Optimization Studies of Radiation Shielding for PIP-II Project at Fermilab

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MARS group – Target Systems Department – Accelerator Directorate

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1) Introduction

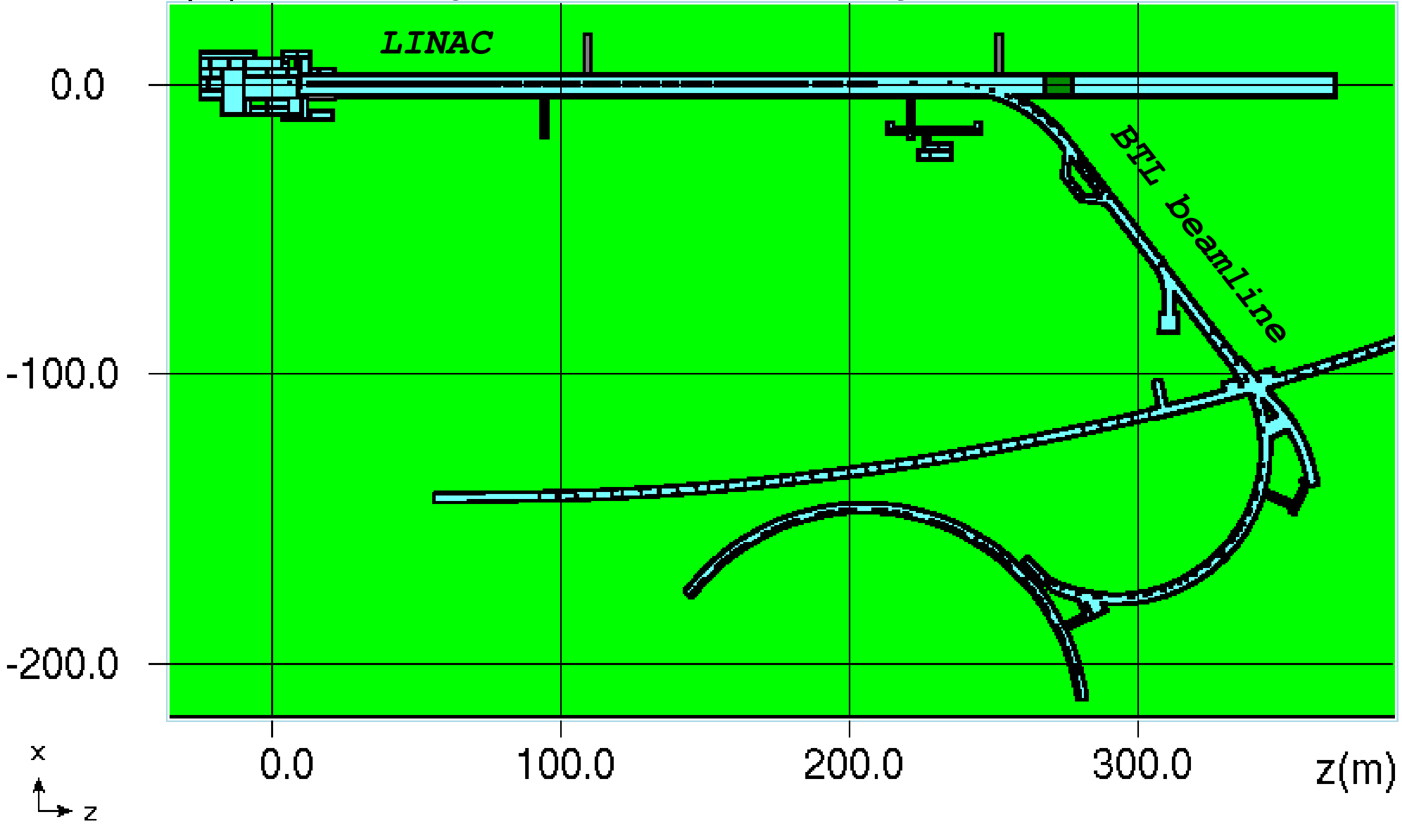
1) Introduction

- The **Proton Improvement Plan-II (PIP-II) at Fermilab** requires the construction of a new addition to the Fermilab accelerator complex – an 800-MeV high-intensity superconducting linear accelerator.

- **Ensuring the safety and regulatory compliance** of this ambitious project is paramount, necessitating thorough **dose rate assessments under both normal operational and accidental scenarios** to align with the Fermilab Radiological Control Manual (FRCM) standards.

- Our analysis included new magnet and collimator models essential for reflecting the current state of PIP-II structure. Within the **simulations conducted with the Monte Carlo code MARS** [1,2,3], a shielding optimization was performed.

Top view of the model layout in MARS



[1] N.V. Mokhov and C.C. James, "The Mars Code System User's Guide, Version 15 (2016)", Fermilab-FN-1058-APC, (2017) https://mars.fnal.gov

[2] N.V. Mokhov et al., "MARS15 Code Developments Driven by the Intensity Frontier Needs ", Prog. Nucl. Sci. Technol., 4, pp. 496-501 (2014)

[3] N.V. Mokhov, "Status of MARS Code", Fermilab-Conf-03/053 (2003)

The work presented here builds on previous PIP-II, BTL, and collimator model developments and studies conducted by other members of the

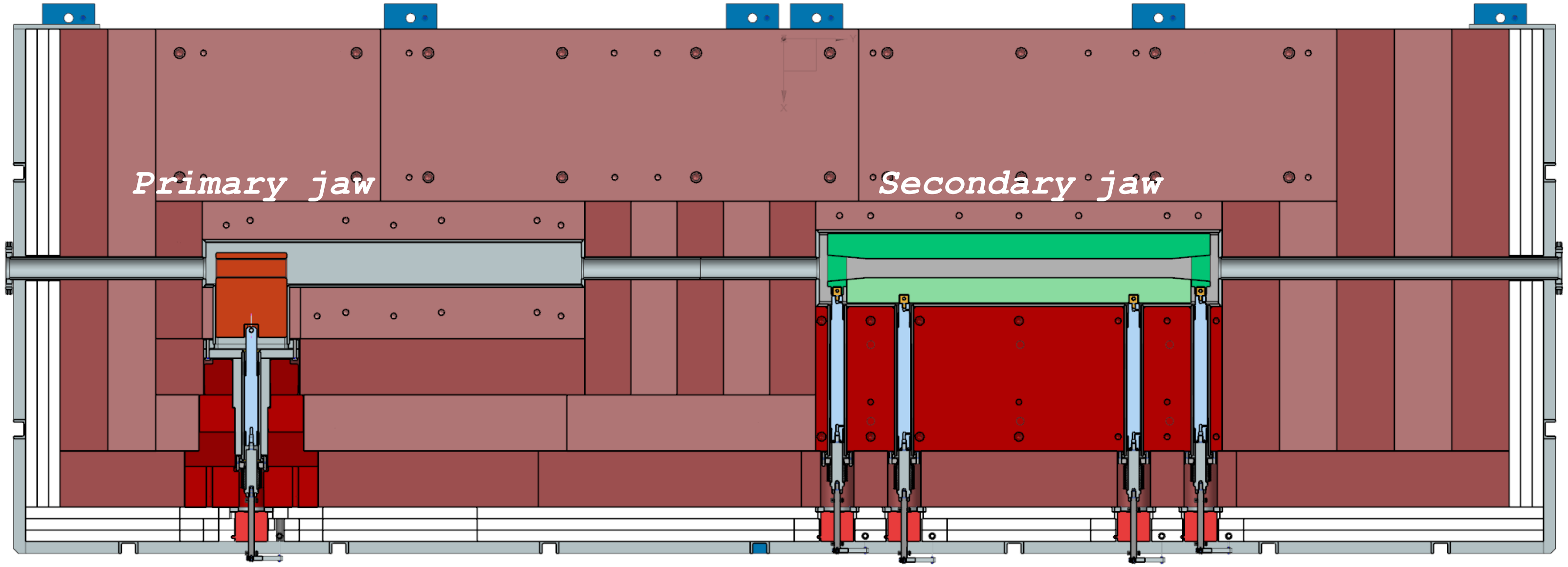
2) Implementation of Parametric Geometry

2) Geometry implementation – Horizontal and Vertical PIP-II collimators – CAD geometry

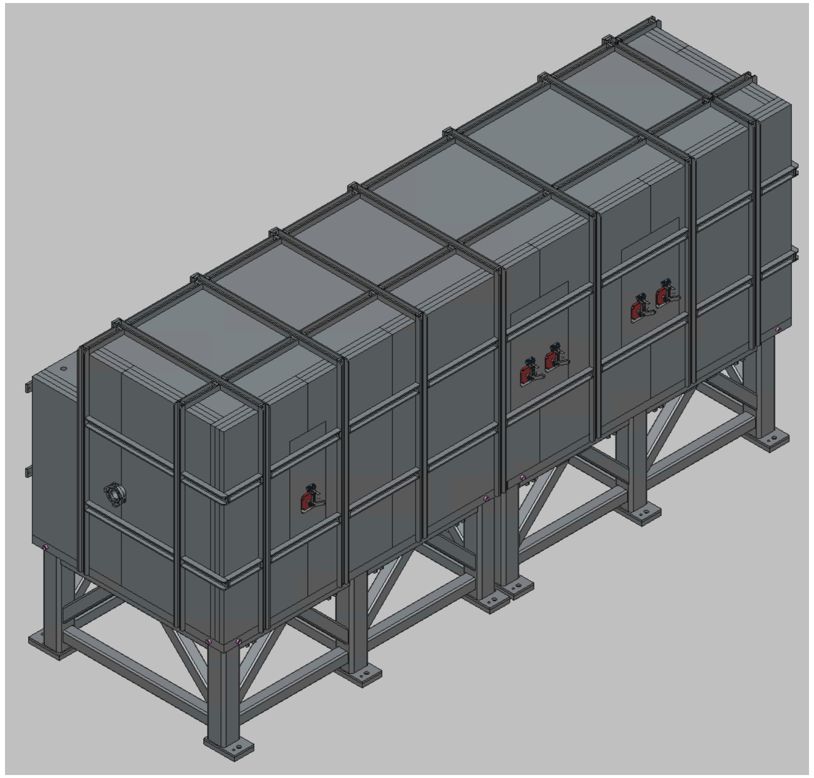
Motivation:

- Ensuring the MARS model remains a reliable and comprehensive tool for the many individuals working on the PIP-II project by adding these collimators and magnets
- Updating the existing model by integrating two collimators and two magnets

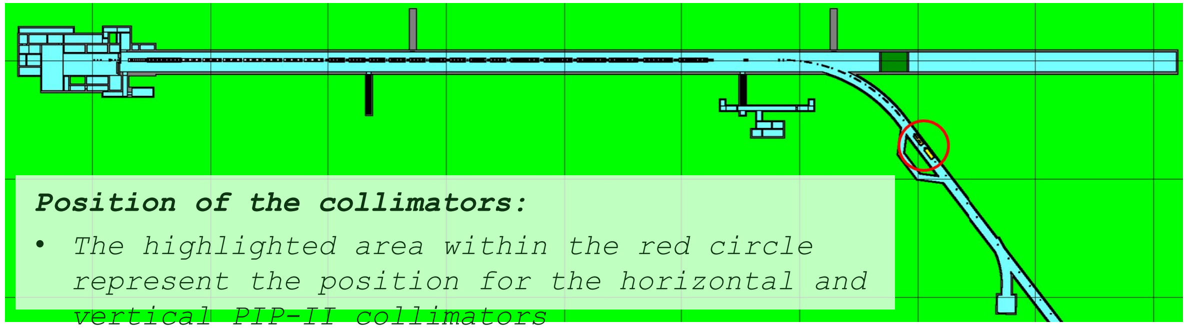
Cross-sectional depiction of the horizontal PIP-II collimator's CAD model



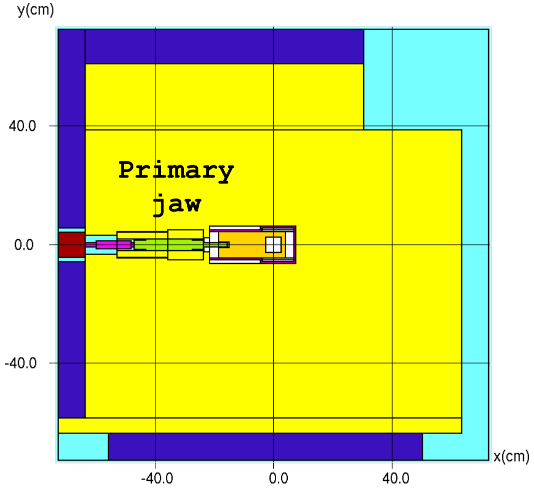
3D view of the horizontal PIP-II collimator's CAD model



