Muon Campus Plans

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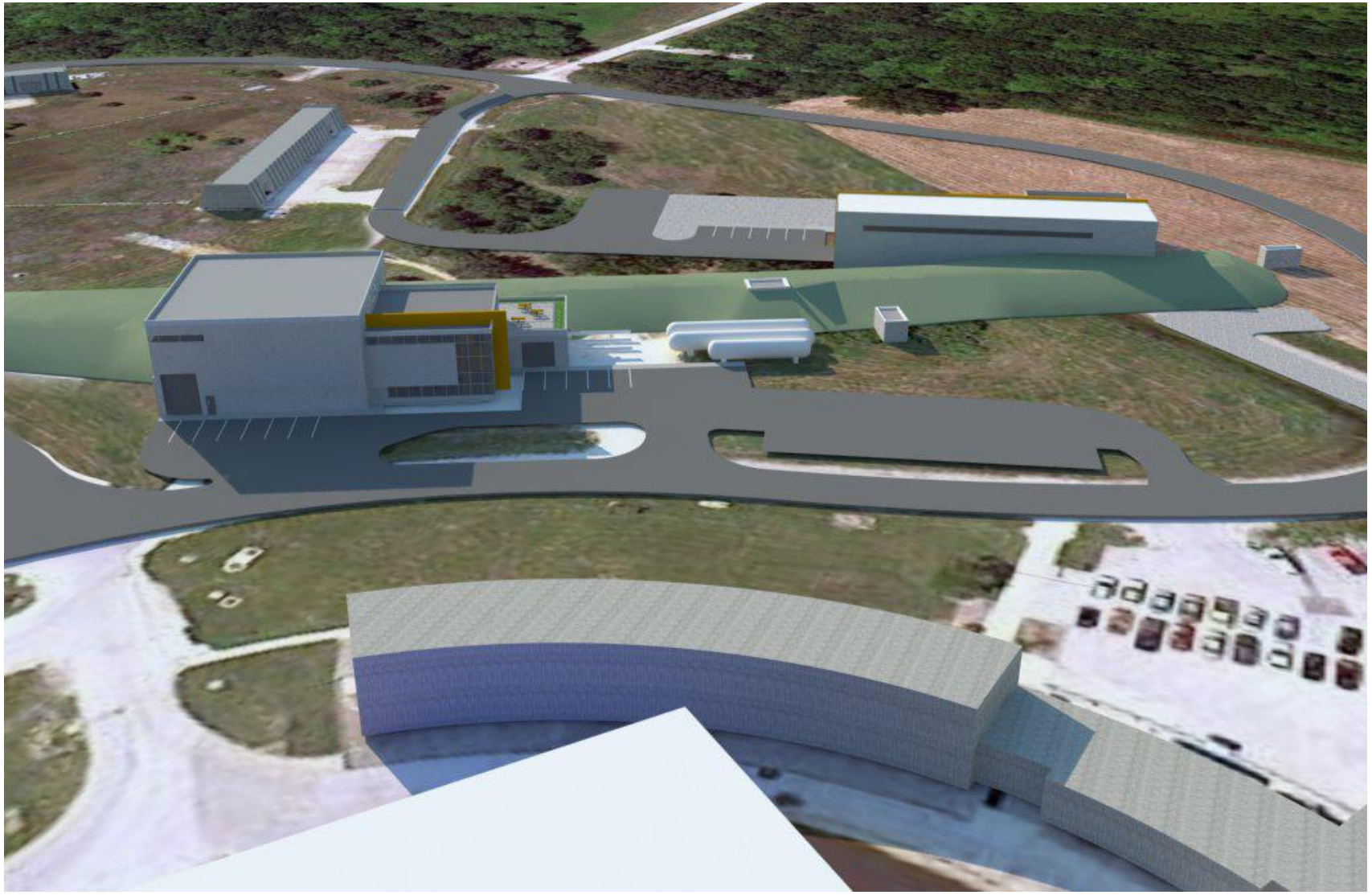
Accelerator Division, Muon Department
1/10/13

Muon Campus layout

Looking toward the Muon Rings

View from Wilson Hall



Thanks and disclaimers

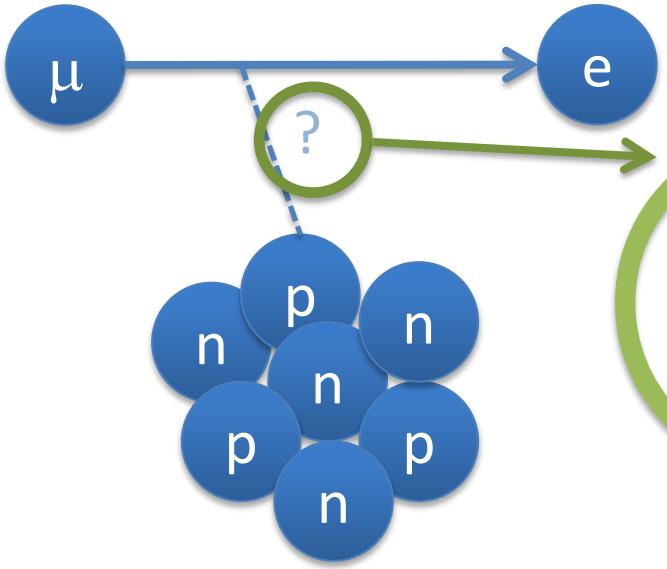
- Thanks in advance to everyone I “borrowed” content from
  - including Russ Alber, Jerry Annala, Brendan Casey, Brian Drendel, Doug Glenzinski, Arkadiy Klebaner, Ioanis Kourbanis, Tom Lackowski, Nikolai Mokov, Jim Morgan, Hogan Nguyen, Chris Polly, Ron Ray, Dean Still, Steve Werkema, …

- I have been involved with g-2 for a little over a year, and the broader Muon Campus planning for about 2 months
  - I am not at all an expert on Mu2e

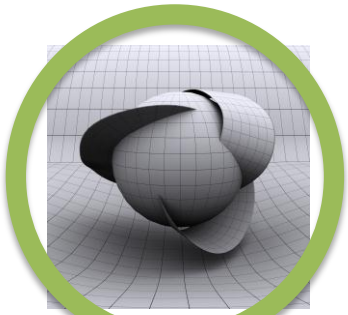
Mu2e

Mu2e

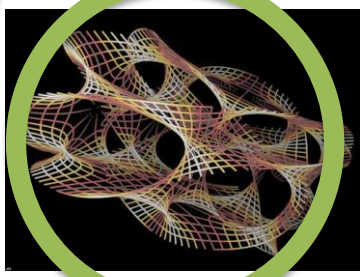
- Muons regularly decay to electrons and neutrinos $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$
- Mu2e will search for charged lepton flavor violation ($\mu N \rightarrow eN$)
  - Neutrino flavor oscillations already observed



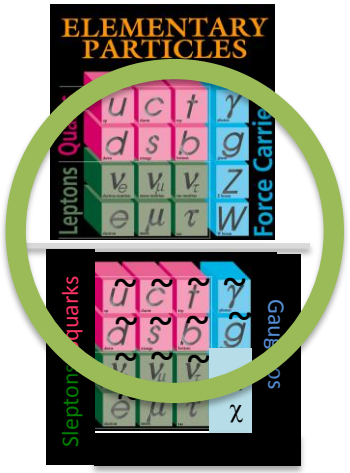
Not Yet Thought Of



Extra Dimensions



Super Strings

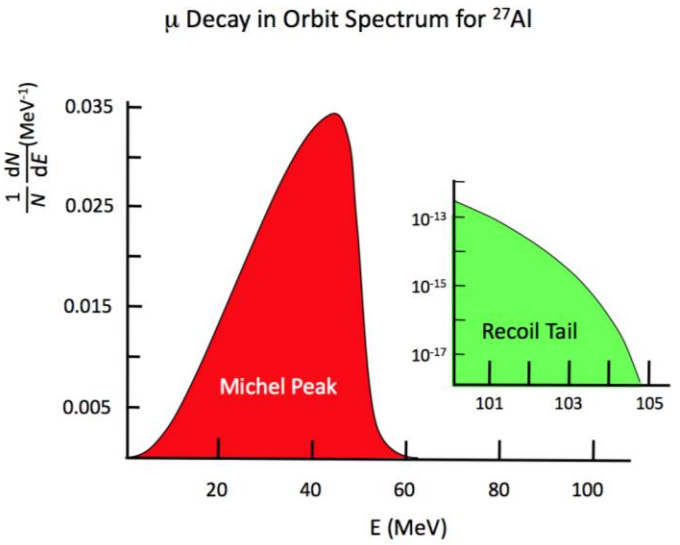


Super Symmetry

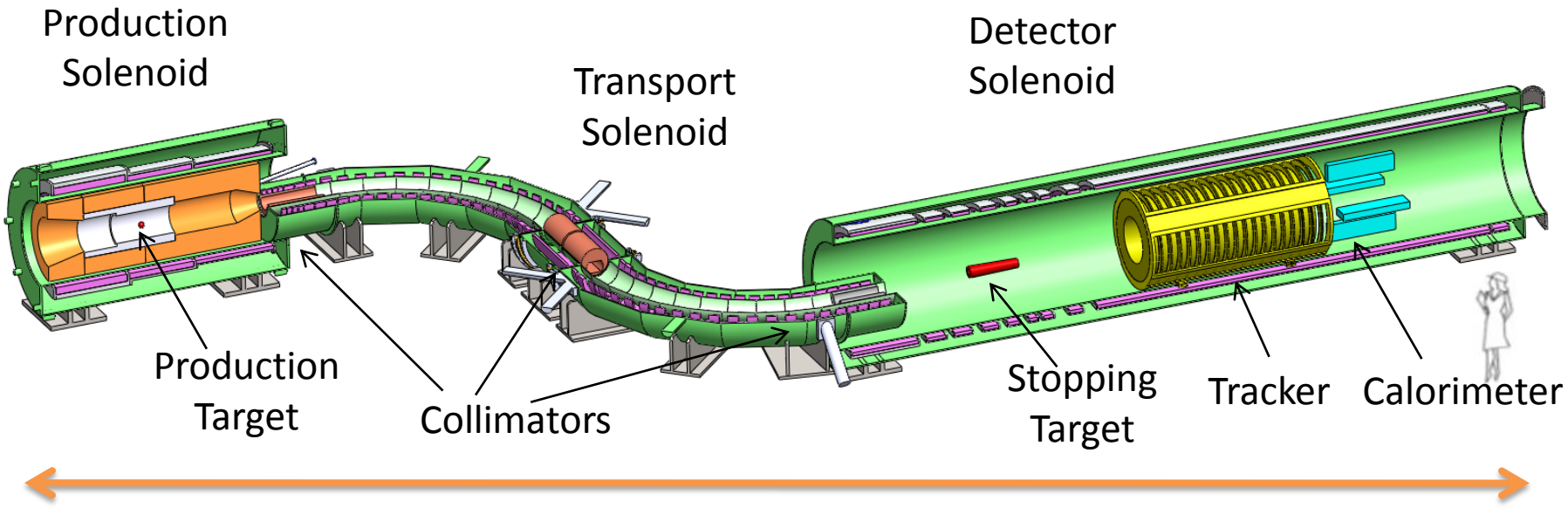
- Conversion rate distinguishes between different theories

Mu2e

- Generate beam of low-momentum μ^-
- Stop the muons in a target
  - Aim to improve sensitivity by 10^4 over previous experiments
  - requires ~10^{18} stopped muons
- Stopped muons are trapped in orbit around the nucleus
  - Using Aluminum target (nucleus):
    - characteristic time τ_μ^{Al}=864 ns
    - conversion-electron energy 104.97 MeV
    - (maximum decay-e energy 52.8 MeV)
- Extinction system (AC dipole) to prevent prompt background from out-of-time protons hitting production target

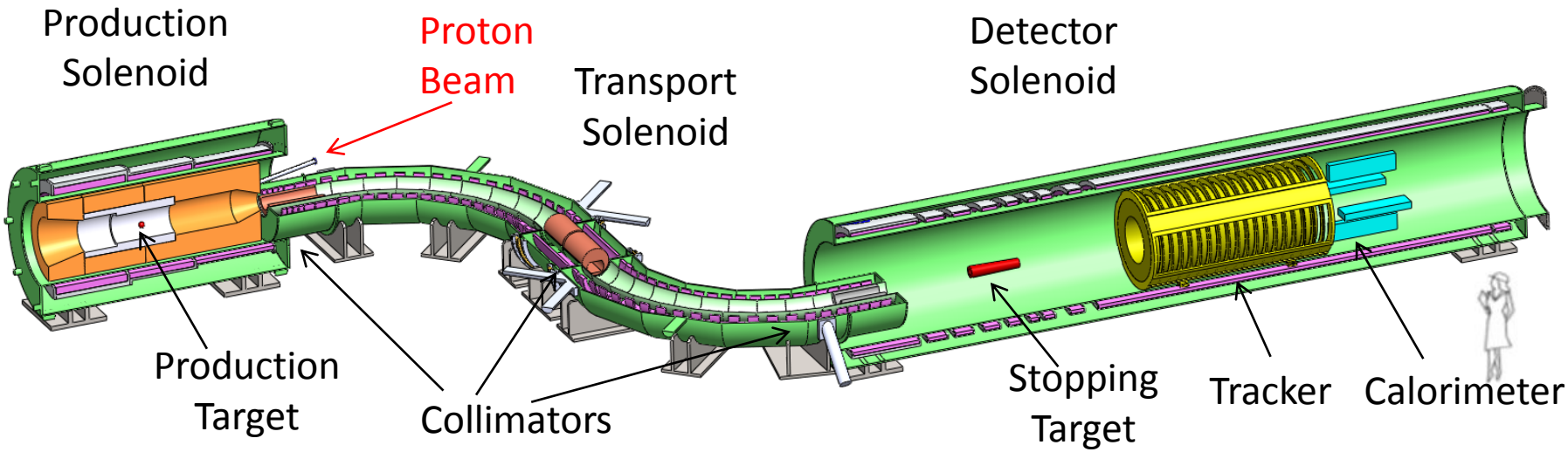


Mu2e Apparatus



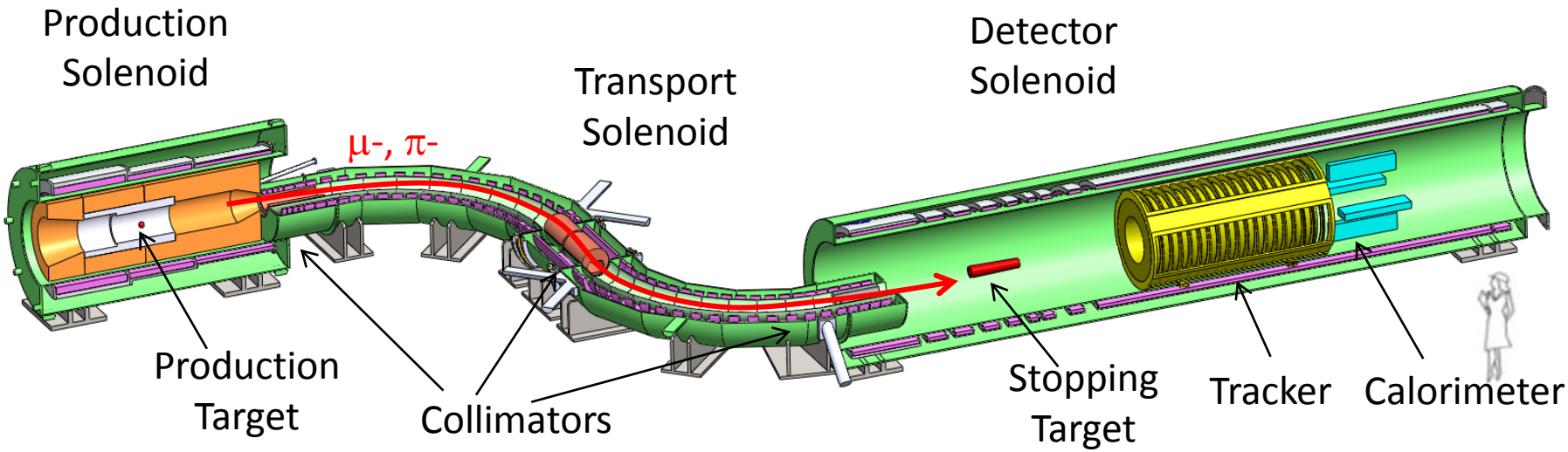
about 75 feet end-to-end

Mu2e Apparatus

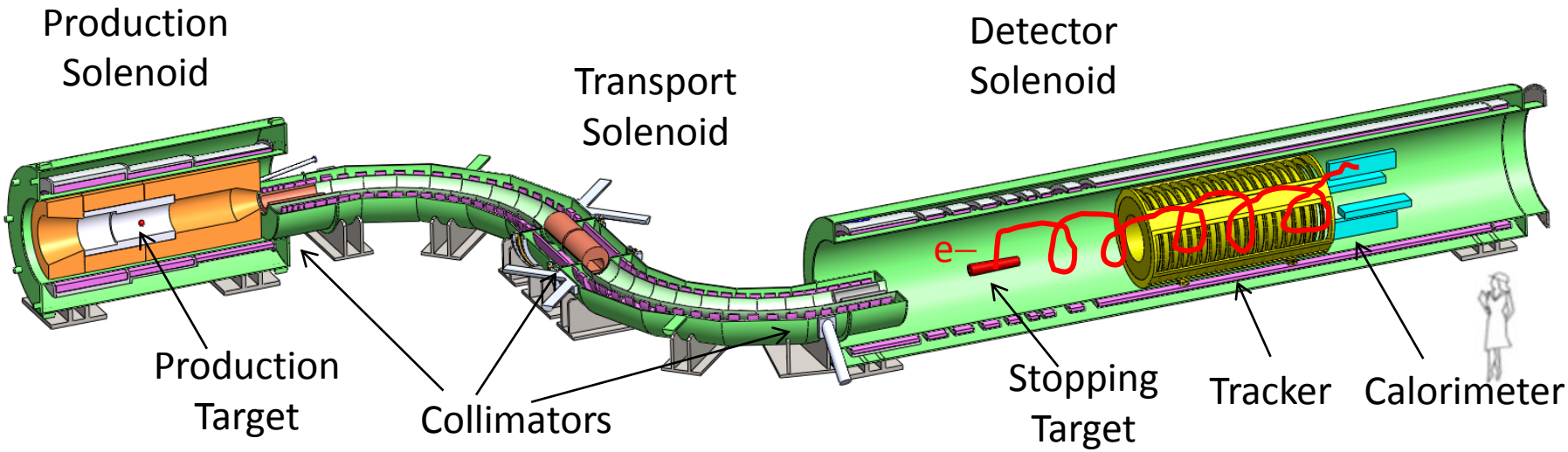


Proton Beam delivered to the production target via the former Pbar beamlines followed by an external beamline

