PROCEEDINGS OF SCIENCE

RF R&D for Muon Ionization Cooling Channels

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Large emittance muon beam must be reduced or cooled both longitudinally and transversely before it can be accelerated in an accelerator complex for a neutrino factory or a muon collider. In practice, ionization cooling is considered to be one of the most promising transverse cooling schemes for muon beams. When traversing an ionization cooling channel, which consists of absorbers and low frequency (~ 201-MHz) RF cavities and superconducting solenoidal magnets, a muon beam loses its energy in the absorbers first and then re-gains the lost longitudinal energy from the RF cavities, therefore results in a net transverse emittance reduction. In principle, this cooling process can be repeated over many times depending on the cooling requirement. Moreover, muons have finite lifetime (~ 2 micro-second at rest), manipulation of the muon beam, such as the transverse cooling, has to be fast. This requires the normal conducting low frequency RF cavities have the highest possible accelerating gradient. This paper reports the status and progress of RF cavity R&D for muon ionization cooling channels with emphasis on RF cavity conditioning and operation in a strong magnetic field. The research work is supported and conducted in MUCOOL collaboration under the US NFMCC (Neutrino Factory and Muon Collider Collaboration).

10th International Workshop on Neutrino Factories, Super beams and Beta beams
Valencia, Spain
30 June – 05 July, 2008

[1] Speaker

PoS(Nufact08)080

1. Introduction

Muon ionization cooling channel is one of the key components for a neutrino factory or a muon collider. Progresses have been made in the past year on the research and development for the cooling channel hardware in the US NFMCC (Neutrino Factory and Muon Collider Collaboration) and MICE (Muon Ionization Cooling Experiment) collaboration [1]. Muon beams are typically generated with very large six-dimensional emittance; their emittance must be reduced or cooled significantly before it can be accelerated by an accelerator complex for a neutrino factory or a muon collider. Ionization cooling is considered to be one of the most promising transverse cooling schemes in practice. An ionization cooling channel consists of absorbing materials, RF cavities and superconducting solenoidal magnets. Muons lose energy in absorbers (in all directions) and gain only the lost longitudinal energy from RF cavities, as a result, the transverse emittance is reduced or cooled. This cooling process can be repeated by letting muon beams go through a series of the cooling channels continuously. In addition to having large emittance, muons decay and have short life time (~ 2 micro-second at rest), superconducting solenoidal magnets are needed for focusing the muon beams, and high accelerating gradient RF cavities are necessary to compensate for the longitudinal energy losses in the absorbers. The RF cavity must be low frequency and normal conducting due to external magnetic fields and large six-dimensional emittance. Therefore designing, engineering, building and operating a low frequency and high gradient normal conducting RF cavity in a strong magnetic field is critical for the success of a muon ionization cooling channel.

The hardware development for muon ionization cooling channel has been mainly conducted in MUCOOL program under the US NFMCC. Two normal conducting RF cavities at frequencies of 805-MHz and 201-MHz have been designed, built and tested at MTA (Muon Test Area) of Fermilab. The cavities use thin beryllium windows to terminate otherwise conventional open beam irises to increase the cavity shunt impedance. Most of the experimental studies were conducted using the 805-MHz cavity for cases with and without external magnetic fields [2].

