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Mu2e

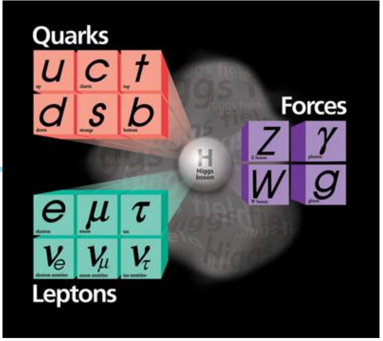
A Search for Muon to Electron Conversion at Fermilab

George Ginther

Accelerator Physics and Technology Seminar

24 February 2015

Charged Lepton Flavor Violation (CLFV)



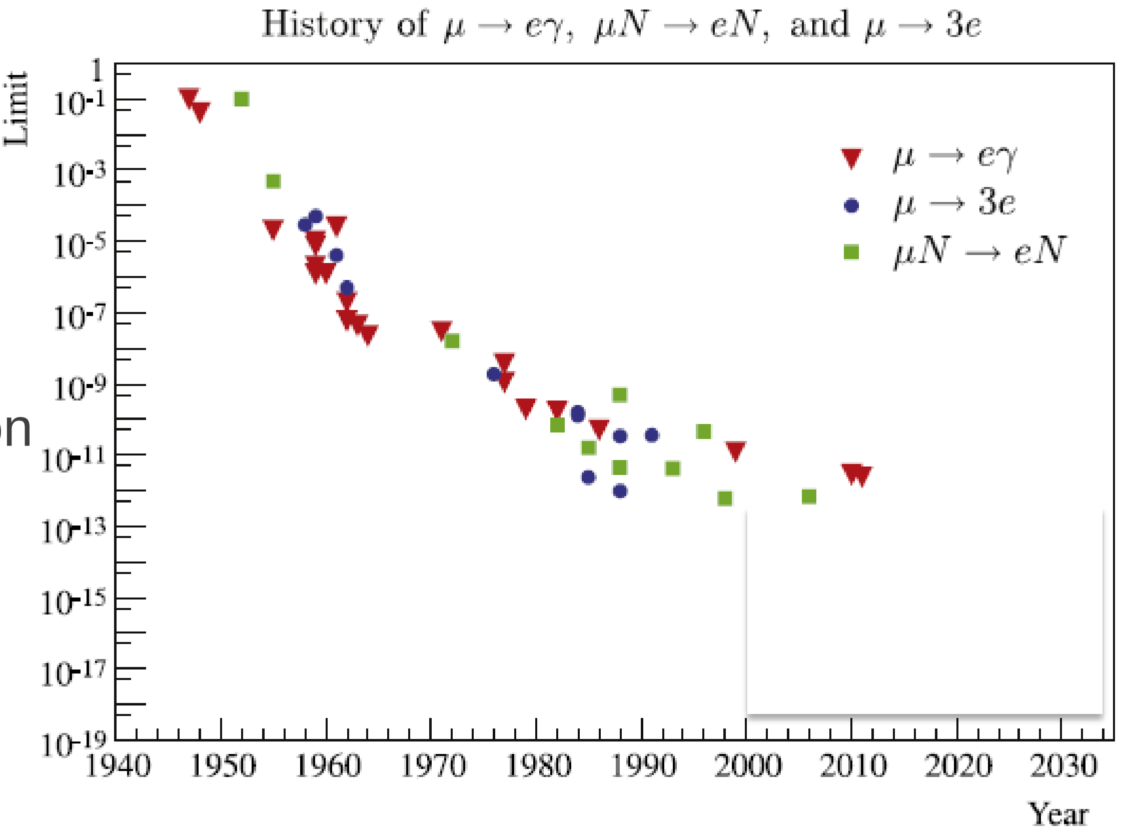
- Searches for transitions such as

$\mu^+ \rightarrow e^+\gamma$	BR < 5.7x10^{-13}
$\mu^- N \rightarrow e^- N$	$R_{\mu e}$ < 7.0 x10^{-13}
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0x10^{-12}
$\tau \rightarrow \mu\gamma$	BR < 4.4x10^{-8}
$\pi^0 \rightarrow \mu e$	BR < 3.6x10^{-10}
$K_L \rightarrow e\mu$	BR < 4.7x10^{-12}
$D^+ \rightarrow K^+ e^- \mu^+$	BR < 2.8x10^{-6}
$B^+ \rightarrow K^+ e \mu$	BR < 9.1x10^{-8}

referred to as charged lepton flavor violation have a long history

- Frequent improvements in sensitivity
- No evidence of a signal to date

R.H. Bernstein, P.S. Cooper / Physics Reports 532 (2013) 27–64



BR limits from K. A. Olive *et al.* (PDG), Chin. Phys. **C38**, 090001 (2014) and $R_{\mu e}$ limit from W. Bertl et al., Eur. Phys. J. C47 337 (2006)

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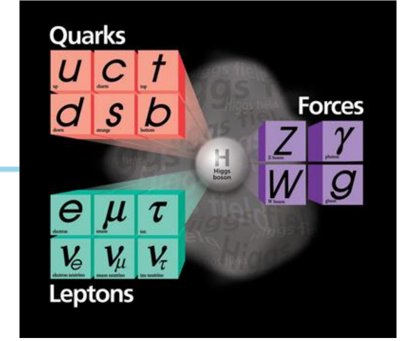

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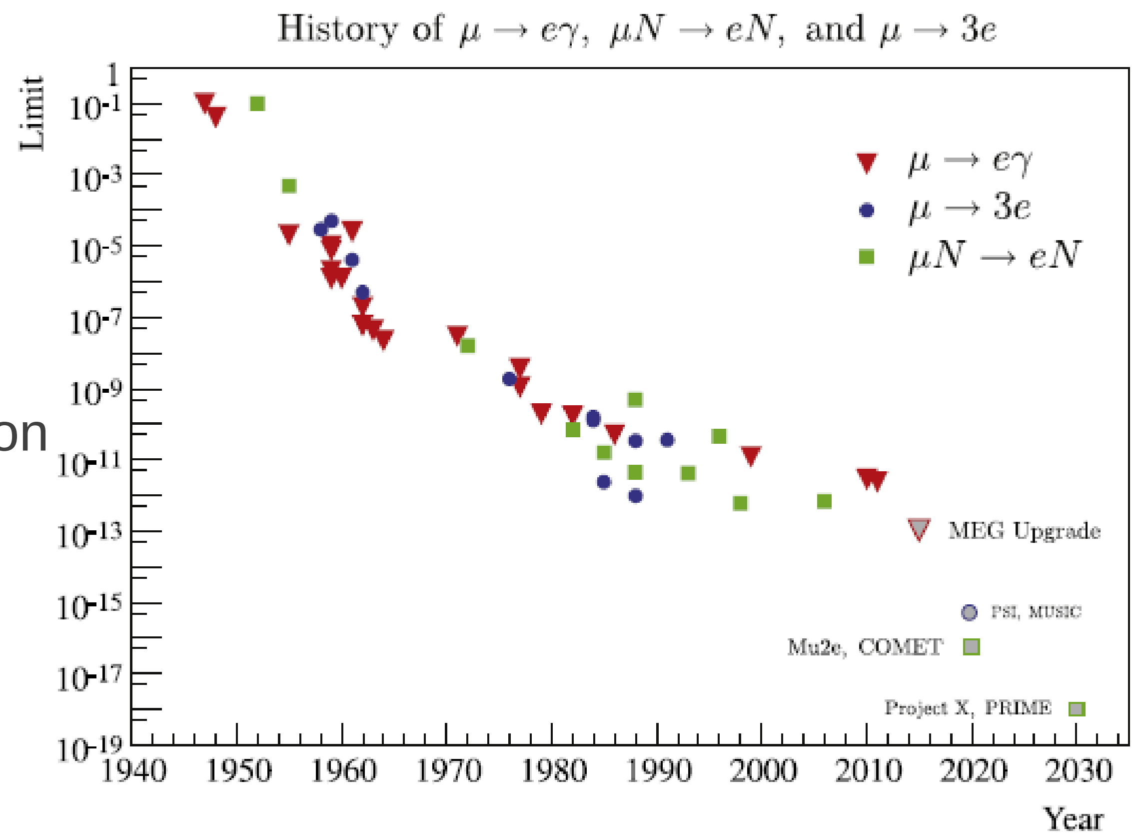

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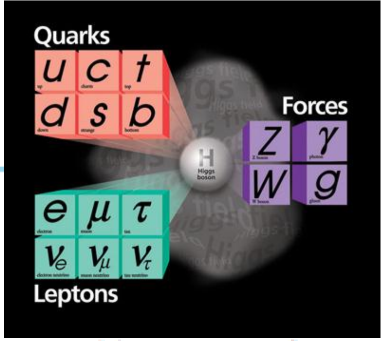
Excerpt from current Particle Data Group compilation



Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C38, 090001 (2014) (URL: http://pdg.lbl.gov)

μ^+ modes are charge conjugates of the modes below.

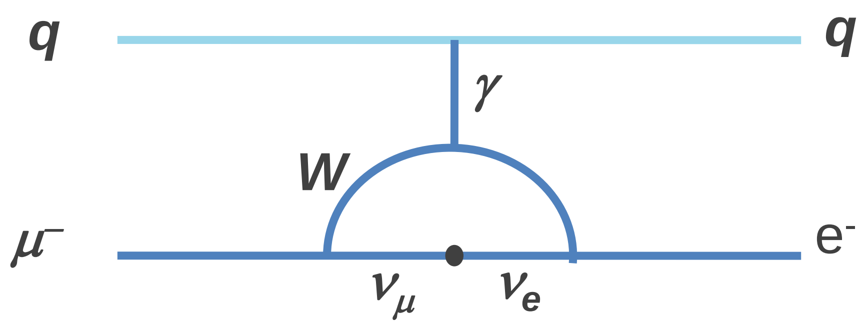
μ^- DECAY MODES			Fraction (Γ_i/Γ)		Confidence level	p (MeV/c)
$e^- \overline{\nu}_e \nu_\mu$			$\approx$ 100%			53
$e^- \overline{\nu}_e \nu_\mu \gamma$		[d]	(1.4 ± 0.4) %			53
$e^- \overline{\nu}_e \nu_\mu e^+ e^-$		[e]	$(3.4\pm0.4) \times 10^{-5}$			53
Lepton Family number (*LF*) violating modes						
$e^- \nu_e \overline{\nu}_\mu$	*LF*	[f]	< 1.2	%	90%	53
$e^- \gamma$	*LF*		< 5.7	$\times 10^{-13}$	90%	53
$e^- e^+ e^-$	*LF*		< 1.0	$\times 10^{-12}$	90%	53
$e^- 2\gamma$	*LF*		< 7.2	$\times 10^{-11}$	90%	53

$\mu^- N \rightarrow e^- N$

- Mu2e is a search for evidence of charged lepton flavor violation

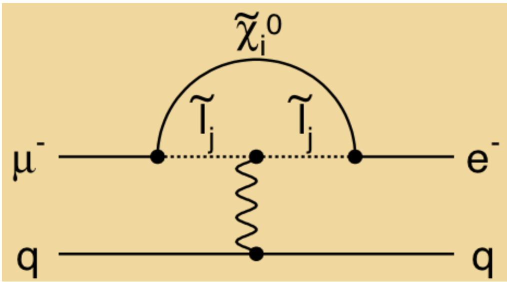
  $\mu^- N \rightarrow e^- N$

- The observation of neutrino oscillations indicates that CLFV should occur

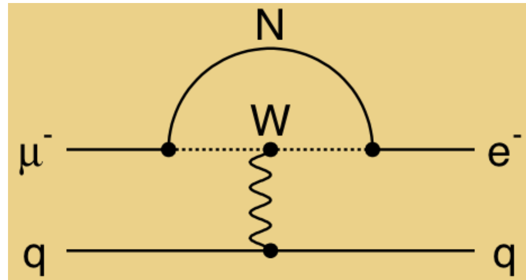


- However, the expected rate from this mechanism is extremely small, well beyond experimental reach
  - Anticipated rate $\sim \Delta m_\nu^2 / M_W^2 < 10^{-50}$
- Consequently, unambiguous detection of a signal would represent clear evidence of physics beyond the current Standard Model
- Many models predict rates that may be within reach of the next generation searches
  - Such searches have been assigned high priority by P5

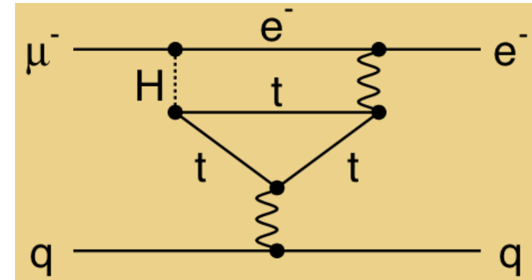
Candidate New Physics Contributions to $\mu^- N \rightarrow e^- N$



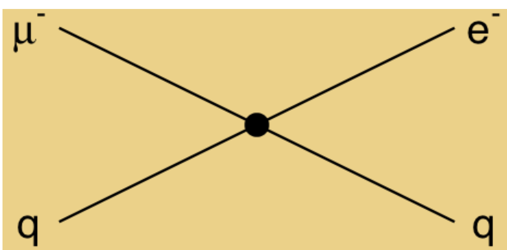
Supersymmetry



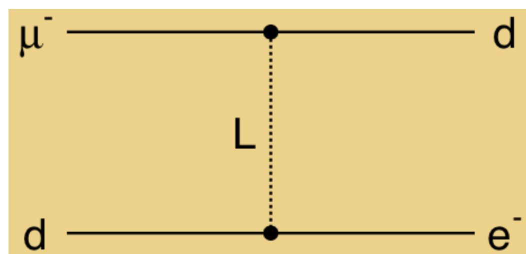
Heavy Neutrinos



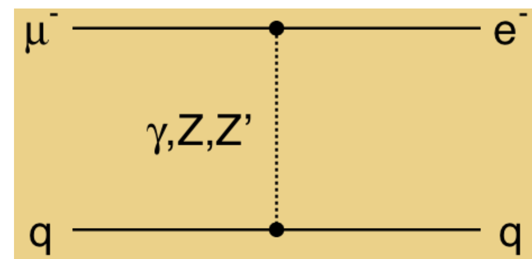
Two Higgs Doublets



Compositeness



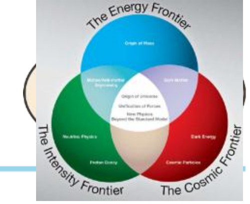
Leptoquarks



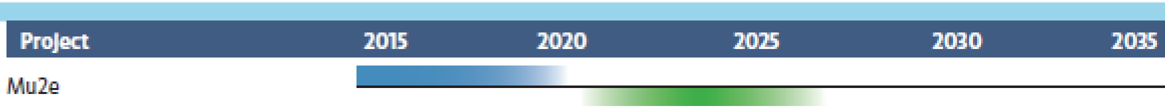
New Heavy Bosons /
Anomalous Couplings

- $\mu^- N \rightarrow e^- N$ *is* sensitive to a wide array of New Physics models

P5
Particle Physics Project Prioritization Panel



- From the May 2008 report "*US Particle Physics: Scientific Opportunities A Strategic Plan for the Next Ten Years*"
  - A muon-to-electron conversion experiment at Fermilab could provide an advance in experimental sensitivity of four orders of magnitude. The experiment could go forward in the next decade with a modest evolution of the Fermilab accelerator complex. Such an experiment could be the first step in a world-leading muon-decay program eventually driven by a next-generation high-intensity proton source. Development of a muon-to-electron conversion experiment should be strongly encouraged in all budget scenarios considered by the panel.
  - **Recommendation The panel recommends pursuing the muon-to-electron conversion experiment, subject to approval by the Fermilab PAC, under all budget scenarios considered by the panel.**
- From the May 2014 report "*Building for Discovery Strategic Plan for U.S. Particle Physics in the Global Context*"
  - The Mu2e and muon g-2 projects represent a large fraction of the budget in the early years. These are immediate targets of opportunity in the drive to search for new physics, and they will help inform future choices of direction. The science case is undiminished relative to their earlier prioritization. The programmatic impacts of large changes at this point were also discussed and determined to be generally unwise, although the Mu2e profile could be adjusted by a small amount if needed.
  - **Recommendation 22: Complete the Mu2e and muon g-2 projects.**

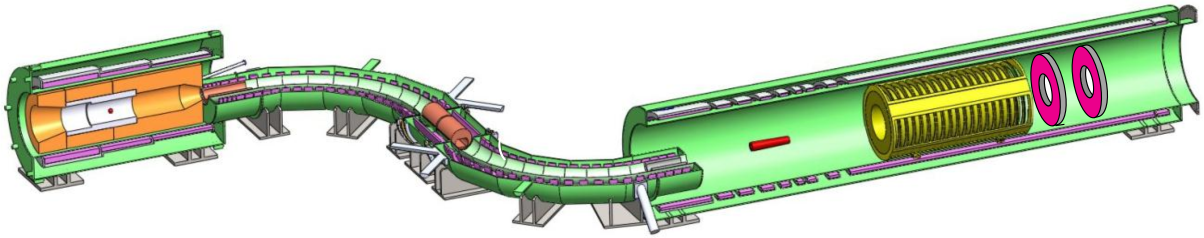


An overview of a search for evidence of muon to electron conversion

- Measure the rate of coherent neutrinoless conversion of negatively charged muons into electrons in the field of a nucleus

- Generate an intense beam of low momentum muons
- Stop muons in an appropriate target and monitor the rate of muon stops
  - Muons rapidly transition to the 1s state (emitting telltale photons along the way)
  - Muons typically decay in orbit or are captured by the nucleus
  - Mu2e plans to use an aluminum target
    - Resulting muon lifetime is 864 ns — D.F. Measday Phys. Rep. 354 2001 → J. L. Lathrop *et al*, PRL 7 107 1961
    - 39% of stopped muons decay in orbit on aluminum
- Look for signature of conversion of captured muon into electron $\mu^- N \rightarrow e^- N$
  - Coherent process—the nucleus remains intact and the signature electron emerges with an energy determined by the rest mass of the muon, the nuclear recoil and binding energy of the muon to the target nucleus
  - On aluminum, the conversion electron energy is ~104.97 MeV

- The Mu2e project includes
  - A new building to house the experiment
  - Modifications and additions to the accelerator complex
  - Mu2e apparatus including
    - Superconducting solenoids
    - Tracker
    - Calorimeter
    - Cosmic ray veto
    - DAQ
    - Associated infrastructure



- In addition to the effort provided by the project and the Mu2e collaboration, Mu2e also relies upon lab infrastructure and muon campus common projects and infrastructure delivered as part of the Nova project

Mu2e Mission Need

- Critical Decision 0 Mission Need Statement for a Muon to Electron Conversion Experiment (Mu2e)
  - As the Large Hadron Collider (LHC) commences operations we anticipate the possibility of profound new discoveries that will change the way we view the submicroscopic world. Additional experimentation will be needed to understand the detailed nature of the LHC discoveries or to probe higher mass scales should new discoveries prove elusive. The conversion of a muon to an electron in the field of a nucleus provides a unique window on the structure of potential new physics discoveries and allows access to new physics at very high mass scales. The Particle Physics Project Prioritization Panel (P5) identified this opportunity as a top priority, but no capacity currently exists to exploit such a measurement.
  - Approved by the Director of the Office of Science, W. F. Brinkman on 24 November 2009

Mu2e Project

- Critical Decision 1 Alternative Selection and Cost Range of the Muon to Electron Conversion (Mu2e) Project at Fermilab
  - The purpose of the Mu2e Project is to design, construct and install the Mu2e detector and to modify the Fermilab accelerator complex in order to achieve the physics goals set out in the Mu2e Proposal.
  - DOE Total Project Cost range 200 to 310 M$
  - DOE CD-1 Review 5-7 June 2012
  - Approved by W. F. Brinkman on 11 July 2012
- Critical Decision 3a Long Lead Procurement for the Muon to Electron Conversion (Mu2e) Project
  - CD-3a approval and superconductor long lead procurement helps the project stay ahead of any superconductor production issues and enables advancing the start of solenoid fabrication by up to 6 months, saving up to $6M. Following a February 2014 briefing to DOE SC and OHEP, contract options for the critical path DS superconductor production were exercised in March 2014 under an early procurement authority.CD-3a approval will enable the Mu2e Project to exercise contract options for the PS and TS superconducting cable, for a total amount of $5.1M
  - DOE CD-3a Review 10 June 2014
  - Approved by Acting Director Patricia Dehmer 10 July 2014

Mu2e Project Status

- Critical Decision 2/3b Performance Baseline for technical scope, cost and schedule (CD-2) and Procurement and Fabrication for the experimental hall and the Transport Solenoid superconducting magnet modules (CD-3b)
  - DOE CD-2/3b Review 21-24 October 2014
  - DOE CD-2/3b Follow-Up Review 4 February 2015
    - Total Project Cost 273.7 M$
    - 14.6M$ for the Mu2e Detector Hall
    - 8.8M$ for the Transport Solenoid modules
  - Eagerly anticipating approval
- Aiming at Critical Decision 3c reviews early in calendar year 2016 in anticipation of timely authorization of the remaining procurements and fabrications to keep Mu2e on a technically driven schedule

An Excerpt from the February 17 2015 All Hands Meeting

Priorities Update: once a quarter (changes in red)

- LCLS-II (we must deliver….and we are)
- PIP-II (as per P5, quick start to enable LBNF, competitive ad)
- CMS Phase 1 upgrades (go go go)
- Muon g-2 (go go go)
- Mu2e (will move here after CD-2/3 ESAAB, go go go)
- Operations in order:
  - NOvA,
  - MicroBoone
  - Everything else
- LBNF design work (focus on far site) CD1 refresh/CD2a/CD3a
- SBN (small but fast track)
- Cosmic projects and ops (small but leveraged)
- R&D (a core competency) accelerators & detectors

Fermilab

39 All hands 2/17/2014

The challenge(s)

- Generate and stop a sufficient number of muons to achieve the desired sensitivity

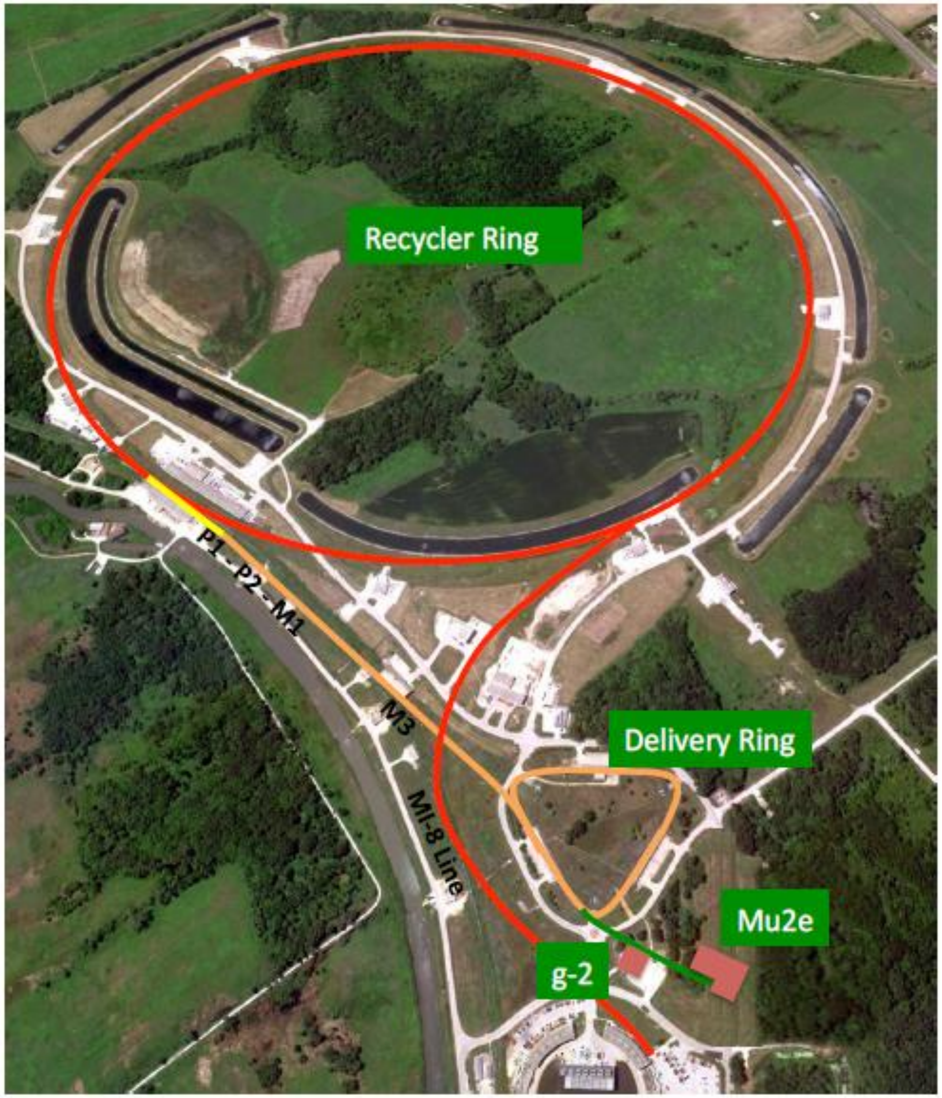
$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)}$$

  - Mue2 currently projects a single event sensitivity of 2.87×10^{-17}
    - Current best experimental limit is 7×10^{-13} (90% CL) by the SINDRUM II experiment at PSI

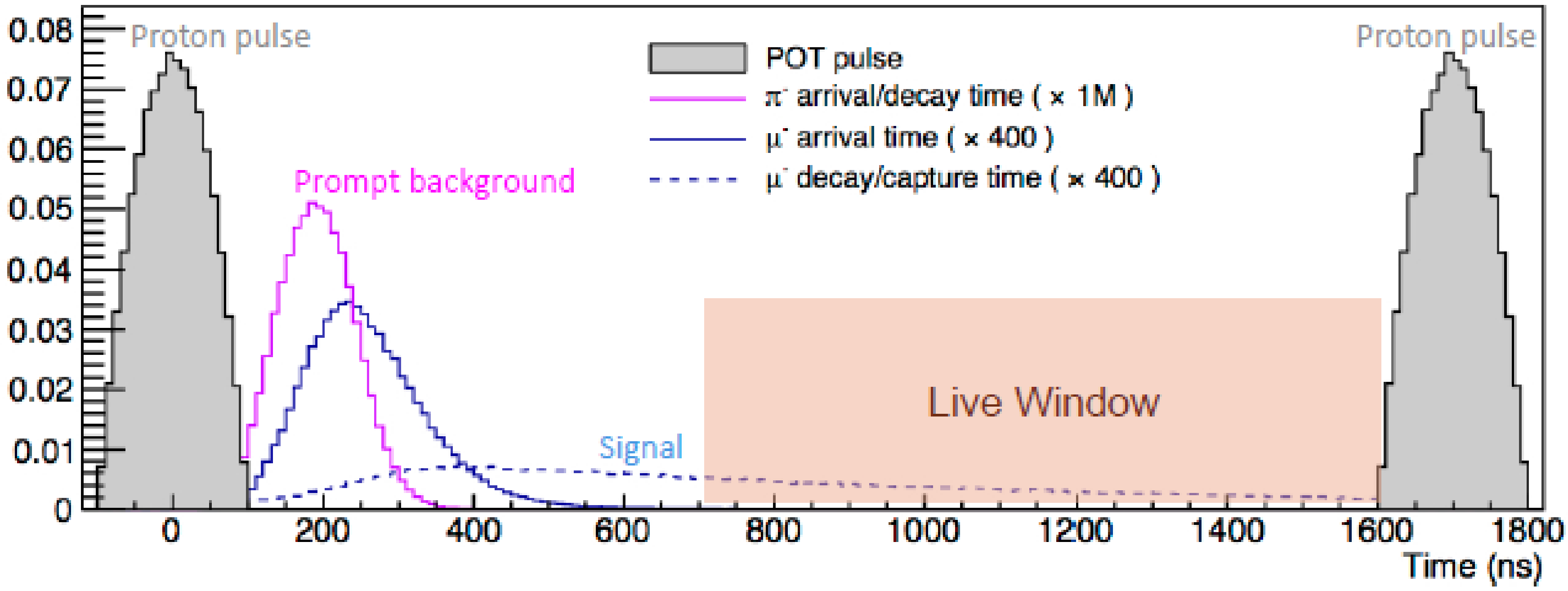
      W. Bertl *et al*, Eur. Phys. J. C47, 337 (2006)
  - Requires $\sim 10^{18}$ stopped muons
    - 3.6×10^{20} protons on target during three years of running in addition to time (and beam) for commissioning and calibration
- Identify, control, suppress and eliminate backgrounds to the level required to achieve the target sensitivity
  - The crucial technique to provide the improved suppression of backgrounds is to deliver an intense intermittent beam and only search for conversions between beam pulses
    - so that the experiment signature may not be overwhelmed by the residue of the incident beam or other backgrounds

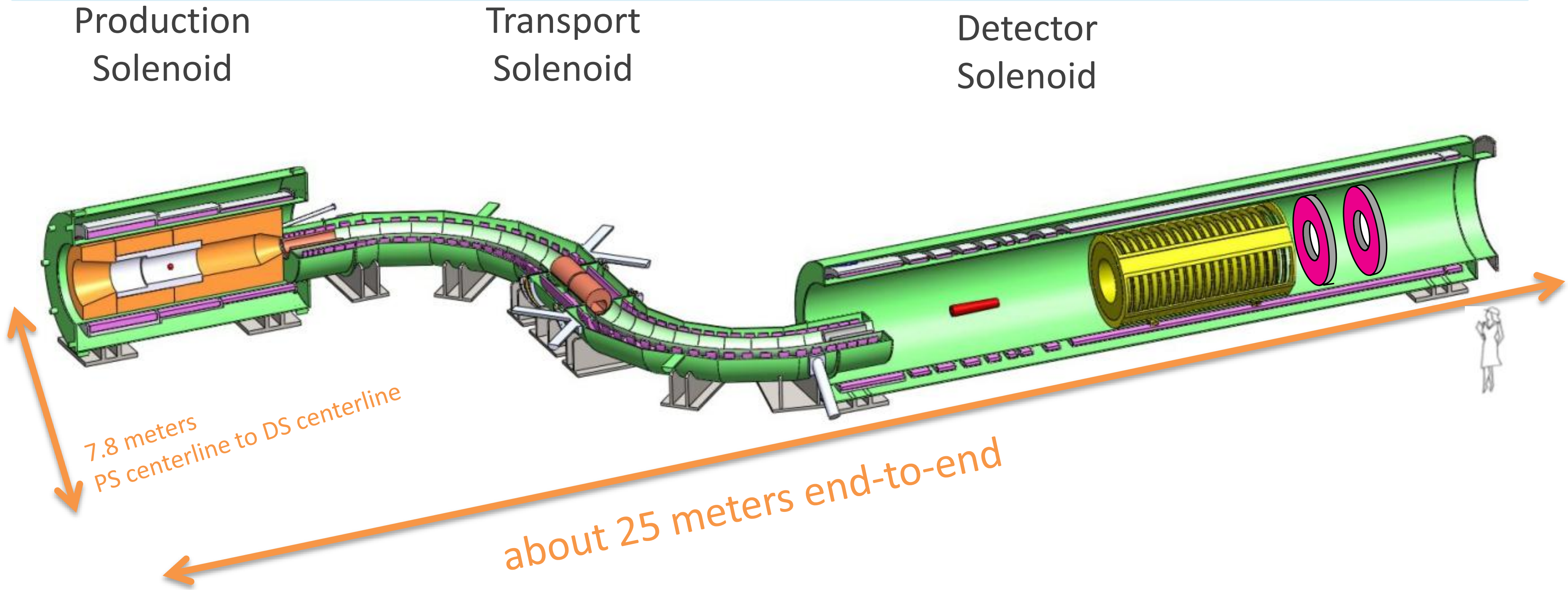
Proton Beam

- Booster batch transported to Recycler Ring
- Rebunched into four bunches in the Recycler Ring
- A bunch is extracted and transported to the Delivery Ring
- That bunch is resonantly extracted from the Delivery Ring in pulses of ~10^7 protons every 1695 ns (over a period of ~54 ms) and delivered to a target in the Mu2e Production Solenoid
- Residual beam between these pulses suppressed via a fast AC dipole in the M4 beamline that diverts that beam into collimators

