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A STUDY OF A COOLING CONFIGURATION FOR AN OFHC COPPER REBUNCHER

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Abstract

A four gap OFHC copper rebuncher is developed at SNRC as a research study and a risk reduction for the MEBT of SARAF Phase II proton/ deuteron linac. The rebuncher is designed to bunch a 5 mA CW beam at 176 MHz. The required cavity voltage according to beam dynamics evaluation is 150 kV with a beam aperture diameter of 40 mm, beam energy of 1.3 MeV/u with a Q value of 8000. Considering utilizing this cavity for enhancing the beam energy, the cooling configuration is explored for a cavity voltage of 300 kV, consuming 20 kW dissipated power, at a peak electric field of 14 MV/m, equivalent to the Kilpatrick limit. The electromagnetic study conducted with the CST MW Studio was reproduced at ANSYS HFSS. The simulated dissipated power was assigned to the ANSYS Fluent model to explore the resulted temperature map. Several evolved cooling configurations were studied, including cooling of the drift tubes. In this configuration the temperature rise along the cavity is in the range of 30 K. A detailed design of the four gap rebuncher is following this study.

INTRODUCTION

An Oxygen Free High Conductivity (OFHC) copper 4 gap rebuncher is developed for the proton/ deuteron 5 mA Continues Wave (CW) SARAF linac at 176 MHz. The rebuncher beam energy is 1.3 MeV/u (beam β = 0.053) [1-3]. The required cavity voltage according to beam dynamics simulation is 150 kV with an aperture diameter of 40 mm with a Q value of 8000 [4]. We consider applying this cavity for enhancing the beam energy in order to reduce the ion velocity mismatch upstream the RFQ. In this case the peak electric field on the cavity surface is 14 MV/m (1 Kilpatrick Criterion) and the expected cavity voltage and dissipated power are 300 kV and 20 kW respectively. For normal functioning as a rebuncher the maximum field is 50% and, thus, the dissipated power is 25%. The rebuncher cooling configuration for 20 kW dissipated power is explored in this study.

MODEL ANALYSIS

The rebuncher configuration is shown in Fig. 1. The main components are: the RF cavity chamber, the upper fork with two drift tubes and the base cone with a drift tube. All these elements are made from OFHC copper. The electro-magnetic properties were simulated with CST MW Studio using the eigenmode solver (Fig. 2).

The next stage of the research was to simulate the 20 kW injected power regime. The coupler (Port 1) and the pickup antenna (Port 2) were introduced into the CST MW Studio and HFSS designs. The driven modal HFSS solver (Fig. 3) reproduced the similar results pattern that was generated by the CST eigenmode and driven modal solvers.

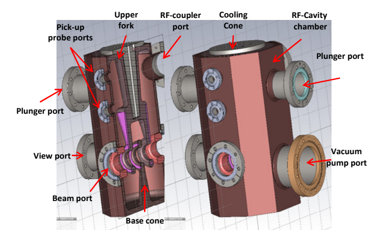

Figure 1: The rebuncher design.

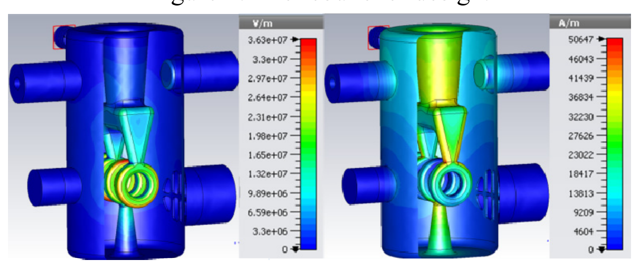

Figure 2: The induced eigenmode surface electric field (left) and magnetic field (right) at 176 MHz normalized for a 1 Joule rebuncher stored energy received from CST MW studio.