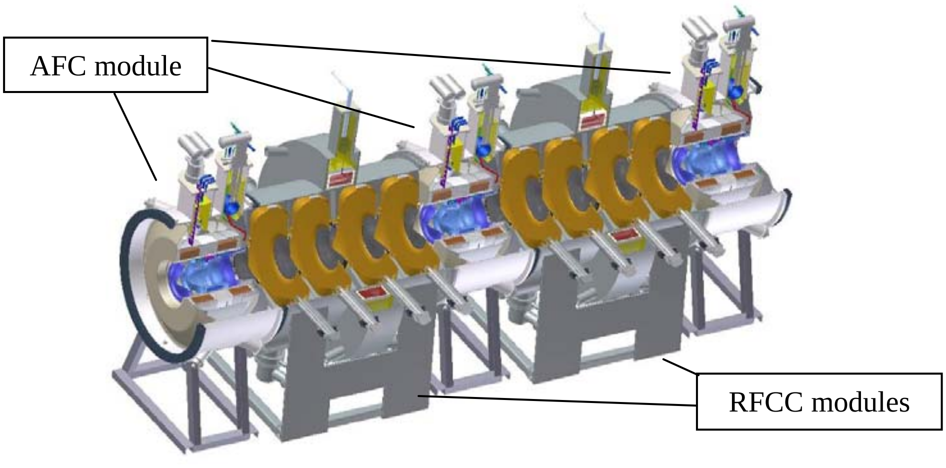

Figure 1: International MICE cooling channel: three AFC (Absorber and Focusing Coil) and two RFCC (RF cavity and Coupling Coil) modules.

In addition, two sections (modules) of muon ionization cooling channel (based on the US Feasibility Study II for neutrino factory) are being designed, engineered and fabricated for the international MICE. Figure 1 shows an engineering model of the MICE cooling channel where eight 201-MHz normal conducting RF cavities, five superconducting magnets and three liquid hydrogen absorbers are employed.

This paper reports recent progress on normal conducting RF cavity R&D for muon ionization cooling channels that include hardware development (design and engineering), latest test results and challenges remained in operating high gradient RF cavity in a strong magnetic field. Preliminary physics models in understanding RF breakdown in a strong magnetic field are being developed.

2. RF Cavity for Muon Ionization Cooling Channels

RF cavities for muon ionization cooling channel must be normal conducting due to external strong magnetic fields, and must have highest possible accelerating gradient due to short lifetime of muons. In order to achive high cavity shunt impedance, the conventional open beam iries of the cavity are terminated by thin and low-Z material, i.e. beryllium, by taking davantage of muon beam's penetration property. The cavities then resemble a round-pillbox cavity geometry. Figure 2 shows the 805-MHz RF cavity design and the cavity test setup at MTA, Fermilab.

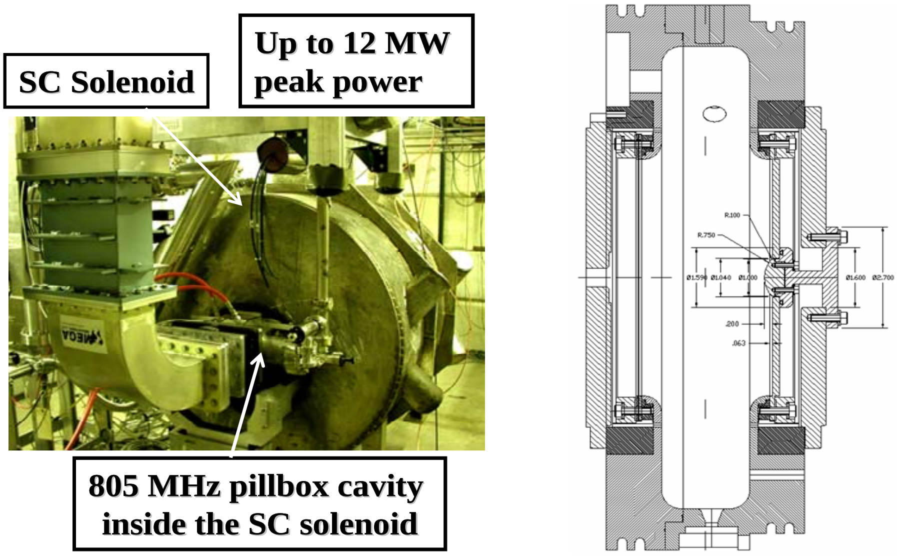

Figure 2: The 805-MHz cavity test setup at MTA of Fermilab (right): the cavity is mounted inside the warm bore of the superconducting solenoid, a rectangular waveguide feeds RF power to the cavity; the cavity design (left) where a RF button is added for RF breakdown studies. The cavity design accommodates removable windows for the termination of open beam iries. Up to 12-MW peak RF power is available at MTA, the superconducting magnet can be powered in either solenoidal or gradient modes with magnetic fields up to 5-Tesla.

In addition to RF tests at 805-MHz, a 201-MHz RF cavity was designed and built to explore engineering challenges in cavity fabrication and large, thin beryllium windows and tests and RF breakdown studies with magnetic fields. Figure 3 shows the 201-MHz cavity at MTA.

