

# Superconducting RF Cavity Performance Degradation after Quenching in Static Magnetic Field

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**Abstract:** In accelerating cryomodules of high-power superconducting linear accelerators, to reduce power loss in walls of RF cavities, magnetic field on the surface of the cavities must be below  $\sim 10 \mu\text{T}$  [1]. As inside magnetic focusing elements installed in the cryomodules magnetic field can be well above 6–7 T, proper magnetic shielding must be used; this complicates designs of both focusing lenses and cryomodules [2].

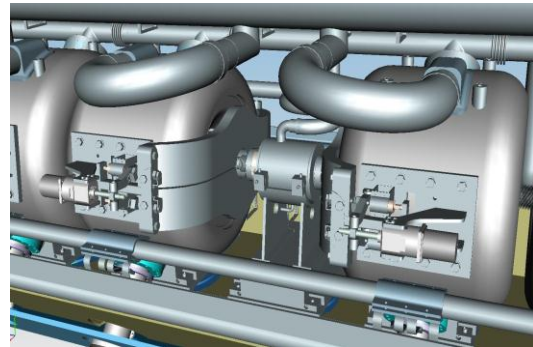
Superconducting walls of cavities, made of niobium (Nb), being diamagnetic, can serve as a natural magnetic shield, but their shielding effect is compromised by events of quenching. At quench, a part of the cavity wall becomes normally conducting, diamagnetism of this part vanishes, and magnetic field penetrates through the normally conducting opening inside the cavity. As this field remains trapped in the wall after quench, existence of a normally conducting zone associated with each trapped flux quantum results in the increase of RF power loss. In this report, a method of predicting possible degradation of cavity performance after quenching in magnetic field is described; results of corresponding modeling are compared with the measured performance of cavities experiencing quenching in static magnetic field.

**Keywords:** Superconducting cavity, quench, flux trapping.

## 1. 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 low-energy parts of the accelerators where charged particles move relatively slow. As a result, magnetic focusing elements (focusing lenses) in the beam line of the low-energy parts of linacs must be positioned inside cryomodules, which are vacuum vessels where cryogenic environment for superconducting accelerating RF cavities is created. Fig. 1 shows a part of a

cryomodule designed for PXIE test facility at FNAL [3]; here a focusing lens is placed between two spoke-type (SSR1) cavities.



**Figure 1.** Focusing lens between RF cavities in a cryomodule of a PXIE test facility at FNAL.

Power loss in superconducting RF cavities is a major source of heat influx in the cryomodules. As this power loss can be affected by magnetic field trapped in superconducting walls of the cavities, they must be thoroughly magnetically shielded. Diamagnetism of superconducting niobium can be naturally employed to shield the cavities; an obstacle on this way is cavity quenching - thermal instability in the cavity wall that causes abrupt dissipation of electro-magnetic energy stored in the cavity. During quenching, a part of cavity surface warms up above the superconductivity threshold, forming a normally-conducting opening in the superconducting wall. Magnetic field penetrates inside the cavity through this opening and becomes trapped in the cavity wall after it becomes superconducting again. Experimental studies of the flux trapping show that, with moderately high magnetic field, up to 100% of the magnetic flux that penetrates inside the cavity can be trapped [4]. The amount of magnetic flux trapped in walls of a quenching cavity depends on the level of the magnetic field inside the cryomodule and on the size of the normally conducting opening. This trapped flux increases surface resistance and, hence, the power loss; corresponding cavity performance degradation is manifested by reduced quality

factor. Quench can happen occasionally in each cavity of any linac; frequency of its occurrence cannot be neglected, unfortunately. So, practical approach to design of cryomodules shall include making an attempt to keep degradation of cavity performance after quenching under control. As a part of this attempt, understanding practical limits to the level of magnetic field at the location of superconducting cavities was a motivation for this study.

## 2. Trapped flux criterion

RF power dissipation associated with the trapped magnetic flux is defined by the level of the surface current density at the location of quench and by the surface resistance; it can be evaluated using the next expression [5].

$$P_n = (\Lambda \cdot W) / (\mu_0 \cdot V) \cdot R_s \cdot \xi_0^2 \cdot \Phi_{tr} / \Phi_0 \quad /1/$$

Here  $W$  is the energy stored in a cavity with the volume  $V$ ,  $R_s$  is surface resistance of normally conducting Nb, which depends on frequency and temperature,  $\xi_0$  is the coherent length in Nb:

$$\xi_0 = 3.9 \cdot 10^{-8} \text{ m},$$

$\Phi_{tr}$  is the value of trapped magnetic flux crossing superconducting surface of the cavity after quench,  $\Phi_0$  is the flux quant:

$$\Phi_0 = 2 \cdot 10^{-15} \text{ Wb},$$

and  $\mu_0 = 4\pi \cdot 10^{-7} \text{ H/m}$ . Also in this expression  $\Lambda$  is the energy density factor:

$$\Lambda = \mu_0 \cdot H_t^2 \cdot V / (2 \cdot W), \quad /2/$$

which is defined by a ratio of the magnetic energy density at the location of quench (proportional to the local tangential magnetic field  $H_t$ ) to the average energy density in the RF cavity. This factor only depends on the geometry of the cavity.

