CW ROOM-TEMPERATURE BUNCHING CAVITY FOR THE PROJECT X MEBT*

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Abstract

The Project-X, a multi-MW proton source based on superconducting linac, is under development at Fermilab. The front end of the linac contains a CW room temperature MEBT section which comprises ion source, RFQ and high-bandwidth bunch selective chopper. The length of the chopper exceeds 10 m, so seven re-bunching cavities are used to support the beam longitudinal dynamics. The RF and mechanical designs of the re-bunching cavity including stress and thermal analysis are reported.

INTRODUCTION

In the Project X facility [1], a 3 GeV, H^- CW beam is delivered to three users simultaneously by way of selectively filling appropriate RF buckets at the front end of the linac and then RF splitting them to three different target halls. The linac medium-energy beam transport line (MEBT) [2] contains a chopper [3] that provides a special beam time structure in order to deliver the beams of required properties for each user. In order to achieve the beam longitudinal stability, MEBT contains seven room-temperature re-bunching RF cavities, operating at 325 MHz.

RF DESIGN

The main cavity requirements have been specified by the MEBT beam dynamics design [2]: a resonant frequency of 325 MHz, a relatively large aperture of 30 mm and an effective voltage of 46 kV. The shape of the cavity has been optimized using CST MicroWave Studio in order to obtain large shunt impedance, a reasonable space for the bunchers in the beam line and low maximum surface electric field to avoid any possible breakdown. In general the RF design is very close to the CCL type 324 MHz re-bunchers developed in [4,5].

A cavity RF volume as modeled by MWS can be seen in Fig. 1 along with simulated RF power loss distribution.

The power coupler and plunger tuner designs have been borrowed from the re-buncher cavity design for HINS [6]. Matching of the power coupler and estimation of the plunger tuning range have been also performed using CST MWS and HFSS. The main parameters of the re-buncher are presented in Table 1.

MECHANICAL DESIGN

The CW re-buncher mechanical design has two major challenges to meet.

The surface currents induced in the re-buncher generate a 0.92 kW heat load mainly concentrated on the drift tube noses. To remove this heat from the very inconvenient volume a complex cooling system has to be designed and its performance has to be simulated.

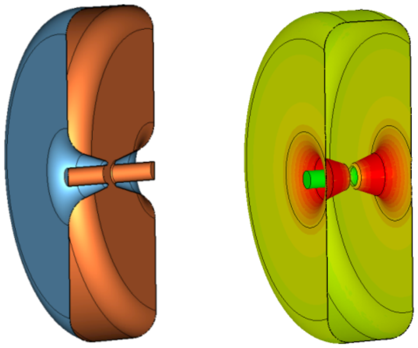

Figure 1: The 3D model of the chosen geometry from CST MWS and the power loss distribution.

Table 1: Cavity Main Parameters

Parameter	Value	Unit
Frequency	325	MHz
Particle energy	2.5	MeV
Effective voltage	46	kV
Q	28135	
Effective shunt impedance R_{sh}	2.3	MOhm
Power dissipation	0.92	kW
Peak electric field	10.3	MV/m
R_{sh}/Q	81.7	MOhm
Inner cavity diameter	555	mm
Bore diameter	30	mm
Gap	13	mm
Cavity length (wall-to-wall)	159	mm
Plug tuner range	450	kHz

Due to the internal vacuum, the mechanical structure of the cavity must withstand an inward differential pressure of 1 atm on all the outer surfaces. Taking into account the cavity diameter and extreme sensitivity of the cavity operating frequency to the gap distance, the quite thick end walls would be required to prevent cavity detuning. Besides they must be actually double walls consisting of a

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inner copper wall for electrical and thermal conductivity and a outer steel wall to withstand the pressure.

The main body of the cavity is made of Cu-OFE copper. To accommodate cooling channels inside the end walls while assuring RF performance, structural integrity and limiting the overall longitudinal space, the end walls are designed using an outer 6.35 mm thick stainless steel plate and a 20.44 mm thick copper plate. These plates are separated by a 4 mm gap (see Fig.2). Such end wall design has been successfully used in the HINS RT CH cavities [7]. The predicted maximum von Mises stress for the outer stainless steel plate is 204 MPa and its maximum deformation is 2.7 mm. The deformation of the inner copper plate is instead only a few µm.

