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FERMILAB GENERAL ACCELERATOR DEVELOPMENT PROGRAM

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1 INTRODUCTION

The Fermilab General Accelerator Development (GAD) Program supports the missions of the Office of High Energy Physics (OHEP) and the U.S. HEP community by nurturing and developing those technologies that are critical for enabling the accelerator facilities of the future. Fermilab's GAD program is grounded in a rich history of technology development and deployment, going back to the foundation of the laboratory, and embodied in the first large scale application of NbTi superconductor technology in the construction of the Tevatron.

Fermilab's GAD program is directed at developing technologies that are critical for advancing knowledge on both the Energy and Intensity frontiers of particle physics. GAD activities are squarely aimed at expanding knowledge on the Energy Frontier by developing key technologies required for LHC upgrades, future LHC beam energy increases, and next generation lepton colliders. The following are the basic Energy Frontier activities:

- Develop superconducting magnet technology to provide ever-increasing magnetic fields, and
- Perform fundamental R&D on superconducting strands and cables

Likewise, GAD activities are squarely aimed at expanding knowledge on the Intensity Frontier by developing key technologies required for future high-power proton accelerators for neutrino physics and for the front-end of a future muon collider. The following are basic Intensity Frontier activities:

- Develop superconducting radio-frequency (SRF) structures suitable for the acceleration of high average current, non-relativistic, proton/H- beams
- Perform fundamental materials R&D to understand limitations to achievable cavity gradients and quality factor
- Develop front-end injector and RF system technologies for high intensity proton/H- beams

As has been borne-out by the history of the field, developments in accelerator technologies, such as those outlined above, required to answer the most pressing questions in particle physics have found application in accelerators used as tools of discovery in fields as diverse as materials science, nuclear physics, biology and medicine.

The General Accelerator Development (GAD) program at Fermilab is conceptually positioned between the General Accelerator Science program, dedicated to general accelerator physics research and investigation of new accelerator concepts, and more focused Programs or Projects dedicated to the development or construction of specific equipment or production facilities. The GAD function is to:

- take a <u>need</u> from General Accelerator Science (such as the need to develop a high intensity proton accelerator, or new lepton or hadron colliders)
- <u>develop</u> and <u>prototype</u> the appropriate tools and technology to address this need (sometime performing basic R&D to facilitate this process, such as R&D on bulk materials or surface physics)
- <u>deliver</u> actual or conceptual prototypes to a construction project, or <u>support</u> an existing program with more focused goals.

The Fermilab GAD mission is comprises the following objectives:

- Production and publication of new science and knowledge, in the form of basic understanding of materials and technology properties that make the construction of advanced accelerator equipment possible.
- Development and engineering of new accelerator equipment, in forms and with specifications never used or developed in previous applications. This development phase is frequently

aimed at the production of a prototype driven by a set of technical specifications. The prototype goal is to demonstrate the feasibility of the new technology.

- Establishment of new tools, infrastructure and procedures to help further our technology knowledge and support continued R&D through the GAD program. It is important to realize that the tools and infrastructure developed by GAD are aimed at R&D functions and are not a contribution to infrastructure for a construction project.

Fermilab's GAD program leverages the substantial resources at the laboratory, in the form of infrastructure (magnet measurement stands, vertical test-stands, cryogenics, etc., etc.), local universities with active interest in accelerator science and technology (IIT, NIU, Northwestern), close proximity to Argonne National Laboratory, and substantial computational capabilities. In addition, the program leverages the many existing collaborative activities underway at the laboratory, as is described in detail below.

The Fermilab General Accelerator Development R&D portfolio is aligned principally with the following programmatic thrusts:

- Accelerator and Injector Systems: Activities include the development of a proton/H- injector system and low-velocity normal and superconducting radiofrequency structures suitable for future high-intensity, high-power linear accelerators
- Superconducting Magnets and Materials: Activities include the development of high-field magnets and supporting technology, development of superconducting strand and cable, and fundamental R&D on superconducting materials and their practical limitations.
- Other Research: Activities include accelerator modeling and computational support

Table 1 and figure 1 summarize the budget and FTE information including actual costs in prior years, and the request for funding in support of the proposed program for FY11-FY13

Table 1: Budget (in fully burdened then-year k$) and FTEs for the Fermilab GAD program. The FY11-FY13 columns show the requested funding in support of the proposed program assuming OH rates of 90% for SWF and 15% for M&S.

Project Title:	**Fermilab GAD Program**				
Organization:	**Fermilab**				
FY:	**2009**	**2010**	**2011**	**2012**	**2013**
Total Funding	**25,913 k$**	**18,676 k$**	**15,140 k$**	**18,638 k$**	**24,695 k$**
non-SRF Accelerator & High Power RF Activities	7764 k$	6734 k$	3117 k$	1295 k$	650 k$
SRF Accelerator Activities	5555 k$	4322 k$	5626 k$	9556 k$	15689 k$
3.9 GHz Activities	2862 k$	599 k$	236 k$	118 k$	118 k$
SC Magnets	3380 k$	2297 k$	2326 k$	3560 k$	3998 k$
SC Materials R&D	3866 k$	2504 k$	2397 k$	2534 k$	2648 k$
Other Activities	2487 k$	2221 k$	1436 k$	1575 k$	1592 k$
ARRA (VHFSMC)		**745 k$**	**639 k$**		
FTE	**~92**	**~62**	**~52**	**~61**	**~73**

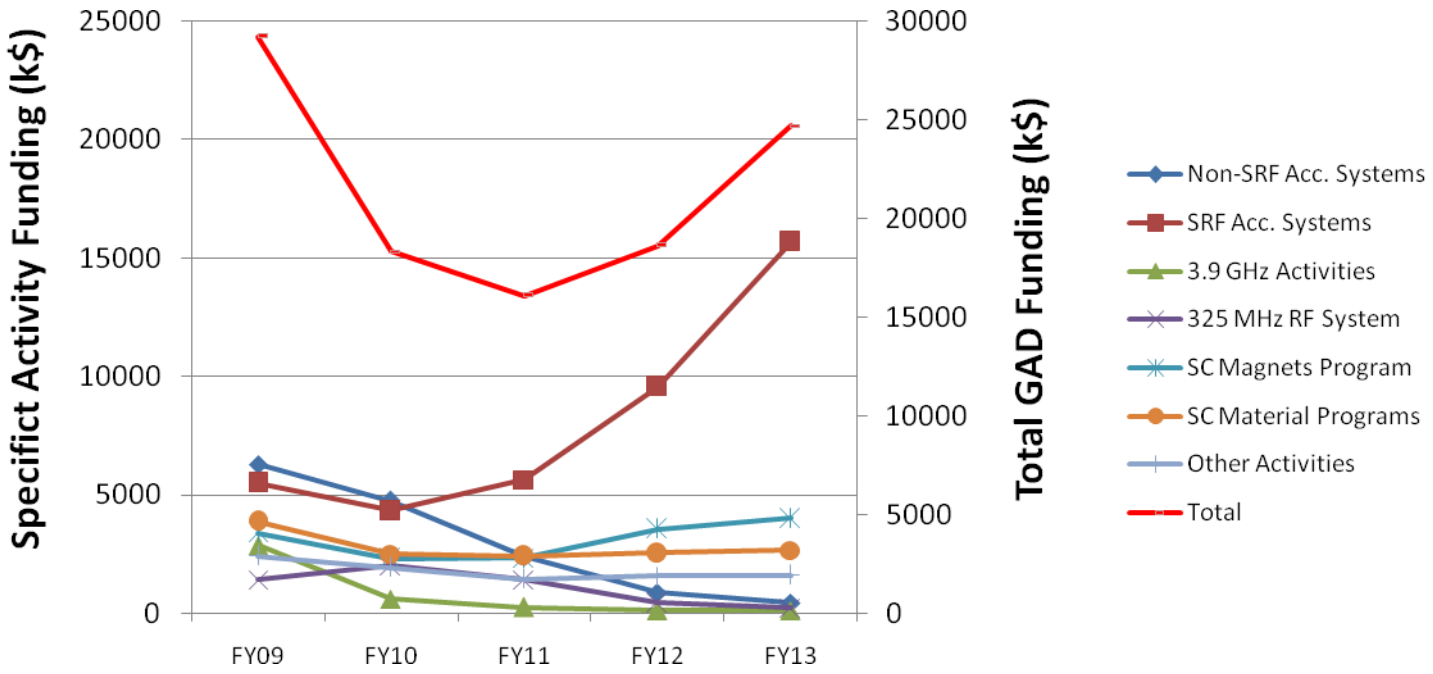

Figure 1: FY09-FY10 funding and FY11-FY13 funding requests for the General Accelerator Development activities at Fermilab. Each sub-program, described in the text and for which a detailed summary is presented, is characterized by a curve whose total funding is shown on the left-hand axis in k$. The total GAD activities funding is shown in red and the corresponding axis, in k$, is on the right-hand side of the plot.

In the following, for each R&D thrust we present a description of the goals and significance of the program, a summary of recent achievements (with emphasis on the 2009-2010 period) and a proposal for the R&D program in the 2011-2013 timeframe. Synergies between the R&D programs and other Laboratory and Collaborative activities will be discussed, and, finally, resource needs will be presented.

2 ACCELERATOR AND INJECTOR SYSTEMS AND HIGH POWER RF SYSTEMS: NON-SUPERCONDUCTING RF ACTIVITIES

2.1 DESCRIPTION OF THE R&D PROGRAM, GOALS AND SIGNIFICANCE

The Accelerator and Injector Systems component of the GAD activities at Fermilab began in 2006 with the High Intensity Neutrino Source (HINS) program. This program had the objectives to demonstrate the critical technologies required for the low-energy front-end of a future high-intensity, high power proton/H^- Linac, while fostering collaborative activities with other institutions on topics relevant to high intensity (especially H^-) beams. As such, the program was aligned with the long-term strategic goals of the US HEP program by developing technology required for a future state-of-the-art Intensity Frontier proton accelerator. The plan was to construct a modern Linac of several tens of MeV at Fermilab to demonstrate:

- Beam acceleration using spoke-type superconducting RF (SRF) cavity structures starting at a beam energy of 10 MeV
- High power RF vector modulators controlling multiple RF cavities driven by a single high power klystron for acceleration of a non-relativistic beam
- Control of beam halo and emittance growth by the use of solenoid focusing optics
- Fast, 325 MHz bunch-by-bunch, beam chopping

The HINS program of technology development has broad significance for a wide-range of potential applications of high-intensity hadron beams, not only in HEP, but in other fields that require high average hadron beam power. The significance of the program was recognized by the Fermilab Accelerator Advisory Committee, an external expert review panel, which first evaluated the program in May, 2006. The Executive Summary of the meeting report states:

> *"…The committee considers it important that capabilities are developed and R&D carried out to maintain options for an experimental HEP program in U.S., beyond Run II, based on a strong neutrino program at Fermilab. The committee supports the proposed accelerator developments leading to improved performance using existing accelerator assets, and an R&D program to pursue further enhancements with a new high-power proton injector."*
>
> *"…The HINS program includes many R&D topics and there are clear synergies between this R&D and the Radioactive Isotope Accelerator (RIA), as well as more generic accelerator R&D. In some cases, there are also clear synergies with the ILC accelerator R&D and possibly the ILC construction project."*

The plan required design and construction of an accelerator section with solenoid focusing to provide 10 MeV beam for the superconducting spoke cavity section. It required development of 325 MHz superconducting spoke RF cavities and associated processing procedures. It required development of the high power RF vector modulator devices. It required installation of a megawatt-class 325 MHz pulsed, RF power source and cavity test facilities. It required development of a state-of-the-art beam chopper.

