First Draft
2.2 Normal Conducting RF R&D Program

edited by Ralph J. Pasquinelli, Fermilab, July 23, 2008

2.2.1. Overview

High-performance RF systems are used throughout the proposed Neutrino Factory and Muon Collider facilities. RF is used in the capture and phase rotation, rebunching, muon cooling channel and the acceleration sections. Baseline concepts for all RF requirements are contained in published documents. [1,2,3,4,5] Although a number of RF frequencies are in the baseline designs for the various sub-systems, 201 MHz and 805 MHz are used exclusively in the R&D program due to their availability. High gradient operation is essential for desired performance. For 201 MHz and 805 MHz, accelerating gradients of 16 MV/m and 35 MV/m respectively are planned. Understanding and improving performance of breakdown of RF fields within the cavities immersed in a magnet field is a primary goal of the R&D program. This R&D plan will cover only room temperature RF cavities. Superconducting RF (SRF) will be required in the final Factory or Collider, but will not be covered in this chapter.

The Muon Test Area (MTA) at Fermilab is a dedicated research space for the Muon project located at the end of the 400 MeV linac. Current capabilities include availability of 201MHz at 5 Megawatts and 805 MHz at 10 Megawatts. The RF power is delivered on dedicated transmission lines from the two test stands that support "hot" spares for the operational Fermilab linac. A 5 Tesla (T) superconducting 43 cm bore solenoid is available for testing cavities near or immersed a magnetic field. The facility also has a cryogenic plant that is in the final phase of construction. Current cryogenic needs are met with liquid filled Dewars. Near term plans include finalization of the beam line to deliver 400 MeV protons for beam testing with various cavity designs. First beams of protons are expected before the end of calendar year 2008.

2.2.2 R&D Program

2.2.2.1 MTA

The ongoing R&D program has tested prototype cavities that meet the baseline criteria.[6,7] In fact, the test cavities have significantly exceeded these benchmarks: 19MV/m for the MICE 201 MHz prototype cavity and greater than 50 MV/m in our 805 MHz pillbox cavity in the absence of a magnetic field. In actual operation in the Neutrino Factory and/or Muon Collider sub-systems, the cavities must operate in a magnetic field with field strength as large as 3T. Initial testing has shown significant reduction in cavity gradient as a function of induced magnetic fields. Figure 1 shows the maximum stable operating gradient for the 805 MHz pillbox cavity as a function of magnetic field.

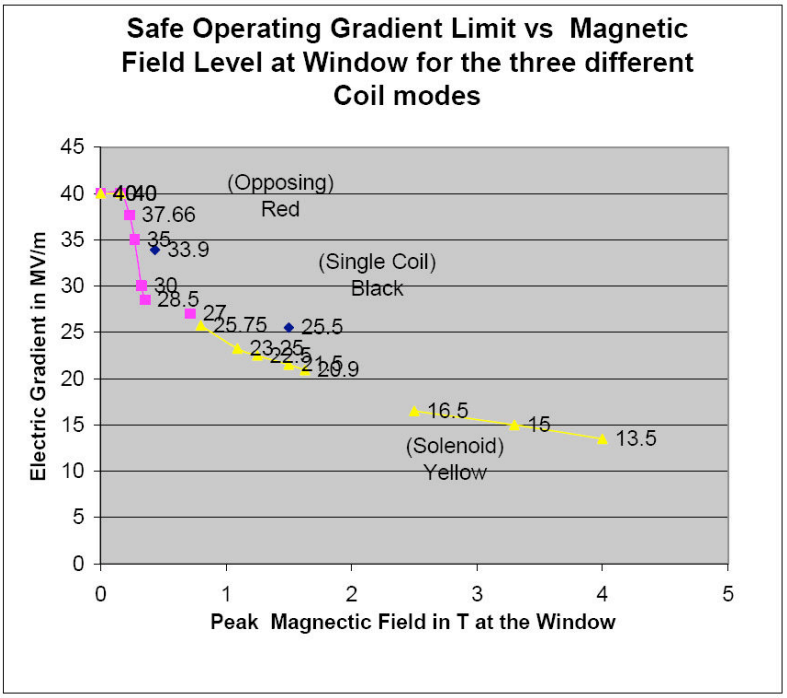


Figure 1. Maximum stable operating gradient vs. magnetic field (B) for 805 MHz pillbox cavity

At 3T the 805 MHz cavity's maximum operating gradient has been reduced by more than 50%. Although a detailed model describing this effect is still being developed (see 2.2.2.5 below), the root cause is due to magnetic field focusing of field emission in the cavity when B is parallel to E. A simple imaging technique to make this claim apparent has been implemented. By putting Polaroid films next to a thin window on one face of the 805 MHz pillbox cavity, images of this effect have been captured (Figure 2). At the gradient indicated in the curve in Figure 1, the energy in the beam reaches a level in which the damage produced by the breakdown negates any conditioning.

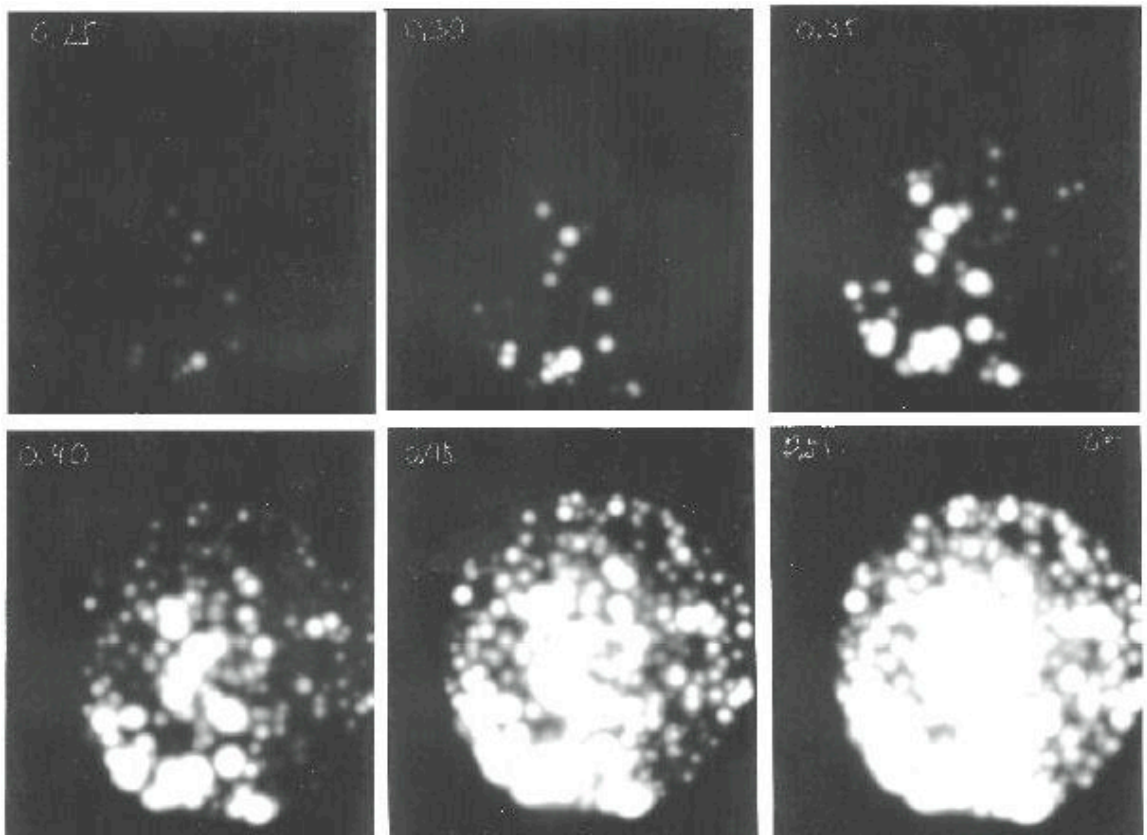


Figure 2. Breakdown events in the 805 MHz pillbox cavity as imaged with Polaroid film. From upper left to lower right: 8.8 to 17.6 MV/m.

