An Optimized Design for the NSLS 53 MHz RF Cavities and the Ancillary Components

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Abstract

RF cavities are among the most complex components of a particle accelerator. They perform optimally when all electrical, mechanical and vacuum requirements are fully integrated. This paper focuses on the mechanical design features of the new 53MHz room-temperature RF cavities (including their ancillary components) for the X-ray Ring at the National Synchrotron Light Source (NSLS). Differences between the new and previous designs of the RF cavities, input couplers, Higher-Order-Mode (HOM) dampers, and cooling and vacuum systems are reviewed. Thus far, two out of four units have already been constructed, tested, and installed into the X-Ray ring, and two additional RF cavities are planned. The features incorporated into the new all-copper RF cavities have already demonstrated superior performance over the original copper-plated steel design. The operating performance results along with some of manufacturing challenges are presented.

Keywords: RF cavities, input couplers, HOM, HPF, tuner

1. Introduction

The National Synchrotron Light Source (NSLS) is a dedicated user facility operating since early 1980. The NSLS facility consists of a Linac, three transfer lines, a Booster ring and two electron storage rings (VUV and X-ray), each with numerous User beam lines that provide intense focused synchrotron light spanning the electromagnetic spectrum from the infrared through x-rays. Each of the RF systems in the three rings has the identical resonant frequency of 52.887 MHz even though they have different geometric designs and output powers.

Four single-cell RF cavities currently provide the required energy to accelerate and maintain 280 mA of electrons initially injected at 800 MeV up to a final energy of 2.8 GeV. Before the X-ray ring could be increased to 2.8 GeV operation however from the previous 2.6 GeV operation, NSLS conducted a study to determine which components would have thermal problems. Following recommendations from this study, a number of storage ring components were upgraded to withstand the higher thermal loads associated with 2.8 GeV operation. Also as part of the effort to operate the X-ray ring at 2.8 GeV, NSLS built additional RF power units as required that would increase I^2R losses beyond the design limits of the existing cavities. New RF cavities were therefore required.

The original cavities were designed in the late 70's and were constructed from copper-clad steel, Fig. 1. Economic restrictions at the time dictated the choice of material. Unfortunately the original copper-clad steel construction had both mechanical and electrical deficiencies. These deficiencies included poor heat transfer, joints that were vulnerable to vacuum leaks, poor interior surface quality, the presence of water-to-vacuum joints, and difficulties in tuning. These problems, especially with new higher-energy operating conditions, have necessitated replacement of the RF cavities with a new all-copper design [1].

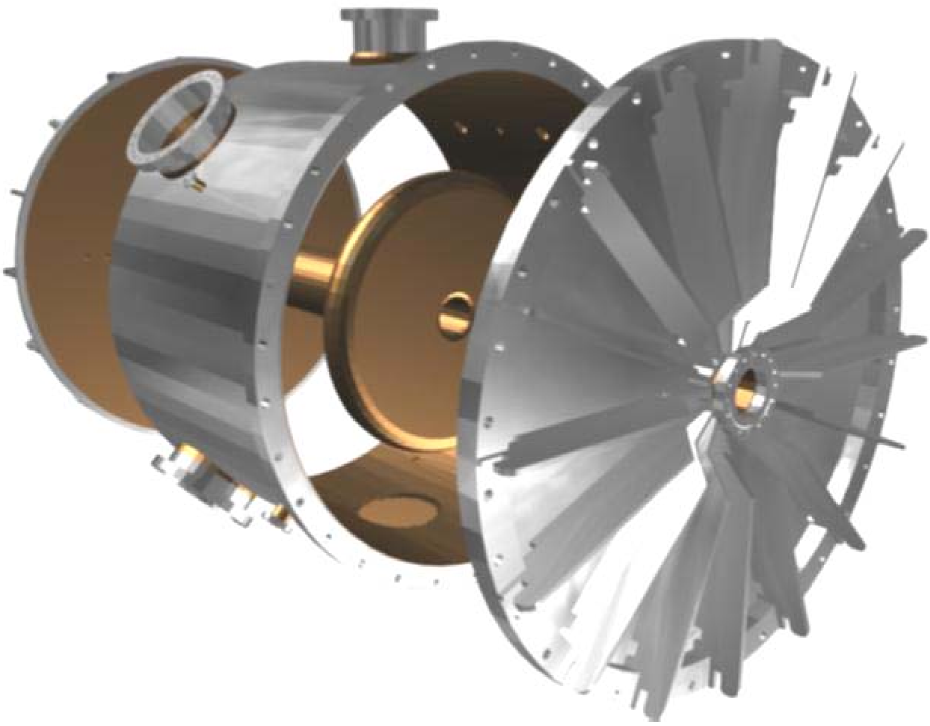

Fig. 1: RF cavity, original design.

