PERFORMANCE DEGRADATION OF A SUPERCONDUCTING CAVITY QUENCHING IN MAGNETIC FIELD*

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Abstract

Performance degradation of superconducting RF (SRF) cavities induced by magnetic field trapped in its walls is fairly well understood phenomenon; nevertheless, criteria for setting requirements for acceptable level of magnetic field generated inside cryomodules after cooling down have not been well established. Superconducting walls of cavities in cryomodules protect the cavities from this component of the magnetic field unless thermal breakdown (quench) happens; magnetic flux penetrates inside the cavity through normally conducting opening generated during the quench and becomes trapped in the walls after it cools down again. The amount of the trapped magnetic flux depends on the size of normally conducting zone developed in walls of the cavity during quenching; it can be evaluated by modelling quench propagation (QP). In this study, we compared performance degradation of several cavities of different shapes and frequencies predicted by the QP modelling with the data obtained by direct RF measurements; the magnetic field was generated by superconducting coils mounted in the vicinity of quenching cavities. A criterion is suggested for establishing a requirement for the maximum magnetic field generated inside cryomodules; it can be used for any RF structure and magnetic system.

INTRODUCTION

To reduce beam loss in high power superconducting linear RF accelerators of ions (linacs), focusing period in the beam line must be sufficiently short. Especially this is true for the sections of the accelerators where charged particles move relatively slow ($\beta \ll 1$). In this case, having focusing lenses inside cryomodules provides sensible advantages; this approach was used in many existing accelerators and those in development [1].

Power loss in superconducting RF cavities is a major source of heat load in the cryomodules. As this power loss can be affected by magnetic field trapped in superconducting walls of the cavities, the cavities must be thoroughly magnetically shielded, which can be a challenge if the allowed field is low [2]. Diamagnetism of superconducting niobium can be naturally employed to shield the cavities. This protection is broken though when the cavity quenches as part of its surface warms up above the superconductivity threshold. During quenching, magnetic flux penetrates inside the cavity through normally conducting opening and becomes trapped in the cavity wall after superconductivity is restored. Experimental studies of the flux trapping show that, with moderately high magnetic field, up to 100% of the magnetic flux crossing the cavity wall can be trapped [3]. The fraction of the trapped flux depends on the purity, texture, and the treatment history of niobium [4].

The main motivation for this study was an attempt to formulate practical criterion that could be used for setting limits on the magnetic field generated inside cryomodules of linacs and verification of this criterion by direct measurements using superconducting RF structures.

TRAPPED FLUX CRITERION

Performance degradation of an RF cavity is manifested by the drop of its quality factor. Trapped magnetic flux that reduces the unloaded quality factor Q_0 to the level $Q_1=\eta\cdot Q_0$ can be found using the next expression [5]:

$$\Phi_{tr} = \frac{2\mu_0\Phi_0}{R_s\xi_0^2}\cdot\frac{fV}{\Lambda Q_0}\cdot\frac{1-\eta}{\eta}. \qquad (1)$$

In this expression $\mu_0=4\pi\cdot10^{-7}$ *H/m* is the permeability of empty space, $\Phi_0=2\cdot10^{-15}$ *Wb* is the magnetic flux quant, $\xi_0=3.9\cdot10^{-8}$ *m* is the coherence length in *Nb*, *f* is the frequency of the cavity, R_s is the surface resistance of *Nb* at this frequency, *V* is the volume of the cavity, and Λ is a dimensionless parameter that defines magnetic energy density at the location of the quench relative to the average energy density in the cavity.

The first multiplier in (1) is fully defined by the properties of superconducting material. The second one is cavity-specific with Λ depending on quench location. The last multiplier relates the acceptable degree of degradation η with corresponding level of the trapped flux: if $\eta = 1$, no trapped flux is allowed; as $\eta \to 0$, more flux can be tolerated. Consequences of smaller quality factor after quench can be assessed at different quenching scenarios, and corresponding choice of η can be made taking into account available cooling power and distribution of RF magnetic field (or the energy density factor Λ) and expected static magnetic field on the cavity surface.

The amount of the trapped magnetic flux is defined by the size of a normally-conducting opening in cavity wall during quenching; it can be found by modelling propagation of the quench.

QUENCH PROPAGATION

The surface density *p* of RF power loss in normally conducting walls of cavities can be expressed as

$$p = \frac{2\Lambda}{\mu_0 V}\cdot W R_s\,, \qquad (2)$$

where *W* is the total energy stored in the cavity and the value of Λ is taken at the location of the quench. Then the rate of the energy dissipation in the cavity

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$$\frac{\partial W}{\partial t} = -\frac{2\Lambda}{\mu_s V}\cdot \iint W R_s ds\,, \qquad (3)$$

where the integral is taken along the normally conducting surface of the quenching cavity. To find how the temperature in the wall changes in time, this equation must be solved in the time domain simultaneously with the heat transfer equations.