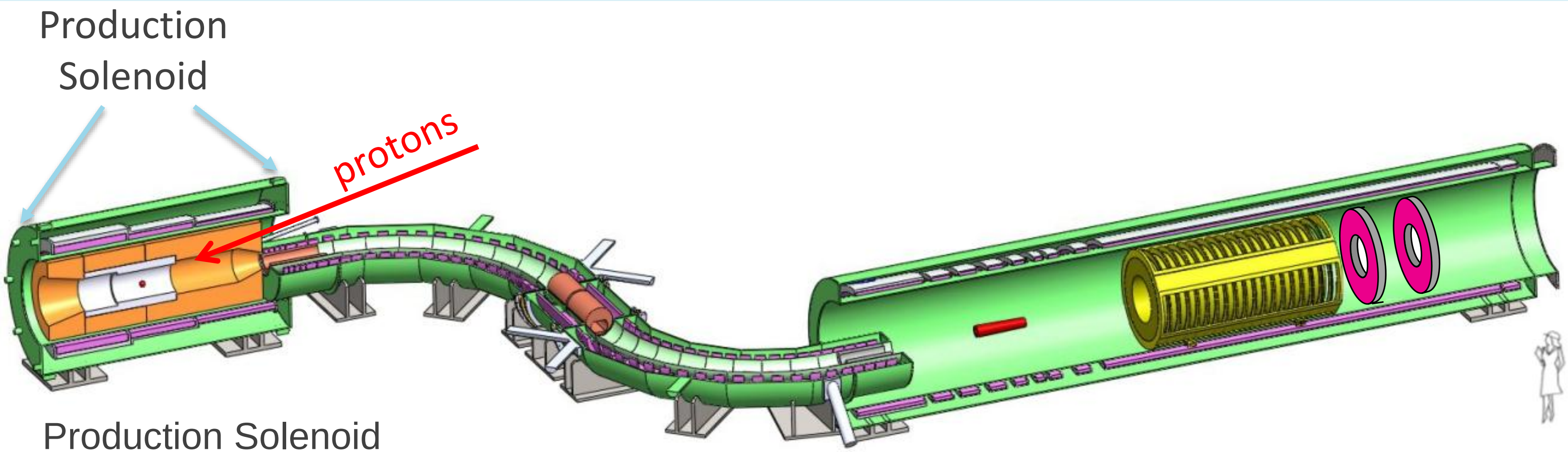


- Protons interact with a target mounted in the Production Solenoid
- Resulting pions decay and generate the muon beam
  - Secondary beamline selects and transports muons of appropriate momentum and charge
- A delayed live gate is adopted to minimize sensitivity to the prompt backgrounds

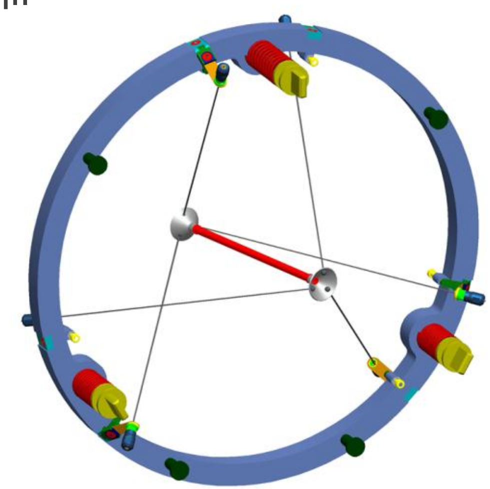


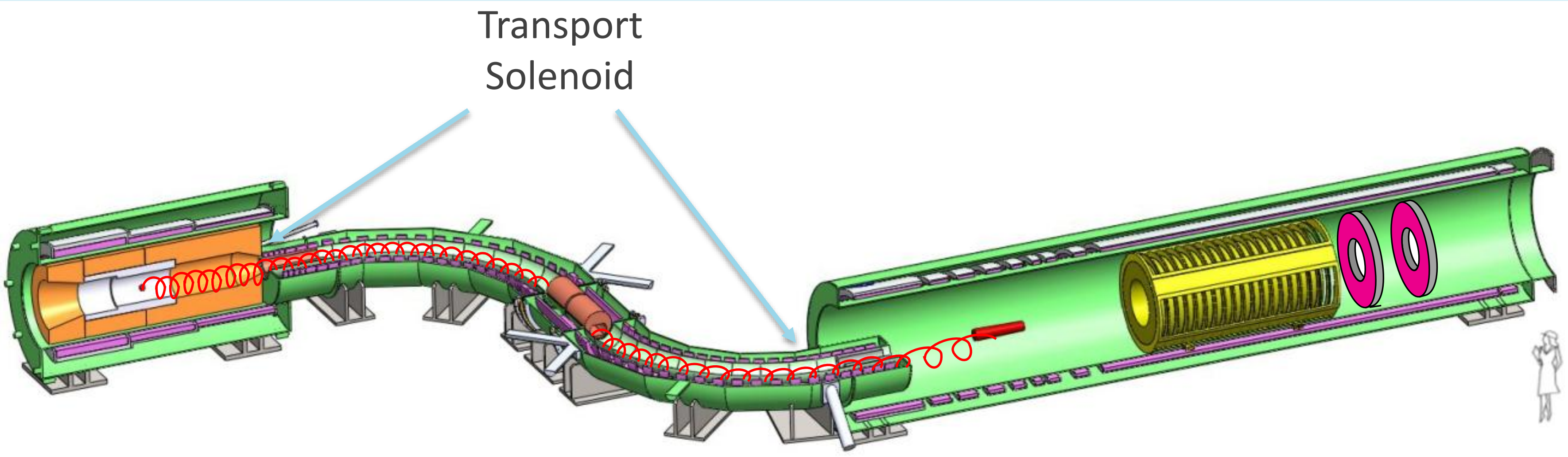


- Solenoids capture pions, generate the secondary muon beam, preserve the time structure of the beam and provide the field necessary for the momentum analysis of candidate signal events and rejection of background
- Derived from MELC concept of R. M. Djilkibaev and V. M. Lobashev

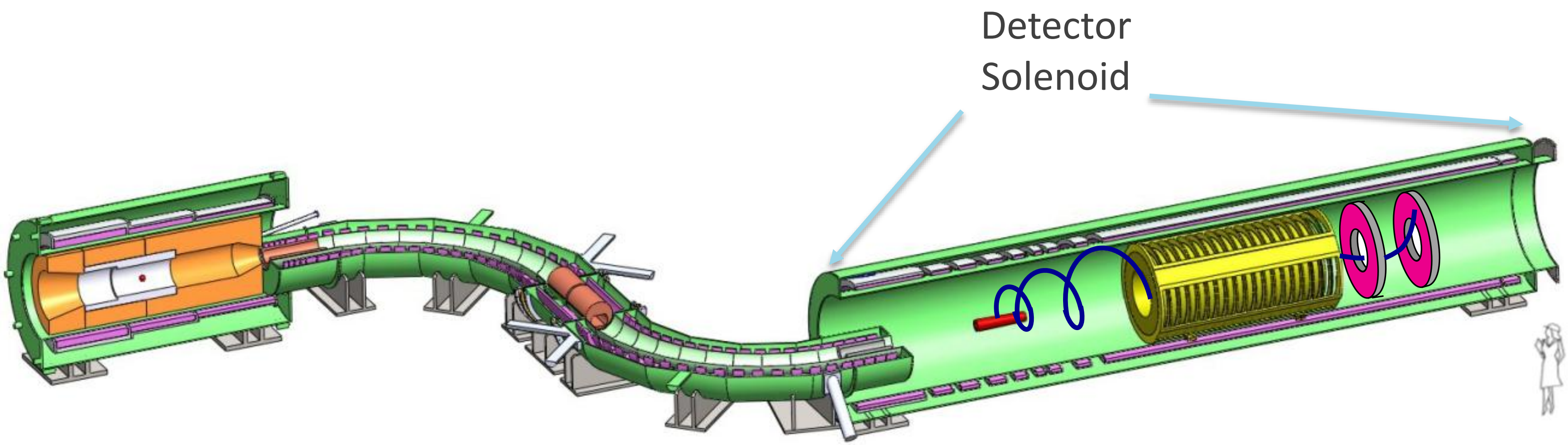


- Production Solenoid
  - Heat and Radiation Shield mounted inside Production Solenoid
    - Stainless steel vessel containing water cooled bronze to limit radiation damage to the Production Solenoid coils
    - Heat and Radiation Shield includes mounting fixture for primary target
  - 8 GeV protons interact with the primary target to produce μ^- (from π^- decay)
  - Primary target
    - 6 mm diameter and 16 cm long tungsten
    - Radiatively cooled target
    - The beamline is evacuated to 10^{-5} torr to improve target lifetime

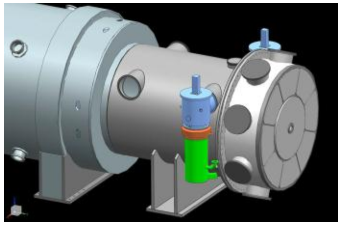




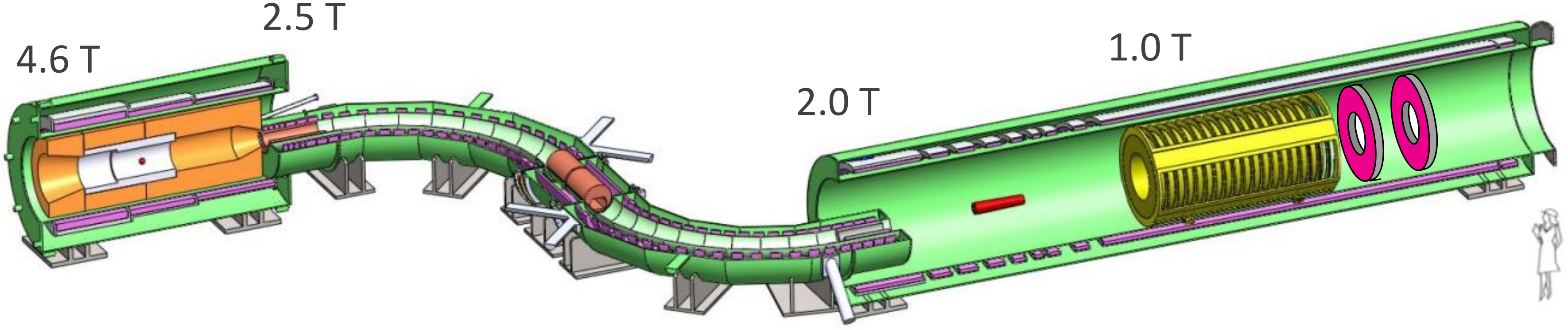
- Transport Solenoid
  - Captures π^- and subsequent μ^- and transports that beam
  - Momentum and sign selects beam incident on muon stopping target mounted in the Detector Solenoid
  - Housed in two independent cryostats
  - Four collimators inserted in the warm bore of the Transport Solenoid
  - Absorbers mounted in warm bore to provide antiproton suppression



- Detector Solenoid
  - Muon stopping target mounted inside warm bore
  - Tracker mounted inside warm bore
  - Calorimeter mounted inside warm bore
  - Internal shielding and muon beam stop (not shown)
- Combination used to collect, identify and momentum analyze candidate electrons emerging from the muon stopping target

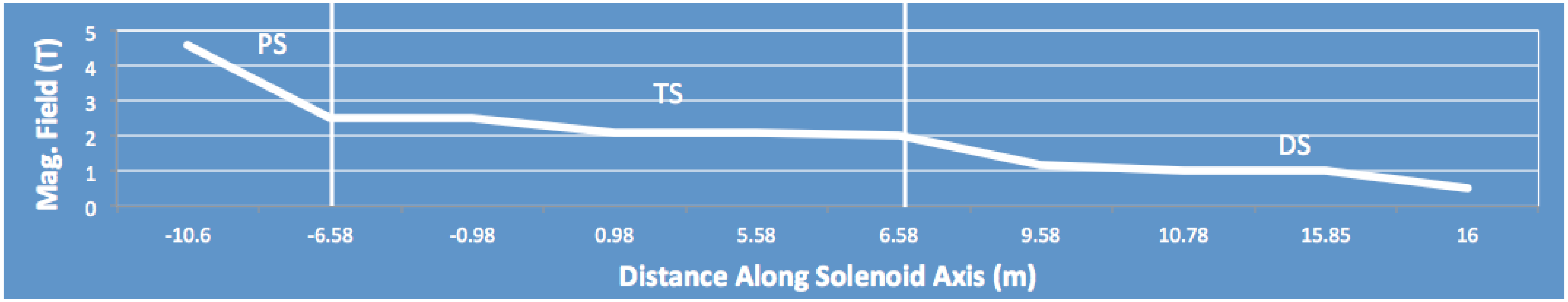


- Warm bore is evacuated to ~10^{-4} torr so that scattering in the gas in the detector region is negligible

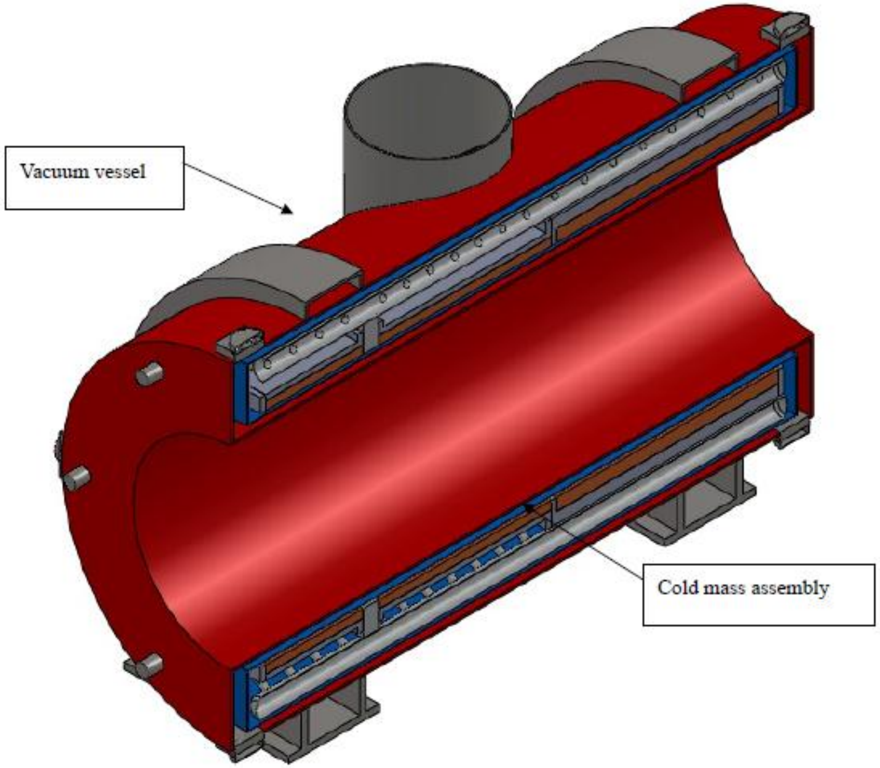


Graded fields in the solenoids important to suppress backgrounds, to increase muon yield, and to improve geometric acceptance for signal electrons

Uniform field in tracker region

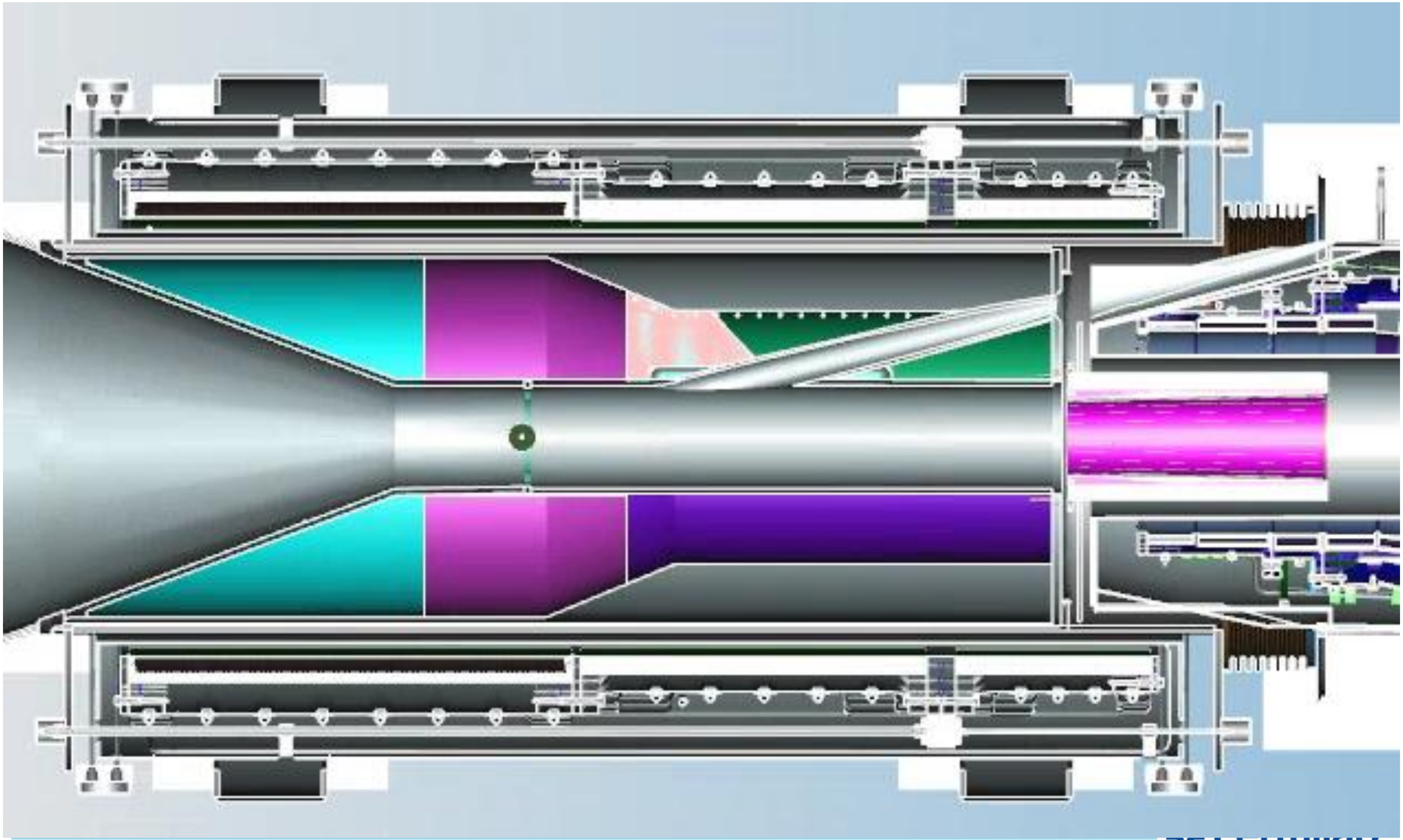


Production Solenoid

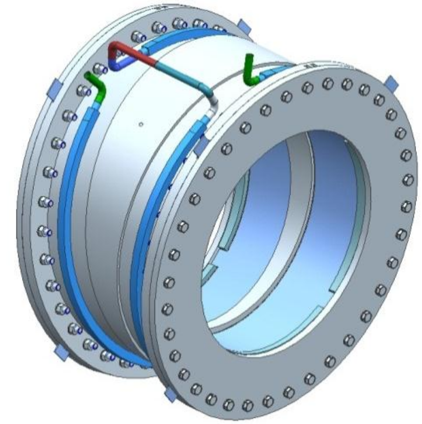


- Peak axial field 4.6 T
- Operating current ~10kA
- Three superconducting coils on aluminum shells
- 1.5 m diameter warm bore
- 4.5 m long cryostat
- Harsh radiation environment
- PS coils protected by massive Heat and Radiation Shield
  - Bronze and water filled stainless steel vessel to be inserted into warm bore of PS (~37 tons)
- Reference design for the Production Solenoid has been produced
- The Production Solenoid will be fabricated in industry
  - Contract for final engineering design signed last week

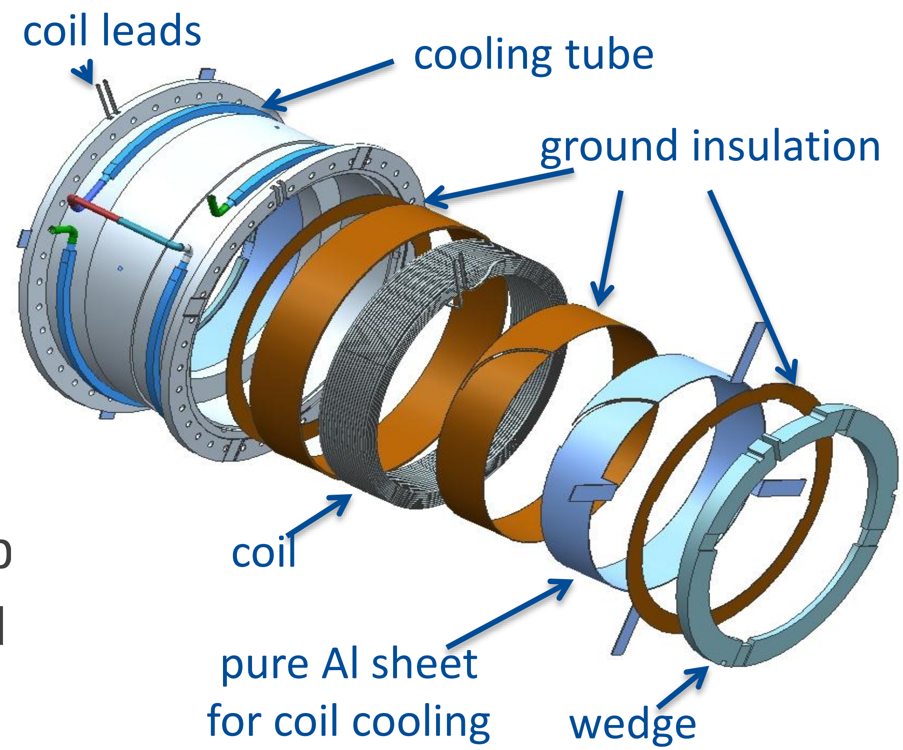
Cross section view of Production Solenoid Region



Transport Solenoid

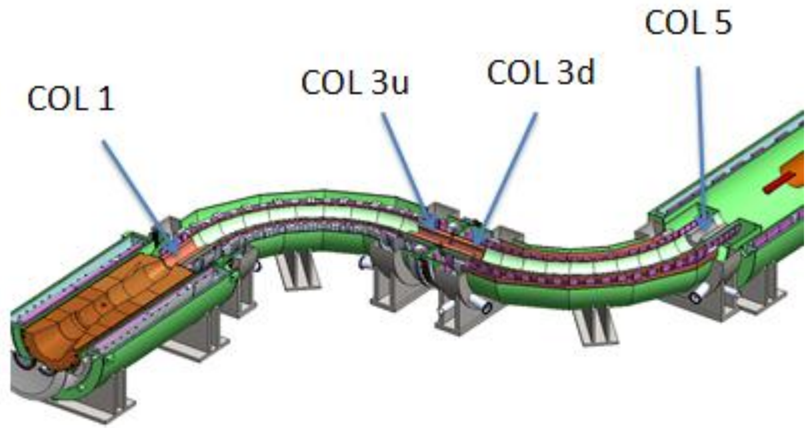


- 27 modules
  - 13 in the upstream TS
  - 14 in the downstream TS
- Modules composed of outer aluminum shell supporting typically two superconducting solenoid rings
- Modules bolted together to form the required geometry which will facilitate transport of muons while suppressing high energy charged particles and line of sight neutrals
- Modules to be built in industry
- Final assembly and tests at Fermilab
- Coil module design is well advanced
- Prototype module under preparation for testing at Fermilab

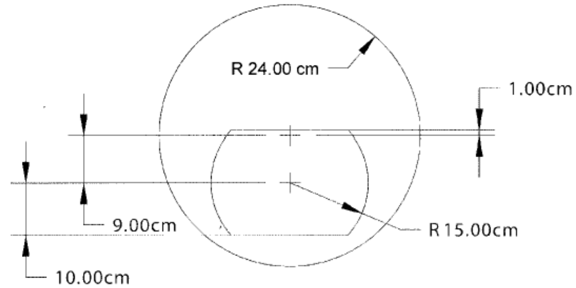


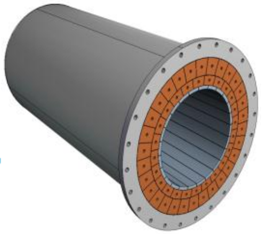
Transport Solenoid Module Prototype

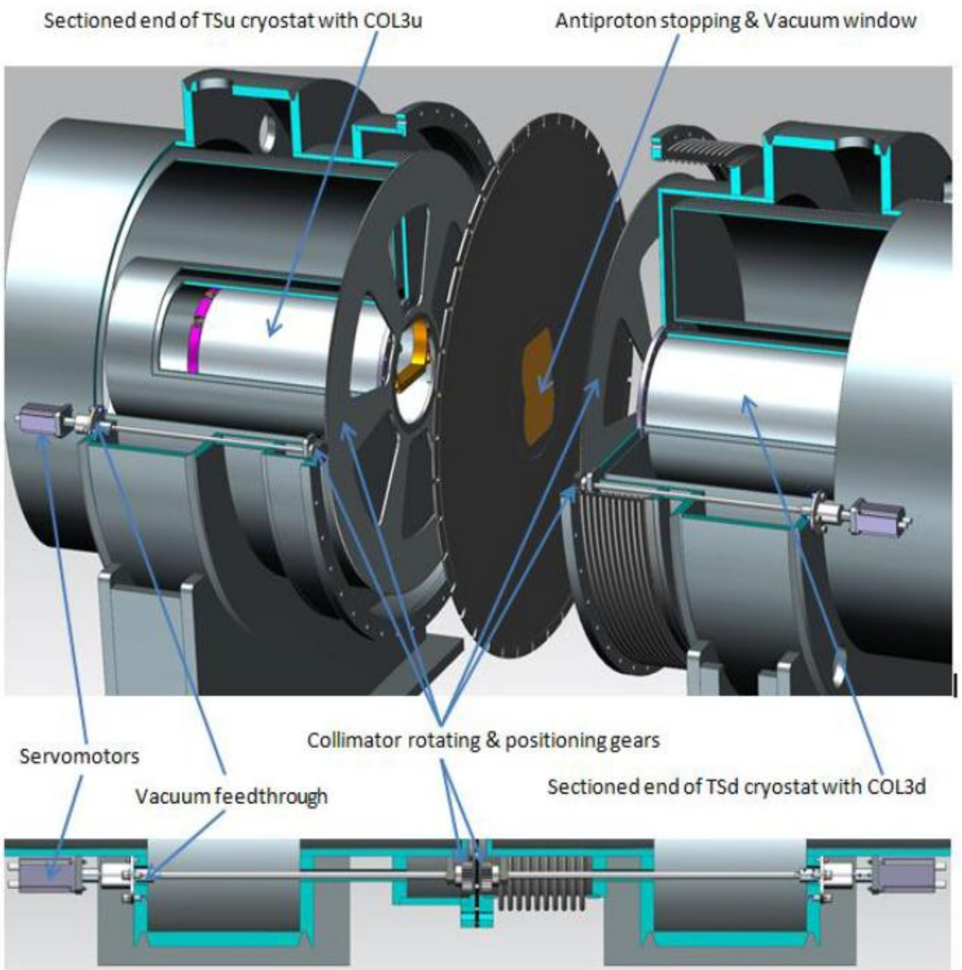
Muon Beamline Collimators



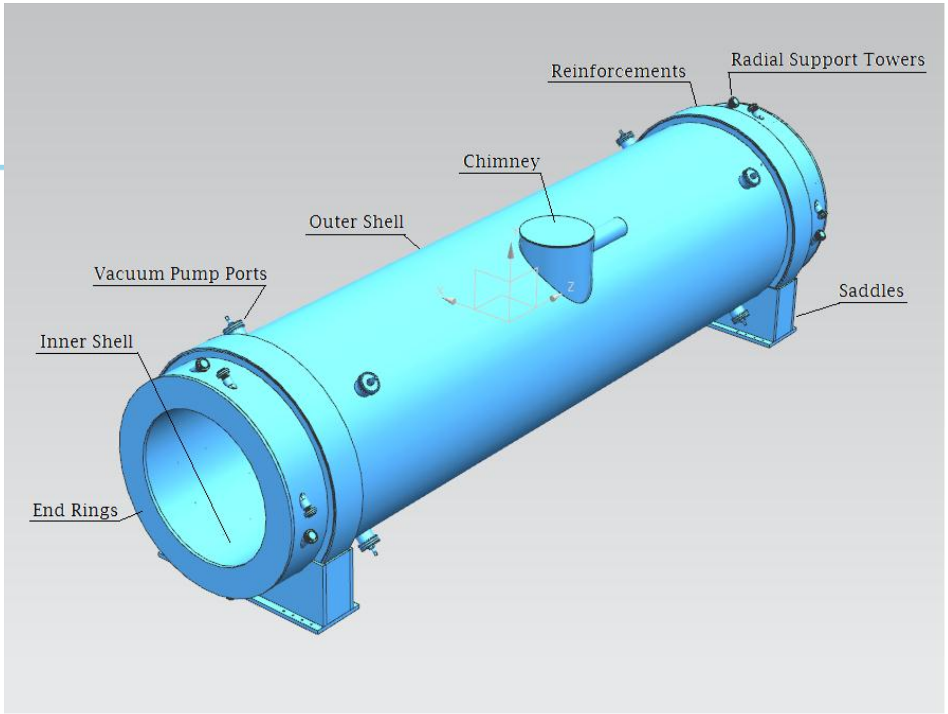
- COL 1, COL3u and COL3d are (primarily) copper
- COL 5 is polyethylene
- COL3u and COL3d have an offset aperture to provide the appropriate sign selection
  - can be rotated to select positive charge for calibration purposes
- Antiproton window also isolates upstream from downstream vacuum space







Detector Solenoid

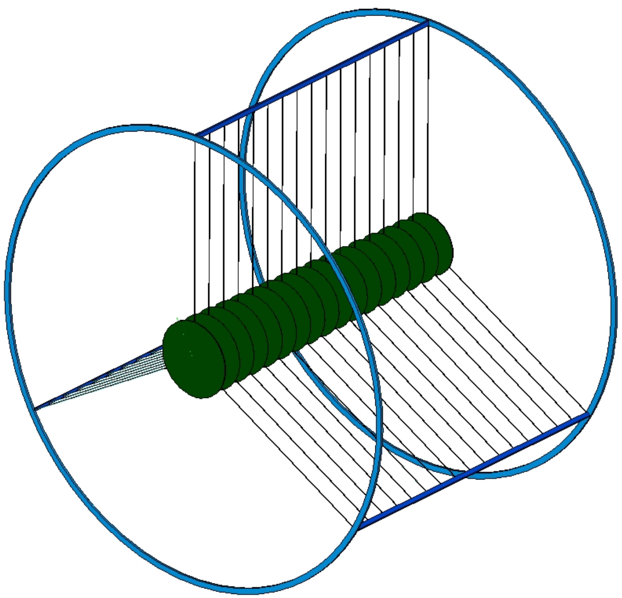


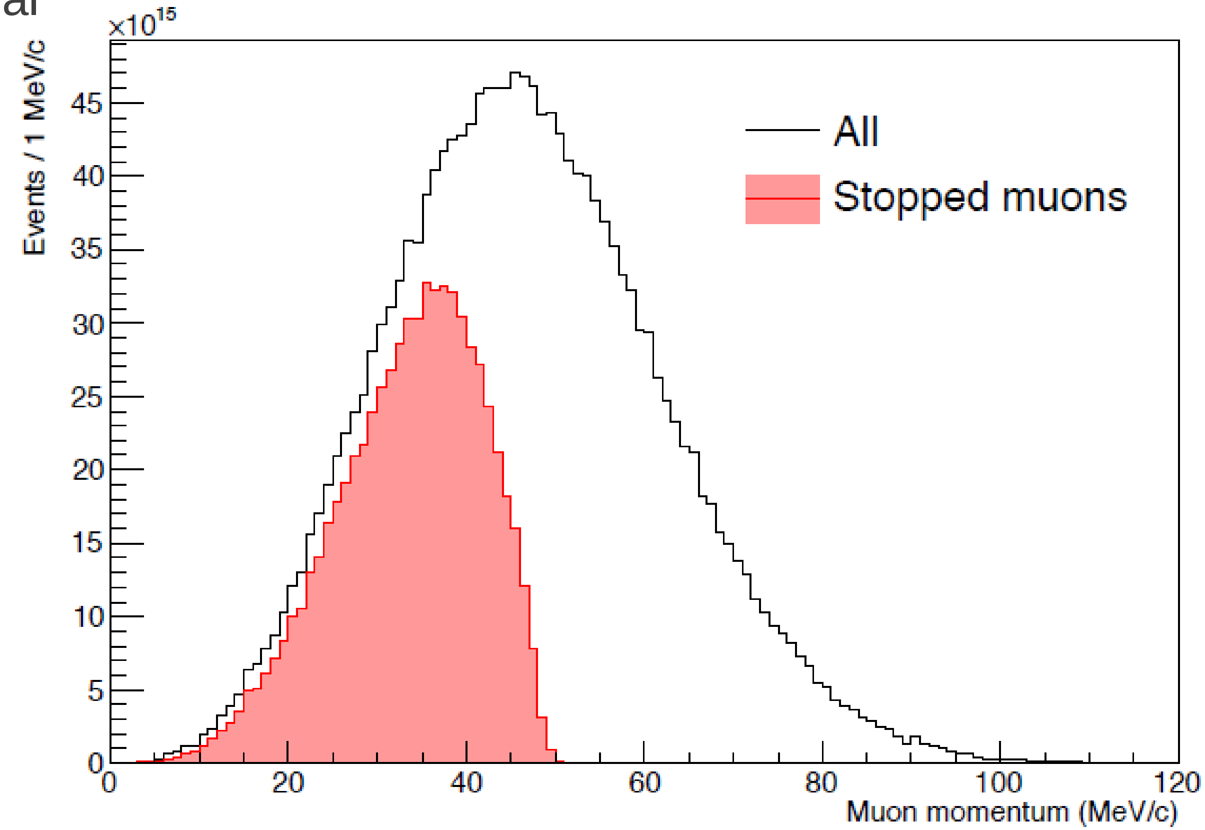
- Upstream portion of field designed transition from 2 T to 1 T
- Spectrometer section of the field designed to be nearly uniform at 1 T
- 11 superconducting coils supported on aluminum support shells
- 1.9 m diameter warm bore
- 10.9 m long cryostat

