Fermilab's General Accelerator R&D Proposal

White Paper submitted to the 2014 HEPAP Accelerator R&D Subpanel

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This *White Paper* outlines proposed Fermilab's GARD Program *Elements*, matched to the *National GARD Thrusts I to VI*, recommended to the HEPAP GARD Subpanel by the Fermilab General Accelerator R&D Priorities Working Group and presented at the Subpanel's meeting at Fermilab on 09/27/2014, namely:

I. High-Field Magnets and Materials

1. SC magnets and materials R&D

II. Novel Techniques For Multi-MW Beams and Targets

1. Experimental R&D on novel techniques for high intensity accelerators at IOTA
2. High power targetry program

III. Cost-Effective SRF Technology

1. Cost-effective SRF technology for HEP accelerators

IV. Advanced Accelerator Concepts

1. Very high gradient/high-Q SRF cavities for TeV scale $e+e-$ colliders

V. Accelerator Science, Modeling & Design

1. Accelerator science, modeling and design of high intensity accelerators: high performance computing for beam simulations (instabilities, SC, losses and halo, energy deposition and collimation), beam studies and code validation, design concepts for next generation multi-MW beam facility.
2. Experimental studies and characterization of high intensity beam instabilities and losses
3. SRF science underlying the performance of superconducting cavities

VI. Core Accelerator Competencies

1. Accelerator training and education

The requested resources in FY16-FY20 for the Fermilab's proposal are discussed in Appendix 1.

Executive Summary

The 2014 Particle Physics Project and Prioritization Panel (P5) provided an updated strategic plan for the US HEP program necessary to realize a twenty-year global vision for the field. On the basis of the P5 vision, taking into account the needed balance between domestic and world priorities, between mid- and long-term, between theory, modeling, experiment and training, and between science and technology, the Fermilab's General Accelerator R&D Priorities Working Group have come out with following recommendation for the thrusts of the US National GARD Program (presented in detail in a separate White Paper submitted to the HEPAP Subpanel):

1. High-Field Magnets and Material
2. Novel Techniques For Multi-MW Beams and Targets
3. Cost-Effective SRF Technology
4. Advanced Accelerator Concepts
5. Accelerator Science, Modeling & Design
6. Core Accelerator Competencies

Fermilab's main R&D thrust toward a 100 TeV scale pp collider will continue to be the development of low-cost high-field accelerator quality magnets based on the Nb_3Sn technology in the near-term and on the hybrid of Nb_3Sn with the high temperature superconductors in the long-term.

We also propose an R&D program to explore transformative concepts enabling the next generation cost-effective multi-MW proton beam facility for neutrino research. Superconducting multi-GeV CW linacs could become a feasible option with substantial cost reduction in high power SRF technology. Alternatively, attainment of the required beam intensities in typically less expensive ring synchrotrons could be possible with greatly reduced particle losses due to space-charge forces, and collective and incoherent beam instabilities. For both avenues, high-power targetry technology needs to be considerably enhanced to contribute to the cost and feasibility of any multi-MW superbeam facility. Correspondingly, our proposal includes:

a) experimental studies of novel techniques to control beam instabilities and particle losses, such as integrable beam optics and space-charge compensation
b) exploration of the SRF capital and operating cost reductions through transformational R&D on high-Q cavities and innovative materials such as Nb-Cu composites, Nb films

and Nb_3Sn; cavity performance upgrades through novel shapes and field emission elimination

c) understanding the issues in multi-MW beam targets and developing mitigation techniques, new technologies and new designs

In order to support the above key mission of the Laboratory's program, it is critical to carry out experimental studies of high-intensity effects and to establish a center of excellence in beam theory, modeling and high-performance computation, so we can describe and reliably predict the behavior of the existing and new Fermilab accelerators in the multi-MW era.

The Fermilab program is designed to be a fully coordinated with other National Laboratories and complemented by strong University partnerships focusing both on science and education. Training of the next generation accelerator scientists and engineers remains a high priority.

I.1 SC Magnets and Material R&D

Rationale: According to the recent P5 report (May 2014), "*…a very high-energy proton-proton collider is the most powerful future tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window… The U.S. is the world leader in R&D on high-field superconducting magnet technology, which will be a critical enabling technology for such a collider*." The P5 report endorses (recommendation 24): "*Participate in global conceptual design studies and critical path R&D for future very high-energy proton-proton colliders. Continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs*."