Surface resistance  $R_s$  can be calculated for any frequency  $f$  if the electric conductivity of the material  $\sigma$  is known:

$$R_s = (\sigma \cdot \delta)^{-1},$$

where the skin depth

$$\delta = (\pi \cdot \mu_0 \cdot f \cdot \sigma)^{-1/2}.$$

For high purity Nb with the residual resistance ratio RRR = 300, at 2 K,  $\sigma \approx 2.2 \cdot 10^9 \text{ (Ohm} \cdot \text{m)}^{-1}$ , so at 325 MHz  $R_s \approx 7.6 \cdot 10^{-4} \text{ Ohm}$ .

Using /1/, the value of the trapped magnetic flux  $\Phi_{tr}$  that reduces the unloaded quality factor of quenching cavity  $Q_0$  to the level  $Q_1 = \eta \cdot Q_0$  can be written as

$$\Phi_{tr} = 2\mu_0 \Phi_0 / (R_s \cdot \xi_0^2) \cdot f \cdot V / (\Lambda \cdot Q_0) \cdot (1 - \eta) / \eta \quad /3/$$

The first multiplier in this expression is fully defined by properties of used superconducting material, niobium in our case. The second one contains only parameters of the quenching RF cavity; of these parameters, only  $\Lambda$  changes depending on quench location. The last multiplier can be called a risk factor; it is zero if  $\eta = 1$  (that is no reduction of the quality factor is expected) and increases as  $\eta \rightarrow 0$ . Possible risks related to the change in the cavity quality factor at different quenching scenarios can be assessed, and corresponding choice of the parameter  $\eta$  can be made taking into account available cooling power in a cryomodule and distribution of RF magnetic field (or the energy density factor  $\Lambda$ ) on the cavity surface.

For 325 MHz spoke type cavities [6] built for use in accelerating cryomodules of PXIE (SSR1 cavities with  $V = 0.0473 \text{ m}^3$ ), expression /3/ can be re-written in the form:

$$\Phi_{tr} \cdot \Lambda \cdot \eta / (1 - \eta) = 6.7 \cdot 10^{-6} \text{ Wb} \quad /4/$$

With known distribution of RF field (or factor  $\Lambda$ ) inside the cavity, and accepted risk tolerance (by choosing proper  $\eta$ ), it is straightforward to use /4/ to establish a limit for the magnetic flux trapped in the walls after quench. The highest RF magnetic field for the SSR1 cavity is on the spoke, which is located inside the cylindrical body of the cavity and is shielded from the external magnetic field by superconducting walls. Because of this shielding effect and as a probability of quenching on the end wall is lower due to lower RF magnetic field, a higher risk factor can be chosen, and hence a higher trapped flux can be tolerated.

The trapped flux criterion /3/ can be applied to a cavity with any shape and any frequency. To find a value of the trapped flux  $\Phi_{tr}$  used in this expression, one needs to know the size of a normally-conducting opening in the cavity wall during quenching. This information can only be obtained by studying quench propagation.

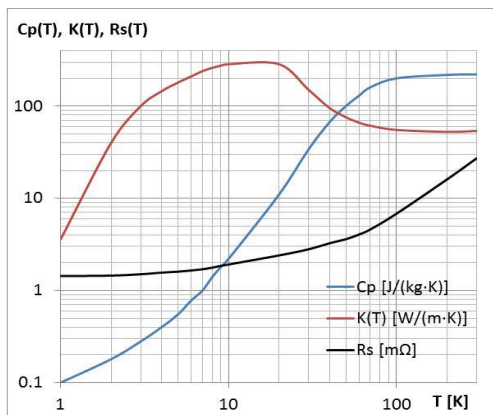
## 3. Quench propagation in walls of superconducting RF cavities

Even in the superconducting state, the surface of RF cavities dissipates some energy. Effective surface resistance strongly depends on the temperature, being several orders of magnitude lower than it is in the normally conducting state if the temperature is ~2 K and

exponentially approaching this level as the temperature is getting closer to Nb superconductivity threshold of 9.3 K. RF surface current, while passing through areas with higher surface resistance, produces more heat. If at some point the surface temperature exceeds the superconductivity threshold, corresponding area becomes normally conducting. The energy stored in the cavity dissipates around this hot spot, resulting in further growth of the temperature and the size of the normally conducting zone; this process is usually called “quench propagation”.

