US-Geant4 Consortium
Multi-year Roadmap for Geant4 Development and Support

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Abstract

The Geant4 toolkit[1] fulfills a critical need for the simulation of high energy physics (HEP) detectors at the LHC and at other existing and future experiments and facilities. As LHC detectors come on line, the demand for support of Geant4 has increased. In order to meet this demand, the US component of the Geant4 collaboration should be strengthened and expanded.

US involvement in the development of Geant4 has been substantial since its early stages, and has increased with time. Several key Geant4 functionalities, including core framework and hadronic physics, are lead by SLAC staff, while significant contributions to the areas of hadronic physics and performance are made by the FNAL team. The involvement of LLNL and Northeastern University are foreseen in hadronic physics and multi-thread Geant4 development for multi-core CPUs, respectively. The lack of US involvement in the Geant4 electromagnetic physics working group has caused difficulties in the immediate support of US users. The importance of this domain prompts the need to increase US participation in this area.

The formation of a US Geant4 Consortium has strengthened the position of US institutions within the Geant4 Collaboration and increased their visibility and availability to Geant4 users in the US and around the world. It will also facilitate the participation of smaller institutes and universities, generating expertise among younger users and improving detector simulation support for the US HEP research program.

The core effort to develop and support Geant4 to meet the needs of the HEP program was historically funded out of the SLAC and FNAL base budgets for HEP. There is now a need to separate clearly the experiment specific support, which is not part of this roadmap, from the Geant4 specific work, and establish an appropriate level of commitment and funding for the latter. The present roadmap seeks to address this issue and sets out an initial three year program that is expected to start in FY 2011. An FY 2010 funding request, to be viewed as a transition to the roadmap, is being prepared separately.

1. Introduction

High energy and nuclear physics research as we know it today would not be possible without simulations. The massive production of event samples similar to those expected in the real experiments is an integral part of the process to design, build, and commission the highly complex accelerators and detectors utilized in experimental particle and nuclear physics. Simulations are also essential to develop the software tools, stress-test computing infrastructure, and analyze the data collected by the experiments.

1.1 The Geant4 Tool kit in HEP and Nuclear Physics

Geant4 is a toolkit for simulating elementary particles and nuclei passing through and interacting with matter[1]. It describes the tracking of particles through a geometry composed of different materials, their interactions with the electrons and nuclei they encounter and the creation of other particles in these interactions. Geant4 is the fully re-engineered Object-Oriented successor to Geant3, and a pioneering project to successfully adapt modern software engineering techniques to detector simulation in particle and nuclear physics. The tool kit is designed to model all the elements associated with detector simulation: the geometry of the system, the materials involved, the fundamental particles of interest, the generation of primary events, the tracking of particles through materials and electromagnetic fields, the physics processes governing particle interactions, the response of sensitive detector components, the generation of event data, the storage of events and tracks, the visualization of the detector and particle trajectories, and the capture and analysis of simulation data at different levels of detail and refinement.

Geant4 offers important advantages over other simulation packages, such as MCNP[2], EGS[3], or Fluka[4], also used within the HEP and nuclear physics communities. These include the ability to handle the most complicated and realistic geometries, coverage of most of the known physics processes for all kinds of elementary particles and nuclei required for detector simulation, the availability of several alternative physics models which allow the user to choose among them based on their needs of accuracy and speed, easy adaptation to users' software frameworks, and easy extension by users according to their particular needs.

The US HEP community of Geant4 users is very large. Most projects recommended by the US Particle Physics Project Prioritization Panel (P5) use Geant4 as their detector simulation engine[5]. This is the case for the ATLAS[6], CMS[7], and LHCb[8] experiments at the CERN Large Hadron Collider (LHC)[9]; the fourth LHC experiment, ALICE[10], is going through a migration process to Geant4. Geant4 is also the preferred simulation tool for generic detector R&D, as well as for all world-wide simulation activities which are part of the feasibility studies for the International Linear Collider (ILC)[11]. The demands on the Geant4 Collaboration are growing rapidly as the LHC experiments focus on quality physics and faster and more robust software, and also as new HEP projects adopt Geant4 as their main simulation engine. Nuclear physics experiments are also turning to Geant4, thus increasing the demand for support and development of low energy physics and scoring methods.

1.2 Geant4 in other Research Fields

Geant4 is a clear example of HEP software technology with transformational applications to other areas of scientific research. The Geant4 community of developers and users extends beyond HEP and nuclear physics into other areas such as space engineering, medical physics, education, and industrial applications.

In space engineering, Geant4 has been used to evaluate the amount of radiation in a space craft, to calibrate onboard detectors when a craft is in operation, to estimate the radiation dose received by astronauts and electronic devices in the International Space Station and in future manned missions to the Mars, and to simulate the radiation effects on semiconductor devices in space radiation environments.

Throughout the world of Medical Physics, the use of Monte Carlo simulation is growing. In many particularly exciting areas, such as particle therapy, mixed-mode imaging, and on-board imaging for dose verification, Geant4 has been the simulation tool of choice. Medical users value Geant4 because of its ability to simulate the dynamic motion of the geometries of patients and the treatment apparatus.

For developing educational software, Geant4 is an ideal tool not only because of its comprehensive physics coverage and flexible geometry description, but also because of its powerful visualization and interactivity. Several ongoing projects are aimed to teach the nature of fundamental particles and properties of radiation to college-level and even younger students.

Industry has also adopted Geant4 as a tool to design non-destructive systems for inspection and testing.

1.3 The US Geant4 Consortium

Geant4 development started with the CERN RD44 project[12] in 1994 and evolved into an international collaboration of more than 80 scientists from 30 institutions and 15 countries in 1999. SLAC was among the pioneer institutions, which also included CERN (Europe), KEK (Japan), IN2P3 (France), and INFN (Italy).

The SLAC group was involved since the early stages in both the Geant4 project and the BaBar experiment, which was the first HEP experiment in the world to officially adopt Object-Oriented techniques, C++ and Geant4. The SLAC team currently holds official leadership roles within the "international" Geant4 Collaboration in the areas of development, maintenance, and validation of the Geant4 framework (Asai), hadronic physics (Dennis Wright), and visualization (Perl). Makoto Asai also serves as deputy spokesperson of the Geant4 Collaboration. Asai, Banerjee, Perl and Dennis Wright are also members of the Geant4 Steering Board. SLAC experts provide support for the ATLAS and BaBar experiments, Fermi Gamma-Ray Space Telescope (FGST)[13] project, and the ILC detector design studies. The SLAC group also organizes and delivers training sessions for the HEP, nuclear, space, and medical application users throughout North America.

FNAL joined the Geant4 Collaboration in 2007 undertaking major responsibilities in the areas of hadronic physics validation, and code performance and robustness. FNAL has provided support to the large US CMS community of users at the Fermilab-based LHC Physics Center (LPC) since 2004, and has also been involved in supporting the generic detector and ILC research activities. Members of the FNAL group have recently served as coordinators of the CMS simulation group (Elvira) and calorimeter simulation task force (Banerjee). The FNAL team possesses extensive experience in the areas of parallel computing[14], hadronic and electromagnetic cascades and particle transport, as well as simulation of accelerator facilities. Groups from Lawrence Livermore National Lab (LLNL) and Northeastern University (NU) have expressed their interest in joining the Geant4 collaboration to contribute to hadronic physics and the development of multi-threaded Geant4 for multi-core CPUs, respectively.

