Modeling of Electromagnetic Heating in RF Copper Accelerating Cavities

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Abstract — Electromagnetic heating is a critical issue in normal conducting copper RF cavities that are employed in particle accelerators. With several tens to hundreds of kilowatts dissipated RF power, there must be an effective cooling scheme whether it is water or air based or even a combination of both. In this paper we investigate the electromagnetic heating in multiple cavities that were designed at Fermilab exploring how the electromagnetic and thermal analyses are coupled together to properly design the cooling of such cavities.

Index Terms — Normal conducting RF cavities, electromagnetic heating, frequency shift due to thermal stresses.

I. INTRODUCTION

Normal conducting copper cavities are essential components in particle accelerators whether it is designed for proton or electron particle beams. Particle accelerator machines are typically categorized as either linear or cyclic machines depending on how the particles are being propelled inside the machine. Often they are also categorized according to the beam energy namely, high energy (>100 MeV), medium energy (10-100 MeV) and low energy (<10 MeV) machines.

Despite the current blooming of superconducting RF technology that enabled modern high energy particle accelerators with alternative superconducting cavities that offer much lower RF losses, normal conducting cavities are still the technology of choice for low energy machines. Normal conducting cavities have the advantage of being cheaper (when compared to SRF cavities) and doesn’t require the associated relatively complicated cryogenic systems. That is why particle accelerators for industrial and medical application are mostly employing copper cavities in their systems.

On the other hand, even for high energy physics that have very large scale accelerators, copper cavities are typically employed in the early stages of particle acceleration. For proton machines, radio frequency quadrupoles (RFQ) are employed in the warm front end of the machine after the ion sources to get the proton beam focused and accelerated to few hundredth the speed of light. Re-buncher copper cavities are then used to keep the beam bunched.

Meanwhile, cyclic synchrotron machines that have the beam cycle thousands of times in fixed radius path essentially require tunable cavities because of the fact that when the beam acquires more energy, frequency of the RF cavities need to be adjusted to keep the beam synchronous with accelerating field in the fixed radius path. The tunability feature in RF copper cavities are usually attained by loading the cavities with ferrites biased by variable magnetic field.

Electromagnetic heating critically affects normal conducting RF cavities whether it is fixed frequency cavities for linear machines or frequency-tunable cavities for cyclic machines. In fact the electromagnetic heating become even serious issue for tunable cavities because of the high loss in the ferrites. In this paper, we will explore how the electromagnetic heating is modeled in various RF cavities for particle accelerators addressing issues of excessive heating, and frequency shift due to thermal stresses.

II. MODELING OF ELECTROMAGNETIC HEATING

Modeling of electromagnetic heating basically requires coupling the electromagnetic and thermal analyses. By solving first the electromagnetic problem, fields inside the cavity can be computed then the thermal loads due to these electric and magnetic fields can be found depending on the material properties of the medium filling the cavity. Two kinds of losses are associated with the electromagnetic fields. First volume losses in case of lossy media filling partially or completely the cavity. In such cases, the energy loss density (in W/m³) for electric and magnetic losses are

$$ W_{E_{loss}} = \frac{1}{2} \omega \varepsilon |E|^2 $$

$$ W_{H_{loss}} = \frac{1}{2} \omega \mu |H|^2 $$

where “ε” and “μ” are the imaginary parts of the permittivity and permeability, respectively. Second kind of losses is due to the resistivity of the cavity wall. The surface losses density (in W/m²) on the cavity wall are

$$ W_{S_{loss}} = \frac{1}{2} R_{s} |H|^2 $$

where $R_s$ is the surface resistance and $\sigma$ is the conductivity of copper walls.

Modeling electromagnetic heating in cavities follow the scheme shown in Fig.1, summarized in the following steps:

1. Solving the electromagnetic problem to find the resonance frequency of the cavity and the electromagnetic fields.
2. Applying thermal loads induced by the electromagnetic fields consisting of volume losses in case of dielectrics and surface losses on the cavity walls.
Computation of displacement caused by thermal stresses by means of a solid mechanics solver.

4. Deforming the mesh according to the computed displacement.

5. Re-computing the cavity’s frequency to capture the frequency shift caused by thermal stresses.

III. FIXED FREQUENCY CAVITIES

In this section, we explore the electromagnetic heating in some of the cavities commonly used in linear particle accelerators. Frequency shift due to thermal stresses is typically a concern in those cavities.

a) Radio Frequency Quadrupole (RFQ).

RFQ cavities are employed in protons (or generally heavy ions) particle accelerators to focus and accelerate the charged particle beam at the very early stages of acceleration after the ion source. RFQs are typically long sections (several meters long) of copper rods or vanes arranged in quadrupole fashion. Vanes are gradually modulated to match the beam velocity. Figure 2 Shows simulation results of Fermilab’s RFQ that is being built for proton improvement plan (PIP-II) [1]-[2]. It operates at 162.5 MHz with vane to vane voltage of 60 kV. Fermilab’s RFQ should accelerate the proton beam from 30 keV to 2.1 MeV. Cross-sectional electric and magnetic fields are shown in Fig. 2(a) and (b) respectively.