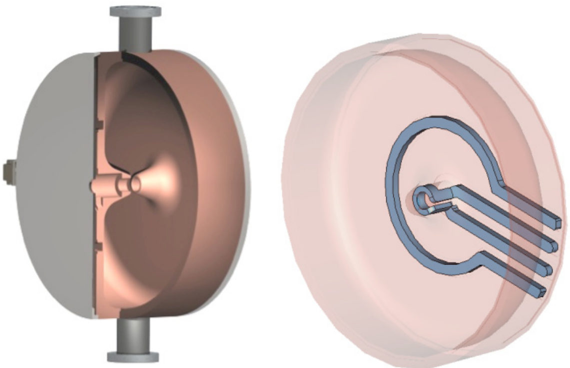

Figure 2: The cavity general view and the cooling channels cut out in the copper walls and the drift tubes.

The cooling channels are cut out in the copper walls and the drift tubes, and then covered with the brazed formed lids (Fig.2). The channels for the walls and the drift tubes are separate for easier manufacturing. They can be combined later outside the cavity or still be used separately to provide differential temperature tuning.

COUPLED RF, THERMAL AND STRESS ANALYSES

A series of RF and thermal analysis have been performed to verify the cooling scheme of the main body and the temperature distribution inside the tuner and the coupler.

The analyses are performed with the Finite Element code ANSYS Multiphysics and consist of combined RF and thermal-mechanical simulations. The power distribution assessed with the RF simulation is used as an input in the thermal analysis to evaluate the temperature profile inside the cavity and the consequent mechanical deformations. These deformations are then imported in an RF simulation to evaluate the frequency shift due to the power losses.

Cooling Scheme Analysis

The cooling scheme is shown in Fig. 2 and foresees two rectangular channels (circa 10 x 20 mm) cooling the cavity main body and the nose separately.

For the simulation work, we considered a water velocity inside the channels of 0.28 l/s, we approximated the channels with a round pipe with diameter 15 mm and we considered an inlet water temperature of 35° C. These values lead to a convection coefficient of 7250 $W/m^2/K$ convection coefficient [8] that we used in the analyses.

A combined RF and thermal analysis assessed the expected temperature distribution inside the copper body (Fig. 3) and the resulting frequency shift during cavity operation, at a voltage of 75 kV. The voltage of 75 kV instead of 46 kV shown in the Table 1 was used to have a good safe margin, since the MEBT design is not finalized yet and voltage increase is not excluded.

The temperature gradient in the area of the nose, where the maximum of the detuning effect is expected, is 4° C (Fig. 3). This leads to a deformation (Fig. 4), which reduces the cavity gap by 6 µm. The gap reduction causes a major frequency shift of -18 kHz. The frequency shift due to the overall cavity deformation is –23 kHz.

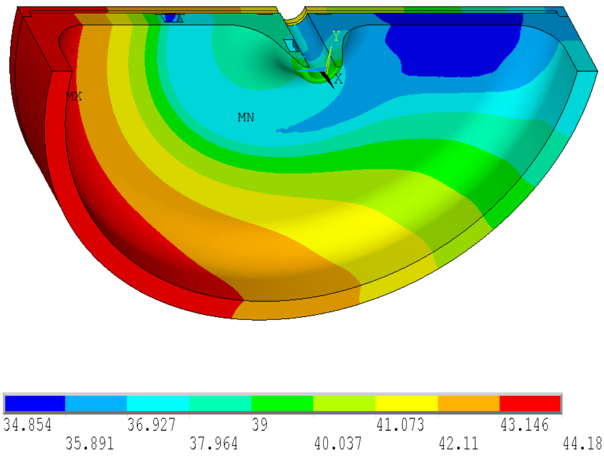

Figure 3: Temperature distribution inside the cavity; maximum 44° C, minimum 35 ° C, at the nose 39° C.

