Phase I-SBIR/STTR Fiscal Year 2007

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FIRM NAME:	RESEARCH INSTITUTION:
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PROJECT TITLE: **Compact, Tunable RF Cavities**

TECHNICAL ABSTRACT (Limit to space provided)

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

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.

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.

An innovative design of a compact RF cavity that uses orthogonally biased ferrite for fast frequency tuning and liquid dielectric to adjust the frequency range will be developed using computer models, prototyped, and tested. The parameters will be chosen to make this type of cavity useful in a variety of FFAG accelerators.

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

RF cavity designs that employ liquid dielectric and orthogonally biased ferrite for use in FFAG accelerators will be investigated via computer modeling. Appropriate materials and configurations for the dielectric and the ferrite will be chosen and, when necessary, samples will be characterized to assess their utility for this approach to cavity tuning. A prototype cavity will be designed in Phase I for construction and testing in Phase II.

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

Rapid-cycling FFAG synchrotrons are a promising way to provide high intensity beams for a variety of applications such as proton drivers for neutron or muon production, rapid muon accelerators, electron accelerators for synchrotron light sources, and medical accelerators of protons and light ions for cancer therapy. The successful development of compact tunable accelerating RF cavities for these machines will establish or enhance the feasibility of FFAG machines for basic research and for medical and other applications.

Key Words: RF, cavity, ferrite-tuned, liquid dielectric, FFAG

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

Innovative accelerating structures are being developed for fixed-field alternating gradient synchrotrons to provide high intensity beams of ions, protons, muons, and electrons for basic research and for cancer therapy.

NARRATIVE SECTION

Compact, Tunable RF Cavities

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a. Identification and Significance of Problem or Opportunity, and Technical Approach

Identification and Significance of Opportunity

FFAG synchrotrons are attractive for accelerators that must have high repetition rates. In an FFAG machine, as the acronym implies, the magnets that guide the particles are held at constant field, whereas in conventional rapid-cycling synchrotrons the magnetic guide fields ramp quickly. FFAG accelerators thereby eliminate several problems inherent in conventional rapid-cycling synchrotrons, problems related to the eddy currents induced in the magnets and in the beam pipe and to the many devices that must track the magnetic field. Consider, for example, the Fermilab Booster. The ramping magnets for such a machine are difficult to build, requiring thin laminations to control eddy currents and having limited field range due to sensitivity to saturation effects. The resonant magnet system with its many chokes and capacitors is expensive. In order to reduce eddy currents in the vacuum chamber, the chamber encloses the whole magnet; however, without a metallic beam pipe, the beam sees the impedance of the magnet laminations, leading to beam disruption.

In an FFAG synchrotron, on the other hand, the primary devices whose parameters must vary rapidly are the RF cavities, the subject of this proposal. Since cavities can be tuned faster than guide field magnets can be ramped, higher repetition rates are possible in FFAG accelerators than in conventional rapid-cycling synchrotrons.

Recent conceptual developments related to non-scaling FFAG synchrotrons [1] show considerable promise, but have yet to be tested in real accelerators. A very important feature of these non-scaling machines, relative to the scaling ones or to conventional synchrotrons, is that the frequencies of transverse oscillations of the beam pass through many resonant values during the acceleration cycle. It is believed that this will be tolerable to the extent that the resonance crossings are made so quickly that the transverse emittances of the beam do not increase significantly. Thus the viability of the non-scaling FFAG approach depends critically on the ability to accelerate the beam quickly. Furthermore, rapid acceleration is essential for unstable particles, such as muons, that have short lifetimes. For these reasons, the RF cavities must have sufficient gradient and tuning speed to achieve the required acceleration rates. We will address the fast tuning requirement by using orthogonally biased ferrite tuners having appropriate parameters. By making the cavities compact, we address the gradient question in the sense that more cavities can be inserted into the space that is available in the lattice along the beam direction. Reducing the transverse size of the cavities also provides practical advantages, especially to allow lower rf frequency cavities to fit into accelerator enclosures.

Technical Approach

Design Concepts for Compact Tunable RF Cavities

Figure 1 shows the conceptual design of the compact RF cavity that we wish to develop for FFAG applications. The fundamental design is based on a pillbox cavity. Ferrite occupies the region of high magnetic field, and a fluid dielectric occupies the region of high electric field, as shown in the figure. The fluid is also used to cool the ferrite. Fast tuning is accomplished with a solenoidal biasing coil that surrounds the cavity. The frequency range is determined by the dielectric constant of the fluid, which can be chosen according to the requirements of a particular machine. An iron return yoke surrounding the cavity shunts the biasing return field and reduces its effect on the beam. An important feature of this design is that the solenoidal biasing magnetic field is orthogonal to the RF magnetic field. There is reason to believe that the orthogonal biasing will have advantages in faster tuning and less RF heating loss [2].