As of October 1st 2008, the total number of full time equivalents (FTE) active within the Geant4 Collaboration was 24.8 FTE. Among these, US institutions are contributing 3.9[2]. The core effort to develop and support Geant4 to meet the needs of the HEP program was historically funded out of the SLAC and FNAL base budgets for HEP. There is now a need to separate clearly the experiment specific support, which is not part of this roadmap, from the Geant4 specific work, and establish an appropriate level of commitment and funding for the latter. This roadmap sets out a plan to build a strong US Geant4 Consortium of institutions and researchers with the skills and motivation to address the remaining challenges which Geant4 faces in the areas of core software infrastructure and physics. We propose to expand the Geant4 involvement of US institutions to 14 FTE, 7 of which are new hires, as a necessary step to sustain the growing needs of the US HEP and nuclear physics communities in light of their strategic plans for the decades to come. In the following sections, we describe the state of the major core Geant4 components and related activities where US Geant4 developers are currently involved, as well as the work plan to be executed by the US Geant4 Consortium.

2. Project Categories

We have identified five project categories or areas where we propose that the US Geant4 Consortium contribute: hadronic physics, electromagnetic physics, software framework, performance & Q/A, and documentation & user-support. Each of these categories typically corresponds to a working group within the Geant4 Collaboration.

2.1 Hadronic Physics

Hadronic interactions are complicated. Due to the non-elementary nature of the hadrons themselves, no single theoretical description is sufficient to cover the range of energies and kinematics observed in high energy physics detectors. It is therefore natural to combine several of these models to describe hadronic interactions over a wide range of energy; Geant4 has adopted this strategy and provides users with physics combinations of models known as “physics lists”.
One of the most difficult regions to describe is the so-called intermediate energy domain, namely

2 The SLAC core Geant4 effort has been reduced by 3 FTEs with respect to October 2007 due to budget limitations.

from a few hundred MeV to 20-30 GeV of incident hadron energy. Nuclear physics models break down at these energies and models based on QCD are applicable only above 20-30 GeV. Physics models in this energy range are critical for calorimeters because they determine energy resolution and many aspects of hadronic shower shape. Three models are currently available in this domain, the Bertini-style cascade[15], the Geant4 Binary cascade[16], and the Low Energy Parameterized (LEP) model. The latter model is a re-engineered version of the Fortran code GHEISHA[17], depends largely on parameterizations of hadronic showers, and is used at least in part in all Geant4 physics lists. The Geant4 Binary cascade uses a theoretical treatment of hadron resonances and the intra-nuclear cascade to predict the hadronic final state, but it is somewhat slow. The Bertini-style cascade model lies conceptually, and in time performance, between the LEP and Binary cascade model. It performs a detailed simulation of the intra-nuclear cascade, but employs more parameterization than the Binary cascade. The Bertini model is currently favored by the ATLAS and CMS experiments, on the basis of comparisons with test beam data. At higher energies there are two theory-driven models: Quark Gluon String (QGS)[18] and Fritiof string (FTF)[19]. In addition there is the High Energy Parameterized (HEP) model which originates from GHEISHA. These models have different levels of success in explaining the data and are somewhat complementary with respect to each other. The QGS and FTF models are sometimes coupled with the theory-driven CHiral Invariant Phase Space Model (CHIPS)[20], which is used to describe the decay of highly excited nuclei. Within Geant4 it is applied to the capture of stopped particles, certain low energy, in-flight interactions, and the de-excitation of the remnant nucleus after high energy interactions.
The low energy regime is important not only to nuclear physics experiments, but also to LHC experiments. By far the most accurate treatment of neutron backgrounds, a perennial problem in HEP detectors, is obtained with the High Precision (HP)[21] neutron model, a mostly data-driven model, which is valid for neutrons of 20 MeV and down to thermal energies. HP depends on neutron data from at least seven separate sources, some of which are subject to export control laws. A good treatment of low energy neutrons is central to nuclear physics experiments, not only for shielding and background studies, but also for reaction rate studies and cross section measurements. Models describing low energy photons, protons, neutrons and light ions are also essential, and are provided by the evaporation and pre-compound models in Geant4.

Physics models need to be validated against existing experimental results, both from thin target experiments, and real HEP detector configurations. When more than one model is available in a given regime, validation results can be used to choose among them and combine them into optimal physics lists.

2.1.1 Current US Geant4 Effort in Hadronic Physics

The SLAC team is in charge of the LEP and Bertini codes. This includes development, maintenance, bug fixes and documentation. SLAC and FNAL currently collaborate on the upgrade of the Bertini code. The FNAL team is responsible for physics validation of all Geant4 hadronic codes in the intermediate energy region. Feedback from validation has already resulted in significant improvements to the Bertini code. Test beam validation work has also unveiled flaws in the Bertini code that require further study. The LEP model, based on experimental results of the 70's and 80's, is showing its age. This model will not be enhanced any further, and only non-physics-related bugs will be fixed in the future. Continuous maintenance of this package is, however, essential in order to retain performance and consistency with other Geant4

updates. The development of the Re-Parameterized GHEISHA (RPG) code to replace LEP, a joint project of SLAC and FNAL, is currently underway but is understaffed. The final tuning of RPG will require significant resources, be time consuming, and depend heavily on the validation results in the medium energy region.
The FNAL performance team has recently made changes to the CHIPS code that yielded gains in memory and time performance. Several key improvements were made to CHIPS in the area of elastic and quasi-elastic scattering, and in the treatment of stopping particles. The factorization of CHIPS following a code review will be important to allow its different physics functionalities to be used separately.

The Quantum Molecular Dynamics (QMD) model to describe nucleus-nucleus collisions is under development by the SLAC group, and still needs significant validation and testing before its formal release. SLAC also holds responsibility for the maintenance and bug fixing of the High Precision neutron code. To remedy problems related to shortcomings and export control restrictions associated with HP, a replacement model is being developed by a collaboration of LLNL and SLAC. LLNL is currently evaluating low-energy nuclear data as part of its national security mission. For this reason, LLNL has produced and maintains, under separate funding, a unified and modern method of accessing data from all world-wide nuclear reaction data sets, such as ENDF, JENDL, JEFF, CENDL, and Maslov. In collaboration with SLAC, LLNL will develop an interface that would allow Geant4 to easily incorporate these data into a new, data-driven nuclear interaction model.

The FNAL team is developing and maintaining a website summarizing the results of validation of the physics models with published data.

2.2 Electromagnetic physics

The electromagnetic (EM) interactions of charged particles and photons with matter are modeled in Geant4 by two separate packages. The Standard EM Physics package[22] simulates EM interactions in the 1 KeV to 10 PeV energy range; it was optimized to cover the needs of the HEP community, including BaBar and the LHC experiments[23]. The Low Energy EM Physics package[24] targets mostly the space and medical communities, modeling photons and electrons down to 250 eV and even lower, and other charged particles down to1 KeV. Following the recommendations from the 2007 external review[25], the G4 collaboration has recently embarked in combining the two packages in a unified environment.

The response of a HEP detector to incident charged particles is dominated by the EM interactions. A simulation tool with a precise description of the underlying EM physics processes is a first step to achieve an accurate modeling of the signals associated with photons, electrons, and all other charged particles in calorimeter and tracker systems. Along this direction, the Standard EM Physics package was recently improved to achieve more stability of energy deposits as a function of simulation parameters, such as the thresholds on the production of secondary particles and the step size used in the integration of the equation of motion. Detectors with a thickness as small as a few tens of microns can now be reliably modeled. This required substantial improvements in the physical detail of the multiple scattering and ionization models which were introduced at the cost of an increase in execution time. With fine-grained detectors becoming the norm in HEP, performance optimization is essential to deal with limited computing resources.

2.2.1 Current U.S. Geant4 Effort in Electromagnetics

Apart from the involvement of SLAC in the validation studies of the Geant4 electromagnetic physics in relation to the needs of Fermi Gamma-ray Space Telescope (FGST), there has been no significant US participation in the development or optimization of the Geant4 EM physics packages. The EM physics effort is weak within the whole Geant4 collaboration, and it is particularly understaffed in the areas of validation, time and memory performance. It is of strategic importance for the US Geant4 consortium to contribute to these tasks and gain the necessary expertise to provide support to the community of users in the US.

