

Research paper

A magnetic persistent current switch at milliKelvin temperatures



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ABSTRACT

We report the development of a magnetically driven Persistent Current Switch operated in a dilution refrigerator. We show that it can be safely used to charge a 60 mH coil with 0.5 A at 11 mK, which heats up the dilution refrigerator to 60.5 mK. Measurements at 4 K on a 440 μ H coil reveal a residual resistance of $R \leq 3.3 \text{ p}\Omega$.

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1. Introduction

There are many applications in which a stable, low noise magnetic field is desired, such as in MRI, NMR or qubit studies. An elegant way of establishing such a magnetic field is by the use of a Persistent Current Switch (PCS). In a PCS a superconducting coil is shunted by a superconducting shortcut such that together they form a closed resistanceless circuit. The coil can be charged by briefly switching the shortcut to the resistive state. The circuit then becomes an RL -circuit, and a power source can be connected to inject a current into the coil. Back in the superconducting state, the flowing current is in principle stable and low-noise, and, hence, so too is the magnetic field induced by the current in the coil.

The switching of the shortcut can be accomplished in a number of ways: one can heat the shortcut to above its critical temperature, as is most often done for large magnets, or one can create a magnetic field higher than the shortcut's critical field [1–5], or even mechanically interrupt it [6,7].

We intend to do SQUID-based experiments on the mixing chamber stage of a dilution refrigerator cryostat, which means that aside from being sensitive to magnetic noise, we are also concerned about heat input. It is our wish to place a PCS close to our experiment on the mixing chamber stage such that the wiring between PCS and experiment can be kept short – shorter wires are less susceptible to noise and also mechanically less vulnerable – while keeping the heat input manageable. The magnetic PCS presented in this paper provides us with a solution that suits our needs.

2. Design and fabrication

We set out to design a PCS that:

1. Can be operated in a dilution refrigerator, i.e. an environment with very little cooling power, on the order of 1 μ W.
2. Introduces only a low (ideally zero) resistance such that it may be used with small coils of 0.1 mH–0.1 H and still yield a long lifetime τ .
3. Can be charged with a user-adjustable current in the range of 0.01–1 A.
4. Has reasonable dimensions, preferably smaller than 5 cm.

To our knowledge, a PCS that combines all of these features has not yet been constructed.

In a magnetic PCS we distinguish two coils. The experiment coil L_{exp} , which is to be charged with a current I_{exp} and used to perform the experiment of choice, and the switch coil L_{sw} with current I_{sw} , which is used to bring a superconducting shortcut to the normal state. Fig. 1 gives a schematic overview.

We fabricate experiment coils from 100 μ m diameter NbTi wire with a 13 μ m Formvar insulating layer. We measure the inductances of our experiment coils by integrating the voltage response upon charging them:

$$\int V(t)dt = L_{exp}\Delta I_{exp}. \quad (1)$$

The experiment coils discussed in this paper have inductances $L_{exp} = 60 \text{ mH}$ and $L_{exp} = 440 \text{ }\mu\text{H}$. For convenience, we charge the experiment coil from empty $I_{exp} = 0 \text{ A}$ to $I_{exp} = I_0$ in a single step

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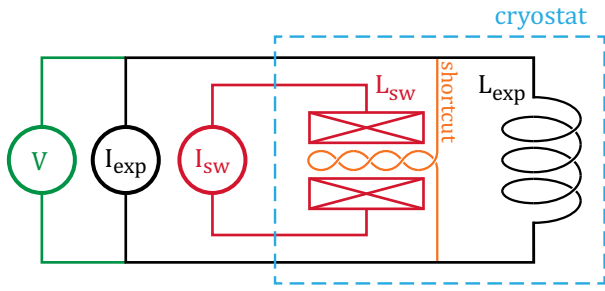


Fig. 1. In black the basic electrical circuit for making a magnetic field with a coil L_{exp} and a current source. Added are a superconducting shortcut that is brought to its resistive state by a switch coil L_{sw} . The response is measured by a voltmeter. The blue dashed box contains the parts that are at low temperature inside a cryostat, either thermally attached to the mixing chamber stage of a dilution refrigerator, or in a vacuum dipstick inserted in a liquid Helium Dewar. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and we power up the switch coil as fast as our setup allows for. The energy dissipated in the shortcut while charging then totals $\frac{1}{2}L_{exp}I_0^2$, as we will see later.