In the cryogenic environment, the material properties are temperature-dependent, with some of them changing by orders of magnitude in the temperature range between 2 *K* and 300 *K*. Needed data for thermal conductivity, specific heat, and surface resistance of Nb in this temperature range can be readily found in handbooks.

The initial phase of quench propagation can be considered adiabatic, but the maximum size of the normally conducting opening in the superconducting wall of quenching cavity is defined by cooling of the cavity surface by liquid helium (LHe). Available data for the heat transfer from Nb into 2 *K* LHe mainly refer to tests made using small samples of different shapes and orientations. Graph in Fig. 1 shows accepted for this study dependence of the heat transfer coefficient *h* on the surface temperature *T* for the 2 *K* LHe; corresponding data set was compiled using several sources of information, including [6].

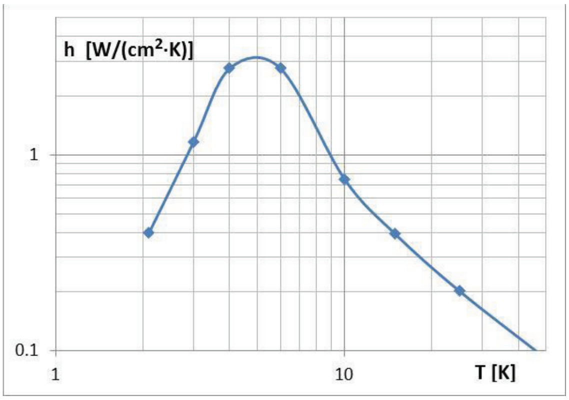

Figure 1: Heat transfer coefficient into LHe at 2 *K*.

There are several stages in the cavity quenching process [7]. First, the boundary of the normally-conducting zone ($T \approx 9.3$ *K*) propagates along the surface heated by RF current; simultaneously, more slowly, this boundary moves into the depth of the cavity wall. No magnetic field penetration occurs at this point as the outer surface of the cavity wall remains superconducting. After the boundary of the normally conducting zone reaches the outer surface of the wall, which is cooled by liquid helium, the external magnetic field starts to penetrate inside the cavity. At this point, most of the energy stored in the cavity has already dissipated in the skin layer, elevating its temperature; it can often reach and exceed the room temperature level. Next, the heat propagates along the cavity wall; the cooling process gradually makes this propagation slower and, at some point, reverses its direction. Finally, the normally conducting opening shrinks, collapsing very fast in the end. Fig. 2 illustrates this process for the case of a one-cell 1.3 GHz elliptical cavity with the initially stored energy W_0 = 14 *J* and the quench starting point corresponding to Λ = 1.5; in the figure, the radius of the normally conducting opening in the superconducting wall is shown as a function of time.

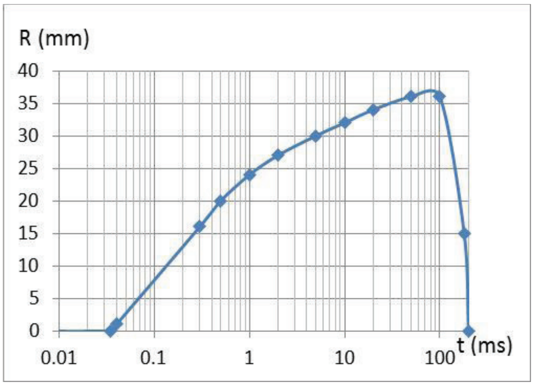

Figure 2: Radius of normally conducting opening in the superconducting wall of RF cavity: f = 1.3 *GHz*, Λ = 1.5, W_0 = 14 *J*.

As the maximum size of the normally-conducting opening in the wall of a quenching cavity becomes known, it is straightforward to find the magnetic flux that crosses this surface using appropriate magnetic modelling tool. The found flux must be compared with the allowed limit expressed by (1) to judge on the adequacy of the magnetic shielding means in the cryomodule.

The described algorithm is not restricted by the choice of a specific magnetic system or RF structure; it needs to be verified though to be accepted for practical use. This verification was made by testing several superconducting cavities in the environment of known magnetic field.

