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The aim of this report is to summarize a study of the propagation of a quench in a HOM damper probe of the 56 MHz superconducting storage cavity for RHIC and provide guidance for machine protection.

The 56 MHz cavity [1] is designed to operate as a beam-driven superconducting quarter-wave resonator in the RHIC ring. Four Higher Order Mode (HOM) dampers [2] are used to prevent beam instabilities [3] in RHIC. These are inserted in the back wall of the cavity (the high magnetic field region) through ports that also serve for rinsing the cavity with high-pressure deionized water as well as the fundamental power coupler and pick-up ports.

Figure 1 shows the outline of the cavity [4,5].

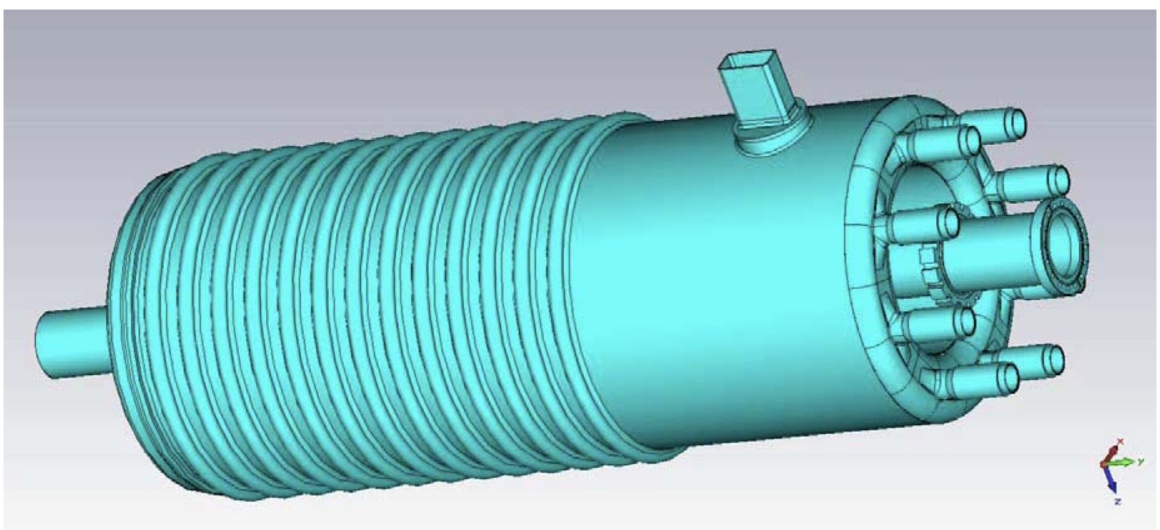

Figure 1. The 56 MHz cavity, showing the 8 port on the shorted end of the cavity which also serve t insert the 4 HOM damper probes.

The HOM damper probe has a magnetic coupling loop which penetrates the cavity as shown in Figure 2 [5]. The loop is cooled by conduction to the 4.3K helium system, thus any sudden, significant amount of heat dumped on the loop will cause local heating.

The peak magnetic field on the loop can reach about 7.4×10^4 amperes per meter at a cavity voltage of 2.5 MV [5]. The scenario we present here is that a small region on the loop quenches.

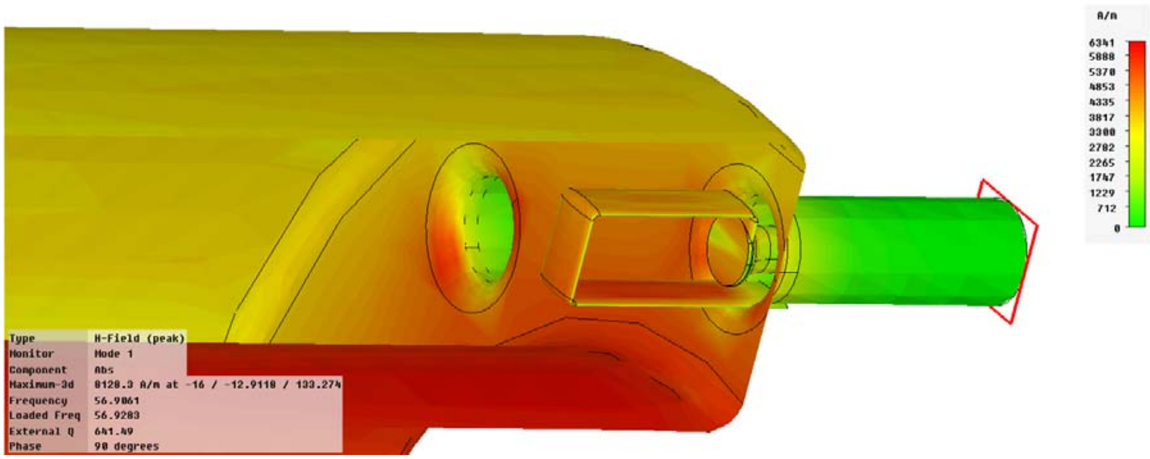

Figure 2. One of the HOM damper loops inserted in the 56 MHz cavity.

