The MAP Normal Conducting RF R&D Program

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Abstract

This document (i) describes the Normal Conducting RF (NCRF) requirements for a Muon Collider facility, (ii) compares these requirements with the present state of the art, (iii) identifies the main R&D issues, and (iv) describes the MAP RF R&D program we are proposing to address these issues, and its prospects for success.

1. INTRODUCTION AND REQUIREMENTS

Muons from pion decays are necessarily born within a very large 6D phase space. At the end of a 1.5 T solenoid decay channel the muon population typically has a radius of ~50 cm, and transverse momentum components that are comparable to the longitudinal momentum, which is *O*(200) MeV/c. In Muon Collider and Neutrino Factory front-end designs, a system of RF cavities is used to capture the muon population into a bunch train by decelerating the early, higher-energy, bunches and accelerating the later, lower-energy, bunches (phase rotation), so that all bunches have the same average energy. To keep the muons captured radially during this bunching and phase rotation process, they are confined within a solenoid channel with an axial magnetic field of a few tesla. This bunching and phase rotation scheme leads to the following requirements for the RF cavities (see Table 1):

i) Normal conducting RF (NCRF) that can operate at high gradient within a few-tesla magnetic field.

ii) Low frequency cavities to provide a sufficient aperture for the beam. In practice this means frequencies *O*(200) MHz.

iii) High gradient operation to provide a deep enough potential well to capture the muons within bunches and to reaccelerate them quickly. Simulations suggest ~15 MeV/m is adequate at *O*(200) MHz (see Figure 1).

Table 1: RF parameters for the front-end of MC or NF.

Parameter	Value	Unit
Buncher cavity frequency range	233.6 – 319.6	MHz
Maximum buncher cavity gradient	8.0	MV/m
Phase rotation cavity frequency range	202.3 – 230.2	MHz
Maximum phase rotation cavity gradient	12.0	MV/m
Initial cooling channel cavity frequency	201.25	MHz
Initial cooling channel cavity gradient	15.25	MV/m

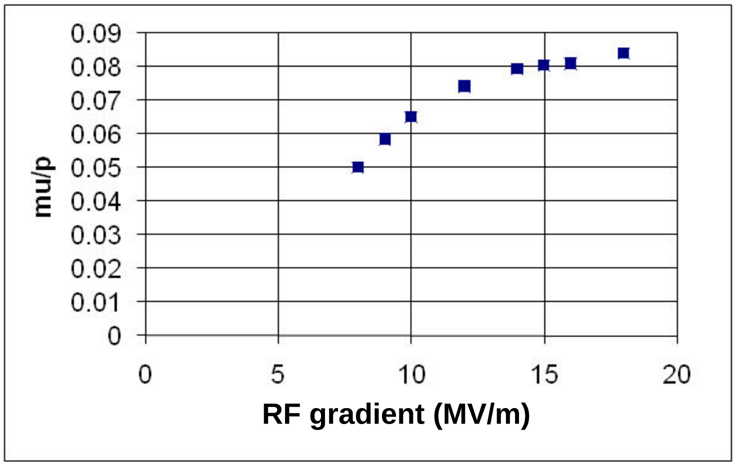

Figure 1 Muon per proton ratio at the end of the channel vs. RF gradient.

Following the bunching and phase-rotation channel, the muons must be cooled by a factor of $O(10^6)$ to obtain sufficiently bright beams for a high luminosity Muon Collider. The cooling must be achieved rapidly, before the muons decay, which excludes electron cooling and/or stochastic cooling. It is proposed to use ionization cooling, in which muons lose longitudinal and transverse momentum by ionization losses as they pass through material. The energy is then restored by acceleration in the longitudinal direction using NCRF cavities, and this process can be repeated many times. As a result, the transverse momentum components are reduced (transverse cooling). To fight against scattering in the energy-loss material, which ultimately limits the transverse cooling, efficient ionization cooling requires a magnetic channel that provides radial focusing with a focusing angle that is much larger than the typical multiple scattering angle. In practice our designs use a solenoid channel with an axial magnetic field of a few tesla in the early stages of cooling, increasing to $O(10)$ Tesla in the later stages, and several times 10 Tesla in the final stages. For this scheme to work, the RF requirements for an ionization cooling channel are (see Table 1):

i) Normal conducting RF (NCRF) that can operate within the magnetic channel[1].

ii) At the beginning of the channel, low-frequency high-gradient RF, to provide a sufficient aperture for the beam and to keep the beam bunches captured longitudinally while reaccelerating in the longitudinal direction. In practice, this means frequencies $O(200)$ MHz and gradients ~15 MV/m. As shown in Figure 1, with somewhat lower gradients, the channel will continue to operate, but with increased losses and reduced efficiency. Note that, over a broad range of maximum RF gradient, the decrease is at the percentage level, that is, performance degrades gracefully.

iii) Towards the end of the cooling channel the cavity apertures can be reduced, permitting the use of higher-frequency higher-gradient cavities. The present scheme uses 805-MHz cavities operating with gradients ~30 MV/m. Once again, with somewhat lower gradients the channel will continue to operate, but with increased losses and reduced efficiency. In addition to these RF requirements, there are some extra features that are highly desirable, e.g., the cavities should have high shunt impedance. The present cavity design uses a round pillbox geometry in which the normally open irises are closed by thin beryllium windows. For a given peak input power, this effectively increases the accelerating gradient on axis by a factor of $\sqrt{2}$, and therefore reduces the overall peak power requirements for the channel by nearly a factor of 2. This

[1] It is possible to design lattices in which the cavities are in lower fields, but this increases the challenge of arriving at an effective cooling channel design, and is likely to result in a longer, more expensive, and less efficient channel.

reduction in peak power needs (and hence power source) is not essential for technical feasibility, but is highly desirable for cost effectiveness.

