QUENCH DYNAMICS IN SRF CAVITIES*

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Abstract

Quench is a fundamental process in SRF technology, limiting the maximum accelerating gradient of an SRF cavity. Better understanding of its nature provides us with time-dependent variables like temperature, normal zone radius, energy, etc. Some of them cannot be measured by existing experimental setup. Nevertheless, these physical quantities are essential for understanding of quench process and for future improvements of the cavity performance. We present here our current algorithm to solve the system of nonlinear equations describing the quench process and discuss the obtained results.

INTRODUCTION

Superconducting radio-frequency (SRF) cavities is the leading technology for future linear accelerators[1]. A quench often is the limiting factor of a cavity performance. It is widely assumed that quench is caused by some abnormality: either a surface defect or a localized material contamination near RF surface of the cavity. To study the nature of this defect we put forward a quench process model, which can be implemented in terms of the nonlinear equations.

Quench is usually caused by some defect on the inner surface of the cavity. The surrounding area resistance is significantly higher (due to various factors) than the resistance of the superconducting niobium. As a result, this area becomes normal conductor at the temperature lower than critical temperature of niobium and starts heating while dissipating RF energy. Surrounding niobium, heated up to its critical temperature, becomes normal conductor as well. Thus normal zone continue to expand.

We need to solve the system of nonlinear equations, which describes stored energy dissipation, caused by Joule heating of normal conducting niobium, and heat transfer in both superconducting and normal conducting niobium. In this paper we discuss modeling results, problems arisen, and prospective computational techniques.

QUENCH MODEL DESCRIPTION

In our model quench is a heat propagation in niobium with a heat source is due to dissipating of electromagnetic field energy, stored in the cavity. Thermal conductivity, heat capacity, and bulk resistance of the material in this case are strongly and nonlinearly dependent on temperature [2][3][4]. Thus, this problem could be solved only by numerical methods. We assume the quench to arise from a defect, which is normal conducting at any temperature. Its bulk resistance at some temperature is supposed to be equal to normal conductor extrapolated resistance at the same temperature. Superconducting niobium residual resistance is negligibly small compared to normal conducting niobium resistance. If the temperature increases to 9.22 K, niobium surface resistance steps up from zero to several mOhm. [1] Normal conducting area absorbs the RF energy and heats up. We can use a uniform field approximation to solve our problem, provided that (a) the cavity radius of curvature is much greater than linear dimensions of the area under study and (b) the time period of RF wave is much smaller than the quench process characteristic time. Normally, a quench origin is located near the weld of the cavity, so the peak magnetic field can be used as a uniform field value.

Stored energy in the cavity

$$W = \frac{1}{2}\mu_0 \int\limits_V |\mathbf{H}|^2 dv. \qquad (1)$$

Using uniform field approximation

$$W = \frac{1}{2}\mu_0 \overline{|\mathbf{H}|^2} K_v, \qquad (2)$$

where K_v is a volume constant. Thus, the loss power

$$P = \frac{dW}{dt} = \frac{1}{2}\mu_0 K_v \frac{d(\overline{|\mathbf{H}|^2})}{dt}. \qquad (3)$$

On the other hand loss power can be defined through the average magnetic field and the urface resistance as follows:

$$P = \frac{1}{2}\overline{|\mathbf{H}|^2} \int\limits_S R_s ds. \qquad (4)$$

Thus,

$$\mu_0 K_v \frac{d(\overline{|\mathbf{H}|^2})}{dt} = \overline{|\mathbf{H}|^2} \int\limits_S R_s ds. \qquad (5)$$

Surface resistance is a function of bulk resistance and frequency and is equal to

$$R_s = \sqrt{\rho \pi f \mu_0}. \qquad (6)$$

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[1] In numerical computing an instability often follows any physically incorrect discontinuity. Thus, one has to smooth over this discontinuity on a finite time interval.

Temperature is defined by the normal heat transfer equation with variable coefficients:

$$\mathrm{div}(\kappa(T)\cdot\ \mathrm{grad}(T)) + Q(T) = C_p(T)\rho(T)\frac{\partial T}{\partial t}, \quad (7)$$

where $Q(T)$ is power, dissipating in a cubic unit. Penetration depth of the RF field

$$\delta = \sqrt{\frac{\rho}{\pi f \mu_0}}, \quad (8)$$

which is about a micrometer. Thus, heat is generated only in a layer of thickness δ.

