MULTI-PHYSICS ANALYSIS OF THE FERMILAB BOOSTER RF CAVITY*

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Abstract

After about 40 years of operation the RF accelerating cavities in Fermilab Booster need an upgrade to improve their reliability and to increase the repetition rate in order to support a future experimental program. An increase in the repetition rate from 7 to 15 Hz entails increasing the power dissipation in the RF cavities, their ferrite loaded tuners, and HOM dampers. The increased duty factor requires careful modelling for the RF heating effects in the cavity. A multi-physic analysis investigating both the RF and thermal properties of Booster cavity under various operating conditions is presented in this paper.

INTRODUCTION

Fermilab is committed to a wide program in the high energy physic intensity frontier. This program requires doubling the current proton source throughput, while maintaining a reliable operation of an already 42 years old Booster through 2025 before the advent of Project X. In an effort to fulfil this commitment a proton improvement plan (PIP) is being enacted [1]. The plan addresses the necessary hardware modifications both for increased repetition rate and reduced beam loss, while ensuring viable operation of the proton source [1-2].

Specifically, PIP addresses the necessary changes in the current proton source in order to increase its throughput from the current 1.0E17 protons/hour (at 7 Hz) to 1.8E17 protons/hour (at 12 Hz) by May 1, 2013 with the launching of the NoVA experiment. A second increase in the throughput to reach 2.25E17 protons/hour (at 15 Hz) is planned by January 1, 2016 with the startup of the g-2 experiment, as shown in Figure 1. Moreover, PIP aims to maintain the proton source availability better than 85%, and to limit the residual activation within acceptable levels, while ensuring operating life of the proton source through 2025 [1-2].

In fact, an increase from the current 7 Hz repetition rate to 12 Hz and, eventually to 15 Hz increases the power dissipation in the RF system of the proton source. To ensure a reliable operation at the required higher duty factors, the present design of Booster cavities need to be carefully examined to study the consequences of increased repetition rate on their operation.

In this paper, a thorough multi-physic study investigating both the RF and thermal properties of the Booster cavity under various operating conditions is presented. The study is geared towards addressing the concerns of voltage breakdown, and heating in the high RF current connections in the Booster cavity with 15 Hz repetition rate.

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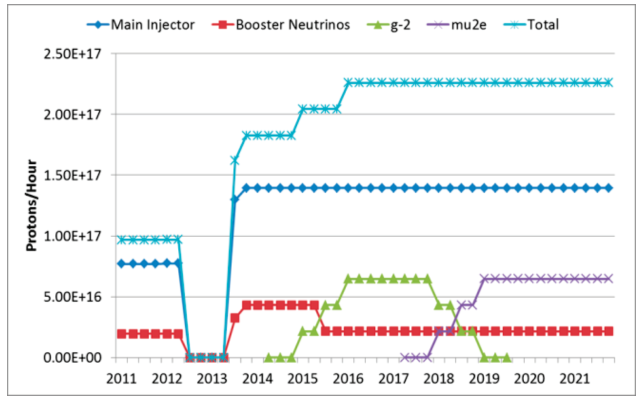

Figure 1: Fermilab's proton improvement plan.

BOOSTER CAVITY

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 [3].

Each RF cavity is a half-wave resonator, as shown in Figure 2(a), loaded with three coaxial ferrite tuners separated by 90° rotation angle and the cavity is fed by a tetrode power amplifier located at the fourth 90° angle [3-4], as shown in Figure 2(b).

Each half ferrite tuner consists of 14 concentric ferrite rings of 1" in thickness separated by copper washers of 0.25" in thickness, as shown in Figure 2(c). 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 2a.

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.

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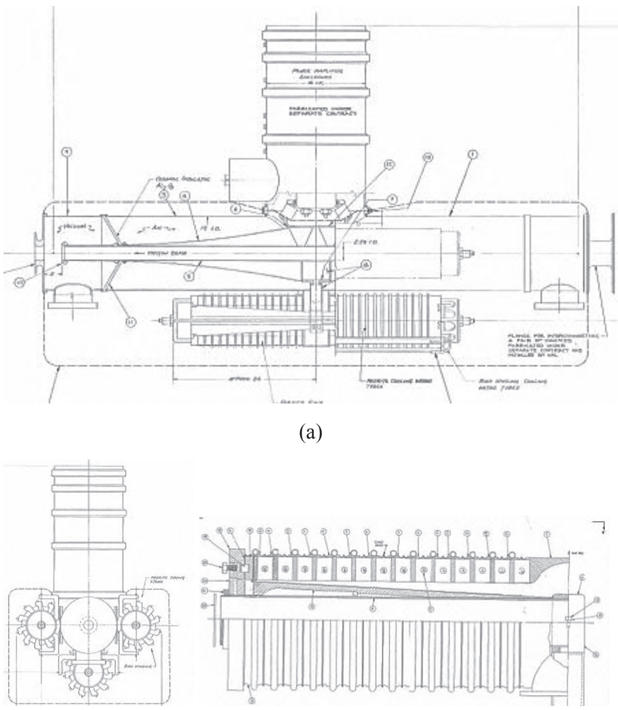


