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MARS Code Status *

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Abstract

Recent developments of the MARS Monte Carlo code system for simulation of hadronic and electromagnetic cascades in shielding, accelerator and detector components in the energy range from a fraction of an electronvolt up to 100 TeV are described. These include hadron production model, unified treatment of heavy particle electromagnetic interactions and absorption, interface to MCNP for low-energy neutrons, and newly created electromagnetic shower modules (down to 1 keV), *MAD-MARS Beam Line Builder* and Graphical-User Interface.

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1 Introduction

The MARS Monte Carlo code system [1], which has been developed over 26 years, allows fast and reliable inclusive and exclusive simulation of 3-D hadronic and electromagnetic cascades, and the transport of muon, neutrino and low-energy neutron/photon particles, through shielding, accelerator and detector components, with energies ranging from a fraction of an electron-volt up to about 100 TeV. The performance of the previous version of the code, MARS13 [2, 3], has been demonstrated in numerous applications at Fermilab, CERN, KEK and other centers as well as in special benchmarking studies. The most recent developments to the current version MARS14 [4] further increase the code reliability, applicability and user friendliness, and are briefly described here.

2 Physics Model

Hadron Production. New compilations, parameterizations and integration algorithms for total and partial cross sections σ_{hN}, σ_{hA} and $\sigma_{\gamma A}$ are implemented covering a hadron kinetic energy range 1 MeV$<$E$<$100 TeV [3]. Hadron-nucleus elastic scattering at 10 MeV$<$E$<$5 GeV is improved and further work is underway. The hadron production model is improved, especially for pions and kaons in the 2 to 50 GeV energy region, and also for photonuclear interactions. The full exclusive production simulation at 1 MeV–5 GeV is now the default, using the latest cascade-exciton model CEM97 [5]. At higher energies, an inclusive approach is a default, with an optional use of the (time-consuming) DPMJET [6] exclusive event-generator, although currently only for the very first nuclear collision in the cascade. By default, deuteron-nucleus interactions are described within a model developed in Ref. [3]. In the exclusive mode, information on the nuclides generated in nuclear collisions is now scored, or tallied and reported in the results of the simulation.

Neutrino Interactions. A special weighted neutrino interaction generator has been developed [3, 7] and incorporated into MARS. This model permits the selection of the energy and angle of each particle (ν, e, μ and hadrons) emanating from a simulated interaction. These particles, and the showers initiated by them, are then further processed in the code in the usual way. Four types of neutrinos are distinguished throughout ($\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$) and the model identifies all possible types of neutrino interactions with nuclei. The corresponding formulas for these processes as well as results of Monte Carlo simulations for muon colliders and storage rings are described in [7].

Interface to MCNP. Once the energy of neutrons falls below 14 MeV, all subsequent neutron interactions are described using the appropriate MCNP4 [8] subroutine modules. Recent implementation in MARS of the accurate treatment of MCNP4 generated recoil protons, as well as heavier recoils and photons from the thermal neutron capture on ^{6}Li and ^{10}B, allows the detailed description of corresponding effects in hydrogenous, borated and lithium-loaded materials [9].

Electromagnetic Interactions of Heavy Particles. Electromagnetic interactions of muons and charged hadrons in arbitrary composite materials are simulated down to several tens of keV. Radiative processes and atomic excitation and ionization with energy transfer ε greater than a cutoff ε_c are considered as discrete events involving production of δ-electrons, e^+e^--pairs, and bremsstrahlung photons which are followed explicitly [10]. Energy losses with $\varepsilon < \varepsilon_c$ (so-called restricted losses) are considered as continuous. Their distribution is described by Vavilov function—with redefined parameters—which approaches a Gaussian with decreasing ε_c. Independent of energy, material or thickness traversed, the quality of the Gaussian approximation is governed by the average number of events (κ_n) one chooses to evaluate individually and becomes acceptable for most purposes when $\kappa_n > 10$. Bremsstrahlung and direct e^+e^- production differential cross-sections used in the code are as given in Ref. [11]. Multiple Coulomb scattering is modeled from the Moliere distribution with nuclear form-factors included [12]. A very careful treatment is done in MARS of processes near and below the Coulomb barrier in hadron and muon transport (ionization absorption *vs* nuclear interaction *vs* decay) as is further described in Ref. [3].