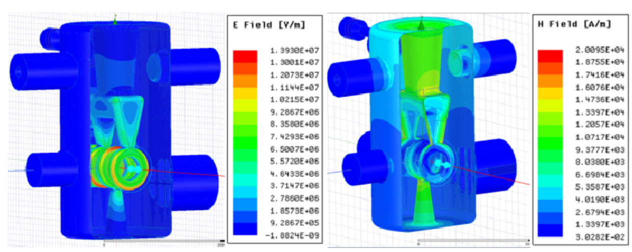

Figure 3: The induced surface electric field (left) and magnetic field (right) for 20 kW input power received with the driven modal HFSS solver.

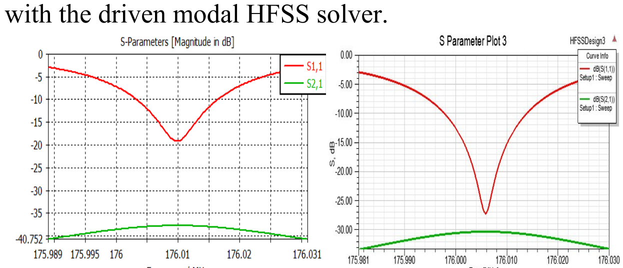

Figure 4: S-parameters of the rebuncher results from driven modal solvers of CST (left plot) and HFSS (right plot) - S11 (red curve) and S21 (green curve). The frequency range is the FWHM value (S21 -3dB level).

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Results of HFSS and CST driven mode solvers are shown in Fig. 4. The resonance frequency/Q-factor are 176.05MHz/3667 in HFSS simulation and 176.01MHz/4193 in CST. Small differences between the resonance frequencies and the Q-factor are well fitted into the tuning range of the system. The external coupling will be matched by the coupler antenna rotation; the resonance frequency will be tuned by two plungers.

The temperature mapping and the heating power flow were received by the rebuncher ANSYS Fluent solver and the HFSS driven solver co-simulations. Several evolved cooling configurations were studied. The basic cooling configuration is shown in Fig. 5. It includes cooling of the upper fork, base cone and the surrounding RF-cavity chamber.

The surrounding body temperature and the inlet water temperature are taken as 300 K. The water velocity at the entrance to each pipe was defined as 5 m/s. The temperature rise for the basic cooling geometry at 5 kW dissipated power is 46 K above the surrounding temperature (Fig. 6). Review of the obtained temperature map shows that the drift tubes are overheated and the outer wall is overcooled. The main goal of the future improvements of the cooling system design is to reduce the maximal temperature on inner surface of the rebuncher and reduce the temperature gradient along the rebuncher due to uniform of the thermal deformation of the structure.

The basic configuration was updated as follow: the cooling channels were included in the top drift tubes; four pipes in the central upper stem were replaced with two-pipe configuration (to reduce the manufacturing effort); the central drift tube was cooled by the long coaxial cone channel which penetrates the drift tube body up to the center of the ring wall (Fig. 7).

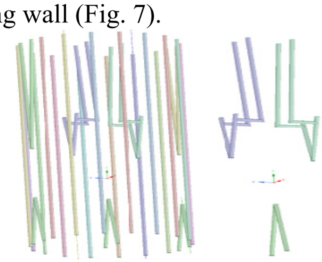

Figure 5: Basic cooling geometry: main chamber + central bodies (left) central bodies only (right).

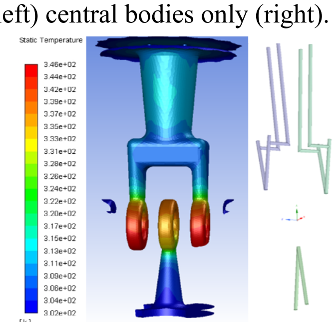

Figure 6: Temperature map on inner surface of the rebuncher due to 5 kW dissipated power (left) utilizing central cooling configuration basic model (right). All surfaces with a temperature increment less than 2 K are filtered out.