Development of advanced SC high-field magnets (HFM), materials and technologies for present and future particle accelerators is one of Fermilab's core competencies. During the past decade the FNAL HFM program aimed at the 10-15 T accelerator magnets based on Nb_3Sn superconductor and demonstrated the first series of 10-12 T accelerator-quality dipoles and quadrupoles, and Nb_3Sn technology scale up, forming a strong foundation for the success of US LARP. This program also supported the development of magnet design and analysis methods and tools, extensive fabrication and test infrastructure, instrumentation, and provided a platform for training of young magnet scientists and engineers.

FNAL HFM R&D program, as a core part of a coordinated national and international effort, will develop and demonstrate next generation accelerator magnet technologies for the future world-wide Energy Frontier Programs, including the planned LHC upgrades and feasibility studies for a Future Circular Collider (FCC), and assess magnet cost reduction strategies.

Goals:

In collaboration with the U.S. national laboratories (LBNL, NHMFL), universities and industry

- Develop 15-16 T SC dipole magnets, suitable for the future 100 TeV pp collider design, based on Nb_3Sn superconductor and innovative approaches which would lead to a substantial reduction of magnet production, installation and operation costs.
- Develop very high field, 20-25 T, accelerator magnets beyond the limits of Nb_3Sn technology based on combination of LTS (Nb_3Sn) and HTS (Bi-2212 or YBCO) coils.
- Develop suitable SC materials (strands, cables, structural materials, etc.) for 15-25 T accelerator magnets.

Activities:

Phase 1: FY15-17.

1. *Development and test of a small-aperture 16 T* Nb_3Sn *dipole*. The baseline magnet design will use 4-layer cos-theta coils and cold iron yoke. To reduce the program cost and the development time the two innermost coil layers will use 60-mm aperture coils developed for the 11 T dipole with stress management based on an innovative "slotted" cos-theta coil design. This magnet could be used to test the first small HTS inserts in the framework of the proposed National HFM program.
2. *Design study and cost optimization*. Design concepts of twin-aperture 16 T dipoles based on the larger cables, graded coils, cold and warm iron yokes will be developed and compared with the goal of reducing the Nb_3Sn magnet cross-section by 50% and increasing its length by a factor of 1.5-2 to reduce magnet cost by a factor of 3-4 with respect to the present LHC main dipole. Results will be available for FCC CDR planned to be released by 2018.
3. *Development and study of* Nb_3Sn *and Bi-2212 strands and cables.* The work on the Nb_3Sn strands and cables will focus on the increase of the conductor current density at high fields and the cable transport current in collaboration with CDP and OST. The work on Bi-2212 strands and cable will concentrate on the development and demonstration of 10-20 kA class Bi-2212 cable for HTS dipole inserts. The Bi-2212 strand and cable R&D at Phase 1 will be partially funded by a FNAL Early Career Award (T. Shen) which will be integrated into the FNAL HFM program.

Phase 2: FY18-20.

4. *Development and test of a large-aperture aperture 16 T* Nb_3Sn *dipole*. This phase is an important step towards a 20+ T dipole. The large-aperture Nb_3Sn dipole will provide 15 T background field for the 5-10 T HTS insert providing a substantial reduction of magnet total cost. The Nb_3Sn magnet design will use 4-layer Nb_3Sn coils based on the slotted

cos-theta design developed in Phase 1. This development will also demonstrate the feasibility of large-aperture high-field magnets required for FCC interaction regions.

5. *Development and test of a small-aperture Bi-2212 5 T dipole insert.* Based on the results of Phase 1, the work will focus on the development of the design and fabrication technologies of Bi-2212 dipole inserts. A series of 0.4-0.5 meter long Bi-2212 dipole coils will be fabricated using overpressure HT and tested in background fields up to 15 T produced by Nb_3Sn magnets developed in Phase 1 and 2.
6. *Nb_3Sn and HTS strands and cables R&D.* Studies and optimization of Nb_3Sn and Bi-2212 strands and cables will continue in collaboration with Conductor Development Program (CDP), universities and industry in support of the HFM Program.

Phase 3: FY21-25.

7. *Development and test of a small-aperture 20-25 T accelerator-quality dipole based on HTS/LTS coils*. Based on the results of Phase 2 a series of 5-10 T HTS dipole inserts and 15 T Nb_3Sn dipole outserts with stress management to reduce conductor degradation and magnet training will be designed, fabricated and tested. Magnet operation margin, field quality and quench protection issues will be experimentally studied and demonstrated.
8. *Nb_3Sn and HTS strands and cables R&D.* Studies and optimization of Nb_3Sn and HTS strands and cables will continue in collaboration with CDP, universities and industry in support of the HFM Program.

