A MULTIPLEXED RTD TEMPERATURE MAP SYSTEM FOR MULTI-CELL SRF CAVITIES*

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Abstract

A new multiplexing scheme is presented for scanning through thousands of RTD sensors to obtain fast temperature maps of the walls of operating SRF cavities without undue cabling out of the liquid helium dewar. None of switching elements are located inside of the dewar. For *n* sensors placed on a cavity having *m* cells, the number of wires to be routed out of the dewar using this switching scheme would be approximately $2\sqrt{n \cdot m}$.

INTRODUCTION

Obtaining temperature maps of the exterior walls of SRF cavities during operation in vertical tests has been a useful research tool in diagnosing causes of cavity Q-slope and quench [1-3]. The temperature maps are typically obtained by placing Resistance Temperature Detector (RTD) sensors against the exterior walls of the cavity immersed in the liquid helium bath. An RTD sensor having the desirable large variation of resistivity with temperature in the 2K regime is the venerable 100 Ω, 1/8 W Allen-Bradley carbon resistor, though no longer in production. The resistivity increases from the 100 Ω room-temperature value to about 10 kΩ at 2K. For this type of RTD, a 2-wire sensing scheme per RTD has been used with the sensing current in the range 1-100 μA. For thorough mapping of a single-cell SRF cavity, this method requires about 750 sensors and 1500 wires routed out of the helium dewar. To map a 9-cell SRF cavity in a similar manner, there would have to be 7000-10000 wires routed out of the helium dewar, which is not a practical solution. To reduce the number of wires to temperature map a 9-cell cavity, systems using fewer thermometers that are rotatable around the cavity [4] and systems using multiplexing of sensors [5] have been developed. It is still desirable to improve the temperature resolution and to further reduce the wire count of 9-cell temperature mapping systems. Presented here is the design of a new type of RTD multiplexing scheme that will further reduce the wire count, reduce the time required to scan all of the RTDs, and could match the temperature resolution of single-cell mapping systems.

MULTIPLEXING SYSTEM

Sensor and Signal Processing Boards

The RTD sensor pc boards are traditionally contoured to match the shape of an SRF cavity [1-5]. The RTDs can be mounted on pogo pins at the edge of the board and the two wires per RTD routed to a connector on the pc board, as shown in Fig. 1. The sensor boards can be spaced azimuthally around the cavity, such as every 15°, to have 24 boards around the azimuth. A simplified schematic of the sensor and signal processing boards is shown in Fig. 2, representing: 24 sensor boards around a cavity with 25 RTDs wired to a connector per board, the ribbon cables, and the signal processing circuit external to the helium dewar. There is red and blue highlighting of the wires in Fig. 2 to help guide the following circuit description.

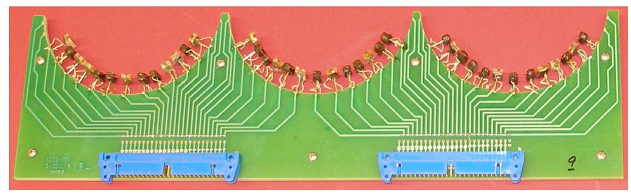

Figure 1: An RTD sensor pc board contoured to match the shape of an SRF cavity.

Switching Scheme

In this multiplexing scheme, node #2 of all of the RTDs per sensor board are connected together and routed to one pin on the connector, with a different pin used for each board around the cavity azimuth, for example incrementing from pin 26 to pin 49. Node #1 of each RTD per sensor board is routed to a unique pin per board, for example incrementing from pin 1 to pin 25. This can be seen on the right side of Fig. 2 where the ribbon wire resistance of 0.4 Ω and the inter-wire capacitance of 0.1 nF are also indicated. A 50-conductor ribbon cable can be wrapped around the azimuth of the cavity with 24 IDC connectors crimped onto the cable in parallel, and then the ribbon cable is routed out of the helium dewar. In this example, there are then 24×25=600 RTDs connected by a single 50-conductor ribbon cable. (In the specific design for a 9-cell SRF cavity, the sensor boards would be stacked along the axis of the cavity and 6 such ribbon cables would be routed out of the helium dewar.).

