Indirectly Cooled Superconducting Power Supply for the CMD-3 Thin Solenoid

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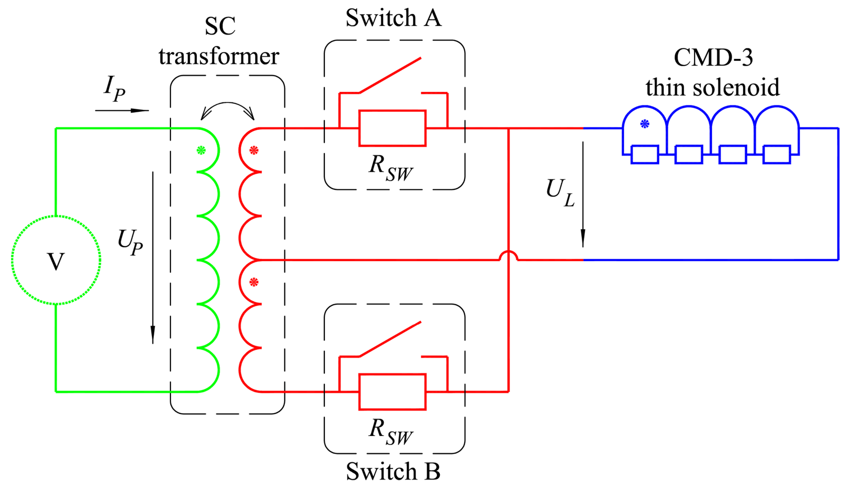
Introduction

A thin superconducting solenoid is used to provide magnetic field inside the CMD-3 particle detector at BINP.

The solenoid is powered by a fullwave AC/DC superconducting rectifier. The rectifier provides charging of the solenoid, long-term magnetic field stabilization and discharging of the solenoid. The special feature of the rectifier is its cooling method. Previous rectifiers, developed in BINP, were cooled with liquid helium bath. The CMD-3 solenoid is indirectly cooled from one end by heat conduction through its support cylinder and the high-purity aluminum strips glued on its surface along the axis.

Therefore, the indirect cooling method is used for the CMD-3 superconducting rectifier.

Principles of the Power Supply

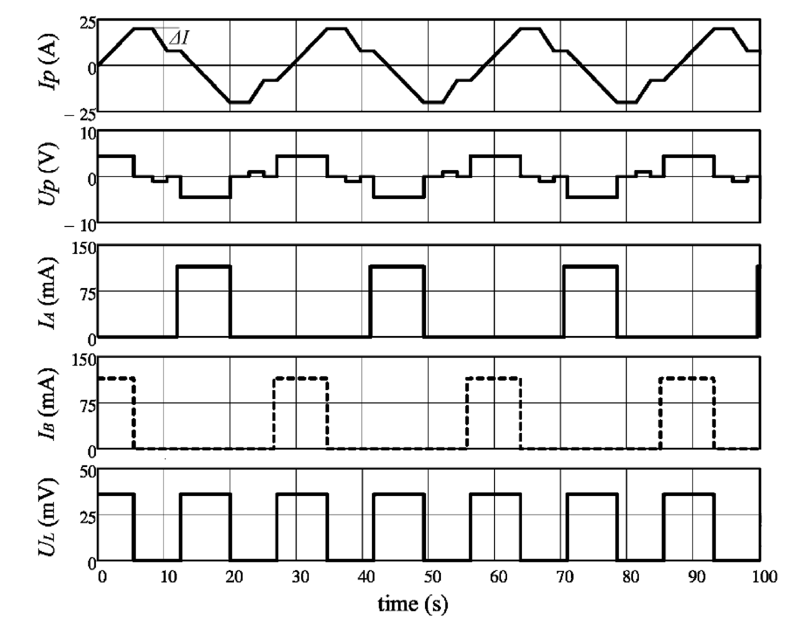


Schematic of the CMD-3 solenoid power supply system. U_P – primary voltage, I_P – primary current, U_L – output voltage of the rectifier, I_L – current through the load coil, R_{SW} – resistance of a switch in resistive state.

The power supply system consists of the AC voltage source operating at room temperature and fullwave superconducting rectifier. The rectifier consists of SC transformer and two SC switches.