By solving this system of equations one can obtain time-dependent temperature and magnetic field.

The problem is two-dimensional due to the circular symmetry on the metal surface: one axis is a radius-vector on the surface, another axis is normal to the surface.

ONE-DIMENSIONAL MODEL

All the modeling was implemented in FlexPDE programming environment [5]. One-dimensional approximation assumes the temperature gradient of the niobium plate to be zero along the normal axis. Thus, the only dimension left is the radius-vector on the plate surface. Heat capacity in this case is normalized to the cavity walls thickness d = 2.8 mm.

This model is inconsistent with experimental results, because the time constant of the modeled process (Fig. 1) is several times smaller than the time constant of the real experiment. Fig. 2 depicts the experimental data of RF field decay.

Temperature (Fig. 3) and normal zone radius values seem to be in agreement with the experiments [6].

TWO-DIMENSIONAL MODEL

Solving the given system of nonlinear equations in two dimensions requires great computational power, because physical skin layer of the RF field (micrometers) is much smaller than the thickness of the cavity wall (2.8 mm). As a result we need to use a very fine mesh size, which in turn requires a very small time step to make the numerical scheme stable.

We vary computational skin layer, i.e. the thickness of the layer which is heated up by RF electromagnetic field in the cavity. We assume that increasing the actual physical skin layer to a certain extent has a weak influence on the physics of the process. Also, a scaling law can be derived from dependence of RF signal amplitude on different cavity-thickness/skin-layer ratio. It can help us to calculate the true values by scaling the data obtained in the solution of the problem with computational skin layer few orders of magnitude thicker than the actual one.

In Fig. 4 one can observe pseudo-skin calculation data approaching the experimental data for field decay plot, where H is RF magnetic field amplitude. In Fig. 5, as the cavity-thickness/skin-layer ratio is increasing, field amplitude is monotonously approaching experimental value at the fixed time point. We need to collect more model data to extrapolate correctly field decay — ratio dependence and to calculate scaling coefficient. However, processing of even small ratio of 50-120 requires several days of calculation.

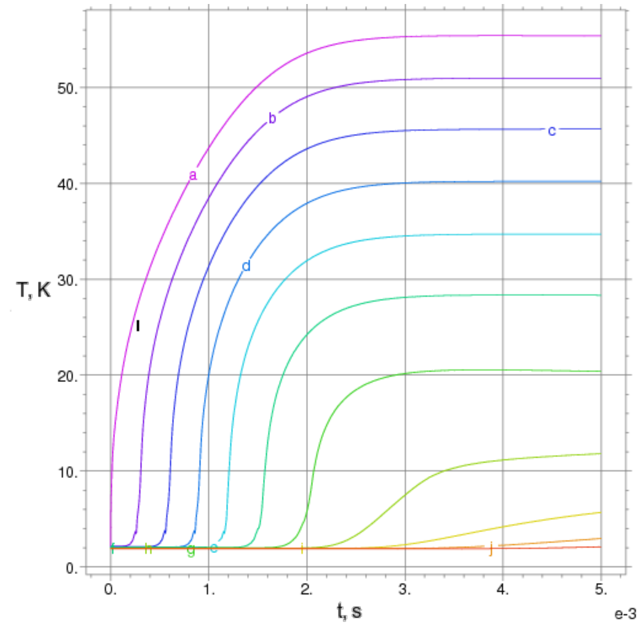

Figure 1: 1d time-dependent RF energy stored in the cavity.

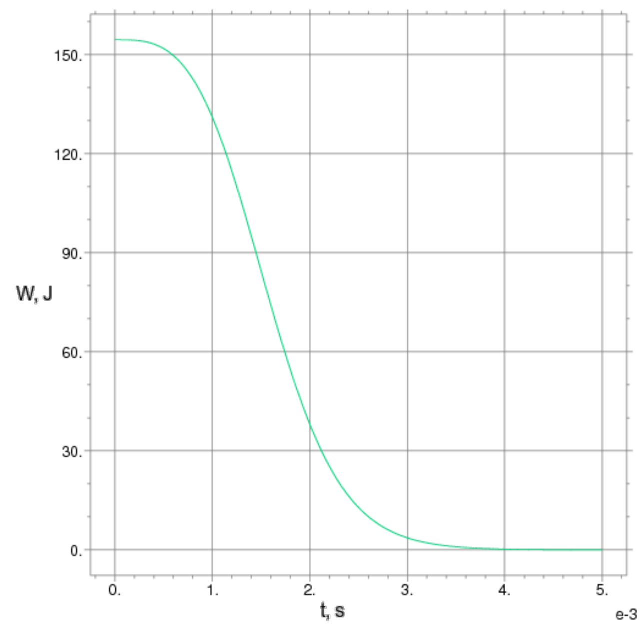

Figure 2: Exeprimental RF energy dissipation data as measured at Fermilab VTS [7].