Dissipation can also come from other sources. There is Ohmic dissipation in the current lines towards the coils, which we find to be negligible if care is taken to use superconducting wiring from 4 K to the mixing chamber stage of the dilution refrigerator and if care is taken to thermalize the wiring well. Further, the rapid change in magnetic field in both the experiment coil and the switch coil may cause dissipation due to eddy currents that are generated in normal metals in their vicinity.

The superconducting shortcut is made of an insulated Niobium wire, 50 μm in diameter. We twist the wire around itself, such that the mutual inductance to the switch coil is minimized, thereby minimizing the noise input through this channel. We have chosen to make the shortcut out of Niobium because of its high critical current density and critical temperature and its relatively low critical field. This means that at the currents we intend to use, quasi-particle dynamics are of no concern, and that tests in liquid Helium are possible.

All superconducting connections are made by spot welding [8] the wires to Niobium sheets of 100 μm thickness. In order to get a good superconducting connection we strip the wires of their Formvar insulation with a knife and clean them with IPA. We clean the Niobium sheets by sanding them lightly with sand paper and then wiping them with IPA. We spot weld the NbTi wires to the Nb sheets with 20–25 W s and the thinner Nb shortcut wire with 8–10 W s. The superconducting closed circuit comprised of the experiment coil and the Nb shortcut wire, contains two spot welded joints (Fig. 1). To realize a residual resistance as low as possible, we use about 10 spot welds per wire, and furthermore we let the wires cross one another on the Nb sheet, such that they are spot welded to the Nb sheet, and also to each other. We have also tried to laser weld the connections, but this resulted in higher contact resistances as well as less mechanical stability.

The switch coil should be able to deliver at least $B_{c2} = 400$ mT, the upper critical field of Niobium at 0 K [9]. We construct it from 100 μm diameter Copper clad single core NbTi wire, 62 μm diameter NbTi core, with a 13 μm insulating Formvar layer. The Copper cladding is necessary to thermalize the switch coil. The spindle on which the switch coil is wound is made from PEI and allows for a coil with an inner diameter of 9 mm, an outer diameter of 22 mm and a length of 18 mm. In the center of the spindle we leave a hole of 3 mm diameter through which the shortcut is put. For sturdiness, we give the spindle 4 mm thick walls on either side of the coil and apply a layer of Stycast 2850FT to the whole after winding. We

were able to put $N = 8672$ windings on the spindle. The inductance of the switch coil is about $L_{sw} = 0.5$ H.

The NbTi wire leads of the switch coil are twisted and led from the mixing chamber stage of the cryostat, where the switch coil is mounted, uninterrupted to the 4 K stage, thermalized at the intermediary stages on Copper bobbins. From 4 K to room temperature, the wires are from Copper. We should avoid sending too high currents, because these could cause dissipation in the non-superconducting parts of the wiring. We aimed for a switching current I_{sw} on the order of 1 A, at which the switch coil makes a field of

$$B_{sw} = \frac{\mu_0 N I_{sw}}{l} = 600 \text{ mT} > B_{c2}. \quad (2)$$

3. Results and discussion

We placed the PCS with an experiment coil of $L_{exp} = 60$ mH on the mixing chamber stage of a dilution refrigerator which reached a minimum temperature of 10.5 mK. After some tweaking, we found that we could charge and discharge the experiment coil without dangerously warming up the cryostat by using a switch current of $I_{sw} = 2$ A through the switch coil L_{sw} during 2 s. Fig. 2 shows a typical voltage response for the case that we charge L_{exp} from $I_{exp} = 0$ A to 0.5 A.

If we left the switch activated for longer than ~ 10 s, we saw a sudden, vigorous increase in temperature. The cause of this is, we suspect, the non-superconducting connection of the switch coil's leads at the 4 K stage of the cryostat. To avoid having to recondense the ^3He into the dilution refrigerator every time we switch, we therefore limit ourselves to quick switches. Alternatively, one can choose to charge the experiment coil at a higher temperature when there is more cooling power available and cool further down afterwards. As we will see, the superconducting contacts have such a low resistance that there is ample time before the stored current is appreciably diminished, making this a viable possibility. However, we wanted to verify that it is possible to charge a coil even at the lowest temperature attainable in our cryostat without introducing a worryingly high heat input.

