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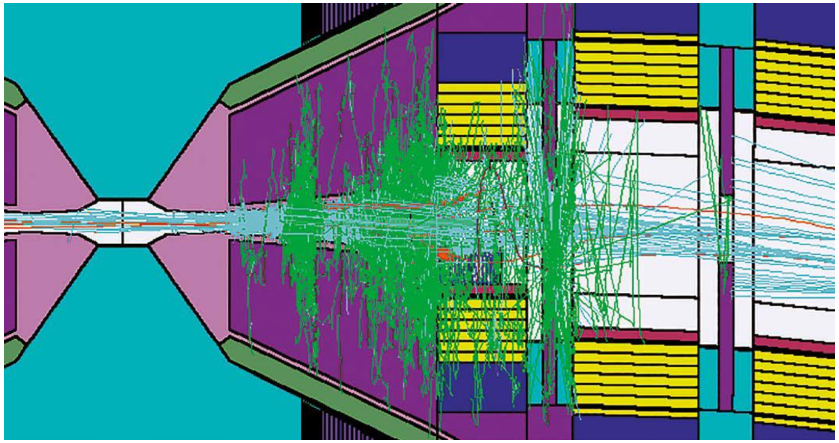
Beam-Material Interactions and Fermilab MARS Code



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Fermilab

Accelerator Advisory Committee @ Fermilab
December 9, 2020

AAC Charge Questions Addressed in the Presentation

Beam Energy Deposition and Fermilab MARS Code:

Assess the Fermilab's effort in beam energy deposition and particle/radiation production modeling. What are the long-term plans for this effort? Is the MARS code effort adequate to sustain future Fermilab program demands?

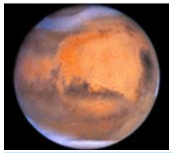
This presentation reminds what MARS is, describes recent efforts on the code development and MARS applications to the major Fermilab projects, long-term plans as well as challenges and path forward to sustain future Fermilab program demands.

Beam-Matter Interaction Simulations

The consequences of controlled or uncontrolled impacts of high-intensity or/and high-power or/and high-energy beams on components of accelerators, beamlines, target stations, beam collimators, absorbers, detectors, shielding, and environment can range from minor to catastrophic.

All forces govern beam interactions with complex components in presence of electromagnetic fields ➔ simulations are only possible with a few well-established Monte-Carlo codes: **FLUKA and MARS15** being the leaders in full-scale accelerator applications.

Due to the extensive use of these codes in numerous applications and massive benchmarking **the simulations have reached an unprecedented accuracy**.



MARS Code System

The MARS code system is a set of Monte Carlo programs for detailed simulation of coupled hadronic and electromagnetic cascades, with heavy ion, muon and neutrino production and interactions, in an arbitrary geometry of shielding, accelerator, detector and spacecraft components.

Current MARS15 combines well established theoretical models and databases for strong, weak and electromagnetic interactions of hadrons, heavy ions and leptons with a system.

Especially powerful in accelerator lattice, beamline and machine-detector interface applications.

It was originated by NM at MEPhI (Moscow), and developed since at IHEP (Protvino), SSCL (Texas) and Fermilab.

300 official users & 40 sites worldwide, https://mars.fnal.gov

MARS15 Key Features

- A model can be built out of a million objects ranging in dimensions from microns to hundreds kilometers in the same setup with up to 500 composite materials, with arbitrary 3-D magnetic and electric fields.

- Recently developed powerful **integrated MARS-MADX-PTC** system (now in beta-tests) is highly-efficient for particle tracking in SRF (with time-dependent electromagnetic fields and Dark Current production), quadrupole and dipole magnets and Machine-Detector Interface for use in the 10^{-5} eV < E < 100 TeV energy range.

- Semi-automated (currently) use of CAD models, bilateral geometry model exchange (GDML format) with Geant4, nuclide production, decay, transmutation and calculation of the activity distribution with the built-in DeTra code, accurate radiation damage calculations based on theoretical models and the newly generated cross-section database.

- User-friendly Graphical-User Interface (GUI), various tagging, biasing and other variance reduction techniques, and hydrodynamic tunneling.

MARS Use and Support

- The code is installed and supported on 40 MARS sites: at the DOE Labs, US universities, CERN, PSI, GSI, ESS, KEK, J-PARC, RIKEN, several Japanese Universities, Korean PAL etc.
- At Fermilab, MARS is installed, supported and used on the AD MARS clusters (heimdall, heimdallr, gulltoppr and thudpucker), and Fermigrid (marslbnf, marsmu2e, marsgm2, marsaccel and marspip2 groups)
- At Argonne Leadership Computing Facility (ALCF supercomputing, petaflop platform)
- Protected by the DOE Copyright and MARS User's Agreement
- User's Guide – need substantial update (need to find time to do that)
- Regular (in the past) MARS tutorials in US and worldwide
- All of the above – free of charge, some changes are possible - under consideration with Office of Partnership and Technology Transfer

MARS Group

- Five PhD holders (theor & math physics, physics of atomic nuclei and elementary particles, nuclear engineering, beam physics & accelerator techniques, simulations of solar and stellar convection and oscillations) and systems admin III/computer professional VI.
- Knowledgeable and experienced in MARS use, with four currently capable in development of its modules. The group member's expertise is in great demand in AD, projects and other applications.
- Predominantly, work for accelerator and experiment projects: targetry and particle production, beam loss/collimation, shielding design and verification, radiation loads, heating and damage, shielding assessments etc.
- MARS is an integral part of that process, with not much time remained for its general long-term developments, documentation and tutorials; mainly, immediate application-driven needs (e.g., recent H^- beam and processes in SRF etc.)