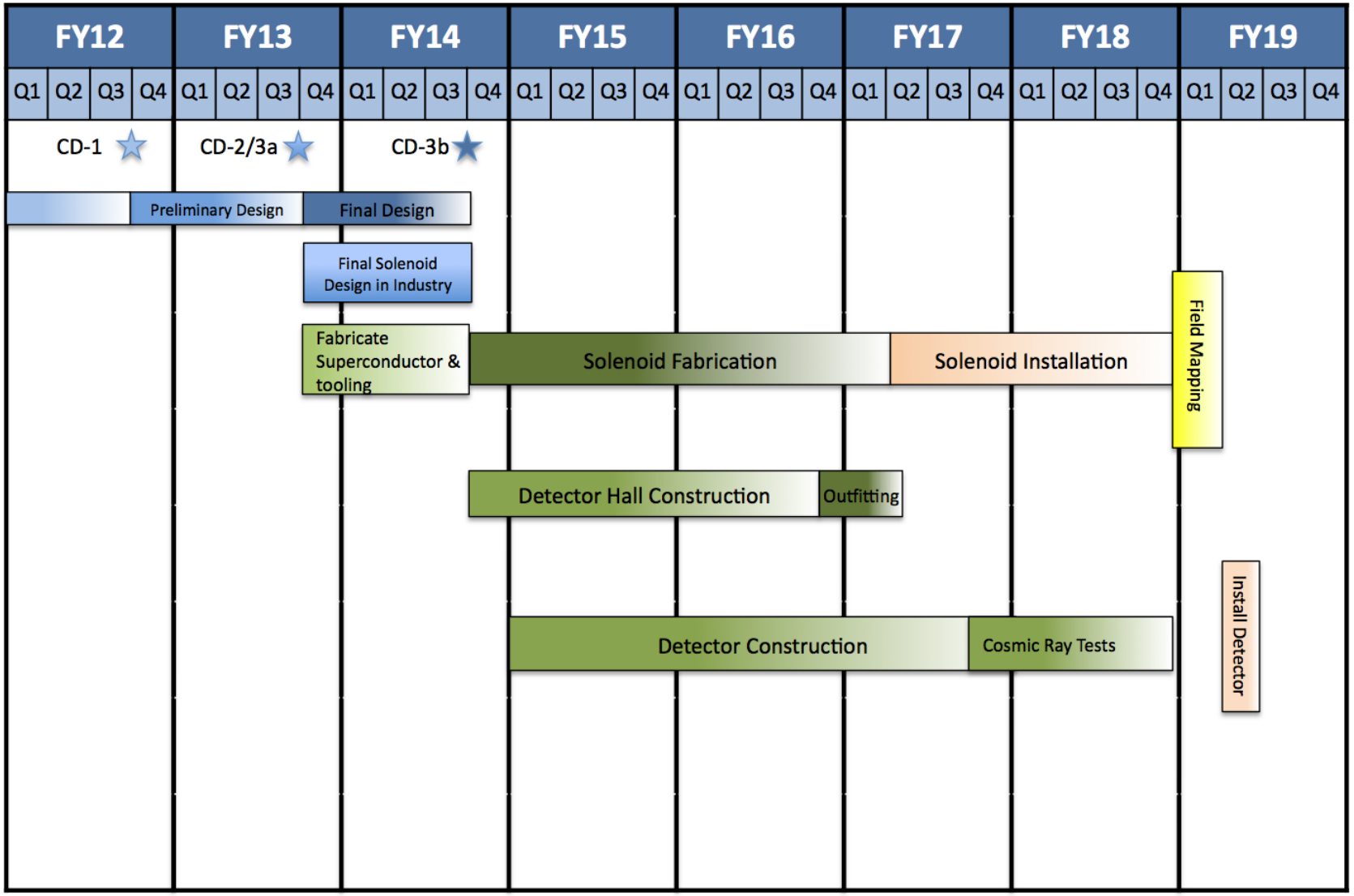
Mu2e Apparatus



Mu2e Apparatus



Mu2e schedule

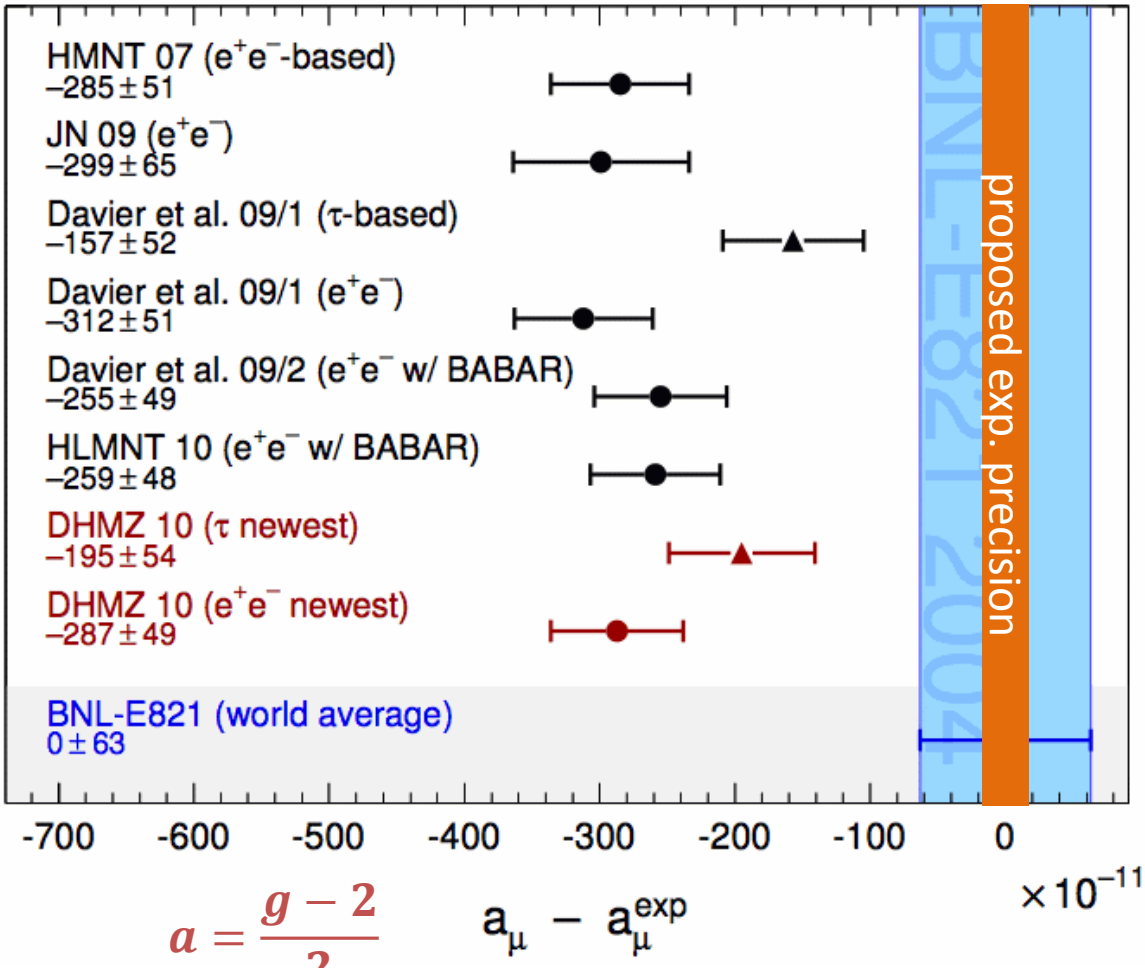


g-2

The anomolous magnetic moment and g-2

- g≈2 but higher-order corrections
  - QED, EW, hadronic, new physics?

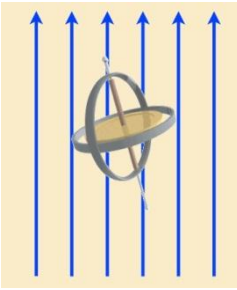
$$\vec{\mu} = g_s \left(\frac{q}{2m}\right) \vec{s}$$



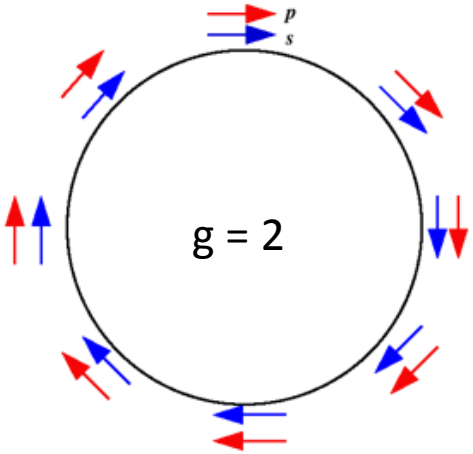
- Currently ~3σ discrepancy between theory and experiment
- New muon g-2 experiment at Fermilab expected precision could yield ~5σ

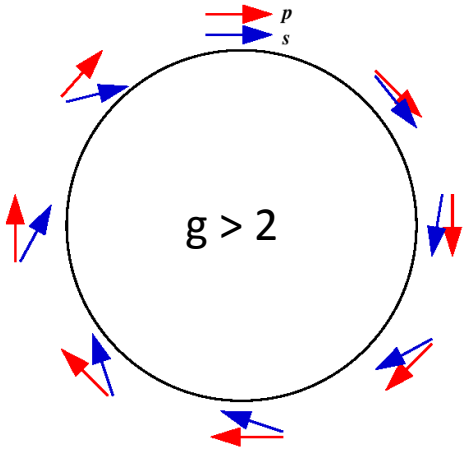
Measuring g-2

- Polarized muons in magnetic field precess with Larmor spin precession frequency $\vec{\omega}_s = -\frac{eB}{\gamma mc} - \frac{e}{mc} a\vec{B}$ $\quad a = \frac{g-2}{2}$



- Measure g-2 using cyclotron





$$\vec{\omega}_c = -\frac{e\vec{B}}{\gamma mc}$$

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{e\vec{B}}{2mc}(g-2)$$

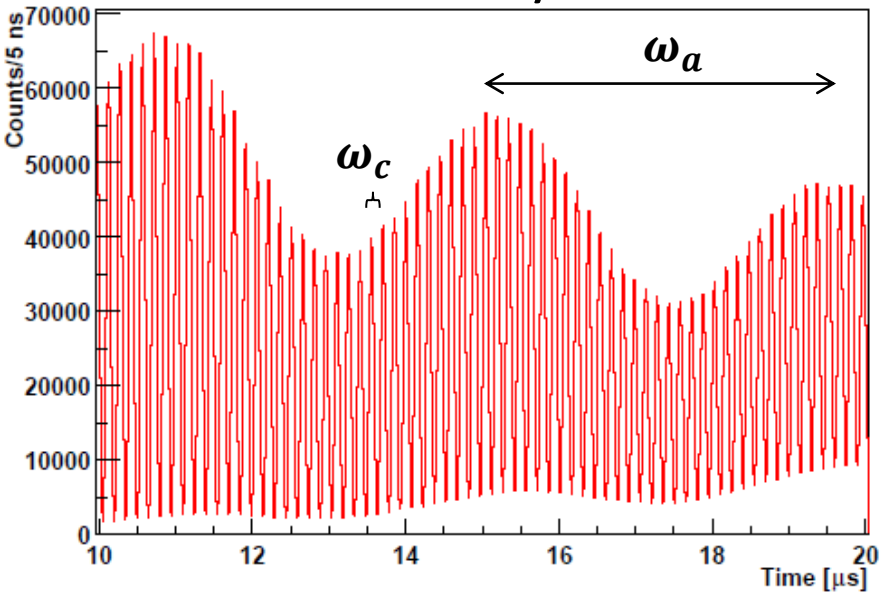
- Requires precise measurements of $\boldsymbol{\omega_a}$ and of the magnetic field

Measuring ω_a

- One more trick:
  - Polarized muons in storage ring with vertical focusing by electrical quadrupole field

$$\vec{\omega}_a = -\frac{e}{mc}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}\right]$$

  - At magic momentum p_μ = 3.094 GeV/c (γ = 29.3), g-2 precession frequency ω_a independent of electric field
- Distribution of decay electrons as function of time

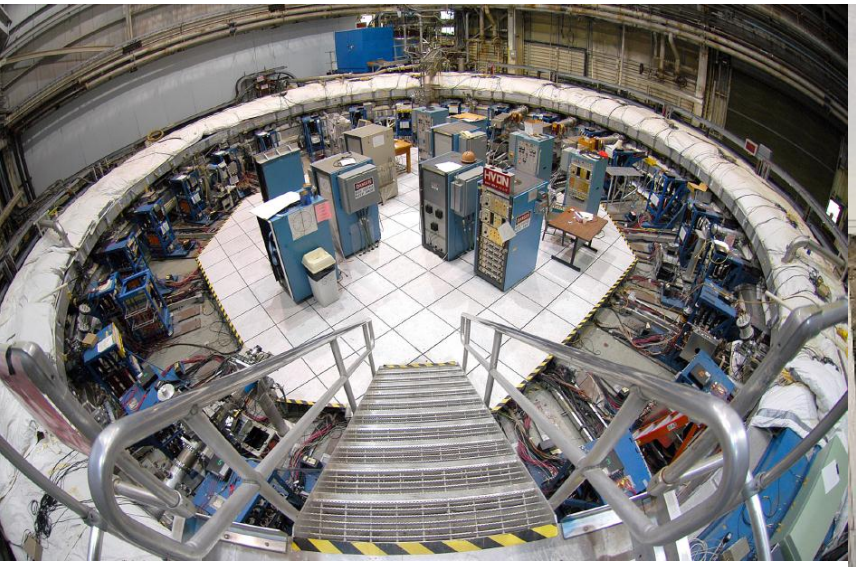


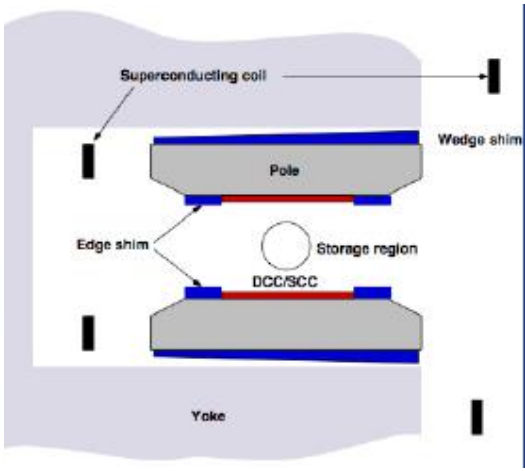
$$N(t) = N_0 e^{-t/\gamma\tau}[1 - A\cos(\omega_a t + \varphi)]$$

Intensity at a single detector station shortly after injection
Phys. Rev. D73 (2006) 072003

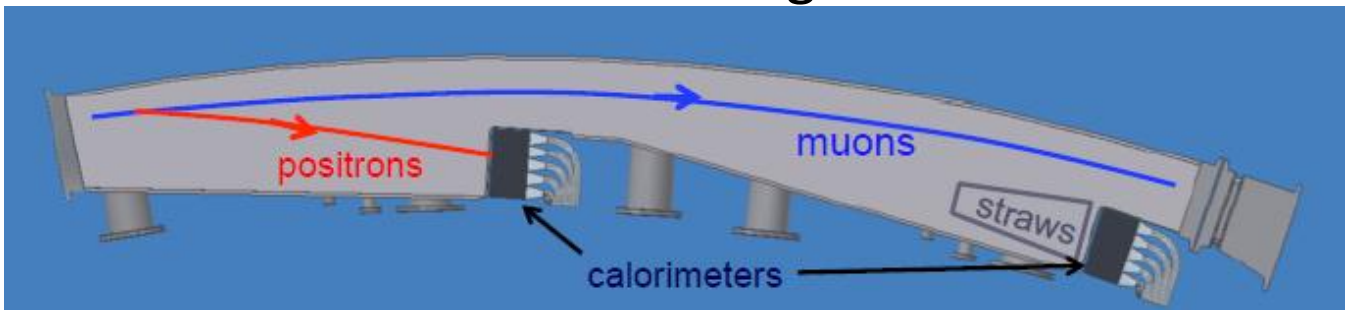
g-2 apparatus

- Reusing storage ring from BNL g-2 experiment





- New calorimeters and straw-tube tracking



Planned improvements

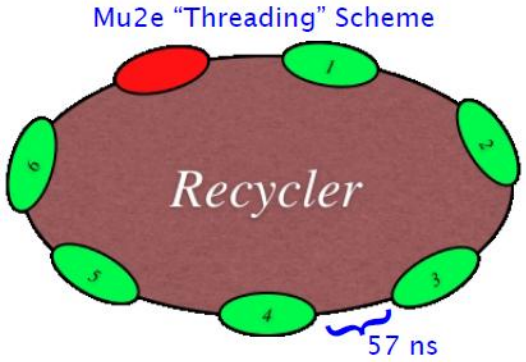
- Rebunch high-intensity beam into multiple bunches to lower the instantaneous rate
- Increase the detector segmentation to reduce the instantaneous rate in a given cell
- Modify secondary beamlines to store as many muons from pion decays as possible
- Remove pions and protons from muon beam to prevent hadronic flash in calorimeters
  - Allows analysis of more (earlier) decay e+
  - Longer beamline for pion decay
  - Let heavier protons separate in time from pions/muons and kick them out
- Improve beam dynamics in storage ring
- Improve storage ring field uniformity and the measurement and calibration system

g-2 schedule

- Preparing for CD1 review this spring
- MC1 building complete early FY14
- g-2 storage ring ships early FY14
- Ring reassembly starting FY14
- Cryo ready to cool ring early FY15
- Ring magnetic field shimming starting mid FY15
- Recycler and Muon beamline work FY14-15
- New beamline enclosure beneficial occupancy mid FY15
- Beam to g-2 early 2016

Beam to Mu2e

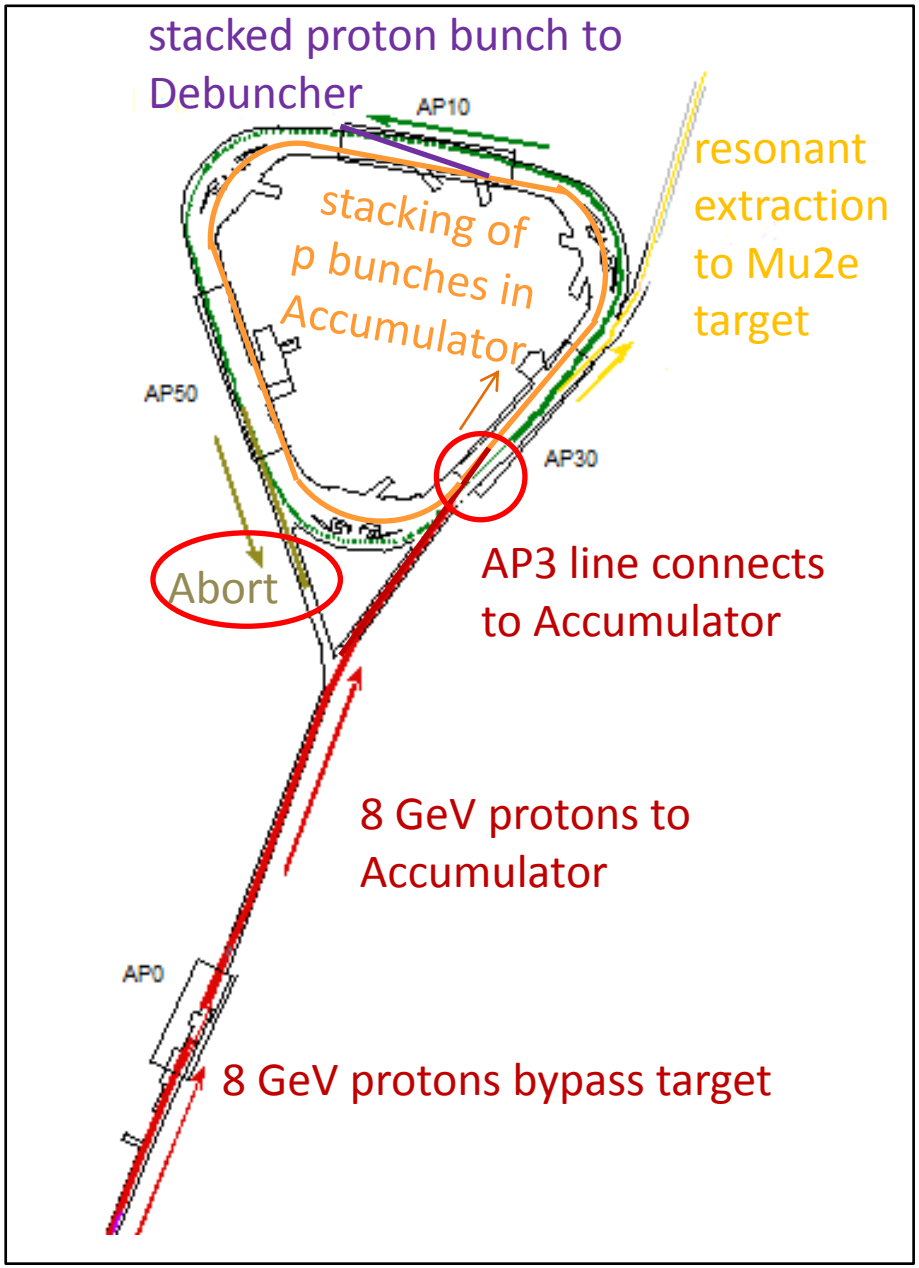
- Primary (8 GeV) proton beam resonantly-extracted from Debuncher
- Extinction of out-of-time beam
- Original plan for increased flux involved "threading" Mu2e batches between NOνA batches, stacking proton bunches in Accumulator, and rebunching / resonant-extraction in Debuncher

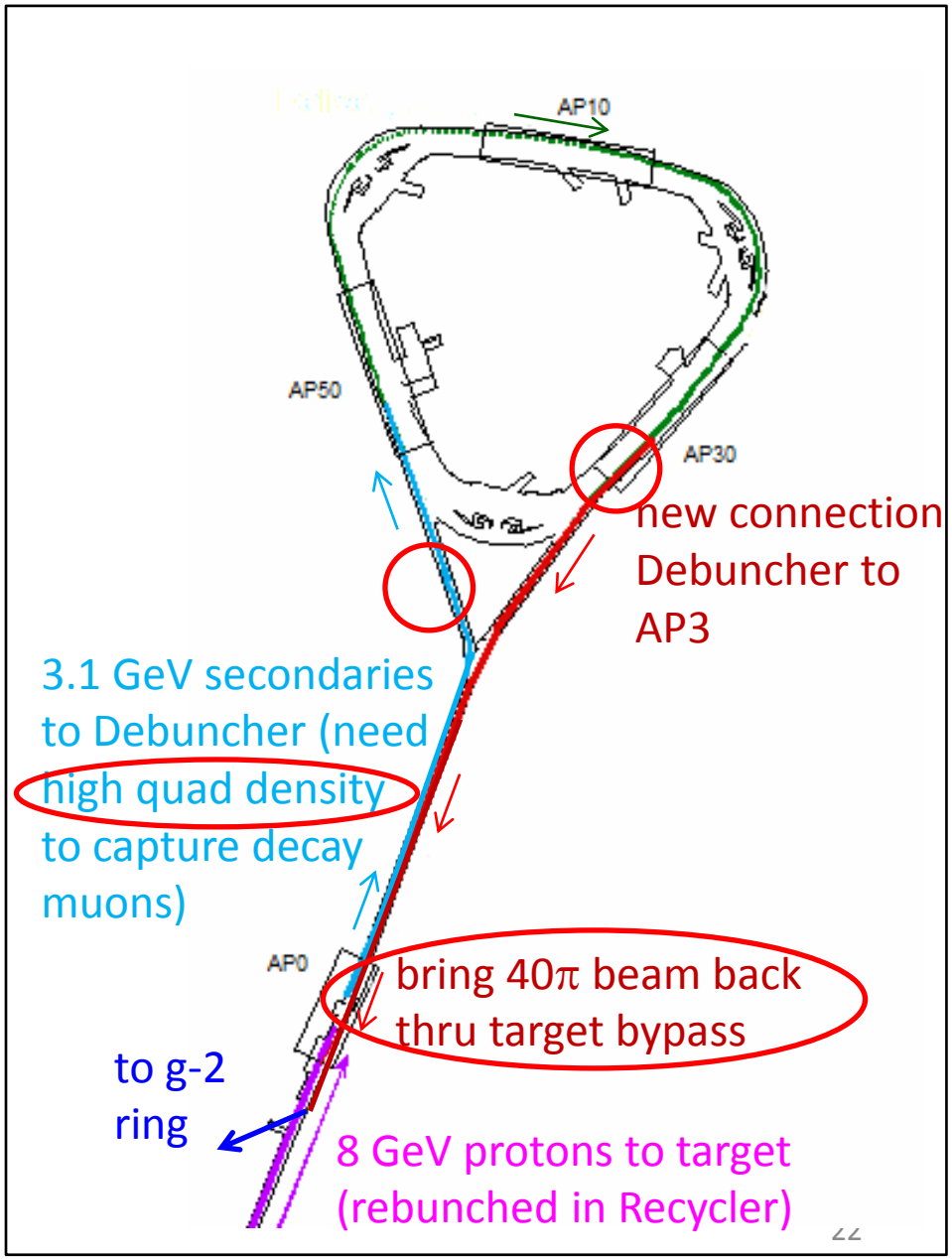


Beam to g-2

- Rebunch primary (8 GeV) protons so that rate in detectors is not too high, bunch length < ring revolution time of 147ns
- Create 3.1 GeV secondary pions off a target
- Beamline long enough for ~all pions to decay
- Capture 3.094 GeV ("magic momentum" muons)
  - aim for 40π acceptance
- Limit secondary pions and protons making it into g-2 storage ring (cause "hadronic flash" in calorimeters)

