Fermilab

Mu2e CD-2 DOE Review
Accelerator Radiation Safety Improvements
475.02.04

A. Leveling

L3 Manager, Accelerator Radiation Safety 10/21-24/2014

WBS 475.02.04 Radiation Safety Improvements

Scope includes:

- Beam enclosure interlocks
  - Radiation Safety Systems
  - Electrical Safety Systems
- ODH for the Solenoid Rooms
- Muon Campus Total Loss Monitor systems
  - AP1 line to Delivery Ring
  - Delivery Ring
  - M4 beam line
- In Tunnel shielding
  - Delivery Ring at AP30 extraction
  - Temporary shield wall at the M4/M5 intersection
  - M4 line shield wall at Diagnostic Absorber
- Other
  - Friskers, wallflowers, air monitors

Requirements

- Fermilab Radiological Controls Manual (FRCM)
  - Key requirements:
    - Prompt radiation dose rate outside beam enclosure shields
      - Includes radiation skyshine
    - Residual activation in the beam enclosures
      - Most notable are AP30 extraction and PS Room
    - Entry Controls
      - AP30 service building not accessible during operations
    - Radiological Postings
      - Muon campus beam lines will require Controlled Area posting
    - Air activation
    - Surface water activation
    - Groundwater activation
    - Preliminary shielding assessments
      - Required before going out for construction bids
    - Exemption Request to allow use of interlocked radiation detectors in lieu of passive shielding
- The Radiation Safety Plan has to accommodate 8 kW operation

Design Assumptions

- Antiproton Source Facilities designed for 13 watts, 8 GeV
- Repurposed facilities now to operate at 8 kW, 8 GeV
- Available passive shielding is insufficient to meet requirements of FRCM
- Design basis:
  - the distribution of beam power lost
  - <u>not</u> the beam power delivered
  - this point will be illustrated
- The design must simultaneously:
  - meet all requirements for the FRCM, e.g.,
    - Limit the severity of single-pulse, beam loss within the time-weighted average FRCM dose limits
  - Not require inordinate beam operation interruption to recover from interlocked radiation detector trips
    - Implies a critical level of shielding is required for the facility
  - accommodate normal beam losses

Design Assumptions

- Known loss points
  - AP30 extraction region
  - Delivery Ring cleanup abort dump
  - Extinction Collimators
  - Diagnostic Absorber
  - Mu2e Production Solenoid
  - Mu2e Main Beam Absorber

- Other potential loss points
  - Delivery Ring Injection
  - Delivery Ring Cleanup Abort beam line
  - Delivery Ring distributed losses due to beam scattering at extraction region

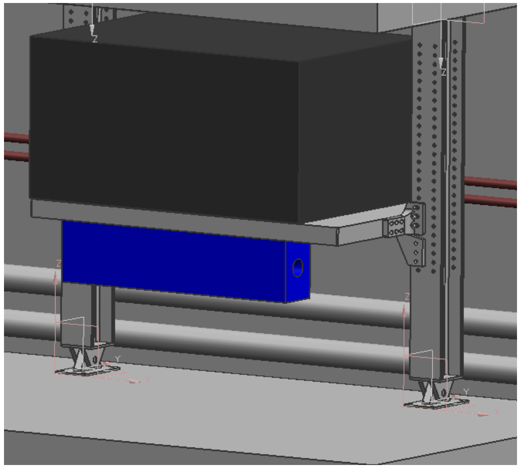
- The design assumes:
  - beam loss at known loss points
  - no significant losses at other potential loss points

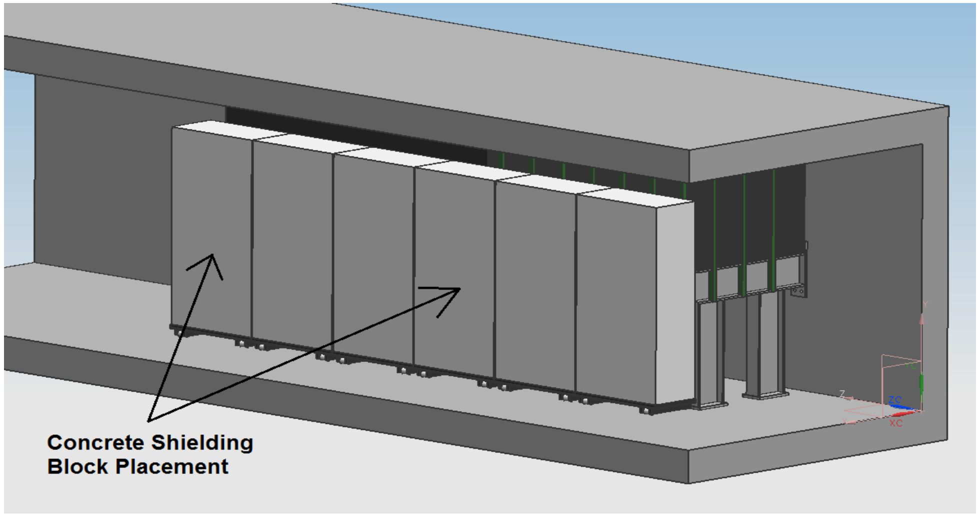
Design Activities

- An in-tunnel shield design has been produced to shield the AP30 extraction region
  - Can be adapted to other locations if found to be required
- A new radiation beam loss detector has been developed and characterized
  - Total Loss Monitor System
    - Provides continuous coverage of beam loss through areas of common shield thickness
    - Conservatively limits total beam loss based upon trip levels established for single point beam loss
    - Serves as active protection in the capacity of a credited safety system
      - Preliminary approval has been given by the ESH&Q Section
    - Complete systems are now being deployed at Booster accelerator
- MARS simulations for TLM detector have been produced to predict response
- MARS simulations and measurements have been made to study shield/TLM design combinations for beam loss conditions

In-tunnel shielding at AP30 extraction region

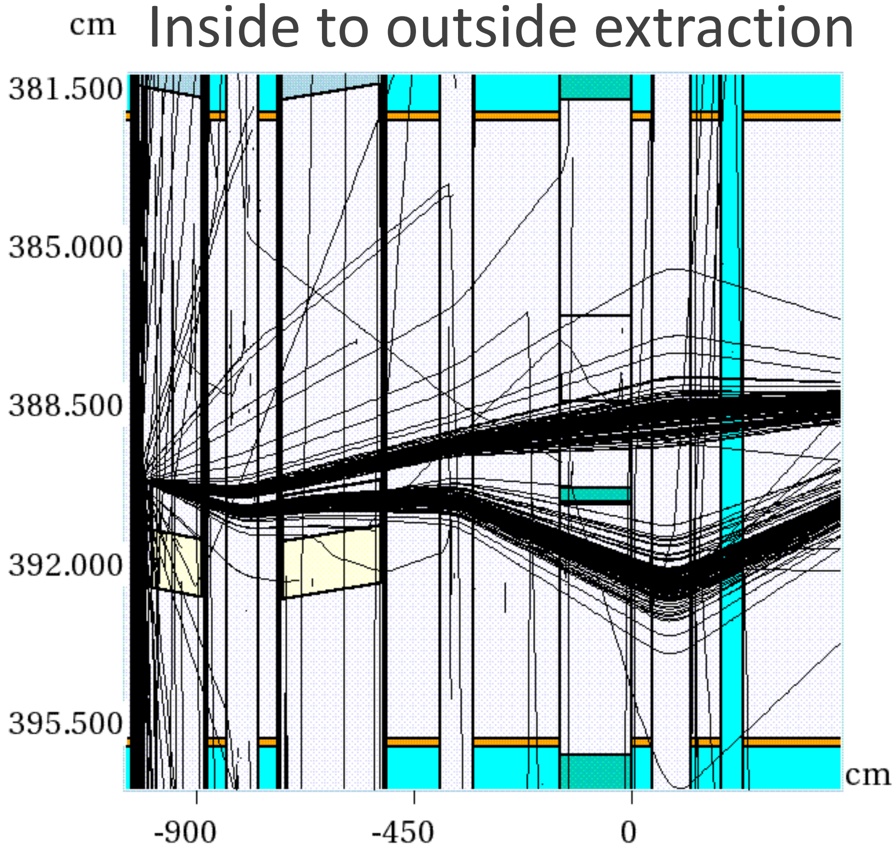
- The design for in-tunnel shielding has been created
  - Modular
  - Requires unobstructed clearance above the loss points
  - Cable trays, especially at AP30, have to be re-routed
    - This is already underway
  - Aisle shield is included to limit worker radiation exposure (ALARA)
  - Shield design has been incorporated into the resonant extraction line MARS simulation

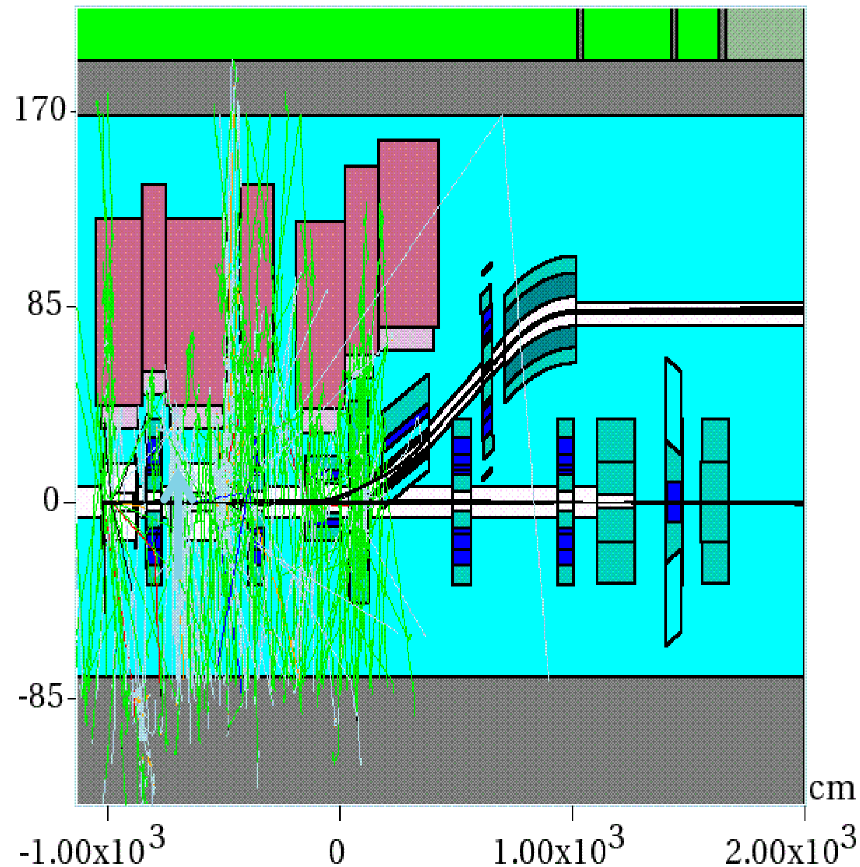




MARS simulation is used to predict beam loss and prompt radiation effective dose with in-tunnel shielding

Inside to outside extraction



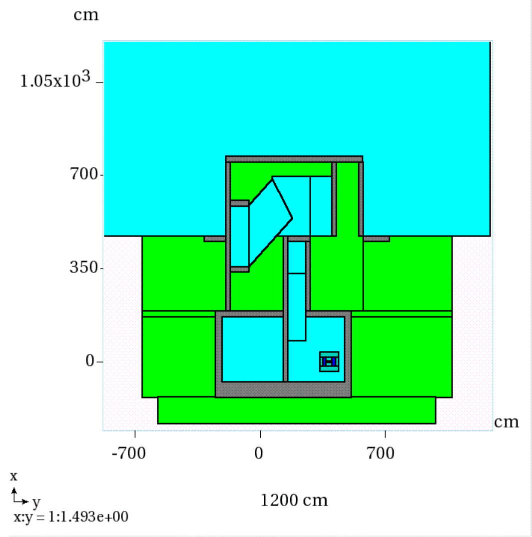


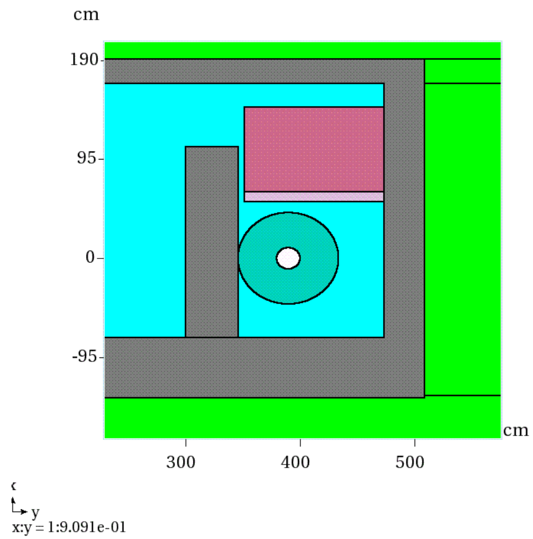
Plan view
Proton beam through the Electrostatic septa, quads, Lambertson, and cmagnet

Elevation view
Full extraction system model with in-tunnel shielding

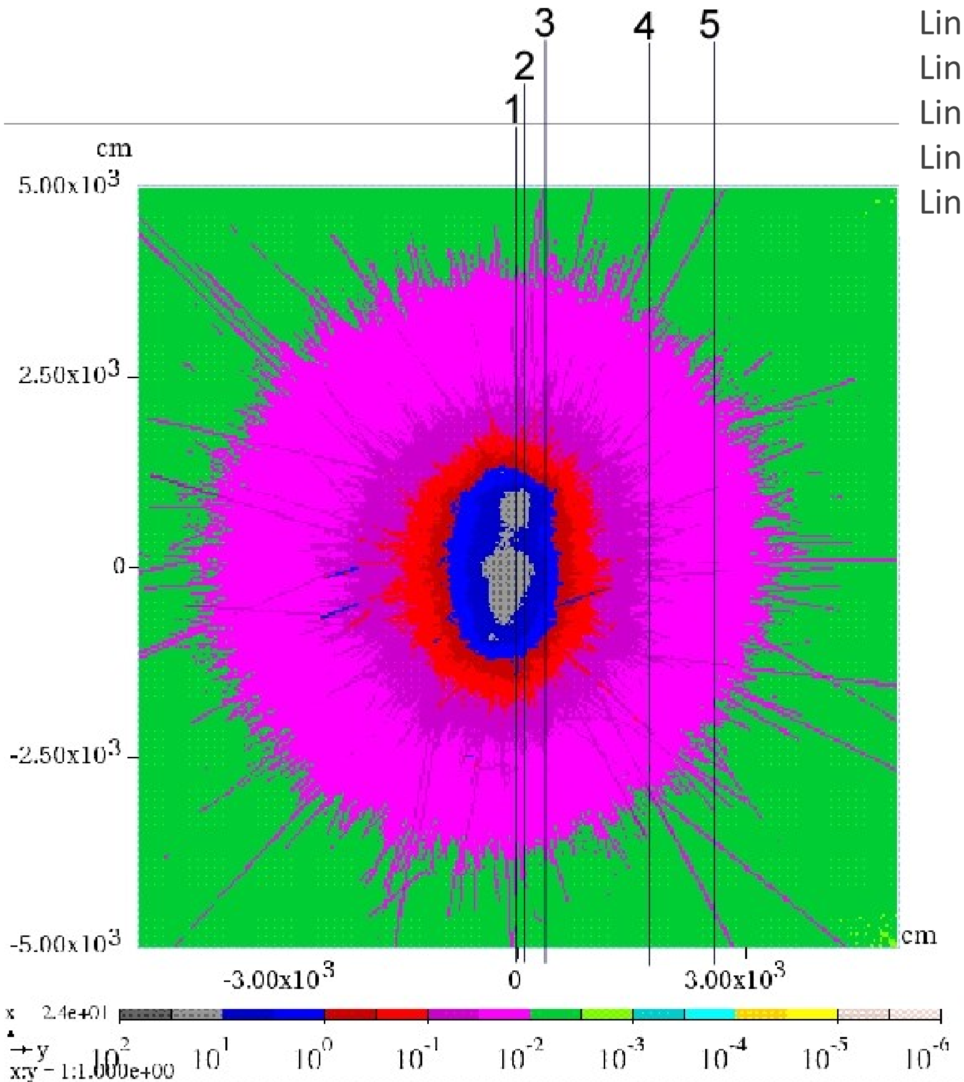
Extraction system model detail

- A detailed model of the aisle shield and the exit stairway near the extraction region is included in the MARS simulation





MARS simulation results for AP30 service building region



Line 1: Delivery Ring centerline – 24 mrem/hr

Line 2: Tunnel outer concrete edge – 1 to 5 mrem/hr

Line 3: Edge of service building

Line 3/4: Parking Lot 0.05 to 2 mrem/hr

Line 5: Edge of Indian Road <0.05 mrem/hr

Normal losses at extraction region running at 8 kW

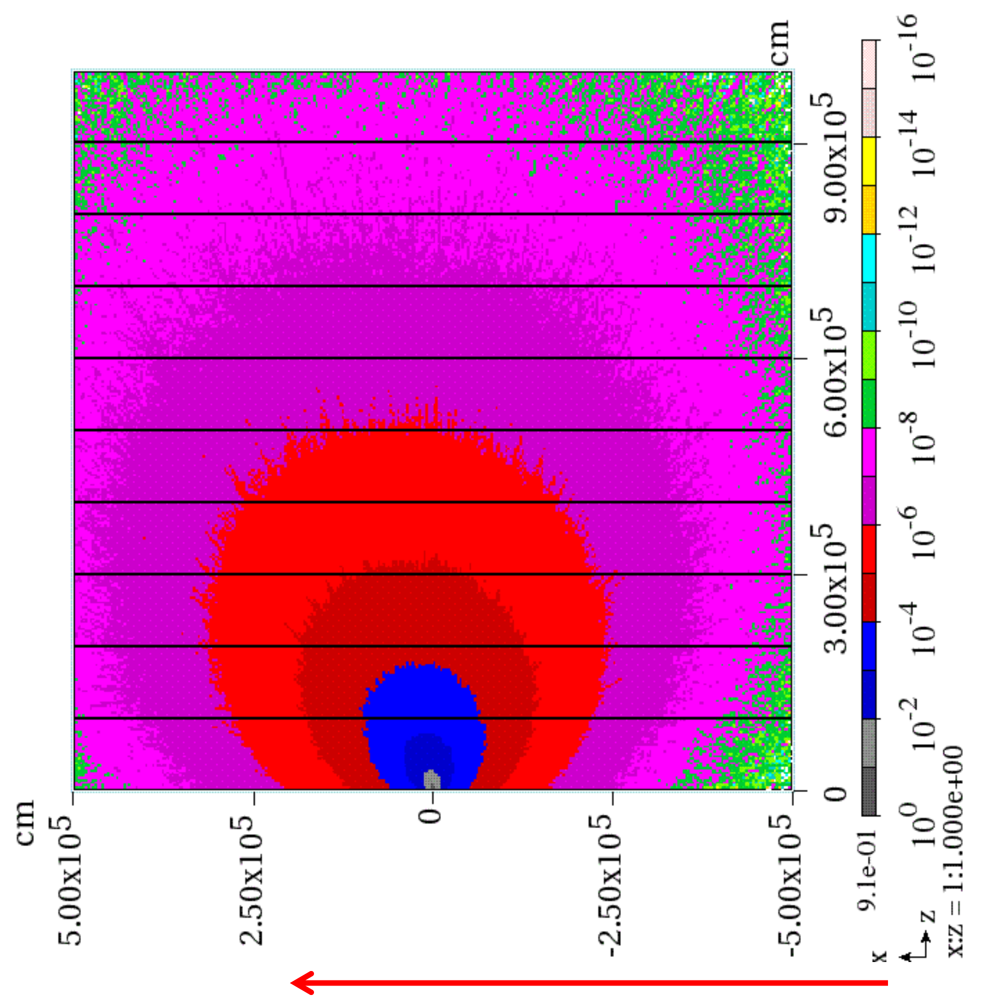
Includes direct and skyshine contributions