MARS Mission

- Increase physics output by maximizing useful particle yields from target systems and minimizing backgrounds in detectors
- Model 3D distributions of particle flux, energy deposition density, prompt and residual doses, nuclide production, radiation damage and spectra by primary and secondary beams for complex accelerator and detector configurations
- Optimize performance of those **predictive virtual particle accelerators and experimental setups**
- Ensure safe designs and operations of accelerator systems and experiments
- Make MARS even more capable, trustable and usable in practically arbitrary parameter phase space

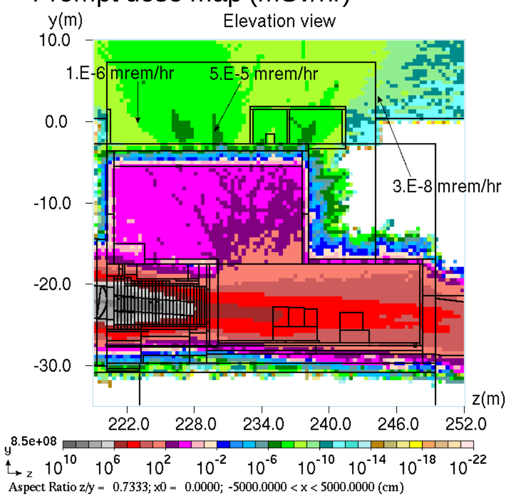
MARS15 (Fermilab) Applications

MARS15

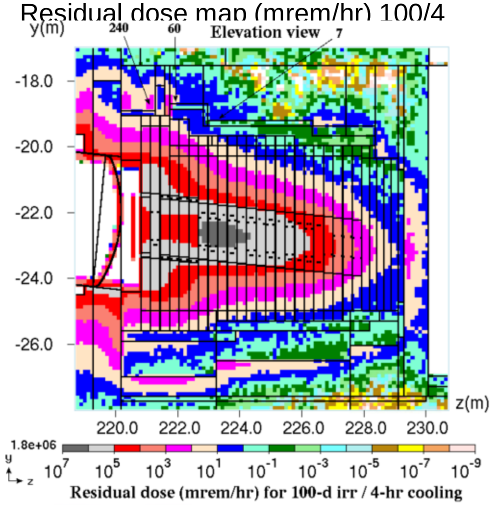
- Particle yields: p,n,π,K,μ,Σ,HI
- Nuclide inventory
- Radiation damage: DPA, dose, H/He, soft errors (SEE)
- Background suppression, MDI
- Beamline optimization, beam loss, particle capture and collimation, SC magnet quench
- Prompt and residual radiation, shielding, impact on environment
- Targetry: power dissipation, integrity (shock & buildup), magnetohydrodynamics

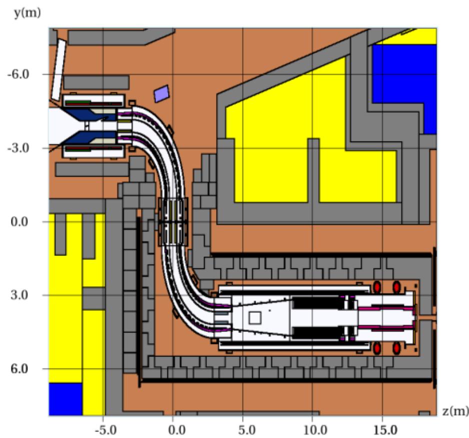
MARSLBNF and MARSMu2e

LBNF Hadron Absorber complex
Prompt dose map (mSv/hr)



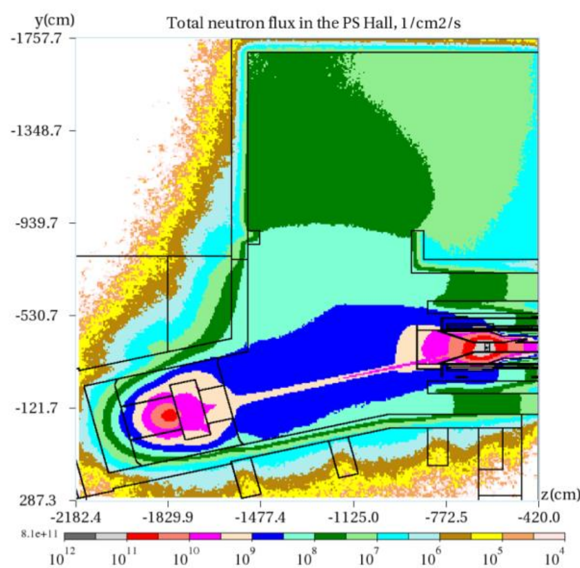
LBNF Hadron Absorber
Residual dose map (mrem/hr) 100/4

