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Title:

FINITE ELEMENT ANALYSIS AND FREQUENCY SHIFT STUDIES FOR THE BRIDGE COUPLER OF THE COUPLED CAVITY LINEAR ACCELERATOR OF THE SPALLATION NEUTRON SOURCE

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FINITE ELEMENT ANALYSIS AND FREQUENCY SHIFT STUDIES FOR THE BRIDGE COUPLER OF THE COUPLED CAVITY LINEAR ACCELERATOR OF THE SPALLATION NEUTRON SOURCE*

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Abstract

The Spallation Neutron Source (SNS) is an accelerator-based neutron scattering research facility. The linear accelerator (linac) is the principal accelerating structure and divided into a room-temperature linac and a superconducting linac. The normal conducting linac system that consists of a Drift Tube Linac (DTL) and a Coupled Cavity Linac (CCL) is to be built by Los Alamos National Laboratory.

The CCL structure is 55.36-meters long. It accelerates H^- beam from 86.8 Mev to 185.6 Mev at operating frequency of 805 MHz. This side coupled cavity structure has 8 cells per segment, 12 segments and 11 bridge couplers per module, and 4 modules total. A 5-MW klystron powers each module. The number 3 and number 9 bridge coupler of each module are connected to the 5-MW RF power supply. The bridge coupler with length of 2.5 $\beta\lambda$ is a three-cell structure and located between the segments and allows power flow through the module. The center cell of each bridge coupler is excited during normal operation. To obtain a uniform electromagnetic filed and meet the resonant frequency shift, the RF induced heat must be removed. Thus, the thermal deformation and frequency shift studies are performed via numerical simulations in order to have an appropriate cooling design and predict the frequency shift under operation. The center cell of the bridge coupler also contains a large 4-inch slug tuner and a tuning post that used to provide bulk frequency adjustment and field intensity adjustment, so that produce the proper total field distribution in the module assembly.

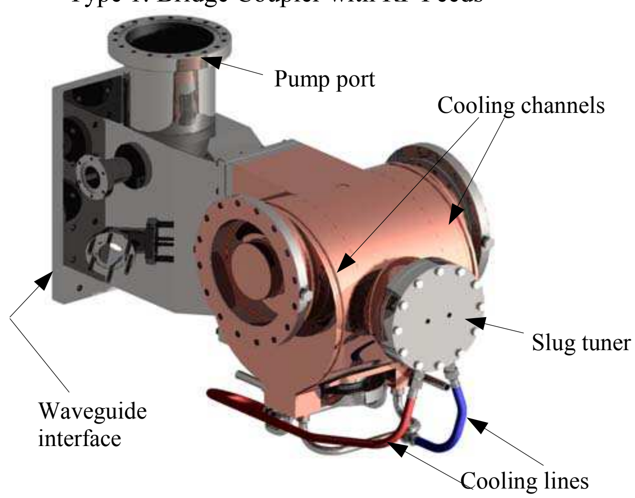
INTRODUCTION

The Spallation Neutron Source (SNS) is an accelerator-based neutron source that produces pulsed neutron beams by bombarding a mercury target with intense beams of 1-GeV protons. It is being designed to meet the needs of the neutron scattering community in the United States well through the 21st century. The SNS is scheduled for completion in December 2005 at Oak Ridge National Laboratory (ORNL).

The Project is being carried out by a multi-laboratory collaboration, led by ORNL and comprised of five other National Laboratories. Los Alamos National Laboratory (LANL) is one of them, and responsible for design and construction of the room temperature linear accelerator (Linac), while Jefferson National Laboratory builds the superconducting Linac. The normal conducting linac consists of a drift-tube linac (DTL) and a coupled-cavity linac (CCL). The total length of CCL section is 55.36-meters. It accepts beam from the DTL at 86.8-Mev and delivers it to the superconducting accelerator at 185.6-Mev. It operates at a radio frequency (RF) of 805 MHz. the CCL has 4 modules. A 5MW klystron is utilized for each module that consists 12 segments and 11 bridge couplers. The number 3 and number 9 bridge coupler of each module are connected to the 5 MW RF power supply. The feed is through a slot iris in the center-powered cell. The body of the coupler is copper. The flanges and the waveguide transition section are copper plated stainless steel. The bridge coupler final design was changed to welded assembly from brazed assembly at the preliminary design [1]. The copper cooling covers are attached at the outer surface with e-beam welds. All welds are full-penetration face welds with designed backing material in the joints. The improved design includes that a large 4-inch slug tuner port that allows considerable tuning range and access to the center cell for shorting during tuning. The tuner is water-cooled. A previous tabbed post design was replaced with a single rod from top.