2.2 RECENT PROGRAM ACHIEVEMENTS

In the five years since this program began at Fermilab, it has delivered:

- One PhF – Wai-Ming Tam, 2009, Indiana University/Fermilab Accelerator Physics PhD Program, "Characterization of the Proton Ion Source Beam for the High Intensity Neutrino Source at Fermilab".
- A radiation-shielded facility for testing 325 MHz RF cavities, normal and superconducting
- A RF-shielded facility for power testing non-radiation producing 325 MHz RF power components

- A radiation-shielded enclosure and utilities infrastructure for the Linac beam line
- A 2.5 MW pulsed, 325 MHz RF power system with the flexibility to serve the cavity test facility, the RF power component test facility, or the Linac
- An operating 50 keV proton ion source
- A prototype magnetron-type H^- ion source delivering beam suitable for injection into an RFQ
- A 50 keV to 2.5 MeV, 325 MHz RFQ
- A proton beam accelerated to 2.5 MeV through the RFQ
- Production high-power, 325 MHz RF vector modulators: one designed and tested to 500kW and 18 designed and tested to 70kW
- Sixteen 325 MHz normal-conducting spoke-type accelerating cavities, all RF power tested, designed to accelerate beam to 10 MeV
- Nineteen production superconducting solenoid magnets, some with integral dipole steering coils, designed for the normal conducting Linac section
- Two 325 MHz, $\beta = 0.2$, superconducting spoke-type RF cavities that have achieved world-class accelerating gradients in RF tests (see section on SRF activities)
- First time measurements of the sensitivity of superconducting spoke-type cavities to on-axis magnetic fields

Some of these deliverables are shown in fig. 2 and fig. 3.

Figure 2: 2.5 MW 325 MHz Klystron installation (left), beam-line enclosure (center) with Ion Source and RFQ visible in the background, close-up of the Ion Source and RFQ assembly (right).

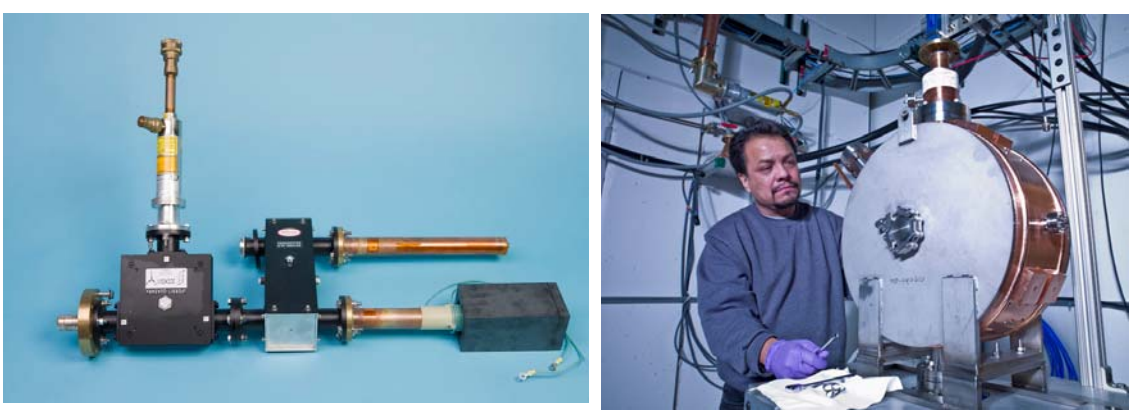

Figure 3: 70 kW 325 MHz Vector Modulator (left) and one of the 325 MHz normal-conducting spoke-type accelerating cavities designed to accelerate beam to 10 MeV

The program technical achievements are reported in more than 15 papers in the proceedings of Particle Accelerator, Superconducting RF, and Magnet Conferences and listed in the "PUBLICATIONS" chapter.

2.3 SYNERGIES WITH OTHER LABORATORY AND/OR COLLABORATIVE ACTIVITIES

From the inception of the HINS programs, collaborations were established with Argonne National Laboratory, Brookhaven National Laboratory, and Lawrence Berkeley National Laboratory in the US, Inter University Accelerator Center in India, and, informally, Imperial College/Rutherford Appleton Laboratory in the UK. The collaborative facets of the program have delivered:

- From BNL:
  a) Analyses and simulations of the transport and multi-turn injection of 8 GeV H^- ions including stripping, foil heating, phase-space painting, and injection beam absorber considerations
  b) A prototype laser-wire beam profile monitor based on neutralization of H^- ions, now installed in the Fermilab Linac to Booster transfer line
- From LBNL:
  a) Design, fabrication and delivery of two 325 MHz normal-conducting buncher cavities
- From ANL:
  a) Design and particle tracking simulations of a pulsed 8 GeV superconducting Linac ("Physics design of the 8 GeV H-minus linac", P.N. Ostroumov, 2006 New J. Phys. 8 281)
  b) Improvements to the TRACK particle tracking code, including Fermilab contributions of a comprehensive H- stripping module and extensive TRACK vs. ASTRA cross-verifications with resulting improvements to each code
  c) Contributions to SRF spoke-type cavity development, fabrication, and processing
- From India Inter University Accelerator Center (IUAC):
  a) Agreement that IUAC fabricate two superconducting spoke-type RF cavities from Fermilab supplied niobium; cavity fabrication is currently underway
- From Imperial College London/Rutherford Lab Front-End Test Station (FETS) program:
  a) Exchanges of ideas on RFQ, beam chopper, and beam diagnostic systems and visits to Fermilab by FETS personnel

In addition to the above-mentioned collaborative efforts, the scientific significance, merit and feasibility of the research is indicated by the active interest and eager anticipation, shown by both CERN and the European Spallation Source project, to see the first results from a multi-cavity, RF vector modulator controlled beam acceleration demonstration. Fermilab management has actively supported this work in the past and encourages its continuation into the future. This program leverages substantial infrastructure in the form of building space, cryogenics, and other utilities provided by the laboratory.

2.4 PROPOSAL FOR R&D PROGRAM IN 2011-2013 TIMEFRAME

The quality and impact of this GAD-seeded research and its relation to the overall HEP mission is clearly demonstrated by the fact that the bulk of these non-SRF activities are being subsumed by the proposed Fermilab Project X into its R&D program. As such, the HINS front-end will be utilized for, and supported by the Project X R&D program for the development of the fast chopper system and instrumentation required for Project X Other spin-offs to HEP from these efforts include an early prototype fast beam chopper now installed in the Fermilab Linac and incorporation of GAD-funded H- ion source developments into the Fermilab Linac Front-End Upgrade project.

The remaining objective of the non-SRF portion of this line of research that is not directly supported by the proposed Project X R&D program is the demonstration of beam acceleration through multiple high-power 325 MHz cavities controlled by Vector Modulators. This test is

scheduled for 2011 and 2012 and is called the "Six-Cavity Test". The plan is to equip a beam line with six vector modulator controlled normal-conducting multiple-spoke cavities, to demonstrate phase and amplitude of the distributed RF power, and to accelerate beam through the RFQ and the six cavities with focusing provided by normal-conducting quadrupoles (fig. 4).

An additional objective is to complete the installation of 3-4 superconducting solenoids, designed for focusing low energy beams, in their respective cryostats for a full characterization of construction and alignment procedures. This is to understand how to achieve the alignment precision and reproducibility required between solenoids and cavities, which is vital in the Project X front end to maintain an axially symmetric beam and to minimize beam halo growth and resulting beam losses.

Figure 4: 325 MHz normal-conducting crossbar spoke-type accelerating cavity and preliminary Six-Cavity Test installation

2.5 RESOURCE NEEDS

Table 2 shows the requested funding for the proposed R&D program in "Accelerator and Injection Systems: non-SRF Activities" + "High Power RF Activities.

Project Title:	**Non-SRF Accelerators and Inj. Systems: Fermilab High Intensity Neutrino Source (HINS)**		
Organization:	**FNAL/AD-TD-APC**		
FY:	**2011**	**2012**	**2013**
Total (k$): Non-SRF Accelerator and High Power RF Activities	**3,117 k$**	**1,295 k$**	**650 k$**
M&S (k$):	**445 k$**	**168 k$**	**85 k$**

2.6 DESCRIPTION OF THE R&D PROGRAM, GOALS AND SIGNIFICANCE

The scope of the SRF activities in GAD includes the development of a 3.9 GHz cryomodule and the development of 325 and 650 MHz cavity and cryomodule systems. The general approach is to establish the required competencies and expertise at Fermilab to develop and utilize SRF technology for general accelerator applications. The activities included in the GAD program are complementary to and leverage those that are funded by the ILC program.

The development of superconducting low-velocity accelerating structures for high-current beams is fore-front, state-of-the art R&D with wide-ranging applicability and significance. The activities carried out in this programmatic thrust are aimed at the strategic goals of the national HEP program by developing key technologies required for exploration of the Intensity Frontier of particle physics utilizing high-power proton beams. In addition, the technology required to produce high power beams for particle physics is the same technology required for future spallation sources (such as the European Spallation Source), future accelerator-driven reactor systems (such as the MYRRHA project in Belgium) and future accelerator-based irradiation facilities.

The 325 and 650 MHz development encompasses the design of multiple SRF cavities and associated cryomodules spanning the velocity range from β =0.11 to β =0.9. The development of 325 MHz single-spoke resonators (SSR) and the 650 MHz elliptical cavities responds to the need of providing superconducting accelerating components for high-intensity proton beams, such as those that may be needed by Project X at Fermilab as well as other potential future facilities that require high average current proton beams. Fundamental goals of the R&D include maximizing the cavity gradient and quality factor, and developing cavity and cryomodule systems capable of accelerating high-average current beams.

The 3.9 GHz cryomodule was the first cryomodule designed, fabricated, and delivered by Fermilab. It was built in collaboration with DESY and is presently installed and operating at the FLASH facility at DESY where it is performing according to expectations (http://www.desy.de/news/desy_news/2010/flat_flash/index_eng.html). As part of this collaboration DESY provided a 1.3 GHz cryomodule kit to Fermilab. This kit was assembled at Fermilab by a joint DESY/FNAL team and is presently undergoing testing at the Fermilab New Muon Lab facility, as an element of the ILC-S2 goal.

