# BOOK OF PAC09 Muons, Inc. ABSTRACTS

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## Title

## High Power Co-Axial SRF Coupler

## Authors

**Michael Neubauer, Muons, Inc.**
**Robert A. Rimmer, JLAB**

## Abstract

There are over 35 coupler designs for SRF cavities ranging in frequency from 325 to 1500 MHz. Two-thirds of these designs are coaxial couplers using disk or cylindrical ceramics in various combinations and configurations. While it is well known that dielectric losses go down by several orders of magnitude at cryogenic temperatures, it not well known that the thermal conductivity also goes down, and it is the ratio of thermal conductivity to loss tangent (SRF ceramic Quality Factor) and ceramic volume which will determine the heat load of any given design. We describe a novel robust co-axial SRF coupler design which uses compressed window technology. This technology will allow the use of highly thermally conductive materials for cryogenic windows. The mechanical designs will fit into standard-sized ConFlat® flanges for ease of assembly. Two windows will be used in a coaxial line. The distance between the windows is adjusted to cancel their reflections so that the same window can be used in many different applications at various frequencies.

## Acknowledgements

Supported in part by DOE SBIR grant DE-FG02-08ER85171
Supported in part by USDOE Contract DE-AC05-84-ER-40150

**Title**

# $H^-$ Ion Sources for High Intensity Proton Drivers

**Authors**

**Vadim Dudnikov, Galina Dudnikova, Rolland Johnson, Muons, Inc.**
**Martin Stockli, Robert Welton, ORNL**

**Abstract**

Spallation neutron source user facilities require reliable, intense beams of protons. The technique of $H^-$ charge exchange injection into a storage ring or synchrotron can provide the needed beam currents, but it is limited by the ion sources that have currents and reliability that do not meet future requirements and emittances that are too large for efficient acceleration. In this project we are developing an $H^-$ source which will synthesize the most important developments in the field of negative ion sources to provide high current, small emittance, good lifetime, high reliability, and power efficiency. We describe planned modifications to the present external antenna source at SNS that involve: 1) replacing the present 2 MHz plasma-forming solenoid antenna with a 60 MHz saddle-type antenna and 2) replacing the permanent multicusp magnet with a weaker electromagnet, in order to increase the plasma density near the output aperture. The SNS test stand will then be used to verify simulations of this approach that indicate significant improvements in $H^-$ output current and efficiency, where lower RF power will allow higher duty factor, longer source lifetime, and/or better reliability.

**Acknowledgements**

Supported in part by USDOE Contract DE-AC05-00OR22725

## Title

## Improved DC Gun Insulator

## Authors

**Carlos Hernandez-Garcia George Neil, Jlab**
**Kevin Beard, Michael Neubauer, Richard Sah, Muons, Inc.**

## Abstract

Many user facilities such as synchrotron light sources and free electron lasers require accelerating structures that support electric fields of 10-100 MV/m, especially at the start of the accelerator chain where ceramic insulators are used for very high gradient DC guns. These insulators are difficult to manufacture, require long commissioning times, and have poor reliability, in part because energetic electrons bury themselves in the ceramic, creating a buildup of charge and causing eventual puncture. A novel ceramic manufacturing process is proposed. It will incorporate bulk resistivity in the region where it is needed to bleed off accumulated charge caused by highly energetic electrons. This process will be optimized to provide an appropriate gradient in bulk resistivity from the vacuum side to the air side of the HV standoff ceramic cylinder. A computer model will be used to determine the optimum cylinder dimensions and required resistivity gradient for an example RF gun application. A ceramic material example with resistivity gradient appropriate for use as a DC gun insulator will be fabricated by glazing using doping compounds and tested.

## Acknowledgements

Supported in part by USDOE Contract No. DE-AC05-84-ER-40150.

**Title**

# Laser Stripping for $H^-$ Injection

**Authors**

**Viatcheslav Danilov, Yun Liu, ORNL**
**Kevin Beard, Rolland Johnson, Vadim Dudnikov, Muons, Inc.**
**Michelle Shinn, Jlab**

## Abstract

Spallation neutron source (SNS) user facilities require reliable, intense beams of protons. The technique of $H^-$ charge exchange injection into a storage ring or synchrotron has the potential to provide the needed beam currents, but it will be limited by carbon or diamond stripping foils, which have intrinsic limitations. A laser in combination with magnetic stripping has been used to demonstrate a new technique for high intensity proton injection, but several problems need to be solved before a practical system can be realized. Technology developed for use in Free-Electron Lasers is being used to address the remaining challenges to practical implementation of laser controlled $H^-$ charge exchange injection for the SNS. These technical challenges include (1) operation in vacuum, (2) the control of the UV laser beam to synchronize with the $H^-$ beam and to shape the proton beam, (3) the control and stabilization of the Fabry-Perot resonator, and (4) protection of the mirrors from radiation. The first objective is to demonstrate successful power recycling in the resonator and to design the system of mirrors to be located in the accelerator vacuum chamber with required optical and thermal stabilization.