The final thermal/structural analysis and frequency shift studies for the improved CCL bridge couplers have been presented at the CCL final design review [2]. Figure 1 shows the final designed two types of CCL bridge couplers.

Type 1: Bridge Coupler with RF Feeds



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Type 2: Bridge Coupler without RF Feeds

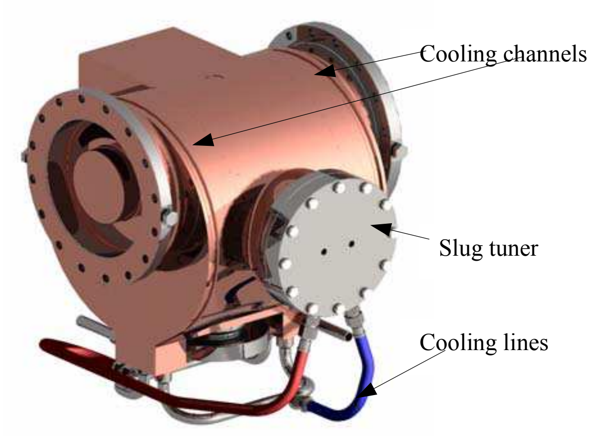


Figure 1: Coupled Cavity Linac Bridge Couplers

The bridge couplers are supported from the adjacent CCL segments and are free to axially expand or contract with the segments, as shown in Figure 2.

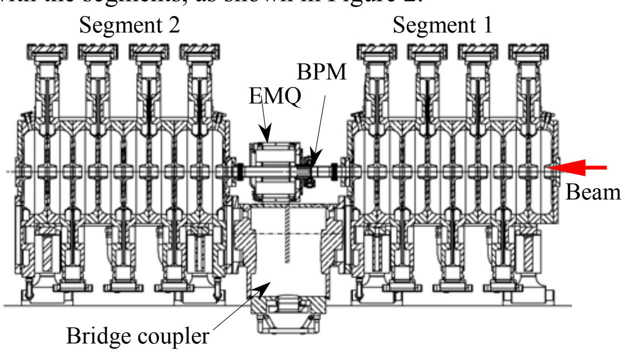


Figure 2: Bridge Coupler Location between segments

RF power is dissipated on the center cell walls. The thermal expansion that results from RF heating causes a resonant frequency shift and also mechanical loading of the structure. A cooling system has been designed to mitigate the affects of the RF frequency shift and to adequately reduce induced thermal stress levels in the system. To guide the cooling system design, studies of the thermal performance, associated induced stress levels and frequency shift have been performed via numerical simulations.

RF HEATING AND COOLING SCHEME

The SNS bridge couplers are 3-cell structures of 2.5-βλ total length. The cross section of powered cell geometry is shown in Figure 3. Only the center cell is subject to the significant surface heating. The center cell length for all 44-bridge couplers increases along the CCL from 22.4 cm to 35.6 cm. The two end lateral cells are of constant length throughout the CCL. Each bridge coupler joints two CCL segments, coupling them together forming a multicavity accelerating structure. The two end cells are connected to the center cell via slots in the dividers or nose plates. Thus, the bridge coupler accommodates RF power transmission from one segment to the next with proper phase matching. Presence of the resonant electro-magnetic fields creates electrical currents on the interior skin of the coupling cell and thus deposits thermal energy into the cell walls that causes thermal distortions which result in a resonant frequency shift and induced stresses.