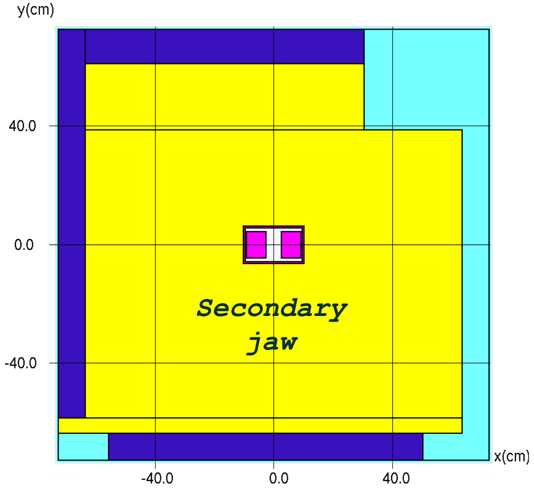
2) Geometry implementation – Horizontal and Vertical PIP-II collimators – MARS geometry



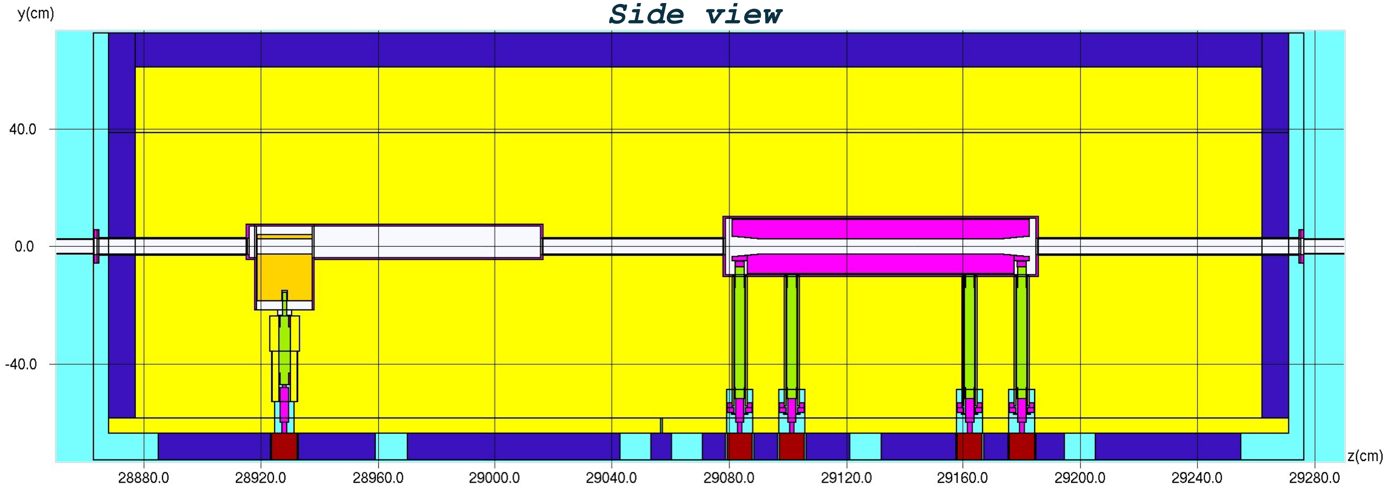
Horizontal collimator



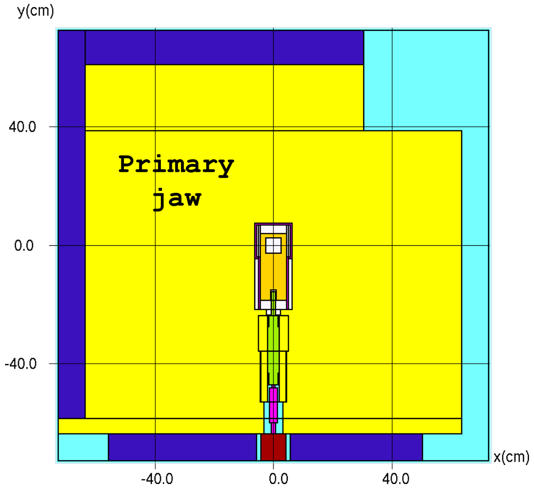
Horizontal collimator



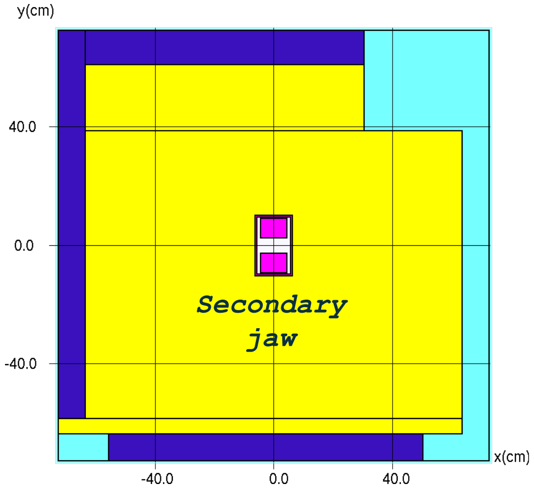
Vertical collimator – Side view



Vertical collimator



Vertical collimator



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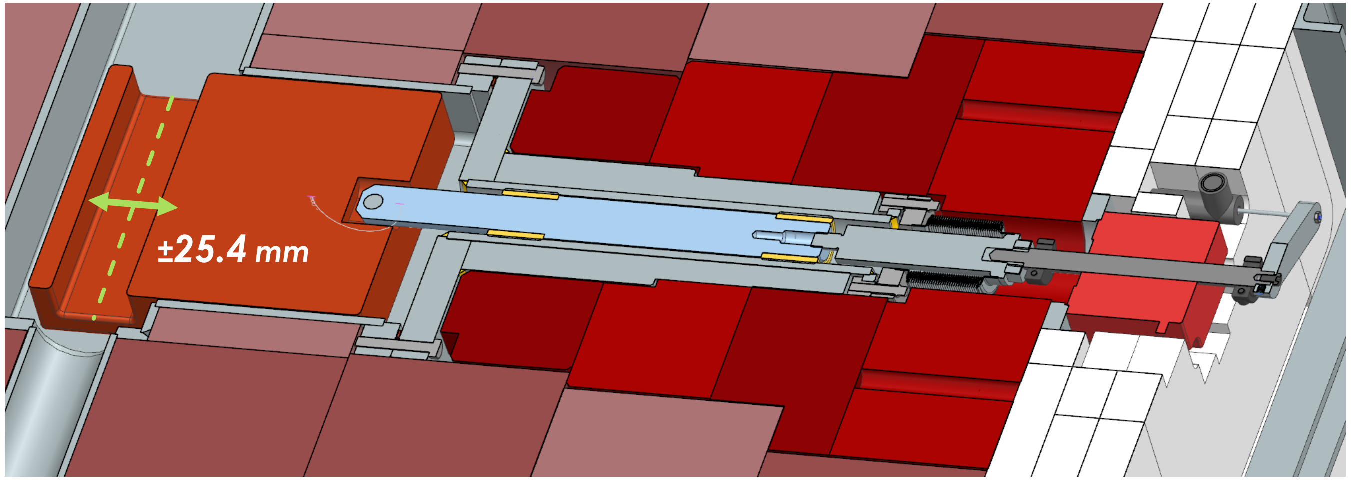
2) Geometry implementation – Horizontal and Vertical PIP-II collimators – Primary jaw

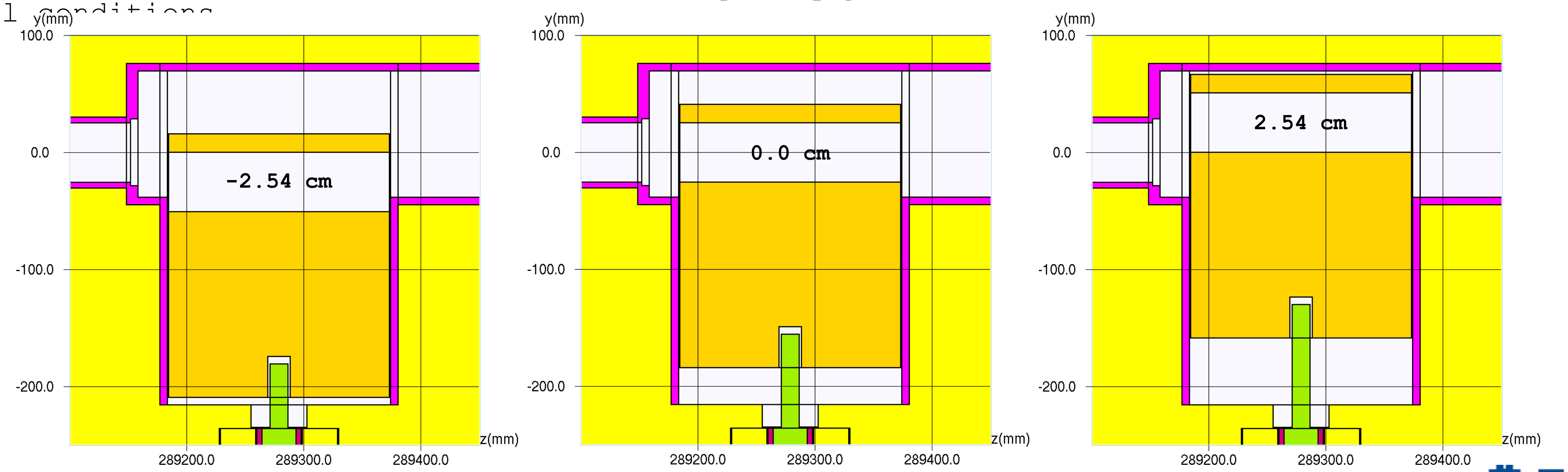
Primary Jaw:

- The **primary jaw** of the horizontal and vertical PIP-II collimators **can shift ±25.4 mm from its nominal centered location**, with a "hard stop" safeguard to prevent contact with the vacuum chamber.
- Using features provided by ROOT TGeo (https://root.cern.ch), the primary and secondary **jaws and their surroundings were designed to allow parametrized movement of the jaws**, supporting various operational and accidental conditions

Primary jaw (copper)



Movement of the primary jaw model in MARS



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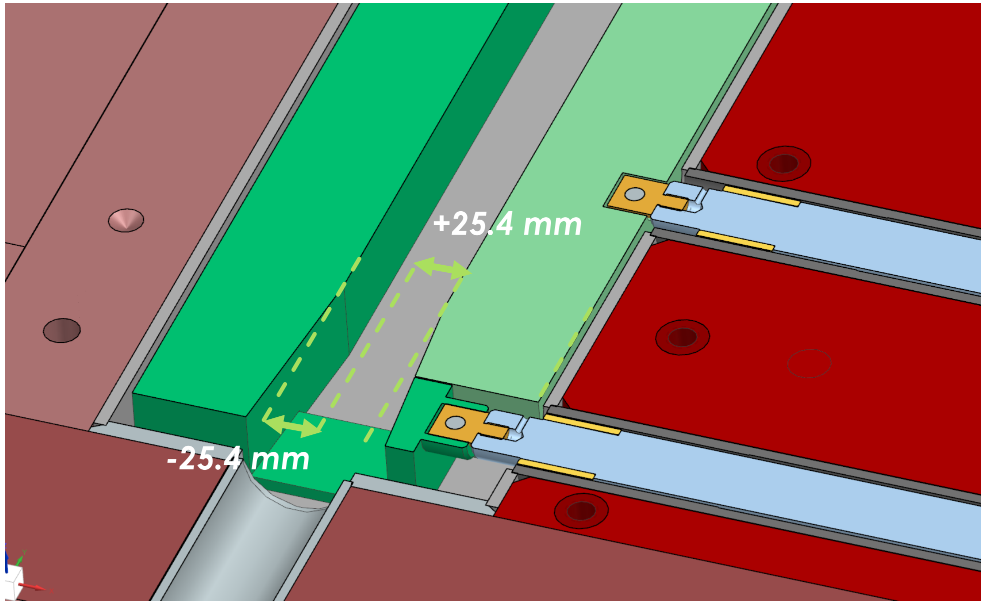
2) Geometry implementation – Horizontal and Vertical PIP-II collimators – Secondary jaw

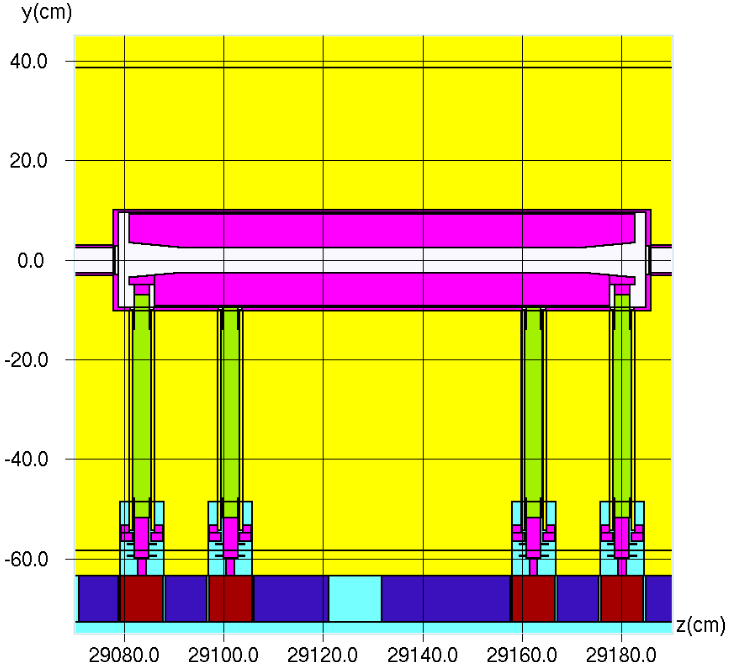
<u>Secondary Jaw:</u>

- For the secondary jaw, both sides operate independently, moving 25.4 mm inward but not outward from their nominal positions.

