Characterization of the microwave multiplexing readout and TESs for HOLMES

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Abstract.

A powerful tool to determine the effective electron-neutrino mass is the calorimetric measurement of the energy released in a nuclear beta decay. Performing a precision measurement of the end point of the Electron Capture decay spectrum of $^{163}$Ho, HOLMES aims at pushing down the sensitivity on the neutrino mass below 1 eV. In its final configuration HOLMES will deploy an array of 1000 microcalorimeters based on Transition Edge Sensors with gold absorbers in which the $^{163}$Ho will be ion implanted. The best technique to easily read out such a number of detector with a common readout line is the microwave frequency domain multiplexing. Therefore, the TESs are coupled to multiplexed rf-SQUIDS operated in flux ramp modulation for linearization purposes. The rf-SQUIDS are then coupled to superconducting quarter wavelength resonators in the GHz range, from which the modulating signal is finally recovering using software defined radio techniques. In the last two years an extensive R&D activity has been carried out in order to maximize the multiplexing factor while preserving the performances of each detector which fulfil the HOLMES requirements (i.e. an energy resolution of few eV and a time-resolution of a few microseconds). We report here the progress made towards the characterization of the multiplexing system together with the results of the characterization of the HOLMES detectors.

1. Introduction

One of the most compelling issue in particle physics is the neutrino mass measurement. To date, a model-independent method to determine the neutrino mass is the calorimetric measurement of the energy released in a nuclear beta decay involving neutrino. Performing a calorimetric measurement of the $^{163}$Ho Electron Capture decay spectrum, as proposed in 1982 by De Rújula and Lusignoli [1], the HOLMES [2] experiment aims at reaching a sensitivity on neutrino mass as low as 1 eV. For reaching such target, HOLMES will deploy an array of 1000 microcalorimeters characterized by an energy and time resolution of $\sim 1$ eV at the end point and of $\sim 1$ $\mu$s,
respectively. A good time resolution is an important element in this kind of experiment since the sensitivity is strongly dependent on the unresolved pile-up fraction in the region of interest. The 1 $\mu$s time resolution is obtained applying pile-up resolving algorithms to pulses with 20 $\mu$s rise time sampled at 500 kHz [3, 4].

A complete description of the current status of the HOLMES experiment is reported in [5].

2. The microwave multiplexing readout

A promising approach to read out a large number of detectors using a common transmission line is the microwave multiplexing read out. This can be leveraged to multiplex the signals from many detectors with large signal bandwidth and high energy resolution. Therefore, the HOLMES detectors are read out with the microwave multiplexing system ($\mu$mux) [7], which is based on the use of the rf-SQUIDs as input devices. Their response is linearised using a flux ramp modulation [8]: a sawtooth signal is applied to a common line inductively coupled to each rf-SQUIDs. The modulated rf-SQUID signals are read out coupling the rf-SQUID to a superconducting $\lambda/4$ wave resonators in the GHz range. By tuning the resonators at different frequencies it is possible to read many SQUIDs with a set of RF carries. The modulated signal is finally recovered using Software Defined Radio (SDR) technique: in this scheme frequency tones in the MHz range are generated by a digital to analog converter, up-converted in the GHz range by means of an IQ mixer and combed together to probe the resonators. Then, the output signal is down converted by another IQ mixer and digitized by an analog to digital converter. Finally, the individual channel recovery is performed via software. The SDR technique in HOLMES exploits the Reconfigurable Open Architecture Computing Hardware (ROACH2) [9] board with a Xilinx Virtex6 FPGA. The SDR is implemented in the firmware of the ROACH2 board by NIST [10]. We are currently using a version of the firmware which is able to multiplex 16 channels. The ADC sampling frequency $f_{ADC}$ sets the total bandwidth available for each ROACH2 board. The bandwidth of the ADC boards currently available for ROACH2 is 550 MHz. Considering a 500 MHz ADC bandwidth $BW_{ADC}$, the multiplexing factor is given by:

$$N_{TES} = \frac{BW_{ADC}}{N_{S} \times f_{ramp} \times N_{\Phi_{0}}}$$  \hspace{1cm} (1)$$

where $f_{ramp}$ is the sampling frequency of the TES signal and $N_{\Phi_{0}}$ is the number of rf-SQUID oscillation per ramp, which is set to 2. To properly reconstruct the TES signal while providing
a reasonable multiplexing factor, the frequency separation and the bandwidth of the resonators in the multiplexing chip need to be precisely controlled. A spacing between resonances \(N_S\) of at least 14 MHz assures a negligible cross-talk, while a bandwidth of 2 MHz for each resonators allows to sample the TES signal at 500 kHz. In this configuration, the number of TES detectors which can be multiplexed is 36.

