A METHOD FOR ESTABLISHING Q-FACTORS OF RF CAVITIES*

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Abstract

The distribution of electromagnetic fields in an RF cavity is primarily determined by the geometry of the RF cavity. The quality factor (Q-factor) of an RF cavity characterizes RF losses in the cavity: an RF cavity having a higher Q-factor is a more efficient user of RF power. However, a cavity having a lower Q-factor can operate on a wider range of frequencies, shorter filling time and may be more stable and less sensitive to input power perturbations. A method is discussed in this paper for an RF cavity that provided a desired Q-factor for the cavity while enabling the desired field distribution for electron acceleration within the cavity. The structure forming the inner wall of the RF cavity may be comprised of different types of material (such as copper and steel). Using different materials for different portions of the inner walls forming a cavity may cause different Q-factors for the cavity while the shape of the cavity remains constant.

INTRODUCTION

Particle accelerators have been used for a number of years in various applications. For example, one common and important application of particle accelerators is for industrial irradiation. In such an application, a particle source, such as an electron, may be coupled to an input cavity of an accelerator and provide a source of charged particles or a particle beam to the accelerator. The accelerator may include number of RF cavities through which charged particles beam travels. Electric and magnetic fields present within the cavity and acting on the charged particles provide the acceleration. The distribution of fields in an RF cavity is primarily determined by the geometry of the RF cavity. The accelerator accelerates the charged particles to produce an accelerated output beam for use directly, or for conversion to x-ray.

The quality factor of an RF cavity characterizes the quality of the cavity with respect to RF losses in the cavity. The Q-factor of an RF cavity is defined as [1]

$$Q = \frac{\omega U}{P} \qquad (1)$$

Where ω is the angular frequency (2πf), *U* is the cavity stored energy, and *P* is the power dissipated in the walls per radian of the RF cycle. The maximum stored energy U in the cavity is determined by the cavity shape and volume while P is determined by the resistivity and magnetic permeability of the material of the inner wall of the cavity.

An RF cavity having a high Q-factor is a more efficient user of RF power. Thus, for the same cavity shape and the same amount of RF power, the accelerating field produced in the cavity is higher in a cavity having a higher Q-factor. However, operational bandwidth of an RF cavity is inversely proportional to the cavities Q-factor. As a result, a cavity having a lower Q-factor can operate on a wider range of frequencies and may be more stable and less sensitive to input perturbations.

It would be advantageous to provide a method to construct an RF cavity that provided a desired Q-factor for the cavity while enabling a desired field distribution for electron acceleration within the cavity.

CASE STUDY

Electrons are generated from an electron gun and accelerated in RF cavities in an industrial linear accelerator. The length of the cavities is not uniform. The first few cavities are usually shorter than the following cavities, since the velocity of the electrons in the first few cavities are much smaller. The length of the cavity should match the time for the electrons to travel through a cavity, which should be equal to half of the RF cycle. In other words, the electrons' motion is synchronized with RF waves.[2]

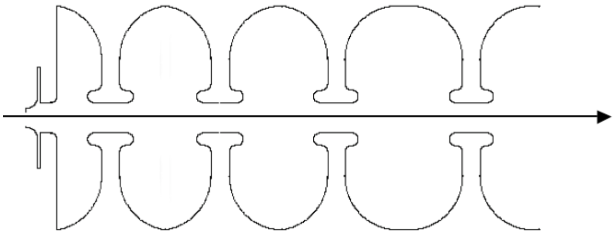

Figure 1: First few cavities of an industrial linac.

As mentioned above, some applications may require that each cavity may have different Q values. The effect of Q values of an RF cavity for a linear accelerator is studied with code SUPERFISH[3], which simulates radio-frequency electromagnetic fields in either 2-D Cartesian coordinates or axially symmetric cylindrical coordinates. The programs generate a triangular mesh fitted to the boundaries of the problem geometry. The RF solvers FISH and CFISH iterate on the frequency and field calculation until finding a resonant mode.

The quality factor Q is calculated by SFO, which stands for SUPERFISH Output. SFO reads the electromagnetic field solution written by FISH or CFISH and segment material property file defined by user, then calculates the Q and other parameters of interest to the accelerator designer.

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Full Cavity

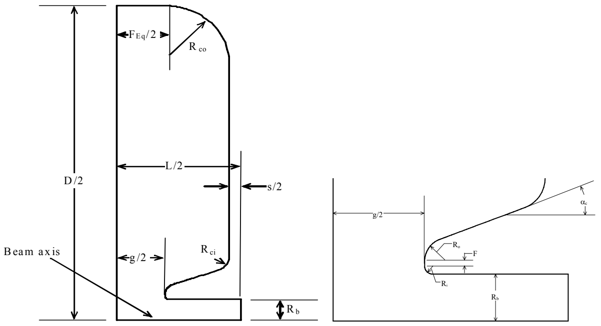

Figure 2: The half cell set up by the code CCLfish (one of input formats for SUPERFISH). The cell is a figure of revolution about the beam axis, which is at the bottom of the figure. The left edge is a symmetry plane. Right Figure shows more details near the nose.

The dimensions for a typical full cavity of an S-band linac are labeled in Figure 2. The corresponding input dimensions for the SUPERFISH input is summarized in Table 1.

