SIMULATION OF QUENCH DYNAMICS IN SRF CAVITIES UNDER PULSED OPERATION*

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Abstract

As has been well verified both theoretically and experimentally in steady state, the thermal stability of SRF (superconducting radio-frequency) cavities strongly depends on the material properties of niobium such as RRR (residual resistivity ratio) and the presence of material defects on the surface. Recently, SRF technology has been chosen for pulsed machines such as the Tesla Test Facility (TTF), the Spallation Neutron Source (SNS), and the European Spallation Source (ESS). In order to guide the selection of operational limits and materials, an understanding of dynamics of quenching in pulsed operation is important. For this purpose, a universal thermal stability analysis algorithm is set up. With the help of 3D FEM codes, a series of transient, non-linear and self-correlated analyses are carried out. This scheme may be used for any stability analysis in SRF cavities with arbitrary conditions such as 3D structure, varying material properties, transient behavior, non-linear material properties, etc.

INTRODUCTION

Thermal breakdown in SRF cavities is one of the major factors that limit the maximum achievable accelerating field and accordingly the operating point. Considerable effort has been made to better understand this topic both theoretically and experimentally. The effects of related parameters on the thermal stability have been systematically quantified [1]-[6].

As the interests for SRF technology in pulsed machines increase, there is need to have more understanding of the dynamics of thermal stability in connection with all the parameters, which include 3D structure, varying material properties, non-linearity of material properties, transient behaviors, realistic thermal loads along with the rf surface dissipations, etc.

In this paper the simulation algorithm of dynamic thermal stability, taking into account general relations among the parameters, and some examples by taking the realistic situation are briefly shown.

PHYSICAL PARAMETERS AND THEIR RELATIONS TO THERMAL STABILITY

The general relations of parameters that determine the thermal stability in SRF cavities are shown in Fig.1. As can be seen, many parameters are correlated and some parameters such as RRR (residual resistivity ratio), Kapitza resistance, etc, should have experimental verification. As an example, the power dissipation per unit area due to the surface rf current is expressed via $P = \frac{1}{2} R_S H^2$,

where, *Rs* is the surface resistance in Ohm, and *H* is the magnetic field strength on surface in A/m. The surface resistance is, however, a strong function of temperature as seen in Fig.2 and the temperature is actually the final determining factor of the thermal stability, results from all relations of parameters such as RRR. RRR is one of the most importance material properties for the thermal stability. The thermal conductivity *k* versus temperature data for various RRR's in Fig.3 are taken from [1], [3], and [4], in which the RRR values from RRR1 through RRR8 are 40, 270, 525, 90, 250, 400, 140, and 840 respectively. The *k* is known to have an approximate relation with RRR, which is *k*=RRR/4 at 4.2 K. But it is difficult to apply the same rule to *k*'s of the higher temperature that are actually more important for the thermal stability. The k dependence on RRR should be carefully checked experimentally.

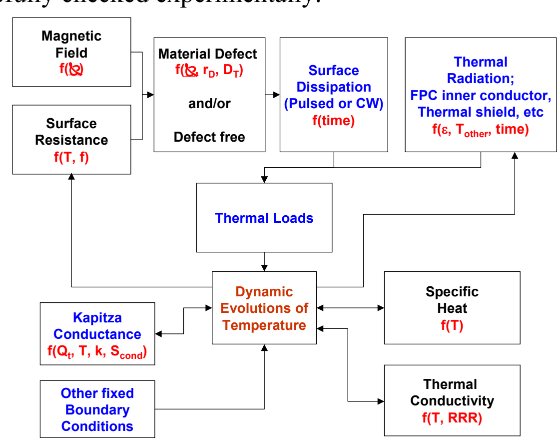

Figure 1: Parameter relations for the thermal stability. (f: function of; $\underline{\nabla}$: location; r_D: defect radius; D_T: defect type; ε: emissivity; T_{other}: temperatures of other structure; RRR: residual resisvity ratio; Q_t: thermal flux; f: frequency; k: thermal conductivity; S_{cond}: surface condition; T: niobium temperature which is also a function of location)

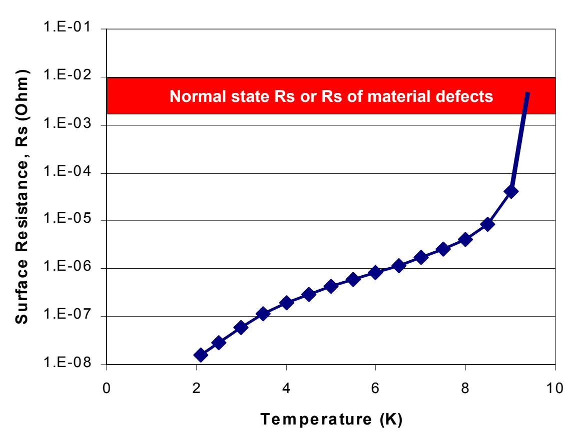

Figure 2: Surface resistance of Nb at 805 MHz. 10 nΩ of residual resistance is assumed.

