INFLUENCE OF FOREIGN PARTICLES ON THE QUALITY FACTOR OF SUPERCONDUCTING CAVITIES*

Valery Shemelin#, Georg Hoffstaetter
Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE), Ithaca, NY 14853

Abstract
The quality factor of superconducting (SC) cavities of the Cornell Energy Recovery Linac (ERL) Injector measured in its horizontal cryostat appears systematically lower than in vertical tests. Furthermore, this lower value of the Q factor is scattered in a range of about ±50%. A similar Q degradation has been observed in many accelerators. Here, an explanation of these effects is presented taking into account contamination of the cavities by microscopic particles of ferrite used in the higher order mode (HOM) loads and other particles present in the vicinity of cavities during assembly of the horizontal cryostat. The average Q degradation and the scatter of Q values are used to estimate the size and the number of contaminants per cavity. We also analyze, which materials have relevant contaminants.

INTRODUCTION

Assembly of the SC niobium injector cavities [1] of the Cornell ERL [2] proceeds in a Clean Room of class 100, i.e. the number of particles of size 0.5 μm or larger permitted per cubic foot of air is 100. One cannot avoid all foreign particles in the cavity volume and some particles will settle down on the cavity walls. However, a class 100 Clean Room seems adequate because in most of the experiments the values of the Q factor are close to theoretical values.

In the ERL Injector Cavities a degradation of Q has appeared three times after successful tests in a vertical test cryostat: once in a horizontal test cryomodule (HTC) and twice in the Injector Cryomodule (ICM) incorporating the whole injector string of 5 cavities with their couplers and 6 HOM loads. The first observation of a low Q was in the HTC [3] when the cavity intrinsic quality factor of $\approx 1.5\times10^9$ was measured at 1.8 K, about one order of magnitude below the expected value. One cavity only was tested in the HTC but this was a "fully dressed" cavity with two HOM loads and two symmetric input couplers. In this case, a contamination of the cavity occurred when two ferrite tiles fell off and broke into pieces during cool down; as revealed after opening the HTC. More attentive study of the surfaces of survived tiles detected microscopic cracks that can be a starting point for further contamination or at least of dust development.

Following the full system test of a single cavity HTC, the full ERL injector SRF cryomodule has been fabricated and assembled. The broken tiles in the damaged HOM load were replaced by tiles of the same size but made of one of two other RF absorbing materials used in the loads [4]. However, all 5 cavities also have shown intrinsic quality factors below 10^{10} at 2 K even at low fields [5]. Two measurements of the effective Q of all 5 cavities operated together, spaced in time by several months, showed a further reduction in the quality factors. After deflection of the beam showed that absorber tiles charge up at low temperatures [6], the absorbers were further altered.

The absorbing tiles in the HOM load are placed on two sides of a plate; one side is faced to the axis of the beam pipe, the other side to bellows on the outer wall, see Fig. 1 (top).