II.1 Experimental R&D on Novel Techniques for High Intensity Accelerators at IOTA

Rationale: Progress of the Intensity Frontier accelerator based HEP is hindered by fundamental beam physics phenomena such as space-charge effects, beam halo formation, particle losses, transverse and longitudinal instabilities, beam loading, inefficiencies of beam injection and extraction, etc. The IOTA facility at Fermilab is being built as a unique test-bed for transformational R&D towards the next generation high-intensity proton facilities. The experimental accelerator R&D at the IOTA ring with protons and electrons, augmented with corresponding modeling and design efforts will lay foundation for novel design concepts, which will allow substantial increase of the proton flux available for HEP research with Fermilab accelerators to multi-MW beam power levels at very low cost. The facility will also become the focal point of a collaboration of universities, National and international partners.

Goals:

- Construct and commission the IOTA storage ring and its proton and electron injectors, and establish reliable and time-effective operation of the facility for accelerator research program.

- Carry out transformative beam dynamics experiments such as *integrable optics* with non-linear magnets and with electron lenses, and *space-charge compensation* with electron lenses and electron columns.

Activities: Phase 1: FY15-17

1. Construction of main elements of the IOTA facility: a) IOTA ring; b) electron injector based on existing ASTA electron linac; c) proton injector based on existing HINS proton source; d) special equipment for AARD experiments.
2. Commissioning of the IOTA ring with electron beam.
3. Study of single-particle dynamics in integrable optics with electron beams.

Phase 2: FY18-20

4. Commission IOTA operation with proton beams.
5. Carry out space-charge compensation experiments with nonlinear optics and electron lenses.

Phase 3: FY21 and beyond.

1. Study the application of space-charge compensation techiques to next generation high intensity machines.
2. Expand the program beyond these high priority goals to allow Fermilab scientists and a broader accelerator HEP community to utilize unique proton and electron beam capabilities of the IOTA/ASTA facility

II.2 High Power Targetry R&D program

Rationale: Advances in targetry are central to future physics facilities using intense, high-power particle beams. Fermilab has developed expertise in targetry through the experiences of designing and operating the Anti-proton Source target station, the MiniBooNE target station, and the 400 kW NuMI/NOvA target facility (now upgraded to 700 kW). These experiences have made Fermilab uniquely suited to identify and conduct targetry R&D activities required to meet the needs of the HEP program. Future plans for the Fermilab accelerator complex, guided by the recommendations from the 2014 Report of the Particle Physics Project Prioritization Panel (P5 Report), include a world-class 1.2 MW neutrino target facility (LBNF) in the mid-term and a multi-MW power upgrade to the neutrino facilities and to next generation, high-intensity rare process experiments in the far-term. Innovation in targetry is required to support this program. The P5 Report also expressed this sentiment on page 47: "*…high power targets, as noted at Snowmass, will address critical needs and should be included in GARD*."

Mega-watt class target facilities present many technical challenges, including:

- Radiation damage
- Rapid heat removal
- High thermal shock response
- Highly non-linear thermo-mechanical simulation
- Radiation protection
- Remote handling

The High Power Target R&D program (HPT) at Fermilab is focused on the development of enabling technologies for high power target systems and facilities to meet these challenges. Present work can be generally categorized into two areas of research, radiation damage and thermal shock.

Goals (10-year program):

- To enable well-justified design simulations of high intensity beam/matter interactions using realistic, irradiated material properties for the purposes of designing and predicting lifetimes of multi-MW neutrino and muon target components and systems. This requires:
    a. Irradiated material properties to be measured/evaluated for relevant targetry materials over a range of temperatures (300 – 1300 K), radiation damage (0.1 – 20 DPA (Displacements Per Atom)) and relevant helium production rates (500 – 5000 atomic parts per million/DPA)
    b. Thermal shock response to be evaluated for relevant targetry materials over a range of strain rates (100 – 10000 s^{-1})
    c. Development and validation of simulation techniques to model material response to beam over the time of exposure (accounting for accumulation of radiation damage and high spatial gradients)
- To develop enabling technologies in target materials, manufacturing techniques, cooling technologies, instrumentation, radiation protection, and related systems to meet the targetry challenges of multi-MW and/or high intensity (> 500 MW/m^3 peak energy deposition) requirements of future target facilities.