2. R&D ISSUES AND PRESENT STATUS

The design and performance of the bunching, phase rotation and ionization cooling channels depend critically upon the assumed performance of the NCRF cavities. This is particularly true for the cooling channel, for which the assumed RF cavity design and performance influence the requirements for the magnetic lattice to be employed. It is therefore crucial to establish the operational parameters that should be assumed for the RF cavities in the cooling channel design, and to demonstrate that the assumed RF gradient can be achieved for a cavity operating within the required magnetic field configuration.

Thus, the proposed MAP NCRF program is focused on establishing and demonstrating the required NCRF cavity operation within a magnetic field configuration that corresponds to an ionization cooling channel lattice, and measuring the achievable operating gradient.

The NCRF R&D program for Neutrino Factories and Muon Colliders has been pursued over the last decade, and has resulted in notable achievements:

i) The MuCool Test Area (MTA) has been constructed at the end of the Fermilab 400 MeV Linac. This area (see Figs. 2 and 3) is equipped with

   (a) RF power sources at 805 MHz (12 MW) and 201 MHz (5 MW);

   (b) A 4-Tesla superconducting solenoid with a bore sufficient to accommodate an 805-MHz cavity;

   (c) A 250-W cryogenics plant to support the solenoid operation and tests using liquid hydrogen cooling channel absorbers.

   (d) A newly constructed beam line to bring a 400-MeV proton beam to the MTA will be available in the near future.

   The MTA is a unique R&D facility for the study of muon ionization cooling channel components. Its primary purpose at this time is to support the MAP NCRF R&D program and, in particular, to enable studies of cavity operation within a few-tesla magnetic field. Utilization of this facility is an important ingredient in the MAP R&D plan.

(a)

(b)

Figure 2: MTA entrance (a) and layout (b) showing 20 ft by 40 ft experimental area.

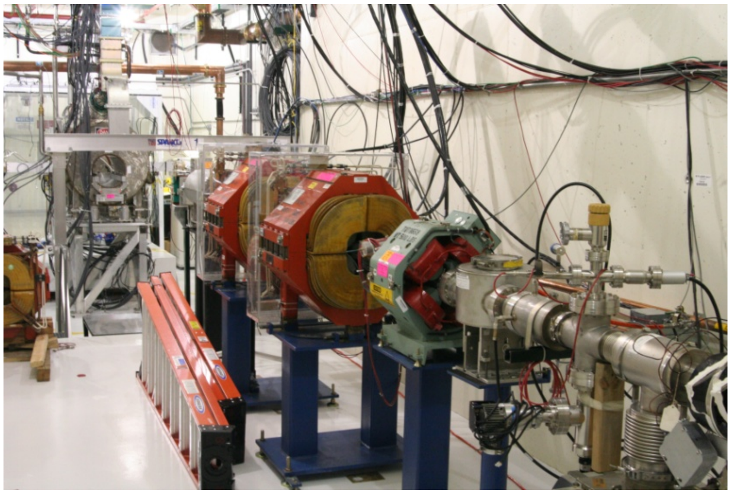

Figure 3 a): MTA Beam line installation.

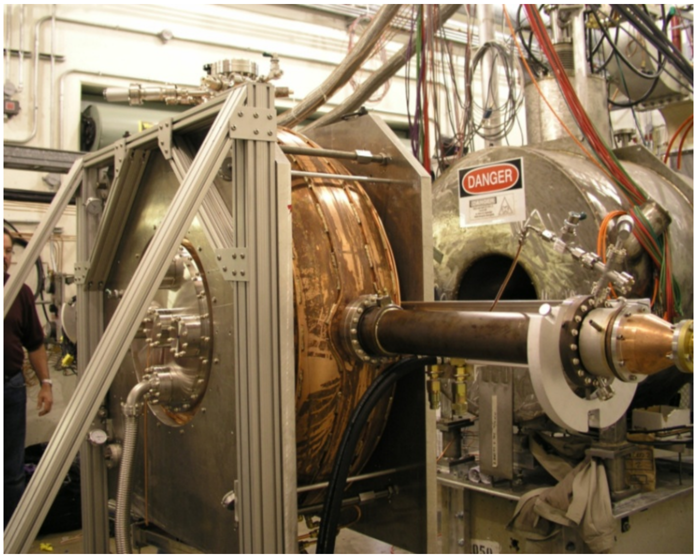

Figure 3 b): 201-MHz normal conducting cavity at MTA.

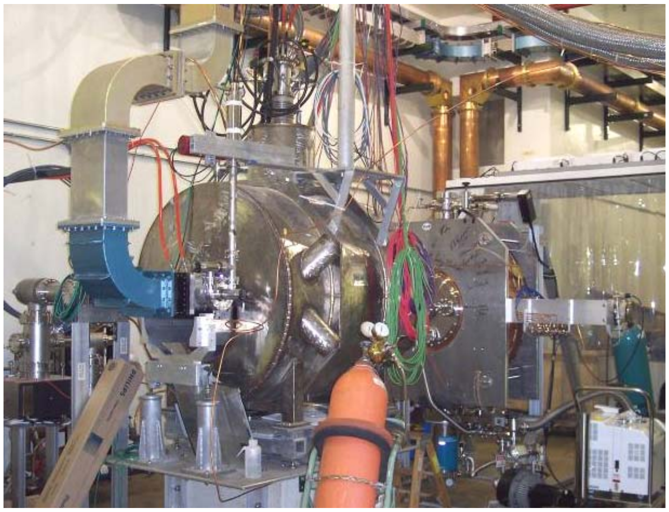

Figure 3 c): 4-T superconducting solenoid magnet with the 805-MHz pillbox cavity inside the warm bore.

