Hydrogen-filled RF Cavities for Muon Beam Cooling

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Batavia, IL 60510**NAME of PRINCIPAL INVESTIGATOR: **Dr. Charles Ankenbrandt**PHONE NUMBER: **(757) 740-1085**PROJECT TITLE: **Hydrogen-filled RF Cavities for Muon Beam Cooling****Topic 50a****TECHNICAL ABSTRACT (Limit to space provided)**

Statement of the problem or situation that is being addressed - typically, one to three sentences.

Ionization cooling requires low-Z energy absorbers immersed in a strong magnetic field and high-gradient, large-aperture RF cavities to be able to cool a muon beam as quickly as the short muon lifetime requires. RF cavities that operate in vacuum are vulnerable to dark-current-generated breakdown, which is exacerbated by strong magnetic fields, and they require extra safety windows that degrade cooling, to separate RF regions from hydrogen energy absorbers.

General statement of how this problem is being addressed. This is the overall objective of the combined Phase I and Phase II projects

RF cavities pressurized with dense hydrogen gas will be developed that use the same gas volume to provide the energy absorber and the RF acceleration needed for ionization cooling. The breakdown suppression by the dense gas will allow the cavities to operate in strong magnetic fields. Measurements of the operation of such a cavity will be made as functions of external magnetic field and charged particle beam intensity and compared with models to understand the characteristics of this technology and to develop mitigating strategies if necessary.

What was done in Phase I – typically, two to three sentences.

Fermilab MuCool Test Area (MTA) delays precluded beam tests during Phase I, allowing more diagnostic and simulation development, including an important experimental breakdown study with SF₆ dopant to verify the computer model. An optical fiber system was added to the test cell to be used in the first beam tests. A 1.3 GHz test cell was built and tested which can operate under pressure or in vacuum in order to extend our understanding of RF breakdown as a function of frequency and geometry and to correlate with previous vacuum cavity experience.

What is planned for the Phase II project - typically, two to three sentences.

The Fermilab MTA will be exploited to extend measurements of maximum stable RF gradient in strong magnetic fields and in the presence of ionizing radiation. Beam-induced gas breakdown will be studied by improving computer simulation models that include the use of electron-absorbing dopants, external magnetic fields, and variations of cavity geometry and materials. RF cavities will be built or improved to verify the models using MTA RF, beam, and magnetic field.

COMMERCIAL APPLICATIONS AND OTHER BENEFITS as described by the applicant. (Limit to space provided).

Bright muon beams are needed for many commercial and scientific reasons. Potential commercial applications include the use of muon beams to screen cargo containers for homeland security, low-dose radiography, and muon catalyzed fusion. Scientific uses include low energy muon beams, muon spin resonance, and muon beams for neutrino factories and muon colliders.

KEY WORDS: hydrogen, RF cavity, muon, collider, ionization, beam cooling, high pressure, gas breakdown.

SUMMARY FOR MEMBERS OF CONGRESS: (LAYMAN'S TERMS, TWO SENTENCES MAX.)

Hydrogen-filled RF cavities are being developed to create small, intense muon beams to enhance their utility for many purposes, from homeland security to energy frontier muon colliders.

NARRATIVE SECTION

Hydrogen-filled RF Cavities for Muon Beam Cooling

Table of Contents

Project Summary	Error! Bookmark not defined.
Table of Contents	4
Project Overview	5
Proprietary Data Legend-Not Applicable	7
Significance and Background Information, and Technical Approach	7
Background	7
Technical Approach	9
Anticipated Public Benefit	10
Degree to which Phase I has Demonstrated Technical Feasibility	11
Models and Simulations with Voss Scientific	11
The Phase II Project	17
Technical Objectives	17
Phase II Work Plan	17
Responsibilities	17
Performance Schedule	18
Facilities/Equipment	18
Consultants and Subcontractors	19
Phase II Funding Commitment (Commercial Contribution)	20
Letter of Support from Fermilab	20
Phase III Follow-on Funding Commitment	21
References	21
Appendix I: PAC09 draft Doped H₂-filled RF cavities for muon beam cooling	23
Appendix II: PAC09 draft RF Breakdown of Metallic Surfaces in GH₂ at 805 MHz	26
Appendix III: MuCool Note on the Diagnostic Optical Fiber	29
Appendix IV: PAC09 draft 1.3 GHz RF Test Cell	31
Appendix V: PAC09 draft Travelling Wave RF	34
Appendix VI: PAC09 draft Dielectric-loaded RF	37
Appendix VII: Status of the MTA Beam Line	40
Appendix VIII: The Phase I Proposal	45

