Fermilab

Mu2e External Beamline

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External Beam Line
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*standing in for Eliana Gianfelice-Wendt
Most of talk written by Carol Johnstone

WBS 475.02.07 External Beamline

- The Mu2e external beam line, *or M4 line*, must
  - cleanly separate and transport resonantly extracted beam from the Delivery Ring to the Mu2e production target,
  - deliver beam with the required spot size for the experiment
  - perform inter-bunch extinction of out-of-time particles, and
  - as part of the Muon Campus complex, the M4 beamline must support beam operations for the g-2 experiment (M5 beam line)
    - *Note: experiments cannot run simultaneously*

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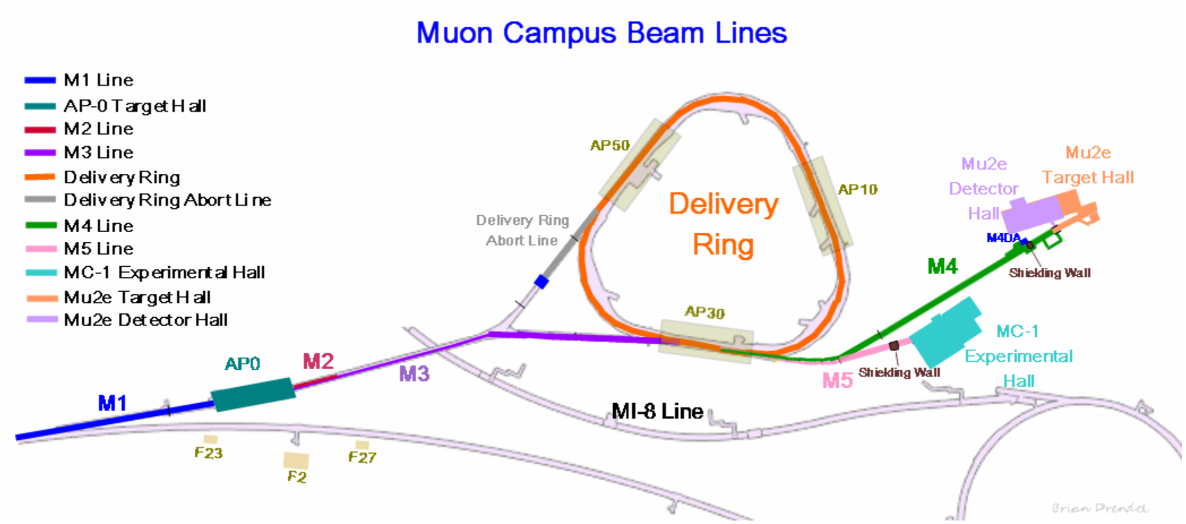
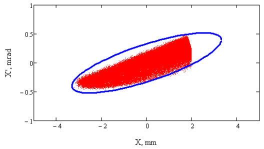
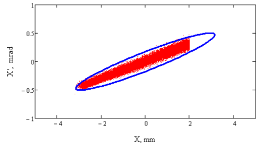