- Reference design for the Detector Solenoid has been produced
  - Fabrication technology similar to Production Solenoid
- The Detector Solenoid will be fabricated in industry
  - Contract for final engineering design signed last week

Muon Stopping Target

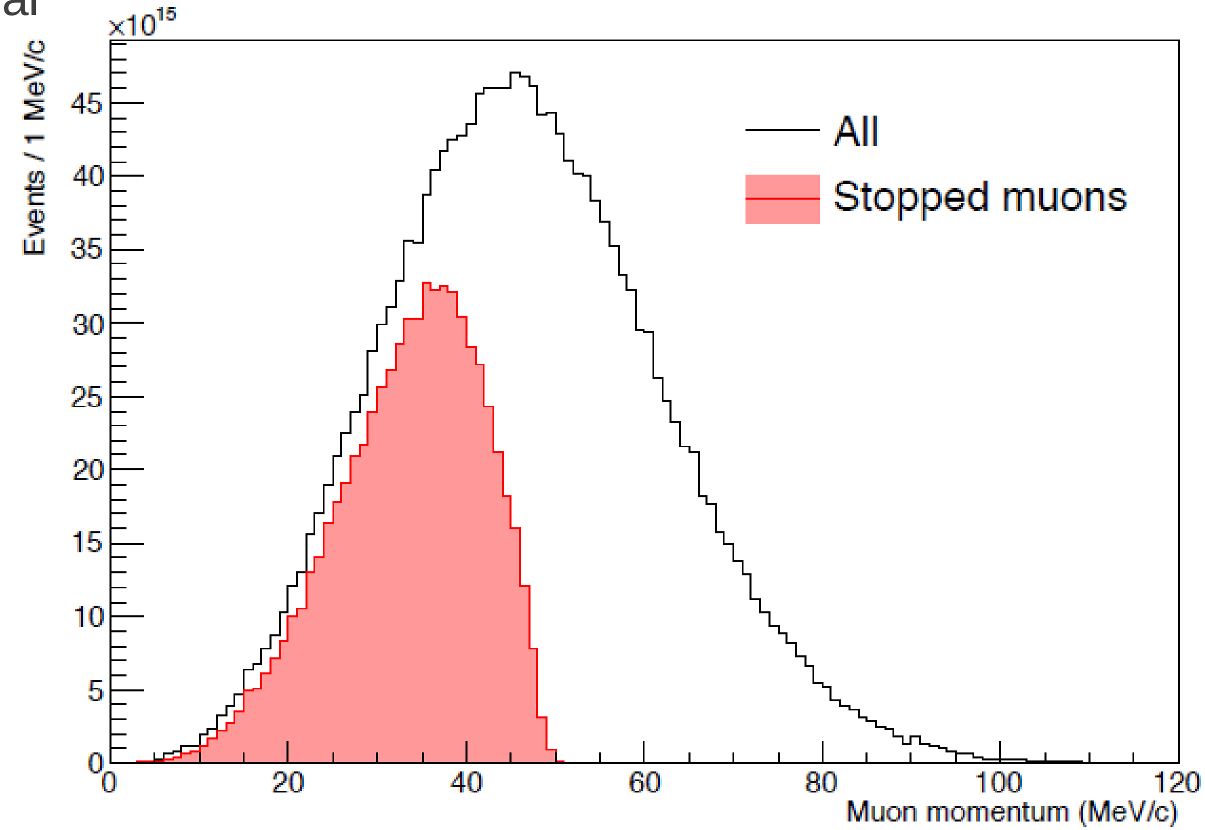
- Seventeen 200μm thick aluminum sheets individually supported via 3 mil (76 μm) diameter tungsten wires supported on an external frame at 5 cm spacing along the axis of the Detector Solenoid
- Target geometry a result of optimization of muon stopping power versus potential energy degradation of signal





Muon Stopping Target

- Seventeen 200μm thick aluminum sheets individually supported via 3 mil (76 μm) diameter tungsten wires supported on an external frame at 5 cm spacing along the axis of the Detector Solenoid
- Target geometry a result of optimization of muon stopping power versus potential energy degradation of signal

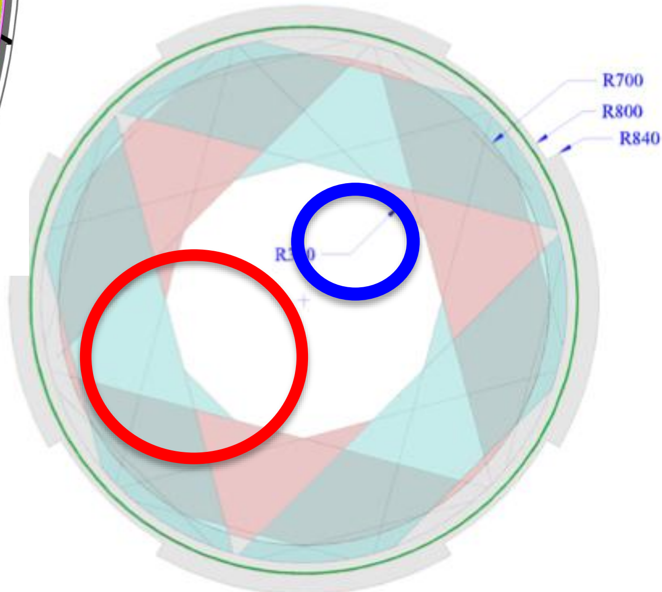


Mu2e Tracker

- Low mass straw tracker instruments the large radius region of Detector Solenoid warm bore and allow passage of low momentum backgrounds through uninstrumented central region

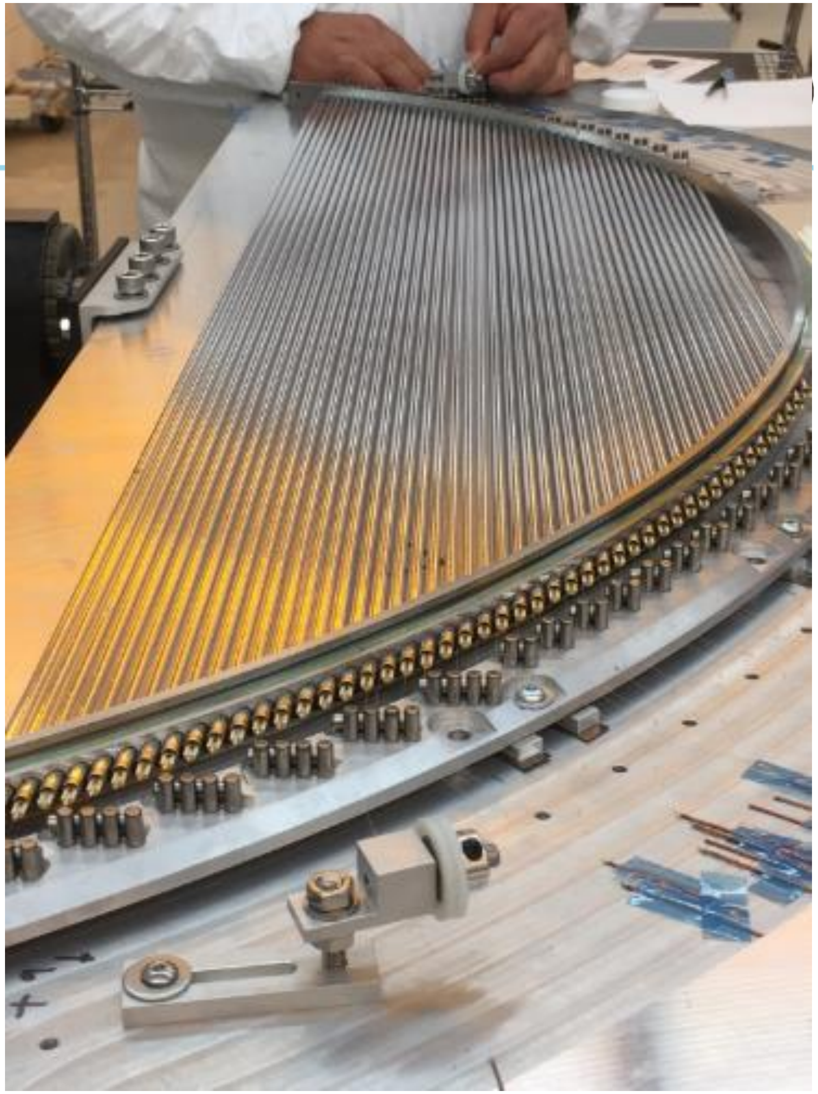
Total tracker length ~3 m

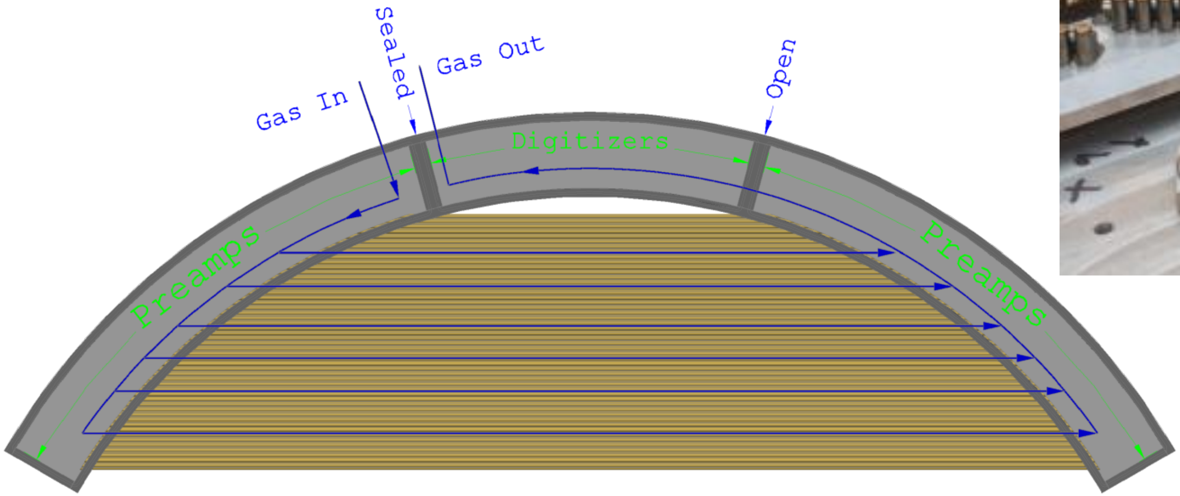
- 5 mm diameter 15 µm thick metalized Mylar straws
- 25 µm gold plated tungsten sense wires
- 96 straw per panel
- Six panels per station
- 18 to 20 stations and >20k straws total
- 80/20 Ar CO_2 gas



Tracker Panel

- Mechanically and electrically independent, but requires stiffening to remain flat
- Sensitive region from ~40cm to ~70cm in radius (transverse to the Detector Solenoid bore and aligned with the axis of that bore)

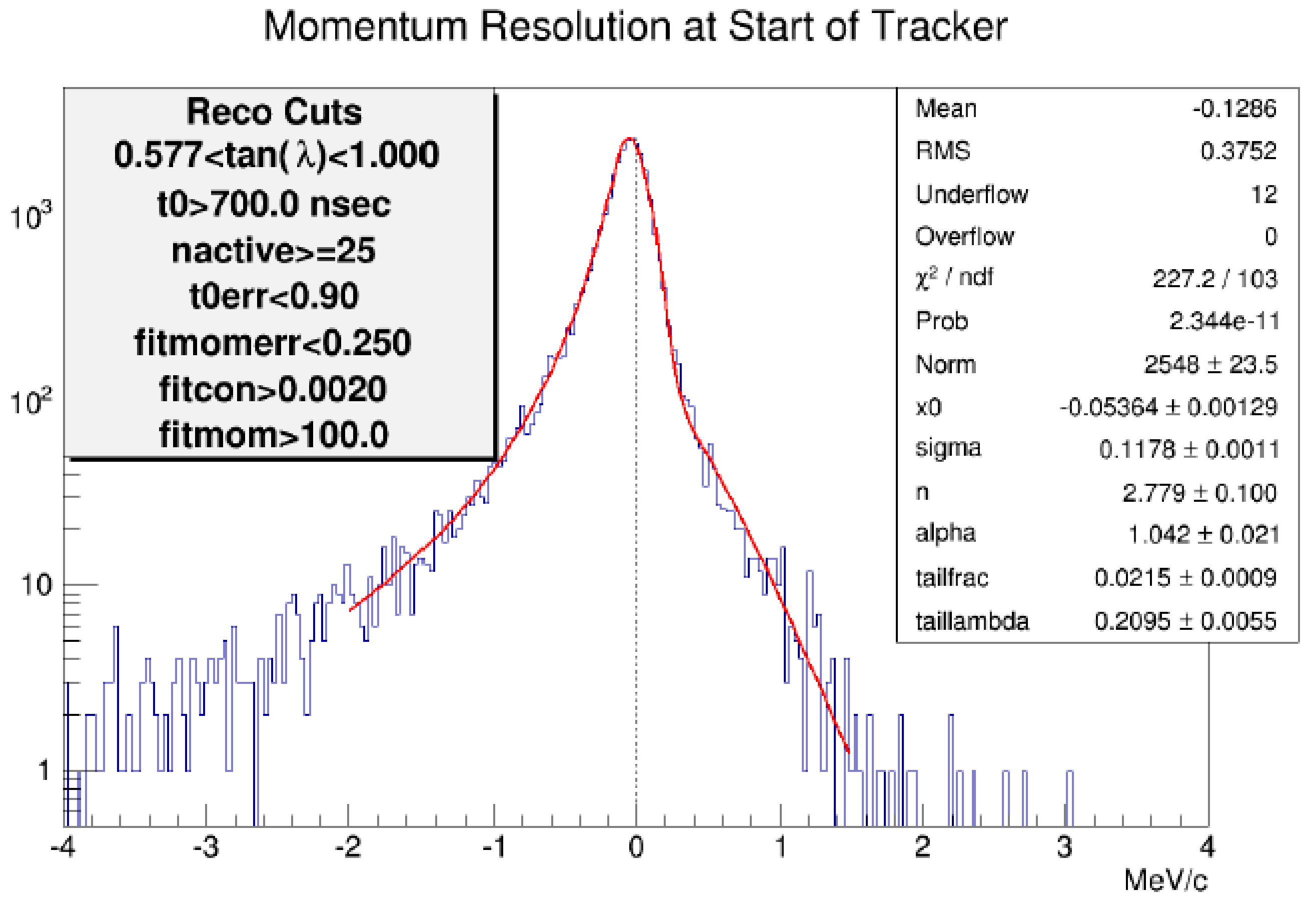




Momentum Resolution of Tracker

- Intrinsic resolution of the tracker for conversion electron candidates is estimated to have a core width of 118 keV/c

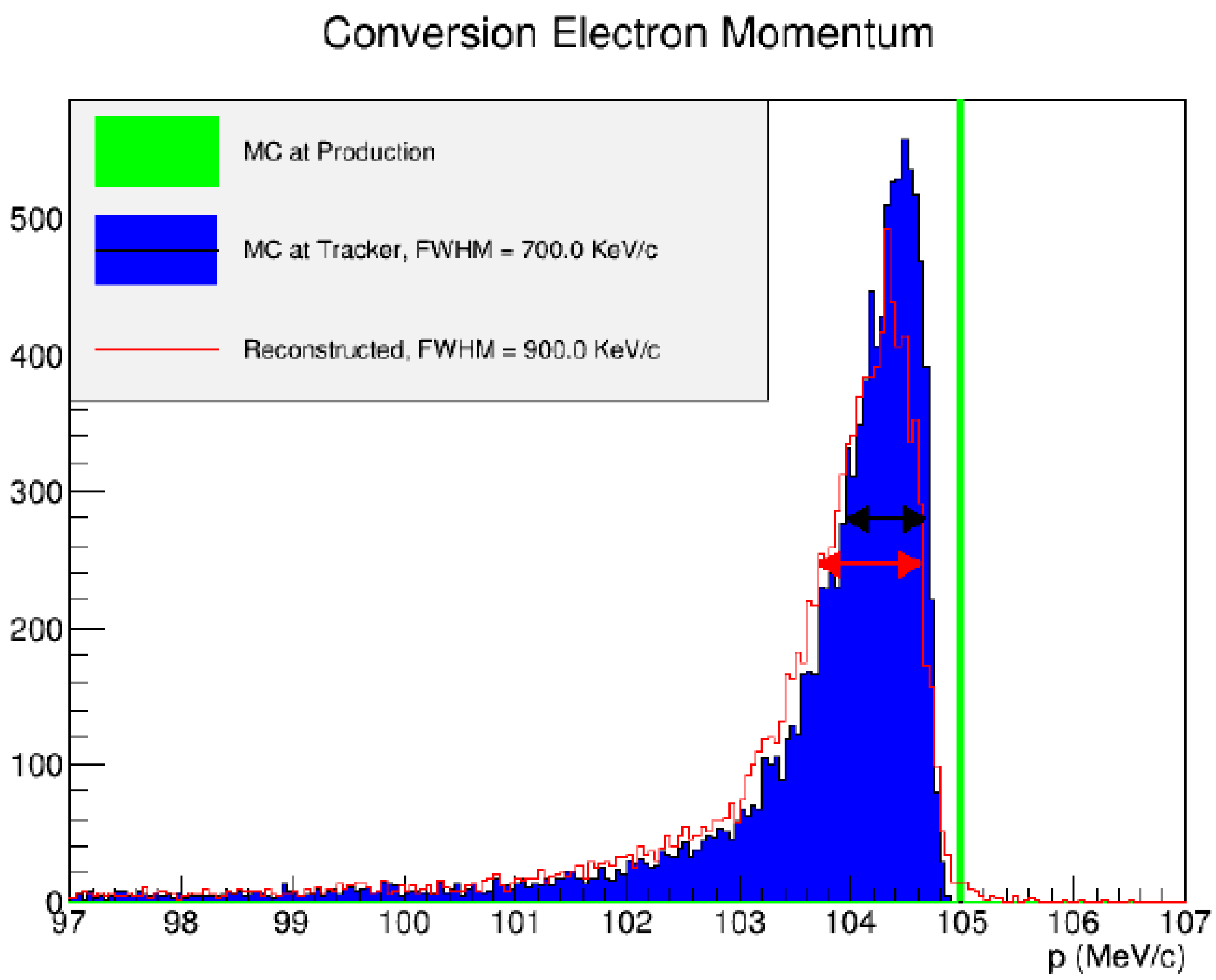
- Acceptance x efficiency for conversion electrons using this version of track definition is 0.093



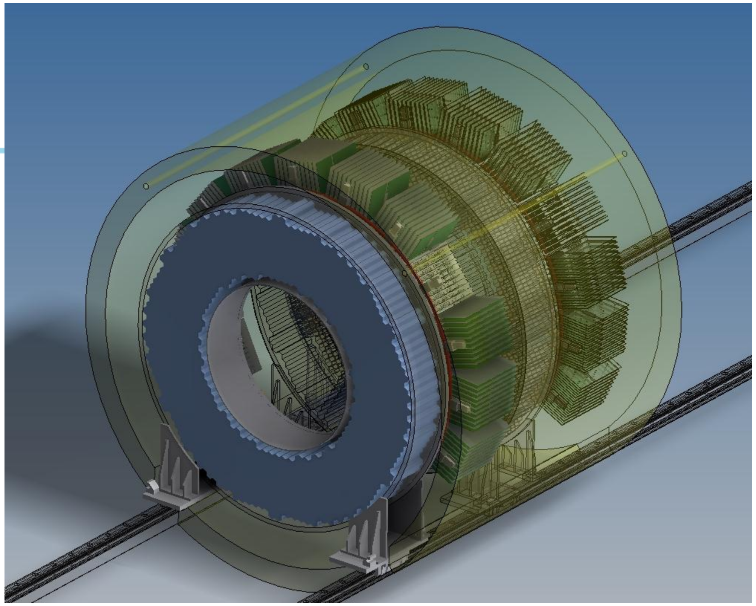
Energy Loss and Multiple Scattering

- Material upstream of the tracker results in energy loss and multiple scattering, shifting and smearing the signal

- Largest effect is stopping target material
- Residual gas in the detector solenoid at 10^{-4} torr has negligible impact



Mu2e Calorimeter



- Provides additional background rejection
  - Complementing the tracker and confirming pattern recognition
- Requires good timing and energy resolution
  - <1 ns timing resolution
  - 5% energy resolution at 100MeV
  - Position resolution better than 1 cm
- Calorimeter is also expected to provide a trigger
- Crystal calorimeter (~2000 crystals total)
- Two arrays arranged to provide coverage for high momentum particles
  - Each crystal instrumented with two photo sensors
  - Inner radius of each array is 36 cm
  - Baseline design uses Barium Fluoride with solar blind APD
- Studies and characterization of prototype crystals, beam tests and evaluation of options ongoing

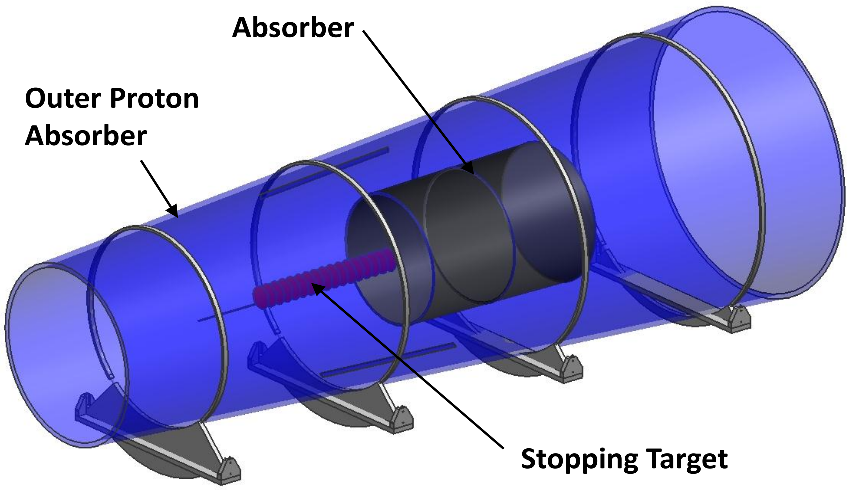
Mu2e Calorimeter

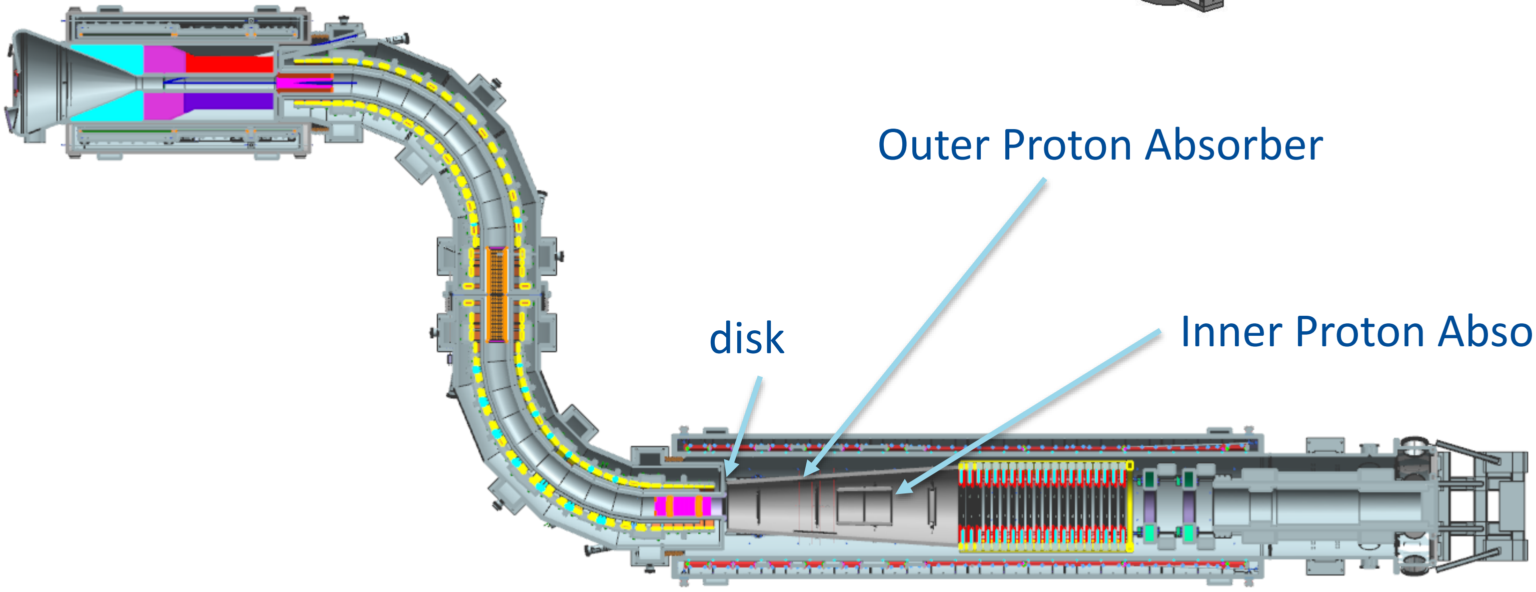
- Radiation hard and non hydroscopic

	BaF_2
Density (g/cm3)	4.89
Radiation length (cm)	2.03
Moliere Radius (cm)	3.10
Interaction length (cm)	30.7
dE/dX (MeV/cm)	6.52
Refractive index	1.50
Peak luminescence (nm)	220 (300)
Decay time (ns)	1 (650)
Light yield (rel. to NaI)	5% (42%)
Variation with temperature	0.1% (-1.9)% / deg-C

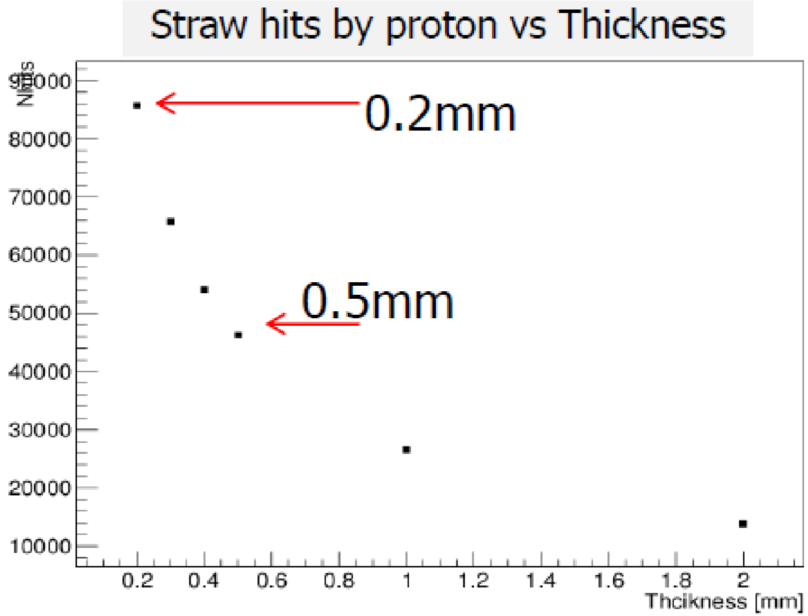
Detector Solenoid Internal Shielding to Reduce Rates in the Detectors

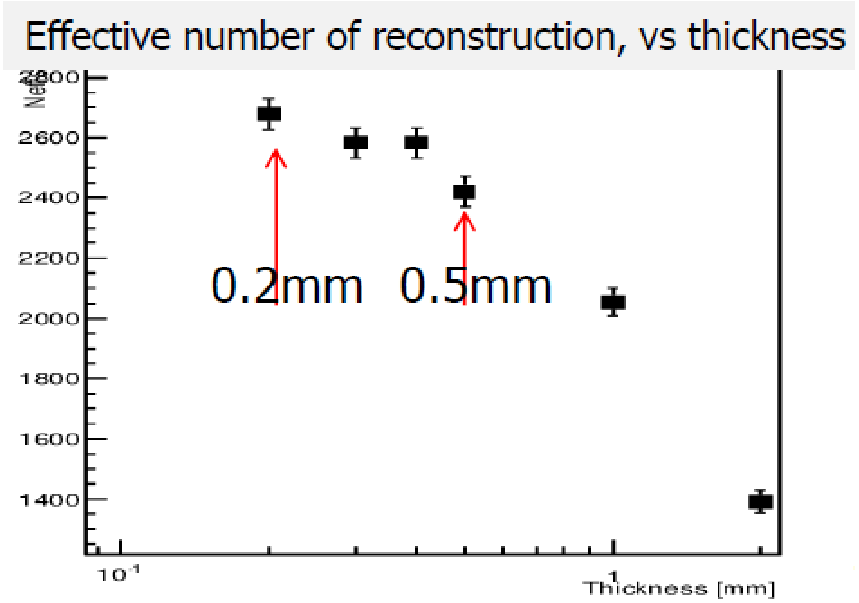
- 0.5 mm thick polyethylene covering the downstream end of the TSd cryostat vacuum jacket (with central hole on beam axis)
  - 30% rate reduction with ~0.2% impact on conversion electron acceptance
- Inner Proton Absorber
  - 0.5 mm thick polyethylene
- Outer Proton Absorber
  - 20 mm thick polyethylene





Inner Proton Absorber Optimization

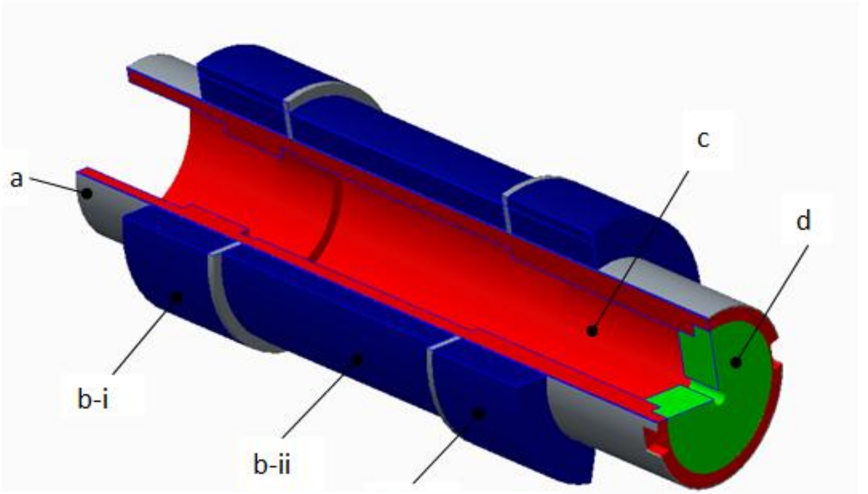


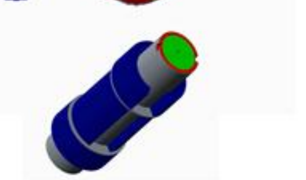


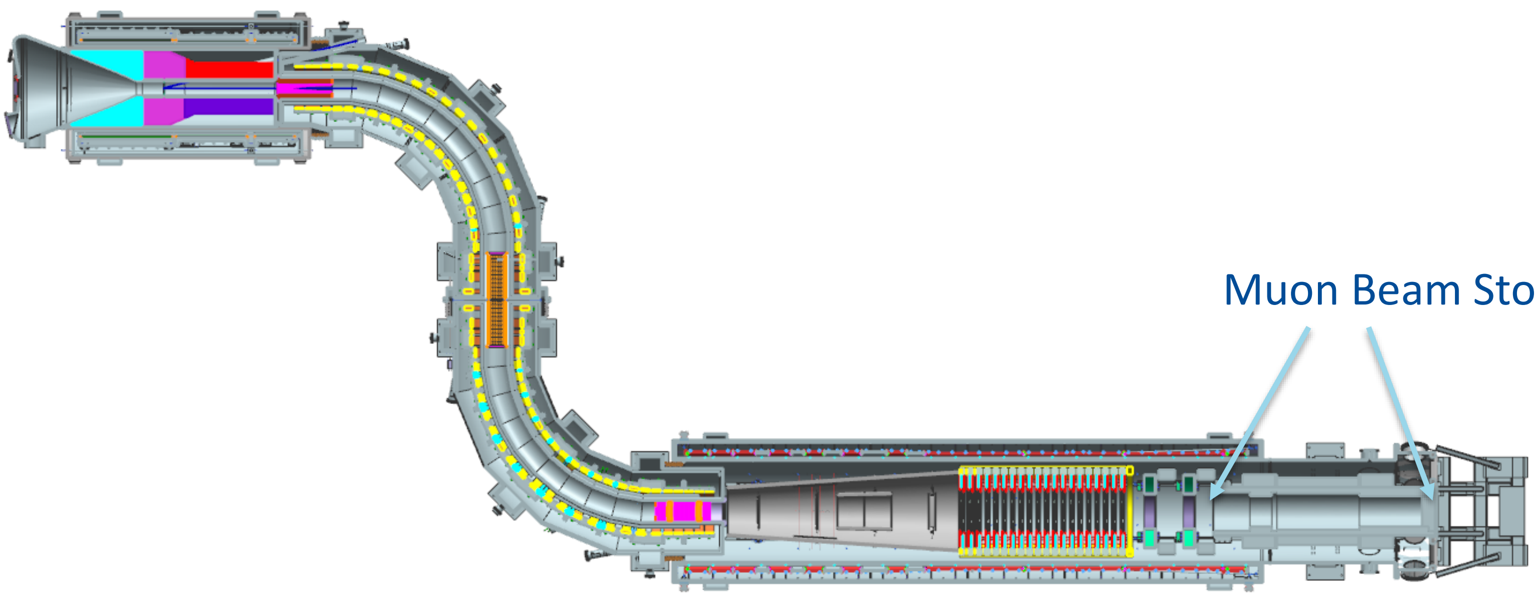
- Number of tracker hits due to protons as a function of the thickness of the inner proton absorber
- Number of reconstructed conversion electrons as a function of the thickness of the inner proton absorber