Electromagnetic Showers. New modules for simulating electromagnetic showers based on current knowledge of physics of electromagnetic interactions were recently developed and have been implemented into the code [13]. The main focus is given to electron and photon interactions in arbitrary composite solid, liquid and gaseous materials at low energies (1 keV to a few MeV). The entire shower, and such processes as emission of synchrotron photons, photohadron production, $\gamma Z \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \mu^+\mu^-$, can be treated—in the spirit of the MARS framework—either analogously or inclusively with corresponding statistical weights. The choice of method is left for the user to decide, via the input settings.

3 Materials, Tracking and Histograming

The precise treatment of individual elements in mixtures and compounds defined through the weight or atomic fractions, is done for all the electromagnetic and nuclear elastic and inelastic processes. Homogenization (averaging) of materials thus becomes obsolete and is strongly discouraged. Up to 50 composite materials may be present in a run. Material-dependent energy cutoffs, boundary localization precision and pilot steps can now be defined by the user region by region or material by material; this feature allows noticeable improvement of both a CPU performance and physics description accuracy in the regions of interest. The appropriate parameters for particle transport in arbitrary magnetic fields are chosen automatically, providing extremely high accuracy of tracking. The user can now choose between sampling and forcing π-, K- and μ-decays. Algorithms for splitting and Russian roulette at hA

vertices and in particle transport are also further improved. For 'deep penetration' problems in complex highly non-uniform geometries, algorithms for scoring probabilities, rather than real particle crossings or interactions, take into account all possible processes for both stable and unstable particles and charged as well as neutral hadrons. Use of accelerating field (RF-cavities) is now optional in the code. The I/O sequence as well as the histograming for surface and volume detectors is substantially improved and extended. Interfaces to the ANSYS code for thermal and stress analyses and to the STRUCT code for multi-turn particle tracking in accelerators have also been improved.

4 MAD-MARS Beam Line Builder

The MAD [14] lattice description language has become the *lingua franca* of computational accelerator physics. Any new developments in accelerator physics computational codes and libraries should have the requirements to read and understand lattice descriptions written in MAD. The ideas and modules of Ref. [15] are used in a new interface, which is able to read, parse, and store in memory MAD lattice descriptions, with the ability to generate an output file which translates those descriptions for input to MARS, and can also be used as input to other tracking and CAD applications.

The created interface system—*MAD-MARS Beam Line Builder* (MMBLB)—reads a MAD lattice file and puts the elements in the same order into MARS geometry. Each element is assigned six functions which provide information about the element type/name, geometry, materials, field, volume and initialization. The user specifies the element type and an optional element name. If no name is specified, the element is considered to be a generic one. A building algorithm first tries to match the type/name pair and then substitute a generic element if needed. Once an element is described, it is registered with the system and its name is binded with the respective geometry, materials, volume and field descriptions. For each region search during tracking, MMBLB finds the corresponding type/name pair and calls its appropriate functions. MMBLB calculates a local rotation matrix R_i and a local translation vector L_i. Then a global rotation matrix M_i and a position P_i are calculated and stored for each element

$$M_i = M_{i-1} \times R_i, \quad M_0 = U$$
$$P_i = M_{i-1} \times L_i + P_{i-1}$$

where U is the unit matrix. $R_i = U$ for all elements, except RBEND and SBEND.

