SQUID BASED BEAM CURRENT METER

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Abstract

The concept of a current meter for DC beams based on commercially available SQUIDs has been implemented and tested in a series of prototypes. One of them is expected to be used for monitoring the beam of our Antiproton Accumulator. After a brief explanation of the principles of operation, pick-up-loop design, magnetic and RF shielding considerations these prototypes and the experience acquired with them is described.

Introduction

The measurement of the intensity of a continuos beam of charged particles is usually done by means of capacitively coupled electrodes since these beams are usually bunched. This technique is insensitive to the DC component of the beam. To measure the DC component one usually makes use of the magnetic field created by the beam. The measurement of this field can be done by flux gate magnetometer technique as developed at CERN[1]. An alternative way is to use a Superconducting Quantum Interference Device (SQUID), now commercially available, which has the potential for higher sensitivity, stability and lower noise. It is also the natural device to use when the beam is already exposed to surfaces at liquid helium temperatures, since the extra cryogenic requirements are minimal.

Both methods are similar to the extent that their sensitive device is used as a null detector; i.e. the output is generated by a feedback current that keeps the input of the sensitive device from changing. The linearity of the response is then determined by Ohm's Law across the output resistor R_f.

The SQUID Based Current Meter

For the SQUID based device, use is made of the Meissner Effect on a closed superconducting circuit that includes the pick-up-loop, L_p, and the input-coil, L_s, of the SQUID. The magnetic flux trapped at cool down time in this circuit cannot change. An induced current will flow through it to prevent the magnetic field due to the beam from penetrating into the pick-up-loop. This current in the SQUID input-coil changes the flux in the sensitive SQUID loop. The magnetic field of the feeback current can be introduced at this point (internal feedback arrangement) or inside the pick-up-loop by a wire runnning parallel to the beam (external feedback arrangement). The response of the sensitive SQUID loop is periodic with respect to a quantum of flux ($\phi_o = 2.07 \times 10^{-15}$ Wb). An oscilator and a phase locked amplifier are required for generating the feedback current. The schematic of one such implementation is shown in figure 1. It uses a DC SQUID (2 Josephson Junctions) and an internal feedback arrangement, the commercially available system[2] is shown enclosed by a dashed box.

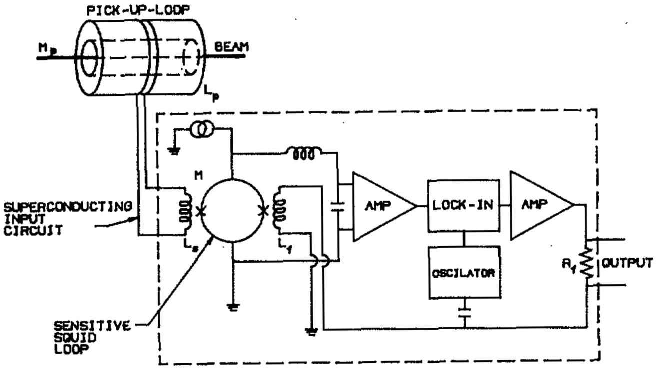

Figure 1. DC SQUID Beam Current Meter

It can be thought of as a black box with a superconducting input impedance, $L_s = 2$ μH, that for a input current of 200 nA generates a full scale output voltage of 10 V with a 200 ohm output impedance. In its fast mode it responds from DC to 50 kHz. It has different modes corresponding to different time constants in the amplifiers and providing a trade-off between speed and stability. It is the frequency selected for the lock-in oscilator that determines the upper limit in the frequency response.

The dynamic range can be extended by automatically reseting the lock and counting the number of resets with an up-down counter, each reset corresponding to a ϕ_o entering the SQUID sensitive loop.

The Superconducting Pick-up-loop

An elegant way to transform the beam current into the current going through the SQUID system input is by means of a superconducting flux transformer consisting of a single pick-up-loop of toroidal geometry around the beam as in the upper left corner of figure 1. In such a transformer the current into the SQUID is approximately independent of the beam cross-section or the beam position relative to the pick-up-loop.