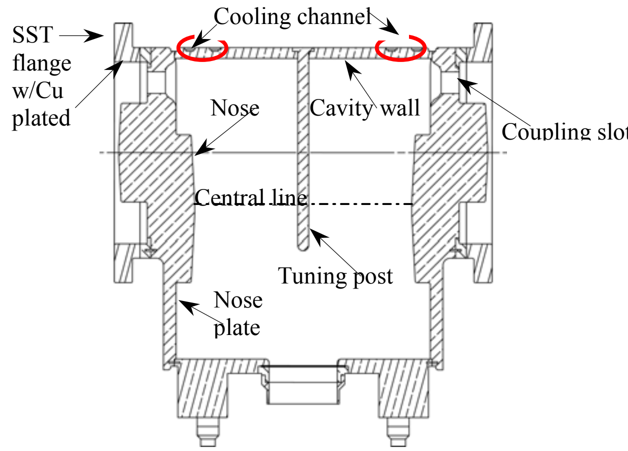


Figure 3: Powered Bridge Coupler

Under normal operation, approximately 292-watts of RF power at 7% design duty factor is dissipated in the center cell walls of the first bridge coupler (β= 0.404), and 555-watts is dissipated in the center cell walls of the last bridge coupler (β=0.55). To achieve the desired resonance frequency, the bridge coupler is actively water-cooled with four cooling lines (.25 inch wide, .063 inch depth) machined in the coupler cavity outer surface. They are circumferentially positioned around the outer edge of the nose plate and around center cell wall. The location of cooling lines relative to the end flanges is constant for all bridge couplers. This provides a simple method for heat removal.

FINITE ELEMENT ANALYSIS

As the bridge coupler is symmetric about two perpendicular planers, an ANSYS 10-node tetrahedron element solid model of a quarter bridge coupler (β=0.404) was created. The applied variable heat fluxes on the inner wall and nose plates of the center cell are calculated with the physics code SUPERFISH. A 5% safety margin has been added to the calculated heat loads. Additional power is added numerically to the ends of both slots to accurately simulate heating effects at the slot ends. This additional power corresponds to 20% of total cavity power. Inlet cooling water of 20^0C at a flow rate of 0.25-gpm through each cooling channel, which corresponds to a water velocity of 1.55-m/s is utilized. Water-cooling within the numerical model is simulated by a forced convection boundary condition with heat transfer coefficient of 0.72 w/cm^{2}K. The calculated hottest area is at the slot edges with a maximum temperature of 24^0C.

Because the cavity is operated under vacuum, the structural analysis was performed with thermal stress and vacuum loading. The maximum calculated von Mises stress that occurs at the weld joints of the cavity wall and plate is approximately 2,000-psi (~ 40% yield stress of OFE copper). The temperature profile and the thermal / structural stress contours resulting from RF heating and external atmospheric pressure for the bridge coupler are shown in Figure 4.

