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MARS Code Developments, Benchmarking and Applications

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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. The physical model of hadron and lepton interactions with nuclei and atoms has undergone substantial improvements. These include a new nuclear cross section library, a model for soft pion production, a cascade-exciton model, a dual parton model, deuteron-nucleus and neutrino-nucleus interaction models, a detailed description of negative hadron and muon absorption, and a unified treatment of muon and charged hadron electromagnetic interactions with matter. New algorithms have been implemented into the code and benchmarked against experimental data. A new Graphical-User Interface has been developed. The code capabilities to simulate cascades and generate a variety of results in complex systems have been enhanced. The MARS system includes links to the MCNP code for neutron and photon transport below 20 MeV, to the ANSYS code for thermal and stress analyses and to the STRUCT code for multi-turn particle tracking in large synchrotrons and collider rings. Results of recent benchmarking of the MARS code are presented. Examples of non-trivial code applications are given for the Fermilab Booster and Main Injector, for a 1.5 MW target station and a muon storage ring.

1 CODE DEVELOPMENTS

The MARS code [1]—widely used in the high-energy physics, accelerator and radiation shielding communities—is under continuous development [2, 3]. The most recent improvements and extensions which increase the code reliability, applicability and user friendliness include:

- Further improvement of the hadron production model, especially for pion and kaon production in the 2 to 50 GeV energy region, with full exclusive simulation at 1 MeV–5 GeV using the latest cascade-exciton model CEM97 [4] (see Figs. 1 and 2) and with an inclusive approach at 5 GeV to 100 TeV with optional use of the (time-consuming) DPMJET [5] exclusive event-generator.
- Improved interface to MCNP4 [6] for better treatment of low-energy neutrons and photons, with new algorithms to treat created recoil protons and heavier particles.
- Improved radionuclide production algorithms.
- Electromagnetic interactions in arbitrary composite materials correctly simulated down to 1 keV for electrons and photons and to 100 keV for muons and charged hadrons.
- Choice of sampled or forced π-, K- and μ-decays.
- Forced neutrino interactions at 0.1 GeV–100 TeV.
- Material-dependent energy cutoffs, boundary localization precision and pilot steps controlled by user.
- Automated choice of parameters for particle transport in arbitrary magnetic fields providing extremely high accuracy of tracking.
- Added accelerating field (RF-cavities) option.
- New powerful user-friendly system for automatic description, arrangement and tune of beam optics elements.
- New user-friendly Graphical-User Interface for geometry, materials, magnetic field, tracks and 2-D histogram visualization (see fig. 8).
- Substantially improved and extended histograming for surface and volume detectors.
- Substantially improved I/O.

Just one example on the event generator is shown in Figs. 1 and 2 which compare data with calculations with MARS/CEM and with FLUKA [9] for the cases of 3 and 4 GeV/c protons incident on aluminum nucleus. The agreement is quite encouraging, although more data is certainly needed to understand existing differences, especially at E<100 MeV.

2 BENCHMARKING

Fig. 3 shows a total yield of neutrons (E<10.5 MeV) from a 60-cm long lead absorber (R=10 cm) irradiated with protons of 100 MeV to 100 GeV kinetic energy. MARS13(99) predictions agree very well with those by the SHIELD

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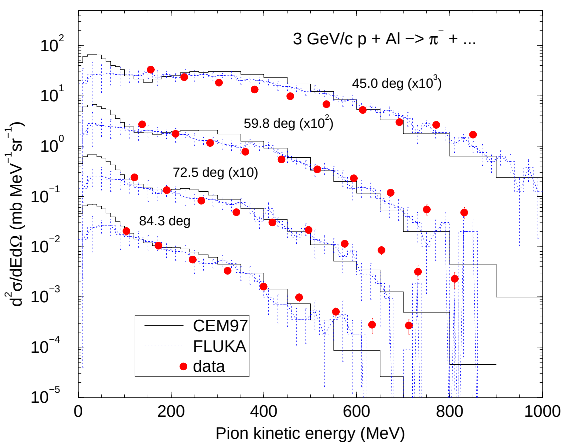

Figure 1: Comparison of MARS/CEM and FLUKA calculated pion spectra to data [7, 8] at incident proton momenta of 3 GeV/c on aluminum nucleus. (Thanks to S. Chiba, A. Ferrari and S. Mashnik for providing us with the numerical data.)