Activities:

In support of these goals, the following areas of research will be pursued:

1. Radiation damage studies - Continuation of studies into materials of interest (currently graphite, beryllium, tungsten and titanium alloys) under the RaDIATE R&D program, expected to include:
    a. Autopsy and Post-Irradiation Examination (PIE) of previously irradiated materials recovered from spent target components (e.g. NuMI proton beam window)
    b. Low-energy ion and high energy proton irradiations at suitable facilities (e.g. University of Michigan's Ion Beam Laboratory (MILB) for low energy ion irradiations; BNL 200 MeV BLIP (Brookhaven Linac Isotope Producer) facility for high energy proton irradiations)
    c. PIE of newly irradiated materials at suitable facilities (e.g. BNL's Isotope Extraction and Processing Facility, BNL/ANL synchrotron facilities, and/or the Radio-chemical Processing Laboratory, RPL, at Pacific Northwest National Lab, PNNL)

   d. Exploration of a cost-effective strategy for high energy proton material irradiations, possibly including a new facility, or upgrades to an existing facility, (greater than 30 MeV) to correlate low energy ion irradiations to high energy proton irradiations
   e. Development of testing techniques and equipment optimized for efficient analysis of irradiated materials (e.g. compact hot-cell compatible fatigue testing machine)
   f. Simulation studies to validate and/or correlate DPA/effects predictions among various simulation methods and existing empirical evidence
   g. Establishment of a web-accessible database of measured properties of irradiated materials of interest to the high power accelerator target community
   h. Continued leadership, organization and hosting of the RaDIATE collaboration (Radiation Damage In Accelerator Target Environments, www-radiate.fnal.gov/) as it expands to include more institutions
2. Thermal shock response studies:
   a. Several in-beam thermal shock experiments (including previously irradiated materials) at relevant facilities (e.g. HiRadMat at CERN)
   b. High strain rate testing of irradiated and unirradiated materials to develop strength and failure models
3. Additional engineering and material science studies needed to advance targetry technologies to meet high intensity, high power accelerator applications. These studies are expected to utilize expertise in nuclear materials and target engineering that exists within current and potential collaborators (e.g. BNL, PNNL, ORNL):
   a. High heat-flux cooling studies to achieve more effective cooling systems for high energy deposition density components
   b. Radiation protection studies to understand and better predict radiation transport and shielding effects (e.g. migration of tritium through shielding materials)
   c. Investigations into enhanced corrosion rates due to radiation and possible mitigation strategies and techniques
   d. Development of manufacturing technologies for advanced targetry applications (e.g. beryllium to aluminum joining technology)
   e. Scoping studies and prototyping of novel target design concepts (e.g. pebble-bed or granular targets)

These goals are shared by the entire high power targetry global community, including spallation source facilities, radioactive ion beam facilities, neutrino facilities, and materials irradiation facilities. Fermilab has coordinated and will continue to coordinate its HPT R&D activities with those and other facilities to enhance the research and leverage complimentary capabilities. This is best evidenced by the RaDIATE collaboration (currently consisting of 30 participants from 5 institutions), founded by Fermilab in 2013 to draw upon radiation damage and materials science expertise in fission and fusion research to implement a research program to benefit high power accelerator projects (www-radiate.fnal.gov).

III.1 Cost-Effective SRF Technology for HEP Accelerators

Rationale:

Fermilab's R&D program towards a cost-effective SRF technology for future HEP accelerators will address the P5 recommendation #26: "*...Align the present R&D program with the P5 priorities and long- term vision, with an appropriate balance among general R&D, directed R&D, and accelerator test facilities and among short-, medium-, and long-term efforts. <u>Focus on outcomes and capabilities that will dramatically improve cost effectiveness for mid-term and far-term accelerators</u>."* and recommendation #23: "*Support the discipline of accelerator science through advanced accelerator facilities and through funding for university programs. <u>Strengthen national laboratory-university R&D partnerships, leveraging their diverse expertise and facilities</u>*."

The proposal consists of two subprograms – cryogenic cost reduction and material cost reduction, and utilizes existing state-of-the-art SRF infrastructure at FNAL while leveraging collaborations with Cornell University, Jefferson Lab, LBNL, Alameda Company, CERN, and INFN.

Goals:

- Explore novel methods for the SRF cryogenic cost reduction
- Explore new approaches leading to the SRF material cost reduction

Activities:

SRF cryogenic cost reduction: SRF cavities enable a broad spectrum of accelerators with high duty factor, but require operation at low temperatures, and therefore expensive and sophisticated cryoplants. We propose three different routes to drastically lower the required power capacity and therefore capital and operational costs of such accelerators.