The switches are controlled with heaters. Heated switch is resistive (open), cold switch is superconducting (close).

The rectifier converts AC input voltage into output unipolar pulses. Each half-period output current goes through that switch which is superconducting. When the non-zero primary voltage is applied, the primary current changes, the load voltage is applied to the solenoid (pumping stage). When the primary current achieves the desired amplitude, the second switch is cooled, the output current is commutated from the first switch to the second by the small pulse of the primary voltage (commutation stage). After that, the first switch is heated, and the cycle of pumping is repeated in the second half-period. Commutation of the output current leads to the change of the primary current by ΔI value, which is called commutation step.



Waveforms of the voltages and currents for the rectifier operating in charging mode. I_A – heater current of the switch A, I_B – heater current of the switch B, ΔI – commutation step of the primary current.

Performance

The CMD-3 magnet system has been commissioned in 2008-2009. It is under operation since 2010.

The CMD-3 solenoid is 0.9 m of length, 0.7 m of diameter and 0.57 H of inductance. Its radiation thickness is $0.085X_0$. It is used with operational magnetic field of 1.3 T (927 A of current).

The rectifier works in three different modes:

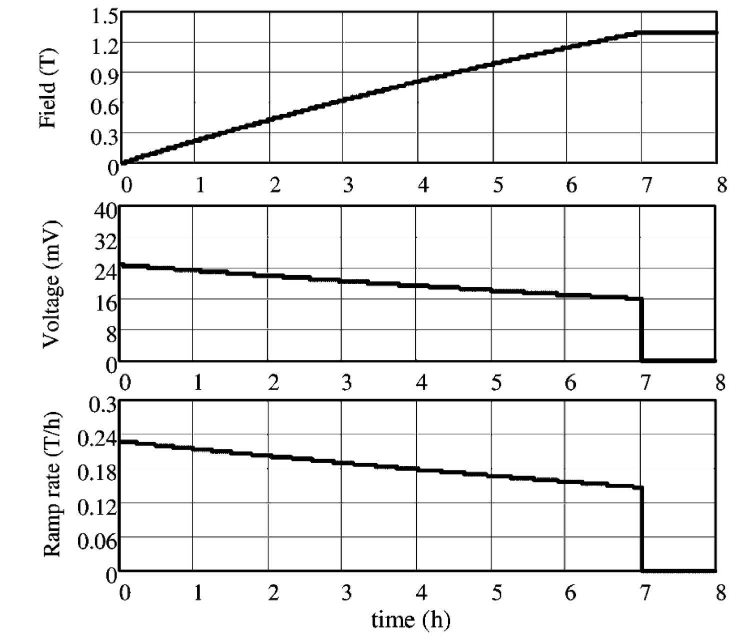
- Solenoid charging: fast increase of magnetic field;
- Magnetic field stabilization: compensation of the energy losses in the soldered joints;
- Solenoid discharging: fast decrease of magnetic field.

Magnetic field ramp rate in stabilization mode should be much lower than in charging/discharging. Because of that, in stabilization mode the rectifier operates with lower amplitudes of the primary voltage and current.

RECTIFIER OPERATIONAL SETTINGS IN DIFFERENT MODES

Parameter	Charging/ discharging	Field stabilization
Primary voltage U_P in pumping stage	±4.5 V	±0.1 V
Output voltage U_L in pumping stage	36 mV	0.8 mV
Primary voltage U_P in commutation stage	1 V	0.2 V
Primary current I_P amplitude	20 A	9 A
Delay for cooling down a switch	2.6 s	2.6 s
Heater current	115 mA	115.mA
Heater power	0.35 W	0.35 W

Charging the solenoid to 1.3 T magnetic field takes 7 hours.
Long-term accuracy of magnetic field stabilization is 2×10^{-5} T.



Magnetic field, average voltage on the solenoid and magnetic field ramp rate during charging.

During charging, the commutation step ΔI continuously increases. It causes increasing the time for commutation in each cycle. As a result, the average voltage on the solenoid and magnetic field ramp rate decrease.

Quench behavior

Since 2007 the system experienced more than 30 quenches because of different reasons. Neither the solenoid nor the rectifier were damaged. When quench occurs in the rectifier, the solenoid quenches at the same moment.