ii) In early work within the muon accelerator NCRF R&D program we:

a) Designed, built and studied the operation of a multi-cell open iris copper 805-MHz cavity [1].

b) Designed, built and studied the operation of a copper 805-MHz pillbox vacuum cavity with thin beryllium windows [2]. Beryllium was chosen to minimize scattering of the muons as they pass through the windows.

c) Carried out Be windows R&D. The window designs evolved from a pre-stressed flat design to a double curvature profile. The windows were TiN coated in order to prevent multipactoring. A combination of the double curvature design, orientation, and the choice of the window thickness minimize the cavity frequency shift due to the RF heating. Experimental studies have indicated that Be windows can withstand very high RF gradient without surface damage (in comparison with copper surfaces). Windows for both the 805-MHz and 201-MHz cavities are shown in Fig. 4.

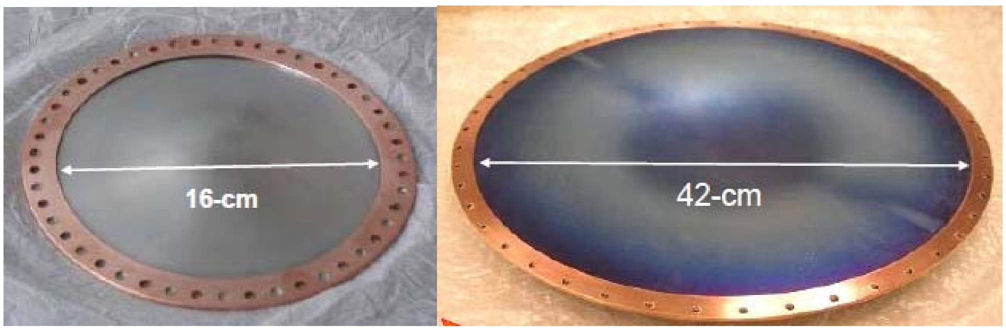

Figure 4: Be window for 805-MHz cavity (left); Be window for 201-MHz cavity (right).

d) Cavities of the type desired for the bunching, phase rotation, and cooling channels have been designed, built and tested within a magnetic field [3,4]. With a zero magnetic field, all the tested cavities have achieved, or exceeded, their design gradients (see Table 2). However, in all cases, reduced performance was observed when these cavities were operated in a substantial external axial magnetic field, with the maximum achievable gradient limited by RF breakdown, that is, we observe decreasing achievable maximum RF gradient with increasing external magnetic field, as shown in Fig. 5. Measurements on the 805-MHz pillbox cavity have been repeated and shown to be reproducible over time and robust against various changes in experimental setup. An examination of the 805-MHz cavities after operating at high gradient in magnetic fields shows severe surface damage due to RF breakdown. However, the damage in the pillbox cavity indicated that much of the observed breakdown was taking place in the coupler area, which is thought not to be a fundamental problem. The pattern of damage suggests that the damaged areas are caused by electrons emitted from high RF electrical field regions and focused by the external magnetic fields. Various competing models have been developed to explain the breakdown mechanism in more detail, and these models lead to candidate solutions that must be explored. Hence, we believe the R&D has (a) identified the primary challenge that must be met if NCRF cavities are to be successfully operated in an ionization cooling channel, namely achieving the required gradient within a magnetic channel, and (b) identified several candidate solutions.

Table 2. Maximum RF gradient observed without magnetic field.

Cavity	Max. surface gradient
805 MHz open-cell [MV/m]	54
805 MHz pillbox (Be or Cu windows) [MV/m]	40
805 MHz high-pressure button cavity [MV/m]	65
201 MHz pillbox (Be windows) [MV/m]	21[a)]

[a)] Limited by RF power source.

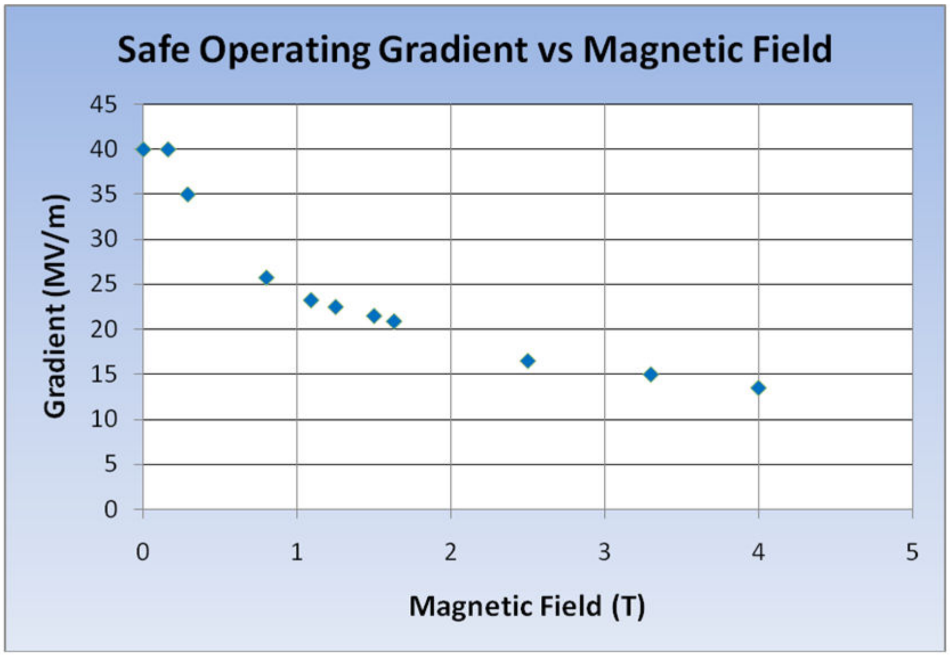

Figure 5: Maximum achievable surface field vs. applied axial magnetic field for a pillbox cavity showing a significant reduction compared with the no-field case.

