Temperature mapping system for single cell cavities

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Introduction

The use of temperature mapping in sub-cooled and superfluid helium has in the last 10 – 15 years contributed significantly to the understanding of limiting phenomena in superconducting cavities. It has been used to detect multipacting, field emitters and field emission trajectories, quenches/defects and spatial distribution of lossy areas on cavity surfaces. It is presently still the most powerful tool to gain further insight in cavity performance issues. Its effectiveness lies in the fact that any loss mechanism ultimately produces heat in the cavity wall.

A state-of-the-art system was built at Cornell, with 756 Allen-Bradley carbon resistors distributed over the cavity outer surface [1]. This kind of resistors has a highly non-linear resistance vs. temperature dependence and sensitivities of the order of tens of ohms per millikelvin can be obtained at 2 K. Similar systems have been built at DESY [2], KEK and Saclay [3].

A system has been built at Jefferson Lab consisting of an array of 576 Allen-Bradley resistors used to measure the temperature of the surface of single cell cavities at 1.5 GHz with the shape as used for the CEBAF accelerator. A useful feature of this system is that the software and the data acquisition are designed to provide a “live” image of the surface temperature during a high-power radio-frequency (rf) test, allowing the operator to follow the evolution of loss mechanisms in real time.

Thermometers

The temperature sensing element is a 100 Ω carbon Allen-Bradley resistor (5 %, 1/8 W) whose resistance increases exponentially with decreasing temperature. At 2 K, the resistance is typically 7 kΩ, the sensitivity is about 10 Ω/mK and very small temperature variations can be detected. However, the resistance of these thermometers changes when they are cycled at room temperature, so that each thermometer needs to be recalibrated for every cavity test.

Low thermal conductivity manganin wires, 0.254 mm in diameter, are soldered to the resistor leads. The resistors are encapsulated in a G-10 housing filled with epoxy (Stycast 2850 FT) to thermally isolate them from the helium bath. The top surface of the resistor (bakelite) is ground away until the carbon elements are exposed and a thin layer of GE-Varnish (7031), 50% diluted with a mixture of toluene and ethyl alcohol, is applied to electrically isolate the resistor from the cavity. Spring loaded pins (“pogo sticks”) are mounted with stycast in recessed holes in the bottom of the G-10 housing. Fig. 1 shows a schematic of the thermometer and a detailed fabrication procedure can be found in [1].

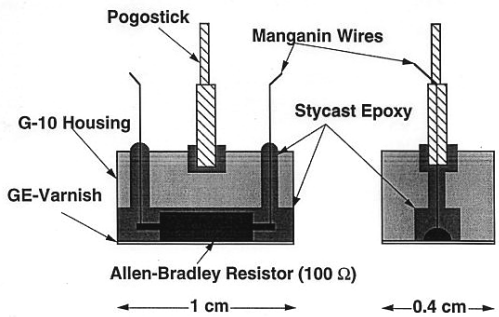


FIG. 1. Schematic of the thermometer used for the temperature mapping system [1].

To place the thermometers in contact with the cavity, 36 printed circuit boards (PCB) of G-10 material (3.175 mm thick) are machined to match the contour of the CEBAF cavity shape, leaving a 1 cm gap. 16 holes (1.38 mm drill bit, 1 cm deep) are drilled perpendicular to the cavity and the pogo sticks are inserted into them. Copper traces on the board link the thermometers to a 3M-3431-5003 34 pin right angle insulation displacement connector (IDC). Fig. 2 shows a picture of a complete thermometer board.

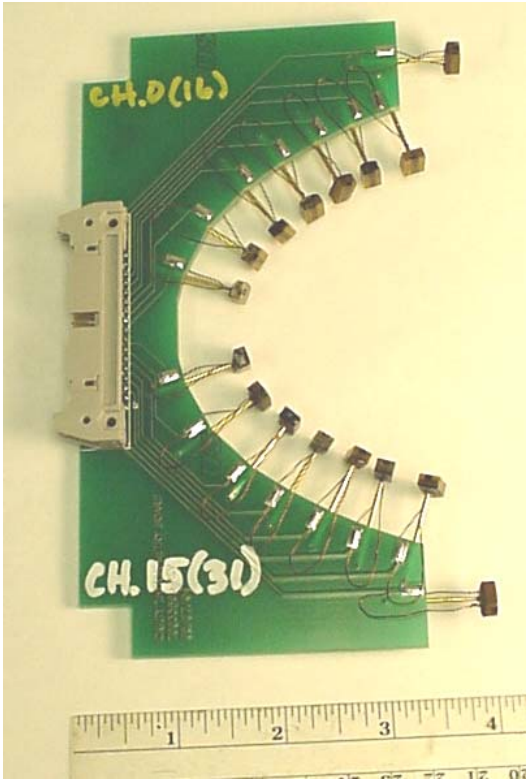
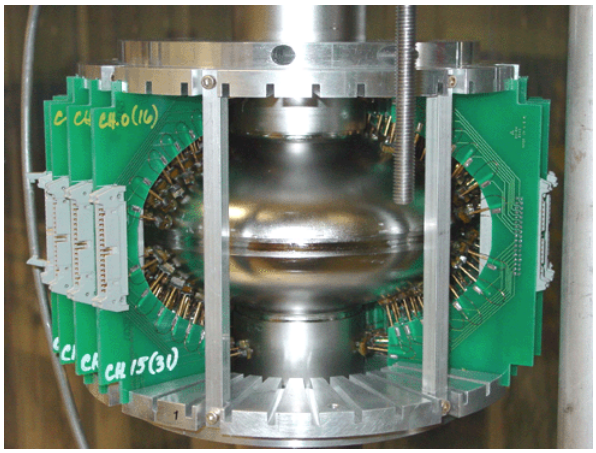


