HFSS SIMULATION OF VACUUM TUBE RF POWER AMPLIFIER

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Abstract

Development and upgrade of rf power amplifiers require comprehensive calculations to predict and optimize various parameters of the system before hardware modifications are applied. ANSOFT HFSS code provides a powerful tool for 3D EM simulation of the amplifier output resonator comprising a vacuum tube as a passive element. Two examples of this kind of simulation applied for upgrade of the TRIUMF Cyclotron rf system are presented in this paper.

INTRODUCTION

The TRIUMF 500 MeV cyclotron main accelerating structure is powered by 1.6 MW rf system based on tube power amplifiers (PA) operating at 23.06 MHz [1]. Continental Electronics had built PA system almost 35 years ago, and now it naturally requires an upgrade. Though the cyclotron demonstrates relatively high availability: over 90% in average, rf system was always responsible for a half of machine downtime (about 200 hours annually). In 2001 we started a comprehensive refurbishing program, which resulted in reducing of rf downtime by factor of 3 last year [2]. Next step in this program involves PA improvements aiming higher reliability. There is another ancillary accelerating resonator in the cyclotron (rf booster) running on 4th harmonic (92.24 MHz) of the fundamental frequency [3]. It improves beam quality and reduces radiation spills. RF booster PA also requires an upgrade to accommodate another type of power tube. We consider rf modeling to be an essential stage preceding PA system modification. Nowadays there are a lot of means to accomplish 3D EM simulation. One of the contemporary codes is HFSS [4]. Both amplifiers were studied using this program.

RF BOOSTER AMPLIFIER

The final stage of the rf booster amplifier was designed for EIMAC tethrode Y-567B. Nowadays the production of this type of tube is discontinued. On the other hand the EIMAC tetrode 4CW150,000E, which is common for other TRIUMF rf systems, gives similar performance and is almost compatible with a present amplifier design except for anode flange dimension. The original tube flange diameter is smaller. In principle a replacement tube can be modified to fit the installation saddle, but there is always a risk of breaking the tube in the machining process. A slight difference in the anode - grid capacitance (measured up to 8%) represents another constraint in direct tube substitution. It causes an output resonator frequency offset, which cannot be compensated by the tuner due to its limited tuning range. The output resonator modification was proposed in order to avoid tube machining and to expand amplifier tuning range. It involves new design of the anode holder and modification of the fixed tuner (detachable bulk copper insertion). In practice, having two different options of anode holder and tuner would give us an opportunity to use either type of two tubes.

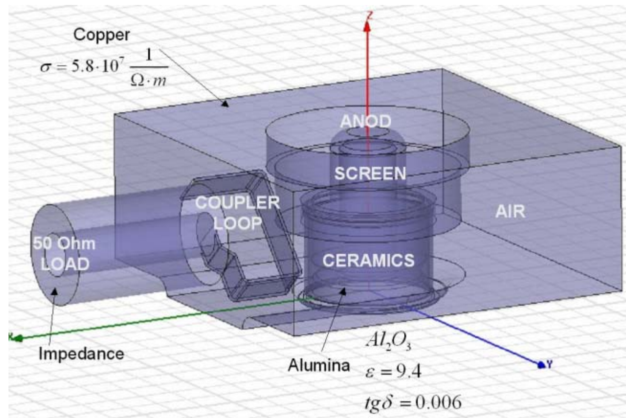

Figure 1: HFSS 3D model of the RF Booster Amplifier.

HFSS model of the output resonator was used to evaluate required modifications of amplifier components and rf parameters of the output resonator. Behavior of parasitic modes was also taken into account.

3D HFSS model is shown on Figure 1 and consists of the resonator, vacuum tube and coupler. The real resonator is furnished with an adjustable frequency tuning plunger, which it is represented in the model by resonator top face. So the resonator height serves as a tuning parameter. The vacuum tube is presented with a set of coaxial electrodes and ceramic isolator. The coupler loop is connected to the 50 W matched coaxial line.

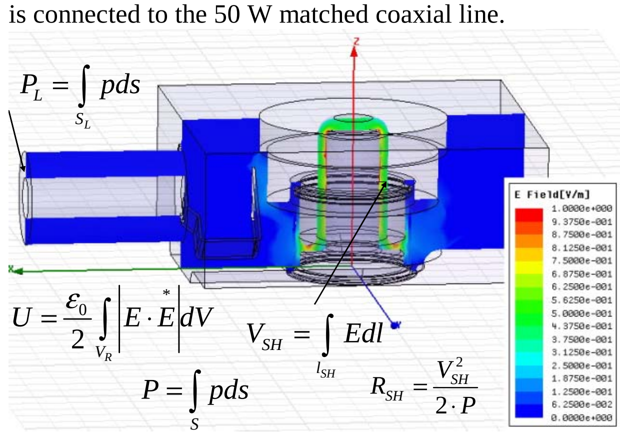

Figure 2: Operating mode electric field distribution in the amplifier output resonator.