1. Mitigating field emission for operating SRF accelerators:

   Field emission remains a crucial additional dissipation source for SRF cavities, especially in some of the completed cryomodules, as demonstrated by the most recent experience of CEBAF upgrade project, and earlier by DESY FLASH. For example, for the CEBAF upgrade, the average onset field for the start of field emission dropped from 18 MV/m in the vertical test to 13 MV/m in the cryomodule, with only few cavities remaining completely free of field emission. Most field emission comes from accidental introduction of dirt during the cryomodule preparation steps of string assembly and coupler introduction. We propose to develop practical methods to reduce field emission by developing in-situ cleaning of cavities inside CM. We will explore CO2 snow-cleaning or wiping the high electric field iris regions to eliminate the accidental dirt introduced during assembly. Both methods have shown promise by work at other labs. If a cavity in a CM falls to below 20 MV/m we propose to investigate high pulsed power conditioning of emitters to lower the dissipated power due to field emission, another technique with proven promise.

2. Capital and Operating Cost Reduction by Raising the Q

   Recently it was discovered at FNAL that quality factors (Q) of bulk niobium cavities can be drastically increased by factors of 2-4 using the nitrogen doping procedure. Furthermore, changing the cool-down procedure around the critical temperature 9.2K was discovered as an additional way to minimize the trapped magnetic flux contribution to rf losses, and thus to preserve the ultralow surface resistance in the cryomodule environment. We propose to establish optimal parameters of doping and cool-down for the high Q Nb technology for different frequencies and operating conditions. We will also explore the underlying physics of both doping and the cool-down effects.

3. Raising operating temperature

   Increasing operating temperature of superconducting accelerator cavities to > 4.2K promises a dramatic increase in the cryoplant efficiency. Furthermore, cryogen-free operation may become possible for smaller-scale accelerators using economical cryo-coolers. The proof-of-principle exists that Nb3Sn cavities provide the same quality factors at >4.2K as bulk niobium cavities do at 2K .We therefore propose to start the development of Nb3Sn cavities at Fermilab in collaboration with Cornell University and benefit from the extensive Nb3Sn expertise gained in Fermilab Superconducting Magnets program. The plan is to start with the vapor diffusion method and use the existing set of advanced cavity characterization tools to understand limitations and guide the development.

SRF material cost reduction*:* The cost of bulk niobium is a major factor for SRF accelerators, especially for those relying upon low frequency (<650 MHz) elliptical cavities since the required amount of Nb per cell scales as $1/f^2$. As a practical example, for a small 100-cavity scale project involving 325 MHz elliptical cavities, the estimated cost of Nb alone is of the order of 10 M$. We propose to cut Nb costs by a large factor by using instead Nb/Cu clad technology or Nb thin films to make such accelerators cost-effective.

4. Nb/Cu composite cavities

   There exists a proof-of-principle that 1.3 GHz Nb-Cu composite based spun cavities, can reach high gradients. We plan to collaborate with Cornell University and use the existing Nb-Cu sheets to spin the cavities at INFN and US industry (e.g. AES) to complete the 650 MHz cavities with flanges as the first step followed by scaling to 325 MHz if successful. Testing of the f<=325 MHz cavities will be done in collaboration with Cornell which has the appropriate infrastructure - one of the Cornell test pits is large enough to fit cavities of such frequencies.

5. Nb/Cu thin films

   Recent breakthrough in Nb film deposition technology allows films of unprecedented quality with the residual resistivity ratio (RRR) approaching or exceeding 200-300, which is currently the standard for bulk SRF cavities . The rf properties of these films have yet to be tested. CERN is also working on improved Nb films by high energy deposition methods. As a first step we intend to collaborate with Jefferson Lab and Alameda Corp to obtain disk samples of these high quality films, and develop a compact host cavity that can measure their rf properties at frequencies down to 325 MHz. We will also collaborate with CERN to test the quality of their films. Given the confirmed low surface resistance on samples we then plan to proceed with 650 MHz Nb/Cu cavity prototyping followed by scaling to 325 MHz.

IV.1 Very high gradient/ high-Q SRF cavities for TeV scale e+e- colliders

Rationale: Vigorous research and development on high-gradient and high-Q SRF cavities is needed to address the P5 recommendation #11: "*...motivated by the strong scientific importance of the ILC and the recent initiative in Japan to host it, the U.S. should engage in modest and appropriate levels of ILC accelerator design in areas where the U.S. can contribute critical expertise. Consider higher levels of collaboration if ILC proceeds*" and attain one of the P5 longer-term goals: *"...For e+e– colliders, the primary goal is the ability to build the future generation accelerators at dramatically low cost, by improving the accelerating gradient, lowering the cost of materials and accelerator components and the power consumption*".