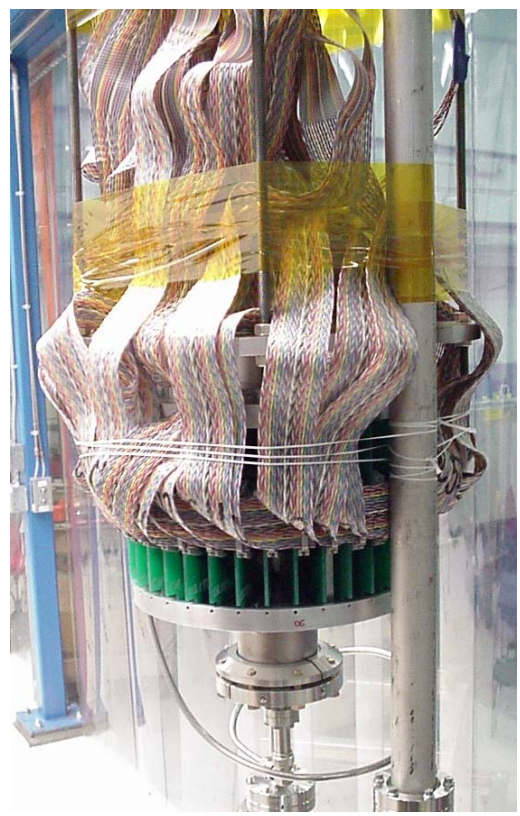
FIG. 2. Thermometer board designed to match the contour of a CEBAF cavity shape, holding 16 thermometers.

Four semicircular aluminum plates are attached to the top and bottom beam tubes of the cavity to form two rings. Each ring has 36 radial grooves (4 mm wide) into which the thermometer boards slide. Two split locking rings each with 36 threaded holes (2.84 mm diameter) are bolted on the aluminum plates. Set screws are inserted in the threaded holes and are used to push the boards against the cavity. Apiezon N grease is applied to the varnished side of the thermometers to assure good contact with the cavity.

The 36 boards are spaced azimuthally 10° apart, the spacing between thermometers on neighboring boards varies from about 0.65 cm at the iris, to 1.7 cm at the equator. The spacing along a board is about 1 cm and the largest gap is across the equator (1.7 cm) due to a recess on the cavity surface because of the equatorial weld. Figure 3 shows a picture of the thermometer boards mounted on the cavity. The main constraint on the design of the assembly was to keep the overall size smaller than the radius (20 cm) of the cryostat used to cool the cavity to 2 K.



a)



b)

FIG. 3. Assembly of thermometer boards on the cavity (a) and completed setup (b).

Electrical connections

A stainless steel feed-through box is mounted on the test stand top plate and provides the interface between the wiring inside the cryostat and to the data acquisition system. A G-10 PCB board (3.175 mm thick) has 36 DB-37 connectors on the air side and thirty-six 34-pin IDC connectors on the helium side. It is very important to have perfect soldering of the connectors pins to the pads on the PCB board since it has to be vacuum tight to the point where less than 8 ppm of air can leak into the dewar. A larger leak will contaminate the

helium recovery system to which the cryostat is connected. The PCB board is mounted on a stainless steel support plate, which acts as reinforcement, and is screwed on the front side of the feed-through box with twenty-two 4.83 mm diameter screws. A ribbon O-ring makes the plate leak tight. A picture of the feed-through box is shown in Fig. 4.

The thermometer boards are connected to the IDC connectors on the top of the test stand top plate by thirty-six 34-conductors (0.32 mm diameter) twisted pair flat ribbon cables. The additional heat leak in the 2 K bath due to the cables was less than 1 W.

FIG. 4. Feed-through box which interfaces the dewar inside with the air side and is able of maintaining a contamination smaller than 8 ppm.

Thirty-six 34-conductors (0.32 mm diameter) 6 meter long shielded jacketed ribbon cables bring the signal from the air side of the feed-through box to 18 PCB boards (two cables/board). Each board has sixty-four 1 MΩ chip resistors soldered in series to the Allen-Bradley resistors (two for each thermometer) which, in conjunction with the driving voltage act as a current source for the thermometer. The thermometers are connected in parallel and they are driven by a Keithley 2400 voltage source, remotely controlled by a computer via general purpose interface bus (GPIB). The PCB board provides also an easy interface between the shielded ribbon cables and the 96-pin connector of the data acquisition card. Fig. 5 shows a picture of the interface PCB board and a schematic of the thermometers excitation.

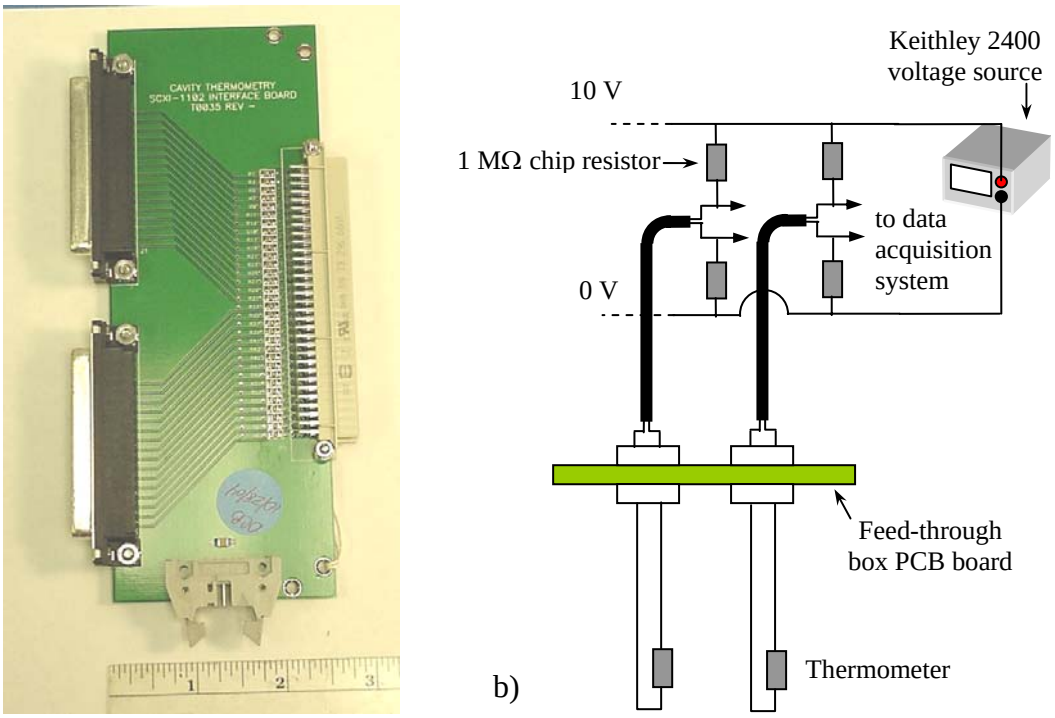


FIG. 5. Picture of the interface PCB board (a) and schematic of the thermometers excitation (b).