Project Overview

The Commercialization and History part of this proposal contains an overview of the R&D efforts of Muons, Inc. The program described there is funded in large part by SBIR-STTR grants to support the development of intense muon sources, where almost all of those projects are complementary to this proposal. Many results of Phase I of this project are described in the appendices to this proposal, most of which will be presented at the 2009 Particle Accelerator Conference (PAC09) in Vancouver, Canada.

Appendix I contains a PAC09 preprint on the measurements of maximum stable RF gradients in the Muons, Inc. test cell as a function of gas pressure for three electrode materials in hydrogen and helium gases, with and without SF₆ doping. This preprint concerns the lower pressure region of the breakdown study, the Paschen region, where the breakdown is determined by the gas and not the metallic properties of the cavity. The preprint contains the comparison of the effect of a 0.01% SF₆ addition to the hydrogen gas with the predictions of the computer model developed by David Rose of Voss Scientific, Inc. Both the experimental data and the computer model show that the maximum stable gradient of hydrogen gas at 325 psi is increased from 25 MV/m to 40 MV/m with the addition of the one part in 10,000 of SF₆ dopant.

This result has given us confidence that the model is adequate for the exploration of other dopants, which might have fewer unattractive features than SF₆. The result further implies that it should be possible to mitigate any difficulties that may be a consequence of long recombination times of the ionization electrons caused by the muon beam that are expected in pure hydrogen gas [1]. The appendix contains the predicted behavior of an intense ionizing proton beam in a SF₆-doped hydrogen-filled based on the same model. The prediction is quite encouraging.

Appendix II contains the PAC09 paper that studied the results of the same experiment from the standpoint of the RF breakdown at higher pressures, where the electrode material determines the maximum stable RF gradient. An unexpected result is that the SF₆ dopant also increased the breakdown voltages in this higher pressure region. This will be an interesting aspect of models that are being developed to explain RF breakdown of metals in general.

Earlier data suggested that the maximum stable RF gradient in the high pressure region increased linearly with the melting point of the metallic electrodes. These data are seen in this preprint along with the most recent measurements, where Sn and Al were chosen to extend the melting point range to test the relationship. The results were unexpected in that the copper electrodes which were used as an experimental control had a higher breakdown gradient than had been seen in previous experiments. Surface analysis after the experiments indicates that the copper electrodes were not the same as had been used before, being a different grade of copper with surface contaminants of machine oil and sulfur, presumably deposited during the doping measurements. So we are intrigued to know why a contaminated surface allows a higher breakdown gradient. We have also learned that SF₆ may not be the best dopant to use, because it probably will lead to sulfur deposits inside the RF cavity.

It should be noted that the melting point is unlikely to be the most relevant independent variable, since a straightforward calculation indicates the energy deposited in a breakdown event should lead to a different dependence. However, the melting point should scale with the bond strength. And the bond strength should be related to other interesting parameters like fatigue limits, as suggested by recent work of Dolgashev and Tantawi [2].

Appendix III contains the first study of the use of an optical fiber that was added to the test cell to look for precursor light to better understand the physics of the breakdown process.

The experimental tests described above and the fiber optic work were supported by the \$100,000 DOE Phase I grant for this project, a 78% contribution by the Fermilab director of indirect charges on the \$30,000 Fermilab subgrant amounting to \$23,400, and by a \$50,000 matching grant from the Illinois Department of Commerce and Economic Opportunity.