We can calculate the current driving the cavity using the RHIC parameters and get the magnetic field as a function of the current, the cavity's intrinsic Q and detuning parameter, however it turns out that within the time relevant for the quench development (a fraction of a second) the cavity field does not change sufficiently to warrant this extra computation. Thus we can assume that the field over the loop is constant.

The damper loop dimensions are not so important, however its cross section is. In the following we assume that the loop's cross-section is 2 cm by 0.3 cm. It is actually rounded in cross section (sharp corners avoided) but we will approximate it as square.

The material parameters taken for the niobium loop (assuming high RRR of about 200) are given in the following stepwise linear approximations.

The surface resistivity in ohms as a function of temperature in degrees Kelvin is given in Figure 3, the thermal conductivity in watt per degree meter as a function of temperature is given in Figure 4 and the heat capacity in Joule per kg as a function of temperature is given in Figure 5.

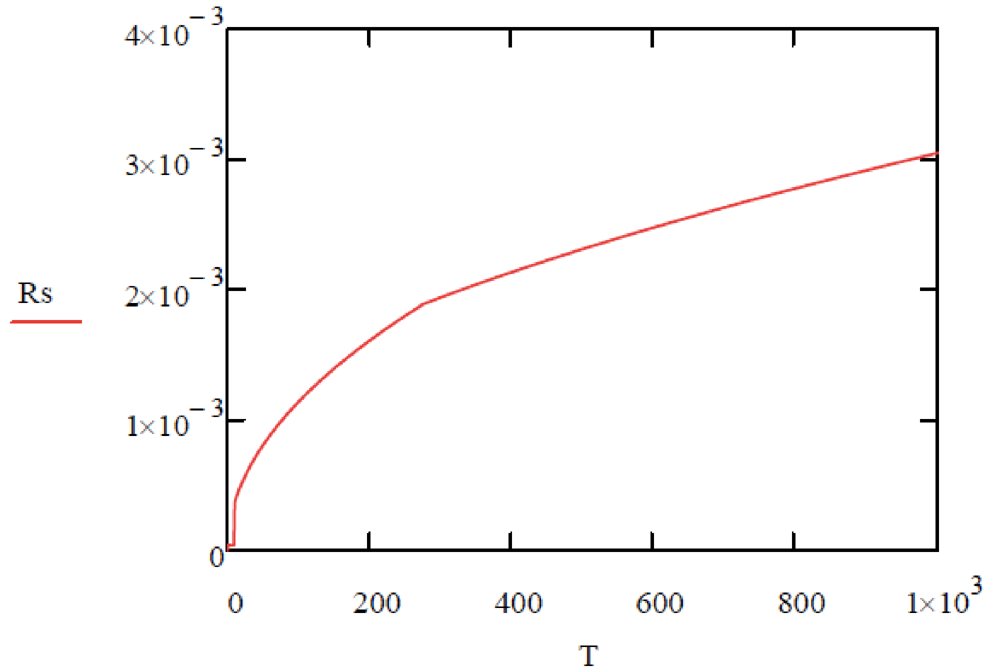

Figure 3. Niobium surface resistivity in ohms as a function of temperature in degrees Kelvin

