage by means of a compensation technique. The threshold of QD is 1V. When there is a quench in one of the magnets, e.g. in M2, the QD fires the strip heaters in M1 and M2, the coils of these magnets are shunted with QBS1 and QBS2, and power supply is turned out to the reverse mode. As a result, the current in magnets M1 and M2 decays very quickly and dissipates its energy inside the coils, whereas current in M3 and M4 falls down with a certain rate through SL1, SL2 and QBS1, QBS2. If during this ramp-down another quench in M3 or M4 takes place, the strip heaters in M3 and M4, as well as QBS3, are activated, power supply is turned off and the thyristor switch TS0 shunts its output. The energy stored in the string is dissipated inside all of the coils.

Numerous voltage taps and potential pairs placed at various parts of the SC circuit (Fig.1) are employed to observe the quench propagation. A 128-channel quench analyzer is used for automatic data acquisition. It allows one to record data before and after quench. The input channels are divided into groups in which data are collected at different rates in order to monitor fast processes (e.g. normal zone propagation) as well as the slow ones (temperature and pressure development). There is 1 Kbyte of memory per each channel. The maximum data acquisition rate is 250 Hz.

Apart from this QD at the string, there is another quench detector based on magnetic modulators (QDMM) [4]. Many advantages of this system in comparison with the compensation QD were revealed during the tests. The QDMM test results are reported elsewhere.

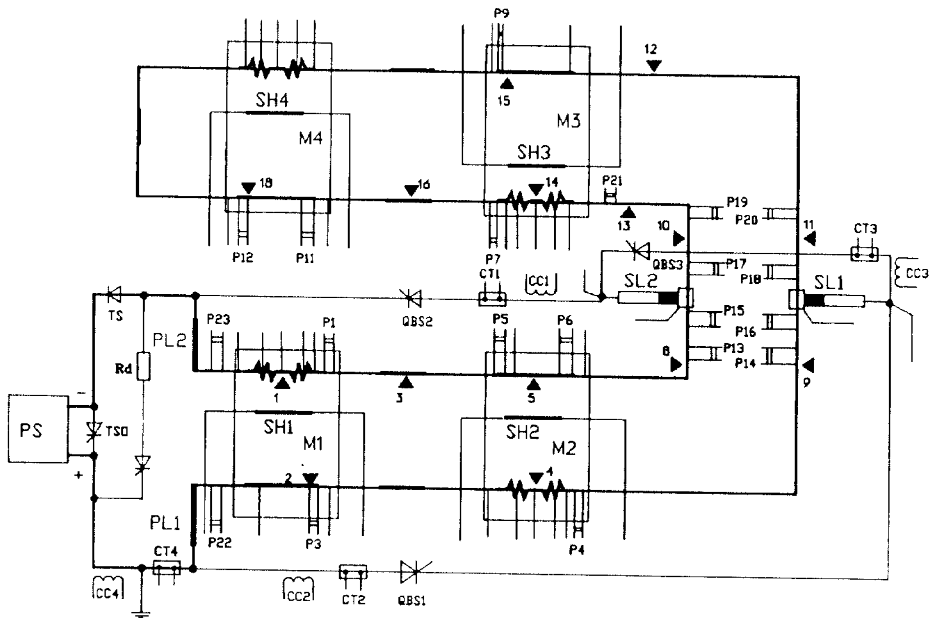

Figure 1. Electrical diagram of 4 magnet string: M1-M4 – SC dipole magnets, PS – power supply, PL – power lead, SL – safety leads, QBS – quench bypass switch, CT – current transducer, OH – strip heater, ▽ – spot heater, P1-P23 – potential taps.

III. TEST RESULTS

After string assembling the cryostats were pumped down to vacuum values of 1×10^{-2} Pa with no leaks. A pressure test of helium vessels was performed at 10 bars with no damages being observed. A 2500 V hipot test of electrical circuit to ground was made in the air. The leakage current was less than 1 μA.

After these tests the string was cooled down to 4.5 K. The value of string vacuum attained was better than 5×10^{-5} Pa. A 1000 V hipot test at 4.5 K showed no leakage current.

All power tests were performed at 2∅ helium with inlet temperature T_{in} = 4.6 K. About 20 induced quenches were imposed at the currents ranging from 1 to 5 kA.

The normal zone in superconductor was initiated by strip or spot heaters.

There were two spontaneous quenches of inner coil in M1 during ramp up at the currents 4390 and 4915 A. They seem to be explained by an uncertainty in cooling condition — we did not control the amount of liquid in 2∅ helium flow. The helium pressure rise after quenches was very small that points out at a large fraction of vapor in the flow. The maximum pressure in all cases did not exceed the opening threshold of quench valves (4 bar), therefore we had no opportunity to test these valves this time. The results of quenches induced with strip heater in M3 are given in Table 1.

Table 1.

Current, A	$\int_{M3}$, $10^6 A^2 s$	$\int_{M4}$, $10^6 A^2 s$	R_3^{max}, $m\Omega$	R_4^{max}, $m\Omega$	$\int_{SL1}$, $10^6 A^2 s$	$\int_{SL2}$, $10^6 A^2 s$	$\int_{QBS3}$, $10^6 A^2 s$
1000	1,21	1,10	45	40	0,25	0,3	0,26
2000	2,87	2,52	113	70	11,6	10,7	11,5
3000	3,83	3,12	350	250	39	39,1	38,8
4000	4,26	3,88	520	280	109	113	111
4500	4,98	4,49	720	350	126	129	128

In this Table $\int_{M3}$, $\int_{M4}$, $\int_{SL1}$, $\int_{SL2}$, $\int_{QBS3}$ denote the quench load $\int i^2 dt$ for M3, M4 coils, safety leads and bypass switch QBS3, correspondingly, while R_3^{max}, R_4^{max} stand for maximum resistivity of M3, M4 coils after quench. When QD has detected quench in M3, the heater in M4 is activated and its resistivity rises after some delay which corresponds to heat transfer from the heater to the coil. This causes the quench load and resistivity in M4 to be lower than in M3. The maximum resistive voltage achieved in M3 coil was 700 V, the maximum coil temperature calculated from quench load — 110 K. These are much less than the tolerable values.