Figure 3: The 201-MHz cavity at MTA. The cavity is sandwiched between two thick aluminum plates since the cavity is made from 6-mm copper sheets and can not support the vacuum load itself. Two RF loop couplers feed the power to cavity. Up to 5-MW peak power is needed in order to reach 19-MV/m accelerating gradient.

3. Experimental Results

Experimental studies conducted earlier using the 805-MHz cavity indicate that achievable accelerating gradient degrades as the increase of external magnetic fields. Increase of cavity surface damage, dark currents and x-rays are observed associated with the increase of the external magnetic fields. However, there is no damage to the beryllium windows. The experiments continued to study RF breakdown in strong magnetic field environment with a replaceable RF button (as shown in Figure 2) to enhance local peak electric field. The button can be made from different materials or coatings [3, 4].

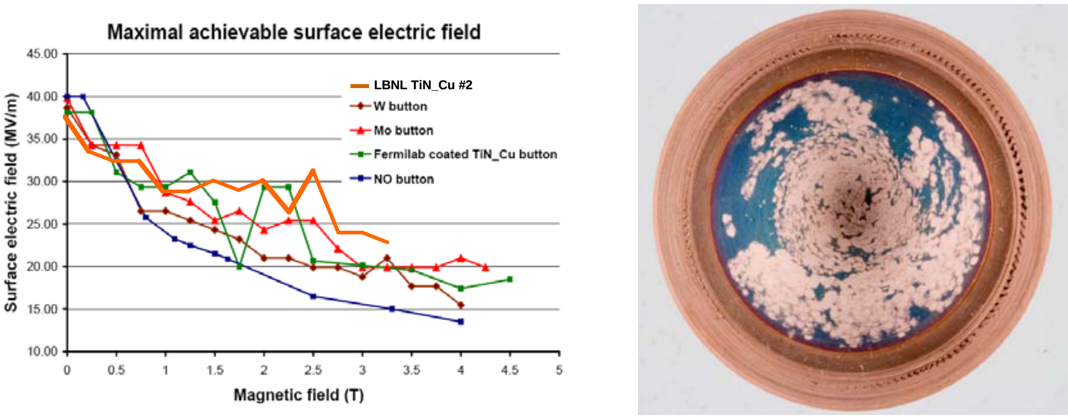

Figure 4: Achievable peak surface field as a function of external magnetic field for different button materials and coatings (left); photo of a damage of the Ti-N coated copper plate that faces to a curved-out beryllium window (right).

Most recent test results are presented in Figure 4, data analysis is under way. The cavity was taken apart for further surface damage inspections. Surface damage was also observed on the cavity wall that faces the kidney-shaped coupling slot of the waveguide. Preliminary analysis indicates that the damage might be caused by electrons emitted from high electric field regions that are being focused by external magnetic fields. The damaged cavity surface is being cleaned now at J-Lab before more tests are resumed at MTA.

The 201-MHz cavity conditioning went well and reached to 19-MV/m quickly without external magnetic fields. The cavity then was moved close to Lab-G magnet for further tests with stray magnetic field on the nearest beryllium window up to 0.75-Tesla. Preliminary tests showed that the cavity can maintain at 14-MV/m, an encouraging result, but need to be confirmed with more tests using a superconducting coupling coil. The superconducting coupling coil for MUCOOL test is being designed and will be fabricated by ICST (Institute of Cryogenics for Superconductivity Technology) of HIT (Harbin Institute of Technology), China through collaboration between ICST and LBNL (Lawrence Berkeley National Laboratory). The coupling coil should be ready for tests one year from now.

Preliminary physics models are developed and numerical simulations are conducted to understand the RF breakdown in strong magnetic fields [5].

4. Summary

Conditioning and operating a high gradient RF cavity in a strong magnetic field remain to be a challenge for the muon ionization cooling. Progresses have been made to understand the RF breakdown, but more experimental and theoretical studies with a stronger magnetic field for the 201-MHz cavity are necessary.

5. Acknowledgements

The authors would like to thank collaborators in MUCOOL and MICE collaborations for their contributions to the work presented in this paper.

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