Study of Quench Development on the String of UNK Superconducting Magnets

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1 INTRODUCTION.

The string of 4 UNK SC magnets was created for investigation of operation of SC magnets connected in series both electrically and cryogenically like in SC accelerator. Tests include cycle mode string operation as well as the quench investigation in different parts of SC circuit at the string current from 600A up to nominal UNK current 5250A. Performances of quench protection system elements: quench detection prototype, quench stopper (QS), safety leads (SL), quench bypass switches (QBS), as well the cryogenic processes during quench: temperature and pressure distribution, safety valve operation — were investigated.

First string test results, when magnets were cooled with two phaze helium were presented earlier [1]. Test results of UNK quench detection prototype are reported elsewhere [2]. Below, string test results in one phase helium cooling mode are given.

2 TEST FACILITY DESCRIPTION.

The test facility consists of 4 superconducting UNK dipole magnets, cryogenic system, power supply, cryogenics control system, quench protection system and data acquisition system.

A simplified cryogenic scheme is shown in Fig.1. The cryogenic system includes a 150l/hr helium liquefier, satellite refrigerator, helium purification system and distribution box. Liquid helium flows through all the magnet coils and returns to the refrigerator via two phase pipes built into the magnet cryostats. The cryogenic system allows to model a nominal cooling mode of the UNK magnets: 100g/s single phase liquid helium flow at 1.7bar and 4.4K at the inlet and two phase helium return flow. A pair of the main current leads in the head box is cooled by 0.5g/s of the single phase helium per each lead.

The intermediate box contains a quench stopper (QS) with safety leads. QS prevents the normal phase propagation in the superconducting cable along the magnet string. It consists of two massive copper blocks connected by the copper plates cooled with helium flow.The superconducting cable is soldered to one of these blocks, the safety lead — to the other one. The safety leads are made from the stainless steel and normally are not cooled.Only after quench they are cooled by helium gas to speed up the leads cooling down.

Quench in the magnet coil causes intensive heating of the helium resulting in the sharp pressure rise. Five fast acting safety valves QV1–QV5 are used to exhaust helium and

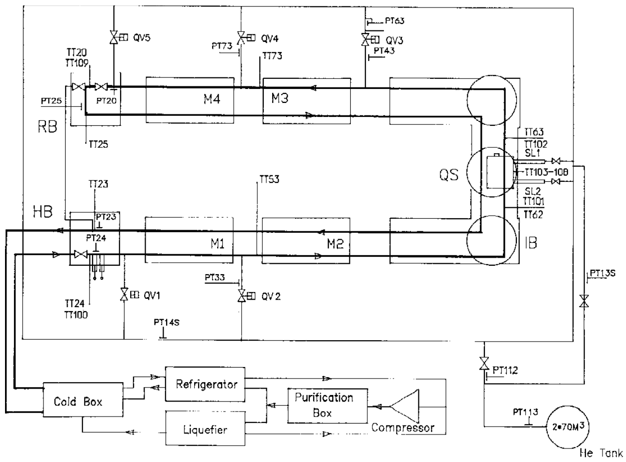

Figure 1: Cryogenic diagram of 4 magnet string: HB — head box, IB — intermediate box, RB — return box, QS — quench stopper, QV — quench valves, SL — safety leads, TT — temperature transducer, PT — pressure transducer.

to release the pressure. The design of these valves is based on the well known Kautzky valve but modified: the steeper the pressure rises the faster the valve opens [3]. One of the valves (QV3) is equipped with the stem position sensor to study its operation. For the safety reasons two 70mm rupture disks are installed on the helium line. Membranes burst pressure is of 20bar.

The cryogenics control system allows to realize automatically all the main operation modes: cooling down and warming up the magnet string, cooling the magnets both with single and two phase helium, helium venting during quench, restoring of the pre-set mode after quench. A number of the temperature (TT) and pressure (PT) sensors are installed in the string to monitor the cryogenic process.