Goals: Two main goals of the proposed R&D program to address the P5 recommendations are:

- To develop a technological path for new-shape-SRF cavities to achieve a gradient 50-60 MV/m for the ILC energy upgrade to 1 TeV, with Q factors four times higher than ILC. The work will extend upon attainment of accelerating gradients ~50 - 60 MV/m which have been recently demonstrated for single-cell cavities with optimized geometries (as proof of principle) at several laboratories. Efforts to achieve this performance level in multi-cell cavities have started, but field emission at the higher surface electric field has been a major barrier.

- To explore the potential of Nb3Sn material to achieve accelerating gradient ~80 – 90 MV/m in multi-cell SRF cavities, together with high Qs necessary for high gradient operation.

  Using high power (MW) with short pulses, Cornell has recently demonstrated that the high temperature (T > 6K) performance of Nb3Sn follows the expected superheating field of the 18 K superconductor. When extrapolated to 2 K this leads to surface magnetic fields of 350 mT, as compared to Nb superheating field of 200 mT. These results imply that a well prepared Nb3Sn cavity with optimal shape will be capable of reaching 80 - 90 MV/m and high Q (due to the higher Tc of Nb3Sn).

Activities:

1. We plan to further optimize the geometry to reduce surface electric fields. Studies will include wakefield and beam dynamics modeling to adopt the best aperture which is a key parameter that sets the peak surface electric field.
2. In collaboration with Jlab and KEK, Fermilab will develop advanced techniques to eliminate field emission at the accompanying higher surface electric fields. These will include novel techniques such as CO2-snow cleaning.
3. RF losses increase with the square of the gradient, so that for gradients of 60 MV/m, Q values will have to increase by a factor of 4 over ILC. Novel techniques have been recently developed which allowed exceeding previously perceived theoretical “BCS barrier” and yield substantially higher Q’s. Fermilab will carry out a combination of high-gradient R&D with high Q R&D by combining the new doping methods with optimized geometry single cell and multi-cell cavities.
4. After the best shape has been determined R&D will be carried out in single cells, to determine the best path to no field emission and high Q. In the following years, the single cell program will be followed by 9-cell cavities.
5. Fermilab will install furnace inserts to fabricate Nb3Sn cavities by the best methods of today. Temperature mapping diagnostics will be carried out during RF tests to determine weak performing spots. After dissection these spots will be analyzed by surface analytic tools to determine process improvement strategies. These steps will be re-iterated until gradients above 80 MV/m can be demonstrated.
6. Parallel fabrication of 9-cell Nb3Sn cavities will be started to establish uniform coating in the complex geometry. The best procedures for 80 MV/m determined from single cell research will then be applied to the multicells.

V.1 Accelerator Science, Modeling and Design of High Intensity Accelerators

Rationale: In the next 10 years, following the P5 roadmap, Fermilab will have to commission and operate the accelerator complex to deliver 700kW for NOvA, and design and commission the PIP-II accelerators to achieve 1.2MW operation for the neutrino program. Furthermore, Fermilab will fully utilize the IOTA facility and its injectors with emphasis on the necessary R&D to advance the high-intensity accelerator program leading to a multi-MW source, and participate in design efforts for the next-generation accelerators that will drive discovery in the field. In order to support this program, we need to continue to develop expertise in theoretical and numerical modeling of high-intensity accelerators, further develop computational tools that will allow quantitative beam loss and beam stability predictions, further develop and maintain the tools necessary to support the high-power target program, and continue to deploy applications in support of Fermilab accelerator operations and design campaigns. We must further develop our computational tools and theoretical models to incorporate and fully understand utilization of non-linear elements that will be studied at IOTA and eventually utilize them to design the next-generation accelerators.

It is our vision that a fully coordinated national program of accelerator science and simulation is created, to provide the HEP community with a comprehensive, integrated set of state-of-the-art numerical and theoretical tools for multi-scale, multi-physics accelerator modelin and design. Within this program, it is our vision that Fermilab becomes *a "center of excellence" for theoretical studies and numerical simulations of high-intensity beam physics*, beam-material interactions and related energy deposition and radiological effects, promoting collaboration and establishing best-practices in this area, while we maintain the manpower and expertise to support design activities for high-energy accelerators such as future colliders.