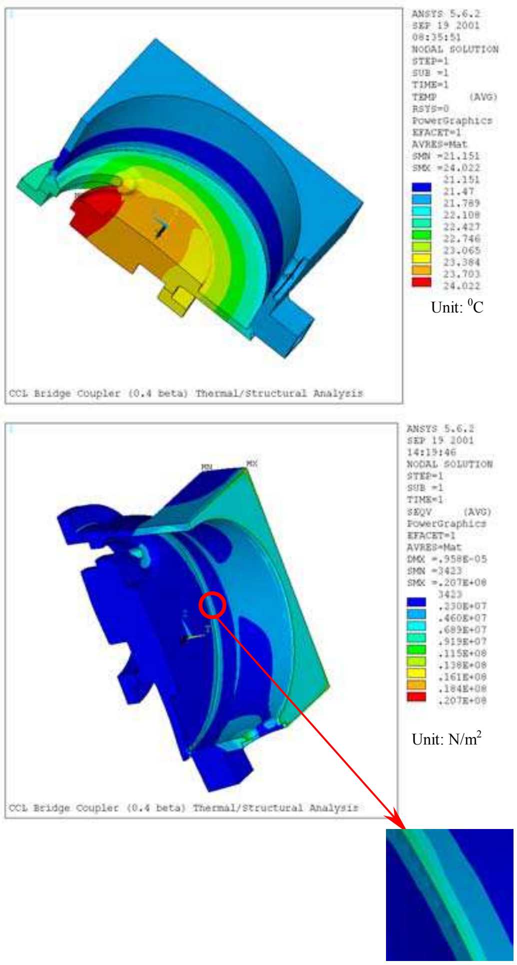


Figure 4: Temperature and von Mises stress contours

As described above, the center cell lengths of the bridge couplers increase with increasing energy along the CCL, simplified two-dimensional axisymmetric models for the first bridge coupler and the last one have been generated from SUPERFISH output files directly. The simulation results show that the calculated stress distribution in regions away from coupling slots matches the results for the 3-D model. Calculated von Mises stress levels at the nose plate and wall weld joint region for the first coupling cell is approximately 2700 psi (48% yield stress of OFE copper). This is slightly higher than the result from 3-D calculation. This is because the 3-D model accurately represents the bridge coupler geometry, where as the 2-D model simplifies the external pressure loading and constraints due to the adjoining coupling cell. Von Mises stress levels at the nose plate and wall weld joint region for the last coupling cell is approximately 3200-psi (58% yield stress of OFE copper). Two-dimensional axisymmetric models were created because they allow easy calculation of resonant frequent shift for any bridge coupler in the CCL. The stress plots for the 2-D models are depicted in the Figure 5.

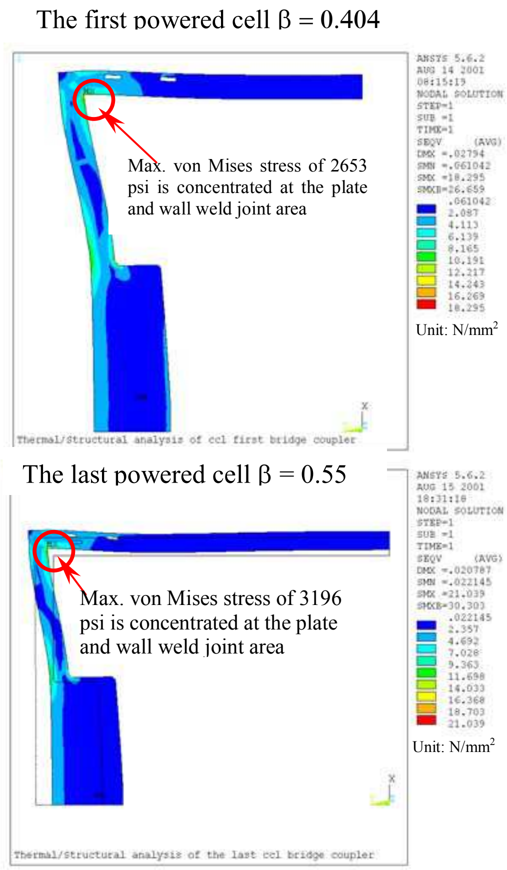


Figure 5: 2-D FEA Model Von Mises Stress Distributions

FREQUENCY SHIFT STUDIES

The thermal distortions caused by RF heating result in an electromagnetic frequency shift. The magnitude of the frequency shift for any given cavity can be calculated using the Slater perturbation theory. The change in frequency is a function of the volume change of an infinitesimal volumes along the RF surface, as well as the magnetic and electric fields on the surface and the cavity stored energy. For the bridge coupler, the deformation of the bridge coupler wall, nose plate, and septum plate all contribute to the total frequency shift.

To accurately frequency-shift, a code [3] that links SUPERFISH and ANSYS has been utilized. The 2-Dimensional axisymmetric models have been generated with heat loads calculated by SUPERFISH for the first bridge coupler of β0.404 and the last one of β 0.55. The axisymmetric elements simulate the cell radial and longitudinal growth. The thermal deformation corresponding to the temperature profile is calculated with the heat transfer solver of the ANSYS code. The vacuum loading is also included for the frequency shift studies because the external atmospheric pressure causes cavity deformed.

Frequency shift calculations were averaged for two different load cases to reasonably predict 3-D behavior with the 2-D axisymmetric models. Figure 6 shows the deformation of the first bridge coupler under two loading cases. The Calculated frequency shift of the first coupler center cell for case 1 is –9.5 kHz, while the Δf for case 2 is –147.2 kHz. The average frequency shift at the first bridge coupler center cell is approximately – 78.4-kHz.