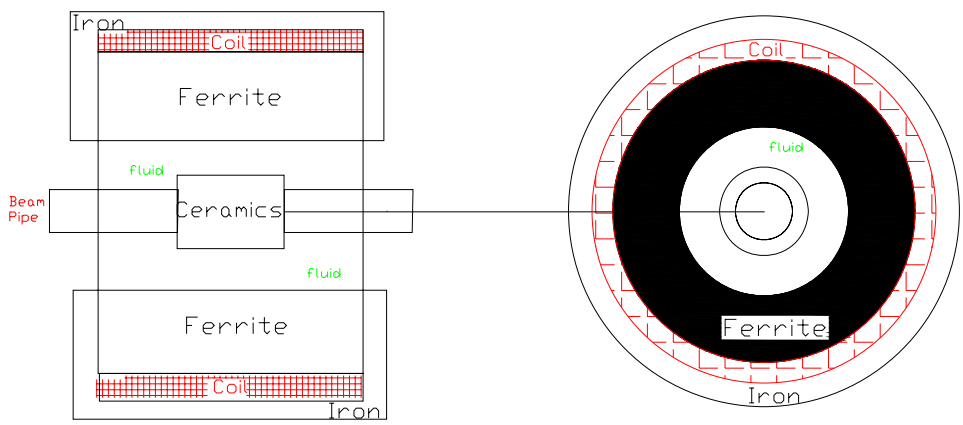

Fig. 1. Conceptual design of a compact RF cavity for FFAG applications based on a pillbox cavity. Ferrite occupies the region of high magnetic field and a fluid dielectric occupies the region of high electric field. The fluid is also used to cool the ferrite. Fast tuning is accomplished with a solenoidal biasing coil that surrounds the cavity and produces a biasing magnetic field that is orthogonal to the RF magnetic field. The frequency range is determined by the dielectric constant of the chosen fluid. An iron return yoke at the outer edge of the cavity shunts the biasing return field and reduces its effect on the beam.

First Computer Modeling Results

We have started to analyze the proposed cavity design with SuperFish and ANSYS. For example, Figure 2 shows a first SuperFish analysis of an RF cavity model based on the ideas discussed above with parameters approximately appropriate for the Fermilab Booster. It is a simple pillbox with a reentrant beam pipe where the accelerating gap is sealed with a ceramic pipe. The fluid inside the cavity has dielectric constant of 4.5 and is used for adjusting the frequency range of the cavity and to cool the ferrite. The biasing coil is a simple water-cooled solenoid. An iron rim that is not shown in the figure is used to return the biasing field flux. The biasing field is parallel to the beam axis and orthogonally biases the ferrite. The values of permittivity ε and permeability μ have not been adjusted to get the exact Booster requirements, but the calculation shows that the cavity will have a reasonable radial size. The radius is about 30cm, and the cavity is 50cm long. The SuperFish results are summarized in Table 1 on the following page.

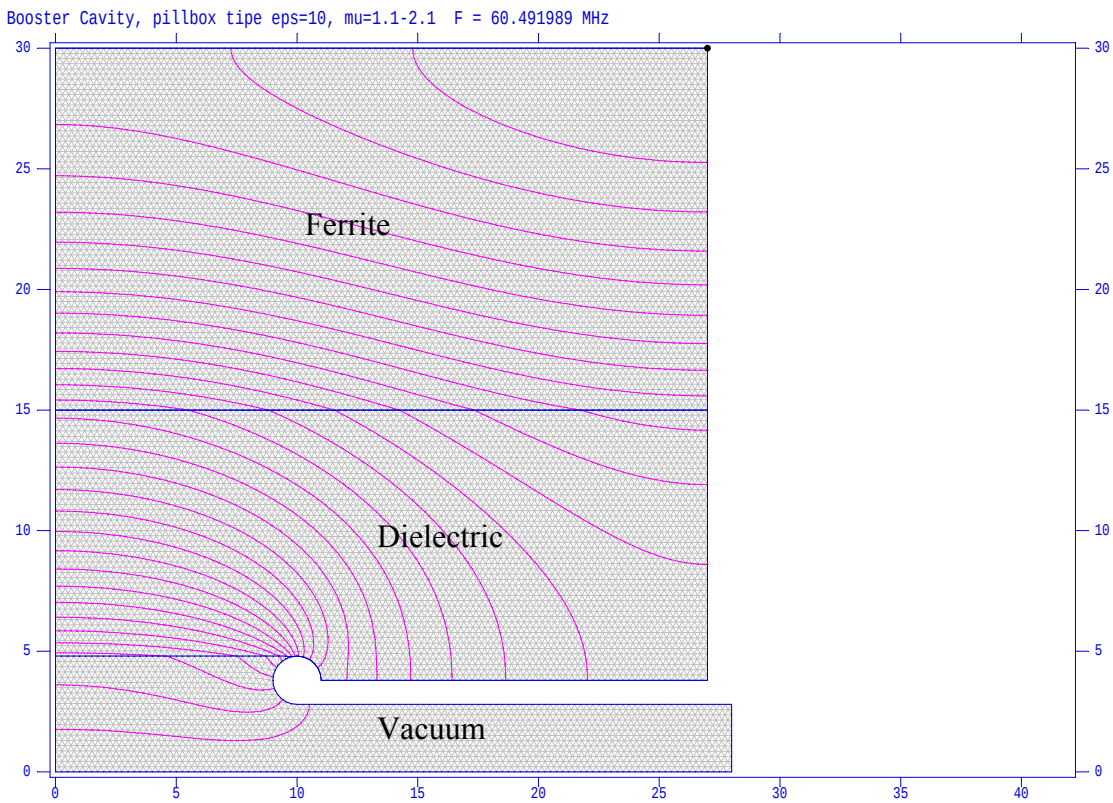

Fig. 2 First SuperFish analysis of an example of the proposed cavity, conceived as a replacement for the Fermilab Booster cavities. The outer radius is 30 cm.