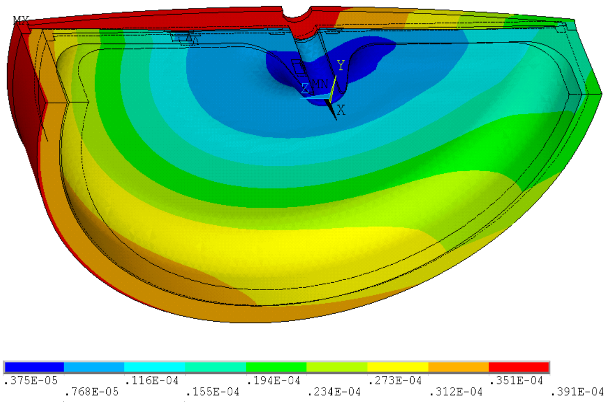

Figure 4: Deformation due to the above temperature distribution.

After the first iteration, we decided to study the dependency of the frequency shift from the water velocity inside the pipes. We additionally repeated the simulation for two acceptable water flow velocity values and obtained the results shown in the table 2 below. The table shows that the deformation and therefore the frequency shift do not depends strongly on water flow velocity. So, the water flow velocity is not a critical parameter at some extent and can be chosen on the basis of general MEBT cooling system.

Table 2: Water Flow Simulation Results

Water velocity (l/s)	0.28	0.4	0.55
Convection coeff. (W/m^2/K)	7250	9500	12750
Frequency shift (kHz)	-22.6	-18.3	-14.4

Tuner Analysis

The tuner, designed and built by JPAW, Inc for the HINS re-buncher, consists of a hollow cylinder attached to a motor that allows a maximum penetration of 60 mm inside the cavity wall. The slug diameter is 44.5 mm. If needed, it can be actively cooled.

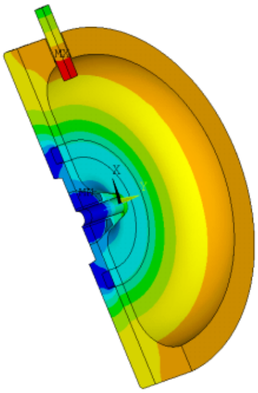

Figure 5: Temperature distribution at the tuner.

The analysis we performed evaluates the maximum temperature of the tuner during operation for an average penetration of 30 mm. The maximum temperature of 45°C is well below any critical temperature for the tuner materials and the brazing design, therefore no active cooling of the coupler is required during operation.

Coupler Analysis

To adapt the design of coupler, borrowed from the re-buncher cavity for HINS, to the needs of this cavity the penetration of the tip has been reduced to a reasonable minimum. Being the coupling still too high, the coupler body has been rotated of 40°.

Furthermore, the coupler design includes a rotatable flange welded to a stainless steel transition to allow independent adjustment of the coupling. An alumina ceramic window is utilized to separate the cavity vacuum from the surrounding air.

The coupler has been analyzed to assess the temperature distribution and resulting deformation due to the power loss during operation. Figure 6 shows that a maximum temperature of 50° C is reached at the tip of the coupler. This value is acceptable.

CONCLUSION

CW operation of the re-bunchers makes an adequate cooling the major challenge for the cavity design. The big cavity diameter and extreme sensitivity of the cavity operating frequency to the gap distance makes a cavity deformation due to atmospheric pressure also a serious issue.

The optimized RF design and the developed mechanical design reduced the impact of these factors to an acceptable minimum. All technical solutions and the re-buncher design in general have been verified by extensive coupled RF, thermal and stress analyses.

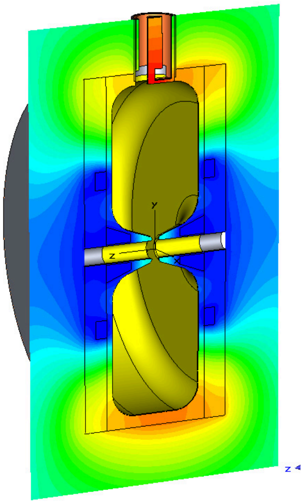

Figure 6: Temperature distribution at the coupler.

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