When quench occurs in the solenoid or current leads, the rectifier stays superconducting for 10 minutes until the liquid helium is boiled away from the support vessel.

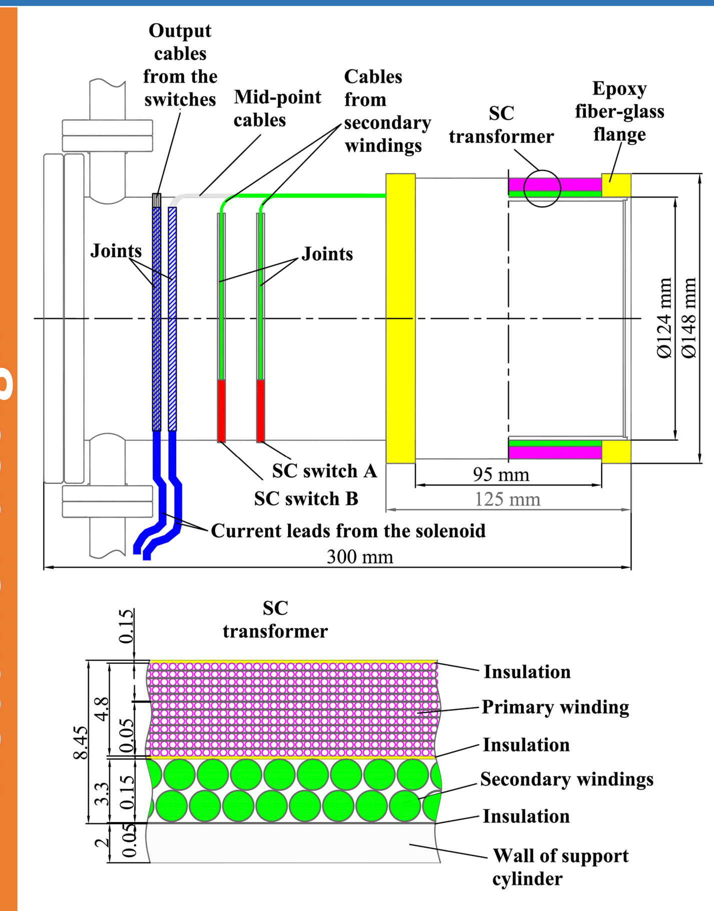
Heating and LHe consumption

Rectifier operation causes liquid helium losses due to heat generation in the parts of the rectifier. Sources of the heat are: 1) heaters of the switches (one of the switches is heated most of the time); 2) AC hysteresis losses in the transformer windings; 3) ohmic losses on the joints resistance. LHe consumption in different modes is as follows:

- With rectifier switched off and zero field – **4.5 l/h**
- In stabilization mode with 1.3 T field – **5 l/h**
- In charging/discharging modes – **7-7.5 l/h**

Because of hysteresis losses during charging or discharging, the temperature of the SC transformer windings cyclically fluctuates with each cycle of primary current in the **4.7 – 6.5 K** interval. This is the main reason why the transformer secondary windings are positioned inside the primary winding.