## Acknowledgements

Supported in part by USDOE Contract No. DE-AC05-84-ER-40150.
Supported in part by USDOE Contract DE-AC05-00OR22725

## Title

## Beam Pipe HOM Absorber for 750 MHz RF Cavities

## Authors

**Michael Neubauer, Richard Sah, Muons, Inc., Batavia, IL**
**Hasan Padamsee, Eric Chojnaki, Matthias Leipe, Cornell University, Ithaca, NY**

## Abstract

Superconducting HOM-damped (higher-order-mode-damped) RF systems are needed for present and future storage ring and linac applications. Superconducting RF (SRF) systems typically contain unwanted frequencies or higher order modes (HOM) that must be absorbed by ferrite and other lossy ceramic-like materials that are brazed to substrates mechanically attached to the drift tubes adjacent to the SRF cavity. These HOM loads must be thermally and mechanically robust and must have the required broadband microwave loss characteristics, but the ferrites and their attachments are weak under tensile stresses and thermal stresses and tend to crack. A HOM absorber with improved materials and design will be developed for high-gradient 750 MHz superconducting cavity systems. RF system designs will be numerically modeled to determine the optimum ferrite load required to meet the broadband loss specifications. Several techniques for attaching ferrites to the metal substrates will be studied, including full compression rings and nearly-stress-free ferrite assemblies. Prototype structures will be fabricated and tested for mechanical strength.

## Acknowledgements

**Cornell NSF**

**Title**

# Low Beta Region Muon Collider Detector Design

**Authors**

**David Hedin, NIU**
**Mary Anne Cummings, Muons, Inc.**

**Abstract**

Detector designs for muon colliders have lacked coverage of the particles emerging from the collision region in the forward and backward angular regions, limiting their physics potential. These regions require massive shielding, mainly due to the intense radiation produced by the decay electrons from the muon beams. Emerging technologies for instrumentation could be used to detect particles in these regions that were filled with inert material in previous designs. New solid state photon sensors that are fine-grained, insensitive to magnetic fields, radiation-resistant, fast, and inexpensive can be used with highly segmented detectors in the regions near the beams. We are developing this new concept by investigating the properties of these new sensors and including them in numerical simulations to study interesting physics processes and backgrounds to improve the designs of the detector, the interaction region, and the collider itself. Simulations that approximate conditions in the forward regions for contemporary muon collider design parameters are being used to specify requirements for large-scale, high-granularity instrumentation for these regions. Bench tests of state of the art sensors and electronics will be made to determine their suitability to extend the physics reach of energy frontier muon colliders.

**Acknowledgements**

Supported in part by the Illinois Department of Commerce and Economic Opportunity

**Title**

# Large Area Photo-detectors with Millimeter and Picosecond Resolution: Simulations

**Authors**

**Henry J. Frisch, University of Chicago**
**Thomas Roberts, Robert Abrams, Valentin Ivanov, Muons, Inc.**

**Abstract**

Many measurements in particle and accelerator physics are limited by the time resolution with which individual particles can be detected. This includes particle identification via time-of-flight in major experiments like CDF at Fermilab and Atlas and CMS at the LHC, as well as the measurement of longitudinal variables in accelerator physics experiments. Large-scale systems, such as neutrino detectors, could be significantly improved by inexpensive, large-area photo detectors with resolutions of a few millimeters in space and a few picoseconds in time. Recent innovations make inexpensive, large-area detectors possible, with only minor compromises in spatial and time resolution. The Geant4-based simulation program, G4beamline, is being used to simulate the inner workings of these detectors, leading to the ability to optimize their performance. Some program enhancements will be required, including interfacing to existing Geant4 facilities and low-energy physics processes. Development will begin on the additional physics processes necessary for the inner surfaces of a micro-channel plate. Simulations of the detectors await funding.

**Acknowledgements**

## Title

### Advances in Multi-Pixel Photon Counter Technology

## Authors

**David Hedin, Vishnu Zutshi NIU**
**Robert J. Abrams, Muons, Inc.**

## Abstract

The multi-pixel photon counter (MPPC) is of great interest as a photon detector for high-energy physics, and other fields. New applications for muon collider detectors will stimulate improvements in MPPCs. Advanced electronic platforms to process their signals and provide integrated application-specific functions are needed to realize their capabilities. We are studying the performance characteristics of MPPCs as particle detectors for scintillating fiber hodoscopes, especially in cryogenic systems, and for calorimetry. A field programmable gate array (FPGA)-based data acquisition system will be used to determine the signal processing functions that are needed for an integrated electronics platform. Then we will design and implement an application-specific integrated circuit (ASIC) that is integrated and packaged with the MPPC, and incorporate it in larger prototype systems. MPPCs from different vendors will be studied to determine pulse characteristics, optimal settings, noise rates, after-pulsing, etc. over a wide temperature range down to liquid nitrogen and liquid helium temperatures. Pre-prototype scintillating fiber counters and calorimeter modules with MPPC detectors will be constructed and tested using sources, cosmic rays and beam.

## Acknowledgements

Supported in part by the Illinois Department of Commerce and Economic Opportunity

**Title**

## HTS development for 30-50 T final muon cooling solenoids

**Authors**

**Frank Hunte, Justin Schwartz, FSU**
**Stephen Kahn, Melanie Turenne, Rolland Johnson, Muons, Inc.**

**Abstract**

High temperature superconductors (HTS) have been shown to carry significant current density in the presence of extremely high magnetic fields when operated at low temperature. The successful design of magnets needed for high energy physics applications using such high field super-conductor (HFS) depends critically on the detailed wire or tape parameters which are still under development and not yet well-defined. HFS is being developed for accelerator use by concentrating on the design of an innovative magnet that will have a useful role in muon beam cooling. A conceptual design of a high field solenoid using YBCO HFS conductor is being analyzed. Mechanical properties of HFS conductors will be measured along with the maximum engineering current density (Je) as a function of temperature and strain to extend the HFS specifications to conditions needed for low temperature applications. HFS quench properties will be measured and quench protection schemes developed for the solenoid.