The UNK SC dipole magnets [4] 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.2. The quench stopper divides the string into two QPUs, each QPU contains two SC dipoles. The SC circuit is monitored with 4-channel quench detector (QD) based on separation of resistive voltage of the coil by means of compensation technique. Spot heaters for normal zone initiation and numerous voltage taps and potential pairs for quench propagation study are placed at various pats of the SC cir-

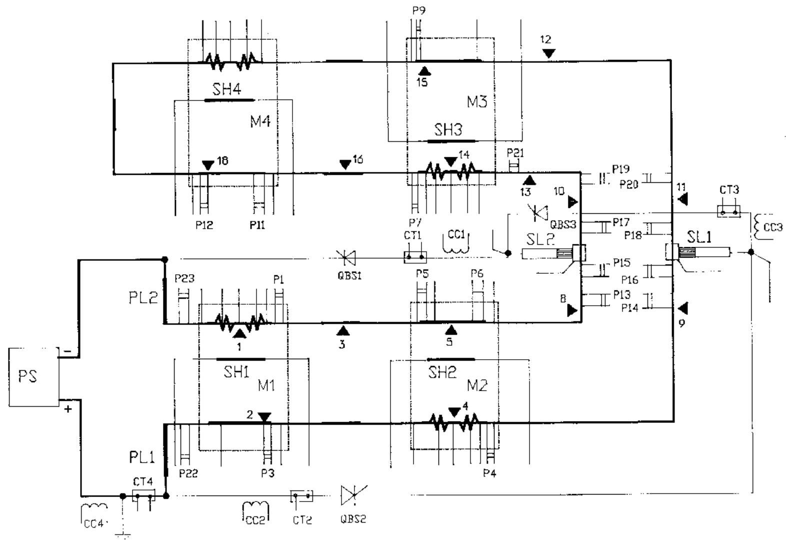

Figure 2: Electrical diagram of 4 magnet string: M1–M4 — SC dipole magnets, PS — power supply, PL — power lead, SL — safety leads, QBS — quench bypass switch, CT — current transducer, SH — strip heaters, ∇ — spot heaters, P1–P23 — potential taps.

cuit (Fig.2). The 128-channels quench analyzer is used for automatic data acquisition.

3 TEST RESULTS.

After the helium channels of the magnets were connected, a pressure and leak tightness test of the whole helium loop was performed. The maximum quench pressure was not higher 3.5bar during the initial string tests when it was cooled with two phase helium [1]. But with single phase helium the pressure spike should be much higher, so the pressure test was performed at 16bar. Neither mechanical damages nor leaks were revealed. At room temperature a hipot test to ground was made only at 500V because of the coils were impregnated with helium after earlier tests. A hipot test was repeated at 1kV after cooling down the string and filling it with liquid helium. With disconnected instrumentation the leakage current was lower 1 microampere.

The first series of string quenches was aimed to determine the maximum helium pressure in the magnet cryostats and to study the operation of the helium venting system.

For these purposes in the nominal cooling mode (single phase helium at inlet temperature 4.4K and pressure 1.7bar) the string was powered and quench was induced simultaneously in all 4 superconducting dipoles with strip heaters. After the quench detector turned off the power supply the current in the string decreased to zero within 1 sec and practically all the stored energy dissipated in the coils. Such quenches were induced at five values of current in the string starting from 800A up to the nominal UNK current value of 5250A.

The distribution of the pressure along the string at current of 5250A is shown in Fig.3. The maximum pressure of 10.5bar was lower than expected. At all currents the pressure gauge PT24 installed in the head box showed the highest pressure while the other pressure gauges readings were approximately equal and significantly lower than PT24. A specific design of the PT24 pressure tap capillary tube could cause this effect if the liquid helium pushed into the upper warm part of the tube close to the sensor quickly evaporates, chokes and it's pressure exceeds that in the magnet.

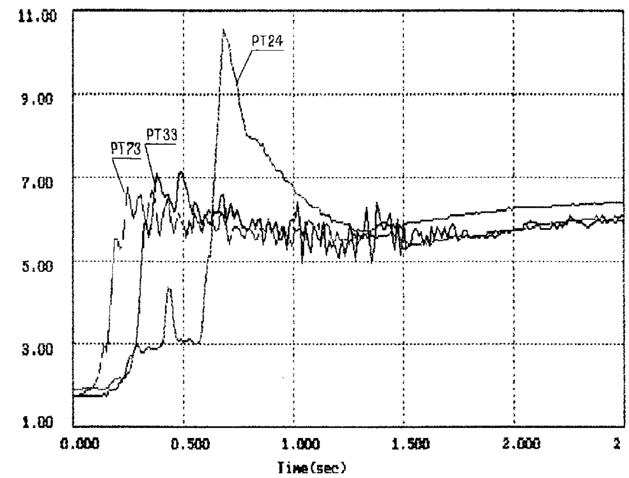

Figure 3: Time dependence of pressure in the string.