2.7 RECENT PROGRAM ACHIEVEMENTS

The 3.9 GHz cryomodule was designed and fabricated at Fermilab and delivered to DESY in Spring 2009 (fig. 5). The cryomodule saw cold testing and installation in the FLASH facility in Fall 2009. This four-cavity cryomodule serves to linearize the otherwise nonlinear beam energy/time profile produced by the 1.3 GHz cavities in the FLASH front end. This linear relationship allows the creation of very short high peak current beam pulses via a magnetic chicane that in turn approximately doubles the FEL light output of FLASH. The nine-cell cavities include higher order mode (HOM) couplers, fundamental power couplers, field probes, and cavity tuning systems. The cavities were chemically processed in collaboration with Argonne National Laboratory and Thomas Jefferson National Accelerator Facility. They underwent vertical and horizontal tests at Fermilab in order to achieve readiness for cryomodule assembly. Significant efforts included the design and implementation of new HOM couplers, the fundamental power coupler, and the cavity tuning system, which employs a blade-type tuner (following work at INFN Milano), and piezoelectric actuators. The shipping of the completed cryomodule to DESY via truck and air transport required extensive analysis, testing and instrumentation to assure the cryomodule survived the transport to DESY. Fermilab personnel participated in the testing and installation of the cryomodule at DESY,

where it is now in routine operation at the FLASH facility. The successful conclusion of this project demonstrated Fermilab's mastery of all aspects of cavity and cryomodule design and fabrication.

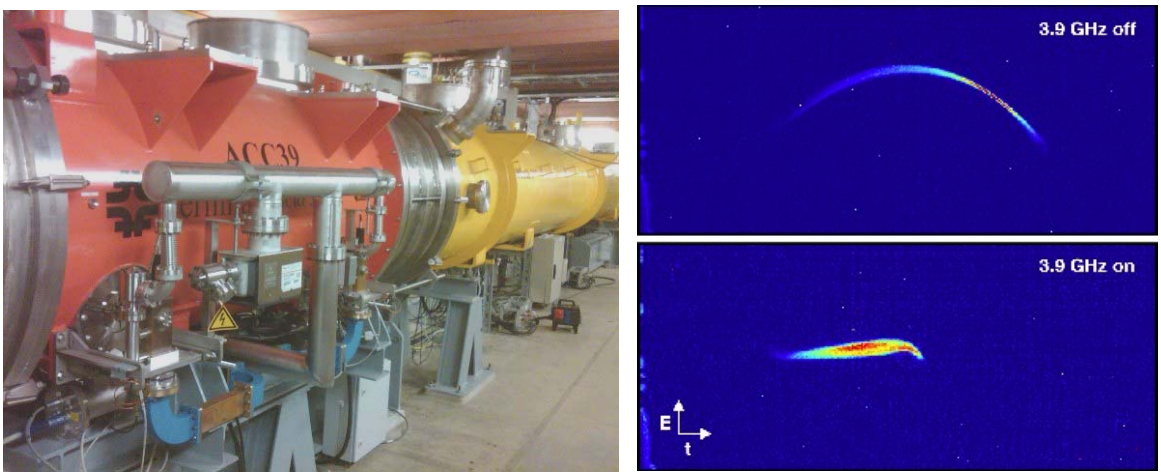

Figure 5: 3.9 GHz cryomodule installed and operational in the DESY FLASH facility (left) and first observation of space linearization in May 2010 (right).

The electromagnetic designs of three 325 MHz single-spoke resonators and two 650 MHz five-cell elliptical cavities have been completed. Two prototypes of the β =0.22 SSR1 have been fabricated and tested (fig 6). One of these cavities was outfitted with a helium vessel and tuning system and is undergoing testing in a horizontal test cryostat (fig. 6 and fig. 7). These cavities have both significantly exceeded their performance specifications achieving a world-wide record in accelerating gradient for Spoke Resonators, as shown in fig. 6. A byproduct of this effort was the development of Spoke Resonators production capability in US industry. Fabrication of ten additional SSR1 cavities is underway at a US vendor.

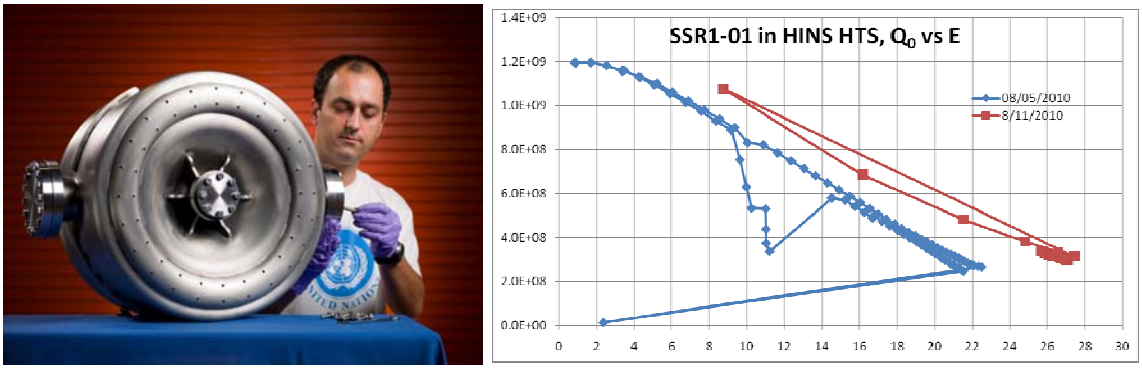

Figure 6: Prototype 325 MHz superconducting cavity (left) with results of test in the 325 MHz Horizontal Test Facility (right).

Figure 7: SSR1 cavity in its helium vessel (dressed cavity) with a unique tuning mechanism (left) and SSR1 dressed cavity undergoing test in the Horizontal Test Cryostat (right).

The development of β =0.11 SSR0 cavities is a unique effort in the world, since no facility under operation is pushing superconducting acceleration of high-intensity proton beams down to energies of ~2-3 MeV. The development of such cavities is presently undergoing design iterations in order to meet the stringent requirements required for beam focusing and acceleration for any low-energy application, such as for the Project X linac. The cavity-to-cavity lattice spacing is small, and fitting the cavities, focusing solenoids, and beam instrumentation into the required lattice is challenging. The major effort at this time is to minimize the cavity frequency sensitivity to helium bath pressure variations, which is critical due to the narrow bandwidth (<100 Hz) of these cavities for CW applications (fig. 8).

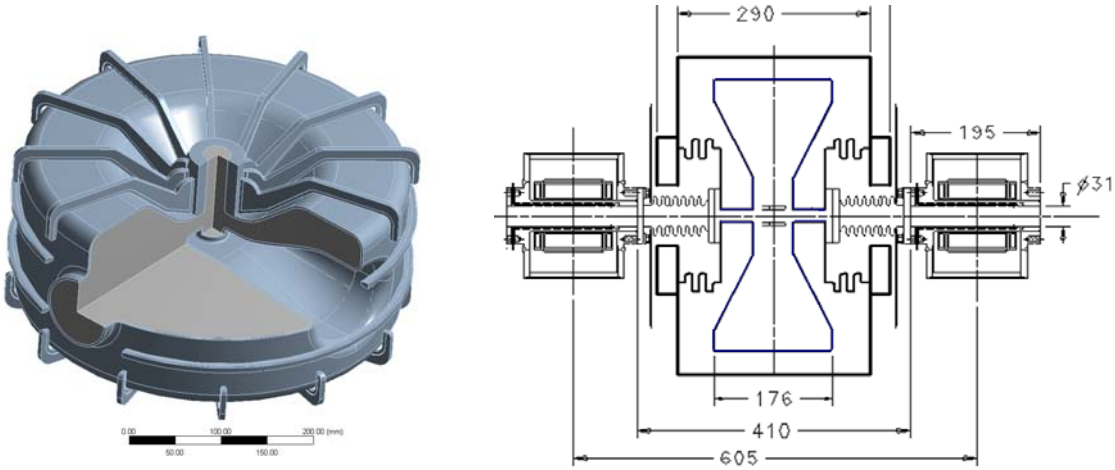

Figure 8: Mechanical model for the SSR0 cavity (left) and preliminary integration parameters for the system of cavities and focusing solenoids (right).

Two five-cell 650 MHz cavities are under development (β =0.6 and 0.9). Single-cell prototypes of the β =0.9 cavity have been ordered from US industry. Jefferson Lab is undertaking the development of the β =0.6 cavity and has initiated fabrication of single-cell prototypes. The β =0.9 five-cell cavity design is proceeding at Fermilab with the plan to initiate procurement of two prototypes in FY11 (fig. 9) with the goals of achieving G=~17 MV/m and Q_0= 1.5 10^{10}. Niobium for the production of single-cell and five-cell prototypes was ordered in FY10; partial deliveries have been received with the balance due in early CY11.

Finally, conceptual designs for 325 and 650 MHz cryomodules have been developed.

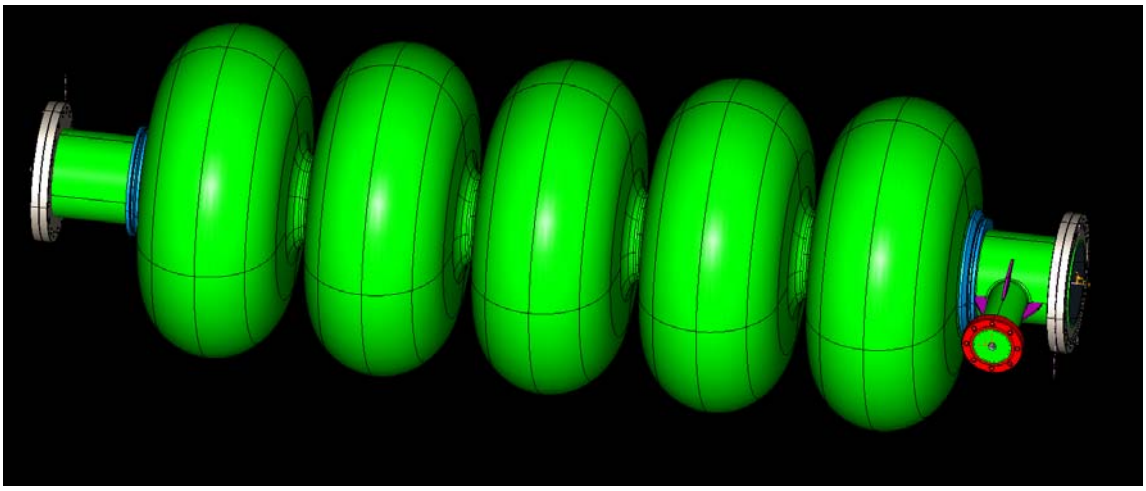

Figure 9: Mechanical model for 650 MHz, b=0.9 elliptical cells cavity developed at FNAL.