2. 3 Software Framework

The software elements which provide the framework or essential functionalities of the Geant4 system form the Geant4 "kernel". Since the mid 1990s, when Geant4 was designed and implemented for the first time, its complexity has grown significantly. Complexity reduces the code robustness and maintainability, and makes it increasingly costly to add functionality. The requirements from multi-core and multi-thread computing also bring the topic of software reengineering to the table. The Geant4 collaboration is therefore scheduling an architecture review within the next few years, targeting the post-LHC startup era. The major involvement of SLAC in the Geant4 kernel, places the US Geant4 consortium in a unique position to make relevant contributions to the redesign of the Geant4 architecture, and implementation of new framework functionalities.
There are two other major areas of work that need urgent attention: the reorganization and enhancement of event biasing techniques, and the extension of scoring options.

Event biasing refers to the enhancement of rare or interesting processes by the manipulation of physical parameters such as cross sections or energy deposition. For example, a probability distribution would be modified to enhance or suppress a particular physics process. The demand of event biasing options in Geant4 is high not only in HEP but also in other fields such as the space and medical sciences; it is also used to develop techniques for non-destructive inspection. This topic is a good example of synergy between the physics, space, medical applications of Geant4, and a good opportunity to leverage effort and funding.

Scoring is a mechanism for recording the values of Geant4 quantities which are not directly measured by a real detector. An example would be the total simulated energy loss of a charged particle in a volume which represents both active and passive elements of a detector. The associated values are typically calculated at the nodes of a net, built along the axes of a Cartesian, cylindrical, or spherical coordinate system depending on the detector geometry. Originally, the demand for a user friendly scoring functionality for commonly used physics quantities, such as maps of dose deposition, came from the space and medical communities. Today the demand arises from the needs of HEP experiments. The design of radiation hard sensors and readout electronics for the LHC upgrade depend on a good understanding of neutron flux and radiation dose distributions.

2.3.1 Current US Effort on Software Framework

SLAC holds responsibility within the Geant4 Collaboration for the development and maintenance of a significant part of the Geant4 kernel, such as the software associated with the concepts of "run", "event", "track", and "particle". New initiatives, however, are largely on hold due to the lack of human resources. These include the development of event biasing and improved scoring options. Geant4 currently offers biasing of the primary particle, radioactive decay, hadronic cross section, etc. The biasing functionality needs to be extended to electromagnetic processes in addition to the current implementation for hadronic processes. It also offers scorers for more than 20 physics quantities represented in a Cartesian coordinate system.

2.4 Performance, Robustness, and QA

Code performance improvement is a vital part of Geant4 development, since key uses of Geant4 involve serious time on large numbers of processors. Reducing the cost of a given calculation also exposes options for increased accuracy, for example by simulating more events, tracking with smaller step sizes, or incorporating more complex (but more realistic) physics models. Another important quality of a major software system is the degree of robustness and maintainability. While Geant4 is neither particularly unstable nor rife with bugs, the code has much room for improvement in maintainability.

As the clock rate of CPUs stopped increasing, the world started to move to multi-core CPU systems. Much of the software systems developed for numerical analysis adapted to this new hardware architecture. HEP software, however, continues to run single-threaded processes under the control of a script. This is possible because HEP individual events are basically independent of one another, apparently allowing HEP to reap the full benefits of Moore's Law with each new generation of CPUs. As HEP computing centers installed 2-core, 4-core and now 8-core computers, the strategy of choice has been to simply run 2, 4, and now 8 independent processes on a computer. This approach does not scale to future multi-core computers, in part because HEP toolkits and their applications consume large amounts of memory which is expensive in dollars, power and cooling, and in part due to memory bandwidth and I/O bandwidth limitations. It is widely agreed that the long term solution for HEP software is to have greater sharing of the data segment among the multiple processes. There are two primary methodologies to accomplish this:

- Multi-processing: forking child processes and taking advantage of copy-on-write semantics to continue to share pages of RAM that each process may have read, but never written to. Initial indications show that although large sharing could be possible in Geant4, the original design had emphasized the best practices of its time: sharing of read-only and read-write data for greater locality of objects. Hence, each page of RAM is typically "polluted" by a small amount of read-write data.

- Multi-threading: representing each original process as a single thread in a new, larger process. This approach has been avoided until recently due to the difficulty of reading through the million lines of Geant4 code. Only a semi-automatic approach would guarantee thread safety with each new release. Separation of read-write data from read-only data in objects is also an issue in this approach.

2.4.1 Current US Effort on Performance, Robustness and QA

The FNAL Geant4 performance team focused on improving time performance by optimizing functions that took more than 2% of total CPU time. To be able to analyze the code at this level of understanding, the FNAL group developed sophisticated performance measurement tools (SimpleProfiler) which allow to deal cleanly with ensembles of jobs run on the grid, track full call paths, and distinguish subroutines and system activities. Taking the CMS simulation application running the QGSP physics list as the benchmark code, and utilizing these analysis tools, the execution time was recently reduced by a total of approximately 7%. Improvements to the method for memory allocation also yielded CPU gains and lower memory consumption.

In addressing the issues of multi-core computing, the Northeastern group has already made a breakthrough, implementing both a multi-processing copy-on-write strategy (forking child processes) and a multi-threaded strategy for Geant4[26]. The semi-automatic process for the multi-threaded implementation affects about 10,000 lines of code and only includes sharing of the physics tables for G4VEnergyLossProcess and G4VMultipleScattering. Even this reduced 22 MB of non-shared data per thread will affect performance in future many-core CPUs. More work is required to fully automate these modifications to the evolving Geant4 code. To address the concern about reliability, a novel algorithm is being proposed by the Northeastern group to efficiently detect any thread race conditions that are introduced by the automated modifications to the Geant4 code. The FNAL group also has substantial experience and expertise on parallel systems, some of which stems from lattice QCD computing. The plan is to leverage work that is starting on multi-core running for CMS.

2.5 Documentation and User Support

It is critical for the Geant4 Collaboration to provide complete and user friendly documentation, given the large and diverse community of users and the flexibility requirements on the Geant4 toolkit. The Geant4 main page1 on the World Wide Web includes a link to a "Users Support" site with information on the tool kit installation procedure, a set of frequently asked questions, instructions on how to report bugs, and a link to the material offered in training courses. The "Users Support" site also contains a set of documents such as guides for application developers and for toolkit developers, a physics reference manual, and a software reference manual. Release notes describing changes in the code and the expected effects of such changes on running applications are also available in the "Download page" under "User Support". A repository of physics validation results is available under "Results and Publications", providing users and developers information on how the various physics models physics list perform and compare with each other.
Contact information is also provided to allow users to interact directly with Geant4 group leaders. Support is also offered through many Geant4 developers involved in HEP and nuclear physics experiments.

Document maintenance to keep up with the additions and improvements to the Geant4 toolkit poses a continuous and significant challenge to the Collaboration. Following comments and recommendations by users and an external review committee to improve documentation to allow users to find what they want easier among the sheer volume of available material, the Geant4 Collaboration recently re-designed its web page, updated the user guides, and expanded the physics validation repository.

2.5.1 Current US Geant4 Effort on Documentation and User Support

US Geant4 institutions are very active within the documentation working group, pioneering efforts to increase user involvement through the organization of user workshops and participating in HyperNews list discussions. The SLAC team is the leading force behind the Geant4 tutorials[27], developing the material and teaching the classes all over North America. Budgetary constraints and the demand of direct involvement of the SLAC Geant4 team in the support of LHC experiments have caused this effort to be curtailed. The FNAL group has recently re-designed and improved the hadronic physics validation repository, and took responsibility for further development and maintenance of this repository and the associated web site[28].