Units are mrem/hr

MARS simulation result for radiation skyshine – mrem/hr

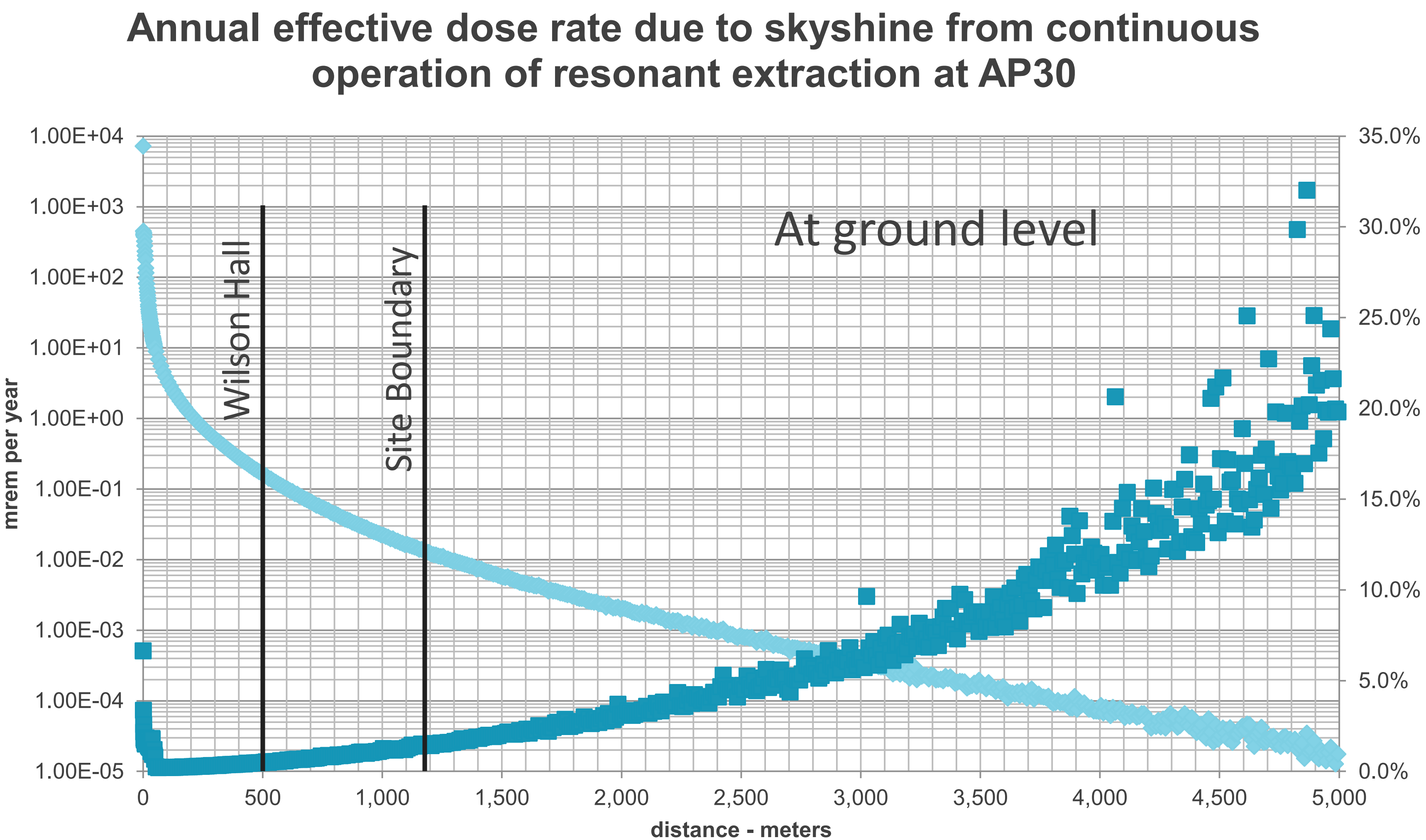
Radiation skyshine has been calculated using the model for slow resonant extraction at AP30.

This model has a radius of 5 km and a height of 10 km.



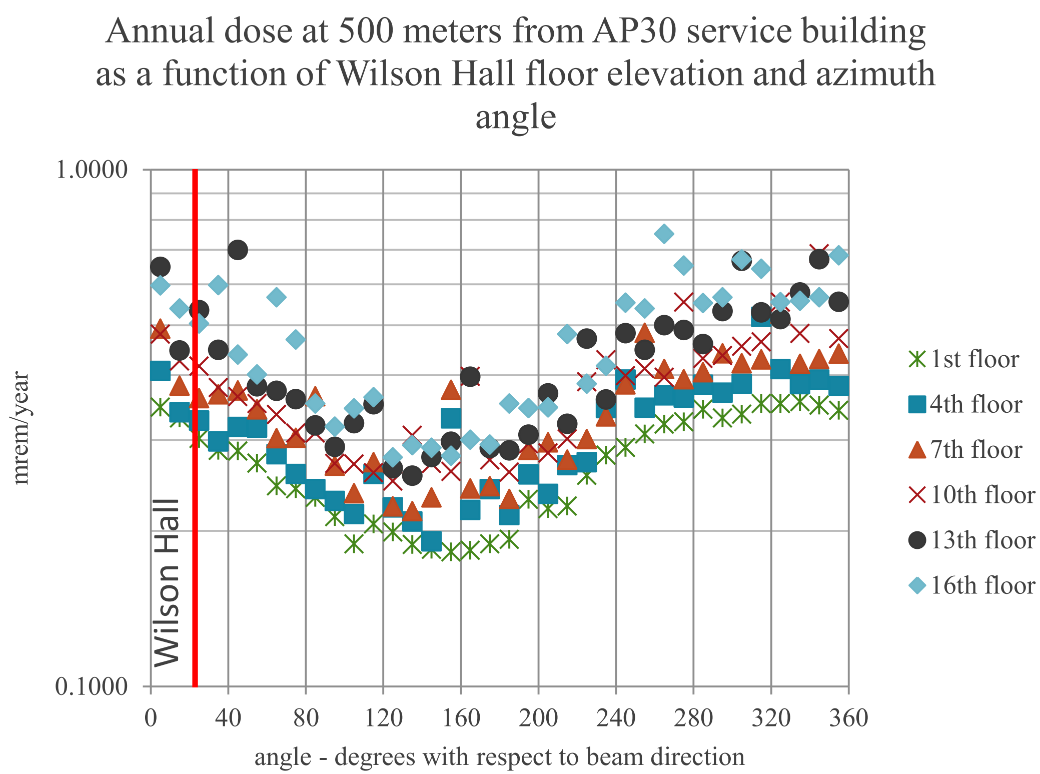
Proton beam direction

MARS simulation result for radiation skyshine

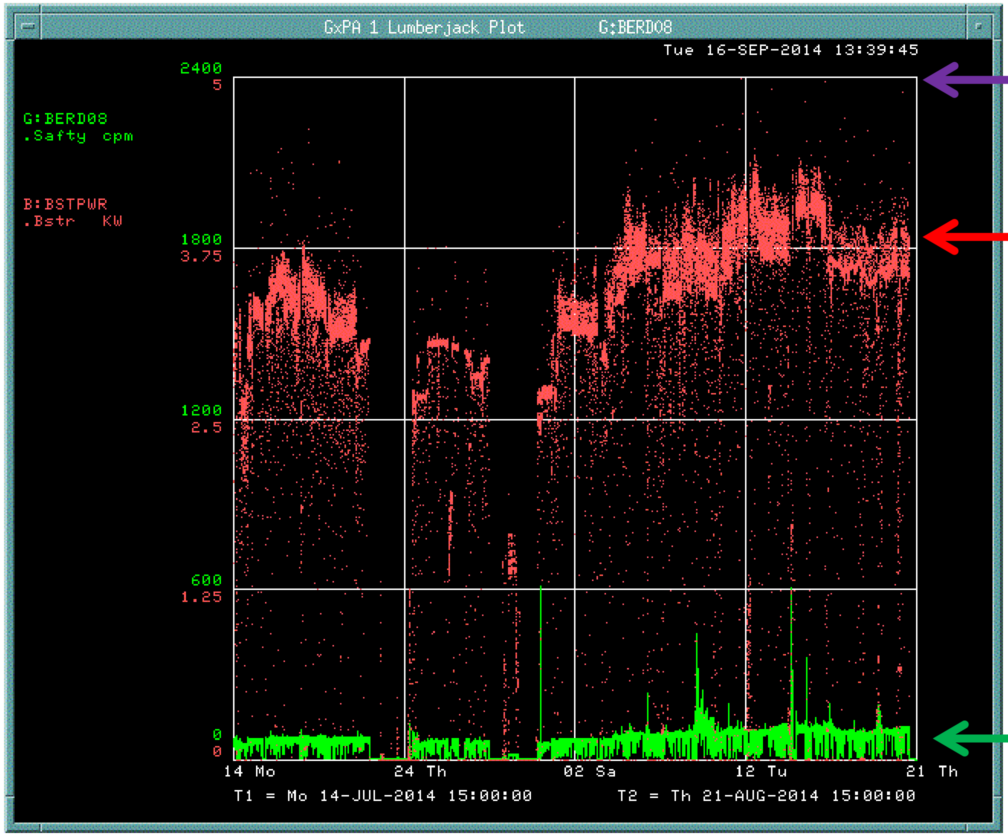


MARS simulation result for radiation skyshine

- In addition, the annual effective dose rate at Wilson Hall as a function of floor has been calculated based on the extraction system model. Radiation dose rates are acceptable



Booster Beam power/beam loss illustration & TLM Response



Proposed TLM trip limit

Booster beam power

Peak 30 to 35 kW

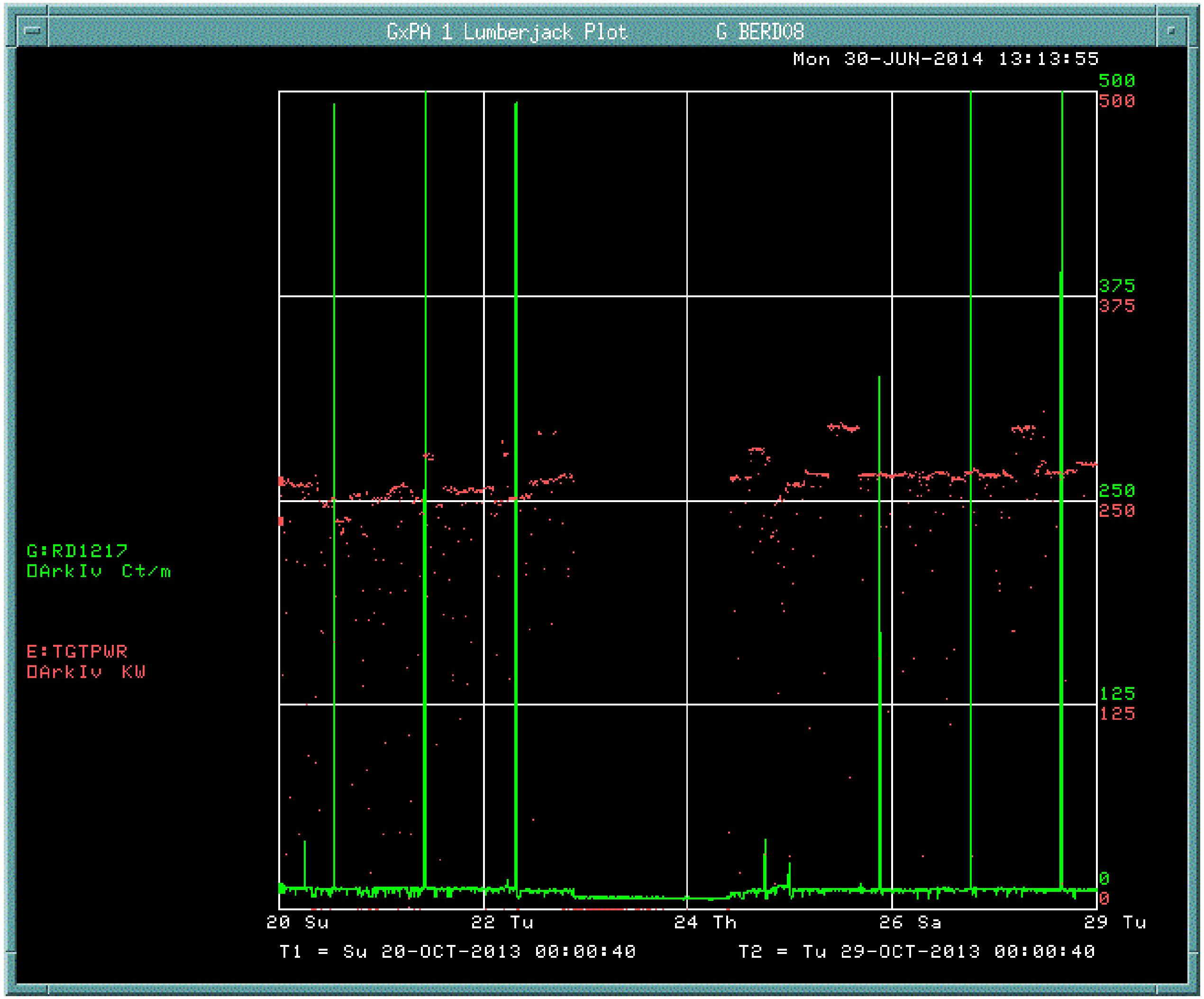
180' TLM response

1/8th of the Booster Ring

A thirty-eight day operating period July 14 -> August 21, 2014

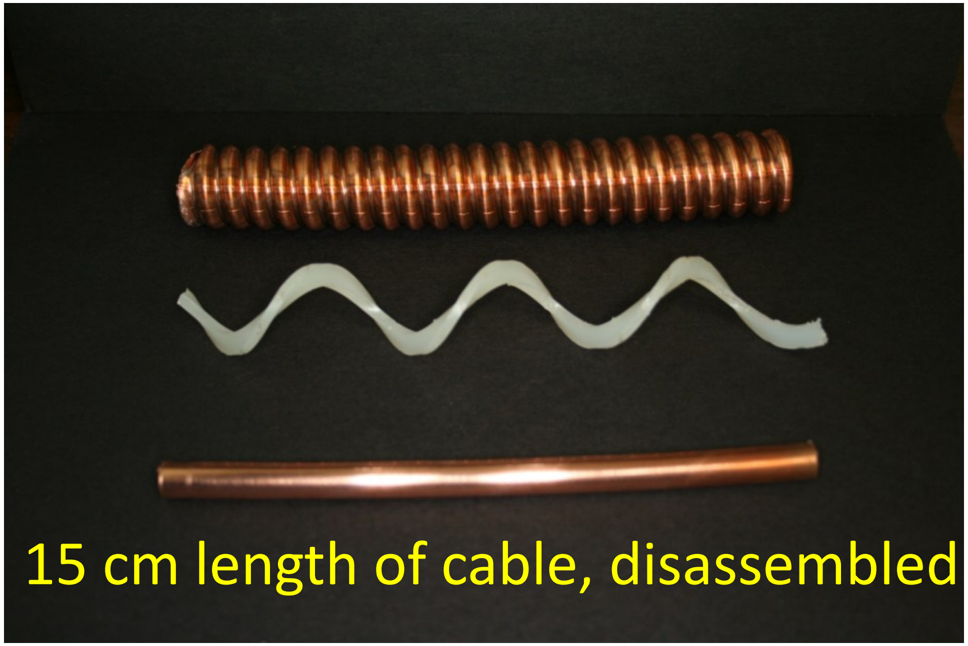
NuMI Beam power/beam loss illustration & TLM Response

- 800 foot TLM installed (green trace) at NuMI
- 250 kW beam transmission (red trace) & minimal losses
- Losses are quite insignificant except when wire chambers are inserted for tuning