2.8 SYNERGIES WITH OTHER LABORATORY AND/OR COLLABORATIVE ACTIVITIES

This scope of work directly informs the pre-conceptual design of Project X at Fermilab and is applicable to many other applications of high power proton beams, such as accelerator-driven systems, spallation neutron sources, or irradiation facilities. The work will be carried out in the context of the Project X collaboration, which includes national and international partners, and is of interest to other projects, such as the European Spallation Source in Sweden and the Superconducting Proton Linac (SPL) at CERN. Collaborative activities are underway with ANL, Jefferson Lab, and several laboratories in India. Furthermore, it is complementary to ongoing International Linear Collider (ILC) R&D being carried out at Fermilab, which is focused on the production of β =1 high-performance cavities and cryomodules and studies in the improvement of cavity gradient and quality factor.

These activities leverage the substantial infrastructure resources available at Fermilab and Argonne, including the FNAL Vertical Test Stand (VTS1) for testing of bare cavities, the Argonne chemical processing and High Pressure Rinsing facilities and the FNAL clean-room assembly areas. In the future it is expected that these R&D activities will leverage the ARRA-funded facilities such as the additional Vertical Test Stands (VTS2 and VTS3), the cavity-baking facilities and, particularly for the 650 MHz cavities, most of the infrastructure developed for the 1.3 GHz systems.

2.9 PROPOSAL FOR R&D PROGRAM IN 2011-2013 TIMEFRAME

The capabilities, infrastructure and collaborative arrangements are in place to make rapid progress in these development activities over the next five years. The SRF part of the GAD program is probably the most demanding in terms of future deliverables. The following goals are presently being pursued:

- 3.9 GHz cavity spares
  a) Two spare 3.9 GHz cavities will be completed and tested in FY11. This includes completion of the cavity fabrication, chemical processing and vertical dewar testing, and high-power testing in the horizontal test cryostat.
- 325 MHz Single-Spoke Resonators and Cryomodules

a) The high-power test of the first dressed 325 MHz SSR1 cavity in the horizontal test cryostat will be completed in FY11. The 2nd prototype cavity will undergo installation of its helium vessel and will subsequently be tested in the horizontal test cryostat.
b) The spoke cavity test facility will be upgraded to support 2K operation.
c) The additional SSR1 cavities will be received from industry. Chemical processing and vertical dewar testing of several cavities is planned for FY11.
d) The SSR0 cavity design will be completed in mid-FY11 along with a complete engineering drawing package.
e) Prototype SSR0 cavities (1-2) will be procured if sufficient funding is available.
f) The cryomodule design will be further developed, with the goal of being ready to initiate fabrication of a prototype cryomodule by FY12-13, dependent on funding.

- 650 MHz Single-Cell and Five-Cell Cavities and Cryomodules
  a) The single-cell β =0.9 prototype cavities will be received in FY11. It is planned to chemically process and vertically test several of these cavities by the end of FY11.
  b) A five-cell β =0.9 cavity design will be further developed, along with engineering drawings, such that two prototype cavities with gradient of ..MeV/m and $Q_0=10^9$ can be ordered from US industry by the end of FY11, subject to funding constraints.
  c) The 650 MHz cryomodule design will proceed; construction of a prototype cryomodule is a longer-term goal to be conducted in the FY12-13 timeframe.

2.10 RESOURCE NEEDS

Table 3 shows the requested funding for the proposed R&D program in "Accelerator and Injection Systems: SRF Activities

Project Title:	**SRF Accelerators and Inj. Systems: Fermilab 325, 650 and 3900 MHz Developments**		
Organization:	**FNAL/AD-TD-APC**		
FY:	**2011**	**2012**	**2013**
Total (k$): **325/650 Funding Request (k$)**	**5,626 k$**	**9,556 k$**	**15,689 k$**
3.9 GHz Funding (k$)	**236 k$**	**118 k$**	**118 k$**
M&S (k$):	**1,381 k$**	**2,559 k$**	**5,629 k$**

3 SUPERCONDUCTING MAGNETS AND MATERIALS: HIGH FIELD MAGNET ACTIVITIES

3.1 DESCRIPTION OF THE R&D PROGRAM, GOALS AND SIGNIFICANCE

The main goal of the SC Accelerator Magnet Program at Fermilab is the development of advanced superconducting magnets and baseline technologies for present and future particle accelerators. The main focus at the present time is on the development on high-field accelerator magnets based on Nb_3Sn superconductor. This program thrust supports also the improvements of magnet design and analysis methods and tools, prototype fabrication and test infrastructure, instrumentation, training of young scientists and engineers in the field of SC accelerator magnets.

The program approach consists of:

- magnet design studies and computer simulations to explore the performance parameter space, development of magnet design concepts, and model magnet R&D directions
- construction of model magnet and component R&D to verify and confirm experimentally the developed magnet designs and technology, and demonstrate magnet performance by fabricating and testing a series of short and long magnet models and prototypes

The scientific outcome and deliverables of the program includes technical reports and scientific papers; superconductor, structural material and magnet specifications; technological "know-how"; operating magnet models and prototypes; proposals and justifications of practically oriented accelerator magnet projects.

This activity has the potential for making a big impact on the future world-wide Energy Frontier programs, including upgrades for the LHC, as well as proving feasibility of certain aspects of muon collider technology. Indeed, this activity is carried out by a well-respected group with a track record of high-impact contributions to the field through its work on high field magnets.

3.2 RECENT PROGRAM ACHIEVEMENTS

The major accomplishments of the superconducting magnet R&D program in 2009-2010 are listed below.

- Development of Technology for Magnets for Hadron Colliders (in support of LARP (LHC Accelerator Research Program) and LHC upgrades):
  a) Demonstration of the 0.7 mm RRP-108/127 strand for operation at 1.9 K, cable with SS core to suppress eddy currents, affordable cable insulation based on E-glass and S2-glass tapes, effects of coil structural materials (bronze vs. Ti poles) and fabrication technology (gaps for expansion, etc.), the effect of coil pre-stress on its quench performance (fig. 10).
  b) Development of the conceptual design and analysis of 120-mm quadrupoles for LHC luminosity upgrade.
  c) Development of collaring techniques for Nb_3Sn coils and their successful demonstration by fabricating and testing a series of short 90-mm quadrupole models with collar-based mechanical structure and LARP TQ coils. This is the first demonstration in the world for the traditional accelerator structure with brittle coils in high-field accelerator magnets (fig. 11).

Figure 10: Nb_3Sn coil studies: 4-m long quadrupole coil made of RRP-114/127 strand (left) and 4-m long Coil Test Structure (CTS) with 90-mm R&D quadrupole coil (quadrupole mirror).

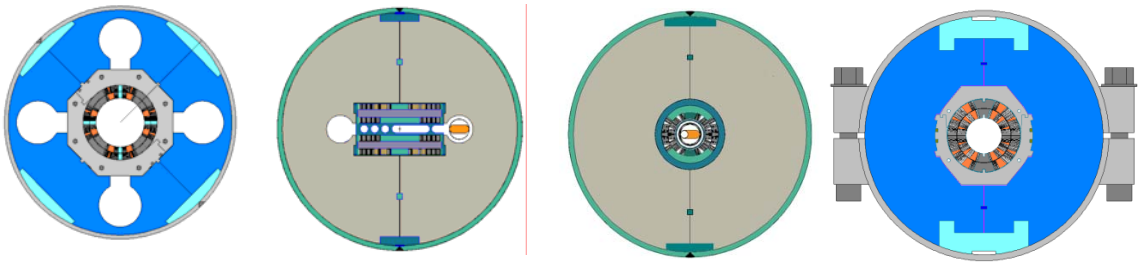

Figure 11: Design Studies: a) 120-mm Nb_3Sn IRQ with midplane Al spacers for LHC; b) open mid-plane and c) cos-theta 10T Nb_3Sn dipoles for MC; d) 60-mm 11 T dipole demo model for LHC.

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d) Development and demonstration of Coil Test Structure for single aperture short and long shell-type quadrupole coils with 90-120-mm aperture. This approach provides significant reduction of cost and turn-around time, and allows for advanced instrumentation development during the magnet R&D phase. Recently it was adopted by the US-LARP for HQ coil design and technology optimizations and is being considered by LARP for the HQ coil scale-up demonstration.
e) Conceptual design studies of an 11 T Nb_3Sn dipole compatible with the LHC lattice and main systems for cold collimators in DS sections (DS Dipole) in collaboration with CERN. These studies provided the technical base for a proposed FNAL-CERN Collaboration on the development of the first double-aperture Nb_3Sn accelerator for use at the LHC (fig. 11).

- Conceptual design of Magnets for the Muon Collider (MC) and/or Neutrino Factory (NF) prior to the formalization and establishment of the MAP (Muon Accelerator Program (MAP) effort (fig. 11):
  a) Fabrication and test of two short large-aperture helical solenoid models based on NbTi cable for the front end of 6D muon cooling channel.
  b) Conceptual design studies of high-field helical solenoids based on HTS coils for the far end of HCC, development and fabrication of a first HTS helical solenoid model.
  c) Conceptual design studies of MC ring arc and Interaction Region magnets (dipole and quadrupoles) based on Nb_3Sn superconductor.
  d) Conceptual design of large magnet system based on SC Transmission line for NF and other detectors.

e) Contributions to MAP and NF short and long term planning.

- Finally, the expertise developed at FNAL in the GAD High Field Magnet effort has supported development of focusing magnets for linear accelerators such as HINS , ProjX, and ILC (fig. 12):
  a) Development, fabrication and test of high-field solenoid prototype with reduced fringe fields for focusing low-energy proton beams in proximity of SC cavities. This development is part of the baseline design for Project X.
  b) Development and fabrication of modular quadrupole with indirect conductive coil cooling for installation in SCRF cryomodule.

The results of the presented works are summarized in more than 20 papers presented at PAC,CEC/ICMC, MT, IPAC and ASC in 2009-2010 alone as shown in the PUBLICATIONS chapter. This work has a track record of engaging Ph.D. students and attracting young Ph.D.s into the magnet science and technology through Fermilab Peoples Fellowship, the most recent addition being Dr. T. Shen in 2010.

Figure. 12: NbTi Magnets: MC Helical Solenoid 4-coils model (left), HINS Solenoid Lens prototype (center) and LINAC Focusing Quadrupole prototype (right).

3.3 SYNERGIES WITH OTHER LABORATORY AND/OR COLLABORATIVE ACTIVITIES

The FNAL GAD effort on High Field Magnet Development is probably a text-book example of an R&D activity that can "spawn" its achievements into applications for more focused programs. The obvious example is the strong inter-dependence between this program and LARP goal of developing the first high-field long quadrupole based on Nb_3Sn technology for the LHC luminosity upgrade. LARP, which is a unique collaboration between multiple US laboratories (LBNL, BNL, SLAC and FNAL) relied heavily on the FNAL GAD program. For instance, the RRP-108/127 strand demonstrated at FNAL by the GAD effort, recently became the baseline conductor for the LARP magnet R&D. In addition, Fermilab's investments in Nb_3Sn magnet design, fabrication and test infrastructures made it possible in the past and will provide in the future efficient LARP magnet and material R&D including Nb_3Sn technology scale-up and testing of short and long models in temperature range from 4.5 to 1.9 K (including superfluid helium).