Original Mu2e and g-2 plans for former Pbar beamlines

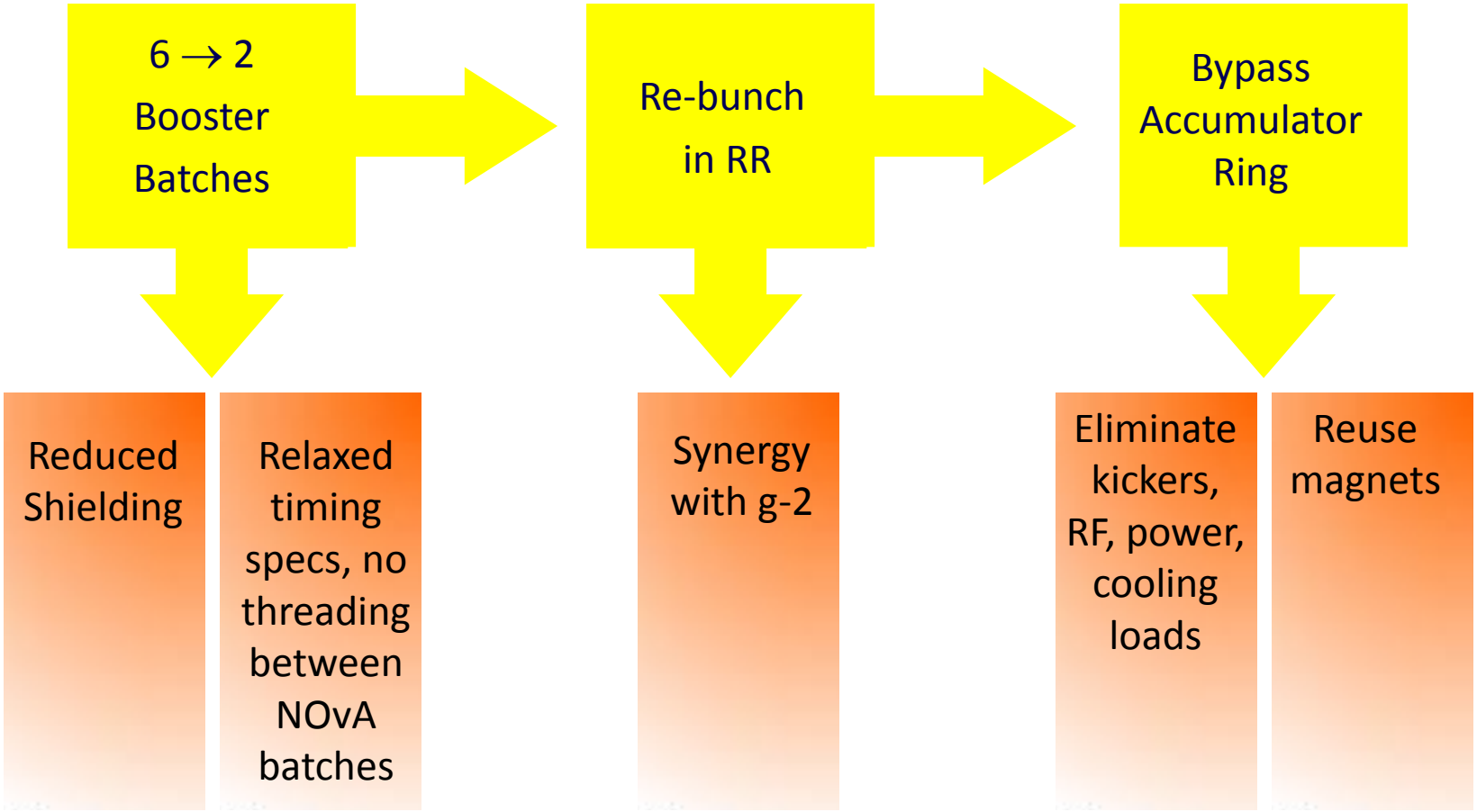




g-2 near Mu2e in “Muon Campus”

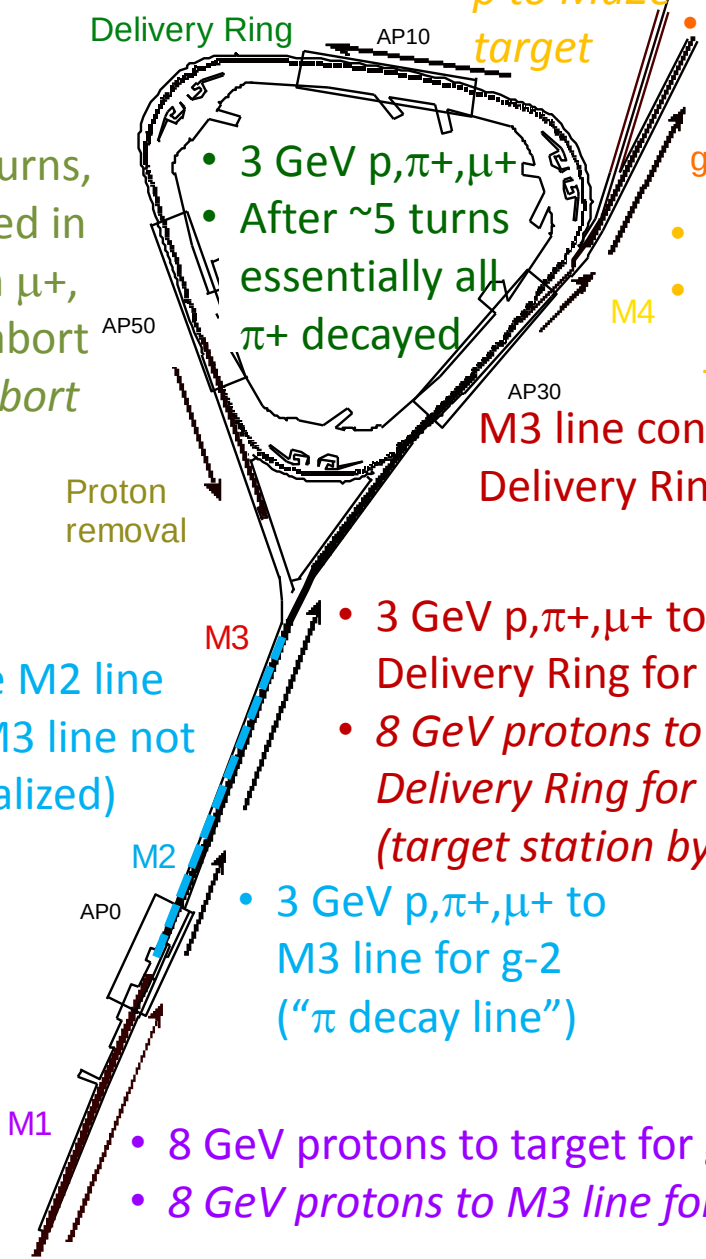
- Locating g-2 experiment near Mu2e has advantages
  - Both g-2 and Mu2e circulate in same direction
    - No need to switch polarity, just energy
    - Frees some magnets in AP2 line for reuse, no conflict with Mu2e plans for primary beam abort in AP2
    - Can use Mu2e abort to remove proton contamination from g-2 secondary beam
  - New building location also much better
    - Old location jammed between road and berm
    - Utility corridor to be rerouted
    - Don’t have to pass g-2 secondary beam back through AP0
  - Can share cryo and other infrastructure
  - Time-dependent stray magnetic fields at g-2 ring smaller near Booster than near Main Injector

Mu2e Accelerator Task Force Cost Savings



- Trade Mu2e rate for run time (3 yrs running vs 1 yr)
- Elimination of Accumulator removes almost every g-2/Mu2e conflict
- Over $100M in savings in the combined program

Muon Campus beamline plan for Mu2e and g-2



- *p to Mu2e target*
- μ+ to g-2 ring
- 3 GeV p,π+,μ+
- After ~5 turns essentially all π+ decayed
- After ~5 turns, p separated in time from μ+, kick into abort
- *Primary abort for Mu2e*
- Extract μ+ for g-2
- *Resonant extraction for Mu2e*

M3 line connects to Delivery Ring (Debuncher)

(where M2 line joins M3 line not yet finalized)

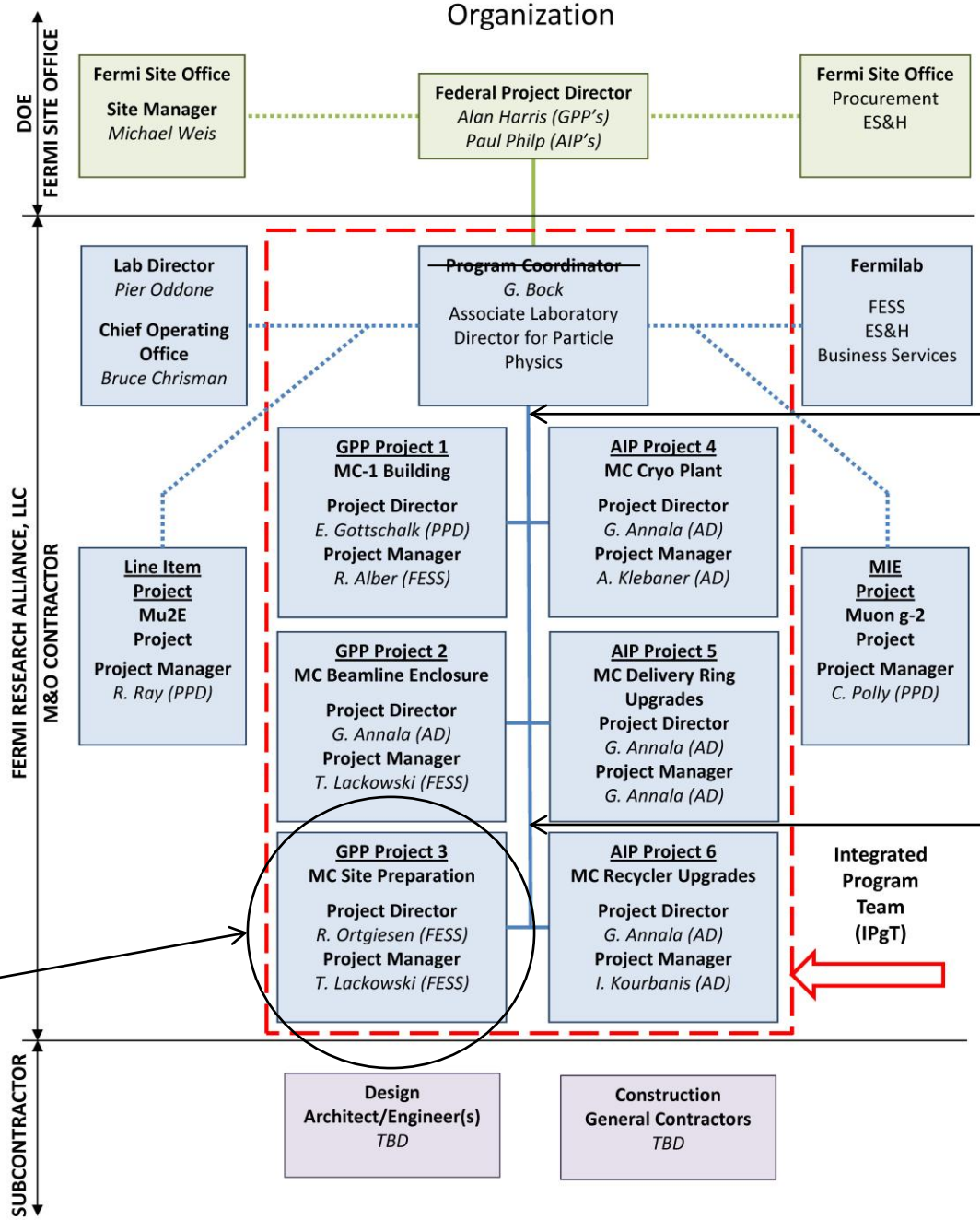
- 3 GeV p,π+,μ+ to Delivery Ring for g-2
- *8 GeV protons to Delivery Ring for Mu2e (target station bypass)*
- 3 GeV p,π+,μ+ to M3 line for g-2 ("π decay line")
- 8 GeV protons to target for g-2
- *8 GeV protons to M3 line for Mu2e*

Shared infrastructure

- Any shared infrastructure needs to be ready in time for g-2
  - Make use of Accelerator Improvement Projects (AIPs) and General Plant Projects (GPPs)
  - MC-1 building houses cryo refrigerators and beamline power supplies in addition to g-2 storage ring / future expts (GPP)
  - Cryo work moves to AIP
  - Extraction-line tunnel moves from Mu2e to GPP
  - First part of extraction line moves from Mu2e to g-2
  - Recycler work was on g-2 project (g-2 drives specs), later moved to AIP at recommendation of Mu2e CD-1 review committee
  - Proton abort and other Delivery-Ring work moved to AIP
  - P1, P2, M1 line 8-GeV aperture improvements moved to AIP
  - Controls and common instrumentation(?) on g-2 project
- Yes, partly this makes Mu2e look less expensive, but there is also a limit on the total cost of the Muon campus program

Muon Campus Program

Organization



Program Coordinator M Convery

need additional AIP to cover costs?

AIP's and GPP's have hard cap at $10M

likely scope change

Packaging into AIPs/GPPs

- Actually the packaging of the work is still in flux
  - Except for MC1 building GPP which is already in progress
- DOE recommendation resulted in acceleration of Mu2e civil construction schedule, had to shuffle work between Mu2e and other Muon Campus projects
- AIPs and GPPs have a hard cap of $10M, don't include conceptual design
  - As designs are becoming more mature and in some cases work is pushed later, cost estimates indicate that the work may not fit in the planned packages
- Internal AD review later this month to make sure nothing is missing between all these packages and to look for ways to reduce costs
- Following the review, we will propose how to package the individual pieces into AIPs and GPPs

Rough funding plan for GPPs and AIPs

on critical path for g-2

longer lead time for RF

on critical path for g-2

Funding breakout for AIP/GPP [$M]						
GPP & Pond Work	FY13	FY14	FY15	FY16	FY17	Total
MC-1 Building GPP	7.5	1.0				8.5
MC Beamline Enclosure GP	0.4	3.7	5.1			9.2
A0 Cooling Pond		0.5				0.5
GPP Total	7.9	5.2	5.1			18.2
GPP Guidance	7.9	5.4	7.6			20.9

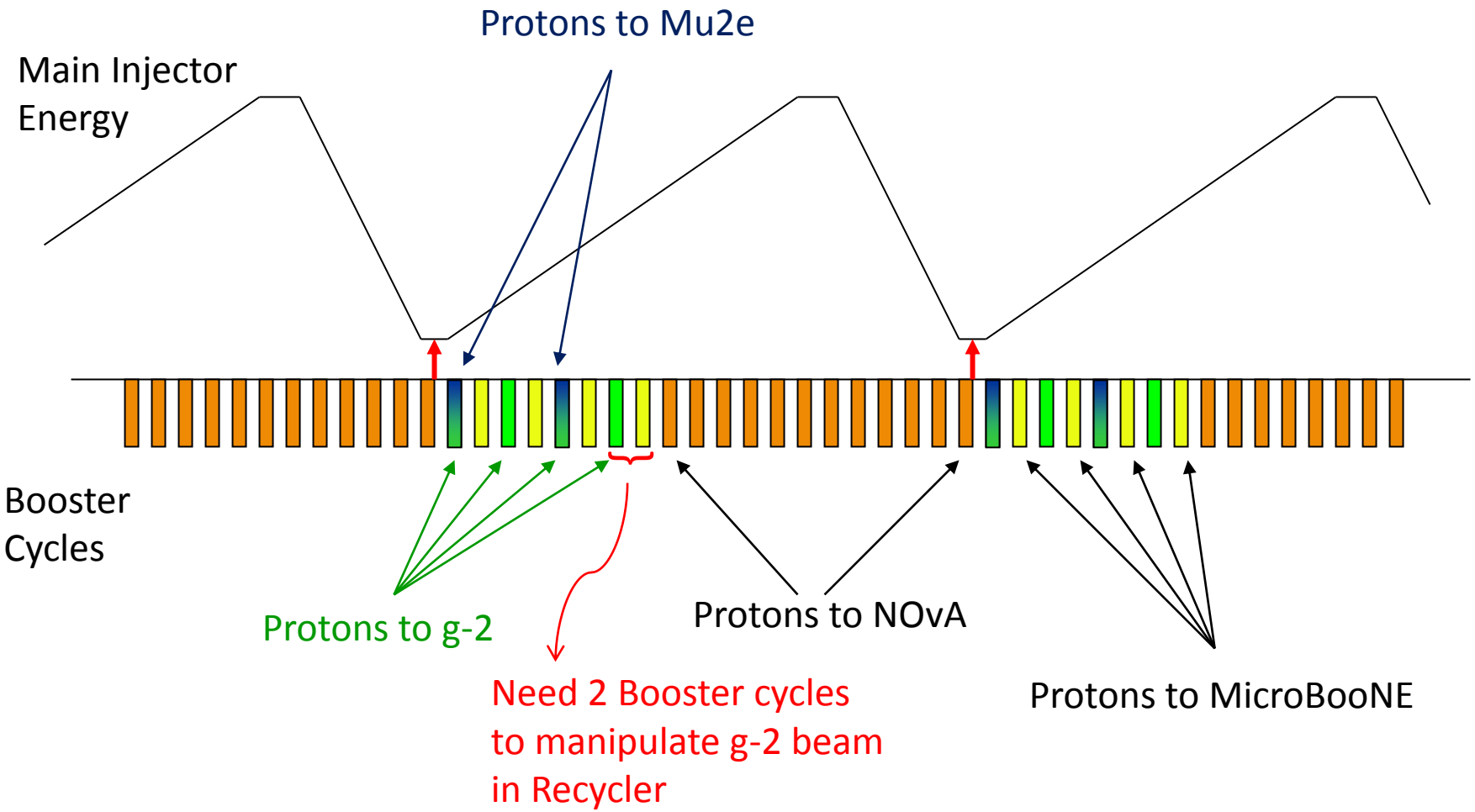
AIP	FY13	FY14	FY15	FY16	FY17	Total
Recycler AIP						
Accelerator work	0.6	5.3	2.6			8.5
MI-52 Extension	0.1	0.7				0.8
Delivery Ring AIP	0.8	1.0	7.2	0.7		9.7
Cryo Plant AIP	1.1	5.2	0.6	2.5	0.4	9.8
AIP Total	2.6	12.2	10.4	3.2	0.4	28.8
AIP Guidance	2.2	12.4	9.8			

	FY13	FY14	FY15
AIP+GPP Total	10.5	17.4	15.5
AIP+GPP Guidance	10.1	17.8	17.4

- The additional site power feeder that was part of site-prep GPP ($1M) is not included here, may be needed in 2017 or 2018

Protons to the Muon Campus

Protons available



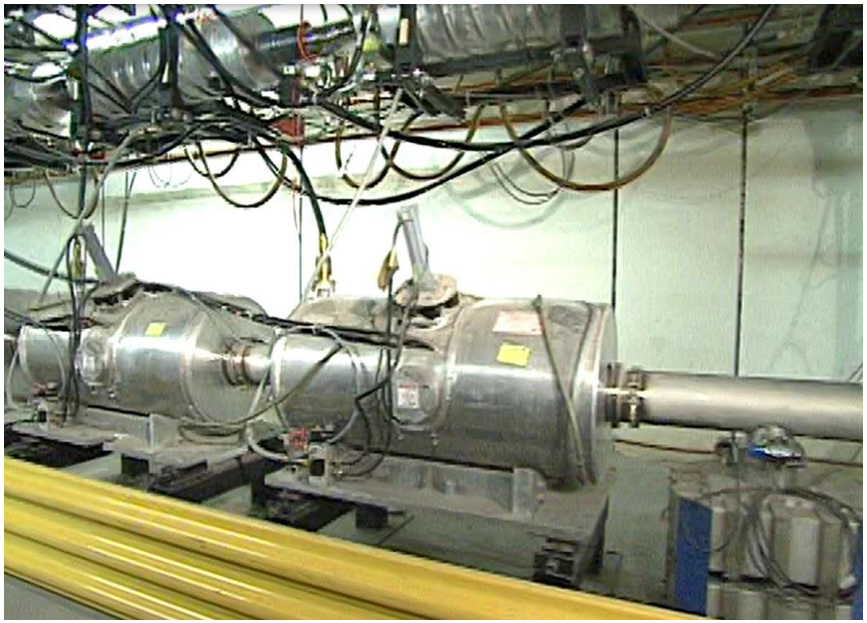
- (Mu2e and g-2 cannot run simultaneously)

Re-bunching beam in Recycler

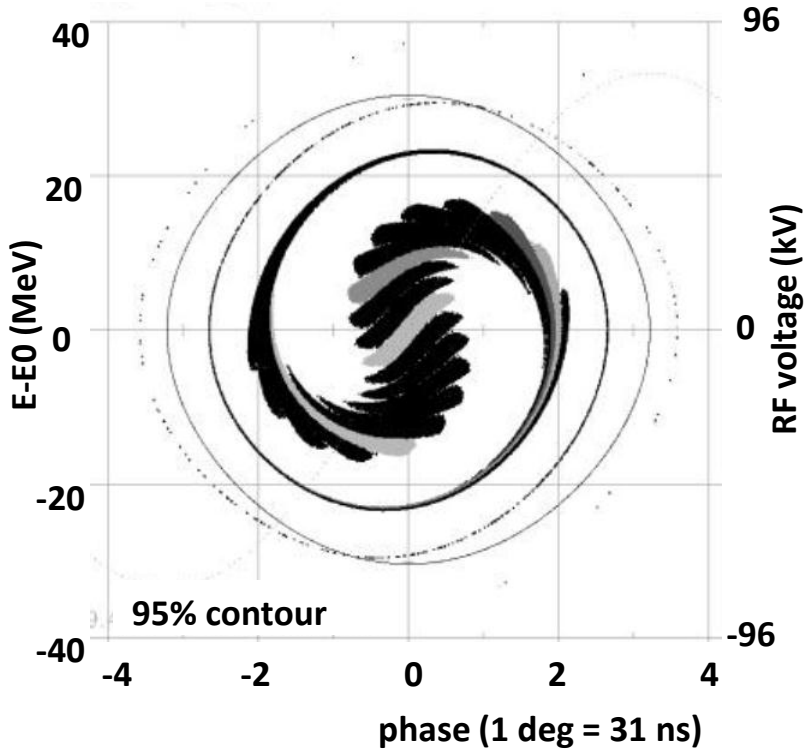
- 53 MHz bunches ($4x10^{12}$ protons) reformed into 4 bunches ($1x10^{12}$ protons) at 2.5 MHz
  - Reduce pile-up in detector
  - Build new cavities for 2.5MHz system
- g-2 needs beam pulses out of Recycler not longer than ~100ns
  - Muon storage ring revolution time 147ns
  - Balance efficiency, momentum spread, and longitudinal extent
  - Achieve pulses with 95% of beam within 120ns
- Beam pulses should be separated by ~10ms for the muons to decay in the g-2 storage ring and data to be recorded
- Mu2e specs are less stringent than g-2

