The MARS15 Code

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MARS15 CODE INTRODUCTION

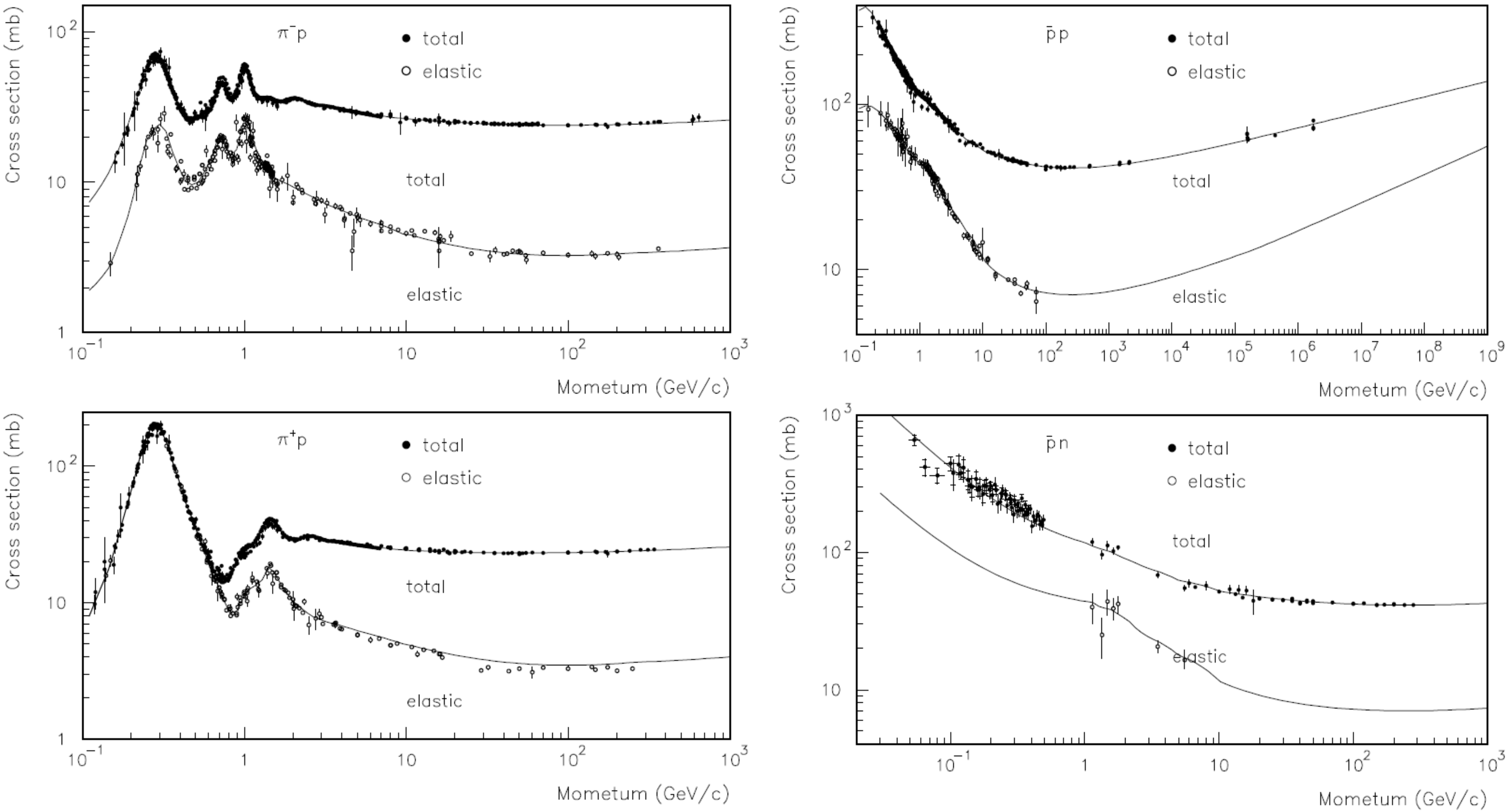
The MARS code system is a set of Monte Carlo programs for detailed simulation of hadronic and electromagnetic cascades in an arbitrary 3-D geometry of shielding, accelerator, detector and spacecraft components with energy ranging from a fraction of an electronvolt up to 100 TeV. It has been developed since 1974 at IHEP, SSCL and Fermilab. The current MARS15 version combines the well established theoretical models for strong, weak and electromagnetic interactions of hadrons, heavy ions and leptons with a system which can contain up to 10^5 objects, ranging in dimensions from microns to hundreds kilometers. A setup can be made of up to 100 composite materials, with arbitrary 3-D magnetic and electric fields. Powerful 2-D and 3-D user-friendly GUIis used for visualization of the geometry, materials, fields, particle trajectories and results of calculations. MARS15 has 5 geometry options and flexible histograming options, can use as an input MAD optics files through a powerful MAD-MARS Beam Line Builder, and provides an MPI-based multiprocessing option, with various biasing and other variance reduction techniques.

PARTICLES TRANSPORTED IN MARS15

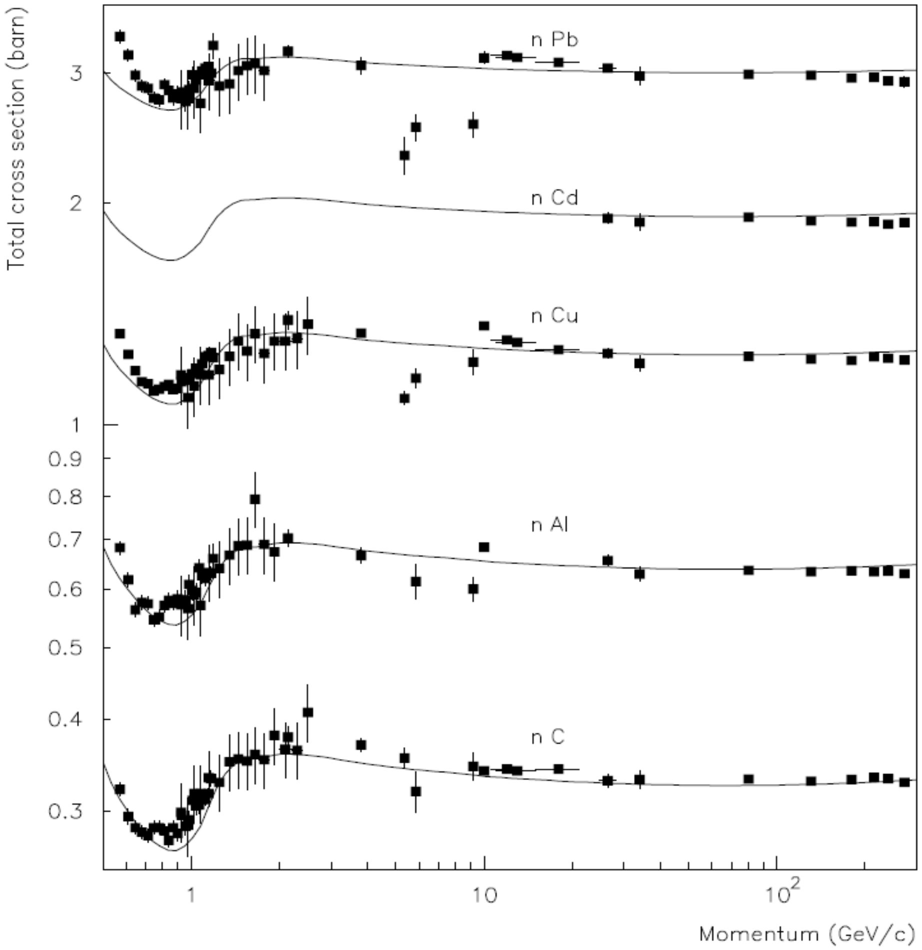
All important elementary particles with their corresponding decay modes are transported in the code. Arbitrary heavy ions with atomic mass A and charge Z are fully treated by MARS15. Their ID are coded as $ID = 1000Z + A - Z$.