Our vision is motivated by recommendation 26 of P5, focusing our plan on developing the infrastructure necessary for pursuing the physics associated with neutrino mass and exploring new particles, interactions, and physical models (two of the five physics drivers). Our activities aim to satisfy recommendations 14 (for PIP-II) and 24 (future proton collider), while our program execution follows recommendation 29 by establishing the framework for collaboration on software infrastructure.

Goals:

- High-fidelity modeling of collective effects in high-intensity accelerators to achieve quantitative beam-loss and beam stability prediction
- Development of theoretical models and highly accurate modeling of beam-induced radiation effects in machine components
- Theoretical and numerical modeling of non-linear accelerators leading to the conceptual design of the next-generation machines with integrable beam motion and/or space-charge compensation
- Establish a collaboration framework with the theory and simulation groups of US accelerator laboratories, CERN, and J-PARC, and coordinate numerical modeling work with the LBNL and SLAC high-performance computing programs. Within this framework establish partnerships with local universities to pursue specific R&D topics and train students.

Activities:

3. Computational tools development
    a. Development of algorithms for multi-particle effects that utilize co-processors (GPUs, MIC architecture) to allow for multi-million step simulations, necessary for accurate loss modeling. Incorporate to the Synergia beam-dynamics framework.
    b. Development of common interfaces and data representations necessary for interoperation of BDF and other accelerator codes

   c. Development of numerical models for non-linear elements and incorporation to Synergia.
   d. Develop detailed RF-cavity models for linac simulations and incorporate to BDF.
   e. Further improvements of the MARS code for highly-accurate simulation of beam interactions with accelerator and target components at the intensity frontier.

4. Theoretical model development
   a. Development of analytical and semi-analytical models to describe beam dynamics problems in accelerators.
   b. Further developments of theoretical models for microscopic and macroscopic impact of high-intensity beams on accelerator components.

5. Model validation
   a. Multi-particle and collective effect model validation and verification of quantitative beam-loss prediction with data from experiments at the FNAL Booster, Recycler, and MI.
   b. Verification of non-linear element theoretical and numerical model fidelity with data from IOTA experiments.
   c. Validation of tools for targetry using high-intensity beam data.

6. Design and modeling applications
   a. Booster, Recycler, and MI applications for 700KW operations (guidance for loss minimization).
   b. PIP-II accelerator chain for performance optimization, leading to 1.2MW.
   c. Design concept development for the next-generation booster for the post-PIP-II multi-MW accelerator complex upgrade.
   d. Support upgrades of existing and design of next-generation proton-proton colliders.
   e. Support new collider concept development (hadron and lepton beams)

7. Optics measurement
   a. Further development of the computational tools and their implementation for linear and non-linear optics to be applied to the FNAL complex accelerators leading to PIP-II

V.2 Experimental Studies and Characterization of Beam Instabilities and Losses

Rationale: Fermilab deals with instabilities and beam loss on a daily basis, but development theory, simulation tools and a comparison of predictions to observations should allow us to make reliable calculations of beam stability limits and to envisage means of beam stabilization for future higher-current and higher-power beams. Experimental R&D program needs to cover a number of important accelerator science and technology issues:

Electron cloud instability

Advanced extraction techniques

Collimation techniques

Novel injection and beam shaping techniques

Halo diagnostics

Fast feedback systems / dampers

Fermilab will carry out research at existing accelerators and test facilities to meet the needs of present and future high-intensity beam facilities.

Goals:

- Establish techniques to measure, suppress, and predict the formation of the electron cloud, and its effects on intense beams.
- Develop means of injecting and extracting beams in fast and slow configurations, using advanced techniques: laser-stripping, stochastic approaches, and extremely-high extinction.
- Pursue tools for the measurement and removal of halo beam and controlling losses, including halo measurement from 1% to 1 ppm of the beam, and two-stage collimation systems.
- Develop fast measurement, calculation, and feedback schemes to measure and suppress instabilities, including multi-bunch, and intra-bunch
- Study coherent beam stability limits in the machines with integrable optics

Activities:

1. Electron cloud experiments in the Fermilab accelerators. Several already exist in the Main Injector, but need to be extended to the other machines. A campaign is underway to measure the mitigation effects of various materials in the machines. Also need to establish on-line SEY monitoring and measurement techniques for electron cloud in dipoles.
2. Optimization of multi-turn foil stripping injection and interception of particle loss originating from injection
3. Laser stripping of H^- beam. An effort is underway to strip a small portion of the H^- beam in the Linac for injection notching. We will extend it to high-bandwidth chopping for the PIP-II Linac, then pursue R&D towards H^- injection via laser stripping at future, higher-proton energies. This last effort may be pursued in collaboration with ORNL/SNS.
4. Halo instrumentation / collimation
5. Dampers, including damping of high-order head-tail motion by bunch-bunch dampers
6. Study of beam stability in IOTA