The records of PT43 and QV3 stem position allowed to determine the opening pressure of the safety valve. It depends essentially on the pressure rise rate at the valve inlet and at current of 5250A it appeared to be 2.6bar while the valves were set to 3.5bar. The pressure drop across the valve did not exceed 1.5bar during a steady interval of the venting process. These values are in a good agreement with the calculated results obtained from a computer simulation of the safety valve. The visual observation of the valves operation during and after quench allowed to conclude that valves close well and are sealed when the pressure released.

Other series of quenches was induced with spot heater $\nabla 10$. This heater is placed at the SC cable connecting QS and the magnet M3 at the distance of 25cm from QS (Fig.2). The normal zone was propagating along the cable into the coil of dipole M3 and was detected by QD as a quench in M3. After that the heaters in M3 and M4 are activated, QBS3 is switch on and the current in M1 and M2 lineally decreases with time constant of 170A/c through safety leads and QBS3. Some parameters of these quenches are given in Table.

Table 1:

Current, A	τ_{QD}, s	$\int_{8M3}$, $\times 10^6 A^2 s$	$\int_{BUS}$, $\times 10^6 A^2 s$	$\int_{SL}$, $\times 10^6 A^2 s$
1500	26.6	2.6	62.4	8
3100	5.64	5.0	59.2	61
4160	3.00	6.3	58.2	141
4550	2.38	6.2	55.6	193
5100	1.97	6.8	58.0	272

In this Table τ_{QD} — a time delay between activation of the heater $\nabla 10$ and quench detection in the magnet M3,$\int_{M3}$, $\int_{BUS}$, $\int_{SL}$ — means the quench load $\int i^2 dt$ for M3, SC cable and safety leads, correspondingly. The maximum M3 coil temperature calculated from quench load — 140K. It is much less than tolerated values. As it is seen from Table, the quench load in SC cable connecting QS and M3 practically does not depend from the current and the maximum cable temperature calculated from quench load does not exceed 100K.

Knowing the normal zone onset time moment at pairs P19 and P21 one can calculate the normal zone propagation velocity in the SC connecting cable. It was found to be 1.6m/s at 5100A. It is nearly 4 times less than the value measured in previous experiment with two phase helium cooling mode [1]. This confirms that the cooling conditions do significantly affect on the normal zone propagation process in the string. Measured values of normal zone propagation velocity in the connecting SC cable at different string current are well agreed with results obtained earlier on the copper stabilized SC cable samples [5].

The maximum value of quench load for safety leads indicated in the Table corresponds to nominal value for UNK operating conditions ($260 \times 10^6 A^2 s$). The measured resistance of safety leads increases during current dump only on 15% (at the current of 5200A), this indicates the weak warming-up of SL. The maximum temperature of QS does not exceed 6.5K (Fig.4).

Totally more than 25 quenches induced by strip or spot heaters in different points of SC circuit were made at different currents from 600A up to 5250A. In all the cases when the normal zone was induced in one QPU no quench propagation through QS was observed. The long time string operation (during more than 1 hour) was performed in the UNK cycling mode — 600A–6250A–600A with current ramp up and down of 125A/s.

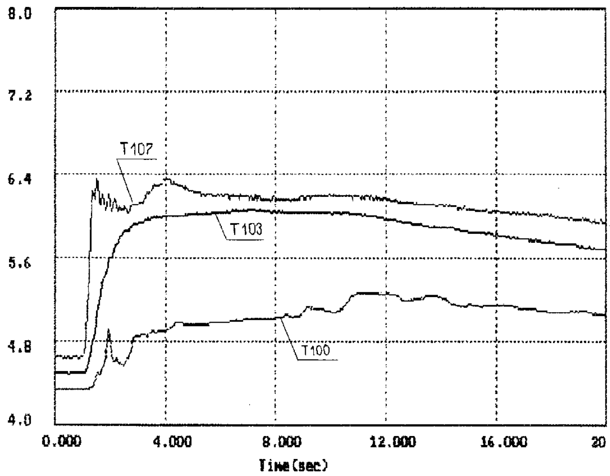

Figure 4: Time dependence of temperature during quench induced by $\nabla 10$: T100 — inlet helium temperature, T103, T107 — temperature of QS near SC cable soldering.

4 CONCLUSION.

The string tests demonstrated a good operation of UNK SC dipoles arranged in two quench protection units. The results obtained confirm the right design of main quench protection elements — quench detection system, quench stopper, safety leads, quench bypass switches, connecting cables. All these elements were tested in the conditions close to the UNK operational mode. However, the definitive conclusion about behavior of these elements, voltage distribution along the SC circuit as well as energy distribution and heating of coils and SC cables could be made only on a string containing at least two fool scale quench protection units with fool set of elements of UNK arc cell.

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