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Niobium Superconducting Cavity for Radio Frequency: A Review

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Abstract— Superconducting (SC) cavities are made up of superconducting material named niobium which is used in particle accelerators whose performance is limited at radio frequency. There are mainly two phenomena called Field Level Quench and Field Emission Loading Result which affects on Superconducting RF cavities. In few years, The developers are working on super conducting radio frequency technology for enhancing the cavity performance by using some surface treatment methods like Chemical polishing, high temperature treatment etc. These cavities work as superconductors whose resistance is near to 0 Ω at cryogenic temperature (2K). In this paper, the performance parameters and loss mechanisms of the SCRF cavity is described.

Keywords- *Superconductivity, SCRF, LLRF, Niobium Cavity.*

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I. Introduction

A bimetal chamber that contains magnetic attraction field is termed frequency (RF) cavity. Initially, it is used for accelerating the charge particles. RF cavities are often structured like beads on a string, where the beads are termed as the cavities and the string as the beam pipe of a particle accelerator, through that particles move in vacuum. To arrange associate RF cavity to accelerate particles, an associate RF power generator provides an electromagnetic field. The RF cavity is shaped to a particular size and shape so that electromagnetic waves become resonant and build up within the cavity. Charged particles moving through the cavity sense the overall force and direction of the resulting electromagnetic field, that transfers energy to push those forwards on the accelerator. The field in associate RF cavity is created to oscillate (Switch direction) at a given frequency, therefore temporal order the arrival of particles is very important [1].

The term superconductivity was introduced when discovery of development of zero ohmic resistance occurring in pure metals below a characteristics temperature additionally also critical temperature (T_C). It had been discovered by Dr. Heike Kamerlingh Onnes at University of Lriden in Holland once he found that resistivity of mercury reduced to zero at 4.2K temperature. After this discovery, it had been found that electrical conduction is sort of a standard development that can be exhibited by many pure elements, several compounds and alloys. Superconductors are extensively utilized in several applications lately. They need become Associate in Nursing integral a part of fashionable high energy accelerators. SC magnets and SCRF cavities are primary alternative for prime energy accelerators. Superconducting RF (SCRF) cavities are fabricated from superconducting materials that have prime quality factor and high acceleration gradient compared to traditional conducting cavities. Superconducting cavities are in operation routinely for several years in an exceedingly type of accelerators for high energy physics, low energy to medium energy physical science research, and free electron lasers. Before authorisation to super conducting cavities for operations in accelerators, the cavities got to be tasted so their most acceleration gradient will be well known.

There are two types of superconductors used in SCRF Cavities:

Superconductor Type 1-

The elements containing Pb, Sn, Hg, Al and others comes below this class. These parts do not turn out magnetic field within the bulk material and these are within the state of superconducting that provides the applied field below a critical field B_C that could be function of temperature.

Superconductor Type 2-

All superconducting alloys as Pb-Ti, Nb-Sn, Nb-Ti and additionally Nb belong to the most important class of type-II superconductors. These superconductors are characterized by two important fields named B_{c1} and B_{c2}. Below the sector B_{C1} of these substances are within the Meissner phase with complete field expulsion whereas within the range $B_{c1} < B$ and $B < B_{c2}$ type-II superconductor enters the mixed innovate that field of force will penetrate the majority material within the type of flux tubes. Higher essential fields for Type-II superconductors build them additional favourable for practical applications.

Superconductors with high critical vital magnetic field and high critical temperature are thought-about best for accelerator, application however criterion which has fabricated processes, surface conditions, heat transfer capabilities etc are necessary issues. For the cavity operated in CW mode, materials with higher critical temperature and lower surface resistance are chosen to cut back dynamics heat losses. Niobium (Nb) is that the favourite material in RF electrical conduction and accelerator cavity construction. It is highest critical temperature 9.2 k and also the highest magnetic field among all the pure metals [2].

II. BEHAVIOUR OF SCRF CAVITY

A superconducting cavity is generally used for the appliance of accelerator that is usually made-up on Niobium (Nb) sputtered on copper or Nb. Its response to excitation by RF energy is delineated by 2 parameters, Its Q-value and its realizable fast gradient [3 and 4]. Quality factor of a cavity is outlined because the quantitative relation of the stored energy (W) within the cavity to the ability (P) lost within the cavity walls per RF cycle

$$Q_0=W / (P/\omega)$$

Q_0 is reciprocally proportional to the surface resistance (R) which may be expressed as:

$$Q_0=G/R$$

Where, G is geometry factor.