e) Exploration of possible solutions to the magnetic field challenge has begun. The solutions which seem promising, and are under study, include the following:
   (a) *Using beryllium*: after operation in a few-tesla axial magnetic field, the observed breakdown damage in the 805 MHz pillbox cavity was limited to the copper surfaces. No damage was observed on the beryllium windows. Beryllium is a harder material than copper, and it is thought that an all-beryllium cavity (or one in which there is beryllium wherever the surface fields are high), will enable cavity operation at high gradient within the required magnetic field. Design of such a cavity is under way.
   (b) *Using high-pressure hydrogen*: it has been proposed [5] to use a NCRF cavity filled with high-pressure hydrogen gas to suppress breakdown. An 805-MHz test cell has been built and the maximum achievable gradient measured as a function of pressure and magnetic field (Fig. 6). The required maximum gradients have been achieved with no appreciable degradation at high magnetic field. However, the measurements have not yet been made with the high-pressure hydrogen-filled RF cavity exposed to an ionizing beam. The delay in getting beam to the MTA has allowed more analytical work, including comparisons of measurements and simulations of breakdown behavior as functions of surface gradient, gas species, SF_6 dopant, and external magnetic field. As a consequence of these studies, we believe that the cavity will not break down when pressurized with the very dense hydrogen gas needed for the Helical Cooling Channel (HCC) useful for the 6-D cooling of muon beams, even in strong magnetic fields and with the heavy ionization

produced by intense muon beams. Figure 7 shows a simulated RF pickup signal in a high-pressure RF cavity with a high-intensity proton beam passing through the cavity. This experiment will be carried out in the fall of 2010.

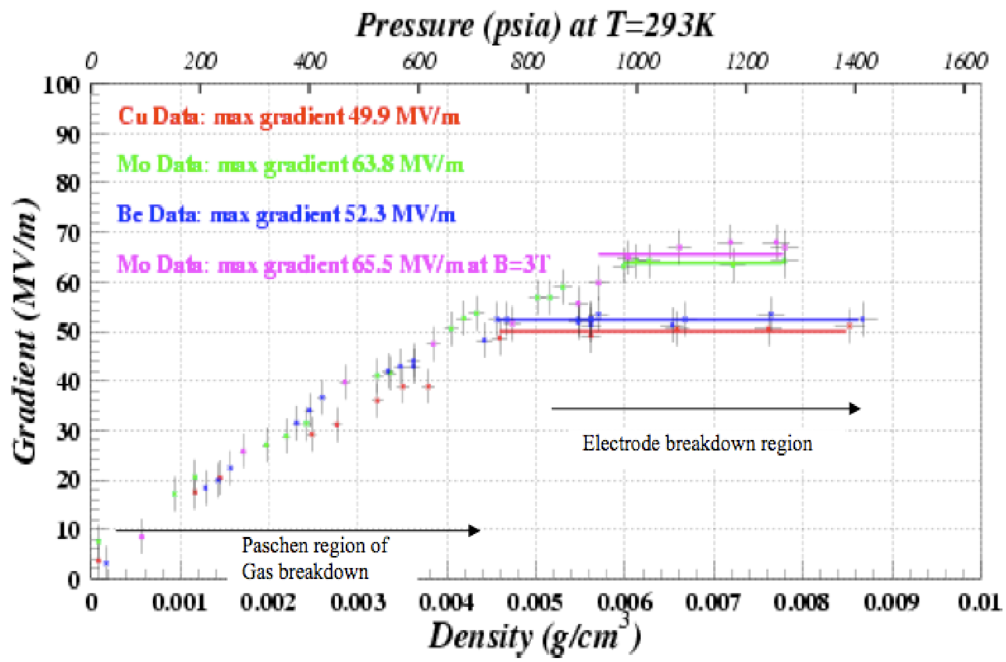

Figure 6: Achievable gradient in H_2-gas-filled 805-MHz cavity *vs*. gas density. The upper lines show identical performance of Mo buttons with and without a 3 T applied magnetic field. See [1].

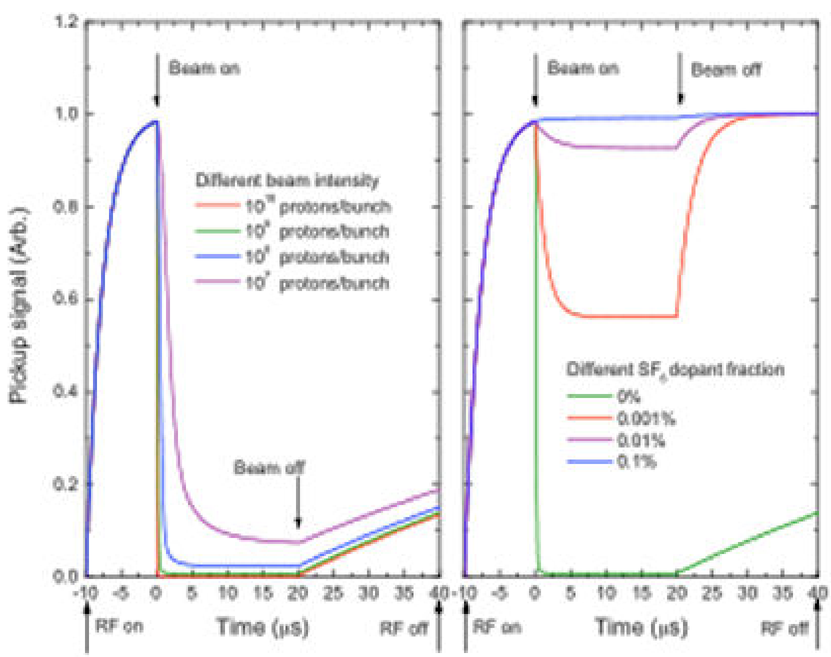

Figure 7: RF signal in H_2 filled cavity when exposed to beam. Without SF_6 dopant (left) and with SF_6 (right).