More recently, the FNAL GAD effort to design Nb_3Sn magnets consistent with the Muon Collider beam dynamics and radiation heat deposition will find its natural home in the MAP activities.

This work leverages the substantial infrastructure available at the laboratory and inherited from the LHC focusing triplets construction project. In particular, most of the LHC magnet assembly tooling has been refurbished and re-adapted to the HFM goals. In addition, the LHC Vertical Magnet Test Facility (the only facility in the continental US capable of testing ~4m long magnets at superfluid—He temperatures) is consistently used by the HFM program.

3.4 PROPOSAL FOR R&D PROGRAM IN 2011-2013 TIMEFRAME

In FY11 Fermilab has started collaboration with CERN on the development of 11 T 11-m long double-aperture Nb_3Sn dipole magnets compatible with the LHC lattice and major systems to replace several regular LHC dipoles (MB) and provide the required space for cold collimators in DS area. It is believed that these magnets can be also used in the future to provide space in the LHC lattice for different insertion devices such as dynamic collimators based on the electron lens concept, corrector magnets, BPMs, etc. Following a successful demonstration and selection of these magnets for the LHC phase II collimation system upgrade, planned for 2016, a joint FNAL-CERN project to fabricate five (or more) 11 T 11-m long dipoles will be proposed. The R&D plan developed and coordinated with DOE and CERN includes the following activities and deliverables:

- Development, fabrication and test of one 60-mm single-aperture ~2-m long 11T DS dipole demonstration model based on Nb_3Sn superconductor - FY11-12
- Development and test of two 2-m long collared coils for the first 2-in-1 DS dipole short model – FY12
- Fabrication and test of the first 5.5-m long dipole coils for DS dipole prototype – FY13
- Fabrication of 5.5-m long collared coil for the first 2-in-1 5.5-m long cold mass prototype – FY13-14

Specific features of this program, besides its technical challenges, are its limited development time (3-4 times shorter than usual) and resources (see below). Nevertheless, the success is possible due to the high skill of Fermilab's magnet group, our previous successful experience with the development of 10-12 T Nb_3Sn dipoles and quadrupoles, well established productive collaboration with CERN magnet group, and the laboratory resources that are leveraged for this effort.

In the longer term, this program will build on the 11 T effort and drive the development of accelerator magnets (dipoles, quadrupoles, multipole correctors, etc.) with operation fields above 20 T. Accelerator magnets with this level of nominal fields will be needed for MC Storage Ring and for a possible LHC energy upgrade. The progress towards this latest goal will rest on the successful accomplishment of Nb_3Sn accelerator magnet R&D as well as on the progress with new superconducting materials suitable for use in high-field accelerator magnets.

3.5 RESOURCE NEEDS

The following improvements to the Fermilab's magnet R&D infrastructure are needed in FY11-13 to extend its capabilities and provide support to the described above R&D activities:

- Commissioning of long welding press - 2011
- Upgrade and re-commissioning of SELVA winder for long coil – 2011-12
- Upgrade of long coil measuring system – 2011-12
- Installation and commissioning of long coil collaring press – 2012-13
- Installation and re-commissioning of warm magnetic measurement system – 2012-13

These improvements will be also used later in magnet R&D for MC and LHC energy upgrades and they will require and additional funding of ~150k$/year in M&S.

In order to upkeep the R&D effort for the development of the 11 T magnets, we also request funding for additional SWF support to the levels of FY09 and M&S support for the procurement of sufficient Nb_3Sn conductor.

Table 4 shows a summary of the requested funding for the proposed R&D program on the "Superconducting Magnets" program.

Project Title:	**Superconducting Magnets: Fermilab Super Conducting Magnets Development**		
Organization:	**FNAL/AD**		
FY:	**2011**	**2012**	**2013**
Total (k$): Super Conducting Magnets	**2,326 k$**	**3,560 k$**	**3,998 k$**
M&S (k$):	**374 k$**	**700 k$**	**750 k$**

4 SUPERCONDUCTING MAGNETS AND MATERIALS: SC MATERIALS FOR MAGNETS

4.1 DESCRIPTION OF THE R&D PROGRAM, GOALS AND SIGNIFICANCE

This program seeks to understand and improve scientific and engineering aspects of superconducting strands and cables that are used to make accelerator magnets, including dipoles, quadrupoles, and solenoids. The outcome of this work provides conductor specifications and essential engineering data for design and construction of accelerator magnets. Coordination of work with industry improves performance of superconducting strands and cables, and collaboration with other laboratories and universities improves fundamental understanding of strands, cables, and magnets.

For near-term magnets for LHC luminosity upgrades with the 11-15 T nominal fields, emphasis is given to industrial low-temperature superconductors, such as Nb_3Sn and Nb_3Al, and their behavior during cable fabrication and magnet operation, including critical current density at high fields, strand and cable magnetization, thermo-electromagnetic stability, mechanical stress/strain sensitivity, and so on. This work is coordinated with the DOE Conductor Development Program (CDP). Far-term magnets with magnetic fields above 20 T for a possible muon collider and LHC energy upgrade will require materials outside of the niobium family. Emphasis at the present time is given to high-field high-temperature superconductors such as $Bi_2Sr_2CaCu_2O_{10+x}$ (Bi-2212) round wires and to $YBa_2Cu_3O_7$ (YBCO) tapes. This work is coordinated with the Very High Field Superconducting Magnet Collaboration (VHFSMC) funded by DOE to make high-current cables and coils, investigate their properties, and apply the fundamental work topics started for Nb_3Sn to Bi-2212 and YBCO. An opportunity to investigate expensive but highly strain tolerant Nb_3Al cable in collaboration with Japan and CERN is also supported at a low level. Cabling, coil winding, strand and cable testing, strand processing, and materials science infrastructure are integrated to carry out comprehensive investigations and to coordinate studies with magnet construction needs.

The work carried out in this thrust plays a key role in and has the potential for very high impact on the future Energy Frontier activities of the field of high-energy physics. The high quality of the scientific research has been recognized, for example, by the awarding of the prestigious Superconductor Science and Technology Prize to Fermilab investigators and Japanese collaborators for their recent work.

4.2 RECENT PROGRAM ACHIEVEMENTS

The R&D program on SC cables for High Field Magnets applications has been ongoing for several years, and can count many important achievements. The most notable are the following:

- Thermo-electromagnetic stability of Nb_3Sn strands produced using the Restack Rod Process (RRP) has been improved by increasing the number of sub-elements and their spacing in the strand cross-section, in collaboration with Oxford Instruments – Superconducting Technology (OI-ST). The relatively unstable RRP-54/61 design has now been replaced with a RRP-108/127 design as a baseline strand for LARP and other accelerator magnet R&D programs. Studies of critical current, flux-jump instability, magnetization, matrix RRR and cabling deformation conducted at Fermilab gave vital feedback and directed the development of the improved product by OI-ST (fig. 13).
- Collaborations between Fermilab, which conducted comprehensive short strand and cable sample studies, and several industry vendors showed that Nb_3Sn strands with large number (>500) of sub-elements and small effective filament diameter (d_{eff}< 20 μm) required for practical accelerator magnets are feasible. The high critical currents obtained in short lengths

suggest that an eventual industrial engineering product could meet conductor specifications for accelerator magnets.

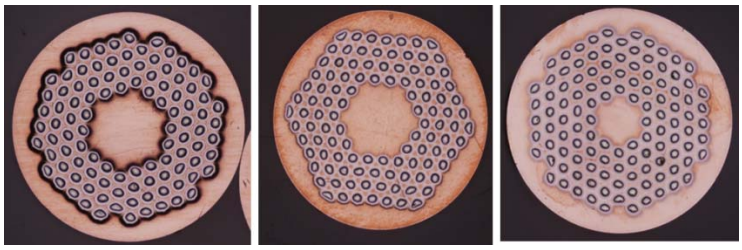

Figure 13: Nb_3Sn RRP-102/127 (left), RRP-108/127 (center) and RRP-114/127 (right) strand designs with optimized sub-element spacing developed by Fermilab and OI-ST.

- The unique small-scale cabling facility at Fermilab was used to make short and long (up to 300 m) Nb_3Sn Rutherford cables with or without stainless steel cores. The core strengthens the cable as well as reduces interstrand coupling in the cable. Both cable designs produced low (<5%) critical current degradation.
- Nb_3Sn cables with very high aspect ratio, stainless steel core, and 40 or 41 strands 0.7-mm in diameter were successfully developed for the 11 T DS dipole demonstration model.
- While Nb_3Al is very expensive, its superior strain tolerance compared to Nb_3Sn makes Nb_3Al attractive for high-field high-stress magnet applications. During FY06-FY10, copper-stabilized Nb_3Al strands were developed within a NIMS-KEK (Japan) and Fermilab (US) collaboration, and used to produce high-current Rutherford cables at Fermilab. In FY10, the prestigious Superconductor Science and Technology Prize was awarded to Fermilab investigators and Japanese collaborators for this work.
- Bi-2212 cables were developed and studied in FY2005-2010, recently in conjunction with the VHFSMC. As many as 27 strands were cabled successfully, a substantial increase compared to 14 strands when this work was last attempted a decade ago. Degradation of critical current was less than 20% at the optimal 85% packing factor, a result consistent with previous work and showing successful scaling of the cabling technique to larger strand number.
- Rolling round strands flat to simulate cabling damage, a technique previously developed and used at Fermilab for Nb_3Sn and Nb_3Al strands, was used also as a diagnostic test to determine suitability for cabling among different Bi-2212 billets in conjunction with the VHFSMC. Unexpectedly, strands made from coarse granular Bi-2212 powders showed a more homogenous and consistent transport behavior than those made from fine powder, even though finer powders conform to deformation more easily. This counter-intuitive result has led the VHFSMC to conclude that air trapped between granules, which is more easily removed for coarse powder, eventually produces pores that prevent good granular connections along the wire. That is, much of degradation thought to be due to cabling is actually related to the intrinsic properties of the strand, and improvement of strand quality is therefore needed.
- Current density as a function of field up to 30 T, field orientation, temperature up to 60 K, and bending strain were measured for tapes to provide engineering data for small solenoids. A double pancake solenoid winding technique without inter-layer splice was developed (fig. 14). A double pancake solenoid wound from the 4-mm wide YBCO tape reached a field of 4.7 T at 4.2 K in a background of 13.5 T producing a maximum field of 18.2 T on the conductor. This reflects peak current at 100% of the short-sample limit. The solenoid test establishes Fermilab competency for winding and testing YBCO solenoids.

