3D magnetometer for a dilution refrigerator

S Uchaikin\textsuperscript{1}, A Likhachev, F Cioata, I Perminov, H Sanghera, I Singh, P Spear, P Chavez, X Han, C Petroff, C Rich
D-Wave Systems, 100-4401 Still Creek Dr, Burnaby, BC, V5C 6G9, Canada
E-mail: uchaikin@dwavesys.com

Abstract. In this report, we describe a development of a three dimensional system for measurements of magnetic field at a wide temperature range of 300K-4K. The system is based on 8 AMR sensors and allows for control of the magnetic environment in a dilution refrigerator during the cool down of a superconducting processor. With a low noise signal processing electronics and a special sensor saturation circuit, a magnetic induction resolution below of 1 nT was achieved.

1. Introduction
D-Wave’s quantum processor is based on the compound-compound Josephson junction (CCJJ) rf-SQUID flux qubits [1]. Characteristics of the qubits as well the other processor elements can suffer from an external magnetic field. The processor has a complicated multilayer structure from superconducting wires and planes, each of them could trap a number of magnetic flux quantum and keep it for an infinite time. To protect processor from Earth and interference magnetic field, a special magnetic vacuum system (MVS) was developed.

In the specification of the Rainer\textsuperscript{TM} processor, it is required that the magnetic be less then 1 nT in the entire volume of the processor in all three directions. In order to achieve this low of magnetic field there must be sensors which have the resolution and accuracy in a subnanoT region in a wide temperature range of 4K-300K. Taking all things into consideration, anisotropic magnetoresistive (AMR) sensors where chosen [2].

2. Anisotropic magnetoresistive sensor
Magnetoresistance is defined as the property of a material to change the resistivity when an external magnetic field is applied. In ferromagnetic materials there are a few types of the magnetoresistance effects. The one we are interested is the resistance change due to the angle between the magnetization and current [3]. The resistivity of a material showing such behavior can be modeled by

$$\rho(\theta_{M,J}) = \rho_0 + \rho_\Delta \cos^2(\theta_{M,J})$$

where $\rho_0$ is the zero-field resistivity, $\theta_{M,J}$ is the angle between current and field direction and $\rho_\Delta$ is material constant. The resistance change is maximum when the current and magnetization are orthogonal to each other. Near the origin, the resistance change is very small, being zero for $H=0$. In order to overcome this lack of sensitivity and also non-linear output, a so-called barber pole structure is used. It has a series of high

\footnote{To whom any correspondence should be addressed}
conductive strips. The strips change the direction of the bias current on an angle 45° relative to the easy axis. As a result, the sensor output is shifted into the linear region. This is called the barber pole bias.

Figure 1. AMR Wheatstone bridge element. $V_b$ - bias voltage (taken from Honeywell’s HMC1002 datasheet).

The AMR sensor which was chosen for this application was the Honeywell HMC1002 sensor. The HMC 1002 sensor is composed of four identical thin film elements made out of a Nickel-Iron alloy (Permalloy). These Permalloy elements are aligned in the barber pole bias with shorting bars separating the thin films. The shorting bars cause the current in the “pole” to flow at 45° in the Permalloy elements. The four resistive elements are arranged in a Wheatstone bridge configuration (Figure 1) to provide an accurate measurements over a large range of temperatures and also over time.

In addition, the HMC 1002 sensor allows for two modes of operation referred to as set and reset mode. Each mode differs from each other by having their easy axis of magnetization at 180° to each other. This causes the response of the sensor to be opposite in each mode. It allows for the compensation of the dc offset coming from a bridge imbalance.

In addition, the set/reset capability of the sensor allows for compensation of cross-axis effects [5] (perpendicular component of the field that is trying to be sensed in the plane of the thin film). By looking at the difference of the set and reset voltage, the cross axis effects become negligible.

3. Design
In order to achieve the required field in the MVS, multiple sensors, scattered around the cap which encloses the sample holder, were needed. This would allow for a measure of the field at multiple points and also approximate gradients of the different components. The electronics used to control the sensor board utilizes an FPGA for its digital circuitry. It has various DACs and ADCs to control signals as well as read them.

The circuit for the AMR sensors has gone through two revisions. The first revision of the circuit was made using flex PCBs. This was chosen in order to wrap the board around the sample holder cap. The PCB has four Honeywell HMC 1002 sensors aligned equal distances apart and also one Honeywell HMC 1001 sensor (1-axis) which was mounted on a small horizontal flap at the bottom of the PCB. This was used in order to gain a measurement of the gradient of the Z component of the magnetic field in the Z direction. There are four HMC 1002 sensors and one HMC 1001 sensor, nine sensors in total. Out of the nine, eight of them are wired up and share a common offset and set/reset line. Each sensor is measured serially using a multiplexer for the input bridge voltage and the output voltage lines.

There were numerous problems with the mechanically reliability of the board and thus there was a revision to it. The second revision was made using regular rigid PCBs. The PCBs are shown in Figure 2.
4. Results
Various experiments were run at different operating environments to test the functionality of the AMR sensors. The three main operating environments were at temperatures of 300K, 77K and 4K. By running the (sweep - offset) command to produce the AMR sensor’s voltage vs. magnetic field curves, outputs as shown in Figure 3 were seen the majority of the time. There are two curves for each sensor. These two curves represent the measurements after the set pulse and the measurements after the reset pulse. The difference between the set curve and reset curve is the negative response to field change as compared to the set curve.

Figure 3. An example of the AMR transfer function of mV vs. offset field (arbitrary units).
After tests, the sensor PCBs were placed into a dilution refrigerator. During the cool down of the dilution fridge from room temperature (300K) to approximately 9K, the magnetic field was recorded using the AMR sensors and a fluxgate sensor. The fluxgate sensor was mounted in the z direction about 2 inches from the processor. The AMR sensors were setup to take measurements every 20 minutes and the fluxgate was setup to take measurements every 1 min. The results are shown of Figure 4.

![Figure 4. AMR sensor, temperature and fluxgate measurements during cool down of the dilution fridge.](image)

All eight of the sensors were operational throughout the entire cooldown. A large change of field was seen at a temperature of about 40K due to the stainless steel parts inside the fridge which have not been annealed.

5. Conclusions
Operation of Honeywell’s AMR sensors HMC1002 has been investigated at low temperature. It has been shown that the sensors can be used to monitor magnetic environment of a processor in a dilution fridge.

[1] Johnson M W et al. 2011 *Nature* **473** 194-198
[2] Checkelsky J 2004 *Anisotropic Magnetoresistance of Fe_{x}Co_{1-x}S_{2} (Claremont: Harvey Mudd College)*
[3] Hauser H, Stangl G, Fallmann W, Chabicovsky R 2000 Magneto resistive Sensors *Preparation, Properties, and Applications of Thin Ferromagnetic Films: Proc. Workshop at the Vienna University of Technology (Vienna, Austria, 15-16 June 2000)* ed K Riedling pp 15-27
[4] *Handling of Sensor Bridge Offset Application Notes (Honeywell)*
[5] *Cross Axis Effect for AMR Magnetic Sensors Application Notes (Honeywell)*