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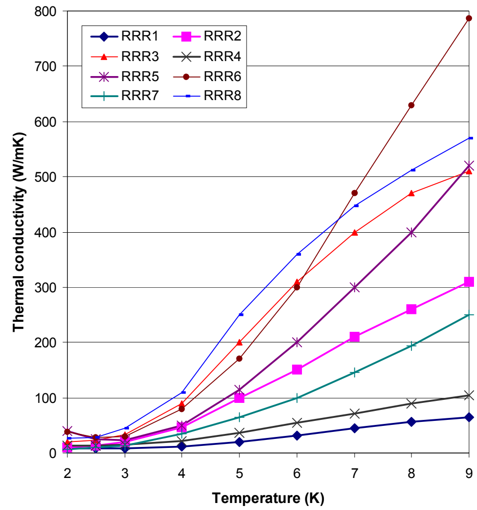

Figure 3: Thermal conductivities for various RRR's

Kapitza resistance is a function of many factors, one of which is the specific surface condition followed by different surface treatments [6]. The simulations shown in the following used the Kapitza resistance as expressed in [7]. The specific heat is a sort of pure thermodynamic property, which is taken from [8].

QUENCH DYNAMICS: EXAMPLES

By taking into account all the relations explained in Fig.1 and with the help of a 3D FEM code (ANSYS) incorporated with script programs correspond to blocks and arrows in Fig.1, a series of algorithms for 3D, transient, non-linear, self-correlated and coupled field problem has been set up. For benchmarking, comparisons have been done with steady state results [1] and show good agreement.

A series of systematic simulations have been carried out in terms of Nb thickness, *k*, magnetic field strength, etc, which gives proper guidance not only for the material selection and the thermal design, but also for operation regimes. The details of these analyses are planned to be reported in a separate paper.

One example introduced in this paper contains an explanation regarding quenching dynamics. The typical temperature evolutions in the thermally stable system are shown in Fig.4. The test sample used here is 2 mm thick niobium

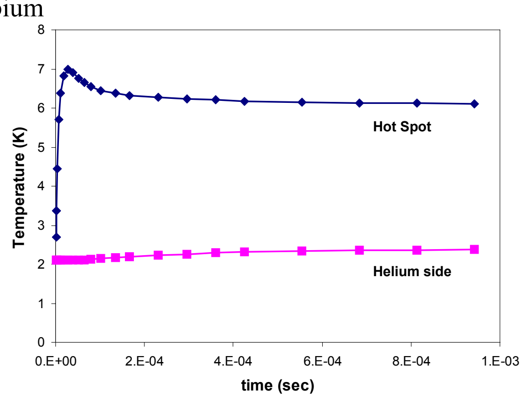

Figure 4: Typical example of the temperature evolution when a SRF cavity system is thermally stable (stabilized).

having RRR2 as in Fig.4 on which a 70 mT field was applied and a material defect corresponding to 0.05 W was introduced. Fig. 5 and 6 show the temperature evolutions and the corresponding snapshots when a system is thermally unstable. In this example, a material defect of 0.1 W is used under the same conditions. Though the time scale of quenching development depends especially on the field and *k*, quenching develops with the following sequences.

Phase I; Surroundings are still keeping SC state. Hot region is very small. Thermal conduction is weak. The main heat dissipation areas are only the places very near the material defect.

Phase II; Only small adjacent regions near the material defect becomes normal state. Hot spot size is still small, so the thermal conduction (diffusion) is very weak, which results in the steep temperature increment.

Phase III; Surroundings become hotter but still keep SC state except the hot spot at the material defect and small adjacent region. Main quench propagation does not start yet. Thermal conduction is better than region II, that's why there's some decrement in the hot spot temperature. The duration of this meta-stable phase is a function of *k*, defect size, magnetic field strength, etc. A certain combination of parameters could sustain this phase during a long pulse or CW.

Phase IV; Normal regions are expanding. Growth rate of surface dissipation is much larger than that of thermal diffusion to the bulk Nb and eventually to helium. Quenching propagates.

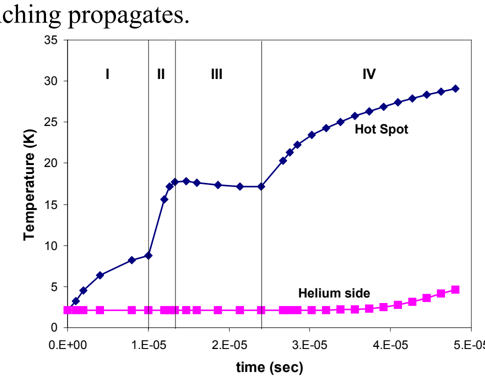

Figure 5: Typical example of the temperature evolution when a SRF cavity system is not thermally stable (thickness; 2mm, 70 mT, RRR2 in Fig. 3, 0.1W material defect).