Appendix IV is a draft of a PAC09 paper that contains a description of the design, construction, and first test parameters of the new 1.3 GHz high-pressure test cell that was tested under vacuum at the Argonne Wakefield Accelerator facility. Besides being a useful research instrument, its construction and first tests serve as a demonstration that such a device can be designed, constructed, and put into operation in less than a month for less than \$20,000. This capability will be useful for the Phase II plans proposed here.

Appendix V is a draft of a PAC09 paper that discusses a travelling wave solution for high pressure cavities in helical cooling channels.

Appendix VI is a draft of a PAC09 paper that discusses the use of dielectric materials in a pressurized cavity to allow smaller radial dimensions so that lower-frequency high-pressure cavities can be placed inside the coils of helical cooling channel magnets.

Appendix VII is an update on the status of the MTA beam line preparations. There is every reason to believe that the beam will be available for HPRF tests this fall.

Appendix VIII is the Phase I proposal for this project.

In Phase II of this project, we will use the MTA infrastructure of RF power, ionizing proton beam, safe hydrogen gas capabilities, and high magnetic field, to develop pressurized RF cavity techniques that will satisfy the needs of a muon cooling channel for a muon collider.

The Muons, Inc. Principal Investigator for the second Phase of this project will be Dr. Charles Ankenbrandt, who last year became a full-time Muons, Inc. employee after 35 years at Fermilab. His broad range of experience demonstrates that he is fully capable to lead this effort, and his full-time location at Fermilab and his collegial relationships with Fermilab staff will facilitate the handling of project-management issues. Dr. Rolland Johnson, who initiated the study of hydrogen-pressurized RF cavities several years ago, will still be heavily involved in the project, with more time to spend on technical issues because of fewer managerial responsibilities.

Significance and Background Information, and Technical Approach

Ionization cooling requires low-Z energy absorbers immersed in a strong magnetic field and high-gradient, large-aperture RF cavities to be able to cool a muon beam as quickly as the short muon lifetime requires. RF cavities that operate in vacuum are vulnerable to dark-current-generated breakdown, which is exacerbated by strong magnetic fields, and they require extra safety windows to separate RF regions from hydrogen energy absorbers. The scattering in those windows degrades the cooling performance of channels based on separate vacuum RF and hydrogen absorbers.

Background

Future research facilities, such as Neutrino Factories [3] or Muon Colliders [4], which require intense beams of muons, are dependent on a scheme to quickly reduce or cool the emittances of a muon beam before it can be injected into a practical accelerator. Ionization cooling of a muon beam involves passing a magnetically focused beam through an energy absorber, where the muon transverse and longitudinal momentum components are reduced, and through RF cavities, where only the longitudinal component is regenerated. After some distance, the transverse components shrink to the point where they come into equilibrium with the heating caused by multiple Coulomb scattering.

The equation describing the rate of cooling is a balance between these cooling (first term) and heating (second term) effects:

$$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2} \frac{dE_\mu}{ds} \frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3} \frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0}.$$

Here ε_n is the normalized emittance, E_μ is the muon energy in GeV, dE_μ/ds and X_0 are the energy loss and radiation length of the absorber medium, $\beta_\perp$ is the transverse beta-function of the magnetic channel, and β is the particle velocity in units of c .

Setting the heating and cooling terms equal defines the equilibrium emittance, the smallest transverse emittance that can be achieved with the given parameters:

$$\varepsilon_n^{(equ.)} = \frac{\beta_\perp (0.014)^2}{2\beta m_\mu \frac{dE_\mu}{ds} X_0}.$$

One can see that the figure of merit for a cooling absorber material is the product of the energy loss rate times the radiation length. Up to now, liquid hydrogen has been the energy-absorbing medium of choice, with $dE/ds = 30$ MeV/m and $X_0 = 8.7$ m. Superconducting solenoid focusing is used to give a small value of $\beta_\perp \sim 10$ cm.