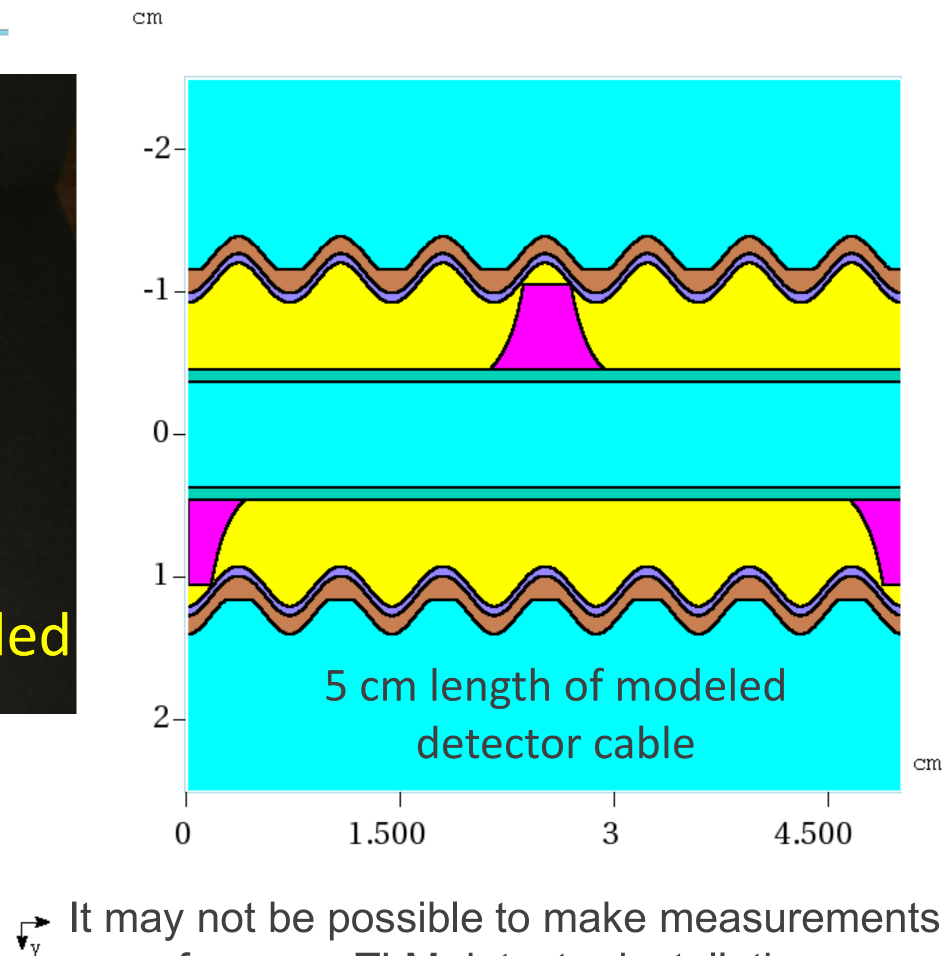


A nine day operating period October 20-> October 29, 2013

TLM detector cable



MARS model of detector cable components has been produced; MARS simulations have been compared with experimental data



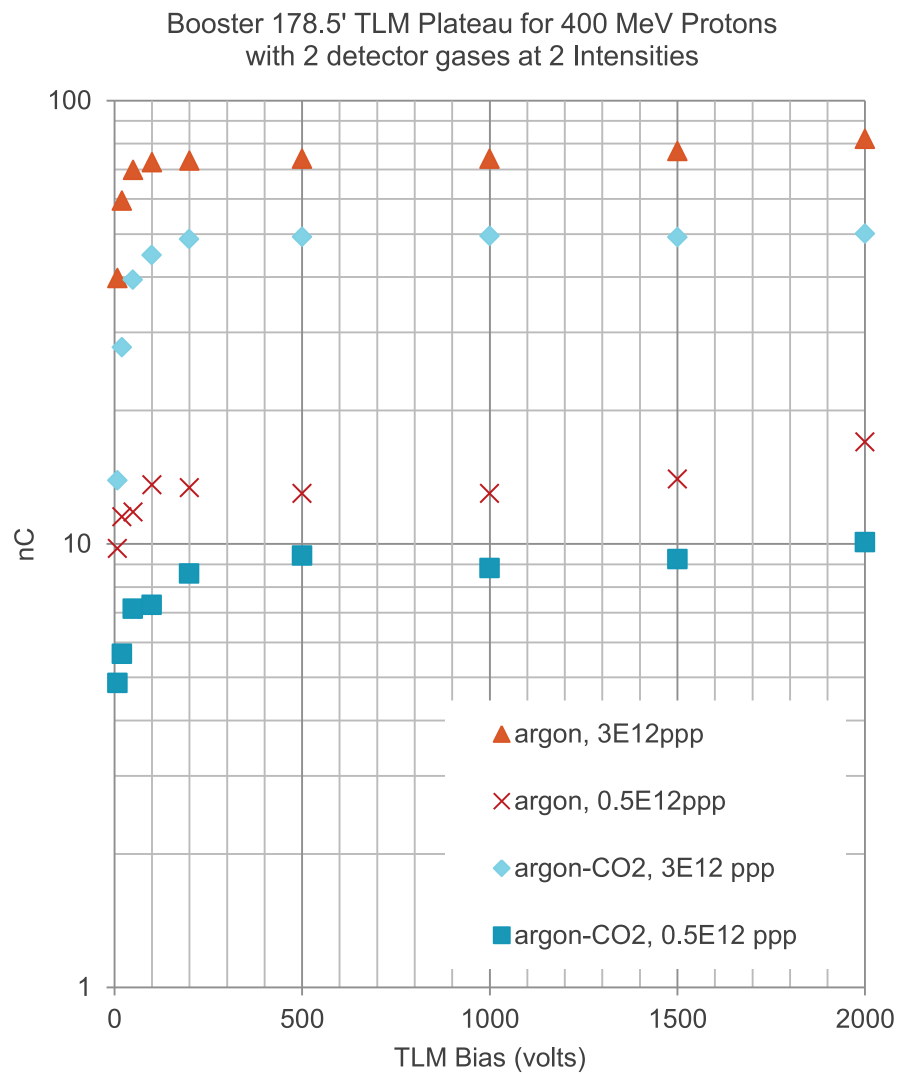
It may not be possible to make measurements for every TLM detector installation; consequently, it is important to have a method to predict TLM response

Changes since CD-1

- Developed detailed MARS models for
  - Slow resonant extraction system
  - In-tunnel shielding
  - Skyshine
  - TLM detector cable
- Developed a remote method to monitor TLM detector gas flow at 25 cc/minute with commercially available detector
- Added scope - external beam line shielding walls
  - M4/M5
  - M4 line DS of diagnostic absorber
- Developed TLM electrometer & heartbeat
- Expanded our understanding of TLM system response (Booster, NuMI, pbar)
- Found an application of the TLM system which should accelerator the approval process
  - Booster CY14

Value Engineering since CD-1

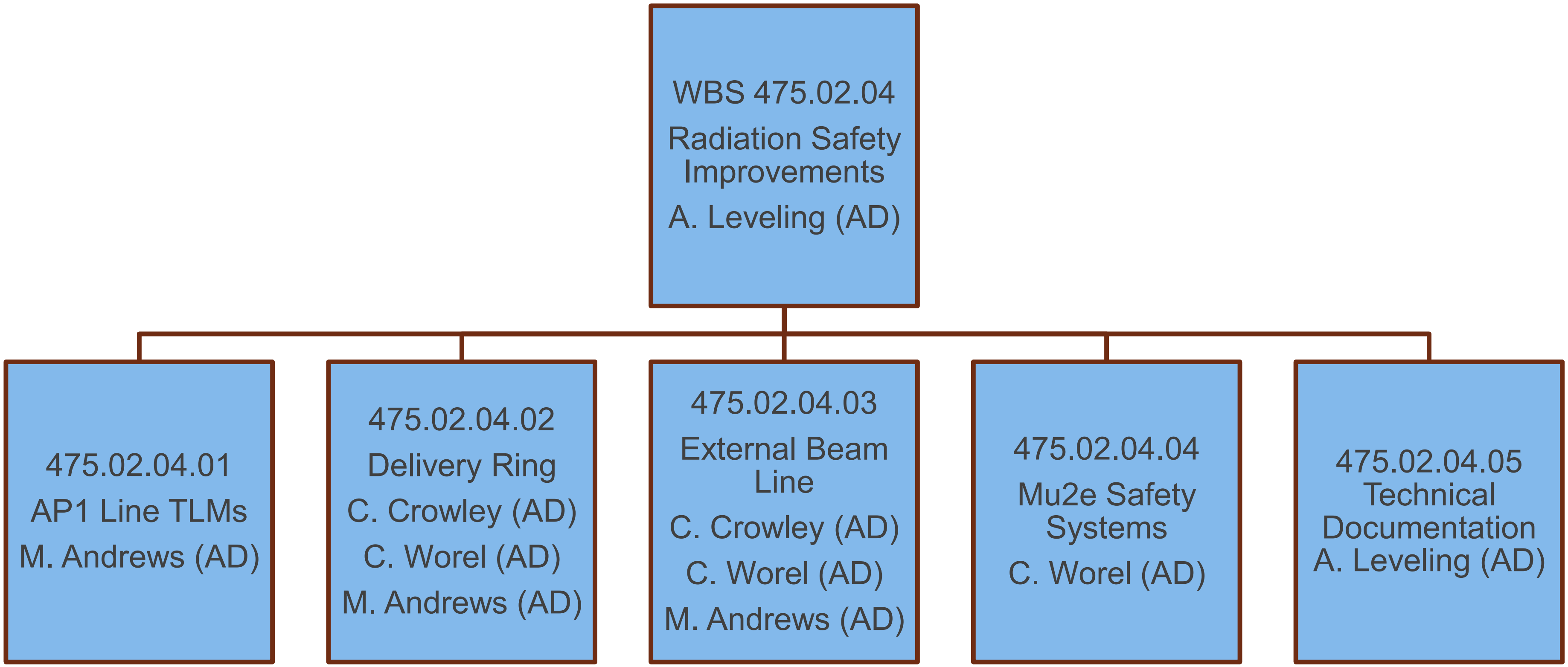
- Changed TLM detector gas from argon to argon/CO_2
  - Lower sensitivity
  - flatter response
  - Lower detector gas cost
  - Increases the dynamic range of the TLM system



TLM review status

- TLM testing continues following preliminary approval
  - Entire Booster has been outfitted with detector systems
  - 1/8 of the Booster has a parallel redundant TLM system
  - Existing credited safety system inputs (chipmunks) will run in parallel with the new TLM system
  - Upon completion of a test period and system documentation, we will seek final approval from ESH&Q Section
  - Additional MARS simulations, measurements, and inter-comparisons are planned
    - MI-52
    - MI-30
    - NuMI
    - ASTA
  - TLM approval is expected well in advance of Mu2e

Organizational Breakdown



Quality Assurance

- ***In-tunnel shielding***
- AD mechanical engineer created structural design
- Design is documented in an engineering note
- Design is subject to two reviews:
  - Facility Engineering Services Section reviewed the design for compatibility with tunnel enclosure structures
  - AD Mechanical Review committee
- Installation oversight is by AD Mechanical Support Department engineers
-
- ***Radiation and Electrical Safety Systems***
- Proven design in use for decades at the Laboratory
- The RSS and ESS designs are subject to review and approval by the ESH&Q Section
- RSS and ESS undergo thorough testing every 6 months

Quality Assurance

- ***TLM system design***
- System design is subject to review and approval by the ESH&Q section.
- TLM system installation is under the purview of the AD ES&H Department Interlocks Group.
- Initial testing of the detector and electrometer installation is by AD ES&H Department Interlocks Group
- The TLM system will be subject to periodic calibration and testing by AD ES&H Department Interlocks Group
- Specific applications of TLM systems are subject to review by the Laboratory's Shielding Review Committee (SRC) in conjunction with the shielding review process
- Final approval is by the ESH&Q Section Head

Risks – Radiation Safety Improvements

Risk ID	Risk Form	Risk	Impact	Probability	Action
ACCEL-020[1]	3333	TLMs cannot be used to limit the intensity and duration of beam loss	Technical, Schedule	Very Low	pending
ACCEL-017[2]	3332	Radiation levels outside of the mu2e facility are too high	Schedule	Low	Transferred to operations
ACCEL-152[3]	3838	Need to install additional Delivery Ring tunnel shielding (list B)	Technical	Medium	Transferred to operations
ACCEL-150[3]	3839	Need to install additional DR tunnel shielding (list C)	Cost	Low	Transferred to operations

NOTES:

1. Preliminary Approval has been received for TLMs. Expect final approval in CY 2015.
2. Improved MARS simulation with extraction device details indicate losses will be low enough. We will need to tune up machines to reduce losses to acceptable levels and believe this will be possible.
3. Based upon observation of losses at other machines, we believe it is possible to run with very low losses, e.g., NuMI, Booster. We will need to tune up machines to reduce losses to acceptable levels and believe this will be possible.

ES&H

- Air activation
  - No unusual issues
- Surface water activation
  - No unusual issues
- Groundwater activation
  - No unusual issues
- Residual radiation
  - ALARA planning
    - Extraction Region Maintenance
    - Target change out

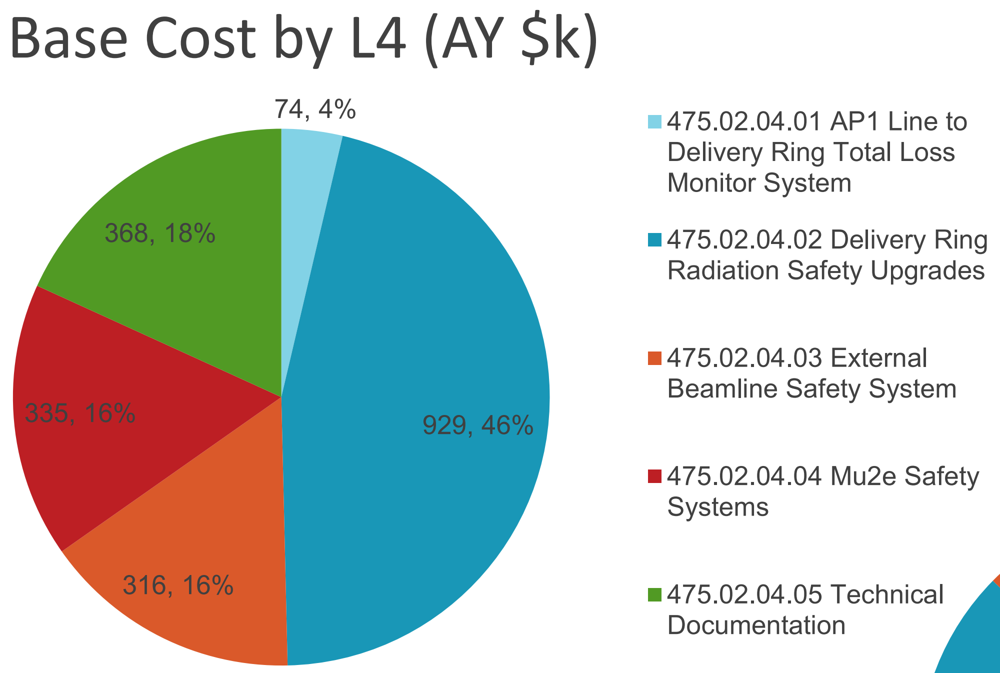
Cost Table

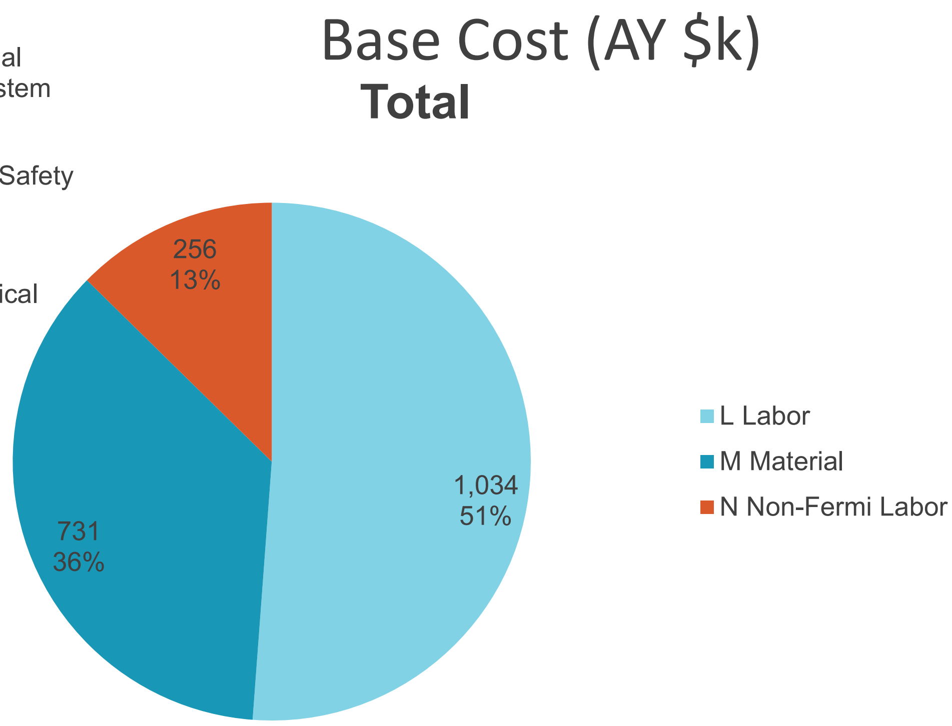
WBS 2.4 Accelerator Radiation Safety Improvements

