

CAVITY DESIGN, FABRICATION AND TEST PERFORMANCE OF 750MHz, 4-ROD SEPARATORS FOR CEBAF 4-HALL BEAM DELIVERY SYSTEM

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Abstract

A short version of the original CEBAF normal conducting 4-rod separator cavity has been developed into a 750 MHz one [1] since the concept of simultaneous 4-hall operation for CEBAF is introduced [2]. This work has been advanced further based on the EM design optimization, bench measurement and by conducting RF-thermal coupled simulation using CST and ANSYS to confirm the cavity tuning and thermal performance. The cavity fabrication used matured technology like copper plating and machining. The cavity flanges, couplers, tuners and cooling channels adopted consistent /compatible hardware with the existing 500 MHz cavities. The electromagnetic and thermal design simulations have greatly reduced the prototyping and bench tuning time of the first prototype. Four production cavities have reached a typical 1.94 MV kick voltage or 3.0 kW wall loss on each cavity after a minor multipactoring or no processing, 7.5 % overhead power than the design specification.

INTRODUCTION

Delivering CEBAF electron beam simultaneously to four experimental halls A-B-C-D scheme has been proposed by Kazimi in 2013 [2]. In this scheme, all halls have to run 250MHz repetition rate and one of A-B-C halls has to share the 5th beam pass with Hall D as shown in Fig. 1. To achieve this goal and not dismount existing 500MHz beam separation systems for Halls A-B-C, a 750 MHz RF separator system to kick beam bunches horizontally as the way shown in Fig. 2 is needed. Other hardware development and initial 750 MHz 4-rod type separator cavity were recognized [2].

Primary electromagnetic design optimization was done immediately after this proposal based on the existing 500 MHz, 4-rod type, normal conducting, deflecting cavities used at the CEBAF for 3-hall beam delivery system [1].

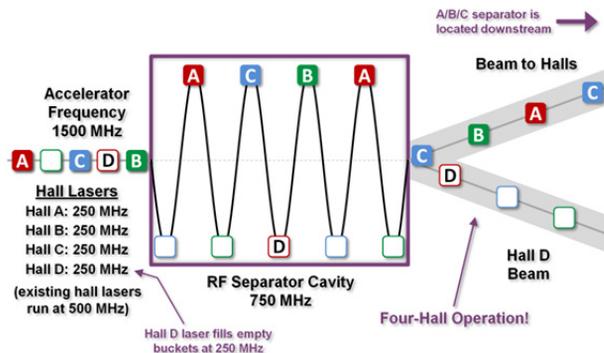


Figure 1: 4-hall beam operation with 750 MHz separator system proposed in ref. [2].

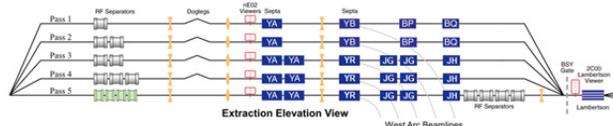


Figure 2: Four 750MHz separator cavities (in green colour) are installed on the 5th pass of CEBAF beam extraction system for horizontal deflection.

CAVITY DESIGN AND SPECIFICATION

Primary design optimization shows that the TEM 4-rod type deflecting cavity has a relative high shunt impedance R_t compared to elliptical and TE type cavities as long as the beam aperture to wavelength ratio is small. So we used the same aperture diameter (15 mm) as the 500 MHz cavities for the new 750 MHz design. By varying the rod diameters from 2 cm, 2.5 cm, 3 cm to 4 cm, we found the 2 cm's design gives the highest R_t versus the thicker rod diameters. Using the same cavity structure, tuner, body, mid and end flanges hardware as the original 500 MHz's cavity, only shortening the rods and body lengths were needed for the new design. So we were able to quickly prototype and produce these new cavities.

The cavity design parameters and specification are listed in the Table 1. To get a 170 μ rad kick angle for the 11 GeV beam, the total peak transverse kick voltage is 1.87 MV. If 4 cavities are to be used, each cavity has to run at 2.79 kW in peak power.

Table 1: Cavity Design Parameters

Frequency (π mode, MHz)	748.5
0-mode frequency separation (MHz)	+5.944
Cell-to-cell coupling (%)	1.21
Beam aperture (mm)	15
R_t/Q including TTF ($=V_t^2/(\omega U)$, k Ω)	17.71
Q_0 (calculated, for room temp. copper)	4426
Q_{ext}	4426
Klystron Power/cavity (KW)	2.79
Peak power loss density (W/cm ²)	28.1
Total cavity number	4
Total deflecting angle (μ rad)	± 170
Deflecting beam energy (GeV)	11.0

Both the 500 MHz and 750 MHz cavities' CAD models were generated started from the early engineering drawings. The electromagnetic (EM) and thermal

combined simulations using CST and ANSYS codes were carried out to confirm these design modifications as shown in Fig. 3 and 4. The mixed traveling (TW) and standing (SW) EM fields were generated in CST for the designed power input [3], then the power density field map was exported to ANSYS for the further thermal analysis [4].

