Phase I-SBIR/STTR Fiscal Year 2008

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FIRM NAME: **Muons, Inc.**	RESEARCH INSTITUTION: **Fermi National Accelerator Lab** **Dr. Katsuya Yonehara, subgrant PI**
ADDRESS: **552 N. Batavia Ave.** **Batavia, IL 60510**	ADDRESS: **P.O.Box 500,** **Batavia, IL 60510**

NAME of PRINCIPAL INVESTIGATOR: **Dr. Rolland Johnson** PHONE NUMBER: **(757) 870-6943**

PROJECT TITLE: **Hydrogen-filled RF Cavities for Muon Beam Cooling**

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 - typically, one to two sentences.

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 to overcome them.

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

A pressurized RF cavity will be designed, built, and tested that will be used to extend measurements of maximum stable gradient in strong magnetic fields and in the presence of ionizing radiation. Beam-induced gas breakdown will be studied by improving simulation models that include the use of electron-absorbing dopants, external magnetic fields, and variations of cavity geometry.

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 beams for rare process searches, muon spin resonance, muon beams for neutrino factories and muon colliders as Higgs factories or energy-frontier discovery machines.

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

Muon accelerators have many commercial and scientific uses. A new way to accelerate muons in hydrogen-filled RF cavities is being developed to create small, intense beams to enhance their utility for many applications, from homeland security to energy frontier muon colliders.

2008 Phase I-SBIR/STTR Cover Page/Summary

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FIRM NAME:	RESEARCH INSTITUTION:
Muons, Inc.	**Thomas Jefferson National Accelerator Facility** **Dr. Robert Rimmer, subgrant PI**
ADDRESS: **552 N. Batavia Ave.,** **Batavia, IL 60510**	ADDRESS: **12000 Jeffferson Avenue** **Newport News, VA 23606**

NAME of PRINCIPAL INVESTIGATOR: **Dr. Rolland P. Johnson** PHONE NUMBER: **(757) 870-6943**

PROJECT TITLE: **Rugged Ceramic Window for RF Applications**

TECHNICAL ABSTRACT (Limit to space provided)

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

High-current RF cavities that are needed for many accelerator applications are often limited by the power transmission capability of the pressure barriers (windows) that separate the cavity from the power source. Most efforts to improve RF window design have focused on alumina ceramic, the most popular historical choice, and have not taken advantage of new materials.

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

Alternative window materials such as sapphire, aluminum nitride, and ALON™ will be investigated and tested for material properties. The chosen candidate will be used in a window for high power testing.

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

In Phase I, properties of candidate materials will be investigated. Samples of those materials that meet the design requirements will be purchased and tested at the test stand at Thomas Jefferson National Accelerator Facility. Based on this study, a material will be chosen for Phase II window construction and full power testing.

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

Alternative window material that makes high average power RF windows stronger and more robust will have immediate applications to both superconducting and room-temperature accelerating systems. With higher peak and/or average power windows available, many areas currently dominated by room-temperature accelerators will be able to take advantage of higher frequency superconducting cavities.

Key Words: RF, RF window, high power window

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

Robust RF windows to help feed power into superconducting accelerating structures are being developed. New material choices will increase window power handling capabilities and mechanical strength over existing designs.

a. 2008 Phase I-SBIR/STTR Cover Page/Summary

(All information provided on this page is subject to release to the public.)

FIRM NAME: **Muons, Inc.**	RESEARCH INSTITUTION: **Lawrence Berkeley National Laboratory** **Dr. Derun Li, subgrant PI**
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NAME of PRINCIPAL INVESTIGATOR: **Dr. Richard Sah** PHONE NUMBER: **(510) 338-0181**

PROJECT TITLE: **RF Breakdown Studies using Pressurized Cavities**

TECHNICAL ABSTRACT (Limit to space provided)

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

Many present and future particle accelerators are limited by the maximum electric gradient and peak surface fields that can be realized in RF cavities. Despite considerable effort, a comprehensive theory of RF breakdown has not been achieved and mitigation techniques to improve practical maximum accelerating gradients have had only limited success. Part of the problem is that RF breakdown in an evacuated cavity involves a complex mixture of effects, which include the geometry, metallurgy, and surface preparation of the accelerating structures and the make-up and pressure of the residual gas in which plasmas form.

