**Accelerator Controls**:

1. **Camac and Links:**

The existing accelerator service buildings will continue to use the legacy controls infrastructure that is currently in place. These service buildings include all of the Main Injector service buildings, as well as F0, F1, F2, F23, F27, AP0, AP10, AP30 and AP50. Future Muon Campus service buildings, including MC1 and Mu2e, will be upgraded to a more modern controls infrastructure which will be discussed later in this document. Migration of the existing buildings to the more current controls standard is preferred and is being considered; however, sufficient funding is not available to start the upgrade path and it is believed that the existing infrastructure will be adequate for g-2 operations.

CAMAC crates exist in each service building and communicate with the control system through a VME style front-end computer over a 10MHz serial link as shown in Figure 1. Both digital and analog status and control of many accelerator devices occur through the CAMAC front ends. There should be no need to install additional CAMAC crates, as there is excess capacity in most of the existing crates. An inventory of existing CAMAC crates in the Muon Department service buildings shows that about 25% of the slots are unoccupied and could be used for additional CAMAC cards [1]. In addition, further slots have become available that were used to interfaces devices that became obsolete with the retirement of Collider Run II operations. It is anticipated that there will be ample CAMAC crate coverage for g-2 operation in the existing Muon Department service buildings, and very few crates will need to be added or moved.

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| Figure 1: Legacy CAMAC crates interfacing VME front ends via serial links provide both analog and digital status and control of accelerator devices and will continue to be used in existing Muon Department Service Buildings [2]. |

There are serial links that are distributed through and between the service buildings, via the accelerator enclosures, that provide the necessary communications paths for CAMAC as well as other necessary signals such as clock signals and the permit loop. Links can be run over multimode fiber optic cable or copper Heliax cable. Most Muon Department links that run through accelerator enclosures are run over Heliax which should function normally in the radiation environment expected for g-2 operations.

Accelerator device timing that does not require synchronization to the RF buckets will remain on the existing 10MHz Tevatron Clock (TCLK) system. The existing TCLK infrastructure will remain in existing service buildings and new TCLK link feeds will be run via multimode fiber optic cable from the Mac Room to the new MC1 and Mu2e service buildings.

Accelerator device timing for devices that require synchronization to the RF buckets will continue to be handled through the Beam Synch Clocks; however, a few changes will be required to maintain functionality. The F0, F1 and F2 service buildings will need both 53MHz Main Injector beam synch (MIBS) for SY120 operations and 2.5MHz Recycler beam synch (RRBS) for g-2 and Mu2e operations. These buildings already support multiple beam synch clocks. An obsolete 53MHz Tevatron beam synch (TVBS) feed in the MI60 control room will be replaced with a 2.5MHz RRBS feed to provide the necessary functionality. The remaining Muon Department service buildings currently use 53MHz MIBS, but will require 2.5MHz RRBS for g-2 and Mu2e operations. This functionality can be obtained by replacing the MIBS feed at F0 with RRBS and using the existing infrastructure. Further upgrades and cable pulls will only be required if it is later determined that both MIBS and RRBS are required in these service buildings. New beam synch feeds to the g-2 and Mu2e service building will be run via multimode fiber optic cable from the Mac Room.

The Delivery Ring permit loop provides a means of inhibiting incoming beam when there is a problem with the beam delivery system. The Pbar beam permit infrastructure will be used in the existing buildings. The CAMAC 201 and 479 cards, which provide the 50MHz abort loop signal and monitor timing, will need to be moved from the MAC Room to AP50 to accommodate the addition of the abort kicker at AP50. Existing CAMAC 200 modules in each CAMAC crate can accommodate up to eight abort inputs each. If additional abort inputs are required, spare CAMAC 200 modules will be repurposed from the Tevatron and will only require an EPROM or PAL change to bring into operation. The permit loop will be extended to the g-2 and Mu2e service buildings via multimode fiber optic cable from the Mac Room. Abort inputs for these buildings will plug into a Hot-Link Rack Monitor abort card as will be mentioned below.

Permit scenarios still need to be developed to determine necessary operational scenarios. We will need the capability of running beam to the Delivery Ring dump when Mu2e and g-2 are down, and running to either experiment while the other is down.