We have characterized a preliminary version of the HOLMES multiplexing chip (\(\mu\text{mux}17\text{A}\)) which was developed and produced at NIST. The chip has 33 resonances in 500 MHz frequency interval with an average separation of 14 MHz. The resonance width is around 2 MHz. The transfer function \(|S_{21}|\) of the resonators on the multiplexing chip is shown in figure 1, while the resonances linear distribution and spacing are displayed in figure 2. The big frequency gap between resonance 17 and 18 corresponds to the centre of the multiplexing chip and its presence is required by the read out system.

3. TES performances
The requirement of low pile-up probability for reaching a sensitivity on neutrino mass as low as 1 eV sets strict constraints on the detector design. A fast rise time requires a large electrical bandwidth which is limited by the ratio between the stray inductance \(L\) and the total resistance \(R\) in the bias circuit (left side of figure 3). Therefore, \(L\) must be kept as small as possible. The decay time is set by the ratio between the thermal capacity \(C\) of the absorber and the thermal conductance \(G\) toward the heat sink. Since the value of \(C\) is set by the request of full containment of the energy in the absorber, the only way to have fast decay time is to increase \(G\). The selected design is 125×125 \(\mu\text{m}^2\) Molybdenum-Copper bilayer TESs on Si\(_3\)N\(_3\) membrane with 2 \(\mu\text{m}\) thick gold absorber in which the \(^{183}\text{Ho}\) will be ion implanted \([11, 12]\). The 200×200 \(\mu\text{m}^2\) gold absorber lays aside of the sensor (side-car design) in order to avoid proximity effects between the sensor and absorber itself. The thermal conductance \(G\) is increased by the addition of a Cu thermal radiating perimeter. \(C\) is around 0.8\(\text{pJ/K}\) while \(G\) is about 600\(\text{pW/K}\). A sketch of a single pixel is reported in right side of figure 3.

The rise time of 20\(\mu\text{s}\) is obtained by tuning the stray inductance in the TES bias circuit. A study on the variation of the rising time at different working point is reported in \([13]\). The decay time is of the order of 100\(\mu\text{s}\).

We have studied the energy resolution at different energies illuminating the detectors with a X-ray fluorescence source. The source is based on \(^{55}\text{Fe}\) as primary source which irradiates targets of Al, Cl, Ca. As a consequence, the detectors are exposed to the Rayleigh scattered \(K_\alpha\) and \(K_\beta\) X-rays of Mn and to the fluorescence \(K_\alpha\) X-rays at 1.5, 2.6, 3.7\(\text{keV}\) excited in Al, Cl, Ca. The results are reported in figure 4.
Figure 4. Energy spectra acquired in the presence of the fluorescence calibration source. The FWHM of the fitted peaks is 4.7 eV at 1.5 keV; 5.7 eV at 3.7 keV and 6.3 eV at 5.8 keV.

The results proved that the HOLMES read out based on ROACH-2 combined with the multiplexing system allow us to properly sample fast pulses without significant energy resolution degradation.

4. Conclusion

HOLMES is a calorimetric experiment aiming at reaching a sensitivity on neutrino mass as low as 1 eV by means the study of the EC decay of $^{163}$Ho. In order to reach such target there are strict requirements not only on the multiplexing system for reading out 1000 detectors but also on the single detector. In fact, as many detectors as possible must to be read in parallel without deteriorating the energy and time resolutions. In this contribution we have presented the characterization of the microwave multiplexing read out and we have shown that a multiplexing factor of 33 preserves the performances of each detectors in term of energy and time resolutions.

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