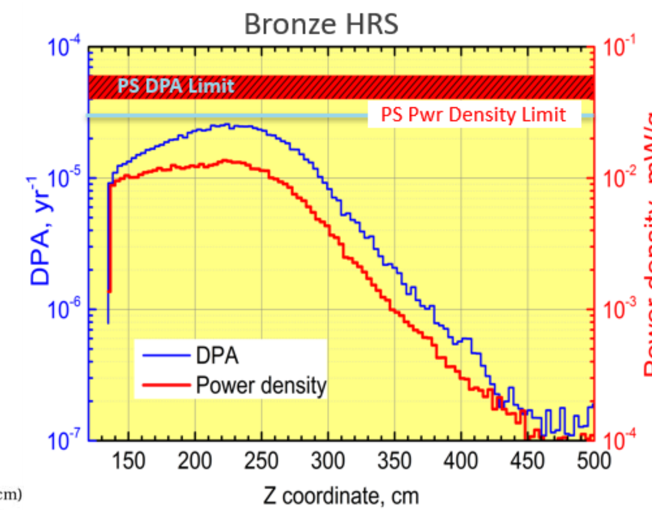




Mu2e

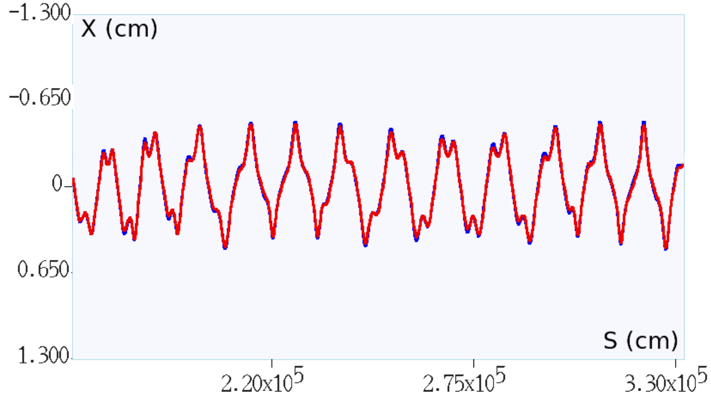
Several years of efforts to optimize with MARS15 the Mu2e Production, Transport and Detector solenoid systems w.r.t. **their performance, lifetime, shielding and cost**





Newest MARS15-MADX-PTC Integration

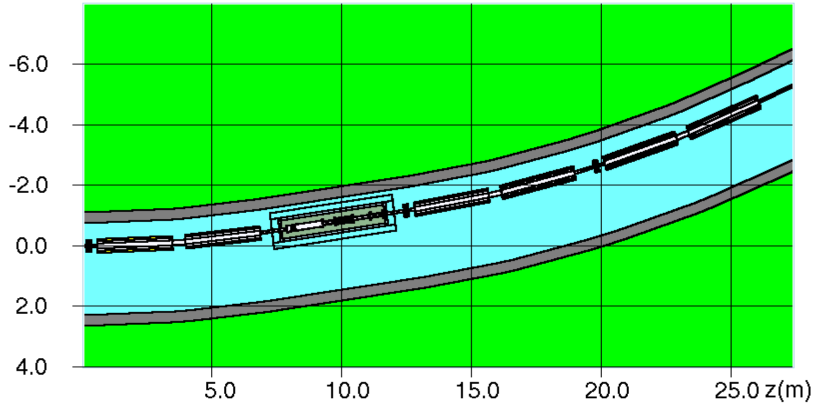
- Cross-talk of MAD-X PTC module with MARS geometry and tracking ones
- Arbitrary boundary conditions and cross-talk points.
- A library containing functions and C++ classes which interfaces MARS with MADX is now packed with the MARS15 distribution.
- For particles transported in PTC, check is performed of boundary crossing against the ROOT geometry in MARS15; the particle is forwarded to the MARS15 stack.
- 3-D TGeo ROOT geometry model is created for the sequence described in a MADX-PTC input file. Alignment of elements is performed by means of the MAD-X survey table.

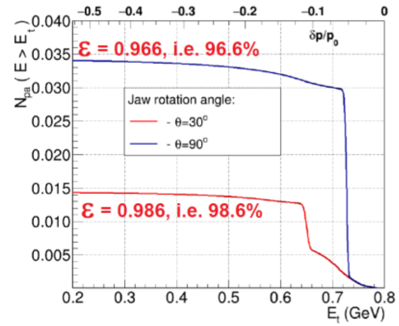


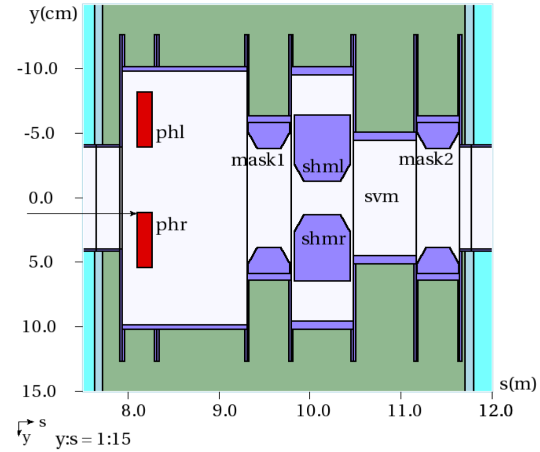
Beam orbits in the Fermilab 8-GeV Recycler calculated with MAD-X PTC module (blue) and MARS15 native stepper (red)