(c) *Using magnetic insulation*: it has been suggested [6] that damaging breakdowns can be suppressed if the magnetic lattice is designed so that, at the region of high surface electrical RF fields, the magnetic field is parallel to the surface. This will force the electrons (which otherwise cause damage) to follow the magnetic field lines without gaining energy from RF electrical fields. The paths and acceleration of these electrons within a "magnetically insulated" cavity have been simulated to theoretically demonstrate the principle. Recently, an 805-MHz box cavity that can be rotated within the MTA 4-T solenoid has been built and we have the results from preliminary testing. Measurements in a configuration in which the high electrical field was perpendicular to a 3-T magnetic field demonstrated operation at a gradient around 30 MV/m, much higher than the 15 MV/m we observed with the pillbox cavity where E was parallel to B. However, breakdown did start to limit the maximum stable RF gradient and cause breakdown when the cavity was rotated by only 3°, see Fig. 8. The data in Fig. 8 give the mean gradient at which a spark occurred during the full run as a function of the angle of the electric field with respect to the magnetic field in degrees. These preliminary results show a clear degradation at 3° and 4°. The total number of pulses for each data set is approximately 3.4M, 1.6M, 0.5M and 2.0M at 0, 1, 3, and 4 degrees of cavity rotation, respectively. Studies with this cavity are continuing.

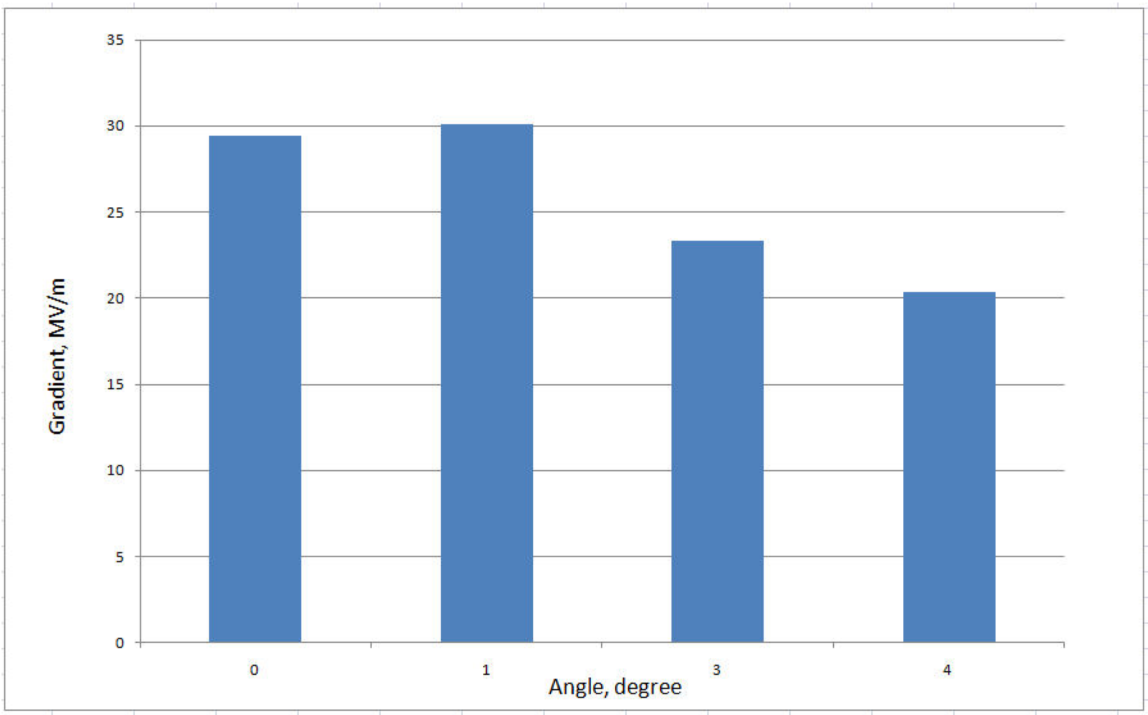

Figure 8: Recent test results of the box cavity with 3-tesla magnetic field.

(d) *Using alternative materials and surface preparation*: careful choice of materials and surface preparation can help suppress field emission, and therefore RF breakdown. The MAP NCRF program has included studies that investigate using alternative materials and surface preparation. One notable success is that a 201-MHz copper pillbox NCRF cavity with beryllium windows has been constructed (see Fig. 3b)) using a surface preparation recipe similar to that employed for SRF cavities. In a zero magnetic field, this cavity achieved full gradient (21 MV/m, limited by the power supply) without much conditioning. This cavity has also been operated in the fringe field of the MTA magnet. There was a modest degradation in maximum achievable gradient with a field of 0.75 T at the nearest Be window, which suggests that this particular surface preparation recipe does not, by itself, solve the problem. However, the indication was that the radiation levels rose more slowly with gradient than was true for the 805-MHz cavity. Further tests in a more uniform magnetic field will be made when a large diameter magnet is available, toward the end of 2011.