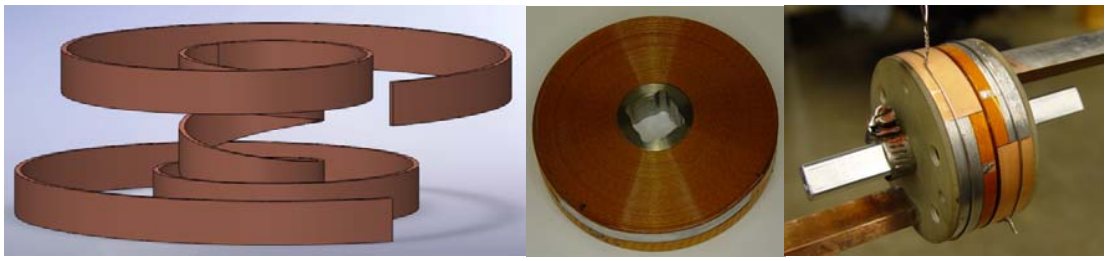

Figure 14: YBCO double-pancake coil concept (left), complete double-pancake (center) and pancake coil prepared for testing (right).

- A Roebel cable made from YBCO tapes by a New Zealand company was successfully tested in liquid nitrogen. This innovative cable design provides an unique opportunity of making high-current cables using tapes. Successful development of this cable type will open wide opportunities for using YBCO tapes in accelerator magnets.
- A unique cable test facility with large-aperture external 14 T solenoid and 30 kA SC transformer was developed and commissioned at Fermilab. This facility significantly expands Fermilab's and U.S. capabilities in testing high-field high-current cables used in advanced accelerator magnets.

The work performed by this R&D thrust was internationally recognized in 2010 by the Forum of Superconductivity Science and Technology (recognized by the Science and Technology Agency of the Prime Minister's Office in Japan) which awarded E. Barzi and R. Yamada with the Superconductor Science and Technology Prize for the "Development of Cu Stabilizing Technology for RHQT Processed Nb_3Al Conductor and Pioneering of its Application for High Current Capacity Cable".

In addition, the program has resulted in four Italian Laurea thesis: M. Danuso (Sant'Anna -2008) with a thesis on "Parametric analysis of forces and stresses in superconducting magnets windings.", G. Norcia (Pisa University, 2009) with a thesis on "Design of Modular Test Facility for HTS Insert Coils.", G. Gallo (Pisa University, 2010) with a thesis on "Mechanical modeling of superconducting Rutherford-type cable fabrication" and A. Bartalesi (Pisa University, 2010) with a thesis on "Design of High Field Solenoids made of High Temperature Superconductors".

All these results are summarized in more than 30 peer reviewed papers presented at PAC, CEC/ICMC, MT, IPAC and ASC in 2008-2010 as shown in the PUBLICATIONS chapter.

4.3 SYNERGIES WITH OTHER LABORATORY AND/OR COLLABORATIVE ACTIVITIES

The R&D pursued by this program finds direct applications in (and is therefore synergetic with) LARP, the LHC 11T dipole program and future LHC IR upgrades. The presence of senior investigators sharing their time between the SC cables for magnets R&D program and the magnet development programs mentioned before ensures a tight communication and resolution of needs.

The recently established VHFSMC (Very High Field Superconducting Magnet Collaboration) and MAP (Muon Acclerator Program) are also beneficiaries of the tools and infrastructure developed by the GAD supported SC cables R&D program, as well as providing seminal inputs for further development on new HTS such as Bi-2212 and YBCO.

Finally, the SC cables R&D program has supported an average of ~1 Engineering Laurea student/year from Italy and Russia, allowing the participants in this program to obtain first-hand experience in SC activities. Several of these students have applied for jobs in the field.

4.4 PROPOSAL FOR R&D PROGRAM IN 2011-2013 TIMEFRAME

Direct support of Fermilab's accelerator magnet R&D programs is the main thrust of planned work. The plan described below outlines the main SC material R&D activities planned at Fermilab in 2011-13 and beyond in support of the HFM Program funded by GAD. The plan does not include SC material development funded by US-LARP, VHFSMC, MAP and Project X/ILC.

Work will seek Nb_3Sn strands which meet the target requirements of practical accelerator magnets, in particular the 11 T DS dipole for LHC, in collaboration with industry, the DOE Conductor Development Program, and other laboratories. Fermilab will work with OI-ST and other vendors to deliver several different designs with 217 or more sub-elements and $d_{eff} < 20$ μm. Each design will involve finite element modeling and complete testing of critical current, stability, and other properties at Fermilab to guide the development of the subsequent design in industry. By the end of FY12, an optimum design should be reached for production during FY13.

In parallel, cable samples of advanced strands will be developed, and the cabling degradation, stability, magnetization and other behavior will be explored to assess strand suitability for the LHC 11 T dipole program. The low waste of Fermilab's cabling facility permits cables of testable length to be made from relatively short lengths (~0.2-0.3 km) of strand. Requirements of low eddy current magnetization by the 11 T dipole program will require resistive cores to be integrated with the cable. Studies and modeling of rolled strands (fig. 15), along with some metallographical analyses, will be continued to aid the design of cables and assess and correct sources of degradation.

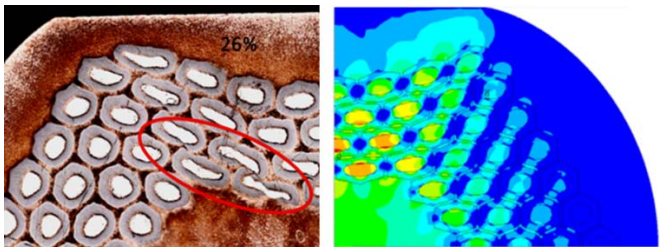

Figure 15: Rolled strand cross-section optical analysis (left) and ANSYS modeling (right).

In the framework of a Japan-US-CERN collaboration, during 2011-2012 Fermilab will develop and produce several 20-30-m long pieces of Nb_3Al Rutherford cable for a 13.5 T Nb_3Al/Nb_3Sn dipole model. Strand and cable samples will be tested using Fermilab's test facilities.

This program will continue to understand and improve the scientific and engineering aspects of Nb_3Sn, Bi-2212, YBCO, and other emerging materials that provide magnet capability beyond 20 T at 4.2 K as well as in environments where decay of particles deposit significant heat into the coils. Testing of the conductors in the specific implementations of cables and accelerator magnets, including stability, tolerance of strain, and other factors will also continue. Since technological forms of these conductors will likely evolve slowly, coordination of engineering needs with vendors will strive to provide magnet programs with suitable conductor at all stages.

4.5 RESOURCE NEEDS

At the present time the SC material program supports ~2 FTE/year. In the future, when the R&D effort on the 11 T dipole will increase, the number of FTE's needs to be gradually increased at least to the level of ~3-3.5 FTE.

The M&S budget in FY11 is ~0.08 M$ including 30 k$ for SCRD Lab relocation to IB3A. To provide an adequate SC material R&D in support of the 11 T dipole program and other related activities the yearly M&S budget needs to be on the level of 100 k$ per year starting from FY12.

Table 5 shows the requested funding for the proposed R&D program on "Superconducting Materials for Magnets".

Project Title:	**Superconducting Materials for Magnets Applications**		
Organization:	**FNAL/TD**		
FY:	**2011**	**2012**	**2013**
Total (k$): **SC Materials for Magnets**	**476 k$**	**590 k$**	**687 k$**
M&S (k$):	**77 k$**	**100 k$**	**102 k$**

5 SUPERCONDUCTING MAGNETS AND MATERIALS: SC MATERIALS FOR RF APPLICATIONS

5.1 DESCRIPTION OF THE R&D PROGRAM, GOALS AND SIGNIFICANCE

This part of the GAD program seeks an understanding of the limits of quality factor Q and accelerating gradient of superconducting RF cavities, both in terms of the ideal niobium material conditions for superconductivity and in terms of the practical conditions after the application of forming, polishing, and cleaning procedures during cavity fabrication. The outcome of research underpins improvement of fabrication yield, validation of processing recipes, the transformation to fabrication routes that reduce environmental impact, and fundamental improvement of the cavity material. Activities interweave processing of single-cell SRF cavities with materials science of flat niobium coupons, pieces cut from cavities, and coupons processed in actual cavity tools using new Fermilab-designed cavities fitted with openings. Basic studies probe topography, defect structures, composition, dissolved impurities, atomic arrangement, and surface layers using recently upgraded microscopes at Fermilab, as well as tools available by virtue of synergistic collaborations with universities and other laboratories. These analyses are coordinated with characterizations of bulk and surface superconducting properties, measurements of cavity quality factor and electric field, and theoretical and computational modeling. New processing ideas and implications of coupon studies are tested on single-cell cavities through specially designed and built research tools, the integrated cavity processing apparatus (ICPA) and the tumbling apparatus. Rapid feedback is obtained because ICPA also incorporates its own clean room with a high-pressure rinse tool and assembly station to prepare processed cavities for test.

Superconducting RF technology is central to the plans for accelerators at both of the accelerator-based frontiers in particle physics. This work therefore has the potential to impact the field in significant ways. Deeper understanding of the fundamental limitations to cavity gradient and quality factor that leads to improved performance and yield has important consequences for the cost and operability of future accelerators.

5.2 RECENT PROGRAM ACHIEVEMENTS

The main goal for the GAD SC materials for RF R&D efforts in the past years was to establish the capabilities for carrying out a definitive research program to understand fundamental performance limitations in SRF cavities, while establishing, at the same time, appropriate collaborative efforts with Universities. In particular, the following milestones were achieved:

- The ICPA (Integrated Cavity Processing Apparatus) was completed. This is a significant milestone for Fermilab, since it is the first apparatus capable of chemically polishing and rinsing 1.3 GHz SRF cavities to be located on the Fermilab site (fig. 16).
- A key component of ICPA is a Fermilab/ANL-designed electropolishing (EP) tool heavily instrumented with controls and sensors. This tool was designed from the start for R&D purposes, with isolation and control over cavity processing variables not possible at production facilities.
- Mechanical polishing of cavity surfaces, including 9-cell 1.3 GHz cavities, has been shown to be feasible using Fermilab's new tumbling apparatus. Initial efforts yielded a single-cell ILC cavity with 40 MV/m accelerating gradient as well as non-acid bulk processing of a 9-cell cavity.
- A new EP tool was constructed to polish niobium coupons under flowing acid conditions that closely resemble the conditions inside cavities. Experiments found that pits, similar to those observed at locations where SRF cavities quench, tend to form easily if the niobium is in a cold-worked state but not if it is annealed. Pitting also worsened when the meniscus

inside a rotating cavity was simulated. These results suggest annealing half cells prior to welding, annealing cavities prior to bulk chemical polishing, and maintaining high electrolyte viscosity could reduce or prevent pits.