Data acquisition

The data acquisition system for the voltage across the 576 thermometers is based on the SCXI™ system from National Instruments: two SCXI-1001 chassis are placed outside the radiation shielding around the dewar and contain eighteen SCXI-1102 modules, each of which is capable of multiplexing 32 differential inputs. These modules are designed for high accuracy thermocouple measurements, they include an instrumentation amplifier with programmable gain of 1 or 100 and they have 333 kS/s maximum sampling rate. The typical thermometers excitation voltage is 10 V at 2 K, so that the voltage drop across the 7 kΩ resistor is about 35 mV. The analog signal from the SCXI-1102 modules are routed to a personal computer (PC) via a 2 m long SH68-68 shielded cable and they are digitized by a National Instrument PCI-6052E 16 bit analog to digital converter (ADC). The maximum rate of conversion is 333 kHz. A LabVIEW™ program controls the SCXI modules, the voltage source and a Lakeshore 218 temperature monitor. This last instrument makes a four-wire measurement of the resistance of four calibrated Lakeshore germanium thermometers (GR-200A-250), excited by a 10 μA current, used to monitor the helium bath temperature (T_b). The resistance is converted into temperature using calibration curves in the LabVIEW™ program and the average value is calculated. A LabVIEW™ program on a laptop computer in the control room, about 7 m away from the dewar, runs the program on the remote PC using a virtual instrument (VI) server connection through the laboratory network. It also retrieves the data from the remote computer and reads the incident, reflected and transmitted power from the power meters via GPIB to calculate the quality factor and accelerating field of the cavity.

Thermometer calibration and map acquisition

The voltage across each thermometer (ΔV) is obtained as the average between the absolute voltage measured with one polarity of the voltage source and with opposite polarity. By doing this, any contact voltages or amplifier offsets are canceled out. The thermometer resistance is then calculated as the ratio between ΔV and the excitation current, which is given by the ratio between the voltage source and the 2 MΩ resistances of the chip resistors. This operation can be repeated multiple times to obtain an average value of the thermometer resistance for better accuracy.

During the pumping on the helium bath to lower the temperature from 4.3 K to 2 K, the resistance (R_i) of each thermometer is measured at about 0.1 K intervals to obtain curves of R_i versus T_b. The data are well described by a third-order polynomial fit of $1/T_b$ as function of $x_i = \ln R_i$:

$$1/T_b = a_i + b_i x_i + c_i x_i^2 + d_i x_i^3 \qquad i = 0,1\ldots575 \tag{1}$$

where a_i, b_i, c_i and d_i are fit parameters to be determined for each resistor.

For each thermometer the square deviation between the measured data and the fit is computed. Thermometers are deemed faulty if this value exceeds the mean of all thermometers by a factor of ten. Bad thermometers are subsequently ignored during the acquisition of the temperature maps.

Figure 6 shows a picture of the LabVIEW™ program used for the calibration of the resistors. The sliding cursors on the top and on the side of the graph allow the operator to select any of the 576 thermometer and view the calibration data together with the curve fit. The program saves three separate files. The first one contains 577 columns, the first being the He bath temperatures, the remaining are the resistances of each thermometer. The second file is a matrix of 576 rows with four columns, representing the values of the fitting coefficients *a*, *b*, *c* and *d*. The last data file contains the sequential number of the faulty thermometers.

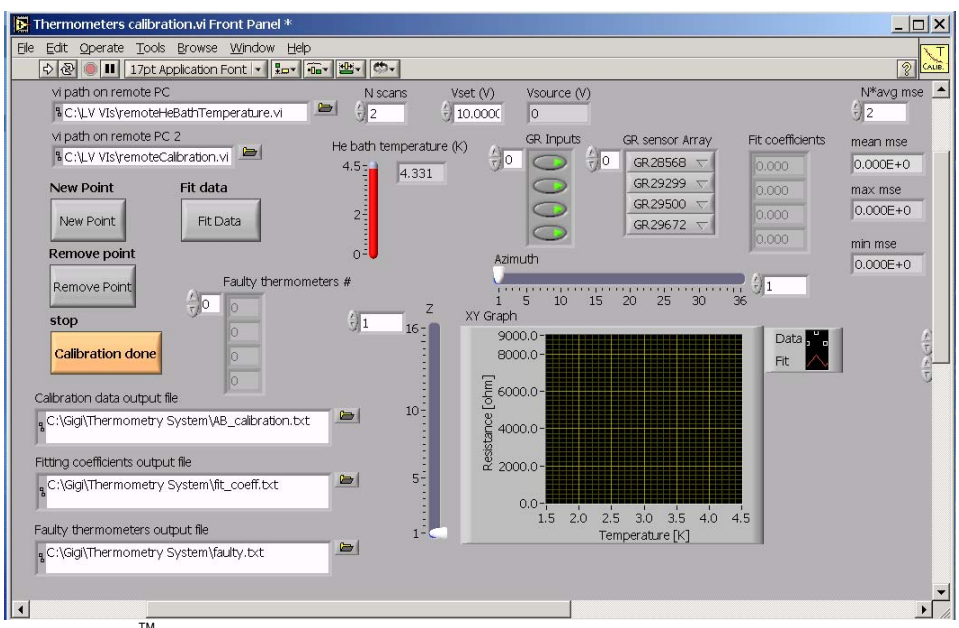


FIG. 6. LabVIEW™ program used for the calibration of the 576 resistors. The graph plots the resistance as function of T_b for each thermometer, selected through the slide cursors at the side and on top.

Figure 7 shows a typical calibration curve for one Allen-Bradley thermometers used in this system.