In order to investigate other surfaces and materials in a cost effective and efficient manner, the 805-MHz pillbox cavity was modified to accommodate interchangeable high-surface-field inserts (RF buttons). Several RF buttons with different materials have been tested, and the test results are shown in Figure 9. Finally, it has been shown that using an advanced *in situ* surface preparation technique, ALD (Atomic Layer Deposition), can enhance the performance of SRF cavities [7-9]. The ALD technique has a potential to eliminate the surface field emission completely, and is therefore also a candidate technique for improving the performance of pillbox NCRF cavities, thus mitigating the breakdown problem within a magnetic channel.

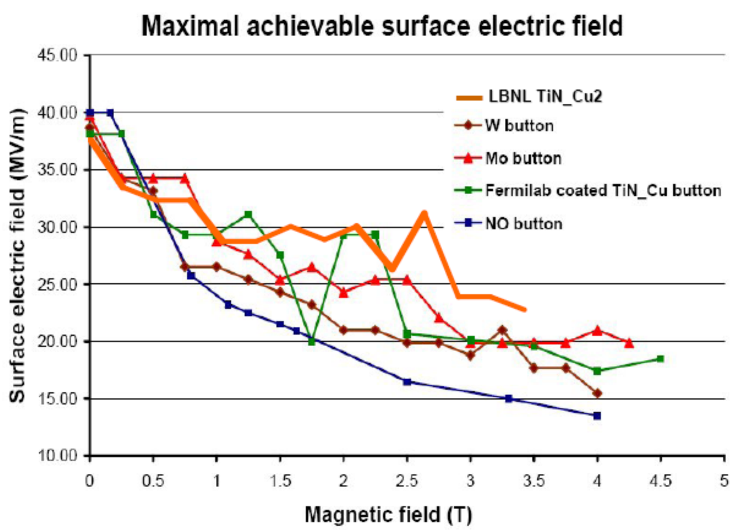

Figure 9: Experimental results of RF button tests.

In summary, the R&D program to date has (1) established an R&D facility to study NCRF cavity operation within a magnetic field; (2) established the performance of pillbox cavities with thin and curved beryllium widows when operated in zero magnetic field; (3) shown that, within an external axial magnetic field, RF breakdown limits the achievable gradient and causes damage to copper vacuum cavities; and (4) begun to investigate ways to mitigate the problem.

3. PROPOSED R&D PROGRAM

The NCRF R&D goal for the proposed MAP program is to demonstrate cavity operation within a magnetic field configuration appropriate for an ionization cooling channel, and measure the maximum gradient that can be achieved. The R&D plan has two distinct phases:

Phase 1, which will last for ~2 years, will seek to find at least one solution that mitigates the breakdown of a NCRF cavity within a magnetic channel. Phase 1 will end when an 805-MHz cavity employing this *solution has been demonstrated to achieve a surface gradient of ~30 MV/m in an appropriate but simple magnetic field test* (using the MTA solenoid). For the high-pressure hydrogen-filled cavity, the test must be made in the presence of an ionizing beam. Phase 1 will end with the selection of the successful RF technology for the baseline cooling channel studies in the out-years.

Phase 2, which will last for the remainder of the proposed MAP R&D program, will design and build the cavities needed for a bench test of a short cooling channel section to demonstrate cavity performance in a realistic magnetic channel, and ensure that all of the engineering and safety details that affect cavity operation are well understood.

3.1 Beryllium Cavity R&D Plan

Experimental studies at 805 MHz on vacuum RF cavities operating in magnetic fields have shown significant damage to copper surfaces, drilled a hole through a titanium window (multi-cell open-iris cavity), and in most cases, reduced the maximum sustainable RF gradient. It has been hypothesized that this damage, and the resulting loss of operating gradient, arise from the thermal cycling of spots where field emitted, RF accelerated, and magnetically focused, electron beamlets strike surfaces in the cavity. But, in several of the experiments, there were beryllium surfaces of beam windows that were never visibly damaged. In addition there was no evidence that breakdowns were coming from electron bombardment of these surfaces, and the analysis of dust in the cavity after operation, while containing much copper, contained no beryllium. The explanation for this, with the above hypothesized mechanism, is that beryllium's low density allows the electrons to penetrate the surface more deeply, or even pass through a window, without generating enough heat to cause damage. An experiment in a pill-box cavity, with two opposed beryllium buttons, will soon test this hypothesis. If it is confirmed, then efficient pill-box cavities with beryllium coated internal surfaces, or cavities made from beryllium, could be used. Besides cost and fabrication difficulties, the only disadvantage in this approach, is a slight reduction in Q due to beryllium's somewhat higher resistivity at room temperature. At lower temperatures, however, beryllium is a better conductor than copper, and could thus offer a somewhat higher Q.

3.2 High Pressure Hydrogen Cavity R&D Plan

The high pressure hydrogen cavity R&D has been carried out in collaboration with Muons, Inc. Recent numerical and analytical studies indicate that the cavity will not break down when pressurized with the very dense hydrogen gas needed for the Helical Cooling Channel useful for the 6-D cooling of muon beams, even in a strong magnetic field or with the heavy ionization produced by intense muon beams. The beam to the MTA will only provide a necessary but not sufficient test to verify the theoretical studies because the instantaneous bunch intensity from the Fermilab 400 MeV Linac beam will be two orders of magnitude less than in a HCC for a muon collider (i.e., 10^{10} electrons/bunch versus 10^{12} muons/bunch). Consequently, the confidence to extrapolate to the conditions necessary for a muon collider will have to be made using detailed comparisons of computer models to sophisticated measurements using the MTA beam until an intense muon beam is available. For example, optical fiber studies of hydrogen spectra will be used to understand the details of breakdown phenomena, especially near low-gas-density breakdown thresholds, as a function of beam intensity.