The Neutrino Factory and Muon Collider Collaboration (NFMCC) has carried out much of the work on ionization cooling. The studies of practical designs so far, such as the neutrino factory designs at Fermilab [5] and Brookhaven [6], and the proposal for “An International Muon Ionization Cooling Experiment (MICE)” [7] have been based on a scheme for ionization cooling using liquid hydrogen flasks placed at regular intervals with RF cavities between them. Figure 1

shows an engineering drawing of the cooling lattice from the Brookhaven study [6], a slightly updated version of which is to be installed in the MICE experiment [8] at the Rutherford Appleton Laboratory (RAL) in England.

Figure 1: 200MHz RF cavities (red) are placed between liquid hydrogen flasks (blue). Each flask provides about 35 cm of hydrogen, or 10 MeV of energy absorption. To optimally cool a beam of 200 MeV muons requires about 20 absorbers. Superconducting solenoidal coils (hatched red) are shown near the flasks and outside of the cavities. The solenoidal magnetic field alternates from parallel to antiparallel to the beam direction at the absorber positions, as shown by the cyan curve.

In these designs, clever arrangements of solenoidal coils with regular reversals of field direction produce a periodic variation in the beta function with minima at the points where the absorbers are placed. As seen in the equations above, the small beta function at the absorber location is very good for cooling. Since accelerating gradients for large aperture RF cavities are limited to 10 MeV/m or less when the requirement of large bucket area is included, the RF regions occupy most of the length of the cooling channel. This periodic beta function arrangement allows the longer RF sections to easily fit between the absorbers where the larger beta function is not detrimental.

There are challenges with this liquid hydrogen scheme for an actual neutrino factory cooling channel: 1) the aluminum windows of the liquid hydrogen containers degrade the cooling performance, not only as seen by the equations above, but also by causing muon losses from large angle scattering along the channel. 2) The absorbers are engineering challenges with many difficult aspects. For example, muon fluxes of more than 10^{14} muons per second will heat the liquid hydrogen causing unwanted density variations. 3) The absorbers take up space so that the channel is longer than one would like. 4) The absorbers are inflexible in that the density and

corresponding dE/ds cannot be changed to compensate for operational changes in the RF parameters due to component failures or operational improvements, although selected absorbers can easily be emptied, which allows some adjustment for low-gradient cavities.

However, the most important challenge of the technical approach being demonstrated by MICE may be with the evacuated RF cavities themselves. Figure 2 shows measurements of an evacuated closed-cell 800 MHz cavity that demonstrate a significant degradation of maximum stable gradient as the external magnetic field is increased. Similar tests with a 200 MHz MICE prototype cavity will take place next year when magnet coils capable of creating a similar field will be delivered to the MTA from the manufacturer in Harbin, China. It is possible that the degradation of maximum gradient will be more severe for the lower frequency MICE cavity, with its larger surface area to produce dark currents to be focused by the external field. If so, the closed-cell approach may need to be abandoned, which would imply a lower accelerating gradient than was originally envisioned.

A. Moretti, NF&MCC Meeting, UCLA

01/31/2007

14

Figure 2: Maximum stable surface gradient for an 800 MHz evacuated cavity as a function of externally applied magnetic field as measured in Fermilab Lab G and MTA experiments [9].

Technical Approach

RF cavities that are pressurized with dense hydrogen gas will be developed that use the same real estate to provide the energy absorber and the RF acceleration needed for ionization cooling, where the absorption of dark currents by the dense gas will allow the cavities to operate in strong magnetic fields. Systematic measurements of the operation of a hydrogen-filled cavity will be made as functions of external magnetic field and charged particle beam intensity and compared with models to understand the limitations of this technology and to develop mitigating strategies.

Anticipated Public Benefit

COMMERCIAL APPLICATIONS AND OTHER BENEFITS as described by the applicant. (Limit to space provided).

Bright muon beams are needed for many commercial and scientific reasons. Potential commercial applications include the use of muon beams to screen cargo containers for homeland security, low-dose radiography, and muon catalyzed fusion. Scientific uses include low energy muon beams, muon spin resonance, and muon beams for neutrino factories and muon colliders.

Degree to which Phase I has Demonstrated Technical Feasibility

Phase I of this project has been successful and has generated interesting results. Many details of the research done in Phase I are contained in the Appendices to this proposal.