- A new model of Q-drop compares explicitly, for the first time, limitations on cavities caused by roughness and contamination. This model predicts that clean but rough surfaces limit the superconducting RF behavior about as much as dirty but smooth surfaces.
- Several techniques were developed to diagnose and repair cavity defects. Routine techniques were developed to apply silicone replicas and extract topographical information from the interior of cavities. Also, use of a laser to melt and subsequently flatten the profile of major pits was demonstrated in a single-cell cavity and has been engineered to 9-cell cavities.
- Significant upgrades to materials characterization facilities at Fermilab were completed. The scanning electron microscope was equipped with orientation-sensitive imaging, which permits structural features such as grain texture to be associated with other observations. Installation of a new laser confocal scanning microscope provides assessment of topographical information 30 times faster than profilometry with comparable resolution.
- Fundamental studies improved understanding of the limits to RF behavior. Much more hydrogen than expected was found just under the niobium surface by helium atom recoil spectroscopy, even after very light processing. In view of recent microscopy studies suggesting that mild baking separates hydrogen from niobium defects, hydrogen must therefore play a major role in the improvement of cavities after baking at ~120 °C. This possibility has not been appreciated by the SRF community before.
- Additional studies revealed further evidence for magnetic defects in surface oxides. Since the oxide is typically 10 nm thick, magnetic defects are in communication with superconducting electrons, which can induce pair breaking and Q drop. Computational studies confirmed substantial magnetic moments located on oxygen vacancies in the Nb_2O_5, as suggested by earlier materials work. These results imply that severe roughness and thick oxidation produce cavity hot spots.

Figure 16: ICPA chemical hood during construction (left) and first pre-operational shakedown test of the newly constructed electropolishing tool for R&D activities (right).

5.3 SYNERGIES WITH OTHER LABORATORY AND/OR COLLABORATIVE ACTIVITIES

A collaborative effort with several local Universities and Laboratories has been established during the last year and has allowed some of the achievements mentioned previously. These collaborations rely on common interest and use of specialized tools not available at Fermilab. The study on the presence of hydrogen by helium atom recoil spectroscopy was carried on in collaboration with the University of Michigan. Collaboration with Illinois Institute of Technology and ANL allowed the study of magnetic defect in the surface oxides, and the computational studies showing the presence

of substantial magnetic moments located on oxygen vacancies in the Nb_2O_5 was performed in a collaborative effort with Northwestern University.

These collaborative activities exploit the synergistic interests and capabilities of Fermilab and those of the collaborating universities and Laboratories. The ICPA provides a tremendous test-bed that is poised to make rapid contributions to the field. The capabilities that are now in place are ideal to support a vigorous R&D program that has already attracted one Peoples Fellow (A. Romanenko) and several Ph.D. students (2 as of FY10).

5.4 PROPOSAL FOR R&D PROGRAM IN 2011-2013 TIMEFRAME

ICPA operations will commence mid-way through FY11 after operational clearance and shake-down trials. Qualification runs will be completed using standard processing settings to attain process repeatability and high gradients in single-cell cavities. At the end of the qualification period, the same benchmark settings will continue to be used to process single-cell cavities to qualify vendors and to prepare benchmark cavities for other R&D purposes such as eco-friendly processing by external vendors.

At the end of the qualification period, scientific investigation of chemical processing will begin on 4 main thrusts:

- Chemical processing studies
  a) Cooling the outside of cavities with water to improve temperature control and evaluate "cold" processing at temperatures and acid flow rates not accessible by present tools. At present, acid flow is the primary coolant, so high cooling therefore results in excessive flow and breakdown of a quiescent polishing film.
  b) Adjustment of final acid removal and rinse steps to investigate passivation, or lack of passivation, of the niobium surface. Since passive coatings of Nb_2O_5 affect hydrogen de-gassing later, treatments at the end of an EP cycle such as an HF-only rinse may result in better kinetics.
  c) Bulk removal processing for 9-cell cavities will be transferred to cavity production activities.
- Mechanical processing/improvement studies
  a) Evaluation of single-cell cavities that have been annealed prior to welding and prior to electropolishing.
  b) Re-entrant 1.3 GHz cavities, which achieve 30% higher accelerating field than standard elliptical 1.3 GHz cavities, will also be explored, since mechanical polishing could provide a breakthrough by polishing of blind areas without residues of trapped acid.
  c) Early in FY11, R&D began exploration of final polishing in addition to bulk removal, and this resulted already in a single-cell cavity with the smoothest surface finish observed so far by any processing route. In fact, a final light EP, which improves the surface finish of chemically polished cavities, degrades the best surface finishes by mechanical polishing. This work will be given high priority to find processing recipes that completely remove dependence on acids.
  d) Adaptation of these processing routes to 650 MHz cavities will be explored to assess potential
- Fundamental materials science
  a) Monitoring of fluorine ion content via Raman, infra-red, and magnetic resonance spectroscopy as a function of processing time and parameter settings since the fluorine ion concentration gradient in proximity of the surface to be electropolished is believed to be critical to the success of the EP process.
- Nb coatings and substrate preparation

a) Ultra-smooth cavity surfaces provide ideal templates for film deposition. Mechanical polishing will be used to prepare copper or aluminum cavities as substrates for niobium deposition by collaborators. This approach could ultimately reduce the cost of 650 MHz cavities by reducing the niobium fraction at comparable cavity performance.

Both ICPA and the tumbling apparatus will use new coupon cavities. These unique cavities fit into processing tools and can be processed in an identical manner as single-cell cavities, and they contain openings that allow convenient extraction of small niobium samples for comprehensive study by probes of structure, composition, and properties. A wealth of knowledge is expected, including direct feedback for various processing parameters, assessment of how laboratory experiments on small coupons simulate real conditions inside cavities, rapid identification of tendencies that lead to major flaws, and so on.

Fundamental materials science studies will continue to focus on hydrogen and niobium hydride formation near dislocations, vacancies, interstitial oxygen, oxides, and other defects. Work during FY09-FY10 indicates this is now the most important area for understanding limits of SRF performance. Experiments will coordinate electron microscopy, various spectroscopy techniques, and numerical modeling. Work will ascertain how hydrogen associates with defects, whether defects are nucleation centers for hydrides, and how hydride precipitates change superconducting properties. The impact of these investigations will be improved understanding of how to optimize RF superconductivity, strategies to passivate the niobium surface, and treatments to reduce or remove the population of nucleation sites.

Work will also develop diagnoses, repairs, and metrics of quality for different processing stages. Laser melting and silicone replica techniques will be transferred to 9-cell cavity production activities.

One thrust of long-term work is the engineering of new SRF cavity processing innovations. Preparation of clean and mirror-smooth cavity surfaces is a means to tailor substrates for films and coatings. Long-term work may therefore expand toward R&D of niobium coatings on cheap substrates, multilayers, protective coatings, and superconductors other than niobium, and will exploit recent breakthroughs such as metal-plasma and atomic-layer deposition routes.

Since the important length scales that control superconducting properties lie between 5 and 200 nm, fundamental materials R&D will continue to be the primary means by which an understanding of how properties evolve from, or are impacted by, changes in structure, composition, and topography brought about by processing. Thus, a second thrust is to provide the foundation for processing techniques to validate their effectiveness, optimize their implementation, and determine targets for perfection. Such understanding will also point out opportunities for further innovations and breakthroughs.

5.5 RESOURCE NEEDS

Table 6 shows the requested funding for the proposed R&D program on "Superconducting Materials for RF Activities".

Project Title:	**SC Materials for SRF Applications**		
Organization:	**FNAL/AD**		
FY:	**2011**	**2012**	**2013**
Total (k$): SC Materials for SRF Applications	**1,921 k$**	**1,944 k$**	**1,961 k$**
M&S (k$):	**449 k$**	**428 k$**	**437 k$**

6 OTHER ACTIVITIES: ACCELERATOR MODELING AND JOINT APPOINTMENTS

6.1 DESCRIPTION OF THE R&D PROGRAM, GOALS AND SIGNIFICANCE

This research thrust gathers together multiple R&D activities. The Accelerator Modeling discussed here is supported by approximately 70% of the budget available in this category. The remainder 30% supports mostly joint appointments and PhD student appointments, not discussed in this document.

Accelerator modeling plays an important role in maximizing the performance of the existing accelerator complex, developing the beam dynamics designs for future Energy and Intensity Frontier accelerators, and for supporting the technology development activities.

The mission of the Computational Accelerator Physics activity area at Fermilab is to:

- develop computational tools with emphasis on realistic modeling of the physical system, including both beam dynamics and accelerator components
- develop applications of these tools working in collaboration with machine physicists and engineers
- provide expertise on the deployments and utilization of such tools, either developed at FNAL or by the community at large.

We emphasize the utilization of High Performance Computing (HPC) because of its benefits to high priority accelerator modeling activities at the lab. Fermilab leads ComPASS, a multi-institutional HPC accelerator modeling project funded by SciDAC, and has been a major center for developing and operating HPC clusters for lattice QCD for more than a decade, so our accelerator modeling strategies are well matched to strengths of the FNAL program.

The effort for the accelerator modeling activities discussed here is concentrated in CD/ADSS, but activities are closely coordinated with AD and TD personnel, in the context of the APC, to develop accelerator modeling applications. In addition, there is effort in CD/HPPCF to deploy and operate our local HPC accelerator modeling facility, used for quick turnaround of medium size HPC jobs that are inefficient to run on the dedicated supercomputing centers because of high queue latency.

Our activities are highly leveraged: synergies between project and capability development objectives allow us to use multiple sources of funding. There is a total of 5.5 FTE that is funded ~50% from GAD funds and ~50% from project funds: SciDAC ComPASS, Mu2e, and Project-X (and ILC in the recent past). The rationale for determining the funding source of a given computational activity is as follows: the development of new computational algorithms and codes is funded through the SciDAC project, high-level physics code development is funded by GAD , and application development and deployment is funded through project funds (for Project-X and Mu2d) or program funds (for ILC).

6.2 RECENT PROGRAM ACHIEVEMENTS

Regarding Accelerator Modeling Capability Development, the GAD program funded the development and support of the Synergia multi-particle beam dynamics framework and the CHEF single-particles optics code. Synergia is a PIC framework with full 3D capabilities. It includes many models, both native to the framework and through interfaces to other codes. Synergia emphasizes modeling of space charge and impedance effects, employing realistic descriptions of apertures and boundary conditions. It has both single-bunch and multi-bunch capabilities and its flexible design allows for fully dynamic simulations including ramping, feedback, etc. Synergia utilizes the CHEF libraries for single particle dynamics. CHEF, which was originally developed at Fermilab starting in the early 90's, is a single-particle optics code with full dynamics. During this period the GAD program added functionality to the multi-bunch capabilities in Synergia, implemented a model for

impedance calculations of laminated surfaces, developed new space-charge solvers, and developed a test suite to help development and users.

Examples and documentation to CHEF (aiming both general users and to help educate PARTI summer students) were completed, and model additions necessary for the Mu2e extraction design (fig. 17) were added.

