SIMULATION AND DESIGN OF A 70 MeV CYCLOTRON RF SYSTEM

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Abstract

The electromagnetic and mechanical design of the resonant cavity for a 70 MeV compact commercial cyclotron has been conducted by Best Cyclotron Systems Inc. Various resonator configurations have been studied for a radial, single-stem design and an optimal solution was selected with excellent electromagnetic properties and minimized construction and operational costs. Rapid model iterations during the design, using CST Microwave Studio* and ANSYS†, allowed for accurate tuning of geometry to precisely define the shape of the accelerating voltage profile, surface current distribution, and total power loss. The RF system of the BEST 70p cyclotron will operate at the fourth harmonic with two $\lambda/2$ separated resonant cavities shielded at the center allowing for beam modulation techniques to be applied through phase modulation of the accelerating voltage.

INTRODUCTION

General Description

This paper describes the simulation and design methodology for a single-stem, room temperature, copper resonator operating on the fourth harmonic. The RF system is designed to accelerate $700\mu A$ of H^- ions to $70MeV$ with the relevant performance requirements outlined in Table 1.

Table 1: Relevant Design Parameters

Resonant Frequency	$56.2MHz$
Max Temp. Change	$14°C$
Dee Tip Voltage	$60.0kV$
Voltage Stability	$5 \cdot 10^{-4}$
Phase Stability	+/– 0.1°

Using the 3D CAD program SolidWorks‡, a model of the resonator was created. This model, Fig. 1, consists of the copper resonant structure and an enclosing vacuum box which is the spatial boundary of the model as defined by the magnet valley. To reduce construction costs the resonator stems and dee-plates are made from standard size copper components. The dee-plate is created by forming a thin copper plate into a slight dome shape, raised towards the central stem interface. All copper is oxygen-free high conductivity (OFHC). For this study, mechanical interfaces between components are considered perfectly connected, both thermally and mechanically.

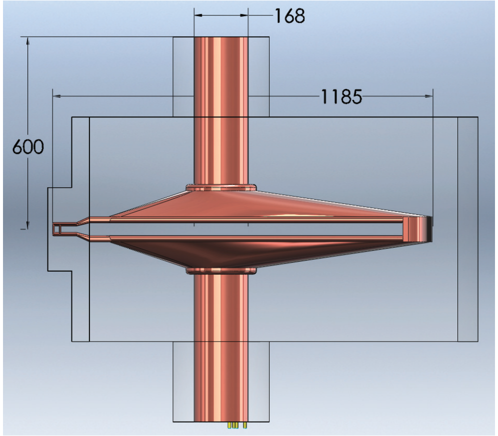

Figure 1: General geometric dimensions of the resonator structure in mm.

Stable resonator temperatures are crucial during the operation of the cyclotron and, as such, special attention is given to the design of the cooling mechanisms. Two independent cooling lines are used per quarter of the resonator with a third line for the ground electrode. Each dee stem is composed of an inner and outer pipe with the gap between the two utilized in creating a helical cooling channel. A second cooling line is run along the dee plate and comprises the second cooling circuit.

Coupling and Tuning

Each resonant cavity will have a capacitively coupled power input connected to a rigid coaxial line. An externally mounted stepper motor allows for adjustment of the coupler in and out of the cavity to compensate for beam loading effects. The linear vacuum motion is implemented with copper bellows.

In addition, each cavity has two tuners similarly controlled by external motors for coarse and fine tuning of the cavity frequency. These allow for frequency tuning of the two independent resonators as well as fine adjustment during thermal expansion to ensure phase stability of the resonant system.

SIMULATION RESULTS

Electromagnetic Response

Of primary concern when designing resonators is their electromagnetic characteristics. Thorough studies were

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[*] http://www.cst.com/

[†] http://www.ansys.com/

[‡] http://www.solidworks.com/

conducted to properly characterize the RF system and to correlate the RF performance with different geometric configurations. Having studied both a two-stem and non-circular stem structure, it was found that a simple single stem design performed best when considering power loss, voltage profiles and mechanical stability [1]. Using the CST Microwave Studio eigenmode solver, the resonator's parameters were determined and the results are summarized in Table 2.