**Acknowledgements**

**Title**

# Epicyclic Helical Channels for Parametric Resonance Ionization Cooling

**Authors**

**Alex Bogacz, Slava Derbenev, JLab**
**Andrei Afanasev, Valentin Ivanov, Rolland Johnson, Guimei Wang, Muons, Inc.**

## Abstract

Muon beam ionization cooling is a key element in the design of next-generation low-emittance and high-luminosity muon colliders. Present designs, however, have limitations that need to be addressed with new approaches. To obtain low-emittance muon beams, a new concept is being developed that combines ionization cooling in a Helical Cooling Channel (HCC) with a parametric resonance, where the excellent field homogeneity of the HCC allows the beam to be controlled near strong resonances. An essential novelty is that the z-dependent dispersion function required for this cooling is created in a HCC by imposing an additional helical field with opposite helicity. Thus the dispersion is small at the wedge-shaped absorbers to allow emittance exchange and control of momentum spread and the dispersion is large at the positions of the chromatic aberration correction elements. In this project we develop a theoretical description of a muon transport line that includes a solenoid with superimposed transverse helical dipole fields that vary with two characteristic periods. An analytical theory for parametric resonance ionization cooling in such a transport line is described.

## Acknowledgements

### Title

## Achromatic Interaction Point Design

### Authors

**S. Alex Bogacz, Yaroslav Derbenev, JLab**
**Charles Ankenbrandt, Andre Afanasev, Valentin Ivanov, Rolland Johnson, Guimei Wang, Muons, Inc.**

### Abstract

Designers of high-luminosity energy-frontier muon colliders must provide strong beam focusing in the interaction regions. However, the construction of a strong, aberration-free beam focus is difficult and space consuming, and long straight sections generate an off-site radiation problem due to muon decay neutrinos that interact as they leave the surface of the earth. Without some way to mitigate the neutrino radiation problem, the maximum energy of a muon collider will be limited to about 4 TeV. A new concept for achromatic low beta designs is being developed, in which the interaction region telescope, optical correction elements, and final focusing magnets are installed in the bending arcs. The concept, formulated analytically, combines space economy, a preventative approach to compensation for aberrations, and a reduction of neutrino flux concentration. An analytical theory for the aberration-free, low beta, spatially compact insertion is being developed including analysis beyond second order aberration terms. Dynamic aperture, momentum acceptance, and error sensitivity studies have been initiated for comparison to previous designs.

### Acknowledgements

## Title

## Quasi-Isochronous Muon Collection Channels

### Authors

**David Neuffer, Fermilab**
**Cary Yoshikawa, Charles Ankenbrandt, Muons, Inc.**

## Abstract

Intense muon beams have many potential commercial and scientific applications, ranging from low-energy investigations of the basic properties of matter using spin resonance to large energy-frontier muon colliders. However, muons originate from a tertiary process that produces a diffuse swarm. To make useful beams, the swarm must be rapidly cooled before the muons decay. A promising new concept for the collection and cooling of muon beams to increase their intensity and reduce their emittances will be investigated, namely, the use of a nearly isochronous helical cooling channel (HCC) to facilitate capture of the muons into several RF bunches. Such a distribution can be cooled quickly and then coalesced efficiently into a single bunch to optimize the luminosity of a muon collider. Optimal ways to integrate such a subsystem into the rest of a muon collection and cooling system will be developed by analysis and simulation. The application of quasi-isochronous helical cooling channels for RF capture of muon beams will be developed analytically. Simulations will be performed to optimize an HCC for muon capture. A preliminary examination of the integration of this subsystem into the rest of a muon collider facility will be carried out.

## Acknowledgements

**Title**

# Simulation Tools for the Muon Collider Feasibility Study

**Authors**

**Richard Fernow, BNL**
**Thomas Roberts, Muons, Inc.**

## Abstract

The U.S. muon collider community is mobilizing itself to produce a "Design Feasibility Study" (DFS) for a muon collider. This is happening on an aggressive schedule and must include the best possible simulations to support and validate the technical design. The DFS for a muon collider will require innovative new approaches to many aspects of accelerator design, and the simulations to support it will require tools with features and capabilities that are equally innovative and new. Two computer programs have emerged as the preferred and most commonly used simulation tools within the muon collider community: ICOOL (primary author: Dr. Fernow), and G4beamline (primary author: Dr. Roberts). We describe the ongoing development and testing of both tools for the DFS, including a common suite of tests to ensure that both tools give accurate and realistic results, as well as innovative user-friendly interfaces with emphasis on graphical user interfaces and windows.

## Acknowledgements

Supported in part by DOE STTR grant DE-FG02-06ER86281.

## Title

## Neutrino Factory Muon Collider Front End Simulation Comparisons

### Authors

**Cary Yoshikawa, Muons, Inc.**
**David Neuffer, Fermilab**

## Abstract

Earlier studies on the front end of a neutrino factory or muon collider have relied on a single simulation tool, ICOOL. We present here a cross-check against another simulation tool, G4beamline. We also perform a preliminary study in economizing the number of RF cavity frequencies and gradients. We conclude with a discussion of future studies.

## Acknowledgements

Supported in part by DOE STTR grant DE-FG02-05ER86252.