External Beamline Requirements

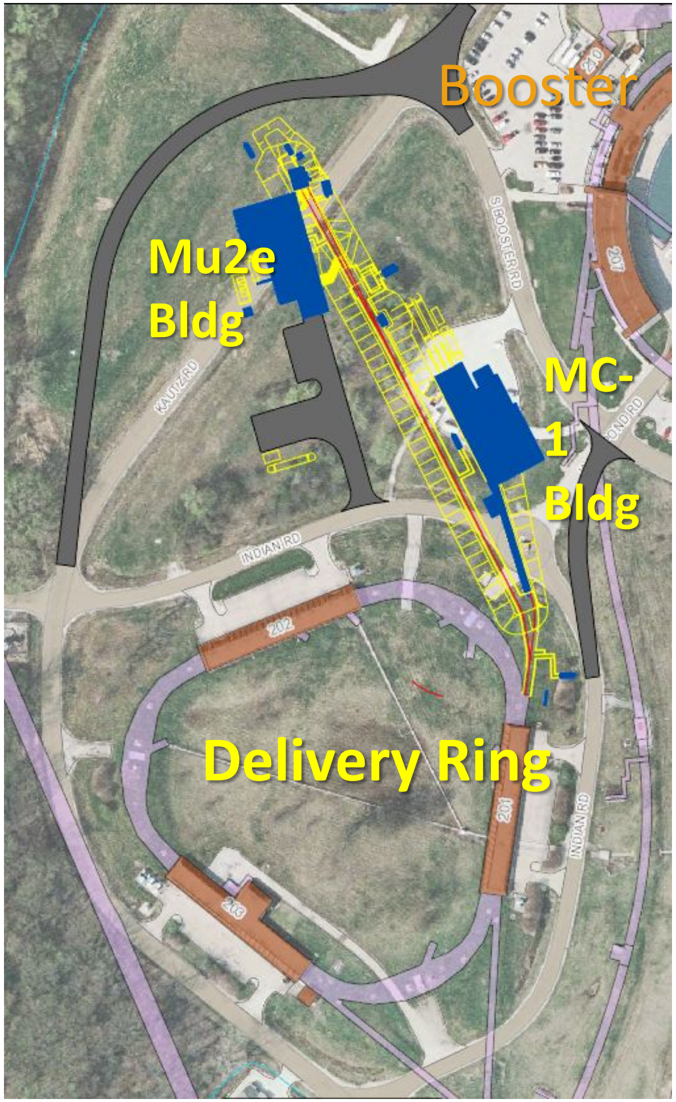
- Mu2e Proton Beam Requirements (Mu2eDoc-1105)
  - Resonantly extracted phase space
  - Bunch structure provided by Delivery Ring period
- Beam requirements on production target (Mu2eDoc-887
  - Transverse Spot Size 0.5 to 1.5 mm (rms)
  - Divergence < 4 mr (rms)
  - Alignment/target scans +/- 1 cm and +/- 0.8°



Two examples of extracted phase space

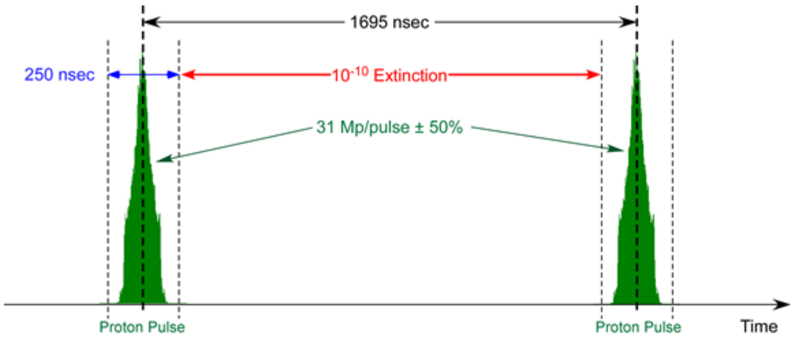


- Final focus: 7 m to final focus
  - Accommodate elevation change for shielding
  - accommodate solenoid systems
  - Instrumentation, target scans and protection collimator



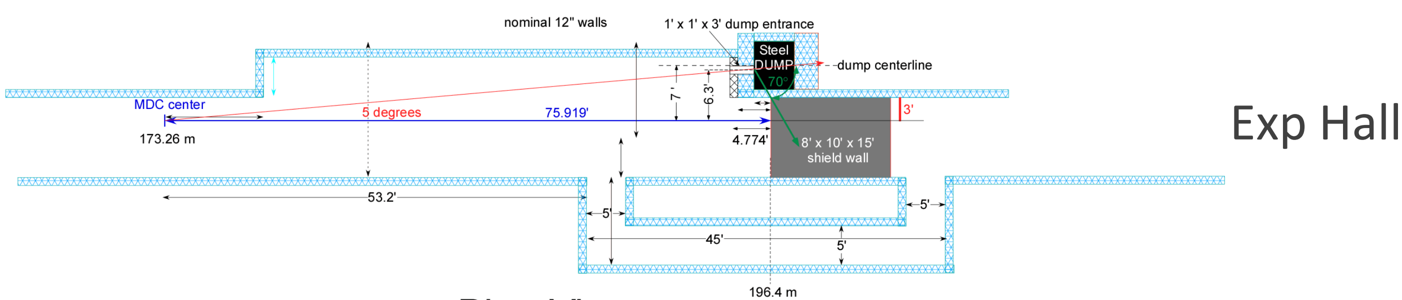
External Beam line Requirements

- Beam Extinction Requirement for Mu2e (Mu2e-doc-1175)
  - 10^{-10} total extinction of out of time beam
  - 10^{-7} provided by beamline