Delays in the development of the Fermilab MuCool Test Area (MTA) precluded beam tests during Phase I, allowing more diagnostic and simulation development, including an important experimental breakdown study with SF₆ dopant to verify the computer model. An optical fiber system was added to the test cell to be used in the first beam tests. A 1.3 GHz test cell was built and tested; it can operate under pressure or in vacuum in order to extend our understanding of RF breakdown as a function of frequency and geometry and to correlate with previous vacuum cavity experience.

Modeling and Simulations with Voss Scientific

Ionization cooling produces a population of free electrons that can gain energy from the RF field of an accelerating cavity. At sufficiently high electric field strength, secondary ionization by these electrons can lead to avalanche breakdown of the H₂ gas so that the gas is no longer a good insulator. The field threshold for this to occur can be increased by introducing small amounts of a gas such as SF₆, which has a large attachment cross-section at low electron energy, to act as a sink for the free electrons.

In Phase I, we investigated the gas breakdown threshold and the effect of dopants in numerical simulations. These numerical techniques have been validated against experimental data. The first technique, which gives rapid turnaround, uses an approximate Boltzmann equation to calculate the electron energy distribution function (EEDF) at a specified electric field strength and gas density [10,11]. The calculation uses a database of cross-sections for all the relevant interactions. The output from the calculation gives the rate of growth (or decay) of the free-electron population, as well as other rates obtained by integration over the EEDF. The second technique is the so-called PIC-MCC (particle-in-cell with Monte Carlo collisions) method [¹²] in which the free-electrons are followed as a function of time in applied and self-generated electric and magnetic fields. This technique is equivalent to solving the full time-dependent Boltzmann equation. It allows one to include conductor shapes and spatially-varying electric and magnetic fields, whereas the EEDF code has no spatial dimensions. The PIC-MCC calculations use the same cross-section database as the EEDF code.

Figure 3: Results from LSP and EEDF for H₂ at 100 Td. (a) electron temperature in eV, (b) drift velocity (normalized by c), (c) electron energy distribution, (d) log of electron number density.

A sample calculation comparing EEDF to a PIC-MCC calculation (using the LSP code) for H₂ is shown in Figure 3. A detailed description of such a comparison, for He instead of H₂, is given in Ref. [13]. The figure shows that at a ratio of electric field to gas number density $E/N = 100$ Td (a “Townsend” is defined as: $1 \text{ Td} = 10^{-17} \text{ V-cm}^2$), the PIC-MCC calculation evolves in time with an exponentially-increasing number of free electrons and an energy distribution that remains essentially constant after an initial transient.

As is typical of a particle method, the PIC-MCC calculation has a statistical noise component. Nevertheless, the agreement between these different techniques is good. To carry out this test, LSP was run in “0D” mode, with no spatial dimension, i.e., the electron velocities were updated on each timestep, but not their positions. These results were validated by comparing with experimental data for H₂ [Rose:2007]. Figure 4 shows that there is good agreement with both the EEDF and PIC-MCC calculations for E/N in the range 60-160 Td. The data indicate a breakdown threshold of about 50 Td for pure H₂ gas.

Figure 4: Ionization rate for H₂ vs. electric field strength. Experimental data tabulated by Engelhardt and Phelps [14] are compared to some results from LSP and EEDF.

The following quote describes our Phase I plan for this activity: “In Phase I we will primarily use the EEDF technique because of its speed. We will calculate the breakdown threshold of H₂ as a function of different dopant levels of SF₆ and CO₂. For many gases, including SF₆, some important cross-sections are difficult to measure accurately. Following common practice, we have compiled a set of cross-section tables for SF₆ which have been scaled to be consistent with experimental data on breakdown. We will use these cross-sections in the breakdown calculations. We will carry out some 0D PIC-MCC calculations using LSP as a check on the EEDF predictions. The breakdown thresholds will be used to guide Phase II experiments. Time permitting, we will prototype 2D PIC-MCC calculations to capture additional effects, including spatial diffusion of the free electrons, and the finite dimensions of the accelerating cavity.”