The accelerating gradient (E or Eacc) is outlined because the most energy a charged particle can gain within the time variable RF fields by traversing an accelerating gap divided by the gap length. The accelerating gradient is proportional to the root of the hold on energy:

$$E_{acc} \propto \sqrt{PQ_0}$$

III. PERFORMANCE PARAMETERS OF THE CAVITY

Cavity performance is characterised on the idea of quantities like hold on energy, power dissipation, quantity issue, shunt electric resistance etc. it is necessary to grasp these quantities before cavity style so as to work out best form and size of cavity that satisfy operation needs. This section addresses these quantities of cavity performance.

a) Stored Energy

Cavity stores EM energy that is used to accelerate charge particle beam. The electromagnetic energy density is [5].

$$U_d = \frac{1}{2}\bar{D}\bar{E} + \frac{1}{2}\bar{B}\bar{H}$$

And thus total energy stored in a cavity is

$$U = \frac{1}{2}\int U_d\, dv$$

Where V is the volume enclosed by the RF cavity.

b) Peak Surface Fields

Stored energy in a cavity is proscribed by the most surface fields that cavity will maintain. We tend to therefore introduce two fields, the peak surface electric field (E_{pk}) and therefore the peak surface magnetic field (H_{pk}). These fields verify the most accomplishable accelerating gradient in cavities. The surface electric field is most close to the irises and therefore the surface flux is at its most close to the equator of the elliptical form cavity. For SCRF cavities, high field of force may end up in emission (FE) that produces electrons within the cavity that absorbs RF energy and build spare power losses. Thus, SCRF cavities are operated below this FE region.

c) Transit Time Factor

The charge particle takes finite time to traverse through a cavity. Therefore, energy gain of a particle passing through harmonically time variable field is totally different once it passes through a static field. The ratio of energy gain of charge particle during a time variable field to energy gain in static field is termed as transit time factor (TTF). TTF measures the energy point that a cavity will work with efficiency.

d) Power Dissipation

We know that the cavities have excellent conducting walls. So as to support the cavity fields, current flow at intervals a thin surface layer of the walls [6]. Even a superconductor contains a little resistance at RF frequencies, so the wall currents that sustain the fields dissipate energy. The losses will be characterised by the surface resistance (R_s), that is outlined via the ability dissipate per unit space (dP_c/ds) because of joule heating:

$$\frac{dP_c}{ds} = \frac{1}{2}R_s|H|^2$$

Where, H is local magnetic field. Typically, R_s is several tens of nano-ohms for a well prepared niobium superconducting surface, whereas for copper the value is in the milliohm range.

e) Quality Factor

The quality issue (Q) could be a universal figure of advantage for resonators and is outlined within the usual manner because the quantitative relation of the energy hold on within the cavity (U) to the energy lost (Pc) in one RF period times of π or 2 range of RF cycles it takes to lose total energy hold on within the cavity. It is the measure of the quantity of oscillations a resonator can bear before dissipating its hold on energy. The letter depends on the microwave surface resistance of the metal. The standard issue (Q) of a cavity is directly associated with power lost within the cavity.

f) Shunt Impedance

Shunt resistance of a cavity is another necessary amount that measures effectiveness of producing a fast voltage V_C for a given power dissipation P_C within the cavity. It is given as:

$$R = \frac{V_C^2}{P_C}$$

g) Geometrical Factor

Geometrical issue is often wont to compare power dissipation of various geometries. It is another figure of benefit of cavity and may be a operation of cavity geometry. It outlined as product of surface resistance and quality issue of the cavity and is given by:

$$G = R_S Q_0$$

IV. Loss Mechanism

The various anomalous loss mechanisms that are encountered during a typical cavity, the losses are referred to as “anomalous” as a result of they are not expected by the BCS theory of superconductivity. Impacts of those limitations on cavity quality issue and accelerating gradients are shown in figure 5. In ideal scenario, Q_0 of cavity remains constant however in sensible Q_0 drops step by step (Medium field Q slope) at medium accelerating field and drops very powerfully (high field Q-slope) at high accelerating fields.

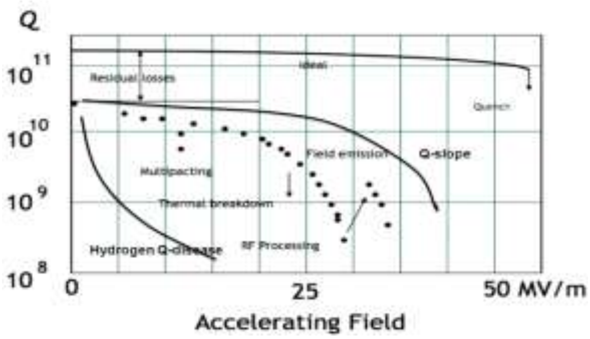

Figure 5: E_{acc} & Q_0 curve – impact of multipacting, thermal instability, field emission and Field losses on cavity performance [7].