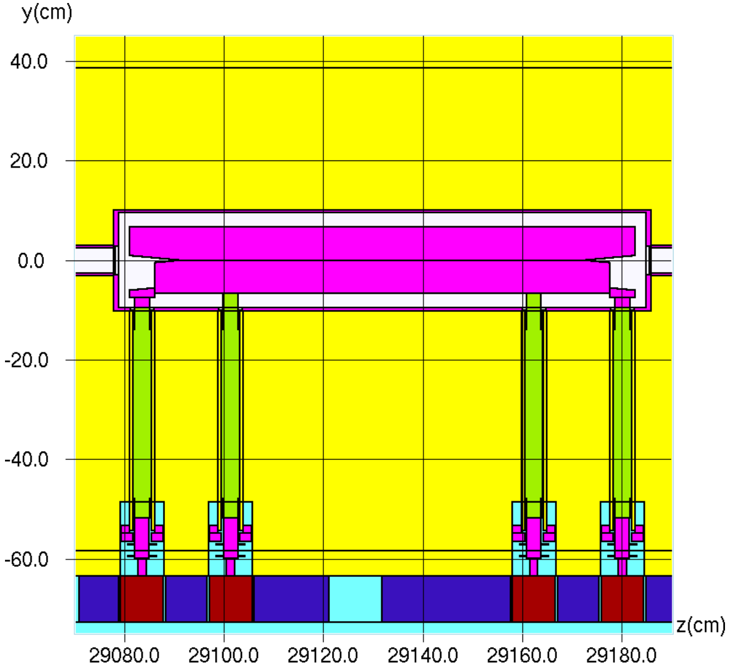
Secondary jaw (stainless steel, SS-304)



Vertical collimator – secondary jaw – Side view



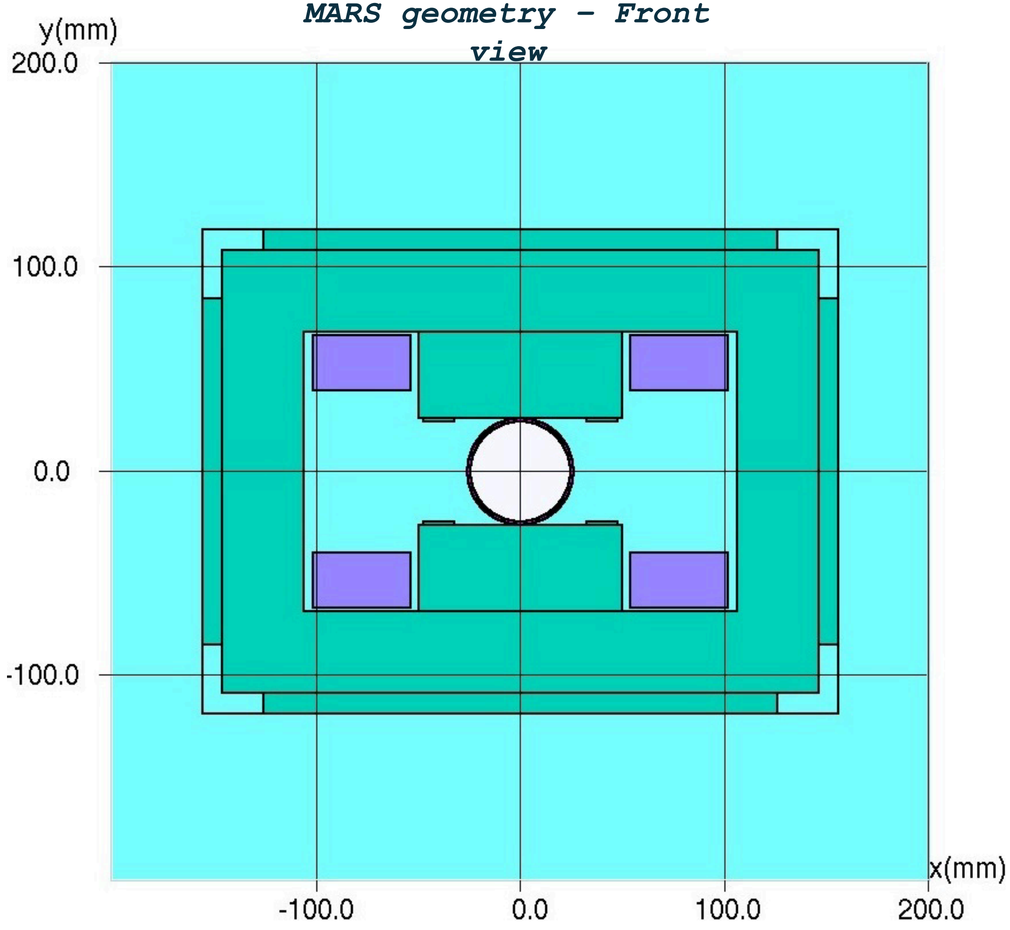
Fully open



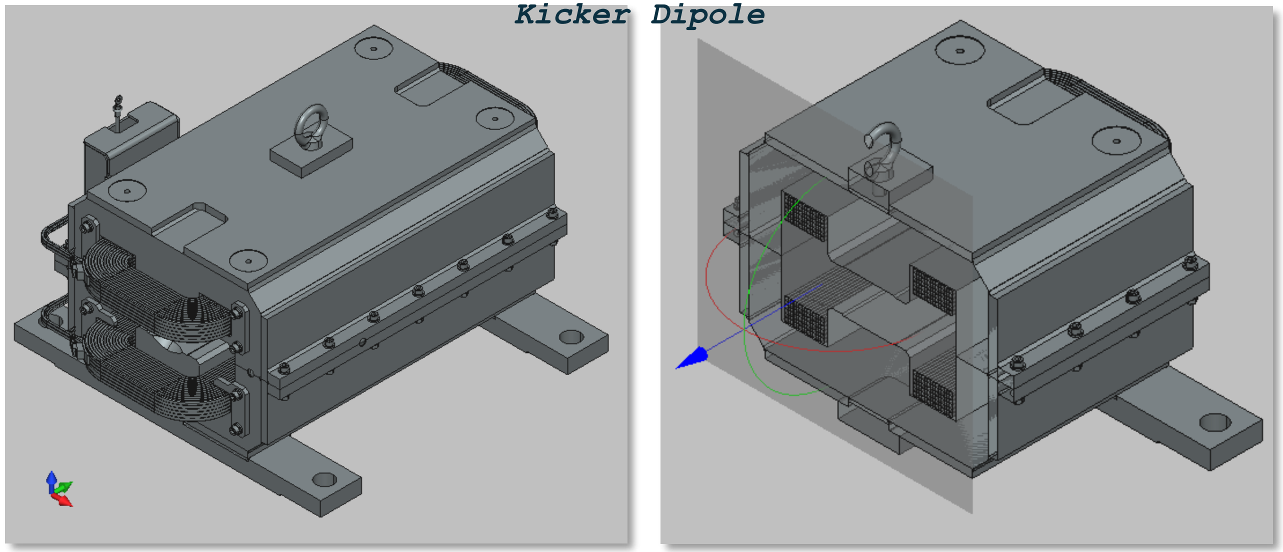
Fully closed

2) Geometry implementation – Fast Kicker Dipole

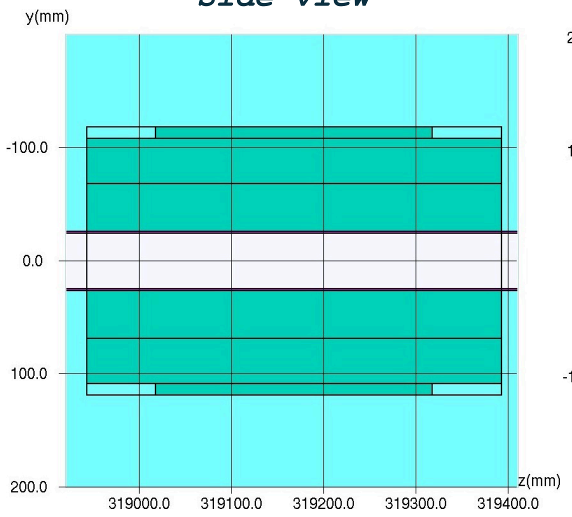
MARS geometry – Front view



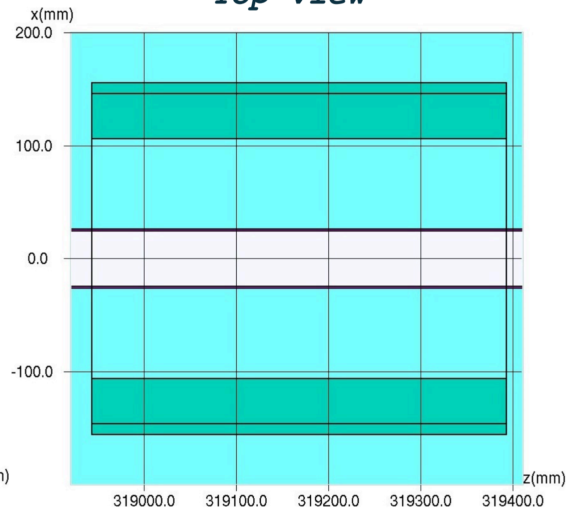
3D CAD view of Fast Kicker Dipole



Side view

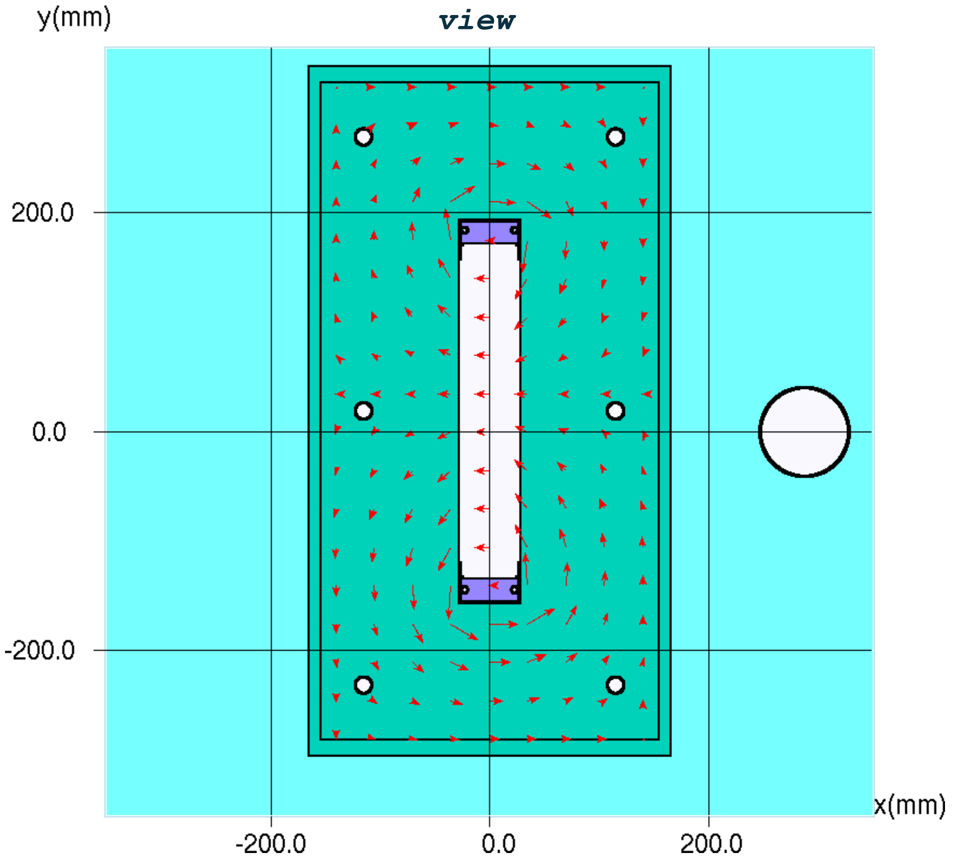


Top view



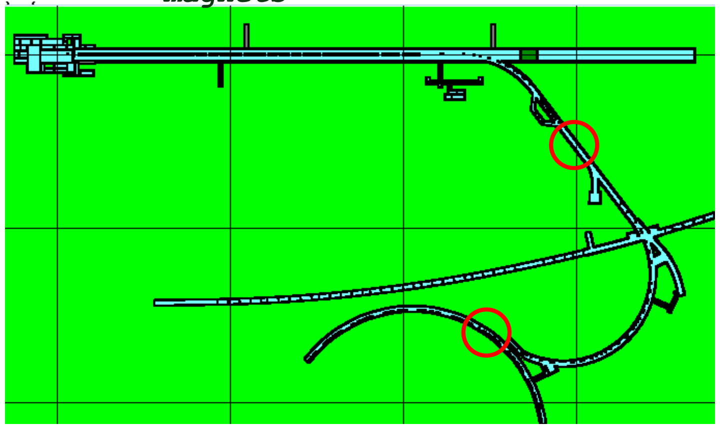
2) Geometry implementation – BoosterInjORBE