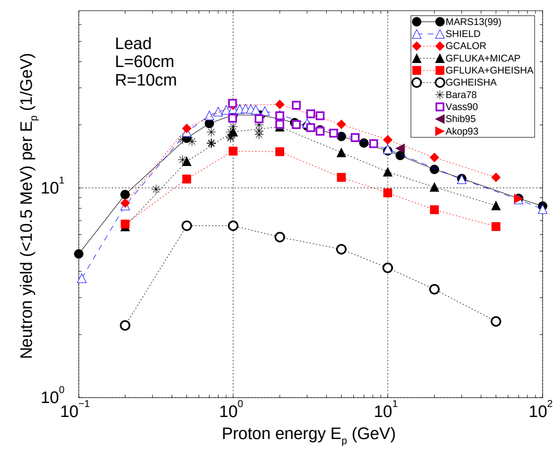

Figure 3: Neutron yield (E<10.5 MeV) per incident proton energy E_p out of a cylindrical lead target (L=60 cm, R=10 cm) *vs* E_p as calculated with the MARS, SHIELD [10] and GEANT [15] codes and measured by several groups [11, 12, 13, 14].

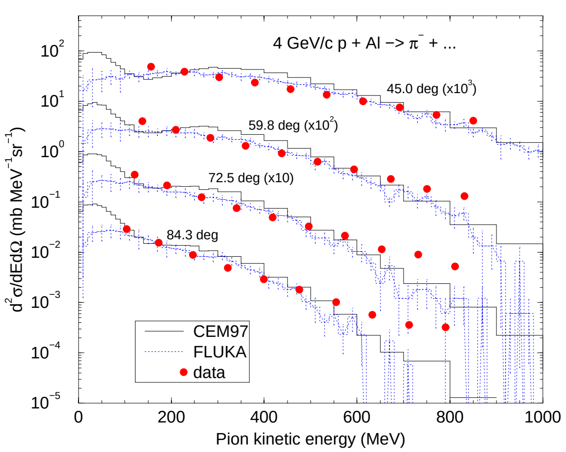

Figure 2: Comparison of MARS/CEM and FLUKA calculated pion spectra to data [7, 8] at incident proton momenta of 4 GeV/c on aluminum nucleus. (Thanks to S. Chiba, A. Ferrari and S. Mashnik for providing us with the numerical data.)

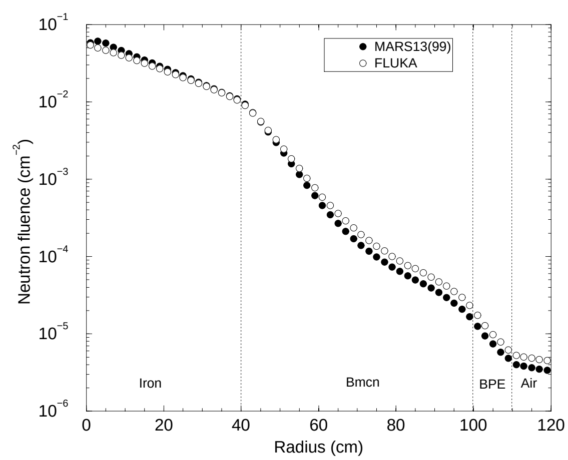

Figure 4: Total neutron fluence at 50< z <100 cm in a 2-m composite cylinder (with heavy concrete in the middle) irradiated by a 10 GeV/c pencil proton beam as calculated by MARS and FLUKA. (Thanks to M. Huhtinen for providing us with FLUKA results.)

code [10] and data [11, 12, 13, 14]. At the same time, the results of calculations with the GEANT code [15] (provided by L. Khein) depend strongly on the GEANT mode used: GCALOR predictions are much closer to the data than those by GFLUKA+MICAP, GFLUKA+GHEISHA and especially GHEISHA.

Figs. 4 and 5 show radial distributions of total neutron and photon fluences at 50< z <100 cm in a 2-m long cylinder irradiated by a 10 GeV/c pencil proton beam. The absorber consists radially of iron (0< r <40 cm), borated magnetite concrete (Fig. 4) or iron (Fig. 5) at 40< r <100 cm, borated polyethylene at 100< r <110 cm and air at 110< r <120 cm. One sees that both MARS and FLUKA [9] reproduce similarly the physics of interactions in different materials.