3. Roadmap Work Plan

The deep involvement of the majority of the scientists on this roadmap in the simulation activities of the LHC experiments and the wider US high energy physics program will continue. This will ensure the proper focus and relevance of the Geant4 work that we propose. We will leverage the experience of the core group of senior scientists who will take responsibility for ensuring the execution of the work, using the majority of the proposed funding for young physicists working under their guidance.

The following sections provide a general description of the activities associated with the roadmap work plan in the different areas. Detailed information about human resources, deliverables, and times lines is provided in Appendix B.

3.1 Hadronic Physics

For nuclear physics and HEP experiments it is of fundamental importance to be able to trust the simulation application to model hadronic showers with accuracy. Geant4 is the simulation engine used by most of the current and future generation of experiments. We therefore plan to address long-standing and urgent issues that need resolution in the area of hadronic physics. The US Geant4 consortium should continue and expand involvement in the development and maintenance of critical hadronic models such as Bertini Cascade, Low and High Energy Parameterizations (LEP, HEP), and Chiral Invariant Phase Space (CHIPS). We also plan to develop the Re-Parameterized Gheisha (RPG) model as a modern replacement for LEP, implement new data-driven neutron models to replace existing ones, continue the work on the Quantum Molecular Dynamics (QMD) model and its validation, and strengthen the validation software effort including a repository of related documentation.

3.1.1 Management

- Continue to coordinate the Geant4 Hadronics Group (SLAC).

3.1.2 RPG Model

- Full implementation of conservation laws for discrete symmetries (FNAL).
- Extend the parameterizations for all stable particles beyond pions, kaons, and protons. This involves research for available experimental data and software implementation (SLAC, FNAL).
- Tune model parameters and validate against all data, both from thin targets for code verification and complex HEP detectors. (SLAC, FNAL).

3.1.3 LEP, HEP Model

- Maintain the LEP and HEP code by providing user support and bug fixes (SLAC).

3.1.4 Bertini Cascade Model

- Improvement of quasi-elastic scattering model for incoming particles with the nucleus (SLAC).
- Addition of theoretical features missing in the original Fortran implementation, including correct angular distributions (SLAC).
- Code verification and validation of the energy domain covered by the Bertini model and the transition region against available data (FNAL).

3.1.5 CHIPS Model

- Factorization of physics elements in the CHIPS model, for example the handling of elastic scattering and stopping particle (FNAL, SLAC).
- Algorithmic changes in the CHIPS code, as suggested by the software performance team. This may introduce different numerical calculations, while keeping similar physics results (FNAL).

3.1.6 New Models and Features

- Benchmarking and refining event generators for arbitrary projectile particle or heavy ions in the phase space regions where Geant4 has shortcomings (FNAL).
- Integration of recently developed modules for muon interactions and photo-production in the poorly understood low energy region below a few hundreds of MeV, including particle production and X-ray emission for stopped muons (FNAL).
- Generation of displacements-per-atom (DPA) in detectors or accelerators components due to radiation damage (FNAL).
- Code verification, benchmarking, and validation against available data of each new model (FNAL).

3.1.7 High Precision Neutron Models

- Maintenance of the current HP model supported by Geant4 (SLAC).
- Development of a replacement for the High Precision neutron model. This includes the implementation of inelastic scattering, capture and fission reactions, and the interface to the

LLNL database (SLAC, LLNL).
- Improve data-driven low energy neutron simulation (SLAC).

3.1.8 Validation Repository

- Identify regions of phase space where validation has not been performed and a community of experimenters and power users willing to contribute to the validation activity (FNAL).
- Comprehensive search for available data useful for validation of hadronic models, and periodic updates to the web based validation repository (FNAL).

3.1.9 QMD Model

- Validate model over current range of applicability (SLAC).
- Extend data sample to be used for model validation (SLAC).
- Identify models which can extend the energy range to below 50 MeV/N and above 10 GeV/N (SLAC).
- Develop or extend the identified models (SLAC).

3.2 Electromagnetic Physics

We plan that US institutions should take the responsibility in the areas of model validation and testing (SLAC and FNAL in close collaboration with CERN), and optimization for memory and time performance (SLAC based on FNAL code review).

3.2.1 Optimization for Memory and Time Performance

In the current design of the EM physics and material description modules, materials constructed from exactly the same constituent elements but differing in density must be defined separately. This results in large EM cross section tables that take significant memory resources. One use case is the simulation of air showers, where the density of the atmosphere varies as a function of altitude. Time and memory performance can be greatly improved by defining a single cross section table per material, based on its unit density where each EM interacting particle stands.

3.2.2 Validation and Testing

The physics validation of the full Geant4 electromagnetic suite is a challenging enterprise which is largely incomplete. Users and reports from Geant4 external reviews have indicated that the existing validation suite should be expanded in breadth and depth. Although a few key processes and specific applications are available, the validation suite does not cover the full range of high energy applications. We propose the following plan of work:

- Redesign of validation suite, data search and expansion of suit to include tests of newly available data, unit and system testing (SLAC in close collaboration with CERN).
- Compare Geant4 to MARS[29], a Monte Carlo code for inclusive and exclusive simulation of three-dimensional hadronic and electromagnetic cascades. Benchmark the two simulation tools against data to understand differences observed in simulation of accelerators and beams (FNAL). Part of the difference is attributed to the different treatment of multiple Coulomb scattering in Geant4 and MARS.

3.3 Software Framework

The moment has come for a careful review of the Geant4 architecture and eventual redesign in view of the challenges of the post-LHC startup era. We plan to leverage SLAC's current involvement in the Geant4 software effort by expanding the US contribution in the following areas: reorganization and enhancement of event biasing techniques, extension of scoring options, and review of architecture for future reengineering.

3.3.1 Reorganization and enhancement of event biasing options

The current level of activity in this area is close to non-existent due to the lack of man-power; the first goal is therefore for a new hire to resume the effort working closely with SLAC experts. In addition to the implementation of biasing in the geometry and physics models, we propose to implement a Reverse Monte Carlo in close collaboration with CERN and other European institutions. This tool is useful in cases where the dimension of the whole detector is much bigger than its sensitive parts, and the source is extended (not a beam). While the traditional Monte Carlo method spends most of the computing time in tracks that do not contribute to the detector signal, the Reverse Monte Carlo performs backward tracking from the sensitive region to the external source.

3.3.3 Development of a roadmap for re-engineering Geant4 software

SLAC is in a privileged position to contribute to this topic given their leadership role within the Geant4 global architecture team. This activity includes a review of the Geant4 architecture, the development of a re-engineering roadmap with a risk assessment, and the achievement of consensus within the Collaboration. Close communication with all working groups is essential for the success of this challenging task. The re-engineering itself could start within the period covered by the current roadmap, but will take several more years to complete.

3.4 Performance, Robustness, and QA

We propose that the US Geant4 Consortium continue to pursue or initiate: the completion and productization of performance analysis tools, the identification and exploitation of opportunities to improve speed, as well as reviews and other QA-related efforts aimed at code robustness. In addition, we intend to meld information available on modern chips, about cache behavior and other relevant multi-core data, into performance analysis tools, and use these to investigate getting superior multi-core performance.

3.4.1 Profiling

- Polish and productize the SimpleProfiler tool, developed at FNAL and in use for Geant4 analysis at this time. Make it available in a useful form to the Geant4 collaboration (FNAL).
- Use performance analysis tools to obtain a quantitative evaluation of the CPU cost of different physics choices. Make this information available in a form useful to Geant4 users (FNAL).
- Create a basis for estimating how much performance improvement might still be available, and at what cost in software effort (FNAL).

3.4.2 Coding Technique and Algorithmic Improvement

- Identify, implement, and measure the effect of pure code technique improvements, which in principle do not change the output but improves execution speed or memory usage (FNAL).
- Develop mathematically equivalent implementations of algorithms, which can result in speed improvements in places identified as taking significant execution time. Validate that the results are identical in physics content (FNAL).
- Investigate possible yield of algorithmic changes, which need to be considered both from the physics and the computing points of view. These potentially can result in large speedups. This sort of activity will be done in concert with the physics experts (FNAL).