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

Recent studies have shown that high gradients can be achieved quickly in 805 MHz RF cavities pressurized with dense hydrogen gas without the need for long conditioning times, as was expected because the dense gas can practically eliminate dark currents and multipacting. In this project we will use this high pressure technique to suppress effects of residual vacuum and geometry found in evacuated cavities to isolate and study the role of the metallic surfaces in RF cavity breakdown as a function of magnetic field, frequency, and surface preparation.

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

An RF test cell and pressure barrier capable of operating both at high pressure and in vacuum will be designed, built, and tested. The test cell will have replaceable electrodes (e.g. Mo, Cu, Be, W, and Nb) that are compatible with analysis devices such as scanning tunneling microscopes and atomic force microscopes to measure microscopic work function variations.

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

The understanding of the role of the metals in RF breakdown will lead to better designs of RF cavities for many applications, including the International Linear Collider. An increase in the operating accelerating gradient, improved reliability, and shorter conditioning times, as may be expected if this project is successful, can have very significant cost savings in this and many other projects.

Key Words: RF, cavities, breakdown, ILC

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

A new technique using high-pressure gas is being developed to study the breakdown mechanisms of RF cavities needed for particle accelerators. A successful outcome would provide cost reductions and performance improvements for many accelerator projects, including the International Linear Collider.

Phase I-SBIR/STTR Fiscal Year 2008

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FIRM NAME: **Muons, Inc.**	RESEARCH INSTITUTION: **Jefferson Lab** **Dr. Alex Bogacz, subgrant PI**
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NAME of PRINCIPAL INVESTIGATOR: **Dr. Rolland Johnson** PHONE NUMBER: **(757) 870-6943**

PROJECT TITLE: **Pulsed-Focusing Recirculating Linacs for Muon Acceleration**

TECHNICAL ABSTRACT (Limit to space provided)

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

Neutrino Factories and Muon Colliders require rapid acceleration of short-lived muons to multi-GeV and TeV energies. A Recirculating Linear Accelerator (RLA) that uses International Linear Collider (ILC) RF structures can provide exceptionally fast and economical acceleration to the extent that the focusing range of the RLA quadrupoles allows each muon to pass several times through each high-gradient cavity. However, the technical feasibility, ultimate limitations, and cost effectiveness of such schemes have not been fully developed.

General statement of how this problem is being addressed. This is the overall objective of the combined Phase I and Phase II projects - typically, one to two sentences.

A new concept of rapidly changing the strength of the RLA focusing quadrupoles as the muons gain energy will be developed to increase the number of passes that each muon will make in the RF cavities, leading to greater cost effectiveness. We will develop the optics and technical requirements for RLA designs, using RF cavities capable of simultaneous acceleration of both μ^+ and μ^- species, with pulsed Linac quadrupoles to allow the maximum number of passes.

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

A single-Linac RLA that incorporates pulsed focusing quadrupoles will be designed at 1.3 GHz for intended use with ILC-type SRF accelerating structures. Technical solutions for fast pulsed quadrupoles and droplet arc magnets will be investigated to determine feasibility and potential cost savings. The design will include the optics for the multi-pass Linac and droplet-shaped return arcs, including chromatic compensation.

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

Future large scale facilities such as Neutrino Factories and Muon Colliders will benefit from more effective use of RF cavities by having RLA designs with more recirculation passes. Cost savings will follow from the value of the reused RF relative to the cost of the droplet arcs.

Key Words: recirculating linear accelerator, lattice design, muon-beam, collider

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

A new fast acceleration technique is being developed for future Neutrino Factories and Muon Colliders to take advantage of the high gradient RF cavities that are being developed for the International Linear Collider.

Phase I-SBIR/STTR Fiscal Year 2008

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FIRM NAME:	RESEARCH INSTITUTION:
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NAME of PRINCIPAL INVESTIGATOR: **Dr. Rolland Johnson** PHONE NUMBER: **(757) 870-6943**

PROJECT TITLE: **Multi-purpose Fiber Optic Sensors for HTS Magnets**

TECHNICAL ABSTRACT (Limit to space provided)

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

Magnets using new high temperature superconductor (HTS) materials are showing great promise for high magnetic field and/or radiation environment applications such as particle accelerators, NMR, and the plasma-confinement systems for fusion reactors. The development and operation of these magnets is limited, however, because appropriate sensors and diagnostic systems are not yet available to monitor the manufacturing and operational processes that dictate success.