Rectifier design

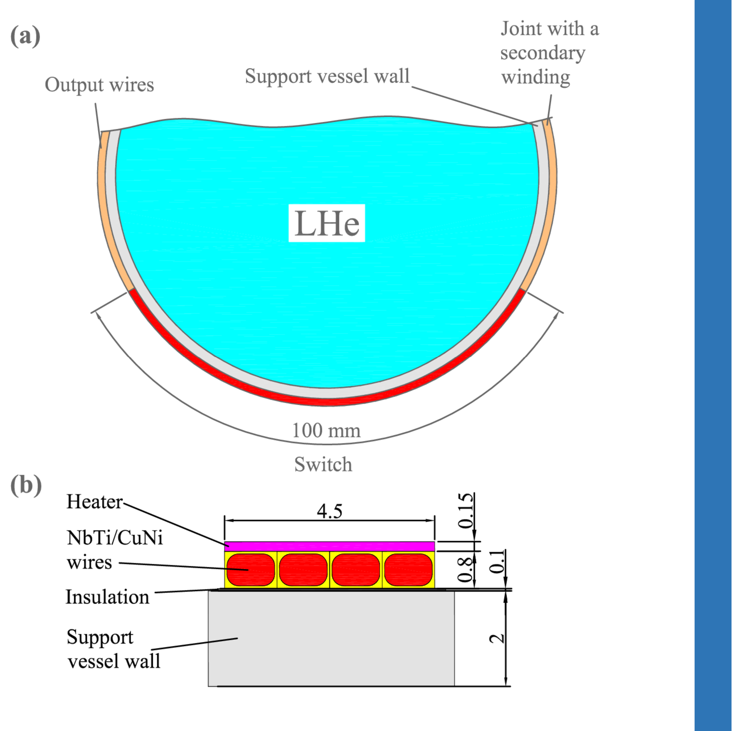


Layout of the rectifier and structure of the SC transformer.
The rectifier is mounted on the outer surface of the stainless steel cylindrical vessel.

SC transformer parameters
Primary winding
Material: NbTi/Cu wire, single filament in matrix, Ø0.35 mm, NbTi:Cu = 1:1. Number of turns: 3050 in 12 layers. Inductance: 1.1 H
Secondary windings
Number of windings: 2 Material: NbTi/Cu wire 210 filaments in matrix, Ø1.5 mm, NbTi:Cu = 1:1. Number of turns: 27 in 2 layers.

Switch parameters	
Material: Showa Wires Co. NbTi/Cu-10%Ni, 931 NbTi filaments in matrix. Rectangular crossection 1.01×0.67 mm with corner radius 0.25 mm. Linear resistance at 10 K – 0.295 Ω/m	
Resistance at 10 K	7.5 mΩ
Heater current	115 mA
Heater resistance	27 Ω
Heater power	0.35

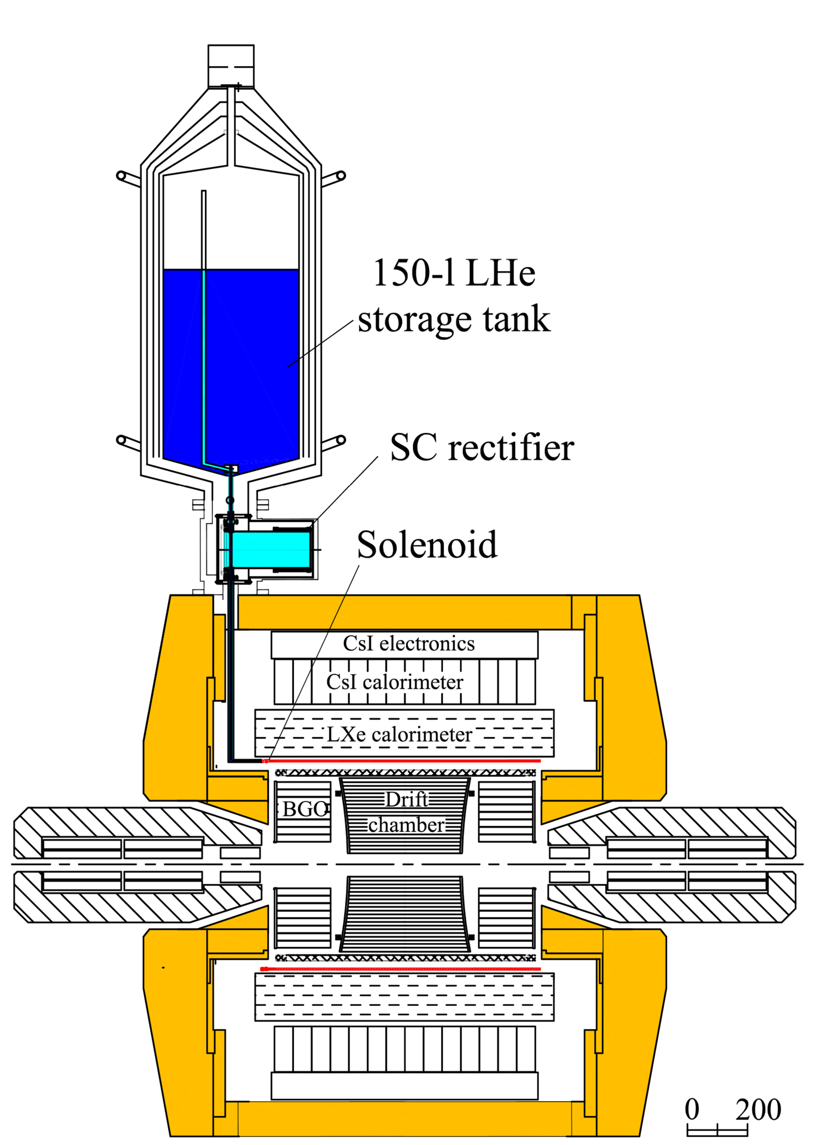
Epoxy compound used for the rectifier manufacturing: STYCAST 1267