Problem file: C:\MPFish\NewBoosterFish\BOOCAV.AM 11-28-2005 19:39:30

Parameter	Unit	Unbiased Value	Biased Value
EZEROT	MV/m	2.00000	2.00000
Frequency	MHz	38.18920	53.52650
rest mass energy	MeV	938.271998	938.271998
Beta		0.8500000	0.8500000
Kinetic energy	MeV	842.865	842.865
Normalization factor for E0=2.004MV/m		14920.021	20226.849
Transit-time factor		0.9980552	0.9961707
Stored energy	Joules	6.1504693	5.7884696
Surface resistance	milliOhm	1.61225	1.90873
conductor resistivity	microOhm-cm	1.72410	1.72410
Operating temperature	C	20.0000	20.0000
Shunt impedance	MOhm/m	560.341	260.254
Z*T*T	MOhm/m	558.164	258.264
r/Q	Ohm	212.494	161.088
Average magnetic field on the outer wall	2.39587 W/cm^2	3707.82 A/m,	5010.41 A/m
Maximum H (at Z,R = 0.0,25.8621)	2.37226 W/cm^2	3700.29 A/m,	4985.67 A/m,
Maximum E (at Z,R = 0.0,0.171429)	0.427349 Kilp.	3.90856 MV/m,	3.89042 MV/m,
Bmax/Emax	mT/(MV/m)	1.1897	1.6104
Emax/E0		1.9505	1.9378

Table 1: SuperFish calculations of cavity parameters for the unbiased ferrite and the biased ferrite cases. All calculated values refer to the mesh geometry only, using standard room-temperature copper. Here, the ceramic permittivity is not included, unlike the ANSYS case below. This is an ideal calculation without loss factors so its shunt impedance in practice must be corrected when losses are considered.

Figure 3 on the next page shows the first ANSYS calculation mesh that was used. The ANSYS results are shown in Table 2. Table 1 is the ideal calculation without loss factors, so those shunt impedances must be corrected when losses are considered. In Table 2, an ANSYS calculation, losses have been considered and the shunt impedances listed are closer to what is expected. The measurements we expect to make will provide us with the data that are needed for ANSYS to model the cavity more accurately.

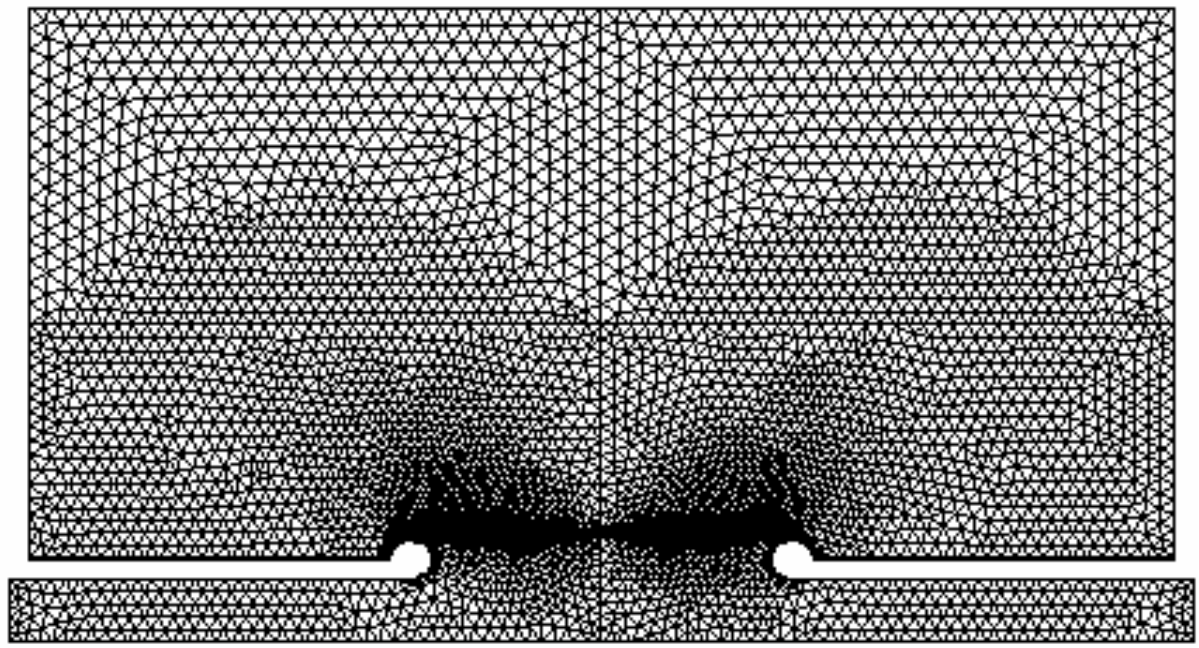

Fig. 3 ANSYS mesh used for analysis. This model includes a 0.5 cm ceramic vacuum-dielectric liquid barrier with a dielectric constant of 9.

Parameter	Unbiased Ferrite	Biased Ferrite
Frequency	23.57 MHz	51.89 MHz
Q-dielectric loss	31066.28	6336.37
Q- surface loss	158215.42	86160.50
Q-total	25967.46	5902.30
Shunt impedance	92.0 MOhm/m	17.8 MOhm/m

Table 2: ANSYS calculations of cavity parameters for the unbiased ferrite and the biased ferrite cases. The relative permittivity of the Fluid, Ceramic, and Ferrite are 4.5, 9, and 11 respectively. The permeability of the ferrite is 12 when biased and 6 when unbiased. In this calculation, losses have been considered and the listed shunt impedances are closer to what is expected.

Ferrite Testing

Figure 4 shows a schematic of a ferrite test system. A measurement of Q with and without the test material would allow the determination of the Q_o and RF loss factor of the material. The cavity as shown with diameter and length of 16 cm and capacitor gap of .25 cm resonates at a frequency of 50 MHz. It has a Q_o of 6000 without the ferrite. The orthogonally biased measurements will be made as a function of the field of the test magnet, where the coils are indicated. Parallel biased measurements can be made by applying a DC bias current to a coil wrapped around the ferrite ring as was done in the ferrite testing apparatus in reference [3]. The dimensions can be adjusted for the available ferrite rings to be tested.