(a)

(b) (c)

Figure 2: Geometry of the Booster cavity.

RF MODEL AND ANALYSIS

A full 3D cavity model with all required details has been created in Comsol Multiphysics [5], as shown in Figure 3. Utilizing the symmetry of the structure by enforcing perfect magnetic conductor boundary conditions on the symmetry planes allows simulating just one quarter of the structure, thus reducing the complexity of the computation.

Figure 4 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 3.28 MV/m in the gap. It is quite far from the Kilpatrick break down criteria ~10 MV/m. Therefore, in principal, sparking in vacuum area shouldn't be a concern if 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 17 kV/cm, which is 57% of the field breakdown limit in air (30kV/cm) as shown in Figure 4(b). It is worth noting that, the maximum field value depends largely on the blend radius of the cavity edges, as shown in Figure 4(c).

Given that the material properties change during the frequency sweep from the injection frequency (37.77 MHz) to the extraction frequency (52.81 MHz), we have tried to match our simulation model to the actual measured quality factor of the cavity during normal operation. Figure 5 shows the simulated curve (solid blue) compared to the measured actual value (dotted red). Good agreement between the simulated values and the measured values was obtained by adjusting the material properties in the model. This step was imperative in order to get realistic losses and temperature profile. The overall quality factor of the cavity ranges from 280 at the injection frequency to 1100 at the extraction frequency.

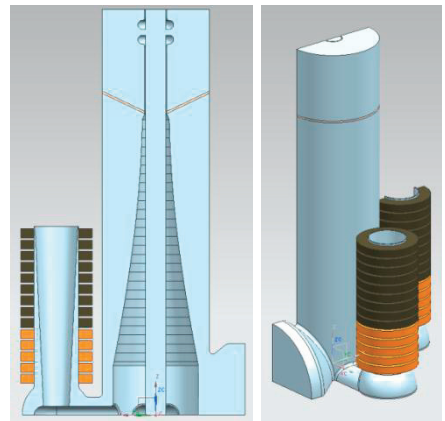
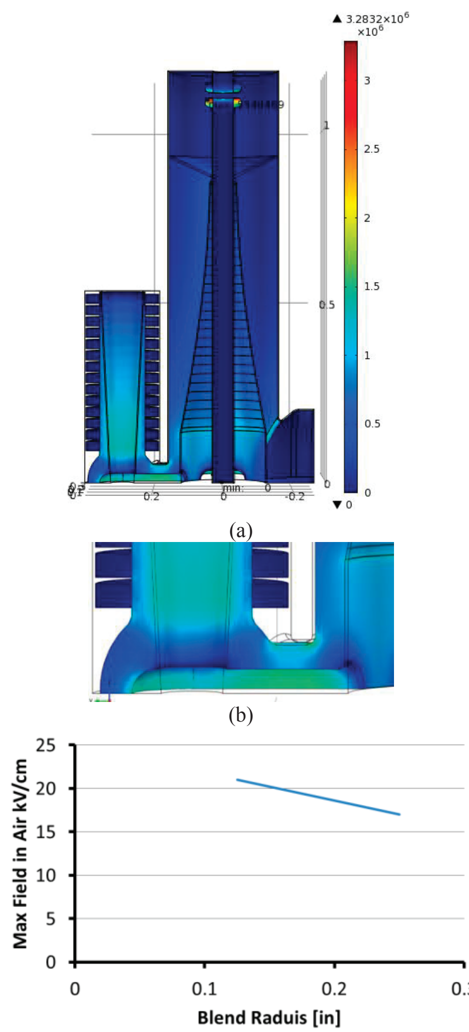


Figure 3: 3-D simulation model for a quarter of the Booster cavity.



(a)

(b)

(c)

Figure 4: Simulated electric field (55 kV gap voltage): (a) on the surface of the Booster cavity ,(b) on the tuner connection, (c) maximum electric field in air versus edge blend radius.