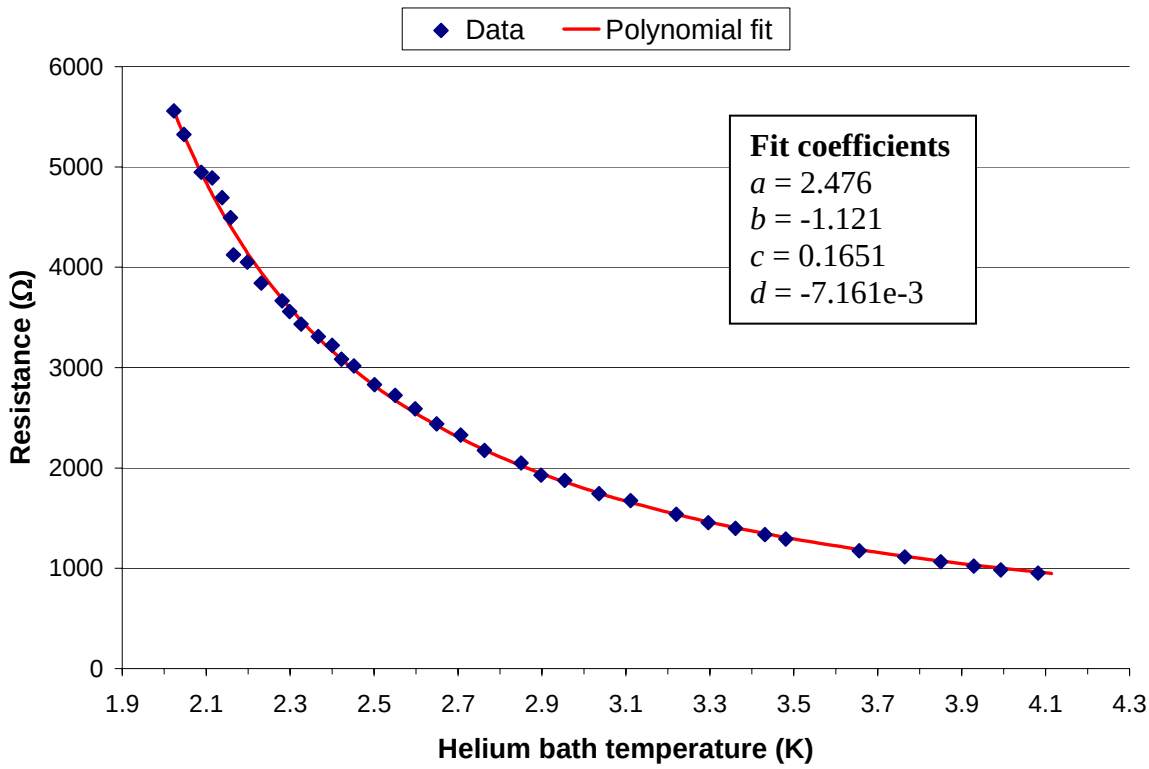


FIG. 7. Typical resistance vs. temperature curve for an Allen-Bradley resistor between 4 K and 2 K.

Once the calibration is completed, the temperature of each thermometer with zero field in the cavity (T_{0i}) is obtained through the polynomial coefficients and the difference with the helium bath temperature T_{b0} is plotted on a 2D view of the cavity surface. Once the rf field is switched on in the cavity, the temperature of each thermometer (T_i) is continuously acquired and the helium bath temperature (T_b) is subtracted. The difference between $T_i - T_b$ and $T_{0i} - T_{b0}$ is plotted, resulting in a "live" temperature map of the cavity surface. It takes about 128 ms for a single scan to be plotted, but multiple scans are preferred for better accuracy.

Studies performed on the kind of thermometers used for this system [4] showed that their efficiency (defined as the ratio of the measured temperature rise to the theoretical temperature rise) is about 35 % ± 13 % and their response is linear for power flux values between 1 μW/cm^2 and 1 W/cm^2. The temperature error due to self-heating is also linear and is about 1 mK with 5 μA excitation current at 2 K.

Fig. 8 shows the user interface of the LabVIEW™ program used for the temperature map. The program reads the fitting coefficient file and the faulty thermometers file generated by the calibration program and the calibration factors (Ci, Cr, Ct, 1/L sqrt(R/Q), Qext2) input by the operator. These constants are used with a measurement of the incident, reflected and transmitted power to calculate the quality factor and accelerating gradient of the cavity. By pressing the "Get data" button, after the "zero field calibration", a color map of the corrected

ΔT between the cavity surface and the helium bath is continuously plotted on the main graph. The operator can look at the temperature profile along a board (top to bottom of the cavity) on the bottom graph and azimuthally around the cavity (on the bottom-right graph) by moving the sliding cursor shown on the main graph. A map can be saved by pressing the "Save map" button. Once the test is completed, a map can be viewed with the "Recall map" button.