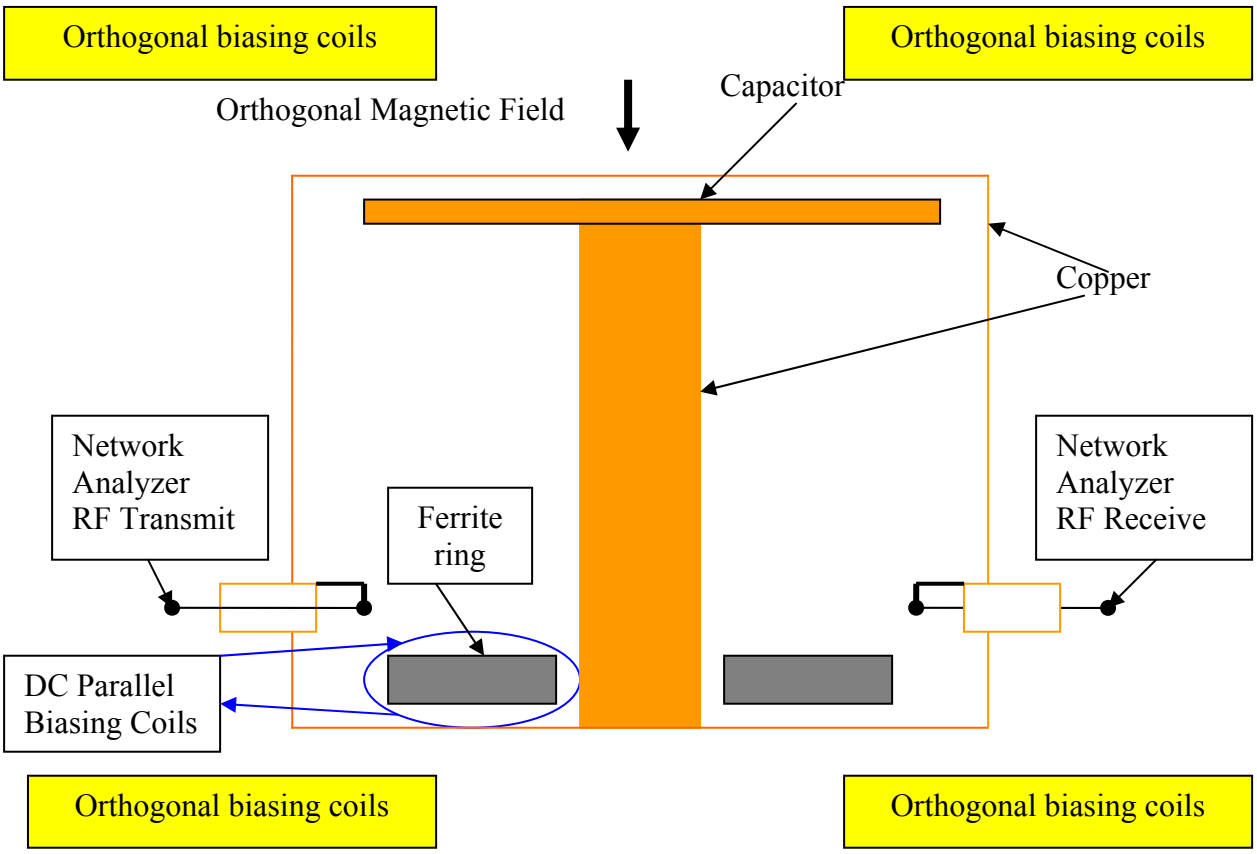

Fig. 4 Conceptual schematic of a small test cavity that can be made to fit in a DC test magnet to select and survey a large number of Ferrite and garnet materials.

b. Anticipated Public Benefit

Muons, Inc. has been particularly interested in two potential applications of FFAG machines: accelerating protons and accelerating muons for a muon collider or a neutrino factory. First, a rapid-cycling, high-intensity proton driver is needed to produce the muons. Secondly, FFAGs may represent the most cost-effective way to accelerate the muons to high energy. (??Ref to NFMCC study 2A where the BNL folks made the case??) The muon lifetime sets the scale of desired repetition rates for both machines. For example, in a 2.5 TeV on 2.5 TeV muon collider, the muon lifetime is about 50 ms, which implies that the muon production system should operate near 20 Hz for optimum performance. For a lower energy collider, the lifetime and luminosity are smaller, so the repetition rate should be even higher. In the case of a 20 to 50 GeV muon storage ring used as a neutrino factory, the muon lifetime is close to 1 ms, so cycle rates as high as 1 kHz would be useful to improve the neutrino flux.

Another reason for our interest is that the commercial applications of the RF cavity that we wish to develop are promising. A proton driver based on a FFAG synchrotron could be used for neutron production, waste transmutation, medical proton therapy, and radioisotope production. The ability to accelerate carbon ions for cancer therapy is also becoming very interesting. (??Ref to Russian proposal for carbon 11??) The acceleration of electrons also could have application to the production of high-intensity synchrotron radiation.