Studies have begun on the 201 MHz cavity in magnetic field. A line drawing of the 201 MHz MICE prototype cavity is shown in Figure 3. This cavity was fabricated from spun copper and processed using superconducting RF processing procedures: namely electro polishing (EP) and high pressure (HP) rinsing. Figure 3 shows the cavity body, stiffening plates and the field terminating curved Be windows that form the pillbox.

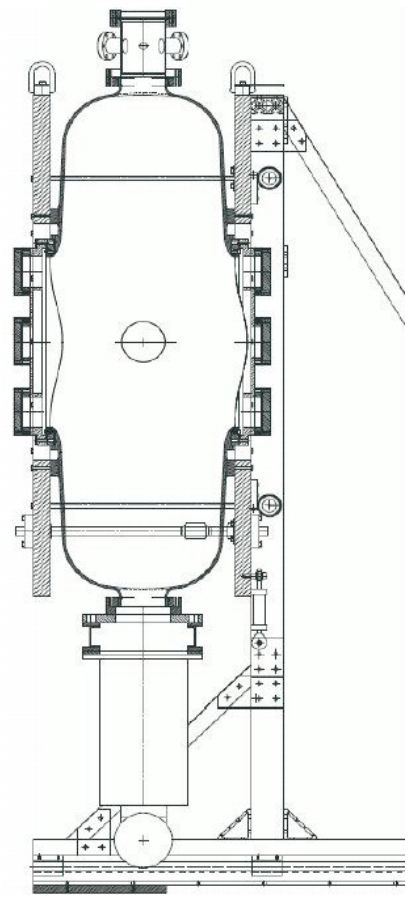


Figure 3. MICE prototype 201 MHz Cavity

Preliminary results look more encouraging than the data from the 805 MHz cavity. With a field of approximately 0.75T at the window of the 201 MHz cavity, a maximum stable operating gradient of 14MV/m has been achieved. Taken at face value this 23% reduction in maximum stable operating gradient is much less severe than the 37% reduction seen with the 805 MHz pillbox. In addition, the gradient-limiting mechanism seen with the 201 MHz cavity tests was more consistent with multipactoring than with sparking. To date, limited 201 MHz power has slowed progress on cavity conditioning through this region. The cavity is tuned to 2 MHz below 201 MHz with tuners in the extreme position. It is expected that with further conditioning, the performance benchmark of the 201 MHz cavity will improve.

There are three fundamental approaches to solving the magnetic field effect problem: 1. Eliminate field emission at the required operating gradient, 2. Change the cavity geometry and/or use magnetic insulation to prevent E X B from being equal to zero, 3. Use a base metal in the cavity that is much less susceptible to damage from breakdown events, i.e. improved work function.

2.2.2.2 Material testing with "buttons" on a 805 MHz cavity

Testing the best high gradient performance of materials by using a modified pillbox cavity with one end wall configured to accept buttons fabricated from a variety of different conducting materials is underway at MTA. Initial test results show that significant arcing has taken place on the cavity iris, forcing a need to refurbish the existing 805 MHz pillbox cavity. A diagram of the existing setup is shown in Figure 4.

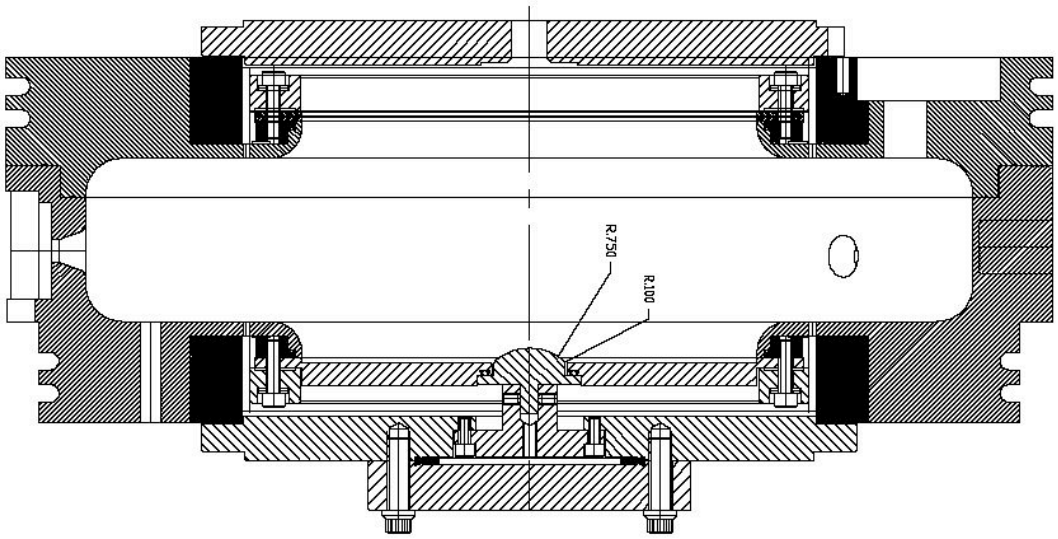


Figure 4. Line drawing of the 805 MHz pillbox cavity with button holder replacing one of the flat copper windows.

The concept for these tests is to force a breakdown event to occur at the button. The fixture was designed to allow changing the buttons with relative ease, allowing for rapid turnover in the process. A plan on how to proceed is currently being devised.

2.2.2.3 201 & 805 MHz model

Need input or I need to understand exactly what is intended for this subchapter.

2.2.2.4 Atomic Layer Deposition (ALD)

ALD[9] can grow multiple, epitaxial (or amorphous), monolayer coatings of a variety of materials on a variety of substrates with a usefully fast deposition rates (μm/hr). Moreover it is a parallel, non line of sight, conformal coating technique. Thus research here should easily translate into the growth of films on complex cavity structures. Although the technology of ALD is fairly well advanced (now used industrially both for gate dielectrics in integrated circuit manufacture and for electroluminescent displays), the specific requirements of high gradient accelerators are unexplored. It will be necessary to

learn how to grow films of pure Nb, Al_2O_3, MgB_2, TiN, NbN, and other materials on both acceptable surfaces and on themselves. It will be key to test these composites.

Figure 5 is a scanning electron microscope image showing before and after coating of a atomically sharp tips on a cavity surface. The tip, initially about 4 nm, has been rounded to 35 nm radius of curvature by growth of an ALD film. This smoothing of surface features improves breakdown performance of the cavity.