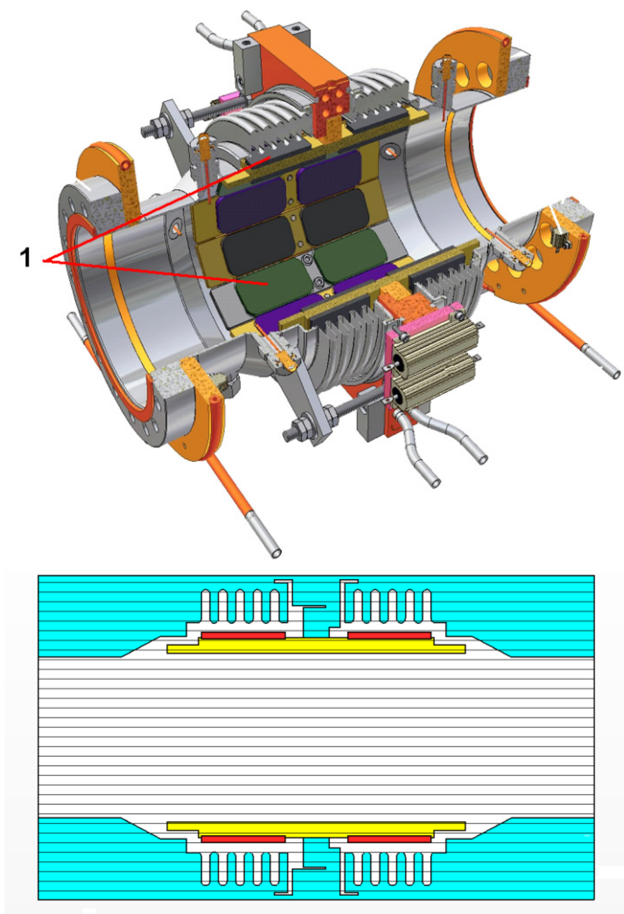

Figure 1: HOM load. Top: 1 – absorbing tiles on both sides of plate. Bottom: MWS model of the load without inner tiles.

In the latest, second cool down of the ICM [7], to prevent charging, the tiles of absorbers were left on the outer side of the plates only, see Fig. 1 (bottom). Extreme precautions were taken to clean cavities, HOM loads, and other components, more accurate measurements of Q of each cavity were done: in the vertical and horizontal (in the ICM) tests, see Table 1.

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#vs65@cornell.edu

The quality of the beam improved and no more charging up has been detected. The values of Q also increased, but the Q factors of the cavities were still lower than in the vertical test. However, no further degradation of Q has been observed.

Table 1. Quality factor of the cavities at 6 MV/m in the vertical cryostat, and after assembly in the ICM.

Cavity number	1	2	3	4	5
$Q_V/10^{10}$, (vertical)	1.7	1.7	1.7	1.6	1.7
$Q_H/10^{10}$, (in the ICM)	0.7	0.6	0.52	1.2	0.75
Q_V/Q_H, (degradation of Q)	2.4	2.8	3.3	1.3	2.3

It has been suggested that microscopic particulates of ferrite and/or other materials can degrade the Q factor. In this case, the values of measured Qs as well as their scatter could be explained. It is worth pointing out that especially close location of the HOM loads to the cavities to make the whole string shorter makes also easier a transport of particles from the loads to the cavities.

STATISTICS OF PARTICLES ON THE SURFACE

Quantity and size distribution of particles on the niobium surface will not correspond to that in air. The cleanness of the surface has its history and one of the last operations in the surface preparation is High Pressure Rinsing (HPR) by deionized water with a pressure of about 1000 psi. When the process of HPR after several hours is stabilized, one can still find some particles in the outgoing water with help of special counters. One of results obtained with such a counter is shown in Fig. 2.

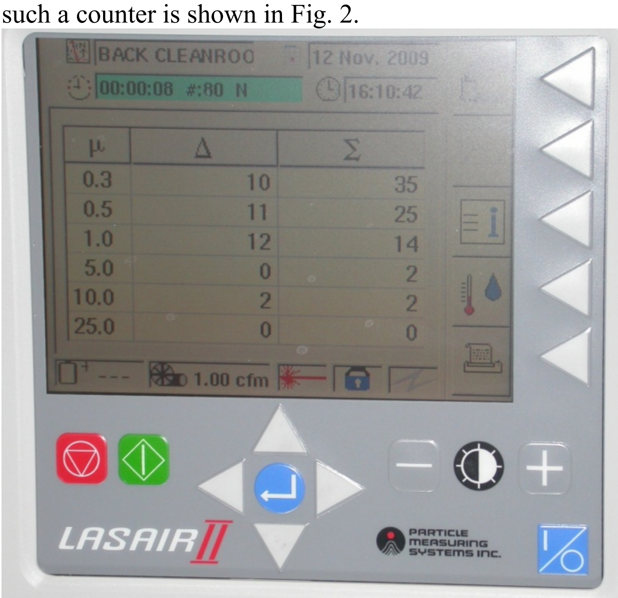

Figure 2: Count of particles in the outgoing water.