New Results Completed Under Phase I:

Using the 0D PIC-MCC model described above, we have verified the Paschen breakdown limit for the 805 MHz test cell experiment for pressures less than the electrode-dominated regime [BastaniNejad:2008, Sah:2008]. The same model was also used to predict the enhancement of Paschen law limit for a small SF₆ dopant ($R=n_{\text{SF}_6}/n_{\text{H}_2}=10^{-4}$). For example, at 325 psi the breakdown limit for the test cell operating at 805 MHz was increased from 25 MV/m in pure H₂ to 39 MV/m with $R=10^{-4}$ [Yonhara:BNL presentation]. The simulation result of approximately 38 MV/m is in good agreement with the experimental measurement, and confirms the potential benefits of this electronegative gas additive technique to increase the operating field gradient of the accelerating cavity. The time-dependent simulations indicate that this increase in the maximum operating gradient is only possible for an RF cavity, as the time dependence of the competing electron ionization (of H₂) and electron attachment (to SF₆) must be balanced to prevent continued electron buildup and eventual cavity breakdown. This result suggests that dopant levels will need to be tuned to both the desired maximum operating field as well as the operating frequency. The PIC-MCC simulations can be used in conjunction with the experiments to identify suitable dopants and optimize concentration level.

Figure 5: Particle densities a) below and b) above threshold from the 0D PIC simulations for 325 psi H₂ with SF₆ dopant at $R=10^{-4}$. For these simulations, an initial “seed” population of electron and H₂⁺ ions is initialized at 10^{10} cm⁻³.

Figure 6: 0D PIC simulations of breakdown at 325 psi H₂ with and without SF₆ ($R=10^{-4}$). The dashed lines are fits to the experimental results.

As an example, we have considered several candidate dopants and have compared their respective electron attachment cross sections relative to SF₆. As an example, we note that CO₂ has a small electron attachment cross section, so small admixtures of CO₂ to the high pressure H₂ is not expected to result in a significant increase in breakdown characteristics relative to pure H₂ (we have confirmed this in our 0D PIC model). As part of this Phase II effort, we will explore these and other candidate dopants [Devins:1980] to increase the breakdown thresholds for high pressure H₂ in an RF system.

1D Streamer-like Breakdown

As part of the Phase I research, we have begun to look at higher dimensional effects using the PIC model. One topic of interest is the propagation speed of a localized breakdown region occurring in the gas volume, well removed from the electrodes. We have carried out simple 1D simulations of this effect for H₂ at 325 psi with a uniform applied RF field of 40 MV/m. As we have seen above, this gradient is well above the Paschen Law breakdown limit for this pressure. We initialize a localized seed electron-H₂⁺ ion population of $2 \times 10^{17} \text{ cm}^{-3}$ in a single computational cell ($\Delta x = 2 \times 10^{-4} \text{ cm}$). The simulation volume is 0.3 cm in length and utilizes periodic boundary conditions. The electric field is solved on the computational grid using a standard SOR algorithm, and the total field (SOR solution plus applied RF field) is interpolated to the particle positions. Figure 7 gives a sample result. The initial plasma seed location ($x = 0.15 \text{ cm}$) is shown on the left, and the plasma density after 9.5 ns is shown on the right. The breakdown evolves in a streamer-like fashion, with charge non-neutrality at different sides of the evolving plasma as the RF field cycles. (A streamer is usually defined as a two-dimensional plasma structure with field enhancement at the head due to differential charge mobility leading to enhanced gas breakdown.) Here, plasma breakdown occurs at the front of the plasma region, and the plasma region grows with each RF cycle.

Figure 7: RF-driven breakdown from a 1D PIC simulation. For this case an 805 MHz RF field at $E_0 = 40 \text{ MV/m}$ drives the breakdown of H₂ gas at 325 psi from a localized plasma seed initialized at $x = 0.15 \text{ cm}$.