1. **Hot-Link Rack Monitor**

New controls installations will use Hot-Link Rack Monitors (HRM’s) in place of CAMAC. A HRM runs on a VME platform that communicates with the control system over Ethernet. Unlike CAMAC, no external serial link is required, minimizing the need for cable pulls between buildings. Each HRM installation provides 64 analog inputs channels, 8 analog output channels, 8 TCLK timer channels and 8 bytes of digital I/O. This basically rolls the features of multiple CAMAC cards into the chassis. Like CAMAC, when additional functionality or controls channels are needed, additional cards can be added to the VME crate. As an example, a HRM version of the CAMAC 200 module will be constructed to provide inputs into the Delivery Ring permit system. One or two HRMs will be installed in both MC1 and Mu2e buildings and should provide ample controls coverage for both accelerator and experimental devices.

HRM’s are expected to eventually replace legacy CAMAC systems in the existing buildings. This migration will start by replacing existing 12 bit MADCs and CAMAC 190 cards for analog readings with 16 bit HRM channels. This option was being considered before g-2 operation, but was determined to not be cost effective due to lack of available funding, limited legacy Ethernet connectivity in three of the Muon service buildings and the determination that the existing CAMAC would likely provide adequate performance for g-2 operations.

1. **Ethernet:**

Many modern devices have some form of Ethernet user interface. In addition, many devices and remote front ends use Ethernet to interface the control system instead of using the traditional CAMAC. The results are an increasing demand on the Controls Ethernet. Figure 2 is a map of the Muon Controls network. All of the current Muon Ring service buildings have Gigabit fiber optic connections from the cross-gallery computer room to Cisco network switches centrally located in each service building. These will provide ample network bandwidth and connections after the reconfiguration for g-2 and Mu2e. A central Ethernet switch that fans out to the other Muon Department buildings is currently located in AP10, but will need to be moved to AP30 as will be discussed later in this document.

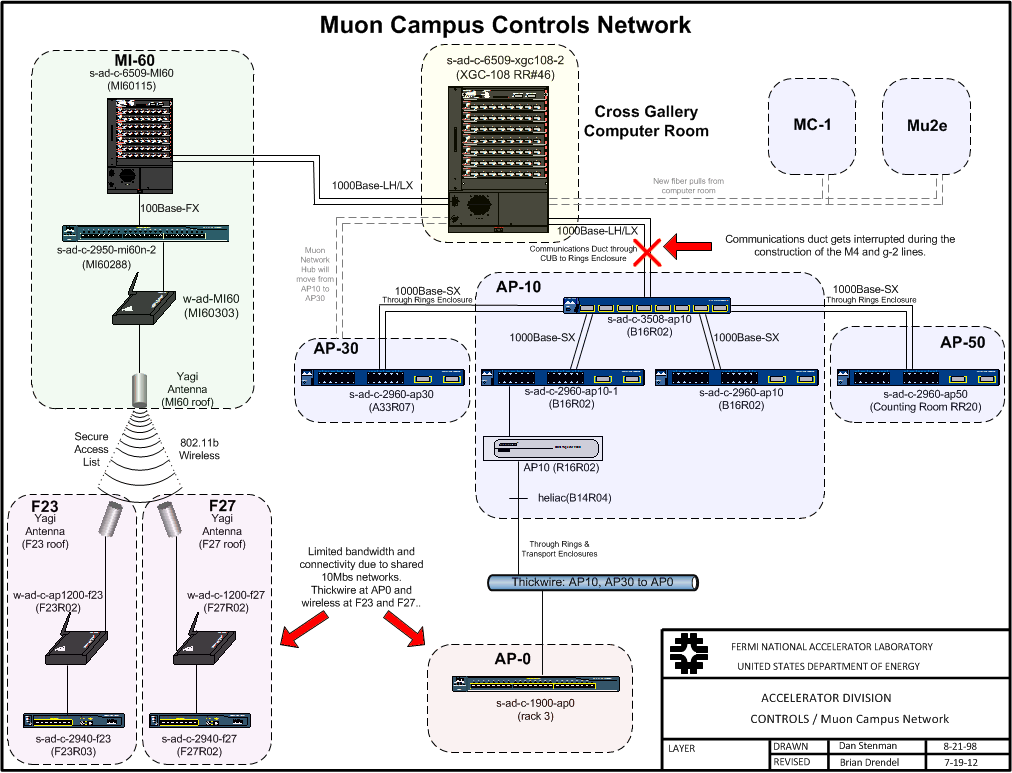


Figure 2: Controls Ethernet to the Muon Department Service Buildings should be adequate for g-2 operations. The central switch at AP10 will be moved to AP30. Legacy networks at AP0, F23 and F27 have limited bandwidth and connectivity.