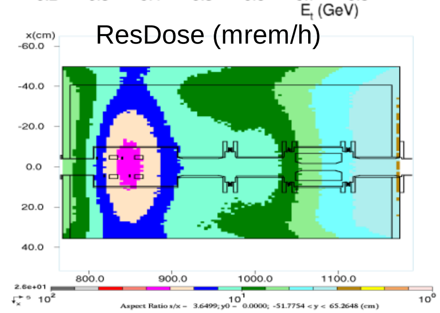
MARS-MADX-PTC Fusion Allows Effective Use of both ABP and Particle-Matter Interaction Code Strengths (1)

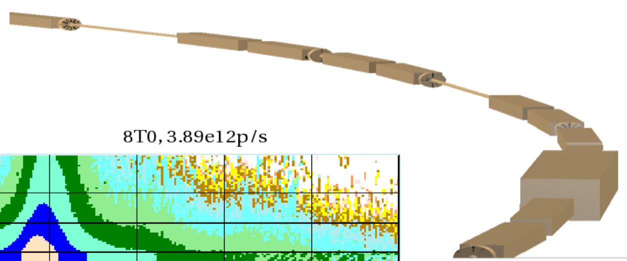
New PIP-2 Booster Collimation

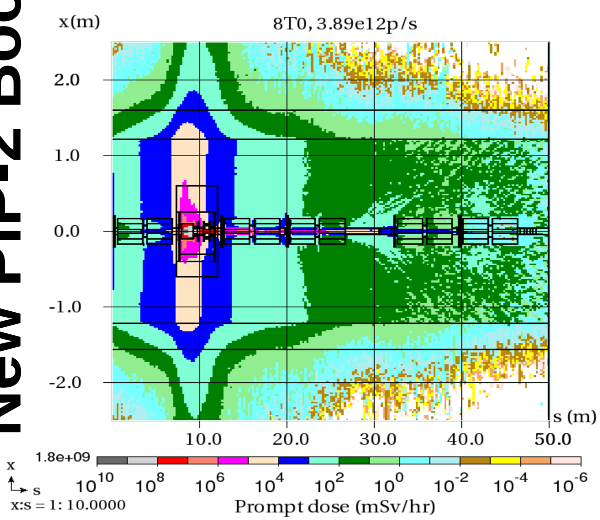