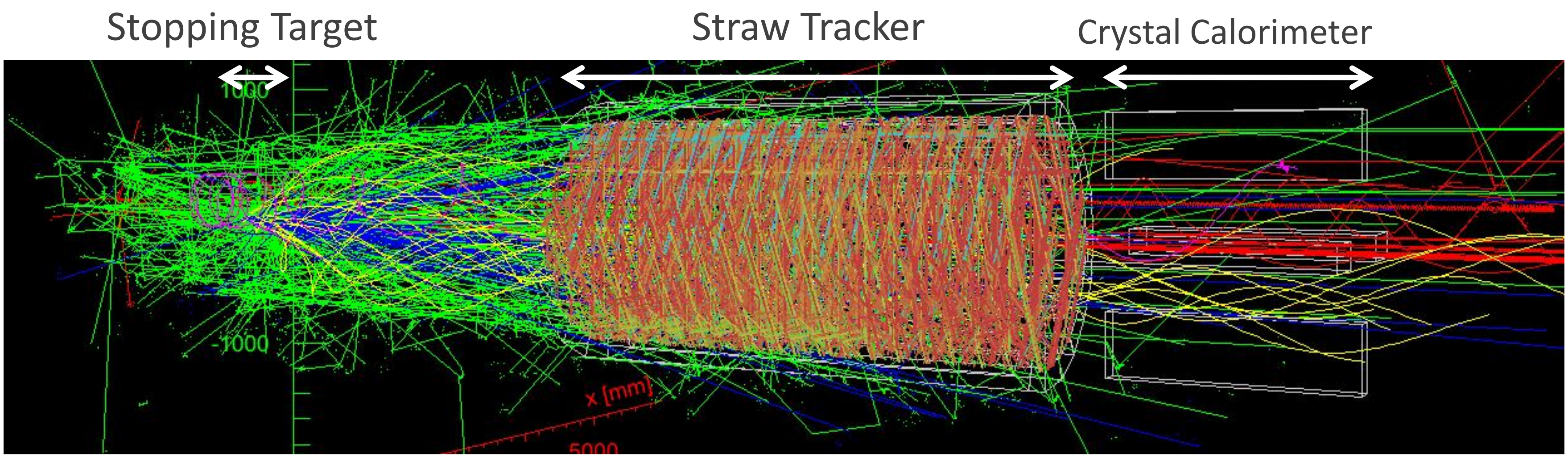
Muon Beam Stop

- Designed to absorb the beam that does not stop in the target, while minimizing the rates on the nearby detectors
- Stainless steel tube supporting polyethylene both inside and outside
- Hole through the downstream end for line of sight to the muon stopping target monitor

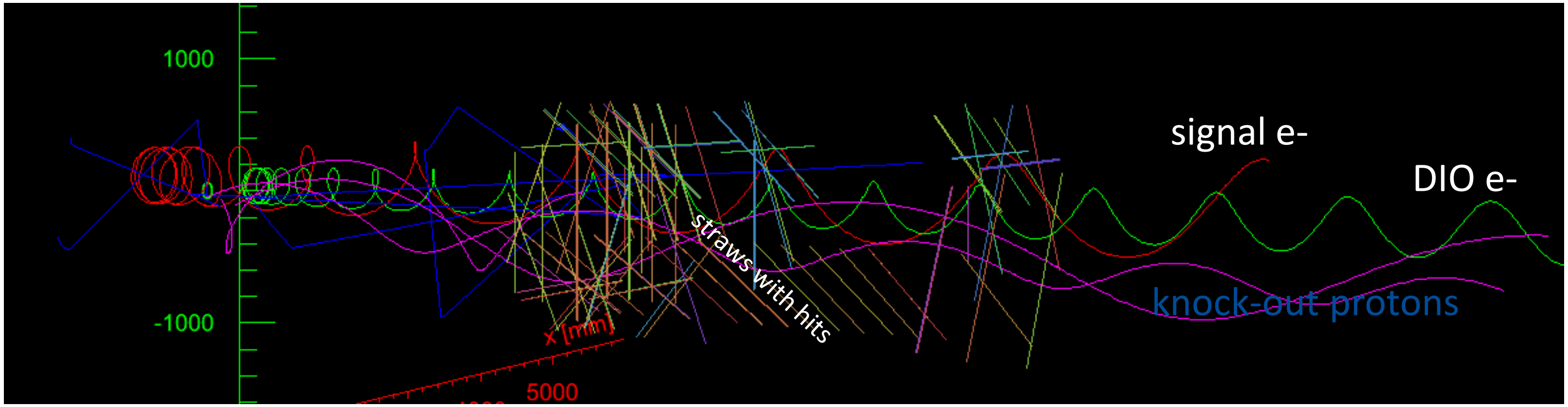








- A signal electron buried amongst the other simulated activity from a single live beam window



particles with hits within +/-50 ns of signal electron t_{mean}

Sources of Backgrounds

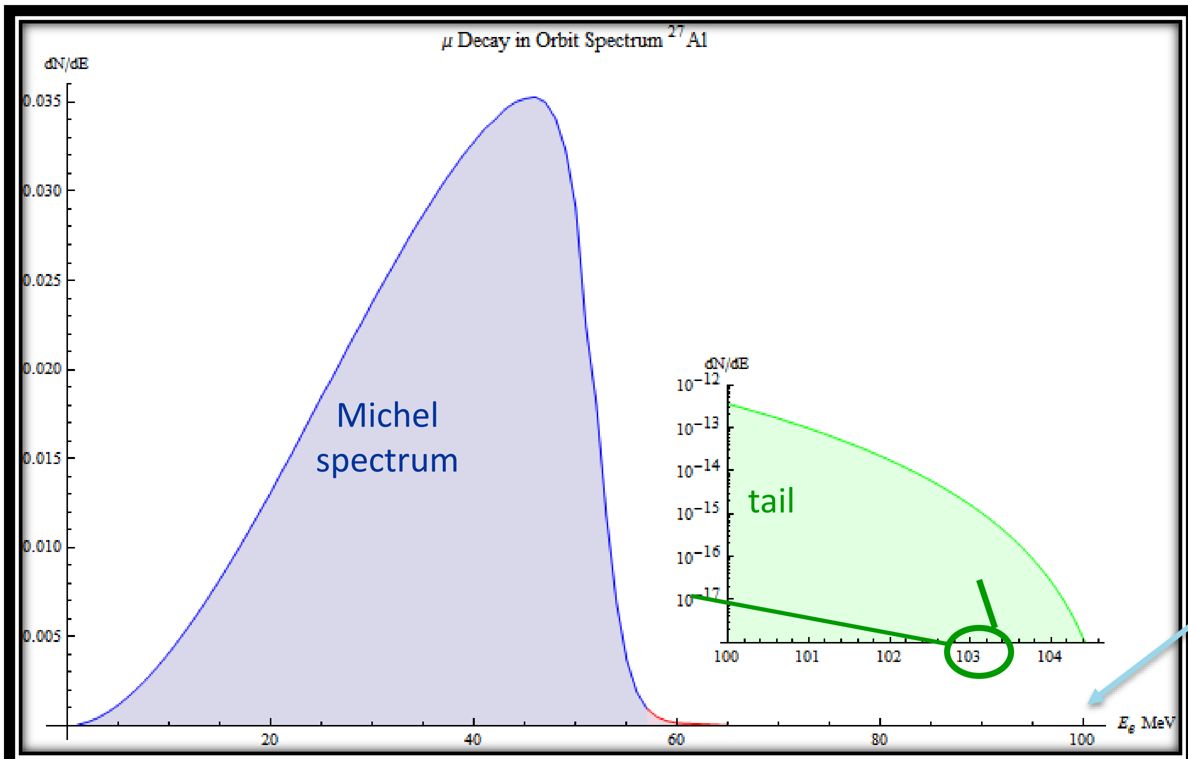
- Intrinsic sources
  - Scale with the number of stopped muons
    - μ decay in orbit (DIO)
    - Radiative muon capture $\mu^- Al \rightarrow \gamma \nu Mg$
      - γ conversion has potential to yield background electron
      - the endpoint is 101.9 MeV on aluminum
- Late arriving sources
  - Scale with the number of late incident protons
- Other sources
  - Antiprotons
  - Cosmic-rays

Decay in Orbit

- In aluminum, 39% of the stopped muons will decay in orbit

$$\mu^{-} N \rightarrow e^{-} \nu_{\mu} \nu_{e} N$$

- The resulting electron spectrum has a tiny tail out to 104.97 MeV
- Sensitivity to this tail is suppressed by minimizing material in the path of and via the excellent resolution of the low mass tracking detector

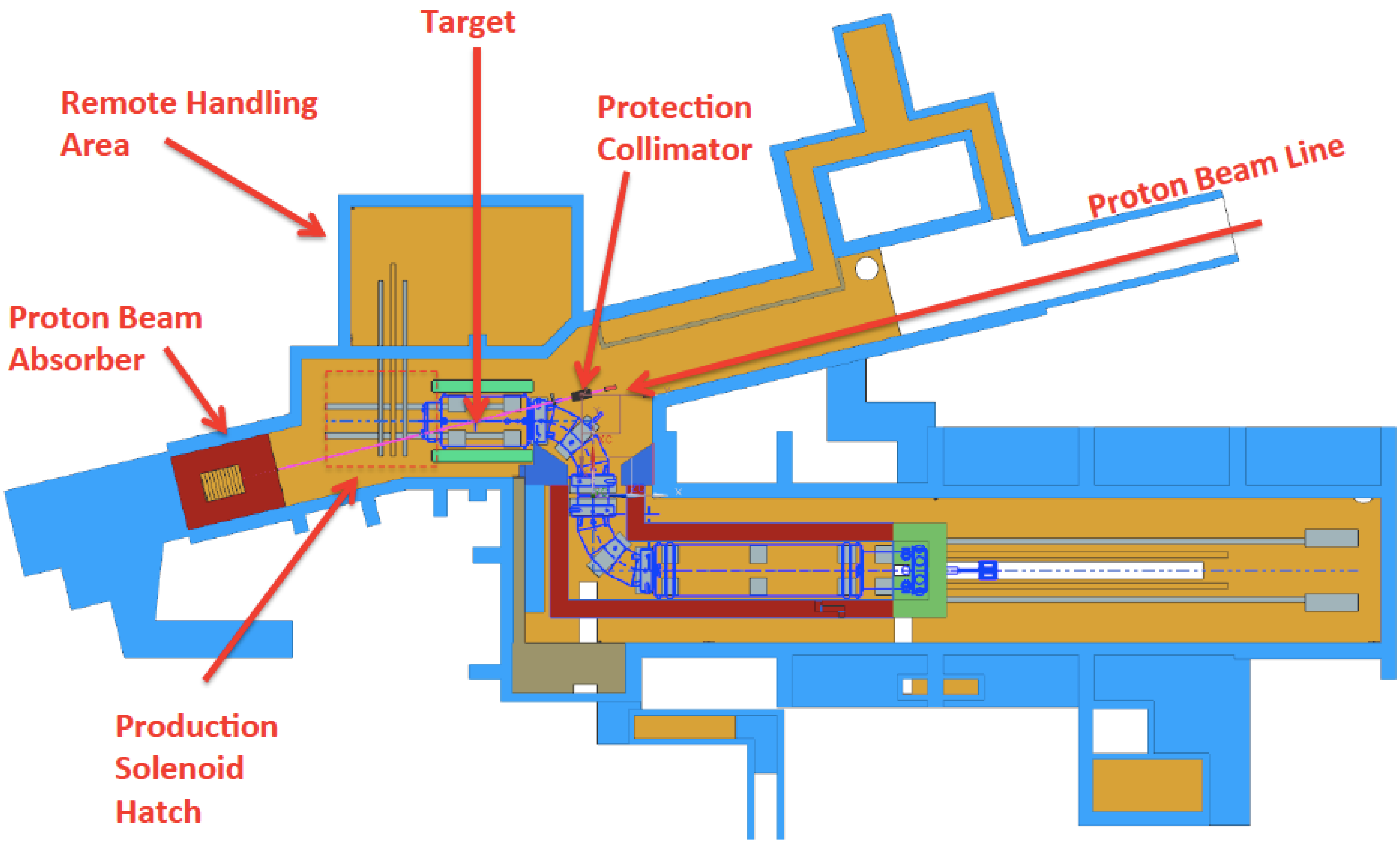


Electron energy in MeV

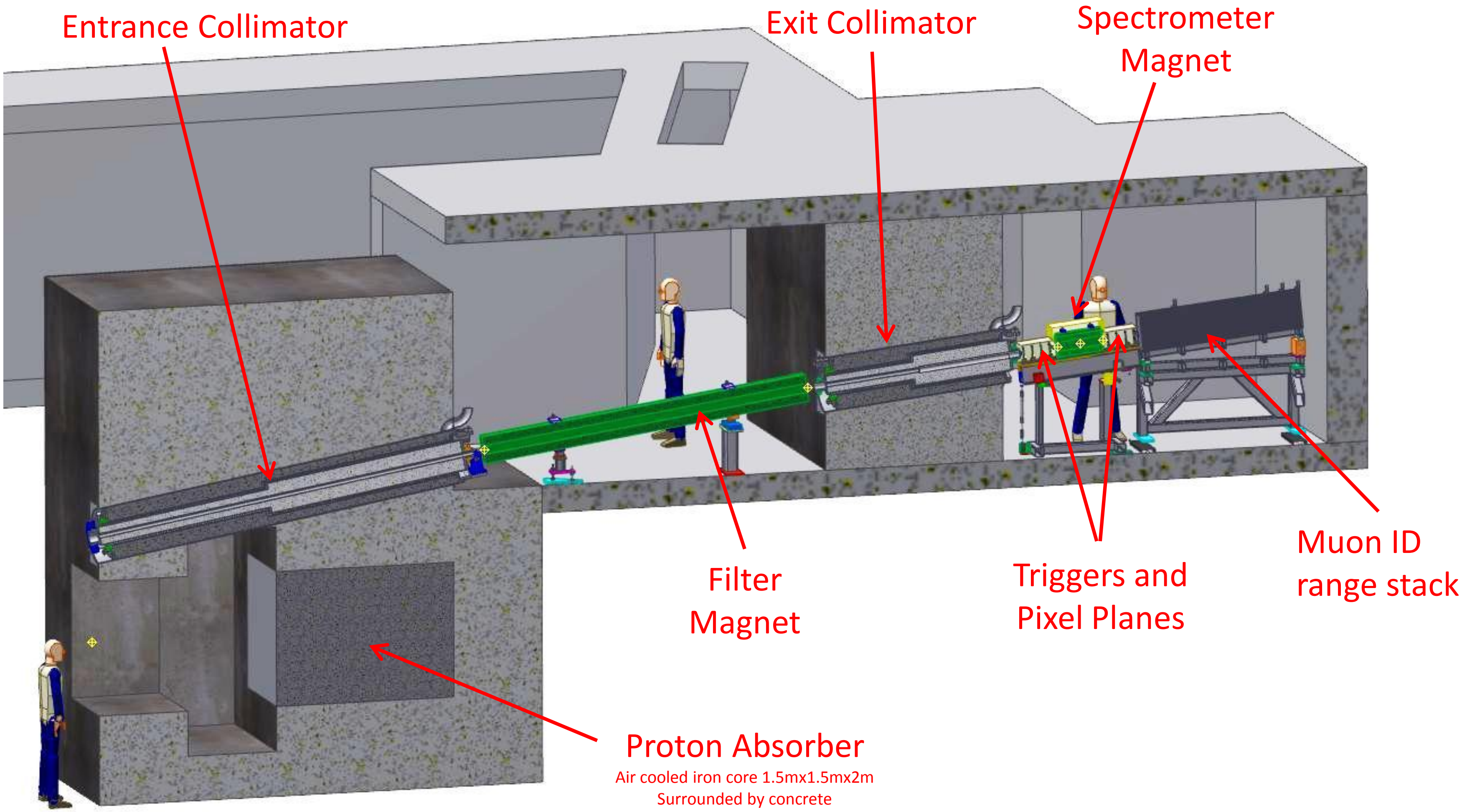
Suppressing Backgrounds

- Backgrounds from residue initially generated by interactions at the production target
  - The overwhelming majority of these backgrounds arrive promptly
    - Suppressed by adopting the delayed live window which opens about 700 ns after the arrival of the proton pulse
  - Late arriving particles must also be suppressed
    - Solenoid design avoids particle traps that would otherwise serve as a source of late arriving particles
- Also need to suppress out-of-time incident protons, which could otherwise generate backgrounds in the signal window
  - Addressed via the extinction system
    - RF structure of the proton beam combined with the fast AC dipole designed to suppress the total out of time protons relative to the in time protons at least 10 orders of magnitude
  - Monitored via dedicated detector downstream of the primary target

Plan View of Mu2e Layout



Proton Absorber and Extinction Monitoring



L. Bartoszek docdb 3949

- Elevation view through the proton absorber and the extinction monitor region

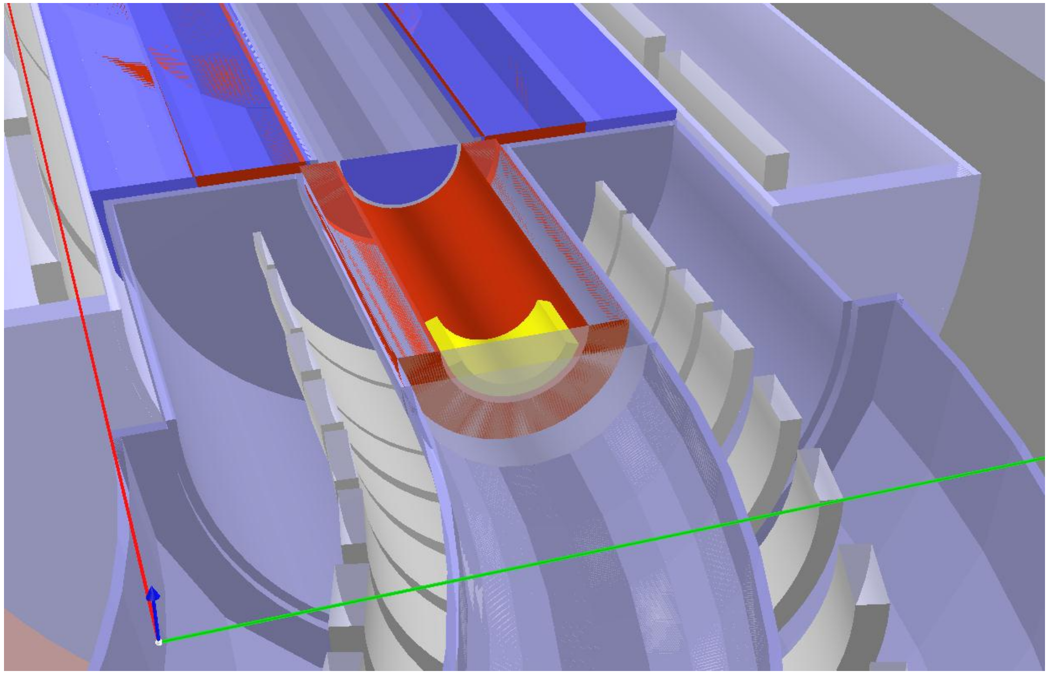
Late Arriving Backgrounds

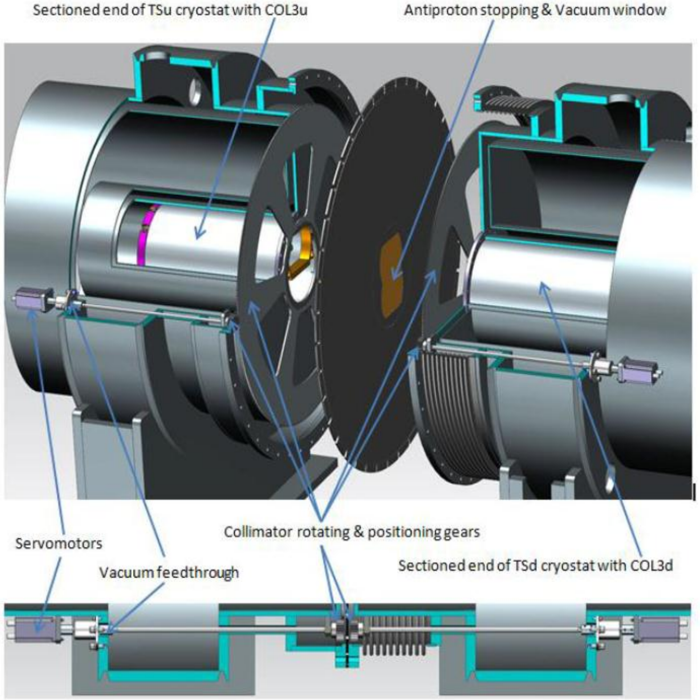
- Contributions from
  - Radiative π Capture
    - $\pi^- N_Z \rightarrow N^*_{Z-1}\ \gamma$
    - γ conversion has potential to yield background electron
    - E_γ extends out to ~m_π
    - For Aluminum, the ~ 2% Radiative π Capture fraction
  - μ and π decay in flight
  - Beam electrons
    - Originating from upstream π^- and π^0 decays
    - Electrons scatter in stopping target to get into detector acceptance

- Taken together these backgrounds from late arriving particles are estimated to account for <10% of the total background and scale *linearly* with the number of out-of-time protons

Another potentially important source of backgrounds --- Antiprotons

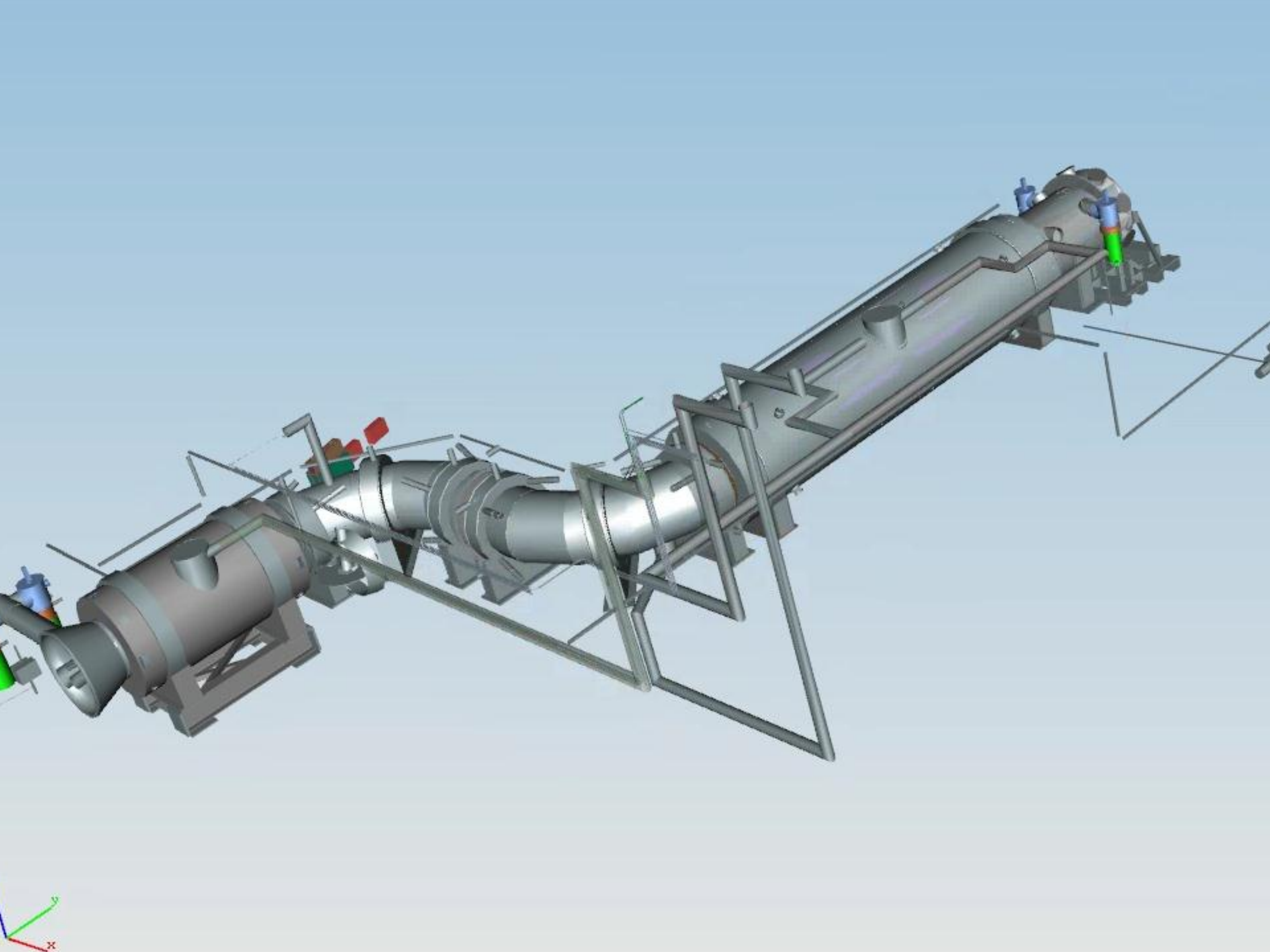
- Incident proton beam energy is above the pbar production threshold
- Since such pbars are low momentum, they have the potential to generate false signals within the live window of the experiment
- Antiproton transmission is suppressed by insertion of thin windows in the muon beamline and by sculpting the shape of the collimator in the Upstream Transport Solenoid to preferentially suppress pbar transmission





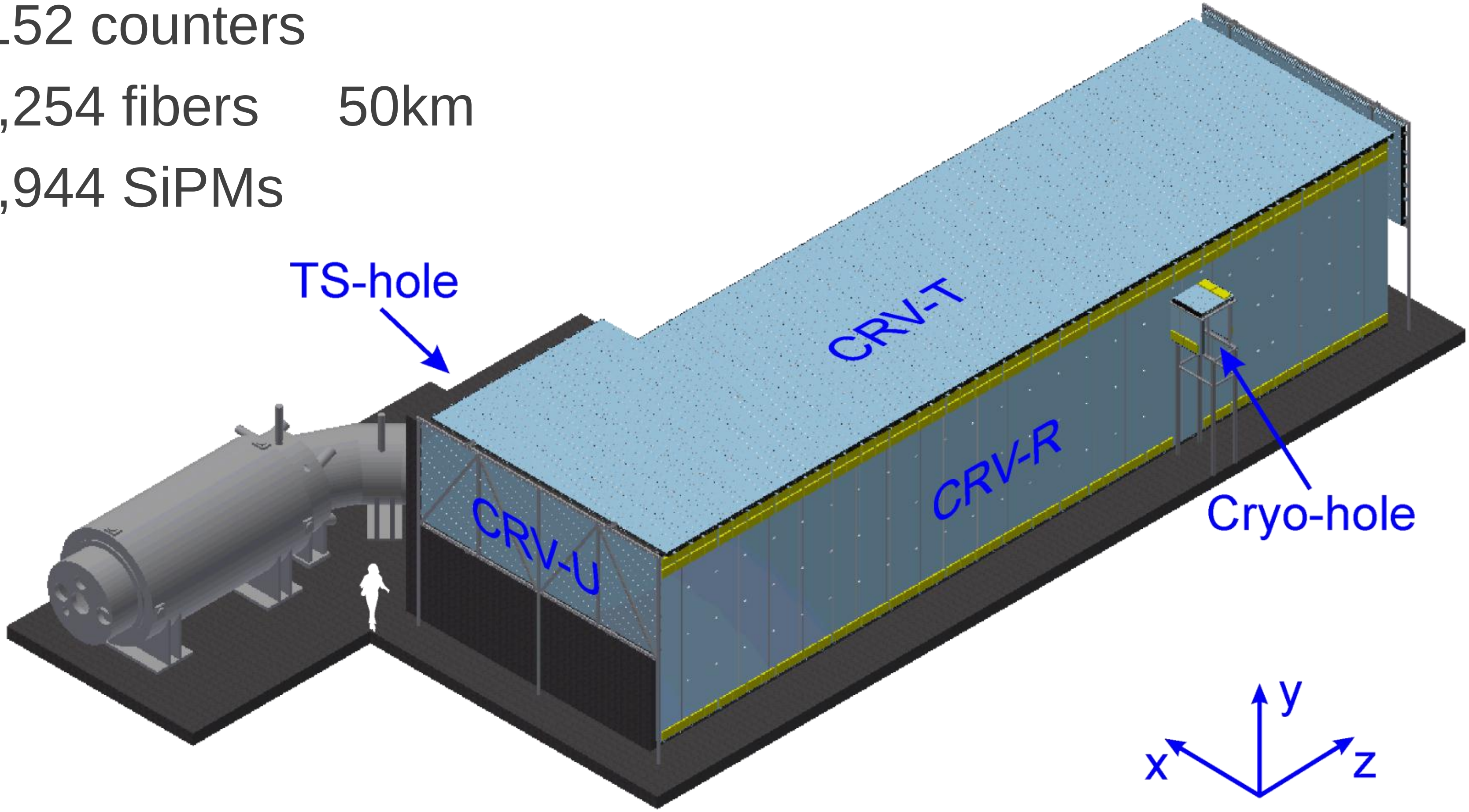
Yet another potentially important source of backgrounds --- Cosmic Rays

- Cosmic rays μ can decay in flight or interact in the apparatus, which could yield an e^- or a ɣ that could mimic the signal
  - Expect ~ 1 conversion-like electron per day from cosmic ray muons
- Cosmic rays suppressed by six foot thick overburden and actively tagged by cosmic ray veto (CRV) system
  - Goal is to limit cosmic rays contribution to background to < 0.1 event
  - CRV configuration and beamline shielding designed to reduce the rate from the beamline into the CRV to a level that will allow >90% livetime
    - Four layers of extruded polystyrene scintillator counters with embedded wavelength shifting fibers
      - Two 1.4 mm diameter WLS fibers per 2 cm thick counter
      - SiPM readout of each end of most fibers
      - Aluminum absorber between counter layers
    - Plan to use the CRV as an offline veto
    - Capable of providing trigger
    - Design for 99.99% efficiency

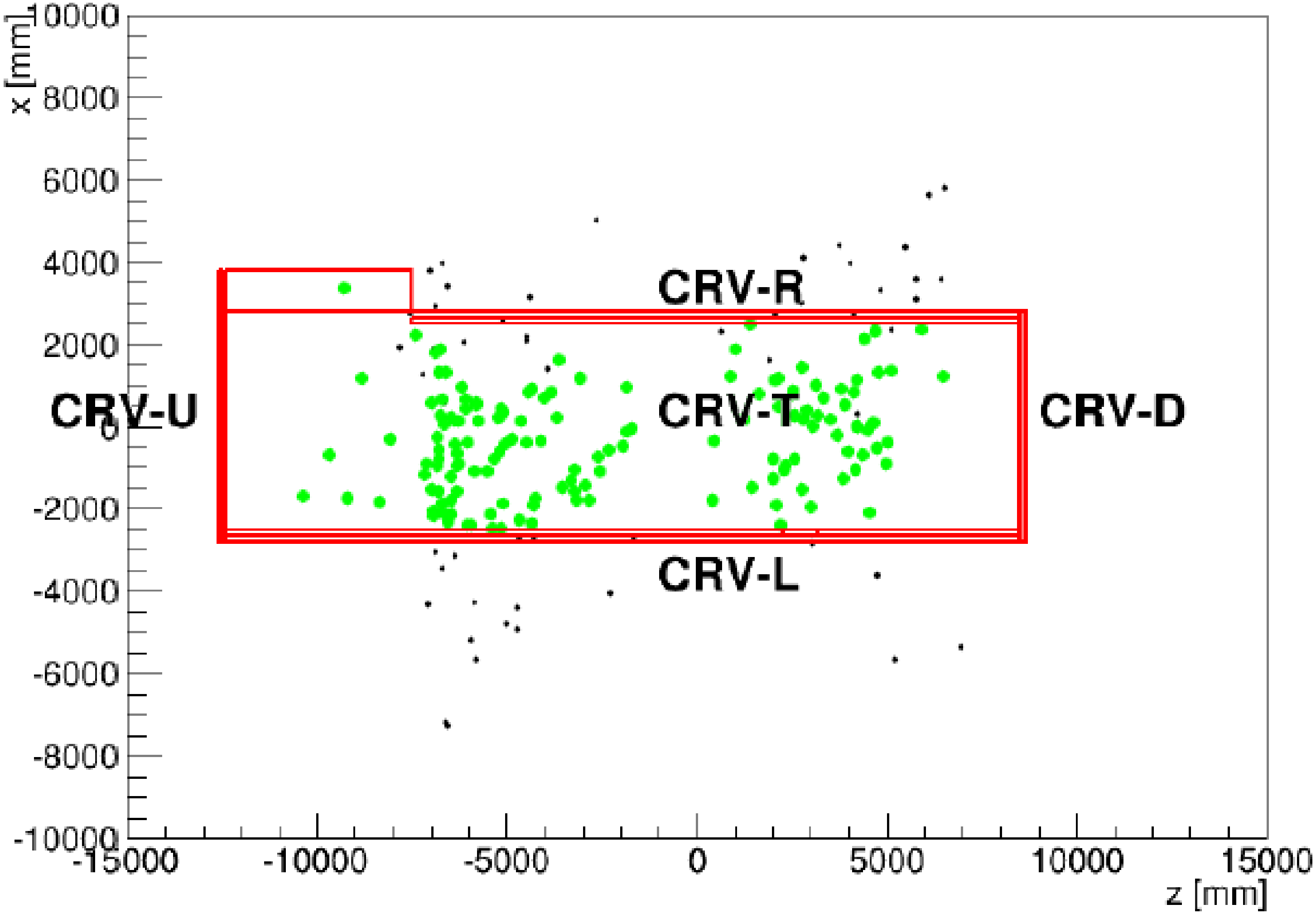


Cosmic Ray Veto (CRV)