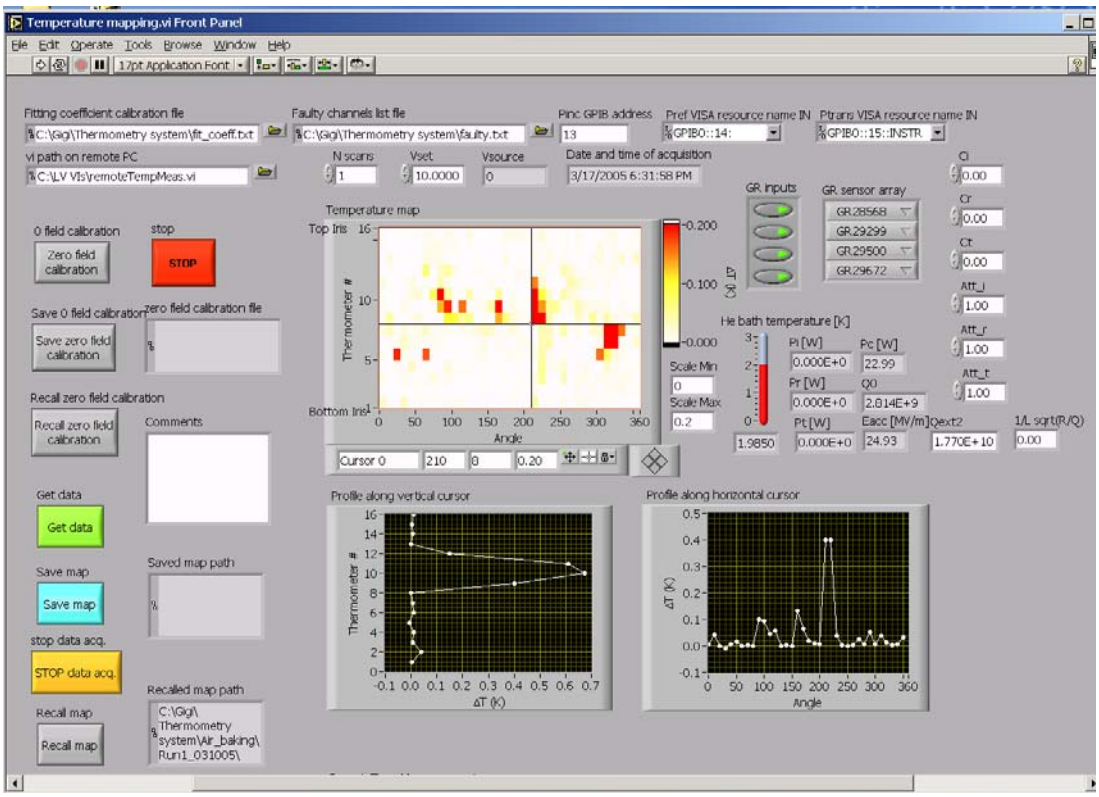
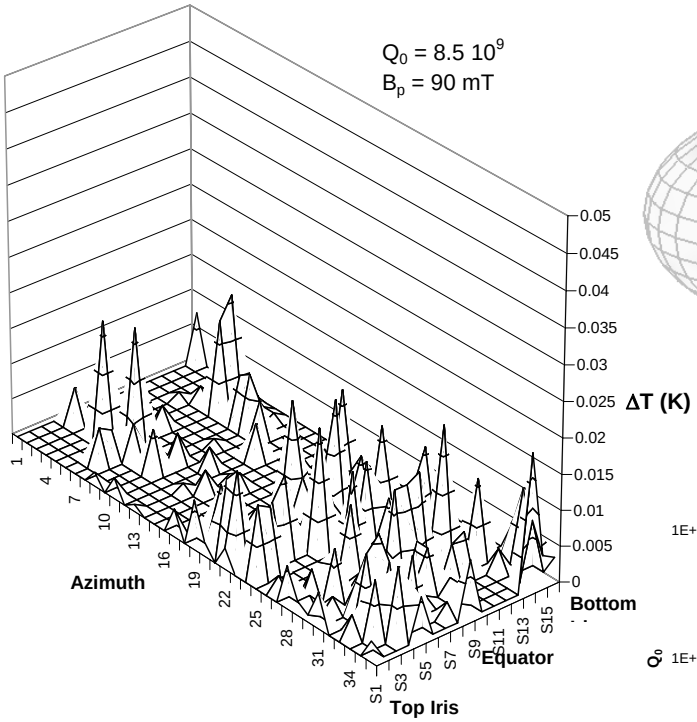


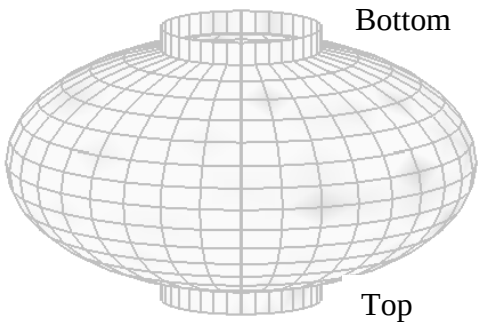
FIG. 8. LabVIEW™ program used for the temperature mapping of the cavity surface.

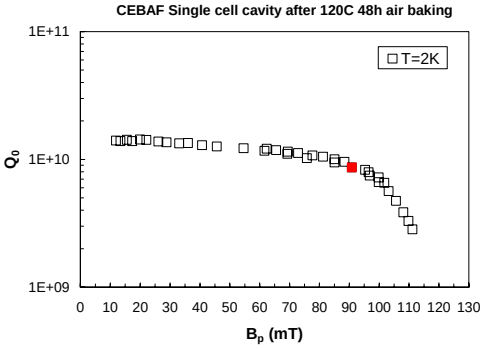
Test results

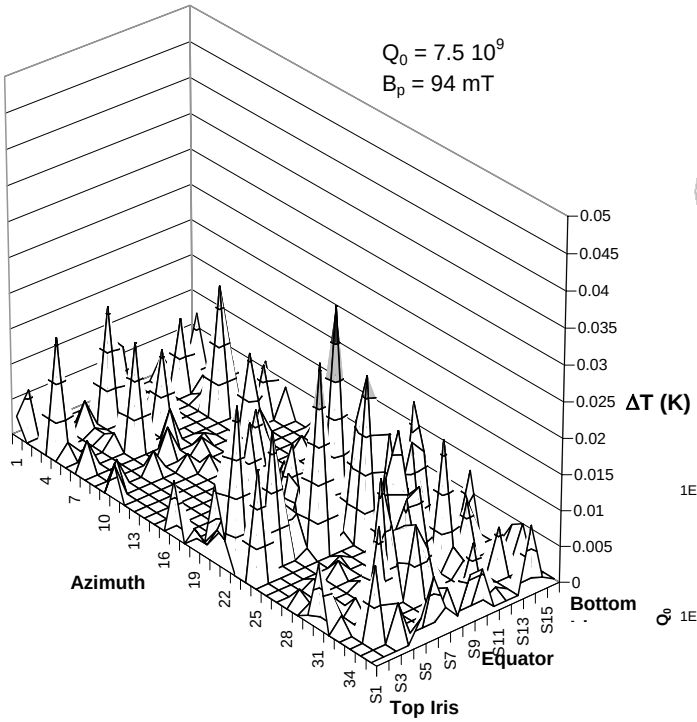
In this section, we present the results from the first test of the temperature mapping system applied to a single cell cavity made of RRR ≈ 300 niobium. The quality factor of the cavity started to drop at a peak surface magnetic field of about 95 mT and the temperature maps revealed localized losses around the equator of the cavity (high magnetic field region).

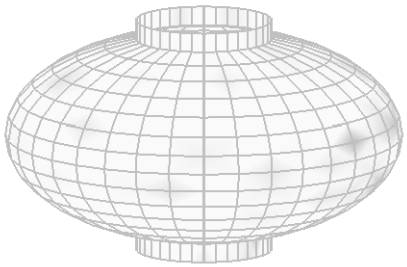
The following graphs show a 3D view of the relative surface temperature and a topological graph of the cavity surface with darker color showing hot-spots for different values of peak surface magnetic field (red square in the Q vs. B_p curve).

