Development of transition edge sensors with rf-SQUID based multiplexing system for the HOLMES experiment

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Abstract. Measuring the neutrino mass is one of the most compelling issue in particle physics. HOLMES is an experiment funded by the European Research Council for a direct measurement of neutrino mass. HOLMES will perform a precise measurement of the end point of the Electron Capture decay spectrum of $^{163}$Ho in order to extract information on neutrino mass with a sensitivity as low as 1 eV. HOLMES, in its final configuration will deploy a 1000 pixel array of low temperature microcalorimeters: each calorimeter consists of an absorber, where the Ho atoms will be implanted, coupled to a Transition Edge Sensor thermometer. The detectors will be kept at the working temperature of $\sim 70$ mK using a dilution refrigerator. In order to gather the required $3 \times 10^{13}$ events in a three year long data taking with a pile up fraction as low as $10^{-4}$, detectors must fulfill rather high speed and resolution requirements, i.e. 10 $\mu$s rise time and 4 eV resolution. To ensure such performances with an efficient read out technique for very large detector arrays kept at low temperature inside a cryostat is no trivial matter: at the moment, the most appealing read out technique applicable to large arrays of Transition Edge Sensors is rf-SQUID multiplexing. It is based on the use of rf-SQUIDs as input devices with flux ramp modulation for linearisation purposes; the rf-SQUID is then coupled to a super-conductive $\lambda/4$-wave resonator in the GHz range, and the modulated signal is finally read out using the homodyne technique.

1. Introduction

In order to reach the desired 1 eV sensitivity on neutrino mass [1], each HOLMES detector will have an activity as high as 300 Bq and, at the same time, it is necessary to reduce the fraction of unresolved pile-up events to a fraction as low as $10^{-4}$; this can be achieved using very fast detectors and a proper sampling rate, so that pile-up resolving algorithms can be successfully applied. In 2016 we have reached the desired 500 MHz sampling rate of our $10 \mu$s rising edge fast detectors. The measured prototype detectors are produced at NIST, Boulder, Co, USA and have been measured both at NIST and in Milan with different readout techniques: at NIST, using a time domain multiplexing, a 4 eV resolution has been reached, while in Milan, measuring the devices with the HOLMES rf-SQUID multiplexed system, we have reached a 7 eV resolution. In this contribution we outline the performance and special features of the multiplexing system.
Figure 1. Circuit scheme for a two channel microwave multiplexed readout of a TES array [4]. Each rf-SQUID is coupled to: the input coil of the TES line (red); an input coil for the flux ramp modulation (green); the LC resonator (black).

and readout methods chosen for HOLMES and we present the last results on the performances of the HOLMES-like detectors tested with the rf-based set up at the Cryogenic Laboratory of the Physics Department of Milano-Bicocca University, where HOLMES is hosted.

2. HOLMES detectors
In a calorimetric measurement the energy released in a beta decaying process is entirely contained in the detector, except for the fraction taken away by the neutrino. This approach eliminates all the issues related to excited final states that affect spectrometric measurements. The region of interest for the neutrino mass measurement is the upper tail of the spectrum: for a non zero neutrino mass a shift of the end point is expected.

The most suitable detectors for calorimetric measurements are low temperature thermal detectors, where all the energy released into an absorber is converted into a temperature increase that can be measured by a sensitive thermometer directly coupled to the absorber [2].

The most promising detectors that can satisfy the demanding performances for HOLMES are Transition Edge Sensors (TES) [3]. A TES is a superconductive thermomether kept at the bottom of the phase transition so that the strongly temperature-dependent resistance variation is exploited for measuring a temperature increase [3]. The TES is coupled to an absorber, where the $^{163}$Ho will be implanted. The detectors for HOLMES are Mo/Cu TES coupled to a Gold absorbers, placed aside on a Si$_2$N$_3$ membrane.

3. HOLMES multiplexing and read-out
The readout for HOLMES not only has to carry the signal from the detectors, coupled to the mixing chamber of a dilution refrigerator, to the room temperature electronics, but it also has to maintain the single detector performance over a 1000 detectors array. The multiplexed readout is a key element for HOLMES, and much care has to be payed in order to provide an efficient readout with a high multiplexing factor.

In HOLMES, each TES is coupled to a rf-SQUID with flux ramp modulation for linearisation purpouses, as described in [4]. Any signal in the TES causes a current variation in the bias circuit, which varies the magnetic flux linked to the rf-SQUID, resulting in a phase shift in the
SQUID response with respect to the free ramp induced SQUID oscillation. The phase shift after each ramp cycle is the effective sample of the pulses in the TES.

The phase modulation applies to all SQUIDs on a chip using an extra line coupled to all the SQUIDs. The modulated rf-SQUID are read-out by inductively coupling the SQUID to a $\lambda/4$ resonant circuit in the GHz range (shown in black in Fig. 1), which is used to extract the signal information using the homodyne detection technique. The multiplexing is achieved by tuning each of the resonators at a characteristic and unique frequency.

4. Results and conclusions
We have successfully tested prototype detectors and proved the performance of the readout system for HOLMES. The TES were illuminated with a Mn K-alpha X-ray emitting source and showed a thermal response with 10 $\mu$s rise time, as required. The resolution measured in Milan using the rf-SQUID multiplexed readout was 7 eV, shown in Figure 3. A similar detector measured at NIST showed in Figure 2, had a resolution of 4 eV; the device was tested at NIST with a more conventional time domain multiplexed readout.

Currently, the resolution is limited by a low frequency noise source and we are working on improving the thermal stability of the detectors. We are confident that we will be able to fully reproduce the NIST results in the next test run.

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