Muons have a potential of producing well-characterized neutrino beams for precise, high sensitivity studies as well as being a candidate particles for collider reaching multi-TeV energies.

To efficiently cool the muon beam, some designs require high gradient operation of RF cavities in strong external solenoidal focusing magnetic field. It was experimentally shown that the problem of RF breakdown is aggravated if external magnetic field is applied. The MuCool Test Area (MTA) is a unique accelerator R&D facility, built specifically to test RF components for a muon ionization cooling channel in external multi-Tesla solenoidal field with and without the presence of a beam. As a part of MTA experimental program, high-gradient performance of 805 and 201MHz cavities as well as dielectric loaded high-pressure 805MHz cavities was tested. This talk will cover a review of MTA experimental program and will discuss the most interesting and promising results.

1 Introduction

1.1 Motivation

Muon-based facilities provide unique potential for capabilities at both the Intensity Frontier with Neutrino Factories and the Energy Frontier with Muon Colliders. A realistic scenario for staged facilities with significant physics potential has been under development. Figure 1 demonstrates the conceptual designs of Muon Collider and Neutrino Factory. One of the most crucial stages for both frontiers incorporates the concept of Muon Cooling - reduction in 6D phase space of muon beam in relatively fast time span. Investigated designs of the cooling stage rely on operating normal conducting RF cavities in strong solenoidal magnetic fields up to several Tesla.

1.2 MTA facility

The MuCool Test Area (MTA) is a unique accelerator R&D facility, built specifically for testing components for muon ionization cooling channel. Facility includes a cryoplant, underground experimental hall, clean room for component inspection and assembly. Cavities of 201 and 805MHz can be tested under high power with or without the presence of 400-MeV proton beam supplied from Fermilab’s Linac through special beamline. A superconducting solenoidal magnet with a maximum field strength of five Tesla is used to provide a magnetic field for both 201
and 805 MHz cavity operations. Two types of RF cavity designs have been studied at MTA: dielectric-loaded high pressure gas-filled cavities and vacuum pillbox-type cavities.

Automated RF cavity conditioning controls have been implemented in MuCool Test Area using LabView software. Important features of this system include cavity waveform analysis during each pulse and breakdown detection; cavity tuning algorithm; gradient ramping and recovery from breakdown; capability for saving regular waveforms, triggered breakdown waveforms and text log files to disk for future data analysis.

### 201 MHz MICE cavity program

International Muon Ionization Cooling Experiment (MICE) aims to demonstrate the feasibility of muon ionization cooling concept. The experiment comprises one cell of the cooling channel along with detectors to measure initial and final 6D beam emittance. MICE design assumes stable operation at gradient of 10.3MV/m in fringe fields of multi-Tesla solenoidal magnetic field. MTA experimental group has tested 201MHz cavity module very similar to that of the full ionization cooling demonstration in MICE. Table 1 shows the comparison of MTA run configuration of cavity during tests and MICE design parameters.

The testing of MICE cavity prototype under operating conditions close to MICE has been successfully completed. The stable performance of the cavity in both zero external magnetic field and B=3T external fringe field was demonstrated for copper and beryllium windows. For all configurations, no breakdown events were detected at MICE design peak gradient of 10.3MV/m and measured radiation rates were within limits for tracker backgrounds. A lot of experience was gained with surface preparation, cavity design and operation that is relevant for
next generation of RF systems for MICE. Figure 2 shows the schematic of vacuum vessel for the cavity and the cavity itself.

3 Gas filled cavity program

3.1 Breakdown behavior

Proposed Helical Cooling Channel (HCC) designs for ionization cooling stage use hydrogen-pressure RF cavities in the magnet system with solenoid, helical dipole and helical quadrupole components that provide continuous dispersion needed for emittance exchange in efficient 6D beam cooling. In addition to providing emittance exchange mechanism, high pressure gas is also acting as a mitigator of RF breakdown. Compared to other gases, hydrogen is an ideal absorber candidate due to relatively large radiation length and stopping power.

The RF breakdown of dense hydrogen gas between metallic electrodes has been studied as a part of a program to develop gas-filled cavities for muon ionization cooling. A pressurized 805MHz test cell cavity was used in MTA to measure the increase in breakdown threshold as a function of gas density, the effect known as the Paschen curve. Summary of test results is presented in Fig 3. As expected, the maximum gradient tends to increase with gas pressure according to the Paschen law. However, at high gas pressures gradient behavior is dominated by metallic RF breakdown. It is important to note that gradient was not affected by the external magnetic field and baseline 20 MV/m gradient required by HCC designs was demonstrated for gas pressure as low as 20 atm.

3.2 Beam considerations

For cooling channel to be stable and efficient, muon beam passing through the gas-filled cavity must not trigger breakdown event. Earlier experiments at MTA showed that such problem does not arise. Additionally, a beam traversing a cavity ionizes the gas resulting in plasma loading effect which leads to degradation of accelerating gradient and, therefore, needs to be minimized. Plasma loading is believed to be manageable for beam intensities specified in design requirements for muon collider (up to $10^{12}$ muons per bunch for 325MHz RF system).