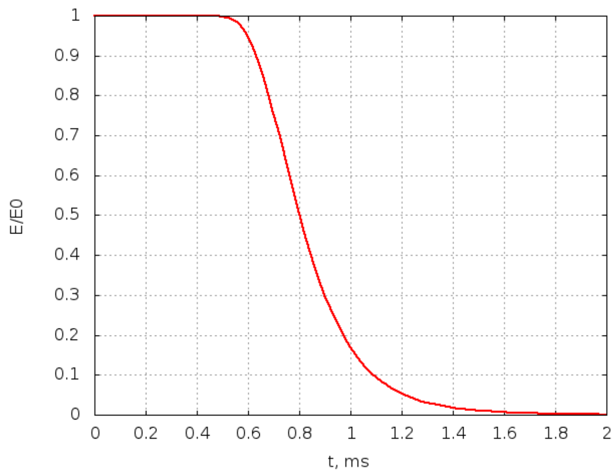

Figure 3: 1d time-dependent temperature of the niobium plate with 1 cm step.

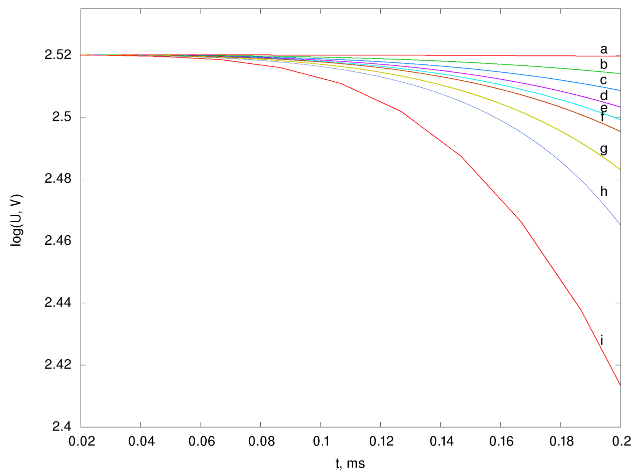

Figure 4: 2d field decay plots for ratio (a) 1, (b) 10, (c) 15, (d) 20, (e) 30,(f) 40, (g) 50, (h) 80, (i) 120 and (j) experimental data.

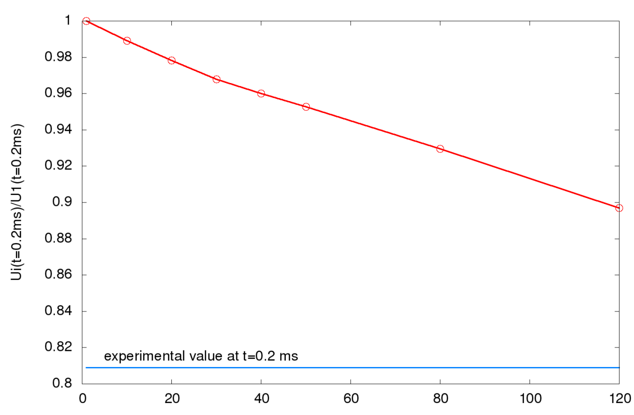

Figure 5: 2d Relative amplitude at t=0.2 ms versus cavity-thickness/skin-layer ratio.

CONCLUSION

We developed both one- and two-dimensional modeling of quench process by solving numerically the heat transfer equation with a heat source is due to dissipated RF energy. The one-dimensional approximation of the quench process was proven to be inadequate and inconsistent with experimental data, though it is of interest too. The two-dimensional model calculation with different computational skin layers seems to produce a scaling and converge to the real experimental data. Though it is highly unstable and requires great computational power. An alternative technique is to describe the heat source as a boundary condition. Further research can help us to implement this particular method.

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