Pressurized cavity models indicate a potential difficulty with a muon beam if the recombination rate is too slow for electrons liberated by the ionization cooling process. In this case, the free electrons will vibrate far enough in the cavity RF field to hit and heat the hydrogen gas molecules, thereby effectively reducing the cavity quality factor. SF_6 dopant studies have shown that the recombination rate can be enhanced to overcome this problem, if it exists. However, SF_6 has nasty residues and will not allow low temperature operation. If dopants are needed, better ones will have to be found.

The Muons, Inc. 805-MHz test cell that has been used up to now, and will be used for the first beam tests, does not have the geometry of the pillbox cavity assumed in beam cooling simulations. A new pressurized pillbox-like cavity will be designed and built to allow for more realistic tests, including studies of low-*Z* material pillbox windows.

3.3 Magnetic Insulation Cavity R&D Plan

As discussed above, significant damage has been observed on copper surfaces in cavities operated in external magnetic fields. If the above hypothesis on cavity surface damage is correct, then the mechanism could be eliminated if the magnetic field lines were arranged to be parallel to all field emitting surfaces. Emitted electrons would then be constrained close to their emitting surface, and would not gain enough energy (from the RF electrical field) to cause damage. Recent experiments testing a simple rectangular box cavity, operated at differing angles with respect to a 3 T external field, appear to confirm the theory. Coil arrangements for muon beam focusing, and appropriately shaped accelerating cavities have been designed, and there is a proposal to test such a combination (see Figure 10). Unfortunately, the required cavity geometries have open irises, and significantly lower the cavity shunt impedances compared with the preferred closed pill-box like cavities. The acceleration, relative to maximum surface fields, is also less.

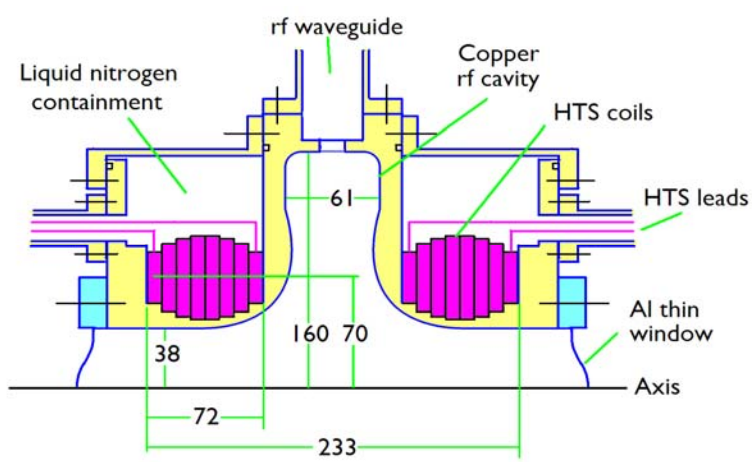

Figure 10: Concept of magnetic insulated RF cavity.

3.4 Materials and Surface Preparation R&D Plan

There is strong evidence that one of the main causes of surface breakdown in RF cavities is high local electric fields that exist on surface asperities. High local fields have been measured in a variety of environments using either x-rays or field emission currents. Recent RF and DC results (including initial Lab-G measurements in 2001) indicate that local surface fields in the range of 7 to 10 GV/m are the breakdown field threshold. At these fields, Coulomb explosions, likely aided by local heating and fatigue (creep at the atomic level) should be sufficient to tear the surface apart and trigger breakdown. Numerical modeling of the complete RF breakdown process will be conducted using a variety of techniques.

Electric fields of this strength may exist in RF cavities as a result of very small, sharp asperities, where $E \sim 1/r$, with r being the local radius of the asperity. Since high electric fields come from small radii, it should be possible to reduce the local fields in cavities by increasing the radii of asperities. Increasing the local radii can be realized in a controlled way using conformal coatings applied with Atomic Layer Deposition (ALD). This procedure extends the common sense argument of not having sharp corners in RF cavities from large radii (mm scale) to much smaller scale (nm scale). Recent analysis has led to the conclusion that the active breakdown sites have dimensions on the order of a few nm, although it should be possible to cope with dimensions perhaps two orders of magnitude larger.

ALD is a proven technology for nanofabrication of materials that uses gaseous precursor chemicals to produce self-limiting, sequential synthesis of monolayer coatings. The method has been well developed in the past two decades, and a large variety of metals and compounds have been produced. The technique is in common use in the semiconductor and optical industries and in the development of new technologies for batteries, solar cells and other applications. We already have an experimental program to develop superconducting structures to improve the gradients and Q of superconducting accelerating cavities. Preliminary tests have shown that the ALD technique has succeeded in increasing both the gradient and Q of a superconducting RF cavity.

In principle it should be possible to apply almost any ALD deposited metal, since the coatings (a few nm thick) would be so thin that the bulk properties (resistivity, thermal conductivity, etc.) would not be relevant (the material becomes "bulk" above ~ 30 nm), and the surface properties, (work function, chemical properties, etc.) could be controlled by monolayer "capping" compounds such as Nb_2O_3. The coatings are highly conformal and AFM measurements have shown that they do not contribute to surface roughness. We have successfully tested the application of ALD coated surfaces in a superconducting cavity at JLab (see Figure 11) at a surface field of around 75 MV/m, higher than the fields in the pillbox 805 MHz cavities. We expect these coatings should be able to eliminate both field emission and breakdown.