3.3 Dielectric Loaded Pressurized Cavity

Helical Cooling Channel designs require operation of 325 and 650MHz cavities. However, present magnet technology does not allow structures of that size to fit in bores of the magnets. One of the possible solutions of this problem explored in MTA is loading the cavity with dielectric material to decrease resonant frequency. Such concept was tested in specially designed dielectric loaded high pressure cavity with alumina donut insert.
Results operating dielectric loaded cavity demonstrate gradient limitations by alumina: depending on alumina purity and gas composition gradient achieved is in the range between 11 and 17MV/m$^{12}$. The addition of small electrodes affected the distribution of peak fields inside the cavity and improved the accelerating gradient while maintaining peak surface field on alumina. That indicates the feasibility of meeting cooling channel gradient requirements with a combination of dielectric loading and reentrant geometry.

4 Study of vacuum RF breakdown in 805MHz cavities

4.1 A model explaining the effect of RF breakdown in strong magnetic fields

Multi-Tesla external magnetic fields have shown to affect the breakdown rate in normal-conducting cavities$^{13,14}$. A model has been proposed to explain the effect of strong magnetic fields on RF breakdown rate$^{15}$. In this model, field emission from surface defects is focused by external solenoidal field into so-called “beamlets”. These beamlets may persist over multiple RF cycles, causing degradation of surface by cyclic fatigue which eventually leads to an increased local breakdown probability. As a consequence of this model, there are potential mitigators of the problem of RF breakdown in external magnetic field, such as careful surface preparation that decreases number and magnitude of surface defects, geometrical solutions that decrease the impact energy of field emitted electrons (such as changing the RF gap of the cavity) and use of higher radiation length materials (such as Beryllium) that allow electrons to pass through without causing substantial damage. The model also shows that the effect of external magnetic field diminishes for values higher than 0.5 Tesla, where the space charge effects of electron beam start to counteract the focusing effect of solenoidal field. Using estimates of safe pulse heating temperature for copper, the model predicts the maximum achievable gradients for 805MHz pillbox cavity depending on external magnetic field value.

Several 805MHz pillbox-like cavities have been tested in MTA in external solenoidal magnetic fields up to 5 Tesla$^{16}$. The graph summarizing the gradient behavior of these cavities is shown on Figure 4. In general, the experimental results follow the trend of model predictions, however there are some factors that may affect the quality of the fit. Thus, so-called “All-Seasons Cavity” had a long RF gap length that decreased the impact energy of dark current electrons. The model also shows that the effect of external magnetic field diminishes for values higher than 0.5 Tesla, where the space charge effects of electron beam start to counteract the focusing effect of solenoidal field. Using estimates of safe pulse heating temperature for copper, the model predicts the maximum achievable gradients for 805MHz pillbox cavity depending on external magnetic field value.

Figure 3 – Measurements of the maximum stable gradient as a function of hydrogen gas pressure with no magnetic field for three electrode materials: copper (red), molybdenum (green) and beryllium (blue). The cavity was also operated in a 3T solenoidal magnetic field with Mo electrodes (magenta).
field enhancement region and therefore was an additional source of systematic error for studying the problem of RF breakdown.

Figure 4 – Peak surface electric field vs external magnetic field for various 805MHz pillbox-like cavities. The black line corresponds to prediction from model discussed above.

4.2 Pillbox 805MHz “modular” cavity

New cavity was designed and built with the goal of better experimental flexibility and improved control over sources of systematic error\textsuperscript{17}. The flat walls of the cavity can relatively easy be removed for inspection or reconditioning of inner surfaces and allow for materials swap, hence the structure is referred to as the “modular cavity”. The cavity walls were chemically polished and special design of input coupler provides a factor of \textasciitilde 5 suppression of field around coupler region compared to on-axis field of TM010 mode.

The cavity with the set of fresh copper endplates was run in zero magnetic field first and reached gradient of 45MV/m\textsuperscript{18}. The visual inspection of the damage on inner surface of flat endplates revealed barely visible microscopic damage of typical size of few hundred micron. No correlation between damage on opposing endplates was observed. The cavity was then run again with the same set of endplates in external magnetic field of 3 Tesla. The maximum achieved gradient of 12MV/m limited by high rate of breakdown events was achieved and another visual inspection of inner surfaces was performed. Figure 5 demonstrates the comparison between the surface condition of the same endplate after operation in zero magnetic field and three Tesla field. It can be seen that the damage is easily visible and more “violent” when magnetic field was present. Additionally, perfect correlation between all 354 damage locations on opposing flat endplates was found as shown on Figure 6, which supports the hypothesis of RF breakdown being connected with focused dark current beamlets inside the cavity.

Figure 5 – Inner surface of flat window after high power test at zero external magnetic field (left) and at three Tesla field (right).
The next set of high power tests will be conducted with Beryllium endplates. According to the model previously outlined, due to higher radiation length of Beryllium compared to copper, the breakdown triggers are expected to be mitigated resulting in better overall gradient performance. Additionally, Beryllium allows for direct measurement of dark current (for ex. using Faraday cup) and transverse emittance of dark current beamlets (using sensitive films).

5 Summary and conclusion

Significant progress in operating RF cavities in strong external magnetic field has been shown in last several years at MTA. General solution to the problem of suppressing the RF breakdown in strong magnetic fields was demonstrated via using cavities filled with high-pressured gas. Stable operation of several 805MHz vacuum cavities at magnetic fields up to 5 Tesla was demonstrated and appears to be an encouraging results towards feasibility of vacuum-based ionization cooling channel. Applying advanced surface preparation techniques resulted in meeting design gradients for 201 MHz MICE cavity. A variety of exciting results are coming from studying the problem of RF breakdown, in particular from modular cavity program. Both experimental and analytical work is ongoing and promises exciting potential in better understanding of mechanism of RF breakdown.

References

3. http://www.mice.iit.edu/mta/
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