- Diagnostic beamline
  - Low-intensity commissioning and beam studies – no beam to experiment
    - Requires separate diagnostic beam absorber
    - Requires component-free shield wall in primary beamline to permit access to hall

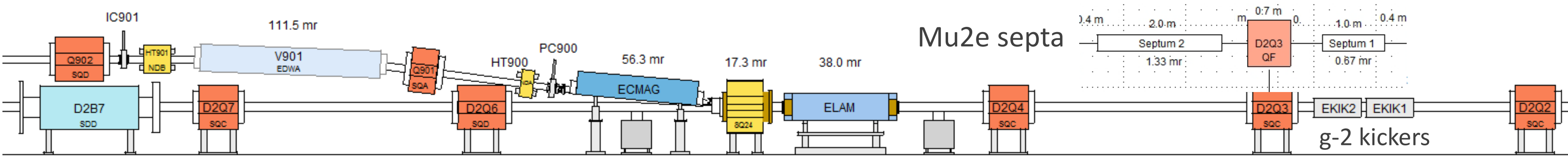
M4 line diagnostic beam dump location plan



Plan View

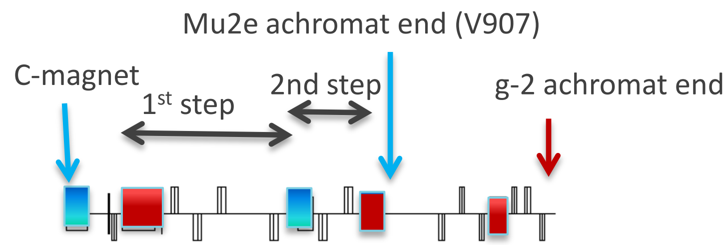
Mu2e/g-2 Extraction and Upstream Design

- Except for Mu2e septa, the extraction and M4/M5 beamline hardware and installation *not* part of M4 cost and schedule
- Designed to optimize acceptance for Mu2e resonant extraction
  - Delivery Ring lattice very similar to Debuncher pBar lattice
  - g-2 kicker extraction system will be replaced by Mu2e septa
  - Lambertson for vertical extraction
  - An 8" aperture quad is required at D2Q5 location (BNL 8Q24)
- Design provides a common extraction channel
  - 40 π-mm-mr acceptance as required for g-2