2. New Design Criteria

Most conventional RF cavities are fabricated from copper or aluminum. Aluminum however presents some difficulties due to poor vacuum characteristics. Aluminum tends to adsorb water leading to oxidation that increases the coefficient of secondary electron emission, a phenomena that is unacceptable for storage rings.

The combined electrical, mechanical and vacuum characteristics of copper make it a better choice for this application. However, the relatively large physical size, the large quantity of access ports needed, and the anticipated difficulties in joining similar or dissimilar materials to the main body were obstacles that had to be overcome.

A basic goal of the new design was to ensure uniform material properties throughout the RF cavity. Other goals included: increased reliability by eliminating water-to-vacuum joints, improved temperature control, to provide a capability that allows easier tuning, to eliminate the stainless steel Conflat flanges, and to reduce the number of potential leak paths by providing considerably fewer external welds and braze joints. The redesigned all-copper RF cavities have met all of these goals.

Oxygen Free High Conductivity copper (OFHC) was the material of choice. To reduce the number of potential leak paths, the number of joints was kept to a minimum by constructing the entire cavity from four forged pieces, Fig. 2.

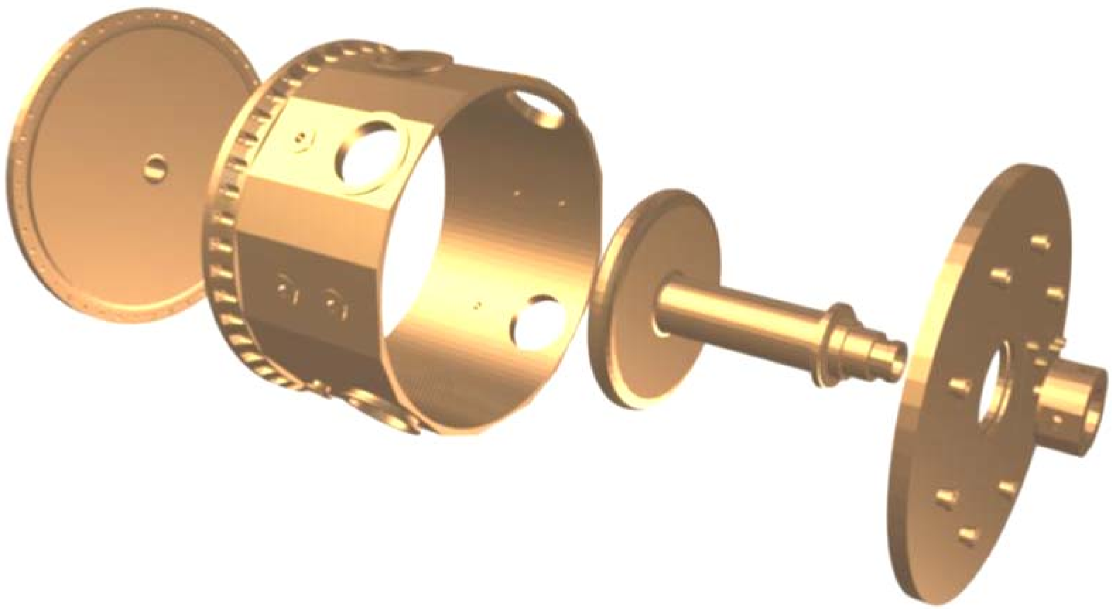

Fig. 2: RF cavity basic design concept.

The use of Stainless Steel Conflat flanges was eliminated by work-hardening the base copper material to achieve an adequate hardness of >40 RB for vacuum sealing. Peripheral port flanges, mostly on the main body, were integrally machined using Marmon-type configurations. Helicoflex seals were selected for both vacuum and RF sealing. An annealed, copper-jacketed seal of approximately 1 meter diameter × 8 mm cross section furnishes RF contact and provides a vacuum seal for the front cover. The Helicoflex seal has also a sufficient deflection range for initial frequency tuning.

Electron Beam Welding (EBW) was selected as the only joining technique used in order to preserve the hardness and prevent grain enlargement. Unlike brazing, EBW transfers minimal heat to the copper base material, creating the smallest heat-affected zone of all potential vacuum-compatible permanent joining processes, Fig. 3.