The shape of $V(t)$ can be understood by assuming that the normal state resistance of the superconducting shortcut arrives at its final value R_{ns} exponentially with a time constant τ_{ns} upon switching [1]

$$R_{pcs}(t) = R_{ns}(1 - e^{-t/\tau_{ns}}). \quad (3)$$

The values of R_{ns} and τ_{ns} depend on a multitude of factors including the switching field B_{sw} ($\propto I_{sw}$), temperature and cooling power.

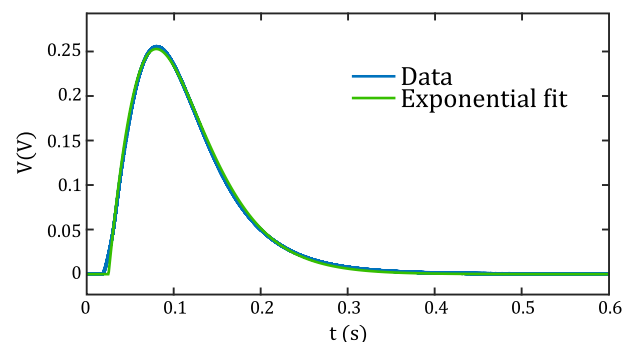


Fig. 2. The voltage response of an $L_{exp} = 60$ mH coil at $T = 11$ mK when charged with $I_{exp} = 0.5$ A using $I_{sw} = 2$ A. The shape of $V(t)$ is determined by the time-dependent normal state resistance $R_{pcs}(t)$ of the shortcut; assuming it be exponential, Eq. (3), we find $R_{ns} = 1.4 \Omega$ and $\tau_{ns} = 73$ ms.

The general solution for the PCS's voltage response with time-varying $R_{pcs}(t)$ when charged $I_{exp} = 0 \text{ A} \rightarrow I_0$ is given by

$$V(t) = I_0 R_{pcs}(t) e^{-\int_0^t \frac{R_{pcs}(t')}{L_{exp}} dt'} \quad (4)$$

Fitting this to the measurement, using the exponential $R_{pcs}(t)$ of Eq. (3), we find that $R_{ns} = 1.4 \Omega$ and $\tau_{ns} = 73 \text{ ms}$.

The energy that is dissipated in the shortcut due to (dis) charging of the experiment coil is

$$E_{diss}(t) = \int_0^t P_{diss}(t') dt' = \int_0^t \frac{V^2(t')}{R_{pcs}(t')} dt' \quad (5)$$

For large t , it is easy to show that $E_{diss}(t)$ converges to $\frac{1}{2} L_{exp} I_0^2$: the energy that needs to be dissipated in the shortcut is exactly the energy that is stored in the experiment coil. The heating effect from this contribution to the dissipation can be made smaller by charging the experiment coil in a number of steps rather than in a single step as is done now. However, in our experiment it is not the dominating factor – presumably because eddy currents near the switch coil dominate, which we shall explain shortly.

During (dis) charging of the coils, we monitor the temperature of the mixing chamber stage onto which the PCS is mounted. Fig. 3 shows the temperature of the mixing chamber stage as a function of time during the switch of Fig. 2. At the moment of switching, the temperature quickly increases to 60.5 mK and gradually decreases again afterwards. Our calibration of the cooling power versus temperature $P_{cool}(T)$ allows us to convert the temperature to power dissipation, and, consequently, integration yields the energy extracted by the dilution refrigerator from the mixing chamber stage during the temperature peak. We estimate $E_{diss} \approx 100 \text{ mJ}$, see the inset in Fig. 3.

Note that this is much more than the energy dissipated in the shortcut, $\frac{1}{2} L_{exp} I_0^2 = 7.5 \text{ mJ}$ when $L_{exp} = 60 \text{ mH}$ and $I_0 = 0.5 \text{ A}$. (Also, E_{diss} is much less than the energy in the switch coil $\frac{1}{2} L_{sw} I_{sw}^2 = 1 \text{ J}$, for $L_{sw} = 0.5 \text{ H}$ and $I_{sw} = 2 \text{ A}$, which we expect to be dissipated (mostly) in the internal resistance of the current source.)