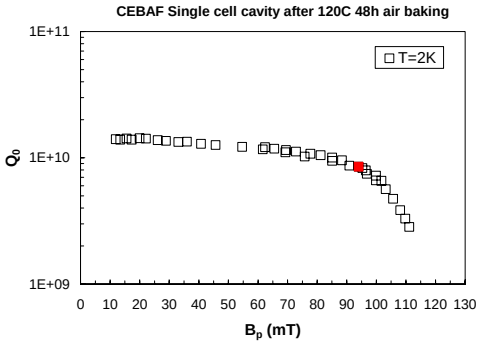

Q_0 = 8.5 10^9
B_p = 90 mT
ΔT (K)
Azimuth
Bottom
Equator
Top Iris

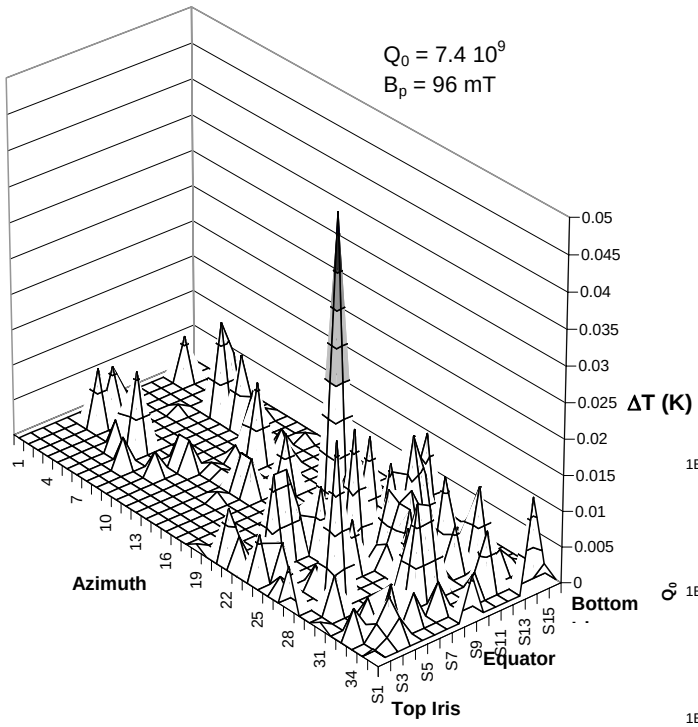

Bottom
Top

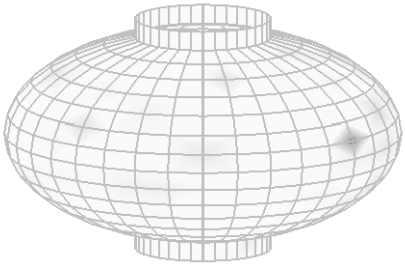

CEBAF Single cell cavity after 120C 48h air baking
T=2K
Q_0
B_p (mT)

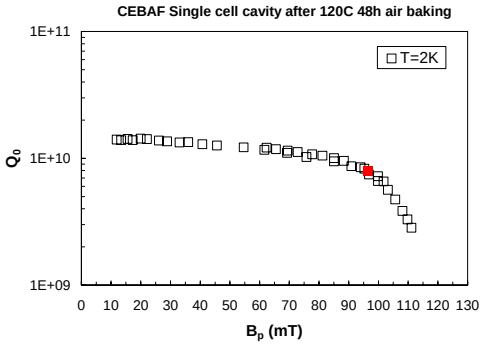

Q_0 = 7.5 10^9
B_p = 94 mT
ΔT (K)
Azimuth
Bottom
Equator
Top Iris

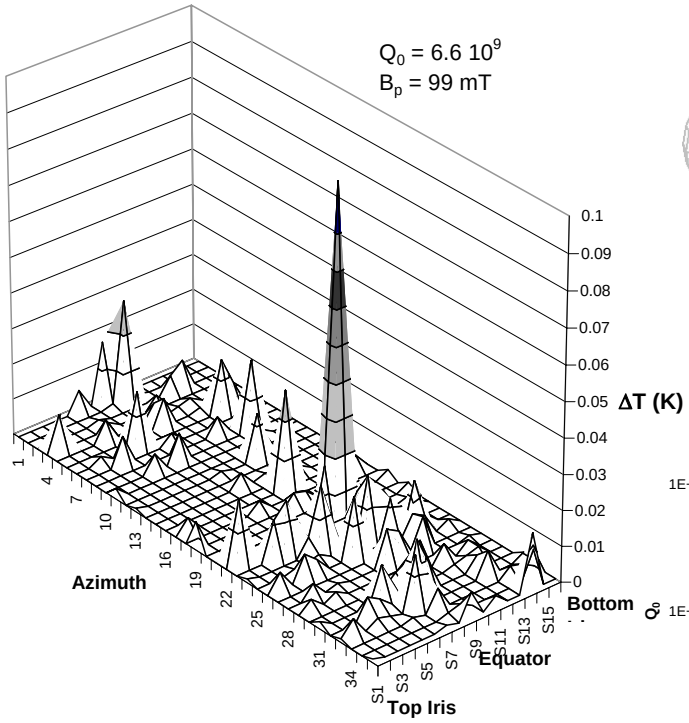


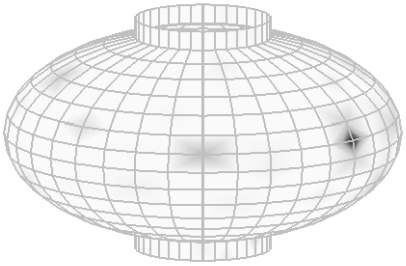

CEBAF Single cell cavity after 120C 48h air baking
T=2K
Q_0
B_p (mT)