The design of the RF cavities was initially guided by SUPERFISH analyses. Thermal loads extracted from SUPERFISH runs were then used with ANSYS thermal Finite Element Analysis software to optimize the cooling channel configurations of the structure. ANSYS Finite Element Analyses models were run iteratively to guide the cooling channel configuration and to determine the cooling flow requirements and thermal/pressure deformation. A series of rectangular cooling channels were machined on the body at optimum locations and covered with copper plates sealed by EBW. From SUPERFISH, it was determined that the center electrode receives 80% of the thermal load, whereby 58% is deposited in the stem section The center electrode therefore required elaborate cooling passages. Since this cavity is mostly capacitively loaded, a precision cooling system was designed to supply cooling to the center electrode while keeping it at a very stable temperature (± 0.1 °C).

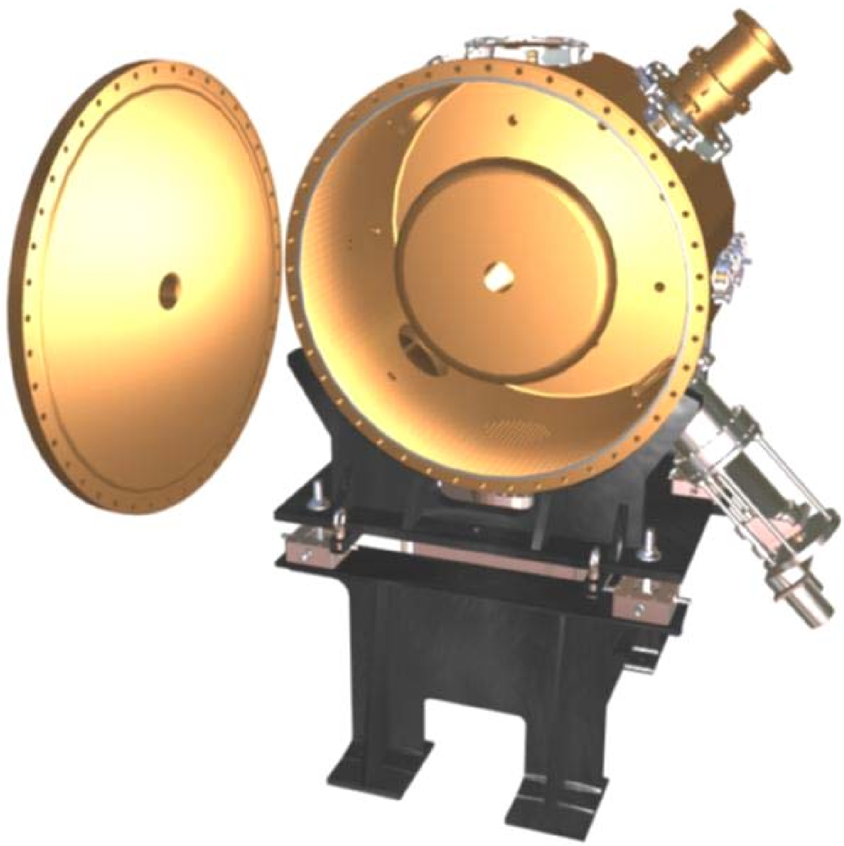

Fig. 3: 52.887 MHz, RF cavity assembly.

3. Input Coupler

The original design was a disk-type aluminum oxide ceramic brazed to Kovar material and integrated to the main body which was mainly made of copper-plated stainless steel. This again had inherently poor thermal transfer capability even at a low RF power level of about 90 KW. To accommodate higher RF power transfer to the cavity and to eliminate previous deficiencies, new water-cooled, 6" coaxial input couplers were designed, built, tested and installed into the new cavities. Similar basic philosophy was adapted which included use of OFHC copper as the base material and a minimum number of joints. The main manufacturing challenge was the brazing of a coaxial ceramic disk to the copper sleeve material. Here two opposite expansion shrinkage conditions existed during the temperature ramp-up and ramp-down periods. This problem has been overcome through long periods of trail-and-error by different methods/vendors. A USbased company, Bodycote AlphaBraze of Fremont California, is now manufacturing several of these components. In order to prevent charge leakage and to prevent multipactoring, the vacuum side of the ceramic surface is coated with approx. 20Å of titanium nitride. These windows have successfully been tested and are in operation with an input power of 150-160KW, Fig. 4.