Of course, absence of particles about 5 micrometers big in Fig. 2 is due to poor statistics. On the other hand it is quite reliable that the upper limit of sizes is somewhere between 5 and 25 microns.

FERRITE PARTICLES IN THE EQUATOR AREA

Maximal RF losses in a ferrite particle can happen if this particle is in the maximal RF magnetic field, i.e. near the cavity equator. To calculate these losses, a CLANS [8] model of the injector cavity was used with a small ring with a semicircle cross-section filled with the ferrite as indicated in Fig. 3.

For the parameters of the ferrite TT2-111R it was checked in the CLANS simulation that losses are proportional to the volume. The diameter of this semicircle was changed from 0.15 to 0.3 mm. One can suppose that for a separate particle losses are also proportional to its volume.

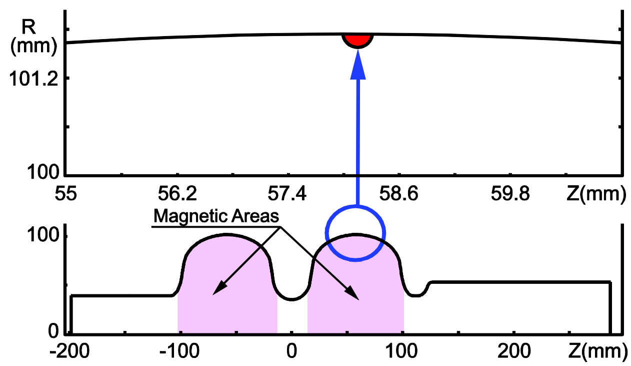

Figure 3: Geometry of the injector cavity with a lossy ring.

Properties of ferrite TT2-111R and of some other material were measured at a cryogenic (77 K) and at the room temperature in a wide range of frequencies [9]. At the frequency of the ERL injector cavity, 1.3 GHz, the magnetic permeability and the electric permittivity are:

$\mu = 2.7 - 12i$, $\varepsilon = 12 - 0.6i$ at 20° C, and

$\mu = 3.9 - 5.3i$, $\varepsilon = 11 - 0.3i$ at 77 K.

For the cold ferrite, the volume decreasing Q 2 times is $4.5 \cdot 10^4 \mu m^3$, so the diameter of the particle (if one) is about $D = V^{1/3} = 36\mu m$ (particles have irregular shape, so it doesn't make sense to calculate their size more accurately). If we use data for the warm ferrite, $D = 27\mu m$.

Actually, the Q decreases on average by factor of 2.4. So, the volume of the ferrite should be $6.3 \cdot 10^4 \mu m^3$ if we accept the "cold" parameters and $2.8 \cdot 10^4 \mu m^3$ if we believe that the material is warm.

Now, let us return to the statistics of sizes. One can see from the Fig. 2 that the volume of particles others than 10 micron big is less than 1 % of the whole volume. So, mainly particles close to this size (from 5 to 25 micron) define the lossy volume. If the particle volume is $1000 \mu m^3$, then the number of these particles is 28 for the warm case. Variance of this value is $\sqrt{28} \approx 5.3$. In statistics, it is known that 99.7% of the distribution falls in the interval equal to plus/minus 3 standard deviations. So, in our case, the number of particles within this range can be from 12 to 44. If we calculate values of Q for these quantities of particle, we will have a decrease of Q_V/Q_H (see Table 1) from 1.6 to 3.2. If we will accept a slightly bigger size of the particles we will have less number of particles and bigger scatter. But from the obtained values of Q_V/Q_H one can conclude that the sizes of the particles are close to 10 micrometers in accordance with the experimental values of Q_V/Q_H for 5 injector cavities presented in Table 1. For definiteness sake, all the comparisons here are done for the Q measured at the accelerating field $E_{acc} = 6$ MV/m.