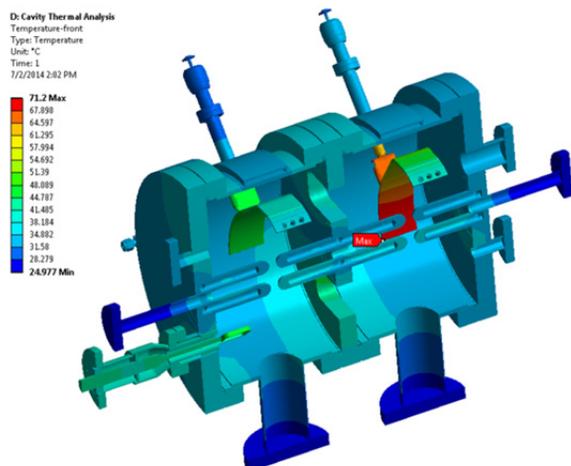


Figure 3: Temperature field by ANSYS thermal simulation.

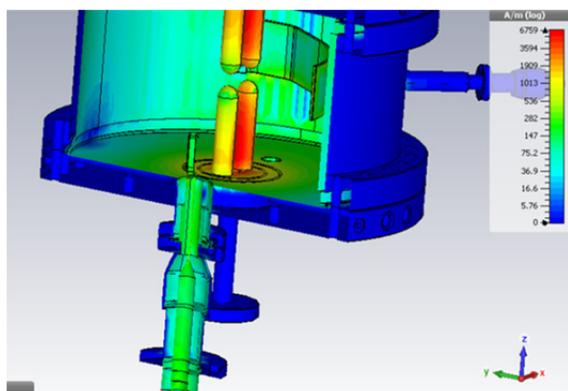


Figure 4: H-field contour plot from the CST simulation [3], where the RF coupler has traveling wave fields and rod structure has the standing wave fields.

The CST EM simulations found that loop coupler position, rotation angle and tuner paddle position have both functions of frequency and field flatness change between two cells. The frequency increase nears the critical coupling rotation angle is ~ 110 kHz. To get three parameters on target was also a numerical simulation challenge. An early designed coupler loop size had not considered the tuner paddle effect, thus a reduced loop size or pulling back the coupler insertion by a few mm was suggested. This problem has been also found during the bench measurement of the first prototype cavity. So a thicker (3.8 mm) copper gasket for the coupler flange was used instead for the insertion reduction. All production cavities use a smaller coupler loop size and move coupler hole's center by 1.4 mm closer to the rod than the original design to compromise these tuning issues.

The ANSYS thermal simulation was only performed for the structure's steady state temperature profile with the forced water cooling channel in a serial line connection. The power density from the CST was driven by 1.62 kW input RF power which is used as the heat source. The cooling water at inlet is 32°C at 2.3 gpm. The total heat removal in the ANSYS simulation has confirmed this power rate with a water temperature rise of 2.63°C . The steady-state peak temperatures for the paddle (pickup cell side), rods and coupler loop are 71.2 , 38.4 , and 45.2°C respectively. Based on the lessons learned from 500 MHz cavities, those anchor seats of tuner paddles were modified to achieve this performance. The cavity frequency tuning range and sensitivity analysis by the ANSYS were not done since it involves another EM simulation by ANSYS than CST. Instead a semi-analytical analysis was done based on a circuit model in which the rod-end capacitance changes due to the thermal expansion[3]. This analysis has been confirmed by the experimental data obtained from a 500 MHz cavity high power test. So the predicted tuning sensitivity for the 750 MHz is $12.6\text{ kHz}/^\circ\text{C}$, higher than 500 MHz's measurement in $8.3\text{ kHz}/^\circ\text{C}$.

CAVITIES' FABRICATION

The new cavity fabrication procedure has followed the 500 MHz cavity procedure since in the prior year two of these cavities were produced and installed at CEBAF. The cavity rods and tuner paddles are made of OFHC copper. Each rod has a blind cooling hole drilled on its axis. The cavity cylinder wall, mid and end plates are copper plated. All cavity parts and assemblies went through CNM survey, Micro-90 chemical cleaning (MCC) and ultrasonic DI water soaking (UWS) process. The cavity assembly was done in the Class-100 clean room.

