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Contamination Issues in Superconducting Cavity Technology*

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The application of radio-frequency superconductivity technology in particle accelerator projects has become increasingly evident in recent years. Several large scale projects around the world are either completed or close to completion, such as CEBAF, HERA, TRISTAN and LEP [1]. And superconducting cavity technology is seriously being considered for future applications in linear colliders (TESLA), high current proton accelerators (APT, spallation neutron sources), muon colliders and free electron lasers for industrial application [2].

The reasons for this multitude of activities are a matured technology based on a better understanding of the phenomena encountered in superconducting cavities and the influence of improved material properties and contamination and quality control measures.

Figure 1 describes schematically the behavior of a superconducting niobium cavity operated at a frequency of 1500 MHz and a temperature of $T = 1.8K$.

For comparison the theoretically expected behavior is also shown. Plotted is the Q-value (as a measure of the surface losses) as a function of the ratio of rf-magnetic field H_{rf} to the theoretically predicted magnetic field H_{sh}. Four distinct deviations are noticeable:

a). the observed Q-value is significantly lower due to a **Residual Surface Resistance** caused by anomalous losses or defects

b). at certain distinct fields in the cavity ($E_{peak} = 2 \times E_{acc}$, $H_{rf}/E_{acc} \approx 45$ Oe/MV/m) the Q-value might drop to lower values caused by **Resonant Electron Loading** ("Multipacting")

c). above a certain field level in the cavity - typically $5 \text{ MV/m} < E_{acc} < 10 \text{ MV/m}$ - the Q-value decreases exponentially due to **Non Resonant Electron Loading** ("Field Emission")

d). the experimentally observed electromagnetic field, at which the superconducting state disappears ("Quench"), is typically much lower than the critical magnetic field H_{sh} of the superconducting material - app. 2400 Oe for niobium. It has been established that these deviations are caused by **Anomalous Losses or Defects**, which lead to thermal instabilities in the cavity material.

All listed deviations a) - d) from the ideal behavior are to a large extent caused by contamination of either the bulk material or in many cases contamination of the surface.

The challenge then for accelerator builders making use of superconducting cavity technology is to eliminate or at least to control contamination to the desired level of application of the technology.

a). Residual Surface Resistance

BCS theory predicts an exponential decrease of the rf surface resistance $R_{BCS}(T)$ of a superconducting material with temperature, disappearing at $T = 0$ [3]. In reality however,

$R_{BCS}(T)$ is limited at lower temperatures by the temperature independent residual resistance R_{res} of a few nOhm. Contributions to R_{res} have been identified over the years as [4] : frozen-in magnetic flux, normal conducting surface defects, dielectric losses due to adsorbates or particulate contamination, metal-oxide interface losses, chemical stains, hydrogen precipitation.

b). Resonant Electron Loading ("Multipacting") [5]

Multipacting is a high vacuum resonant avalanche effect initiated by emission of secondary electrons in response to impinging primary electrons moving resonantly in the cavity fields. If the secondary electron emission coefficient of the material is larger than 1 - for niobium $50 \text{ eV} < E_{imp} < 2000 \text{ eV}$ - at the energy of the impinging electrons accelerated in the cavity fields, more secondaries are generated. In the high Q superconducting cavities such electron currents can lead to resonance frequency shifts, absorption of additional rf-power and limitations in the achievable gradients ("barriers"). Since multipacting sustains itself by virtue of a secondary electron emission coefficient > 1, remedies against multipacting have been found by a). shaping the cavity fields in such a way that for the electron impact energies of accelerated electrons the secondary emission coefficient is < 1, and b). by keeping the superconducting surfaces as clean as possible with low secondary electron emission coefficients.

