201 MHZ CAVITY R&D FOR MUCOOL AND MICE*

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Abstract

We describe the design, fabrication, analysis and preliminary testing of the prototype 201 MHz copper cavity for a muon ionization cooling channel. Cavity applications include the Muon Ionization Cooling Experiment (MICE) as well as cooling channels for a neutrino factory or a muon collider. This cavity was developed by the US muon cooling (MUCOOL) collaboration and is being tested in the MUCOOL Test Area (MTA) at Fermilab. To achieve a high accelerating gradient, the cavity beam irises are terminated by a pair of curved, thin beryllium windows. Several fabrication methods developed for the cavity and windows are novel and offer significant cost savings as compared to conventional construction methods. The cavity's thermal and structural performances are simulated with an FEA model. Preliminary high power RF commissioning results will be presented.

INTRODUCTION

The Neutrino Factory and Muon Collider Collaboration (NFMCC) evaluates physics opportunities afforded by intense muon beams from a neutrino factory through a muon collider. The development of a muon collider or a neutrino factory requires low emittance muon beams. An approach that could produce the low emittance beams is muon ionization cooling. A demonstration of muon cooling is thus essential to the development of muon accelerators and storage rings [1]. An international Muon Ionization Cooling Experiment (MICE) is to be hosted at Rutherford Appleton Laboratory (RAL) in the UK. MICE will be a demonstration experiment for muon ionization cooling in a configuration that was studied for a cooling channel for a neutrino factory in the US Study-II [2]. Hardware R&D for the muon cooling channel has been actively conducted by the Muon Cooling (MUCOOL) collaboration within NFMCC for many years.

The proposed MICE experiment will test cooling on a low intensity muon beam generated by plunging a target into the halo of the proton beam of the ISIS ring at RAL. The initial muon emittance will be measured in the first detector module using five planes of scintillating fibers within a 4 T spectrometer solenoid magnet. The muon beam then enters the first absorber focus coil (AFC) module containing a low-*Z* absorber surrounded by a pair of superconducting focus coils. The muon beam loses both longitudinal and transverse momentum in the absorber. The RF coupling coil (RFCC) module is used to restore the muon beams to their original longitudinal momentum with RF cavities. The MICE cooling channel consists of three AFC modules separated by two RFCC modules. Once the muon beam exits the MICE cooling channel, its emittance is measured again in a second detector module that is essentially identical to the first detector module. Each RFCC module consists of four 201 MHz normal conducting RF cavities that provide an accelerating gradient of up to 17 MV/m. The peak input RF power per cavity is 4.6 MW with an average dissipated power of 8.4 kW. The cavities are immersed in a 2.5 T solenoidal field generated by a superconducting coupling magnet. A total of eight cavities with thin, curved beryllium (Be) windows are needed for the MICE cooling channel. The MICE cavity is essentially the same design as the 201 MHz cavity developed for MUCOOL. A prototype of such a cavity has recently been built and high-power tested. This paper describes the cavity design, fabrication, analysis and preliminary test results.

THE CAVITY DESIGN

The cavity design consists of a round, closed pillbox profile containing 420 mm diameter beam irises to accommodate the large transverse emittance of muon beam. Curved beryllium windows are used to terminate RF fields at the beam iris. The cavity profile is optimized to minimize peak surface fields, to suppress multipacting by avoiding parallel planes and to facilitate the fabrication process. The cavity therefore has higher shunt impedance and gives a higher accelerating gradient for a given input RF power. The beryllium window diameter is determined by the muon beam profile at the cavity, and the thickness is based on the allowable temperature gradient and thermal stress due to RF heating. The curvatures of the beryllium windows in a cavity are oriented such that they point in the same direction to minimize frequency shift due to deformation of the windows under RF heating [3]. The primary cavity parameters are listed in Table 1. Two RF loop couplers are designed to feed RF power to the cavity. The couplers use ceramic windows that were developed for the US Spallation Neutron Source (SNS).

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Table 1: Main parameters for the 201 MHz cavity

Cavity length	430	mm
Cavity inner radius	610	mm
Cavity body thickness	6	mm
Be window diameter	420	mm
Be window thickness	0.38	mm
Cavity shunt impedance	22	MΩ/m
Cavity quality factor Q_0	53,000	

CAVITY FABRICATION

The construction and assembly of the prototype 201 MHz cavity was a collaborative effort between Jefferson National Accelerator Facility, Lawrence Berkeley National Laboratory and the University of Mississippi. Fabrication techniques used include spinning, brazing, TIG welding, electron beam welding, electron beam annealing and deep drawing [4]. Several novel methods developed during the project offer significant cost savings over conventional construction methods.

