CLOSED-CELL 201.25 MHZ RF STRUCTURES FOR A MUON COOLING CHANNEL*

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Abstract

We report on the research and development of high gradient low frequency closed-cell structures for possible use in a muon cooling channel. The presence of strong magnetic fields precludes the use of superconducting RF. These multi-cell structures have the "beam iris" closed by conducting foils, grids of tubes or other isolating structures. This greatly increases the shunt impedance and also allows the individually powered cells to be set independently to any phase. The isolating structure must be made using a very small amount of low-Z material to avoid unacceptable scattering of the muon beam. Various cell designs and methods of closure are presented and compared. The problems of RF heating and breakdown at high gradient are discussed with regard to the vulnerable isolating structures. RF, thermal and stress analyses are presented and the integration of the RF with the solenoid cryostat and liquid hydrogen absorbers is considered.

1 INTRODUCTION

The RF systems for the buncher and the cooling channel of a neutrino factory or muon collider are required to match the muon beam into and out of the cooling channel and replenish the beam energy lost during ionization cooling. Since they must operate within strong solenoid fields they cannot be superconducting. These systems require a large number of high-gradient RF cavities, and a large amount of pulsed RF power and have therefore been examined during the recent site-specific neutrino factory feasibility studies [1, 2]. The cooling channel simulations in these studies have assumed ideal pillbox cavities with lengths that fit in the space available in the chosen magnetic lattices (and zero space between cavities). The buncher and first part of the cooling channel use a 2.75 m lattice with four cavities per cell, while the downstream part and most of the matching section uses a 1.65 m lattice and two cavities. Table 1 shows the peak cavity fields and other parameters for the most recent study and the klystron power for each section, assuming an RF pulse length of three filling times and pillbox cavities. The buncher, cooling and matching section is approximately 183 m long, contains 184 cavities (plus six 402.5 MHz harmonic cavities in the buncher), and uses 84 klystrons. The total installed power is approximately 780 MW (approx. 1.56 MW average), and the installed voltage is 1080 MV. In practice, rounded cavities with closed beam irises of finite thickness will be used, see figure 1 (lattice 2 dimensions in parenthesis). The efficiency of these shapes makes up for the slightly reduced length, so the pillbox approximation is OK.

*This work was supported by the US. Department of Energy under contracts DE-AC03-76SF00098 and DE-AC02-76CH03000.
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Table 1. Parameters for buncher, cooling, match sections

Section	#cavs	Epk	Veff	Pcav*	Ptot**
		MV/m	(MV)	MW	(MW)
bunch 1	4	6.40	2.07	0.567	2.51
bunch 2	8	6.00	1.94	0.499	4.42
bunch 3	8	8.00	2.59	0.886	7.85
cool 1	68	15.48	5.76	3.646	274.60
cool 2	74	16.72	6.71	4.635	379.91
match	22	16.72	6.71	4.635	112.95
total	184		1080		782.23

Note: the Kilpatrick number is 15 MV/m at 201.25 MHz.
* Real cavity, Q_0 assumed 85% of theoretical,
** Klystron forward power for 3τ filling.

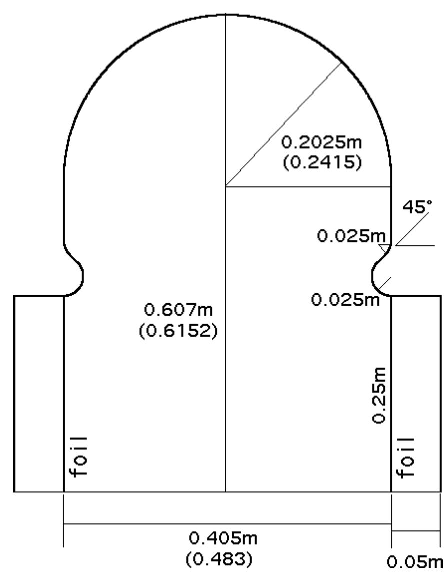

Figure 1. Profile of 201.25 MHz cavities (lattice 2 dimensions in parenthesis).

2 CAVITY DESCRIPTION

The high accelerating gradients required would be impractical with conventional open-iris structures, given the large size of the beam iris needed (~40 cm diameter at the largest point). A great improvement can be made in the shunt impedance of the cavity by closing the iris with a thin conducting barrier. This barrier must use the smallest amount of material to minimize scattering of the muon beam. It is proposed to close the irises with thin beryllium foils. Other methods of closure, such as grids of thin-walled aluminum tubes are also under consideration.

The basic cavity shapes, figure 1, were optimized by 2D simulations in URMEL. The iris thicknesses were made large enough that grids of two rows of tubes could be substituted for the foils. Figure 2 shows a MAFIA model of two half-cells separated by a pair of foils the foils are placed approximately where the surfaces of the grid would be. Any practicable assembly of foils (or grids), requires some space for flanges and access. We have assumed a minimum spacing of 50 mm between cavities. The cavity shape is slightly reentrant in order to maximize the impedance. Although the cavity "nose" is made with a large radius, it still has a field enhancement factor of about 1.7 over the field on axis. However, the highest surface field is only about 1.5 times the Kilpatrick number at this frequency (15 MV/m). One positive aspect of this field concentration is that the peak field is not on the foil but on the solid copper, so an arc to this point may be less of an issue.

