R&D of Vacuum Normal Conducting RF Cavities for the Muon Ionization Cooling

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Muon collider is considered to be one of the most promising contenders for future particle physics discoveries in energy frontier, in terms of the footprint and cost. However, there are technical challenges for muon colliders to achieve the targeted collider luminosity with small emittance and high flux [1]. Presently the most mature design of the muon source is based on proton spallation, pion decay and muon ionization cooling. Muon ionization cooling is one of the most efficient transverse cooling schemes, where the muon beam loses energy when passing through absorber materials and regain only the lost longitudinal energy from RF cavities which leads to the transverse emittance reduction. Due to the large divergence of the muon beam from the pion decay, a strong solenoidal magnetic field produced by superconducting magnets is required to confine the muon beam within the cooling channel. Recent breakthrough experiment by the international Muon Ionization Cooling Experiment (MICE) collaboration in demonstrating the muon ionization cooling has a major step forward to building a muon collider [2].

For a muon ionization cooling channel, the performance of the RF cavities is critical. Although the cavities have not yet been implemented in the MICE experiment, significant progress has been made in the past under the US Muon Accelerator Program (MAP). Due to the presence of a strong magnetic field, the RF cavities become much more susceptible to the RF breakdown [3]. The achievable stable operational accelerating gradient degraded significantly once the superconducting solenoids are turned on, and it became the technical challenge for the design of a high-efficient ionization cooling channel. For the past decades, R&D efforts have been carried out to understand the breakdown mechanism in the presence of a strong magnetic field. We have successfully designed, built RF cavities and demonstrated stable operation at ~10 MV/m or above for the ionization cooling at Muon Test Area (MTA), Fermilab.

At least two normal conducting vacuum cavities have demonstrated the required performance under different circumstances: 1) the 201 MHz for the Muon Ionization Cooling Experiment (MICE) has achieved 10.3 MV/m in the fringe field of a 5T solenoid field [4], 2) the 805 MHz beryllium-wall modular cavity had achieved more than 50 MV/m in the middle of a 5T solenoid field [5]. The success of MICE cavity indicates the importance of good surface quality for avoiding the RF breakdown. The Be-wall modular cavity shows the low Z conducting material such as Be can prevent the formation of surface defects thus suppressing the field emission electrons. Many experiences have been learnt from the R&D of these two cavities on RF design, RF commissioning, mechanical design, and manufacturing techniques.

With all these progresses, there are still considerable work need be done to make realistic cavities for the current cooling channel design. Here we propose the following R&D efforts on the normal conducting vacuum RF cavity:

1) Design the compact multiple-cavity module, with efficient frequency tuning and RF power feeding systems. In the cooling channel, the voltage in each segment requires multiple cavities or one LINAC with multiple cells. In order to have strong solenoid fields, the cavity design should be as compact as possible in the transverse direction. The RF tuning and the power coupling designs should fit into the tight spaces and be resilient to the strong magnetic field background. Novel ideas such as distributed coupling structure [6] can be explored.

2) Study the effects of thin Be walls, such as the thermal deformation and the cooling schemes. Due to the scattering effect, the Be walls should be kept thin especially at the later stage of the cooling channel. As lessons learnt from MICE cavity, thin Be windows introduce new challenges on the mechanical design and the thermal management, and should be carefully examined.
3) Look into cavities at other frequencies such as 325 MHz and 650 MHz. Several current ionization channel designs call for cavities at 325 MHz and 650 MHz [7]. From the conventional wisdom that lower frequency corresponds to lower Kilpatrick limit, they could be more susceptible to the RF breakdown than the demonstrated 805 MHz cavity. Thus, their performance in the strong magnetic field needs to be examined. Also, their transverse sizes are larger than the 805 MHz cavity, which could make it more challenging for the magnet design. How to keep them compact should be explored collectively with the superconducting solenoid design.

In conclusion, RF cavities are critical for the ionization for the future muon colliders. Significant progress has been made and lessons learnt in the past decades on how to build stably operated RF cavities in strong magnetic field. Some recent development of the high gradient normal conducting RF cavities could be implemented for the muon ionization cooling. The R&D work should be carried on towards more efficient and realistic cavity design with the evolving cooling channel design.

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