Table 1: Full Cell Cavity Dimensions

Geometric Description	Dimensions
Length (L)	4.5 cm
Diameter (D)	7.9 cm
Gap_Length (g)	2.9 cm
Outer_Corner_Radius (R_{co})	1.9 cm
Inner_Corner_Radius (R_{ci})	0.22 cm
Outer_Nose_Radius (R_o)	0.22 cm
Inner_Nose_Radius (R_i)	0.22 cm
Flat_Length (F)	0 cm
Cone_Angle (α_c)	0 degree
Septum_Thickness (s)	0.64 cm
Bore_Radius (R_b)	0.5 cm

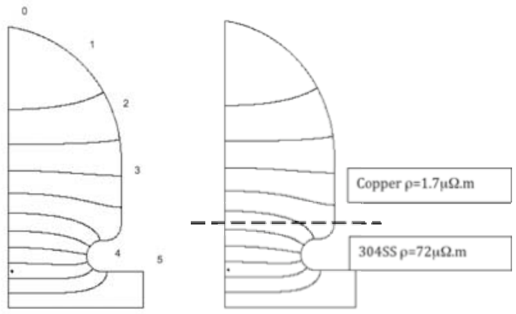

Figure 3: Electric field line in a full cavity. (Only halves are shown, Left sides of both figure are symmetry planes)

The RF losses are related to the current density and field strength on the surface of the cavity. So we plot these values on Figure 4 and Figure 5

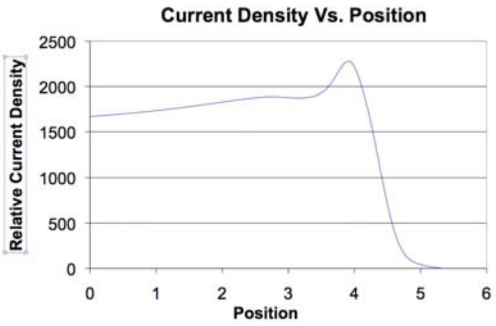

Figure 4: Relative current density on the surface for the full cavity

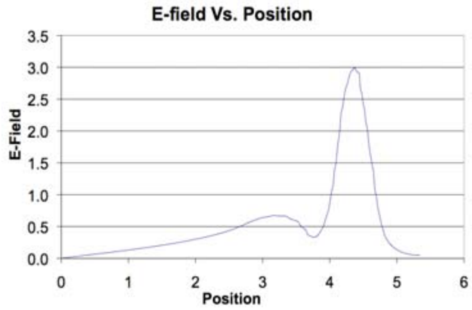

Figure 5: E-field strength on the surface

SUPERFISH graphic output files are shown in figures 3, 4 and 5. The peak current density reaches maximum value close to position 4, which is above the nose cone area. So if one wants to effectively change the Q value, the nose area, position 4 and 5, should be covered by the new material. Two cases have been studied with SFO for the full cavity. If the cavity is made of pure copper with resistivity of ρ=1.7μΩ.cm, as show in left figure of Figure 3, the calculated Q value is 16000.

For another case, as shown in the right of Figure 3, a 304 stainless steel insert, with radius of 1.2cm, is implemented to drop the Q value. SFO calculation uses the steel resistivity of ρ=72μΩ.cm to replace copper from position 4 to position 5 for the cavity surface. The new Q value is 11000. So the 304 stainless steel reduces the Q value by 5000 or about 30%. This low Q cavity is important for some applications.

Half Cavity

Further study shows the Q value of RF cavities is also affected by the permeability. The first half cavity in an industrial linac is studied in this case

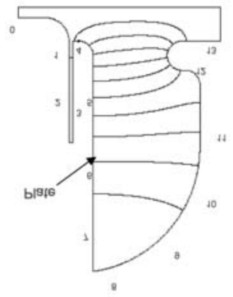

Figure 6: Electric field line in a half cavity (Left side is a metal plate).

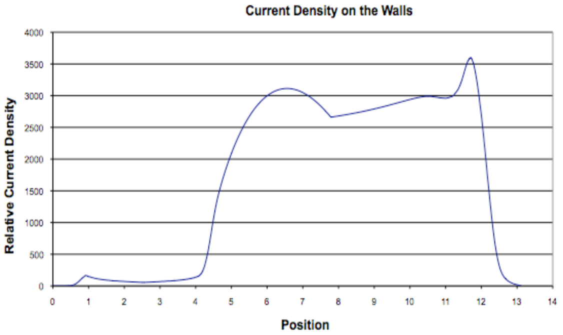

Figure 7: Current Density along the surface of a half cavity

Table 2: Half Cavity Q values

Materials	Q value
Copper Only Resistivity ρ=1.7μΩ.cm	6515
Non magnetic steel only Resistivity ρ=9. 7μΩ.cm	2764
Magnetic steel only permeability μ=180	204
Magnetic steel only permeability μ=1800	65
Copper cavity Non-magnet steel end plate,	4107
Copper cavity, but magnet steel end plate (μ=180)	460
Copper cavity, but magnet steel end plate (μ=1800)	149

The Q value for different configurations is listed in Table 2, since the permeability is not a constant number. It changes with the external magnetic field. So the Q value for RF cavities with magnetic material will be different with different field levels.

CONCLUSION

The Q value can change significantly with different materials. The resistivity and permeability of the materials are the two factors that affect the Q value. Also the material at the relatively high current density position in the RF cavity has a greater effect on the Q value. In addition, External magnetic field can change the Q value if an RF cavity has walls with magnetic steel.

Although the field profile is determined by the shape of the RF cavity and independent of material, the Q value can be established with different material in different positions in an RF cavity

REFERENCES

[1] T. Wangler, RF Linear Accelerators, Wiley, 1998, P46

[2] E.A. Knapp et al, "Standing Wave High Energy Linear Accelerator Structures", Review of Scientific Instruments. 39, 979-991

[3] J. Billen and L. Young, "SUPERFISH/POISSON Manual" LA-UR-96-1834