Statement of Work for SLAC National Accelerator Laboratory for “Fast and full simulations in Geant4 for large-scale detector systems with a plug and play modular approach”

Motivation

Large-scale detector systems, e.g., for the Solenoidal Large Intensity Device (SoLID) experiment or the Electron-Ion Collider (EIC), are designed by larger communities. The simulation efforts start as standalone exercises for each detector component with various levels of maturity, analytical calculations, simplified Monte Carlo exercises (fast simulations), Geant4-based Monte Carlo approaches (full simulations), and are later being extended in several different frameworks.

It is critical in the longer term to perform studies where the information from various detector elements and also the interaction region, support structures and other dead material is taken into account, which is only possible in a comprehensive simulation. This is essential to understand, e.g., the performance at the edges of the detector system or the effect of combining different technologies for the electro-magnetic calorimeter. For studies of the physics reach and detection capabilities, it is important to be able to switch detector options with varying levels of detail, combining full simulations for some detector components with fast simulations for the rest of the detector system. It is also critical to build a sustainable effort for the entire time scale of the experiments with common tunes and commonly validated results for both fast and full simulations.

To support the detector communities, to boost the work towards fully integrated large-scale detector systems, and to ease leveraging new and rapidly evolving technologies, we propose a common and integrated approach for fast and full simulations in Geant4 with a plug and play modular approach.

Requirements

A comprehensive and centrally maintained framework based on Geant4 for both fast and full simulations with a library of potential detector options has to be developed. The initial focus on the development will be:

- ability to reuse existing simulation works,
- ease of switching detector options with comparable levels of detail,
- ease of switching between detailed and coarse detector descriptions,
- ease of leveraging new and rapidly evolving technologies (e.g. AI/ML) and computing hardware (e.g. heterogeneous architectures).

After validation of the Geant4 simulations, we will simplify them (replacing some physics aspects) for fast simulations. This approach will allow us to use everywhere the same geometry (very important to reduce debugging and development time) and to combine full simulation for a subset of detectors with fast simulations for the rest of the integrated detector. Geant4 itself and various NP and HEP experiments already provide sub-systems for fast simulations. This will reduce the development time of the fast simulations substantially.

The framework will be modular, and its development will be targeted. It will provide an interface to the output of Monte Carlo event generators but no further work on generators. The simulation of detector effects and detector responses (digitization) will be clearly separated. There will be a common geometry interface between the detector simulation and reconstruction.

The timely development of a comprehensive, unified and centrally maintained framework for both fast and full simulations to serve the needs of the detector collaborations or groups is no small task. It must take place in the context of strong development teams in the labs together with important contributors in the universities, all with their own ideas embodied in their own software. There have been discussions about a comprehensive, unified and centrally maintained framework in the SoLID collaboration and within the EIC community. For a step beyond legacy software to a new common effort to be successful, we require a carefully developed plan and project under a highly effective, technically expert leader who has the trust and confidence of the full community. Such a leader and senior project manager will have the stature to unify the development, work closely with the full community, and build a sustainable common project based on Geant4 and tailored to needs of NP experiments as they exist today and will evolve to the 2030s.

In Dr. Makoto Asai we identify the individual who can uniquely fill this role. Dr. Asai has been both a Geant4 project leader and deep technical expert for over 20 years. He is well known to and respected by the EIC community with which he has collaborated for many years on NP Geant4 simulation needs. He is the designer and author of Geant4's capability to support both fast as full simulation, which we want to use for large-scale detector systems. He led Geant4 through its multi-threaded reengineering to support high concurrency heterogeneous architectures, with excellent results in the memory economizations achieved. Leveraging and evolving this capability as heterogeneous architectures become ever more prevalent is of great importance for data processing and analyses at SoLID or the EIC. He is expert in the geometry and modular detector definition tools that will be the basis of unified geometry in the detector simulations. No other individual has qualities better tailored to the leader we are looking for. Finally and crucially, Dr. Asai is available for this work if we act promptly.

Work program and deliverables

Dr. Makoto Asai will work four months on the project at a 50% level. The costs per month are USD 21,600. In these four months, he will deliver the following tasks:

1) Create an initial version of the simulation framework

The framework has to be capable to do both fast and full simulations in one application, easily configurable for each detector component. Also, the framework has to easily integrate ("plug-in") already existing standalone simulation applications. These requirements will be fulfilled by utilizing the "region" mechanism of Geant4. Each detector component is represented as a region, where geometry description including different levels of detail, physics options including fast simulation and unique physics model configurations, and detector responses based on geometry and physics options are taken care of. Dr. Asai will develop an initial version of such a framework.

2) Communicate with detector study groups

The existing standalone simulation applications that are to be adapted to the new framework have to be examined and converted to be "plug-able" using the region mechanism. Dr. Asai will communicate with detector study groups and work with them to drive the efforts of integration. Through these interactions the requirements to the framework will be refined as needed. The framework may also integrate beam-test configurations if applicable. The deliverable will be a prototype integration of an existing simulation, the specific target to be chosen in the first month on the basis of importance and available developer effort to work with Dr. Asai during the funded period. Other detector components will be added by the detector community based on the experience from the prototype.

3) Develop and deliver a common physics list

Geant4 offers several alternative physics models. To make comparisons over different detector configurations, one has to use a common set of physics models that is appropriate to NP detectors. Dr. Asai will develop and deliver such a physics list. He will consult with detector study groups and advise on validations of the physics models with beam-test results.

4) Integrate with overall software efforts

Dr. Asai will compile the requirements of detector simulation to the software infrastructure (e.g. common geometry and data formats) to be shared across the whole software chain including physics event generator, simulation, digitization, reconstruction and analysis programs.

5) Deliver a framework extensible to heterogeneous architectures

In the future, simulation jobs may run on computers with heterogeneous hardware configurations, e.g. with GPGPU and/or FPGA, and with cutting edge IT technologies such as AI/ML. Enabling the effective use of such technologies requires design and implementation choices in the framework. Dr. Asai will ensure the extensibility of the framework through the use of a tasking mechanism (either PTL or TBB). He will also support the developers of detector components of the thread-safety of their code.

Sole source justification

The Electron-Ion Collider is a prime example for a large-scale detector system that will benefit from the project on “Fast and full simulations in Geant4 for large-scale detector systems with a plug and play modular approach”. EIC detector simulation development must progress rapidly in order to meet the simulation needs of the detailed detector design and performance studies now ramping up in order to meet the DOE's aggressive schedule for the EIC's experimental program. Today's three simulation frameworks and the communities behind them (EicROOT, Escalate, Fun4All) must transition to a common framework and effort if the EIC community is to be properly served by a unified effort drawing on pooled expertise and offering users what they forcefully request: one simulation infrastructure and standard to learn and use and share with colleagues. The EIC Software Working Group has tried and failed to achieve this unity over almost two years. The developer and user communities of the different frameworks are too strong to be easily drawn to a new common effort. We see one means of achieving this on the needed short timescale, which is the basis of this proposal: seed a new common effort through the leadership of an expert of unique stature and technical expertise, someone who has the trust and confidence of the full community to establish a common effort, while also being a technical expert on the particular aims of the EIC simulation effort. **The same arguments can be made for the simulation efforts for SoLID where various tools are being used and the work from a pre-conceptual detector design to a technical design report will benefit from a common and commonly validated software effort with ease of changing detector options and the level of simulations. The “Fast and full simulations in Geant4 for large-scale detector systems with a plug and play modular approach” can be also used for MOLLER project. This will ensure that any work on AI/ML and running on computers with heterogeneous hardware configurations can be directly used**

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