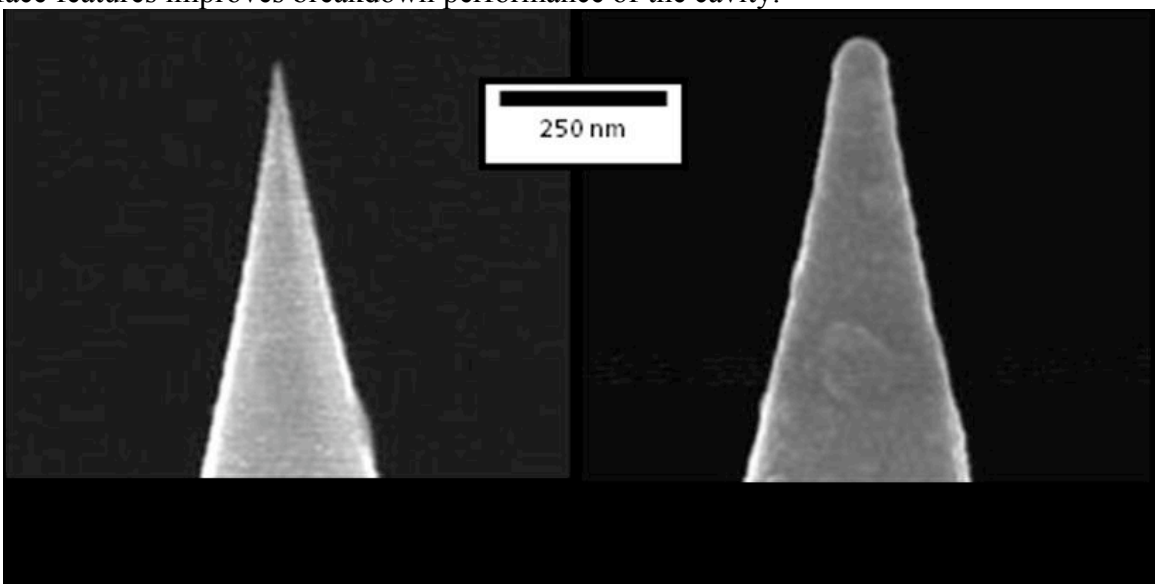


Figure 5. Electron micrograph: left uncoated Si AFM tip, right after 5 nm ALD ZrO_2 + 30 nm ALD Pt

2.2.2.5 Magnetic Insulation

2003 observations of operation of a multi cell 805MHz open cavity in a magnetic fields indicated the maximum achieved surface gradients were quite high and were not strongly dependent on the magnetic fields. However, both X-Rays and dark currents were greatly increased with the magnetic field on, and eventually there was sufficient damage to the end vacuum window sufficient to cause loss of vacuum. These experiments were done with a magnetic field whose symmetry was somewhat displaced from that of the cavity. With these fields it was found that the location of the window damage corresponded to a focused dark current coming from one of the high field irises. In addition, radiation damage patterns were observed showing that many beamlets were formed and focused by the magnetic fields onto the end window. It appears that the asymmetric magnetic field was not such as to focus dark currents from one high gradient iris to another. This may explain why the maximum achieved gradients remained high.

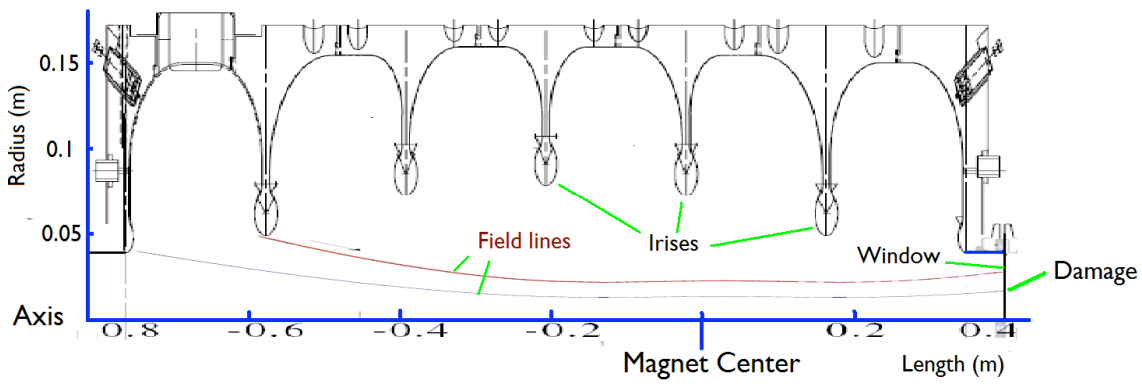


Figure 6. Multi-cell 805 MHz cavity

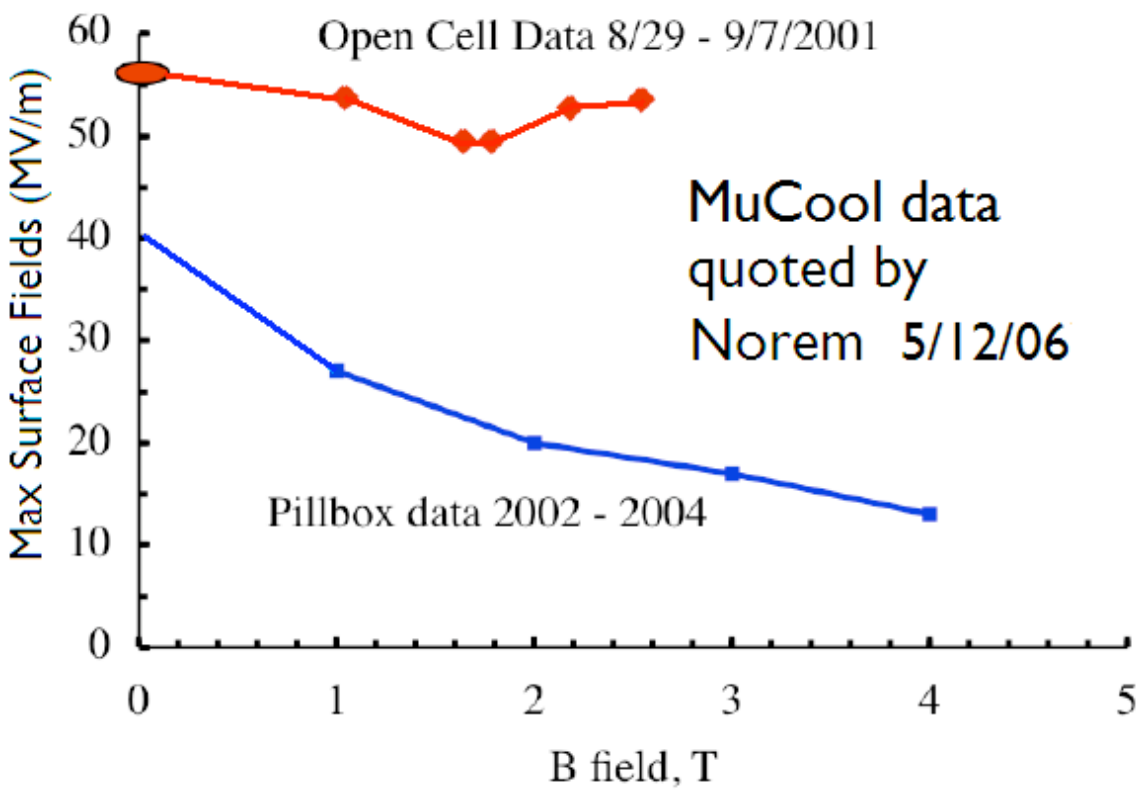


Figure 7. Pillbox cavity observed breakdown in magnetic fields

Unlike the earlier tests of a multi-cell cavity, the single cell pillbox cavity was tested symmetrically in the solenoid. In this case the achieved gradients were found to be strongly dependent on magnetic field. It was also found over time that cavity performance continued to deteriorate. Examination of the insides of the cavity showed severe pitting on the irises. The beryllium windows, themselves, showed no visible damage, but there was a spray of copper over their surface and copper powder in the bottom.