Table 2: A Summary of the Simulation Results

Resonant Frequency	$59.8MHz$
Quality Factor	8275
Shunt Impedance	$135k\Omega$
Power Loss	$12.7kW$
Dee Tip Voltage	$60.0kV$
Dee Outer Voltage	$69.7kV$

In addition to these RF parameters, the electric field shown in Fig. 2 was investigated to identify the mode shape during resonance. By studying the areas of maximum electric field and comparing them to the Kilpatrick Limit, one can predict the likelihood of RF breakdown in a given region [3]. It was found that the electric field along the accelerating gap ranges from $8.2 - 2.0MV/m$ which corresponds to $0.9 - 0.2$ times the Kilpatrick Limit at our designed $56.2MHz$ frequency.

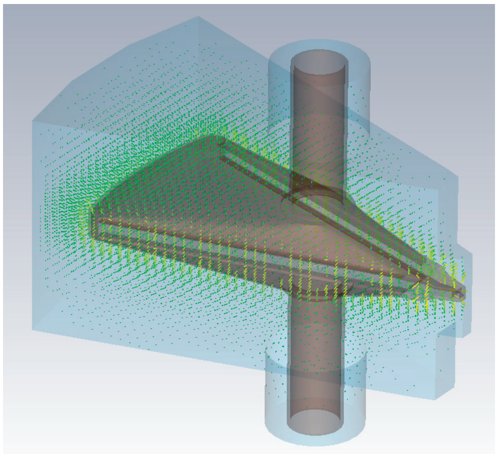

Figure 2: A logarithmic plot of the electric field.

Based on the inflector and central region design, an accelerating voltage of $60kV$ at the dee tips has been selected. Ideally the voltage profile will increase towards outer radii to reduce Lorentz stripping losses at high energies. Figure 3 shows the dee voltage along the accelerating gap scaled to $60kV$ at the tip. These values are calculated on the median plane by integrating the tangential electric field across the accelerating gap at various radii.

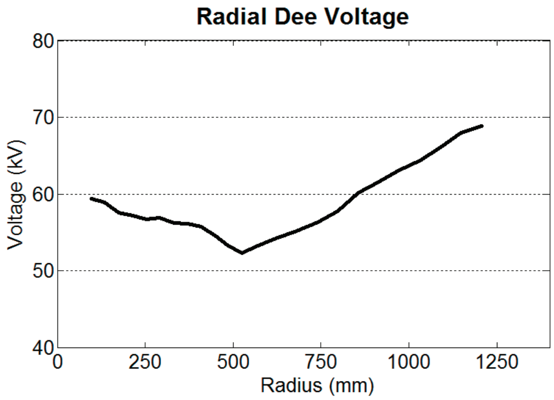

Figure 3: Radial dee voltage profile across the accelerating gap.

Thermal Effects

Resulting from the electromagnetic solution, the current distribution on the copper surface is used as an input heat load for the thermal simulation. A visual plot of the distribution is shown in Fig. 4. It can be seen that the highest current density exists at the inductive stem section as expected. This indicates that cooling will need to be focused in this region.

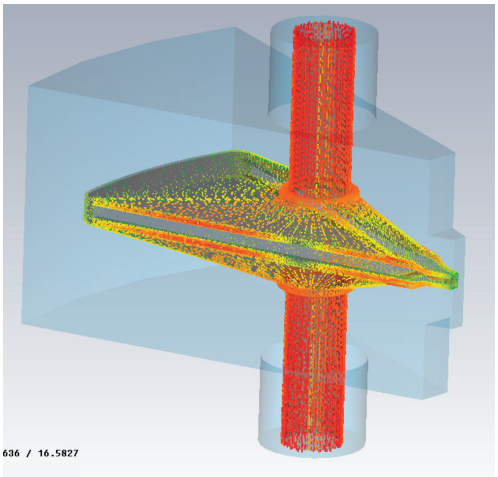

Figure 4: Surface current distribution of the resonator, with a maximum of $4200A/m$ on the stems.