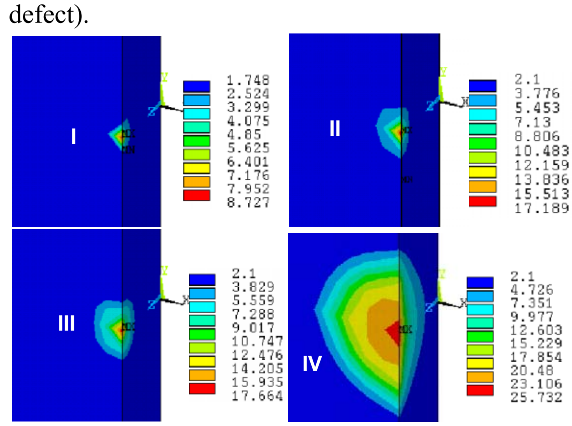

Figure 6: Snapshots of each phase in Fig.5.

The following example is for a cavity end group at the side of coaxial fundamental power coupler where low RRR materials are used and no active cooling exists. The schematics and the surface magnetic field strength along the inner surface of an SNS medium beta cavity are shown in Fig.7. This example contains several special features such as thermal radiation from the inner conductor of the power coupler, varying material properties of niobium, different boundary conditions, full 3D structure, and pulsed operation. Fig.8 is an example where a defect equivalent to 0.1 W is introduced 5 mm from the cell end in order to have clear pictures at the nominal operating condition of SNS. Since the magnetic field strength is small, the quenching propagation is quite slow as can be seen in Fig.8. It is noticeable that the operation for certain duration could be done even after main quenching, but a full recovery is not accomplished during the gap between pulses in this example. The material selections and preparations, surface conditions of niobium and inner conductor, operation conditions such as pulse length, repetition rate, rf power through coupler, etc was found through a series of systematic analyses using this simulation method.

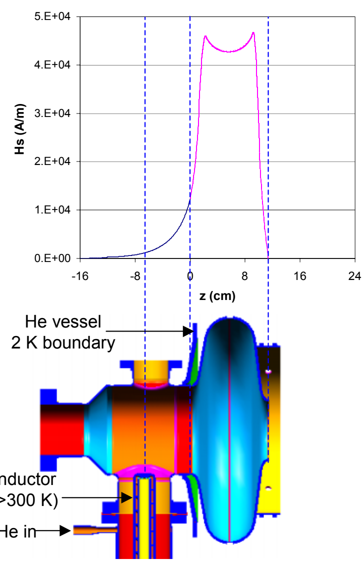

Figure 7: Surface magnetic field along the end group and end cell of the SNS medium beta cavity.

SUMMARY

- General algorithms for thermal stability analysis have been set up.
- Benchmarking showed good agreement with the steady state calculation. A series of systematic analysis has been done, which guide the operational limits and material selection. (to be reported in a separate paper)
- Dynamics of the thermal stability are explained.
- Application of the simulation algorithm to the end-group of the SRF cavity is introduced.
- This scheme may be used for any stability analysis in SRF cavities with arbitrary conditions such as 3D structure, varying material properties, transient behavior, non-linear material properties, etc.

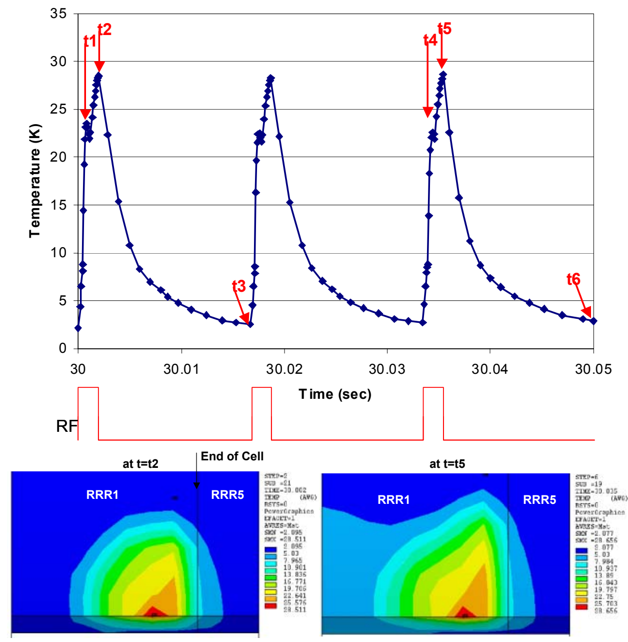

Figure 8: Hot spot temperature evolution through time in 1.5 ms, 60 Hz pulsed operation. A material defect equivalent to 0.1 W is introduced at the distance of 5 mm from the end cell.

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