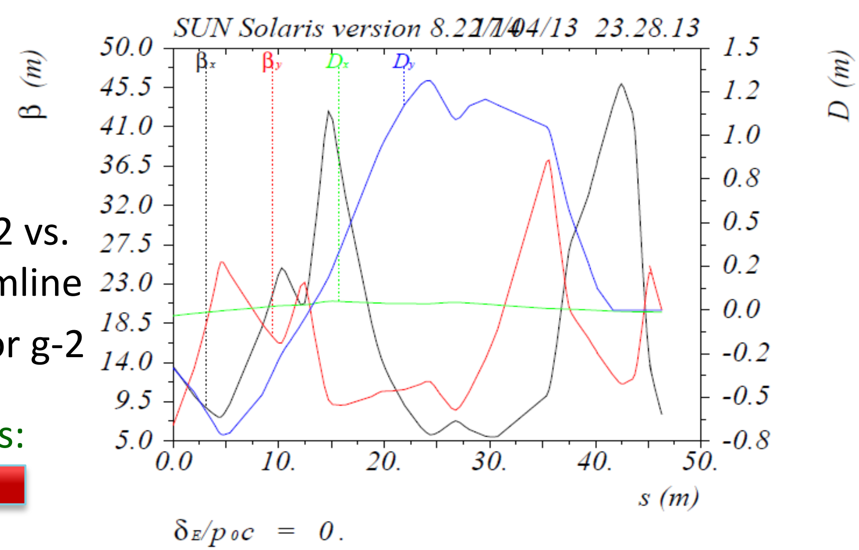


M4 /M5 Common section Design

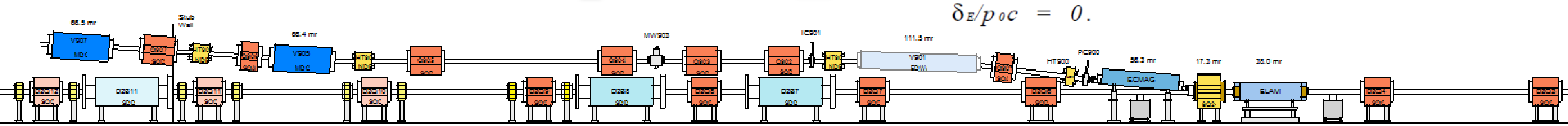
- M4/M5 line installation part of g-2 schedule and cost
- ***Mu2e/g-2 have independent vertical achromats***
  - ***No residual vertical dispersion***



- Elevation change of 48” to final M4 beamline height must occur in two steps for dispersion suppression
  - 1st step 32” to clear Delivery ring magnets
  - 2nd step 16” to final height
  - 5 bends total in achromat
- Vertical dispersion cancelled at V907 for Mu2e
- Two different sets of optics for g-2 and Mu2e
- “Switch” Magnet at V907 reverses polarity for g-2 vs. Mu2e operation to separate g-2 from Mu2e beamline
- Vertical dispersion canceled at V003 in M5 line for g-2

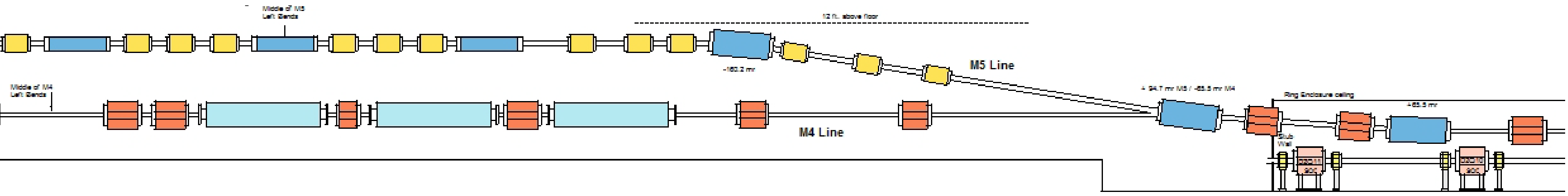


Vertical bend magnets:
UP: DOWN:



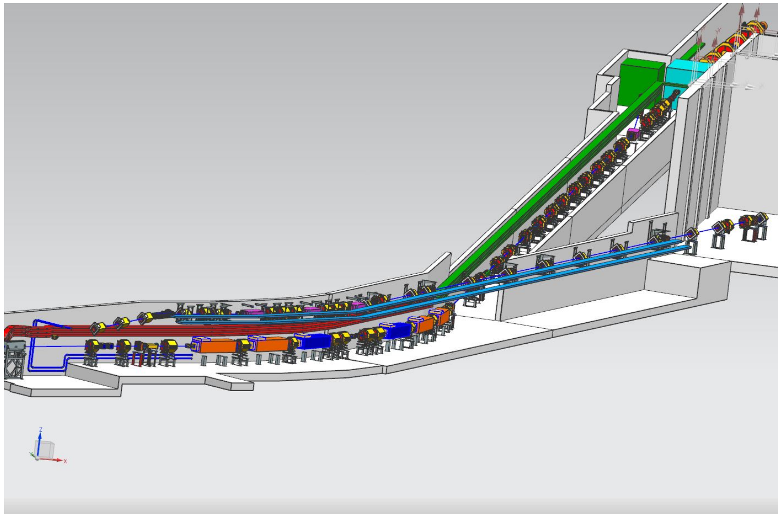
M4 /M5 beamline Separation Design

- Mu2e/g-2 split is now vertical
- Two independent vertical achromats implemented
- No Mu2e/g-2 conflicts past split
  - g-2 will reverse the last Mu2e vert dipole (not an achromat at this point)
  - This bend changes from -3.8° (Mu2e) to +5.5° (g-2). Magnet tilt change will require realignment.
  - g-2 will separate from Mu2e at ~32” above Mu2e in ~5m downstream of the reversed dipole
  - A 9.3° final vertical bend levels the g-2 M5 line
  - Final separation ~6.5’ above Mu2e at level of g-2 ring
  - Realignment of reversing bend will be required between g-2/Mu2e run



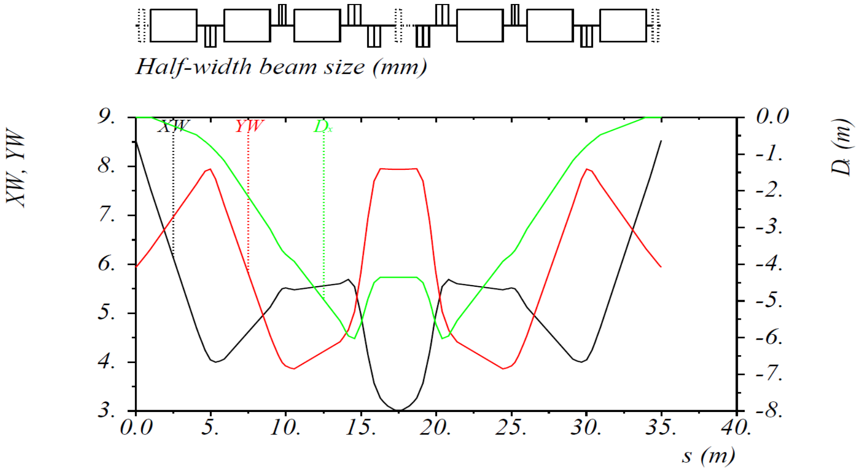
Left Bend and Enclosure Design

- Mu2e/g-2 experiment locations and separate beamline enclosures are achieved through two independent horizontal bend strings.
  - The two left bends determine the bearings and locations of the MC-1 (g-2) and Mu2e experiments.
    - MC-1 location is constrained by road, utility corridors and maximal distance from strong Mu2e magnetic fields
    - 40.5º of total Mu2e bend required to steer away from MC1 building for sufficient shielding
    - Wetlands limit overall length of the Mu2e line



Left Bend Optics Design

- Horizontal Bend details
  - A total of 40.5º generated by two mirror symmetric sections.
    - Each consists of two 6-4-120 type dipole magnets (SDFW) powered in series followed by a stronger 6-3-120 dipole to deliver 2 × 6.25° and 7.75° of horizontal bend, respectively.
  - Bend string as close as possible to last vertical bend;
  - This section must fulfill conditions for a linear achromat; i.e. Phase advance and compact dipole placement for dispersion cancellation highly constrain the optics of this section.
  - Trims have been installed upstream, downstream and center to provide 10% of net bend correction.

