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

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Abstract

We describe the analysis and preliminary design of a high-gradient closed-cell 201.25 MHz RF cavity suitable for use in a proof-of-principle muon ionization cooling experiment. The cavities must operate in a strong magnetic field so they must be normal-conducting. They must have a large beam apertures but the shunt impedance can be kept at a reasonable level by closing the beam irises with thin conducting foils or grids of thin-walled tubes. These are almost transparent to the muon beam but present a conducting boundary to the RF fields, maintaining pillbox-like fields on the beam axis. We describe the electrical, mechanical and thermal analysis of the cavities and possible iris structures. The problems of RF heating, breakdown and dark current at high gradient and the integration of the RF with the solenoid cryostat and liquid hydrogen absorbers are considered. A conceptual design aimed at the proposed international Muon Ionization Cooling Experiment (MICE) is presented.

1 INTRODUCTION

The RF systems for the cooling channel of a neutrino factory or muon collider are required to replenish the beam energy lost during ionization cooling [1, 2]. A large number of high-gradient RF cavities would be required, so efficiency, cost and reliability are very important. The RF cavities would need to be tightly integrated with absorbers, magnets and instrumentation. Demonstration of these technologies under realistic operating conditions is a key step towards proving the feasibility of a neutrino factory. An international Muon Ionization Cooling Experiment (MICE) [3] has been proposed based on a short section of cooling channel operating at full performance. One proposed configuration is based on the study II cooling channel, using a 2.75 m lattice with four cavities per period. Table 1 shows the peak cavity fields and other parameters for the experiment, and the RF power required, assuming a pulse length of three filling times. An alternative proposal would use 88 MHz cavities, based on the CERN cooling channel scheme.

2 CAVITY SHAPE

The cavity shape has a slightly reentrant rounded profile with a large beam aperture, see figure 1. Thin beryllium foils or grids of thin-walled aluminum tubes will be used to close the beam iris to maintain a high shunt impedance. The central cavities in each cooling cell have 21cm radius beam irises, while the end cavities may use 18 cm radii for the apertures closest to the absorbers. The irises are thick enough to accommodate either a pair of foils or a grid of tubes. For study II the cavities were assumed to closed by Be foils with a stepped thickness to minimize scattering of the core of the beam.

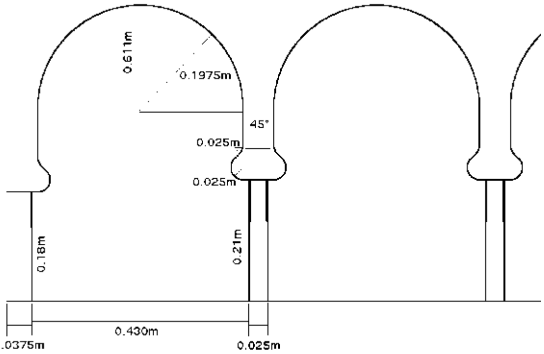

Figure 1. MICE cavity profile

The cavity profile has been updated slightly since study II to allow the foils and grids to be interchangeable with minimal retuning, see figures 2 and 3, and to allow more space between the cavities for the tuner mechanism, figure 4. Based on experiments with pre-stressed Be foils in an 805 MHz cavity the thickness of the foils has been chosen so that the temperature rise at the center of the foil is below the point at which the foils buckle [4]. Table 2 lists the dimensions of the stepped foils for study II and the equivalent flat foil thickness.

Table 1. MICE cavity parameters

V_{eff} (on crest)	5.76 MV
Length	0.430 m (T=0.827)
$E_o$equivalent	16.2 MV/m
E_{pk} on surface	26.5 MV/m
Peak power per cavity*	4.18 MW
Forward power (3τ filling)	4.63 MW
Average power (0.2% duty factor)	8.36 kW

Note: the Kilpatrick number is 15 MV/m at 201.25 MHz.
* Real cavity, Q_0 assumed 85% of theoretical

Table 2. Be foil dimensions

End foil radius (inner/outer)	12/18 cm
End foil thickness (inner/outer)	200/400 μm
Equivalent flat foil	325 μm
Middle foil radius (inner/outer)	14/21 cm
Middle foil thickness (inner/outer)	700/1400 μm
Equivalent flat foil	1152 μm

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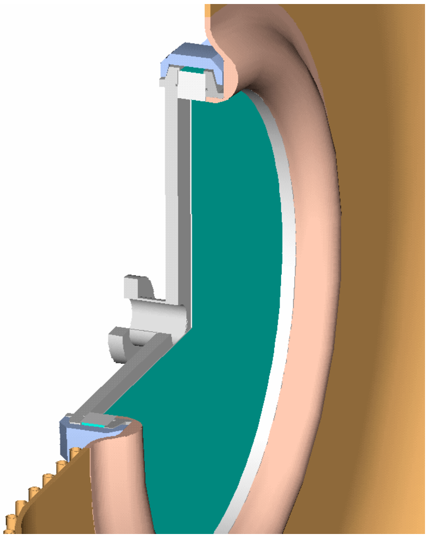

Figure 2. Be foil RF barrier in iris.