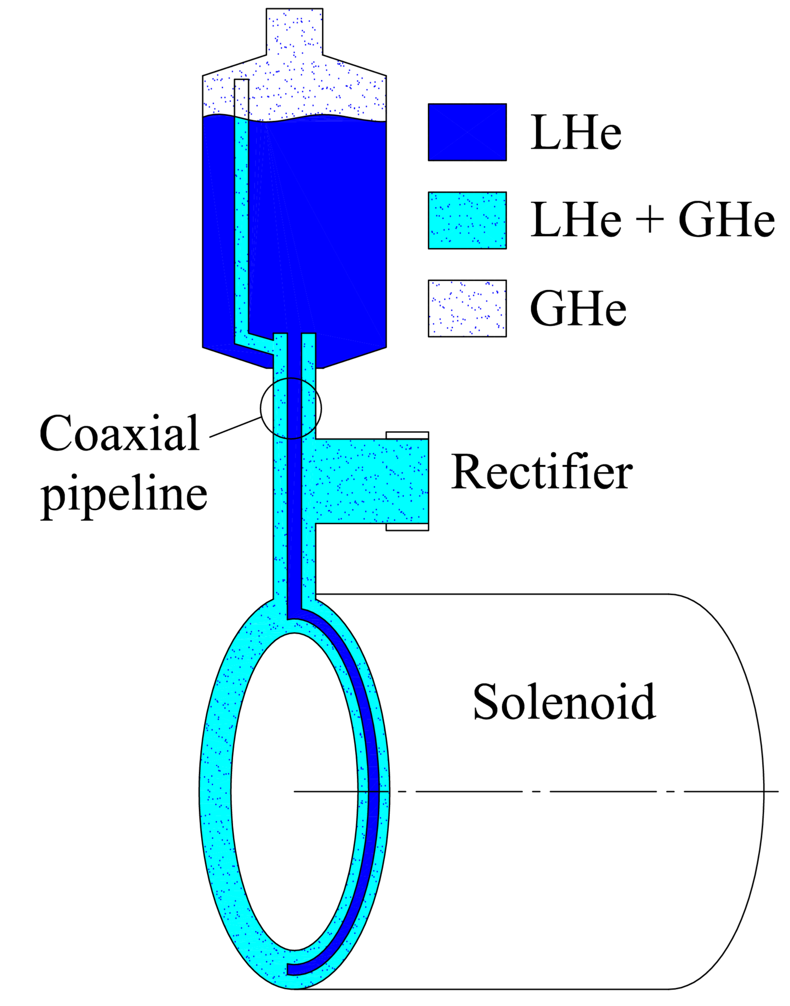
(a) layout of the switch; (b) cross-section of the switch.

The switches are glued onto the surface of the stainless steel support cylinder from the bottom. The heater is glued onto the surface of the 4 parallel SC cables in resistive Cu-10%Ni matrix.