- Area: 323 m^2
- 5,152 counters
- 10,254 fibers 50km
- 18,944 SiPMs

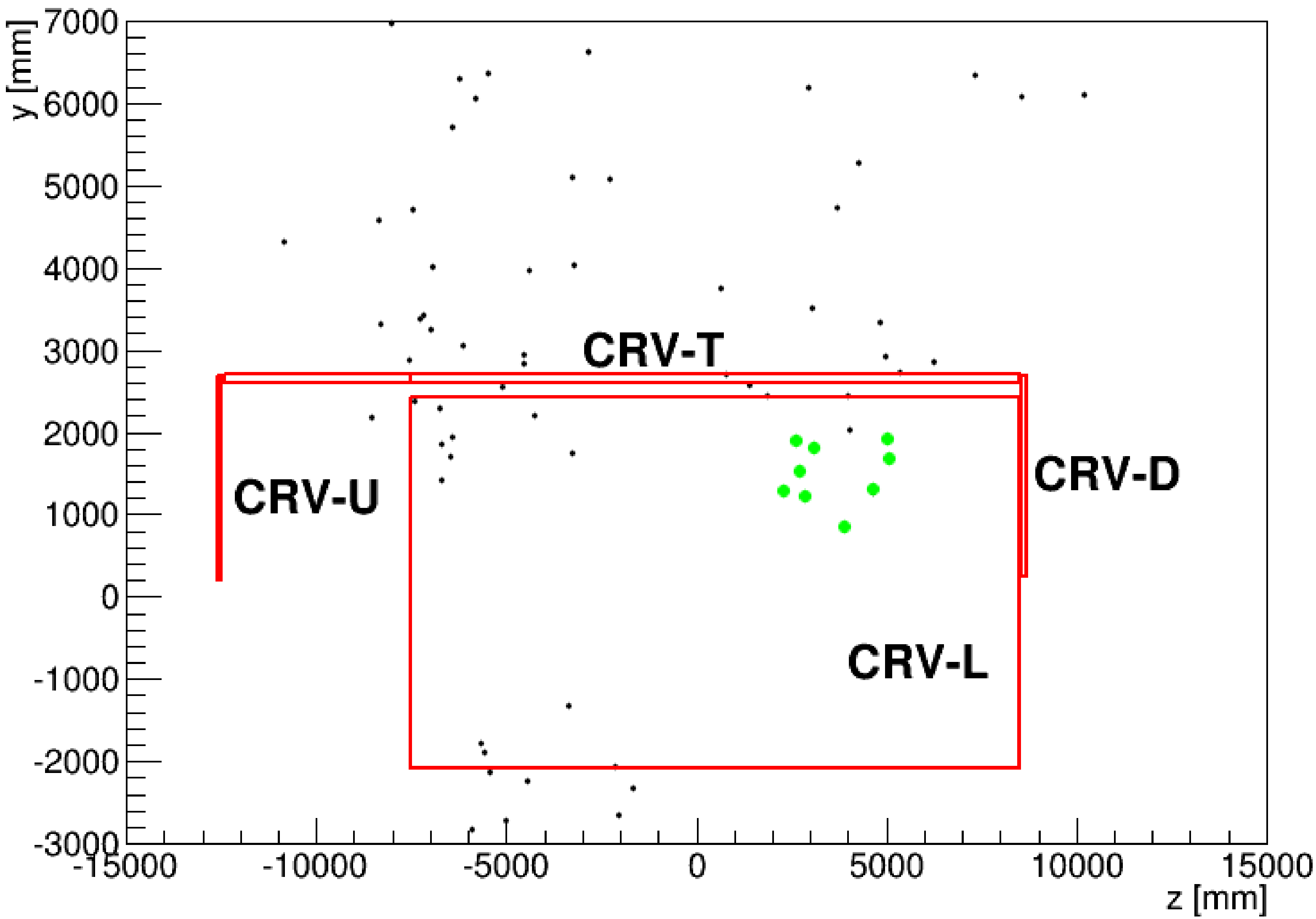


Evaluating CRV Coverage



- CRV coverage evaluated via detailed simulation to identify cosmic rays that produce conversion like background events
- Green points show positions where cosmic rays that generate potential background intersect only CRV-T

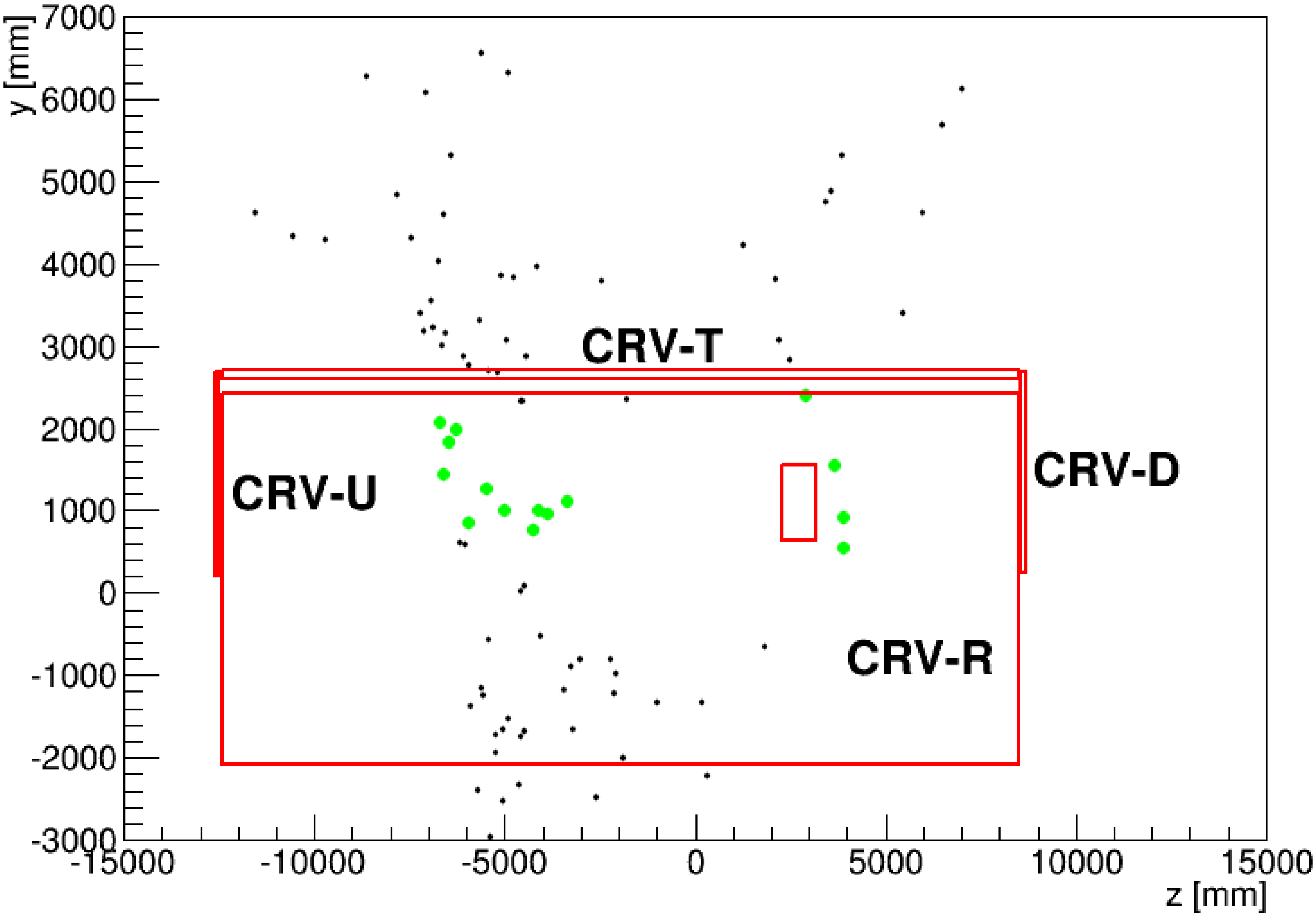
Evaluating CRV Coverage



Combination of general simulations and targeted simulations used to fully evaluate coverage

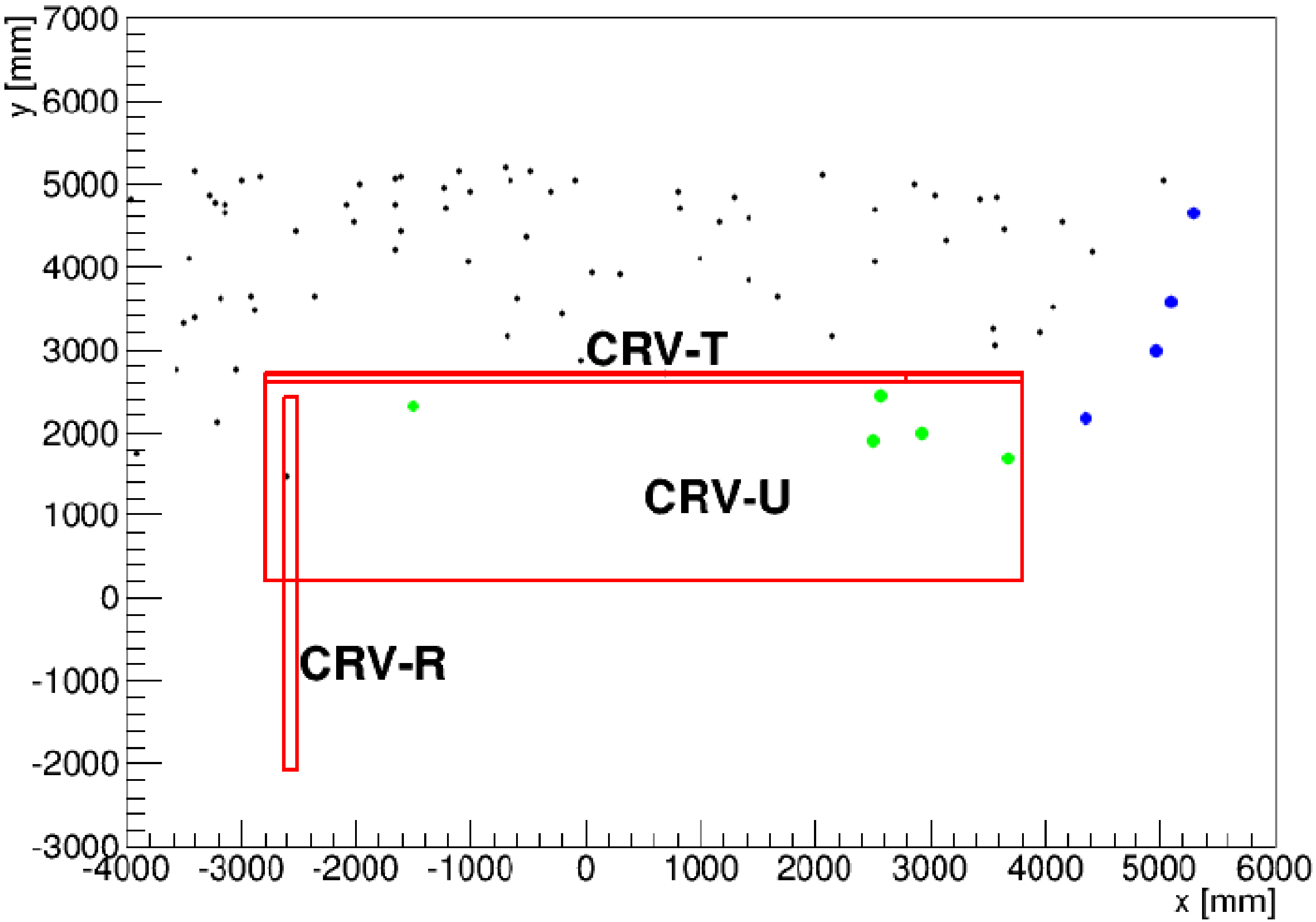
General simulation represents ~2% of anticipated cosmic ray flux, and all candidates would be vetoed by the CRV

Evaluating CRV Coverage



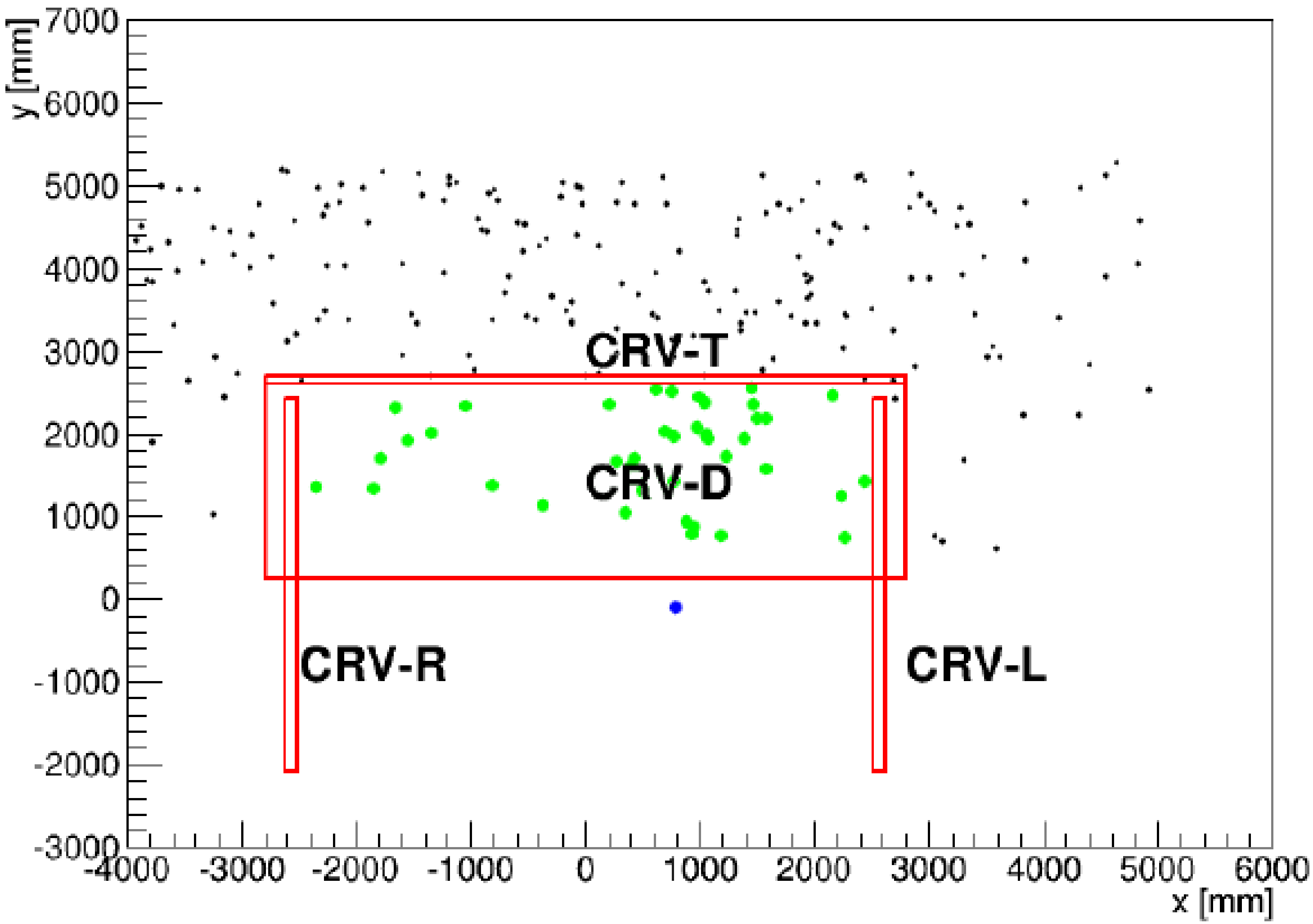
- Targeted simulations represent 100% off the anticipated cosmic ray flux
- Estimate 0.8 cosmic ray induced candidates would escaped detection by the CRV, but would be identified by the calorimeter and tracker particle ID

Evaluating CRV Coverage



- Green points show positions where cosmic rays that generate potential background intersect only CRV-U
- Blue points indicate muons that are not vetoed by any part of the CRV, but are vetoed by particle ID requirements

Evaluating CRV Coverage



- Green points show positions where cosmic rays that generate potential background intersect only CRV-D
- The blue point indicate a muon that is not vetoed by any part of the CRV, but is vetoed by particle ID requirements

Summary of Mu2e Backgrounds

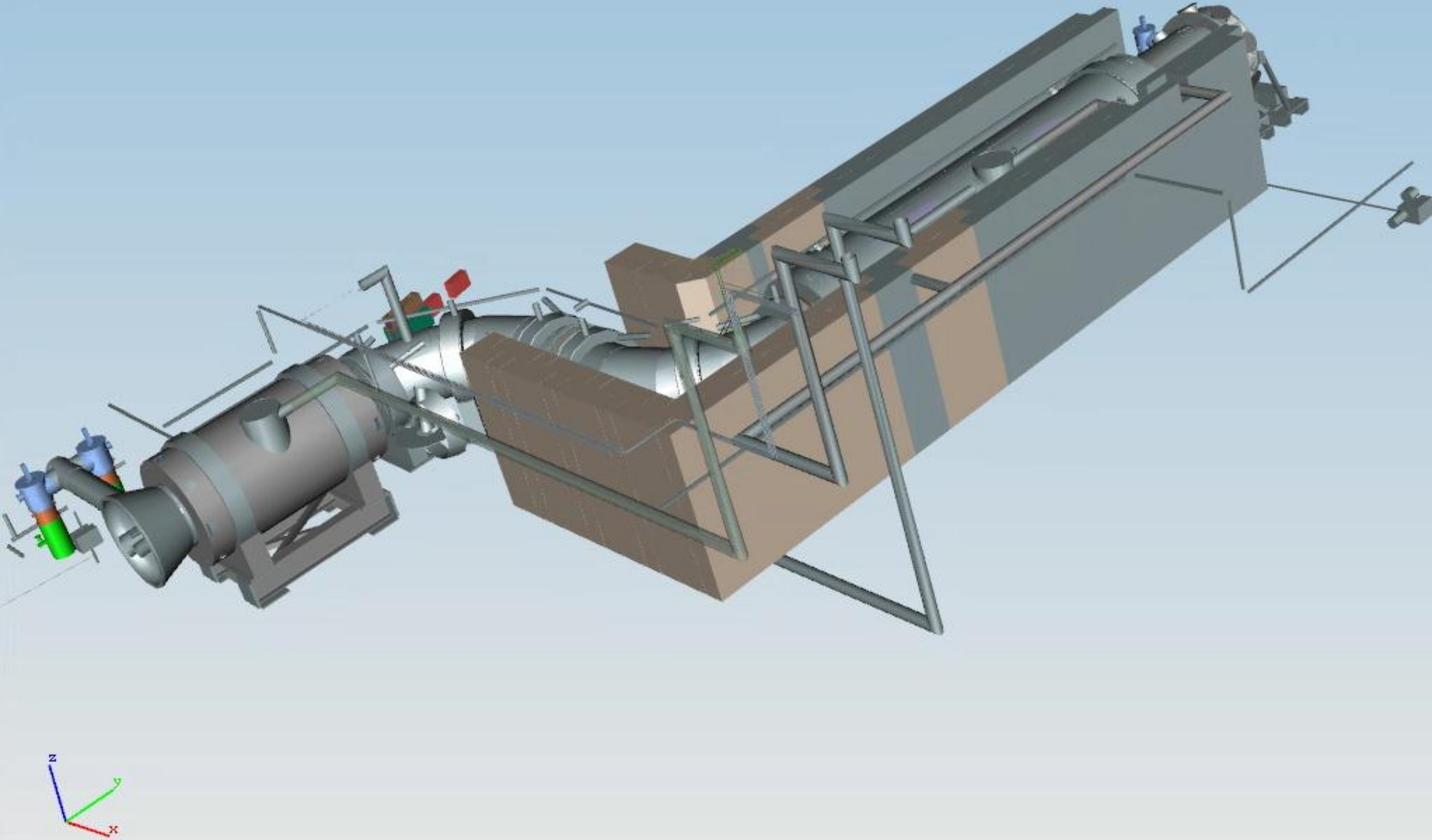
- Invoking the various defenses outlined above (as well as others not explicitly mentioned), the current projected surviving background estimate for 3.6×10^{20} incident protons on target is as follows

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.20 ± 0.09
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	< 0.003
	Pion decay-in-flight (π-DIF)	$0.001 \pm < 0.001$
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.096 ± 0.020
	Total	0.37 ± 0.10

Mu2e Technical Design Report arXiv:1501.05241 Table 3.4

Muon Beamline Shielding

- Beamline contains numerous sources which generate rates in the cosmic ray veto (as well as potentially damages the CRV)
  - Production target, collimators, stopping target, muon beam stop
- Design of the muon beamline shielding has undergone several iterations aimed at reducing the rates in the CRV (to address the CRV livetime requirements) and limiting the radiation dose to an acceptable level
  - While addressing other constraints and attempt to keep the cost contained
  - Current incarnation is primarily a combination of cast in place concrete, concrete blocks, and high density concrete blocks
    - Combined with the previously mentioned internal shielding and muon beam stop
  - Based upon detailed studies using G4Beamline and MARS


z
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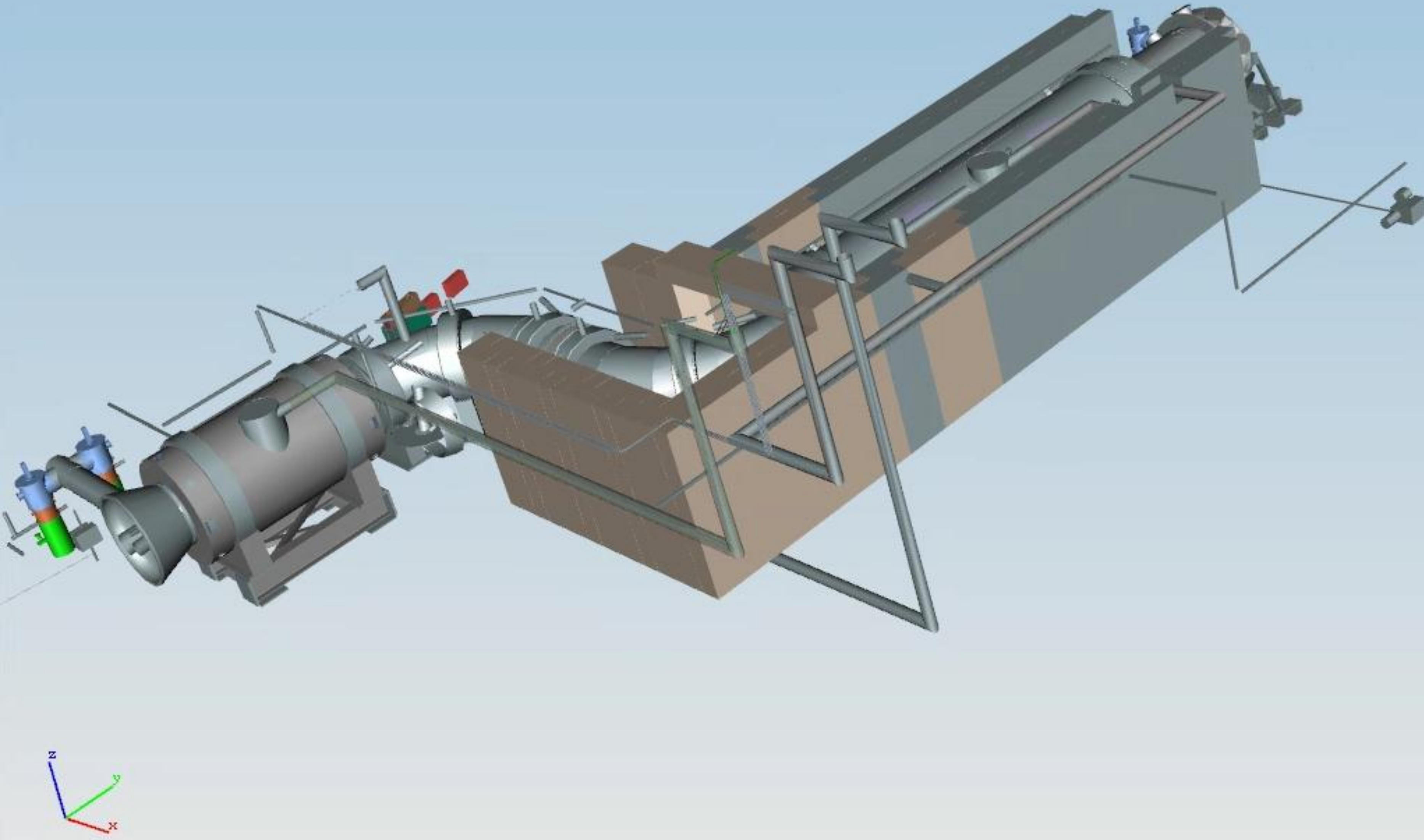
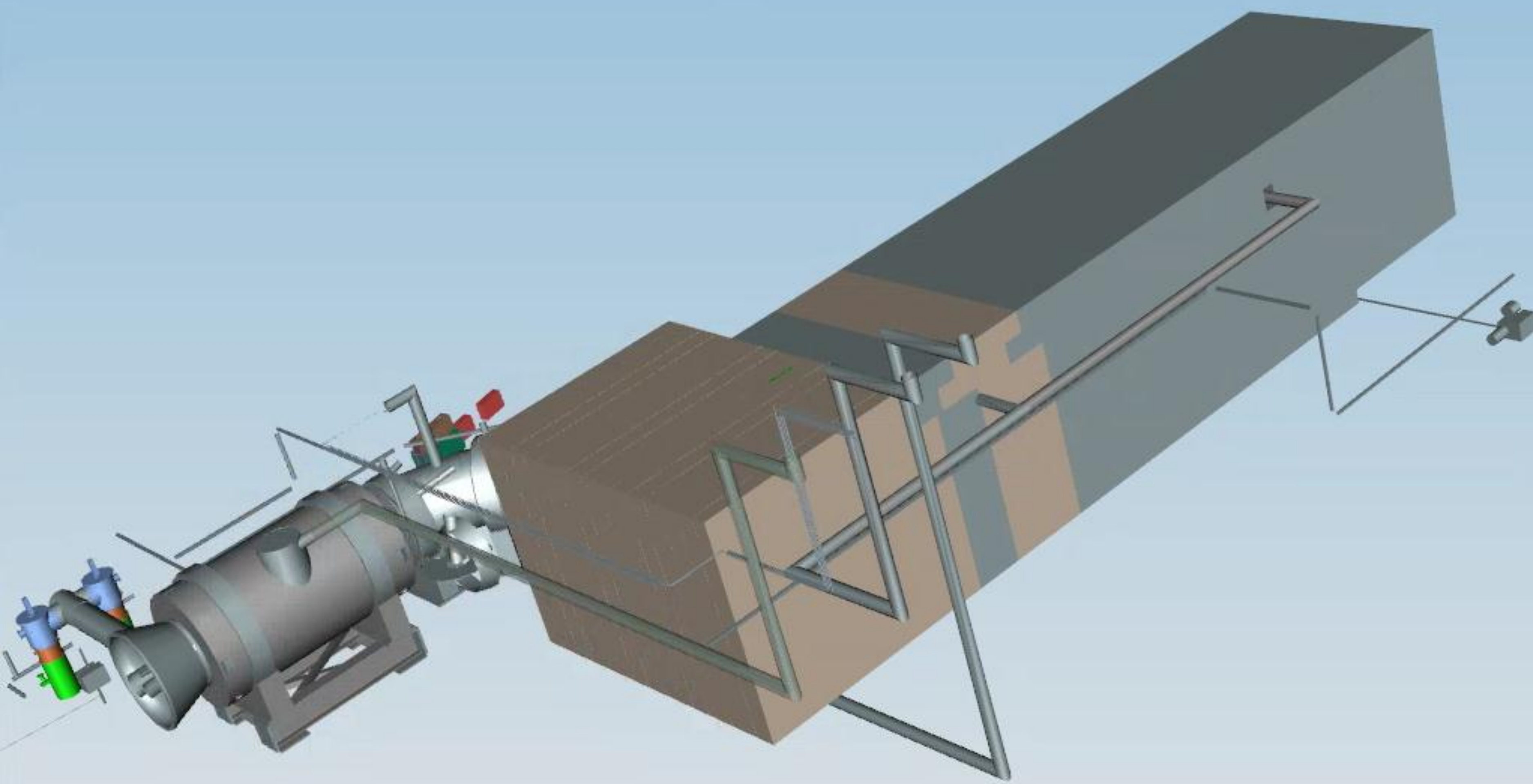
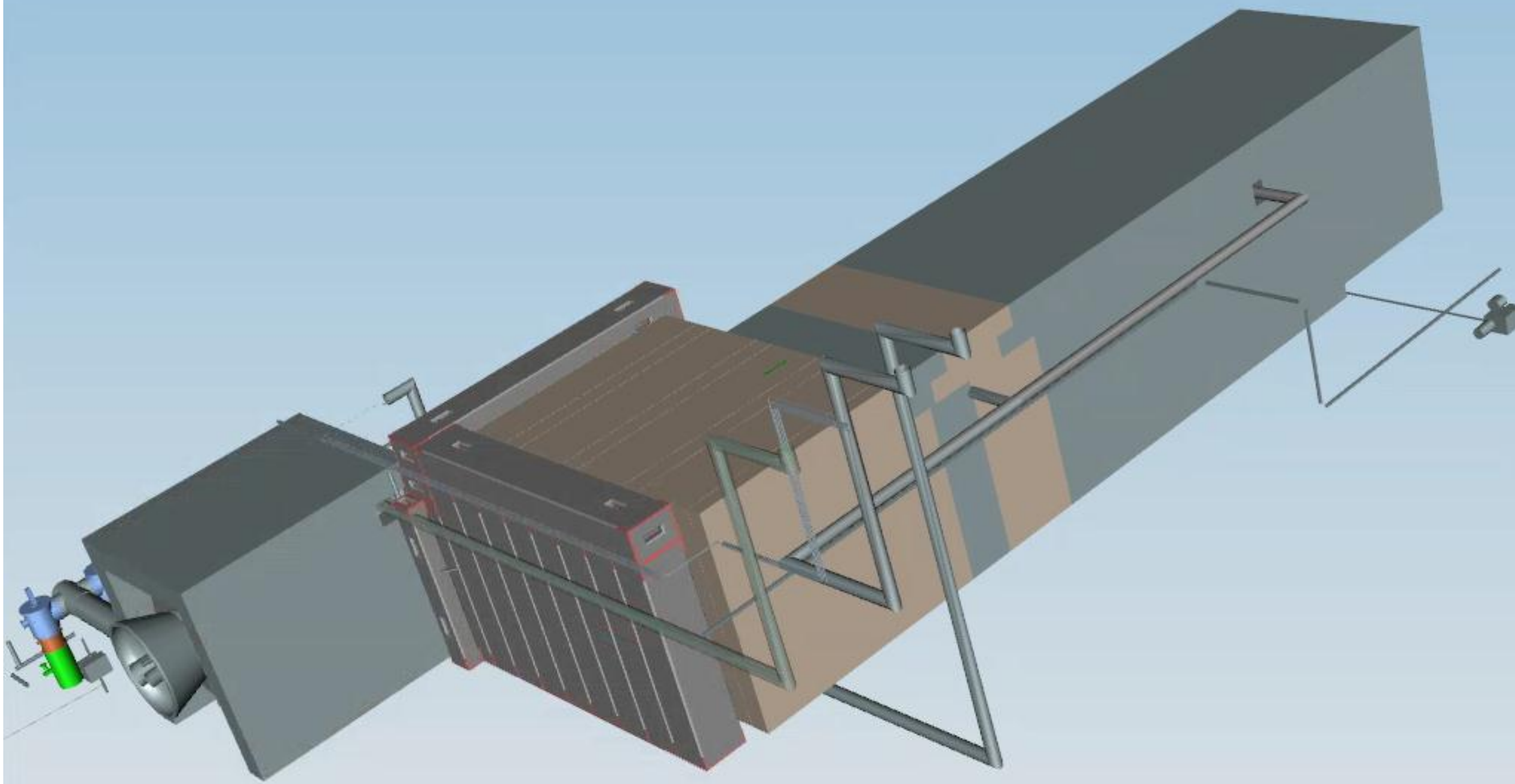

z
y
x

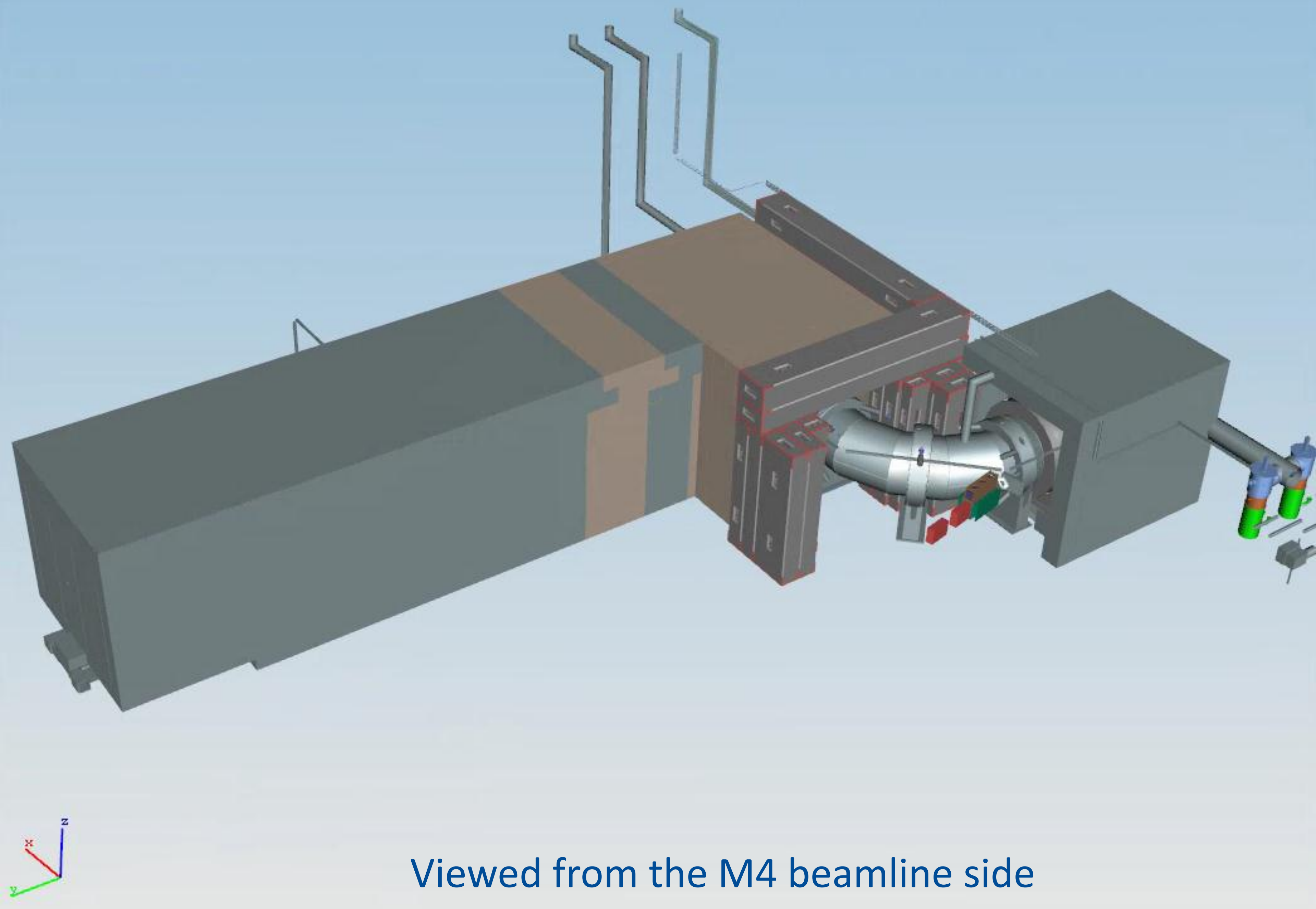


409 tons of high density concrete (shown in brown) and
430 tons normal density concrete (shown in grey)
surrounding the downstream half of the Transport Solenoid and the Detector Solenoid