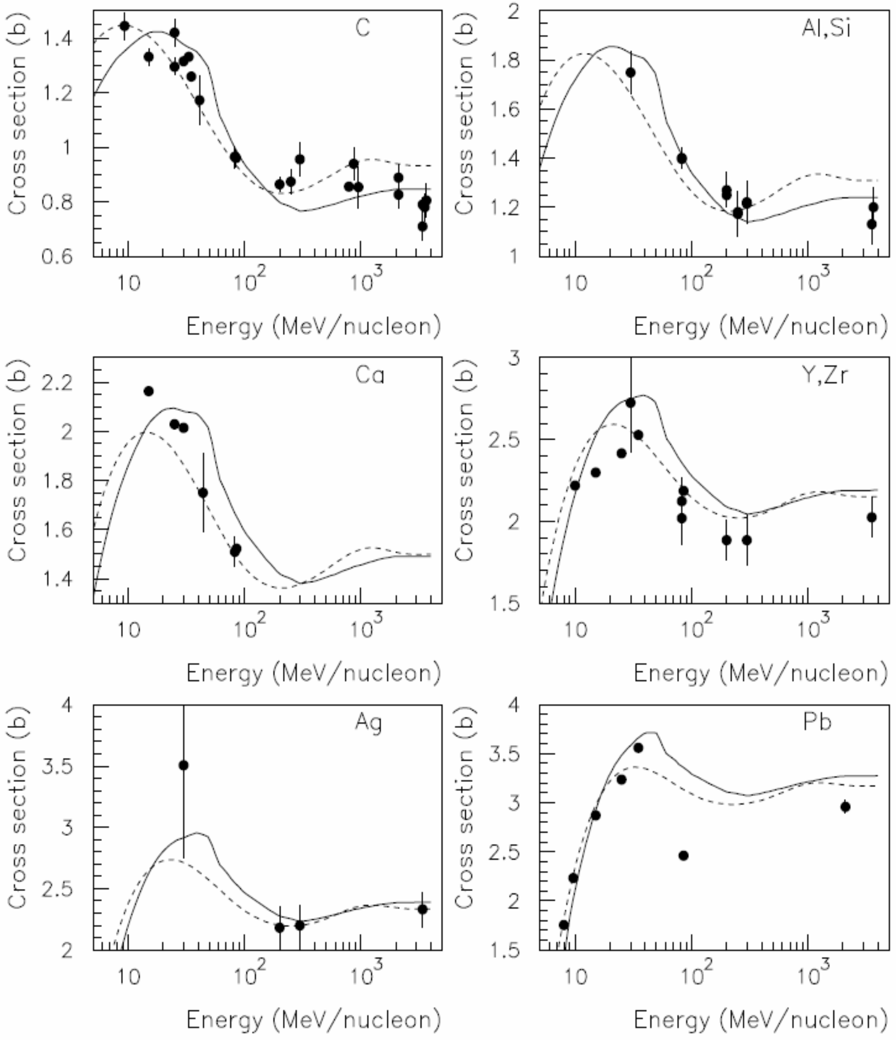
Nucleons & Mesons	Gauge & Leptons	Hyperons
$p\ \overline{p}$	γ	$\Lambda\ \overline{\Lambda}$
$n\ \overline{n}$	$e^+\ e^-$	$\Sigma^+\ \overline{\Sigma}^+$
$\pi^+\ \pi^-\ \pi^0$	$\mu^+\ \mu^-$	$\Sigma^0\ \overline{\Sigma}^0$
$K^+\ K^-$	$\nu_e\ \overline{\nu}_e$	$\Sigma^-\ \overline{\Sigma}^-$
$K^0\ \overline{K}^0$	$\nu_\mu\ \overline{\nu}_\mu$	$\Xi^0\ \overline{\Xi}^0$
$K_L^0\ K_S^0$		$\Xi^-\ \overline{\Xi}^-$
		$\Omega^-\ \overline{\Omega}^-$

PION AND ANTIPROTON X-SECTIONS



NEUTRON- AND CARBON-NUCLEUS X-SECTIONS





^{12}C—nucleus reaction cross section

BIASING

Many processes in MARS15, such as electromagnetic showers, most of hadron-nucleus interactions, decays of unstable particles, emission of synchrotron photons, photohadron production and muon pair production, can be treated either analogously or inclusively with corresponding statistical weights.The choice of method is left for the user to decide, via the input settings.

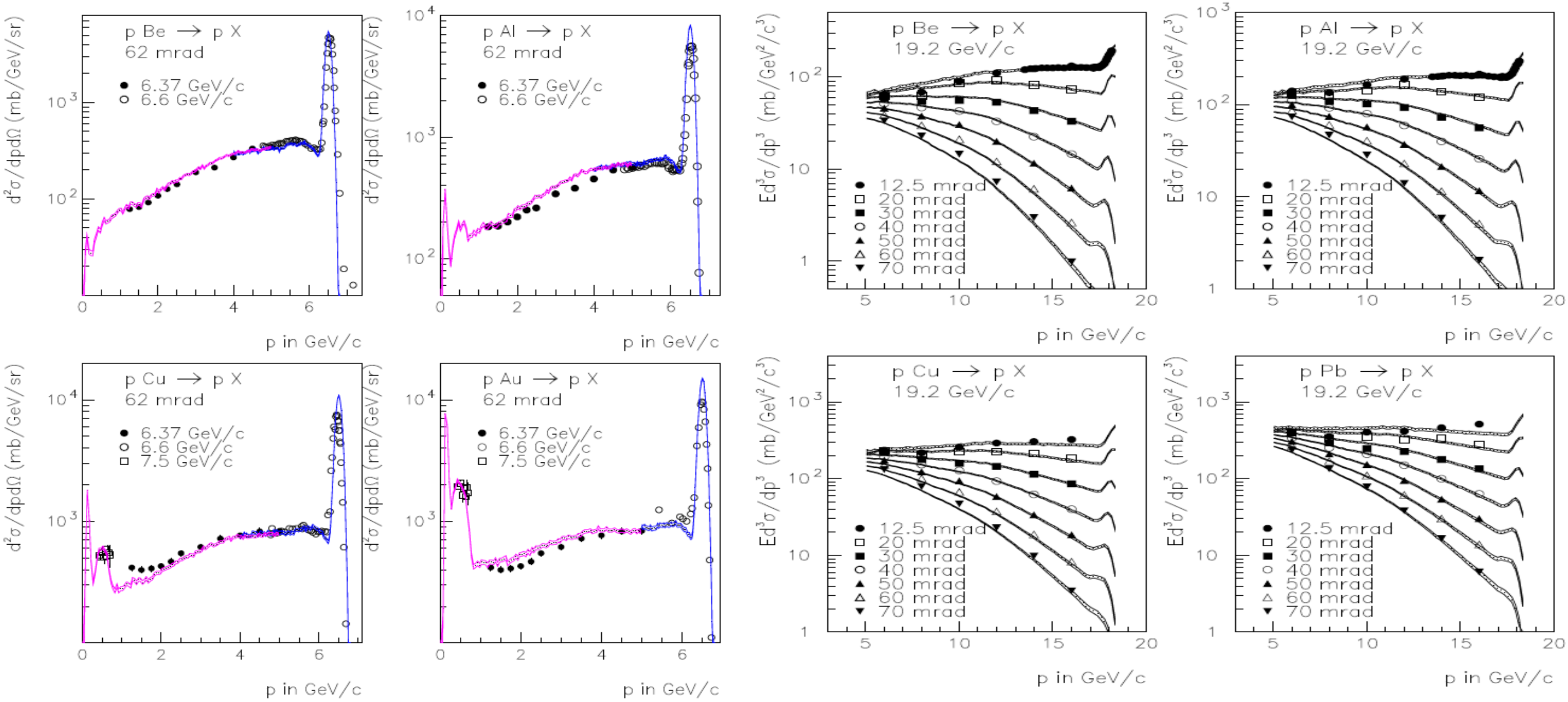
Other variance reduction techniques used in MARS: weight-window, splitting and Russian roulette, exponential transformation, probability scoring, step/energy cutoffs.

Goal: Maximize computing efficiency $\varepsilon = t_0/t$, where t is CPU time needed to get a RMS error σ equal to the one in the reference method with CPU time t_0 provided σ < 20%.

