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Detection of hot spot through inverse thermal analysis in superconducting RF cavities

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Abstract

An inverse heat conduction problem in a superconducting radio frequency (SRF) cavity is examined. A localized defect is simulated as a point-heating source on the inner surface (RF surface) of the evacuated niobium cavity. Liquid helium acts as a coolant on the outer surface of the cavity. By measuring the outer surface temperature profile of the cavity using relatively few sensors, the temperature and location of a hot spot on the inner surface of the niobium are calculated using an inverse heat conduction technique. The inverse method requires a direct solution of a three-dimensional heat conduction problem through the cavity wall thickness along with temperature measurements from sensors on the outer surface of the cavity, which is immersed in liquid helium. A non-linear parameter estimation program then estimates the unknown location and temperature rise of the hot spot inside the cavity. The validation of the technique has been done through an experiment conducted on a niobium sample at room temperature.

Keywords: SRF cavity; Inverse heat transfer; Thermal sensor; Heat conduction

1. Introduction

A key component of the modern particle accelerator is the device that imparts energy to the charged particles. This is the electromagnetic cavity resonating at a microwave frequency at very low temperatures where the material of the cavity is electrically superconducting. Thermal breakdown, or quench, is a phenomenon where the temperature of part or all of the entire RF surface of the cavity exceeds the critical temperature T_c, thereby becoming non-superconducting, rapidly dissipating all stored energy in the cavity fields. Temperature mapping of the outer surface of the cavity thus becomes an essential tool in the diagnostics of the performance degradation of the cavity. In practice, usually the temperature mapping of the outer surface is accomplished using several hundred arbitrarily spaced sensors to identify the local hot spot on the RF surface. Due to the very high sensitivity of the carbon sensors at 1.6 K, detection of a temperature rise of 60 μK above ambient has been reported by Padamsee et al. [1]. However, quantitative estimation of actual temperature rise on the hot spot has not been made in previous research. It is the purpose of this research to quantitatively estimate not only the location, but also the actual temperature rise of the hot spot on the RF surface. In this paper, we shall first present the mathematical model employed in the

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three-dimensional numerical technique. This is done by performing a steady state analysis to determine the minimum number of temperature sensors, with suitable spacing, required at a specific bath temperature to detect a temperature rise of 60 μK above ambient. The numerical data thus obtained shall provide sufficient information to aid in employing an inverse heat conduction technique to make estimates of the unknown parameters, namely the location of the hot spot and the associated temperature rise on the RF surface. Comparing the results of this program with the exact solution provides code verification. Later in this paper, the information obtained from the numerical experiment, along with experimental data, provides not only the desired unknown parameters, but also the validation for the code.

2. Numerical simulations

2.1. Model definition

The region of interest for the SRF 805 MHz cavity is modeled as a rectangular parallelepiped 3-D surface, as shown in Fig. 1. This section of the cavity is chosen to be a representative region. A more detailed view of this three-dimensional surface with sensors installed on the outer (cooled) surface, is shown in Fig. 2. The sensors are encased in an insulated housing to protect against the direct cooling effects of liquid helium. The details of the construction of the housing are given elsewhere [1,2].

2.2. Governing differential equation

From a typical order of magnitude analysis, the transient time constant, known as Fourier number $\left(Fo = \frac{\alpha' t}{L_c^2}\right)$, is quite large for niobium cavities even for small times of several milliseconds (e.g. Fo for 1 mm

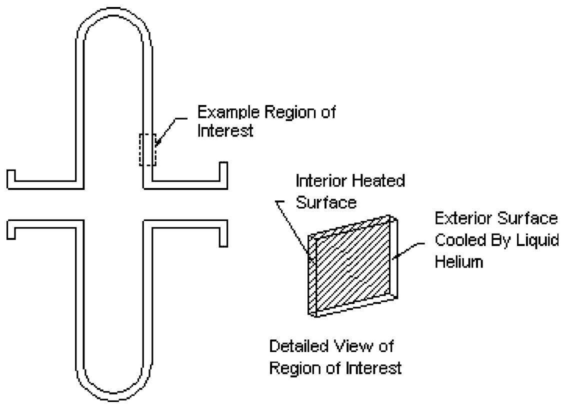

Fig. 1. Region of interest (ROI) on an elliptical superconducting 805 MHz cavity is modeled as a rectangular parallelepiped surface with point heat source on the interior surface and cooled by the liquid helium on the exterior surface.

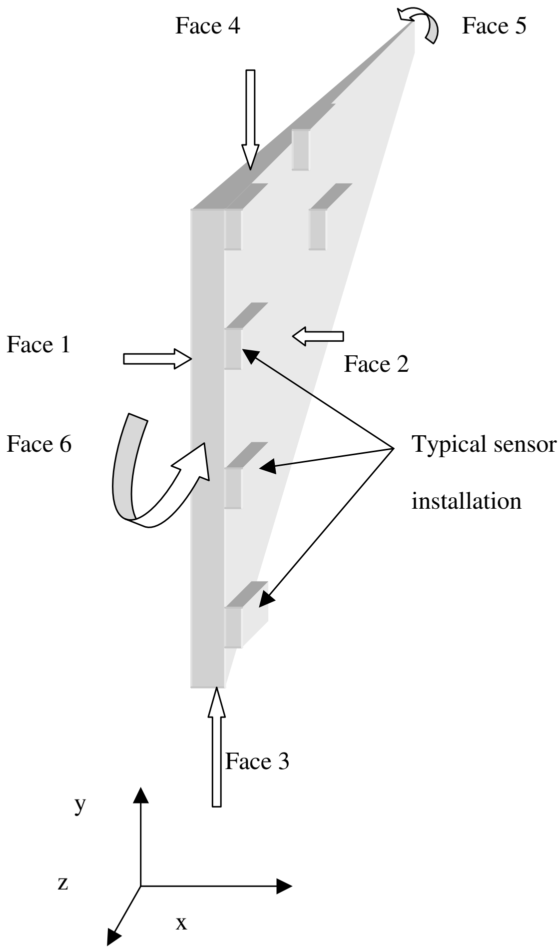

Fig. 2. The rectangular parallelepiped surface of ROI has a heat source on face 1 and the sensors on face 2 are shown placed arbitrarily where liquid helium cools to the desired operating temperature. The x-axis is chosen in the direction along the thickness of the niobium metal.

thick Nb at 50 ms time interval is 775), and steady state conditions are reached very rapidly. In this relation, α' is the thermal diffusivity of the niobium in $\left(\frac{\mathrm{cm}^2}{\mathrm{s}}\right)$, L_c, is the thickness of the niobium in (cm) and, t is time in (s).

For this steady state condition, in the absence of any source of internal heat generation inside the cavity material, the heat transport equation in the cavity is described by

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0 \tag{1}$$

2.3. Boundary conditions

The boundary conditions on each of the six faces are described with respect to the faces identified in Fig. 2.