Ethernet connects between the Muon rings service buildings via multimode fiber optic cable paths that traverse the Rings enclosure on the Accumulator side. The multimode fiber currently in place will remain functional during g-2 operations. However, in the higher radiation environments expected during Mu2e operations, these fiber optic cable pulls will need to be upgraded to single mode fiber at a minimum, or the more costly rad hardened fiber if the single mode fiber if radiation rates are too high.

Most beam line service buildings have gigabit fiber connected to centrally located network switches that provide ample network bandwidth and connections. AP0, F23, and F27 are the only three buildings that do not have this functionality. AP0 runs off a 10Mbps hub that connects to 10Base5 “Thicknet” that runs through the Transport and Rings enclosures back to AP10, while F23 and F27 run off 802.11b wireless from MI60. Both are 10 Mbps shared networks with limited bandwidth and connectivity. It is anticipated that the network in these three buildings may be sufficient for g-2 operations; however, network upgrade options are being considered as will be discussed below.

1. **Restoring Controls Connectivity:**

Civil construction of the M4 and g-2 beams line enclosures will result in the removal of the underground controls communication duct that provides the connectivity between the Accelerator Controls NETwork (ACNET) and the Muon Campus. Included in this communication duct is the fiber optic cable that provides Ethernet connectivity as well as 18 Heliax cables that provide the controls serial links and other signals including the Fire and Utility System (FIRUS). These cables currently connect from this communications duct to the center of the D20 location in the Rings enclosure, and travel through cable trays on the Delivery Ring side to the AP10 service building. After removal of the communications duct, FESS will construct new communications ducts from the existing manholes. These communications ducts will go directly to AP30, MC1 and Mu2e service buildings without going through accelerator enclosures. See Figure 3 for drawings of the current and future controls connectivity paths.

*Restoring Connectivity:*

When the Heliax and fiber optic cables are cut during the above mentioned communications duct removal, controls connectivity will be lost. The base plan for restoring all of the controls links that run over Heliax is to cut and splice the 18 Heliax cables in the manhole outside of Booster West Tower and run new Heliax from the splices through the new communications duct to AP30. If there is not enough space in the existing manhole for the splices, FESS will construct a second manhole. As a result of the redirected Heliax, controls links will fanout from AP30 instead of AP10. This will require some additional controls hardware configuration and labor.

The multimode fiber optic Ethernet cable that will be cut currently runs beyond its design spec and cannot be spliced. New fiber optic cable will be pulled from the MAC room to AP30 through the same communications ducts as the Heliax. Singlemode fiber will be needed for Ethernet connectivity and multimode fiber will be needed for CAMAC and the timing links. There are still some questions about whether there is room in the manhole penetrations between the MAC room and Booster West Tower manhole to complete this new fiber pull. If there is not enough room in the existing duct work, a new cable pull path will need to be determined. As a result of the new fiber pull, the Ethernet will fanout from AP30 instead of AP10. This will require some additional controls hardware configuration and labor.

An alternate solution considered was to try to suspend the Heliax above the extraction enclosure during construction and make duct holes in the new enclosure to maintain the existing connectivity. It was determined that the extraction tunnel will directly intersect the communications duct, making this option technically challenging. This plan would also leave fiber optic cable in the Delivery Ring tunnel which would not function in the radiation environment expected for future Mu2e operations.

Another alternate solution considered was to splice the 18 Heliax cables at the point where the existing communications duct bank intersects the new extraction line tunnel, run the new Heliax through the g-2 and M4 line and Delivery Ring enclosures back to AP30. The fiber optic cable pull would go along the same route. This option was determined to be more costly due to the fact that the fiber optic cable would be run through the D30 extraction area which would require expensive radiation hardened fiber optic cable. In addition there would be extra complications of not damaging the Heliax when the communication duct is cut and finding sufficient room for the splices.

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| 2012 Muon Campus Controls | Future Muon Campus Controls |
| Figure 3: Muon campus controls paths. During construction of the M4 and g-2 beam lines, the communications duct that provides controls connectivity to the Muon Campus will be interrupted. A new communications duct will be built to restore controls connectivity to the Muon Service Buildings. New controls will need to be established at MC-1 and Mu2e. | |

Yet another option considered was to replace the existing Heliax cable with new a new fiber optic cable. CAMAC and timing links require multimode cable. If only singlemode fiber is available, then new singlemode fiber optic repeaters will need to be developed, driving up the cost to unacceptable levels. If multimode fiber optic cable is pulled specifically for this task, new sets of fiber repeaters will need to be built at both cross gallery and AP30.