The MARS code has recently been successfully used to study radiation shielding and ground water activation at the 8-GeV Booster at Fermilab. An excellent agreement has been found between calculated and measured dose rates at the outer surface (R=5.3 m) of the soil shielding of the

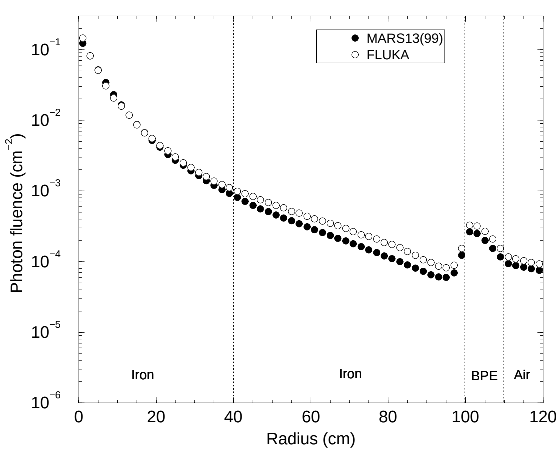

Figure 5: Total photon fluence at 50< z <100 cm in a 2-m composite cylinder (with iron in the middle) irradiated by a 10 GeV/c pencil proton beam as calculated by MARS and FLUKA. (Thanks to M. Huhtinen for providing us with FLUKA results.)

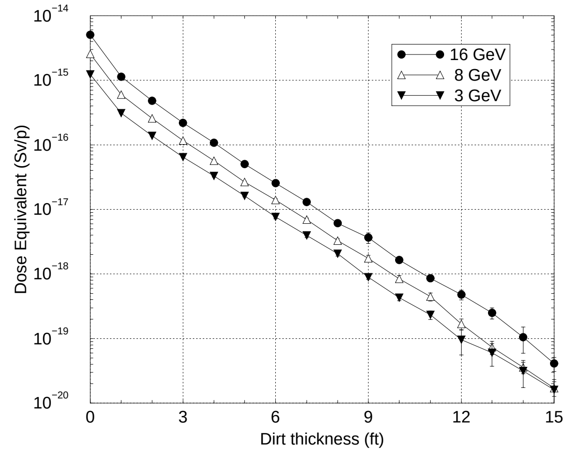

Figure 6: Dose equivalent as a function of the dirt shielding thickness around a new Fermilab booster tunnel per one 3, 8 and 16 GeV proton lost.

tunnel for 0.4 and 7.1 GeV proton beam loss and radionuclide buildup in the soil underneath a concrete floor of the Booster extraction long straight section [16].

3 APPLICATIONS

A list of MARS applications in USA, Europe, Japan and Russia is rather extensive. Just several recent examples are described in this section. The biasing techniques are successfully exploited in MARS for the *deep-penetration problem*. Fig. 6 demonstrates the results of thick shielding calculations for a new high-intensity booster at Fermilab to be used as a proton source for a muon storage ring and for further improvement of the Tevatron performance.

The Fermilab Main Injector extraction system is capable of delivering a 120 GeV proton beam to the fixed target experiments at the rate of up to 4×10^{20} protons per year. Up to 2-4% of the beam can be lost at the extraction septum and the Lambertson magnet. As a result, one expects significant radiation levels in this area. Very sophisticated MARS studies have been performed in a full 3-D model of all the extraction and NuMI beam line elements in a 160 m long region. One of the examples is shown in Fig. 7 for contact residual dose rate on the components in the electrostatic septum to the Lambertson magnet region.

Two new exciting projects—a muon collider and a neutrino factory based on a muon storage ring—heavily rely on the MARS code in several crucial areas: pion production, targetry, protection of superconducting magnets against radiation in the capture solenoid, decay channel and storage ring, backgrounds in the detectors, neutrino-induced hazard and numerous conventional radiation shielding and radiological aspects (see, e. g., Ref. [16, 17, 18]). For in-

