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Muon Campus operation for Mu-, dedicated EDM measurements and AP-0 Target Station capabilities

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May 24, 2021

My interpretation of the subject

- Switching the Muon Campus to minus polarity
  - Summary of how to do it and time required
- Mode Changing between Mu2e and g-2
  - Issues after Mu2e ESS are installed
  - Can Mu2e and a future MC-1 program coexist?
- How low can the beam energy be?
- Running the AP-0 Target Station beyond g-2
  - A short history and description
  - Spares of critical components

Main power supplies, shunts and trims

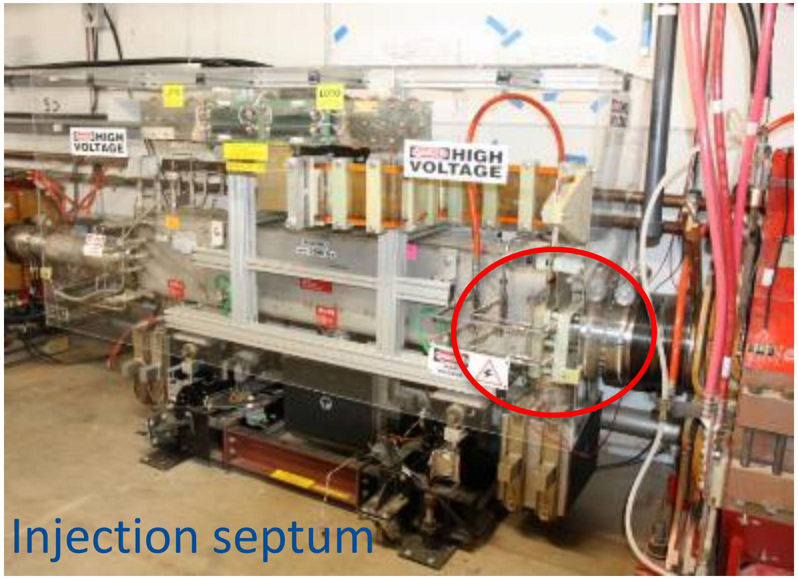
- 83 main power supplies, both SCR and SM types
  - Polarity is changed by swapping leads, SM cabinets cramped
  - E.E. support estimates one person-hour per supply
- 52 quadrupole shunts
  - Leads are flipped in the tunnel at the magnet
- Trim dipole supplies are bipolar, simply setting sign flip


Switch Mode supplies

SCR supplies

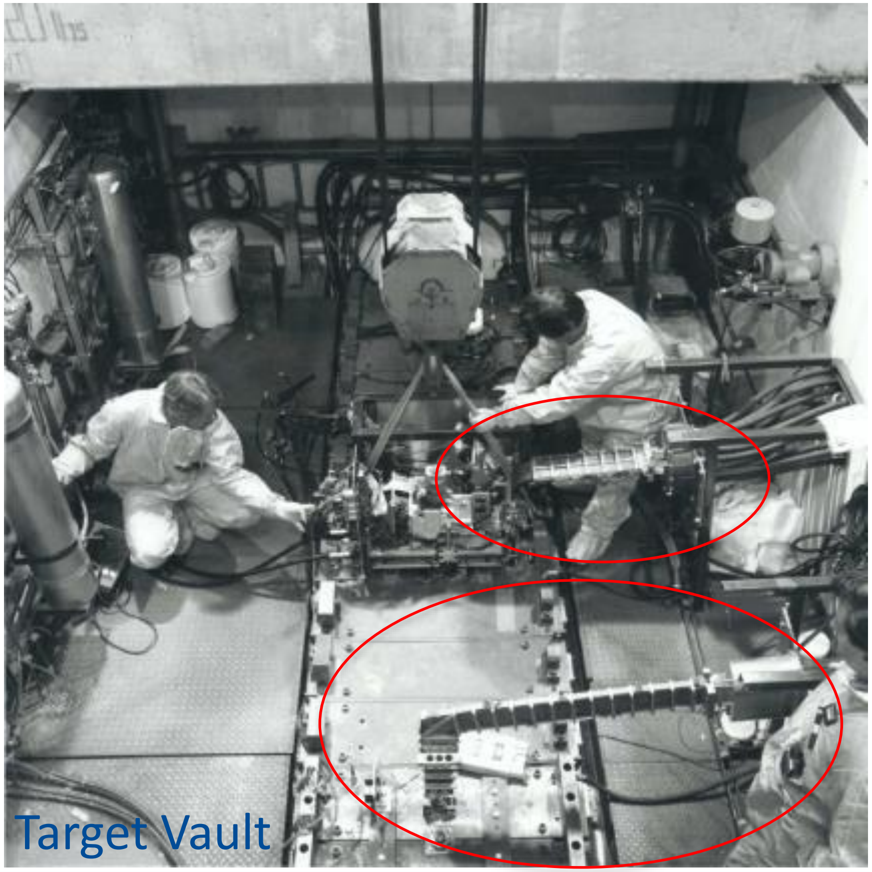
Kickers and septa

- Polarity is changed at magnets
- Three kicker systems and two pulsed septa
- Kickers have RG220 cables swapped from each end
  - Five cables for IKIK and AKIK, four cables for EKIK
- Septa stripline is reoriented at magnet
  - Designed by Sasha Makarov of T.D.