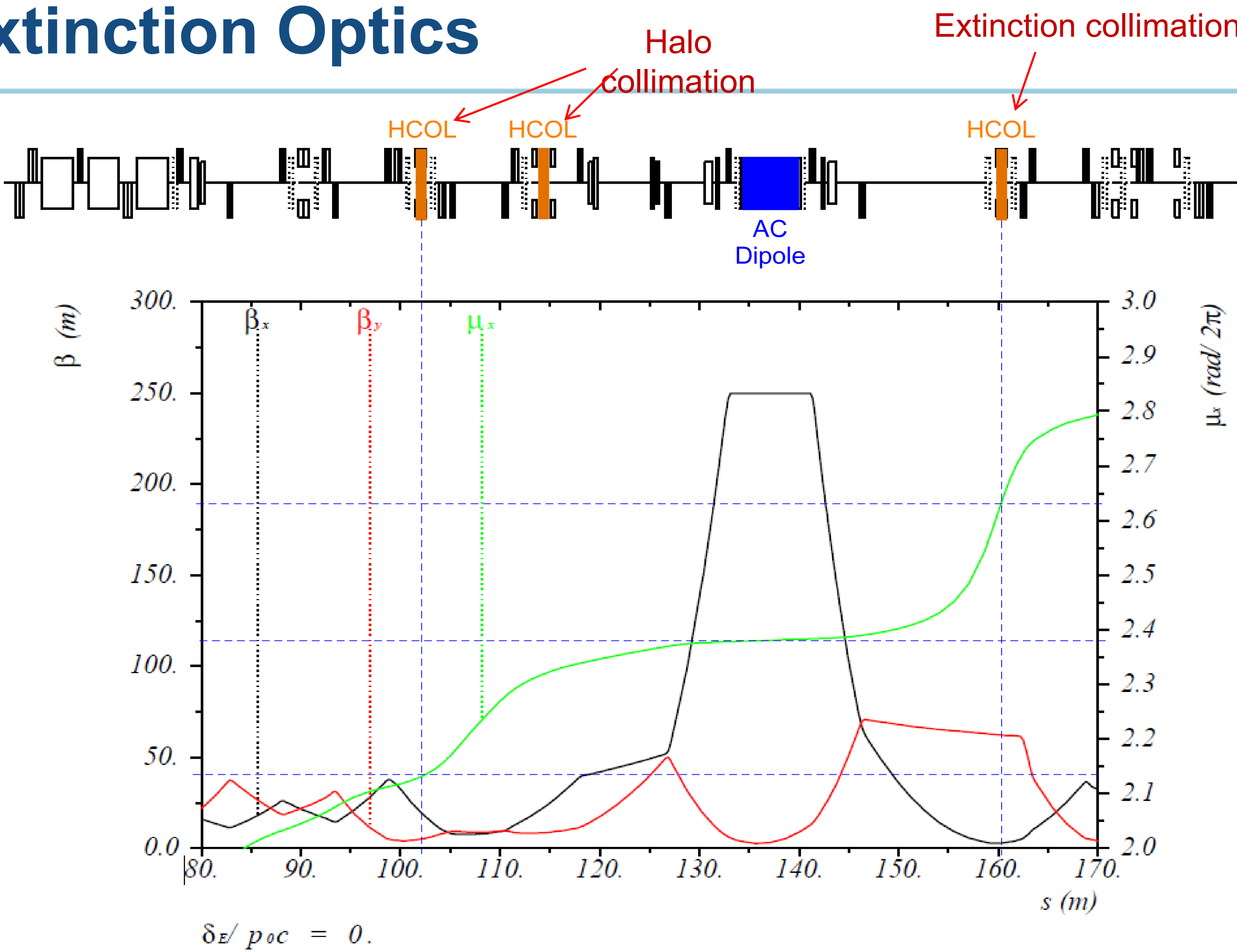


Extinction Section Considerations*

- Extinction is accomplished through a system of resonant dipoles and collimators, such that only in-time (un-deflected) beam is transmitted.
- Somewhat counter intuitively, magnet considerations lead to
  - long, low field magnets (6m total length)
  - high-β (large aperture) in the bend (horizontal) plane (250 m)
  - low-β waist in the non-bend plane
- Need to allow for collimation
  - Upstream of AC dipole system, to remove high-amplitude halo
  - Downstream of AC dipole system to absorb out-of time beam that has been deflected by the magnetic field.
- These considerations result in significant constraints on the beam line design.