MARS geometry – Front view

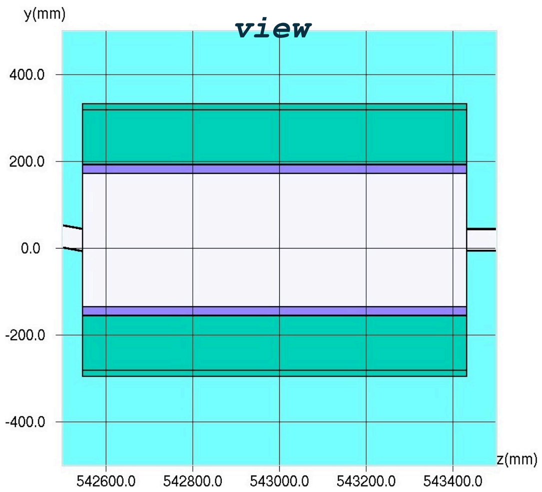


Per-volume assignment of magnetic field

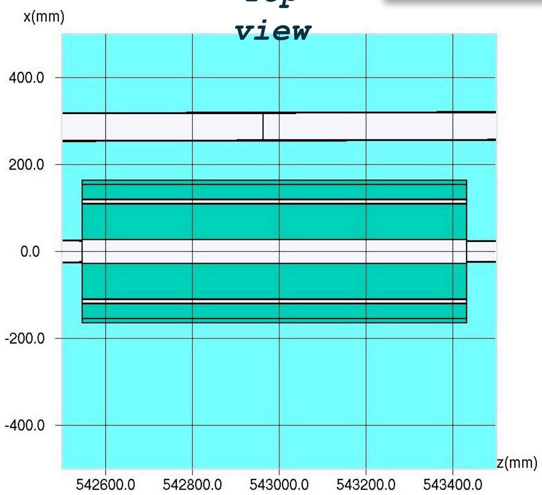
Positions of the magnets



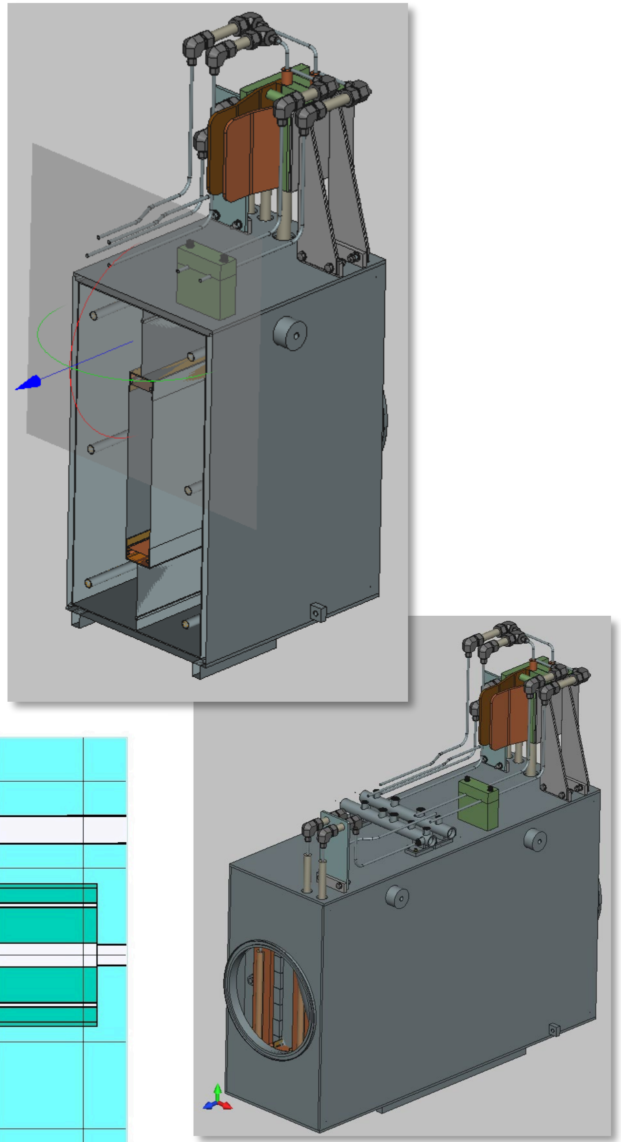
Side view



Top view

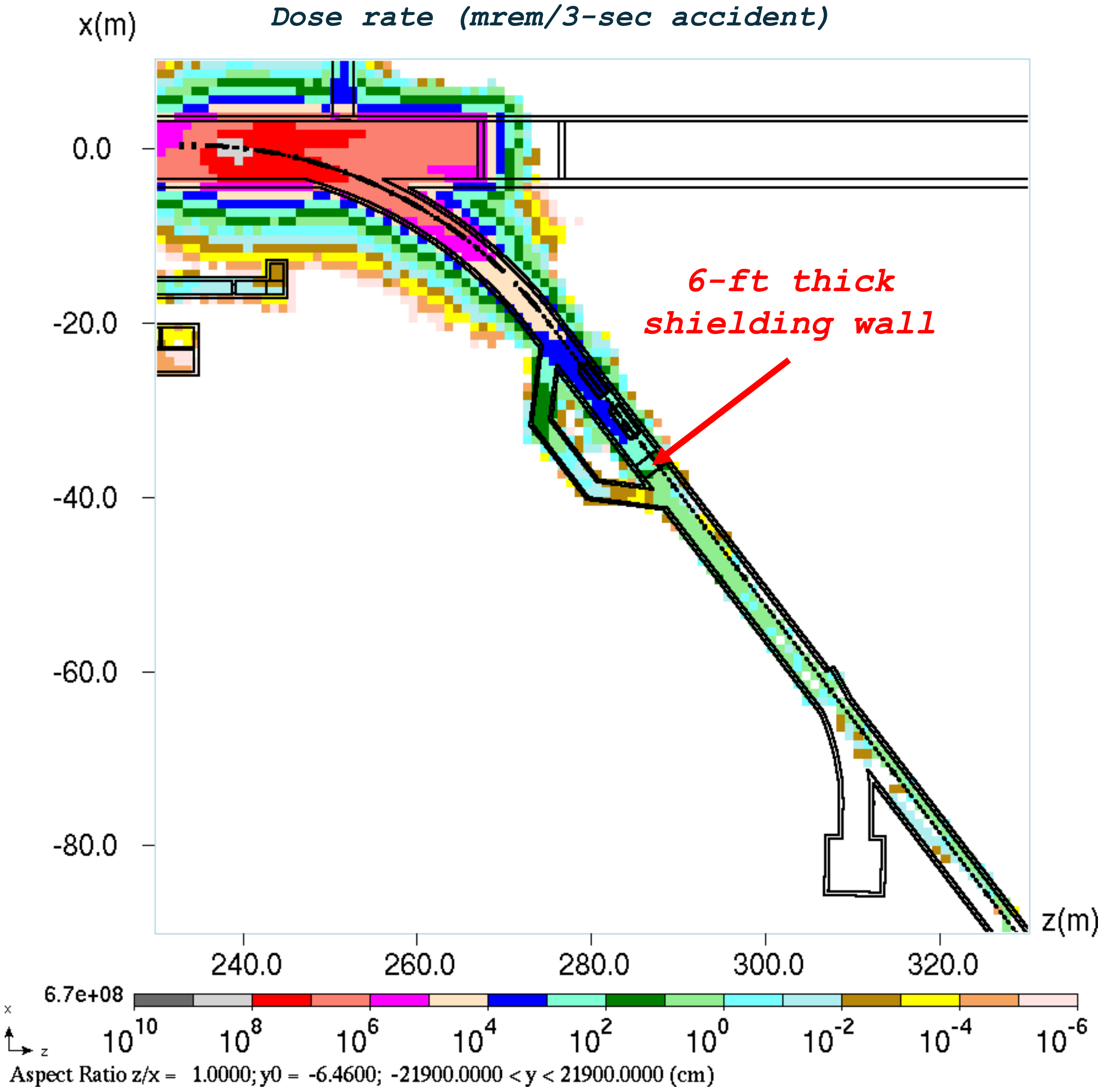


3D CAD view of BoosterInjORBE



3) Application of Importance-Based Splitting Technique

3) MARS simulations without branching for the PIP-II Linac Shielding Assessment (1/2)



Parameters:

- **Accident Scenario** (PIP-2 Linac Shielding Assessment)
  - Incident: **Full Linac beam** at 1 GeV is lost
  - Duration: **3 seconds**
  - In CW mode, this corresponds to: 1.25e16 H-/sec * 3 = 3.75e16 H-/accident
- Accident beam position and directional cosine parameters in 'source.f':
  - X = 22.1318 cm
  - Y = -6.4535 cm
  - Z = 23572.53 cm
  - DCX = -0.0025
  - DCY = 0.0
  - DCZ = sqrt(1.d0-DCX*DCX)
- **Dose rate monitoring** setup ('XYZHIS.INP'):
  - X: -9000 to 1000 cm (100 bins)
  - Y: -137.16 to 43 cm (1 bins)
  - Z: - 23000 to 33000 cm (100 bins)

- Dose rate map based on **8.94e7 histories**
- No branching
- **Runtime: 1 month (x1000 CPU), approximately 83 CPU years**
- Despite the long computational time, there is **low statistical accuracy downstream of the shielding wall.**

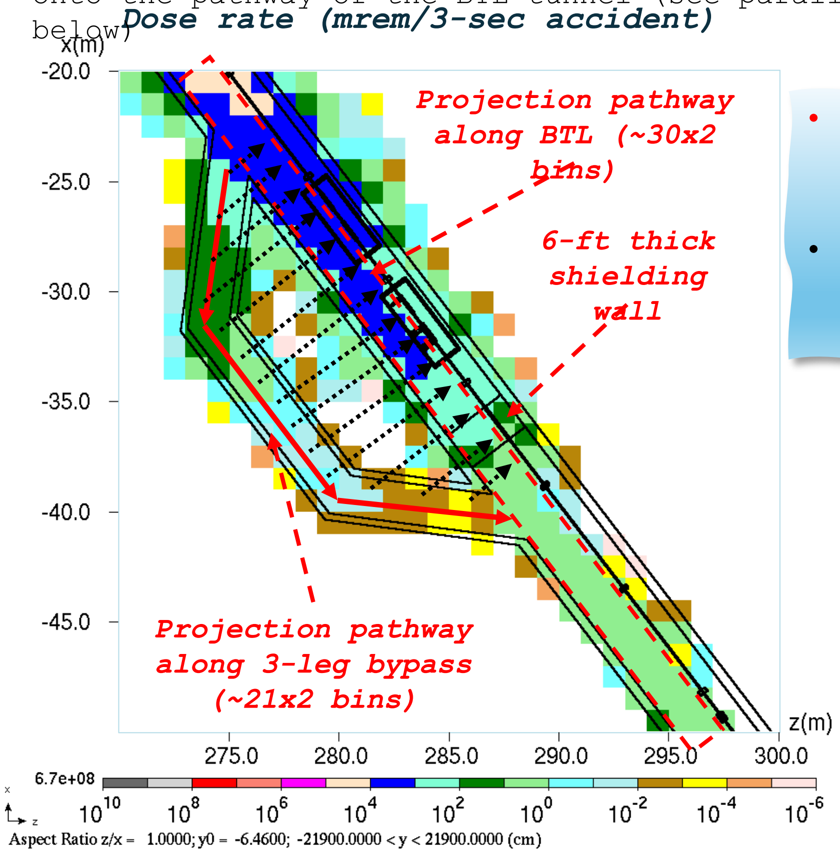
3) MARS simulations without branching for the PIP-II Linac Shielding Assessment (2/2)