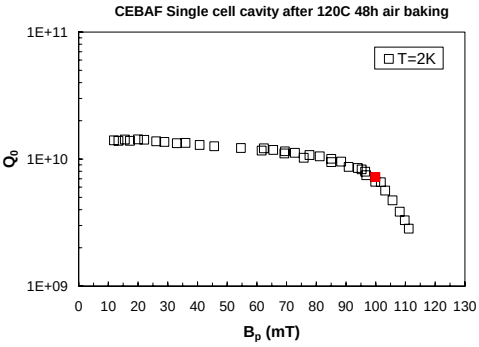

Q_0 = 7.4 10^9
B_p = 96 mT
ΔT (K)
Azimuth
Bottom
Equator
Top Iris

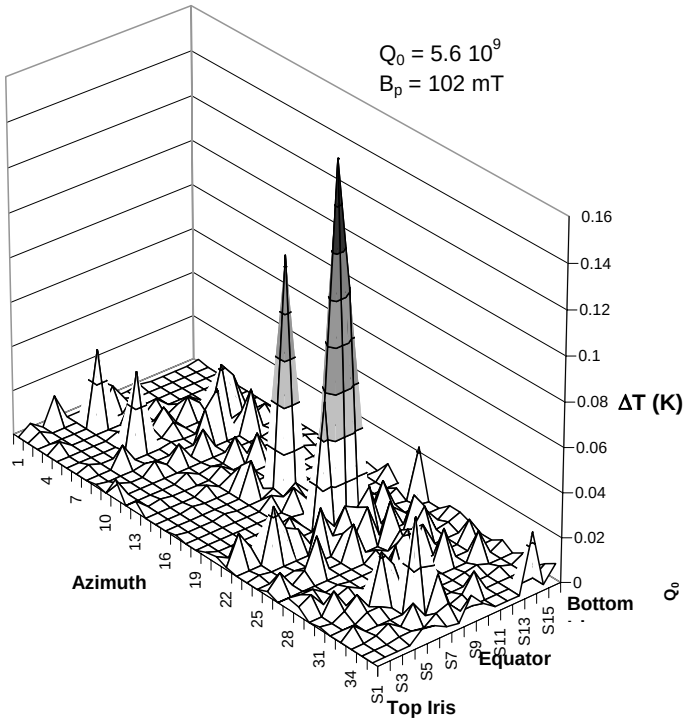


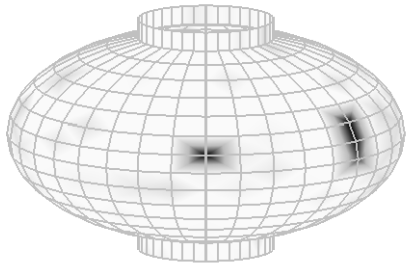

CEBAF Single cell cavity after 120C 48h air baking
T=2K
Q_0
B_p (mT)

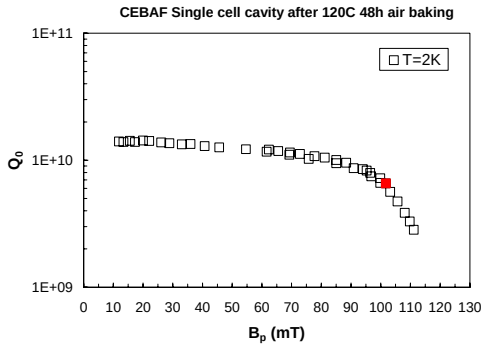

Q_0 = 6.6 10^9
B_p = 99 mT
ΔT (K)
Azimuth
Bottom
Equator
Top Iris

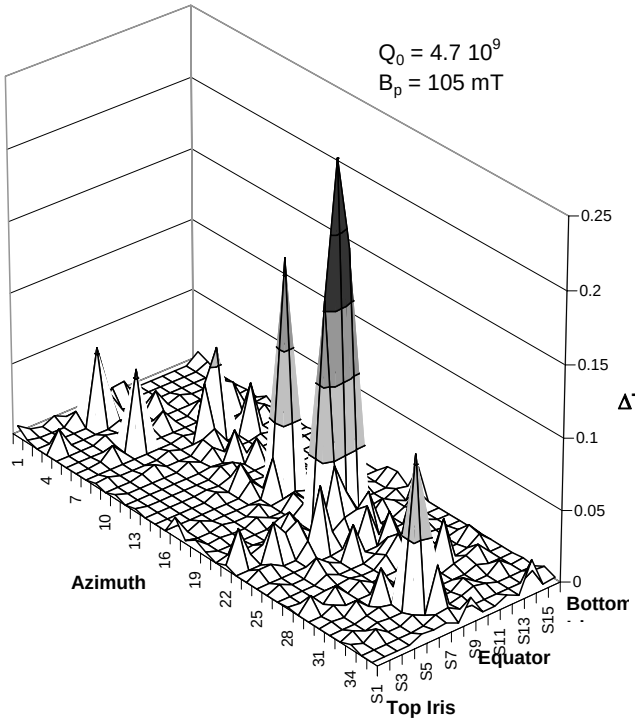


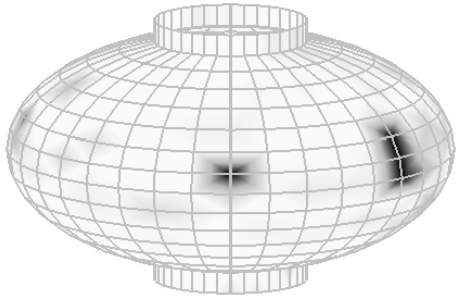

CEBAF Single cell cavity after 120C 48h air baking
T=2K
Q_0
B_p (mT)

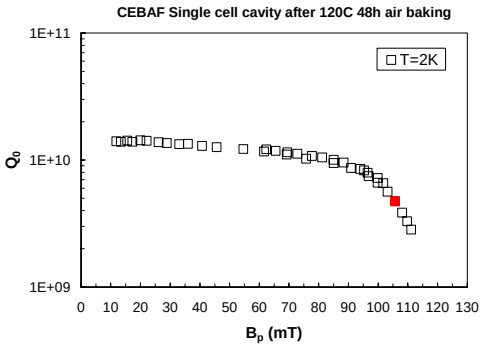

Q_0 = 5.6 10^9
B_p = 102 mT
ΔT (K)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Azimuth
1
4
7
10
13
16
19
22
25
28
31
34
Bottom
Equator
Top Iris
S1
S3
S5
S7
S9
S11
S13
S15