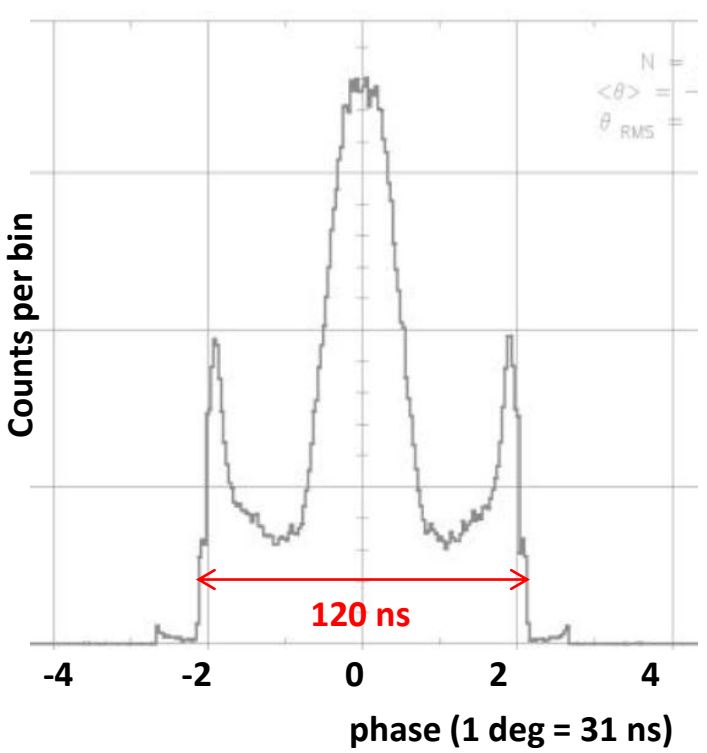
Recycler AIP

- Allows 8 GeV proton beam to be rebunched in the Recycler and extracted to the P1 line for transport to experimental areas
  - 2.5 MHz RF for re-bunching beam
  - Extraction kickers
  - Beamline connection from Recycler to P1 line
  - MI52 building extension for kickers (civil – move to separate FESS project?)
- RF cavity production
  - Cavities must have active cooling
  - Reuse ferrites from MI coalescing cavities
  - Labor intensive
  - 7 RF systems (cavities + PA's) for Recycler
  - 2 cavities for Mu2e to be installed in the Delivery Ring



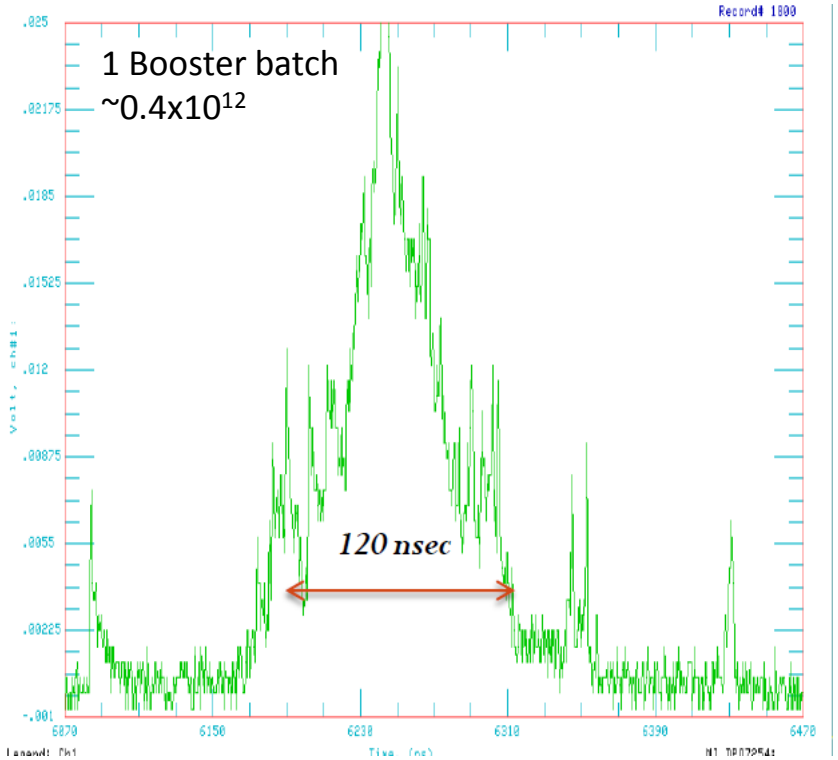
Simulation of rebunched beam

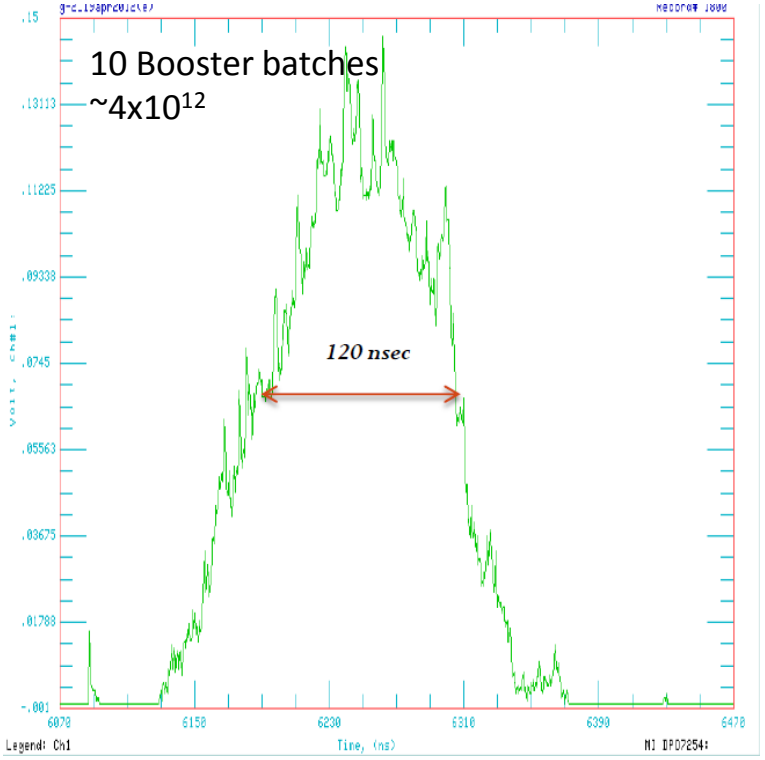




- 95% capture efficiency, 95% of captured beam w/in 120ns

Beam distributions from test in Main Injector

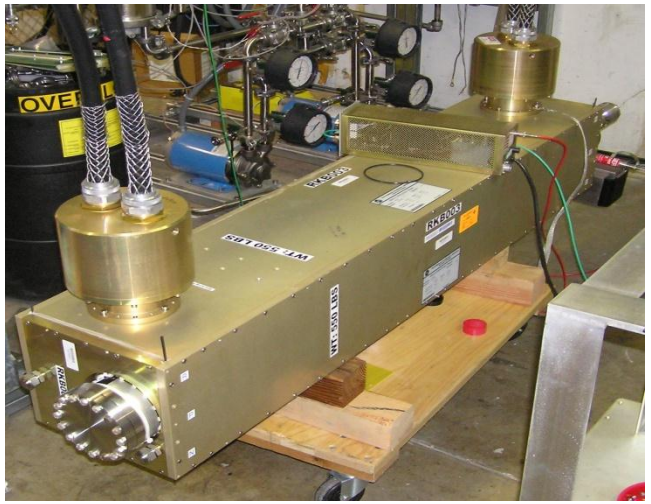




- Very good agreement between simulations and beam data at low intensities
- Beam loading will be much less of an issue in Recycler

Recycler extraction kicker system

Kicker angle	1.37 mrad
Flattop	200 nsec
Field Rise Time	120 nsec
Field Fall Time	400 nsec
Average Rate	12 Hz
Burst Rate	100 Hz

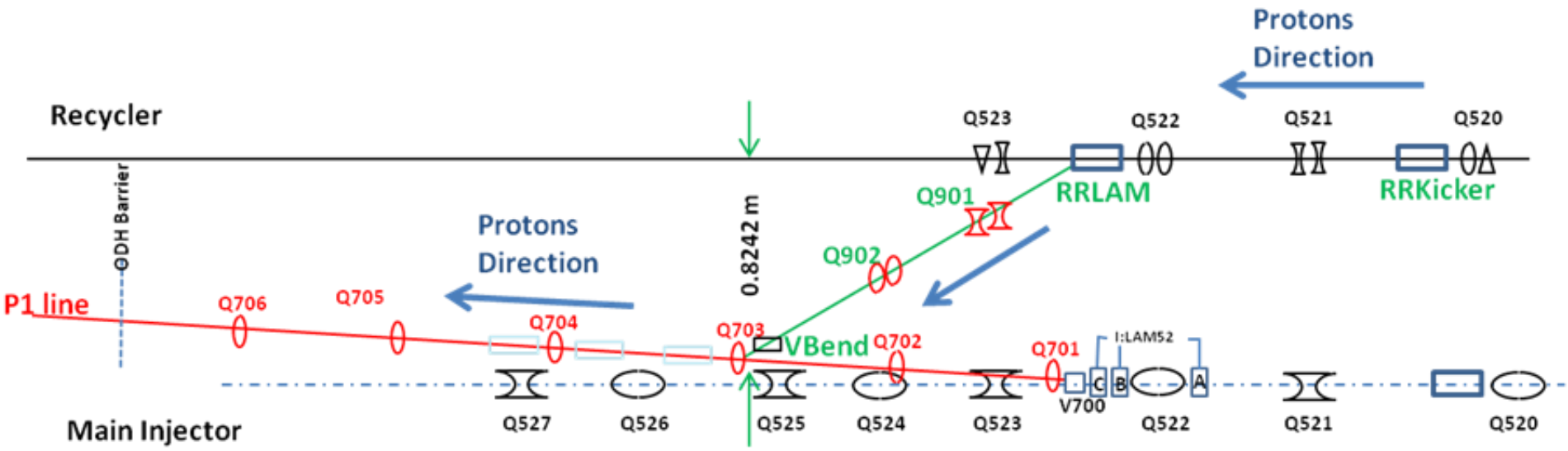


ANU RKB Kicker Magnet

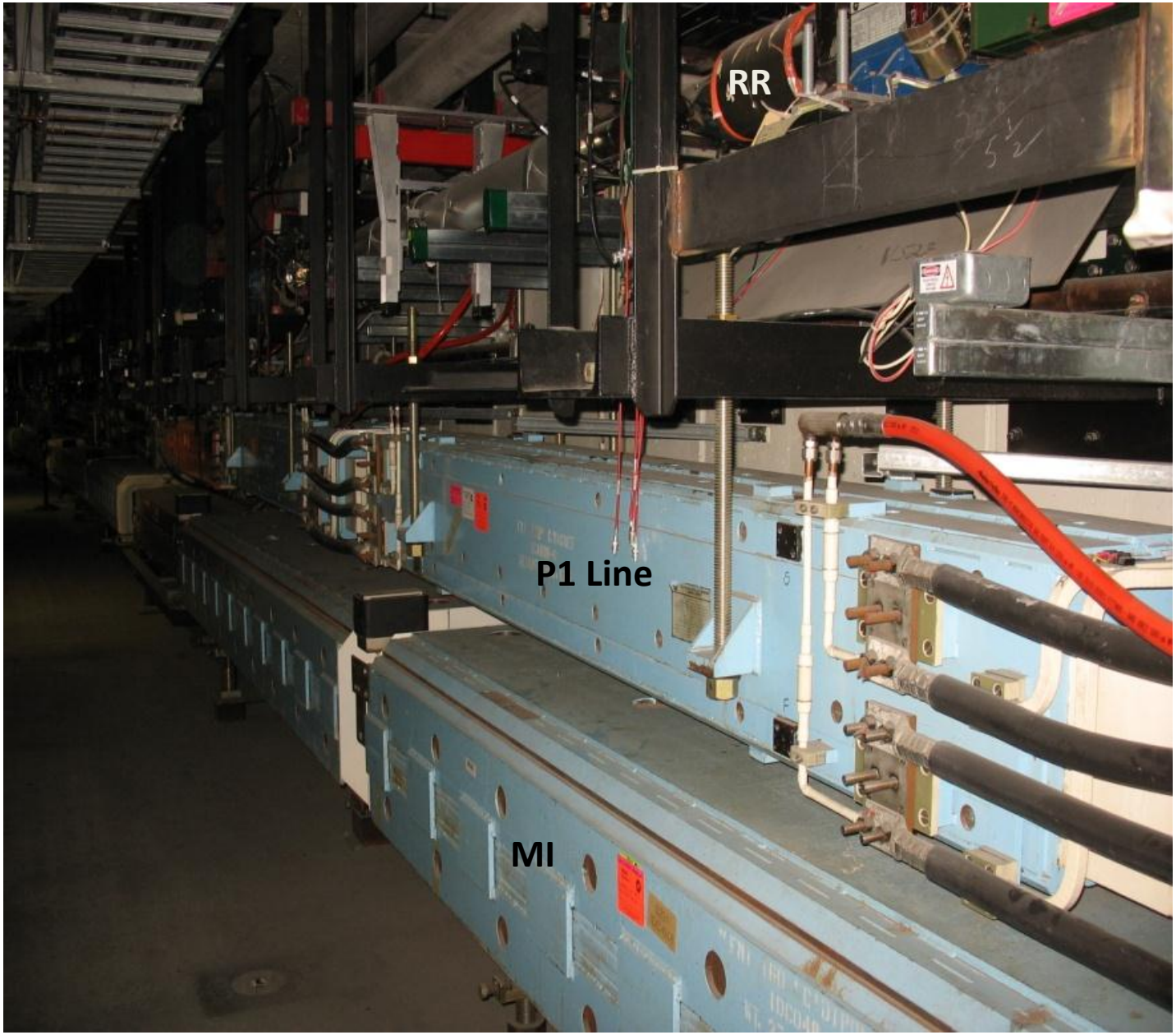
- 2 new kicker magnets of the new RKB style designed for ANU
- Re-use the beam tubes from the recently decommissioned Recycler kicker magnets
- Re-use the PFLs from the Recycler kickers
- Build two new 25 Ohm loads capable of up to 250 W ave power
- Fluorinert cooling skid to cool the loads
- Extend existing building at MI-52 for kicker power supplies

Transporting proton beam to Muon Campus

- New connection from Recycler to P1 line

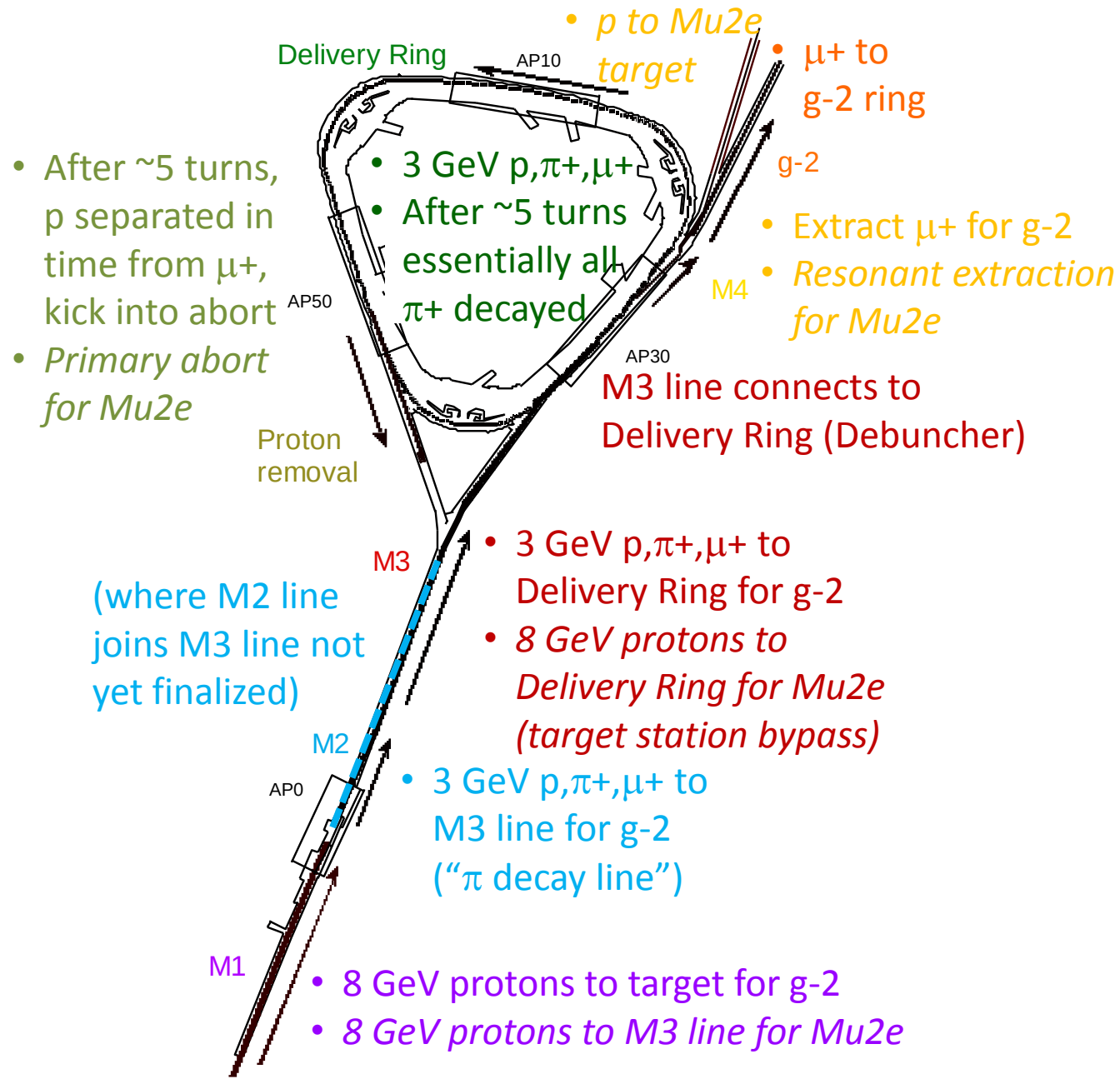


MI-52 Extraction Region

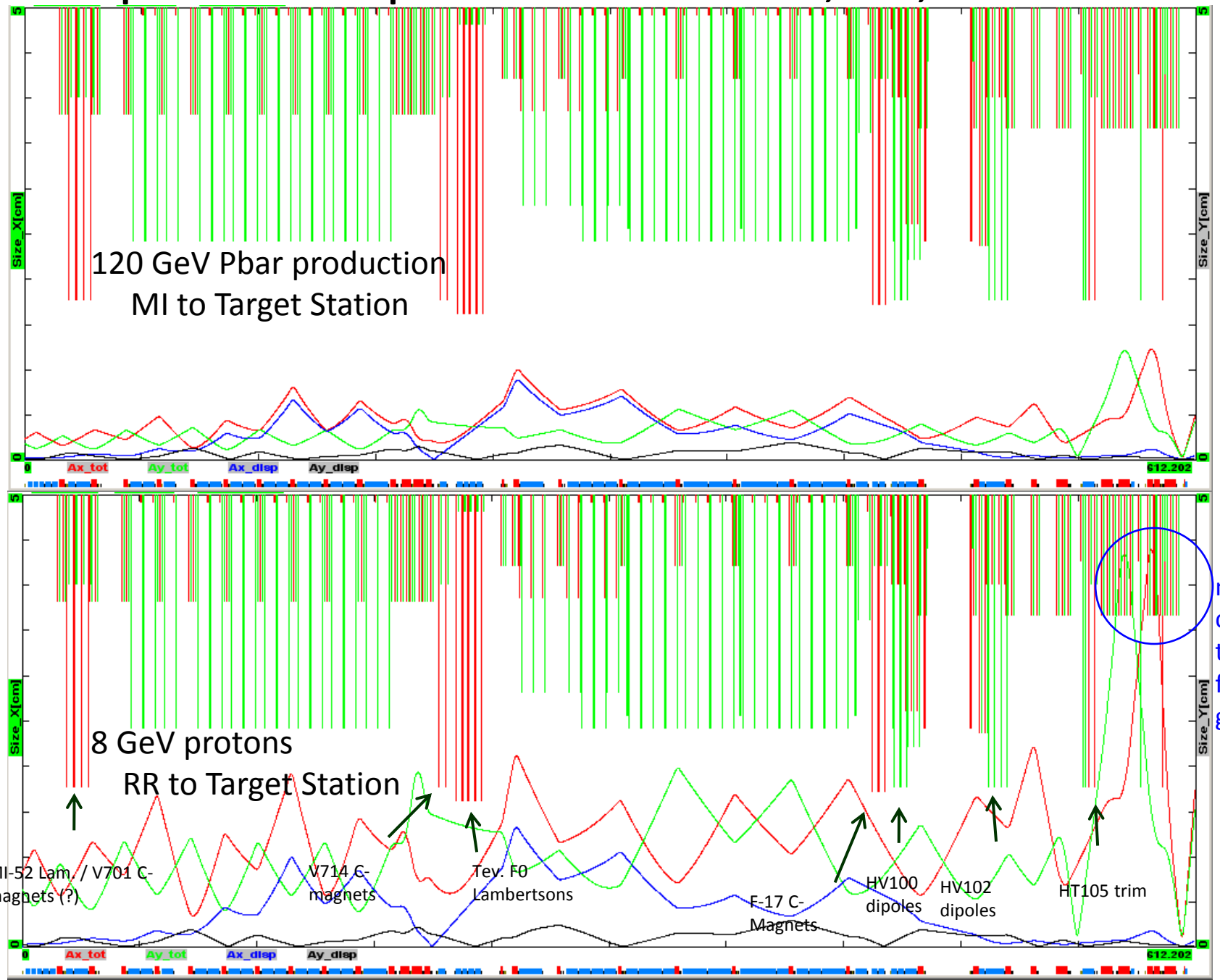


Muon Campus beamlines

New Mu2e and g-2 plans for former Pbar beamlines



Aperture improvements in P1, P2, M1 lines

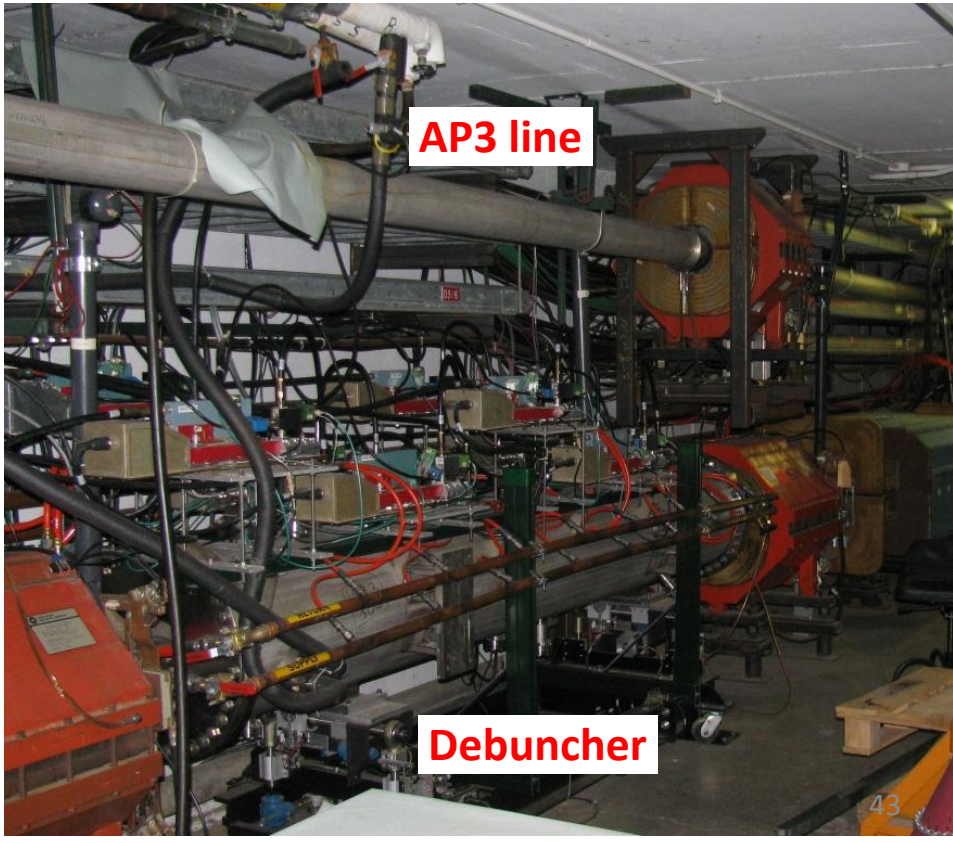


M2 and M3 lines

- M2 line
  - Secondary beamline for g-2
  - Add quadrupoles to create a regular lattice with smaller β functions to capture more muons from decays
  - Beamline magnets from BNL g-2 experiment, also from Accumulator
- M3 line (target bypass section)
  - Acceptable for Mu2e as is but must match to incoming M2 line for g-2
- M2 to M3 connection
  - Need connection that accommodates Mu2e 8 GeV proton beam down M3 while preserving small β functions for g-2