<u>Projection pathway along BTL:</u>

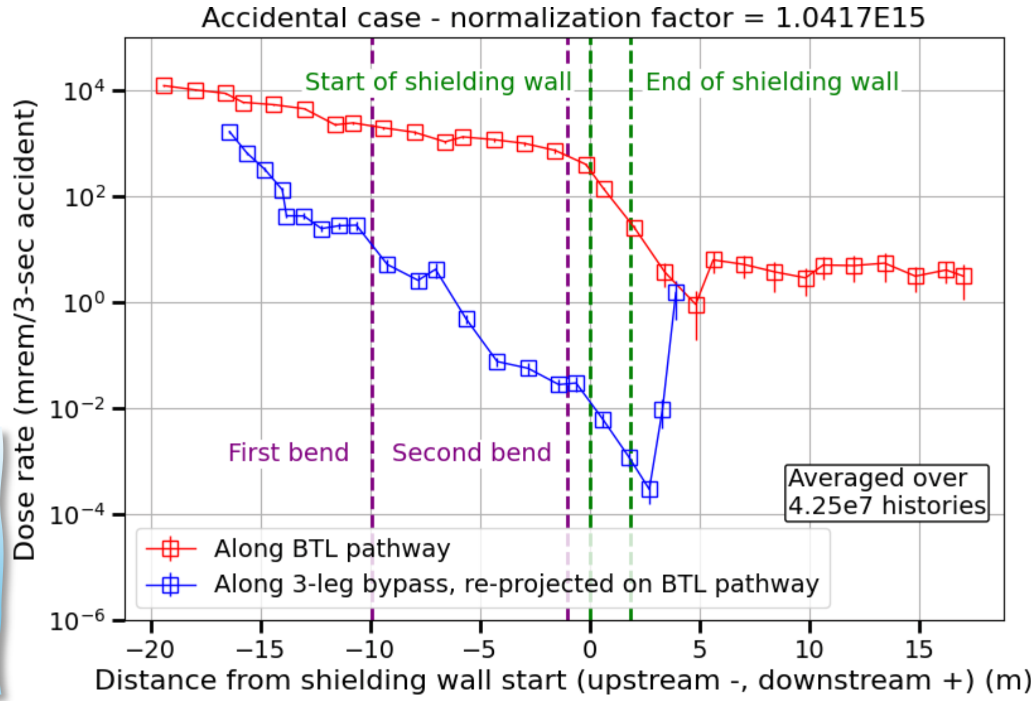
- To capture attenuation effects along the BTL beamline, including the influence of the 6-ft wall
- "Distance = 0" marks the (upstream) start of the shielding wall

<u>Projection pathway along 3-leg bypass</u>

- To show attenuation effects within the 3-leg bypass
- The 1D dose rate projection from the 3-leg bypass is re-projected onto the pathway of the BTL tunnel (see parallel arrows in the image below)

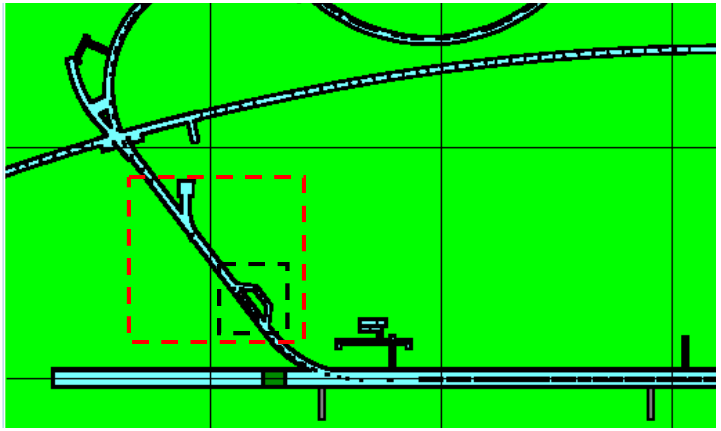


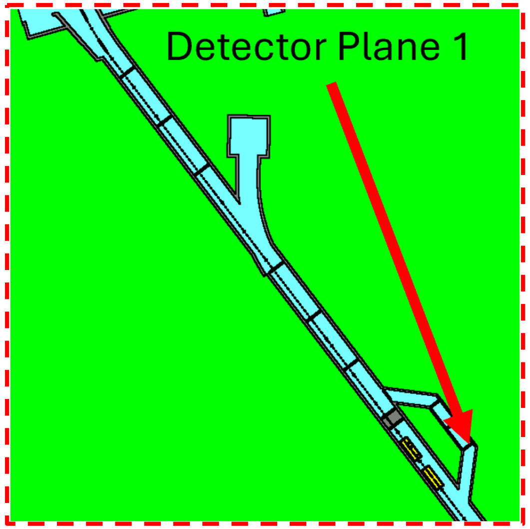
- **Runtime: 1 month (x1000 CPU), approximately 83 CPU years**
- Despite the long computational time, there is **low statistical accuracy downstream of the shielding wall.**



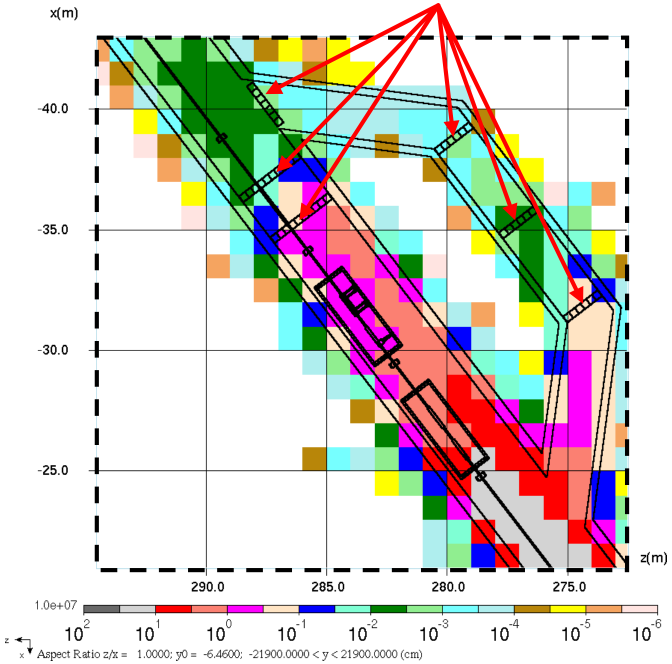
- The 1D projection graph shows that that **the dose rate downstream of the shielding wall is below 10 mrem per accident**, and that the dose rate drops **below 1 mrem per accident between the first and second bends of the bypass tunnel.**
- In the 3rd leg, the dose rate is under 0.1 mrem per accident, however, there's a noticeable increase **towards the end of the bypass**. This **uptrend highlights the contribution from the BTL tunnel** at this point.
- <u>We can conclude that the wall attenuates the radiation level by more than two orders of magnitude, and that the bypass is well designed in the sense that it decreases the stray radiation further than the shielding wall</u>

3) Motivation for developing a particle splitting algorithm



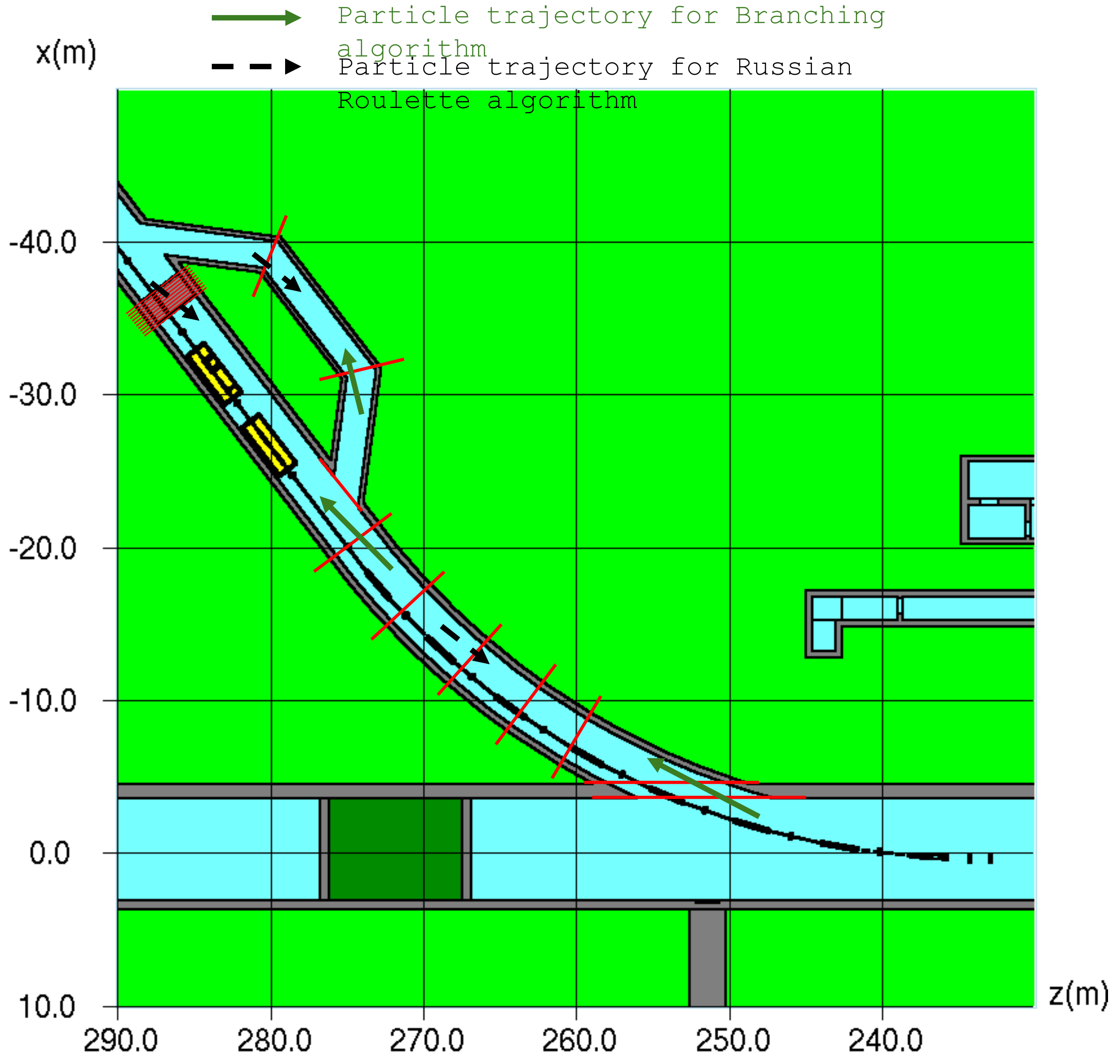


Cubic foot detector planes (12 in total)



- At the **request of the ESH group**, we **added several planes** across the tunnel populated **with cubic foot-sized air cells**, acting **as detectors**, to obtain high-resolution results on a spatial scale comparable to an actual dose monitor.
- Despite their computational demands, the implementation of these high-resolution detector planes enabled us **to gather detailed radiation field data** crucial for optimizing shielding configurations.
- To overcome the significant computational demands, **we implemented a** well-known **branching technique** that drastically reduced simulation runtimes while maintaining statistical integrity.
- This was **achieved through particle splitting and the application of Russian Roulette techniques**, tailored to prioritize regions of interest based on predefined importances and weight limits.