Finally, the RF cavities in some existing machines should be replaced with more efficient and modern designs. For example, a compact, rapidly-tunable RF cavity would be very useful as an upgrade for the Fermilab Booster. The Booster RF system is large and complex, with 18 RF cavities that must tune from 38 MHz to 53 MHz and must provide close to a MV per turn in the middle of the 33 ms ramp. These cavities are expensive to maintain, and RF cavities such as those described herein would provide a high-performance replacement for the Booster cavities, an important spin-off of this proposal.

c. Phase I Technical Objectives

The technical objectives of the Phase I project::

1. RF cavity designs that employ liquid dielectric and orthogonally biased ferrite for use in FFAG accelerators will be investigated via computer modeling.

2. Appropriate materials and configurations for the dielectric and the ferrite will be chosen and, when necessary, samples will be characterized to assess their utility for this approach to cavity tuning.

3. Critical issues of prototype development and engineering concerns will be identified.

4. A prototype cavity will be designed in Phase I for construction and testing in Phase II.

d. Phase I Work Plan

R&D Issues

The cavity design that is being proposed combines several features we must investigate:

1) The ferrite that makes the cavity tunable.
2) The high dielectric constant fluid to make the cavity smaller, with manageable dimensions at low frequency.
3) The tuning solenoid that orthogonally biases the ferrite.
4) The use of the fluid to cool the ferrite.
5) The dielectric window that separates the beam pipe vacuum from the dielectric fluid.

Each of these aspects alone or acting together call for R&D. The questions to be addressed in Phase I are:

Ferrite:
For different frequency regions, different ferrite will probably be needed. We can start assuming three ranges of frequency: 1-10MHz, 30-60MHz, and 100-300MHz. For each range we will need loss curves for orthogonally and normally biased ferrite

Dielectric Fluid:
Depending on size limitations, each frequency range will need a different dielectric fluid such as water with ε=70 or transformer oil with ε~2. Can we just mix these or similar fluids to adjust for different frequency intervals using the same cavity?

Tuning Solenoid
How much magnetic field and biasing current are needed? What is the right iron yoke shape to keep the magnetic field in the ferrite? What is the solenoid field on the beam axis? Do we need a pair of cavities with opposite solenoidal field directions to cancel the field effect on the beam? How many turns can we allow for the tuning solenoid to have small enough inductance for fast frequency change? What is the basic time constant of the ferrite? (An initial guess is around 100 ns.)

Ferrite Cooling
What circulation is needed?

Dielectric Window
How can we insure against leakage of fluid into the beam chamber? Can we make the gap 5 or 10 cm for the electron model that BNL is proposing?

Power Coupling
Is there a better way of coupling the RF power than a loop around the central ferrite ring? Can we make 100kV/cm, or 200kV/cm with a pair of coupled cavities?

Modulators
Can we make the biasing modulators smaller in size, with longer or shorter pillbox dimensions?

Work to be performed by Rolland Johnson and staff and a new postdoc of Muons, Inc. and Milorad Popovic, Al Moretti, and Charles Ankenbrandt of Fermilab.

Responsibilities

Muons, Inc.: The direction of the project is the responsibility of the company and the PI. The development of the computer representation of the conceptual design and the maintenance of the database of scientific and engineering parameters will be the responsibilities of Dr. Alsharo'a.

Fermilab: Milorad Popovic will be responsible for the Fermilab subcontract.

Phase I Performance Schedule

Two months after start of funding:

1) Exploration of RF parameters for possible FFAG designs using ANSYS and SuperFish
2) Ferrite test setup designed
3) Appropriate ferrites procured

Four months after start of funding:

1) Ferrite testing underway
2) Computer models working
3) Investigate barrier bucket technique for the electron model FFAG as a Phase II topic

Six months after start of funding:

1) Preliminary design of test cavity
2) Critical engineering issues defined
3) Draft of Phase II proposal

Nine months after start of funding

1) Phase II proposal

e. Related Research or R & D

It has been proposed that a small electron accelerator be built to investigate fast resonance crossing and other issues related to non-scaling FFAG lattices [4]. In such a ring, the spaces for cavities will be restricted but the required RF voltage will be small. For this purpose we plan to investigate the use of a broadband accelerating structure that was developed by our collaborators at Fermilab to provide the "barrier buckets" for the Fermilab antiproton facility [5].

f. Principal Investigator and other Key Personnel

Muons, Inc. Principal Investigator: Dr. Rolland P. Johnson has been actively involved in particle accelerator research and development for almost 30 years. He has worked on all aspects of synchrotrons, storage rings, and light sources at several institutions. Dr. Johnson has directed several successful accelerator R & D, construction, and commissioning projects. Examples at Fermilab include H^- injection into the Booster, new extraction kickers for the Booster, Booster RF cavity gradient improvement program, Tevatron low beta insertions, Tevatron Collider, and at LSU, the CAMD light source. He directed many software projects at Fermilab, CAMD, and

CEBAF. He also provided technical oversight to several SBIR grants while on detail to the DOE. Dr. Johnson has considerable experience in the area of beam cooling, having participated in the commissioning and improvement programs of the CERN Antiproton Accumulator as well as the design of the Fermilab TeV I project. He has contributed original work involving simulations and implementations of stochastic cooling systems and of their associated RF systems. Besides work on methods to increase the proton flux for better muon production as seen in the Proton Driver Design Report and The Linac Afterburner Proposal, he has worked on improving ionization cooling. His expertise in RF cavity work is extensive: He led a project to improve the Fermilab Booster RF cavity performance that was very successful, involving sensors to limit spark damage in conditioning and higher-mode suppression techniques. He implemented a method to tune the Tevatron RF cavities using feedback loops to control the cooling water temperature. He wrote the RF control programs for the CERN and Fermilab antiproton accumulators. He solved problems of breakdown and failure of ceramic RF cavity windows while directing the commissioning of the LSU synchrotron light source. He is the inventor of high gradient RF cavities pressurized with hydrogen gas for ionization cooling of muon beams.