## Title

# Gridded-Wire Windows for High Pressure RF Cavities

### Authors

**Mohammad Alsharo'a, Rolland Johnson, Muons, Inc.**
**Daniel Kaplan, Michael Gosz, Sudhakar Nair, IIT**
**Alfred Moretti, Fermilab**

## Abstract

In muon RF accelerating cavities, expensive thin, beryllium foils are used to close cavity ends to increase the on-axis electric field, and reduce the RF power requirement; they tend to displace at high power and detune the cavity. Gridded-tube windows, which are grid-like structures composed of tubes, have been proposed but not yet tested for use in vacuum cavities. In this project proposing gridded windows, composed of wires, for use with high pressure RF cavities. Gridded-wire RF windows are being designed to overcome the large displacement problem found experimentally in beryllium foil windows, and consequently to prevent cavity detuning. Complete designs of a gridded-wire window will be devised for use with high pressure RF cavities. The design process will include performing electromagnetic, thermal, and structural simulations in addition to studying the feasibility of fabrication.

## Acknowledgements

## Title

## Dielectric Loaded RF Cavities

### Authors

**Milorad Popovic, Al Moretti, FNAL**
**Michael Neubauer, Muons, Inc.**

Alternative cavity fabrication techniques at low frequencies are needed to improve manufacturability. RF cavities below 800 MHz are large, increase the cost of installation, are difficult to manufacture, require significant lead times and are expensive. Novel dielectric loaded RF cavities will allow smaller diameter cavities to be designed; changing the frequency of a cavity design would be as simple as changing the dielectric cylinder insert material or inner radius of the dielectric in the cavity. A cavity designed for 800 MHz fitted with a ceramic cylinder, high power tested and compared to an 800 MHz cavity without ceramic is described. High power tests at 800 MHz with a ceramic cylinder insert inside of a pill box cavity designed for high pressure hydrogen gas is compared to the breakdown studies in a hydrogen filled 800 MHz cavity operated without a ceramic insert. Assembly processes are investigated to determine the tolerance requirements for ceramic inserts in RF pillbox cavities.

## Acknowledgements

## Title

### Phase and frequency locked magnetrons for SRF Sources

## Authors

**Milorad Popovic, Al Moretti, FNAL**
**Michael Neubauer, Muons, Inc.**

## Abstract

Typically, high power sources for accelerator applications are many megawatt microwave tubes that may be combined together to form ultra high-power localized power stations. The RF power is then distributed to multiple strings of cavities through high power waveguide systems, which are expensive to produce and to operate because of reduced efficiency and lower reliability. Magnetrons are the lowest cost microwave source in $/kW with the highest efficiency, typically greater than 85%, but the frequency and phase stability of magnetrons has been a problem when used as power sources for accelerators. Novel variable frequency cavity techniques have been developed which will be utilized to phase and frequency lock magnetrons, allowing their use for either individual cavities, or cavity strings. Economies of scale will further reduce magnetron costs, in addition to removing the capital, efficiency, and reliability costs of combining and/or distributing power.

## Acknowledgements

## Title

## Compact, Tunable RF Cavities

### Authors

**Milorad Popovic, Al Moretti, FNAL**
**Rolland Johnson, Michael Neubauer, Mohammad Alsharo'a, Muons, Inc.**

### Abstract

New developments in the design of fixed-field alternating gradient (FFAG) synchrotrons have sparked interest in their use as rapid-cycling, high intensity accelerators of ions, protons, muons, and electrons. Compact RF cavities that tune rapidly over various frequency ranges are needed to provide the acceleration in FFAG lattices. An innovative design of a compact RF cavity that uses orthogonally biased ferrite or garnet materials for fast frequency tuning and liquid dielectric to reduce the overall cavity size will be developed using computer models, prototyped, and tested. The ferrite and garnet test cavity and the model cavity that were built in an earlier project will be exploited to determine the range of possibilites for FFAG and other applications. A working prototype cavity will be designed to provide a second-harmonic RF cavity for the Fermilab Booster to improve the capture of protons from the Linac. The same concept, using different magnetic and dielectric materials will be evaluated for FFAG machines, the PS2 upgrade of CERN's Large Hadron Collider, and Femilab's Main Injector proton driver.

### Acknowledgements

## Title

## Particle Refrigerator

## Authors

**Thomas Roberts, Muons, Inc.**
**Daniel Kaplan, IIT**

## Abstract

For studies of the behavior and properties of particles and nuclei, relativistic particle and ion beams are needed having high brightness: low normalized emittance and high intensity. This is especially difficult for beams of particles produced from interactions of other particles, such as unstable ions, antiprotons, muons, etc. The technique of frictional cooling, originally developed for muon beams, can be applied to other particles and ions, producing beams of exceptionally low normalized emittance. However, frictional cooling has the problem that such a channel has a very small momentum acceptance, and thus has not been of practical value. This device increases the momentum acceptance by two to three orders of magnitude, making it possible to handle much larger intensities with much higher transmission, while preserving the exceptionally low normalized emittance of the output. This paper describes simulation studies of the device used to optimize the design and performance of the particle refrigerator for a variety of ions and particles, and presents an inexpensive experiment to test and verify the simulations, using alpha particles from a radioactive source.