3) Integration of a new branching technique – Approach 1: splitting planes (1/2)



Particle splitting algorithm based on strategically placed planes throughout the geometry of interest:

- The algorithm is implemented in the branching.f90 Fortran module
- It utilizes planes defined by parameters within the module
- The module is called at each simulation step

When a particle crosses the plane in the desired direction:

- It is multiplied by a user-defined factor (m)

When a particle crosses the plane in the opposite direction:

- It survives only with a probability of 1/m (using a Russian Roulette algorithm), and its weight is adjusted to the original weight multiplied by m

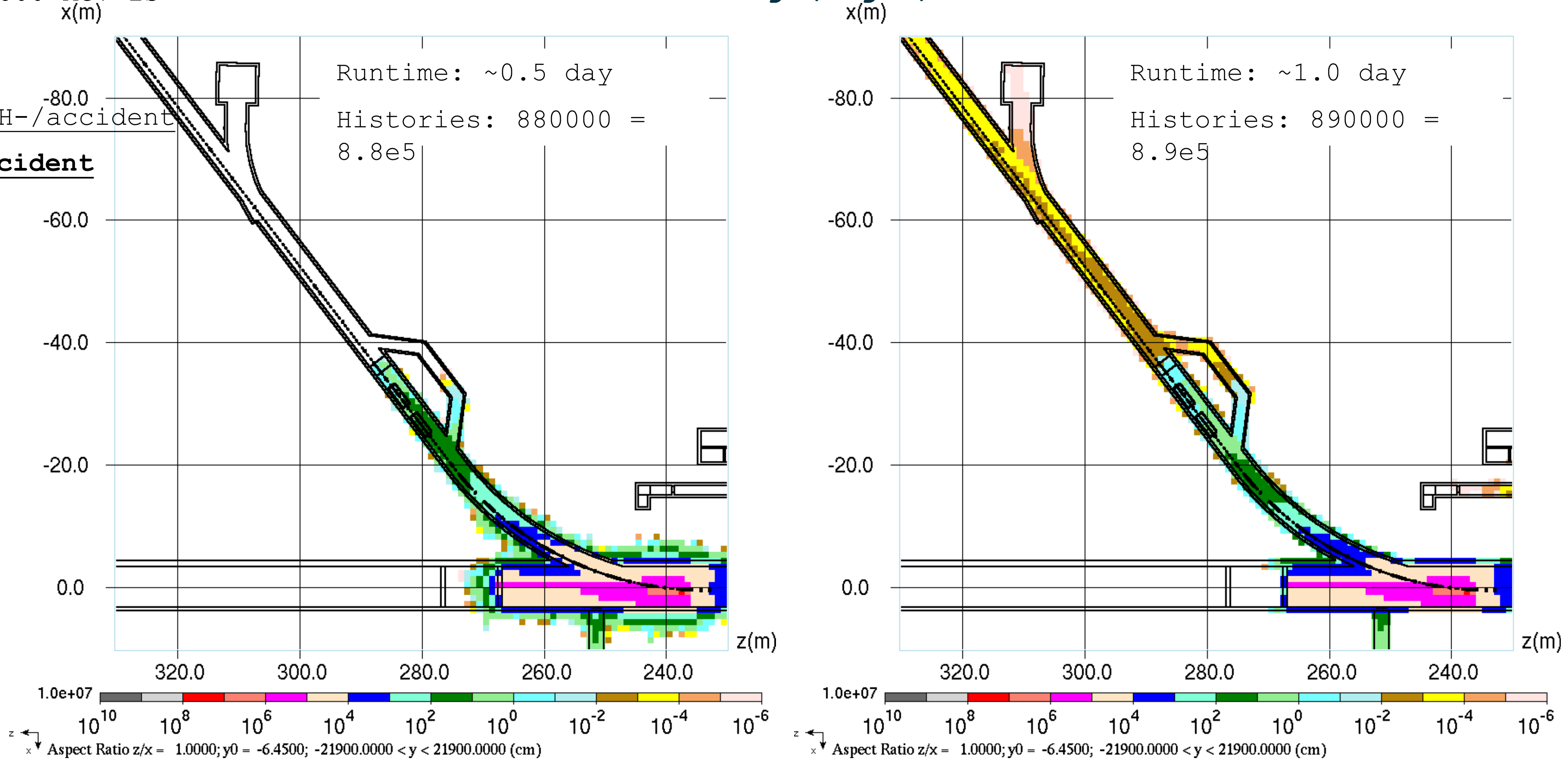
The code is well-optimized to enable efficient propagation of particles in the desired direction

3) Integration of a new branching technique – Approach 1: splitting planes (2/2)

Accident Scenario (PIP-2 Linac Shielding Assessment)

- ARC 1: 550 usec <2ma> 20 Hz (Dipole OFF)
- Incident: Full Linac beam at 800 MeV is lost
- Duration: 3 seconds
- 1.37e14 H-/sec * 3 = 4.12e14 H-/accident
- Dose rate is given in **mrem/accident**

Comparison of Dose Rate Maps: No Branching (left) vs. Branching (right)



3) Integration of a new branching technique – Approach 2: importance-based splitting

- Based on the promising results achieved with the splitting planes algorithm, we decided to implement a more sophisticated method to further improve simulation efficiency.
- This led to the **development of an Importance-Based Splitting technique**, where particle splitting and the application of the Russian Roulette method are guided by predefined importance values assigned to regions of interest.

Algorithm:

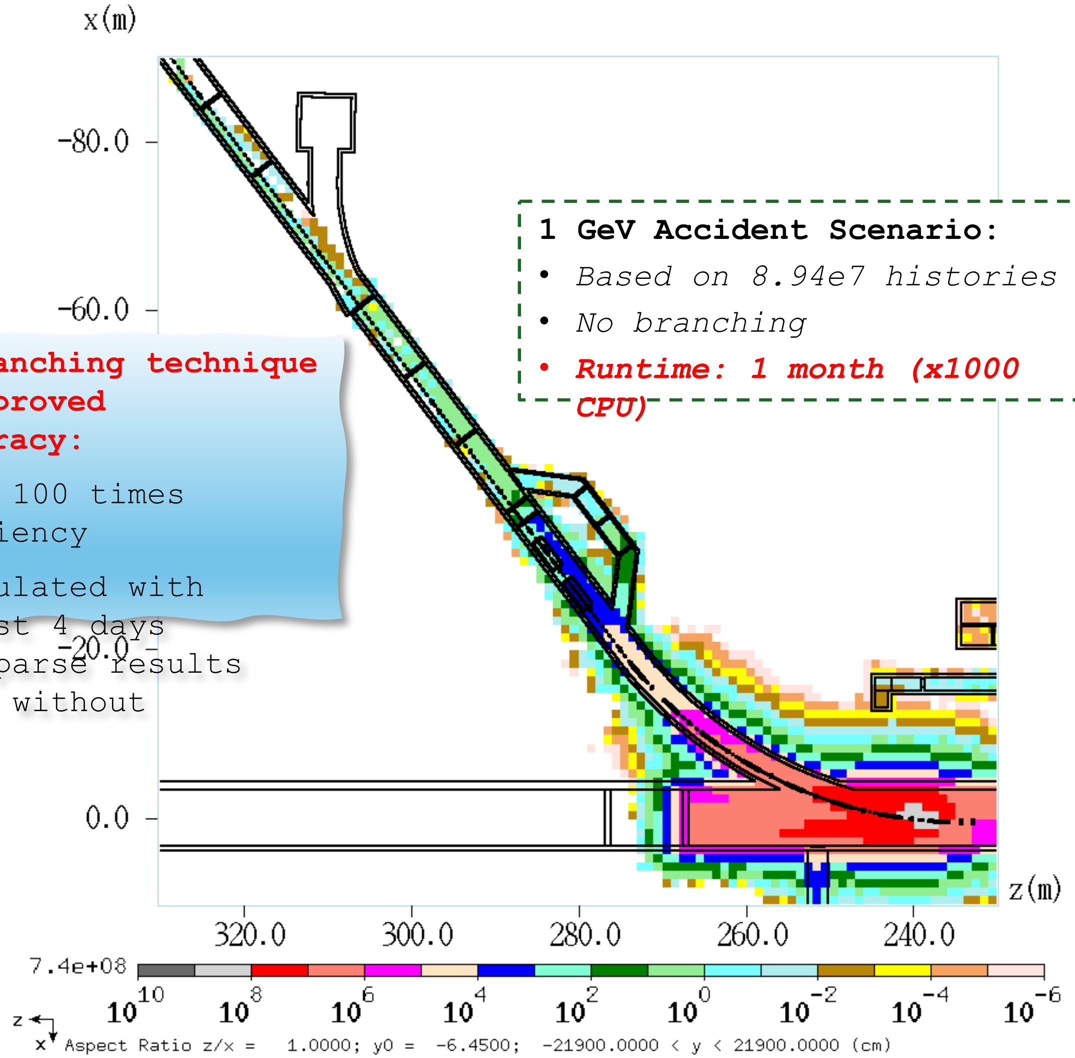
- Initialize a list (ImpList) to store the importance values (impValue) corresponding to specific region numbers (RegList) where branching is needed.
- Regions not listed in RegList are assigned a default importance value of 1.
- ***Russian Roulette Logic:***
  - For particles moving from a high importance region to a lower one (where the multiplication factor, mFactor, is less than 1), the ***Russian Roulette*** mechanism is employed.
  - A random number is compared to mFactor. If the random number is greater, the particle is eliminated. Otherwise, the particle survives with its weight adjusted by dividing by mFactor.
- ***Logic:***
  - At each step, the algorithm checks the initial and final region numbers involved in the particle's movement.
  - The multiplication factor (mFactor) is calculated as the ratio of the importance value of the final region to that of the initial region.
  - If mFactor is greater than 1, branching is applied with a multiplicity equal to mFactor. Otherwise, the ***Russian Roulette*** logic is used.
  - The maximum value of mFactor is capped and can be adjusted by the user through the variable mFactorCap.

3) Comparing dose rate maps: Impact of importance-based splitting on runtime

Dose rate is given in mrem/accident for the maps

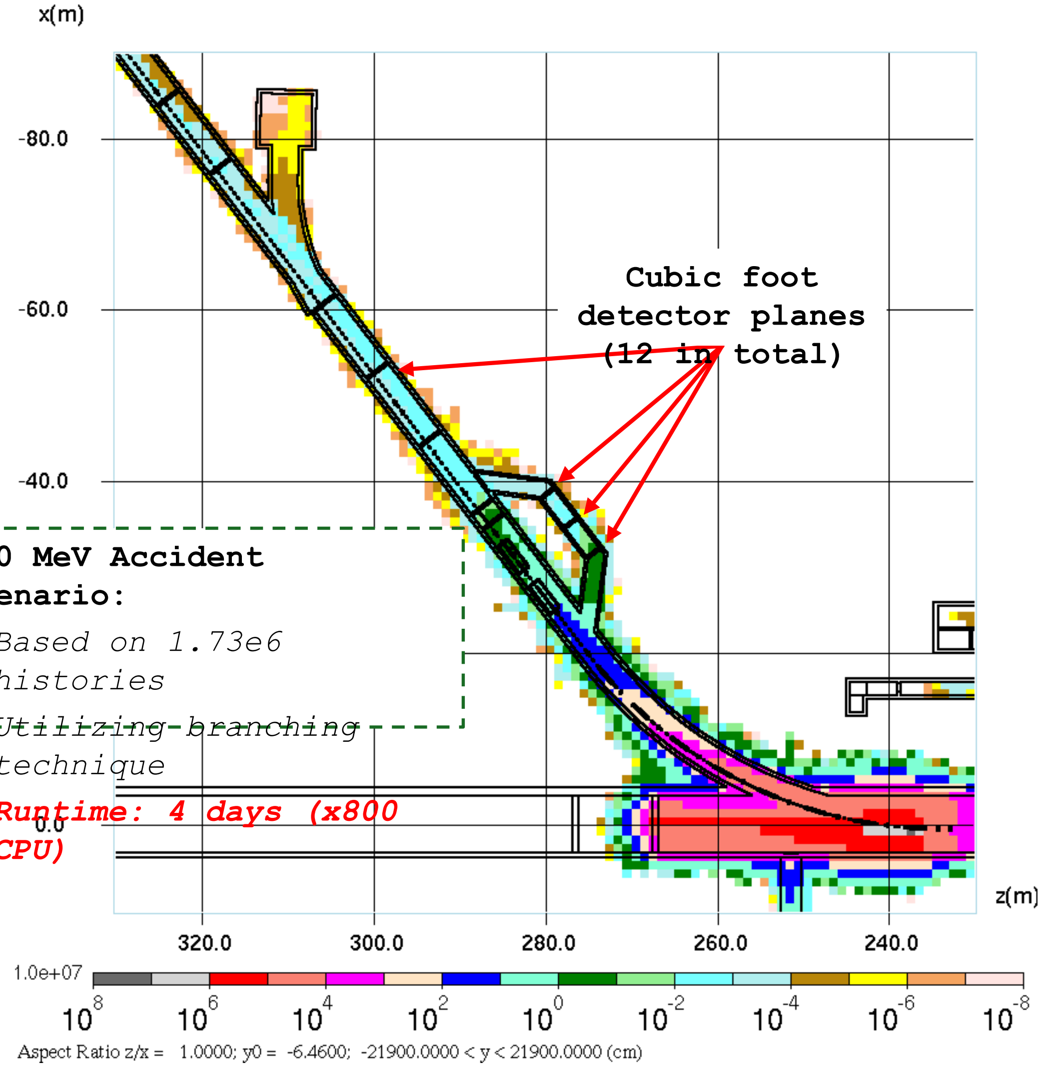
Utilizing the branching technique significantly improved statistical accuracy:

- Achieved over 100 times greater efficiency
- All cells populated with results in just 4 days compared to sparse results after 1 month without branching



1 GeV Accident Scenario:

- *Based on 8.94e7 histories*
- *No branching*
- ***Runtime: 1 month (x1000 CPU)***



800 MeV Accident Scenario:

- *Based on 1.73e6 histories*
- *Utilizing branching technique*
- ***Runtime: 4 days (x800 CPU)***