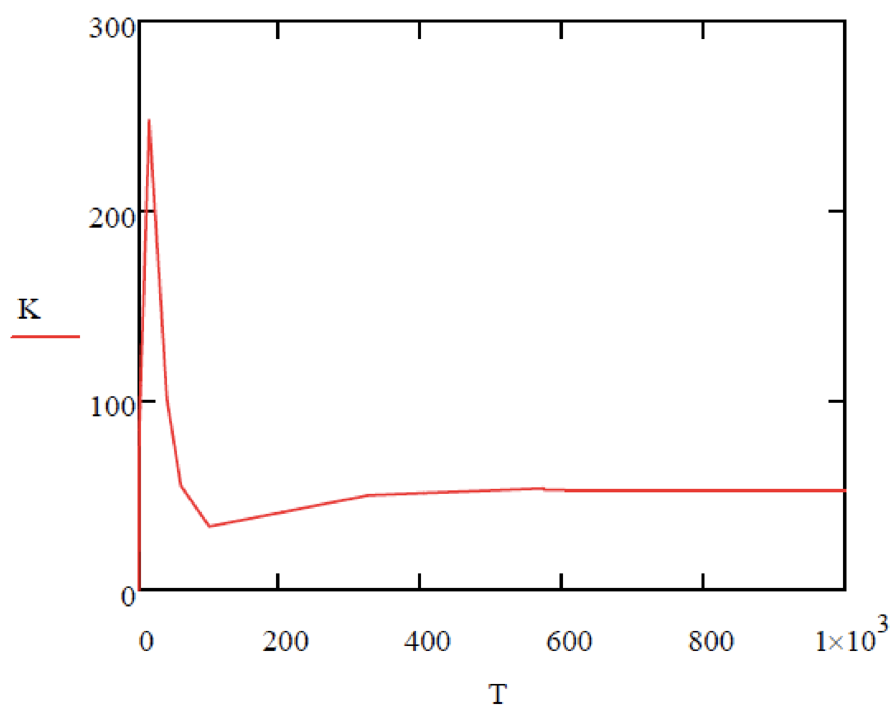

Figure 4. Niobium thermal conductivity in watt per degree meter as a function of temperature in degrees Kelvin

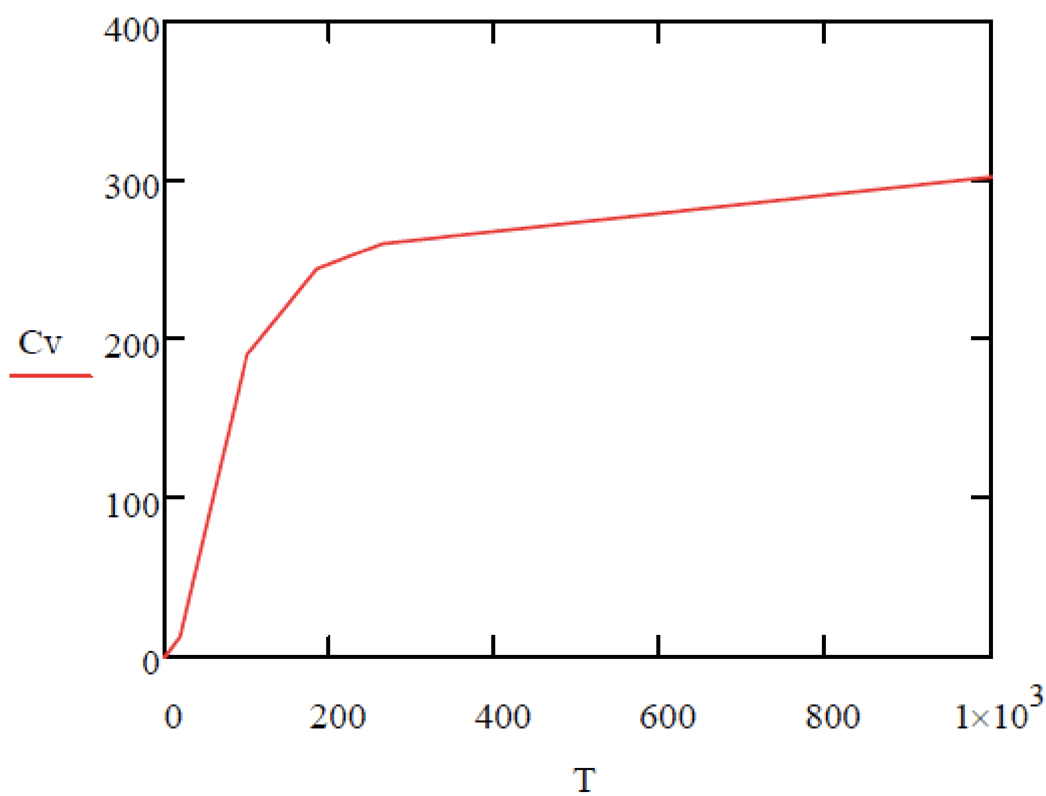

Figure 5. Niobium heat capacity in Joule per kg as a function of temperature in degrees Kelvin.

Another relevant material parameter is the density of niobium, ρ=8.57x10^3 kg per meter cubed.