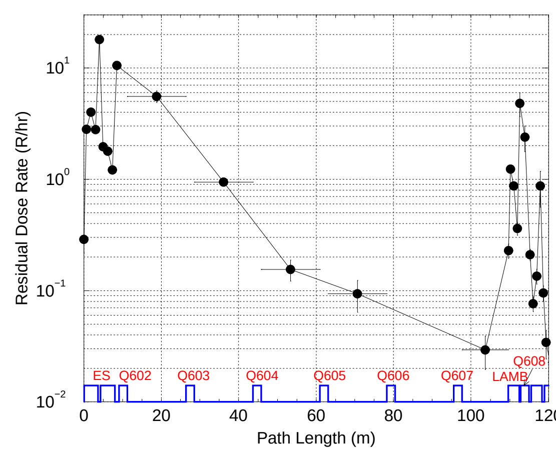

Figure 7: Residual dose rate on the outer surface of the Main Injector and NuMI beamline components due to 30 days of irradiation at the proton intensity of 1.6×10^{13} p/s averaged over that period and after 1 day cooling.

stance, realistic target station 3-D geometry, materials and magnetic field distributions with mercury and carbon targets and a 20-T hybrid solenoidal magnet have been implemented into the MARS code (see Fig. 8) for optimizational design studies.

Detailed calculations of the π/μ-yield have shown that the kinetic energy interval of 30 MeV<E<230 MeV (around the spectrum maximum at $\geq$10 m from the target) is to be considered as the one to be captured by a phase rotation system. The yield grows with the proton energy E_p, but the yield per beam power is almost independent of E_p for high-Z targets at 6< E_p <24 GeV and drops by 30% at 16 GeV from the 6-GeV peak for graphite. The higher E_p

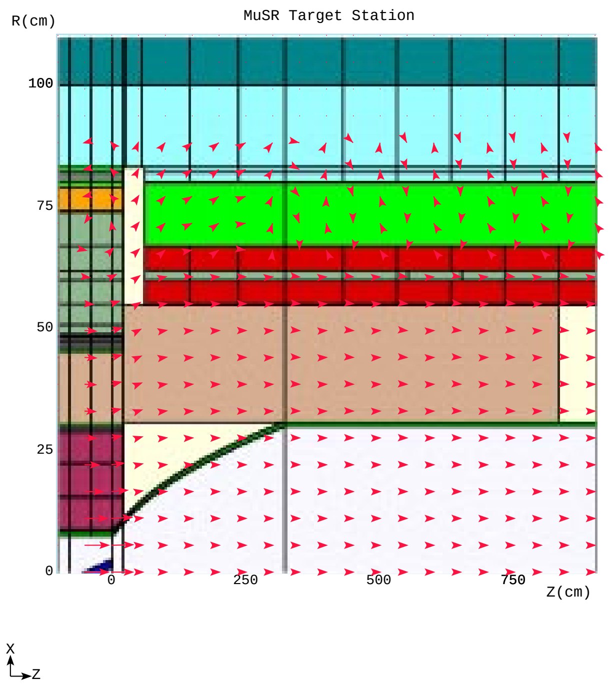

Figure 8: Geometry, materials and magnetic field visualization with MARS-GUI for a muon storage ring target station.

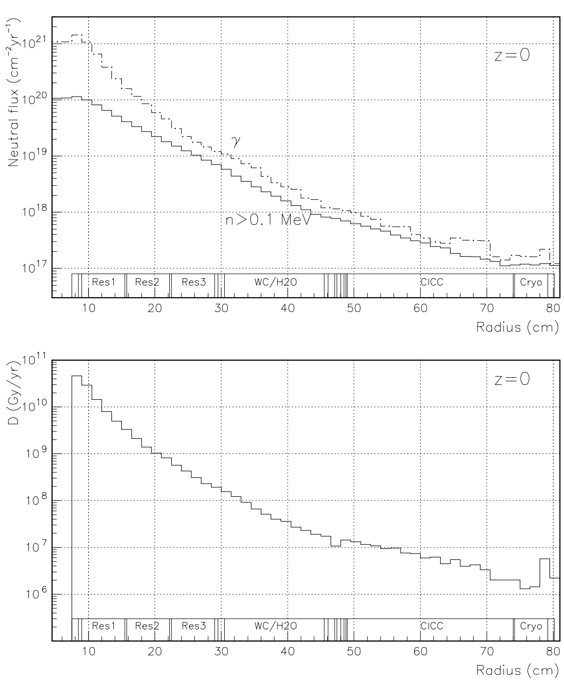

Figure 9: Radial distribution of annual neutron and photon fluence (top) and accumulated dose at the hottest spot in the high-field solenoid (downstream end of a 80-cm long carbon target) for a 1.5 MW 16 GeV proton beam.

reduces the number of protons on target, but results in more severe energy deposition in the target. The yield is higher by up to $\sim$30% for the target tilted by 50 to 150 mrad. Mercury yields to carbon yields ratio varies with the beam energy and with all other beam/target parameters. At 16 GeV it is in the range of 1.5-1.7 for $\pi^+ + \mu^+$ and 1.7-2.19 for $\pi^- + \mu^-$.