A breakdown model without magnetic fields, as discussed by Norem et al (need reference here), has the following sequence of events

1. It is assumed that the surface contains asperities at the top of which the average field multiplied by the Fowler Nordheim field enhancement B_{FN} gives the local field .

2. The electrostatic tension induced by these electrostatic fields is assumed to be strong enough to breaks off a piece of metal, and the small piece now moves away from the remains of the asperity.

3. The piece is now bombarded by field emitted electrons from the remaining asperity and becomes vaporized and ionized.

4. Following this formation of a local plasma a stronger field emission, spread of the plasma or other mechanism, shorts out the cavity leading to breakdown.

It must be noted that in this model, the breakdown is dependent only on the local field and tensile strength of the material. The observed frequency dependence of the average field gradient is explained by a frequency dependence of B_{FN}. This results from the competing processes during conditioning: a) the breakdown destroying or reducing the local asperities, vs. b) the breakdown creating craters that act as new asperities.

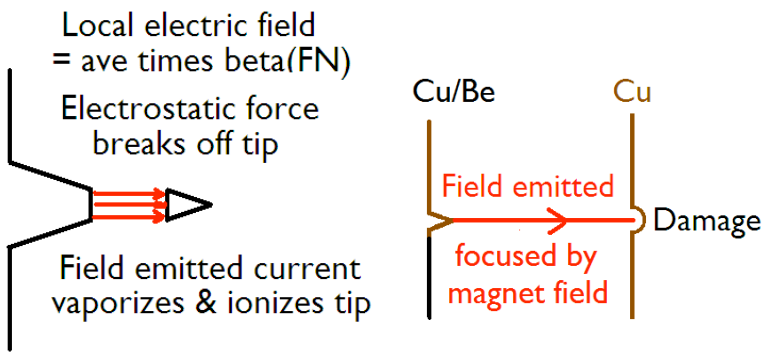


Figure 8 Evolution of a breakdown (better figure description needed)

The proposed breakdown model with magnetic fields in vacuum is quite separate from the mechanism proposed for breakdown in the absence of magnetic fields, and is only active when the breakdown gradient is lower than that from the above mechanism. The elements are:

1. ”Dark Current” electrons are field emitted from an asperity, accelerated by the RF fields, and impact another location in the cavity. In the absence of a magnetic field these impacts are spread over large areas and do no harm.

2. But with sufficient magnetic field they are focused to small spots, where it can melt the surface producing local damage. If the location of such damage is at a low gradient location there is no immediate breakdown, but the damage can accumulate until, for instance, a hole is made in a window.

3. If the electrons are focused onto another location with high surface RF gradient, then the molten metal will be accelerated away from the surface by the electrostatic fields. This metal, as it leaves the damaged location will now be exposed to field emitted electrons from the damaged area and will be vaporized, and ionized leading to a local plasma and subsequent breakdown.

4. The melting will start deeper in the material, where the ionization loss is greater, and expand to the surface. Thus, when the melting reaches the surface, significant quantities of molten metal may be sprayed onto other surfaces in the cavity.

This mechanism will be dependent on a) the Fowler Nordheim field enhancement B_{FN} that determines the strength of the field emitted current, b) the local geometry of the asperity that will determine the initial particle distributions and effects of space charge, and c) on the geometry and magnetic fields that focus the electrons onto other locations. The study of this mechanism is still in its early stages, but with reasonable assumptions it is possible to fit the data from the 'pillbox' cavity data.

Preliminary expectations of these mechanisms at 201MHz: Without an external magnetic field breakdown gradients have been observed to fall roughly as the square root of the RF wavelength. This implies that the conditioned B_{FN} increases roughly as the square root of frequency. The explanation for such behavior can be understood because of the greater stored energy and longer fills times at lower frequencies. These would enhance the creation of damage relative its reduction.

With magnetic fields present, the dependence on frequency requires an understanding of the details of the focusing in the larger cavities. It will depend strongly on the Fowler Nordheim enhancement B_{FN}, because this will set the magnitude of the dark currents that drive the mechanism. A preliminary study (need a reference) indicates the predicted breakdown gradients shown in figure 9. It is seen that this prediction implies that the gradients specified for the MICE experiment (8MV/m at B_ 3 T) should almost be achievable, but the higher gradients specified for Neutrino factory phase rotation and cooling (15MV/m at B_ 3 T) are well above prediction. An effort to build an 805 MHz cavity (same fabrication technique and processing) and re-study magnetic field effects is anticipated.

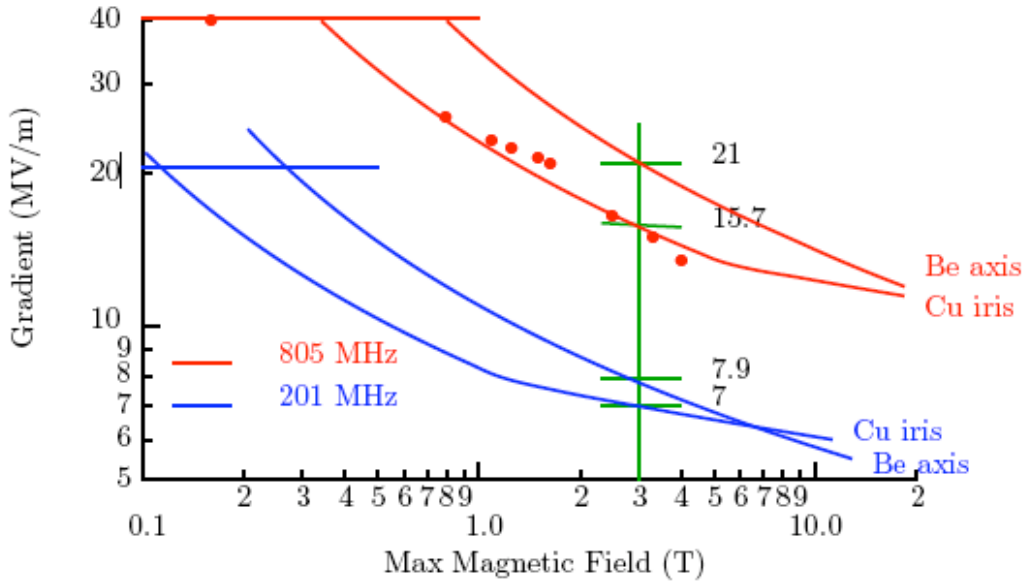


Figure 9. Gradient vs. Magnetic field for… Need better caption of this graph

2.2.2.6 High Pressure RF Cavity

Muons Inc. is pursuing a RF R&D effort with a dielectrically loaded RF cavity. For the cooling channel, such a cavity would have a dual purpose: reduction in the number of breakdowns, and the dielectric medium will act as part of the cooling channel absorber.