BENCH TUNING AND BEADPULL MEASUREMENT

Cavity bench tuning is critical to achieving operation frequency, field flatness between the two cells and critical coupling for the π mode. The original procedure was developed by Wissmann for the 500 MHz cavities before the CABAF installation. It was then modified by Buaphad on a 500 MHz cavity with the help of a bead-pull measurement [5]. During the tuning process, the position of tuner and rotation of drive loop will cause frequency shifts and field flatness changes as well as coupling coefficient. Thus the combination of the tuner position, rotating angle and insertion of the coupler loop will be done interactively in order to obtain all target values. One suggestion on the 500 MHz cavity was to use a hand tuner to change the rod parallel open angle to fine tune the cavity cell's frequency through the vacuum ports after the cavity assembly. A CST simulation also indicated that by moving the rod-pairs closer will give 2.42 MHz/mm tuning sensitivity. A similar bench tuning procedure was only practiced on the 750 MHz cavity prototype with a bead-pull measurement. Fig. 5-6 show the typical tuning

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results on the target values of frequency, coupling and field flatness. The first production cavity 5-1 followed the same procedure without a bead-pull has shown a good high power test performance at both beam off-line and in-line conditions.

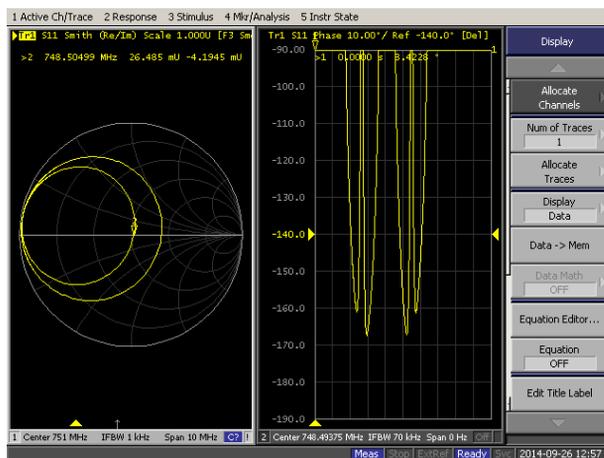


Figure 5: Bead-pulling plot (right) and Smith-chart of S11 (left) at input coupler port after tuning the field flat on the prototype cavity.

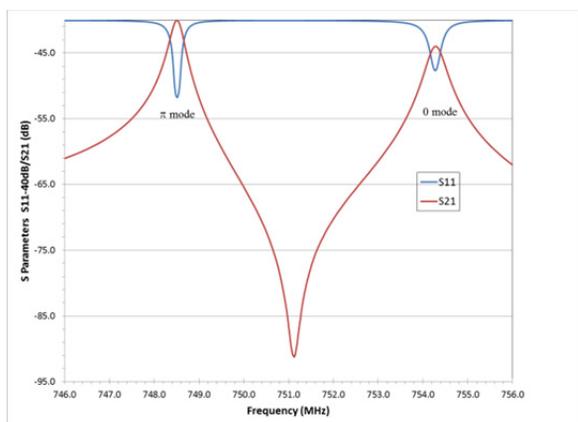


Figure 6: S11 and S21 plots in frequency span of Fig. 5.

HIGH POWER COMMISSIONING

The first prototype and four production cavities all went to an off-line high power test before their in-line installation. The high power rise shown on the 5-1 cavity is representative of all other cavities. It achieved a maximum forward power of 3.27 kW with only 41.1 W reflection in 3.25 hours period with minor vacuum activity at the highest level. The calibrated pickup probe on the cavity wall loss indication was 3.09 kW. The off-line commissioning of the first prototype cavity exhibited a multipactoring (MP) barrier at ~0.8 kW. After pulsing and CW high power processing, the barrier disappeared allowing us to reach >3 kW level. A closed open-inspection after the test indicated that the oxidization residual left from the MCC and the UWS on the brazing grooves near the coupler side of rods could cause this MP as marked in Fig. 7. A better cleaning procedure has been developed on later production cavities and no heavy MP

barrier was found since in later high power tests. With limited test data during the power rise, a preliminary water temperature tuning sensitivity was found to be near -14.9 kHz/°C.



Figure 7: Chemical residual left on the prototype cavity caused a MP barrier and electron activity in its high power test.

All four production cavities have been installed at CEBAF as shown in Fig. 8. The first in-line test with kicked beam was carried out in March in a relative short beam study time. The e-logs recorded primarily dealt with cavity control, beam optics configuration and a failure of a high power phase shifter. New bench tunings on all cavities will be redone this summer and in-line commissioning with beam effort will be resumed this fall.



Figure 8: The 1st and 2nd 750 MHz cavities installed on the 5th beam pass of CEBAF under the 500 MHz cavities.

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