Full simulations have been performed to get accumulated dose and particle fluxes in the target, resistive and superconducting coils in the high-field, transition and low-field regions. This enables determination of adequate tungsten-based shielding, residual dose rates on the system components and estimation of ground water and personnel radiation shielding. Fig. 9 shows calculated radial distribution of particle flux and absorbed dose for a 1.5 MW 16 GeV beam on a carbon target. Corresponding residual dose rates are up to 10^7 mSv/hr on the target, bore tube and the inner resistive coil, 10^3 mSv/hr on the superconducting coil and 10^2 mSv/hr on the vessel, with the requirement for remote control and robotics. Radiation shielding needed is $\sim$2 m of steel followed by a 0.3 m concrete wall to protect ground water followed by up to 5 meters of steel/dirt to provide personnel protection.

Monte Carlo simulations have been performed with MARS in a realistic lattice for the arcs and straight sections of 30 and 50 GeV muon storage rings. Prompt and residual radiation levels have been obtained inside the superconducting magnets, around the arc tunnel and at large distances from the ring and the straight sections (neutrino hazard, see Ref. [18]). At 50 GeV, forced muon decays and induced showers are simulated at the rate of 1.6×10^{10} decays/m/s, which corresponds to the design neutrino–to–detector intensity of $2\times10^{20}\nu$/yr. For a 240 kW beam, there is 84 kW power dissipation in the 1750 m storage ring, or 47.8 Watts per meter on average. Most of this power must be intercepted by a thick tungsten bore tube designed on the basis of these calculations.

Results show that for *non-neutrino* radiation, the normal occupancy limit of 2.5μSv/hr is met by providing 2 meters of dolomite type shielding below, above and radially inward from the arc tunnel enclosure walls. Six meters of such shielding is needed to meet that limit in the radially outward direction (Fig. 10). Power supply rooms and other underground enclosures should be placed inward from the arc tunnel. The off-site limit of 0.1 mSv/yr due to *neutrino-induced* radiation is reached at 50 m outward from the beam orbit in the arcs and at about 4 km downstream of the straight sections [18].

4 CONCLUSIONS

The MARS code possibilities have been substantially extended over the last couple of years. The code's reliability is confirmed by comprehensive benchmarking described in this paper and in Ref. [2, 3, 16, 19, 20, 21]. This—along with the code's unique features—allows its successful use in many projects worldwide. Contributions of O. Krivosheev, S. Mashnik, S. Striganov and A. Van Gin-

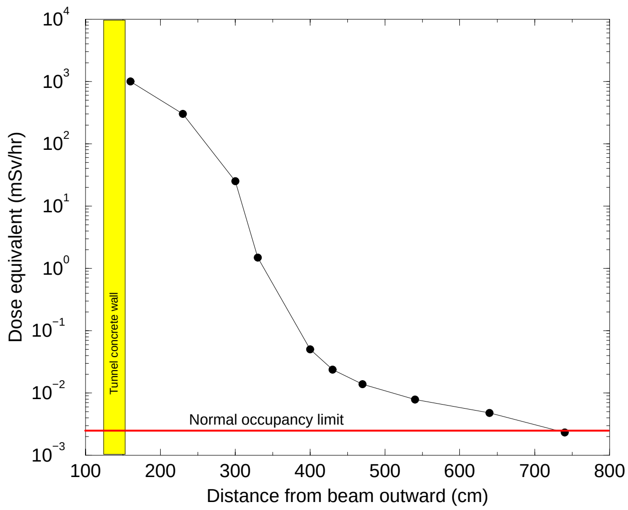

Figure 10: *Non-neutrino* dose distribution radially outward from the arc tunnel enclosure in a 50 GeV muon storage ring.

neken as well as feedback from numerous friendly MARS users were vital for such progress with the code. The official MARS site on the World Wide Web is *http://www-ap.fnal.gov/MARS/*. There is information about the code, its users, its uses and a registration procedure.

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