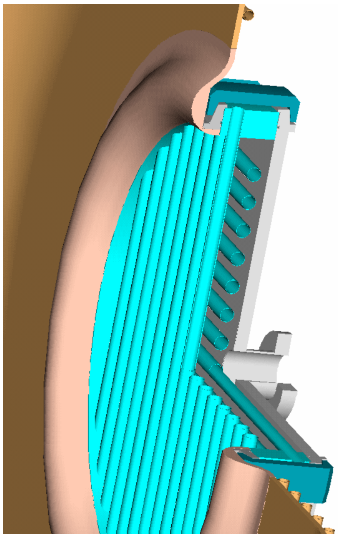

Figure 3. Grid of thin-walled tubes in iris.

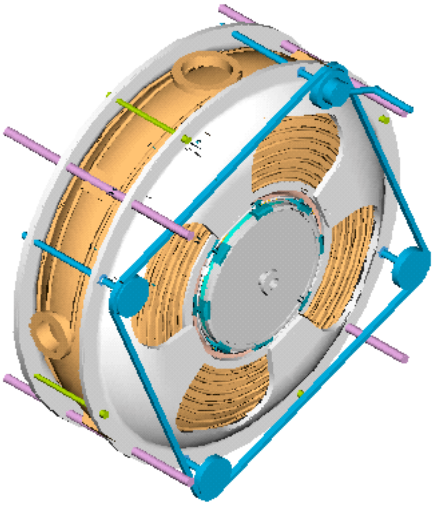

Figure 4. Tuner mechanism.

3 RF AND THERMAL ANALYSIS

Preliminary RF design of the cavity was performed using MAFIA [5]. Thermal analysis has been done using ANSYS. In study II the duty factor is about 0.2% so the average power is quite modest. For the cavity body a simple cooling scheme using external tubes is sufficient, see figure 5. The thin Be foils, however, are only cooled by conduction and the thickness must be sufficient to keep the temperature rise low enough to prevent buckling. If tubes are used the local heating will be enhanced in some areas due to the surface field concentration. It is proposed to cool the tubes by flowing cold gas through them.

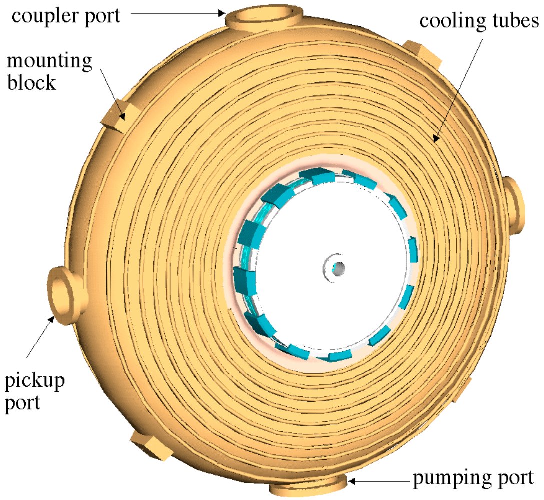

Figure 5. Cavity model showing external cooling tubes.

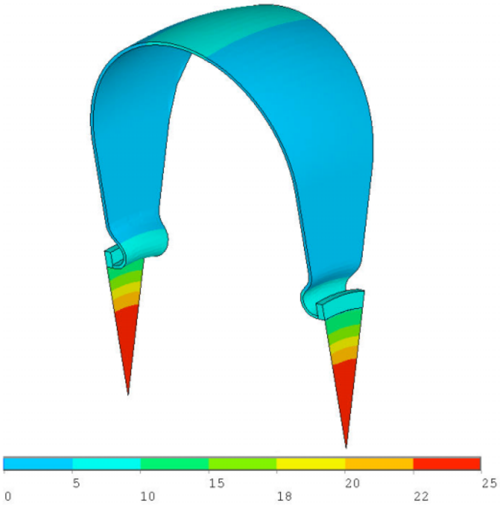

Figure 6. ANSYS temperature calculation.