After the ribbon cable exits the dewar, it is routed to a signal processing board. Each wire of the ribbon on the signal processing board connects to a solid state SPDT switch and a pin of a bilateral solid state SPST multiplexer. The maximum ON resistance for the SPDT is about 20 Ω and for the multiplexer about 180 Ω, but for the present discussion assume zero ON resistance. A specific RTD among the 600 connected to the ribbon cable, such as R2 on board 24 in Fig. 2, is sensed by switching the SPDT connected to node #1 of this addressed RTD to a current source (or a voltage source through a large resistor, red highlighting in Fig. 2), and switching the SPDT connected to node #2 of the addressed RTD to ground (blue highlighting in Fig. 2). Current from the main source is prevented from flowing into other RTDs by switching all of the node #1's of the

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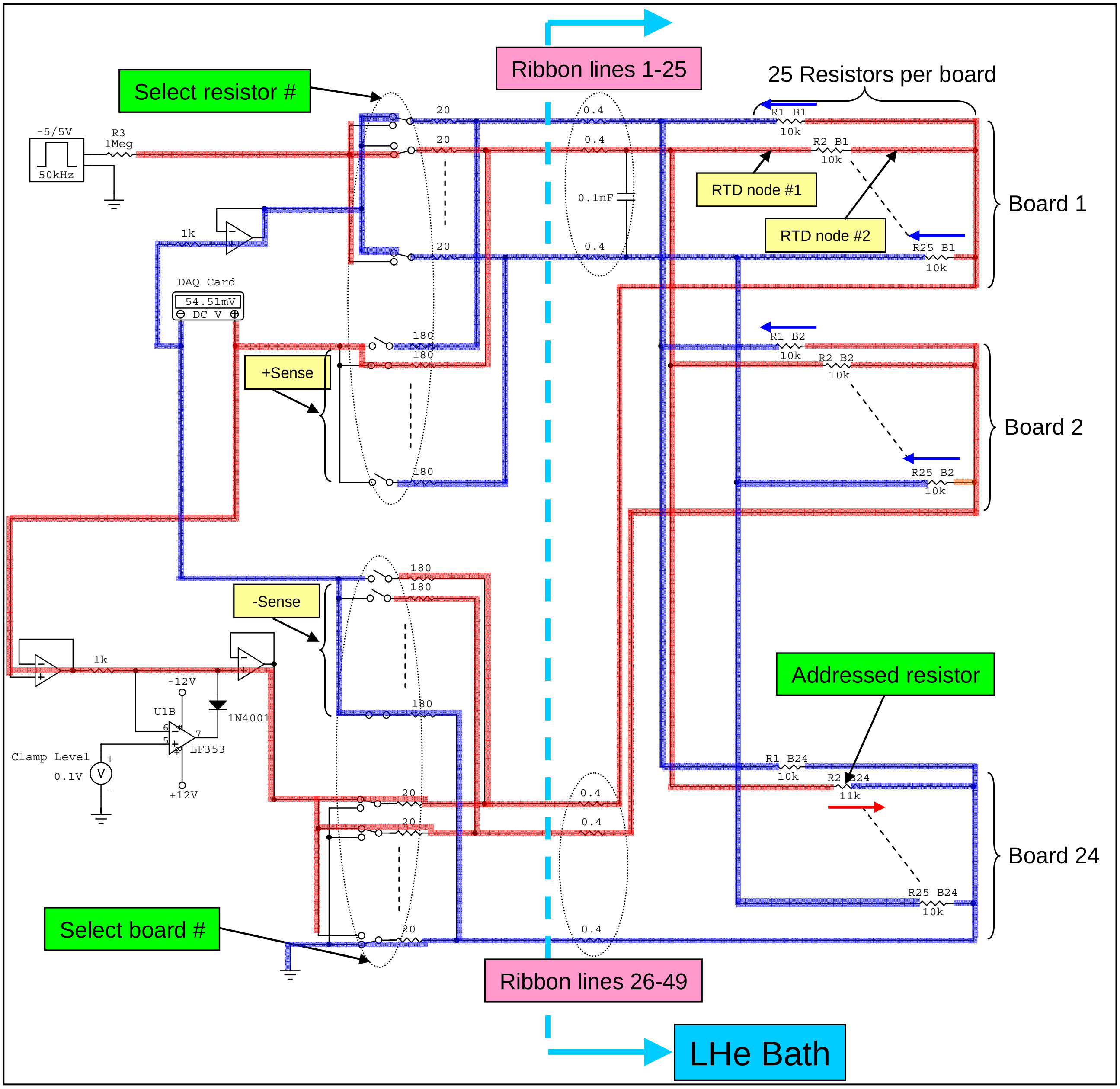