*Establish Connectivity to MC-1:*

New fiber optic cable will be pulled from the MAC Room to the g-2 service building. Singlemode fiber is needed for Ethernet and multimode fiber is needed for the timing links, abort permit loop and FIRUS. The fiber pulls will provide ample connectivity for all Ethernet and controls signals for both the accelerator and experiment. The g-2 experiment anticipates requiring network rates approaching 100MB/sec during production data taking which can be handled easily with the proposed infrastructure.

One alternate solution considered was to pull the new fiber along the existing communicatiuons duct until it intersected the extraction lines enclosure. From there the fiber could be directed along tunnel enclosure cable trays to the MC-1 service buildings. Though this option

*Possible Upgrades for Legacy Networks:*

If the legacy Ethernet networks at AP0, F23, F27 prove to provide insufficient connectivity or bandwidth for g-2 operations, they can be most cost effectively upgraded by replacing the current “thicknet” with single mode fiber optic cable. The path would be from the AP30 service building, to the Rings enclosure, along the cable trays toward the M3 beam line, and down the transport enclosure. From the transport enclosure, the fiber optic cable runs can go to F27 and AP0. An additional fiber optic cable pull from AP0 through the PreVault enclosure provides a path to F23. The largest issue with this upgrade is the single mode fiber optic cable is susceptible to radiation. If the radiation environment in the accelerator enclosures does not allow for single mode fiber optic cable, then rad hardened fiber optic cable can be pulled, but at a higher cost. Other fiber optic cable path options have been considered, but prove to be more costly to implement.

**Accelerator Instrumentation**:

1. Beam types:

Beam monitoring can be divided into distinct zones: primary protons, mixed secondaries, proton secondaries and muon secondaries. The locations of each of these areas are shown in Figure 3. The expected beam properties in each of these areas are showing in Table 1.

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| Beam Type | Particle Species | Beam Momentum | Number of particles | RF Bucket | Bunch Length | Transverse Emittance |
| Primary Protons | Protons | 8.9 GeV/c | 1E12 | 2.515MHz | 120nsec | 18 -mm-mrad (95% normalized) |
| Mixed Secondaries | p, e+ | 3.1 GeV/c | 1E7 to 2E8 | 2.515MHz | 120nsec | 35 -mm-mrad  (95% normalized) |
| Proton Secondaries | p | 3.1 GeV/c | 1E7 | 2.515MHz | 120nsec | 35 -mm-mrad  (95% normalized) |
| Muon Secondaries |  | 3.1 GeV/c | <1E5 | 2.515MHz | 120nsec | 35 -mm-mrad  (95% normalized) |

Table 1: g-2 Beam Requirements [14].

*Primary Proton Beam:*

Primary Proton beam will traverse the Recycler, P1 stub, P1, P2 and M1 lines. Much of the instrumentation needed to measure the primary proton beam during g-2 operation already exists, but needs to be modified for use with the faster cycle times and 2.5MHz RF beam structure. The overall beam intensity is similar to that seen in Pbar stacking operations, and in many cases requires only small calibration changes be made to the instrumentation. Toroids will be used to monitor beam intensity and will be used in conjunction with Beam Loss Monitors (BLM’s) to maintain good transmission efficiency in the beam lines. Multiwires and Secondary Emission Monitors (SEM’s) will provide beam profiles in both transverse planes. Beam Position Monitors (BPM’s) will provide real-time orbit information and will be used by auto-steering software to maintain desired beam positions in the beam lines.

Toroids are beam transformers that produce a signal that is proportional to the beam intensity. There are two toroids in the P1 line, one in the P2 line and two in the M1 line. They will continue to be used in g-2 operation to measure the primary proton beam. The electronics for these toroids are comprised of legacy analog processing inside of NIM crates. The base plan, due to funding limitations, is to continue to use the legacy electronics. If funding becomes available, the electronics would instead be upgraded to a VME-based processing environment, repurposing electronics repurposed from Collider Run II to provide cost savings. The existing toroids provide the majority of the required coverage, though the addition of a second toroid in the P2 line is desirable. The present toroid installation locations will be reviewed and modified as needed to provide adequate coverage. Filters, chokes, and preamps will be added for analog conditioning. Electronics will be modified, where necessary, to calibrate the toroids for g-2 operations.

