HEATING AND STRESS IN THE LANSCE SIDE-COUPLED LINAC RF CAVITIES*

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Abstract

RF heating and related temperature distribution and stress are important problems in room-temperature accelerating cavities operating at high duty factors. To evaluate feasibility of higher duty operations of the Los Alamos Neutron Science Center (LANSCE) side-coupled linac (SCL), we have performed a combined 3-D electromagnetic (EM) and thermal-stress analysis of the SCL RF cavities. In the process, we have developed a procedure for data exchange between the electromagnetic (MicroWave Studio) and engineering (COSMOS, ANSYS) codes for the combined EM-engineering analysis. This procedure can be useful for other applications with room-temperature accelerating cavities.

INTRODUCTION

The LANSCE linac high power operations historically used duty factors up to 10-12%. To evaluate possible higher duty operations, we analyze the 805-MHz cavities of the side-coupled linac (SCL) with modern tools. The original design [1] was done in 2D, with semi-analytical estimates of the 3-D effects due to the coupling slots, and was followed by cavity tuning.

Our goal is to determine whether limitations due to high stresses prevent future high-duty SCL operations with the existing water cooling on the tank outer walls. We use the CST MicroWave Studio (MWS) [2] and the finite-element engineering codes (COSMOS, ANSYS [3]) for a combined 3-D EM and thermal-stress analysis.

SCL CAVITY MODEL

The model cavity for one period of the SCL tank 1 of the LANSCE linac is illustrated in Fig. 1 (only the cavity inner volume is shown, no walls). The accelerator (beam) axis is traced by the blue line. The axisymmetric on-axis re-entrant accelerator cavity (AC) with the dimensions [1] was imported into MWS using the CAD-created SAT file, then two half-AC were added. The coupling cavities (CC) were created in MWS and combined with the AC. The CC-AC overlap creates the coupling slots. The slot sharp edges were blended in the model with the radius 2.5 mm.

The frequency of the TM_{010}-like mode in the single AC with the dimensions [1] was 799.8 MHz. Blending the beam pipe edge in DTs with the rounding radius 4 mm, as should be according to [1], moves the resonant frequency to 804.9 MHz. The mode frequency for a separate CC with the dimensions [1] is 812.4 MHz. The frequency sensitivities to the gap changes for the separate cavities are as follows: in the CC $\Delta f/\Delta g \approx 60$ MHz/mm and in the AC $\Delta f/\Delta G \approx 4.5$ MHz/mm, see notations in Tab. 1.

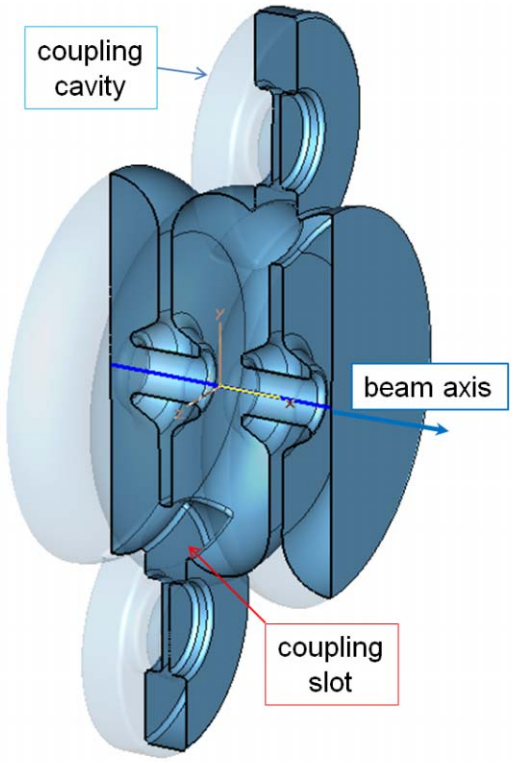

Figure 1: MWS model of one SCL period.

We compute the modes of the combined cavity with the periodic boundary conditions (BC) on the axis end walls. The working mode is tuned to 805 MHz by cutting metal from the DT noses as prescribed in [1], within the MWS. The DT noses are cut by length d, which is the model parameter. After the cuts, the DT edges are blended with radius 4.0 mm. The value in Fig. 1 is d = 2.325 mm, so that the accelerator gap length is $G_1 = G+2d$, where G is given in Tab. 1. This adjustment – the only change of the dimensions in Tab. 1 – ensures the correct frequency of the working mode in the engineering model.