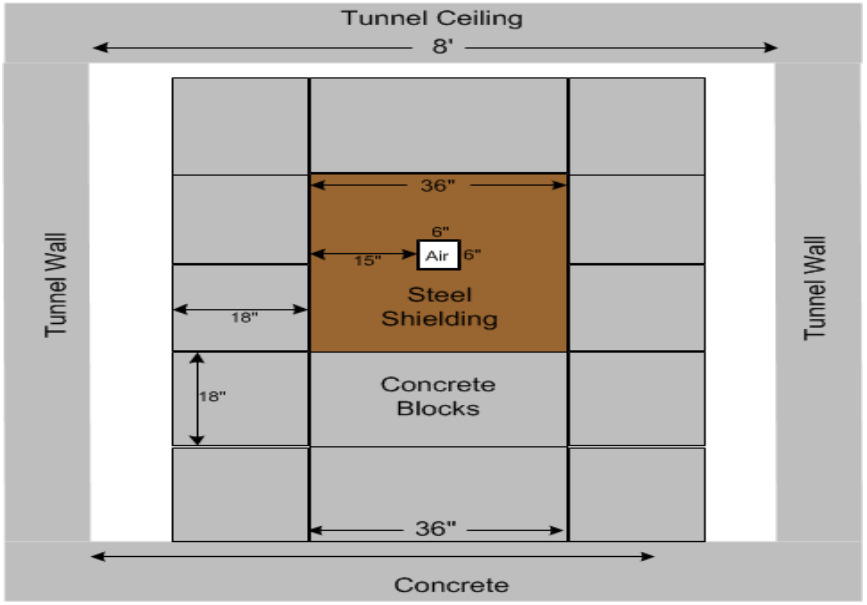
M3 line into Delivery Ring

- New connection to Delivery Ring
  - Two elevation changes and a 5° horizontal bend
  - Confined area for magnet supports in area over Delivery Ring
  - Need enough room between DR and M3 to allow use of existing pbar magnets
  - Match injection into DR and acceptance must be at least 40π for g-2



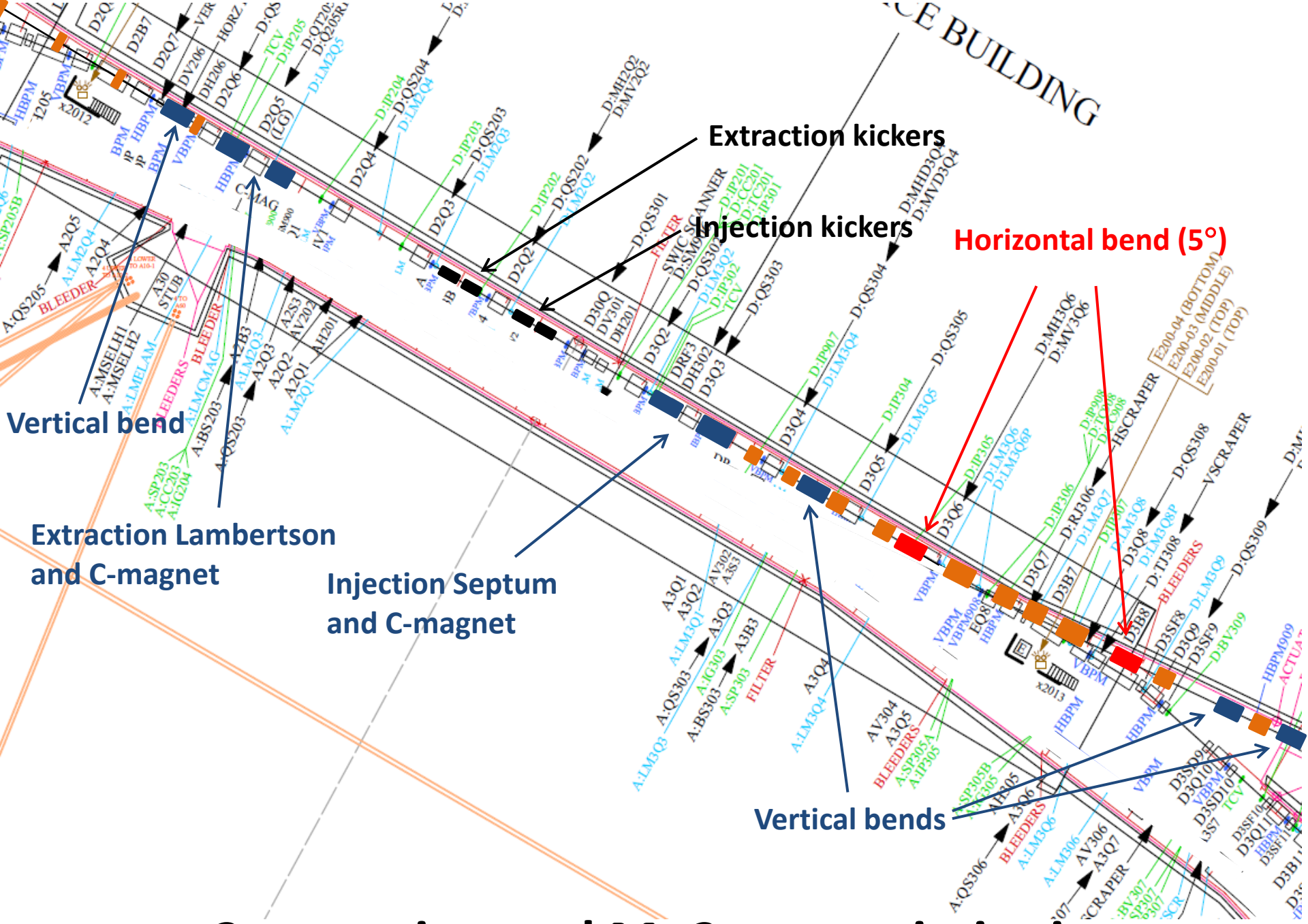
Delivery Ring Modifications

- DR aperture improvements
  - Removal of unneeded devices such as stochastic cooling tanks
- DR abort
  - Beam abort for Mu2e
  - Proton removal for g-2
    - Need a fast-rise kicker
- Electrical infrastructure improvements

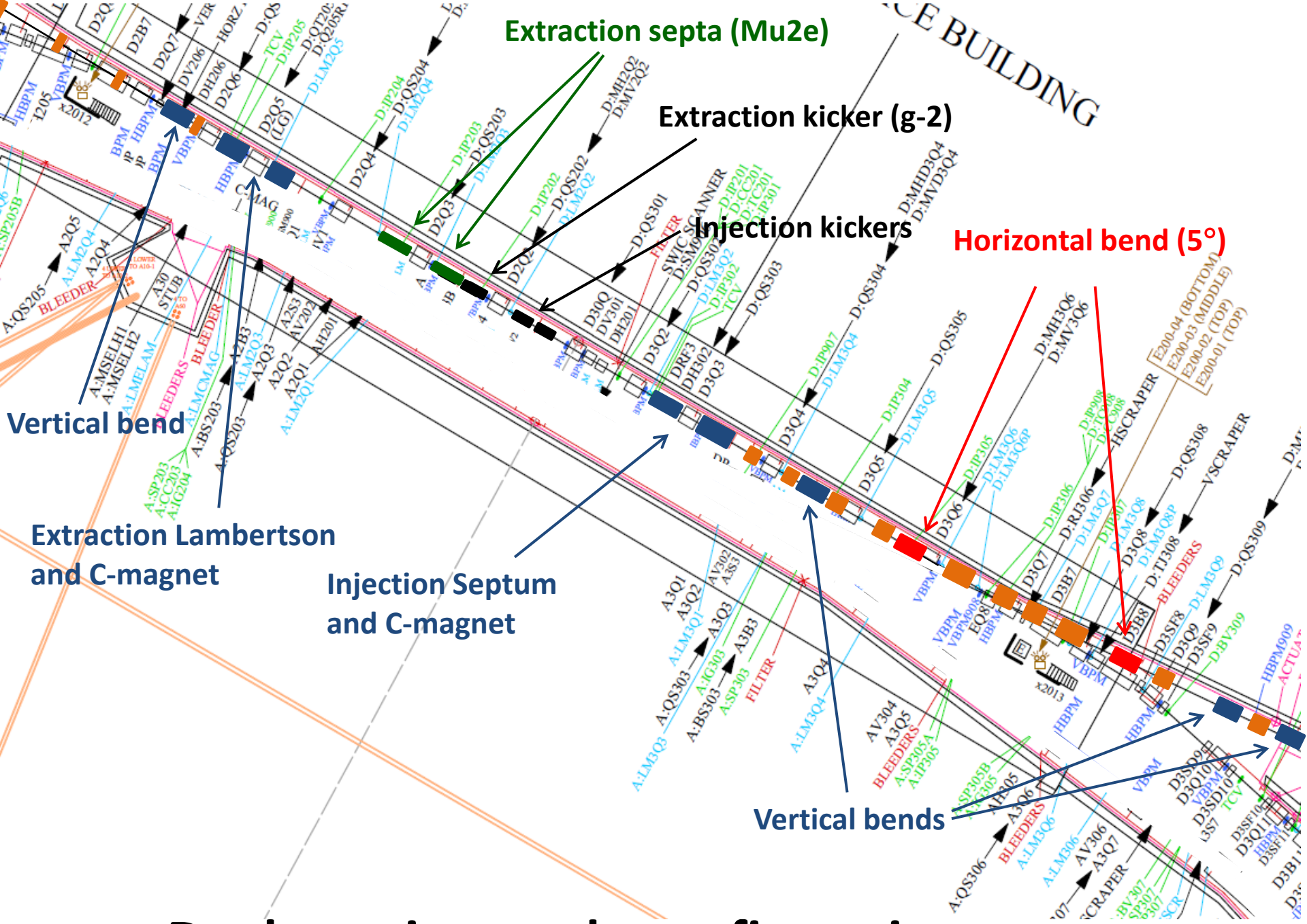


Delivery-Ring injection/extraction strategy

- Keep injection and extraction regions separated (D30 straight)
- Maximum flexibility between g-2 and Mu2e at least expense
  - Reuse existing equipment
  - New devices should be based on existing designs where practical
- Work around Mu2e extraction devices
  - Resonant extraction more difficult to design
  - Requires use of Lambertson
  - Placement of extraction channel defined by resonantly extracted beam
  - Electrostatic septa added for Mu2e operation
- Maximizing acceptance for g-2 (40π)
  - Kicker placement
  - Large vertical(horizontal) bump across injection(extraction) region
    - Motorized quadrupoles (existing) used to create bump for g-2
  - C-magnet used in addition to magnetic septum(Lambertson)
  - Some specialized large aperture quads (existing)



g-2 operation and Mu2e commissioning

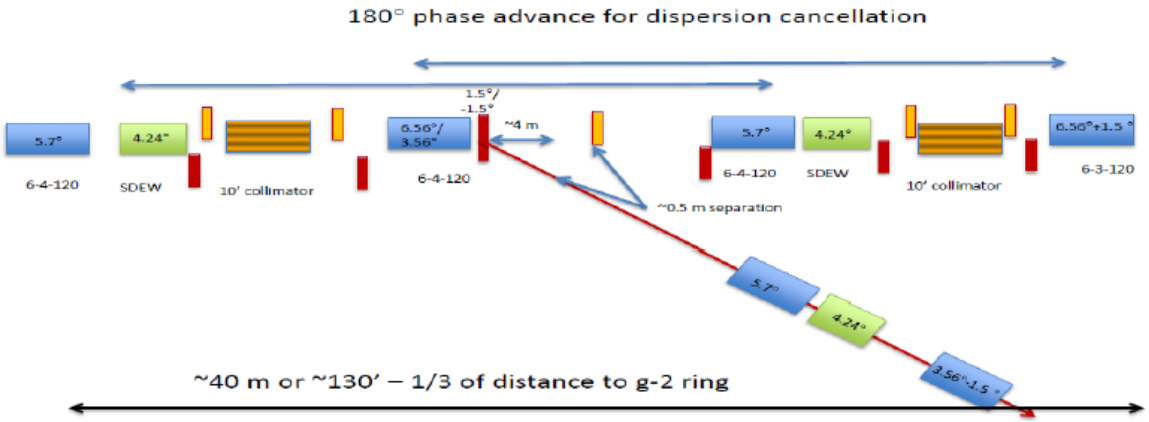


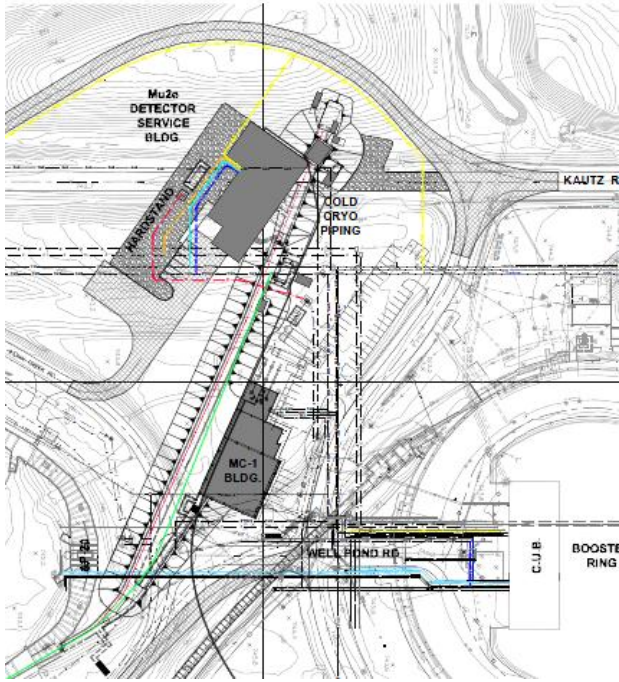
Dual running mode configuration

Extraction lines

- M4 and g-2 beamline design in progress

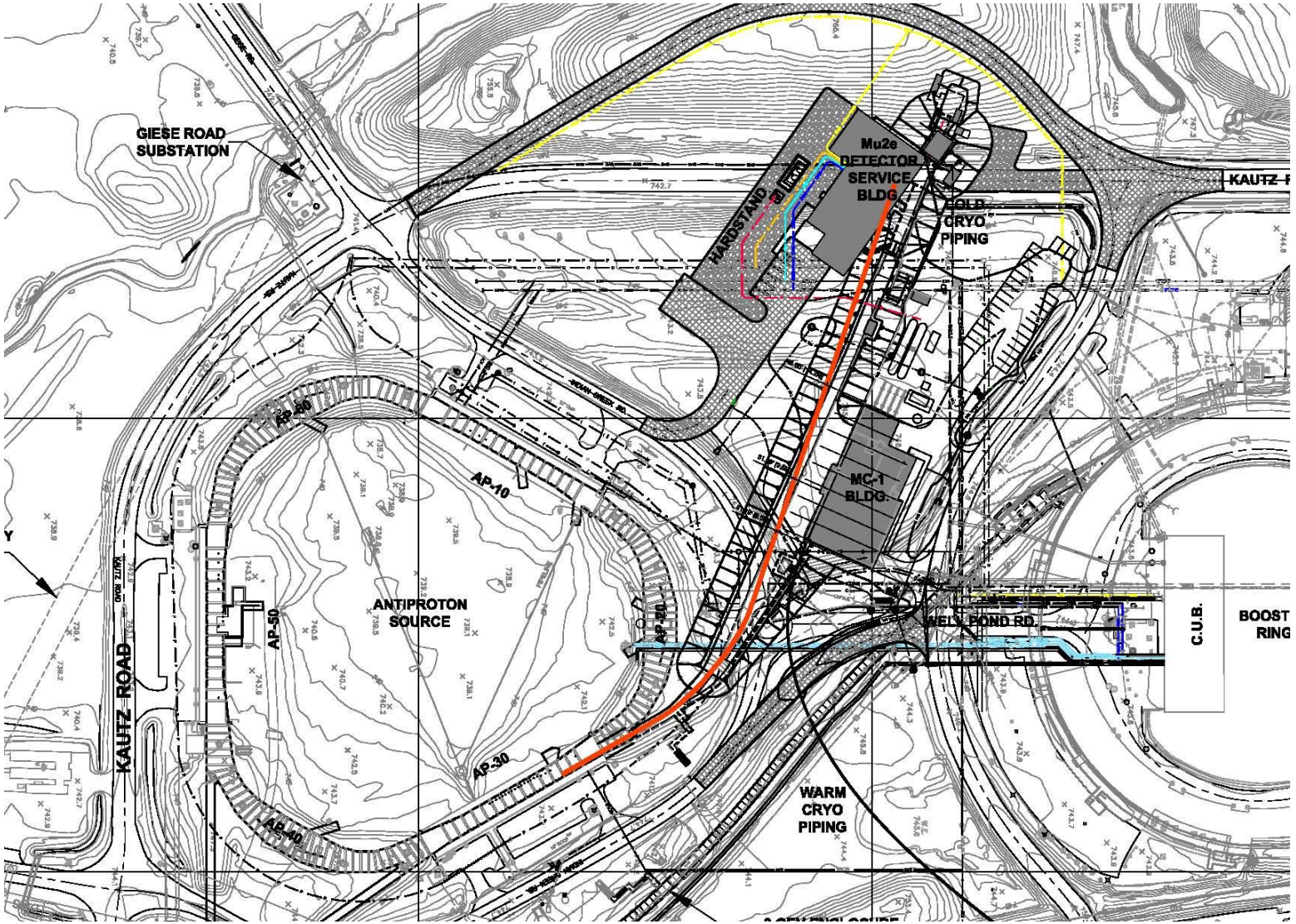
Split between the M4 and g-2 lines





- g-2 line splits from M4 line in the middle of the left bends
- Momentum collimation will be integrated into Left Bend
- g-2 line is roughly 50 m long
- Vertical dogleg will make elevation change to g-2 storage ring
- BNL magnets and other components will populate most of the g-2 line
- Final focus and matching to Storage Ring will be designed in collaboration with Ring Team