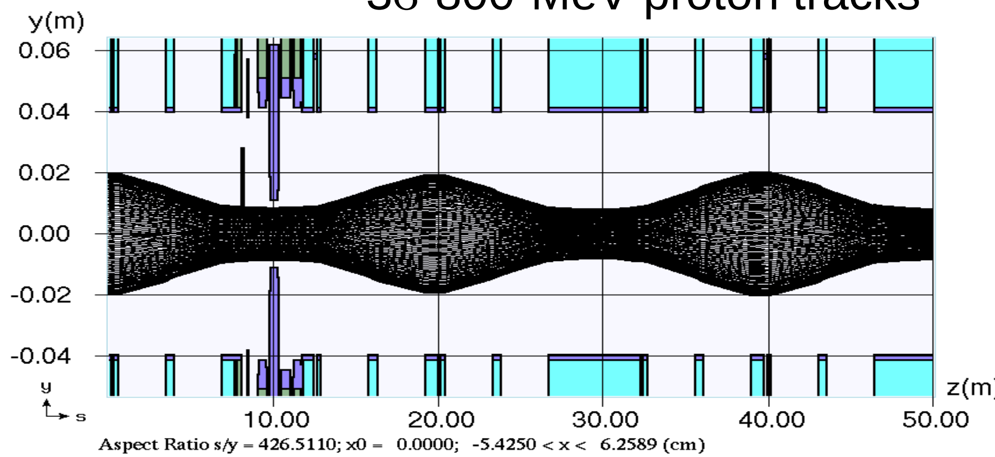






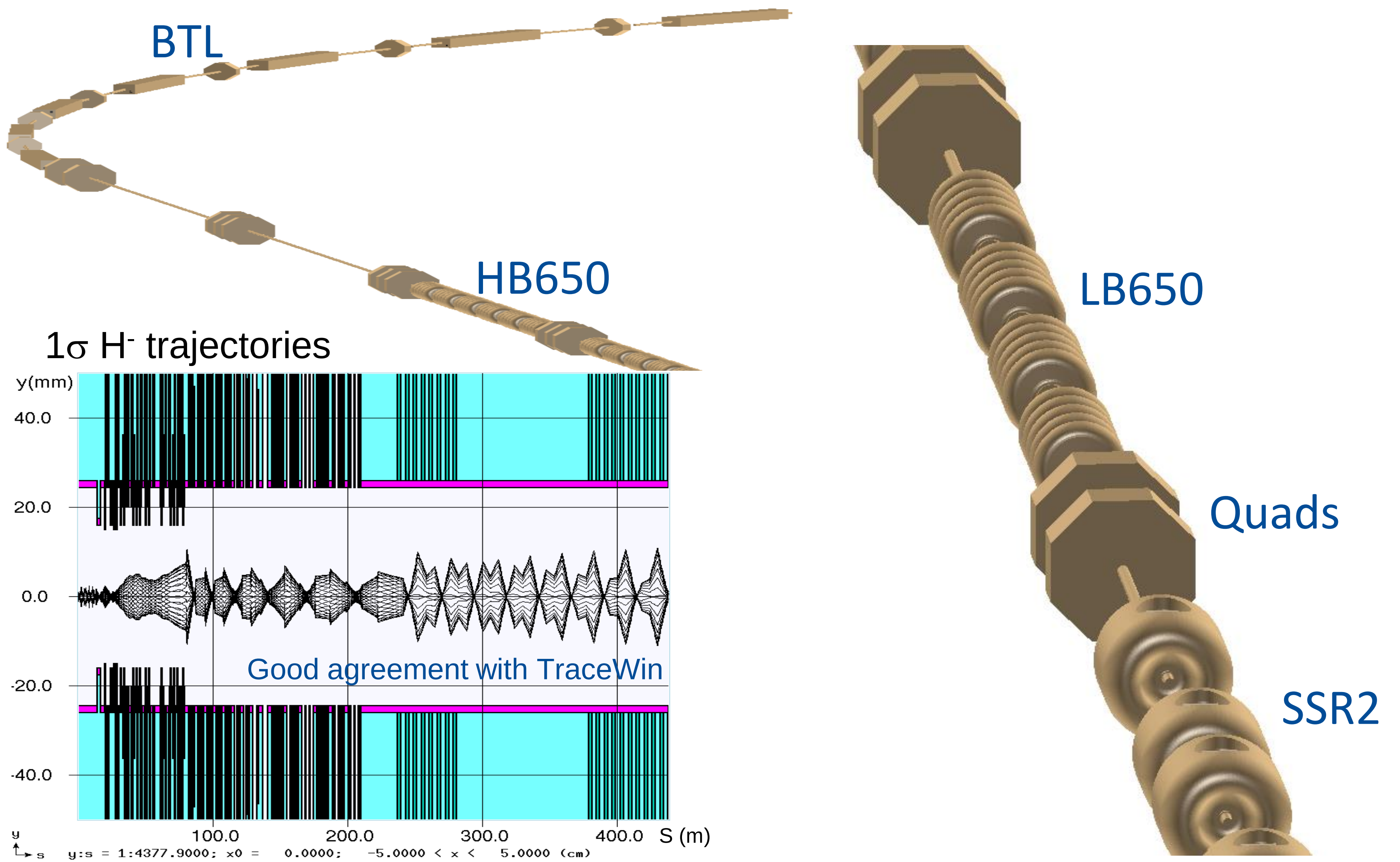


3σ 800-MeV proton tracks



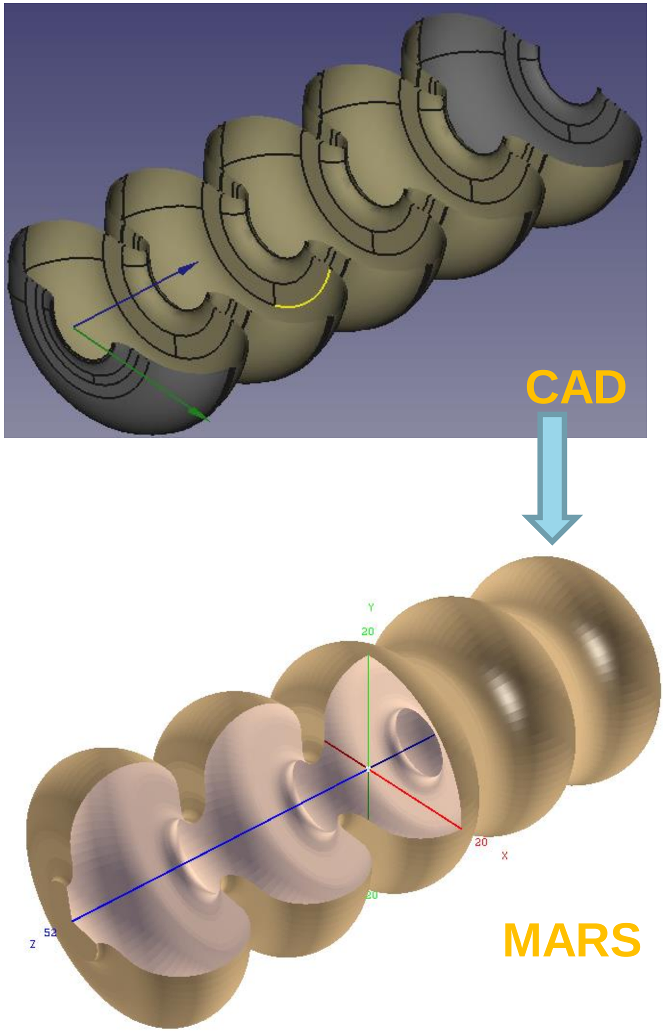
MARS-MADX-PTC Fusion Allows Effective Use of both ABP and Particle-Matter Interaction Code Strengths (2)