## Acknowledgements

## Title

## Fiber Optics for Fusion Applications

## Authors

**Melanie Turenne, Rolland Johnson, Muons, Inc.**
**Justin Schwartz, FSU**

## Abstract

Fusion energy sources require the development of superconducting magnets beyond today's capabilities in order to achieve safe and reliable operation. New electromagnetic noise-immune sensors are needed to provide rapid and redundant quench protection for operational systems as well as to measure temperature and strain for studies of magnet behavior for engineering development. Optical fibers with Bragg gratings are planned to be imbedded within $Nb_3Sn$ and $YBa_2Cu_3O_x$ (YBCO) magnets to monitor strain, temperature, and irradiation, and to detect quenches. Protection methods for YBCO magnets, which have very slow quench propagation velocities, are also being developed. Associated instrumentation will allow real-time measurements to aid the development of high-field magnets that are subject to large Lorentz forces, to allow the effective detection of quenches so that the stored energy of operating magnets can be extracted and/or dissipated without damaging the magnet, and to determine the level of irradiation exposure to the conductor as a function of location.

## Acknowledgements

**Title**

# Multi-purpose Fiber Optic Sensors for HTS Magnets

**Authors**

**Melanie Turenne, Rolland Johnson, Muons, Inc.**
**Justin Schwartz, FSU**

**Abstract**

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. 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. Fiber optic materials are being evaluated for compatibility with HTS magnets, including their physical behavior at high temperature in oxygen to determine their compatibility with Bi2212 processing.

**Acknowledgements**

Supported in part by DOE SBIR grant DE-FG02-08ER85024

## Title

## Rugged Ceramic Window for RF Applications

## Authors

**Michael Neubauer, Rolland Johnson, Muons, Inc.**
**Robert Rimmer, Tom Elliot, JLab**

## Abstract

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. Alternative window materials such as sapphire, aluminum nitride, and ALON™ have been investigated and tested for material properties. A candidate has been chosen to be used in a window for high power testing at Thomas Jefferson National Accelerator Facility.

## Acknowledgements

Supported in part by USDOE SBIR Grant DE-FG02-08ER85171

**Title**

# Hydrogen-filled RF Cavities for Muon Beam Cooling

**Authors**

**Katsuya Yonehara, Moses Chung, Andreas Jansson, Martin Hu, Al Moretti, Milorad Popovic, A. Tollestrup, FNAL**
**Mohammad Alsharo'a, Rolland Johnson, Michael Neubauer, Muons, Inc.**
**David Rose, Voss Scientific**

## Abstract

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 are pressurized with dense hydrogen gas are being 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 are 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. A pressurized RF cavity is being tested that will be used to extend measurements of maximum stable gradient in strong magnetic fields and in the presence of ionizing radiation.

## Acknowledgements

Supported in part by USDOE STTR Grant DE-FG02-08ER86350

**Title**

# Pulsed-Focusing Recirculating Linacs for Muon Acceleration

**Authors**

**Alex Bogacz, JLab**
**Rolland Johnson, Guimei Wang, Muons, Inc.**

**Abstract**

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

**Acknowledgements**

Supported in part by USDOE STTR Grant DE-FG02-08ER86351

**Title**

**Multipass Arc Lattice Design for a Muon RLA**

**Authors**

**Alex Bogacz, JLab**
**Dejan Trbojevic, BNL**
**Rolland Johnson, Guimei Wang, Muons, Inc.**

**Abstract**

Recirculating linear accelerators (RLA) are the most likely means to achieve the rapid acceleration of short-lived muons to multi-GeV energies required for Neutrino Factories and TeV energies required for Muon Colliders. One problem is that in the simplest schemes, a separate return arc is required for each passage of the muons through the linac. In the work described here, a novel arc optics based on a Non Scaling Fixed Field Alternating Gradient (NS-FFAG) lattice is developed, which would provide sufficient momentum acceptance to allow multiple passes (two or more consecutive energies) to be transported in one string of magnets. With these sorts of arcs and a single linac, a Recirculating Linear Accelerator (RLA) will have greater cost effectiveness and reduced losses from muon decay. We will develop the optics and technical requirements to allow the maximum number of passes by using an adjustable path length to accurately control the returned beam phase to synchronize with the RF.

**Acknowledgements**

Supported in part by USDOE STTR Grant DE-FG02-08ER86351

**Title**

# Pulsed Magnet Arc Designs for Recirculating Linac Muon Accelerators

**Authors**

**Guimei Wang, Rolland Johnson, Muons, Inc.**
**Alex Bogacz, JLab**
**Dejan Trbojevic, BNL**

**Abstract**

We have previously considered the application of fast pulsing quadrupoles to increase the focusing of muon beams as they gain energy in the linac region of a recirculating linear accelerator (RLA) in order to allow more passes. In this work we consider the use of pulsed magnets, both quads and dipoles, to reduce the number of beam lines needed for the return arcs of the RLA. We investigate the required relationships between the linac parameters (length and energy gain) and the momentum acceptance of the return arcs and consider the optimum strategy for accelerating both muon charge signs.

**Acknowledgements**

Supported in part by USDOE STTR Grant DE-FG02-08ER86351

## Title

## RF Breakdown Studies using Pressurized Cavities

## Authors

**Derun Li, John Byrd, LBNL**
**Rolland Johnson, Michael Neubauer, Richard Sah, Muons, Inc.**
**Mahzad BastaniNejad, Mageed Elmustafa, ODU**

## Abstract

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. 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, because the dense gas can dramatically reduce dark currents and multipacting. In this project we 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. An RF test cell with replaceable electrodes (e.g. Mo, Cu, Be, W, and Nb) and pressure barrier capable of operating both at high pressure and in vacuum is being designed, built, and tested.