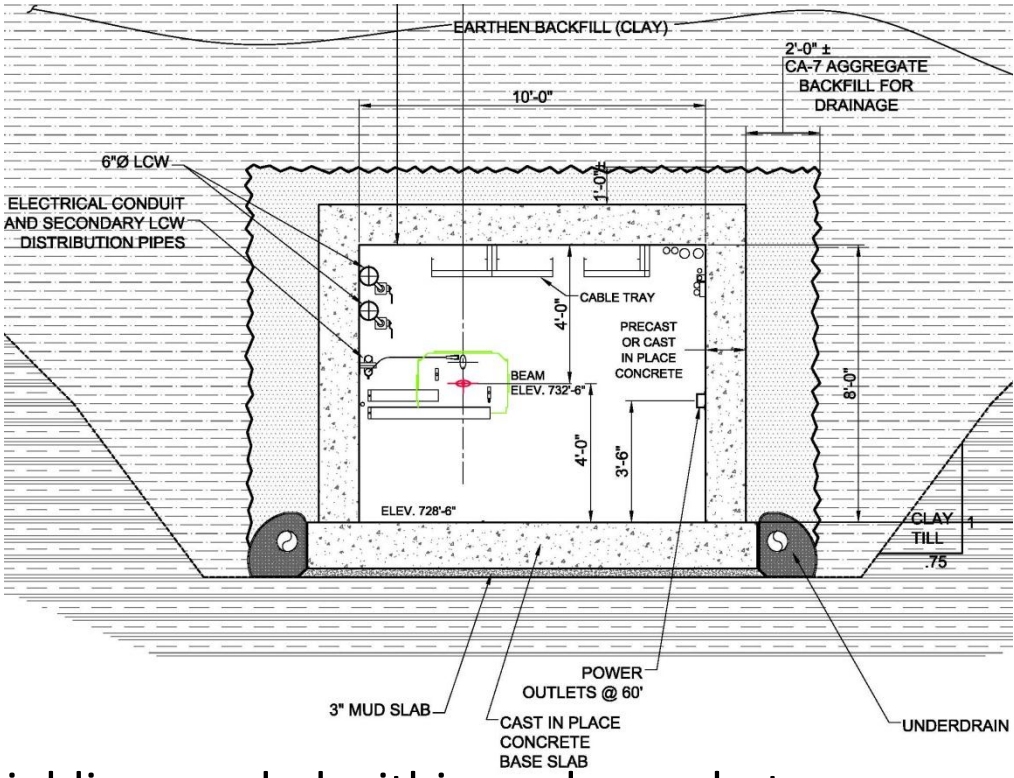
Beamline enclosure and site plan



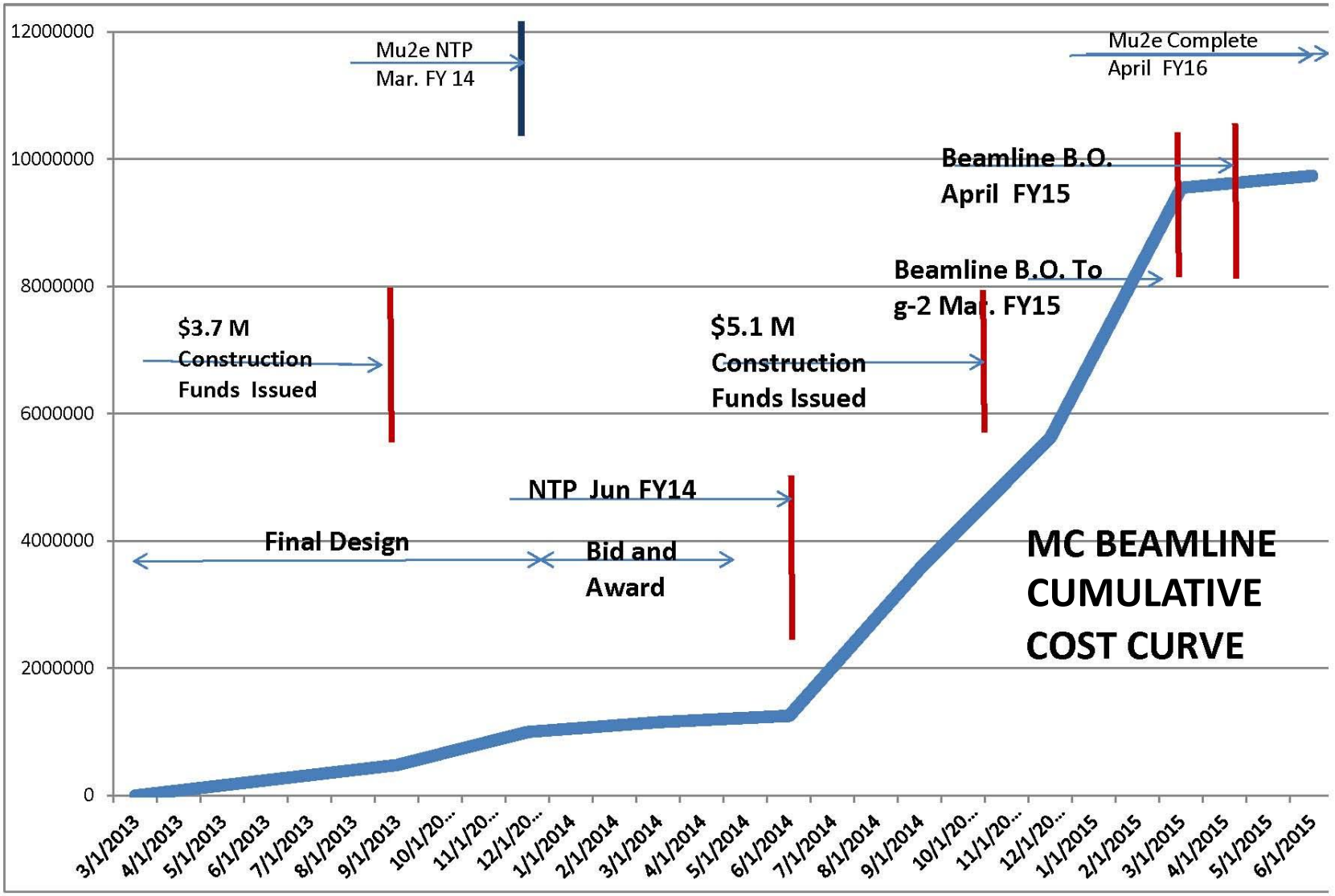
- Details depend on beamline lattice which is not complete yet

External beamline enclosure design

- Main Injector type enclosure
  - 10 feet wide x 8 feet high (typical except near MC-1 where higher ceiling will be required.
  - Painted walls and ceiling, sealed floor. Floor to have 3” cover over rebar to enable stand anchorage.
  - Channel inserts walls and ceiling @ 8’ o/c. (no inserts 5’ from floor on aisle side)
- Shielding
  - 16 feet of earth/concrete for M4 beamline. (w/ beamline 4’ from clg.)
  - 6 to 9 feet for g-2 beamline. Shielding needed within enclosure between MC-1 building and M4 / Delivery Ring.
- Access for magnets is provided directly from Ring enclosure; lift provided for magnet installation. Shielded hatch provided for magnet installation / replacement.



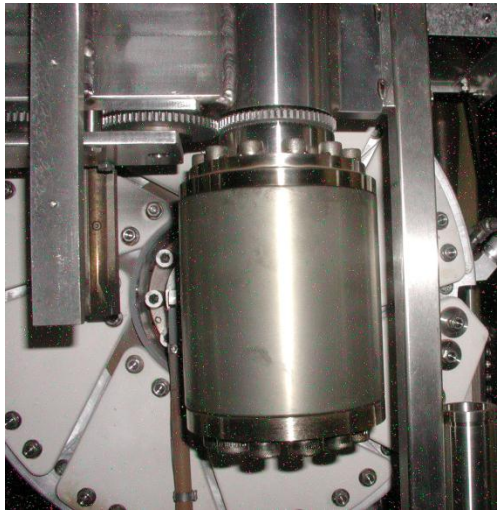
Beamline enclosure timeline



g-2 target station

g-2 target station

- Use existing Pbar target station at AP0
- Fermilab expertise, existing spares, and radioactivity of target vault make it desirable to maintain current setup as much as possible
  - Rotating, air-cooled target
  - Lithium lens for focusing
  - Pulsed magnet for momentum selection



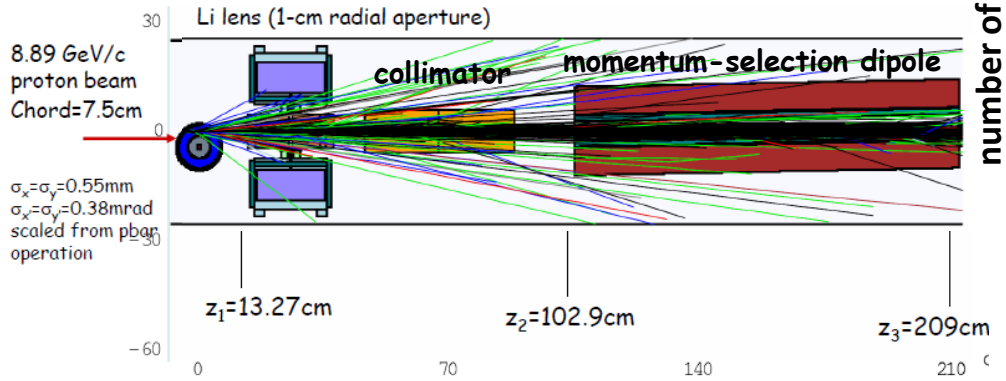
- Simulations indicate that the current setup can deliver the desired yield of ~10^{-5} pion/POT
  - Conducted beam tests to confirm

g-2 beam tests and simulations

Study plan

- Step from stacking to g-2 mode

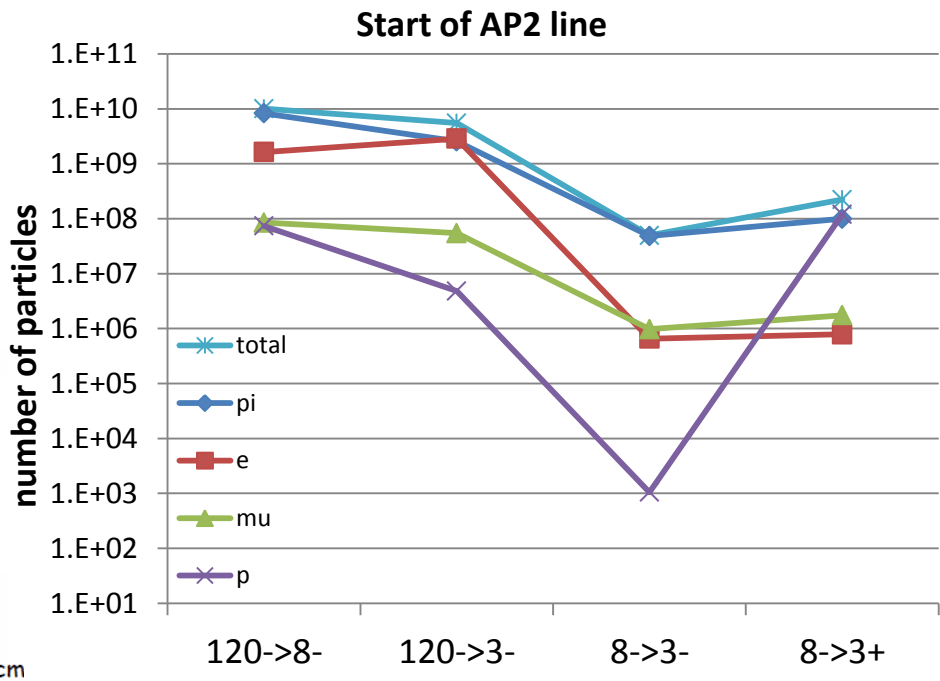
proton mom. (GeV)	secondary mom. (GeV)	charge	
120	8.9	-	Stacking mode
120	3.1	-	Change magnet strengths in secondary beamlines
8.9	3.1	-	"reverse proton" mode beam to target
8.9	3.1	+	Change polarity of lens, magnets in secondary beamline; g-2 mode



Expected number of particles

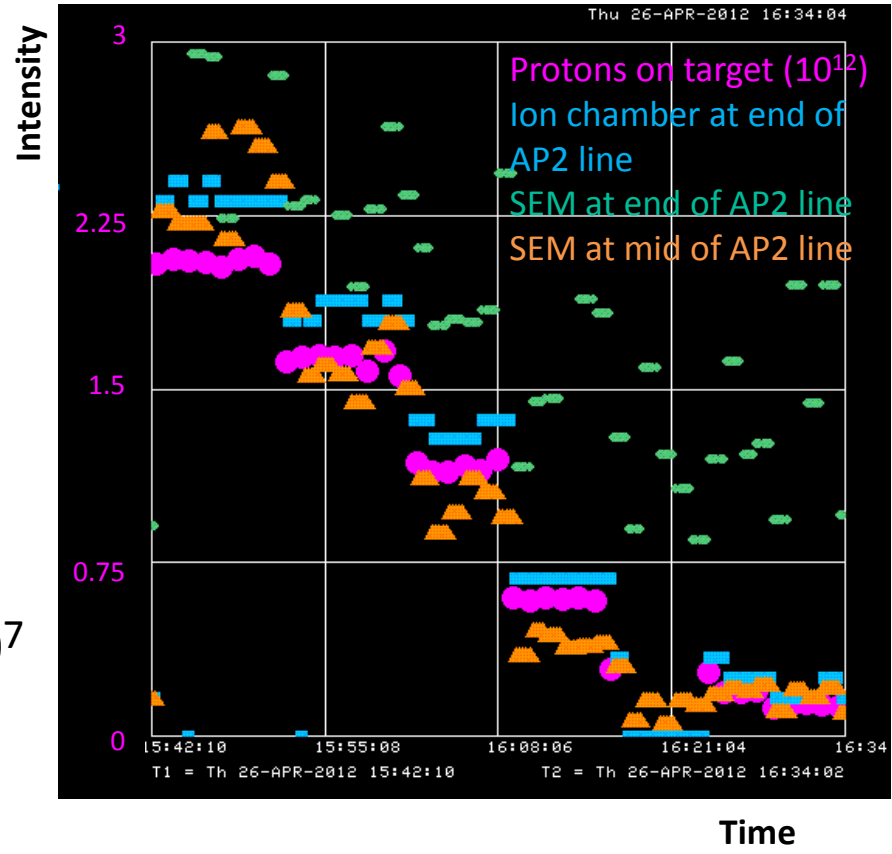
for 1x10^{12} protons on target (g-2 single pulse)

- MARS simulation of target station
  - g-2 mode: yield per POT: ~10^{-5} π+, ~2x as many protons, ~10^{-8} μ+
- G4beamline simulation of start of pion decay line (C Yoshikawa, Muons Inc)



Results of beam test

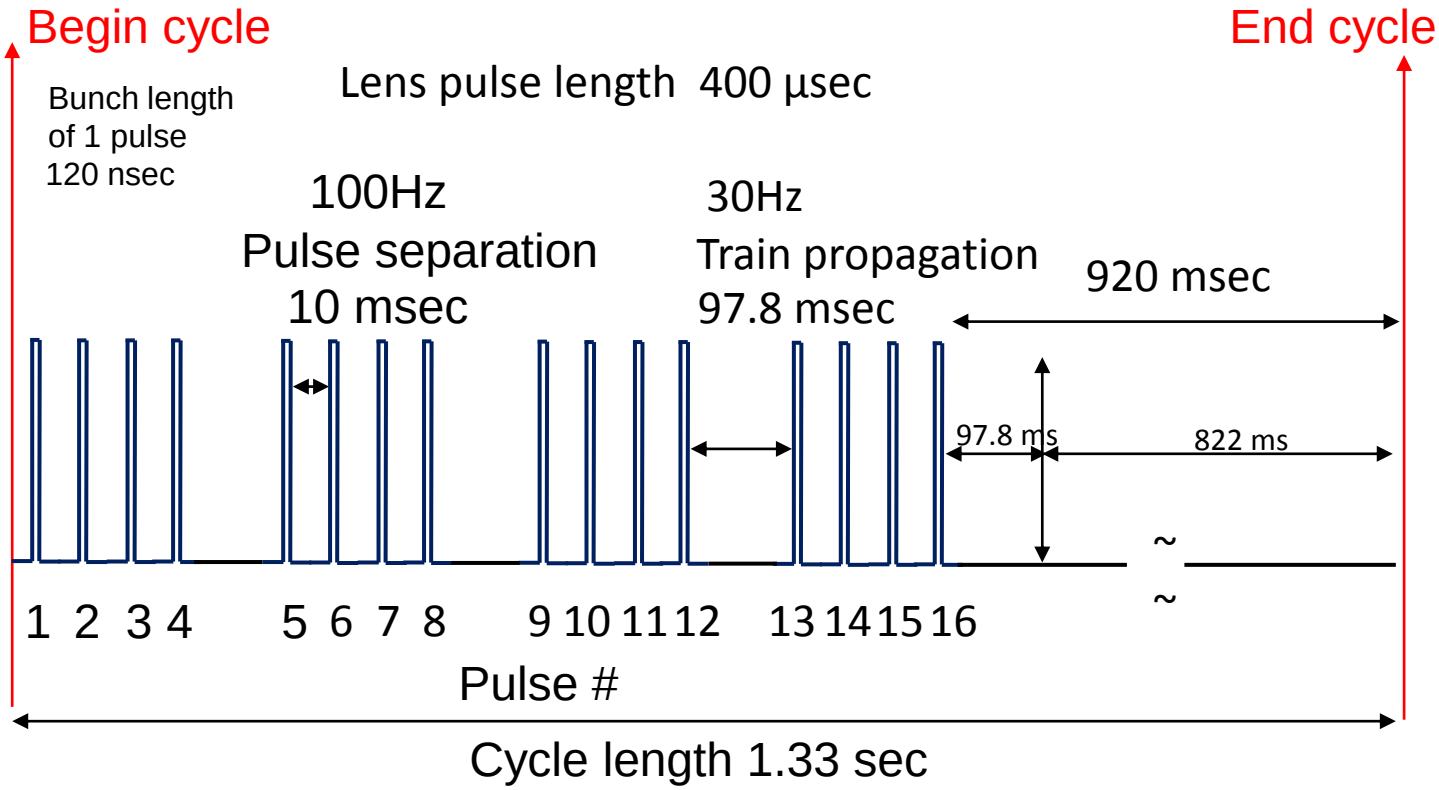
- Intensities track beam on target
- Current monitor at beginning of AP2 line shows expected scaling from 120→8-/120 → 3-
- Ion chamber at end of AP2 line shows order-of-magnitude agreement with predictions: 10^9 particles for 120 → 3- and 10^7 particles for 8 → 3- and 8 → 3+ per 10^{12} protons on target



- Beam profiles seen on Secondary Emission Monitors (SEMs)
- Existing target and lens appear to provide sufficient yield
- Smaller spot size on target will increase yield

Lithium lens in g-2 mode

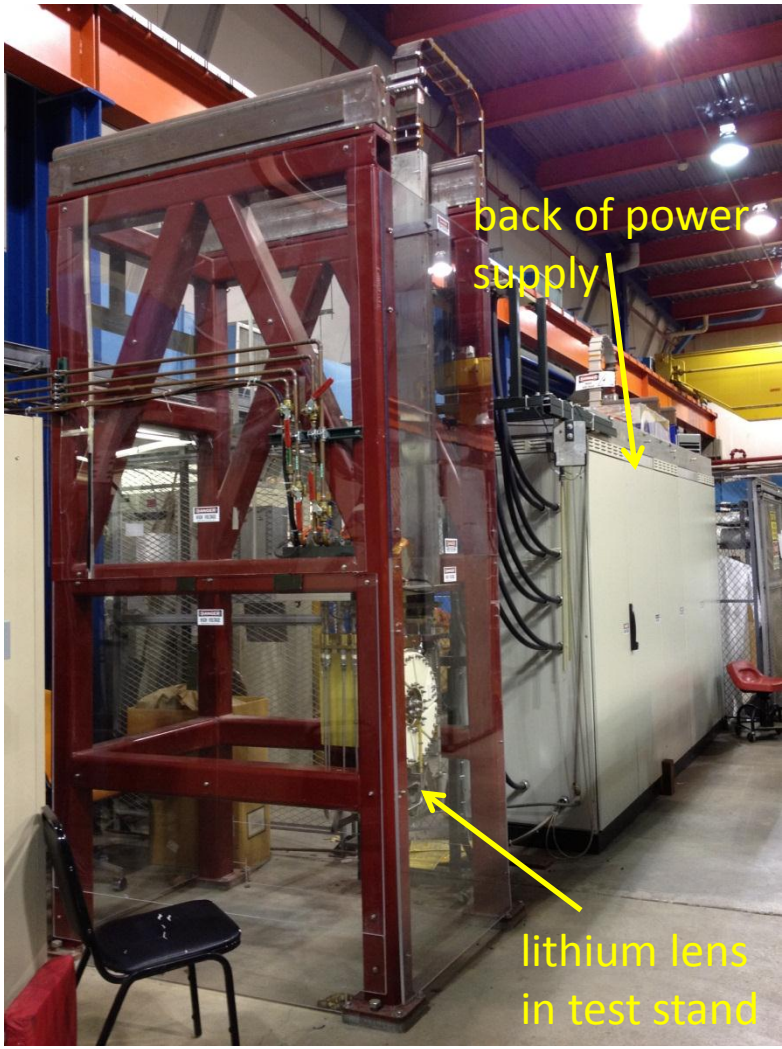
- Higher pulse rate, more complicated cycle than for stacking



- Will need new power supplies for lithium lens and pulsed magnet

Lithium lens modeling and testing

- Lens ANSYS model predicts higher temperatures and stresses for g-2 but fatigue parameters are better
  - Less difference between max and min stresses in cycle
  - Can reduce stresses by reducing pressure of lithium "preload"
- Currently pulse-testing lens in test stand at full gradient (230 T/m) and average 12 Hz repetition rate
  - Running 24hrs/day
  - Have integrated ~18M pulses
  - Pulse lens for months or until we find its limits



Cryogenics for g-2 and Mu2e experiments

Experiment Cryogenics Requirements

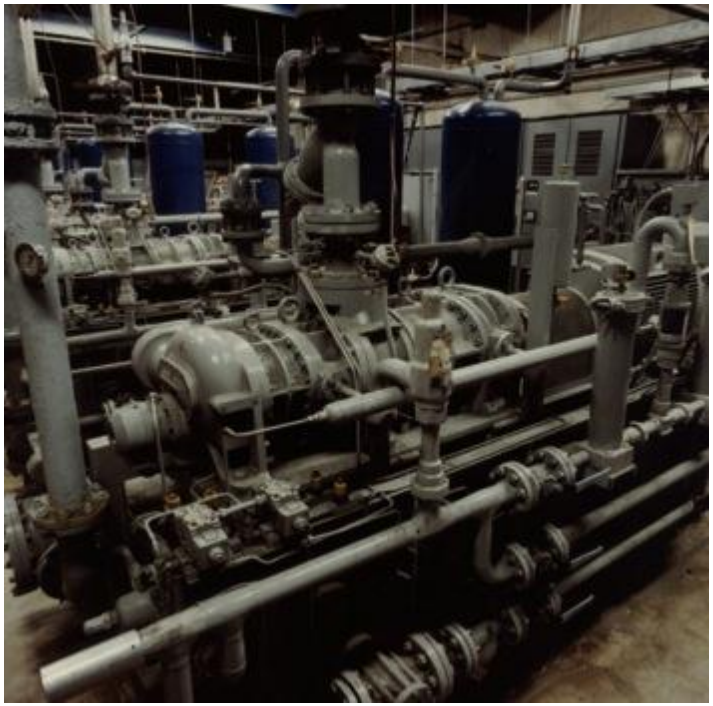
Cryogenic loads:

- g-2 storage ring
  - Liquefaction load – 1.4 [g/sec]
  - Refrigeration load – 300 [W]
  - LN2 Shield flow rate – 1.6 [g/sec]
- Mu2e solenoids
  - Liquefaction load – 0.8 [g/sec]
  - Refrigeration load – 350 [W]
  - LN2 Shield flow rate – 20 [g/sec]

- The Cryogenic System shall support simultaneous steady state operation of both experiments, Muon g-2 and Mu2e. It shall provide for independent operation of the two experiments, including transient modes, e.g. warm-up, cooldown, etc.
- It should be possible to connect and/or isolate Mu2e magnets from the transfer line while under cold conditions

Cryo compressor system

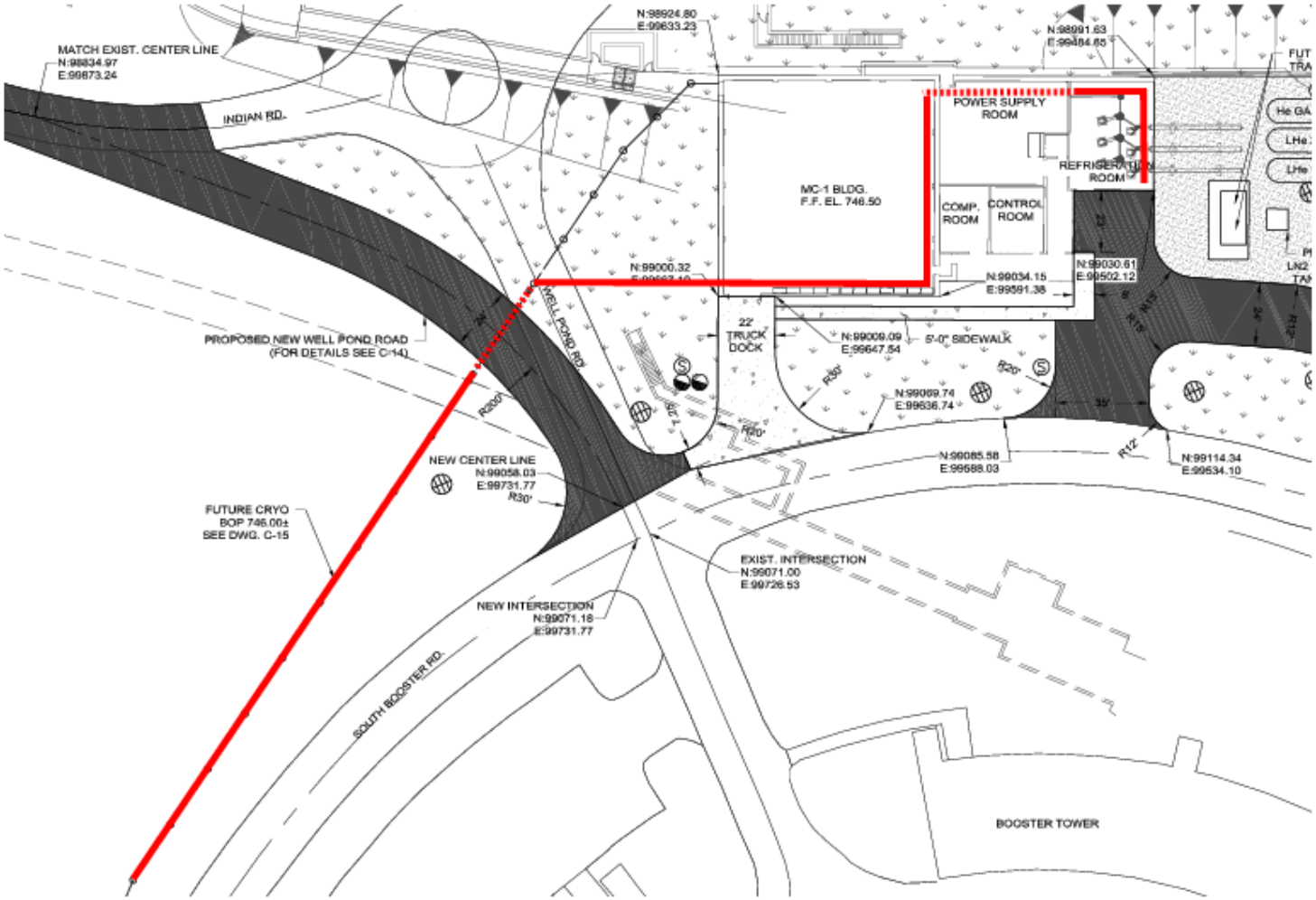
- A0 compressors (four skids)



Two-stage compound oil flooded screw compressor Mycom 2016C

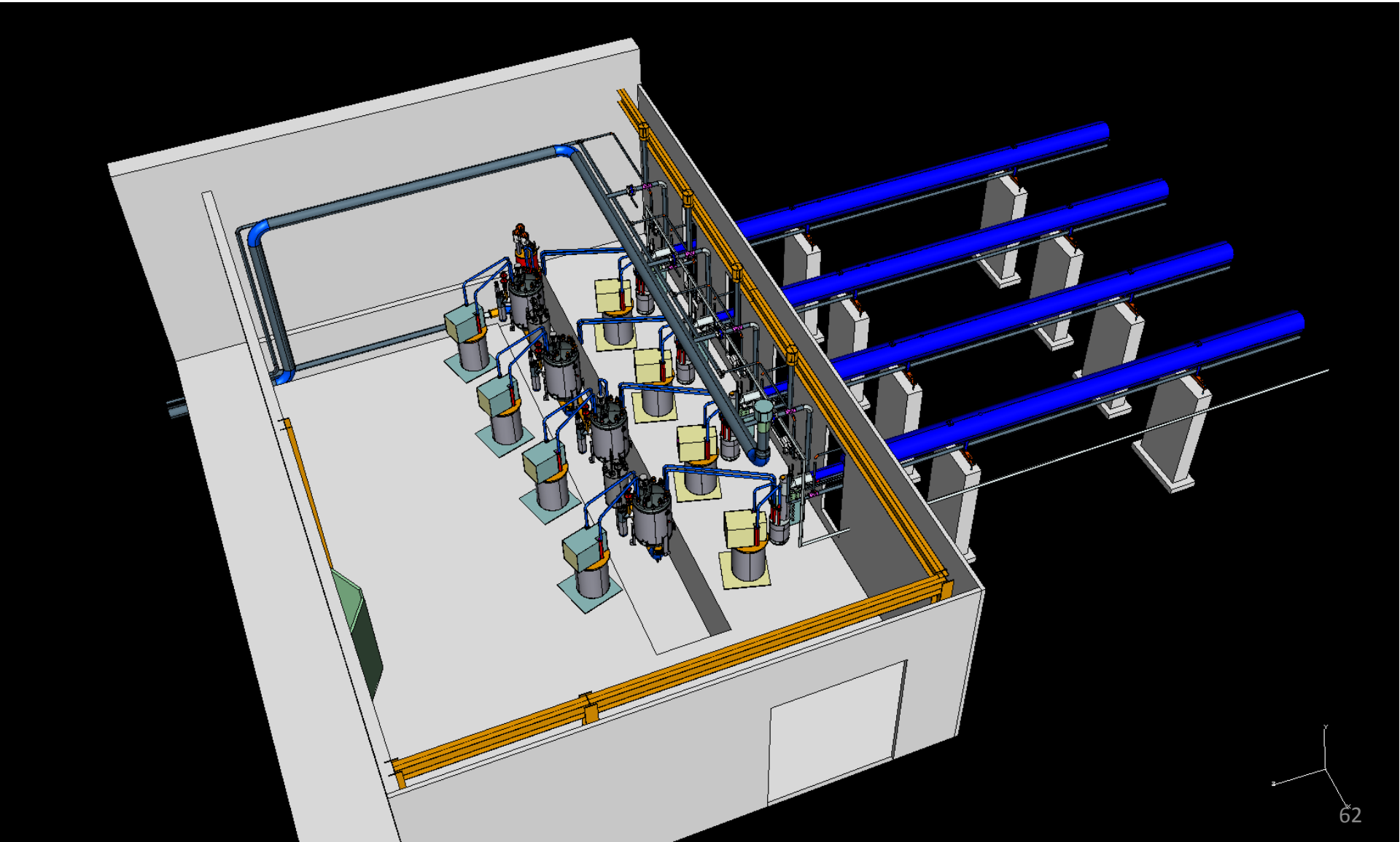
- Each skid consists of the following:
  - Two-stage oil injected screw compressor
  - 300 kW motor
  - 60 g/s capacity
  - Compression from 1 atm to 20 atm
  - Slide valve for capacity control
  - 6 kW oil pump
  - Oil cooler heat exchanger
  - Aftercooler heat exchanger
  - Oil separator
  - Oil removal system
  - Entire system is contained on a single, fabricated steel base skid, oil removal on separate skid

Piping headers

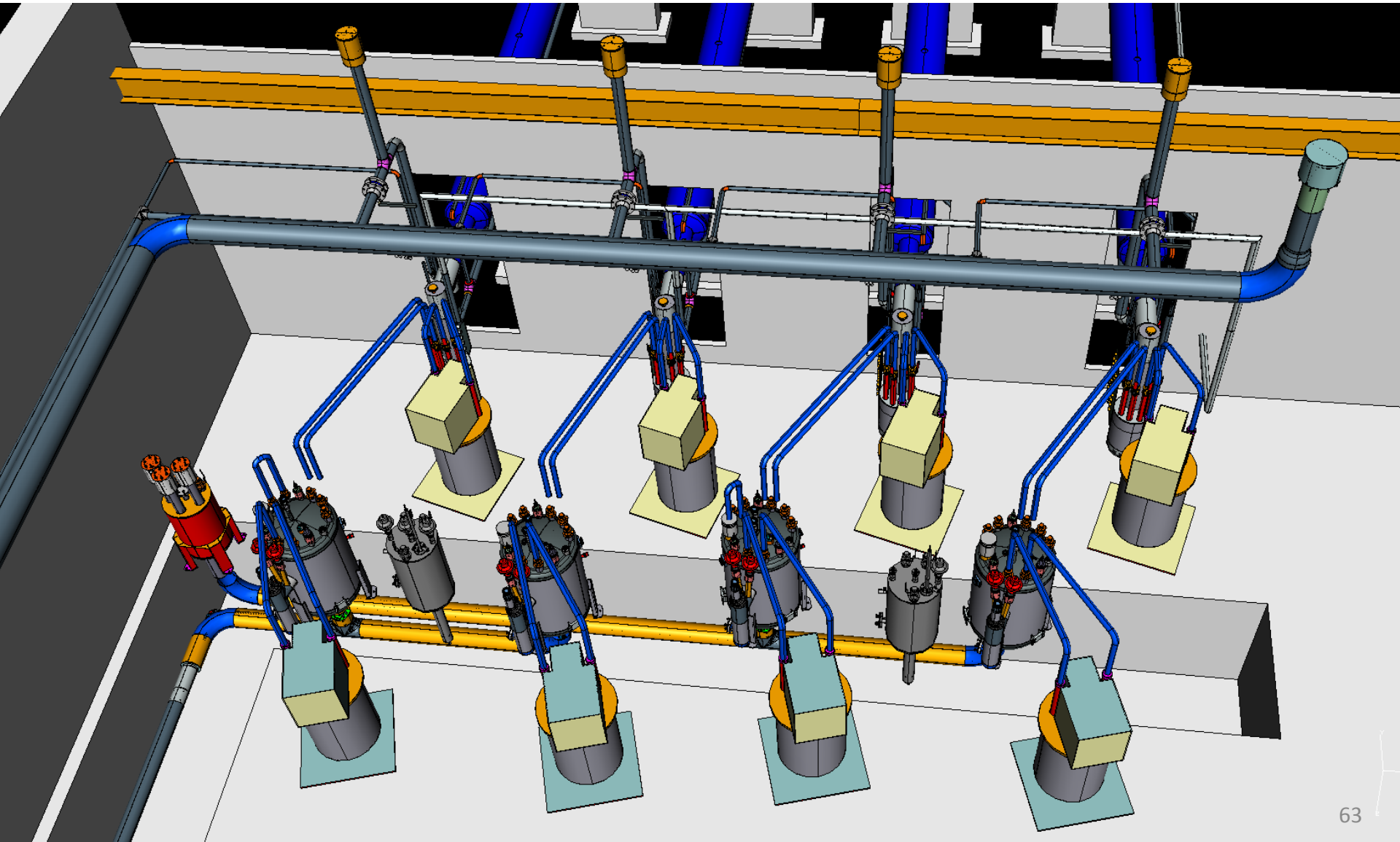


from A0

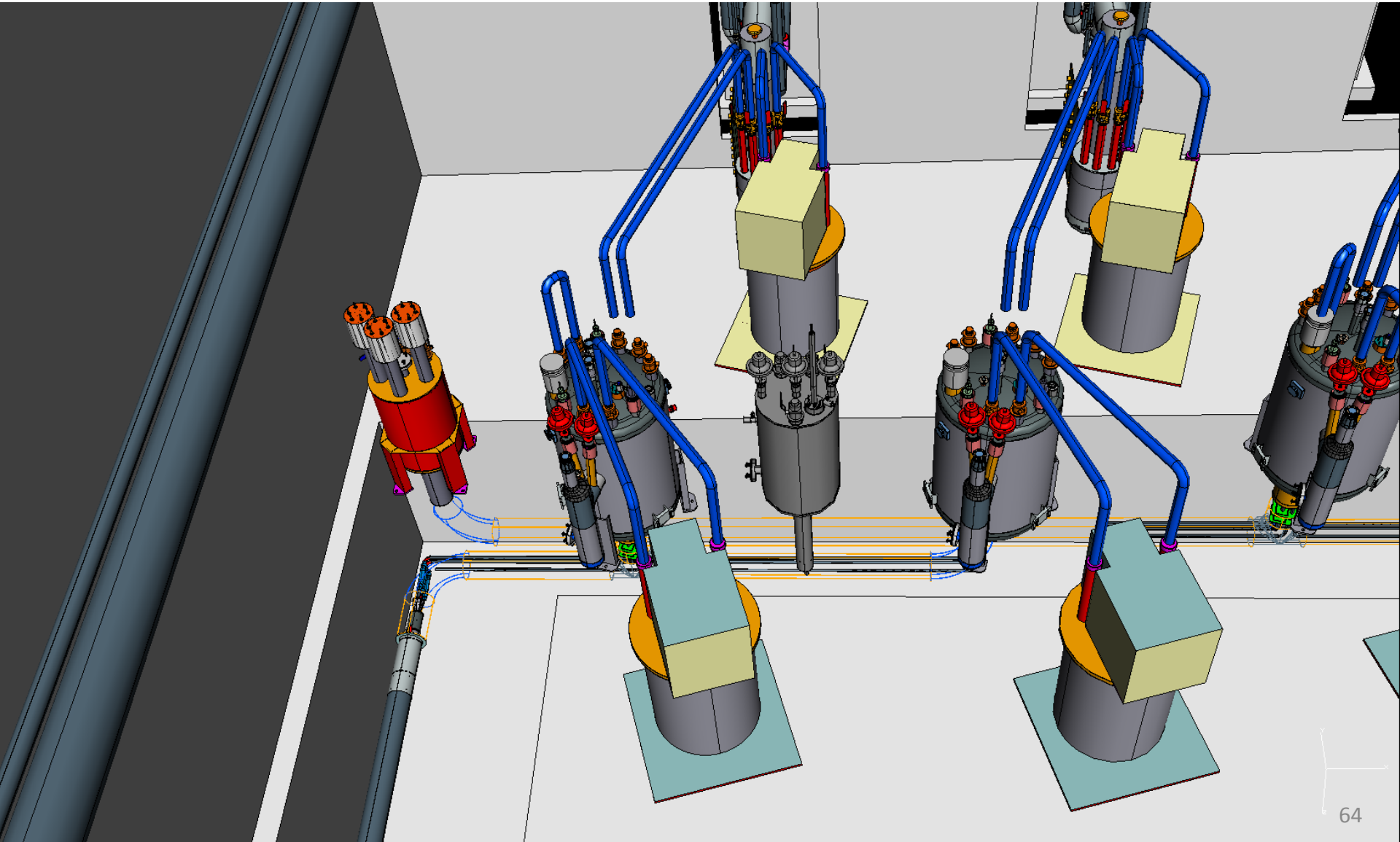
Refrigerator room



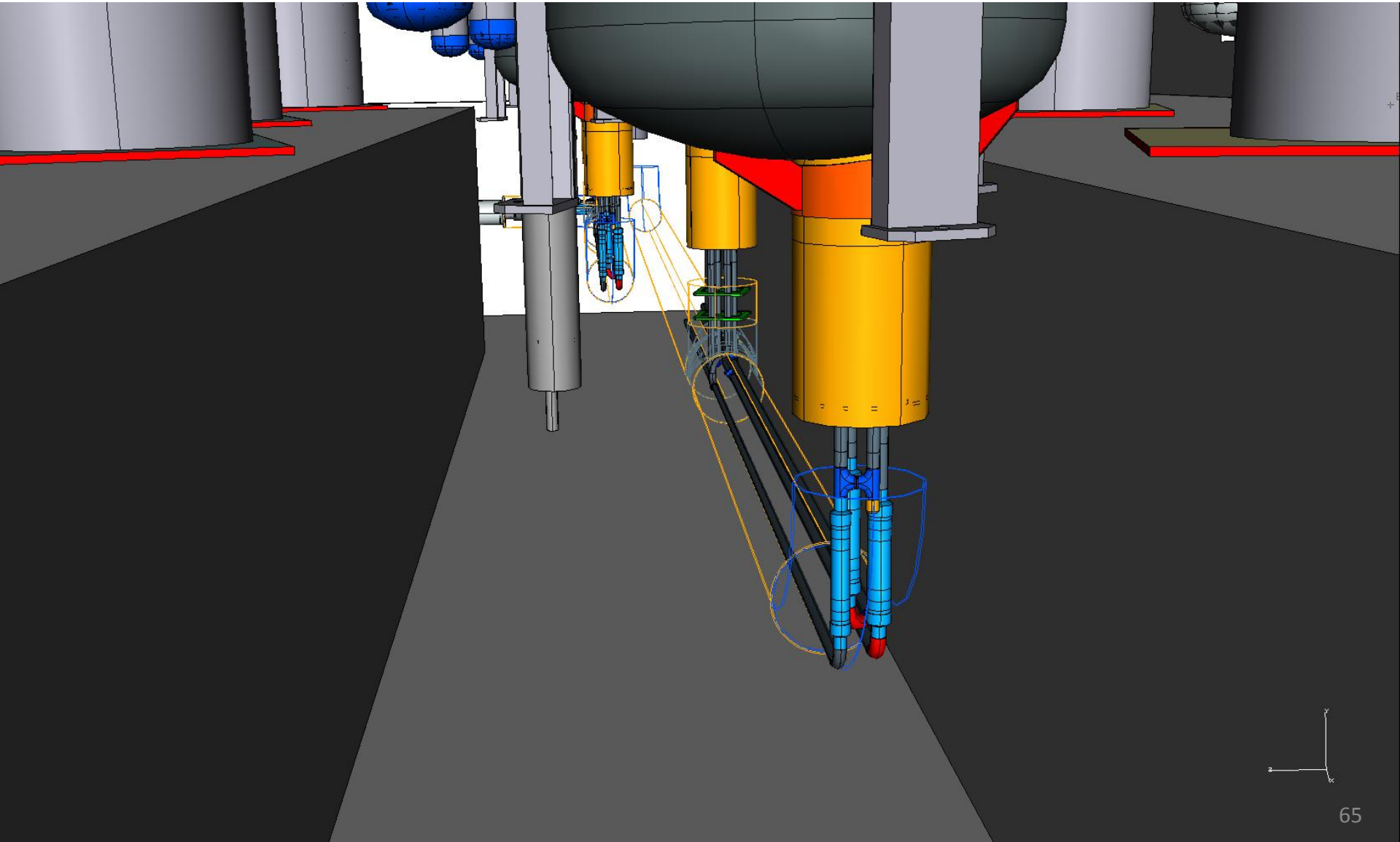
Refrigerator room (cont)



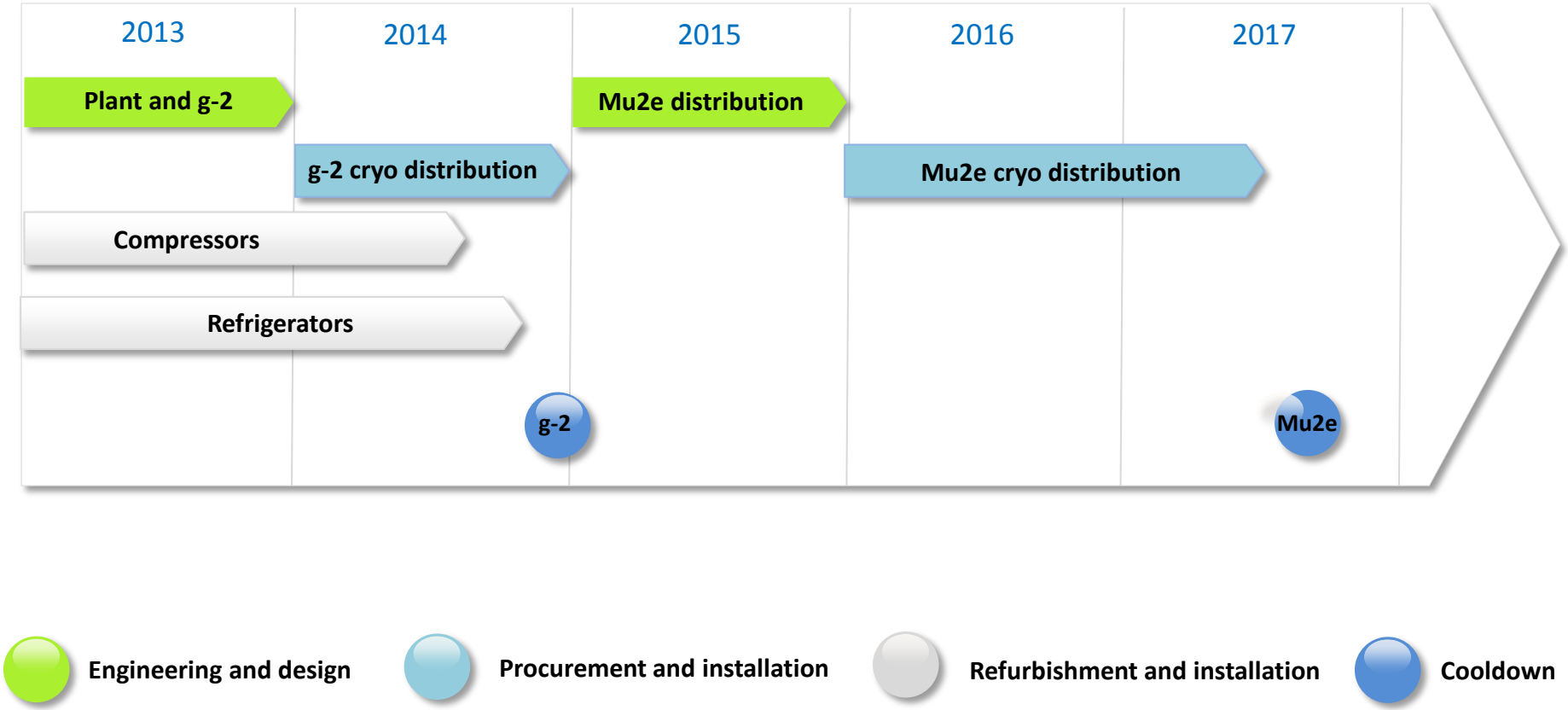
Transfer line



Transfer line (cont)