Figure 2: A simplified schematic representing the RTD sensor boards, the ribbon cables, and the signal processing circuit external to the helium dewar.

other RTDs to the buffered node #2 voltage of the addressed RTD, and all of the node #2's of the other RTDs to the buffered node #1 voltage of the addressed RTD. In this way, no current flows through any RTD R2 on the other boards, nor through any of the other RTDs on board 24. A reverse current flows through the remaining RTDs, but it is supplied by the buffer amplifiers and serves as pre-self-heating of those RTDs. The red and blue highlighting in Fig. 2 is representative of the node #1 and node #2 voltages and should help indicate the current flows just described.

The SPST multiplexers in Fig. 2 are switched in synchronism with the SPDT's and they are integral to the high impedance sensing of voltages by a data acquisition (DAQ) card and the buffer amplifiers driving the unaddressed RTDs. This portion of the circuit draws negligible current from the addressed RTD and allows measurement of its voltage drop, and then the RTD temperature from a calibration table.

Also shown in Fig. 2 is a clamping circuit for the signal to the +Sense buffer. This is in place in the event that there is an open circuit due a broken wire, and the buffered voltage will then be prevented from over-driving the other RTDs. A similar clamping circuit also precedes the -Sense buffer, though it is not shown in Fig. 2.

If the sensing current to the RTDs is selected to be high for better signal-to-noise, the ON resistance of the solid state switches may introduce a large enough voltage drop such that the nodes of the unaddressed RTDs do not sufficiently match the nodes of the addressed RTD. This would cause parasitic currents to contribute to the addressed RTD measurement. To eliminate such error, though not shown in Fig. 2, another set of SPST multiplexers are used to connect the node voltages of an unaddressed RTD to high impedance buffers. These unaddressed node voltages are used in servo loops to drive the unaddressed RTD nodes to equal the addressed RTD node voltages, and result in negligible parasitic currents. (For simplicity in Fig. 2, the unaddressed RTD buffers are driven directly by a shared signal from the DAQ multiplexers.)

Self Heating

Since no current flows through some of the unaddressed RTDs, they would have less pre-self-heating than other RTDs if they were the next RTD to be addressed. To utilize the reverse current that flows through the unaddressed RTDs for pre-self-heating, the consecutive switching sequence should step from board to board (different set of node #2's) and also step to the next RTD number (different set of node #1's). Using the RTD notation in Fig. 2, an example switching sequence is: R1B1, R2B2, R3B3,…,R24B24, R2B1, R3B2, R4B3,… In this way, each newly addressed RTD will have the pre-self-heating current flowing for nominally 22 data acquisition time intervals prior to being addressed. This assumes that an initial warm-up interval occurs prior to initiating the switching sequence so that all of the RTDs are allowed to reach a steady state temperature that includes self-heating. The fastest data acquisition time interval per RTD is envisioned to be about 1 ms, with longer intervals for increased averaging and accuracy.

Wire Count

For the example switching configuration described above, there are 600 sensors addressed by 50 wires in a ribbon cable routed out of the dewar. In general, if there are n sensors placed on a cavity having m cells, the number of wires to be routed out of the dewar using this switching technique would be approximately $2\sqrt{n \cdot m}$. For a system being fabricated to test 9-cell cavities using sensor boards as shown in Fig. 1, there are n=3528 sensors and 6 ribbon cables having 50 conductors each, or 300 wires routed out of the dewar.