MARS INCLUSIVE APPROACH

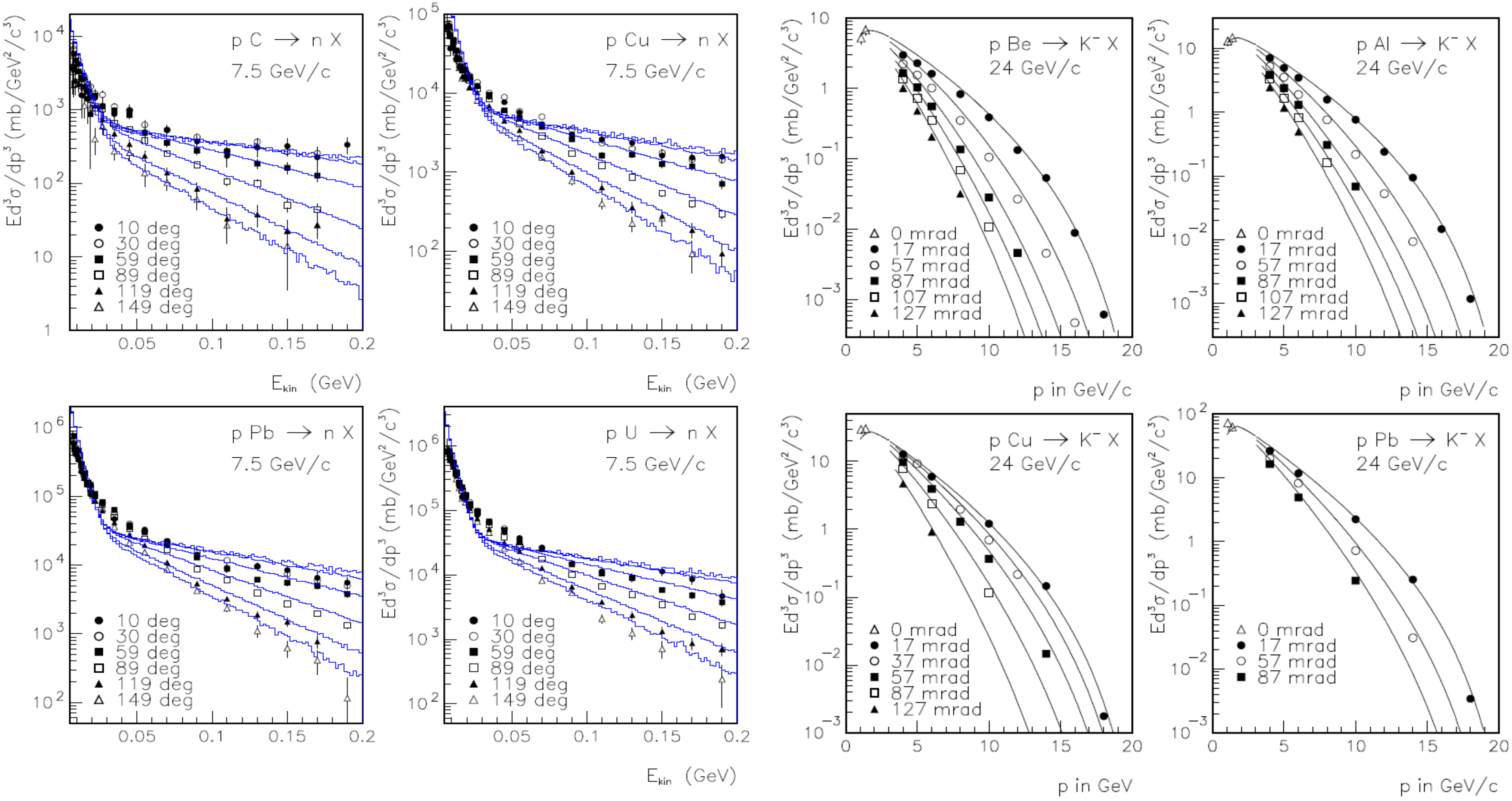
The basic model for the original MARS program, introduced in 1974, came from Feynman's ideas concerning an inclusive approach to multiparticle reactions and weighting techniques. At each interaction vertex, a particle cascade tree can be constructed using only a fixed number of representative particles (the precise number and type depending on the specifics of the interaction), and each particle carries a statistical weight $w = f(x)/S(x)$, which is equal, in the simplest case, to the partial mean multiplicity of the particular event. Energy and momentum are conserved on average over a number of collisions. It was proved rigorously that such an estimate of the first moment of the distribution function $f(x)$ is unbiased. A disadvantage of this approach is the impossibility of directly studying fluctuations from cascade to cascade, or of studying particle production correlations.

INCLUSIVE PROTON PRODUCTION IN MARS15



Proton inclusive spectra in pp-interactions are described in resonance region $x_F > 1\text{-}2.2/p_0$ as a sum of five Breit-Wigner resonances; in diffractive dissociation region $1\text{-}2.2/p_0 < x_F < 0.9$ via triple-Reggeon formalism; in fragmentation region $0.4 < x_F < 0.9$ via phenomenological model with a flat behavior on longitudinal and exponential on transverse momenta; in central region $0 < x_F < 0.4$ via fit to experimental data. For pA, it is factorized then with $R(A,p,p_0)$ function adjusted with additive quark model, with quasielastic scattering and Fermi-motion modeled in addition, supplied with a phenomenological model for cascade and evaporation nucleon production.

INCLUSIVE NEUTRON AND KAON PRODUCTION



MARS15 vs data

MARS15 EXCLUSIVE EVENT GENERATORS

The improved Cascade-Exciton Model code, **CEM03.01**, combined with the Fermi break-up model, the coalescence model, and an improved version of the Generalized Evaporation-fission Model (GEM2) is used as a default for hadron-nucleus interactions below 5 GeV.

The Los Alamos Quark-Gluon String Model code, **LAQGSM03**, was implemented into MARS15 for particle and heavy-ion projectiles at 10 MeV/A to 800 GeV/A. This provides a power of full theoretically consistent modeling of exclusive and inclusive distributions of secondary particles, spallation, fission, and fragmentation products. Further development of this package is underway.

For quite some time, MARS has used the Dual-Parton Model code, **DPMJET3**,for the very first vertex in a cascade tree. This is used in our numerous studies for the LHC 7x7 TeV collider and its detectors, and at very high energies up to 100 TeV.

NUCLEON YIELDS in 0.56 and 8 GeV/A REACTIONS

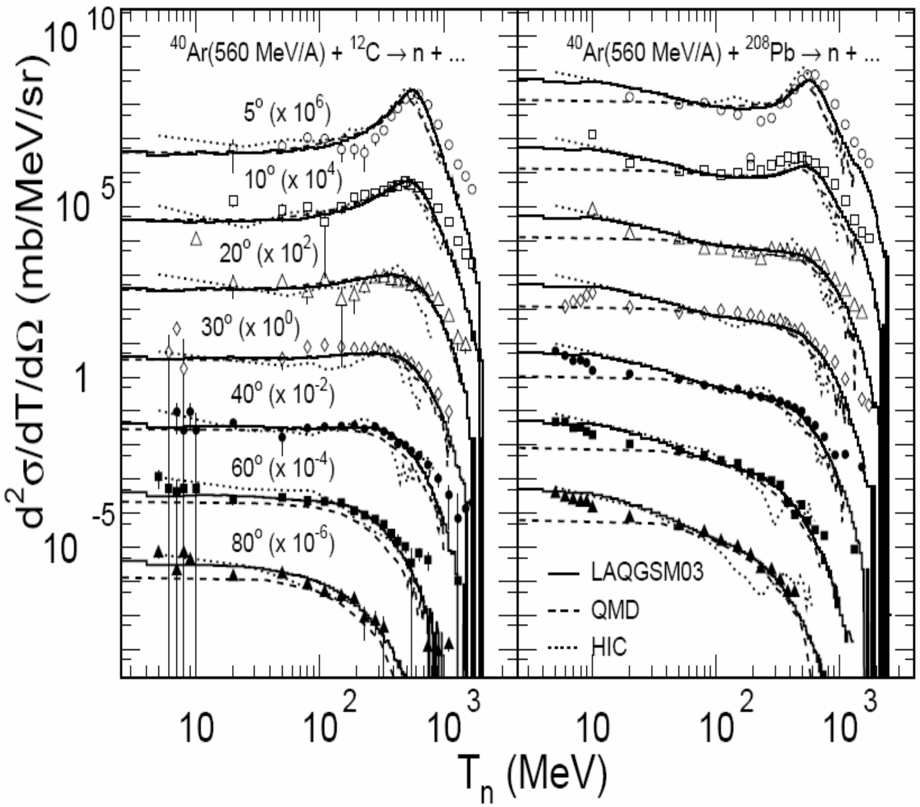


FIGURE 3. Differential cross-sections of neutrons in 560 MeV/A $Ar+C$ and $Ar+Pb$ reactions as calculated with LAQGSM03, JQMD [12] and HIC [13] codes *vs* data [14].