PIP-2 Linac, BTL and Beam Test

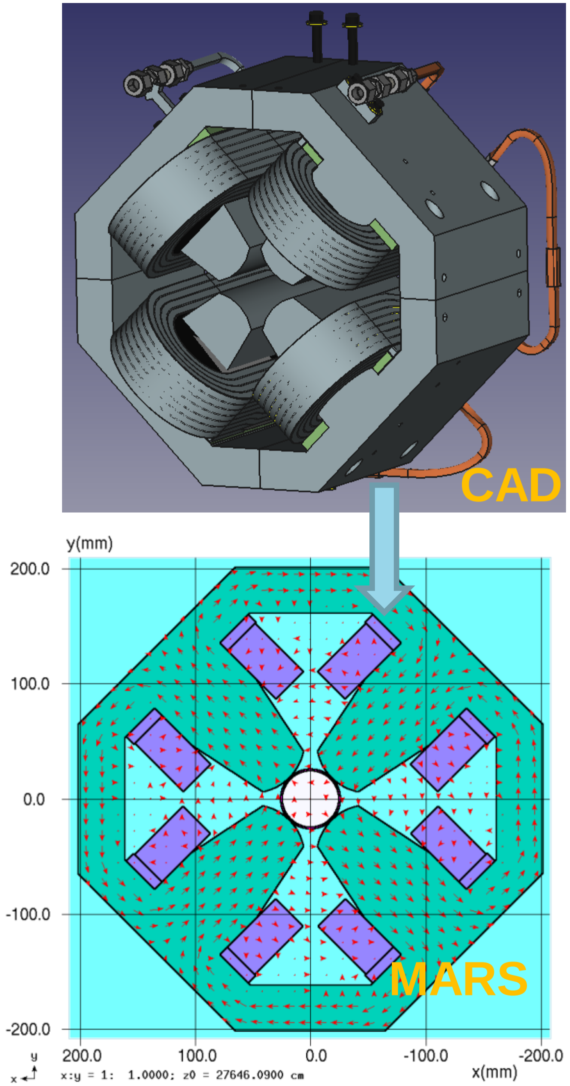


MARS Geometry Models Capture Realistic CAD Details: PIP-2 Linac and BTL

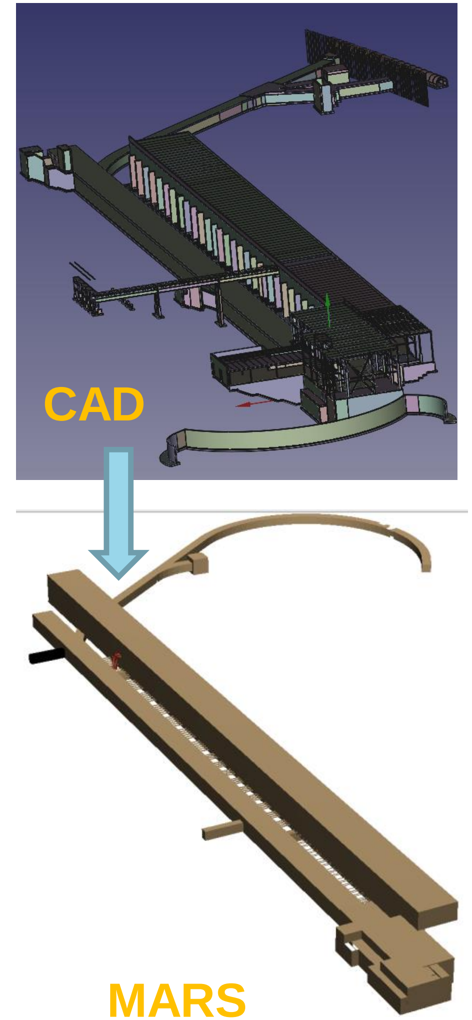
HB650



BTL Quad



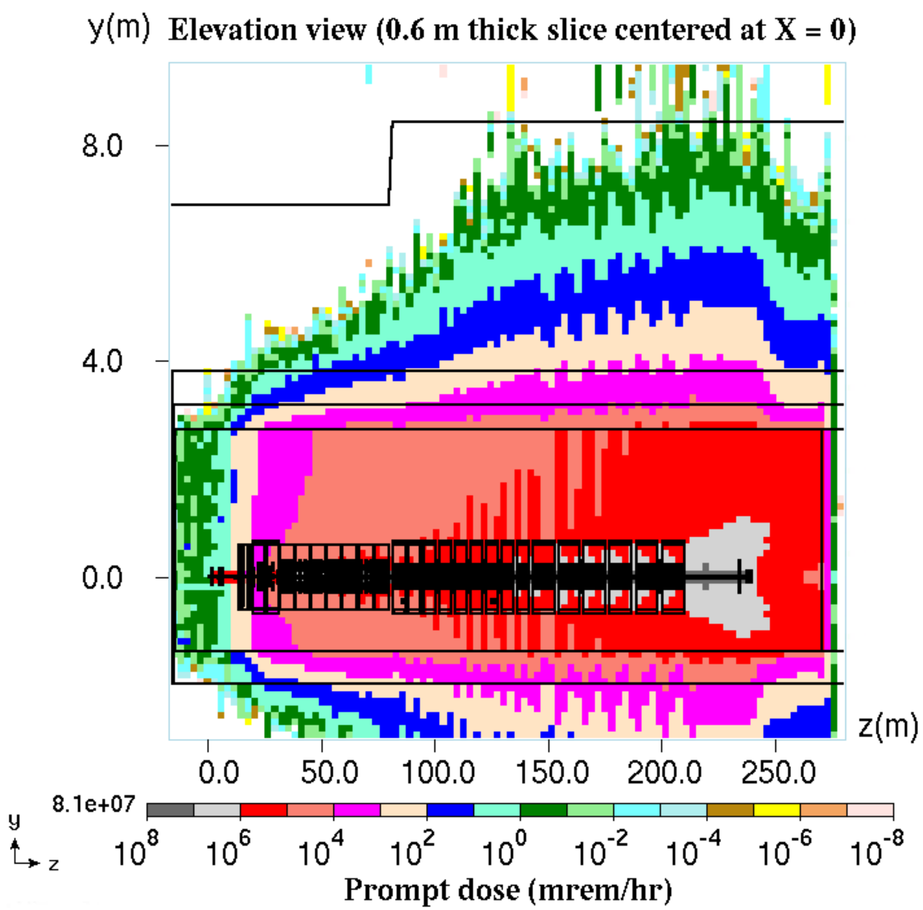