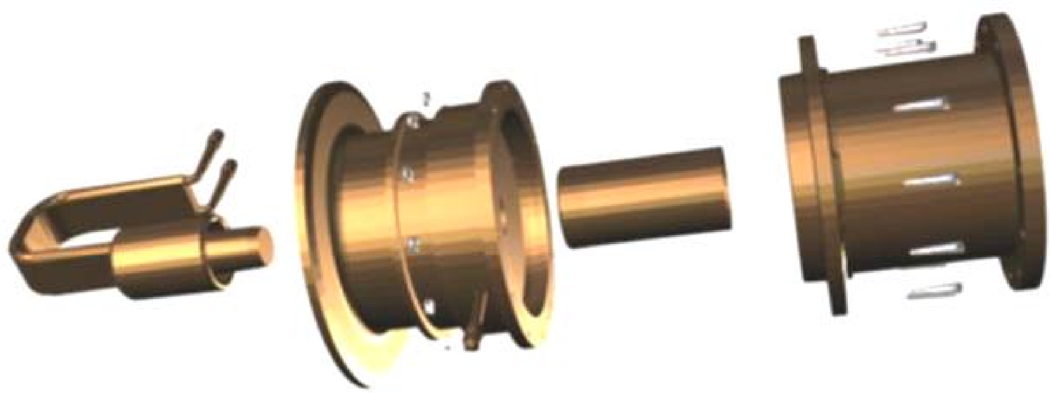

Fig. 4: Coaxial power window, basic design concept.

4. Shorting Loop VS Slug Tuner

To compensate for reactive beam loading and cooling water temperature variations, a motor-driven cavity tuner is required. Initially a slug tuner was used, but its spring fingers continuously burned out due to high cavity wall currents. A shorted-loop design was developed and replaced the slug tuner, Fig. 5.

There are clearly advantages and disadvantages associated with either type. Slug tuners offer great tuning range and distort higher order modes to a lesser degree due to their shallow insertion. As mentioned, slug tuners must however cope with the problem of higher current through sliding spring fingers (>200 amps/inch). Shorted-loop designs in contrast have limited tuning range and strongly affect higher-modes because of their deep insertion into the RF cavity. The current that travels down the loop shaft due to the interception of the displacement current is returned to the ground through a small number of thermally sensitive spring finger contacts. All NSLS RF cavities are presently equipped with shorted-loop tuners.

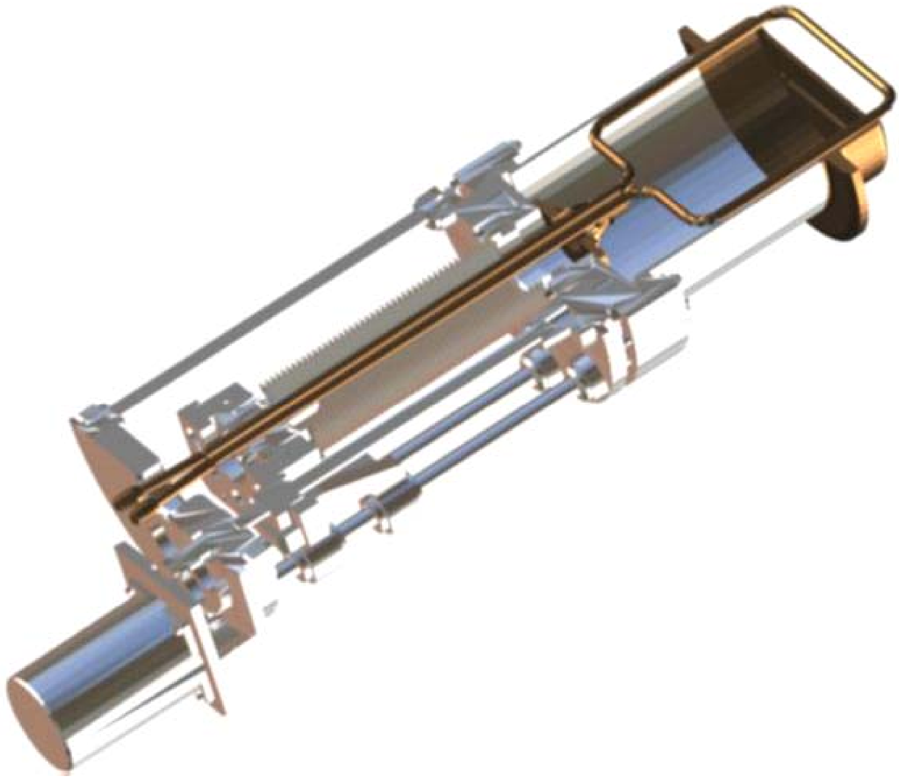

Fig. 5: Shorted-loop, tuner assembly.

5. Higher-Order Modes Dampers

The original cavities had five coaxially water-cooled antennae inserted at various ports for higher order mode damping [2]. They were designed mainly from commercially-available cylindrical ceramic feedthroughs terminated by coaxially water-cooled resister loads. These designs had two major flaws, insufficient cooling and they undesirably intercepted the fundamental field.