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| Figure 3: Beam monitoring can be divided into four different zones, each with different instrumentation schemes. High intensity proton beam will be monitored with Toroids, BPMs and BLMs. Low intensity secondary and proton only secondary beam will be monitored with Ion Chambers, BPMs and SEMs, Muon-only secondary beam will be monitored with Ion Chambers and SWICs. |

Beam line BPMs provide single pass orbit position information with sub-millimeter resolution, and will continue to be the primary beam position devices in the P1, P2 and M1 lines. All BPMs share the Echotek style of electronics that were built as part of the Rapid Transfers Run II upgrade, and is the current standard for beam line BPMs. These BPMs were designed to detect seven to 84 consecutive 53MHz proton bunches and four 2.5MHz antiproton bunches for Collider Run II operations. Minimal electronics modifications will be required to measure the single 2.5MHz bunches of 1E12 particles expected during g-2 operations. Two additional BPMs will be installed in the P1 stub.

BLMs are already in place in the P1, P2, and M1 beam lines. Existing ion chamber detectors will be utilized for Mu2e operation. BLMs will be upgraded to modern BLM log monitor electronics, repurposing unused components from the Tevatron to minimize cost. An optional upgrade is being considered that would add snapshot capability to the BLMs. This feature would allow the loss monitors to distinguish losses from individual 15 Hz pulses of beam. However, this option adds significant cost to the BLM system. Two additional BLMs will be installed in the P1 stub.

There are two types of beam profile monitors in the beam lines, multiwires in the P1 and P2 lines, and SEM’s in the other beam lines. The profile monitors will primarily be used for commissioning, studies, and documentation of the beamlines. General maintenance will be performed on the hardware and electronics to ensure proper functionality. The current location and wire spacing of the monitors will be reviewed and modified accordingly. Two additional multiwires will be installed in the P1 stub.

*Mixed Secondaries:*

Mixed secondary beam will traverse the M2 and M3 lines as well as the Delivery Ring. Changes to existing instrumentation are required in these areas as a result of the secondary beam being approximately two orders of magnitude lower in intensity than the former Antiproton stacking operations. In addition, 2.515MHz bunch structure and faster pulse rate must be taken into consideration. Mu2e beam will have beam intensities four to five orders of magnitude higher than g-2 operations in these areas, so design upgrades must take into account the vastly different beam intensities required for both experiments. Beam studies have been conducted to help determine what instrumentation best suits the low intensity secondaries of g-2 operations [4].

Four toroids are available for use in the secondary beam lines and were the primary intensity measurement device in these lines during Antiproton operations. These will be used for Mu2e operations; however, beam studies show that even with high gain and careful filtering we were only able to measure beam intensities at levels one order of magnitude higher than g-2 operational beam. As a result, toroids will likely not be used during normal g-2 operations [4].

The Delivery Ring used a Direct Current Current Transformer (DCCT) to measure beam intensity. This device will not function for at g-2 operational intensities and cycle time.

Ion chambers will become the primary beam intensity measurement device of mixed secondary beam. They are a relatively inexpensive device that can measure beam intensities with an accuracy of ±5% with as low as 105 particles. Ion chambers were used in the AP2 line in the past, and work was done during beam studies to re-commission the ion chamber that used to be operational near the end of the AP2 line. For g-2 operations, we will implement a one or two ion chambers in the M2 line. Ion chambers are also being considered for the M3 line and the Delivery Ring; however, these would need to be installed in a vacuum can with motor controls to pull them out of the beam during the higher intensity Mu2e operations.

Wall Current Monitors (WCMs) are an alternative intensity measurement device being considered for mixed secondary beam. These devices have the advantage of being completely passive, and not requiring a break in the vacuum, which may make them a better fit in the M3 line where we need to stay compatible with the higher intensities of Mu2e operations, and the Delivery Ring where beam may circulates for approximately 56 milliseconds in Mu2e operations. New WCM designs are being considered that would provide accurate intensity measurements for secondary beam during g-2 operational intensities. The design is based on a WCM being designed for Mu2e extraction. Each slice of the slow spilled Mu2e beam is approximately 2E7, which is consistent with the intensity that we would expect in the M3 line and Delivery Ring during g-2 operations.