V.3 SRF Science Underlying the Performance of Superconducting Cavities

Rationale: The primary objective of the GARD is described in the 2015 DOE budget request to Congress as follows: “HEP General Accelerator R&D focuses on understanding the science underlying the technologies used in particle accelerators and storage rings, as well as the fundamental physics of charged particle beams”. An exact match to this description is the research program to understand all the physical mechanisms affecting the SRF cavity performance, which is the primary goal of basic SRF science. Scientific understanding of performance limiting mechanisms (thermal breakdown, multipacting, field emission, Q disease) made possible past breakthroughs in accelerating gradients and quality factors, and is absolutely necessary to enable future ones. Fermilab's SRF program holds the skilled staff and world-class infrastructure adequate for leading this effort as evidenced by multiple recent discoveries (doping, effect of cooling rates) and physical understanding breakthroughs. The first recent breakthrough - high Q through N doping, which gives Q values higher than BCS limit - demands deeper physical understanding. A second breakthrough is reduction of residual losses by expelling flux leading to even higher Q values. The mechanism of efficient expulsion requires further investigations.

Goals:

- Understand the physical mechanism behind nitrogen doping effect in niobium, which leads to ultra-high Q values increasing with the accelerating gradient
- Understand the origins of the rf field dependence of the quality factor
- Understand the mechanism dominating the dependence of the magnetic flux expulsion on the cooling dynamics through critical temperature
- Extend high Q to highest gradients leading to cavities with high Q at 60 MV/m cavities for the TeV scale e+e- colliders
- Improve understanding of how material defects (i.e. nanohydrides and oxides) within the penetration depth affect the observed performance of SRF niobium cavities
- Use an extensive Fermilab SRF collaboration network with universities and other labs world-wide to complement the effort as needed: Cornell, SLAC, JLab, ANL, UIUC, UChicago, MSU, IIT, NHMFL, SLAC (USA); TRIUMF, UBC, Western Univ, Univ of Toronto (Canada); PSI, CERN (Switzerland); INFN (Italy); DESY (Germany)

Activities:

1. Fabricate cavities of range of frequencies and optimize the path to high Q via N doping and the flux expulsion to establish high gradient and high Q simultaneously.
2. Carry out surface analytical studies for thorough understanding of the surface.
3. Evaluate ultimate gradient limitations for novel preparations.

VI.1 Accelerator Training and Education

Rationale: Accelerator science and technology is inherently an integrative discipline that combines aspects of physics, computational science, electrical and mechanical engineering. As few universities offer full academic programs, the education of accelerator physicists and engineers for the future has primarily relied on a combination of on-the-job training supplemented with intense courses at regional accelerator schools. Fermilab's accelerator training and education program will put particular emphasis on the raising next generation of accelerator scientists and accelerator technologists for the US accelerator-based high energy physics at the Intensity Frontier.

Goals:

- Host and support the US PAS Office and its classes
- Establish a steady and adequate influx of highly qualified young scientists and engineers into the US HEP accelerator workforce through a combination of programs at all levels – from undergraduate to graduate to postgraduate.
- Establish an effective mechanism to get the US University professors and students involved into Fermilab beam physics research and development programs.

Activities:

1. Host and support the US PAS Office
2. Summer programs in accelerators for the US and International students
3. Joint appointments in accelerator science and technology with US Universities

APPENDIX 1

Under the P5 budget scenarios A/B, we propose to support activities I.1, II.1, II.2, III.1, V.1, V.2, V.3 and VI.1. **We propose to support activity IV.1 under the budget scenario C.**

The table below indicates the required resources for the proposed Fermilab's GARD program under the budget Scenario B (M$/Year).

R&D Thrust	M$	**M$**
I. High-Field Magnets and Materials		**5.6**
II. Novel Techniques For Multi-MW Beams and Targets		**9.3**
II.1 High Intensity Accelerators	6.0	
II.2 High Power Targets	3.3	
III. Cost-Effective SRF Technology		**4.3**
IV. Advanced Accelerator Concepts		**0**
V. Accelerator Science, Modeling & Design		**4.4**
V.1 Science, Modeling and Design of High Intensity Accel.	1.8	
V.2 Experimental Studies of Beam Instabilities and Losses	1.0	
V.3 SRF Science	1.6	
VI. Core Accelerator Competencies		**1.8**
Total (M$/year)		**25.4**