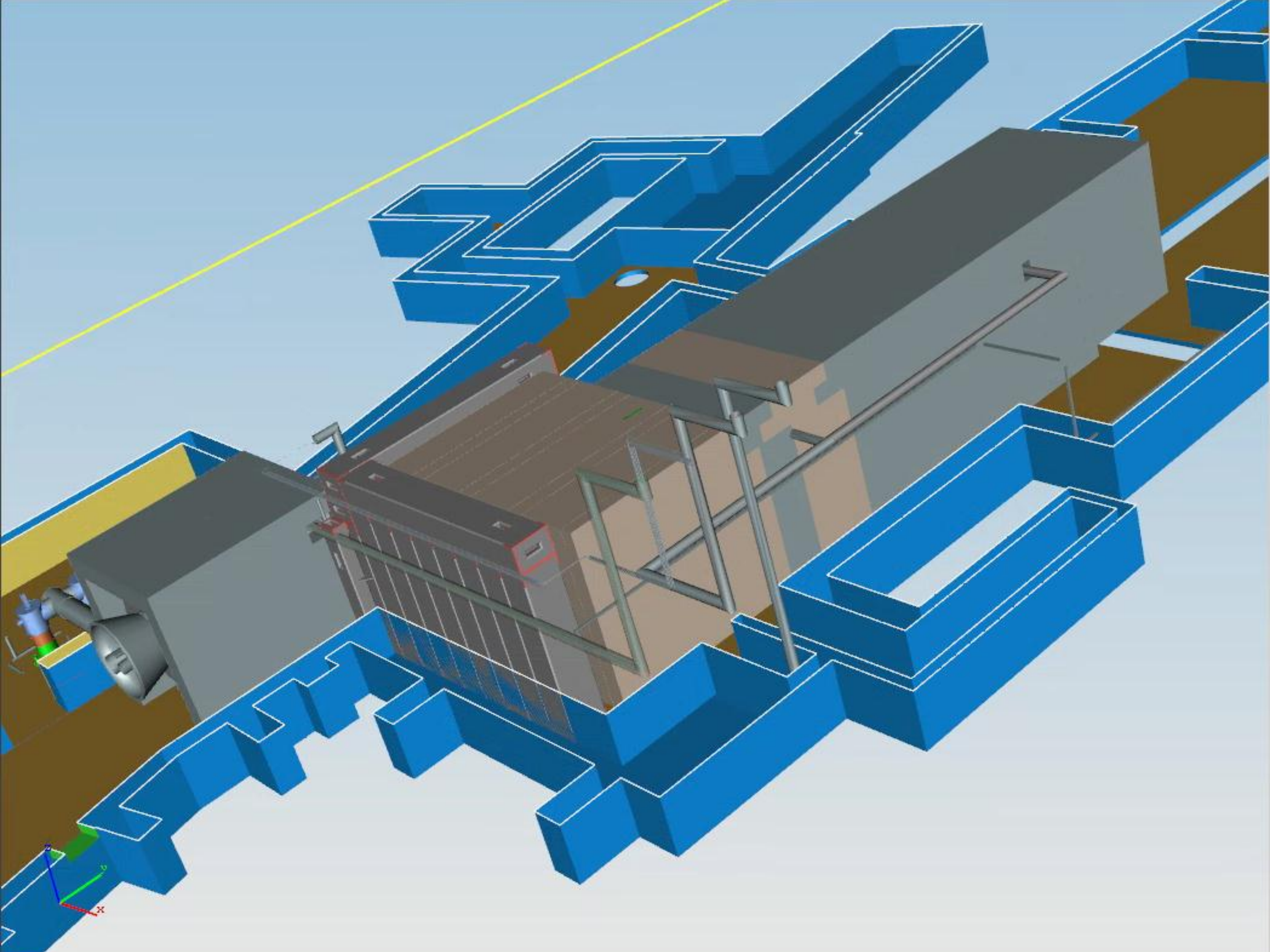


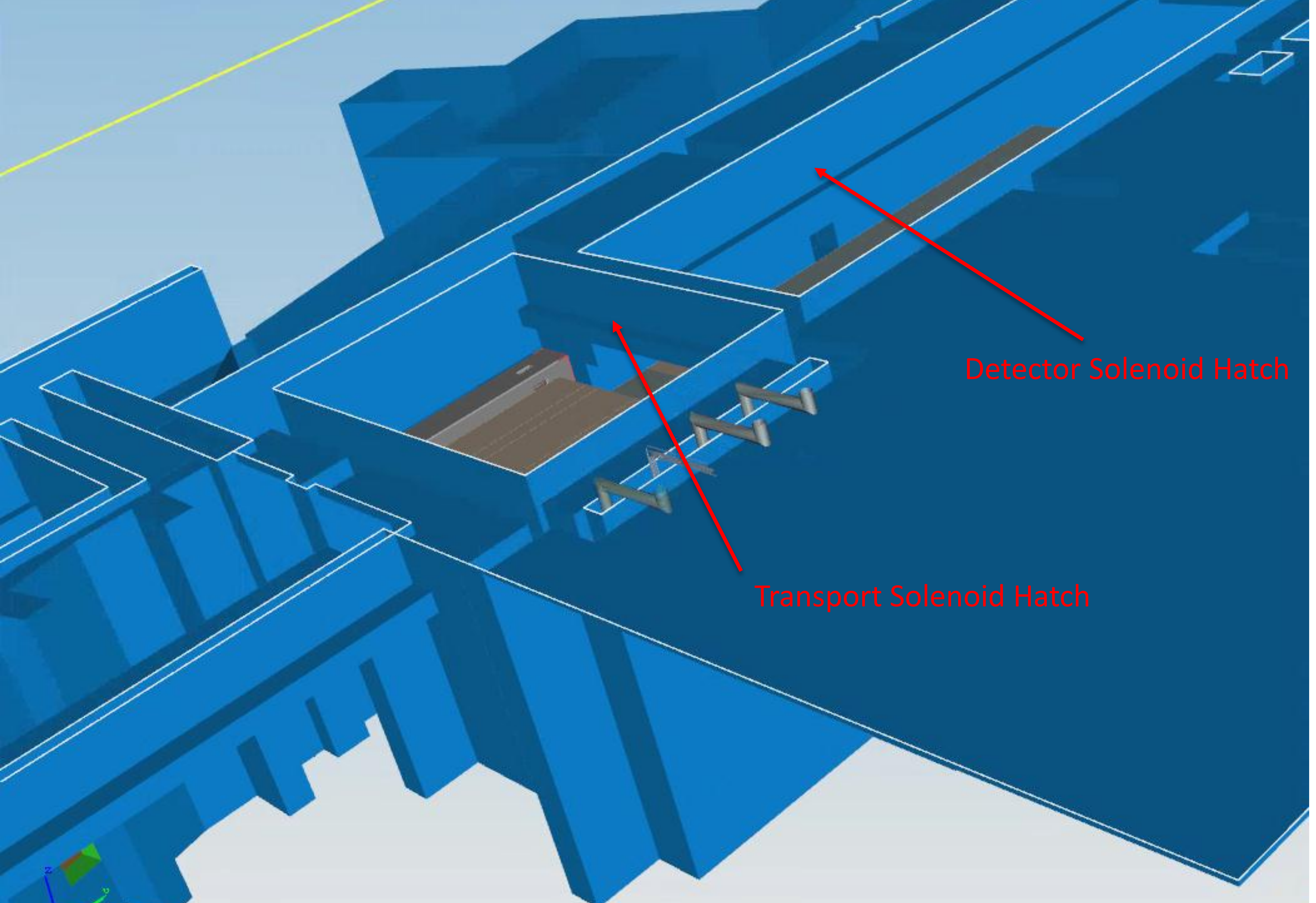
90 tons of concrete surrounding the Production Solenoid

242 tons of high density concrete and 48 tons of normal density concrete near the opening and along the wall of the experiment hall closest to the Production Solenoid



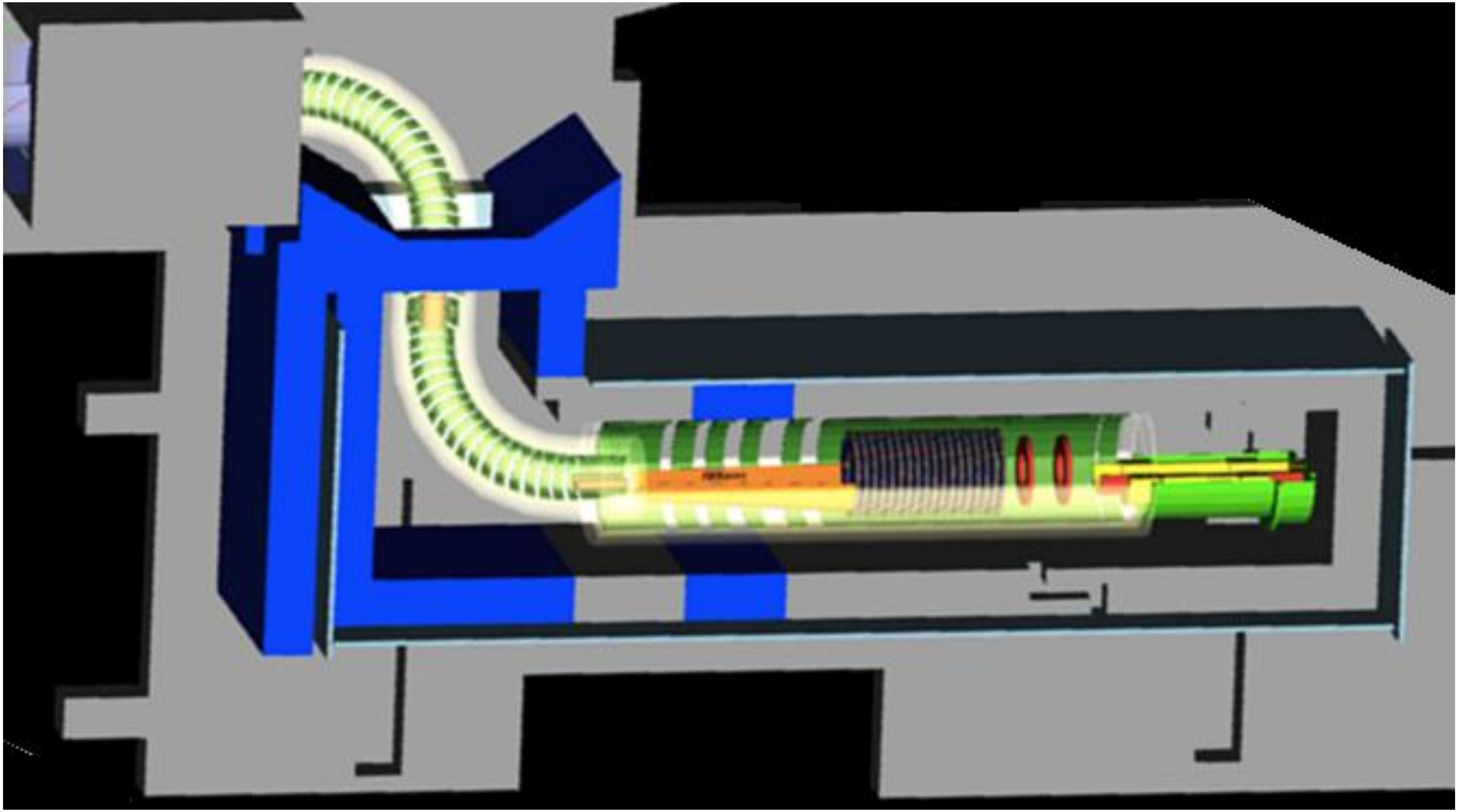
Viewed from the M4 beamline side



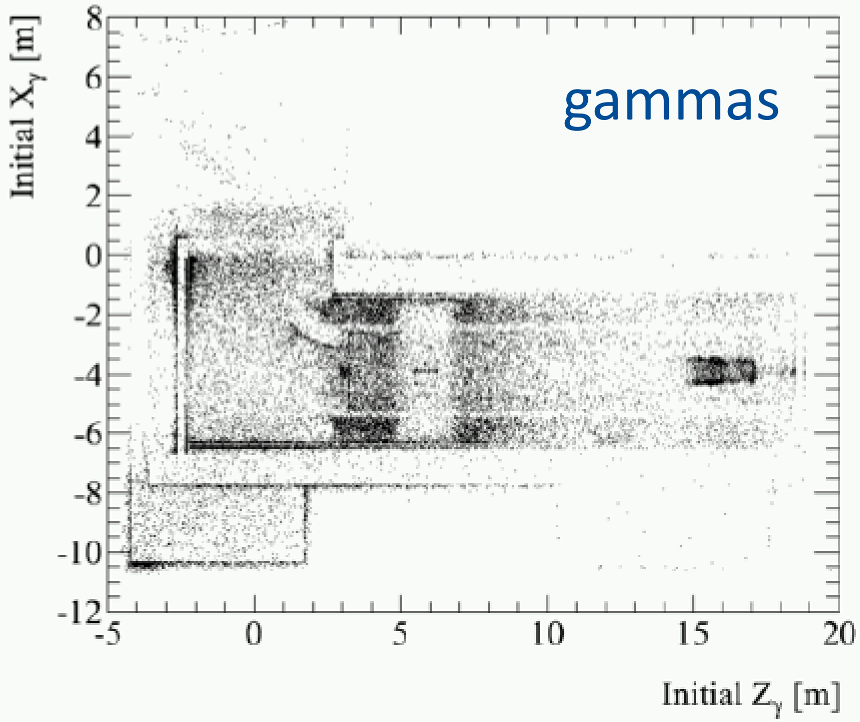


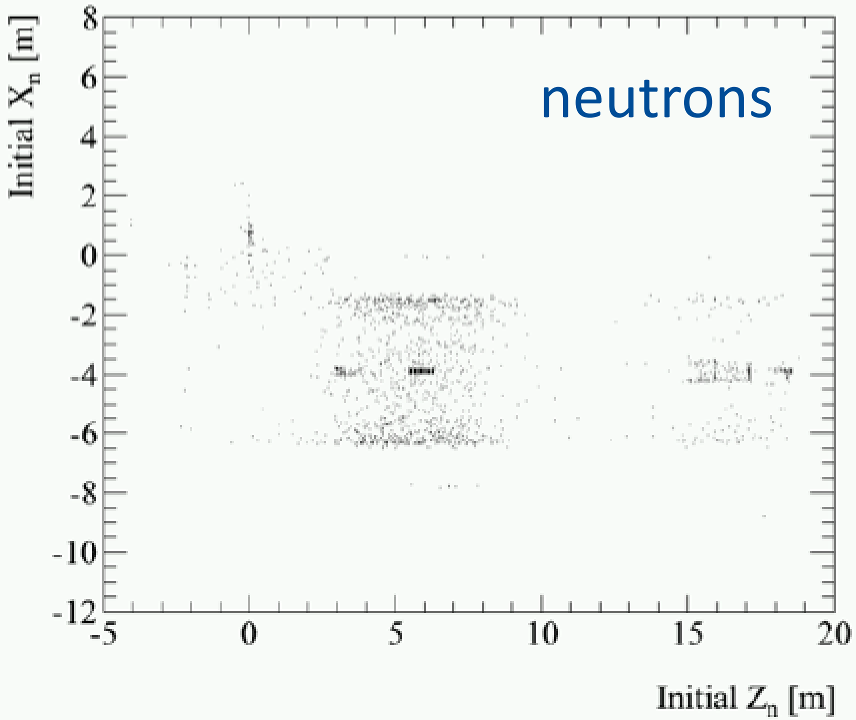
297 tons of concrete blocks loaded into the hatch above the Transport Solenoid
728 tons of concrete blocks loaded into hatch above the Detector Solenoid

Simulation Model
(with top shield blocks suppressed)



Simulation of Potential CRV Rate Sources

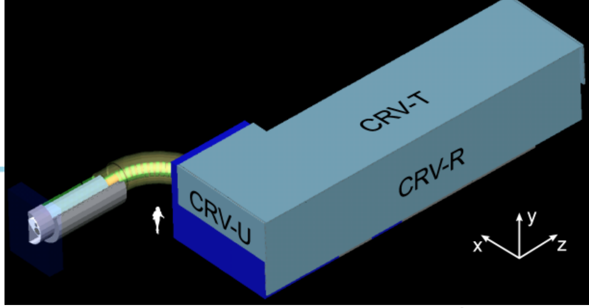


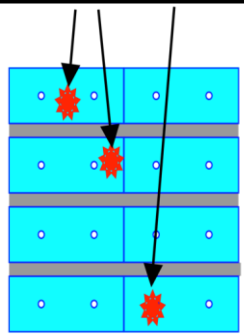


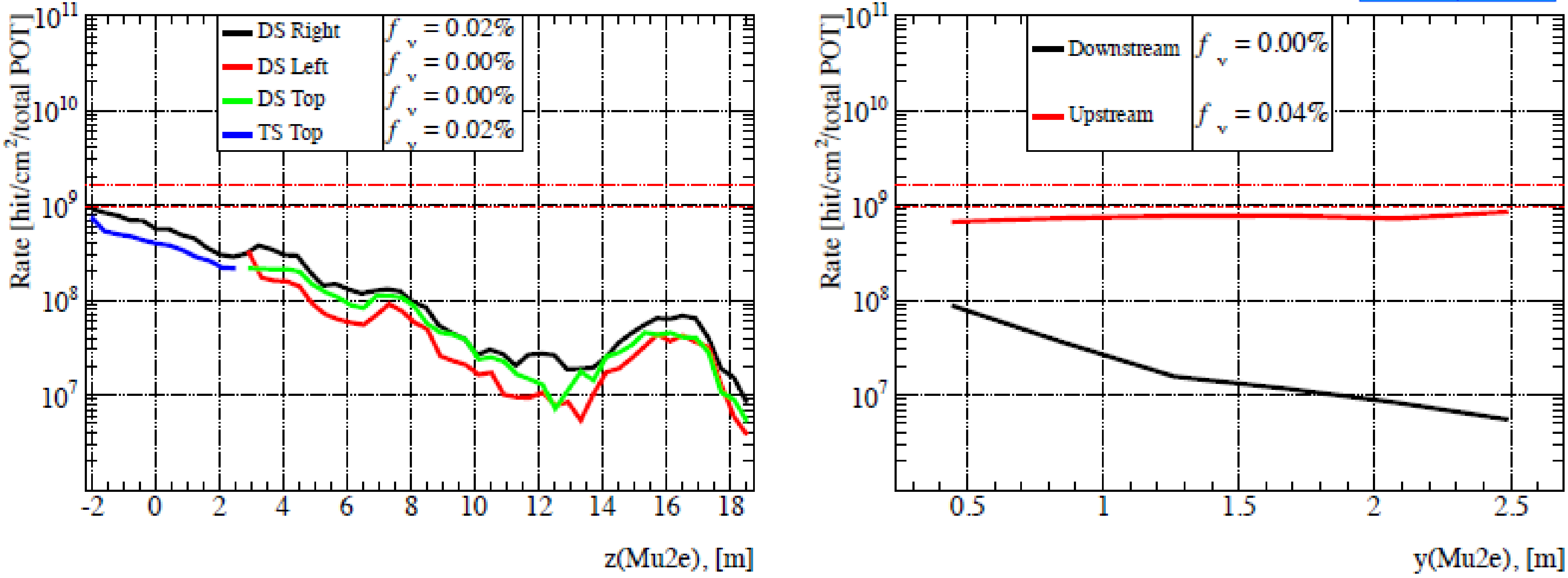
- Plan views of locations of origins of γ and neutrons depositing energy in the CRV
  - Limited to live gate

Accidental CRV Rates

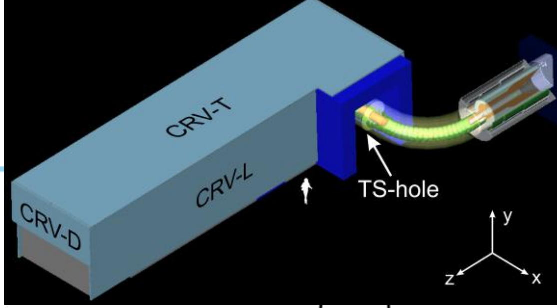
- Accidental hit rates per unit area over the entire running period. Dashed and dotted red lines correspond to 1% and 5% fractional dead time assuming uniform flux distribution.
- CRV deadtime requirement is ≤ 10%

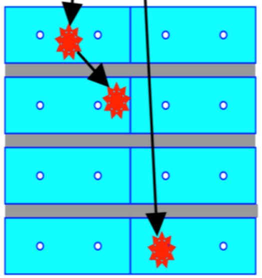




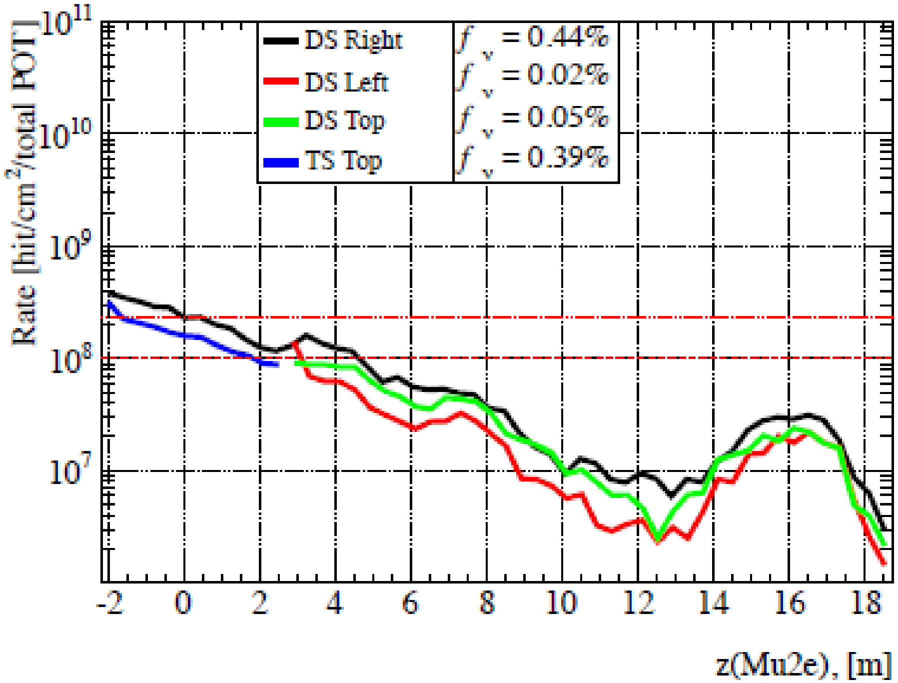


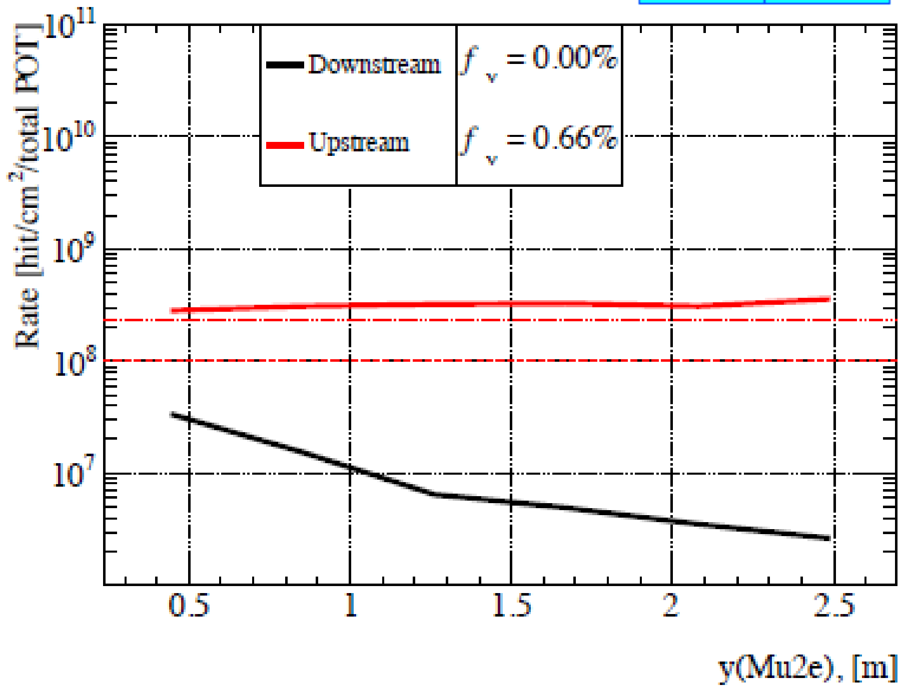
Semi-correlated CRV Rates





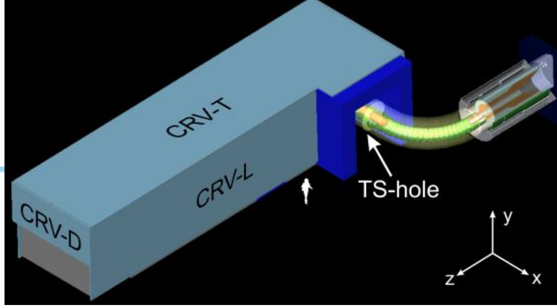
- Semi-correlated hit rates per unit area over the entire running period. Dashed and dotted red lines correspond to 1% and 5% fractional dead time assuming uniform flux distribution.
- CRV deadtime requirement is ≤ 10%

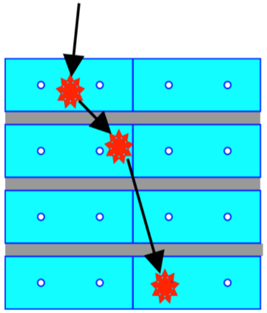




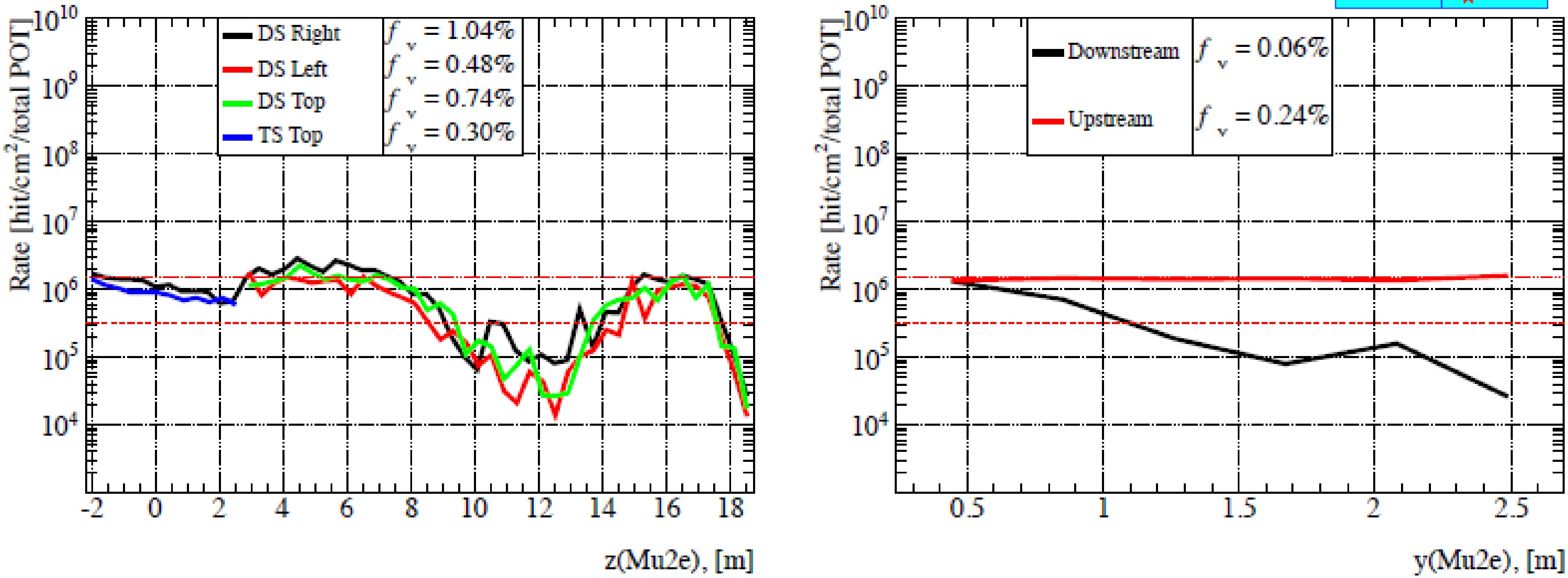
Fermilab

Correlated CRV Rates





- Correlated hit rates per unit area over the entire running period. Dashed and dotted red lines correspond to 1% and 5% fractional dead time assuming uniform flux distribution.
- CRV deadtime requirement is ≤ 10%