The cavity dark current can be suppressed by filling the cavity with high-density gaseous hydrogen. Pressures to 1400 pounds per square inch at 293 Kelvin have been used. The electrons are slowed down and absorbed by the hydrogen molecules. This idea has been tested at MTA (Figure 6). Figure 7 shows the cross-sectional view of the RF test cell. It has two hemispherical electrodes. The electrode is attached on the top and bottom plates by the thread rod, which can be replaced by other electrodes made of various materials in the future. A Copper, Molybdenum, Beryllium and Tungsten electrodes are tested. The hydrogen gas is filled via a gas inlet that is not shown this figure. The RF power is induced from the power coupler. The pick up antenna is used for diagnostics of the RF voltage. The reflection of the RF power is also measured during the test. The acceleration voltage is reconstructed by calibration.

The Paschen curve has been measured as a first test. It has been demonstrated that the RF test cell can operate under the strong solenoid fields without significant field gradient degradation (Figure 8). The upper limit of the breakdown voltage has been observed in the high-density hydrogen region. Interestingly, the breakdown voltage is insensitive from the gaseous density (plateau) at this region. The limit voltage strongly depends on the material of the electrodes.

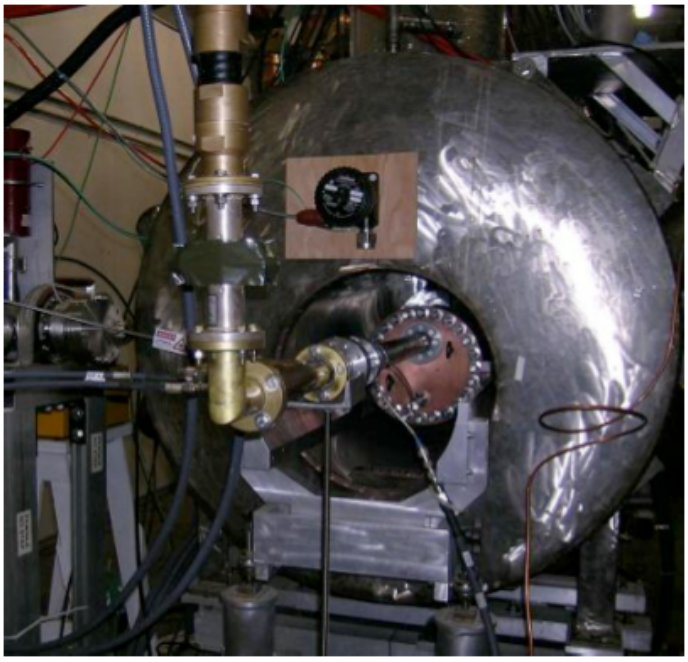


Figure 6: Experimental set up for a high-pressure gaseous hydrogen filled RF cell. The big silver cylinder is a 5 Tesla superconducting solenoid magnet. The brown cylinder that sits in the solenoid magnet is the high-pressure hydrogen gas filled RF test cell. The brass coaxial tube is the RF power coupler. A black cylinder on the magnet is a hydrogen detector to find the leakage in the cell.

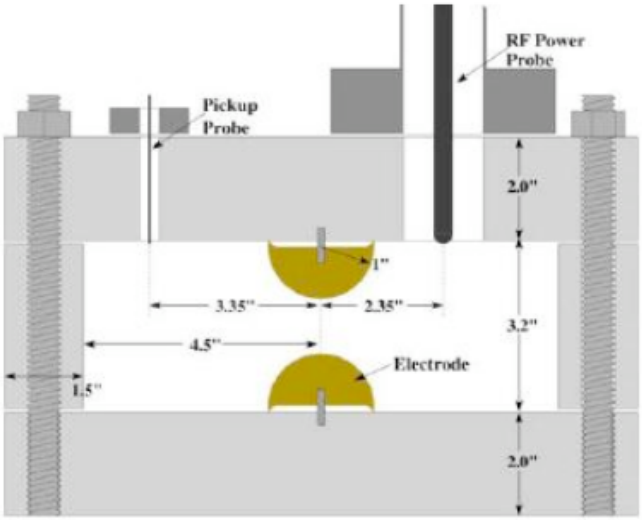


Figure 7: Cross-Sectional view of the high-pressure hydrogen gas filled RF cavity.

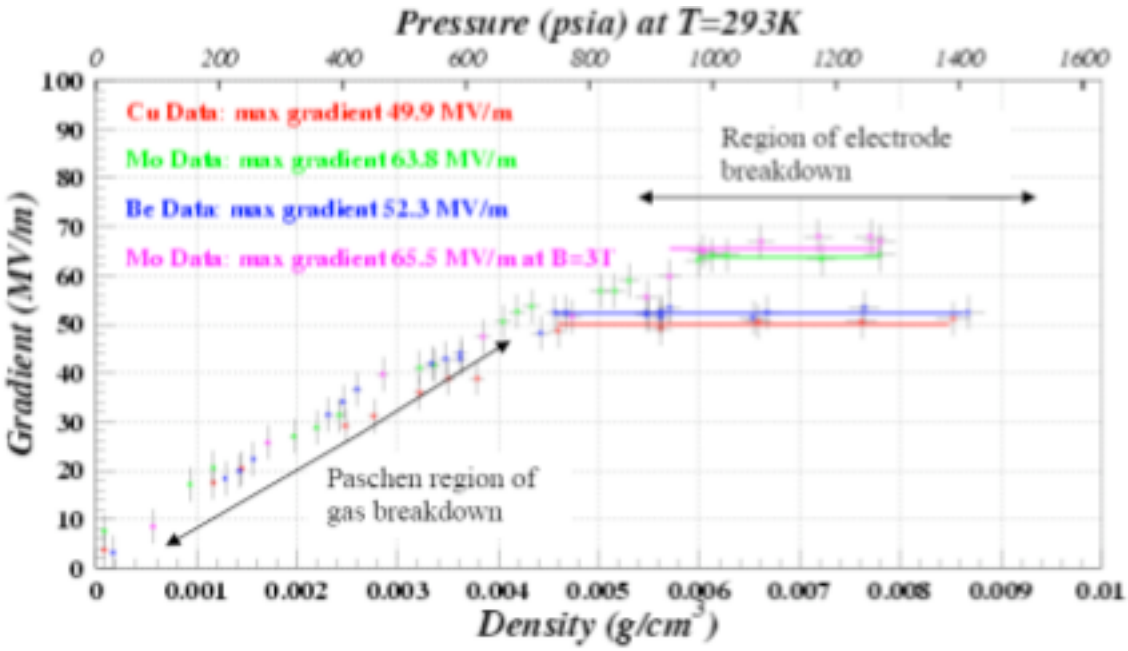


Figure 8: Observed RF breakdown voltage in the high-pressure gaseous hydrogen filled RF test cell as a function of the gaseous density. Red line is the maximum RF breakdown voltage with Copper electrodes, green that with Molybdenum electrodes, blue with Beryllium electrodes, and magenta with Molybdenum electrodes in a 3 Tesla solenoid magnet field. Could use a much clearer graphic here.