HARDWARE

The analog sensing and digital control for the signal processing board is provided by a National Instruments PXI-1033 chassis. In the chassis is a PXI-6123, 8-channel analog input, 500 kHz DAQ module, and a PXI-6509, 96 DIO module for RTD addressing, signal conditioner gain select, carrier waveform select, and reference thermometer control. LabView software on a Windows PC with a PCIe slot will control the PXI chassis.

The baseline data acquisition parameters will have the analog DAQ acquire 512 samples at a 500 kHz sampling rate, with up to 8 RTD signals acquired by the PXI-6123 in 1 ms. Using 6 of the analog input channels for 6 ribbon cables, each addressing 600 RTDs, a temperature map of an entire 9-cell cavity could be obtained in about 1 second, allowing a 40% overhead for switching and data storage. Longer acquisition times may be selected for increased accuracy.

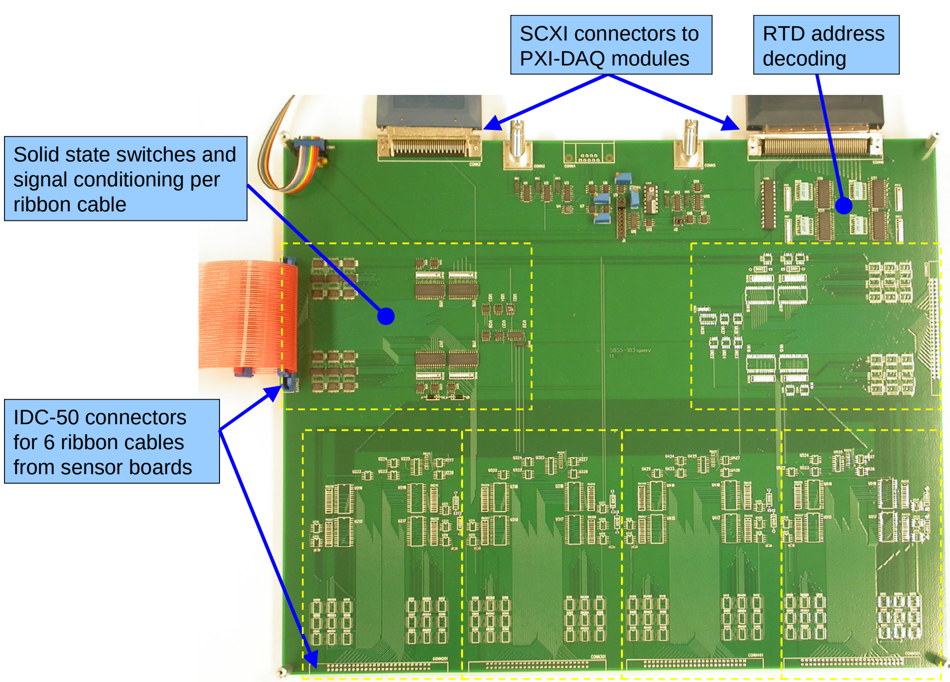

Figure 3: Layout of the switching and signal processing pc board.

The switching and signal processing board fabricated for testing a 9-cell cavity is shown in Fig. 3. It is an 8-layer board with surface-mount components on both sides. There is a section for decoding the RTD address and 6 duplicated channels to process the signals from 6 ribbon cables. The SPDT solid state switches are MUX333A and the SPST multiplexers are DG406. A portion of the signal processing board shown in Fig. 3 has been populated with components for testing one channel of the circuitry.

AC CARRIER AND LOCK-IN SENSING

An option included in the design of the signal processing board is the use of an AC carrier as the stimulus signal to the RTD sensors, followed by lock-in amplifier type demodulation techniques. This technique could extract better temperature resolution from the RTD sensors than available from a simple DC stimulus. The capacitive coupling between wires of the ribbon cable may cause too much cross-talk between sensed RTD signals, but the AC carrier option will be tested.