Fermilab Subcontract PI: **Dr. Milorad Popovic** has worked with Drs. Johnson and Ankenbrandt on many projects. Most recently they have worked together on proton driver issues for a neutrino factory, including a proposal to upgrade the Fermilab Linac to improve the operation of the existing Fermilab accelerator complex. His CV is below.

Fermilab RF Engineer **Alfred Moretti** has over 40 years of experience in high power RF systems at Argonne National Laboratory and at Fermilab. He has a Masters Degree from Northwestern University in Microwave Engineering. His experience includes polarized targets, heavy ion fusion, RF separator systems, and the development of cavities for the Fermilab anti-proton source and Linac upgrade accelerators. He has also worked on normal and super-conducting cavity development. He is now working on a new proton driver design and on muon collider research. He is the chief engineer of the Fermilab Linac.

Fermilab Physicist **Dr. Charles M. Ankenbrandt**, a senior accelerator physicist at Fermilab, has contributed for three decades to the design, operation, and improvement of Fermilab facilities. He has led the Booster Synchrotron Group, the Main Ring Group, and the Accelerator Theory Department. He invented "slip stacking" and co-invented "barrier buckets", techniques used heavily at Fermilab. He is currently a member of the Proton Source Department and the Neutrino Factory and Muon Collider Collaboration.

Consultant **Dr. James E. Griffin** started his accelerator career at Iowa State Univ. (BSEE (1951). PhD Physics (1963)) where he worked with Dr. L.J. Laslett on installation and commissioning of 70 MeV electron synchrotron and was the synchrotron laboratory manager. He joined the FNAL staff in 1969 where he joined in the design, development, construction, installation and operation of the 1 MW 53 -60 MHz Main Ring RF system. He developed a scheme for coalescing adjacent bunches into single narrow bunches for antiproton production and higher luminosity of subsequent colliding proton-antiproton beams. He improved the Booster RF cavities by developing the ferrite tuners and resonance damping techniques and also designed and assisted in development, installation, and initial operation of RF systems for the antiproton source. During subsequent years of gradual retirement he has been involved in the

development and use of non-sinusoidal (barrier), systems for the management and redirection of batches of beams from or to various machines.

g. Facilities/Equipment

Muons, Inc. currently occupies a building of approximately 4000 square feet of floor space equipped with computer workstations and fast internet access in Batavia, Illinois, a short drive to Fermilab. Muons, Inc. also occupies an office equipped with computer workstations in the ARC building adjacent to the Jefferson Lab campus in Newport News, Virginia. The development of designs and their analysis and simulation require knowledgeable people, places to meet, computers for simulations and CAD/CAM, and access to libraries and the web. The Phase II effort will require the facilities and equipment of Fermilab to produce and test prototypes of critical components of the RF cavity. The new Fermilab Muon Test Area at the end of the Linac may be used in this effort.

h. Consultants and Subcontractors

The Research Institution is **Fermi National Accelerator Laboratory**.

The certifying official is **Dr. Bruce Chrisman**, Associate Director, who has provided a letter committing to the research described above at the level of 30% or $30,000 if the grant is funded at $100,000 starting in July 2007 for a period of 9 months. His address is:

Dr. Bruce Chrisman
Fermi National Accelerator Laboratory
P. O. Box 500, MS 200
Batavia, IL 60510
(630) 840-6657
chrisman@fnal.gov

Other Consultants and Subcontractors

Dr. James E. Griffin, retired accelerator physicist from Fermilab and has been a leader in the use of ferrites for tunable RF cavities [6], has agreed to participate in this project.

Date: 11/18/2006 5:47:21 P.M. Eastern Standard Time
From: jgriffin.enteract@rcn.com
To: Roljohn@aol.com

Letter of Commitment
To: Dr. Rolland Johnson
From: Dr. James Griffin
Subject: SBIR Proposal, "Compact, Tunable RF Cavities for FFAG Synchrotrons"
I agree to serve in the manner and to the extent described in the Work Plan section of the grant application. I anticipate approximately 80 hours on this proposal at $65/hour performed between July 2007 and February 2008.
Signed__JAMES GRIFFIN_____Date Nov. 18, 2006

i. Similar Grant Applications, Proposals, or Awards

We have submitted no similar grant applications or proposals. We have received no awards for this project.

Appendix: Overview of Muons, Inc. Program

The projects discussed below are concerned with the production, cooling, and uses of intense and bright muon beams to be used for various purposes. These SBIR and STTR projects represent a coherent, innovative program to reduce the cost of neutrino factories, facilitate designs of high-intensity muon colliders, and provide muon beams with new physics potential.

Muons, Inc. started with the idea that a gaseous energy absorber enables an entirely new technology to generate high accelerating gradients for muons by using the high-pressure region of the Paschen curve. This idea of filling RF cavities with gas is new for particle accelerators and is possible only for muons because they do not scatter as do strongly interacting protons or shower as do less-massive electrons. Additionally, use of a gaseous absorber presents other practical advantages that make it a simpler and more effective cooling method compared to liquid hydrogen flasks in the conventional designs.

Measurements by Muons, Inc. and IIT at Fermilab have demonstrated that hydrogen gas suppresses RF breakdown very well, about a factor six better than helium at the same temperature and pressure. Consequently, much more gradient is possible in a hydrogen-filled RF cavity than is needed to overcome the energy loss, provided one can supply the required RF power. Hydrogen is also twice as good as helium in ionization cooling effectiveness, viscosity, and heat capacity. These facts make it our material of choice.