Below follows a detailed derivation of the number of particles and their volume directly from the experimental data.

Assuming that losses in the contamination are proportional to its volume V, and with a proportionality factor k, we obtain

$$\frac{1}{Q} = \frac{1}{Q_0} + k \cdot V.$$

The proportionality factor can be found taking Q_0 from experiment without contamination (in the vertical test) and Q_c calculated by CLANS for a volume V_c:

$$k = \left(\frac{1}{Q_c} - \frac{1}{Q_0}\right) \Big/ V_c \text{, or } V = V_c \cdot \frac{1/Q - 1/Q_0}{1/Q_c - 1/Q_0}.$$

Suggesting for simplicity that all particles are of the same volume V_0, we have the Q-factor of the n-th cavity:

$$\frac{1}{Q_n} = \frac{1}{Q_0} + k \cdot V_0 \cdot i_n,$$

where i_n is the number of contaminants in the n-th cavity. For a random contamination process i_n should follow Poisson statistics, for which $\mathrm{rms}(i_n) = \sqrt{\langle i_n \rangle}$. This constraint can be used to determine $\langle i_n \rangle$ and V_0 as follows:

$$\left\langle \frac{1}{Q_n} \right\rangle = \frac{1}{N} \sum_{n=1}^{N} \frac{1}{Q_n} = \frac{1}{Q_0} + kV_0 \langle i_n \rangle, \mathrm{rms}\left(\frac{1}{Q_n}\right) = kV_0 \mathrm{rms} \langle i_n \rangle,$$

and, finally,

$$\langle i_n \rangle = \left[\frac{\left\langle \frac{1}{Q_n} \right\rangle - \frac{1}{Q_0}}{\mathrm{rms}\left(\frac{1}{Q_n}\right)} \right]^2,$$

$$V_0 = \frac{1}{k} \cdot \frac{\mathrm{rms}\left(\frac{1}{Q_n}\right)^2}{\left\langle \frac{1}{Q_n} \right\rangle - \frac{1}{Q_0}} = V_c \cdot \frac{\mathrm{rms}\left(\frac{1}{Q_n}\right)^2}{\left(\left\langle \frac{1}{Q_n} \right\rangle - \frac{1}{Q_0}\right)\left(\frac{1}{Q_c} - \frac{1}{Q_0}\right)}.$$

Now, using data from Table 1 we can immediately obtain the number of particles $i_n = 28$ as was found above and its size $D = V_0^{1/3} = 13$ microns. This value is also very close to our initial guess of the size of particles.

STAINLESS STEEL SHAVINGS AND DUST

In the assembly, Dicronited bolts and Silicon-Bronze nuts were used. We found that under some strain these parts can produce a lot of contaminations, as shown in Fig. 4. Hopefully, big stainless steel shavings can hardly penetrate into the volume because they are produced outside the cavity. But they are always present in the vicinity of the cavities and care is required to protect the cavities.

Smaller particles are more volatile and can travel to the volume. Let us estimate the influence of smaller particles of steel on the Q factor, of the same size – 10 microns, if they appear in the volume of a SC cavity. The thickness of skin layer in the stainless steel having conductivity of $1.4 \cdot 10^6$ Sm/m at 1.3 GHz is 12 μ m. So, in these particles the losses are also proportional to their volume.