![Fig. 2. Fermilab’s RFQ for proton improvement plan (PIP-II). (a) Simulated cross-sectional electric field in MV/m. (b) Simulated cross-section magnetic field in KA/m. (c) Temperature profile for the 3D RFQ structure.](image)

The quadrupole mode of operation with electric field vectors pointing as shown in graph secures the beam focusing feature of the RFQ. Electromagnetic heating have been modeled following the aforementioned approach. Assuming cooling channels going through the structure as shown in Fig. 2(c) with water temperature of 25°C, the maximum heating along the structure is happening along the high magnetic field areas where temperature increases to 30°C. Frequency change due to thermal stresses was also computed and was found to be -4.4 kHz. This frequency shift can be compensated by differentially controlling the cooling channels temperatures.

b) Re-buncher Cavity

Re-buncher cavities acts after the RFQ in proton accelerators to re-bunch the beam in several steps. For Fermilab’s Project X (PIP-II), three re-buncher cavities are needed with effective voltage per cavity of 75 kV. Figure 3 demonstrates the electromagnetic heating and the cooling of a copper cavity that was proposed for Project X [3]. Cavity will heat up to 44°C assuming the cooling channel water is at 35°C. Displacement due to thermal stresses is shown in Fig. 3(b), while the thermal stresses are shown in Fig. 3(c). In fact copper yields at 70 MPa, most of the stresses are below 30 MPa except a localized stresses on the beam pipe connection to the plate that covers the cooling channels.

![Fig. 3. Modeling of a re-buncher cavity that was proposed for Fermilab’s Project X. (a) Thermal profile (cavity top plate is uncovered to show the temperature nearby the cooling channels on the right hand side plot). (b) Displacement due to thermal stresses in µm. (c) Thermal stresses in MPa (cavity top plate is uncovered to show the stresses nearby the cooling channels). (d) Multiphysics results comparison between Ansys and Comsol.](image)

Multiphysics simulation has been repeated by two different tools; Ansys and Comsol. Frequency shift due to thermal...
stresses is on average -26 kHz. Comparison of the results obtained by the two different tools is shown in Fig. 3(d). Results in a good agreement.

IV. TUNABLE CAVITIES

As mentioned before tunable RF cavities are needed for synchrotron particle accelerators. The FNAL Booster is a 474.2 m long proton synchrotron with injection energy of 400 MeV and extraction energy of 8 GeV. The magnetic cycle is a biased 15 Hz sinusoid, and the RF system operates at the 84-th harmonic of the revolution frequency. The ring has 19 ferrite-tuned cavities [4].

Each RF cavity is a half-wave resonator, as shown in Fig. 4(a), loaded with three coaxial ferrite tuners separated by 90° rotation angle and the cavity is fed by a tetrode power amplifier. Each half ferrite tuner consists of 14 concentric ferrite rings of 1” in thickness separated by copper washers of 0.25” in thickness. The first five ferrite rings (positioned closest to the tuner connection to the cavity) have zero-current permeability of ~ 20, dielectric constant of 12, and magnetic loss tangent at 50 MHz of 0.007, while the remaining 9 ferrite rings have zero-current permeability of ~12.5, dielectric constant of 10.5, and magnetic loss tangent at 50 MHz of 0.005. Both kinds of ferrite rings have dielectric loss tangent of 0.005.

Inner conductor of both the cavity and the tuners are flared for better impedance matching. Tuners and a large portion of the cavity are in air with only two small end volumes under vacuum, along with the small beam pipe. Ceramic windows are located near the accelerating gaps at both ends as shown in Figure 4.

The Booster cavity frequency sweeps from 37.77 MHz at injection to 52.81 MHz at the extraction. The cavities have an aperture of 2.25 inches and operate up to 55 kV per cavity. Simulation versus measurements of the cavity’s quality factor along the sweep cycle is shown in Fig. 4(b), and they are in good agreement.

Figure 4(c) shows the electric field calculated on the cavity surface at the injection frequency (37.77 MHz) for a gap voltage of 55 kV (27.5kV per gap), indicating a maximum field of 4.06 MV/m in the gap. It is quite far from the Kilpatrick breakdown criteria ~10 MV/m. Therefore, in principal, sparking in vacuum area is not a concern assuming that the cavity surface is relatively clean. On the other hand, the maximum electric field in air occurs nearby the edges of the tuner connection. The corresponding maximum field is about 1.7 MV/m, which is 57% of the field breakdown limit in air (3MV/m), as shown in Figure 4(b).

In order to account for the cooling mechanism used in the actual cavity, a convective heating boundary condition with convective heat coefficient of 8820 W/(m²·K) and temperature of 35°C was enforced on the tuner outer walls.

Fig. 4. Modeling of Fermilab’s booster cavity. (a) Picture of the cavity at test stand. (b) Measured vs. simulated quality factor. (c) Simulated electric field in MV/m. (d) Simulated thermal profile assuming 55 kV gap voltage and 15 Hz repetition rate.

On the other hand, losses have been averaged over the acceleration cycle by integrating the power over it. Figure 4(d) shows the thermal profile of the cavity with the 15 Hz repetition rate (50% duty cycle). Cavity will heat to 59°C dissipating 30 kW of power. Sophisticated water and air cooling are used to remove this power. Obviously, thermally induced frequency shift is not an issue for tunable cavities.

V. CONCLUSION

Electromagnetic heating is critical in copper RF cavities for particle accelerator applications. Thermal stresses and associated frequency shift is the main concern for fixed frequency cavities used in linear machines. Excessive heating is a major concern for ferrite loaded cavities used in cyclic machines. Cooling need to be carefully designed in both cases.

REFERENCES