Table 1: SCL Cavity Dimensions (mm)

Parameter	Value	Comment
AC length L	80.27416	SAT
AC inner radius R	128.27	At equator
AC DT bore radius	15.875	
AC gap length G	25.44572	SAT
DT nose blend radius	4.0	
CC length	30.15	Max wall-to-wall
CC inner radius	82.55	
CC boss radius	31.75	
CC boss gap g	5.646	
Blend radius, all edges	3.25	Undefined in [1]
CC axis displacement	171.196	From AC axis

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EM ANALYSIS RESULTS

We use the MWS eigensolver to solve for the modes in the SCL cavity model. The cavity inner volume shown in Fig. 1 is assumed to be surrounded by a perfect conductor, and the periodic BCs, with the phase shift between the boundaries set to 0, are imposed at $x_{\min}$ and $x_{\max}$. Two iterations were sufficient to tune the frequency of the working mode to 805 MHz by adjusting the value of d. The frequency sensitivity of the combined cavity with respect to the d change is $\Delta f/\Delta d \approx 8$ MHz/mm. Neither the frequency of the working mode nor its field distribution is influenced much by the frequency of the coupling cells. The electric field of the working mode in the cavity symmetry plane is shown in Fig. 2. The fields are normalized to the cavity nominal electric field gradient $E_0 = 1.5$ MV/m. The coupling cells are not excited in the working mode. The electric field distribution along the cavity axis is flat, with equal amplitudes in all accelerating cells.

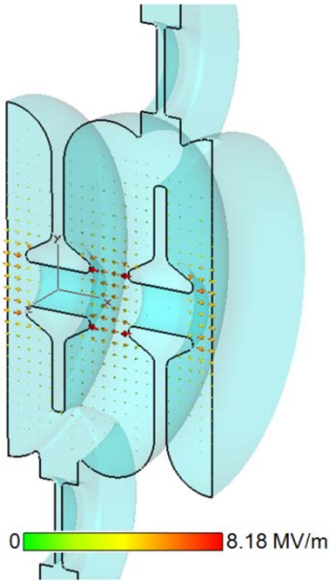

Figure 2: Electric field distribution in the vertical plane.

The surface-current distribution is presented in Fig. 3; the scaling is the same as in Fig. 2, $E_0 = 1.5$ MV/m. The maximal surface currents are near the coupling slots.

The MWS EM computation results are summarized in Tab. 2 for the nominal gradient $E_0 = 1.5$ MV/m and surface conductivity $5.8\cdot10^7$ $(\Omega\text{m})^{-1}$. The power values are given for 100% duty. The maximal surface power density near the coupling slot corners significantly exceeds that on the DT surface, cf. Fig. 3. This maximal value at 100% is extremely high and obviously cannot be handled without a dedicated cooling system, but for realistic duty factors it will be proportionally lower. The engineering analysis in the next Section relates the MWS calculated power flux to the temperatures and stresses produced at various duty factors.

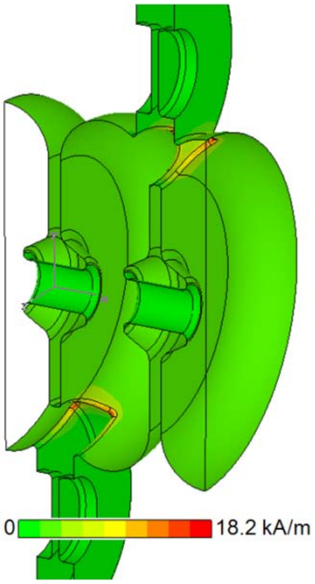

Figure 3: Surface-current magnitude in the SCL cavity.

Table 2: SCL Model Cavity EM Parameters

Parameter	Value	Units
Quality factor Q	18802	
Transit-time factor T ($\beta = 0.43$)	0.8566	
Energy gain per AC	0.5925	MeV
Shunt impedance R_{sh} per AC	3.557	MΩ
Eff. shunt impedance $r_s = R_{sh}T^2/L$	32.51	MΩ/m
Average power dissipation per AC	4.08	kW
Maximal peak electric field	8.18	MV/m
Max. peak surface magnetic field	18.17	kA/m
Same, on DT surface	4.35	kA/m
Max. surface power density dP/ds	122.3	W/cm^2
Same, on DT surface	7.0	W/cm^2

ENGINEERING ANALYSIS RESULTS

We have developed a procedure to transfer surface-loss power data calculated by MWS to the finite-element (FE) engineering codes COSMOS and ANSYS [3]. The important feature of the procedure is that the MWS fields are extracted not exactly at the cavity surface points but with a small offset into the cavity along the normal to each FE out of the FE center point. With this approach, we avoid errors in the surface fields due to hexahedral MWS meshes as well as in the situations when the FE central point is located inside the convex metal wall. The offset point coordinates are generated in the engineering software for a given FE surface mesh using special macros. The magnetic field from the MWS mode solution in these points is extracted, scaled to the required field gradient, and converted to the surface power density (flux) corresponding to the given surface conductivity. The data are then used to calculate the thermal load in the engineering model of the cavity.

The water cooling channels are located on the tank outer side walls: 8 channels 1.5″x0.75″ with the total flow rate 45 GPM, which gives the flow velocity of 0.45 m/s. The inlet water temperature is 22°C. In addition, the usual air convection cooling was taken into account. The model is assumed to be fixed in the horizontal plane but can expand vertically and longitudinally. The boundary conditions are representative for this case; however, for the actual SCL tank 1 consisting of 36 accelerating cavities, the thermal-stress analysis should be modified.

The temperature, equivalent stress, and deformation distributions calculated by ANSYS for the SCL model described above are shown in Fig. 4 at the nominal 10% duty.