General statement of how this problem is being addressed. This is the overall objective of the combined Phase I and Phase II projects - typically, one to two sentences.

Optical fibers will be imbedded within the HTS magnets to monitor strain, temperature and irradiation, and to detect quenches. In the case of Bi2212, the fiber will be used as a heat treatment process monitor to ensure that the entire magnet has reached thermal equilibrium. Real-time measurements will aid the development of high-field magnets that are subject to large Lorentz forces and allow the effective detection of quenches so that the stored energy of operating magnets can be extracted and/or dissipated without damaging the magnet.

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

Fiber optic materials will be evaluated for compatibility with HTS magnets, including their physical behavior at high temperature in oxygen to determine their compatibility with Bi2212 processing. Coating materials to enhance their behavior within magnets will be evaluated and techniques for imbedding the fibers in coil packages, and their effectiveness for process monitoring and quench detection, will be investigated. Effects of irradiation on fiber and fiber Bragg grating behavior will be measured. Design of the sensor system to be built and implemented in phase II will begin.

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

Magnets constructed from HTS will benefit from sensitive diagnostics to monitor strain and temperature for magnet development and day-to-day operation. The sensors to be developed will facilitate HTS magnets for many scientific, medical, military and power applications.

Key Words:

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

Optical fiber based sensors are being developed to monitor and protect the superconducting magnets used for fusion reactors, particle accelerators, and magnetic resonance imaging.

Accelerator Industrialization Research and Development

by

Muons, Inc.
Dr. Rolland Johnson, Co-Principal Investigator

and

Northern Illinois University
Professor David Hedin, Co-Principal Investigator

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Overview

Muons, Inc. and Northern Illinois University will generate at least one proposal for federal funding to develop accelerator physics and physics detector technologies to enhance the probability that Fermilab will continue to flourish in Illinois.

Muon Collider and Neutrino Factory Research for Fermilab's Future

Motivation

The Tevatron Collider at the Fermi National Accelerator Laboratory (Fermilab) is currently the highest-energy research tool in the world and Fermilab is the major high energy-physics facility in the United States, but without a new and sustainable project, Fermilab will be made obsolete by higher-energy machines in Europe and Japan. Without a new project, it is not clear that the federal funding of Fermilab would continue. Closure of Fermilab would lead to the loss to Illinois of over $300 million per year in direct federal support to Fermilab and would cost about 3000 Illinois jobs. Alternatively, if Fermilab is the site of the next major accelerator project to be undertaken in the U.S., the continued existence of the laboratory is assured and, in addition, billions of dollars for the construction and use of the new accelerator would be added to the State economy.

NIU and Muons, Inc. are particularly interested in the health and future prospects of Fermilab as Illinois institutions with close ties to Fermilab. NIU has used Fermilab resources for many research projects and counts heavily on it for collaborations as do many other institutions in Illinois, the US, and the world.

Opportunity

We believe that the next project at Fermilab will be largely built by industry. If Illinois is properly prepared, it could participate in this industrialization of the tools of basic science. The most likely near-term major project at Fermilab is likely to be a superconducting linear proton accelerator (now known as Project-X) that would be, among other things, a first step to a muon collider and a neutrino factory. While the Project-X will be less than 1B$, an energy-frontier muon collider could be ten times as much.

Muon collider technology and its industrialization are the main thrusts of Muons, Inc. research and development. We have a long list of muon collider components that we are developing, some of them like High Field Superconductor, Helical Solenoid magnets, and RF cavities pressurized with dense hydrogen gas, are cutting-edge technologies that are almost ready for industrial partnerships. The NIU-Muons, Inc. collaboration is well suited to the MANX cooling experiment, which will be the demonstration of the six-dimensional muon beam cooling that is required for a muon collider. The design of the interaction regions is also a high-priority for muon collider development. These two potential projects are described below and in the appendices. They each require the beam physics expertise as well as high energy physics detector techniques that are strong points of the Northern Illinois Center for Accelerator and Detector Development.

Approach

Muons, Inc. has received almost $7M in DOE High-Energy Physics Small Business Innovation or Small Business Technology Transfer Research (SBIR-STTR) grants primarily to develop technology for a muon collider. Each project has had a research partner, either a university or national laboratory.