The speed at which this streamer-like breakdown propagates across the gap is of interest. In Fig. 8, we plot the total propagation distance of the breakdown “channel” for cases with $E_0 = 30$ and 40 MV/m , both above the Paschen Law breakdown limit for H₂ at 325 psi. A simple second-order fit to both of these curves (solid lines in Fig. 8) gives a propagation speed, v_0 , of 8.5 and 9.8 cm/ μs for $E_0 = 30$ and 40 MV/m , respectively. These speeds are reasonable, consistent with a variety of plasma breakdown time scales and imply approximate closing times of hundreds of ns across a 1-cm gap. We note that 2D simulations of streamer propagation should result in somewhat higher speeds and shorter gap closure times.

The above analysis provides a good starting point to begin consideration of electrode breakdown, the flat or “non Paschen” region of the experimental data from Fig. 6. The Lsp simulation code has charged particle emission algorithms for Fowler-Nordheim surface breakdown, space-charged-limited emission, and thermionic emission. In addition, a novel electrode plasma desorption model has been developed, to enable treatment of high-density plasma evolution from material surfaces [Rose:2008]. Under the Phase II research program, we plan to utilize this algorithm to examine time-dependent electrode plasma dynamics that may lead to breakdown phenomena *below* the Paschen Law limit (the flat region at higher pressures of Fig. 6) for sufficiently small electrode gaps.

Figure 8: Breakdown longitudinal extent as a function of time from 1D PIC simulations at 325 psi H₂ at 805 MHz, and $E_0 = 30$ and 40 MV/m.

In Phase II, we will carry out self-consistent 1D and 2D PIC-MCC simulations of a beam traveling through a high-pressure RF cavity. This will add finite-geometry effects to the Phase I calculations. We will use the results from Phase I and new calculations to choose an optimal level of dopant to suppress breakdown. The LSP code incorporates an electron-photon transport model [15], so that the effect of ionizing radiation as well as beam-impact ionization can be included. In addition to providing a more complete model to guide experiments, these calculations will be used to predict the effect of a breakdown event on the cavity and on the beam.

The Phase II Project

The Fermilab MTA will be exploited to extend measurements of maximum stable RF gradient in strong magnetic fields and in the presence of ionizing radiation. Beam-induced gas breakdown will be studied by improving computer simulation models that include the use of electron-absorbing dopants, external magnetic fields, and variations of cavity geometry and materials. RF test cells and experimental instrumentation will be built or improved to verify the models using MTA RF, beam, and magnetic field.

The **preliminary work** for the beam tests for this grant was partially supported by the DOE STTR Grant DE-FG02-05ER86252, “Muon Capture, Phase Rotation, and Precooling in Pressurized RF Cavities” (with Fermilab as research partner, Dr. David Neuffer, subgrant PI), which is described in the Commercialization Plan attached to this proposal. This support ended in January 2009. Phase I of the grant proposed here allowed the R&D of pressurized RF cavities to continue and the Phase II award will allow further development.

Technical Objectives

The technical work plan in support of each of these objectives is detailed below.

Phase II Work Plan

The tasks and milestones include:

- 1) Beam test of Mark II Test Cell (~September 2009)
- 2) Calculations for beam-induced gas breakdown developed and compared to experiments
- 3) Specifications for New (Mark III) test cell and test instrument decided
- 4) Mark III test cell modeled, designed, constructed, bench tested
- 5) Initiate safety reviews of Mark III test cell

Responsibilities

Muons, Inc.: The direction of the project is the responsibility of the company and the PI.

Fermilab: Dr. Katsuya Yonehara will be responsible for the Fermilab subgrant.