5 Graphical-User Interface

A Graphical-User Interface, MARS-GUI-SLICE, has been developed. It is based on *Tcl/Tk* and is linked in to the user's executable, however it is active only when specific flags are set in the input file. When the interface is active, no events are generated, but the user's encoded geometry is probed and visually displayed. The interface displays all the details of the encoded geometry, showing the encoded zone numbers, materials and magnetic fields; it is a valuable tool for checking complex geometries before executing event generation. During event generation runs, the user can specify output files holding histograms and particle tracks; these output files can be opened by the *GUI* interface, post-run, and projected onto the visual display of the geometry. The main MARS-GUI-SLICE features are:

- Two-dimensional geometry slice and magnetic field view on a graphical display panel (GDP). Maximum and minimum coordinates along each axis and maximum field components are provided for the given view in corresponding entry fields (EF). They are changed automatically by grabbing a desirable view box on the GDP holding a *CTRL* key and clicking with the mouse left button at the two diagonal box corners. Alternatively, the lower and upper view boundaries can be typed in the EF along with a binning of the magnetic field grid seen on the GDP. There is a *1:1 scale* check field (CF) to return to a *natural* scale.

- A slice plane is chosen by a corresponding radio-button. A magnetic field view can be interactively turned ON and OFF in a corresponding CF.

- Materials distribution in a given view is represented in a color or black and white *wire-frame (contour) mode* or in a *color region-filled mode*, with the mode chosen by a corresponding radio-button. By clicking a corresponding button, a *Materials* window is created, with the CF displaying material index and name and select boxes (SB) showing color of each material in the given view on the GDP. The pre-set materials colors can arbitrary be modified in the corresponding SB individually for each material. The colors can be reset individually or globally. Changing the view automatically adjusts the material info in this window.

- By clicking a left mouse button at any point of the GDP, a *Point Info* window is created with information display fields (IDF) containing coordinates, region number, material name and index, magnetic field module and a value of histogram (see below) for this point. This window keeps the position intact.

- Particle tracks in the given view can be displayed on the GDP by loading a *.PLOT file generated by MARS. Similar to materials, by clicking a corresponding button, a *Particles* window is created, with information similar to the

Materials window: particle ID, name, color and SB displaying color of each particle and allowing color modification. A corresponding CFs allow turning ON and OFF any ID and global track visibility. One can examine tracks by clicking a middle mouse button at any track point on the GDP. A *Track Info* window is created with IDF containing the particle ID, name, as well as the current energy, statistical weight and coordinates at the point.

- After the run, a variety of calculated 2-D histograms can be loaded and overlaped with the geometry view on the GDP. A *.HBOOK file is loaded in the *Load Hist* window and a desirable histogram is selected there from the IDF list by its ID or name. The geometry/histogram view is now handled as a whole. The *Point Info* window allows now for a detailed examination of the histogram values even within the same decade (color).

- The view can be inverted both vertically and horizontally.

- One can add arbitrary texts all over the GDP with a *Text* window activated by the mouse right button. Variety of fonts can be chosen there. Fonts, subscripts and superscripts are handled as in the XMGR plotting tool [16]. Text can be modified, moved around the GDP or deleted.

- Up to 20 of the GDP views can be stored and restored back and then viewed by clicking $<<$ or $>>$ buttons.

- The GDP can be saved as an Encapsulated Postscript file by clicking the *Print* button. The entire window or its arbitrary fraction can be XV-grabbed by clicking the *Grab* button.

- A version exists for a 3-D solid body representation [17].

6 Benchmarking and Worldwide Support

The code's reliability is confirmed by numerous benchmarking as shown at several SATIF/SARE meetings and demonstrated in many applications at Fermilab and other centers (see, e. g., recent Ref. [3, 4, 9, 13]). The code is distributed and supported worldwide for the Unix and Linux operating systems. The official MARS Web site is *http://www-ap.fnal.gov/MARS/* which contains information about the code, its users, and its uses (see Fig. 1).

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Figure 1: MARS web page

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