2.2.2.7 System Engineering

Once the components have proven performance, there is a significant effort to integrate all parts into an operational system. The RF systems for buncher, rotation and cooling channel will consist of a large number of components. Further complication will arise as the design consists of many cavities at frequencies that are not harmonically related. At the outset, the low level RF (LLRF) necessary will need to be a complex digitally generated system. With recent developments in digital RF circuits, source signals with specific phase relationships will need to be digitally synthesized and synchronized. At the very least, an investigation of system parameters and number of channels should be evaluated.

The gradients requested will require significant RF power sources. The 201 MHz triode generated RF source used in MTA is not considered to be the most efficient means of providing the necessary power. The spread in frequencies also would indicate that a number of different bandwidth power sources are necessary. Muon bunches will be short, on the order of nanoseconds in length. The repetition rate for single bunches is estimated to be 10 to 60 Hz. Normal conducting RF cavities with the required gradients of 10-20 MV/meter have typical fill times on the order of tens of microseconds to stable gradient. The RF will only be used for a very short duty cycle making this one of the more

inefficient uses of accelerator RF power. For this reason, a very efficient source of RF power must be developed. Multi-beam klystrons are believed to be a possible solution, but such klystrons have not been developed at the required RF frequencies. Toshiba, CPI, and Thales are manufacturers that are currently developing 1.3 GHz 10 MWatt multi beam klystrons for the International Linear Collider (ILC) and other SRF applications. These vendors should be contacted for their professional opinion on a similar design in the 200-300 MHz frequency band.

This collection of RF systems will rival the complexity of any high power RF systems ever built. As it is not clear at this time how many of the cavities could be inoperable and still enable the complex to deliver high energy physics (HEP), the implications of reliable operation should also be investigated.

2.2.3 R&D plans

2.2.3.1 MTA

Task 1. The 805 MHz cavity used for button testing has experienced significant arcing on the cavity iris. This cavity will need to be refurbished before testing additional buttons can proceed. There are two possible choices for the cavity polishing: electro polishing at JLAB (the preferred but most expensive of the options) or mechanical polishing at Fermilab. High Frequency Structure Simulation (HFSS) analysis also indicates the coupling aperture of this cavity has a radius which is too small to prevent arcing at 36 MV/m. Once refurbished, the cavity will be conditioned without a magnetic field to 36 MV/m followed by magnetic field commissioning to a field of 2.5 Tesla.

Task 2. A new fixture will be designed and fabricated to allow the 805 MHz cavity to be rotated within the solenoid. The intention here is to probe the theory of cavity operation with various orientations of cavity electric and magnetic fields with respect to the solenoid magnetic field.

Task 3. New rectangular cavities are envisioned to test field orientation and ALD testing. Figure 9 shows the preliminary concepts.

Task 4. The 201 MHz cavity is unfortunately not sufficiently close in frequency (about 2 MHz low) to the RF system frequency. With system tuners tuned to their closest settings, the amount of power that can be delivered to the cavity is limited. Testing to date has shown a 14 MV/m gradient was achieved in a 0.75 T magnetic field. A new magnetic coil is being fabricating in the Peoples Republic of China. This core has a bore of 697mm and a length of 485 mm. When delivered, it will be mounted next to the cavity and allow testing in magnetic fields to 2 T.

Task 5. The beam line to the MTA provides beam at an elevation above the floor that is currently 18 inches above the current cavity and solenoid location. The entire test apparatus must be moved upward to match the beam height.

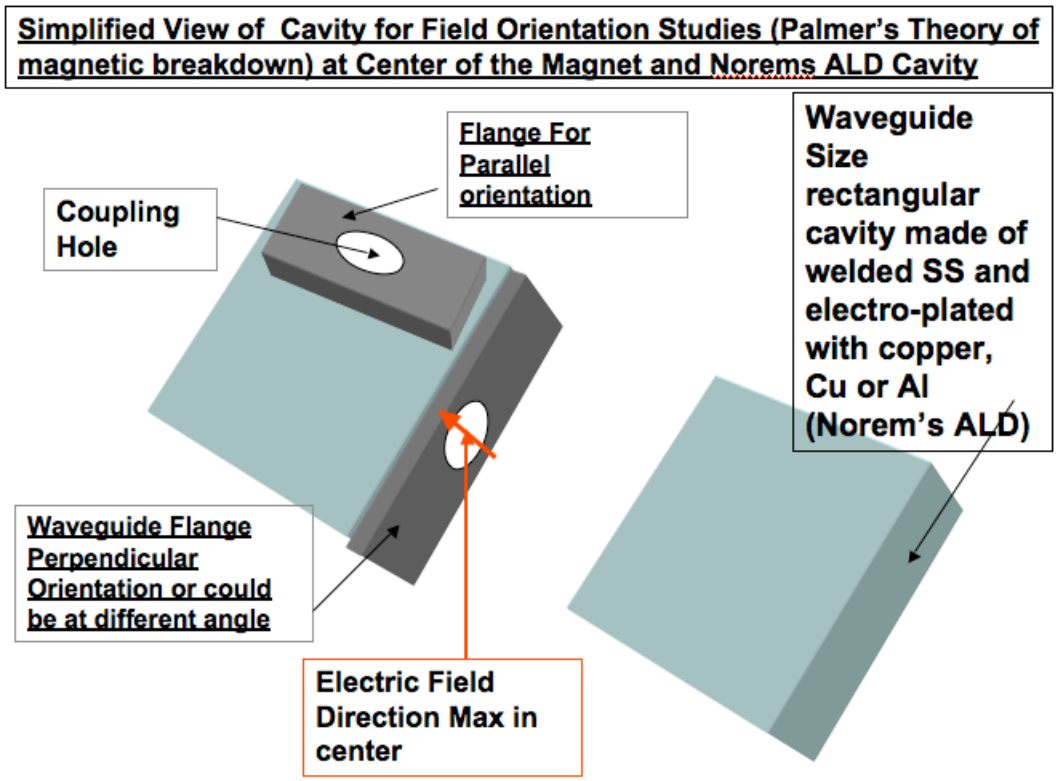


Figure 9. Rectangular cavity concepts for testing within magnetic field orientations and ALD testing.

2.2.3.2 Material testing with "buttons" on a 805 MHz cavity

It is mentioned about refurbishing the cavity, but when and what is planned for next year?

2.2.3.3 201 & 805 MHz model

Need input here.

2.2.3.4 Atomic Layer Deposition (ALD)

- Phase I, Understand the required chemistry. This will involve primarily surface science technology, with measurements using ellipsometry (is this a real word?), Atom Probe Tomography, SIMS (what is SIMS? Acronym should be spelled out first) and other techniques (all of which are presently available at Argonne, Northwestern, IIT and the University of Chicago). In addition a small theoretical effort (perhaps within the superconducting group at Argonne) would be very

helpful. One of the major problems is to be able to preserve the purity of the deposited layers from air and internal, segregated impurities.