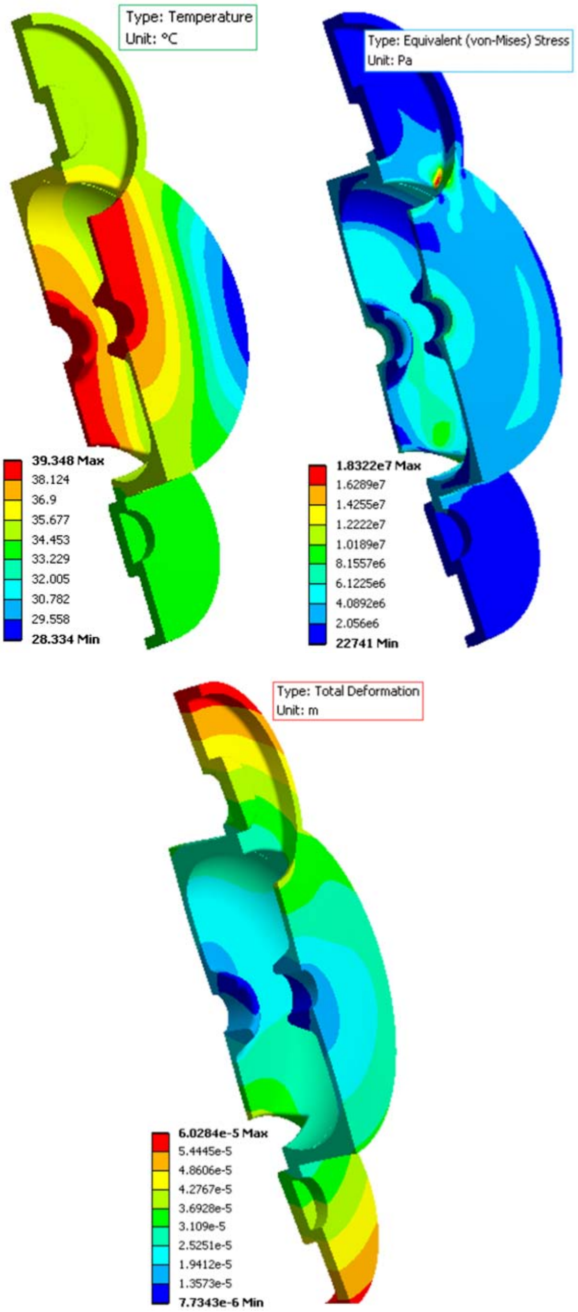

Figure 4: ANSYS results for the SCL model at 10% duty.

For other duty factors the distributions look similar, except for the scale. The results for different duty factors are summarized in Tab. 3.

Table 3: Temperatures, Stress, and Deformation Results

Duty	$T_{\min}$, °C	$T_{\max}$, °C	$S_{\max}$, MPa	$D_{\max}$, μm
10%	28.3	39.3	18.3	60.3
12%	29.6	42.8	22.0	72.3
15%	31.5	48.0	27.5	90.4
20%	34.7	56.7	36.6	120.6
100%	85.3	195.5	183.2	602.3

The typical FE mesh size was about 58K elements, with a local refinement at the coupling slots. As a check, for a couple of cases the thermal-stress analysis was performed with refined meshes of 92K and 318K. The results were found to be very close to those for the original 58K meshes except for the maximal stresses that were slightly lower, by 1-4%. As expected, in all cases the highest stresses are near the end of the coupling slots. The calculated maximal stress values in Tab. 3 should be compared to the copper yield stress 58 MPa. The maximal deformations are at the outer edges of the coupling cavities, which will have a small impact on the working mode, as we know from EM analysis. The deformation magnitudes should be also compared to the typical manufacturing tolerances of 3-4 mils (75-100 μm).

As one can see from Tab. 3, the temperature differences, stresses, and deformation magnitude increase linearly with the thermal load (duty factor) increase. Based on these results, SCL operations at up to 15% duty are safe but at 20% become marginal. For more accurate estimates of the maximal duty with the existing cooling, we should also include the cavities in the other SCL tanks and perform detailed thermal-stress analysis with realistic boundary conditions in longer multi-cavity structures.

SUMMARY

A combined 3-D electro-magnetic and thermal-stress analysis of the RF cavities in the LANSCE SCL tank 1 was performed to evaluate feasibility of higher duty operations. For the combined EM-engineering analysis we have developed a procedure for data exchange between the electromagnetic (MicroWave Studio) and engineering (COSMOS, ANSYS) codes. Our plans include extending this approach to representative cavities in other SCL tanks to provide more accurate estimates of the maximal duty for the LANSCE SCL with the existing cooling scheme.

REFERENCES

[1] L.N. Engel, “Geometrical and Electromagnetic Parameters of the Accelerating and Coupling Cells of the 805 MHz Linac for LAMPF”, MP-3-58, Los Alamos (1968).
[2] CST MicroWave Studio 2008, http://www.cst.com.
[3] COSMOS, SolidWorks, http://www.cosmosm.com; ANSYS, ANSYS, Inc., http://www.ansys.com.