Thermal analysis using ANSYS was conducted on the resonator model to determine surface temperature distributions, thermal deformation and optimal cooling line routing. During design, a large emphasis is placed on reducing the maximum surface temperature as well as reducing the temperature gradient which can lead to mechanical stresses. Figure 5 shows the temperature distribution of the half resonator while dissipating $7.12kW$ of power.

The maximum temperature of the resonator surface is $29.2°C$ which corresponds to a rise of $9.2°C$. It is possible to reduce this temperature gradient further by optimizing the location of the dee-plate cooling circuit. As noted pre-

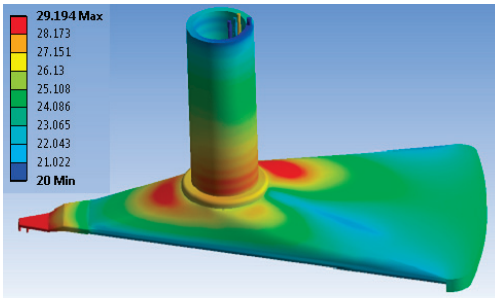

Figure 5: Surface temperature profile of the resonator at $7.12kW$ of power dissipation.

viously, the highest current density (and thus thermal load) occurred on the stems. Accordingly, the simulation results show that the stem cooling circuit dissipates $5.7kW$ of the total input power, whereas the dee-plate circuit only dissipates $1.4kW$.

While no computational fluid dynamics is actually conducted for this thermal simulation, the cooling line elements are still modeled in such a way as to behave as a realistic cooling line. That is, they have a discrete approximation of a continuous heat flux along their length, where the convection coefficient is calculated using the Dittus-Boelter equation for turbulent flow of a cooling liquid [2]. Using this approximation drastically reduces simulation times while maintaining the accuracy of the results.

Mechanical Stability

Two further mechanical simulations were done to determine the stability of the resonators.

Firstly, the static deflection of a resonator due to gravitational loading and thermal expansion was studied. It was found that a maximum deflection of $0.19mm$ occurred at the outermost location of the dee plate, and $0.16mm$ at the dee tip. This deflection is almost entirely in the vertical direction and thus can likely be reduced by introducing structural ribs on the dee plate.

Secondly, a vibrational analysis of the first five harmonic modes was conducted. The modal response is summarized in Table 3, and Fig. 6 shows the shape of the fifth mode. Knowing these resonant frequencies allows us to avoid their excitation during pulsed mode operation of the cyclotron.

Table 3: Mechancial Frequency Response

Mode	Frequency (Hz)
1	45.4
2	66.5
3	97.5
4	118.0
5	129.0

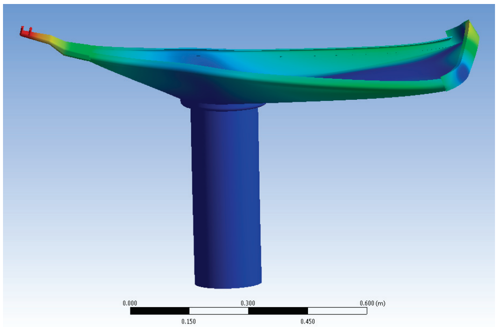

Figure 6: The fifth vibrational mode, occurring at $129Hz$.

CONCLUSION

The initial design has been completed for the Best Cyclotron Systems $70MeV$ cyclotron resonators. They have been designed using modern electromagnetic, thermal, and structural analysis software which made rapid iterations possible. The current theoretical model operates at a resonant frequency of $59.8MHz$ which is higher than the design frequency but will be decreased by adjusting the geometry and re-evaluating. The resonator dissipates $12.7kW$ of power and, when adding a slight margin to bring the power dissipation up to $14.2kW$, the thermal analysis shows that the maximum temperature rise of the resonator is $9.2°C$. The accelerating voltage profile has been optimized by adjusting the resonator geometry, and the cooling line routing is being improved to reduce thermal gradients. In addition, the first five vibrational modes have been determined as well as the static and thermal deflection of the resonators.

The final resonator design will follow based on the results obtained and described in this paper. Fine-tuning of the resonant frequency will occur with further electromagnetic modeling, and the cooling system configuration shall be adapted to minimize temperature gradients. A final cold-test will be performed on the manufactured resonators to match the design frequency by adjusting the stem length.

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