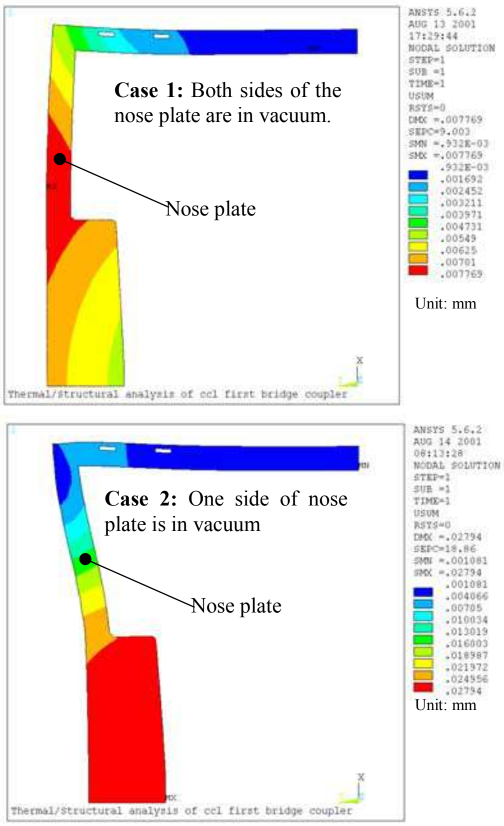
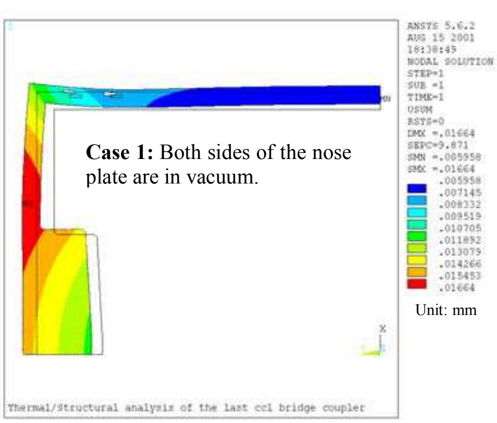


Figure 6: Beta 0.404 Bridge Coupler Deformation Profiles under Thermal and Vacuum Loading

The calculated frequency shift for the last bridge coupler is approximately –54 kHz for case 1 and –156 kHz for case 2. A frequency shift of approximately –105 kHz is predicted for the center cell of the β 0.55 bridge coupler. The calculated deformations of the last bridge coupler for the two loading cases are depicted in Figure 7.



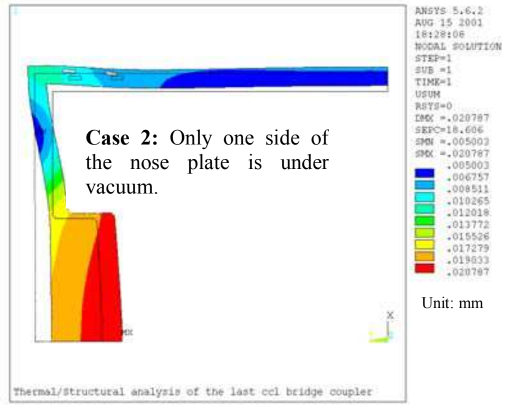


Figure 7: Beta 0.55 bridge coupler thermal/vacuum load displacement profiles

Note that the heat load of the axisymmetric 2-D model does not include the additional heating due to presence of the coupling slots. The calculated maximum temperature rise for the 2-D model is 1.2^0C lower than the calculated value from the 3-D model.

CONCLUSION

This report summarizes the thermal/structural calculation results utilizing finite element analysis for the SNS CCL bridge coupler. At normal operation, the maximum temperature rise for the 44 bridge couplers varies from 2^0 C to 5^0 C. The maximum calculated von Mises stress is no more than 50% of the yield stress of OFE copper. The calculated RF frequency shift caused by thermal and vacuum loading varies from –78 kHz to –105 kHz. The bridge coupler was fabricated for the CCL hot model and has been successfully tested. The frequency shift value is within the tunable range. From a practical standpoint, each bridge coupler will be tuned during final assembly to a pre-determinable frequency to give a nominal 805 MHz resonance during the powered operation.

REFERENCES

[1] Bultman, N. "CCL RF Structures Mechanical Design" at SNS CCL Preliminary Design Review, November 16, 2000.
[2] Chen, Z "Bridge Coupler Thermal/Structural Analysis and Frequency Shift Studies" at SNS CCL Final Design Review, August 28, 2001.
[3] Stovall, J. & Crandall, K. written for TERA project May 27, 1998.