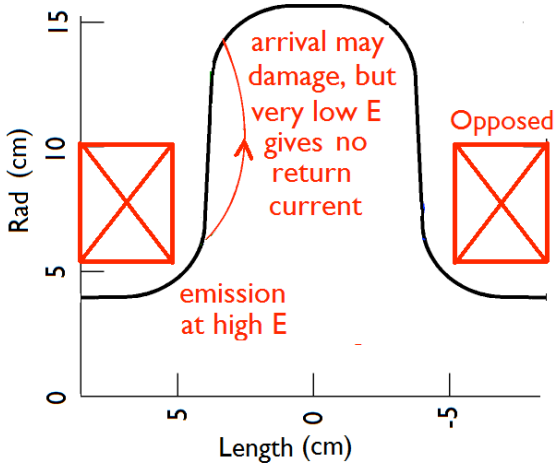
- Phase II, Test coatings in cavities. This work will require the construction of a larger deposition chamber, the use of a variety of cavities, and test equipment, and supplies for high power testing. This could be done at Argonne or Fermilab.

This work is underway as part of a collaboration centered at Argonne, starting with existing ALD deposition systems, involving the Fermilab materials group, Northwestern and other universities. The first tests have shown that ALD can grow ~10 monolayer alumina coatings on niobium that can protect the niobium from oxidation in air, and in fact, reduce the niobium on the surface. Baking this composite at 800^0 has the effect of driving the oxygen into the bulk, producing a clean niobium/alumina interface. Subsequent tests have shown that it is possible to overcoat the alumina with titanium nitride, which would permit the composite to be used in high power tests without multipactoring. It is desired to test a well-characterized RF structure, apply a coating then re-testing at high power. Minor modifications of the deposition chamber would allow coating single cell or high frequency structures.

2.2.3.5 Magnetic Shielding

Task 1. Redesign the phase rotation and cooling channels to use lower RF fields. This approach would clearly hurt performance, and in addition, risks a slow deterioration of performance as occasional breakdown events continue to spray copper around the cavity - as observed in the pillbox tests.

Task 2. Design beam transport lattices with magnetic fields shielded from the RF. The above prediction suggests that so long as the field is less than about 0.2 T, no adverse effects will be observed. Attempts to design such lattices have, unfortunately, shown significantly worse beam transport performance.



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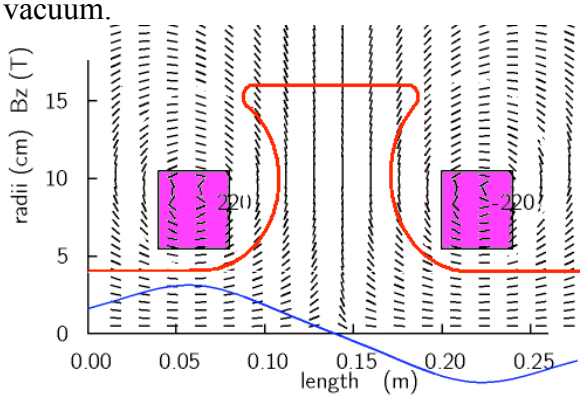
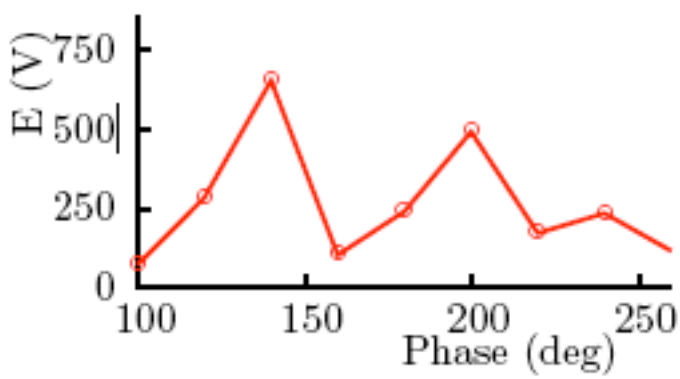
Task 3. Lattices could be designed using multi-cell open cavities, with coils in their irises, and with the coils having alternating currents. In this case, as in the original multi-cell open cavity tests, the focused electrons would be directed to low field regions in the cavity and would thus not initiate breakdowns at lower fields. Nevertheless damage would be presumably done to those locations and molten copper might still be ejected causing eventual deterioration of performance, if not damage sufficient to destroy the vacuum.





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Task 4. Damage could probably be eliminated if cavities were designed such that all high gradient surfaces were parallel to the magnetic fields. This would provide ”magnetic insulation”. In this case dark current electrons would be constrained to within short distances of the surfaces, would gain little energy, would cause no X-rays, and do no damage. The only difficulties might be: a) cavities so designed will not give optimum acceleration for given surface fields, and b) there is the danger of exciting multipactoring now that the energies with which electrons do return to the surfaces are in a few hundred volts where secondary emission is maximal.

2.2.3.6 High Pressure RF Cavity

Observations from previous experiments suggest two new future experimental approaches. First approach is to find the best material to obtain the high field gradient. Analysis of experimental results with a conventional Fowler-Nordheim theory indicates

RF breakdown voltage at the plateau region can be strongly affected by the work function. Measuring the work function before and after breakdown can test this theory. The second experimental approach is the feasibility test by utilizing a high intensity 400 MeV proton beam (~1×10^{13} protons/spill) which will be injected into the highly pressurized hydrogen gas filled RF test cell and measuring RF breakdown phenomena.

Some of the models (reference here?) predict the degradation of the RF breakdown voltage in the high-pressure hydrogen filled RF cell under high radiation conditions. Many secondary electrons are produced by the beam-induced ionization of the hydrogen gas with potential for cavity breakdown. Furthermore, the model predicts that the Q value of the RF cavity may reduce during beam passage. One possible solution to suppress the number of secondary electrons is to add a dopant that can absorb the secondary electron more effectively than the pure hydrogen molecule. This last model is being tested in simulation.

2.2.3.7 System Engineering

Does the collaboration see any merit to investing in this at this stage of the project?

2.2.4 Study Elements

2.2.4.1 MTA SWF and M&S

Manpower and M&S needs

Task I: re-polishing the LBL cavity:

1. If done at JLAB — M&S $10k
   Effort: 2 mech Tech 4 days disassemble, ship, reassemble and install.
2. *if done at Fermilab* — M&S $1k
   Effort: 2 mech Tech 4 days polishing reassemble and install.
3. Magnet Testing monthly — M&S $30k Liquid Helium (assuming the liquefier is ready mid-year) and $3k (miscellaneous parts for all the above)
   Effort: 2 mech tech 48 days (setting-up exp)
   4 Experimenters 192 days

Task II: Vertical Pill-box cavity mounting to study crossed E&H fields:

M&S $8k shops & $5k liquid helium for experiment
Effort: 2 mech Tech 4 days set-up experiment
4 Experimenters 20 days;

Task III: Cavities for Palmer's and Norems test cavities:

M&S $32k for 4 cavities
$12k polishing and cleaning
$4k miscellaneous parts
Effort: 2 mech tech 16 days set-up 4 experiments
4 experimenters 64 days; Continue 4 Years

Task 1V: 201 MHz testing:

M&S $10k Liquid He & Cryo-gens
Effort: 2 mech tech 16 days set-up 4 experiments
4 experimenters 64 days; Continue 3 more years with Coupling Coil.