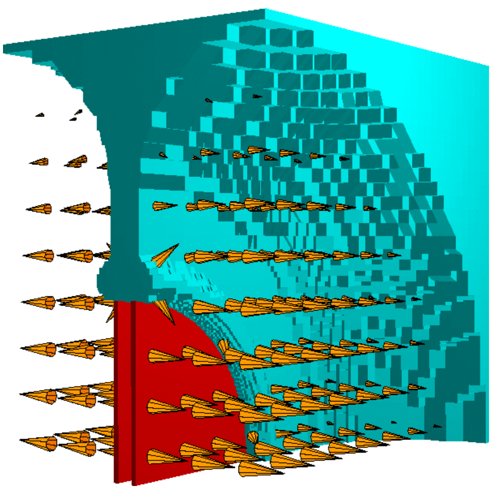

Figure 2. MAFIA model of two half-cells with foils.

The foils must be thick enough to conduct away the heat from the RF currents and keep the temperature to a predetermined level. When the foils are heated by RF, and only cooled by conduction to the edges, they assume a temperature profile slightly flatter than parabolic, see figure 3. The calculated RF-induced profile can be used in ANSYS as a load set for the stress calculations. The foils will be pre-stressed in tension during manufacture in order to keep them flat. This method had been tested experimentally [3] and works well up to the point where the thermal expansion exceeds the pre-stress and the foils begin to move. Figure 4 shows an example of foil deflection when the critical temperature is exceeded. Foil thicknesses have been chosen for Study-II that will keep the temperatures below this critical level. The use of tapered foils, or foils with stepped thickness, figure 5, can reduce the amount of material intercepted by the core of the beam, reducing the amount of scattering significantly. In study-II the foils range in thickness from 100 µm at the end cell of the low-gradient buncher cavity to a 917/1834 µm stepped foil for the middle cell of the high-gradient cooling section.

The normal conducting cells must have some cooling to remove the average power losses in the walls (about 9.3 kW at 0.2% duty factor), and to stabilize the frequency. The Study-II design has been evaluated for room temperature operation, although the option of operating at reduced temperature (e.g. liquid nitrogen), has been kept open. This option would lower the wall resistance and reduce the peak RF power requirements at the expense of adding an additional refrigeration system.

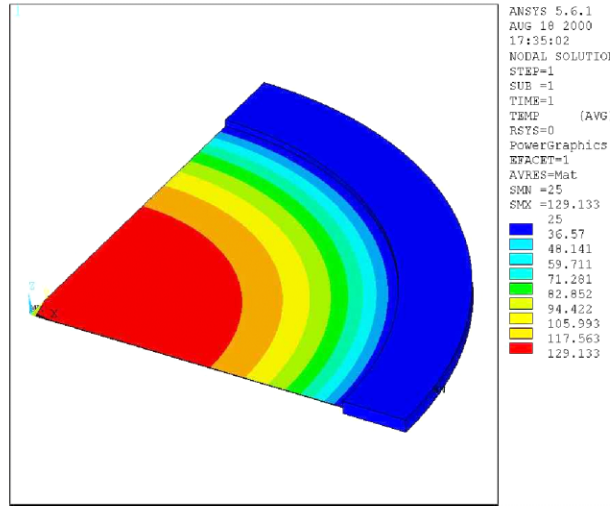

Figure 3. ANSYS calculated temperature profile for thin window with 60W loading.

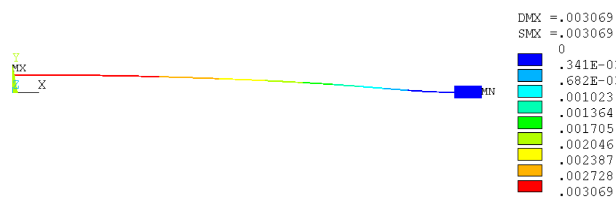

Figure 4. Deflection of foil when pre-stress is exceeded.

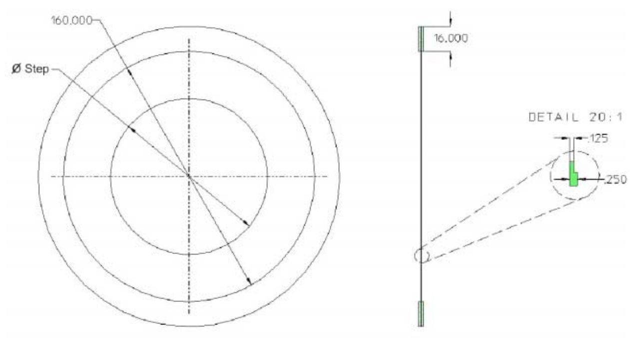

Figure 5. Example of stepped-thickness window.