The resistance of safety lead increases insignificantly during current dump, which indicates the weak warming-up of SL. But it should be noticed that the quench load in this case is 2 times less than the nominal one for the ring operation. This remark is valid for the shunt thyristors too.

For illustration, currents in M3, M4, in safety leads and in the entire string (M1, M2) are given in Fig.2 for current of 4500 A. The current in magnets in which quench is induced is dumped within $\approx 1s$ and the string current falls down for 20s. In all cases of induced quenches in the second QPU, no quenches in magnet of the first QPU were observed. The He temperature rise near QS did not exceed 1.5 K.

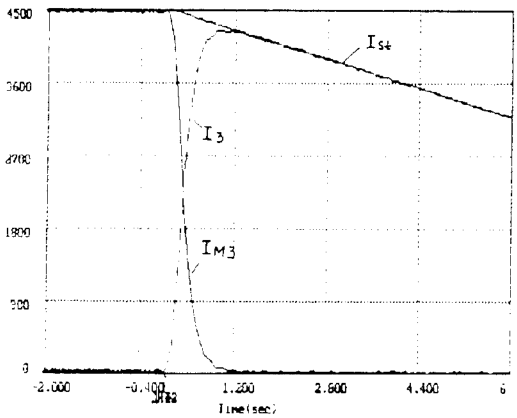

Figure 2. Currents in the string during quench in M3: I_{st} – string current, I_{M3} – current in M3, I_3 – current in QBS3.

For QS testing series of quenches induced by spot heater ▽10 at the currents from 2 to 5 kA have been made. This heater is located at the SC cable near QS (Fig.1). Fig.3a presents voltages from pairs P17, P19 and P21 at current of 5000A. The quench propagates in two directions: to M3 and QS. Normal zone having reached the M3 coil, QD has detected it. No quench propagation through QS was observed (there was no voltage at pairs P15 and P16). Knowing the normal zone onset time moment at pairs P17 and P21 from Fig.3a, one can calculate the normal zone propagation velocity in the SC cable. It was found to be 6 m/s at 5000 A.

The temperatures near QS are shown in Fig.3b. Sensors T101 and T102 pick up the helium temperature from the both sides of QS, sensors T103 and T107 are placed in the copper radiator of QS. One can see from Fig.3b that the helium temperature change is negligible, and the temperature of copper radiator increases up to 8 K, but it is less than critical temperature of superconductor. The maximum temperature of SC cable near QS, as calculated from quench load, does not exceed 55 K.

IV. CONCLUSION

The first string tests demonstrated good operation performances of the UNK SC dipoles arranged in two quench protection units.

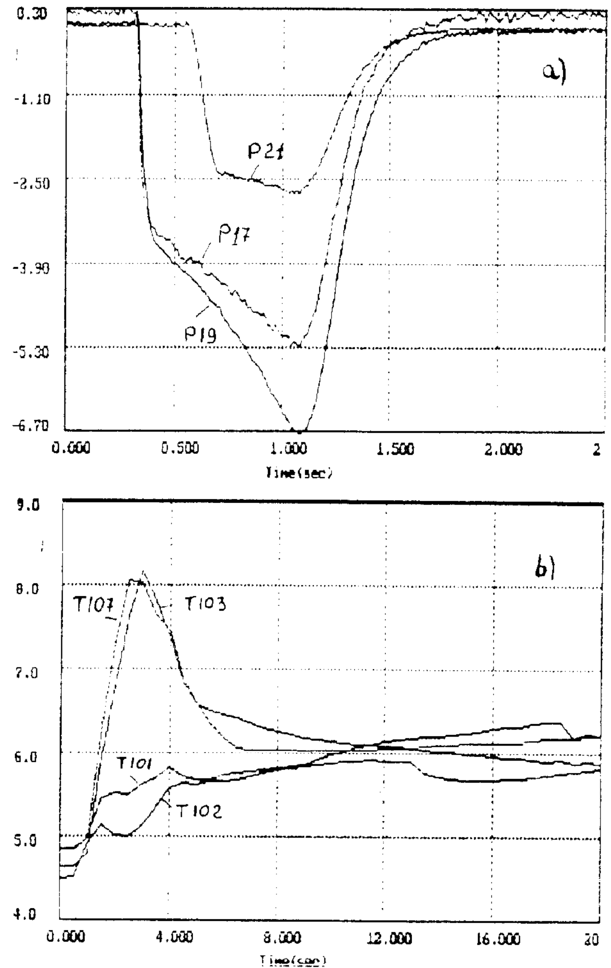

Figure 3. Voltage on the potential pairs (a) and temperature near QS (b) during quench induced by spot heater ▽10.

Parameters of quench protection elements — quench stopper, safety leads, quench bypass switches — correspond to the calculated ones. The string investigations will be continued under condition of 1∅ helium cooling.

V. REFERENCES

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