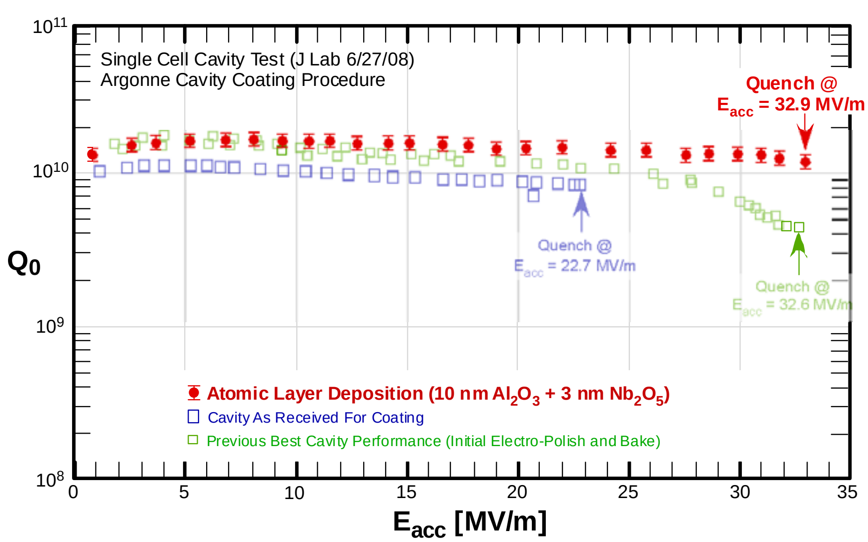

Figure 11: Tests of single cell ALD coated superconducting RF cavity at JLab. These results equaled the best performance without any field emission from previous tests.

Although a large variety of conductors have been synthesized, the most appropriate metal to deposit may be tungsten, which can be fairly rapidly built up on a large surface, and the microscopically smoothest layers can be deposited near room temperature. We propose to design and build an 805-MHz cavity with the ALD coating. Ideally we want to measure the radii of the field emitters and breakdown sites, and this requires deposition of ALD coatings *in situ*. A general experimental system needs to be designed and built. (Funding for this has recently become available). After techniques are proven at 805 MHz, we could immediately begin coating our 201-MHz cavity with the same system, and would then think about a system for MICE.

The reduction in local electric field can be measured through either x-ray radiation levels or dark current intensities. Likewise, measuring improved gradients should be straightforward.

Atomic Layer Deposition requires the use of small amounts of reactive gasses. Techniques for handling these gasses have been developed both by laboratories and commercial vendors of ALD systems. The primary safety requirements are adequate venting and chemical passivation of reaction products before release into the atmosphere.

4. DOWN-SELECTION

Down-selection of RF cavities will be based on the outcome of experimental studies. The cavity must work at an acceptable RF gradient (requirements are, of course, dependent on the position along the channel, i.e., phase rotation, bunching initial cooling, final cooling) in a few-tesla magnetic field. Engineering, fabrication, integration, and cost of the cavity and RF power will also be considered in making our selection.

5. SUMMARY

Solving the RF breakdown problem is arguably the most important challenge that faces the Muon Acceleration Program. The high-gradient operation of normal conducting RF cavities in the presence of high magnetic field is absolutely crucial for a multi-TeV high-luminosity Muon Collider and significantly impacts the potential performance of a Neutrino Factory. The multi-pronged approach that is described in this document addresses this problem head-on and minimizes the technical risk of a future Muon Collider or Neutrino Factory.

References

[1] Wu, Vincent, Thesis: "*Design and Testing of a High Gradient Radio Frequency Cavity for the Muon Collider"*, May 2002.

J. Norem, V. Wu, A. Moretti, M. Popovic, Z. Qian, L. Ducas, Y. Torun and N. Solomey, "*Dark current, breakdown and magnetic field effects in a multicell,805 MHz cavity*", Phys. Rev. STAB **6**, 072001 (2003).

[2] A. Moretti, Z. Qian, J. Norem, Y.. Torun, D. Li, M. Zisman, "Effects of high solenoidal magnetic fields on rf accelerating cavities", Phys. Rev. STAB 8, 072001 (2005).

Y. Torun *et al*., "The MuCool Test Area and RF Program," in Proc. of IPAC10, Kyoto, Japan, 2010.

[3] A. Hassanein, Z. Insepov, J. Norem, Y. Torun, P. Rimmer, D. Li, M. Zisman, D. N. Seidman and Yoon, “Effects of surface damage on rf cavity operation”, Phys. Rev. STAB 9, 062001 (2006).

[4] Z. Insepov, J. Norem, D. Huang, S. Mahalingam, S. Veitzer, “Modeling rf breakdown arcs”, Proceedings of PAC09, Vancouver, Canada, (2009).

[5] M. BastaniNejad *et al.*, “Studies of Breakdown in a Pressurized RF Cavity,” in Proc. 11th European Particle Accelerator Conference, Genoa, June 23–27, pg. 736, (2008).

[6] D. Stratakis, J. C. Gallardo, and R. Palmer, “RF Breakdown in Magnetic Fields: Previous Work, Recent Theory, and Future Plans,” to be published Nucl. Inst. and Methods A (2010).

[7] Th. Proslier *et al.*, “Results from Point Contact Tunneling Spectroscopy and Atomic Layer Deposition,” in Proc. SRF2009, Berlin, Germany, p. 137 (2008).

[8] Z. Insepov, J. Norem, D. Huang, S. Mahalingam, S. Veitzer, “The problem of high gradient limits”, Proceedings of Nufact09, Chicago, (July 1009).

[9] Z. Insepov, J. Norem and A. Hassanein, “New mechanism of cluster field evaporation in rf breakdown”, Phys. Rev. STAB 7, 122001 (2004).