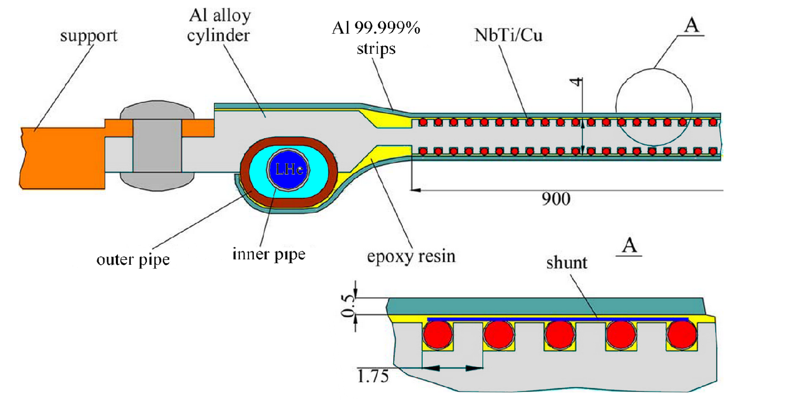
Indirect cooling



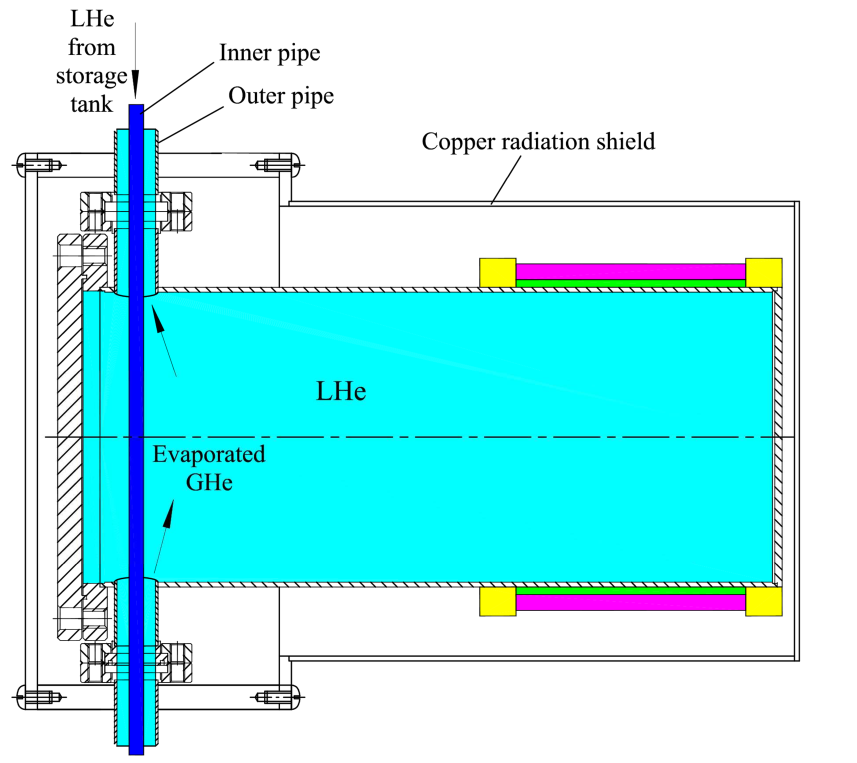
Layout of the CMD-3 magnet system.
Both the solenoid and the rectifier are in a vacuum. The system is cooled with liquid helium from the storage tank on the top of the CMD-3.



Schematic of the liquid helium supply.
Liquid helium goes down to the solenoid through the inner pipe of the coaxial pipeline. The pipeline is attached to the solenoid support cylinder at one end. At the bottom of the solenoid liquid helium goes to the outer pipe. It fills the outer pipe and the support vessel of the rectifier. Evaporated gaseous helium goes up through the outer pipe to the storage tank and then is used for cooling radiation shields in the system.



CMD-3 solenoid structure.
The solenoid is cooled with LHe inside the coalxial pipeline at one end by heat conduction through its support cylinder and the high-purity aluminum strips glued on its surface along the axis.



Cooling of the rectifier.
The rectifier is cooled by heat conduction through the wall of the support vessel. Radiation shield is cooled with GHe from the storage tank.

Conclusion

- ➢ A power supply based on the indirectly cooled fullwave superconducting rectifier is used for powering of the CMD-3 thin solenoid since 2010.
- ➢ The rectifier demonstrates stable operation and durability against quenches in the CMD-3 magnet system.
- ➢ The indirectly cooled and cryogen free superconducting magnets are widely used. This work shows the possibility of successful using the indirectly cooled superconducting rectifier for such the types of magnets.