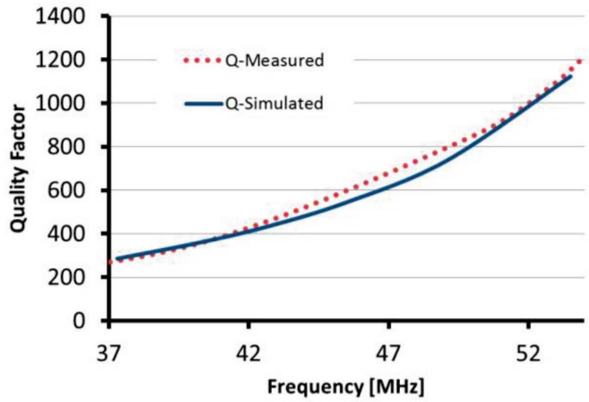


Figure 5: Simulated quality factor versus frequency of the Booster cavity compared to measured curve.

THERMAL ANALYSIS

Thermal analysis was carried out to the model considering the electric and magnetic losses as heating sources, where the energy loss density (in W/m^3) for electric and magnetic losses are

$$WE_{loss} = \omega\varepsilon''|E|^2 \quad , \qquad (1)$$

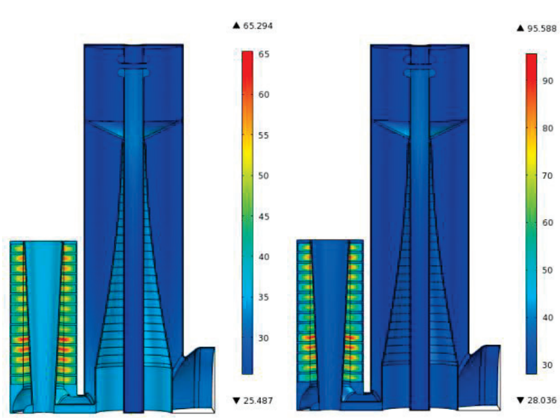
$$WH_{loss} = \omega\mu''|H|^2 \, , \qquad (2)$$

where ε" and μ" are the imaginary parts of the permittivity and permeability, respectively. Also, the surface losses (in W/m^2) on the cavity wall was included

$$WS_{loss} = \frac{1}{2}R_s|H|^2 \ , \ R_s = \sqrt{\frac{\omega\mu}{2\sigma}} \quad , \qquad (3)$$

where R_s is the surface resistance and σ is the conductivity of copper walls.

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/(m^2.K) was enforced on the tuner outer walls. On the other hand, losses have been averaged over the frequency cycle by integrating the power over it. Figure 6 shows the thermal profile of the cavity with the current 7 Hz and for the required 15 Hz repetition rates.



(a) (b)

Figure 6: Thermal profile of the Booster cavity under (a) 7 Hz operation. (b) 15 Hz operation.

Table I summarizes the losses in the different parts of the cavity under both operation scenarios. Losses in the cavity at 7 Hz operation with 55 kV is about 16.6 kW resulting in a maximum temperature in the tuners of 65° C (149° F), while it is projected to increase to 32.8 kW at 15 Hz operation resulting in a maximum temperature of 96° C (205° F).

Table 1: Summary of the Losses in the Booster Cavity with 55kV

	7Hz	15Hz	Units
Max Field in Vacuum	3.3	3.3	MV/m
Max Field in Air	17	17	kV/cm
Electric Loss/Tuner	146	300	W
Magnetic Loss/Tuner	5.1	10.2	kW
Cavity Inner Cond Losses	39	79	W
Tuner Cone Losses	30.5	61	W
Ceramic Losses	22	45	W
Wall Losses	0.65	1.3	kW
Loss/Tuner	5.3	10.5	kW
Total Losses	16.6	32.8	kW

CONCLUSION

Fermilab's Booster cavity has been modelled and analysed to investigate the potential risks of voltage breakdown and overheating associated with increasing the current repetition rate from 7 Hz to 15 Hz. To mitigate the voltage breakdown in air, blending the edges of the cavity with about 0.25" seems to be sufficient to keep the maximum field far lower (57%) than the breakdown limit. The study has shown that the losses in the cavity would increase from 16.6 kW to 32.8 kW and the maximum temperature is projected to increase in the tuners from about 65° C to 96° C, upon increasing the repetition rate from 7 Hz to 15 Hz. Additional cooling inside the tuner is needed to mitigate the increased heating.

ACKNOWLEDGMENT

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