3.4.3 Development multi-threaded Geant4 for multi-core CPUs

Northeastern University, SLAC, and FNAL will collaborate in the following phased tasks:

1. Semi-automatic parallelization via multi-threading; modifications for thread-safe code.
2. Sharing of geometry data structures.
3. Sharing of electromagnetic physics processes.
4. Sharing of additional physics processes based on the patterns previously discovered.
5. Verify that the parallelization and sharing process yields code that scales well to at least 16 CPUs on a chip.
6. Generate software for automating the modifications implemented in previous phases.
7. Cooperative caching.

3.4.4 Code Robustness and Quality Assurance

- Perform a design review of the modules associated with the CHIPs hadronic model (FNAL).
- Organize and extend the coverage of the "unit tests" for Geant4 modules (FNAL).
- Extend code design and validation-coverage reviews to other Geant4 modules, as deemed appropriate by the Geant4 collaboration (FNAL).
- Initiate systematic unit and system testing of Geant4 physics processes (FNAL).
- Apply system testing to Geant4 hadronic processes. Perform physics-aware comparisons to proper cross sections (SLAC).

3.5 Documentation and User Support

Direct involvement in the support of LHC experiments, as well as budget constraints, have caused the SLAC team to drastically reduce its involvement in the teaching of tutorials and the development and maintenance of documentation. This is a very significant setback for the Geant4 Collaboration given that the SLAC contribution represented a large fraction of the documentation and user support effort.

The US Geant4 Consortium proposes to resume these activities. A new effort aimed at thoroughly revising and improving the documentation on physics lists, and maintaining the physics reference manual as new models become available, would be undertaken by both SLAC and FNAL under this roadmap. SLAC and FNAL would strengthen their leading role as user-support centers in the United States.

We propose that all the US Geant4 developers including the new hires contribute to documentation in their area of expertise.

4. Project Management and Reporting

The establishment of a US Geant4 Consortium is strengthening the contribution of the US to the Geant4 project by facilitating communication and leveraging resources among the participating institutions. The main goals are to address major challenges in the areas of software infrastructure and physics, and reinforce the user support teams in the US to sustain the growing demands of the US scientific programs.

The Geant4 Collaboration is supervised by the Oversight Board (OB), which is composed by the representatives of the funding agencies or institutions that provide resources to the collaboration; the Oversight Board periodically commissions external reviews. The Geant4 Steering Board (SB) sets the direction of the Collaboration and consists of representatives from each working group, the spokesperson and the deputy, and people with special roles, such as the release manager. For the US Geant4 Consortium, we propose a management structure that fosters communication between member institutions, alignment with the strategy and tactical plans of the Geant4 Collaboration, accountability, and efficiency in the execution of our program of activities.

The US Geant4 Consortium will be lead by a Management Committee (MaCo), whose members also serve as leaders of the four level 1 (L1) categories or areas of the project:

- hadronic physics (V. Daniel Elvira – FNAL, Dennis Wright – SLAC),
- electromagnetic physics & software framework (Makoto Asai – SLAC),
- performance & Q/A (Gene Cooperman – NE, Mark Fischler – FNAL),
- documentation & user support (TBD – FNAL, TBD – SLAC).

Each institution that expects to receive US Geant4 funds has a Principal Investigator who will also serve on the MaCo if not already part of it as a leader of a level 1 area. The coordinating-PI (Richard P. Mount – SLAC) serves as the Chair of the committee, and the principal contact with the DOE. The Management Committee sets the goals and milestones of the project, and it devises the plans for meeting them. It sets priorities, decides on fund allocation, and ensures that the work is aligned with the targets established by the entire Geant4 Collaboration and completed on schedule. Ms. Teri Church, SLAC Computing Business Manager, will prepare and maintain the WBS of the project; details on project activities, including personnel, milestones, and time lines, are included in Appendix B. The Committee monitors progress and reallocates resources as needed to ensure milestones are met. The Management Committee meets every two months. Decisions are made by consensus; when consensus is not reached, decisions are made by majority vote, with the chair's vote deciding the outcome in case of a tie. The institutional PIs take responsibility for the work carried out at their institution and the L1 category leaders take responsibility for communicating with the corresponding Geant4 working groups and the Geant4 SB. The leaders of each L1 area submit reports twice a year to the MaCo. The coordinating-PI submits progress reports to DOE twice a year and is responsible for tracking the overall project budget. He will be assisted in preparing these reports and in tracking the budget by Teri Church (SLAC).

The US Geant4 Consortium management plan includes an Advisory Board (ABo), representing the stakeholders and assisting the MaCo on priorities, goals, and milestones. Three of the members of the ABo must be members of either the Geant4 SB or the Geant4 OB: John Apostolakis (CERN – Geant4 spokesperson), Gabriele Cosmo (CERN – Geant4 SB member and leader of the simulation group within the LHC Computing Grid Project), Petteri Nieminen (European Space Agency – Geant4 OB Chair) have expressed their willingness to serve on the ABo. Another two members must be users, involved in projects supported by the US DOE Physics program: Jim Shank (Boston University – ATLAS) and Fabio Cossutti (INFN Trieste – CMS) are prepared to serve. The ABo meets annually and submits recommendations to the MaCo. This process should ensure good communication with the stakeholders and alignment with the goals of the Geant4 Collaboration and the US DoE physics program. The coordinating-PI can call for additional ABo meetings if needed. Though most of the efforts will be coordinated through emails and phone conferences, we may hold face-to-face workshops to be attended by most, if not all, of the contributors to this project. We also expect to host the international Geant4 Collaboration Workshop once during this three-year project.

Appendix A: Committees and List of Collaborators

In this appendix we list the membership of the committees responsible for the management of the project, together with the complete collaboration list.

Management Committee

Makoto Asai	SLAC
Gene Cooperman	Northeastern University
V. Daniel Elvira	FNAL
Mark Fischler	FNAL
Richard Mount (Chair)	SLAC
Dennis Wright	SLAC
Douglas Wright	LLNL
TBD (Documentation and User Support)	SLAC
TBD (Documentation and User Support)	FNAL

Advisory Board

John Apostolakis	CERN
Gabriele Cosmo	CERN
Petteri Nieminen	European Space Agency (ESA
Jim Shank	Boston University
Fabio Cossutti	INFN-Trieste

The US Geant4 Consortium

LLNL	Brett Beck, Jerome Verbeke, Douglas Wright
Northeastern University	Gene Cooperman, Xin Dong
FNAL	Sunanda Banerjee, Walter Brown, V. Daniel Elvira, Mark Fischler, Lynn Garren, Krzysztof Genser, Jim Kowalkowski, Nikolai Mokhov, Mark Paterno, Sergei Striganov, Hans Wenzel, Julia Yarba
SLAC	Makoto Asai, Tatsumi Koi, Richard Mount, Joseph Perl, Dennis Wright

Appendix B: Milestones, Resources, Timelines

B.1 Hadronic Physics

The worldwide Geant4 effort on hadronic physics decreased from 9.23 FTE in 2007 to 7.70 FTE in 2008, of which the U.S. provides 2.40.