Beam Position Monitors (BPMs) were a key diagnostic in Antiproton Source operation providing sub-millimeter orbit information in the beam lines and Delivery Ring. BPMs are located at each quadrupole, providing ample coverage. There are 34 BPMs in the AP2 line, 28 BPMs in the AP3 line and 120 BPMs in the Delivery Ring; however, it is believed that the BPMs in these areas will not be able to see the low intensity 2.515Mhz g-2 secondary beam. ~~The existing BPM pick-ups in all three areas should be suitable for g-2 operation with a small amount of hardware modifications in the tunnel. One significant technical challenge is the BPMs in the three areas are run off of three different styles of BPM electronics. The AP3 line BPMs run off of the Echotek electronics mentioned in an earlier section. These electronics can be upgraded for g-2 operations with minimal electronics modifications. In contrast, the AP2 and Delivery Ring BPMs run on legacy electronics systems which are not capable of measuring 2.515MHz beam. These systems will be upgraded to the Echotek electronics. VME crates and processor boards will be repurposed from the Tevatron, and analog transition boards repurposed from the Recycler if possible to minimize the cost. A second technical challenge for the BPM systems is being able to measure the low secondary beam intensities expected for g-2 operations. Initial beam studies showed the signal will be marginal [4], though Instrumentation engineers believe modifications can be made to allow them to function at the lower intensities. A third technical challenge is the making one system that will work for both g-2 and Mu2e beam, when beam intensities in the M3 line and Delivery Ring will be for to five orders of magnitude different between the two experiments.~~

SEMs will be used to measure beam profiles in the M2 and M3 lines as well as the Delivery Ring. There are eight SEMs in the AP2 line, seven SEMs in the AP3 line, three SEMs in the D/A line, two in the Debuncher and one in the Accumulator to draw from. SEM tunnel hardware will require some maintenance and locations where SEMs are moved will require new cable pulls. Beam studies show that special high gain preamps will be required to measure the low intensity secondary beam during g-2 operations [4]. There are only two working high gain preamps, so additional preamps will need to be designed and fabricated. In addition, it is believed that the BPM systems in the M2, M3 and Delivery Ring will not be able to detect the low intensity 2.515 MHz beam for g-2 operations. As a result, additional SEMs will need to be added to the Delivery Ring. The Delivery Ring has two SEMs, but we can also use the spare SEM from the Accumulator and two SEMs that won’t be used from the AP2 line.

BLMs will be used to help maintain good transmission efficiency through the lines. Both Delivery Ring and AP3 loss monitors will use the existing hardware and electronics for g-2 operations, but will be replaced for the higher Mu2e operations. Care will need to be taken to make a BLM plan that allows for switching back and forth between the two separate BLM systems.

*Proton Secondaries:*

Proton secondaries will be in the Delivery Ring abort line and will have a similar beam intensity to that of the Delivery Ring. Existing instrumentation from the downstream AP2 line will be used. A toroid will be used to measure beam intensity for Mu2e operations, but will be out of its operational range for g-2. If intensity measurement is needed, a retractable ion chamber will be added to the line. BPMs, SEMs and BLMs will be used in the same way they are for the mixed secondary lines.

*Muon Secondaries:*

Muon secondaries will traverse the upstream portion of the M4 line and the g-2 line. The largest technical challenge will be measuring muon secondary beam which is expected to be at least two or three orders of magnitude smaller than the upstream mixed secondary beam. Most diagnostics will not work at these beam intensities. Beam intensity will be measured with ion chambers. The ion chamber in the M4 line will need to be retractable to be compatible with Mu2e operations, while the g-2 ion chamber can be permanently in the beam path. New ion chambers will be built for this line. Two options are being considered for measuring beam profiles. The Segmented Wire Ion Chambers (SWICs), which are very similar to SEMs or Multiwires with the exception the beam goes through an ArCO2 gas which is ionized creating an amplification that allows to measure beam intensities down to the 10^5 particle range. The other option is to devlop a Fiber Profile Monitor which replace the wires used in a SWIC with fibers material.

The upstream M4 line will be made compatible with both Mu2e and g-2 operations. Beam in the M4 line will be at least two orders of magnitude smaller than the individual slices of slow spilled beam that the line will see in Mu2e operations. Intensity and profile information will also need to be collected just before and after the inflector, which will likely be achieved with ion chambers and SWICs.

If beam profile information cannot be accurately measured with a SWIC or FPM, one option being considered is to develop a tune-up mode. In this mode, the protons in the Delivery Ring would not be sent to the abort, but extracted toward g-2 with the muon beam. This would result in 10^7 beam in the extraction lines, which is easily measured by ion chambers and SWICs.

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