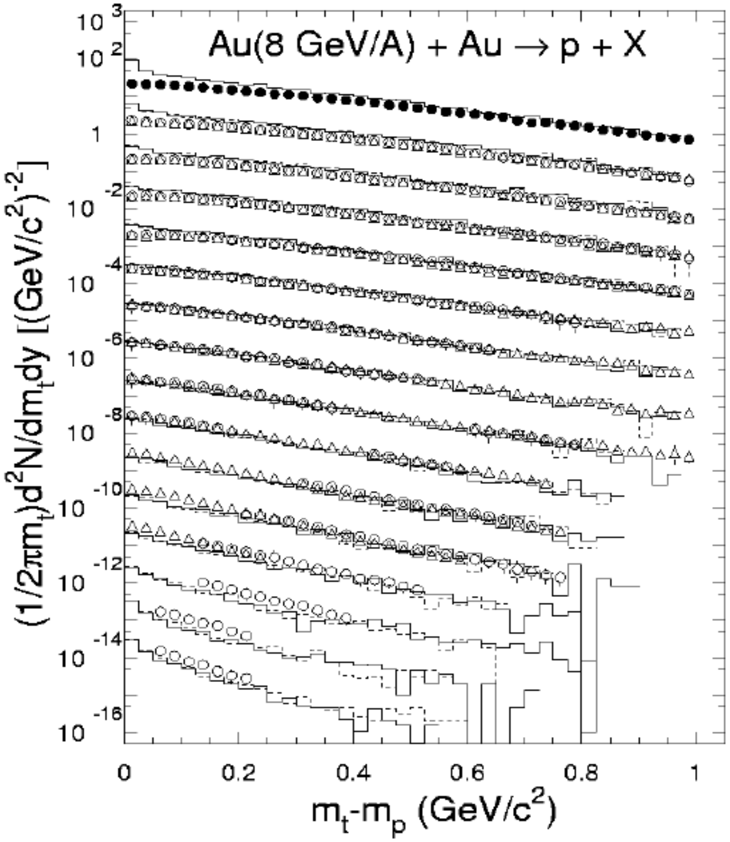
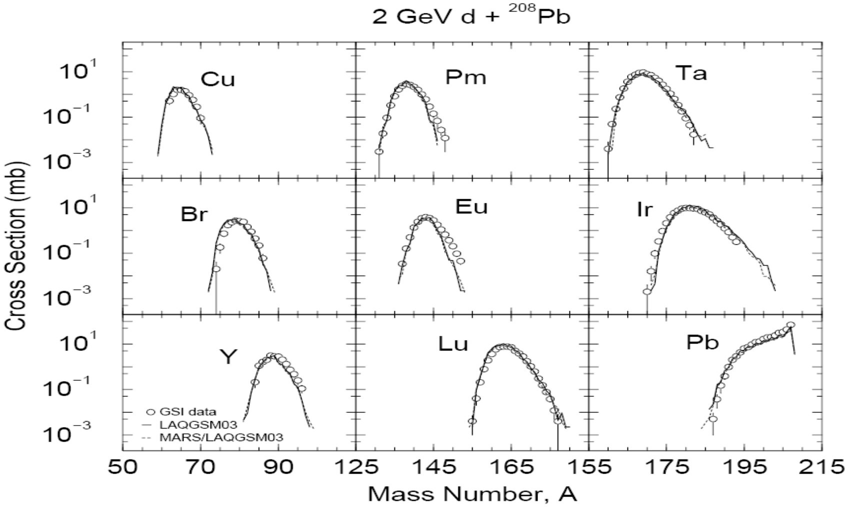
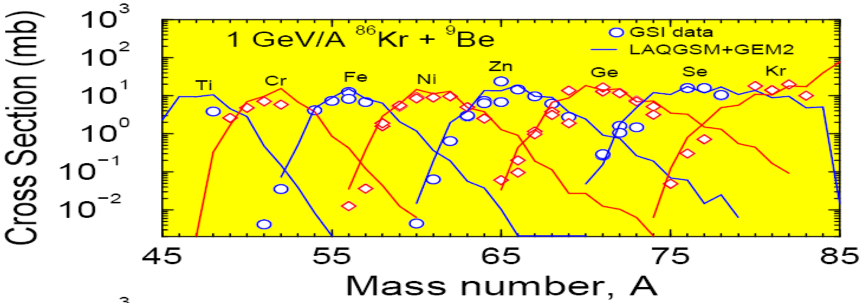
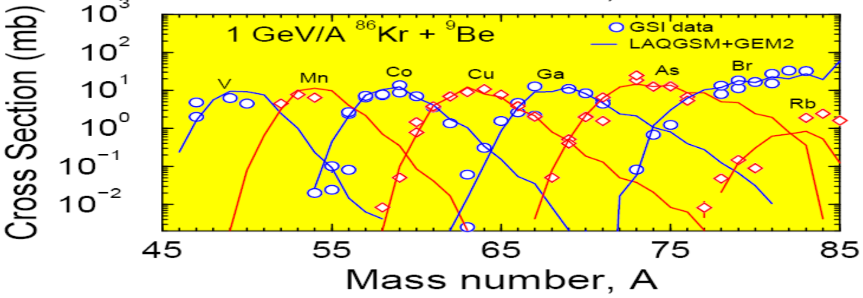


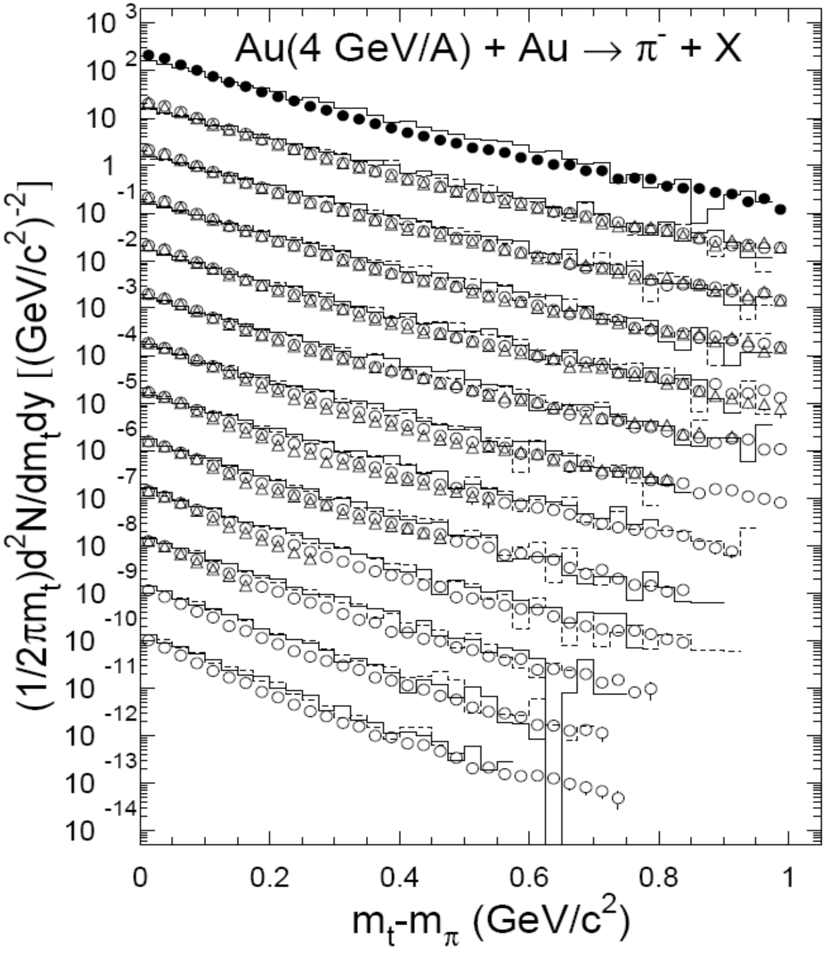
Figure 4. Invariant proton yield per central $Au+Au$ collision at 8 GeV/A as calculated with LAQGSM03 (histograms) and measured in Ref. (12) (symbols). Solid lines and open circles is forward production, dashed lines and open triangles is backward production. Midrapidity (upper set) is shown unscaled, while the 0.1 unit rapidity slices are scaled down by successive factors of 10.