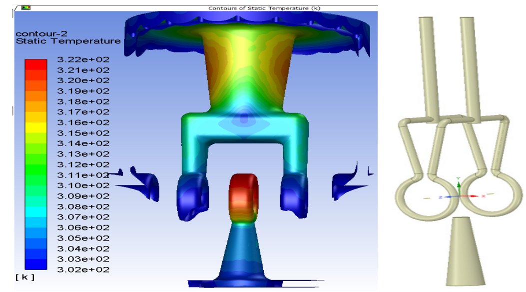

Figure 7: Rebuncher temperature map with two cooling pipes in the central stem and cooling lines in the top drift tubes due to 5kW dissipated power.

The improved configuration demonstrated a significant cooling increment of the drift tubes related to the basic configuration: 4 K compare with 46 K for the top rings and 22 K compare with 38 K for the central ring. On the other hand, the cooling abilities of the upper stem were reduced. As a result of this, the stem temperature increment and the azimuthal temperature deviation were increased from 14 K to 20 K and from 1 K to 8 K respectively.

Based on the previous stages, the derived configuration for the central elements of the rebuncher was introduced. Four cooling pipes configuration with the coaxial cooling channel was adopted for the upper fork. The central drift tube was cooled by an internal cooling line similar to the cooling lines configuration of an upper drift tube.

The 20 kW forward power regime was examined (Fig. 8). The maximal temperature increment 35 K was achieved on the upper fork. The drift tube temperature increment in the area of the peak surface electric field is 12 K. The temperature profile of the central elements is well balanced.

The peripheral elements of the rebuncher were taken into account on the next stage of the study. The coupler and pick-ups, two plungers, vacuum pump and viewport were located on their positions. This caused to the space separation of the cooling pipes located in the external wall of the cavity (Fig. 9). The 20 kW coupler loop and the plungers were cooled by additional water cooling channels. The neutral-convection boundary condition was defined on the external surfaces of the plungers and the pick-ups ports.

The temperature increment for the finalized rebuncher engineering assembly design is 38 K (Fig. 10) for 20 kW dissipated power and 300 kV cavity voltage. The stress analysis, point out that the maximum Von-Mises stress is 7 MPa (Fig. 11). This value is well below the yield strength of OFHC copper (69 MPa). The integrated thermal displacement of the drift tubes is defined as:

$$\Delta L = \alpha_L \Delta T * L$$

where α_L is the linear thermal expansion coefficient, ΔT is the temperature increment, L is the original body length. Under a uniform 38 K temperature increment assumption, the OFHC copper body (α_L = 16*10^{-6} K^{-1}) with the designed length 250 mm (the upper fork length), the integrated thermal displacement is equal to 0.15 mm. The mechanical displacement due to the atmospheric-vacuum

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pressure and the gravity results in the 5 µm displacement of the drift tube (Fig. 11), which may be neglected compare with the thermal one. The maximum off-axis transverse displacement limit, defined by the beam dynamics error study [1], is 1 mm.

Our cooling design presents higher cooling capability comparing to the CADS Injector2 recent two gap rebuncher, designed for a similar frequency (162.5 MHz) 40 mm beam aperture with a copper electroplated stainless steel chamber wall for a 10 mA, 2.1 MeV CW proton beam revealed – 10 kW dissipated power at 135 kV cavity voltage, 22 K temperature rise generated at a location between the stem and the drift tube with 0.1 mm drift tube thermal displacement, utilizing 2.5 m/s water cooled OFHC copper stem and drift tube [5].

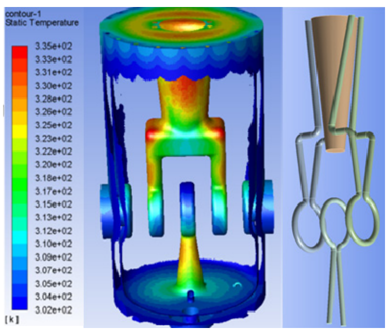

Figure 8: The Rebuncher temperature map for the derived cooling configuration with 4 cooling lines and a coaxial cooing cone at the top fork top cone and a cooling line for the central drift tube due to 20 kW dissipated power.