Since higher-order modes deviate with cavity perturbations, higher-order modes were measured throughout the tuner range and dampers were adjusted to insure adequate suppression at all tuner positions. Collectively, the damping antennae intercepted more than 10 KW of the fundamental field when terminated into 50 ohm loads. To reduce this RF power loss, four of these antennae are fitted with high-pass filters (HPFs) with a cutoff at the first significant higher-order mode (HOM) frequency of 270 MHz, Fig. 6.

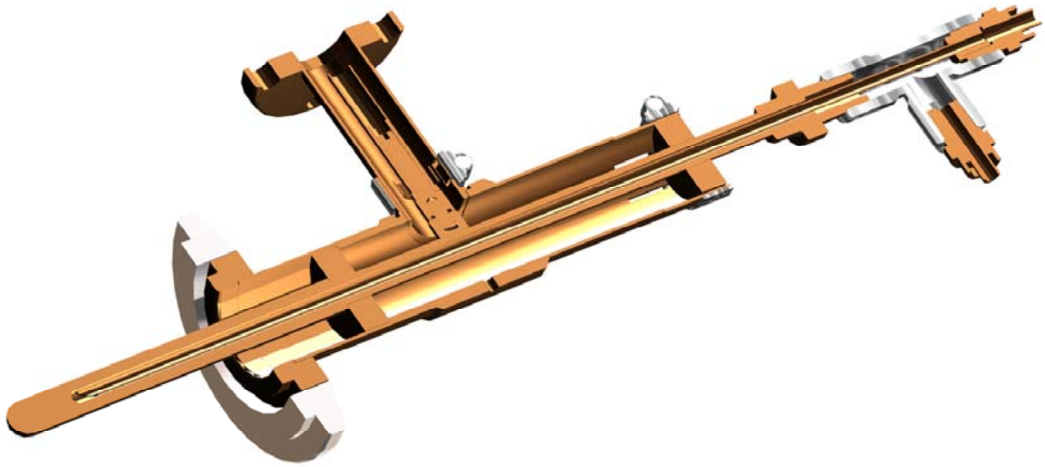

Fig. 6: Typical high pass filter.

Both the HOM's and HPF's have incorporated high thermally-conductive BeO ceramic disks. Three antennae of significant length are located in the shorting wall of the cavity and are heated by RF currents generated by the large magnetic field. They are fitted with three-element HPFs designed to pass cooling water through a shorted stub. In these cases, water is supplied to the long inserted length via a coaxial supply-and-return arrangement where, for the shorter length, cooling is provided to the outer sleeve of the ceramic only, In all cases, NSLS' rule of no permissible water-to-vacuum joints is maintained.

6. Testing

Each cavity is subjected to various rigorous tests prior to installation. The cavity and its installed ancillary components are baked with a specially-designed thermal blanket to 40°C for 48 hours. A single 400 liter/sec ion pump per cavity maintains vacuum in the low 10^{-9} torr range during operation. This vacuum level corresponds to the theoretical value for clean copper surfaces. When RF power was first introduced, several regions of multipactoring were found, but each conditioned out after 24 hours of operation. Each cavity has performed well and the cooling control system has worked as designed, easily surpassing the design specification for 50 KW power dissipations.

7. Conclusion

The replacement of the copper-clad steel RF cavities with solid copper RF cavities in the NSLS x-ray ring is continuing with newly designed peripherals added. ACCEL Instruments in Germany has built all four RF cavities.

Each RF cavity received was tested and then installed with newly-designed ancillary components. The RF, vacuum and temperature stability and control performance have been well within design goals. ACCEL did encounter several manufacturing problems with the material and EBW operation. First, some of their material was rejected due to grain enlargement during the forging process where, in one case, a vacuum leak was detected through an 11 mm thick section. Second, several EBW joints were unsuccessful due to re-crystallization at the start and finish junction. A two cm center electrode-to-end plate joint had to be re-machined, cut, and re-welded. The repeatability and reliability of the Marmon type flanges using Helicoflex seals rely upon the seal quality and sealing surface conditions. Overall, the installation of the first two new RF cavities has markedly increased the reliability of the x-ray RF system. Two additional units are scheduled for installation during the NSLS 2002 and 2003 winter shutdowns.

8. Acknowledgments

This paper describes the work of a large group of people, too numerous to credit individually, who have contributed to the design, fabrication, testing and installation of the project. This work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contact No. DE-AC02-98CH10886.

9. References

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