As discussed below in project 6, recent measurements show that hydrogen pressurized RF cavities do not suffer from a reduction in maximum gradient while operating in intense magnetic fields as do evacuated cavities. Thus it is possible to combine the energy absorber and RF reacceleration in pressurized cavities in regions where large magnetic fields create the required focusing for ionization cooling. This means that pressurized RF cavities have two very significant advantages over any scheme involving evacuated RF cavities: greater gradient in the required magnetic field and the simultaneous use of the hydrogen gas as energy absorber and breakdown suppressant. These two advantages each lead to shorter cooling channel designs, which imply fewer losses of muons by decay and also lower construction costs.

The use of a continuous absorber as provided by a gas-filled RF system implies a new idea (first proposed as an SBIR topic) to provide a natural, very effective means of achieving emittance exchange and true six-dimensional (6D) cooling. Namely, if the superimposed magnetic field provides dispersion down the beam channel such that higher momentum corresponds to longer path length and larger ionization energy loss, the momentum spread can be reduced. Recent simulations of cooling channels using a Helical Cooling Channel (HCC) of superimposed helical dipole, helical quadrupole, and solenoidal fields show a 6D emittance reduction factor of 50,000 in a channel only 150 meters long. That cooling factor is very much larger than that of other cooling channels of comparable length.

Once the beam has been cooled in the HCC other cooling techniques become possible. Recent developments have indicated that special cooling channels employing parametric resonances and/or very high field magnets can produce muon beams with small enough emittance that they can be accelerated using 1.3 GHz RF cavities. Thus we have started thinking about a muon

collider using superconducting RF technology as a possible upgrade to the International Lepton Collider (ILC).

One possibility that was explored at the Low Emittance Muon Collider (LEMC) Workshop [7] (held at Fermilab Feb 6–10, 2006) was to consider the proposed Fermilab 8 GeV superconducting proton driver Linac as a triple-duty machine on the path to an energy frontier muon collider. Namely, it would accelerate protons to produce the muons, which would then be injected into the constant velocity section of the Linac to be accelerated by recirculation for use in a muon storage ring neutrino factory. (The third duty in this case would be to act as an ILC string test.) Such a neutrino factory could be very effective for two reasons. First, the neutrino production would scale with the repetition rate of the Linac and might easily outperform other designs. Second, the acceleration cost of the neutrino factory would be borne by the other uses of the SC Linac and the neutrino factory cost would be incremental.

The next step, first proposed in the Phase I Reverse Emittance Exchange Proposal with the Thomas Jefferson National Accelerator Facility (JLab), and explored at the LEMC workshop, is to replace the muon storage ring of the neutrino factory with a coalescing ring to combine bunches for use in a muon collider. Such a muon coalescing ring could operate at the energy of the neutrino factory storage ring, say 20 GeV. The muon beam for the collider would then be similar to that of the neutrino factory up to the coalescing ring. This approach to a muon collider has several advantages that are very attractive. First, the development of the neutrino factory based on acceleration in the 1.3 GHz RF structures requires significant muon beam cooling and makes the neutrino factory an intermediate step to a collider. Second, the large single bunch intensities that a high luminosity muon collider requires are avoided at low energy where space-charge, wake fields, and beam loading are problematic.

Once the beam has been coalesced into a few high intensity bunches, recirculating Linacs using 1.3 GHz RF can accelerate the bunches to a hundred GeV/c or so for a Higgs factory or to 2 to 3 TeV/c for an energy frontier muon collider.

This path to an affordable neutrino factory and a compelling design of a muon collider has complementary projects that Muons, Inc. is pursuing with SBIR/STTR grants and proposals:

Phase II Projects

1) The development of Pressurized **High Gradient RF Cavities** was the subject of an STTR grant with IIT (Prof. Daniel Kaplan, Subcontract PI), which began in July 2002 and ended in September 2005. In this project, Muons, Inc. built two 805 MHz test cells (TC) and used them to measure the breakdown voltages of hydrogen and helium gases at FNAL with surface gradients up to 50 MV/m on copper electrodes. Phase II started in July 2003 to extend the measurements at Fermilab's Lab G and the MuCool Test Area (MTA) to include effects of strong magnetic fields and ionizing radiation at 805 MHz. A new test cell was built under this grant, passed safety requirements associated with the high pressure hydrogen, and was used to extend Paschen curve measurements for hydrogen beyond 60 MV/m surface gradient (20μs pulse width) using electropolished molybdenum electrodes [8]. This test cell is capable of 1600 PSI operation in the 5 Tesla LBL Solenoid in the MTA, with ionizing radiation from the 400 MeV H^- Linac. IIT,

Muons, Inc. and Fermilab staff members prepared a design [9] for a beam line from the Linac to the MTA using available magnets and other components, but the beam line is not expected to be completed until summer 2007. In the mean time, tests with the existing test cell with and without magnetic field are continuing.

2) **Six-Dimensional (6D) Cooling** using gaseous absorber and pressurized high-gradient RF is the subject of an SBIR grant with Thomas Jefferson National Accelerator Facility (Dr. Yaroslav Derbenev, Subcontract PI), which began in July 2003 and will end in January 2007. A magnetic field configured such that higher energy particles have a longer path length can be used to generate the momentum-dependent energy loss needed for emittance exchange and six-dimensional cooling. In the 6D channel, helical dipole and solenoidal magnets and the RF cavities in them are filled with dense hydrogen so that higher energy particles then have more ionization energy loss. A paper describing the concepts and dynamics of this Helical Cooling Channel (HCC) grew out of the proposal for this grant and has been published in PRSTAB [10]. Recent simulations of a series of four such HCC segments have shown cooling factors of more than 50,000 in a 160 m long linear channel [11]. The 6D grant itself is to support the simulation of the channel by modifying existing computer codes and to optimize the design of the channel.