Costs are fully burdened in AY $k

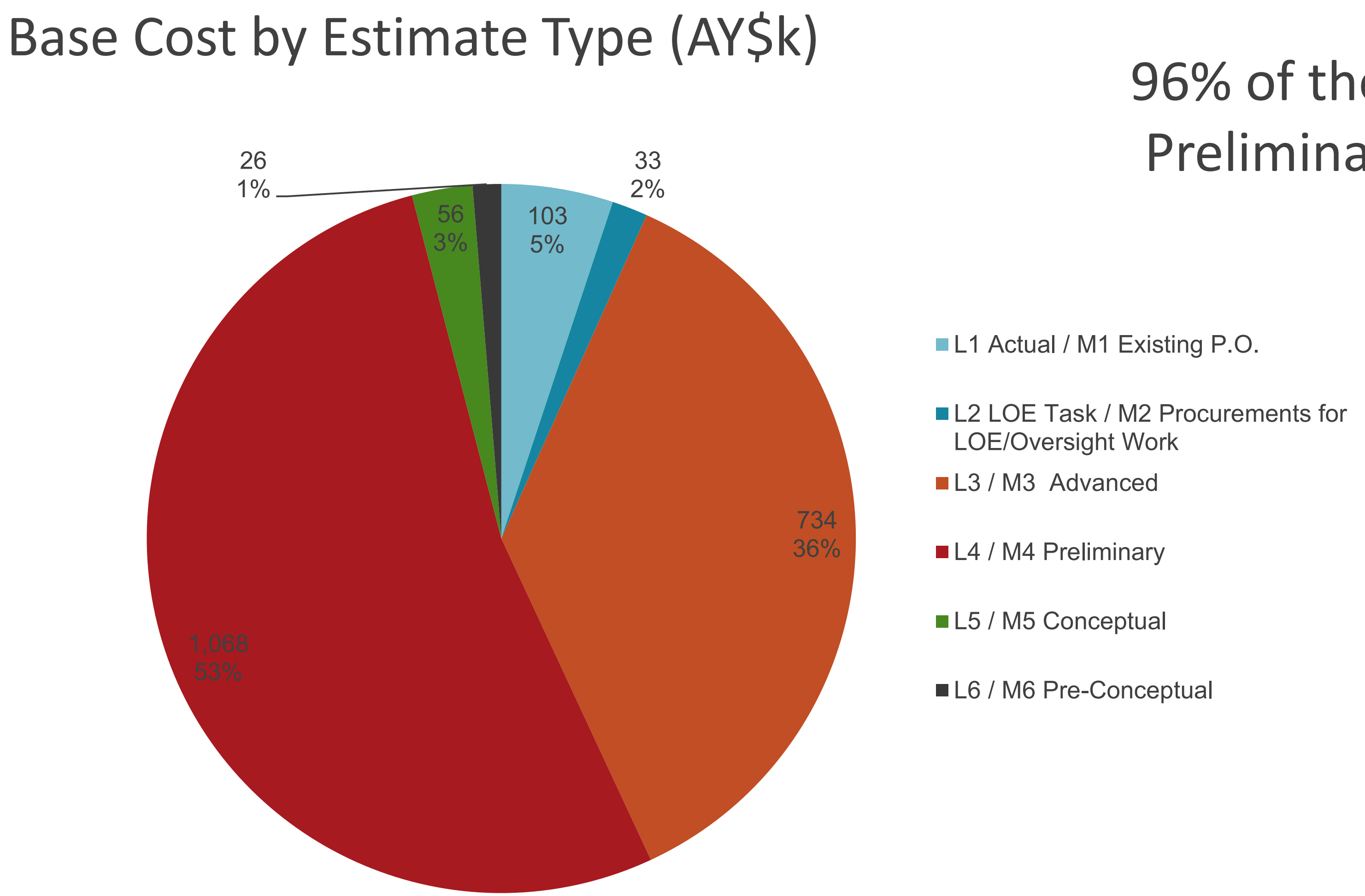
	Base Cost (AY K$)					
	M&S	Labor	Total	Estimate Uncertainty (on remaining budget)	% Contingency on (on remaining budget)	Total Cost
475.02.04.01 AP1 Line to Delivery Ring Total Loss Monitor System	38	37	74	18	30%	92
475.02.04.02 Delivery Ring Radiation Safety Upgrades	597	331	929	236	32%	1,164
475.02.04.03 External Beamline Safety System	180	135	316	102	36%	417
475.02.04.04 Mu2e Safety Systems	171	164	335	74	22%	409
475.02.04.05 Technical Documentation		368	368	67	23%	434
Grand Total	986	1,034	2,021	497	29%	2,517

Cost Breakdown – Radiation Safety Improvements



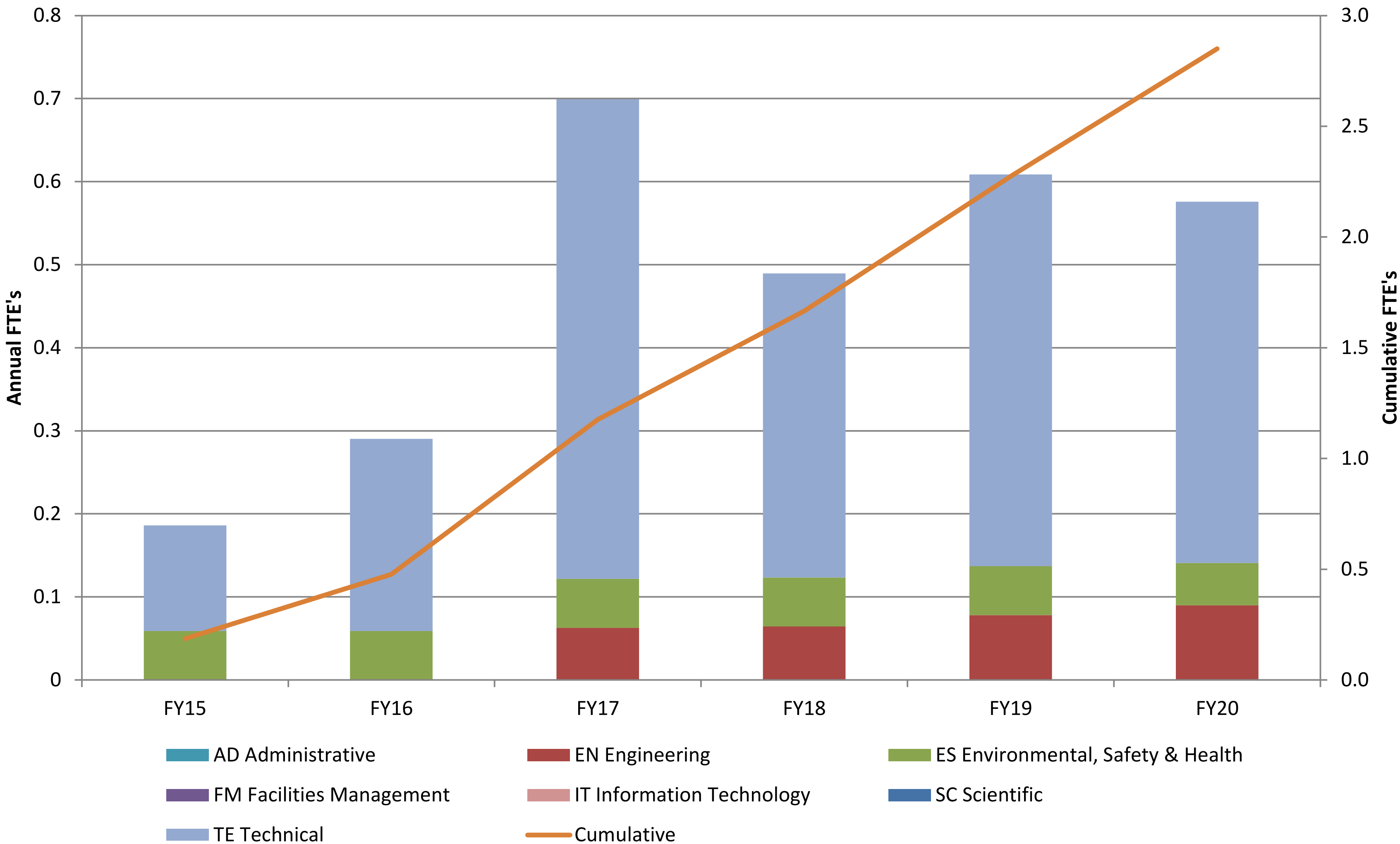


Quality of Estimate



96% of the estimate is Preliminary or better

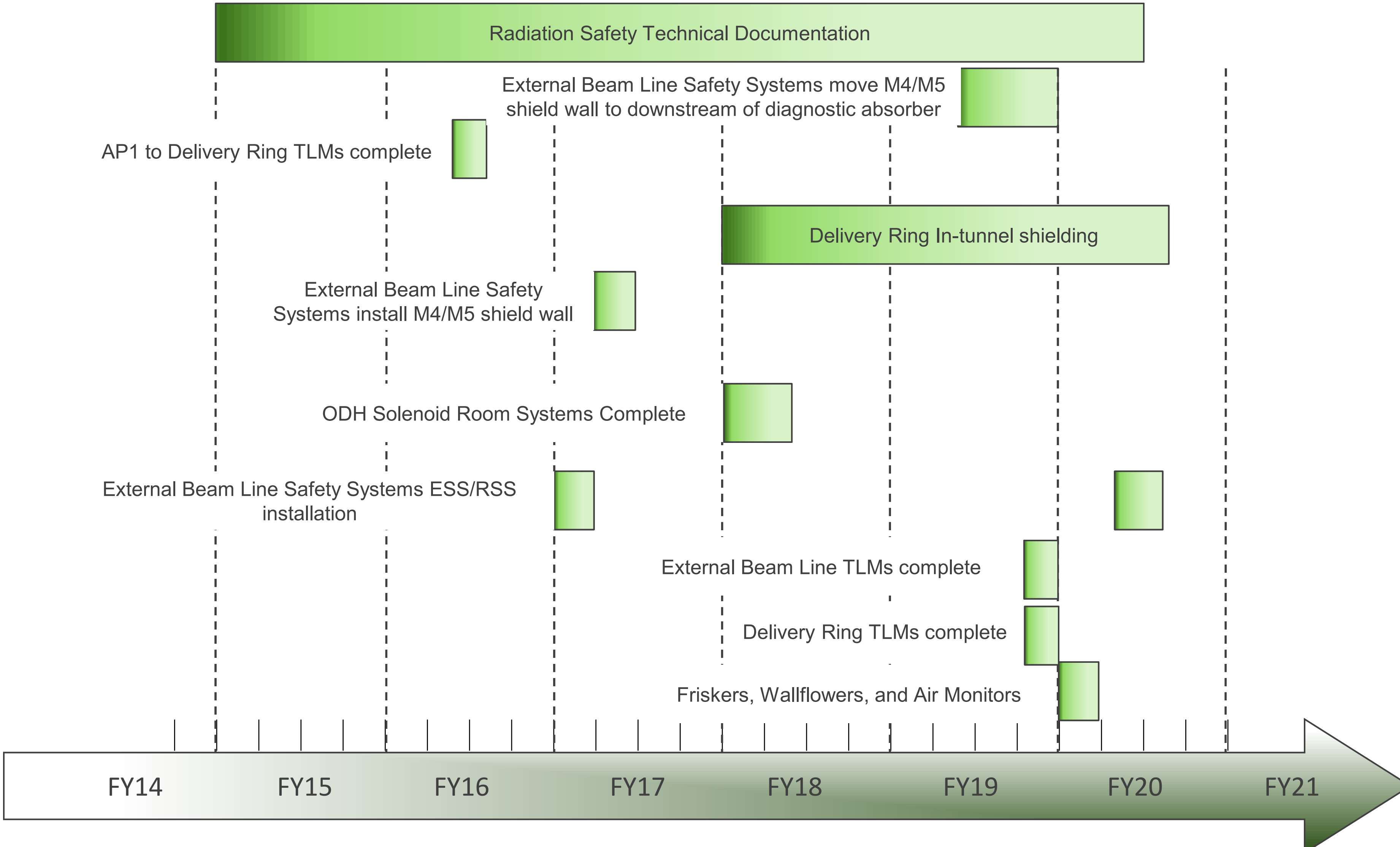
FTEs by Discipline



Major Milestones

47502.04.001050	T5 - Mu2e Radiation Safety System Conceptual Design Complete	28-Jun-12 A	T5
47502.04.001060	T5 - Mu2e Radiation Safety System Preliminary Engineering Design Complete	20-Dec-13 A	T5
47502.04.02.1.001004	T5 - Resolution of revisions to beam line geometry at M4 line at extraction from delivery ring	20-Dec-13 A	T5
47502.04.001090	T5 - M4 Shield Wall Ready for g-2 Beam Operations	28-Feb-17	T5
47502.04.03.1.001080	T5 - External Beamline Safety System Interlocks Complete	18-Apr-17	T5
47502.04.02.1.001075	T5 - Start Procurement for Delivery Ring In-Tunnel Shielding	2-Oct-17	T5
47502.04.04.2.1050	T5 - External Beamline Enclosure Safety Systems Complete	24-Apr-18	T5
47502.04.04.4.1050	T4 - ODH Safety System Installation Complete	25-Apr-18	T4
47502.04.04.1.1110	T4 - Target Hall Safety Systems Complete	18-Jul-19	T4
47502.04.03.3.001087	T5 - Ready to Move M4 Shield Wall to Diagnostic Absorber	3-Sep-19	T5
47502.04.03.3.001110	T5 - External Beamline In-Tunnel Shielding Complete	14-Oct-19	T5
47502.04.02.2.001150	T4 - Delivery Ring TLM System Complete	7-Jan-20	T4
47502.04.1080	T5 - Radiation Safety ready for beam to the diagnostic absorber	29-Jan-20	T5
47502.04.04.001000	T5 - Mu2e Safety Systems Complete	26-Feb-20	T5
47502.04.02.001000	T5 - Delivery Ring Radiation Safety Upgrades Complete	21-Apr-20	T5
47502.04.001082	T3 - Radiation Safety Improvements Complete	22-Jul-20*	T3

Schedule


Radiation Safety Technical Documentation
External Beam Line Safety Systems move M4/M5 shield wall to downstream of diagnostic absorber
AP1 to Delivery Ring TLMs complete
Delivery Ring In-tunnel shielding
External Beam Line Safety Systems install M4/M5 shield wall
ODH Solenoid Room Systems Complete
External Beam Line Safety Systems ESS/RSS installation
External Beam Line TLMs complete
Delivery Ring TLMs complete
Friskers, Wallflowers, and Air Monitors
FY14
FY15
FY16
FY17
FY18
FY19
FY20
FY21

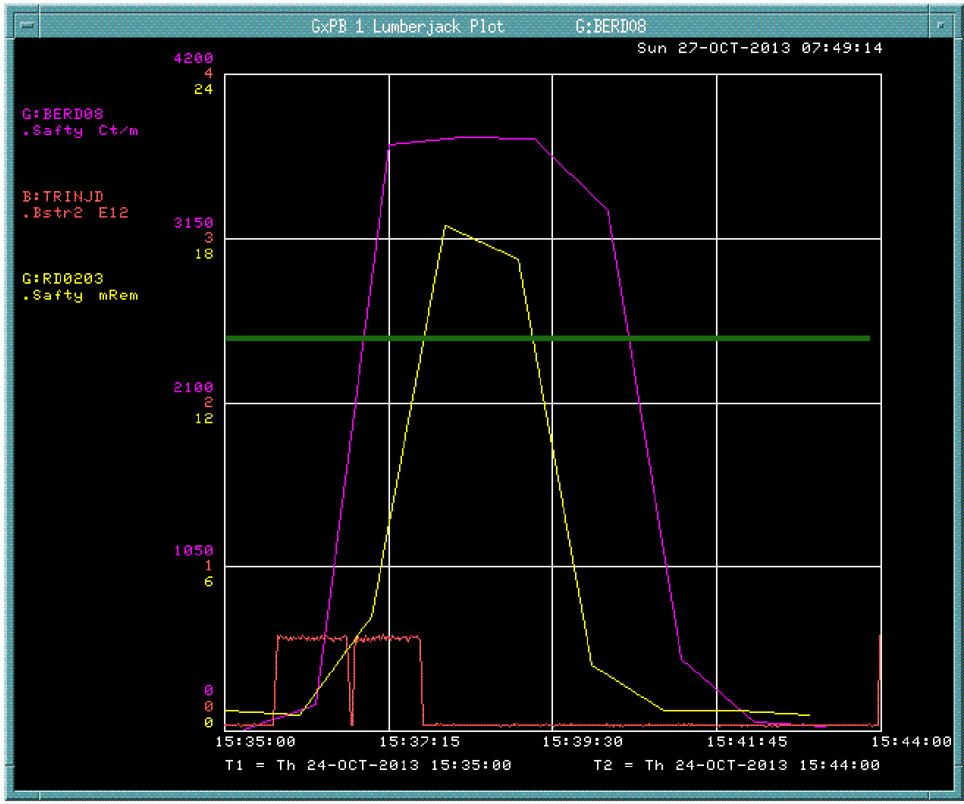
Summary

- A preliminary design for Radiation Safety Improvements is complete
- The design anticipates final approval of the TLM system in CY15

Extra Slides

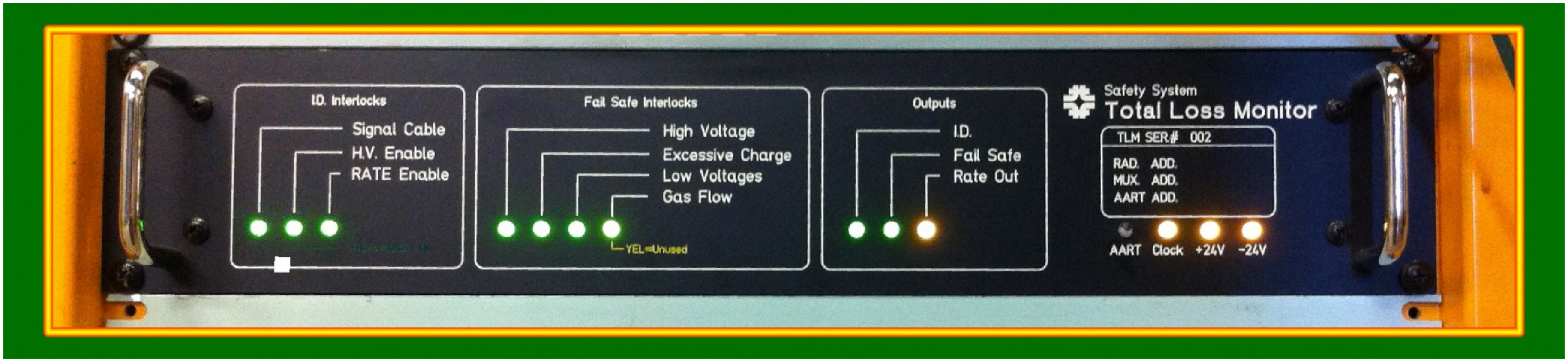
Booster 6 to 8 GeV beam loss study and TLM response

- Booster accident condition, ramping radial position late in the acceleration cycle
  - 6 to 8 GeV
    - TLM response (magenta)
    - Booster beam intensity (red)
    - chipmunk response (yellow)
    - TLM trip level (green)