A grid of thin-walled tubes or some other hollow fabrication would allow the possibility of flowing cooling gas through the structure. To analyze the grids requires a 3D model, Figure 6. In principle this method would allow less wall material and / or larger diameter irises in the cavity, both of which should reduce particle losses in the cooling channel. The effectiveness of gas cooling will be studied quantitatively in the near future. Potential disadvantages of the grids include the possibility of leaks or punctures due to arcing in use or during conditioning. This will be studied experimentally in a high power test cavity. Transverse electric fields are produced near the surfaces of the tubes but the resulting particle deflections are expected to be small compared to other scattering mechanisms in the channel.

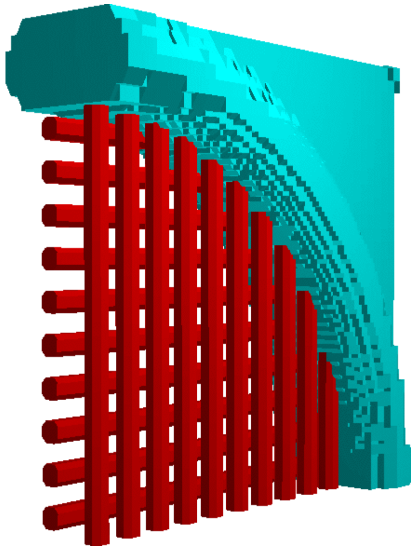

Figure 6. MAFIA model of grid structure.

One issue with the closed-iris structures is the possibility of multipactoring due to the high secondary yield of the beryllium or aluminum (foils or tubes). This could cause heating or breakdown in the cavity, which might damage the delicate structures. Unlike copper, the secondary yield of aluminum does not reduce with RF conditioning because of a stable surface oxide layer. It is expected that beryllium may behave similarly. It is proposed to suppress this problem by the application of low secondary emission coatings such as titanium nitride (TiN). This issue will be investigated experimentally in a high-power cavity as part of the ongoing muon collaboration 805 MHz R&D program [4, 5]. The cavity is designed to use demountable foils or copper blank-off plates and can be tested to very high-gradient using the high-power klystron in the Lab G facility at FNAL. The foils will be coated on one side with TiN and conditioning tests can thus be run with all copper surfaces, uncoated beryllium windows, coated beryllium windows or combinations of these. Windows of various thickness and with flat or stepped profiles will be tested with a wide range of magnetic fields in an available 5 T superconducting solenoid.

The Lorentz pressure in the center of the foils when the RF is on is approximately 0.1 Psi (0.7 kPa) at 16.7 MV/m so the deflection of the foil during the pulse is expected to be minimal. The effect of this impulse and other microphonics will be studied in the 805 MHz tests.

3 SYSTEM INTEGRATION

The cooling channel lattice is a tightly packed assembly of equipment including liquid-hydrogen absorbers, superconducting solenoids, high-gradient RF cavities, instrumentation, vacuum equipment, etc. There are two lattice types in the present buncher and cooling section with 2.75 and 1.65 m cell lengths, containing four and two RF cavities respectively. Our studies show that it is possible to integrate all these components into the available cell lengths. The RF feeds must come out through the wall of the cryostat, and may be angled to give clearance to other hardware. Pumping ports will be short and wide to give good conductance and may also penetrate the cryostat. Clearance is required at the end of each cooling cell to allow for installation or removal of one absorber/RF module from the channel. This is achieved by using a collapsible flange in the outer cryostat wall, which is reinforced after it is made up in order to handle the possible magnetic forces. RF shields will be used to keep beam-induced signals from escaping into the outer cryostat and vacuum system. The space in the cryostat outside of the cavities will be evacuated which will minimize the load on the RF structures. This approach would provide insulation for the cavities if they were operated below room temperature. It also obviates the need for UHV connections between the cavities and the hydrogen absorbers. The flanges are required only to provide RF continuity (for screening) and to separate the UHV of the RF system from the guard vacuum.

4 HIGH-POWER TEST CAVITY

A high-power prototype cavity is currently being designed. It will accommodate either foils or grids and will be tested in the new linac test area at FNAL. An integrated test is planned, including the RF cavity, liquid hydrogen absorber, 5T solenoid and instrumentation. The cavity will have cooling channels so that sustained high-power operation can be tested. The cavity could also be tested at cryogenic temperature if a suitable cryostat is available. The 201.25 MHz RF power will be diverted temporarily from the existing linac test stand.

5 CONCLUSIONS

A closed-cell high-gradient cavity has been designed that is suitable for a muon cooling channel. Closing of the beam iris with a conducting foil or grid of thin-walled tubes increases the shunt impedance significantly. The minimum amount of low-Z material must be used to limit scattering. Technological challenges include holding the foil flat under RF heating or cooling the tubes, suppression of multipactor, conditioning the cavity without damaging the delicate structures and possible microphonics. These challenges are being addressed by an R&D and testing program.

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