## Acknowledgements

Supported in part by USDOE STTR Grant DE-FG02-08ER86352

**Title**

# RF Breakdown of Metallic Surfaces in Hydrogen at 805 MHz

**Authors**

**Mahzad BastaniNejad, Mageed Elmustafa, ODU**
**Katsuya Yonehara, Moses Chung, Andreas Jansson, Martin Hu, Al Moretti,**
**Milorad Popovic, A. Tollestrup, FNAL**
**Mohammad Alsharo'a, Michael Neubauer, Richard Sah, Rolland Johnson, Muons, Inc.**
**David Rose, Voss Scientific**
**Derun Li, John Byrd, LBNL**

## Abstract

In an earlier report, microscopic images of the surfaces of metallic electrodes used in high-pressure gas-filled 805 MHz RF cavity experiments were used to investigate the mechanism of RF metal breakdown of tungsten, molybdenum, and beryllium electrode surfaces. These studies have been extended to include tin, aluminum, and copper. In these experiments, the dense hydrogen gas in the cavity prevents electrons or ions from being accelerated to high enough energy to participate in the breakdown process so that the only important variables are the fields and the metallic surfaces. The distributions of breakdown remnants on the electrode surfaces are compared to the maximum surface gradient predicted by an ANSYS model of the cavity. The local surface density of spark remnants, proportional to the probability of breakdown, shows a power law dependence on the maximum gradient as expected from Fowler-Nordheim behavior of electron emission from a cold cathode, which is explained by the quantum-mechanical penetration of a barrier that is characterized by the work function of the metal. We report results from this high pressure technique to study maximum gradients and breakdown remnant distributions for Sn, Be, Cu, Al, Mo, and W.

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**Title**

# Stopping Muon Beams

**Authors**

**Cary Yoshikawa, Robert Abrams, Charles Ankenbrandt,**
**Mary Anne Cummings, Rolland Johnson, Muons, Inc.**
**Mike Martens, David Neuffer, Milorad Popovic, FNAL**

## Abstract

Physics experiments often use low-energy beams of unstable particles that stop in a target in order to provide high sensitivity to rare processes with reduced backgrounds. However, the stopping rate in the target is limited by the dynamics of the production process and by multiple scattering and energy straggling in the material used to slow the particles. As a result the event rates and sensitivity to rare processes are limited. In this project, we have applied new six-dimensional beam cooling inventions, improved capture techniques, and our new simulation tools to develop designs for low-energy beam lines to stop many muons in small volumes. G4beamline, our Geant4 based program, was used to simulate the mu2e experimental design as a baseline for comparison with the proposed method using a helical cooling channel (HCC) and for general improvements. An entirely new concept for reducing the energy spread of the secondary pion beam was invented and is under development to provide better protection from many sources of background that could limit the sensitivity of the experiment and also to provide the possibility for highly polarized stopping muon beams.

## Acknowledgements

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. **Title**

## Magnets for Muon 6D Helical Cooling Channels

**Authors**

**Melanie Turenne, Stephen Kahn Rolland Johnson, Muons, Inc.**
**Alexander Zlobin, Vladimir Kashikhin, Katsuya Yonehara FNAL**

**Abstract**

The Helical Cooling Channel (HCC), a new technique for six-dimensional (6D) cooling of muon beams using a continuous absorber inside superconducting magnets, has shown considerable promise based on analytic and simulation studies. The implementation of this method of muon cooling requires high field superconducting magnets that provide superimposed solenoid, helical dipole, and helical quadrupole fields. Novel magnet design concepts are being developed to provide HCC magnet systems with the desired fields for 6D muon beam cooling. The Helical Solenoid (HS) features a simple coil configuration that produces these complex fields with the required characteristics, where new high field conductor materials are particularly advantageous. Correction coil schemes to allow larger coil radius for given HCC parameters are being developed to make room for required mechanical structures, including RF cavities for practical HCC designs. Numerical simulations are being used to optimize and verify the muon cooling behavior of the HCC designs.

**Acknowledgements**

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## Title

## STUDIES OF THE HIGH-FIELD SECTION FOR A MUON HELICAL COOLING CHANNEL.

## Authors

**Mauricio L. Lopes, Vladimir S. Kashikhin, Alexander V. Zlobin, FNAL**
**Melanie Turenne, Stephen Kahn, Rolland Johnson, Muons, Inc.**

## Abstract

The Helical Cooling Channel (HCC) is a new technique proposed for 6D cooling of muon beams required for muon collider and some other applications. HCC uses a continuous absorber inside superconducting magnets which produce a solenoid field superimposed with transverse helical dipole and helical quadrupole fields. HCC is usually divided into several sections each with progressively stronger fields, smaller aperture and shorter helix period to achieve the optimal muon cooling rate. This paper presents the results of designs studies of the HCC high field section in terms of magnet aperture limitations, tunability of field components, and field corrections. The maximum field in the coil and the conductor options are also discussed.

## Acknowledgements

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**Title**

**Authors**

# MODELING OF THE HIGH-FIELD SECTION FOR A MUON HELICAL COOLING CHANNEL

**A.V. Zlobin, E. Barzi, M.L. Lopes, M. Yu, M. Lamm, V.S. Kashikhin, FNAL**
**Melanie Turenne, Stephen Kahn, Rolland Johnson, Muons, Inc.**

## Abstract

This presentation will describe conceptual designs of short HTS and Nb3Sn models of Helical Cooling Channel high-field sections which are being built and tested, their parameters, structural materials and conductor choices, fabrication technologies, and other engineering challenges.