Heat Transfer module of COMSOIL can be used for computational analysis of quench propagation; as walls of RF cavities are usually thin, axially symmetric 2D approach is quite appropriate to start the analysis with.

All material properties in the temperature range between 2 K and 300 K are highly nonlinear. Graphs in Fig. 2 show that specific heat  $C_p$ , thermal conductivity  $K$ , and surface resistance  $R_s$  of Nb at 1.3 GHz change by orders of magnitude in this temperature range.



**Figure 2.** Specific heat  $C_p(T)$ , thermal conductivity  $K(T)$ , and surface resistance  $R_s(T)$  for RRR300 Nb.

To take into account the onset of superconductivity at 9.3 K, values of the surface resistance in Fig. 2 were modified by using a multiplier in the form of a step function with the center at the transition point of 9.3 K. Quench was initialized by increasing the temperature of a small area on the surface above this threshold value. Having in mind /2/, density of the RF power loss on the surface of the cavity with the stored energy  $W$  can be written as

$$p = \Lambda \cdot R_s \cdot 2W / (\mu_0 \cdot V). \quad /5/$$

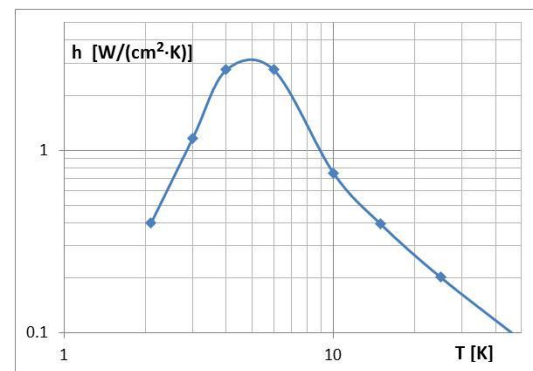
This expression takes into account that the magnitude of the surface current density is defined by the RF magnetic field near the surface ( $J_s = H_t$ ), which, in turn, depends on the energy  $W$  stored in the cavity and the energy density coefficient  $\Lambda$ . For a given energy  $W$ , on the parts of the surface with higher  $\Lambda$ , current with higher density will flow, and hence more heating will be observed. For each specific cavity, the values of the coefficient  $\Lambda$  change along the cavity surface in a unique way.

The heat defined by /5/ propagates in the cavity wall, increasing the size of the normally conducting zone, so the energy dissipation rate can be found only by integrating the power loss density over the normally conducting surface. By combining expressions /2/ and /5/, this energy dissipation can be described as

$$dW/dt = -2\Lambda / (\mu_0 \cdot V) \cdot \int W \cdot R_s \cdot dS. \quad /6/$$

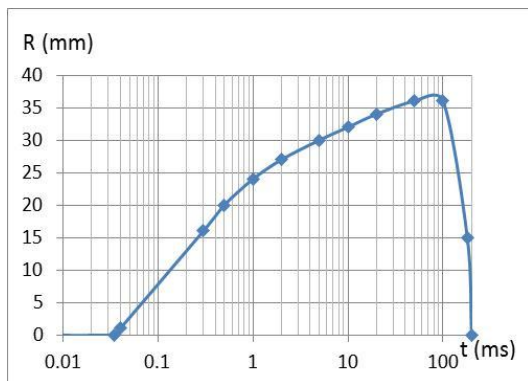
This equation must be solved in the time domain simultaneously with the heat transfer equation and the heat influx equation /5/ to find how the temperature in the cavity wall changes in time; in turn, this temperature controls all material properties and the surface cooling rate.

Although the initial phase of the quench propagation can be considered adiabatic, the cooling of the cavity surface by liquid helium defines the maximum size of the normally conducting opening in the superconducting wall of a quenching cavity. Graph in Fig. 3 shows accepted for this study dependence of the heat transfer coefficient  $h$  on the temperature of the surface  $T$  for the 2 K He; corresponding data set was compiled using different (and scattered) sources of information, including [7].