Linac & BTL



MARS-MADX-PTC: Reliable Simulation of H⁻ Beam Loss-Induced Radiation Loads as well as Prompt and Residual Dose Maps

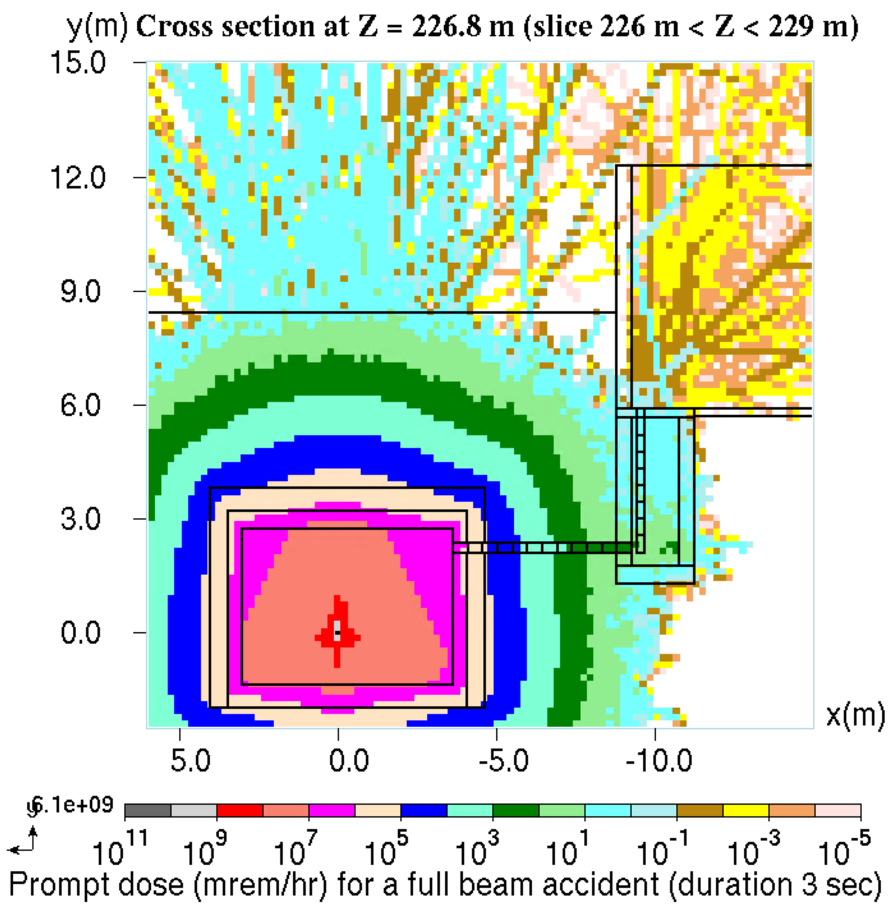
Prompt Dose (mrem/hr) + **residual dose, radiation loads and damage**