Performance Schedule (Tasks and Milestones)

6 months after start of funding:

- 0) Subcontract award in place.
- 1) Safety reviews completed
- 2) Beam line instrumentation commissioned and operational
- 3) Beam tests of the upgraded Mark II RF test cell started
- 4) Measurements of hydrogen parameters relevant to RF breakdown continue
(electron mobility, light output, dopant mixtures for gas breakdown mitigation)
- 5) Different modeling approaches compared, understood

12 months after start of funding:

- 1) First Paschen curves measured for helium and hydrogen in magnetic and radiation fields
- 2) Beam tests of the Mark II test cell extended to operation in the LBNL 5 T Solenoid
- 3) Operational limitations understood by comparing data to simulation predictions
- 4) Mitigation techniques to overcome limitations developed
- 5) Realistic Mark III RF test cell designed that incorporates mitigation techniques

18 months after start of funding:

- 1) Mark III test cell used to extend understanding of limitations of HPRF
- 2) Operational issues of practical HPRF systems explored

24 months after start of funding:

- 1) Mark III measurements extended to the limits of the MTA.
(magnetic field 3.5 T, temperature 77 to 325 K, pressure 1500 psi)
- 2) Results submitted for publication

24 months after start of funding

Facilities/Equipment

Muons, Inc. currently occupies a building of approximately 4000 square feet of floor space in Batavia, Illinois, a short drive from Fermilab. This building is now used as office space, conference rooms, workshop area, and living quarters as needed. Muons, Inc. has several high-performance personal computers and workstations with high-speed net access and sufficient computing power to perform simulations and CAD work. Muons, Inc. also has office space in Wilson Hall at Fermilab (Batavia, IL) and in the ARC building at Jefferson Lab (Newport News, VA).

Fermilab has several million dollars in MTA infrastructure that will be made available for this project, including a 12 MW 805 MHz klystron, 5 T superconducting magnet, and beam from the 400 MeV H⁻ Linac. In addition, the MTA has been created with the necessary controls to allow hydrogen to be used in conjunction with RF breakdown experiments. There is no other facility in the world with these features that are required for this project.

Consultants and Subcontractors

For development of a model of beam-induced breakdown in pressurized RF cavities Muons, Inc will award a subgrant of \$60,000 to Voss Scientific [16]. Founded in 1988, Voss Scientific is an R&D small-business in Albuquerque, New Mexico. It specializes in high-energy-density systems, including high-power, short-pulse lasers, microwave sources, and plasma physics and electromagnetic applications. The Voss computational physics group develops the Lsp electromagnetic simulation code, which is used in the US and abroad for a range of applications, including high-current electron and ion accelerators, intense beam transport in gases and plasmas, and intense laser-plasma interactions. Drs. David Rose and Carsten Thoma of Voss will carry out the calculations of gas breakdown described above.

Our partner Research Institution is Fermi National Accelerator Laboratory. The certifying official is:

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Phase II Funding Commitment (Commercial Contribution)**Letters of Support from Fermilab**

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April 15, 2009

Dr. L.K. Len
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Dear Dr. Len:

Subject: SBIR-STTR Program

This is to confirm that, subject to DOE approval, Fermilab is interested in participating in Phase II of the SBIR project "Hydrogen-Filled RF Cavities for Muon Cooling".

This project has particular relevance to an experiment that is of scientific interest to Fermilab where it might be performed.

Sincerely,

A handwritten signature in blue ink, appearing to read "Bruce L. Chrisman".

Bruce L. Chrisman
Office of Research and Technology Applications

cc: G. Leonard
R. Johnson
P. Oleck

Phase III Follow-on Funding Commitment

Our Phase III funding will depend on the success of this proposed grant and on the future plans at Fermilab to support muon collider research.

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Appendix I PAC09 draft Doped H2-filled RF cavities for muon beam cooling*

THIS WILL BE A 3-PAGE PAC09 PAPER

Appendix II PAC09 draft RF Breakdown of Metallic Surfaces in GH2 at 805 MHz

THIS WILL BE A 3-PAGE PAC09 PAPER

Appendix III: MuCool Note on the Diagnostic Optical Fiber

THIS is a 2-PAGE PAPER

Appendix IV: PAC09 draft 1.3 GHz RF Test Cell

Appendix V: PAC09 draft Travelling Wave RF

THIS CAN BE A 3-PAGE PAPER

Appendix VI: PAC09 draft Dielectric-loaded RF
THIS CAN BE A 3-PAGE PAPER

- **Appendix VII: Status of the MTA Beam Line**

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Appendix VIII: The Phase I Proposal