The US Hadronic Physics Effort in 2008 is 2.40 FTE:

Sunanda Banerjee (FNAL)	0.60
Daniel Elvira (FNAL)	0.20
Tatsumi Koi (SLAC)	0.80
Dennis Wright (SLAC)	0.20
Julia Yarba (FNAL)	0.60

Under this roadmap the US Hadronic Physics effort would increase to 5.85 (5.45 on year 1) FTE:

Sunanda Banerjee (FNAL)	0.60
Brett Beck (LLNL)	0.20
Daniel Elvira (FNAL)	0.20
Tatsumi Koi (SLAC)	0.40
Nikolai Mokhov (FNAL)	0.20 (0.1 on year one)
Sergei Striganov (FNAL)	0.20 (0.1 on year one)
Jerome Verbeke (LLNL)	0.20
Dennis Wright (SLAC)	0.20
Douglas Wright (LLNL)	0.05
Julia Yarba (FNAL)	0.60
New Hire (FNAL)	1.00 (CHIPS, RPG, validation)
New Hire (FNAL)	1.00 (New Models and Features. Reduced to 0.8 on year 1, the remaining 0.2 to be spent on EM physics)
New Hire (SLAC)	1.00 (Bertini, RPG, neutron HP, QMD)

B.1.1 Management

Contributors: Dennis Wright (Geant4 Hadronic Physics Group leader).

FTE in Years 1, 2, 3: 0.10, 0.10, 0.10

Deliverables: Group organization, leadership.

Completion Date: Continuing.

B.1.2 RPG Model

Contributors: Sunanda Banerjee, V. Daniel Elvira, Dennis Wright, Julia Yarba, new hire

FTE in Years 1, 2, 3: 0.70, 0.70, 0.90

Deliverables:

- Year 1: code revision to guarantee energy, charge, strangeness, and baryon conservation.
- Year 2: Completion of parameter tuning for nucleons and pions.
- Year 3:
    - Completion of validation for nucleons and pions.
    - Completion of parameter tuning for kaons and hyperons.

Completion Date: Year 3

B.1.3 LEP, HEP Model

Contributors: Dennis Wright

FTE in Years 1, 2, 3: 0.10, 0.10, 0.10

Deliverables:
- Years 1, 2, 3: Code updates and bug fixes resulting from validation and user reports.

Completion Date: Continuing.

B.1.4 Bertini Cascade Model

Contributors: Sunanda Banerjee, Dennis Wright, new hire.

FTE in Years 1, 2, 3: 0.50, 0.50, 0.50

Deliverables:
- Year 1: Improved of quasi-elastic behavior through modification of internal cross sections and validation.
- Year 2: Corrected angular distributions for scattering below 2.8 GeV (left over from original Fortran code).
- Year 3: Addition of kaon production process from collisions of non-strange particles.

Completion Date: Year 3.

B.1.5 CHIPS Model

Contributors: Sunanda Banerje, Dennis Wright, new hire.

FTE in Years 1, 2, 3: 0.60, 0.60, 0.65

Deliverables:
- Year 1: Analysis of CHIPS code and plan for factorization into elastic and stopping models.
- Year 2: Separate models for elastic scattering and stopping, implemented and validated.
- Year 3: Algorithmic changes to CHIPS aimed at improving performance.

Completion Date: Year 3.

B.1.6 New Models and Features

Contributors: Nikolai Mokhov, Sergei Striganov, new hire.

FTE in Years 1, 2, 3: 1.00, 1.40, 1.40

Deliverables:
- Year 1: Complete comparison and benchmarking of G4 and MARS models for hadrons.
- Year 2:
  - Improvement of G4 hadronic models with new generators.
  - Completion of model integration and benchmarking for muons and photons.
  - Validation against available data.
- Year 3: Tools and concrete examples to compute displacements-per-atom.

Completion Date: Year 3.

B.1.7 High Precision Neutron Models

Contributors: Brett Beck, Tatsumi Koi, Jerome Verbeke, Douglas Wright, new hire.

FTE in Years 1, 2, 3: 0.75, 0.75, 0.30

Deliverables:
- Year 1:
  - Complete of user interface for LLNL neutron database.
  - Bug fixes and improvements to the current high precision model.
- Year 2:
  - Completion of new Geant4 models based on LLNL database.
  - Bug fixes and improvements of existing high precision model.
- Year 3: Validation of LLNL-based models completed, existing HP model phased out.

Completion Date: Continuing.

B.1.8 Validation Repository

Contributors: Sunanda Banerjee, V. Daniel Elvira, Julia Yarba.

FTE in Years 1, 2, 3: 1.30, 1.30, 1.50

Deliverables:

- Year 1:
  - Complete catalog of all areas in hadronic physics where validation is required, and a list of data sources for new validations
  - Validation results for medium-energy models as improvements become available.
- Year 2:
  - Network of experienced users established to carry out validation in their areas of interest.
  - Validation results for medium-energy models as improvements become available.
- Year 3:
  - Completion of improved, expanded validation web sites for new validation effort.
  - Validation results for medium-energy models as improvements become available.

Completion Date: Continuing.

B.1.9 QMD Model

Contributors: Tatsumi Koi, new hire.

FTE in Years 1, 2, 3: 0.40, 0.40, 0.40

Deliverables:

- Year 1: Validation of existing QMD model completed.
- Year 2:
  - Completion of study to determine which models can best extend energy range of nucleus-nucleus collisions.
  - Development of low energy model completed.
- Year 3: Development of high energy model completed.

Completion Date: Continuing.

B.2 Electromagnetic Physics

The worldwide Geant4 effort on EM physics decreased from 8.75 FTE in 2007 to 8.10 FTE in 2008.The US does not currently contribute to this effort. Given the relevance of the EM physics activity, and the high demand from users in the US, we propose to start this new effort at the level of 1.50 FTE.

Under this roadmap the US EM Physics effort would increase to 1.95 (year 1), 1.55 (year 2), 1.50 (year 3) FTE:

Makoto Asai (SLAC) 0.05 (only in years 1, 2)
Nikolai Mokhov (FNAL) 0.10 (year 1 only)
Sergei Striganov (FNAL) 0.10 (year 1 only)
Dennis Wright (SLAC) 0.05
New Hire (FNAL) 0.20 (year 1 only. 0.8 FTE to be spent on hadronic physics)
New Hire (SLAC) 0.75 (0.25 FTE to be spent on documentation/user support)
New Hire (SLAC) 0.70 (the remaining 0.3 FTE to be spent on documentation/user support)

B.2.1 Optimization for Memory and Time Performance

Contributors: Makoto Asai, 2 new hires.

FTE in Years 1, 2, 3: 1.15, 1.15, 0.50

Deliverables:
- o Year 1: First prototype of EM processes with unit-density materials followed by physics validation and performance studies.
- o Year 2: Production-quality version of EM processes based on unit-density materials followed by physics validation, and performance studies.
- o Year 3: Documentation, including examples. Refinements to development based on user input.

Completion Date: Year 3.

B.2.2 Validation and Testing

Contributors: Nikolai Mokhov, Sergei Striganov, Dennis Wright, 2 new hires.

FTE in Years 1, 2, 3: 0.80, 0.40, 1.00

Deliverables:
- o Year 1: completion of data search for validation, and benchmarking against individual electromagnetic processes in Geant4. Benchmarking of multiple Coulomb scattering in Geant4 and MARS against data.
- o Year 2: Completion of new EM validation tests and integration into the existing suite.
- o Year 3: Completion of new unit tests, which will include the EM processes using a single cross-section table per material, based on its unit-density.

Completion Date: Continuing.

B.3 Software Framework

The Geant4 Collaboration has five working groups which share the responsibilities for the development and maintenance of the Geant4 software framework. They are the “Run, Event and Detector Response”, “Tracking”, “Geometry”, “Particle and Track”, and “Generic Processes and Material” working groups. The total effort within the Geant4 Collaboration decreased from 4.15 FTE in 2007 to 3.50 FTE in 2008.

The US Software Framework effort in 2008 is 0.15 FTE:

Makoto Asai (SLAC) 0.15

Under this roadmap the US Software Framework effort would increase to 1.35 (years 1, 2), 1.40 (year 3) FTE:

Makoto Asai (SLAC) 0.20 (0.25 in year 3)
Tatsumi Koi (SLAC) 0.10
Dennis Wright (SLAC) 0.05
New Hire (SLAC) 1.00

B.3.1 Reorganization and enhancement of event biasing options

Contributors: Makoto Asai, Tatsumi Koi, New hire.