Both original and modified models were simulated. For each case an HFSS Eigensolver solution gave us a set of eigenmodes and EM field arrays. Figure 2 presents electric field in the resonator at operational frequency of 92 MHz and some equations determining resonator

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parameters: stored energy (U), power dissipation in the resonator walls (P), power in the 50 W load (P_L), anode rf voltage (Vsh) and shunt impedance of the loaded resonator (Rsh). Anode rf voltage is calculated as an integral of radial electric field component across anode-grid gap. From the figure it is clear that maximum electric filed is localized inside the vacuum tube.

Calculated output resonator frequency dependence on the fixed tuner height (h) is presented in Figure 3. From here we evaluated that fixed tuner height has to be increased by 0.6" to get resonant frequency 92 MHz for the modified output resonator with tetrode 4CW150,000E.

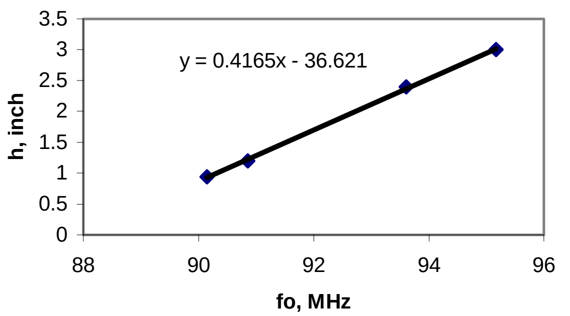

Figure 3: Fixed tuner adjustment curve for the modified output resonator.

Table 1 shows that the rf parameters for modified output resonator are very close to those of original one (rf coupler loop position was intact). Also we have not observed any noticeable change in the parasitic modes spectrum.

Table 1: RF parameters of original (OLD) and modified (NEW) output resonators for the operational frequency.

	h_s, inch	Q	R_{sh}, kΩ
OLD	0.94	57.4	1.48
NEW	1.54	58.6	1.56

Table 2: RF booster PA eigen modes spectrum.

f_0	f_1	f_2	f_3	f_4
92 MHz	145 MHz	179 MHz	200 MHz	255 MHz

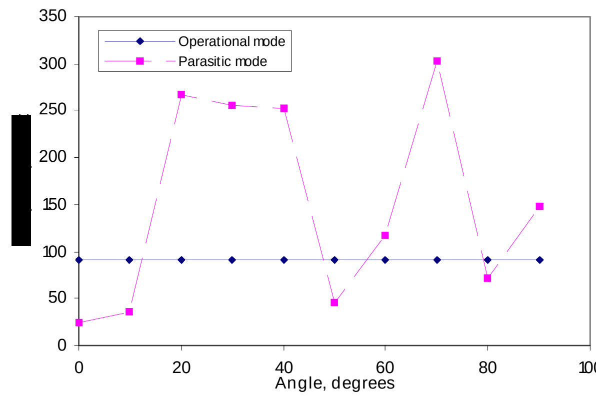

Figure 4: Nearest eigen mode's frequencies dependence on the coupler loop orientation.

MAIN POWER AMPLIFIER

Final stage of the cyclotron rf power generator consists of 4 power amplifiers (PA) running in parallel. Output power is combined to a 35 m transmission line via 3 power combiners. Each PA comprises 2 EIMAC tubes 4CW250,000B working in push-pull mode. Water-cooled l/2 inductor gave us troubles in the past being prone to water leaks in different locations in every PA. We have decided to reconsider inductor design and cooling circuit layout in order to improve system reliability. Facing constrains of limited access to the PA under operation, it was absolutely essential to evaluate the impact of modifications on rf parameters and system overall performance using electromagnetic 3D simulations.

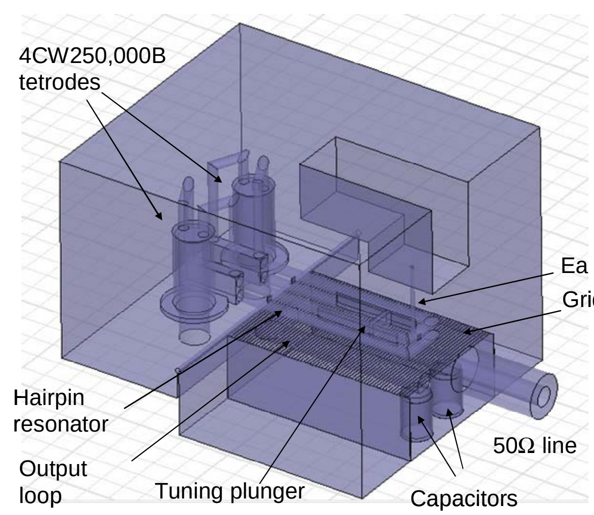

Figure 5: 3D HFSS model of output resonator for push-pull PA with 4CW250,000B tetrodes.