The exact solution of the temperature evolution in time and space involves a non-linear partial differential equation, which must be solved numerically. The calculation is done by simple time step integration, with time steps of t=0.0001 seconds. The loop is divided into small slices, w=0.1 mm wide, with a circumference of d=4.6x10^{-2} meters, cross sectional area of a=6x10^{-5} square meters. The heat input into each slice is the surface heating by the magnetic field:

$$W_H = \frac{1}{2} H^2 t d w R_S(T)$$

In addition, each slice conducts heat to the two adjacent slices. We assume symmetry about a point to one side of the first slice, such that the first slice gets no conducted heat input from that side. The conducted heat per unit time of the n'th slice is given by:

$$W_c = \left(T_{n-1} + T_{n+1} - 2T_n\right)\frac{K(T_n)at}{w}$$

The temperature change in this time step is then:

$$\Delta T = \left(W_H + W_c\right)\frac{t}{C_V \rho a w}$$

A quench is initiated by artificially increasing the temperature of the first slice to above the critical temperature of the superconductor. In each time step the temperature is updated for all slices. The temperature of the slice where the quench started increases monotonically and, if allowed to proceed, can lead to melting the niobium loop. The quench also propagates to the right and left of the initial slice (although due to the symmetry chosen we observe only one direction).
Since the cavity is beam driven, the quenched part of the loop will be heated continuously and could even melt. Thus a machine protection system will be used, as discussed below.

The amount of energy, which is extracted from the beam, can reach many kilojoules and is much larger than the stored energy in the cavity, which is about 200 Joules. The following calculation shows that the Q degradation brought about by this power load is not large enough to make a significant difference in the field of the cavity.

We use a parallel RLC circuit to represent the cavity [1]. The admittance of the parallel circuit is given by:

$$Y = \frac{1}{R} + j\left(\omega C - \frac{1}{\omega L}\right)$$

That results in a voltage V across the capacitor related to the beam current I by

$$V = \frac{I}{Y} = \frac{I}{\frac{1}{R} + \frac{j\delta}{R/Q}}$$

where

$$R = \frac{1}{2\alpha^2 \int R_S \, dA}$$

α is the ratio of the magnetic field H at the loop to the cavity's voltage V, $\alpha \sim 0.03$, and the detune δ is given by

$$\delta = 2\frac{\omega - \omega_0}{\omega}$$

For a large detune value we have

$$V = \frac{I \cdot R/Q}{\delta}$$

and the magnetic field H is proportional to V. Thus, as long as 1/R is negligible compared to $\delta/(R/Q)$ the field will remain practically constant.
A typical detune value is $2\text{x}10^{-5}$, and R/Q is 40Ω, so that $\delta/(R/Q) \sim 5\text{x}10^{-7}$.

We can use R_S from Figure 3 as $3\text{x}10^{-3}$ (a conservative value), the loop dimensions of 4.6 cm in circumference and an estimate of the quench extent of 2 cm to estimate R. We get $1/R{\sim}5\text{x}10^{-9}$, which is still negligible as compared to $\delta/(R/Q)$.

Figure 6 shows the temperature distribution along the loop at 0.15 seconds after the quench initiation.

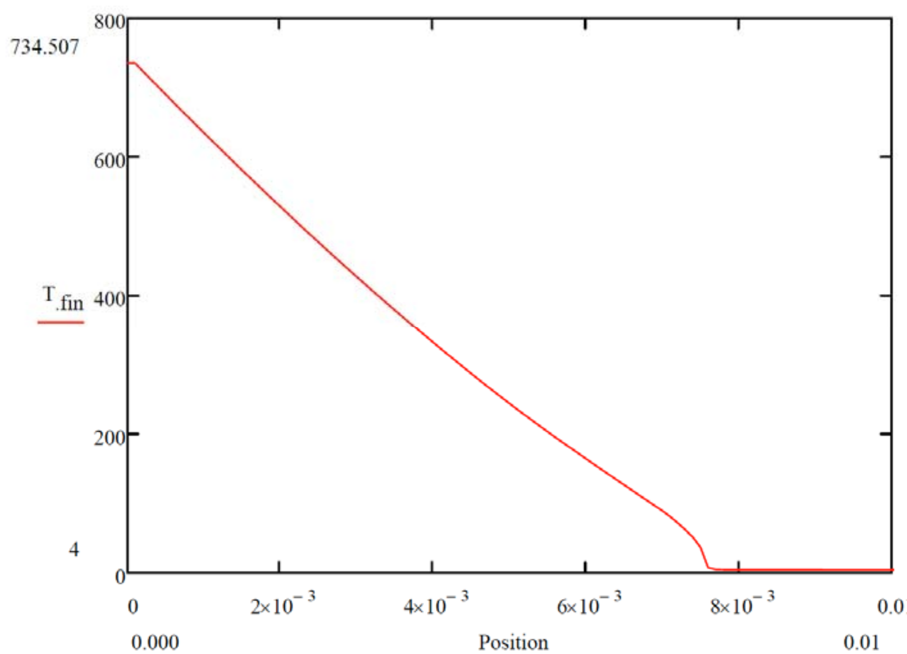

Figure 6. The temperature (degrees K) as a function of distance (meters) from the initial quench point, 0.15 seconds from the quench start time.