Task V: Reconfiguration of the MTA:

M&S $24k RF part only
Effort: 3 mech tech 16 days

2.2.4.2 Material testing with "buttons" on a 805 MHz cavity SWF and M&S
Nothing received as of 7-23-08
2.2.4.3 201 & 805 MHz model SWF and M&S
Nothing received as of 7-23-08

2.2.4.4 Atomic Layer Deposition (ALD) SWF and M&S

In addition to this short term goal, there are a number of interesting application of ALD to warm RF structures that are possible:

1) Coating surfaces with thick layers of insulators to kill field emission now seems straightforward, but what are the limitations of this method and how can it usefully be applied in-situ to working cavities?
2) Coating surfaces with thick layers of metals seems likely to reduce the local fields which cause breakdown and may be able to permanently eliminate breakdown sources in cavities.
3) Coating surfaces with layers of conductor/insulator pairs to eliminate pulse heating also seems to be a useful long-term goal.

The primary problem with this work is that the ALD setup and the RF power supply are usually separated, and moving samples from one to the other introduces particulate contamination, which can complicate any test. The best solution is a *in-situ* deposition system, which could be added to an existing rf system for comparatively modest cost. However the ALD system is likely to coat all parts of the cavity, including diagnostic probes, windows and driveline components. It seems reasonable, then to consider a phased approach.

<u>Phase 1</u> In-situ deposition of insulators. Since we have shown that coatings of alumina and niobium pentoxide can prevent field emission at high fields, the MICE requirement is to develop a technology capable of applying these coatings to a working cavity. In principle, thin insulators should not interfere with the operation of the components of the cavity and the primary experimental question would be compatibility with the other components of MICE.

This work seems to require an ALD system connected to the 805 and perhaps 201 MHz vacuum system (~150k$), and a number of test cavities that could be used for tests (~150k$).

<u>Phase 2</u> The deposition of metallic layers, which would be required to control breakdown, is a more complex problem. No warm RF system is equipped with the standard high pressure rinsing facilities that would be required to clean coated components, and in-situ deposition is complicated by the need to preserve the high power insulators in the driveline and instrumentation. Thus techniques for isolating components must be developed which would coat the regions of cavities exposed to high fields, while preserving the necessary insulators. This seems to require a modest development program to look at thermal barriers, particle free, high RF power valves, gas jet isolation

and perhaps other techniques. This would require perhaps two years of development and the use of the ALD and MTA RF systems, and perhaps an additional 150k$/year.

2.2.4.5 Magnetic Shielding SWF and M&S

Priorities from Bob Palmer
WARNING What follows is VERY subjective and crude
I estimate the 'costs' (C) of each R&D activity in Millions of dollars per year
These are supposed to include overhead and associated instrumentation and controls
I define a Quality Q = N − 2 C
If Q is positive its Q is printed in red These are the 'high priority' items
If Q is negative I print it in blue

Conclusion
• The lowest priority items are the 3 possible cooling experiments
• If we choose one cooling experiment (with acceleration) we have a total of 22 M$/yr plus _ 10 M$/yr needed for simulation, thus requiring _32 M$/year.
More than requested at p5.
• If we drop all cooling demonstrations and concentrate on the component work, then the total comes down to 18 M$/yr which is starting to be more reasonable
The cooling experiments are very expensive, and component testing will tell us almost all we need to know
MICE can soon demonstrate 6D cooling without re-acceleration. Later, replacing a hydrogen absorber with a wedge, it can do it with re-acceleration.
Doing the same thing another way is nice, but not a high priority
• The 10 "High priority" items (positive Q) cost 7 M$ per year
• The highest priority item is an Open Cavity experiment
because vacuum acceleration is needed in all scenarios in most sub-systems, and it is not excessively expensive
• My estimates are very very rough, but I doubt they are underestimates
• One could do everything and do them infinitely slowly. This would be a mistake.

Needed R&D

	cost M$ /yr	1 tgt NF	1 rot MC	2 6D HCC	2 (1) Vac	3 6D L	3 (2) H	4 rev L	4 exch H	5 acc NF	5 ring MC	score	Q
Study effects on Hg jet entering magnet	1/4	1	2									3	2.5
20 T capture solenoid	2	1	2									3	-1
200 MHz rf power sources	1	1	2	1	1							5	3
805 MHz open cavity experiment	1	2	1	1	1	1	1	1	1			9	7
201 MHz cavity with coils in irises	1	1	2	1	1							5	3
201 MHz gas filled cavity	1/4	1	2	1	1							5	4.5
Construct liquid hydrogen wedge	1/2				1	1	1					3	2
6D cooling in MICE	1/4				1	1	1					3	2.5
Small Nb3Sn solenoid R&D	1					1	1					2	0
Section of low $\epsilon_\perp$ 6D cool	1					1	1					3	1
6D cooling to $\epsilon_\perp \leq 400 \ (\pi\ 10^{-6}$ m)	4					1	1					2	-6
Short length of HCC with rf	1			1								1	-1
6D cooling without acceleration in HCC	2			1								1	-3
6D cooling with acceleration in HCC	4			1								1	-7
HTS for 50 T magnets	1							1	1			2	0
Re-start 201 MHz superconducting rf	1									1		1	-1
1.3 GHz SC rf with mode damping	1										2	2	0
Magnetic field on 201 MHz SC rf	1/2									1	2	3	2
Pulsed synchrotron magnet	1/4										2	2	1
Open mid-plane Collider Magnet	2										2	2	-2
Very High gradient quads for IP	1										2	2	0
Kicker Studies	1									1		1	-1
Neutrino detector magnet	1									1		1	-1
TOTAL	28												

Ordered List	cost M$ /yr	scor	Q	Σcost M$ /yr
805 MHz open cavity experiment	1	9	7	1
201 MHz gas filled cavity	1/4	5	4.5	1.25
200 MHz rf power sources	1	5	3	2.25
201 MHz cavity with coils in irises	1	5	3	3.25
6D cooling in MICE	1/4	3	2.5	3.5
Study effects on Hg jet entering magnet	1/4	3	2.5	3.75
Construct liquid hydrogen wedge	1/2	3	2	4.25
Magnetic field on 201 MHz SC rf	1/2	3	2	4.75
Section of low $\epsilon_\perp$ 6D cool	1	3	1	5.75
Pulsed synchrotron magnet	1/4	2	1	6
Small Nb3Sn solenoid R&D	1	2	0	7
Very High gradient quads for IP	1	2	0	8
HTS for 50 T magnets	1	2	0	9
1.3 GHz SC rf with mode damping	1	2	0	10
Kicker Studies	1	2	-1	11
Neutrino detector magnet	1	1	-1	12
Re-start 201 MHz superconducting rf	1	1	-1	13
Short length of HCC with rf	1	1	-1	14
20 T capture solenoid	2	3	-1	16
Open mid-plane Collider Magnet	2	2	-2	18
6D cooling without acceleration in HCC	2	1	-3	20
6D cooling to $\epsilon_\perp \leq 400 \ (\pi\ 10^{-6}$ m)	4	2	-6	24
6D cooling with acceleration in HCC	4	1	-7	28

2.2.4.6 High Pressure RF cavities SWF and M&S

Nothing received as of 7-23-08

2.2.4.7 System Engineering SWF and M&S

Does the collaboration see any merit to investing in this at this stage of the project?

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