## Acknowledgements

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**Title**

**MANX, A 6-D Muon Beam Cooling Experiment for RAL**

**Authors**

**Robert Abrams, Mary Anne Cummings, Stephen Kahn,**
**Charles Ankenbrandt, Rolland Johnson, Muons, Inc.**
**Michael Lamm, Alexander Zlobin, Valdimir Kashikhin, Katsuya Yonehara, FNAL**

**Abstract**

MANX is a 6-dimensional muon ionization cooling demonstration experiment based on the concept of a helical cooling channel (HCC) in which a beam of muons loses energy in a continuous helium or hydrogen absorber while passing through a special superconducting magnet called a helical solenoid (HS). The goals of the experiment include tests of the theory of the HCC and the HS implementation of it, verification of the simulation programs, and a demonstration of effective 6D cooling of a muon beam. We report the status of the experiment and in particular, the proposal to have MANX follow MICE at the Rutherford-Appleton Laboratory (RAL) as an extension of the MICE experimental program. We describe the economies of such an approach which allow the MICE beam line and much of the MICE apparatus and expertise to be reused.

**Acknowledgements**

Supported in part by USDOE STTR Grant DE-FG02-06ER86282

## Title

## Four-Coil Superconducting Helical Solenoid Model for MANX

## Authors

**V.S. Kashikhin, N. Andreev, V.V. Kashikhin, M.J. Lamm, A. Makarov,**
**K. Yonehara, M. Yu, A. V. Zlobin, Fermilab, Batavia, IL**
**R.P. Johnson, S.A. Kahn, Muons Inc**

## Abstract

The magnet for MANX has to generate longitudinal solenoid and transverse helical dipole and helical quadrupole fields. This paper discusses the 0.6 m diameter 4-coil Helical Solenoid model design, manufacturing, and testing that has been done to verify the design concept, fabrication technology, and the magnet system performance. Details of magnetic and mechanical designs, including the 3D analysis by TOSCA and ANSYS will be presented and compared to measurements. The model quench performance in the test setup in the FNAL Vertical Magnet Test Facility cryostat will be discussed. Projected performance and cost will also be presented for the full length MANX magnet.

## Acknowledgements

Supported in part by USDOE STTR Grant DE-FG02-06ER86282

**Title**

# Integrating the MANX 6-D Muon Cooling Experiment into the MICE Spectrometers

**Authors**

**Stephen Kahn, Robert Abrams, Mary Anne Cummings, Muons Inc.**
**K. Yonehara, Fermilab**

**Abstract**

The MANX experiment is to demonstrate the reduction of 6D muon phase space emittance using a continuous liquid absorber to provide ionization cooling in a helical solenoid magnetic channel. The experiment involves the construction of a short two-period long helical cooling channel (HCC) to reduce the muon invariant emittance by a factor of 3. The HCC would replace the current MICE 4D cooling experiment now being setup at the Rutherford Appleton Laboratory. The MANX experiment would use the existing MICE spectrometers and muon beam line. The study reported here considers various approaches to integrate the MANX experiment using the MICE spectrometers. The goal is to match the beam into and out of the MANX experiment so as to minimize losses between the MICE spectrometers and the MANX HCC. The matching schemes, simulated using the G4beamline tracking program, are compared with regard to minimization of losses, minimization of emittance blowup at the MANX and MICE spectrometer interfaces, and cost effectiveness.

**Acknowledgements**

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## Title

## Particle Tracking in Matter-Dominated Beam Lines

## Authors

**Thomas Roberts, Kevin Beard, Muons, Inc.**
**Shahid Ahmed, Daniel Kaplan, Dazhong Zhang, IIT**

## Abstract

Most computer programs that calculate the trajectories of particles in accelerators assume that the particles travel in an evacuated chamber. The development of muon beams, which are needed for muon colliders and neutrino factories and are usually required to pass through matter, is limited by the lack of user-friendly numerical simulation codes that accurately calculate scattering and energy loss in matter. Geant4 is an internationally supported tracking toolkit that was developed to simulate particle interactions in large detectors for high energy physics experiments, and includes most of what is known about the interactions of particles and matter. Geant4 has been partially adapted in a program called G4beamline to develop muon beam line designs. The program is now being developed and debugged by a larger number of accelerator physicists studying muon cooling channel designs and other applications. Space-charge effects and muon polarization are new features that are being implemented.

## Acknowledgements

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**Title**

## Numerical Collective Computations for Muon Beams

**Dazhang Huang, Daniel M. Kaplan, Illinois Institute of Technology**
**Thomas J. Roberts, Muons, Inc.**

**Abstract**

The study of Muon beam optics is crucial for future Neutrino Factory and Muon Collider facilities. At present, the GEANT4-based simulation tools for muon beam tracking such as G4beamline and G4MICE are based on single particle tracking without collective effects taken into account. However, it is known that collective effects such as space charge and wakefields are not ignorable. The study is being carried out with and without image currents: macro-particle, Particle-In-Cell, and analytical methods with known structures. The basic algorithm is particle to particle interactions through retarded electro-magnetic fields. The momentum impulse by collective effects is imposed on every particle at each collective step, and the G4beamline main code is used for tracking. At each collective step, cells are redefined, the size of the macro-particle is recalculated, and the retarded electro-magnetic fields are computed via the Lienard-Wiechert method. Comparisons to LANL Parmela are illustrated and analyzed. Optimizations of the algorithm are also underway.