Cryo AIP timeline

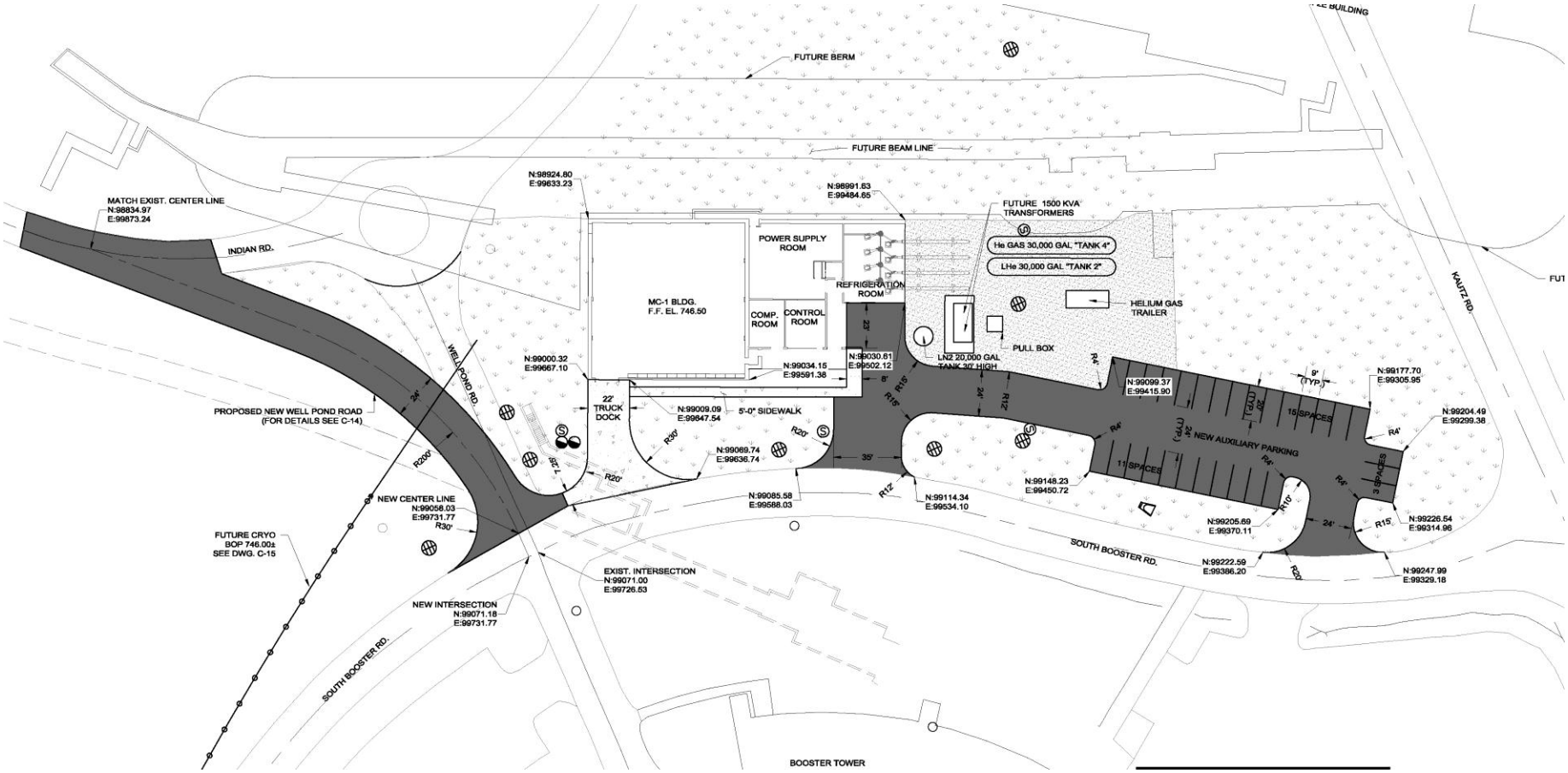


MC-1 Building

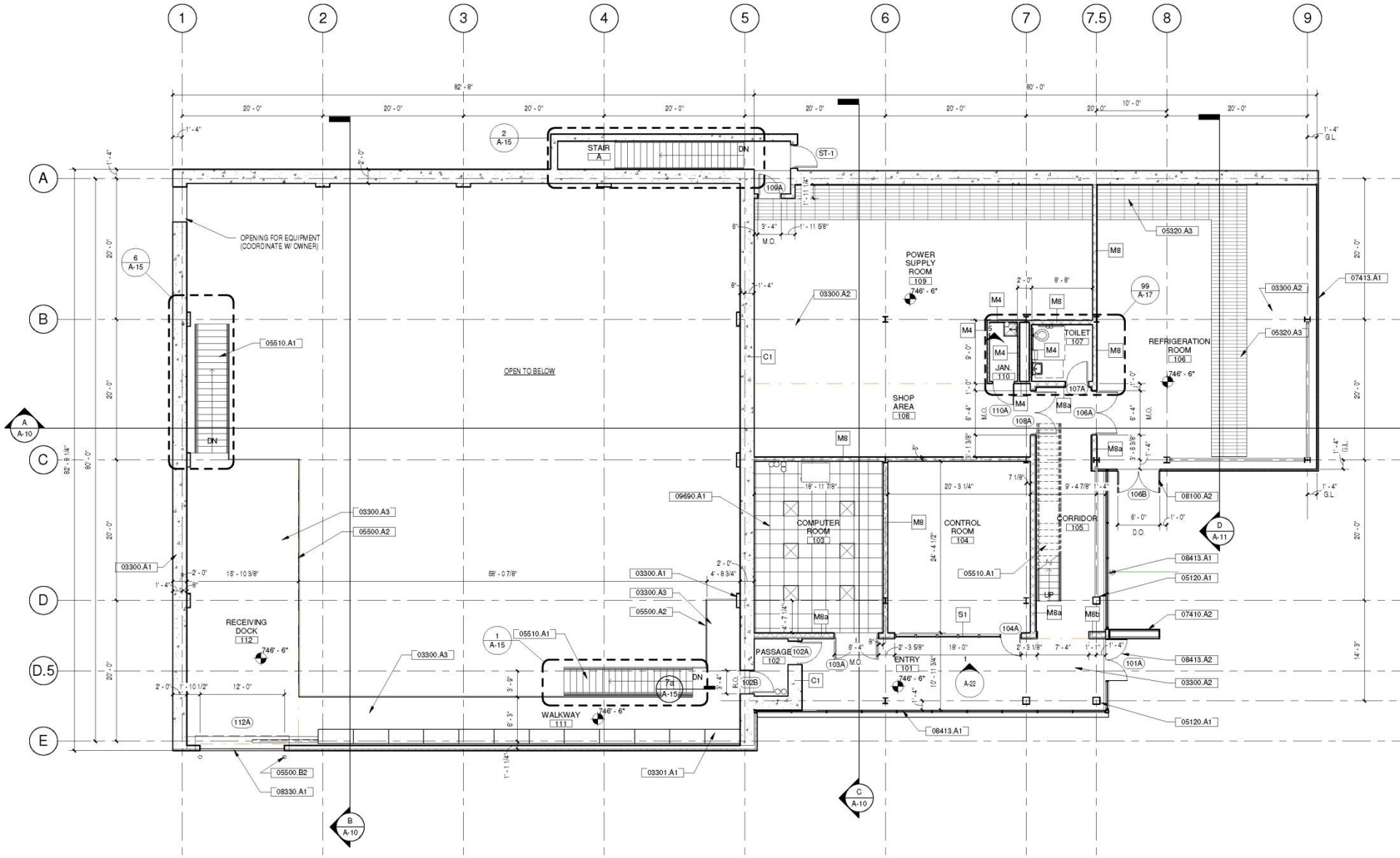
MC-1 Building GPP

- MC-1 building designed to house g-2 and future experiments, cryo system for g-2 and Mu2e, and power supplies for some beamline components
  - 80’ x 80’ high-bay with 30 T crane
  - internal loading dock
  - floor stable, load-bearing to 700 T
  - good temperature control
  - 70’ x 70’ low-bay for staging, assembly, control room

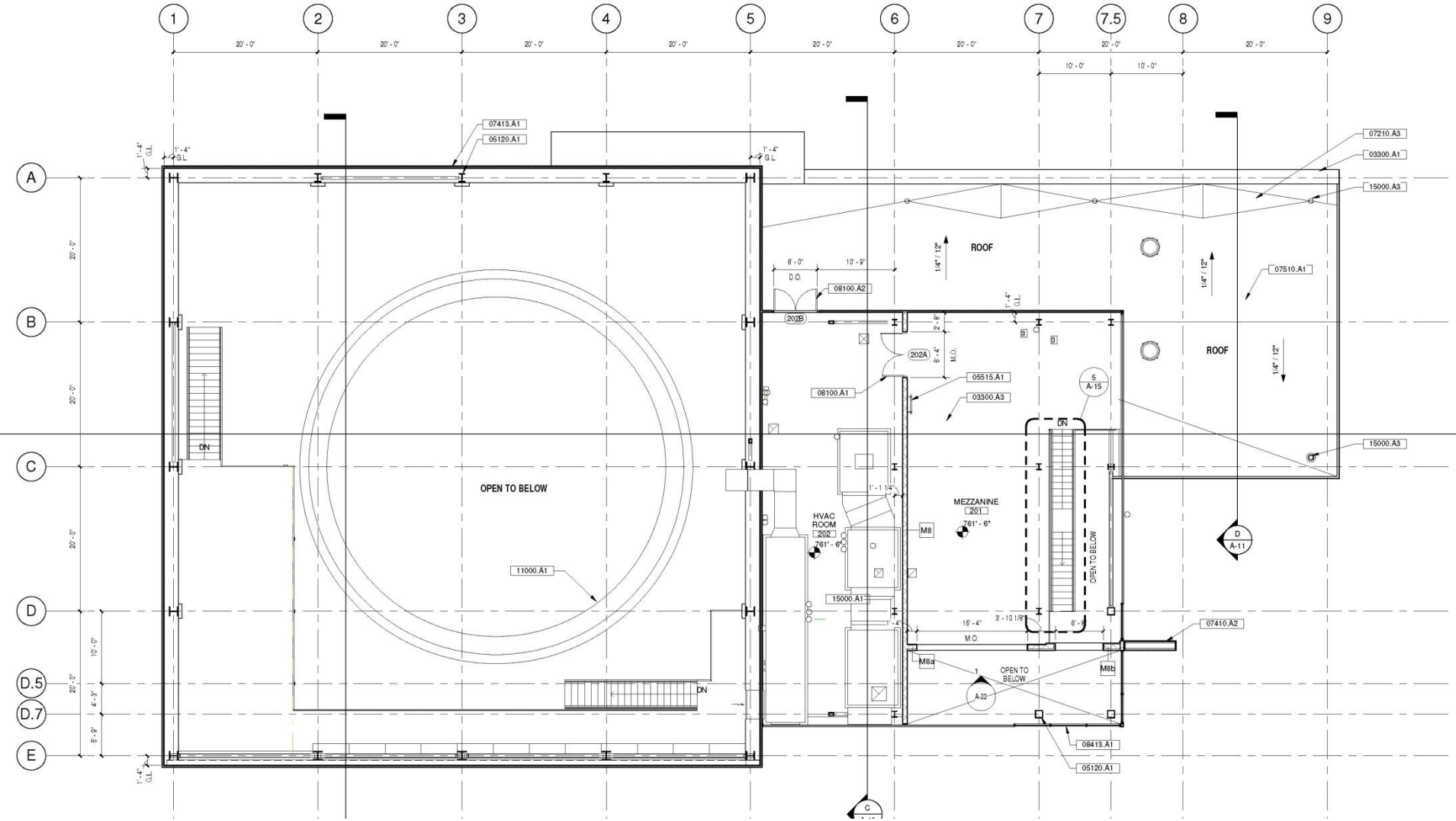
MC-1 Building – Site Plan



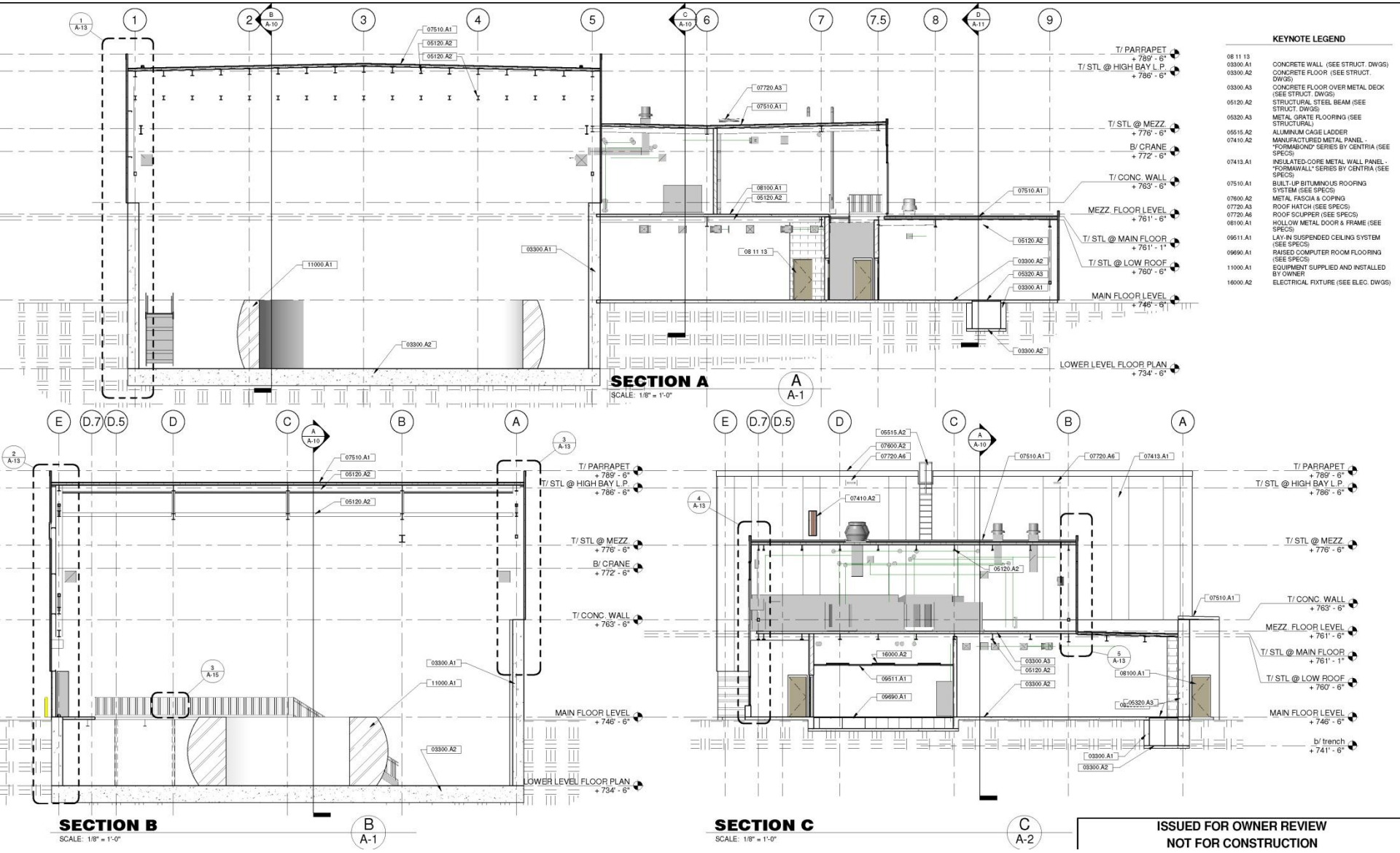
MC-1 Building – First Floor Plan



MC-1 Building – Second Floor Plan



MC-1 Building – Cross Sections



MC-1 Building site prep in progress

- Construction split into two packages to expedite construction
- Goal of site prep package is to
  1) relocate all utilities out of building excavation, and
  2) perform all shutdown work during current shutdown
  - Relocate/tap into utilities
  - Relocate Well Pond Road (shutdown)
  - Install cryo line supports and under-road piping (shutdown)

MC-1 Building

- Building construction will be out for bid in next few months

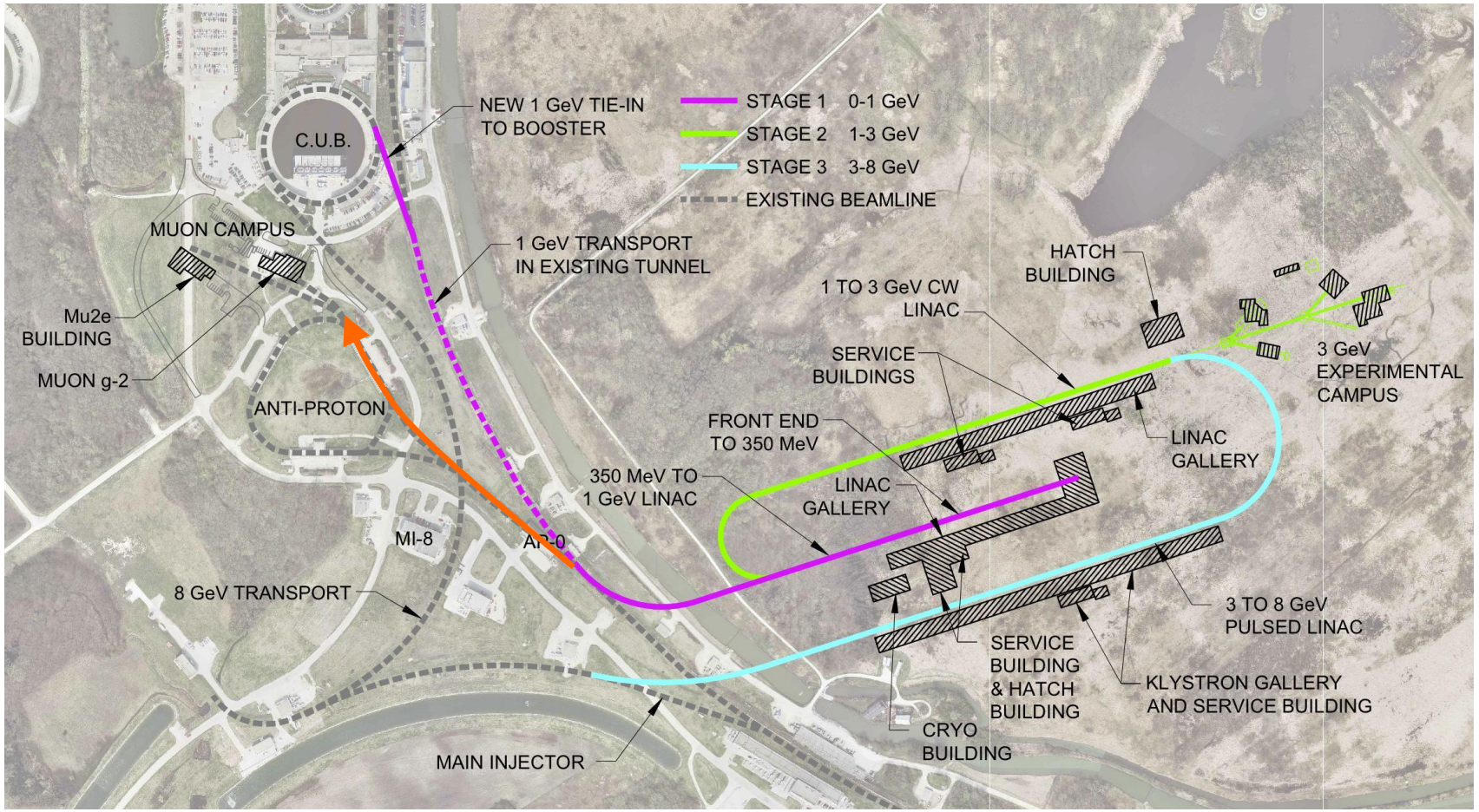
A look ahead and conclusions

Muon Campus offers many advantages

- Distinguishes between project-specific and more general upgrades, needed for g-2 and Mu2e this decade…opportunities for Stage 1 Project X
- Allows GPP/AIP pieces to move forward quickly and meet the combined specifications and timelines
- Recognized over $100M in savings in the total cost of the muon program, Mu2e run time extended to 3 years, added capability for muon g-2

Possibilities for Muon Campus experiments using Project X

- Mu2e upgrade, muon EDM experiments, …



Conclusions

- Plans for accelerator and civil work needed to support g-2, Mu2e, and future Muon Campus experiments are maturing
- Still determining how to best package the work into Projects: g-2, Mu2e, Accelerator Improvement Projects, and General Plant Projects
- Shared infrastructure between Mu2e and g-2 as well as reuse of existing infrastructure enables us to do these projects for significantly lower cost
- Aiming for g-2 beam in early 2016, Mu2e in 2019