NUCLIDE PRODUCTION AND PION SPECTRA FOR AA

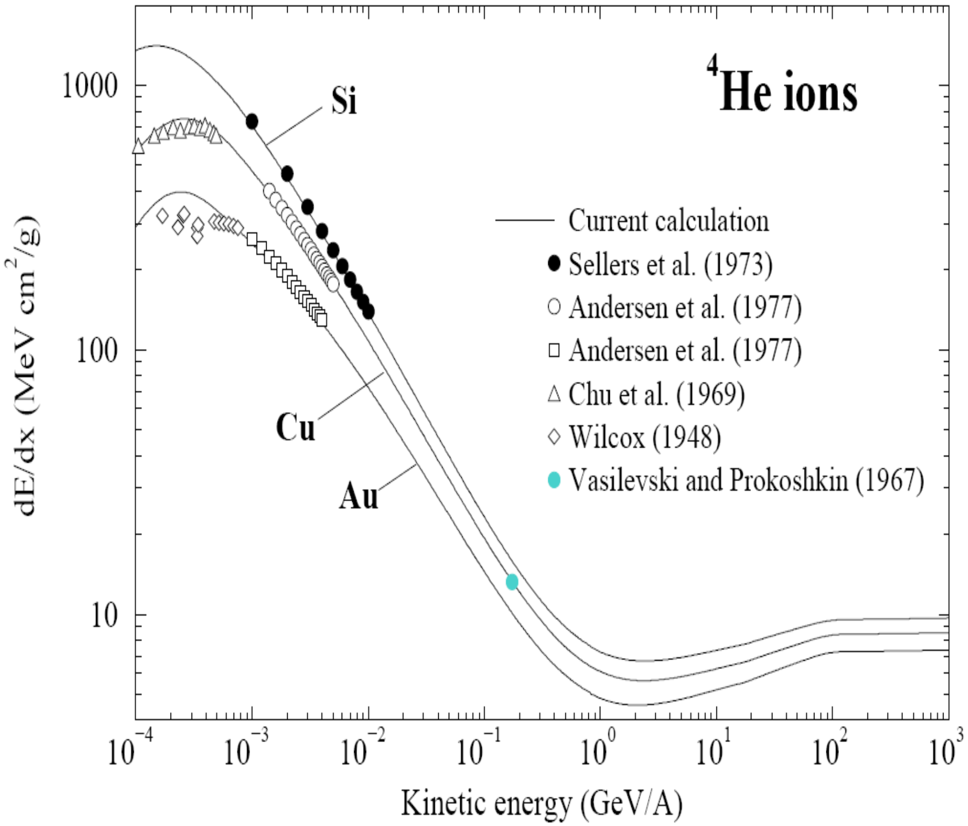


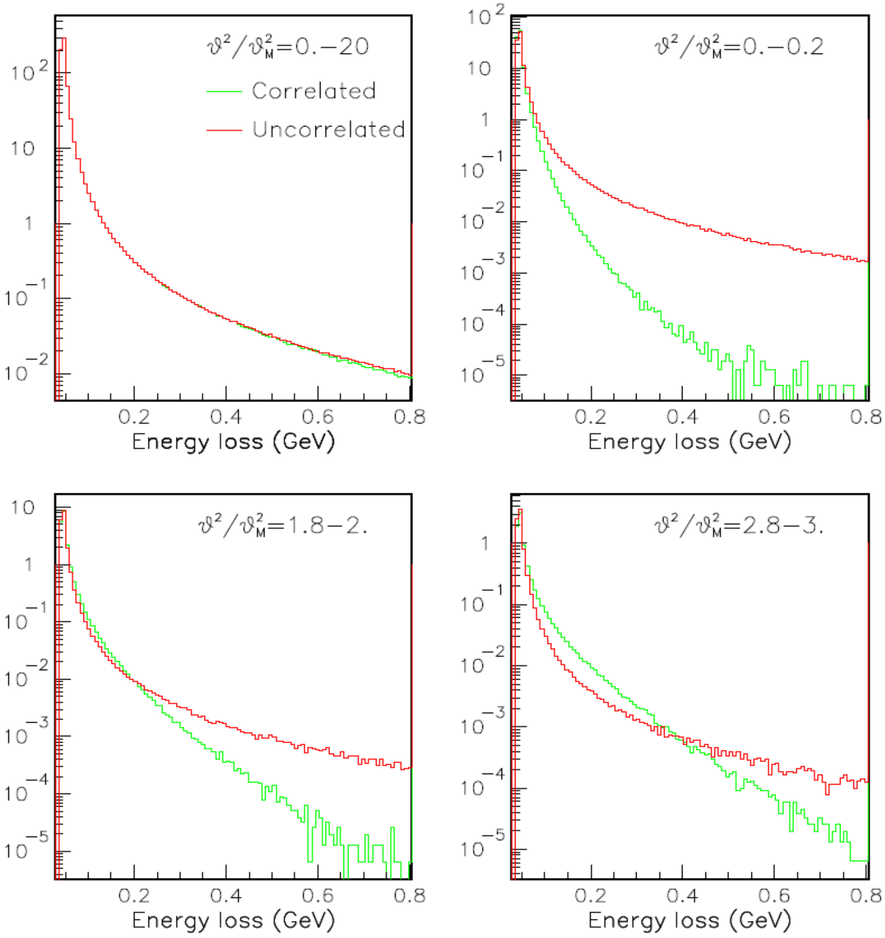






dE/dx and CORRELATED COULOMB SCATTERING





50-GeV protons on 10 g/cm^2 H_2

GEOMETRY DESCRIPTIONS IN MARS15

Five geometry description options

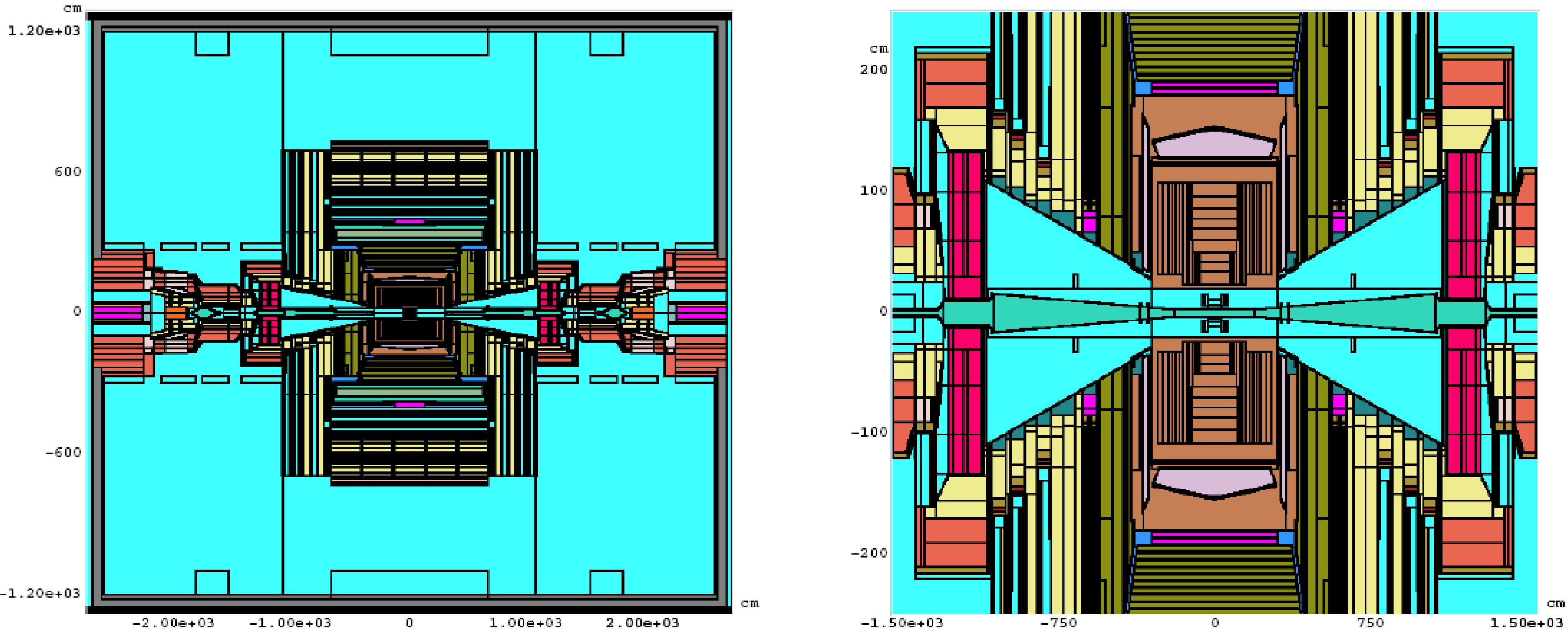
1. **Standard:** heterogeneous $R - Z - \phi$ cylinder.
2. **Non-standard:** arbitrary user-defined in Fortran or C.
3. **Extended:** a set of contiguous or overlapping geometrical shapes, currently, boxes, spheres, cylinders, truncated cones and tetrahedra. Subdivision of volumes into sub-regions, up to 500 arbitrary transformation matrices, automatic adjustment of step sizes along a particle track prevents small regions within a large volume from being skipped over.
4. **MCNP:** read in an input geometry description in the MCNP format.
5. **FLUKA:** read in an input geometry description in the FLUKA format.

GEOMETRIES AND MATERIALS IN MARS15

All five geometry options can co-exist in a setup description. Arbitrary number of regions, with a default of 10^5. Volumes of all regions in MARS15 are auto-calculated for the predefined shapes or using a short session of the program. A corresponding output file provides calculated volumes with statistical errors, and is directly linked to the main code.

A list of the built-in materials has been extended up to 153 with an arbitrary number of user-defined composites on top of that. A separate treatment of gaseous and liquid states of some elements.