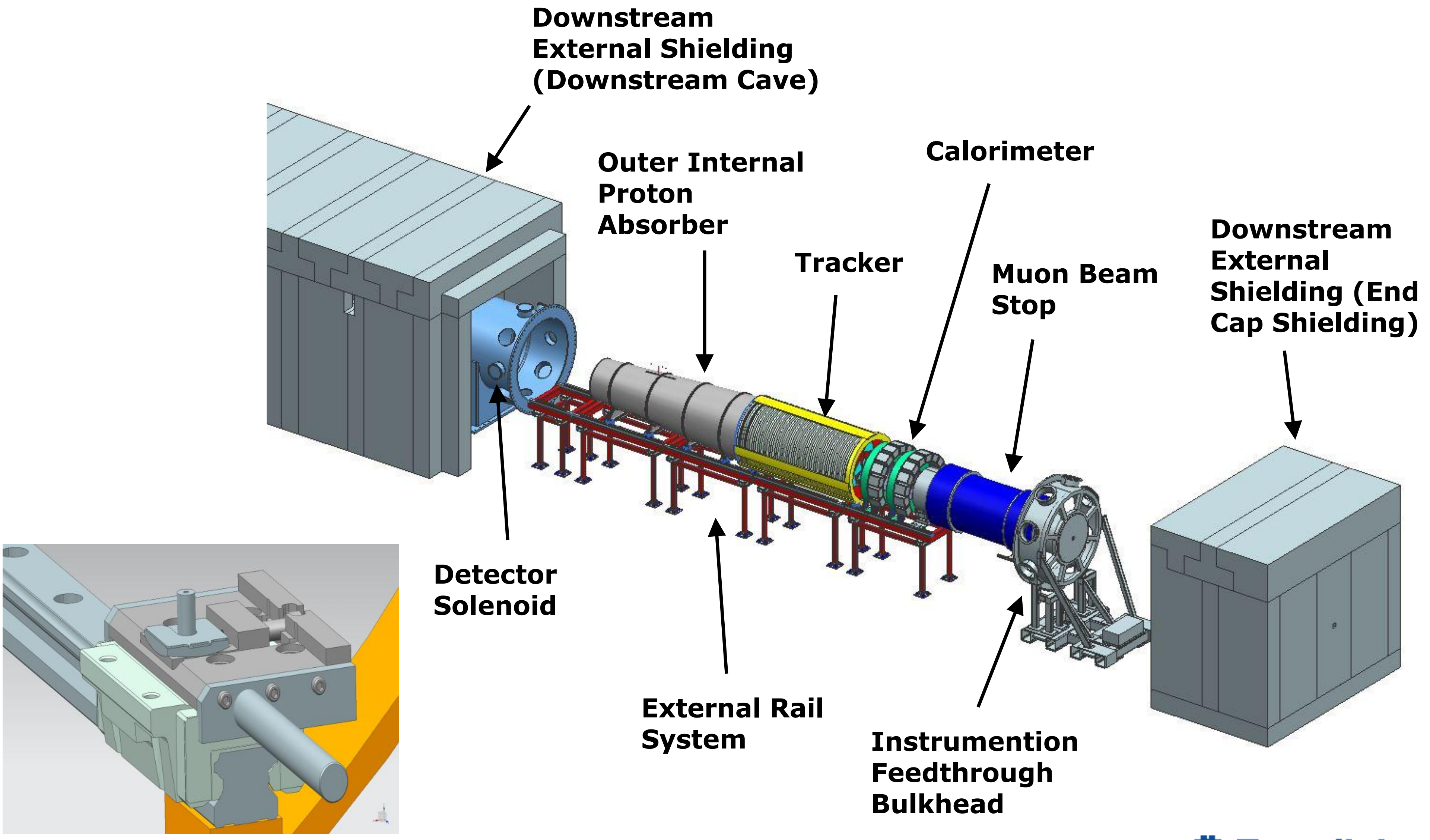
Trigger and Data Acquisition System

- Provides global timing synchronization
- Collect and assemble the locally buffered digitized and zero suppressed data streamed from the tracker and the calorimeter
- Online filtering to reduce recorded data volume by factor of 100
  - CRV data readout for triggered events
- Combines with data from the CRV, extinction and stopping target monitors for transfer to offline storage (< 7 Petabyte/year)

- Servers handle data readout, event building and processing
- Commercial (off the shelf) DAQ hardware interfaced to custom detector readout controllers via optical links
  - Baseline design uses 36 DAQ servers and is scalable
- Software based on art and artdaq
  - Custom DAQ & online processing framework

- Experiment to be operated from the Remote Control Room in Wilson Hall

Detector Support & Installation System




EXIT
DANGER
PINCH POINT

The Muon Campus

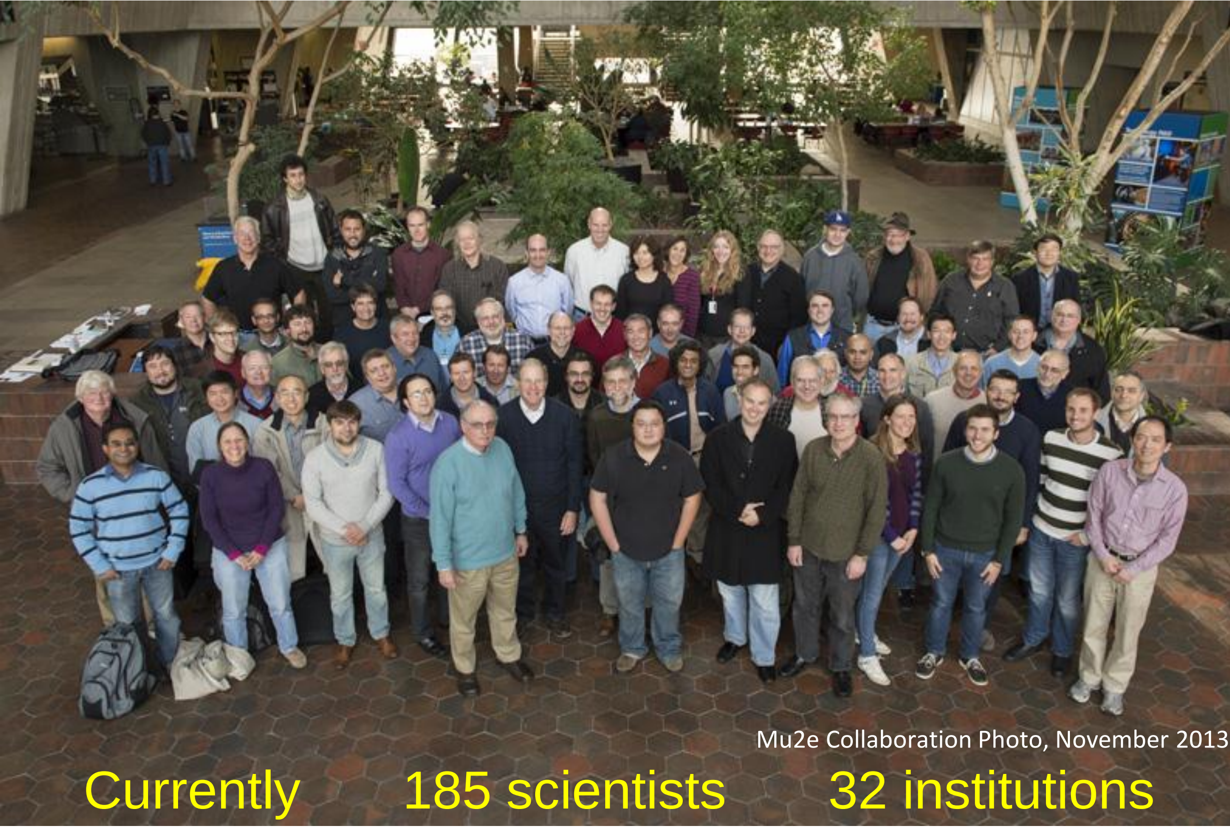
Mu2e Conventional Facilities

- Detector Enclosure   9640 square feet (~25.5 foot below grade)
- Grade Level   12600 square feet
  - Two 30 ton cranes in the high bay with access to the lower level through hatches above part of the Transport Solenoid and the Detector Solenoid
  - Additional hatches provide access for remote handling and extinction monitor


AP30


DEERE

The Mu2e Collaboration



Mu2e Collaboration Photo, November 2013

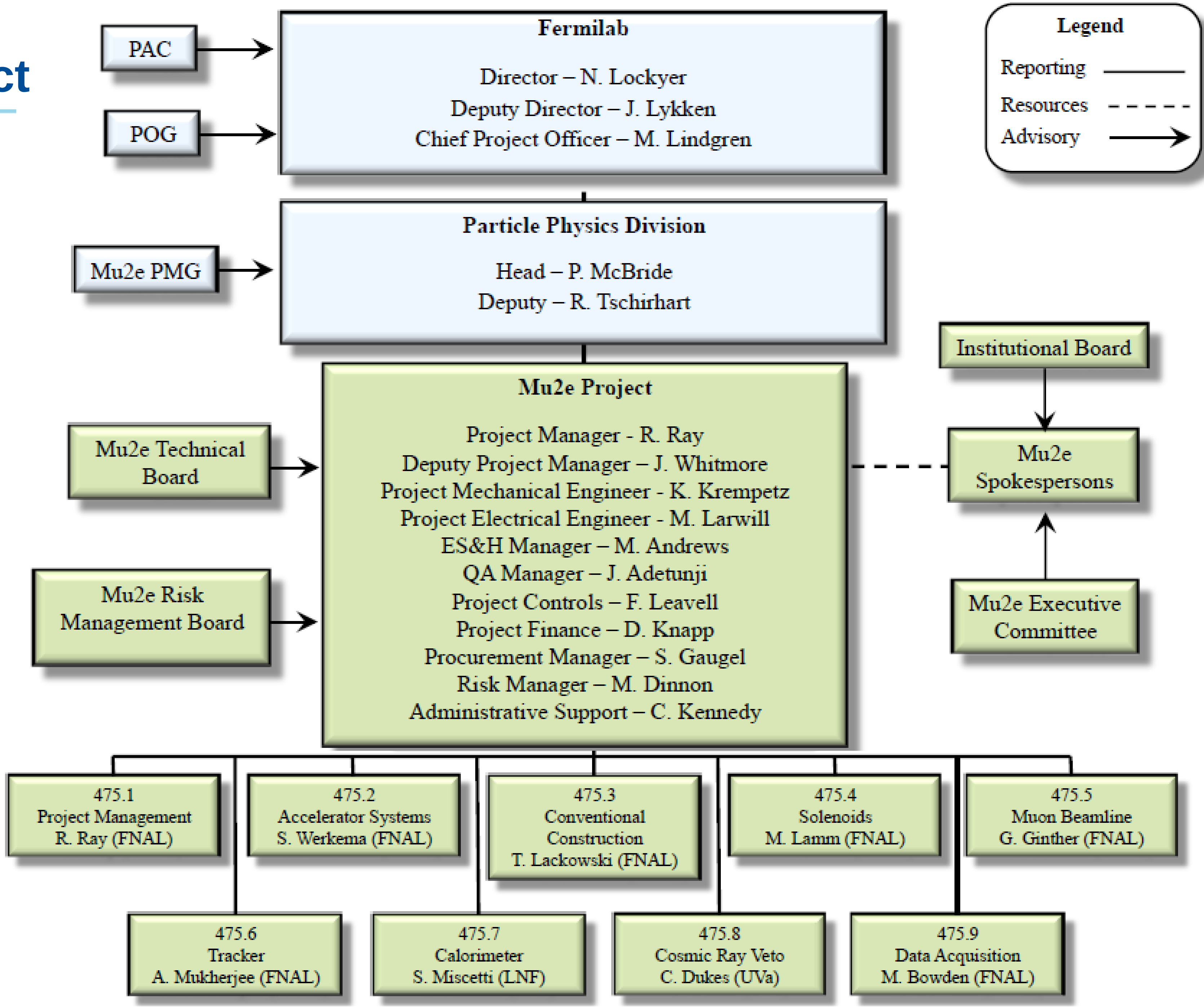
Currently 185 scientists 32 institutions

Argonne National Laboratory
Boston University
Brookhaven National Laboratory
Lawrence Berkeley National Laboratory
University of California, Berkeley
University of California, Irvine
California Institute of Technology
City University of New York
Duke University
Fermi National Accelerator Laboratory
University of Houston
University of Illinois
Lewis University
University of Louisville
University of Massachusetts, Amherst
University of Minnesota
Muons Inc.
Northern Illinois University
Northwestern University
Pacific Northwest National Laboratory
Purdue University
Rice University
University of South Alabama
University of Virginia
University of Washington
Yale University

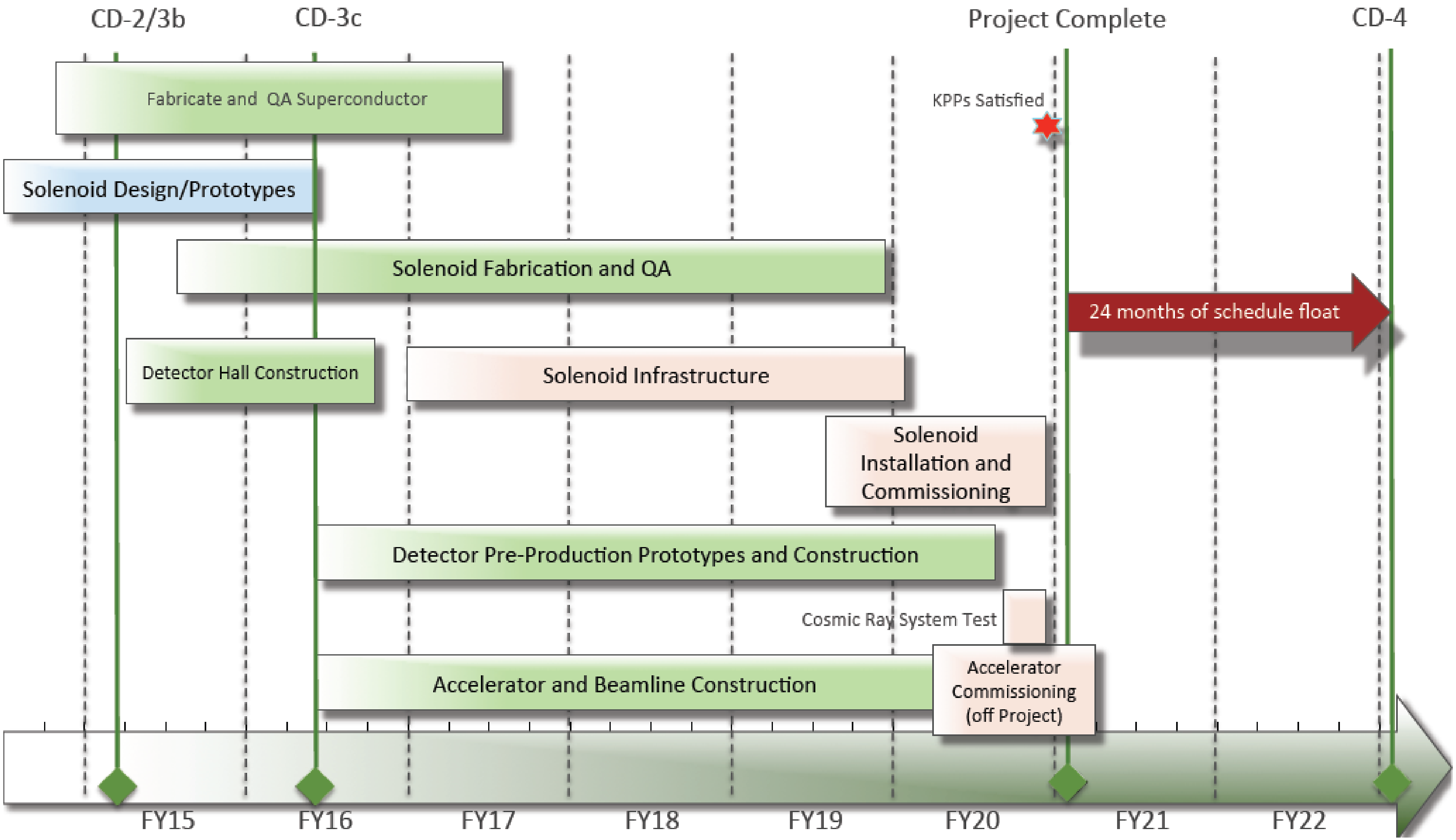
Laboratori Nazionali di Frascati
INFN Genova
INFN Lecce and Università del Salento
Laboratori Nazionali di Frascati and Università Marconi Roma
INFN Pisa

Joint Institute for Nuclear Research, Dubna
Novosibirsk State University/Budker Institute of Nuclear Physics
Institute for Nuclear Research, Moscow

Mu2e Project

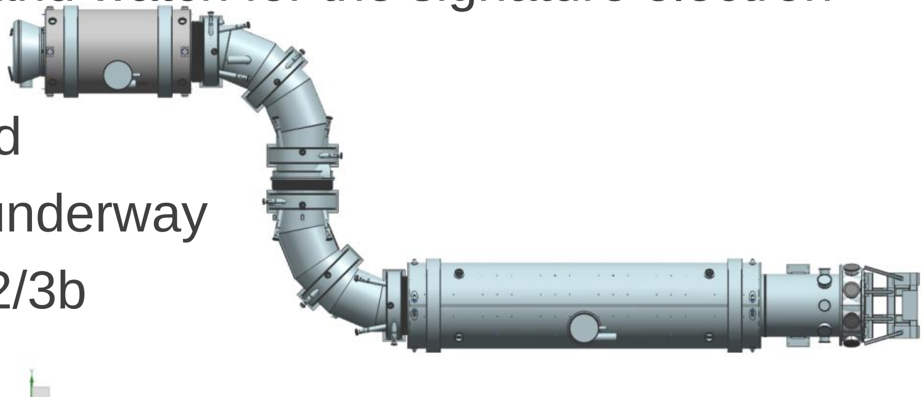


Mu2e Project Schedule (as of CD-2/3b Review)



Summary

- Mu2e will search for evidence of the process $\mu^- N \rightarrow e^- N$
  - Stop muons on aluminum target and watch for the signature electron
- The design is well underway
- Solenoid conductor has been ordered
- Excavation for the muon campus is underway
- Looking forward to Critical Decision 2/3b



- The Mu2e experiment aims to increase sensitivity to this process by several orders of magnitude and has significant discovery potential due to
  - the intense beam
  - the time structure of that beam
  - the design of the apparatus
  - the associated defenses designed to suppress backgrounds

Looking for additional details?

- Additional information on Mu2e is available from numerous sources including
  - Mu2e web page
  - Mu2e Technical Design Report, Mu2e docdb 4299, FERMILAB-TM-2594, arXiv:1501.05241
- Steve Werkema recently provided an overview of the muon campus experiments and projects (25 Nov 2014)
  - http://beamdocs.fnal.gov/AD-public/DocDB/ShowDocument?docid=4716

Tau lepton flavor violation searches (PDG)

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

Lepton Family number (*LF*), Lepton number (*L*), or Baryon number (*B*) violating modes

L means lepton number violation (*e.g.* $\tau^- \to e^+\pi^-\pi^-$). Following common usage, *LF* means lepton family violation *and not* lepton number violation (*e.g.* $\tau^- \to e^-\pi^+\pi^-$). *B* means baryon number violation.

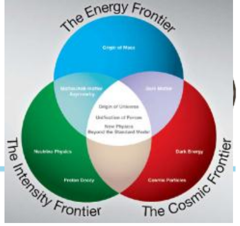
$e^-\gamma$	*LF*	< 3.3	$\times 10^{-8}$	CL=90%	888
$\mu^-\gamma$	*LF*	< 4.4	$\times 10^{-8}$	CL=90%	885
$e^-\pi^0$	*LF*	< 8.0	$\times 10^{-8}$	CL=90%	883
$\mu^-\pi^0$	*LF*	< 1.1	$\times 10^{-7}$	CL=90%	880
$e^-K^0_S$	*LF*	< 2.6	$\times 10^{-8}$	CL=90%	819
$\mu^-K^0_S$	*LF*	< 2.3	$\times 10^{-8}$	CL=90%	815
$e^-\eta$	*LF*	< 9.2	$\times 10^{-8}$	CL=90%	804
$\mu^-\eta$	*LF*	< 6.5	$\times 10^{-8}$	CL=90%	800
$e^-\rho^0$	*LF*	< 1.8	$\times 10^{-8}$	CL=90%	719
$\mu^-\rho^0$	*LF*	< 1.2	$\times 10^{-8}$	CL=90%	715
$e^-\omega$	*LF*	< 4.8	$\times 10^{-8}$	CL=90%	716
$\mu^-\omega$	*LF*	< 4.7	$\times 10^{-8}$	CL=90%	711
$e^-K^*(892)^0$	*LF*	< 3.2	$\times 10^{-8}$	CL=90%	665
$\mu^-K^*(892)^0$	*LF*	< 5.9	$\times 10^{-8}$	CL=90%	659
$e^-\overline{K}^*(892)^0$	*LF*	< 3.4	$\times 10^{-8}$	CL=90%	665
$\mu^-\overline{K}^*(892)^0$	*LF*	< 7.0	$\times 10^{-8}$	CL=90%	659
$e^-\eta'(958)$	*LF*	< 1.6	$\times 10^{-7}$	CL=90%	630
$\mu^-\eta'(958)$	*LF*	< 1.3	$\times 10^{-7}$	CL=90%	625
$e^-f_0(980) \to e^-\pi^+\pi^-$	*LF*	< 3.2	$\times 10^{-8}$	CL=90%	–
$\mu^-f_0(980) \to \mu^-\pi^+\pi^-$	*LF*	< 3.4	$\times 10^{-8}$	CL=90%	–

- Limits on many modes have been documented
- Some of the Tau lepton with the best limits are shown here

Excerpt from Mission Need Statement

- Indeed, searches for lepton flavor violation have had great historical importance in the evolution of the Standard Model and in constraining new physics extensions. For example, non-observation of the decay $\mu \rightarrow e\gamma$ helped establish the muon as a distinct elementary particle rather than an excited electron and later motivated the search for the muon neutrino, a discovery that earned the 1988 Nobel Prize.
- The current Standard Model modified to explain the observed neutrino oscillations, predicts very small rates for charged lepton flavor violating (CLFV) processes. Many models for new physics, for example supersymmetry, predict rates that are measurable by the next generation of experiments. Any observation of CLFV is unmistakable evidence for new, unknown types of physics. CLFV processes can be sensitive to new physics at and well above the TeV scale and are bound to play a key role in uncovering the origin of neutrino masses.
- The discovery of neutral lepton flavor violation in the neutrino sector has had a significant impact on our understanding of the universe and is the first definitive example of physics beyond the Standard Model. The discovery of charged lepton flavor violation could be equally important. A detector to study muon to electron conversion is the next logical step and will augment the ongoing neutrino and LHC programs. In concert with the Department's world-class neutrino program the United States will assume a leadership position in the study of lepton flavor violation and its connection to physics beyond the Standard Model and the matter antimatter asymmetry.

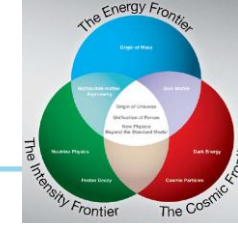
Excerpt from 2014 P5 Report



- In their May 2014 report "*Building for Discovery   Strategic Plan for U.S. Particle Physics in the Global Context*"
- *Detecting the quantum influence of new particles:* The existence of new particles that are too heavy to be produced directly at high-energy colliders can be inferred by looking for quantum influences in lower energy phenomena. There are many examples of such experiments taking place in Europe, Japan, China, and the U.S. The global program includes projects that are complementary to one another using different kinds of particles as probes that are sensitive to different types of new particles and interactions. Some notable examples involve a revolutionary increase in sensitivity for the transition of a muon to an electron in the presence of a nucleus **Mu2e** (Fermilab) and **COMET** (J-PARC), further studies of rare processes involving heavy quarks or tau leptons at **Belle II** (KEK) and **LHCb** (LHC), and a search for proton decay using the large neutrino detectors of the **LBNF** and proposed **Hyper-K** experiments.

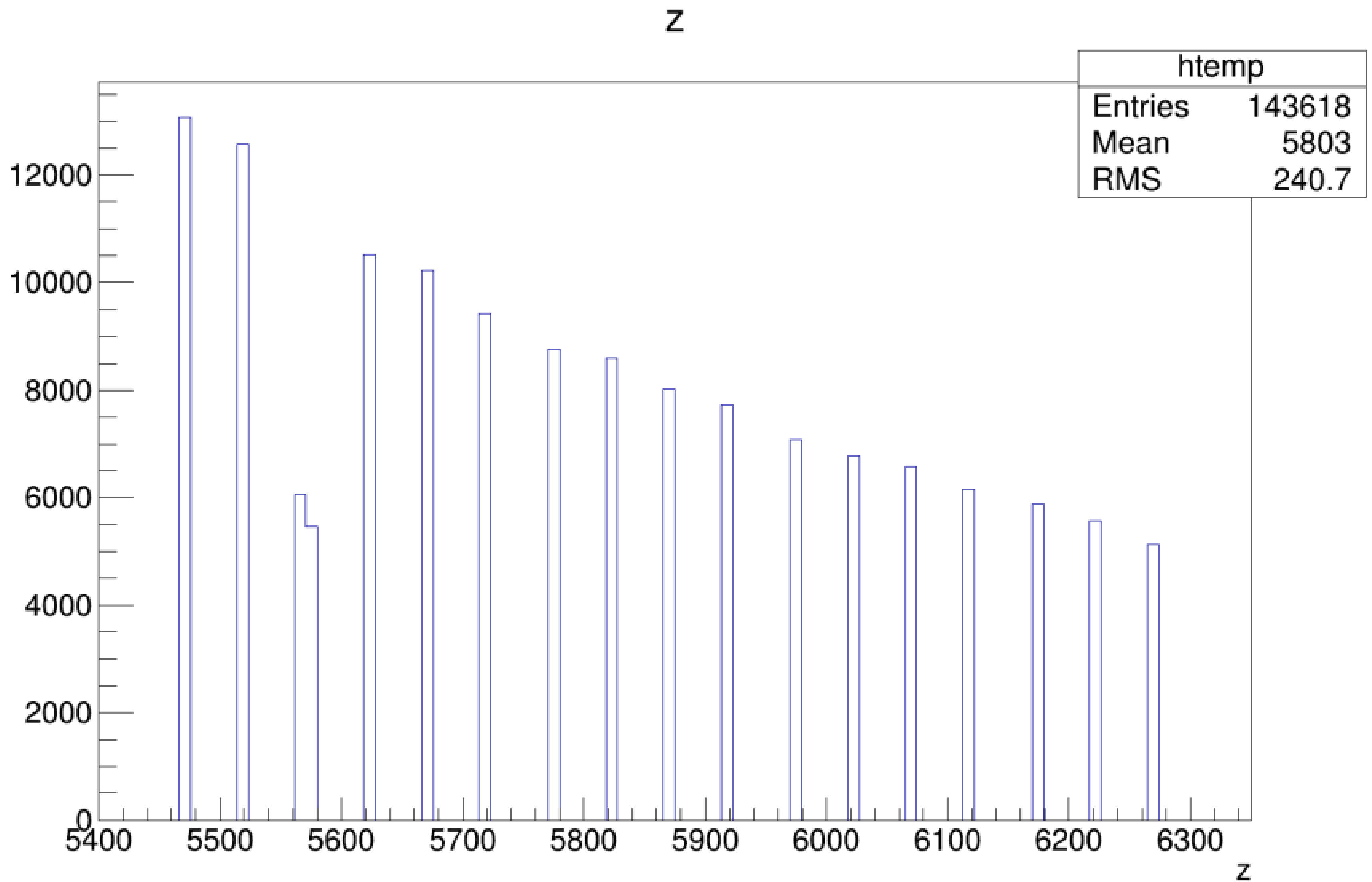
Fermilab

Particle Physics Project Prioritization Panel (P5)



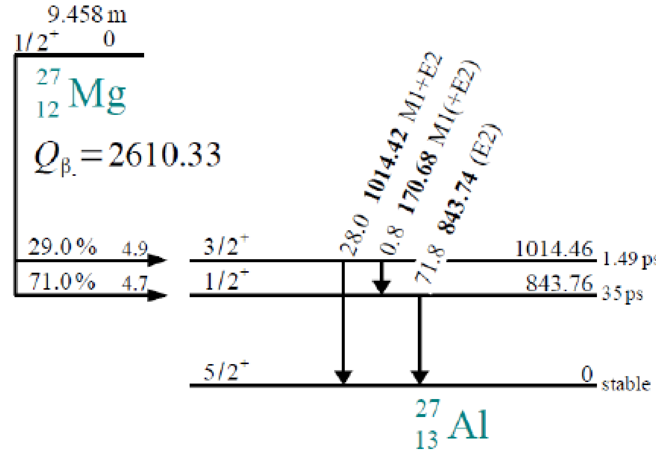
- In their May 2014 report "*Building for Discovery Strategic Plan for U.S. Particle Physics in the Global Context*"
- ***Explore the Unknown: New Particles, Interactions and Physical Principles***
- • *Rare Muon decays and processes:* Observation of charged lepton flavor violation (*e.g.*, a muon changing to an electron) would be a signature of new physics. In the muon sector, a dramatic order of magnitude increase in sensitivity to the scale of such new physics should come from experiments on the decays *μ→eγ, μ→ee+e*–, and muon conversion to an electron in the presence of a nucleus. These experiments will be performed at J-PARC, PSI, and Fermilab.
- Of these three processes, muon conversion to an electron in the presence of a nucleus will give the greatest increase in mass reach for new physics. Very ambitious next-generation experiments aim to be sensitive to conversion rates four orders of magnitude beyond the existing bounds, allowing them to reveal the presence of new particles with masses up to thousands of TeV, well beyond the reach of the LHC. Worldwide, there are two planned muon-to-electron conversion experiments: COMET at J-PARC and Mu2e at Fermilab. Phase I of COMET is designed to achieve a 3x10-15 single-event sensitivity. Phase II of COMET, not yet approved, and Mu2e plan to improve this sensitivity by two more orders of magnitude in a similar time frame.