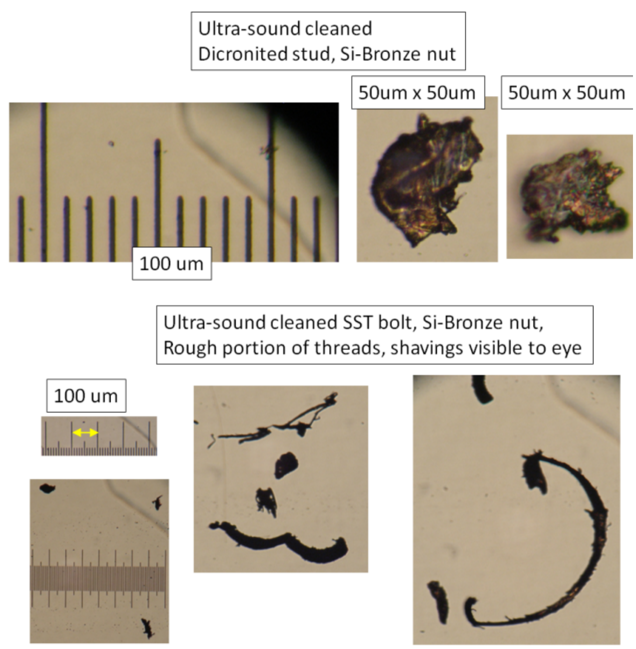

Figure 4: Shavings of stainless steel and silicon bronze.

Area to decrease the Q 2.4 times is in this case 0.055 mm^2, so the size of one particle should be 0.23 mm or there should be about 550 particles 10 microns big. However, this big number of steel particles will give a small, about 4 % scatter for different cavities, so either the particles are bigger or stainless steel particles are not the main cause of the Q degradation.

POSSIBLE CONTAMINATION BY NYLON

Nylon is used as a material for cloth of gowns used in Clean Rooms. So, particles of nylon can present on the surface of cavities. Losses in nylon can be only in the electric field, so let us calculate the *Q* drop for particles of nylon settled in the iris area where the electric field is maximal. Data for electric losses in nylon are not very extensive. According to [10] loss tangent is $1.2\cdot 10^{-2}$ at 100 MHz and $2\cdot 10^{-2}$ at 3 GHz for nylon used in coaxial cables. In our case, no precautions were done for the purity of the material, so let's take for an example the loss tangent of $2\cdot 10^{-2}$ with $\varepsilon = 5$. Calculations analogous to described above but for the iris area give the volume of 1000 mm^3 or a 10 mm big particle that is not probable. If many particles have this volume, the scatter for different cavities would be negligible.

FERRITE ON THE IRIS

Ferrite particles have both magnetic and dielectric losses. Calculations for the ferrite particle settled in the iris area give for degradation of *Q* two times the volume of 0.023 mm^3 or $D = 283\mu m$. This is an order of magnitude bigger particle (if one) or 3 orders more 10 micron size particles than in the case of particles on the equator. So, if the same quantity of ferrite particles is present on the iris as on the equator in the previous analysis, they practically do not influence on the quality factor. They can be a cause of field emission.

WHY THE EQUATORIAL AREA?

So, the ferrite particles on the equator can be the primary source of trouble with the quality factor. The question is – why the particle are there in horizontal test and are absent in the vertical test.

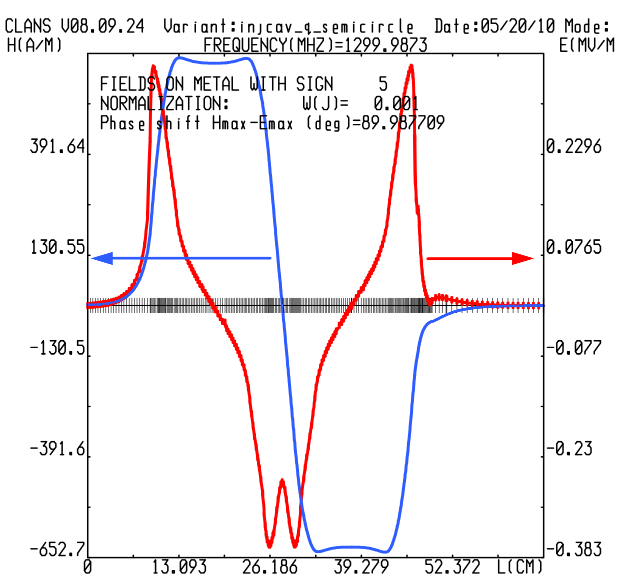

Figure 5: Fields on the profile line of the Injector Cavity. *L* is the coordinate along the profile line.