FTE in Years 1, 2, 3: 1.10, 1.10, 1.20

Deliverables:

- Year 1:
  - Common user interfaces for existing physics-based event biasing options implemented.
  - Cross-section biasing methods in EM and Hadronics physics process merged.
  - Options for shielding, neutron flux studies, and studies of hadron leakage completed.
  - Geometry based biasing options and a first prototype a Reverse Monte Carlo for electrons, positrons, and photons available.
- Year 2:
  - Angular distribution biasing option available.
  - Production quality implementation of Reverse Monte Carlo for electrons, positrons, and photons.
- Year 3: Documentation and examples for all biasing options completed.

Completion Date: Year 3.

B.3.2 Extension of scoring options

Contributors: Makoto Asai

FTE in Years 1, 2, 3: 0.10, 0.10, 0.00

Deliverables:
- Year 1: Command-based scoring functionality for cylindrical geometries; examples.
- Year 2: Command-based scoring functionality for spherical geometries; examples.

Completion Date: Year 2.

B.3.3 Roadmap for a Geant4 software re-engineering

Contributors: Makoto Asai, Dennis Wright.

FTE in Years 1, 2, 3: 0.15, 0.15, 0.20

Deliverable:
- Year 1: Architecture review and list of classes and categories to modified completed.
- Year 2: Benefits, risks, human resource estimates of proposed changes understood.
- Year 3: Work schedule, timeline, detailed list of milestones. Final roadmap agreed within the Geant4 Collaboration.

Completion Date: Year 3.

B.4 Performance, Robustness, and QA

The Geant4 Collaboration spent 1.35 FTE on software management as of October 1st, 2008. This area includes the activities on performance improvements and robustness performed by the US.

The US Performance, Robustness, and QA effort in 2008 is 0.85 FTE:

Gene Cooperman (Northeastern U.)	0.25
Mark Fischler (FNAL)	0.20
Jim Kowalkowski (FNAL)	0.20
Marc Paterno (FNAL)	0.20

Under this roadmap the US Performance, Robustness, and QA effort would increase to 3.85 FTE:

Makoto Asai (SLAC)	0.05
Walter Brown (FNAL)	0.20
Gene Cooperman (Northeastern U.)	0.30
Xin Dong (Northeastern U.)	1.00
Mark Fischler (FNAL)	0.20
Krzysztof Genser (FNAL)	0.30
Jim Kowalkowski (FNAL)	0.25
Marc Paterno (FNAL)	0.25

Hans Wenzel (FNAL)	0.25
Dennis Wright (SLAC)	0.05
New Hire (FNAL)	1.00

B.4.1 Profiling

Contributors: Mark Fischler, Jim Kowalkowski, Marc Paterno, new hire.

FTE in Years 1, 2, 3: 0.60, 0.45, 0.45

Deliverables:

- o Year 1:
  - Completion of SimpleProfiler and associated systems, including database and web.
  - List of areas identified for improvement by profiler analysis; improved code for some areas. The CMS simulation application will be the first use case for Geant4 profiling.
  - Profiling results to evaluate performance of the electromagnetic physics code.
- o Year 2:
  - Improved code for more areas.
  - SimpleProfiler tools ported to more environments and used beyond the CMS application.
- o Year 3:
  - Performance improvements beyond the CMS application.
  - Productization of the system for broader usage, including developers outside the USGeant4 collaboration.

Completion Date: Year 3.

B.4.2 Coding Technique and Algorithmic Improvement

Contributors: Mark Fischler, Krzysztof Genser, Jim Kowalkowski, Marc Paterno, Hans Wenzel, new hire.

FTE in Years 1, 2, 3: 0.40, 0.65, 0.75

Deliverables:

- o Year 1: Code reviews of selected Geant4 packages and related code implantation.
- o Year 2:
  - User document describing techniques to avoid and how to modify and improve existing code without risk of changing results.
  - Identified areas in key packages for mathematically equivalent but computationally faster versions of algorithms.
- o Year 3: Algorithm changes to improve speed implemented and validated for physics.

Completion Date: Year 3.

B.4.3 Development of multi-threaded Geant4 for multi-core CPUs

Contributors: Gene Cooperman, Xin Dong, Mark Fischler, Jim Kowalkowski, Marc Paterno, new hire.

FTE in Years 1, 2, 3: 1.85, 1.75, 1.65

Deliverables:
- o Year 1: Phases 1 through 3; thread-safe Geant4 version; Geant4/parallel sharing geometry and some processes.
- o Year 2: Phases 4 and 5; Geant4 fully multi-thread version; study of scaling properties.
- o Year 3: Phases 6 and 7; Optimized parallel Geant4.

Completion Date: Year 3.

B.4.4 Code Robustness and Quality Assurance

Contributors: Walter Brown, Mark Fischler, Krzysztof Genser, Jim Kowalkowski, Marc Paterno, HansWenzel, new hire.

FTE in Years 1, 2, 3: 1.00, 1.00, 1.00

Deliverables:
- o Year 1:
  - Code design review completed for CHIPS and Bertini cascade hadronic models.
  - Source of irreproducibility located and problems corrected.
  - Scheme for improved unit-test coverage.
- o Year 2:
  - Code design review of electromagnetic and additional hadronic packages.
  - Validation coverage reviews.
- o Year 3: Additional packages to be brought to higher standards identified.

Completion Date: Year 3.

B.5 Documentation and User Support

The worldwide Geant4 effort on documentation and user support decreased from 0.73 FTE in 2007 to 0.60 FTE in 2008.

The US Documentation and User Support effort in 2008 is 0.40 FTE:

Sunanda Banerjee (FNAL)	0.10
Daniel Elvira (FNAL)	0.05
Lynn Garren (FNAL)	0.10
Dennis Wright (SLAC)	0.05

Julia Yarba (FNAL) 0.10

Under this roadmap the US Documentation and User Support effort would increase to 1.00 FTE:

SLAC Geant4 collaborators 0.20
FNAL Geant4 collaborators 0.25
New Hire (SLAC) 0.30 (the remaining 0.7 FTE to be spent on EM Physics)
New Hire (SLAC) 0.25 (the remaining 0.75 FTE to be spent on EM Physics)
Contributors: All members, including 2 new hires.

FTE in years 1, 2, 3: 1.00, 1.00, 1.00

Deliverables:

- Year 1:
  - One Geant4 tutorial event held in the US.
  - Completion of the phyiscs list documentation web site.
  - User support of HEP and nuclear physics experiments.
- Year 2:
  - One Geant4 tutorial event held in the US.
  - User support of HEP and nuclear physics experiment.
  - Completion of the update to the Physics Reference Manual to include all models available at the time.
- Year 3:
  - One Geant4 tutorial event held in the US.
  - User support of HEP and nuclear physics experiments.

Completion Date: Continuing.

B.6 Project Management and Reporting

This effort includes the overall US Geant4 Consortium project management and reporting activities.

Under this roadmap the US Project Management and Reporting effort would increase to 0.40 FTE:

Makoto Asai (SLAC) 0.20 (institutional PI, Deputy Spokesperson responsibilities)
Richard Mount (SLAC) 0.05 (coordinating PI)
Daniel Elvira (FNAL) 0.05 (institutional PI)
SLAC administrative staff 0.10

Contributors: Makoto Asai, V. Daniel Elvira, Richard Mount, SLAC administrative staff.

FTE in years 1, 2, 3: 0.40, 0.40, 0.40

Deliverables:
- Project direction and leadership.
- Timely reports to the MaCo and DOE.
- Prepare and maintain WBS, track grant budget.