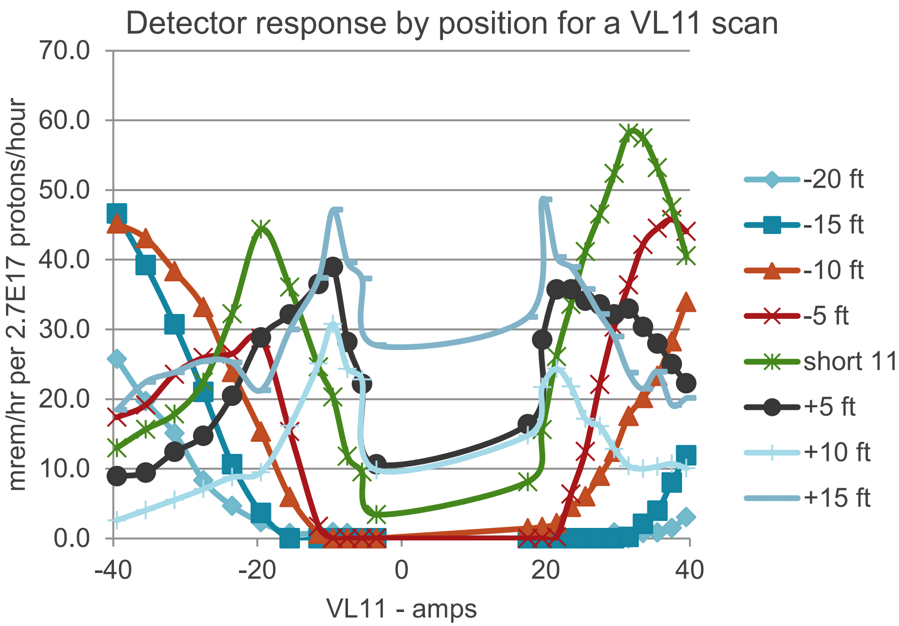


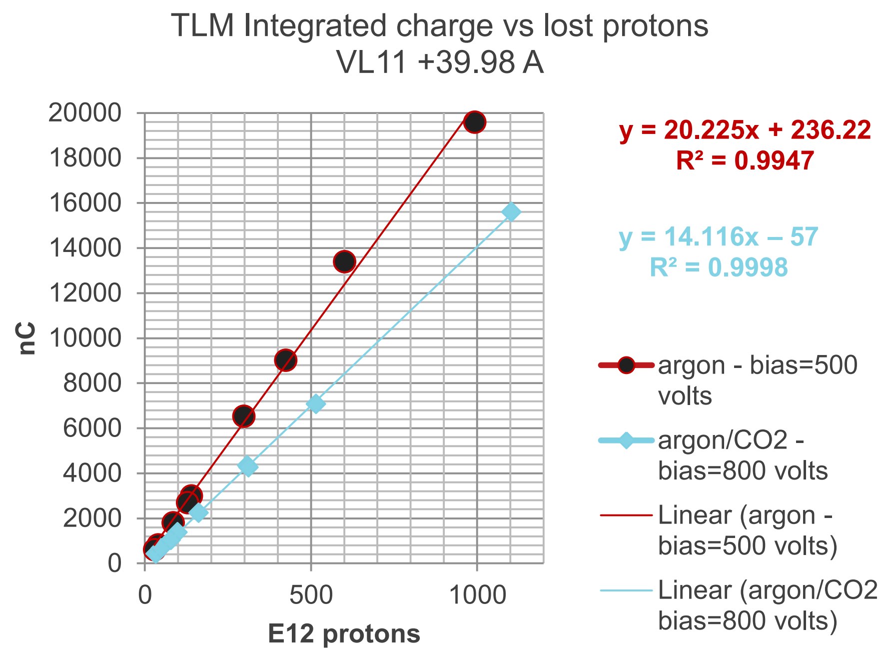
- The TLM trip would occur in seconds rather than in minutes as would occur with the existing protection scheme
- NOTE!!! – Booster operation would not be curtailed by unnecessary safety system trips but is turned off promptly in the event of severe accident condition

TLM prototype electrometer



Booster 400 MeV beam loss study and TLM response



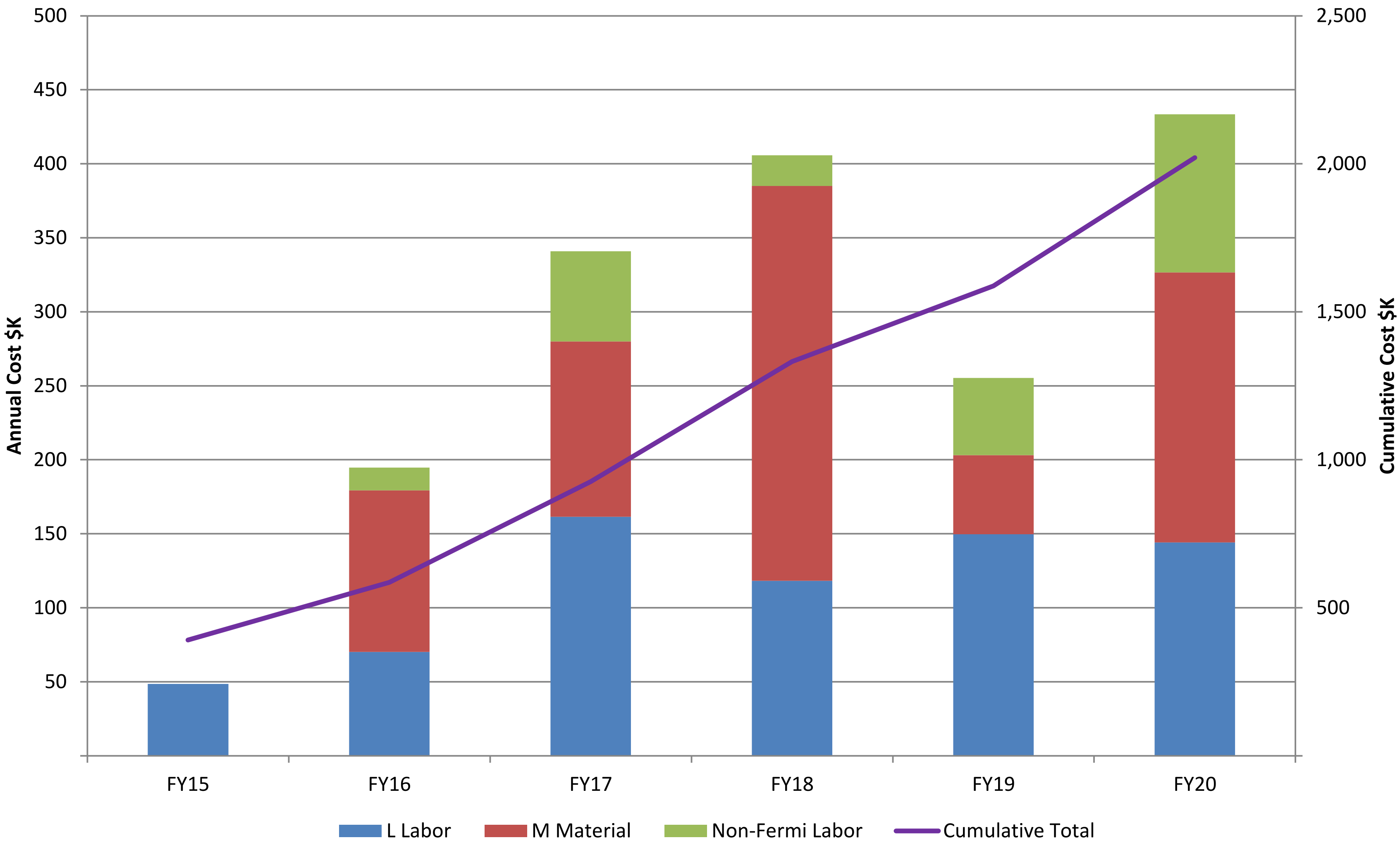


Response for 8 chipmunks spaced 5' apart for various trim magnet currents

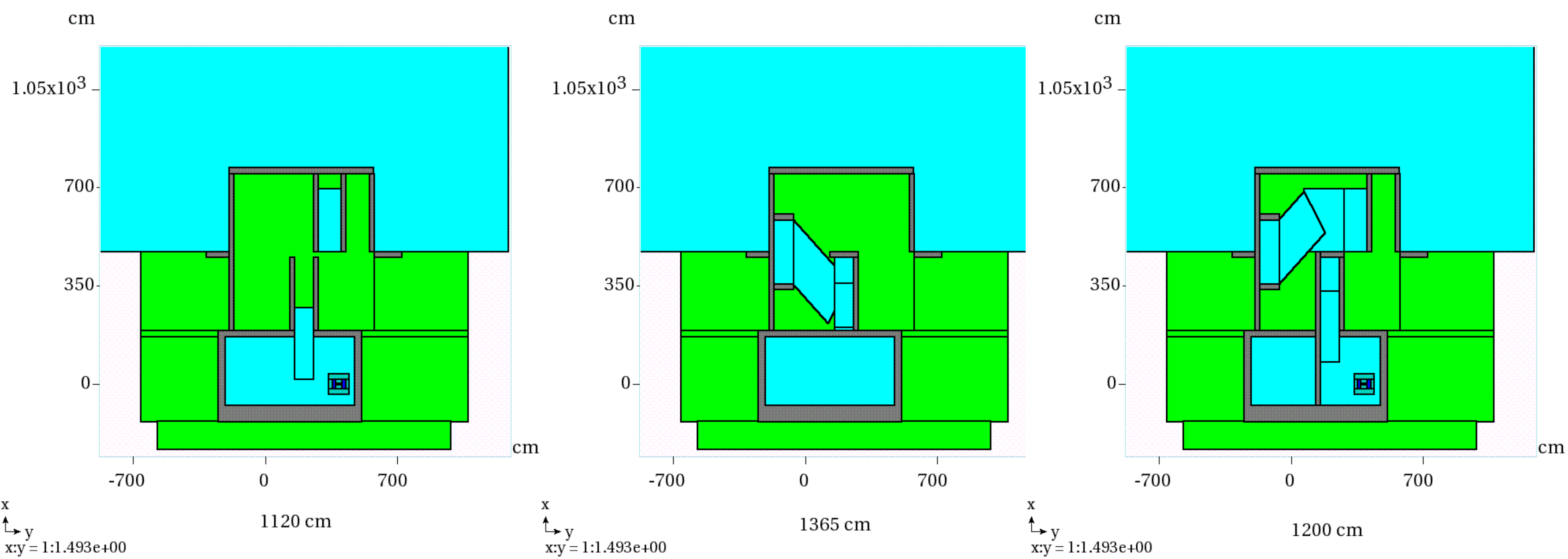
TLM response is demonstrated to be linear over several decades of intensity

The marriage of these data sets is the basis for establishing trip levels

Labor and Materials

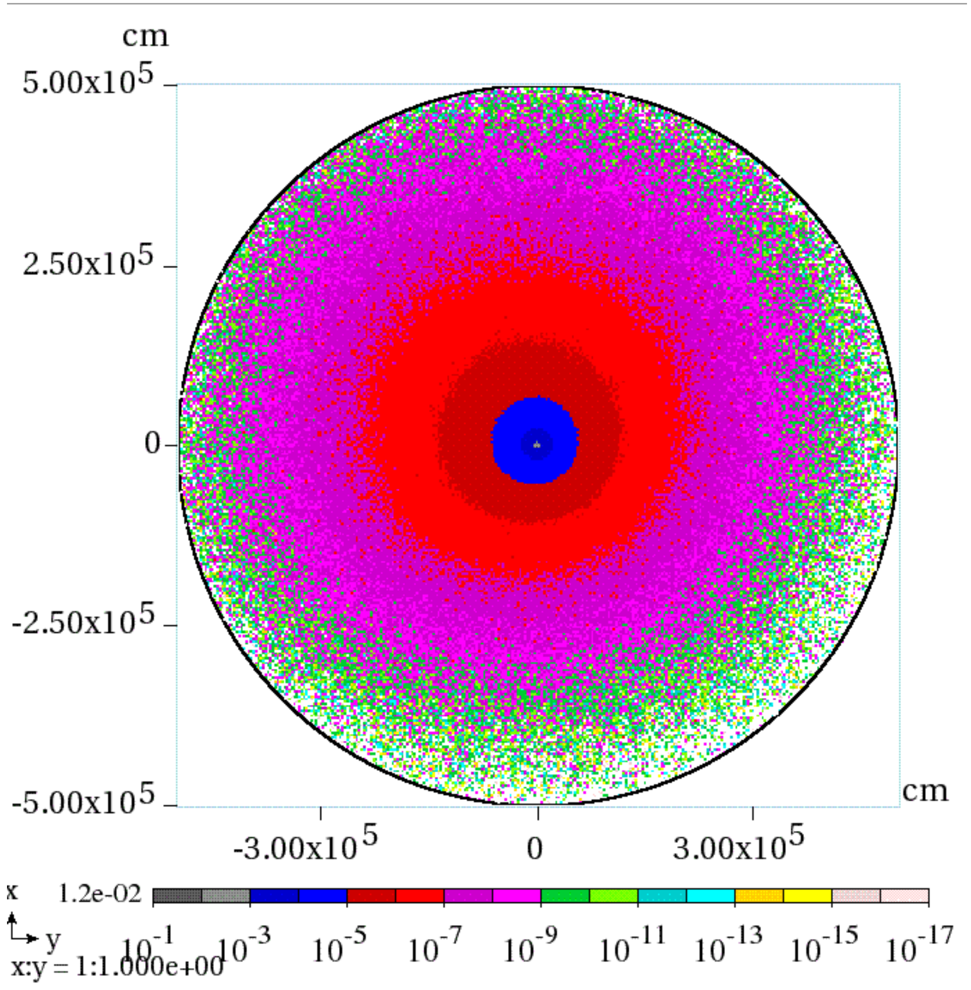


Facility overview



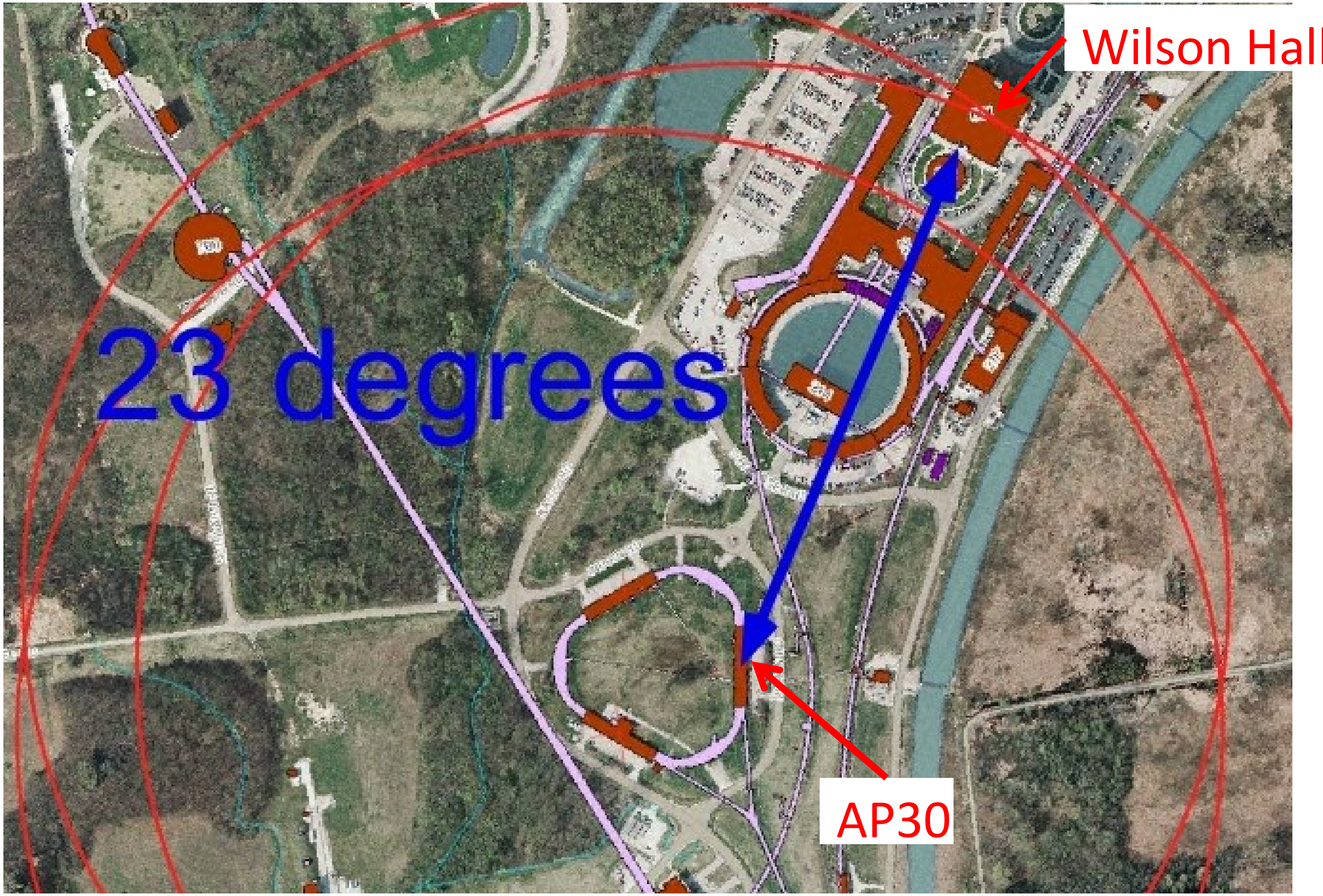
- Exit stairway details are included in the simulation

Normal 8 kW beam operation – Skyshine only
Total effective dose rate (mrem/hr) vs distance in tissue detector