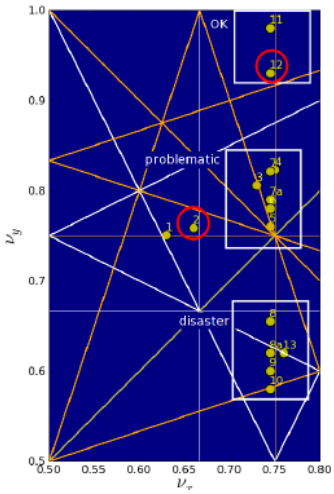

Figure 17: Preliminary studies on Mu2e extraction, showing unacceptable losses and therefore the need to change the extraction design

Regarding Accelerator Modeling Applications, in the past two years the GAD program funded the development of applications in support of high priority FNAL activities, such as RunII, Mu2e, and Project-X. Tevatron parameters were optimized by extending and validating the SciDAC code BeamBeam3D to model the machine. The essential features of the simulation included a fully 3D strong-strong beam-beam particle-in-cell Poisson solver, interactions among multiple bunches and both head-on and long-range beam-beam collisions as well as other effects. The studies were used to support the change of chromaticity at the Tevatron by a factor of two at the squeeze and new operational parameters led to beam loss reduction (fig. 18).

Electron cloud simulations of the Fermilab Main Injector experimental setup for electron cloud measurements were also pursued through the GAD program. Various configurations of the magnetic fields found around the machine and plasma waves associated with the fluctuation density of the cloud were analyzed, providing guidance to the experimental program.

GAD funding has supported efforts to simulate the beam dynamics of Fermilab's 8 GeV booster synchrotron, which serves as an injector to the Main Injector. Special emphasis was given to impedance effects which are thought to contribute significantly to the development of instabilities during the Booster cycle, because of the bare laminations of the combined function magnets that make up about 70% of the surface that the beam sees. In order to model the Booster, new 3D space charge solvers suitable for parallel-planes and rectangular vacuum chambers were included in Synergia. The simulations are in good agreement with measurements of coherent tunes as a function of charge and show that significant (~1%) losses are due to impedance effects in the machine. This is the first time ever that a simulation modeled all 84 Booster bunches, including both 3D space-charge and impedance effects.

On the interface between R&D and Project activities, GAD supported the development and deployment of the Fermilab Main Injector space charge simulations for Project-X parameters. This is a new task, requested by the project. The actual production and analysis effort will be funded by the project whereas the GAD program funded the implementation of the lattice and the evaluation of

numerical stability of the space-charge solvers for these parameters. Additionally, GAD supported space charge simulations of the Mu2E extraction design for the Fermilab debuncher. These are very important studies for the project since the interplay of the resonant extraction process and space-charge generates significant losses if not optimized.

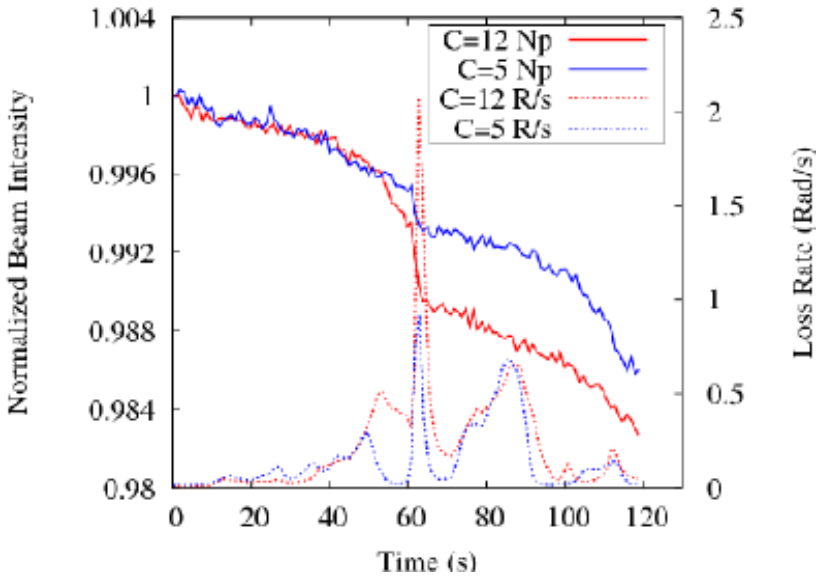

Figure 18: Studies to support change of Tevatron Chromaticity and reduction of losses at squeeze.

On the front of HPC Accelerator Modeling Support, the GAD program supported the commissioning of the RFSIMS cluster (commissioned on Oct 23rd 2007), a high-performance high-memory-per-node cluster dedicated to GdfidL runs and, lately, the new "Wilson" cluster. A list of some major applications that were run on theses clusters to support the SRF technology R&D at Fermilab is:

- GdfidL – Electromagnetic Field simulator for the computation of electromagnetic fields in 3D-structures. (http://www.gdfidl.de/)
- Analyst - Parallel FEM-EM (Finite Element Method-Electro Magnetic) solver. (http://web.awrcorp.com/Usa/Products/Analyst-3D-FEM-EM-Technology/)
- GAMESS - General Atomic and Molecular Electronic Structure System for a wide range of quantum chemical computations. (http://www.msg.chem.iastate.edu/gamess/)
- VASP – Vienna Ab-initio Simulation Package is a package for performing ab-initio quantum-mechanical molecular dynamics using pseudo potentials and a plane wave basis set. (http://cms.mpi.univie.ac.at/vasp/)

In May 2010 a Request for Purchase to procure Intel based nodes for the new Accelerator Simulations cluster was released to vendors and by mid September 2010 the new accelerator simulations cluster named the "*Wilson*" cluster was released to production. The "*Wilson*" cluster is aiming to provide both the functionality that RFSIMS did, and the functionality of heimdal, the APC HPC cluster that will be slowly decommissioned. The emphasis is on medium size HPC jobs that require fast turnaround.

6.3 SYNERGIES WITH OTHER LABORATORY AND/OR COLLABORATIVE ACTIVITIES

The GAD-funded accelerator modeling work leverages substantial resources at the laboratory level (in terms of HPC expertise and hardware) and within the high performance computing community (via the SciDAC program).

Students are part of these activities and although they may be funded by other sources, they work on topics that are either directly funded by GAD or enabled indirectly through GAD funded activities. Work directly funded by GAD includes work with FNAL accelerator graduate students (one graduate in the 2009-2010 period), FNAL summer and PARTI students (6 in the past 5 years).

6.4 PROPOSAL FOR R&D PROGRAM IN 2011-2013 TIMEFRAME

In the next three years we plan to continue the development and deployment of modeling tools and applications in support of the FNAL high intensity frontier program, and for Project-X. The GAD program will also continue to enhance the capabilities of application codes to allow for multi-physics, multi-scale modeling, and will begin R&D on computational algorithms that could be used on the emerging new HPC technologies (multi-core architectures which will require multi-threaded applications). More specifically we intend to:

- Construct a realistic model of the Main Injector, with realistic apertures and fringe fields, and use Synergia to model the beam dynamics at high intensity, namely:
  a) Space-charge effects
  b) Electron cloud effects in beam dynamics (using a semi-self consistent approach, where the electron cloud is calculated in VORPAL)
- Continue to study the Booster, using Synergia's multi-bunch, space-charge, and impedance capabilities. We will work closely with machine physicists and the proton task force to study instabilities and other effects that have been either measured or predicted to have an impact on beam loss and performance.
- Evaluate the Muon Collider design HPC modeling needs (space-charge modeling in cooling channels, beam-beam effects for the collider).
- Begin studying the performance of Poisson solvers and particle tracking on GPUs, using the CD/HPPC R&D GPU machine.
- Continue to support local HPC computations on our accelerator modeling cluster.
- Continue support of Mu2e extraction design. Synergia will be used to model and characterize the performance of extraction design options in the presence of space-charge.

In the long term, the physics and numerical algorithms will be imported to the new generation of supercomputers and the GAD program will continue supporting the FNAL high-intensity frontier and future lepton collider efforts.

6.5 RESOURCE NEEDS

The effort level is adequate for high-intensity frontier and Project-X support, but in order to participate in the Muon Collider effort, the GAD program will need an additional FTE (funded by a mix of project and base funds, following the current funding paradigm). Also, the FY11 request is higher by 0.8 FTE than the FY10, to account for the effort necessary for the new HPC technology R&D on developing numerical algorithms.

Table 7 shows the requested funding for the proposed R&D program.

Project Title:	**Other Activities (Acc. Modeling, JA, etc.)**		
Organization:	**FNAL/APC-CD--TD-AD**		
FY:	**2011**	**2012**	**2013**
Total (k$): **Other Activities**	**1,436 k$**	**1,575 k$**	**1,592 k$**
M&S (k$):	**511 k$**	**521 k$**	**532 k$**

7 CONCLUSION

The previous pages have shown the main thrusts of the Fermilab GAD program. We presented the world-unique achievements of this DOE funded activities with specific emphasis on:

- Development of superconducting magnet technology to provide ever-increasing magnetic fields, and
- Fundamental R&D on superconducting strands and cables
- Development of superconducting radio-frequency structures suitable for the acceleration of high average current, non-relativistic, proton/H- beams
- Fundamental materials R&D to understand limitations to achievable cavity gradients and quality factor
- Development of front-end injector and RF system technology for high intensity proton/H- beams
- Accelerator Modeling studies to understand and/or improve the performance of present or future accelerator facilities.

On all thrusts, the "deliverables" specified for this GAD program have been achieved, with the publication of new science and knowledge, in the form of basic understanding of materials and technology properties that make the construction of advanced accelerator equipment possible, the development and engineering of new accelerator equipment - in several cases achieving unique and world-record performance - and finally, with establishment and development of new tools, infrastructure and procedures to help further our technology knowledge and support continued R&D through the GAD program.

The obligations in FY09-FY10 and the budget request for FY11-FY13 have been presented. A worry-some decrease in the Fermilab GAD funding from FY09 to the just-budgeted FY11 is noticed with a total funding decrease of 7.1 M$. In order to upkeep the vitality of the program and the leadership role of the FNAL and US community in such unique achievements as the High Field Magnet Program or the Superconducting Radio Frequency structures for high-intensity hadron accelerators, we presented a program for FY12 and FY13 requesting a budget increase of approximately 2.3 M$ and 3.0 M$ respectively over the just-budgeted FY11.

8 PUBLICATIONS

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6.2 "Advanced computations of multi-physics, multi-scale effects in beam dynamics"J. F. Amundson, A. Macridin, P. Spentzouris and E. G. Stern J. Phys. Conf. Ser. 180, 012002 (2009). Presented at SCIDAC 2009: Scientific discovery through advanced computing program, San Diego, California, 14-18 Jun 2009

6.3 "Computation of electron cloud diagnostics and mitigation in the main injector" S. A. Veitzer, P. LeBrun, J. R. Cary, P. Spentzouris, P. H. Stoltz and J. F. Amundson [SciDac-COMPASS Collaboration]J. Phys. Conf. Ser. 180, 012007 (2009)

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