We attribute the measured E_{diss} to eddy currents: for the sake of thermalization our coils are securely fastened to the mixing chamber stage of the dilution refrigerator, which is a gold-coated copper disk of 1 cm thickness. Being a normal metal, induced eddy currents are dissipated here and cause a heating that scales with $(dB/dt)^2$ [10]. A straightforward way of reducing this heat input would be to ramp the switch current I_{sw} up and down more gradually and to divide the charging of the experiment coil into several small steps. The eddy currents could be further reduced by keeping

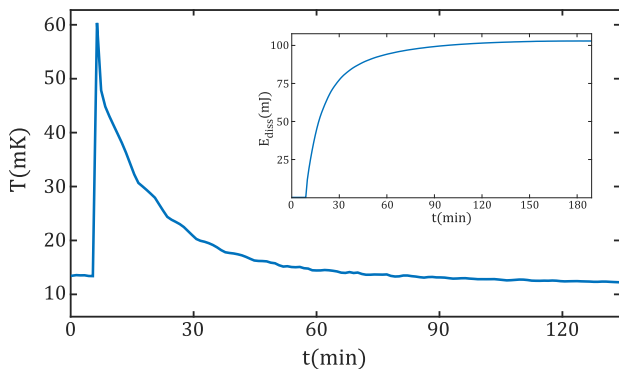


Fig. 3. The temperature of the mixing chamber stage versus time, $\Delta t = 1 \text{ min}$. When charging the experiment coil of $L_{exp} = 60 \text{ mH}$ to $I_{exp} = 0.5 \text{ A}$, the temperature increases to 60.5 mK. The inset shows the dissipated energy E_{diss} in time, which levels off to 103 mJ, and which we estimate by converting temperature to cooling power and integrating over time.

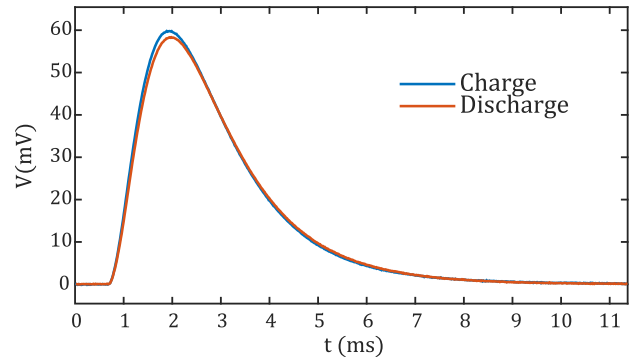


Fig. 4. The voltage responses at 4 K when charging an experiment coil of $L_{exp} = 440 \mu\text{H}$ to $I_{exp} = 350 \text{ mA}$, waiting for a time $t_W = 16.8$ days and then fully discharging. For the discharge voltage response we plot $-V(t)$ to emphasize how little current has been lost. We measure the current still flowing in the experiment coil to be $I_W = 346 \text{ mA}$, therefore $\tau \geq 4.2$ years and $R \leq 3.3 \text{ p}\Omega$.

the switch and experiment coils away from normal metals or encasing them in a superconducting shield and use normal metal only to provide cooling to the coils.

We measured the quality of the spot welded superconducting joints by evaluating the residual resistance R in a long-lasting measurement. Because of the exceptionally low resistance of the joints, there is no measurable decrease in I_{exp} even after a few days. We therefore placed a PCS with an experiment coil of $L_{exp} = 440 \mu\text{H}$ in a vacuum dipstick inserted in a liquid Helium Dewar, charged it from $I_{exp} = 0 \text{ A}$ to 350 mA, and left it untouched for a little under 17 days before discharging. Fig. 4 shows the two voltage responses. Fitting to Eq. (4) gives $R_{ns} = 375 \text{ m}\Omega$ and $\tau_{ns} = 1.1 \text{ ms}$.

The integration of $V(t)$, Eq. (1), when discharging $I_{exp} = I_W \rightarrow 0 \text{ A}$ yields the current still flowing in the experiment coil I_W after waiting a time t_W . It is related to the injected current I_0 as

$$\frac{I_W}{I_0} = e^{-t_W/\tau}, \quad \tau = \frac{L_{exp}}{R} \quad (6)$$

The amount of current thus allows us to measure the residual resistance in the superconducting circuit R . We measure $I_W = 346 \text{ mA}$, which translates to $\tau \geq 4.2$ years and $R \leq 3.3 \text{ p}\Omega$.

4. Summary

We have shown that it is possible to put a 60 mH coil in the persistent mode carrying a current of 0.5 A in a dilution refrigerator at 11 mK using a magnetic Persistent Current Switch. We find that spot welding all wires to each other via Nb sheets ensures a resistance of less than 3.3 pΩ.

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