First answer - because the bodies fall down. In the vertical test, more or less big particles cannot stay in the equatorial area. However, small particles can stay on the slanted and even reversely slanted walls because of van der Waals forces.

Second argument: in the vertical cryostat *Q*-measurements only were performed. No electron beam was in the cavities. The electron beam can charge the dielectric/ferrite surfaces, as discussed above, and make the particles fly from one place to another.

Third: the HOM loads were not connected to the cavities in the vertical test. So, there was no reason of contamination by ferrite yet.

An additional consideration consists in the fact that the surface of "the equatorial area" is big compared to the iris area. In Fig. 3 the area is highlighted where the magnetic field is above 0.707 of the field on the equator, so that losses drop not more than 2 times. Take into account that the radius of the equatorial area is about 3 times bigger than the radius of the iris. Figure 5 shows distribution of the electric and magnetic field along the profile line of the cavity.

FURTHER FORTUNE OF THE DUST PARTICLES

Surface of the cavities after opening was wiped and no traces of contamination were found. Tests in the vertical cryostat immediately after disassembling from HCM (without HPR) give a short *Q* vs *E* curve (not very high electric field was achieved) but the *Q* was high [7].

This can happen if the particles move from the equatorial area to the area of the iris. To move them not only their weight can help but also the air flow by depressurization.

Let us make a guess of temperature the particle can have in the process of measuring *Q*. From the equation $V = \sqrt{Q\cdot P\cdot (R/Q)}$ one can find voltage *V* in the Injector Cavity at power $P = 1$ W, with the specific shunt impedance $R/Q = 218\,\mathrm{Ohm}$ and $Q = 1.7\cdot 10^{10}$: $V = 1.9$ MV. *Q* was measured at 4 MV and above. So, the power dissipated in the cavity was about 4 Watt. If there is a particle decreasing the *Q* 2 times, $P_0 = 2$ W of power are dissipated in this particle. For ferrite, this particle should have a size of about $D = 30$ microns or smaller, see above. A simple, cubic particle model, will give the temperature drop from the top to the bottom of the biggest particle: $\Delta T = \dfrac{P_0}{2\cdot D\cdot \lambda} = 6000$ K! Here, $\lambda = 5\,\mathrm{W/(m\cdot K)}$ is the thermal conductivity, general data for ferrite, we have no data for this specific (TT2-111R) material. For a smaller particle ΔT would be even bigger.

So, the particle will probably melt or even evaporate. But the losses will still persist, because the debris of the particle will remain in the cavity. The particle can also decompose to its element, some of them having higher thermal conductivity (for iron $\lambda = 80\,\mathrm{W/(m\cdot K)}$ at room temperature and drops to $30\,\mathrm{W/(m \cdot K)}$ near the temperature of melting), so the temperature in our case will drop down about 10 times – to 600 K. In this case the remains of the particle can weld to the surface. We can try to find such particles welded to the surface at the lower part of the cavity.

CONCLUSIONS

It is shown that several dozens of ferrite particles with dimensions about 10 microns can decrease Q of the cavities from 1.3 to 3.3 times, the values obtained in the measurements.

Statistical scatter can be explained if the particles have this size and lossy parameters of the ferrite TT2-111R used in the HOM load.

Ferrite tiles can create dust being in the injector string close to the cavities. The dust can come into being due to cracks because of mechanical stresses after their fabrication and deformations in the time of cooling down. The dust can move due to its weight and electrical charging.

Particles can evaporate, settle on the surface as a thin layer and cannot be found after cavity opening. However, their residue can be still lossy.

Other contaminations: stainless steel or other metal shavings, nylon dust from the garment cloth – cannot explain the decrease of Q and statistical scatter at the same time.

The question is still open; no direct confirmations of this hypothesis exist at present.

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