**Figure 3.** Heat transfer coefficient from the Niobium surface into LHe at 2 K.

There are several stages in the quenching process. First, the boundary of the normally-conducting zone propagates very fast along the surface with the RF current; simultaneously, more slowly, this boundary propagates into the depth of the cavity wall. No magnetic field penetration occurs at this point as the outer surface of the cavity wall is still superconducting. After the boundary of the normally conducting zone reaches the opposite side 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, and the temperature of surrounding material becomes quite high, reaching and exceeding the room temperature level of 300 K. Next, the heat propagates along the cavity wall; gradually, the cooling process makes this propagation slower. Finally, the cooling process prevails, and the normally conducting opening starts to shrink, collapsing very fast in the end of the process. Fig. 4 illustrates this process for the case of a 1.3 GHz elliptical cavity with the initially stored energy  $W_0 = 14$  J and the quench starting point corresponding to  $\Lambda = 1.5$ ; the radius of the normally conducting opening in the superconducting wall is shown here as a function of time.



**Figure 4.** Radius of a normally conducting opening in the superconducting wall of an RF cavity;  $W_0 = 14$  J,  $\Lambda = 1.5$ ,  $f = 1.3$  GHz.

Specific features of the graph in Fig. 4 can change depending on the type of the cavity, stored energy, and the location of the initial quench spot. By modeling quench propagation for a spoke type cavity designed for use in the

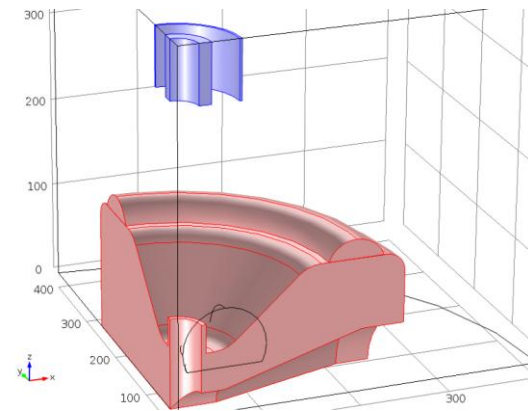
SSR1 of PXIE linac cryomodule ( $f = 325$  MHz) with different initial energies and for different locations of the quench initiation (that is different  $\Lambda$ ), we could come out with a simple empirical formula for calculation of the maximum size of the normally conducting opening:

$$R_m[\text{mm}] = 25.5 + 9.8/\Lambda + 0.8 \cdot W_0[\text{J}]. \quad /7/$$

This expression works quite well for the stored energy between 5 J and 50 J.

#### 4. Calculating trapped magnetic field

Knowing the source of magnetic field inside a cryomodule and the size and location of a normally conducting opening in the wall of a superconducting RF cavity, it is straightforward to calculate magnetic flux penetrating inside the cavity through the opening. For the case of the 325 MHz SSR1 spoke cavity and a focusing solenoid-based lens installed in the beam line of a PXIE linac [3], this calculation has been made by using the AC/DC module of COMSOL to solve static magnetic problem. Geometry for the modeling is shown in Fig. 5.

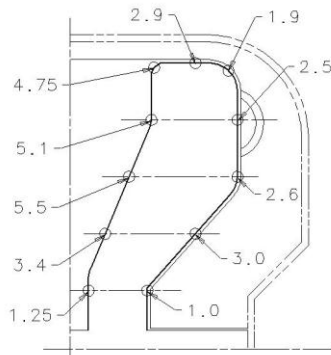


**Figure 5.** Solenoid-based focusing lens in the vicinity of the SSR1 spoke cavity.

To model superconducting properties of Nb, the surface of the cavity was assigned with the “magnetic insulation” boundary condition (red in Fig. 5). For the parts of the cavity surface separated from a quench initiation point by the distance smaller than the radius defined by /7/, this boundary condition was removed, which models the normally conducting opening in the superconducting wall of the cavity.

Focusing lens is described in [8]; it is 140 mm long and 140 mm in diameter. At 100 A, with the maximum field inside the lens of 6.5 T, it provides sufficient focusing for a proton beam in the SSR1 cryomodule of the PXIE linac.

Fig. 6 shows the values of the energy density factor calculated at several locations on the surface of the cavity where quench start points were placed during modeling. For this calculation, we used results of RF modeling made earlier by others [9].