3) **Hydrogen Cryostat for Muon Beam Cooling** is an SBIR project begun in July 2004 and now funded to July 2007 with Fermilab (Dr. Victor Yarba, Subcontract PI) to extend the use of hydrogen in ionization cooling to that of refrigerant in addition to breakdown suppressant and energy absorber. The project is to develop cryostat designs that could be used for muon beam cooling channels where hydrogen would circulate through refrigerators and the beam-cooling channel to simultaneously refrigerate 1) high-temperature-superconductor (HTS) magnet coils, 2) cold copper RF cavities, and 3) the hydrogen that is heated by the muon beam. In an application where a large amount of hydrogen is naturally present because it is the optimum ionization cooling material, it seems reasonable to explore its use with HTS magnets and cold, but not superconducting, RF cavities. However, the Helical Cooling Channel (HCC) cryostat to be developed in Phase I, because of new inventions in the last year, now has more variations than were originally envisioned and there are now several cryostat designs to be optimized. In Phase I we developed computer programs for simulations and analysis and started experimental programs to examine the parameters and technological limitations of the materials and designs of HCC components (magnet conductor, RF cavities, absorber containment windows, heat transport, energy absorber, and refrigerant). As an example, we could design the cryostat for the 6DMANX cooling demonstration experiment (the subject of Project 7 described below).

4) **Ionization Cooling using Parametric Resonances (PIC)** is a project begun in July 2004 and funded to July 2007 with Jefferson Lab as a research partner (Dr. Yaroslav Derbenev, Subgrant PI). The excellent 6D cooling expected from the SBIR Project 2 above leaves the beam with a small enough size and sufficient coherence to allow an entirely new way to implement ionization cooling by using a parametric resonance. The idea is to excite a half-integer parametric resonance in a beam line or ring to cause the usual elliptical motion on a phase-space diagram to become hyperbolic, much as is used in half-integer extraction from a synchrotron. This causes the beam to stream outward to large x' and/or y' while the spatial dimensions x and/or y shrink. Ionization cooling is then applied to reduce the x' and y' angular spread. The Phase II grant is to study the details of this new technique and to develop techniques for correction of chromatic

and spherical aberrations and other higher-order effects using analytical calculations and numerical simulations.

5) **Reverse Emittance Exchange for Muon Beam Cooling,** with Jefferson Lab (Dr. Yaroslav Derbenev, Subgrant PI) begun in July 2005 and funded until July 2008 is a project to develop techniques to shrink the transverse dimensions of a muon beam to increase the luminosity of a muon collider. After the 6D cooling described in Project 2 above, the longitudinal emittance is small enough to allow high frequency RF for acceleration. However, the longitudinal emittance after the beam has been accelerated to collider energy is thousands of times smaller than necessary to match the beta function at the collider interaction point. We plan to repartition the emittances to lengthen the muon bunch and shrink the transverse bunch dimensions using linear cooling channel segments and wedge absorbers. In addition, a new concept developed in Phase I to coalesce muon bunches will be included in the optimization of the longitudinal phase space to enhance collider luminosity.

6) Muon Capture, Phase Rotation, and Precooling in Pressurized RF Cavities, with Fermilab (Dr. David Neuffer, Subgrant PI) was started in July 2005 and funded until July 2008 with complementary computational and experimental goals. The use of gas filled RF cavities close to the pion production target for phase rotation, bunching, and beam cooling will be simulated. In parallel, the project will also involve a continuation of the experimental development in the Fermilab MuCool Test Area (MTA) of high-gradient high-pressure RF cavities operating in a high radiation environment and in strong magnetic fields. Measurements taken in Phase I have shown that pressurized cavities are not affected by external magnetic fields, making them much better for muon cooling applications than evacuated cavities, which are strongly affected by such fields.

Projects Granted in 2006 now being developed for Phase II proposals:

7) Development and Demonstration of Six-Dimensional Muon Beam Cooling with Fermilab (6DMANX). This project is to develop an experiment to prove that effective 6D muon beam cooling can be achieved using an ionization-cooling channel based on a novel configuration of helical and solenoidal magnets. This Helical Cooling Channel (HCC) experiment will be designed with simulations and prototypes to provide an affordable and striking demonstration that 6D muon beam cooling is understood sufficiently well to become an enabling technology for intense neutrino factories and high-luminosity muon colliders.

8) Interactive Design and Simulation of Beams in Matter with IIT. G4BeamLine (G4BL), a beam line design program based on GEANT4 for beams with significant interactions with matter, has been the workhorse for Muons, Inc. and the International Muon Ionization Cooling Experiment (MICE) [12] collaboration to simulate muon cooling channels to explore new techniques. This proposal is to improve the program for more general use, adding a Graphical User Interface and several new and enhanced capabilities.

Although each of these projects is independent, taken together they represent a coherent plan to generate a compelling design for an intense muon source. Muons, Inc. has enthusiastic collaborators from IIT, Jefferson Lab, Fermilab, and now Lawrence Berkeley National Lab,

Argonne National Lab, and Brookhaven National Lab who are part of this effort. The grants described above support six young accelerator scientists. We hope that recent simulation results showing 6D cooling factors of 50,000 for a 4-section helical cooling channel and other cooling innovations will reenergize the muon collider community. The Linac community has likewise shown interest in the pressurized cavity development. This is a lively, creative collaboration dedicated to developing new options for the physics community.

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