The flux, ϕ, due to the beam current, I, being prevented from getting into the pick-up-loop by the Meissner Effect is

$$\phi = M_p I$$

where M_p is the beam to pick-up-loop mutual-inductance which is approximately equal to the pick-up-loop self-inductance L_p. The current, i, that will flow through the SQUID input is

$$i = \phi / (L_p + L_w + L_s)$$

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where L_w is the self-inductance of the twisted leads connecting the pick-up-coil to the SQUID input coil and L_s is the 2.0 μH self-inductance of the SQUID input coil. The flux that is actually detected by the *SQUID* and compensated by its internal feedback arrangement is

$$\phi_s = M I$$

where M is the mutual inductance between L_s and the sensitive SQUID loop (20 nH). So the response of the system will be proportional to

$$\phi = I M M_p / (L_p+L_w+L_s).$$

The self-inductance, L_p of the pick-up-loop can be estimated as follows: The magnetic field at a distance r from the beam is

$$H = (\mu_0/2\pi) I / r$$

the energy being excluded from L_p is

$$\tfrac{1}{2} L_p I^2 = \tfrac{1}{2} \mu/\mu_0 \int H^2 dv$$

substituting and integrating from the inner radius a to the outer radius b for a length c with $\mu = 1$ we get

$$L_p = (\mu_0/2\pi) c \ln (b/a)$$

which for a = 3 cm, b = 6 cm and c = 10 cm yields L_p = .014 μH. The inductance of a pair of wires of *length 10 cm, diameter .02 cm, centers apart by .04 cm* can be calculated to be L_w = .017 μH. These typical values result on i = I/145.

The Superconducting Shield

Both the SQUID sensitive loop and the superconductive input circuit have to be well shielded from changing external magnetic fields in order to work. The natural solution is to enclose them in a superconducting shield, which will freeze inside it the field that existed at cool down time. Lead (Pb) foil soldered (water leak tight) with Sn50%Pb50% solder can yield sufficient shielding if it is rigidly located with respect to the superconductive input circuit. Penetrations into this shield are not just holes, but holes at the end of relatively long *superconducting tubes; the large aspect* ratio (11 in long by 2 in diameter for the beam) of these tubes prevent degradation of the magnetic shielding.

The SQUID system has to be well shielded from radio frequencies (RF) and is built that way. In this application, however, the beam itself might and probably does, have RF components that should not be permitted to reach the pick-up-loop. An RF shield is therefore needed between the beam and the pick-up-loop. Another reason, that requires further reduction of the cut-off frequency of these low-pass filters, is the need to prevent the SQUID from unlocking on the sudden transfer of the accumulated beam. This step function change in the current (from 64 mA to 0) requires the RF shield to have a time constant larger than ≈50 ms, implying rather thick copper walls. Superconducting Pb foils can be used for this purposed reducing the amount of copper *otherwise needed.*

Experience with Prototypes

Five prototypes have been built and tested to date. They were tested using a current carrying wire instead of an actual beam. Except for the first one that had a pick-up-loop machined out of solid niobium (Nb) and was a factor of 10 smaller in beam tube diameter most were built around G-10 toroidal forms (11.43 cm OD, 6.03 cm ID, 12.50 cm long) using Pb foil and are capable of accomodating a 2 in diameter beam tube.

The first and second prototypes use the tube-shield configuration sketched in the top part of figure 2 while the others have the overlapped magnetic shield with separate RF shield shown in the bottom part of figure 2.

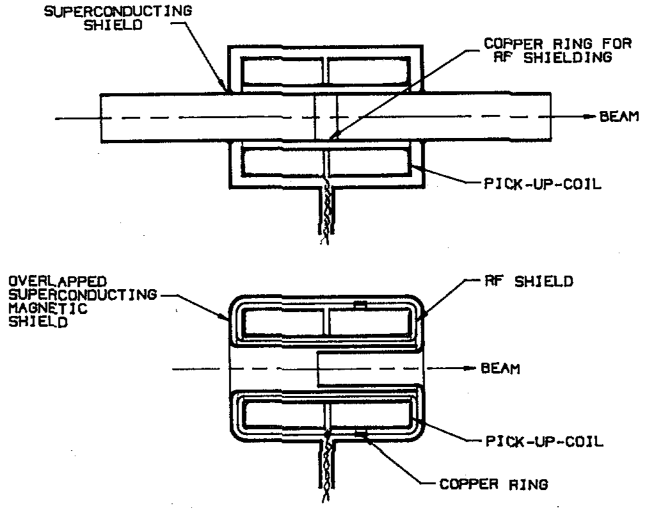

Figure 2. Vertical Plane Cut View of Shielded Pick-up-loops.