1 W/m operational beam loss rate, Elevation view



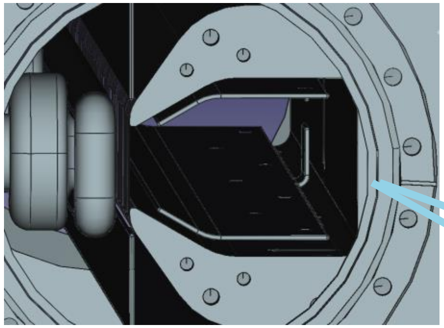
Full beam accident (3 sec), X-Y view

RF waveguide penetrations

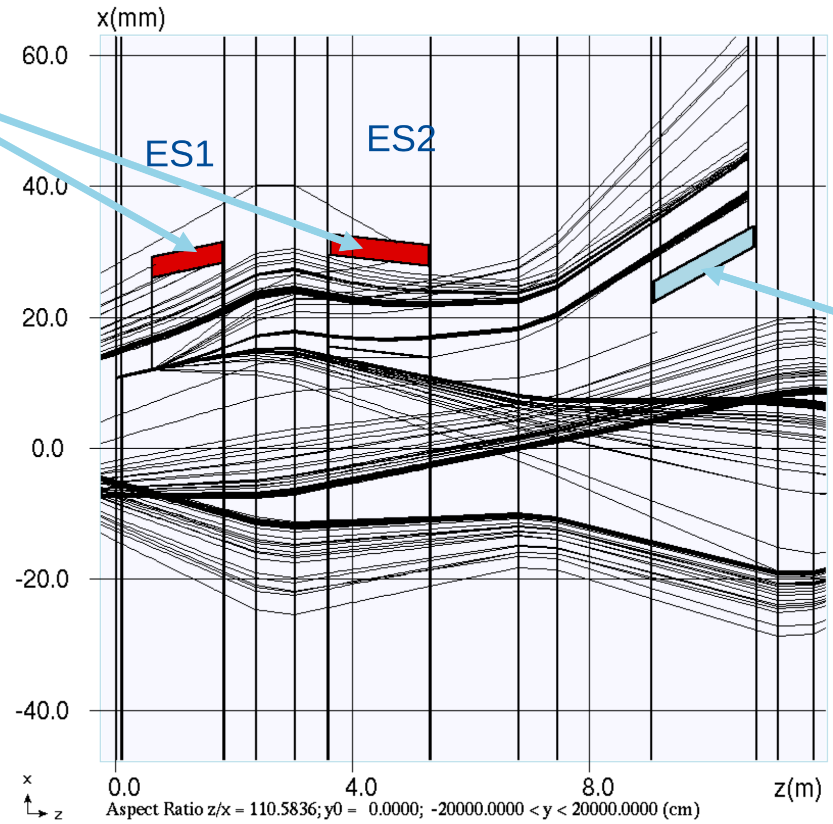


Delivery Ring Model & Consistent Beam Loss Simulations

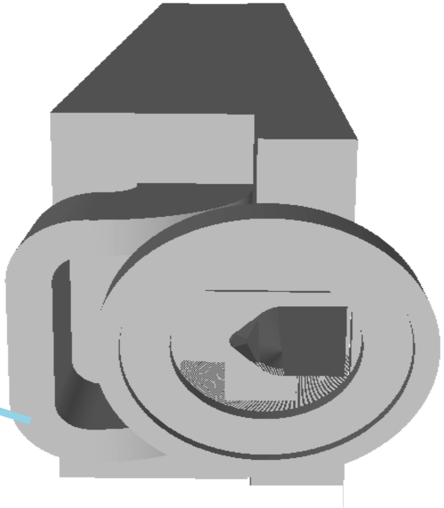
ES Septum



8 GeV, 100 tracks, 4 turns
MARS15-MADX-PTC



Lambertson



Challenges and Path Forward (generic)

- Perfecting predictive virtual accelerator and experiment models
- Further development of SRF modules with all the underlying physics
- Creation of CAD -> MARS_ROOT -> CAD user-friendly geometry converters compatible with strict requirements to simulation in challenging accelerator environment - DOE grant in collaboration with small business company
- User-friendly module to calculate 3D residual dose maps around accelerator equipment in tunnel and other enclosures, with 3D GUI - DOE grant in collaboration with small business company
- There is an interest from Geant4 in collaboration with MARS
- The MARS group needs additional physicist - expert in accelerator applications and code development; the present group is oversubscribed and currently has minimal time for development and support

Challenges and Path Forward (more technical)

- Implement modern code-management techniques, and flatten codebase (Fortran & C++, Hbook & ROOT histograms etc)
- MPI (message-passing interface) and multiple-core jobs (standard for two decades): 10^2 to 10^5 cores routinely; improved submission scripts and built-in averaging
- Minimize a loss in scalability with # of MPI ranks > 4×10^4 on the current **petaflop** (10^{15} fpo/s) platform and prepare to the **exascale** (10^{18} fpo/s) computing era
- Eliminate code distribution, export control and user installation issues
- Update and modernize the MARS User's Guide
- Restore the earlier MARS practice of regular tutorials

Challenges and Path Forward (ABP for MARS)

- Develop a definition and requests to predictive virtual particle accelerators
- Develop beam loss models for linear and circular accelerators and colliders usable in particle-matter interaction codes
- Develop beam halo models for particles hitting the limiting apertures (primary collimators, ES-septa etc.)
- Establish collaboration with accelerator tracking code developers on better x-talk algorithms (preserving all physics and providing the highest accuracy and computing efficiency) between their codes (MAD-X PTC) and particle matter interaction codes (MARS)

Conclusion

- The MARS group and code are important to Fermilab and the community. There are several recent impressive developments, with further enhancements still possible. There are some risks going forward – adequate team for expertise, performance, documentation and maintaining the code.
- Focus on
  - Further code modernization
  - User-friendly CAD to MARS geometry model converter
  - Code management
  - User's Guide update and tutorials
  - Modernization of legal forms and export control issues

Backup Slide: MARS for LHC and HiLumi LHC

- MARS simulations since 1998 helped design the optimal high-luminosity Interaction Regions IR1 and IR5 of LHC, including their TAS, TASB and TAN absorbers, and predict superconducting magnet short-term (quench stability) and long-term (lifetime) performances (e.g., N.V. Mokhov et al., Protecting LHC IP1/IP5 Components Against Radiation Resulting from Colliding Beam Interactions, Fermilab-FN-732 (2003), LHC Project Report 633, CERN (2003))

- "MARS predictions of 16 years ago of energy deposition in the low-beta quads agree within 20% with recent measurements in the real LHC machine. No beam-induced quench has been observed at LHC". **Lucio Rossi, talk at Fermilab, February 2014**

- Note that two decades ago there was no collider experimental data above 1 TeV to verify the code's physics models. These days – working on the HiLumi LHC upgrade - we have a luxury of coherent studies with the FLUKA and MARS codes benchmarked in the TeV energy region.