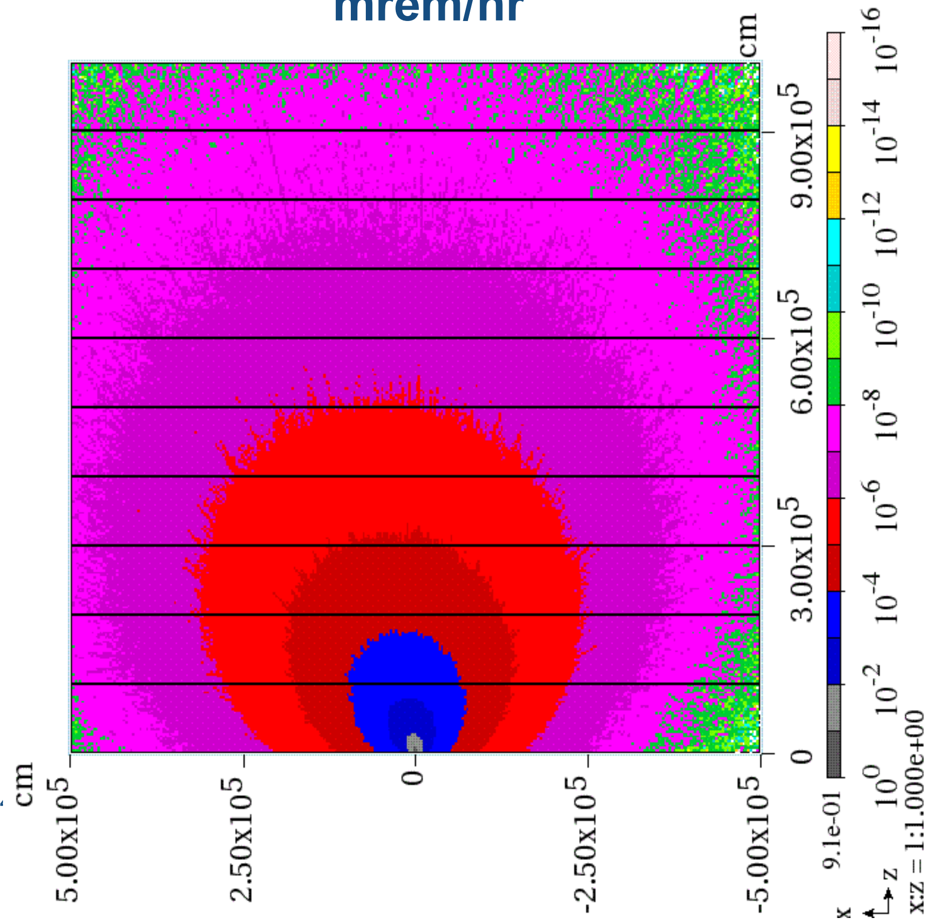


DIRECT model angle of interest

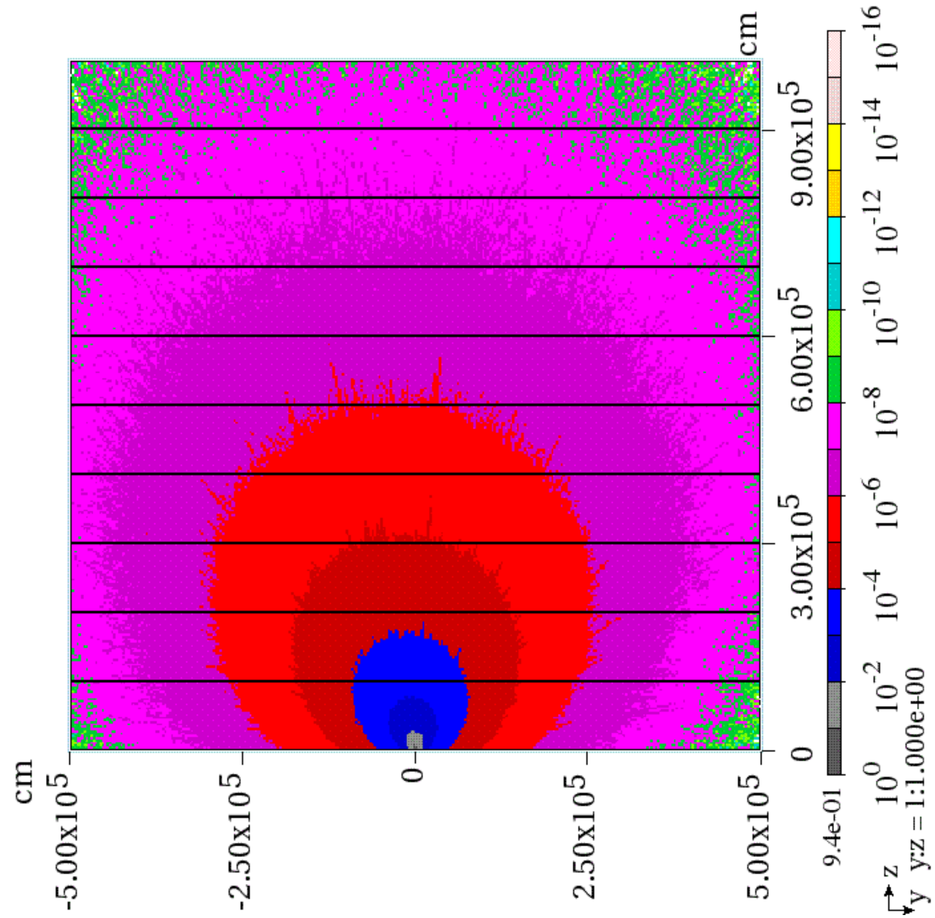
500 m radii circles
Centered on
AP10
AP30
AP50
Service buildings



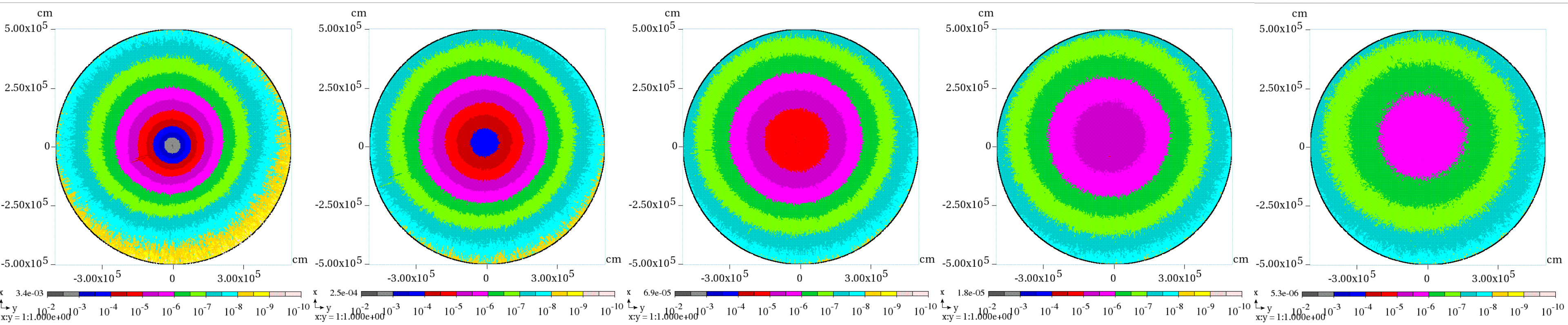
X/Z plane, total effective dose rate mrem/hr



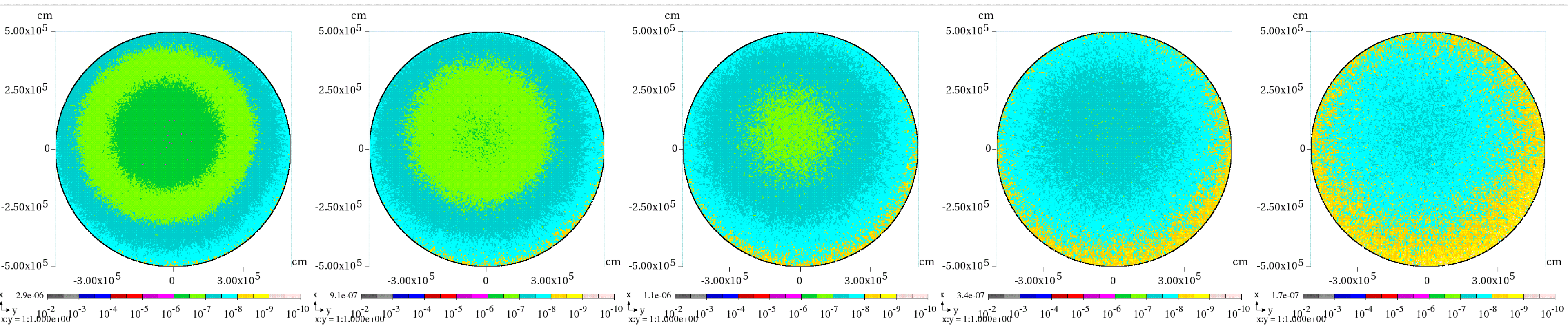
Y/Z plane, total effective dose rate mrem/hr



Effective dose rate (mrem/hr) – 8 kW normal losses vs. altitude

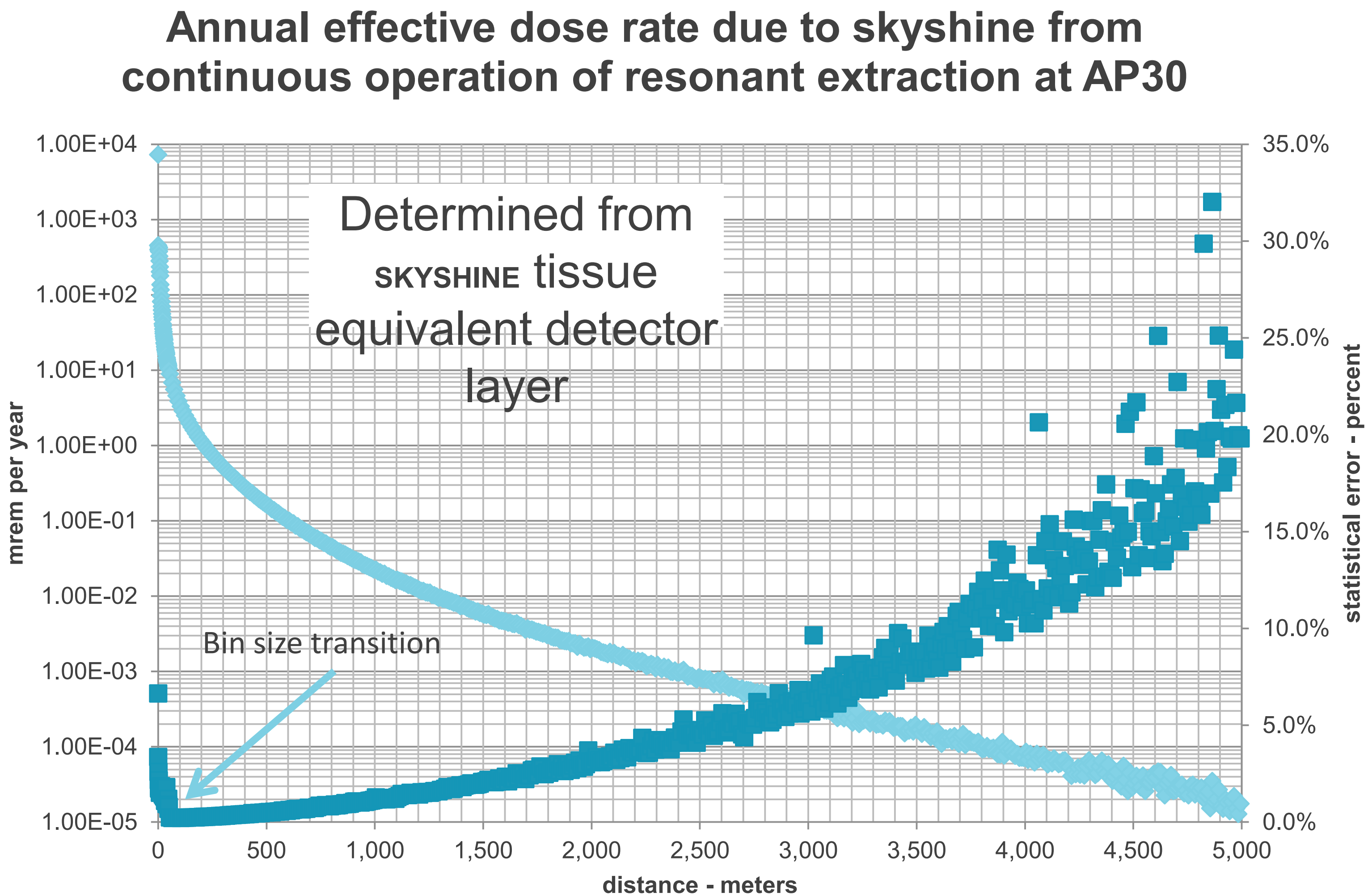


Layers 1 through 5



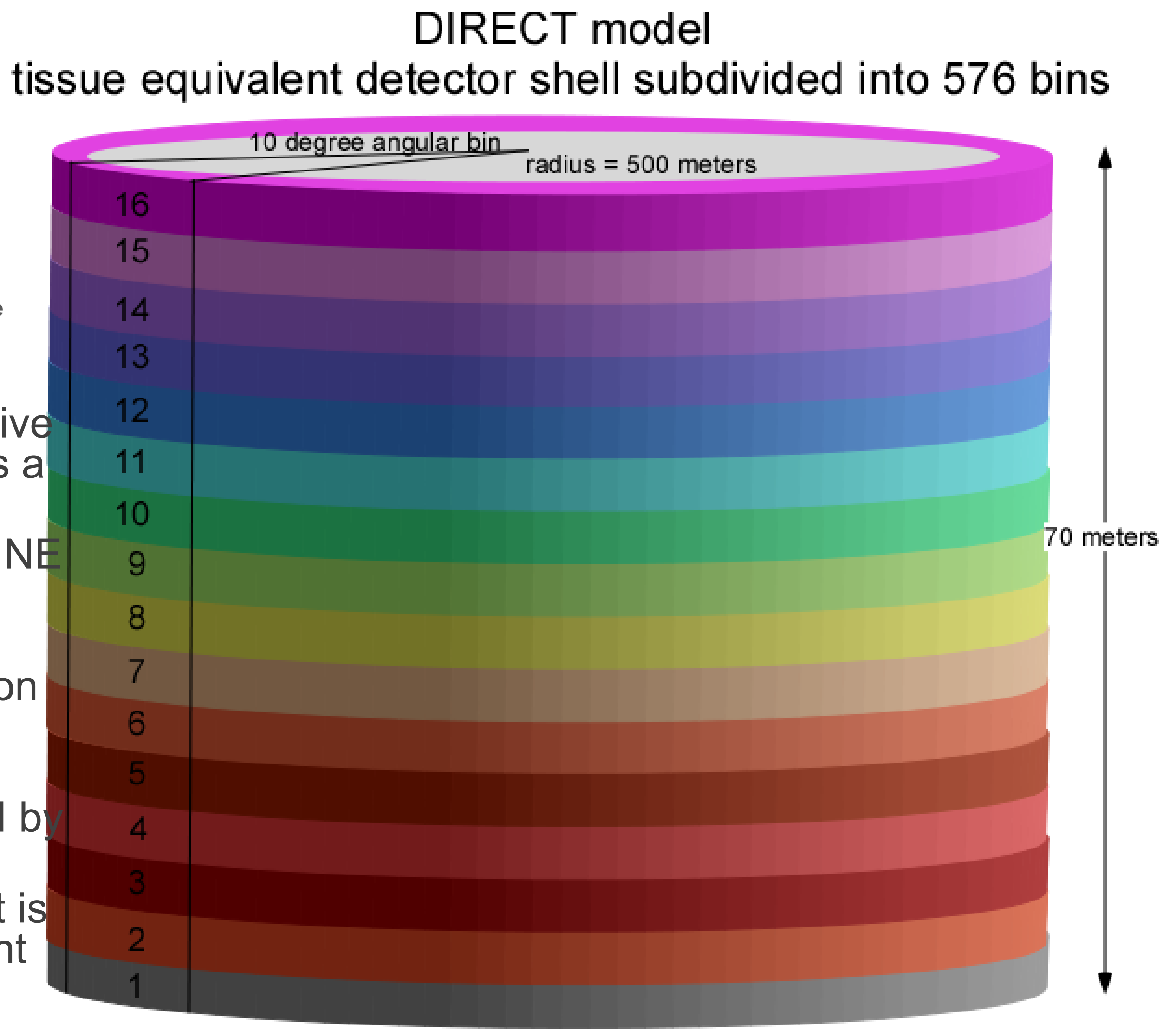
Layers 6 through 10

8 kW beam operation with 1.25% extraction losses



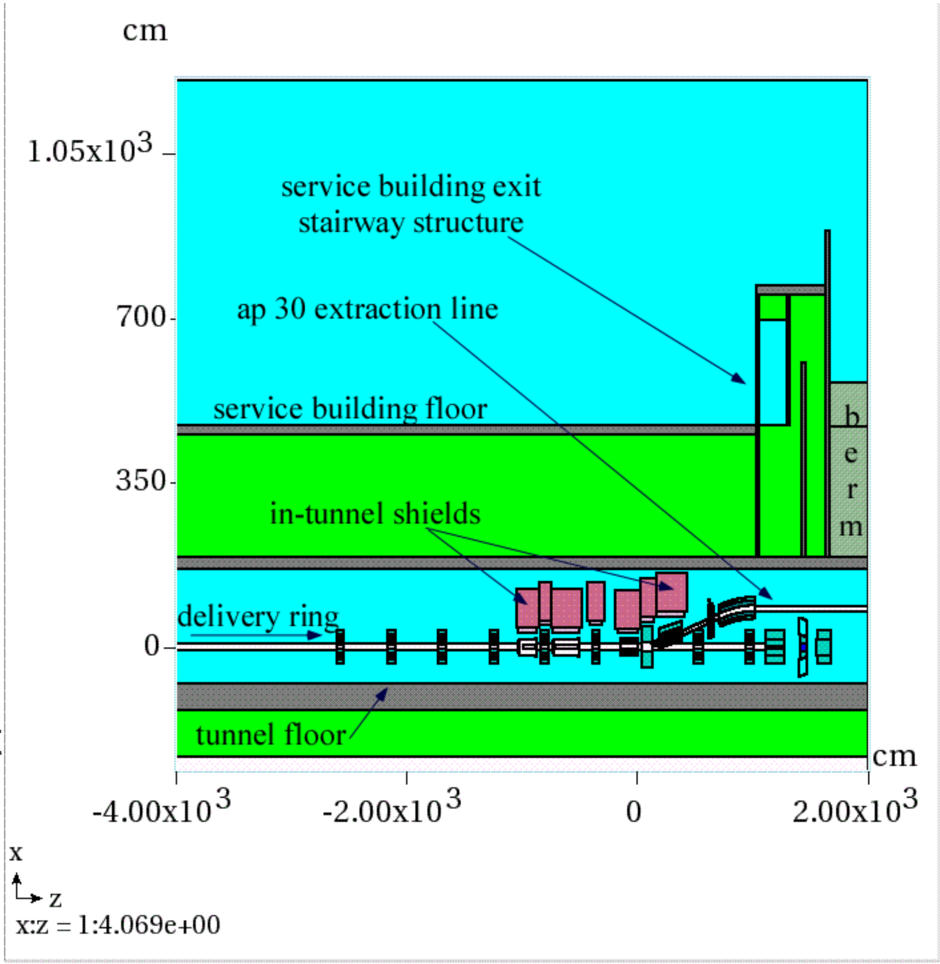
DIRECT model

- Root Geometry:
  - Cylindrical shell
  - 500 m radius
  - 0.3 m thick
  - 70 m high
  - Divided into 16 levels
  - Divided in azimuth into 36 ten degree segments
- Purpose: To capture effective dose rate at Wilson Hall as a function of floor
- An addition to the SKYSHINE model
- Used for determination of effective dose rate at Wilson Hall
- No credit taken for the massive shielding afforded by the concrete structure
- Azimuthal angle of interest is 23 degrees CW wrt incident beam direction