Figure 6 shows the temperature profile of the cavity calculated by ANSYS. The maximum temperature rise is 25°C and the temperature rise across the foil is only about 17°C. The surface current distribution on a grid is more complex. Figure 7 shows a MAFIA calculation of the local power density on a close-packed grid. The optimal size and spacing of the tubes has not yet been determined. The actual temperature distribution with active cooling will be the subject of future investigation.

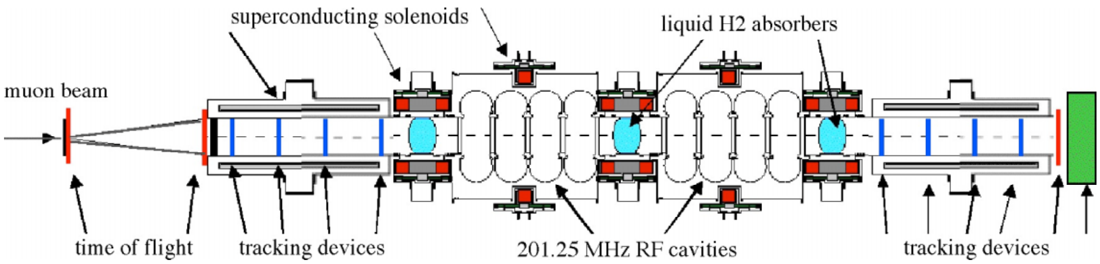

Figure 8. proposed MICE experiment layout.

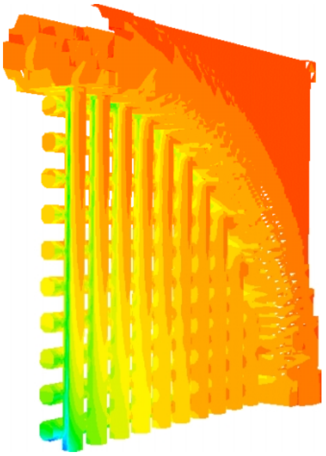

Figure 7. Power density on a grid calculated by MAFIA.

Operation of these cavities in close proximity to other equipment may provide additional challenges. The delicate nature of the foils or grids will require very careful conditioning of the cavities. Sparking in the cavity could damage the structure causing increased field emission or even failure of the pre-stressed foils. Sparking to the tubes could result in a gas leak into the cavity. The presence nearby of the liquid hydrogen absorbers and sensitive instrumentation may place limits on the dark current and X-ray flux that can be tolerated [6]. SRF-type cleaning and handling procedures may be helpful. The presence of strong magnetic may also be a factor. Dark current from field emitters in high electric field regions will tend to follow the magnetic field lines and may cause strong local heating where they hit the wall. If sufficient current is channeled to a sensitive area such as a be foil it may cause an unacceptable temperature rise or even damage. RF arcing may also be more damaging in the high magnetic fields as ions generated by the arc may be similarly constrained. These and other factors are being studied in a series of high-power tests on 805 MHz cavities [7] using an existing test stand at FNAL. Feedback from these tests will be used to refine the 201.25 MHz cavity design.

4 MICE EXPERIMENT

The proposed experiment would take the form of a section of cooling channel, complete with absorbers, magnets and RF, between sensitive tracking detectors in a muon beamline, see figure 6. Analysis suggests that two periods of the study II channel would provide enough cooling to be measurable with reasonable accuracy. A suitable beamline could be made available at RAL using components provided by PSI. The experiment would be staged, starting with the detectors and solenoids, followed by one absorber, then a first RF stage. Further absorbers, solenoids and RF cavities would be added as funding permits. A range of cooling experiments would therefore be possible, with various magnetic configurations, numbers of absorbers and RF voltages. All could be cross checked with simulations to test our understanding of the cooling process.

5 CONCLUSIONS

We have described a closed-cell high-gradient cavity that is suitable for a muon cooling experiment. The beam iris can be closed with a conducting foil or grid of thin-walled tubes to preserve the shunt impedance. Thermal analysis shows that the cooling scheme is adequate and that the foil thicknesses chosen for study II should be acceptable if a similar level of pre-stress can be obtained as in the smaller samples. The thermal analysis will be expanded to study grids in the future. Conditioning with magnetic fields and delicate structures in the cavities will be a challenge. These issues are being addressed by an ongoing R&D and testing program.

6 REFERENCES

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