EXAMPLE OF FLUKA-MARS15 LINK



CMS detector as seen in MARS-GUI

HISTOGRAMING AND TAGGING IN MARS15

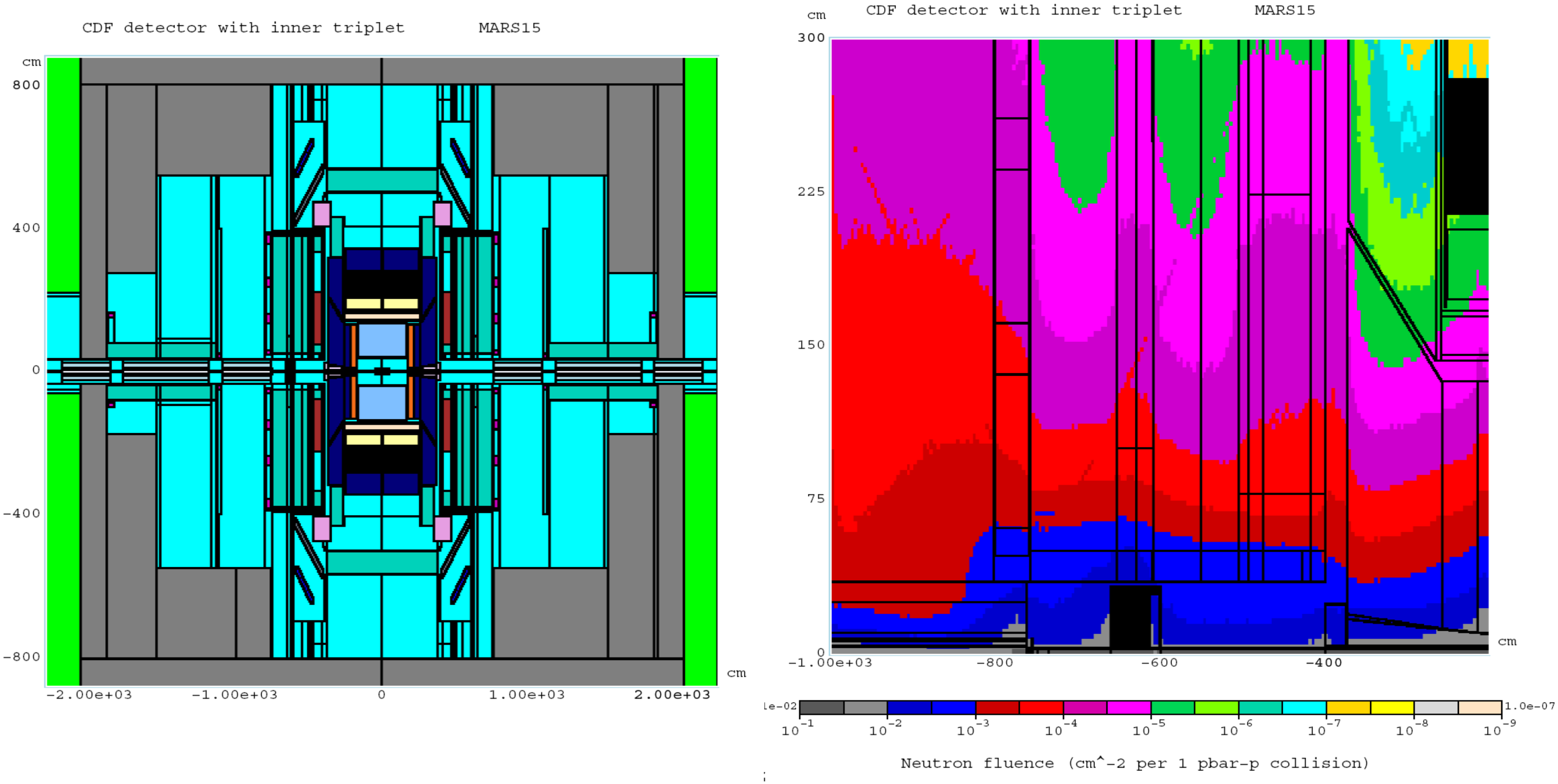
In addition to previous volume and surface tally and histograming options in the code, a new user-friendly flexible XYZ-histograming module in MARS15 allows scoring numerous distributions - total an partial particle fluxes, star density, energy deposition, DPA, temperature rise, prompt and residual dose rates, particle spectra etc – in boxes arbitrary positioned in a 3D system, independent of geometry description.

A refined tagging module in MARS15 allows one to tag the origin of a given signal/tally – geometry, process and phase-space - invaluable in studying a source term and for sensitivity analysis.

GRAPHICAL-USER INTERFACE

The existing Tcl/Tk-based 2D MARS-GUI-SLICE functionality was further improved and extended to 3D, which further extends the power of visualization of the modeled system: geometry, materials and magnetic field descriptions, simulated processes and calculated results. Arbitrary 3-D rotation of a slice is possible. The new module in MARS15 is based on the Open Inventor graphics library, integrated with MARS-GUI-SLICE. It has also been re-implemented using the C++ based Qt-toolkit. The new 3D display capability was developed using open source libraries that should allow redistribution of the code and/or binaries to the MARS user community, free of commercial licensing terms.

MARS MODELING OF CDF DETECTOR



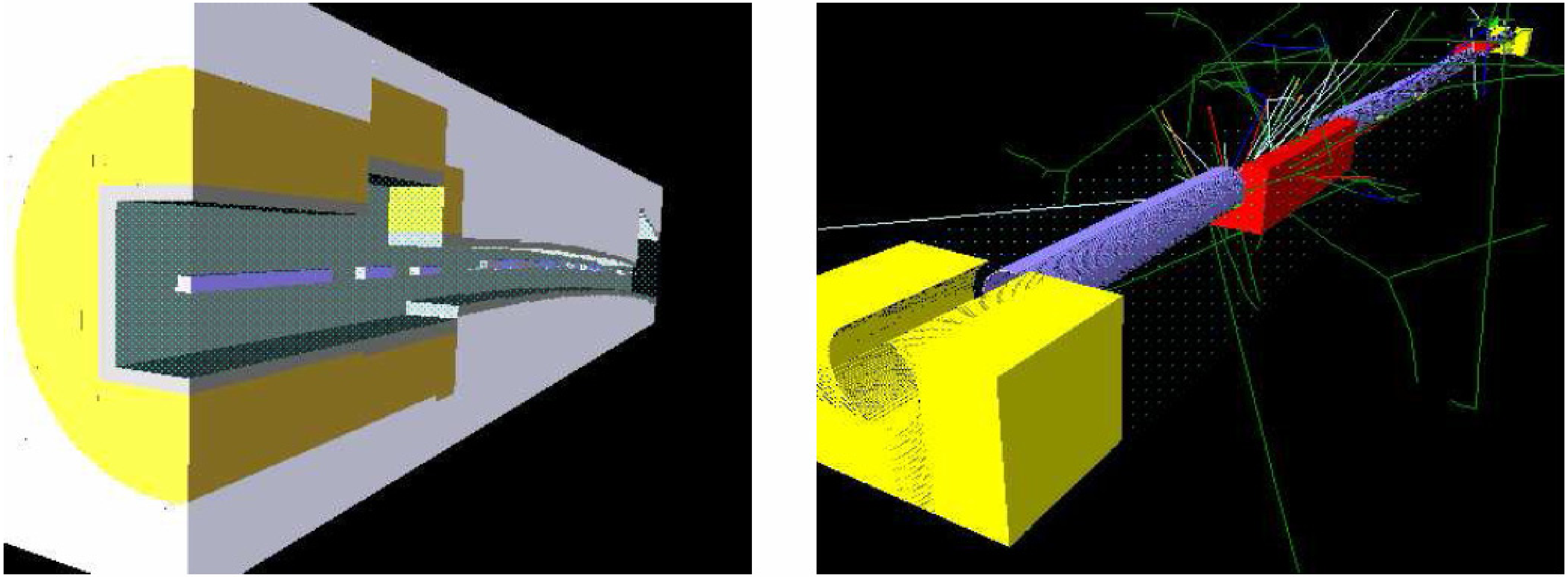
CDF detector, experimental hall, Tevatron beamline elements and neutron fluence isocontours as seen in MARS15 GUI

MAD-MARS BEAM LINE BUILDER

The interface system to build beam line and accelerator models in the MARS format. MMBLB reads in a MAD lattice file and puts the elements in the same order into MARS. Each element is assigned six functions: element type/name, geometry, materials, field, volume and initialization. MMBLB has been substantially extended for MARS15:

- The set of supported element types includes now almost all the elements supported by MAD.
- An arbitrary number of beam lines – arbitrary positioned and oriented – can be put in a MARS15 model.
- More sophisticated algorithms and new data structures enable more efficient searches through the beam line geometry.
- Tunnel geometry can now follow the beam line or be described independently of it.