Completion Date: Continuing

Appendix C: Summary Tables

Activity	Contributors	FTE Year 1	FTE Year 2	FTE Year 3	Completion Date
B.1.1 Hadronic Physics: management	Dennis Wright	0.10	0.10	0.10	Continuing
B.1.2 Hadronic Physics: RPG model	Sunanda Banerjee, V. Daniel Elvira Dennis Wright, Julia Yarba, new hire	0.70	0.70	0.90	Year3
B.1.3 Hadronic Physics: LEP, HEP model	Dennis Wright	0.10	0.10	0.10	Continuing
B.1.4 Hadronic Physics: Bertini cascade model	Sunanda Banerjee, Dennis Wright	0.50	0.50	0.50	Year 3
B.1.5 Hadronic Physics: CHIPS model	Sunanda Banerjee, Dennis Wright, new hire	0.60	0.60	0.65	Year 3
B.1.6 Hadronic Physics: New Models and Feature	Nicolai Mokhov, Sergei Striganov, new hire	1.00	1.40	1.40	Year 3
B.1.7 Hadronic Physics: high precision neutron models	Brett Beck, Tatsumi Koi, Jerome Verbeke, Douglas Wright, new hire	0.75	0.75	0.30	Continuing
B.1.8 Hadronic Physics: validation repository	Sunanda Banerjee, V. Daniel Elvira, Julia Yarba	1.30	1.30	1.50	Continuing
B.1.9 Hadronic Physics: QMD Model	Tatsumi Koi, new hire	0.40	0.40	0.40	Continuing
B.2.1 EM Physics: optimization for memory and time performance	Makoto Asai, 2 new hires	1.15	1.15	0.50	Year 3
B.2.2 EM Physics: validation and testing	Nikolai Mokhov, Sergei Striganov, Dennis Wright, 2 new hires	0.80	0.40	1.00	Continuing
B.3.1 Software Framework: reorganization and enhancement of event biasing options	Makoto Asai, Tatsumi Koi, new hire	1.10	1.10	1.20	Year 3

B.3.2 Software Framework: extension of scoring options	Makoto Asai	0.10	0.10	0.00	Year 2
B.3.3 Software Framework: roadmap for software re-engineering	Makoto Asai, Dennis Wright	0.15	0.15	0.20	Year 3
B.4.1 Performance, Robustness, and QA: profiling	Mark Fischler, Jim Kowalkowski, Marc Paterno, new hire	0.60	0.45	0.45	Year 3
B.4.2 Performance, Robustness, and QA: code techniques and algorithmic improvements	Mark Fischler, Krzysztof Genser, Jim Kowalkowski, Marc Paterno, Hans Wenzel, new hire	0.40	0.65	0.75	Year 3
B.4.3 Performance, Robustness, and QA: development of multi-threaded Geant4 for multi-core CPUs	Gene Cooperman, Xin Dong, Mark Fischler, Jim Kowalkowski, Marc Paterno, new hire	1.85	1.75	1.65	Year 3
B.4.4 Performance, Robustness, and QA: code robustness and quality assurance	Walter Brown, Mark Fischler, Krzysztof Genser, Jim Kowalkowski, Marc Paterno, HansWenzel, new hire	1.00	1.00	1.00	Year 3
B.5 Documentation and User Support	All members, including 2 new hires	1.00	1.00	1.00	Continuing
B.6 Project Management and Reporting	Makoto Asai, V. Daniel Elvira, Richard Mount, Teri Church	0.40	0.40	0.40	Continuing

Hadronic Physics	**Total new hires**	**2.80**	**3.00**	**3.00**	
EM Physics	**Total new hires**	**1.65**	**1.45**	**1.45**	
Software Framework	**Total new hires**	**1.00**	**1.00**	**1.00**	
Performance, Robustness, and QA	**Total new hires**	**1.00**	**1.00**	**1.00**	
Documentation and User Support	**Total new hires**	**0.55**	**0.55**	**0.55**	
All activities	**Grand total new hires**	**7.00**	**7.00**	**7.00**	
All activities	**Grand total all personnel**	**14.00**	**14.00**	**14.00**	

References

1
Geant4 Developments and Applications, J. Allison et al., IEEE Transactions on Nuclear Science **53** No. 1 (2006) 270-278.
Geant4 - A Simulation Toolkit, S. Agostinelli et al., Nuclear Instruments and Methods **A** 506 (2003) 250-303.
http://geant4.cern.ch/ is the Geant4 main web page.

2 http://mcnp-green.lanl.gov

3 http://www2.slac.stanford.edu/vvc/egs

4 The FLUKA code: Description and benchmarking, A. Fasso, A. Ferrari, J. Ranft, and P.R. Sala, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773.

5 US Particle Physics: Scientific Opportunities. A Strategic Plan for the Next Ten Years. http://www.science.doe.gov/hep/files/pdfs/P5_Report%2006022008.pdf

6 http://atlas.web.cern.ch/Atlas

7 http://cms.cern.ch/

8 http://lhcb.web.cern.ch/lhcb/

9 http://lhc.web.cern.ch/lhc/

10 http://aliceinfo.cern.ch/

11 http://www.linearcollider.org/cms/

12 http://greybook.cern.ch/programmes/experiments/RD44.html

13 http://fgst.slac.stanford.edu

14 “Effects of automated transfer coalescing on production physics”, by Mark Fischler. FERMILAB-PUB-93-365, Nov 1993. 4pp. Presented at LATTICE 93: 11th International Symposium on Lattice Field Theory, Dallas, Texas 12-16 Oct 1993. Published in Lattice 1993: Nucl Phys B (Proc Suppl.) 34 (1994) 823:826

15 A. Heikkinen, N. Stepanov, and J. P. Wellisch, "Bertini intranuclear cascade implementation in Geant4", in Proc. Computing in High Energy and Nuclear Physics La Jolla, CA, vol. MOMT008, 2003.

16 G. Folger, V. N. Ivanchenko, and J. P. Wellisch, "The Binary Cascade", Eur. Phys. J. A., vol. 21, 407 (2004).

17 H.C. Fesefeldt, "Simulation of hadronic showers, physics and application". Technical Report PITHA 85/02, 1985.

18 N.S. Amelin, K.K. Gudima, V.D. Toneev, Sov. J. Nucl. Phys. 51 (1990). Kaidalov A. B., Ter-Martirosyan K. A., Phys. Lett. B117 247 (1982).

19 Andersson B., Gustafson G., Nielsson-Almquist, Nucl. Phys. 281 289 (1987).

20 P.V. Degtyarenko, M.V. Kosov and H.P. Wellisch, "Chiral invariant phase space event generator", Eur. Phys. J. A 8, 217 (2000).

21 Geant4 Physics Reference Manual: http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/PhysicsReferenceManual/html/node195.html

22 V. N. Ivanchenko, et al., "Overview and new developments on Geant4 electromagnetic physics", in Proc. Computing in High Energy and Nuclear Physics Interlaken, Switzerland, vol. 320, 2004.

23 J. Apostolakis et al., Journal of Physics: Conference Series **119** (2008) 032004

24 Chauvie, G. Depaola, V. Ivanchenko, F. Longo, P. Nieminen, and M. G. Pia, "Geant4 low energy electromagnetic

physics",
Proc. Computing in High Energy and Nuclear Physics Beijing, China, pp.337-340, 2001.
25 C. Young et al., "Review of the Geant4 Project", April 30, 2007, http://indico.cern.ch/getFile.py/access?resId=0&materialId=0&confId=14946

26 Gene Cooperman and Viet Ha Nguyen and Igor Malioutov, "Parallelization of Geant4 Using TOP-C and Marshalgen", 5th IEEE International Symposium on Network Computing and Applications (NCA-06), IEEE Computer Society Press, 2006, pp. 48-55.

27 Geant4 tutorials conducted by the SLAC Geant4 team: http://geant4.slac.stanford.edu/ ;
CERN Courier Nov, 2006 http://cerncourier.com/cws/article/cern/29747

28 http://geant4.fnal.gov/hadronic_validation/validation_plots.htm

29 http://www-ap.fnal.gov/MARS/