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**Classification:**
Beam Dynamics and Electromagnetic Fields / D05 - Code Developments and Simulation Techniques

**Title**

# Putting Space Charge into G4beamline

**Authors**

**Kevin B. Beard, Thomas J. Roberts, *Muons, Inc.***

**Abstract**

The G4beamline program is based on the well-established Geant4 toolkit used to simulate the interactions of particles and photons with matter. Until now, only a single particle at a time could be tracked and there are no interactions between particles. Recent designs for high pressure RF cavities and other novel devices achieving extreme muon cooling require that the effect of space charge be included in the simulations. A new tracking manager in G4beamline propagates a number of particles (typically 1,000-10,000) in parallel, stepping all particles in time. This allows all of the usual Geant4 physics interactions to be applied, plus collective computations. A simple macroparticle-based model is used to represent ~1E8 charges with an ellipsoidal charge density. At intervals the appropriate macroparticle size and shape are recalculated, the electric and magnetic fields are determined, and an impulse is applied to the simulated particles. Comparisons to standard space charge codes are presented.

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**Classification:**
Beam Dynamics and Electromagnetic Fields / D05 - Code Developments and Simulation Techniques

## Title

## Muon Capture, Phase Rotation, and Precooling in Pressurized RF Cavities

## Authors

**Cary Yoshikawa, Charles Ankenbrandt, Rolland Johnson, Muons, Inc.**
**David Neuffer, FNAL**

## Abstract

Bright muon beams are required for muon colliders, neutrino factories, and intense muon sources. In the most recent neutrino factory simulation study, high energy protons hit a target to generate pions that decay into a diffuse cloud of muons that is: 1) captured in strong magnetic fields, 2) bunched, 3) phase-energy rotated by strong RF electric fields, and 4) precooled by passing the beam through a low-Z energy absorber. These four processes are done sequentially, with inefficiency, extra length and expense, and large muon losses. Pressurized RF cavities will enable higher gradient RF within magnetic fields than is possible with evacuated cavities, thus allowing more options for the initial stages of a muon cooling channel. The status of designs of the capture, phase rotation, and precooling systems of muon beams in pressurized cavities is described.

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**Title**

**Reverse Emittance Exchange for Muon Colliders Authors**

**Valentin Ivanov, Guimei Wang, Andrei Afanasev,**
**Charles Ankenbrandt, Rolland Johnson, Muons, Inc.**
**Slava Derbenev, Alex Bogacz, JLab**

## Abstract

Muon collider luminosity depends on the number of muons in the storage ring and on the transverse size of the beams in collision. Six-dimensional cooling schemes now being developed will reduce the longitudinal emittance of a muon beam so that smaller high frequency RF cavities can be used for later stages of cooling and for acceleration. However, the bunch length at collision energy is then shorter than needed to match the interaction region beta function. New ideas to shrink transverse beam dimensions by lengthening each bunch (reverse emittance exchange and bunch coalescing) will help achieve high luminosity in muon colliders with fewer muons. Analytic expressions for the reverse emittance exchange mechanism are derived, including a new resonant method of beam focusing. Correction schemes for the aberrations were explored, and a lattice to implement them was proposed. To mitigate space charge detuning and wake field effects, a scheme was invented to coalesce smaller intensity bunches after they are cooled and accelerated to high energy into intense bunches suitable for a muon collider

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**Title**

# Traveling Wave RF system for Muon Colliders

**Authors**

**Lars Thorndahl, Michael Neubauer, Rolland Johnson, Muons, Inc.**
**Katsuya Yonehara, Gennady Romanov, Al Moretti, Milorad Popovic, FNAL**

**Abstract**

The great advantage in the helical ionization cooling channel (HCC) is its compact structure that enables the fast cooling of the muon beam 6-dimensional phase space. This compact aspect requires a high average RF gradient, with few places that do not have cavities. Also, the muon beam is diffuse and requires an RF system with large transverse and longitudinal acceptance. A traveling wave system can address these requirements. First, the number of RF power coupling ports can be significantly reduced, which saves space in longitudinal direction. Second, by adding a nose on the cavity, the transverse size of the cavity can be smaller than a conventional pill box type cell. We discuss the design and simulations of the cooling performance of a traveling wave RF system in a HCC, including the optimization of the cavity shape, to reduce its size, and the design of the RF power couplers needed to transfer power into and out of the cavity.

**Acknowledgements**

**Title**

**Abstract**

## RF-Induced Emittance Exchange for Muon Colliders

**Authors**

**Charles Ankenbrandt, Michael Neubauer, Guimei Wang, Muons, Inc.**
**Alex Bogacz, Slava Derbenev, Robert Rimmer, Haipeng Wang, JLab**

**Abstract**

The ionization cooling schemes that have been devised for an energy-frontier muon collider produce beams with transverse emittances that are too large and longitudinal emittances that are unnecessarily small. To make adequate luminosity with those beams, the muon intensities would have to be quite large. The luminosity can be enhanced by exchanging the transverse emittances into the longitudinal phase space emittance in order to reduce the transverse beam sizes; since the concomitant growth in the bunch length is tolerable. Previous schemes to accomplish this goal involve passing the beams through energy-degrading absorbers, leading to various difficulties. This paper discusses a method to exchange transverse emittances into the longitudinal phase space via the use of gradient RF cavities. The necessary beam manipulations will be explored and the requirements on the RF cavities will be examined.

**Acknowledgements**