Multipacting (Multiple Impact Electron Amplification) is determined in RF elements that are operated underneath vacuum like SCRF cavity and couplers. It is a development of resonant multiplication of electron underneath the influence of RF fields or Multipacting could be a resonant multiplication because of the secondary electron re-emission process. Field emission (FE) is another accepted phenomenon that limits most possible accelerating field in SCRF cavity [8, 9, 10].

Once surface electric field is robust, it will result in electron emission from scratches or particles situated on the metal surface through tunnelling to make steady current. The Fe current will increase quickly because the field are accrued. Just like the multipacting development, acceleration of emitted electrons absorbs RF power which might preferably be available for acceleration of beam. Emitted electrons impact elsewhere on the cavity surface, heating the surface and thus increasing surface resistance. It leads to increase in power dissipation of cavity that ends up in increase in cryogenic losses and also the fast decline of the Q_0. In extreme cases, FE heating of the cavity walls leads to termination of SC states. The name quench is often wont to describe the breakdown of electrical conduction however in RF cavities critical temperature TC is reached because of heating method rather than vital field of force. Therefore, Thermal instability is acceptable name to describing breakdown of electrical conduction in cavity. Thermal breakdown originates at millimetre size that has RF losses considerably more than the surface resistance of a perfect superconductor. These regions area unit referred to as defects. These may well be either geometrical imperfections like pits, bumps and hole on cavity surface or external contaminants like chemical residuals, dust etc. The breakdown of RF electrical conduction is explained by a model of thermal instability [11]. The BCS a part of the SC surface resistance has an exponential dependency on temperature. Below steady-state SC conditions the temperature at the inner cavity surface is increased by ΔT as compared to that of the outer surface of cavity (or liquid helium at the outer cavity wall). It's given as:

$$\Delta T = q\left(\frac{d}{\lambda} + R_K\right)$$

Where, q is the heat flux, d is the thickness of the cavity wall, R_k is the thermal resistance between the outer cavity wall and the cooling helium (often known as Kapitza resistance) and λ is the thermal conductivity of the cavity wall.

V. Summery

The Superconducting cavity is mainly used in particle accelerators where the main work of the cavity is to accelerate the charge particle at Constant DC power. During this acceleration, so many factors affect the cavity some of them are cavity parameters and its performance depends on its critical temperature and magnetic properties. When the excess of the power is provided to the cavity at certain parameters then it always reflect back the power which is called quenching. This quenching can be reduced by changing its RF frequency measured by cable calibration. In future, the SCRF cavity performance can be enhance more by using its RF system instruments at more advanced level and it can be a more beneficial application to the medical area.

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REFERENCES

[1] "www.home.cern.ch/about/engineering/radiofrequency-cavities", Radio Frequency Cavities CERN Accelerating Science.

[2] C. Benvenuti et al, "Superconducting cavities produced by magnetron sputtering of Niobium on copper", Proc. SRF Conference, 1987.

[3] J. Halbritter, "Zur Oberflachen - Impendanz von Supraleitem," physics, pp. 209, vol-266, 1974.

[4] P. Kneisel, "High Gradient Superconducting Niobium Cavities A Review of The Present Status", IEEE Transactions on Applied Superconductivity, pp.1023-1029, vol.9, June-1999.

[5] Dr. Kirti Ranjan, Arun, Saini, "Beam Dynamics Studies and the design, Fabrication and testing of superconducting radio frequency cavity for high intensity protron accelerator", Department of physics and astrophysics, university of delho, pp 30, march 2012.

[6] Hasan Padamsee et al, "RF Superconductivity for accelerators",john willey & sons, INC 2nd edition, 2008.

[7] R.L. Geng,"Limits in Cavity performance", tutorials SRF conference, 2011.

[8] Hasan Padamsee et. al, "RF Superconductivity for accelerators", john willey & sons, INC 2nd edition, 2008.

[9] R. Noer, C. Reece, H. Pasamsee, W. hartung and Q.S. Shu," RF Field Emission in Superconducting Cavities", Proc. SRF Conference, 1987.

[10] B. Bonin, Material for superconducting cavities, CAS: "Superconductivity in particle accelerator", pp. 191-200, 1995.

[11] K. W. Shepard, H. Padamsee, R. Sundelin, "Physics an daccelerator applications of RF superconductivity", Ann. Rev. Nuclear science 43, pp 635-86, 1993.