Concerning machine protection, it is important to detect the quench early and initiate the process. Since the propagation speed of the quench is too slow to reach thermal sensors outside the cavity, the best way of detecting the quench is by Infra Red (IR) radiation [6]. Indeed, the cavity is cryogenically cold, providing an ideally quiet IR background, and it is shiny (niobium reflectance of 98% in the IR), allowing reflected IR radiation to make multiple bounces and reach an IR detector.

For the example given above in Figure 6, at 0.15 seconds after quench the radiated power from the heated loop is 0.045 watt, as calculated the using Stefan-Boltzmann law:

$$P = \sigma \varepsilon A T^4$$

Where σ is the Stephan-Boltzmann constant, 5.67×10^{-8} W m^{-2} K^{-4}, ε~0.02 is the emissivity of niobium A is the radiating area and T is the absolute temperature. The wavelength of the peak of the radiation spectrum is given by Wien's law, which is shorter than 5 microns for this case. The reflectivity f niobium in the IR region between 5 and 10 microns is good, ~98%, allowing the IR radiation to undergo multiple reflections to reach the detector.

Once the quench is detected, there are two avenues to stop the heating and thus provide machine protection. One is to abort the RHIC beams, which will stop the heating very fast. However, that leads to lost experiment time. The other possibility is to detune the cavity to a point where the fundamental damper can be inserted, or about 15 to 20 kHz. Taking the tuning speed of the cavity as 3 kHz/second (actually the design number is 3.27 kHz/second [4]), the quench can be stopped at a safe temperature and then the loop can recover once the fundamental damper is inserted. Figure 7 shows the temperature distribution 3 seconds after the quench, assuming that detection takes place at 0.15 seconds and then the tuner is driven at 3 kHz/second. This is a safe temperature for niobium. The total IR power radiated at this time is 0.6 watts.

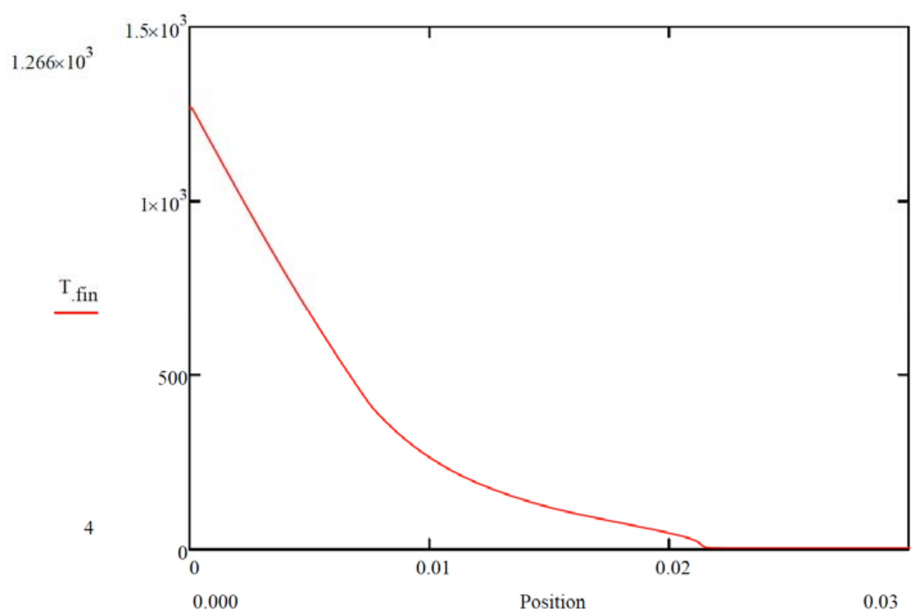

Figure 7. The temperature (degrees K) as a function of distance (meters) from the initial quench point, 3 seconds from the quench start time, with the tuner running at 3 kHz/second from the time the quench is detected, which is assumed to be 0.15 seconds after the quench onset. The temperature is stable.

References

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[2] E. M. Choi and H. Hahn, Higher Order Mode Damper Study of the 56 MHz SRF Cavity, C-A/AP/319, August 2008
[3] M. Blaskiewicz, Longitudinal Stability Calculations, C-A/AP/341, January 2009
[4] The mechanical design of the 56 MHz cavity was done by Chien-Ih Pai.
[5] Qiong Wu, private communication.
[6] Michael Blaskiewicz, private communication.