The well-known principle of the lock-in demodulation technique is illustrated in Fig. 4 for parameters considered for this multiplexed RTD data acquisition system. A desired signal with 20 mV amplitude and 50 kHz carrier frequency is shown in the top trace. The wideband noise shown in the second trace is added to the desired signal, with the summed waveforms shown in the third trace. Demodulating the summed waveforms synchronous with the carrier gives the waveform shown in the fourth trace. Summing all of the data points in the demodulated fourth trace then recovers the 20 mV amplitude of the desired signal to <0.1% accuracy. In general, if a signal is sampled for an acquisition time *T*, the demodulated average will include only the noise in a bandwidth $\Delta f = 1/T$ centered on the carrier frequency. For this multiplexed RTD data acquisition system, a 50 kHz carrier with a 1 ms acquisition time would give measurements that are effected only by the noise in the frequency band 49 kHz to 51 kHz

SUMMARY

A new multiplexing scheme has been presented for scanning through thousands of RTD sensors to obtain fast temperature maps of the walls of operating SRF cavities without undue cabling out of the liquid helium dewar. None of switching elements are located inside of the dewar. The RTD sensor pc boards have been designed and fabricated. The signal processing board has been designed, fabricated, and populated with components for testing one channel of the circuitry. LabView software has be written to perform the initial tests of the system.

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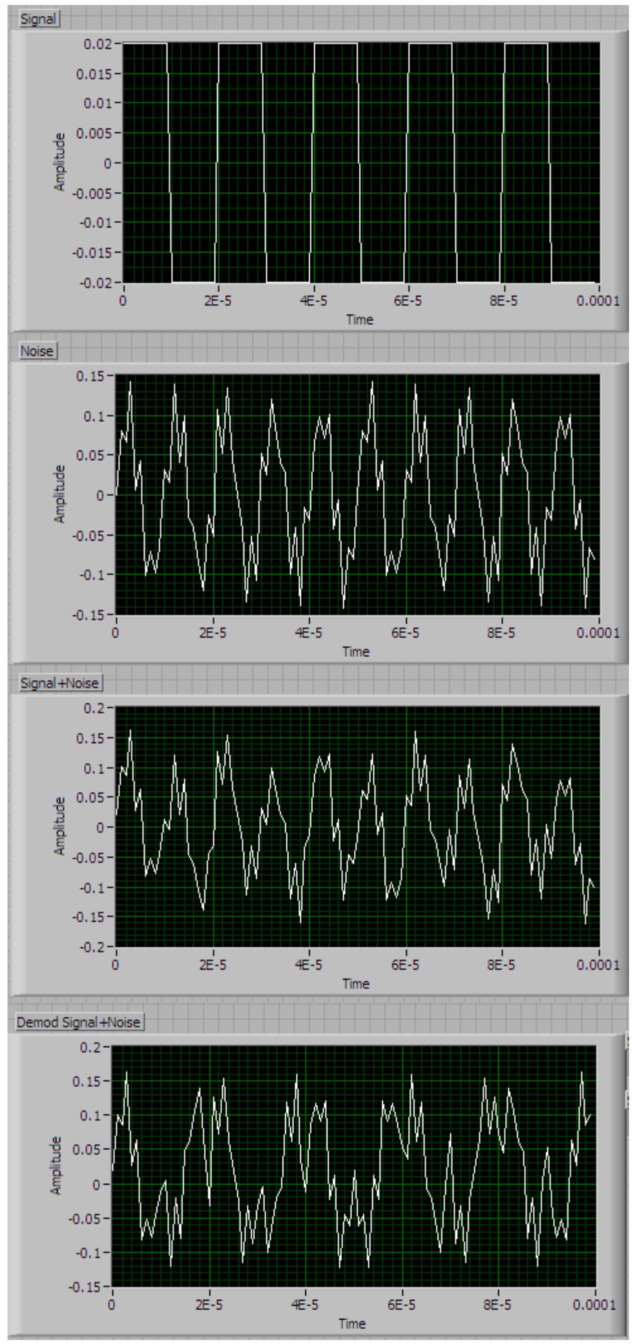

Figure 4: Illustration of the lock-in demodulation technique for parameters considered for this multiplexed RTD data acquisition system. Summing all of the data points in the demodulated fourth trace recovers the 20 mV amplitude of the desired signal in the top trace to <0.1% accuracy.

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