The best performance so far has been obtained with the first prototype using a RF SQUID[2] and no RF shield. The drift in equivalent beam current was less than 1 μA in 15 hours with a short term noise or excursions of less than .08 μA rms (10 Hz filter) and a sensitivity of 22.5 mV output for a 1 μA beam or 88.9μA/ϕ_0. The inclusion of a RF filter consisting of a RRR=500 copper ring joining the Pb tubes (soldered) introduced noise in the system with a considerable detraction from the values quoted above. By coating the copper ring with superconducting solder, reducing the width of the exposed copper we observed the corresponding changes in the time constant of this filter (from 2.3 ms to 99.5 ms). The fifth prototype had an RF shield with a time constant of 28 s, an illustrationof the kind of performance one can easily obtain from a light weight low pass filter made of Pb and Cu foils at 4.2 K.

The second prototype assembled around a stainless steel beam tube, proved that superconducting contact betwween Pb foil and Nb wire can be achieved with soft solder inspite of its cold solder joint appearance. An internal short caused this prototype to have a sensitivity of 340 μA/ϕ_0 instead of the calculated 13.2 μA/ϕ_0. In devising ways for measuring the sensitivity of a prototype we came upon a very accurate and simple technique: with the SQUID system in its SET mode (where an internal ramp generator instead of the feedback current is used to display in an osciloscope the SQUID periodic response to flux) we just count the number of periods (ϕ_0) passing by the screen for a given increase in the beam current.

The third and fourth prototypes were built over identical G-10 toroidal forms with the main difference that the fourth instead of having just one turn covering the toroidal volume had 15 turns. It was gratifying to confirm that its sensitivity of 2.43 μA/ϕ_o is exactly consistent with the sensitivity of the third prototype (13.2 μA/ϕ_o) when M_p is multiplied by 15 and L_p=16 nH is multiplied by 15^2, the other parameters being: L_s=2.0 μH and L_w=17 nH. The time constant of the third prototype is .7 s. Another relevant fact that we found with these prototypes is that the long Pb tube shields can be substituted by a simple internal overlap reducing considerably the size of the cryostat.

The fifth prototype used a smaller toroidal volume (11.43 cm OD, 10.16 cm ID, 12.50 cm long) allowing for a 3.5 in diameter beam tube and presented a sensitivity of 94 μA/ϕ_o.

Having in mind the expected increase of our antiproton beam in steps of 8 μA every 2 seconds and sudden decrease to zero or other value from a maximum of 64 mA (when the accumulated beam is diverted away for proton-antiproton collisions) a convenient sensitivity is $\alpha \approx 100$ μA/ϕ_o (to avoid reseting too often) and a suitable RF shield time constant is $\approx 6.4/\alpha$ s (to keep the SQUID system lock-in amplifier from unlocking at a ϕ_o rate of 10 kHz). Commercially available ϕ_o counters exist only for the RF SQUID. A ϕ_o counter for the DC SQUID is being developed at Fermilab.

At this stage, with RF shielded prototypes, we have achieved stability and noise levels comparable to the flux gate magnetometer type devices. However, we expect substantial improvement over the performance of the third prototype (average drift of 1.5 μA over 15 hours with maximum excursions of ±2.6 μA) by reducing its sensitivity (increasing L_w) and using additional Pb shielding around the SQUID probe.

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References

1. K. Unser, IEEE Trans. Nucl. Sci., NS-28, 2344 (1981).
2. Model BMS (RF SQUID) and Model DBS (DC SQUID), manufactured by S.H.E. Corporation, San Diego, Calif. (619) 453-6300.