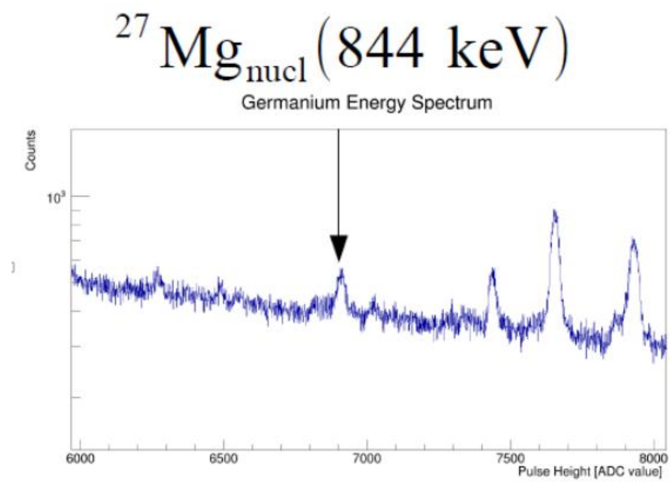
Z distribution of stopped muons in target



Muon Stopping Target Monitor

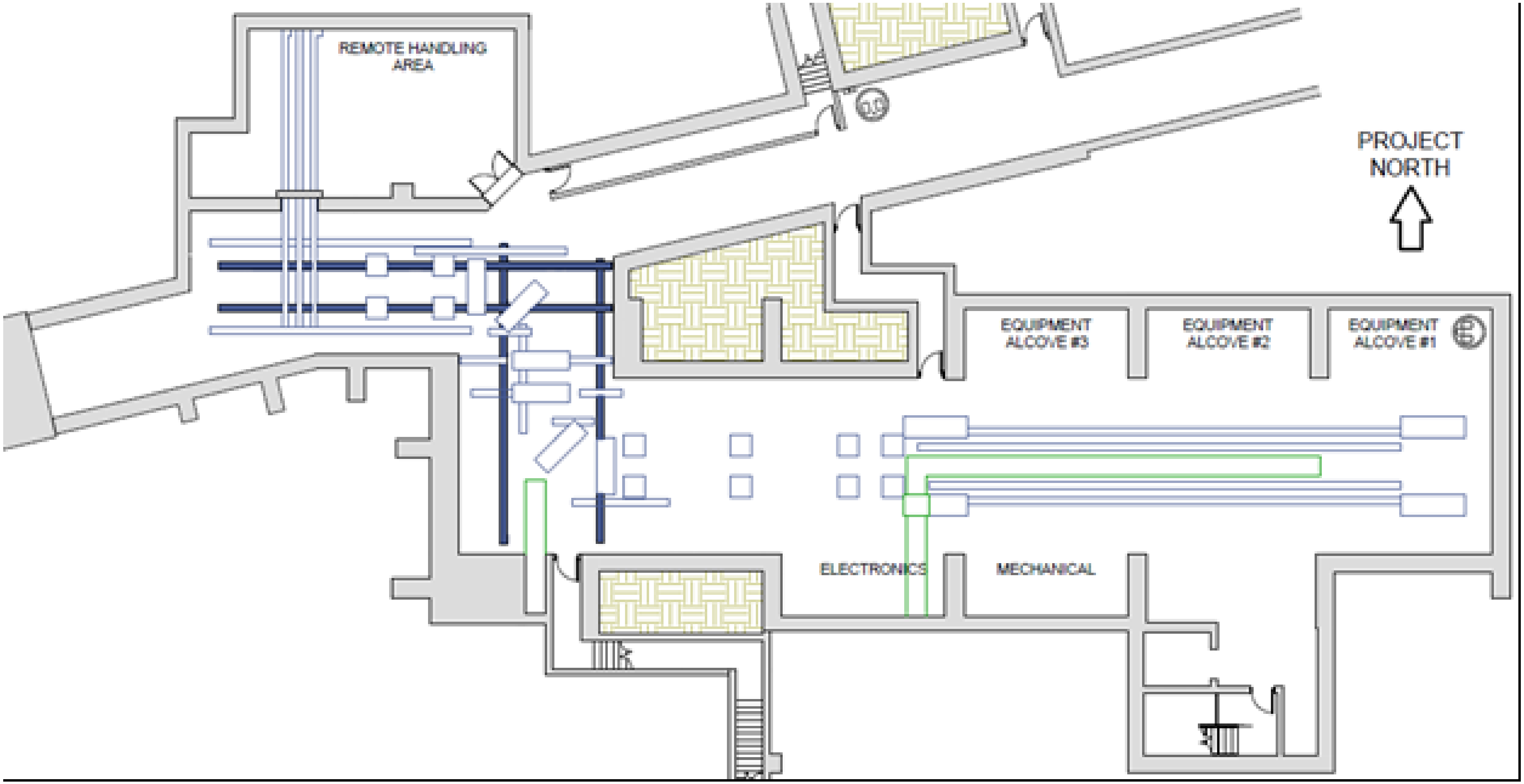
- Stopping Target Monitor is a germanium detector monitoring
- TDR baseline relies upon detection of delayed photons from the de-excitation of ^{27}Mg created by muon capture on aluminum
  - ^{27}Mg decays to excited ^{27}Al with a 9.5 minute half life
    - Detect 844 keV photon from ^{27}Al transition
- Germanium detector located outside vacuum volume downstream in low magnetic field region
- Sweeping magnet
- Beam shutter protects detector from beam flash
- Additional shielding surrounding detector

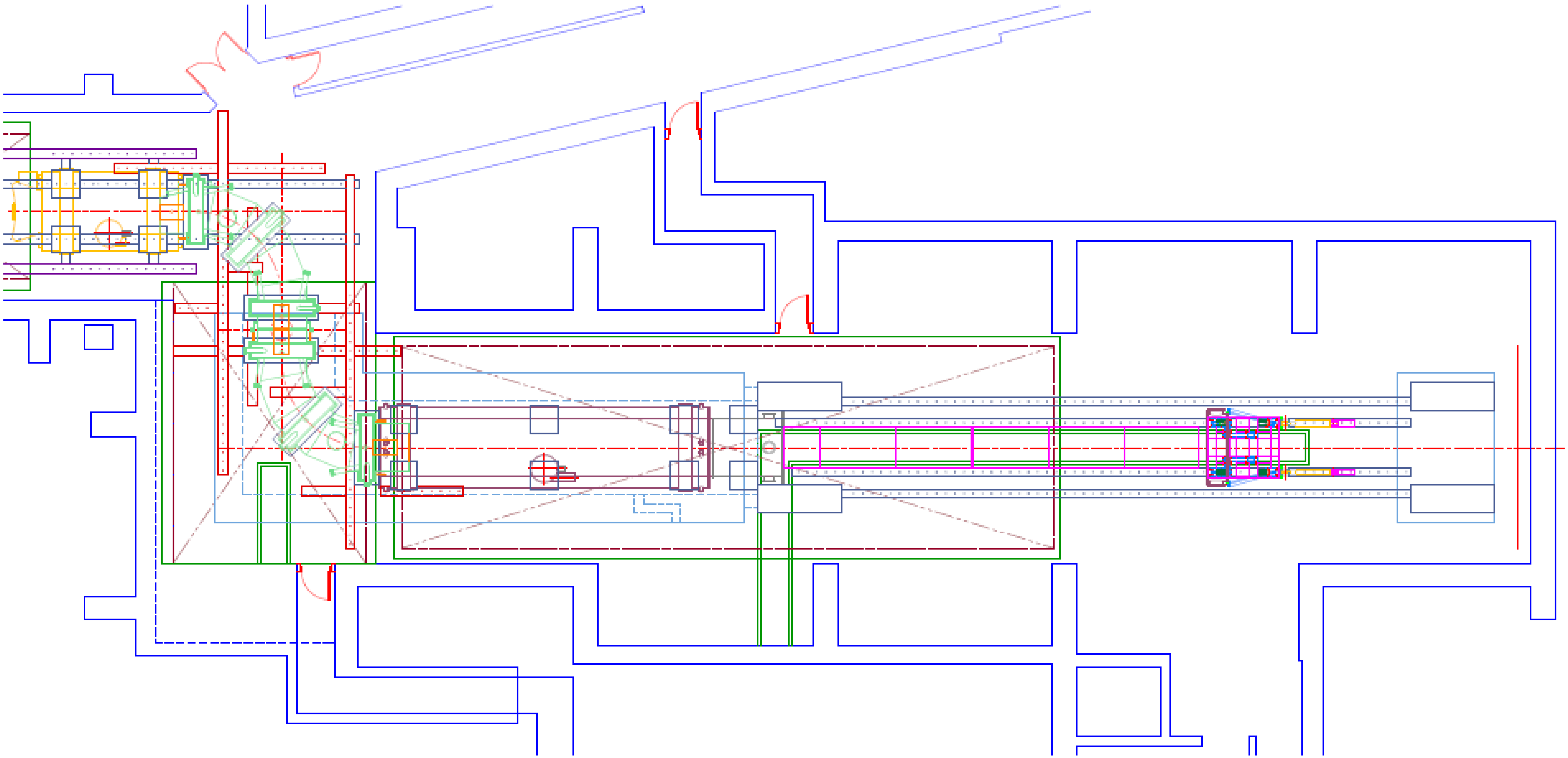




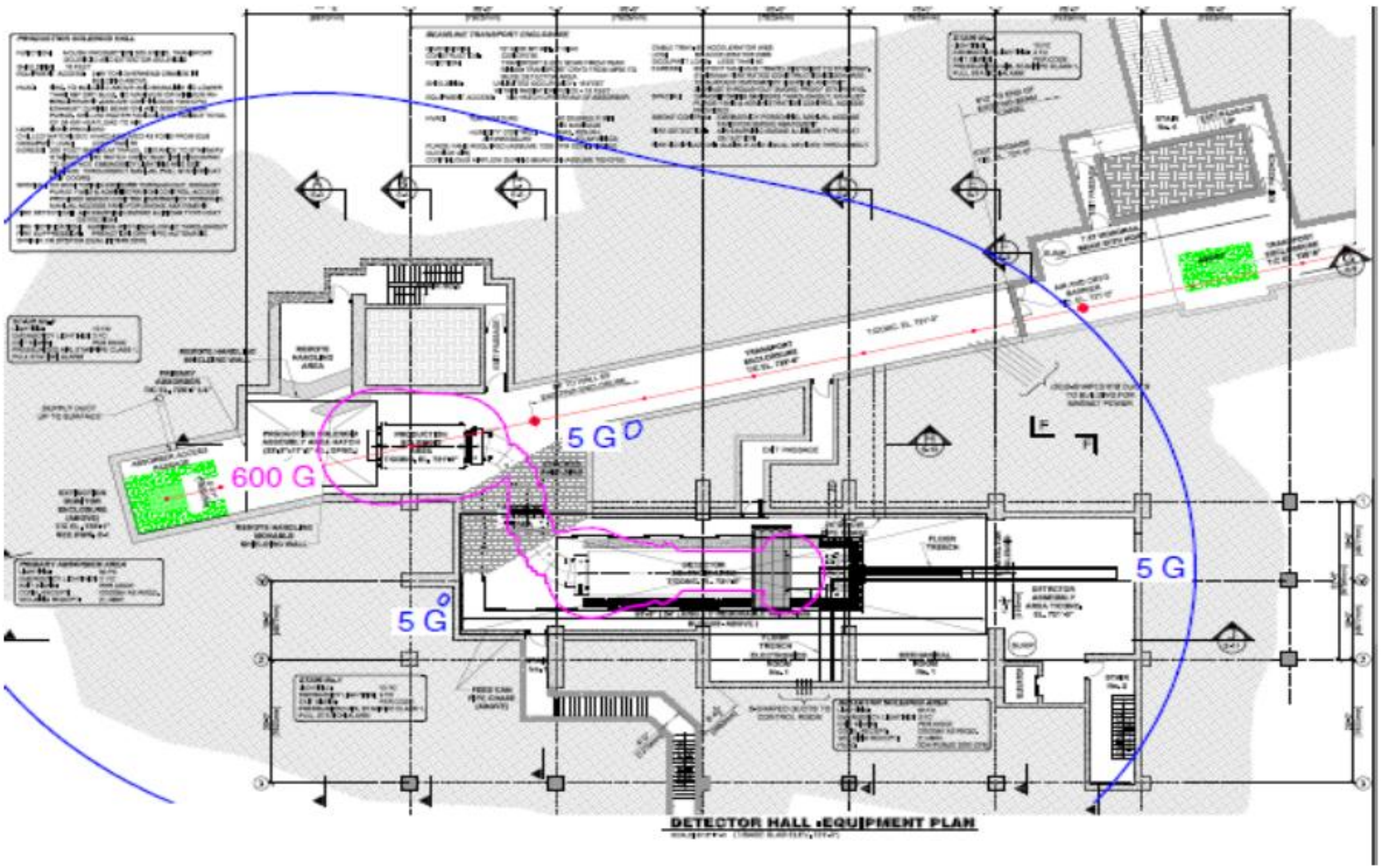
Preliminary data from Dec 2013 AlCap run
Muons stopped on Al target
No timing cuts

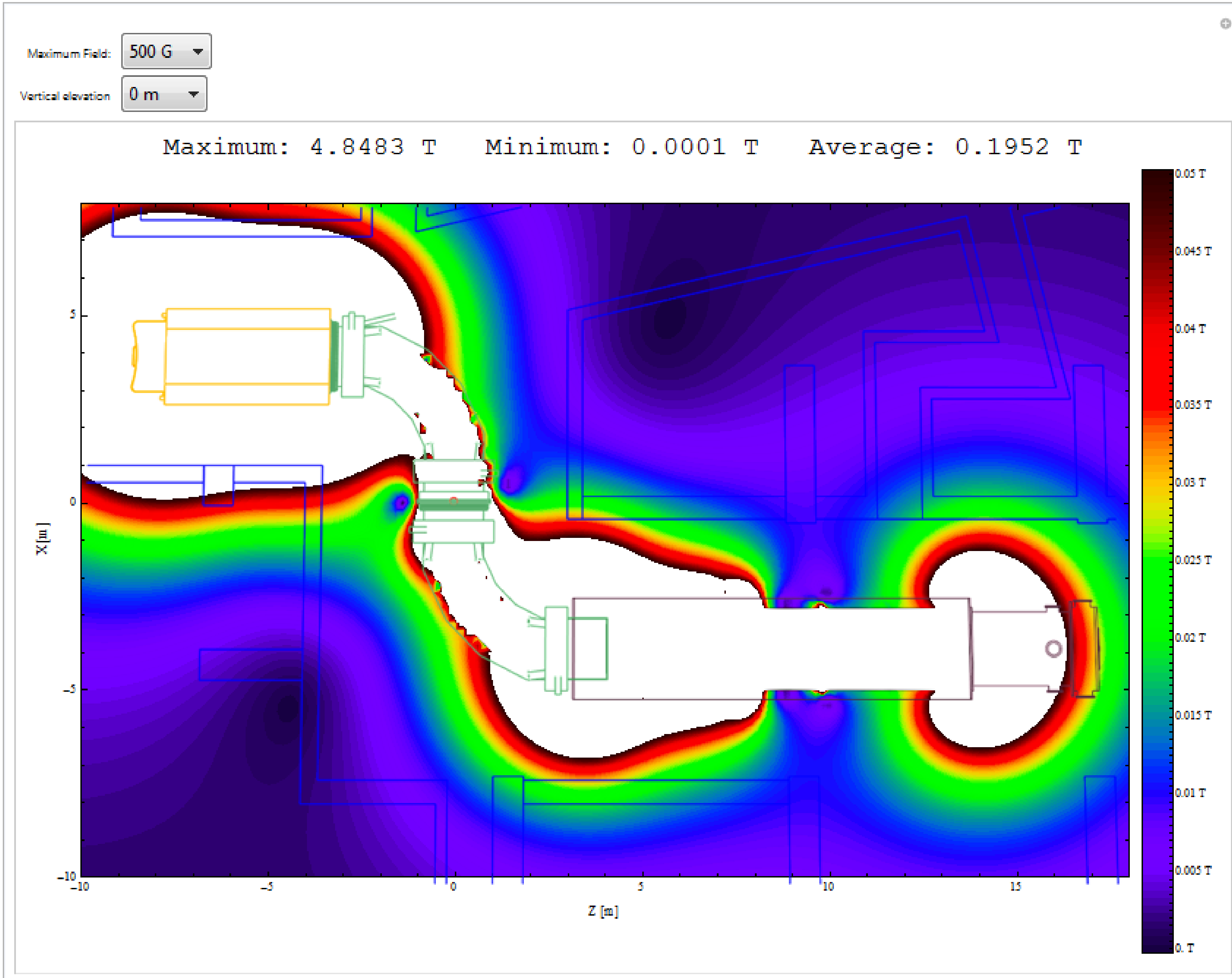
Floor plate layout

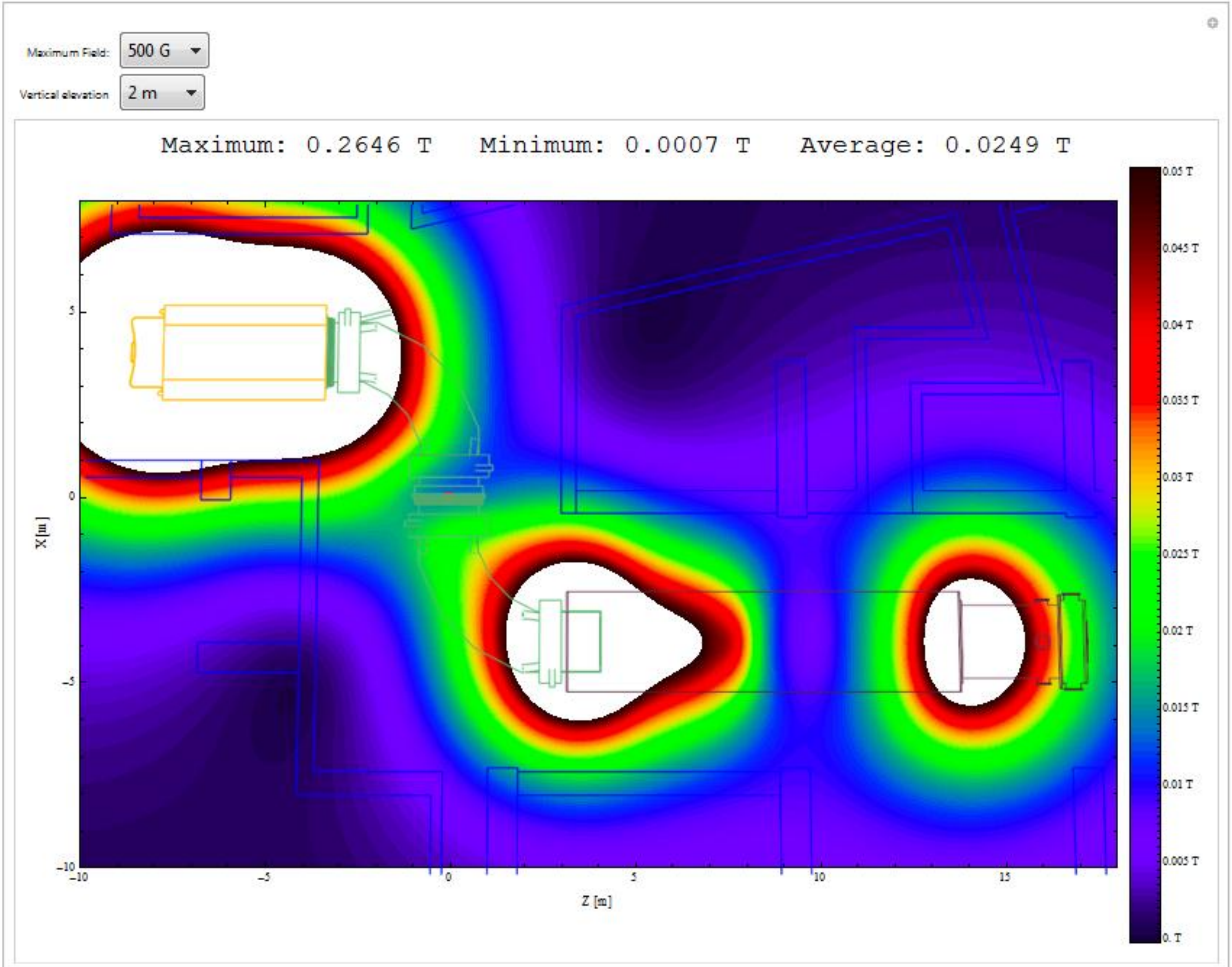




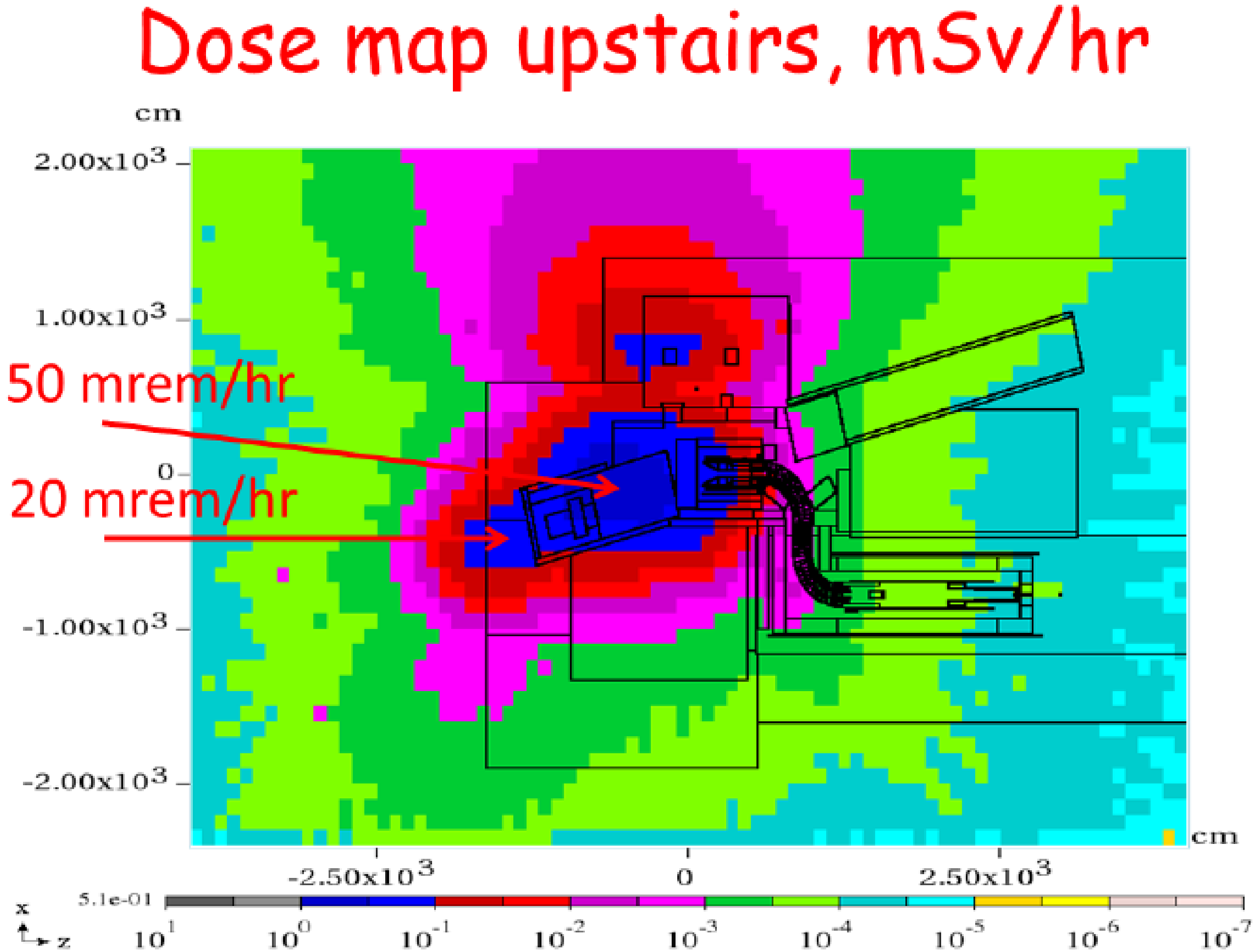
Mu2e Stray Magnetic Fields



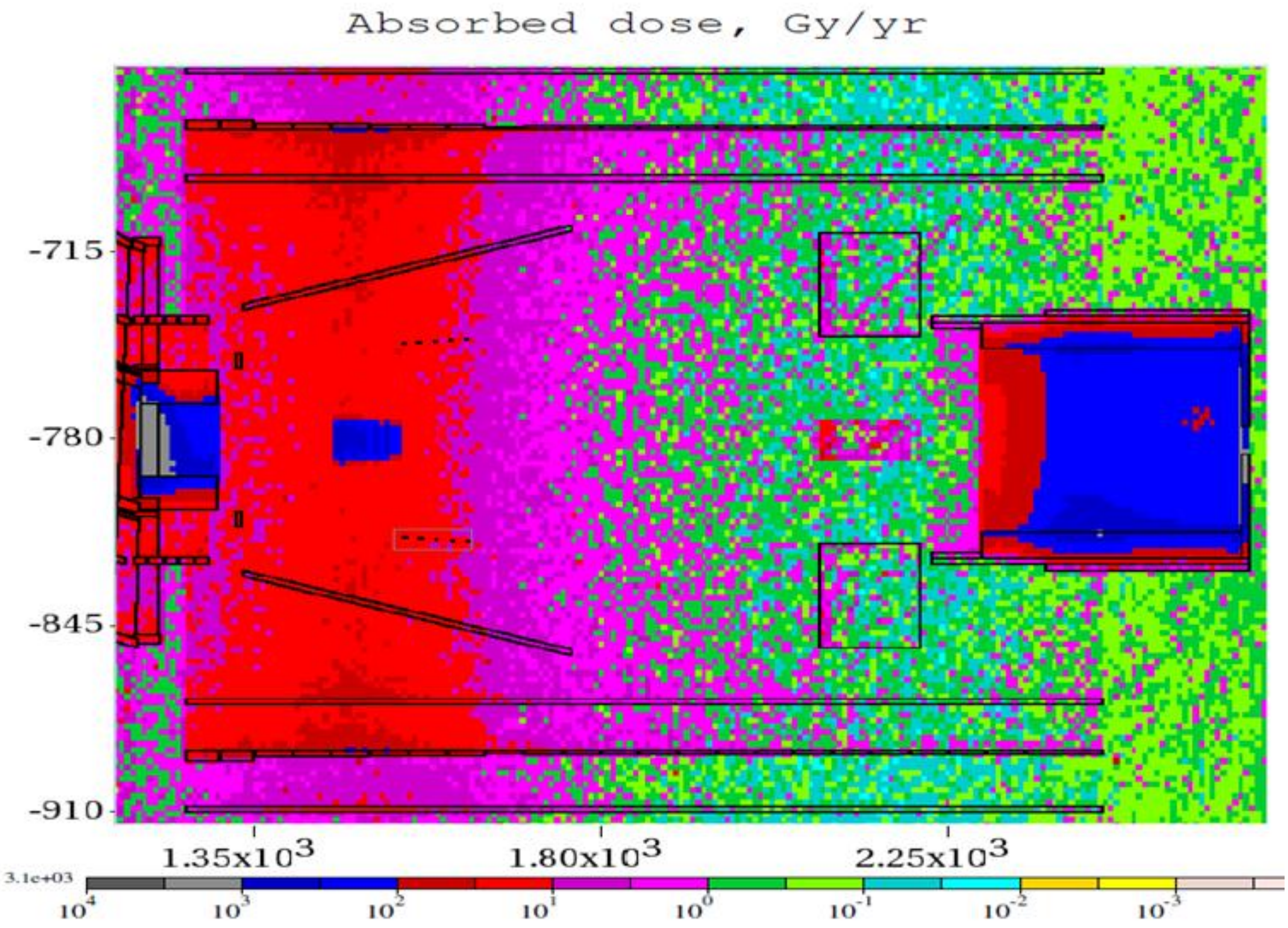

Maximum Field:
500 G
Vertical elevation
0 m
Maximum: 4.8483 T Minimum: 0.0001 T Average: 0.1952 T
X [m]
Z [m]
-10
-5
0
5
10
15
0.05 T
0.045 T
0.04 T
0.035 T
0.03 T
0.025 T
0.02 T
0.015 T
0.01 T
0.005 T
0. T


Maximum Field: 500 G
Vertical elevation 2 m
Maximum: 0.2646 T Minimum: 0.0007 T Average: 0.0249 T
X [m]
Z [m]
0.05 T
0.045 T
0.04 T
0.035 T
0.03 T
0.025 T
0.02 T
0.015 T
0.01 T
0.005 T
0. T

Radiation dose at ground level



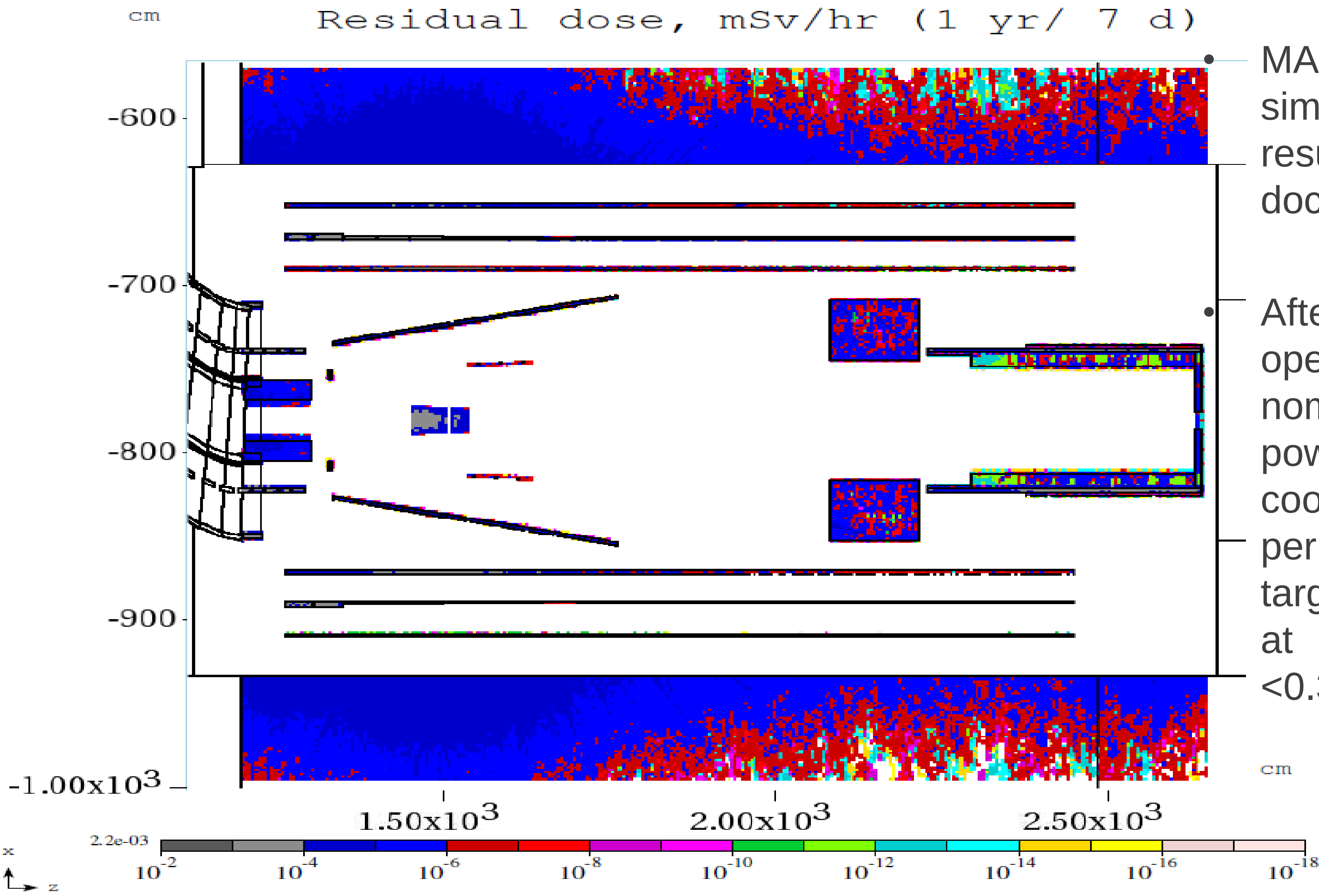
Absorbed Dose in Detector Solenoid Region (Gray/year)



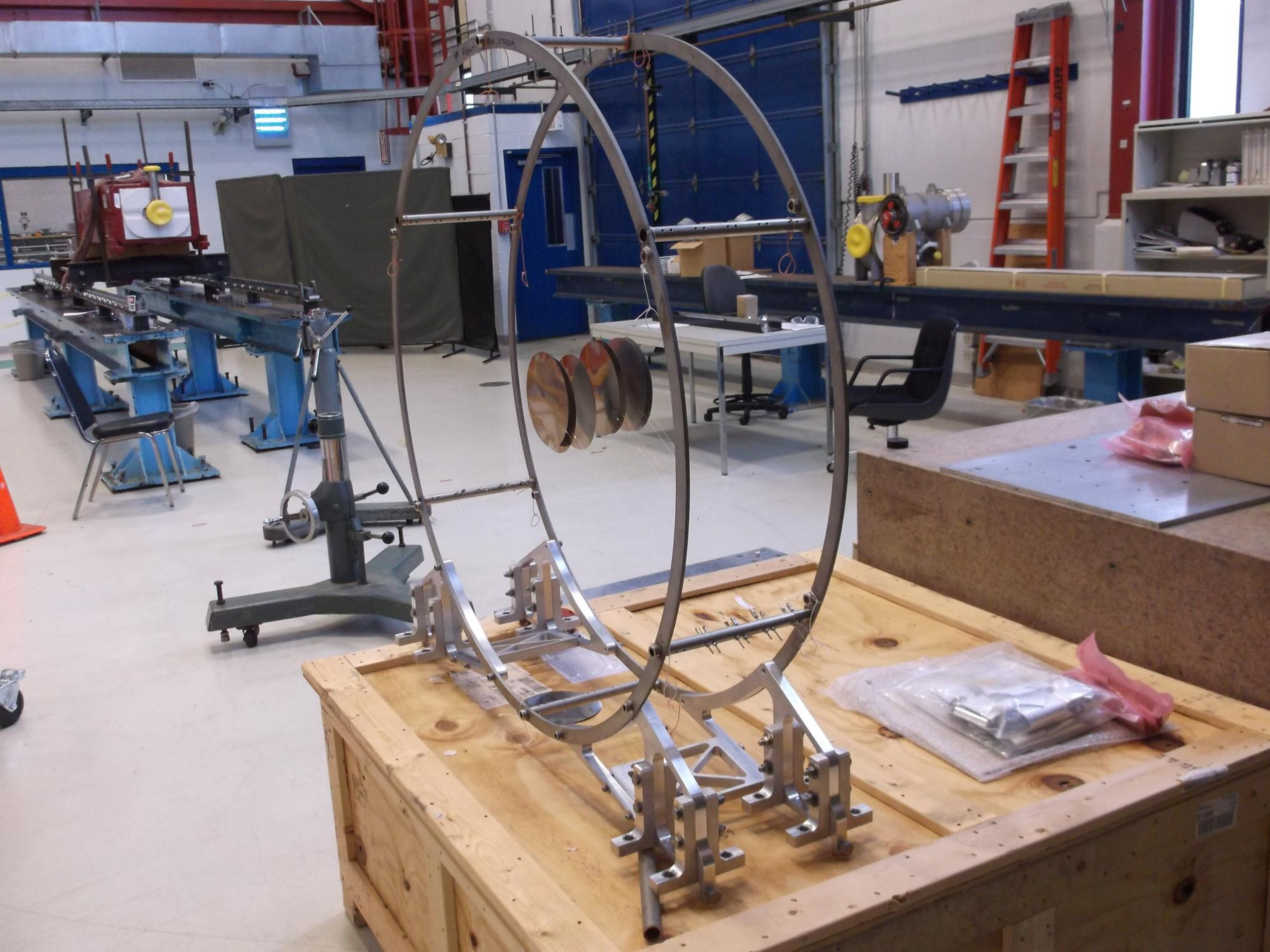
MARS simulation results per docdb 3593

~ kGray per year at the stopping target

Residual Dose in DS Region (mSv/hour)



- MARS simulation results per docdb 3593
- After 1 year of operation at nominal beam power and 7 day cooldown period, stopping target should be at <0.3mrem/hour



Mu2e Framework Simulation

- GEANT4 implementation of detailed geometry including the building, overburden, detector elements, target supports, solenoid coils and cryostats
- Physics list chosen to best describe HARP pion production data in relevant kinematic region. Utilize high precision list for neutrons < 20 MeV. Customized for muon capture/decay.
- Detailed hit-level tracker simulation includes effects of ionization drift in straws, gas amplification, signal transit, and electronic amplification, shaping, and digitization.
  - Also includes overlay of accidental occupancy from beam, μ capture and decay
- Reconstruction based upon simulated digitized “input”, forms hits, using full pattern recognition and track fitting