Cavity Body

The cavity body is made from two half-shells that were fabricated from flat plates by metal spinning. Each half-shell has a stiff tuner ring attached by e-beam welding before the cavity halves are joined together. This ring is initially used for handling and as a datum and will later be used as the mounting point for the tuner mechanism. The center of the shell is cut out for the later installation of the "nose ring" (similar to the nose-cones in a conventional cavity, though there are none in this case). The equator weld consists of a full penetration weld from the outside and a cosmetic pass on the inside to leave a smooth surface. Next, the nose rings were joined to the cavity with a similar two-sided weld. All of the e-beam weld parameters were developed through sub-scale testing.

Cavity Ports

Our original design called for the four 4" equatorial ports to be pre-fabricated and e-beam welded into the body. Instead, the ports were pulled or extruded directly out of the cavity body. To prevent tearing in the heat affected zone of the equator weld, the region around the port was locally annealed with the e-beam welder. This method saved considerable time and cost over the originally proposed method. The port flanges are commercial 6 ¾" Conflat flanges in stainless steel with copper inserts brazed in. The flanges are joined to the cavity by copper to copper e-beam welds (a penetration weld followed by a cosmetic weld, both from the inside).

Couplers

A pair of loop couplers was fabricated using standard 4" diameter RF waveguide and fittings. The individual parts were assembled using torch brazing and metal seal flanges. A small diameter copper tube is incorporated in the actual loop to provide water cooling. The couplers use ceramic, coaxial RF windows developed for the SNS and manufactured by the Toshiba Corporation. The coupler/window assemblies were conditioned to an average power of 10 kW.

Thin Windows

The cavity beam apertures are terminated using two 420 mm diameter, 0.38 mm thick curved beryllium foil windows that were designed to provide the following beneficial characteristics: low thermal stress for a given temperature gradient, ability to deform in a single direction, thinner than alternate designs (less material and less scattering), mechanically stiff (characterized by mechanical resonant frequency) and relatively low cost of manufacture. Since the windows are thin and are cooled only by conduction at their edges, a design was required that would avoid high thermal stresses while also controlling the deflection due to heating. The windows are hot formed into the curved shape from flat Be foil, and a pair of copper rings is brazed to the window OD for mounting to the cavity. A 300 Å thick Ti-N coating is deposited on the Be surfaces to complete the windows.

Cooling and Surface Preparation

The average power dissipation in the cavity is less than 10 kW, so simple cooling tubes are used on the outside of the body, TIG brazed using silicon-bronze alloy in a "stitch" pattern, preventing trapped volumes under the braze joint (for MICE, the cavity will be inside an evacuated chamber).

Heavy field emission could be a serious problem for the liquid hydrogen absorbers or instrumentation in MICE. For this reason it was decided to electro-polish the high field surfaces of the cavity. Mechanical polishing followed by light chemical cleaning preceded the electro-polish. Final preparation included high pressure rinsing and vacuum assembly in a cleanroom.

CAVITY FEA MODELING

A technique using a single ANSYS model to produce electromagnetic, thermal, and structural solutions has been adapted for modeling of the 201 MHz cavity. The sequence of analysis steps and the associated results are presented in detail in a previous paper [5]. The initial phase of the analysis consists of a high frequency electromagnetic analysis of the cavity vacuum volume composed of a solid 3-dimensional volume whose outer surface represents the inner wall of the cavity. The key component in the process is a macro written in ANSYS command language that computes the heat flux from the normalized magnetic field results on the surface of the RF model and applies it to a newly generated solid model representing the cavity walls and the iris windows. The difference in electrical conductivity between the copper cavity walls and the beryllium foil windows is taken into account during these calculations. All features relevant to the thermal performance of the cavity, including water passages with convective cooling, are incorporated in the model. The resulting temperature contours for 20ºC cooling water are shown in Figure 1.

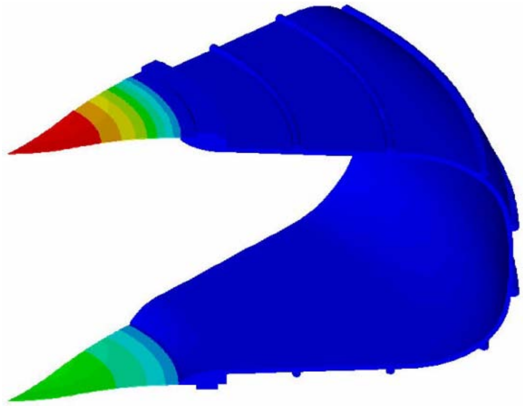

Figure 1: Thermal model with temperature contours.