**Figure 6.** Values of the energy density factors  $\Lambda$  on the surface of the SSR1 (325 MHz) spoke cavity.

Performing direct calculation of the magnetic flux that crosses the “open” boundary in both directions for every quench starting point in Fig. 6 and using the trapped flux criterion allows pinpointing the most sensitive point: it is located on the side wall of the cavity at the distance  $\sim 150$  mm from the center (the point in Fig. 6 with  $\Lambda = 2.6$ ). For the nominal current in the focusing lens, at this point we find

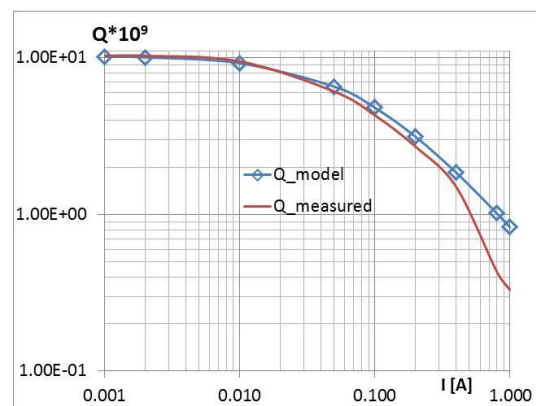
$$\Phi_{tr} = 2.46 \cdot 10^{-6} \text{ Wb.}$$

According to [4], this value of the trapped flux meets the trapped flux criterion with the risk factor  $(1-\eta)/\eta = 0.955$  or the quality factor degradation factor  $\eta = 0.51$ . This means that, after quenching at the point on the surface of the end wall of the SSR1 cavity with  $\Lambda = 2.6$ , the quality factor of the cavity will be twice as low, and corresponding power loss in the cavity will be twice as high. This increase in the heating power, which corresponds to  $\sim 10\%$  of total heating in the PXIE SSR1 cryomodule with eight cavities, can be readily handled by the cryogenic system of the PXIE facility.

## 5. Trapped flux criterion verification tests

Practical importance of the trapped flux criterion is that by using the expression [3] for any configuration of a cryomodule with any magnetic focusing element and any superconducting cavity installed inside it is straightforward to evaluate degradation of the cavity performance after quenching. Potentially this can result in significant relaxation of efforts towards shielding the cavity from the magnetic field generated inside cryomodules.

This practical importance forced us to set several tests with the goal to verify results we obtained by modeling. In these tests, a coil generating magnetic field was placed at different locations near the surface of superconducting cavities in a vertical test cryostat used for SRF cavity acceptance tests. In each test, quench was initiated at a desired spot on the cavity surface by using a spot heater attached to the wall; the cavity quality factor was measured before and after quenching at different levels of magnetic field, which was set by changing the current in the coil. As parameters and the position of the test coil relative to each of the tested cavities were known, magnetic flux trapping modeling could readily be made; the modeling results were compared with the measurements (e.g. see [10]). Fig. 7 illustrates the comparison for the case of the initial quench spot located on the outer surface of the SSR1 spoke cavity with the energy density coefficient  $\Lambda = 2.6$  (Fig. 6).



**Figure 7.** The modeled and measured quality factor after quenching in magnetic field.

Similar comparison was made for several different cavities of the SSR1 spoke type with the quench initiation spot located inside the

spoke (point with  $\Lambda = 5.5$  in Fig. 6) and in the transition zone (point with  $\Lambda = 4.75$  in Fig. 6). Cavities with different frequency were also used for similar tests [10]. For all cases, quench propagation and flux trapping modeling predicted degradation of performance of the cavities which was close to what was observed during testing.

## 6. Conclusions

Relatively simple and straightforward modeling made using COMSOL's AC/DC and Heat Transfer modules allowed us to understand underlying physics of performance degradation of superconducting cavities after quenching in magnetic field. Several simplifications were made. The first one was using a 2D axially symmetric geometry for quench propagation study with the energy density factor  $\Lambda$  constant over the surface of the normally-conducting opening in superconducting wall. More general approach would be using 3D geometry instead with the energy density factor being a function of a position on the surface. As this approach will definitely result in a more complicated shape of the normal-conducting opening in cavity wall, a way to assign proper boundary conditions for the flux trapping study must be found.

Another simplification of the model was assuming uniform RF power loss density in the normally conducting opening. Making it a function of a position on the surface seems to be a natural improvement. Using RF model as a part of a multiphysics problem may be a right way to go, although a complexity of the problem must be weighed against potential gains.

As the size of the normal conducting opening in the wall of a quenching cavity changes in the presence of external static magnetic field, eddy currents on the cavity surface will add to the heating by the RF currents. This new physics can make the modeling significantly more complicated. In the case we analyzed, the energy associated with this additional heating is orders of magnitude smaller than the energy stored in the cavity, so this process can be gladly omitted.

As several high current superconducting linacs are under intensive study now for use in different areas of science and industry, with many of them requiring high degree of reliability (e.g. Accelerator Driven Systems), we hope that

results of this work can be applied to designs of corresponding cryomodules.

## 7. References

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