BEAMLINE MODELING AND VISUALIZATION

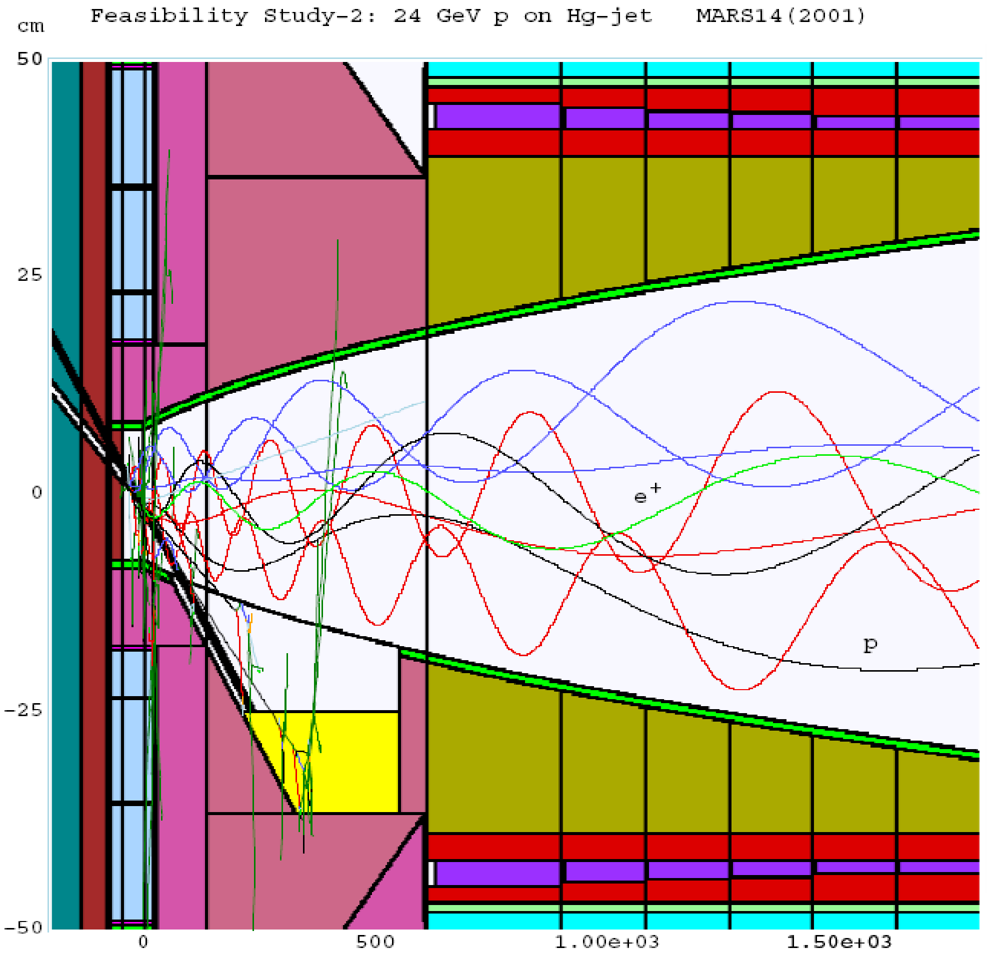


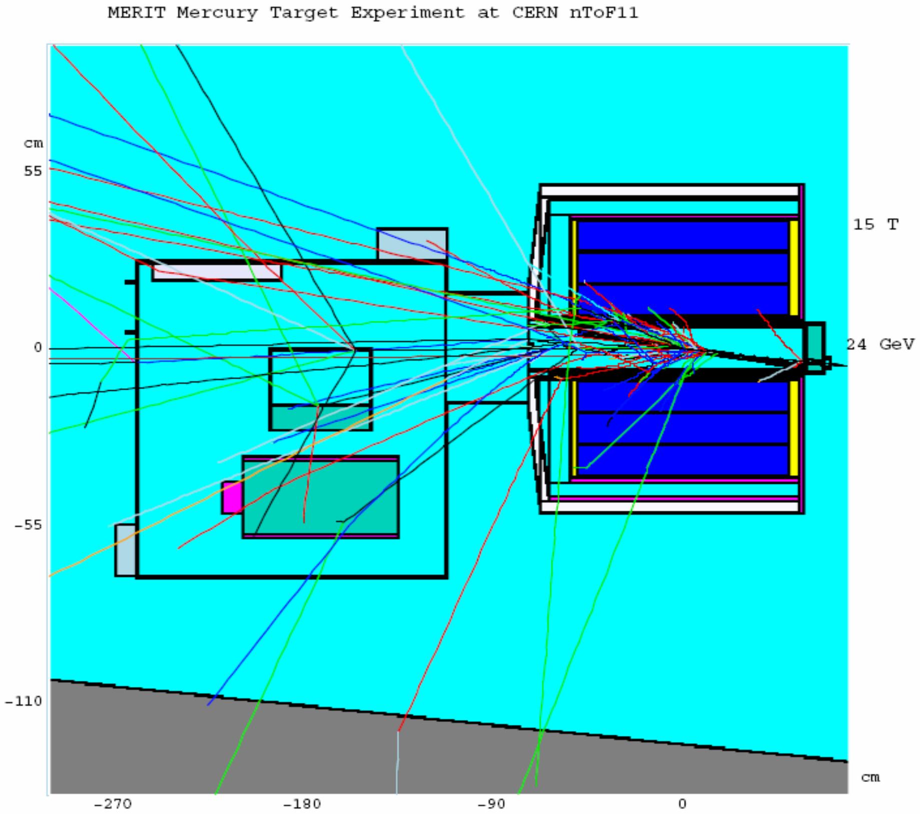
Fragments of MARS models: NuMI beamline (left) and Booster collimators (right) at Fermilab.

MULTIPROCESSING IN MARS15

Since 2004, parallel processing is default in all CPU-hungry applications of MARS15. It is based on the Message Passing Interface(MPI) libraries. Parallelization is job-based, i.e. the processes, replicating the same geometry of the setup studied, run independently with different initial seeds. A unique master process -- also running event histories -- collects intermediate results from an arbitrary number of slaves and calculates the final results when a required total number of events has been processed. Intermediate results are sent to the master on its request generated in accordance with a scheduling mechanism. The performance scales almost linearly with the number of nodes used (up to tens of nodes at Fermilab clusters).