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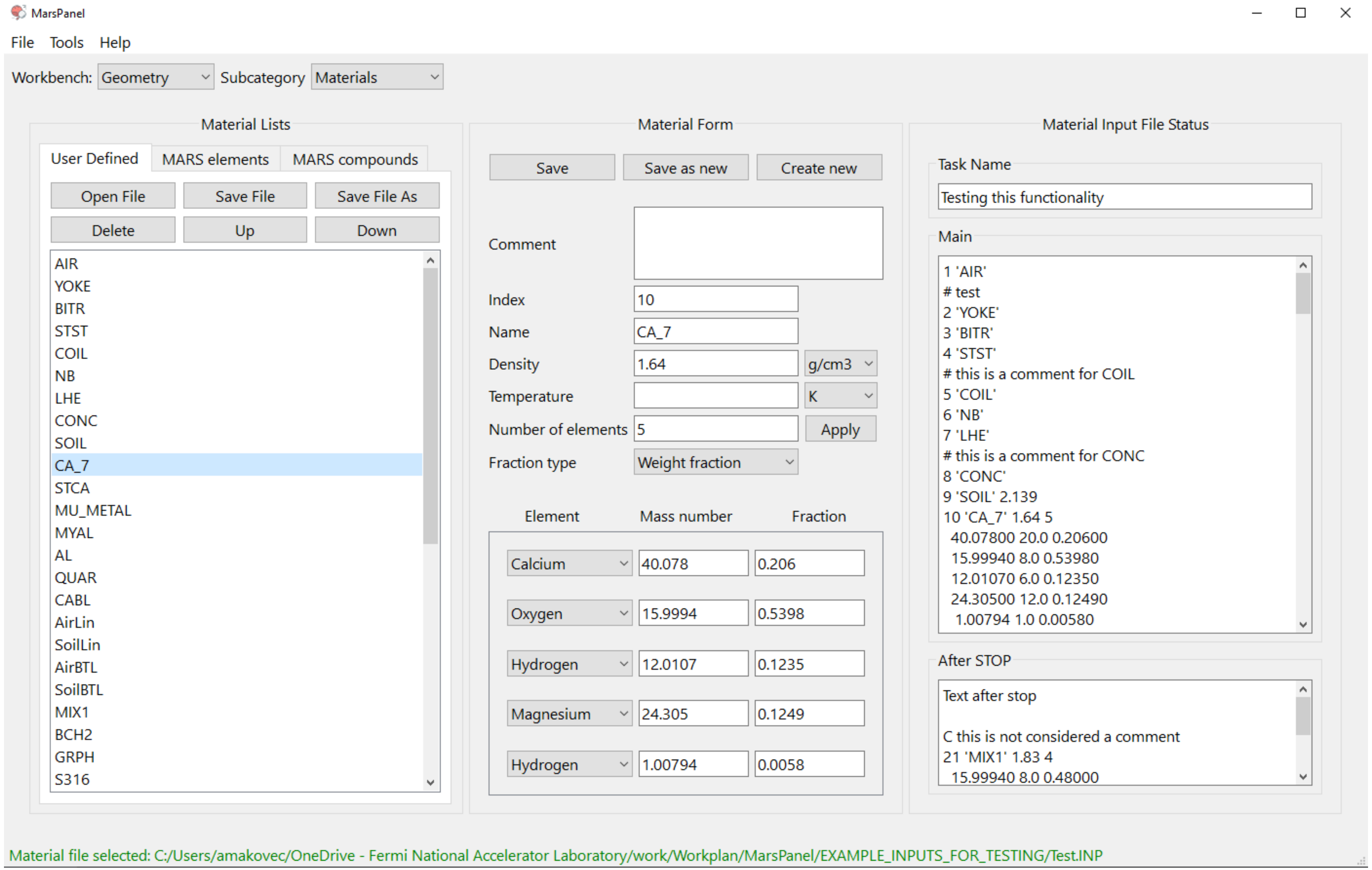
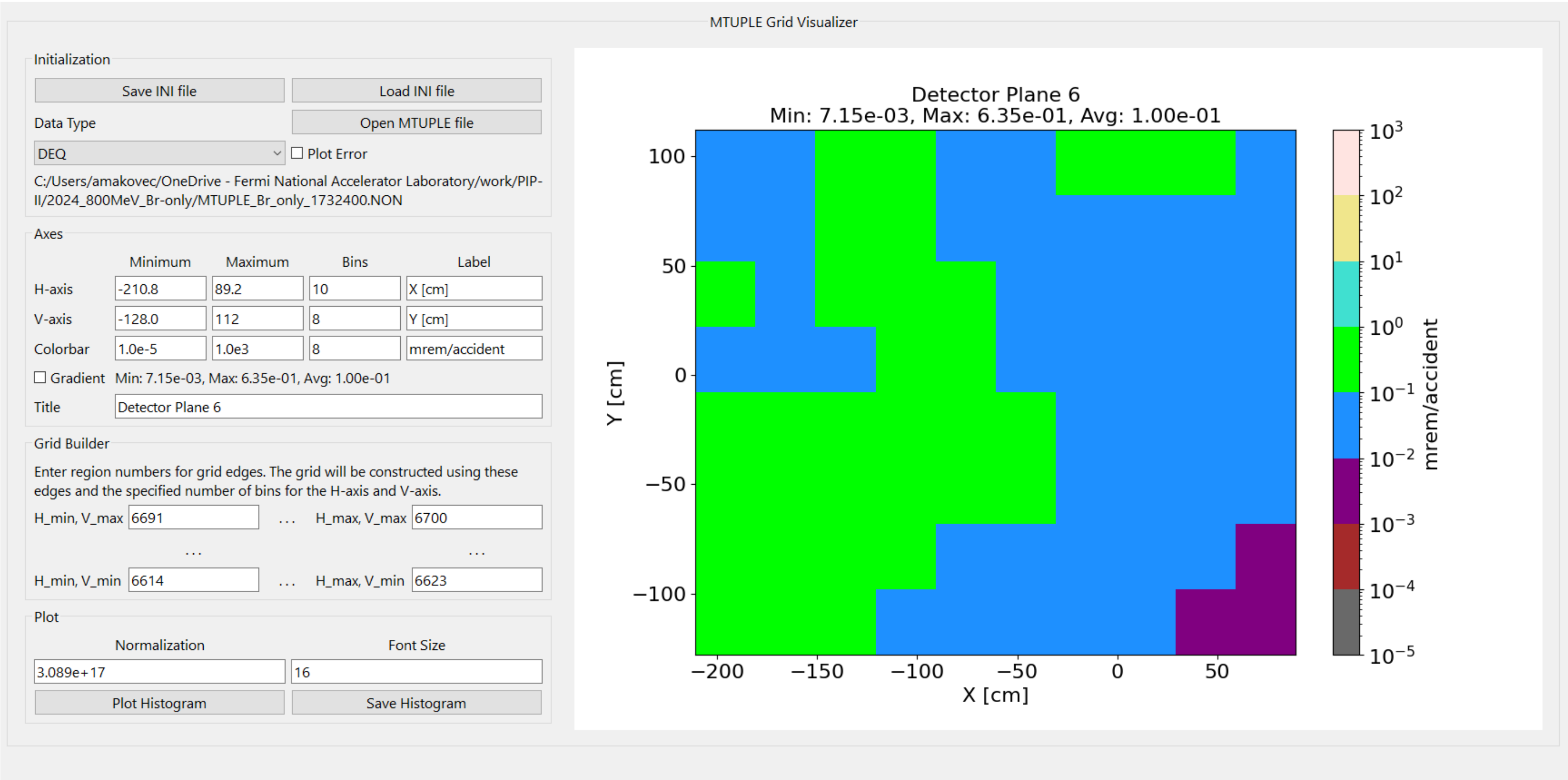
4) Auxiliary Graphical Tools for Data Processing and Visualization

4) Ongoing development of a new, more user-friendly Graphical User Interface (GUI) for MARS



- The new GUI is developed in Python, utilizes the PySide6 and Matplotlib libraries, among others.
- The Main Window was created to facilitate switching among different features.
- The first fully realized feature is the **Material Window**, which **allows** users to:
  - Browse predefined MARS elements and compounds.
  - Clone or copy these into the current material input.
  - Import and export material input files.
  - GUI features include visualization and editing of compounds, with mass conversions between mass and atomic ratios, and temperature conversions between Kelvin and Celsius.

4) GUI tools: The MTUPLE Grid Visualizer (MGV) application

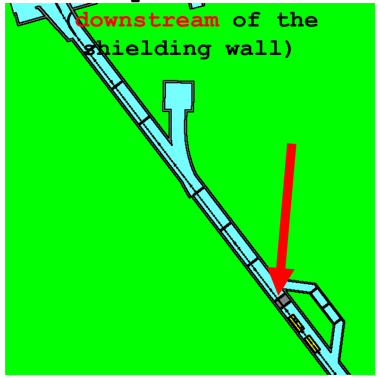


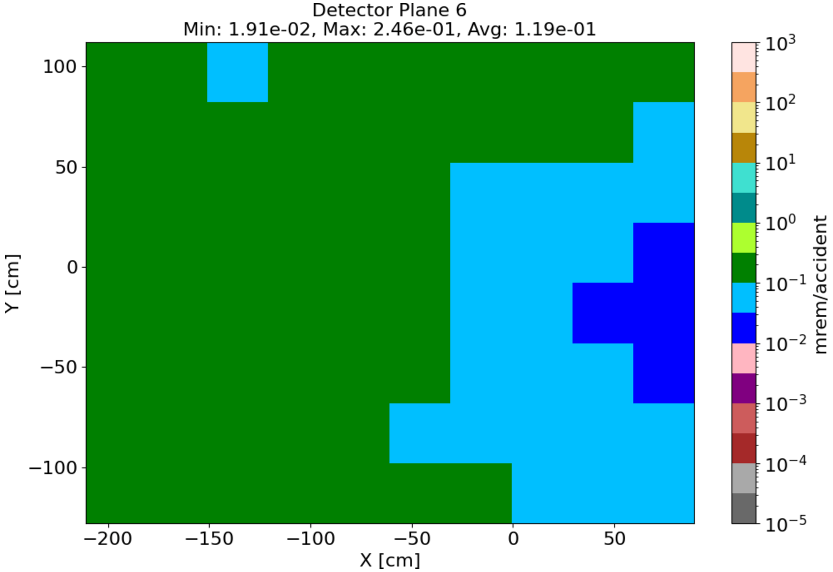
MTUPLE Grid Visualizer:

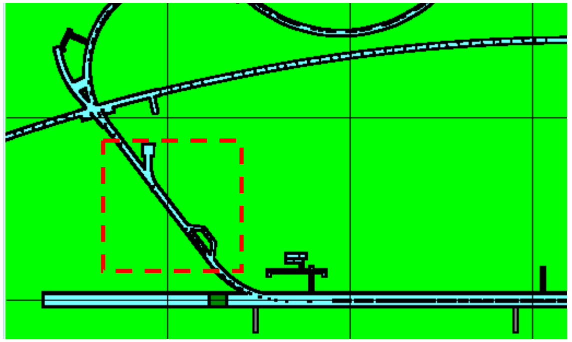
- A tool for visualizing detector plane scoring results from MTUPLE simulation output files.
- Provides a GUI for easy interaction, allowing users to manage .ini files for different detector grid settings, and select MTUPLE input files and quantities for visualization.
- Users must define axes parameters, including minimum and maximum values and number of bins.
- The Grid Builder section requires region numbers corresponding to edges for grid construction.
- Post-construction, users can visualize data in histogram form and save plots.
- The application supports custom normalization

4) Utilizing the MTUPLE Grid Visualizer for the PIP-II Linac Shielding Assessment

Dose rate – Detector plane 6 (downstream of the shielding wall)