3D model of PA output resonator is presented in Figure 5 and consists of the cavity, which is divided by the grid into the resonator and output loop volumes. The resonator itself is a sort of l/2 oscillator loaded with tube's coaxial capacitances and grounded in the middle with anode power supply (Ea). The inductor is constructed from copper pipes, which deliver cooling water to the tubes, and has a hairpin shape. Output loop consists of another inductor loaded with 2 coaxial capacitors and 50 W output coaxial line. The resonator and output loop form the system of coupled circuits. The complete model is very complex, takes a lot of computer resources and still needs to be better developed and understood. Some useful results can be relatively easy obtained from simplified model. Figure 6 presents Eigensolver solution for magnetic and electric fields distributions on the plane between the hairpin and the grid for operating frequency (23 MHz). The output loop was omitted and the grid was presented as a conducting plane. This simplified model gave us satisfactory reference for rf parameters evaluation while dealing with certain structure modifications.

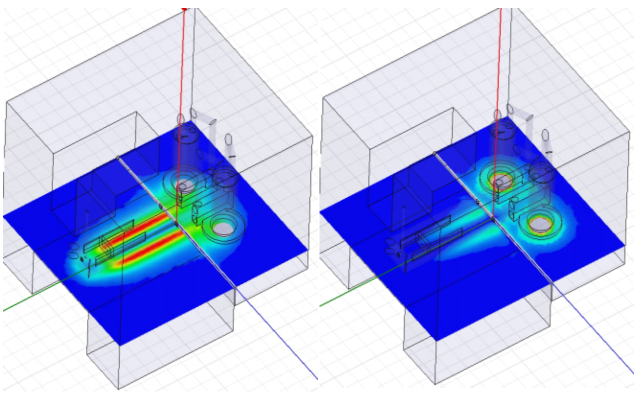

Figure 6: Magnetic and electric field distribution for simplified PA model at operating frequency of 23 MHz.

Exercises with simplified model suggested a useful technique of hairpin tuning, which is desired when power tubes are replaced. Putting a sheet of copper above the amplifier grid one can eliminate coupling to the output loop and thus use only hairpin shortening plunger to compensate frequency offset due to variations in plate-to-grid capacitance of the power tubes. This technique was successfully used for PA fine tuning.

A sample of Eigensolver solution for the full model with magnetic field distribution at operating frequency of 23 MHz is shown in Figure 7.

A number of different layouts for hairpin modification were evaluated in comparison with original design. The most efficient approach has been chosen and being fabricated now. Installation is planned for spring 2006. Also water cooling circuit upgrade was considered and simplified layout has been tested at full PA output power. At present stage the test revealed poor plastic pipe material, which started melting due to excessive heat caused by rf losses. Silicon tubing is being looked at as a replacement water line.

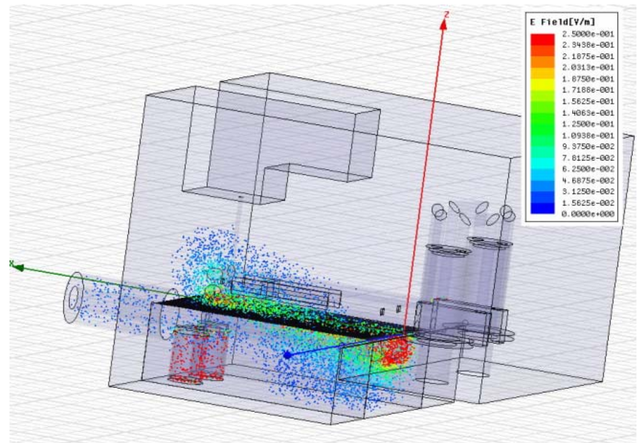

Figure 7. Magnetic field distribution in the cavity at operation frequency obtained from HFSS Eigensolver for full model.

CONCLUSIONS

Two rf power amplifier systems are being modified at TRIUMF basing on the HFSS simulation results. Calculations prevented us from expensive and time-consuming prototyping, which is difficult to afford for the operating year around machine. RF booster amplifier upgrade was proved through simulations. This will allow us to replace outdated vacuum tube with commonly used at TRIUMF 4CW150,000E tube, reducing costs of required spares at the same time.

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