The table below shows the projects that have been granted in the six years of since Muons, Inc. was started.

Muons, Inc Funding and Commercialization History

Year	Project Title	SBIR/STTR Revenues	non-SBIR/STTR source	non-SBIR/STTR Revenues	Research Partner
2002	Company founded				
2002	Consulting for ICAR*			$ 80,000	IIT
2002-5	High Pressure RF Cavity Development*	$ 600,000**	STTR		IIT
2003	Consulting for LSU CAMD Light Source*			$ 10,000	LA State
2003-6	Helical Cooling Channel Development*	$ 850,000**	SBIR		JLab
2004-7	Phase Ionization Cooling*	$ 745,000**	SBIR		JLab
2004-5	MANX Cooling Demo (Phase I only)*	$ 95,000	SBIR		Fermilab
2004-7	Hydrogen Cryostat*	$ 795,000**	STTR		Fermilab
2005-8	Reverse Emittance Exchange	$ 850,000**	STTR		JLab
2005-8	Muon Capture, Phase Rotation, and Precool	$ 850,000**	STTR	$ 149,385	Fermilab
2006-9	6D MANX Cooling Demo	$ 850,000**	STTR	$ 258,300	Fermilab
2006-9	G4Beamline Simulation Software	$ 850,000**	STTR		IIT
2007-8	Stopping Muon Beams	$ 100,000	SBIR	$ 21,909	Fermilab
2007-8	HCC Magnets	$ 100,000	SBIR	$ 22,099	Fermilab
2007-8	Compact, Tunable RF	$ 100,000	SBIR	$ 21,909	Fermilab
	Total	$ 6,785,000		$ 563,602	

* Completed Projects as of January 2008
** Combined Phase I and Phase II funds

(It is thanks to support from the State of Illinois and the Illinois Consortium for Accelerator Research (ICAR) that Muons, Inc. was formed as an Illinois company.)

There are several other Federal agencies that could support the work described here. One of the goals of this proposal is to identify the best agencies and programs to use for future funding applications.

Many relevant papers and reports can be seen at:
http://www.muonsinc.com/

Deliverables

In the same style as Muons, Inc. has developed SBIR-STTR proposals with other research partners, we will develop at least one proposal for funding with NIU as a research partner to be submitted to the agency most likely to fund the activities as developed in collaboration with the NIU physics and NICADD staffs. Here are two examples that we have started to investigate:

1) An attractive example is to collaborate on the MANX experiment, which has been described as a letter of intent (LOI) to Fermilab and is attached as Appendix I to this document. MANX is a demonstration of a technique for cooling based on the new concept of a Helical Cooling Channel (HCC). Simulations of the HCC have indicated that it can be used to achieve a factor of more than five orders of magnitude reduction in the six-dimensional emittance of a muon beam. The success of the MANX demonstration experiment will lead to confidence that effective muon cooling is possible and that a muon collider is the next logical step toward the energy frontier.

Since the LOI was submitted to Fermilab, a new DOE STTR grant has been put in place to develop the experiment and a four-coil prototype section of the magnet that is the heart of the experiment is being constructed at Fermilab to be tested later this year.

In this case, a possibility for further funding could be from the DOE or NSF to participate in the experiment, which will be submitted both to Fermilab and to the Rutherford Appleton Laboratory in England.

2) Another example is a project to develop the design of the interaction region of a high-energy, high luminosity muon collider and develop the corresponding detector technologies. This project would combine the skills of the NICADD accelerator experts with the physicists and engineers who have participated in the Fermilab D0 experiment. Because of new concepts that have been promoted by Muons, Inc., such as the low emittance muon collider approach where superior beam cooling allows high luminosity with fewer muons, the interaction region design is unexplored territory. Muons, Inc. has submitted a DOE SBIR-STTR Phase I grant application in collaboration with Yaroslav Derbenev and Thomas Jefferson National Accelerator Facility to start on the interaction region design. The proposal is attached below as Appendix II.

Each of these examples involve NIU's accelerator group with their experience in phase space manipulations similar to those needed to cool the muon beam or to design the low beta interaction region of the collider and the NIU HEP group that would develop the detectors and experimental techniques for the MANX experiment or the low beta interaction regions.