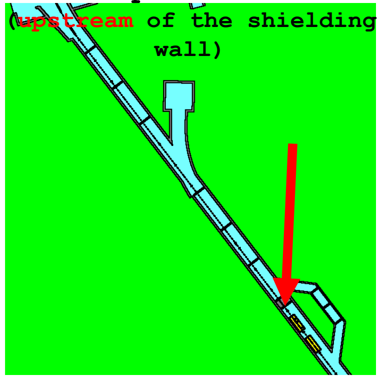


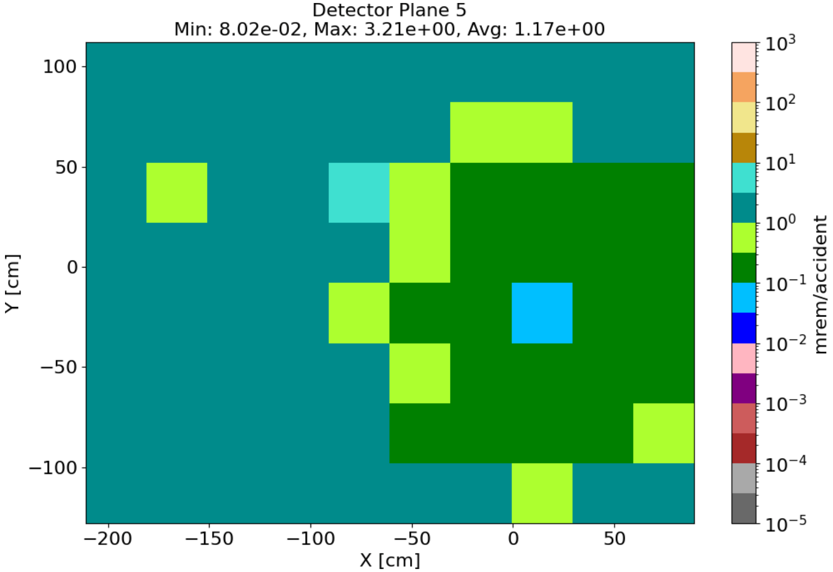




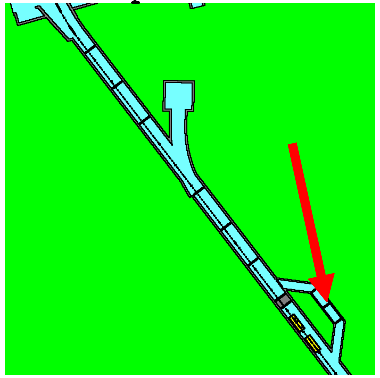
- ARC 1: 550 usec <2ma> 20 Hz (Dipole OFF)
- Incident: Full Linac beam at 800 MeV is lost
- Duration: 3 seconds
- 1.37e14 H-/sec * 3 = = 4.12e14 H-/accident
- Dose rate is given in mrem/accident

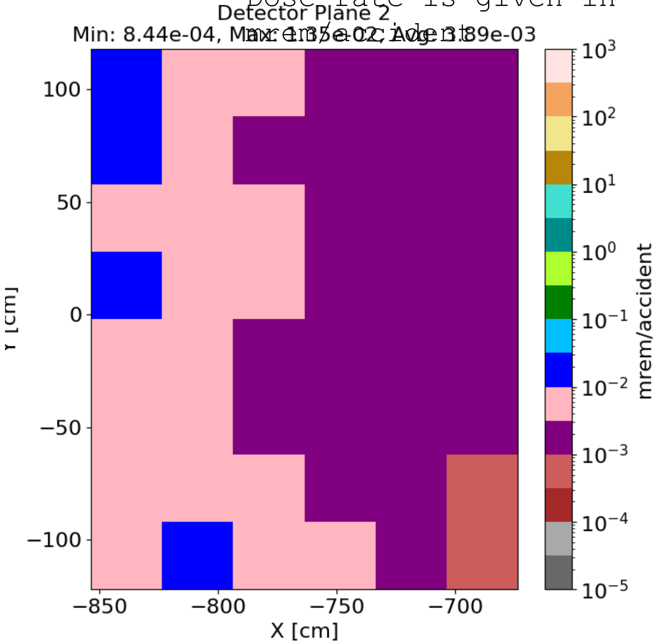
Dose rate – Detector plane 5 (upstream of the shielding wall)



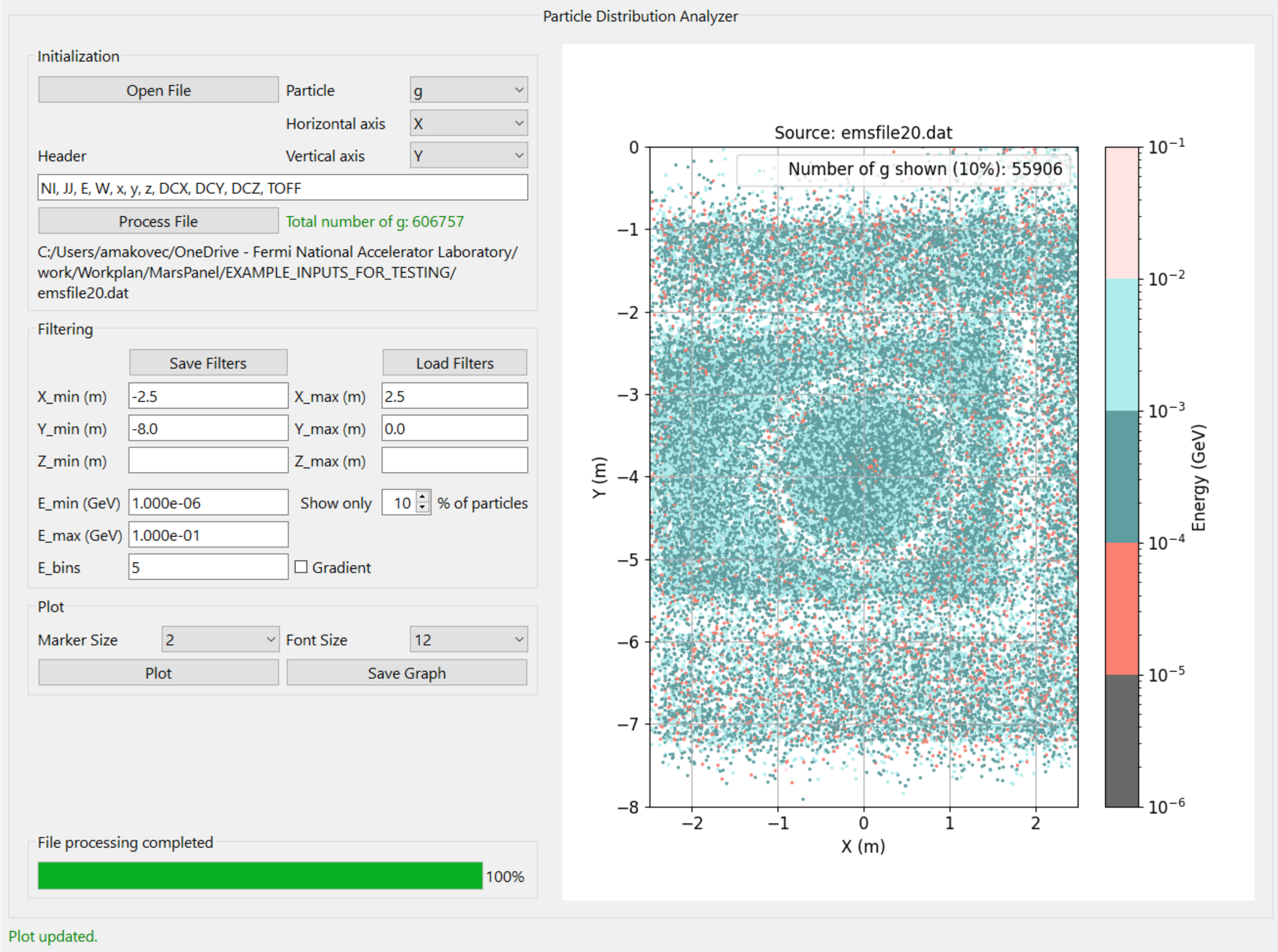


Dose rate – Detector plane 2





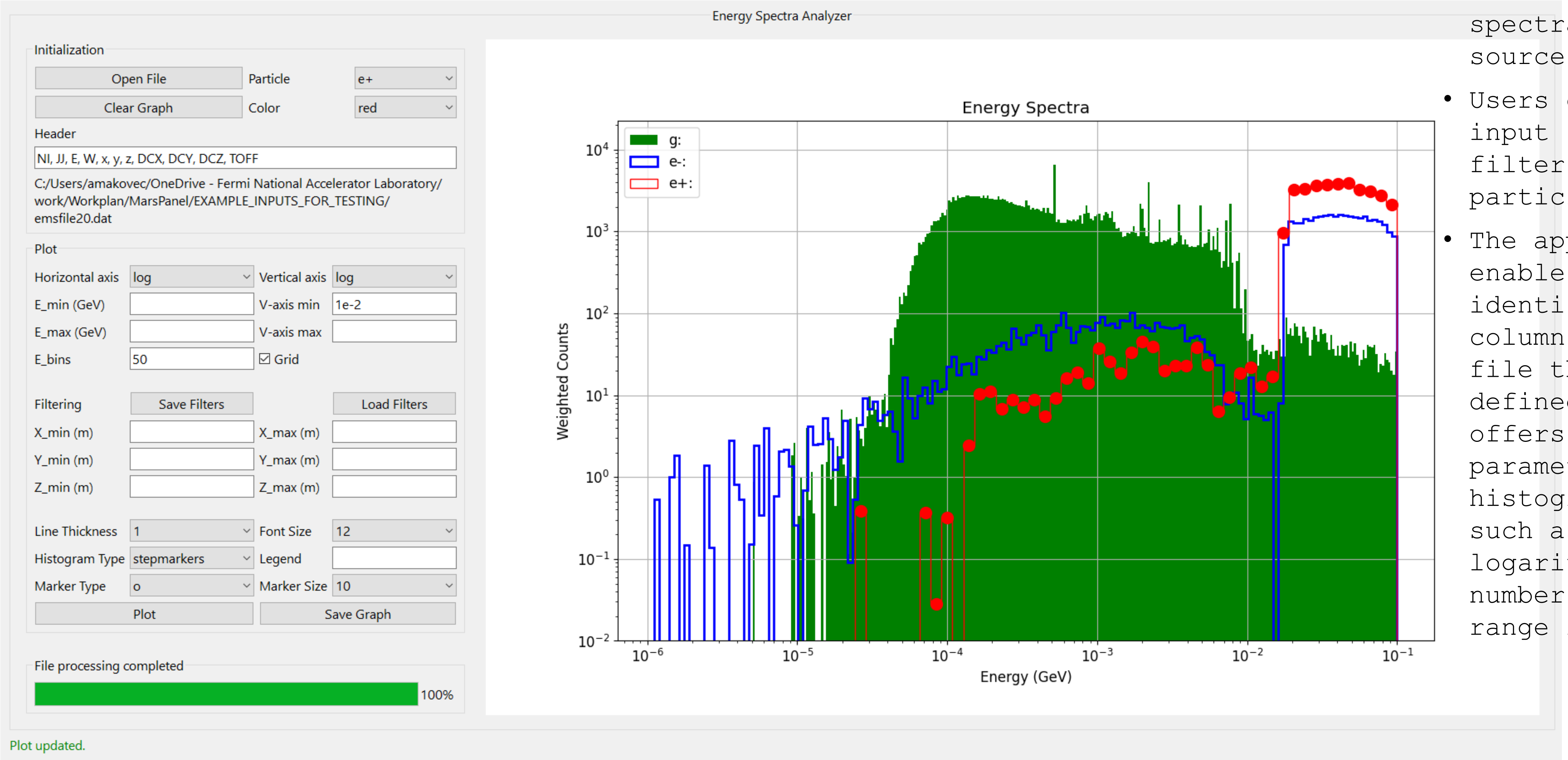
4) GUI tools: The Particle Distribution Analyzer (PDA) application



<u>MTUPLE Grid Visualizer:</u>

- Provides a GUI for the visualization of particle distributions from source files.
- Users can select input files and choose particle types to visualize based on available data.
- The application uses a user-defined header to identify columns in the input file and offers data filtering options.
- It displays particles in a scatter plot, with markers colored by a custom color bar representing the energy of each particle.

4) GUI tools: The Energy Spectra Analyzer (ESpA) application



MTUPLE Grid Visualizer:

- Provides a GUI for visualizing energy spectra from various source files.
- Users can select input files and filter data based on particle type.
- The application enables the identification of columns in the input file through a user-defined header and offers adjustable parameters for histogram creation, such as linear and logarithmic scales, number of bins, and range limits.

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4) Ongoing development of a new, more user-friendly Graphical User Interface (GUI) for MARS

Example of demonstrated features to be added:

- Fast, real-time 2D visualization of geometry for interactive cross-sectional views.
- High-resolution 2D visualization achieved using a single CPU core.
- Potential development of an interactive Geometry Viewer window with three perpendicular 2D cross-sectional views and a 3D geometry visualization.
- Real-time geometry checks during construction and editing, with direct editing through the viewer.

5) Conclusion

5) Conclusion

The PIP-II Linac Shielding Assessment project at Fermilab necessitated rigorous radiation shielding optimization:

- Our comprehensive update of the geometry model and the incorporation of high-resolution detector planes have provided essential radiation field data for this optimization.
- The development of our importance-based branching code has dramatically reduced simulation runtimes while maintaining statistical integrity, enabling efficient modeling of complex radiation environments.
- Additionally, the MTUPLE Grid Visualizer tool enhances our ability to analyze and interpret detector plane scoring results, making the data more accessible.

Overall, our methodologies and tools have significantly improved the efficiency and accuracy of radiation dose assessments for the PIP-II project.

Thank you!

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