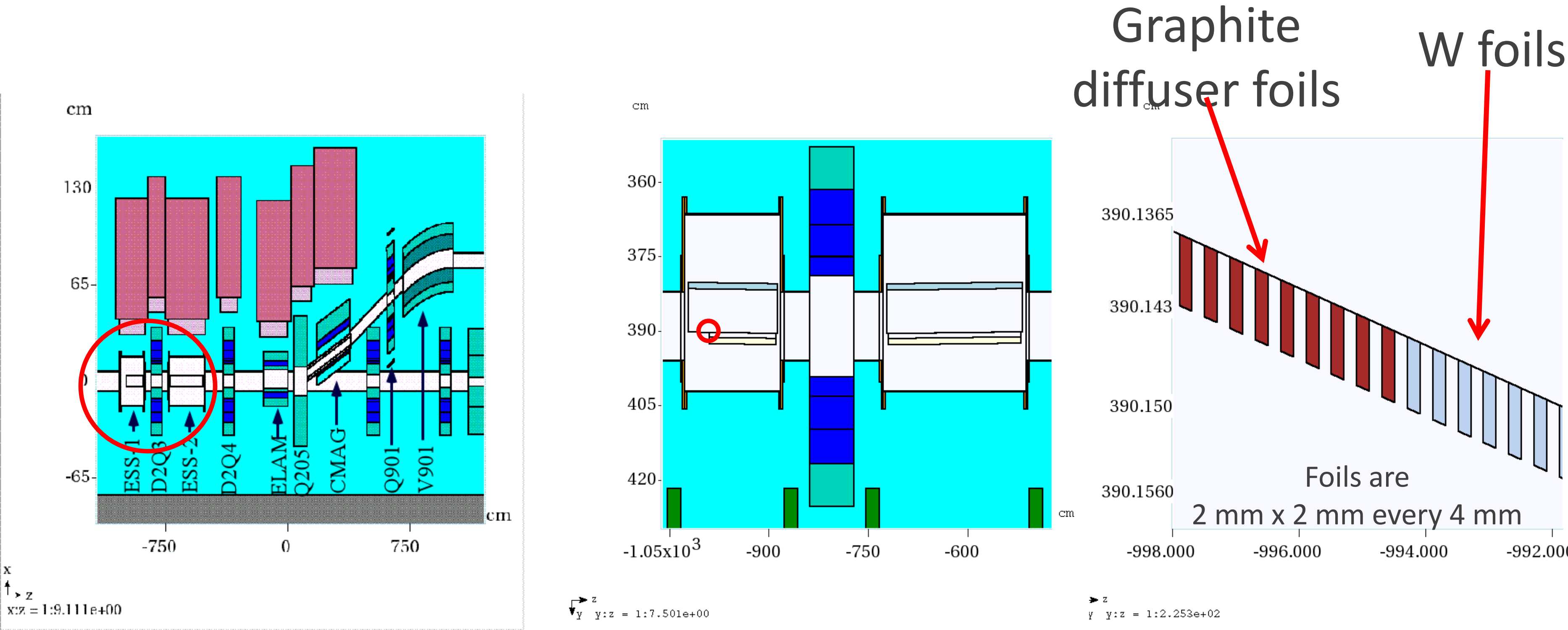
Facility overview

- AP30 Anti-proton source service building
  - 10 foot tunnel shield in service building
    - sufficient for 13 watts of 8 GeV protons
- Building is to be repurposed for mu2e experiment
  - 10 foot shield remains unchanged
    - Mu2e requires 8 kW of 8 GeV protons
    - Beam is to be extracted beneath the service building by 1/3 integer, slow resonant extraction
    - A lossy process
- In addition, there is an exit stairway just downstream of the beam extraction point



Longitudinal elevation view

Extraction system

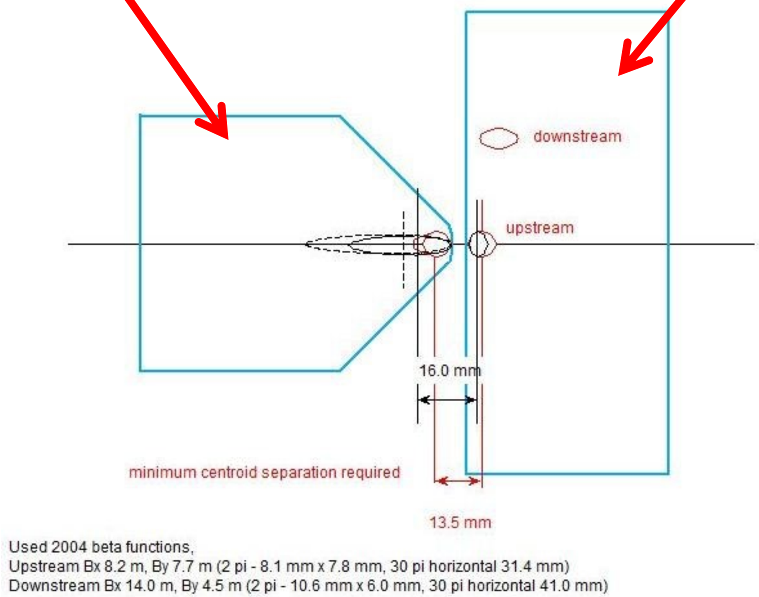


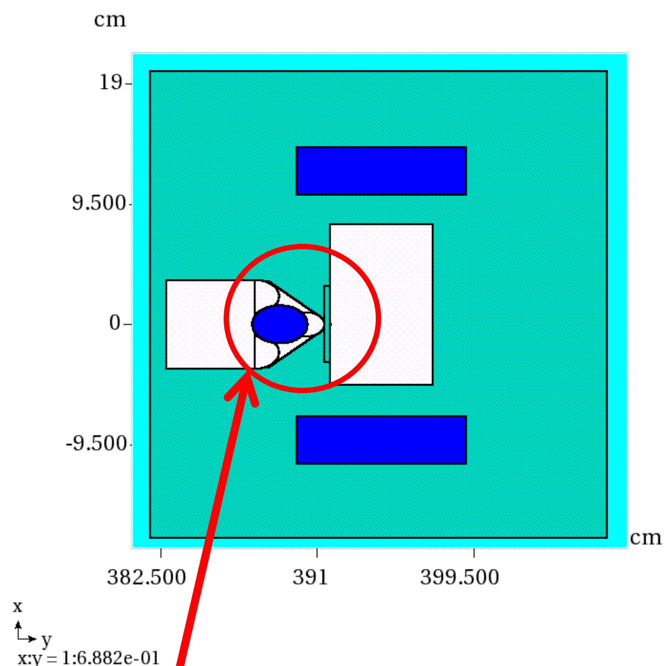
- Extraction system is modeled with full details of magnets, star chambers, magnetic fields, and extraction septa foils (850)

Extraction system

field free region
circulating aperture

vertical bending field
extraction aperture

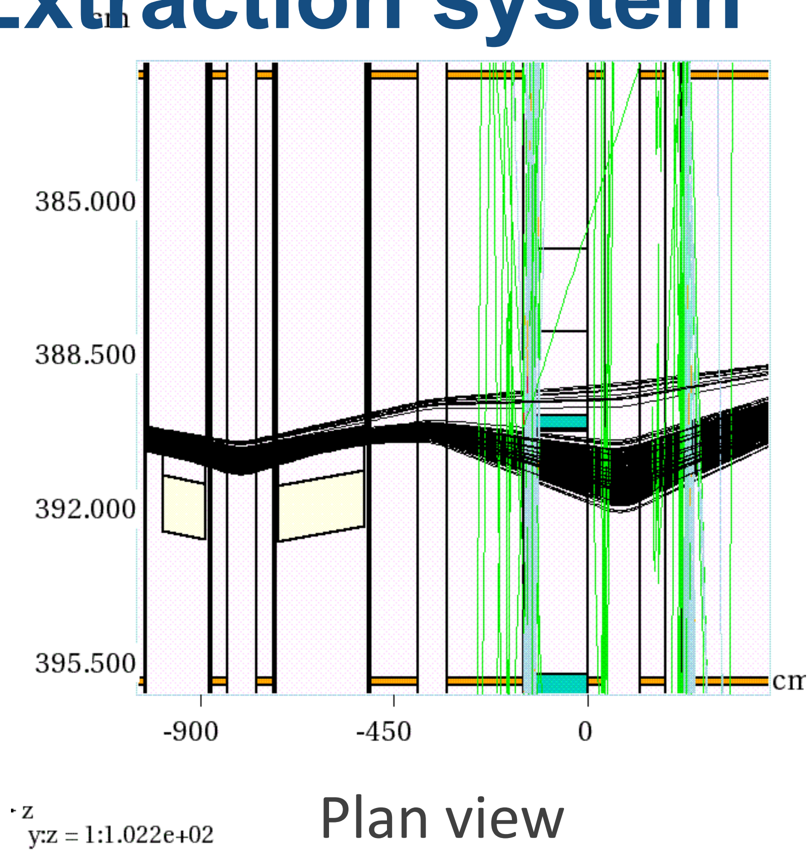




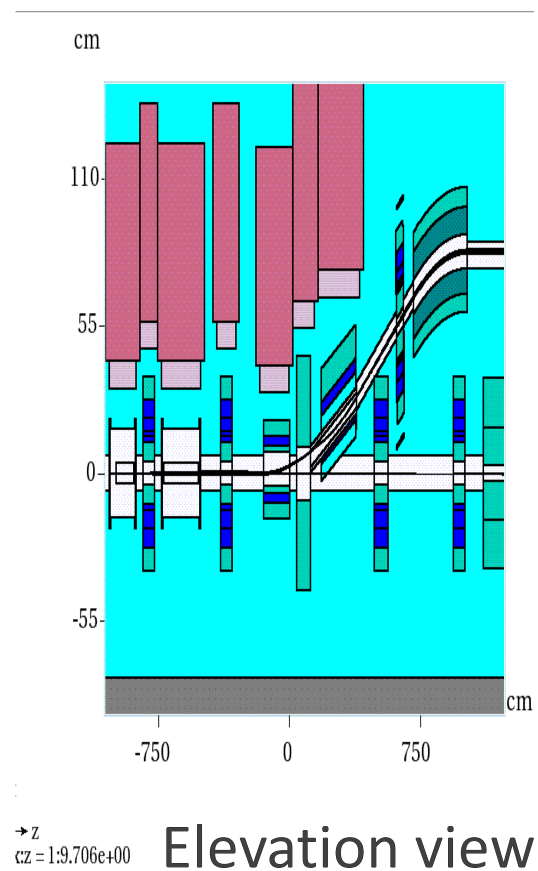
Cross section of
Lambertson Magnet

critical extraction system region where beam loss will occur

Extraction system



Plan view



Elevation view

- Extraction system tuning was required to optimize apertures and minimize losses
  - Diffusion section wires modeled as black holes to eliminate scattering during aperture scans
  - Beam loss is determined to be 1.25%

Supplemental shield system

81 cm thick steel shield

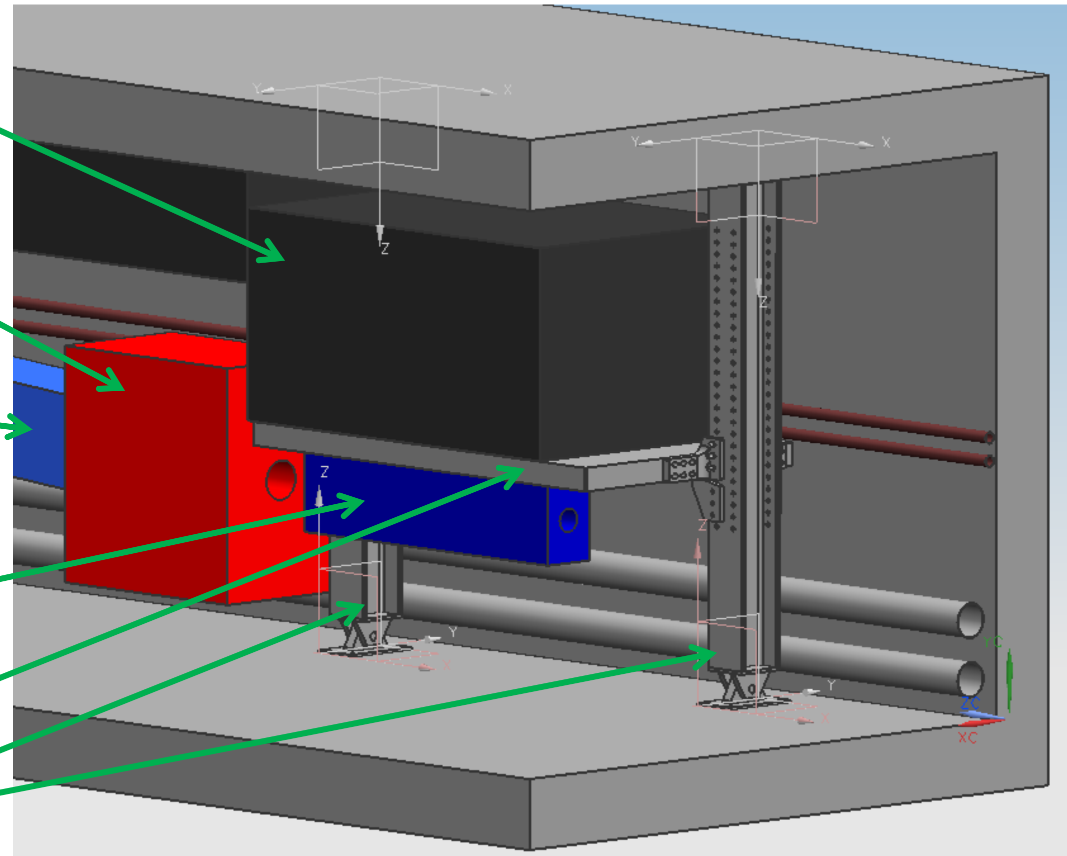
quadrupole

C-magnet

Lambertson magnet

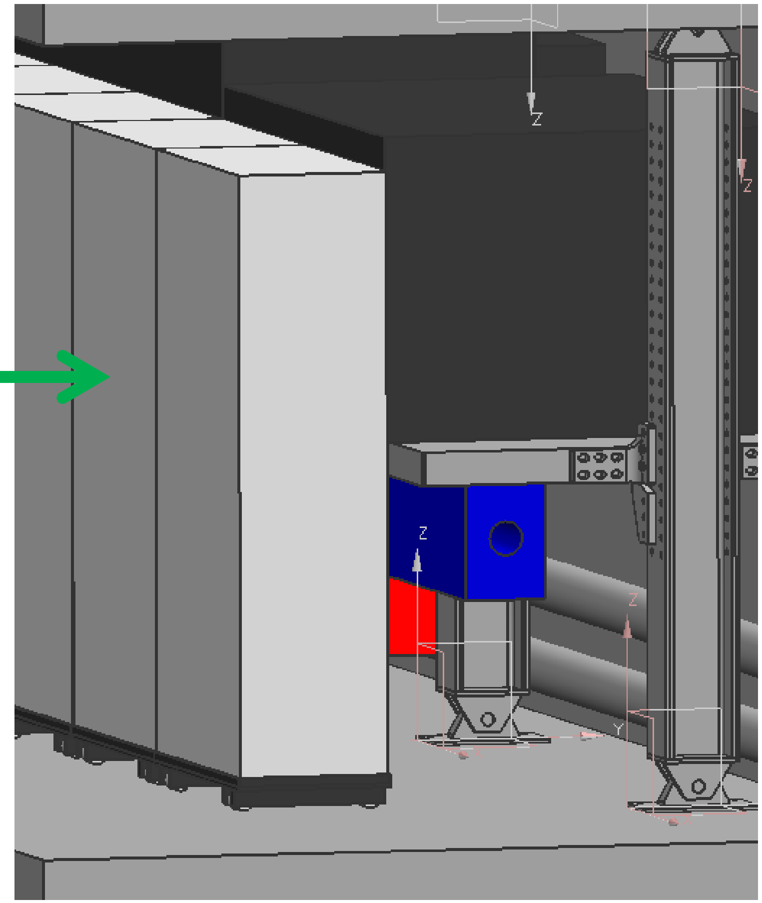
10 cm thick steel shelf

Support columns



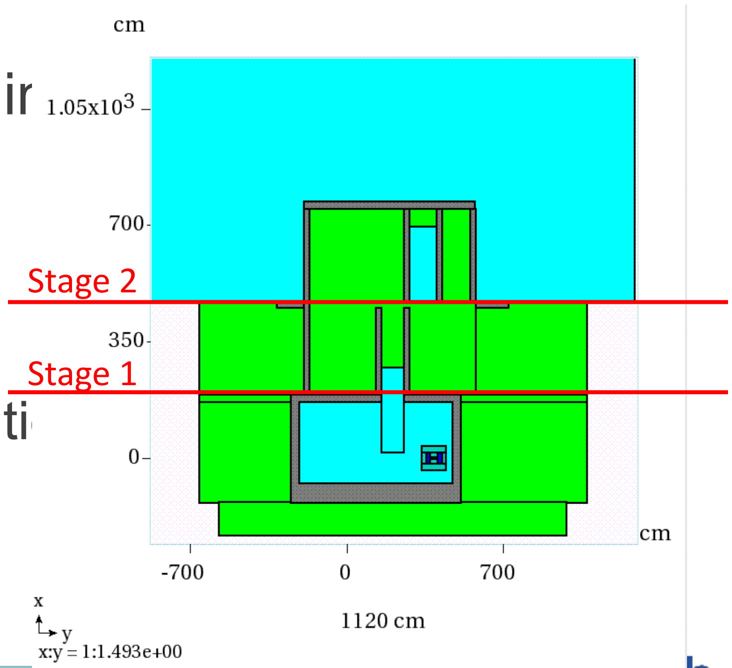
Aisle way shield is required to limit worker exposure during maintenance activities