NEUTRINO FACTORY AND MERIT EXPT TARGETS

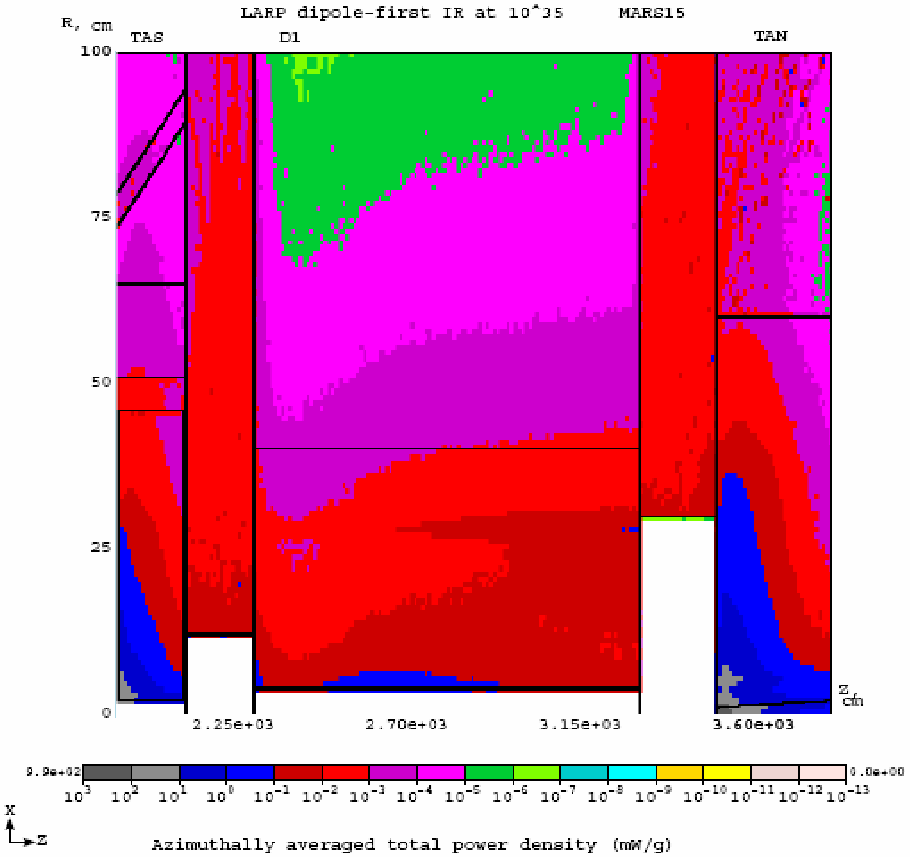


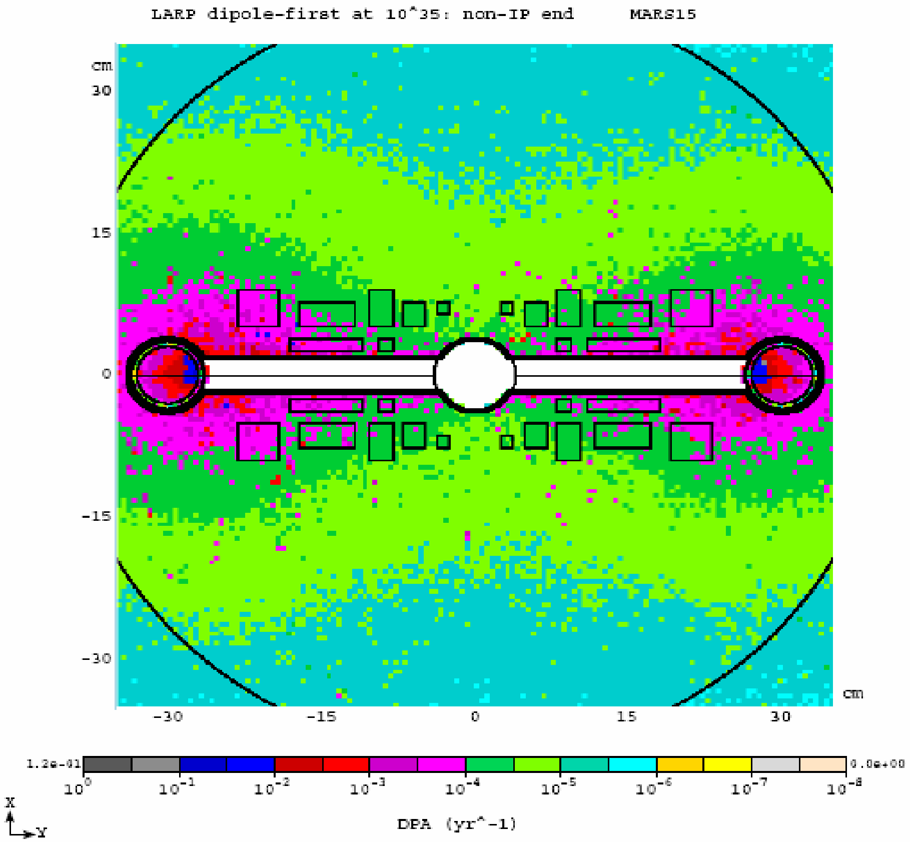


MARS15

MARS14

ENERGY DEPOSITION AND DPA MODELING





DPA is calculated in MARS15 within a damage energy concept, taking into account recoil nuclei in elastic and inelastic hadron-nucleus interactions.

MODELING BEAM ACCIDENT AT TEVATRON

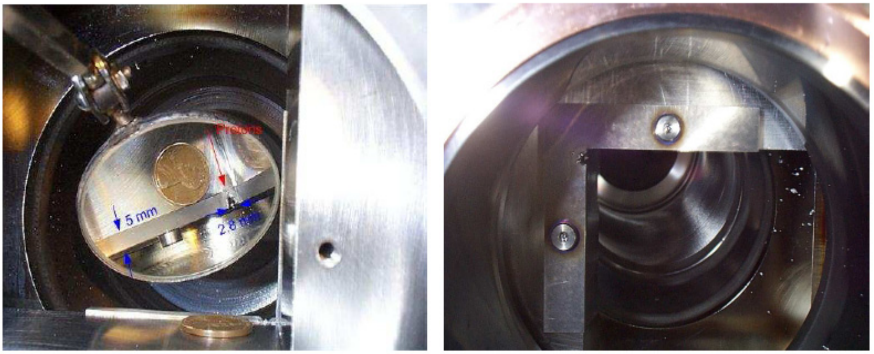
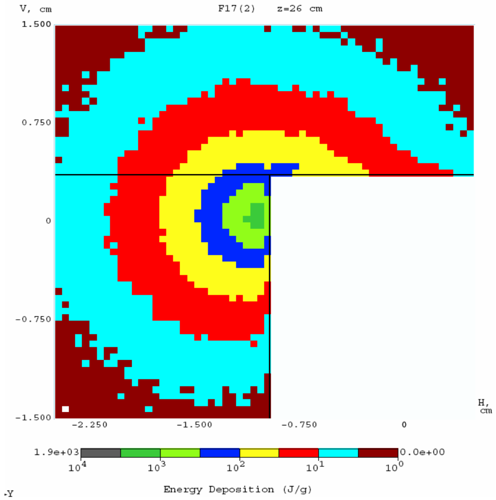
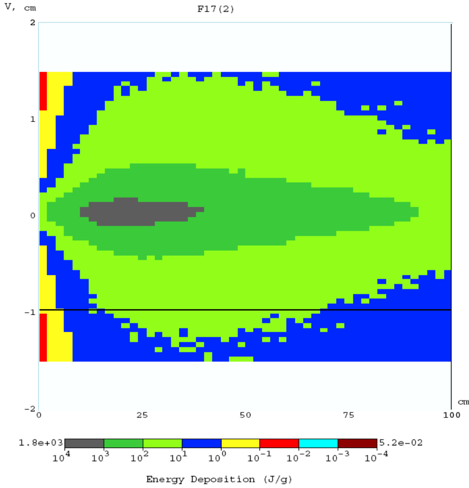
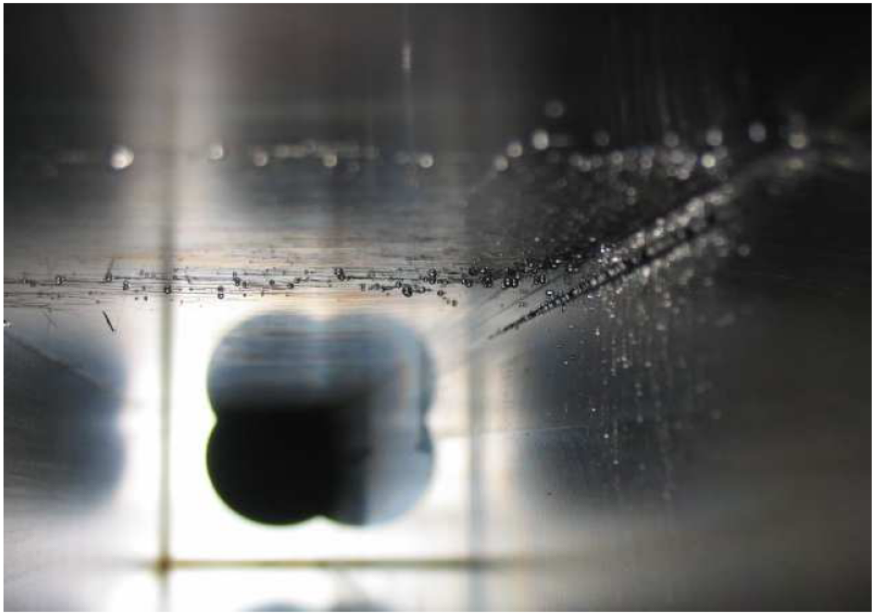


Figure 5: Damage to D49 5-mm thick tungsten primary collimator.







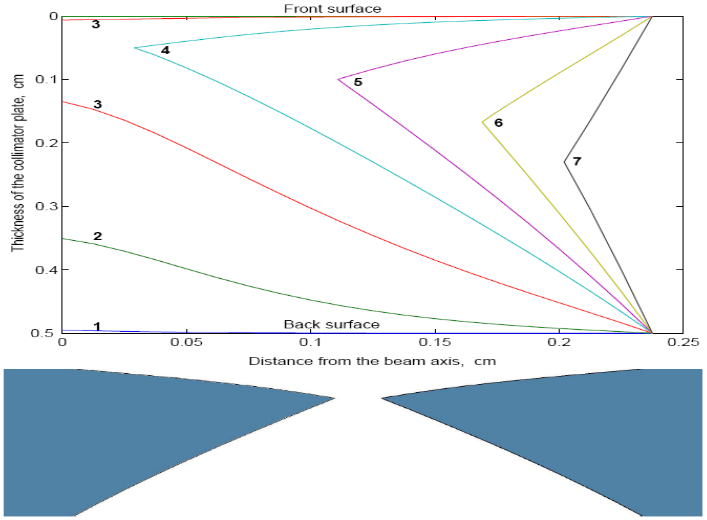


Figure 18: Top: evolution of the front and back surfaces of the tungsten collimator plate from t=0.4 ms (1) through t=1.6 ms (7) with Δt=0.2 ms. Bottom: shape of the hole in the collimator plate at 1 ms.