VERIFICATION TESTS

Three RF structures were tested: 325 *MHz* SSR1 spoke cavity built for PXIE test stand [8], 1.3 *GHz* one-cell elliptical Testla-type cavity [9], and 650 *MHz* one-cell elliptical cavity under study for the Project X program at FNAL [10]. The magnetic field for the tests was generated by a superconducting coil installed in the vicinity of tested RF structures in the vertical test stand (VTS) at FNAL. Position of the coil relative to the cavities in each test was chosen based on available space in the VTS and expected location of the quench. When this location was not known, resistive heaters were attached to the walls of tested cavities and activated by a pulse power supply [8] to initiate quenches.

During the tests, for several settings of current in the test coil, the unloaded (low-gradient) quality factor was measured before and after quenches. If heaters were used, quenches were initiated at the gradients close to the maximum achievable level. For each tested RF structure, the measured dependence of the quality factor on the current in the test coil was compared with corresponding prediction of the modelling.

The measured drop of the quality factor was in good agreement with the predicted degradation for each of the three tested cavities. Results of the tests made using the PXIE SSR1 cavity will be discussed in this report.

Fig. 3 shows modelling (and test) configuration for the SSR1 cavity with the test coil installed above the area that was found to be the most sensitive to the quenching in magnetic field ($\Lambda \approx 2.6$).

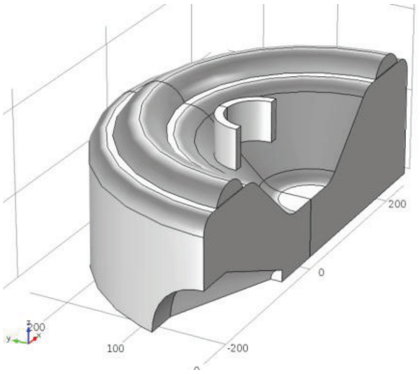

Figure 3: Test configuration with quench on the end wall of the SSR1 cavity.

Quench propagation analysis for this cavity resulted in the next expression for the maximum radius of the normally conducting opening in the superconducting wall with two parameters being the total stored energy W_0 and the energy density factor Λ [8]:

$$R_m\ [mm] = 25.5 + 9.8 \cdot \Lambda^{-1} + 0.8 \cdot W_0\ [J]. \qquad (4)$$

The total energy stored in the cavity corresponding to the effective accelerating voltage of 2 MV is 14 J; in this case, $R_m \approx 40.5\ mm$.

For the setup in Fig. 3, with 1 A current in the test coil, the magnetic flux Φ generated by the coil and crossing the inner surface of the cavity $\Phi = 6.7 \cdot 10^{-6}\ Wb$. Then, having in mind that the volume of the cavity $V = 0.0473\ m^3$, the surface resistance of RRR300 Nb $R_s = 7.4 \cdot 10^{-4}\ Ohm$, and using equation (1), one can calculate the quality factor after quench corresponding to any current in the test coil. Fig. 4 compares results of this calculation assuming 100% flux trapping with the data obtained by the measurements.

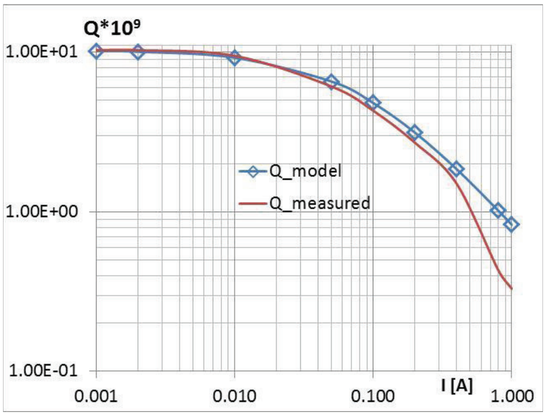

Figure 4: Calculated and measured quality factor of the SSR1 cavity quenching in magnetic field.

Curves similar to shown in Fig. 4 were built for all tested cavities; the measured behaviour of the system was fairly close to the predicted. In all three cases, it was possible to restore the initial performance of the cavity by repeated quenching at the same location in the absence of the magnetic field generated by the test coil. This restoration of cavity performance was full for moderate values of the current - up to ~0.3 A for the case in Fig. 4. The drop of the measured quality factor at higher currents in the test coil is explained by diffusion of the trapped magnetic flux out of the area which can be heated above the superconductivity threshold temperature during quench. One can fight this partial irreversibility with some increase of the RF power.

CONCLUSION

Performance degradation of superconducting RF cavities due to magnetic flux trapped in their walls during quench was investigated by modelling and direct measurements using cavities of different shapes and frequencies. The modelling could predict results of the measurements for all the cases. This degradation can be fully or partially cured by continuing quenching in the absence of the magnetic field.

No restrictions exist to applying the used method for evaluation of performance of any superconducting RF system in magnetic field of any origin.

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