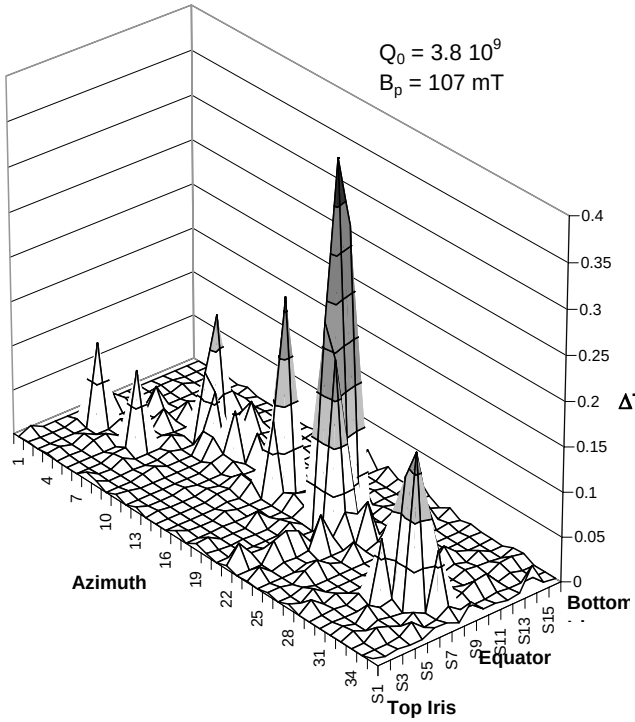


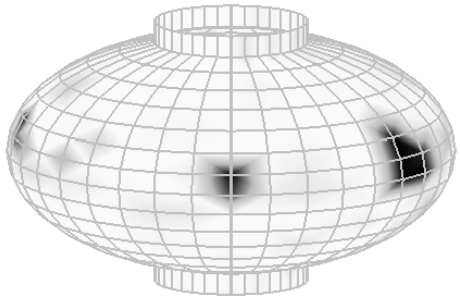

CEBAF Single cell cavity after 120C 48h air baking
T=2K
Q_0
1E+11
1E+10
1E+09
0 10 20 30 40 50 60 70 80 90 100 110 120 130
B_p (mT)

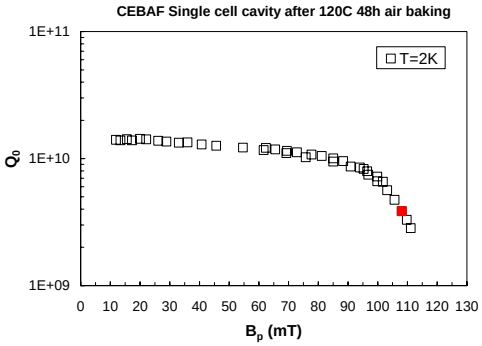

Q_0 = 4.7 10^9
B_p = 105 mT
ΔT (K)
0.25
0.2
0.15
0.1
0.05
0
Azimuth
1
4
7
10
13
16
19
22
25
28
31
34
Bottom
Equator
Top Iris
S1
S3
S5
S7
S9
S11
S13
S15

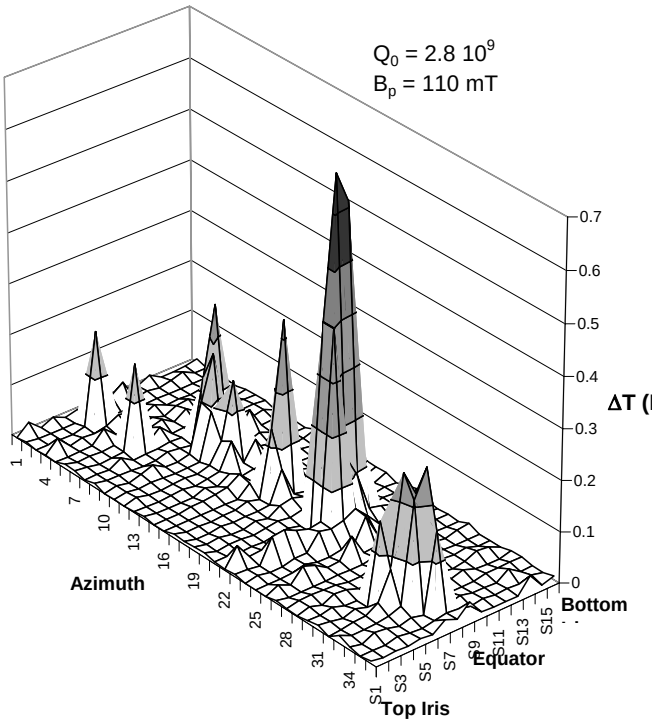


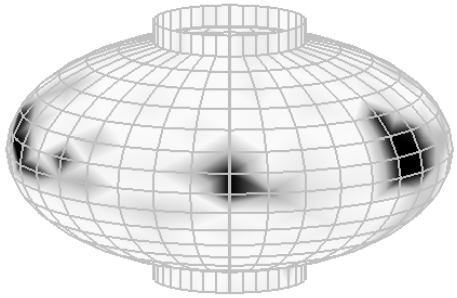

CEBAF Single cell cavity after 120C 48h air baking
T=2K
Q_0
1E+11
1E+10
1E+09
0 10 20 30 40 50 60 70 80 90 100 110 120 130
B_p (mT)

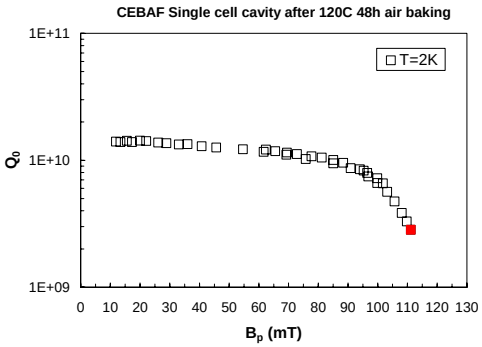

Q_0 = 3.8 10^9
B_p = 107 mT
ΔT (K)
Azimuth
Bottom
Equator
Top Iris




CEBAF Single cell cavity after 120C 48h air baking
T=2K
Q_0
B_p (mT)


Q_0 = 2.8 10^9
B_p = 110 mT
ΔT (K)
Azimuth
Bottom
Equator
Top Iris




CEBAF Single cell cavity after 120C 48h air baking
T=2K
Q_0
B_p (mT)

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