In general, multipacting is no longer limiting achievable gradients in superconducting cavities, but carelessness in the degree of cleanliness can make multipacting barriers reappear with all their deleterious effects.

c). Non-Resonant Electron Loading ("Field Emission") [6]

Beyond a certain field gradient in a superconducting cavity, electrons are drawn out of the surface under the influence of the rf electric surface fields, are accelerated in the rf fields and gain sufficient energy to produce heat and bremsstrahlung when colliding with an opposing surface. This "field emission" grows exponentially with field level and appears as an exponential decrease in the Q-value of a cavity, limiting severely the achievable gradients. Field emission is presently the limiting mechanism in superconducting cavity performance, and overwhelming evidence has been collected that it is caused by artificial contamination of the surfaces, mainly particulates in connection with adsorbates [1]. Careful cleaning of the surfaces with e.g. jets of high pressure ultrapure water [7] or "in situ" methods such as "High Peak Power Processing" [8] or "Helium Pocessing" [9] have successfully been applied to shift the onset of field emission to higher field levels.

d). Anomalous Losses/Defects

Typically, superconducting niobium cavities quench at magnetic field levels significantly below the theoretical field $H_{sh} = 2400$ Oe. The reasons for this inferior behavior have been found in thermal instabilities occurring at localized areas ("defects") of enhanced losses; experimental evidence and simulation calculations have led to these conclusions [10,11]. Such areas - surface imperfections like scratches, holes, crevices, weld splatter, delaminations, chemical residue patches, foreign material inclusions - can be avoided or eliminated by careful handling during fabrication processes, thorough surface inspections and repair procedures such as grinding, thorough chemical cleaning procedures with prolonged rinsing (high pressure) with ultrapure, particulate-free water, and assemblies in high quality clean rooms. The application of these procedures in connection with higher thermal conductivity niobium has continuously improved cavity performance and on occasion resulted in laboratory test cavity results close to the theoretical expectations.

In the last few years the community involved in the application of superconducting cavity technology has increasingly recognized the importance of contamination control measures in surface treatment and assembly of cavity systems for improving cavity performance. The application of various cleaning methods such as megasonics or high pressure ultrapure water rinsing and "in situ" processing methods such as high pulsed peak power or helium processing has resulted in the achievement of cavity gradients > 20 MV/m in multi-cell cavities and values > 30 MV/m in single cell tests. However, such performances are still subject to deterioration in larger, more complex assemblies such as accelerator modules, and one of the main challenges now is the "invention" of ingenious procedures and tooling to eliminate re-contamination of cavity components.

References

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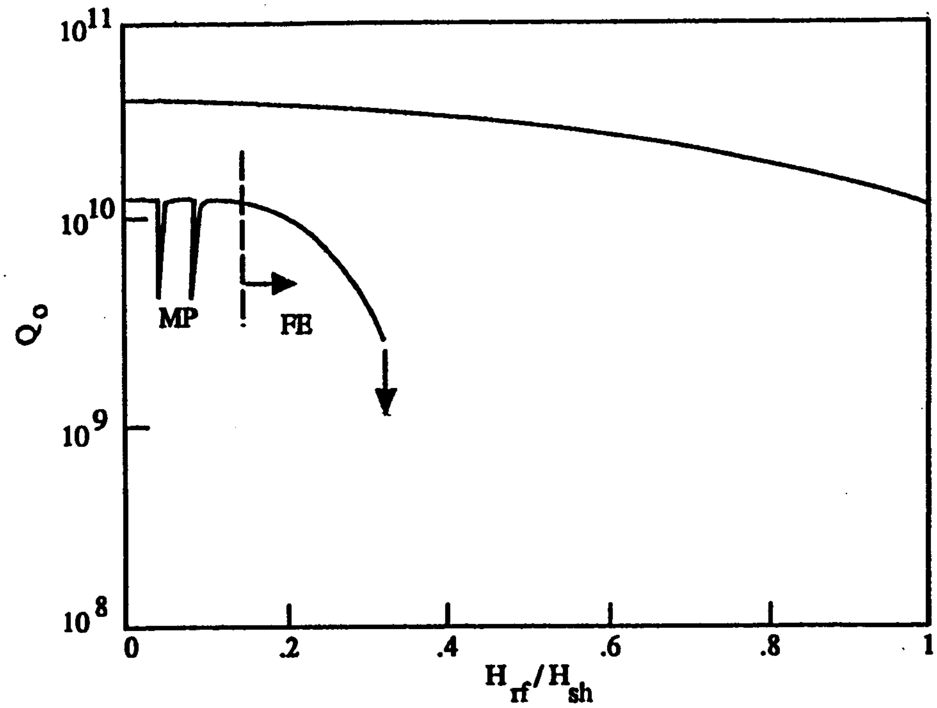

Figure 1 : Schematic behavior of a 1500 MHz niobium cavity at 1.8 K