*details of motivation in E. Prebys' Extinction talk

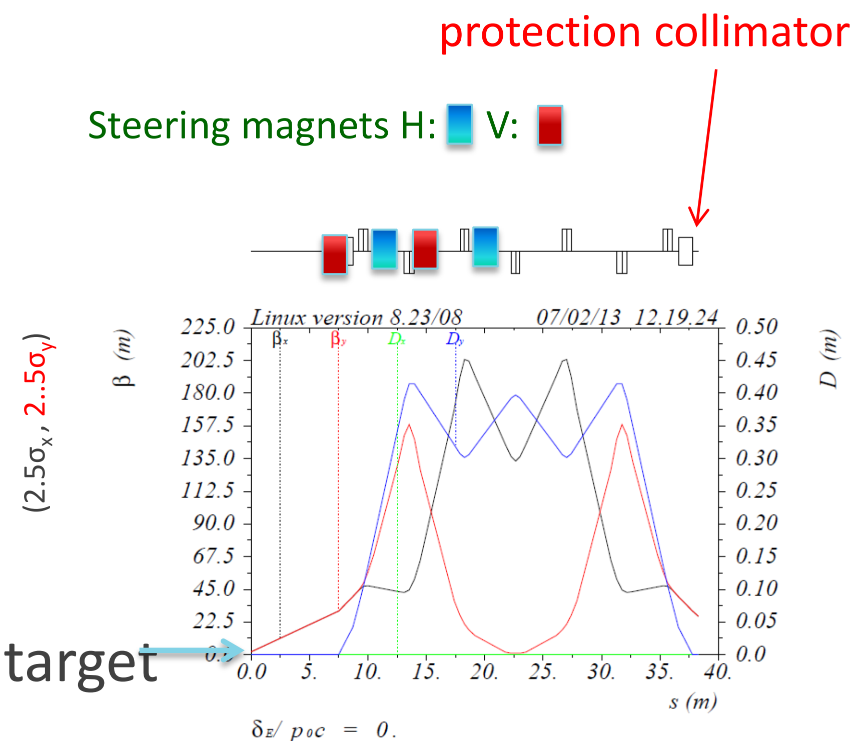
Extinction Optics



Final Focus Design

Target Beam Optics: Final focus requirements

- **Beam Spot**
  1. Small, circular (σ = 1mm) beam spot on a 6 mm target target
  2. 2.8° final declination at entrance to compensate for bending in solenoidal field.
  3. Dispersion-free
- **Target Scan**
  1. Independent position/angle controls in BOTH vertical and horizontal
     1. ±1 cm offset for vert target scan
     2. ±1 cm offset for horz target scan
     3. ±0.8° in horz/vert targeting angle



Final focus optics

Significant Changes since CD-1

- Vertical Mu2e/g-2 separation instead of horizontal
- Location and bearing of g-2 ring established
  - Increased bearing of Mu2e by 4.5°
- Extraction flipped from outside to inside of Delivery ring to permit Lambertson power and water connections (extensive shielding in this area)
- Magnet selection changed – nearly finalized.
- Extinction collimation and high beta region revamped
  - Upstream collimation and fewer collimators overall

Value Engineering since CD-1

- Vertical Mu2e/g-2 separation instead of horizontal, compact, minimizes civil enclosure costs, optimizes available space for beamline
- Roll of C magnet rather than changes to civil enclosure
- Optimal target steering magnet locations to minimize aperture and motion in target scans
- Magnets now selected from inventory of available magnets from Accumulator and BNL
- Minimize vacuum prep work, reuse vacuum pumps and parts inventory from Accumulator

Performance

- Combined Mu2e/g-2 civil constraints were met (utility corridor, roads, wetlands, shielding, stray magnetic field levels, separation of beamlines)
- Upstream beamline supports Mu2e/g-2 combined operation (40π mm-mrad emittance for g-2) with minimal reconfiguration
- Extinction simulations indicate that the collimation and high-beta AC dipole optics design achieves $<10^{-7}$ goal (Mu2e-doc-4054)
- Target spot size, divergence and scan criteria were met in the design of the final focus
- Elevation change and the 2.8° declination angle as required by the fringe field of the production solenoid were successfully combined in the final focus (which sits on a 1.4° incline)

Remaining work before CD-3

- Finalize beamline optics, particularly the extinction section.
- Finalize magnet stand design and installation drawings, including motorized final focus stands.
- Finalize vacuum design.
- Finalize LCW design.
- Finalize installation scheduling.
- Technical documentation of final design.

Summary

- We have a beamline design which satisfies all of the requirements of the Mu2e experiment, including the needs of the external extinction system.
- We are confident we have met the requirements for CD-2 approval.