Thermal elements are converted directly to structural elements to obtain the stress and displacement solutions. Model loading includes the nodal temperatures, symmetry boundary conditions, tuning forces and cavity support constraints. The peak von Mises stress in the cavity body was determined to be only 40 Mpa. The results also indicated that the local magnetic fields at the surface of the window that curves inward were significantly higher than on the outward curving window. The higher fields result in higher temperatures and stresses, although all stresses were found to be below the elastic limit of the beryllium.

The structural solution also provides the displacements of the cavity walls due to the various loading conditions. A new RF model based on the displaced shape is used to predict the resulting changes in cavity frequency. The thermal distortion of the cavity caused a frequency shift of -94 kHz. While some of the shift is caused by the overall expansion of the cavity as the walls heat up, the majority of the shift is due to the fact that the inward curving beryllium window sees more heat flux and deflects more than the outward curving window.

A pair of thick copper rings is welded to the cavity exterior walls to provide an interface for tuning. An external mechanism is used to apply force on the rings, thus distorting the cavity and shifting the frequency. The frequency sensitivity at the tuning ring was found to be +229 kHz/mm, where a positive displacement is outward from the cavity. The tuning range for the cavity is approximately ±500 kHz.

PRELIMINARY HIGH POWER TEST

The cavity surface was treated as a superconducting cavity and was back filled with dry N_2 before being shipped to the MTA at Fermilab. Couplers were assembled to the cavity body in a portable clean room. The couplers were high power conditioned up to 600 kW at traveling and 2.4 MW at standing wave mode at Oak Ridge National Lab prior to final assembly. The two couplers were adjusted and balanced at low power using a network analyzer. Up to 4.2 MW peak power is available at the MTA from a klystron used for the Fermilab 200 MHz linac. The cavity resonant frequency can be adjusted by deforming the cavity geometry similar to the tuning of superconducting RF cavities. An external force is applied by compressing or pulling the cavity body at the attached stiffening rings. Two thick aluminum plates provide the tuning forces as well as vacuum load support.

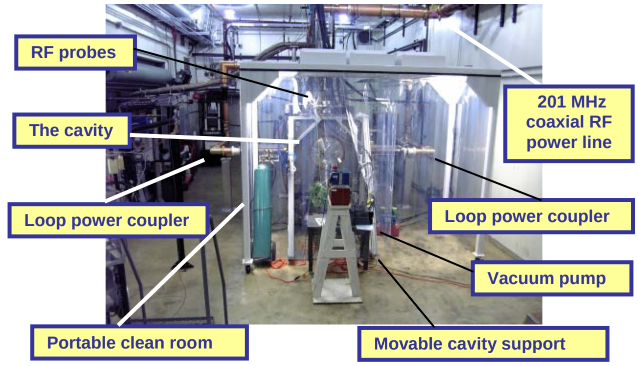

Figure 2: High power RF test setup at MTA, Fermilab.

Figure 2 shows the high power test setup at the MTA. Cavity parameters were measured before applying high power for RF conditioning. Measurement results are listed in Table 2. The cavity frequency is not adjusted to exactly 201 MHz for the testing as long as it remains within the klystron's bandwidth.

Table 2: Measured parameters prior to high power testing

Frequency	199.578	MHZ
Q_0 (with Cu windows)	49,000 ~ 51,000	
Vacuum	High 10^{-9}	Torr
Tuner sensitivity	156	kHz/mm

The cavity conditioning began with two TiN coated, flat copper windows in place and easily reached 16 MV/m within a few days [6]. No hard multipactings and arcs were observed. Careful cavity cleaning such as high pressure water rinsing, electropolishing and careful handing likely contributed to the success. More tests will be conducted soon to study conditioning with external magnetic fields and curved beryllium windows.

REFERENCES

[1] C. M. Ankenbrandt et al., Phys. Rev. ST Accel. Beams 2 (1999) 081001

[2] "MICE and International Muon Ionization Cooling Experiment Technical Reference Document," ed. P. Drumm, October 2004; www.isis.rl.ac.uk/accelerator /MICE/TR/MICE_Tech_ref.html

[3] D. Li, et. al., "Progress on the RF Coupling Coil Module Design for the MICE channel," PAC 2005

[4] R.A. Rimmer, et. al., "Fabrication of the Prototype 201.25 MHz Cavity for a Muon Ionization Cooling Experiment," PAC 2005

[5] S. Virostek and D. Li, "RF, Thermal and Structural Analysis of the 201.25 MHz Muon Ionization Cooling Cavity," PAC 2005

[6] J. Norem, "The MUCOOL RF Program," EPAC 2006