45 cm concrete
10 cm marble (not shown)

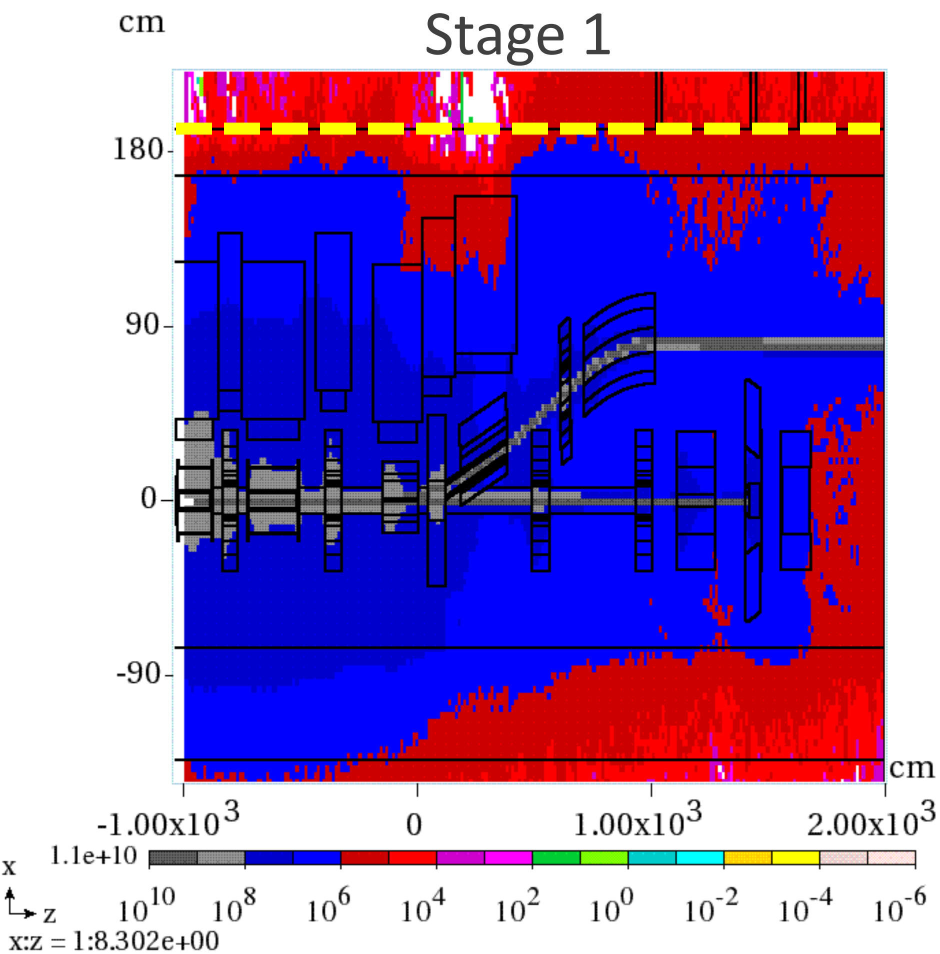


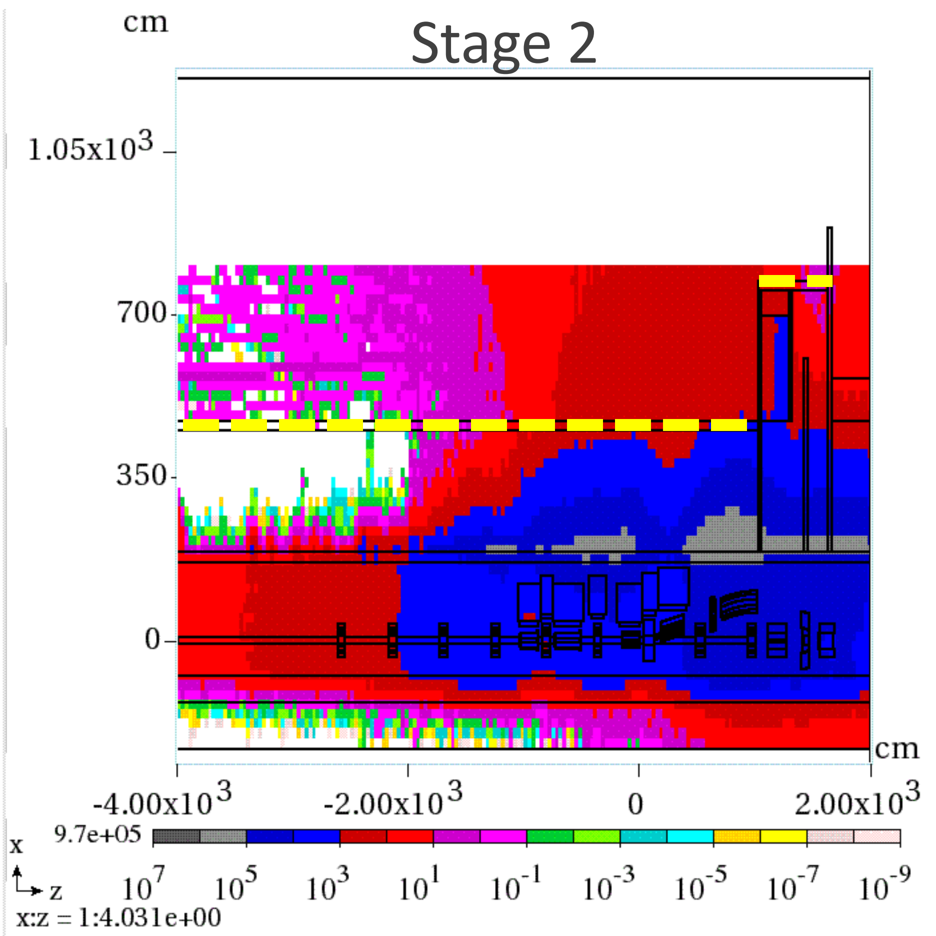
MARS simulations

- Stage 1 – generate a particle source file at an intermediate surface, source term for Stage 2 run
- Stage 2 – generate a particle source file at surface of service building floor for SKYSHINE and DIRECT calculations
- SKYSHINE calculation
  - Effective dose rate at ground level vs. distance from AP30 service buildir
- DIRECT calculation
  - Effective dose rate at Wilson Hall by floor elevation
    - Includes direct and skyshine contributi



Stage 1 & 2 total flux results – mars.hbook histograms



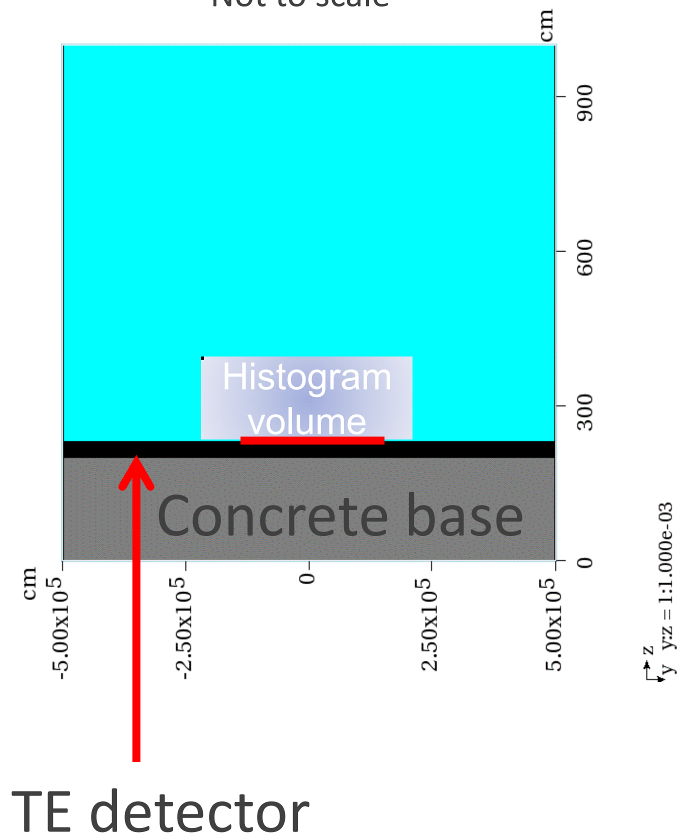


Dashed lines indicate surface of shower particle collection

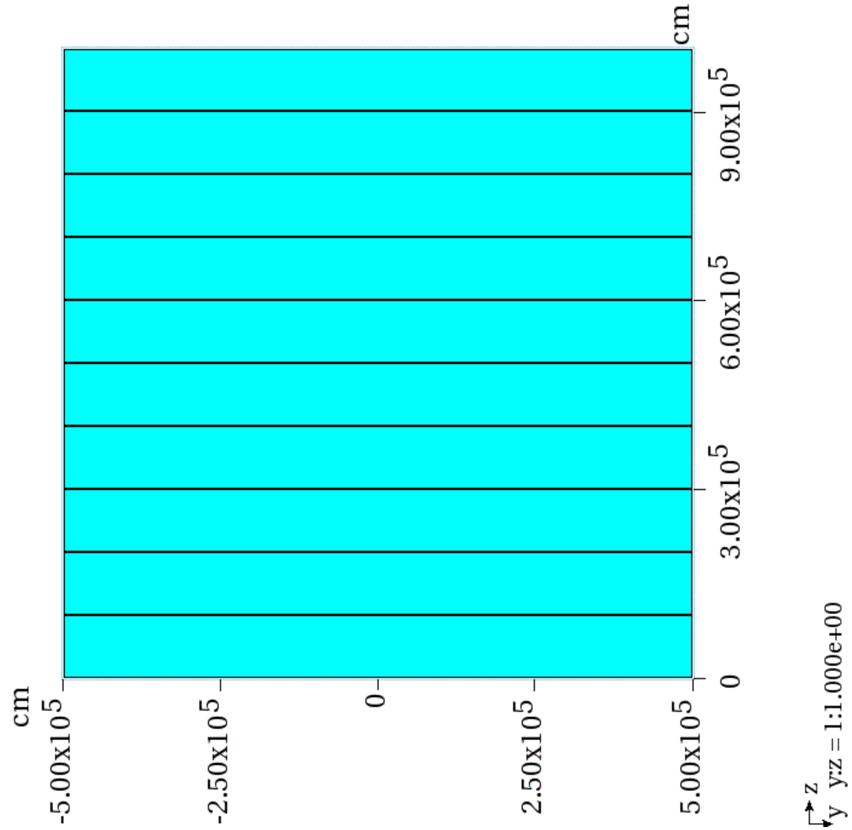
SKYSHINE model

- Concrete base, radius 5 km x 2m
- Tissue equivalent detector, 5 km x 0.3 m
- Atmosphere, 5 km radius x 10 km
- A histogram volume (air) 170 cm high and 100 m x 100 m is used to determine effective dose rates in service building, parking lot, and Indian Road
  - Stage 2 surface lies between TE detector and histogram volume (red horizontal bar)
  - Tissue equivalent detector volume is just below the Stage 2 surface
  - In histogram volume, effective dose contribution from Stage 2 surface and reflected SKYSHINE is calculated
  - The tissue detector only receives reflected shower particles since the Stage 2 surface is above it

Not to scale



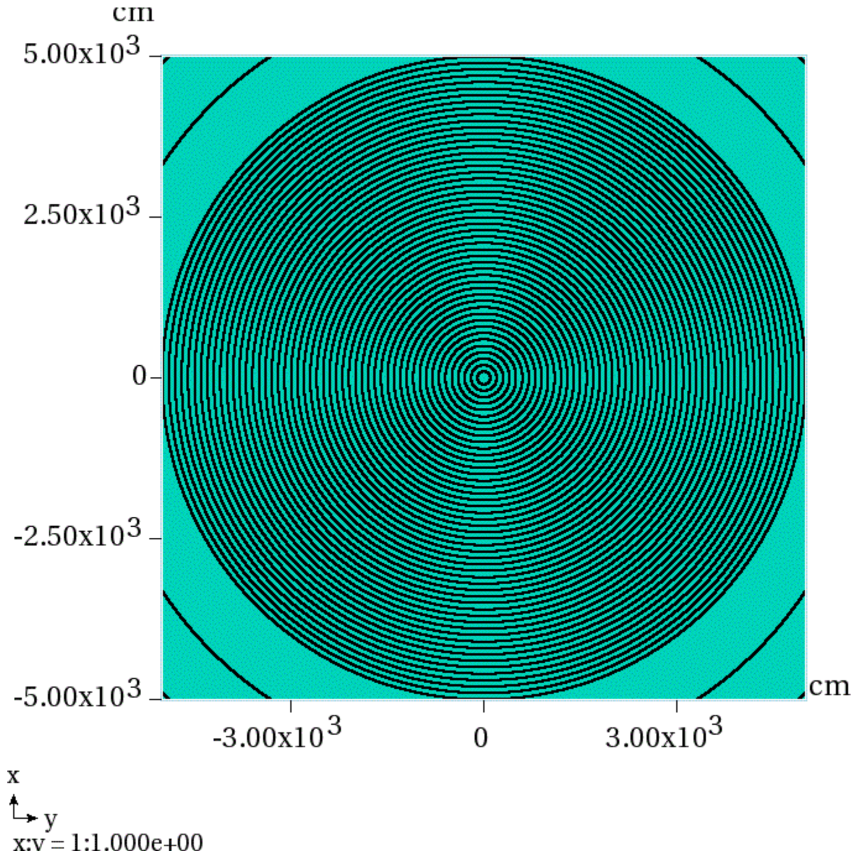
SKYSHINE model



The full model

Atmosphere extends vertically 10 km in 1 km layers

Radius is 5 km

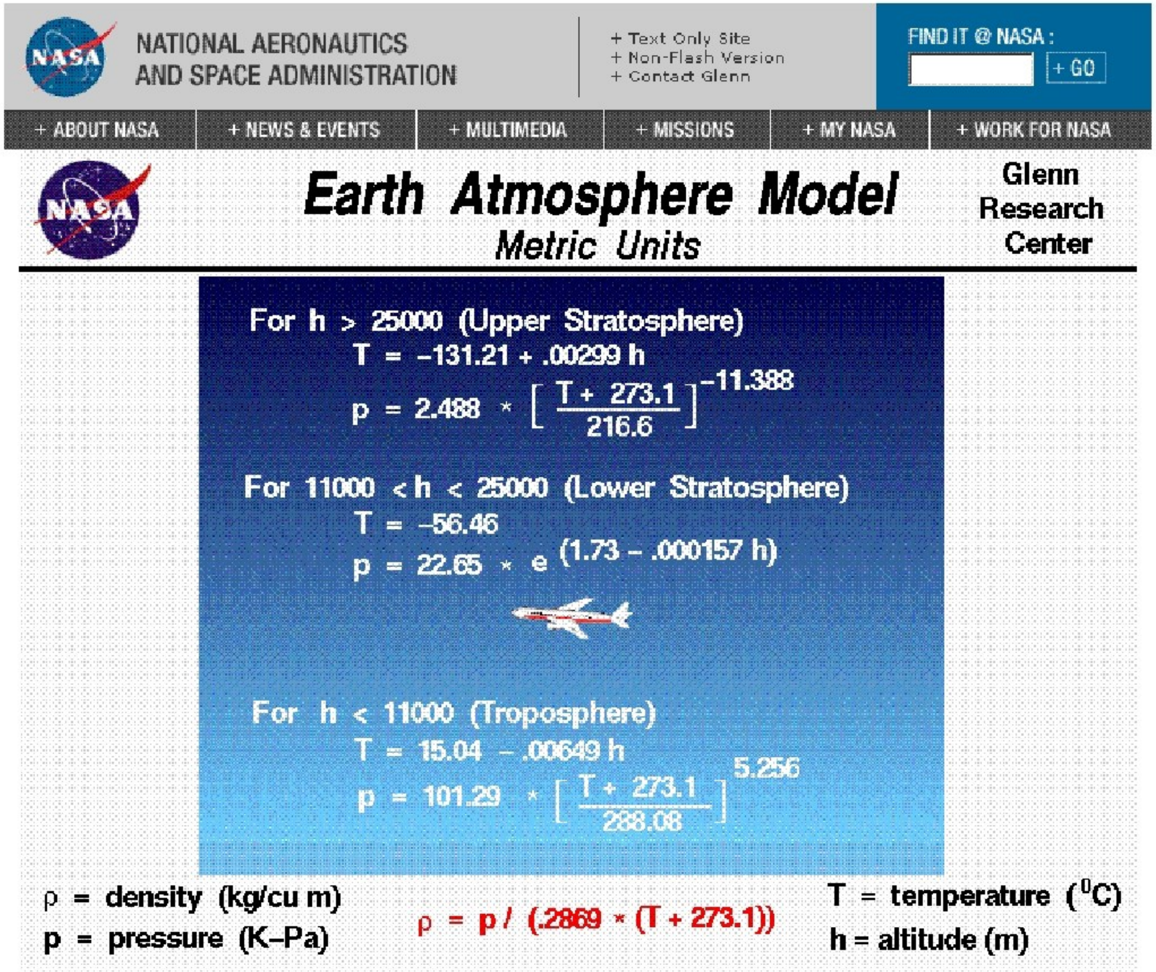


Tissue equivalent detector is subdivided radially

1 m radial bin steps to 50 m

10 meter bins to 5 km

SKYSHINE model – air density correction technique



MATER.INP file
A2B7 SKYSHINE calculation, 5 km - 7/31/13
1 'CONC'
2 'TISS'
3 'AIR' 0.00116889
4 'AIR' 0.00105969
5 'AIR' 0.000958479
6 'AIR' 0.000864832
7 'AIR' 0.00077835
8 'AIR' 0.000698646
9 'AIR' 0.000625341
10 'AIR' 0.000558071
11 'AIR' 0.000496482
12 'AIR' 0.000440233
STOP