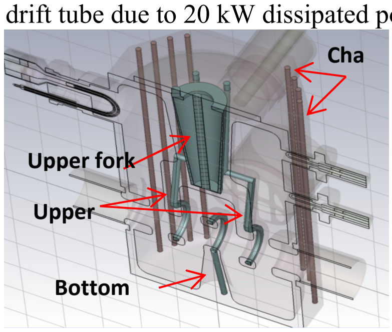

Figure 9: The rebuncher finalized engineering design with the integrated derived cooling configuration.

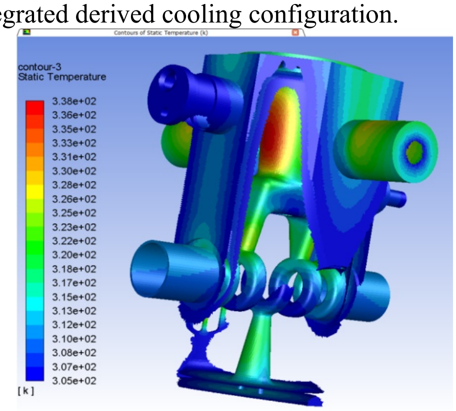

Figure 10: The rebuncher temperature ANSYS Fluent map for 20 kW dissipated power assuming reasonable distilled cooling water velocity of 5 m/s demonstrate modest temperature rise of 38 K.

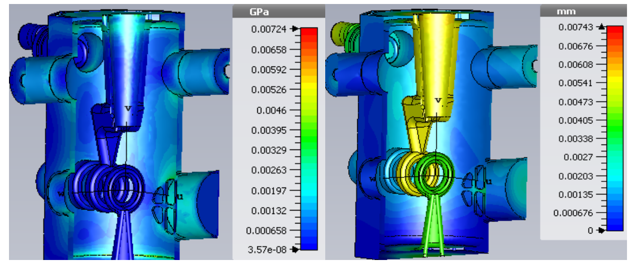

Figure 11: Von Mises Stress and displacement due to 1 bar pressure on the rebuncher external wall (internal vacuum) and self-weight assuming the auxiliary system will be supported independently neglecting the residual moment on the rebunc her- supported around the surrounding of the chamber bottom wall.

VERIFICATION ANALYSIS

The standard K-epsilon model was selected to simulate the fluent flow and heat transfer along the cooling paths. This is a robust model for a turbulent flow with a moderate pressure drop [6]. The inlet fluent velocity was studied in the range of 3-7 m/s for the 20 kW dissipated power.

The temperature profile was examined for the inlet flow velocity of 5 m/s and for cell mesh length of 3 and 4 mm. Comparison of the results for different mesh size does not show any significant deviation (less than 1 K). Due to this fact, all future simulations were run with 4mm cell mesh-length.

A 3D velocity distribution in a cooling channel corner is shown in Fig. 12. It was found that the temperature rise reduces from 38 K to 33 K for coolant inlet flow velocity variates in between 5-7 m/s. At the same time, the simulated pressure drop along the cooling lines increases above 1bar. Based on these simulations, the recommended distilled water flow inlet velocity is 5 m/s.

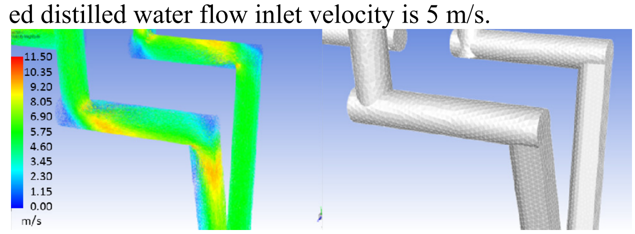

Figure 12: The fluent velocity path (left) for the derived 4 mm cell mesh-length (right)

CONCLUSIONS

An effective cooling configuration was derived in this study for the 4 gap rebuncher. A surface temperature increment of 38 K for 20 kW dissipated power for a reasonable distilled water inlet flow of 5 m/s was achieved. The total water pressure drop in the cooling system is less than 1 bar. The next step is to manufacture the rebuncher and to condition it for 5-20 kW dissipated power.

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