Target Station

- Stripline for Li lens and pulsed magnet reoriented in Vault
  - Requires overhead of Vault access
  - Original Pbar design, so mu- is “normal” polarity

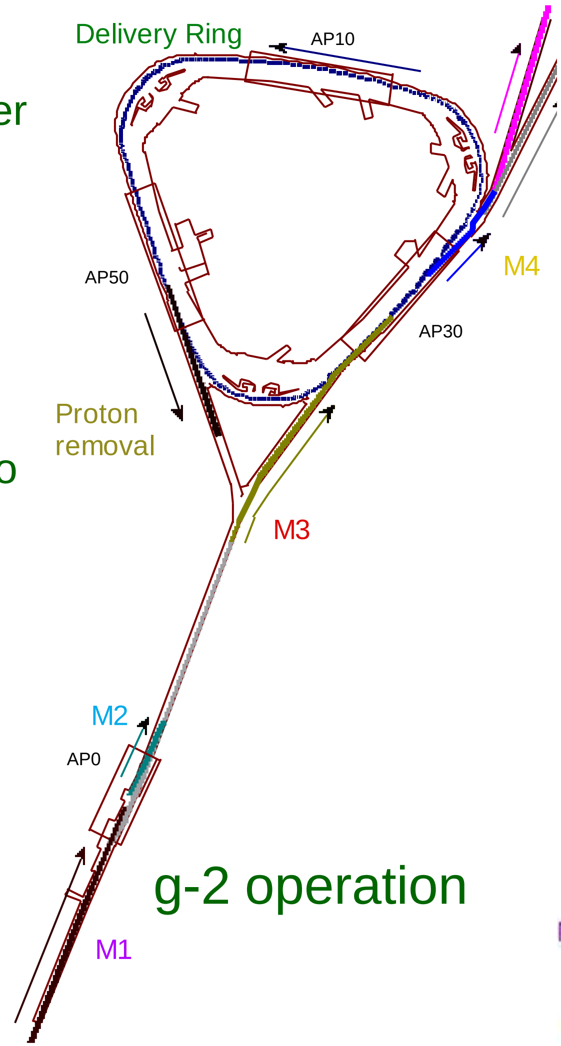


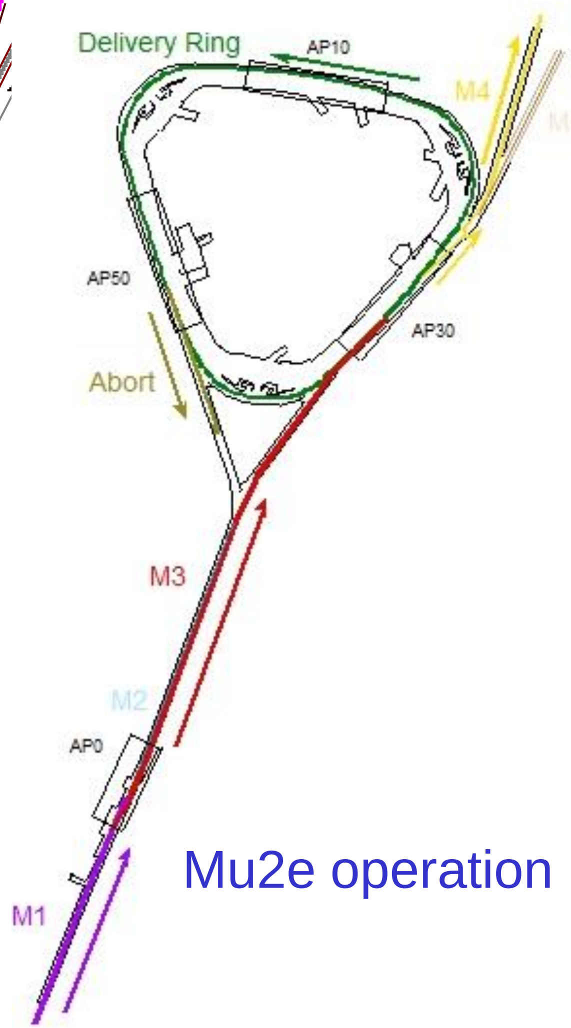
Other comments

- Estimate 1-2 weeks to complete polarity change (each way)
- Instrumentation should be okay
  - Sign of signal will be reversed and weaker due to reduced flux
- Mu- polarity precludes Mu2e studies
- Existing lab schedule not consistent with six-month mu- run
  - Muon beam start-up has begun 11/7 and 11/24 last two years
  - Typically takes weeks to reach 1E12 Protons per pulse
  - Mu2e septa installation March 2023
  - Perhaps 3 or so months of decent running as it stands now
- Need full running period to get six months of Mu- data
  - Polarity change during summer shutdown prior to running
  - Start up in mu- mode, may not go completely smoothly

The differences between g-2 and Mu2e

- 8.889 GeV/c proton beam from Recycler transported to AP-0 Target Station
- A 3.1 GeV/c secondary beam is transported through M2 & M3 to the Delivery Ring
- Beam does four turns in Delivery Ring to separate and eliminate protons
- Single turn extraction into M4 and M5 to the g-2 Ring
- 8.89 GeV/c proton beam bypasses the Target Station and through M3 to the Delivery Ring
- Protons are resonantly extracted from the Delivery Ring over 43 ms into the M4 Line
- Protons are transported through M4 to the Mu2e target, out of time beam is removed using an A/C dipole





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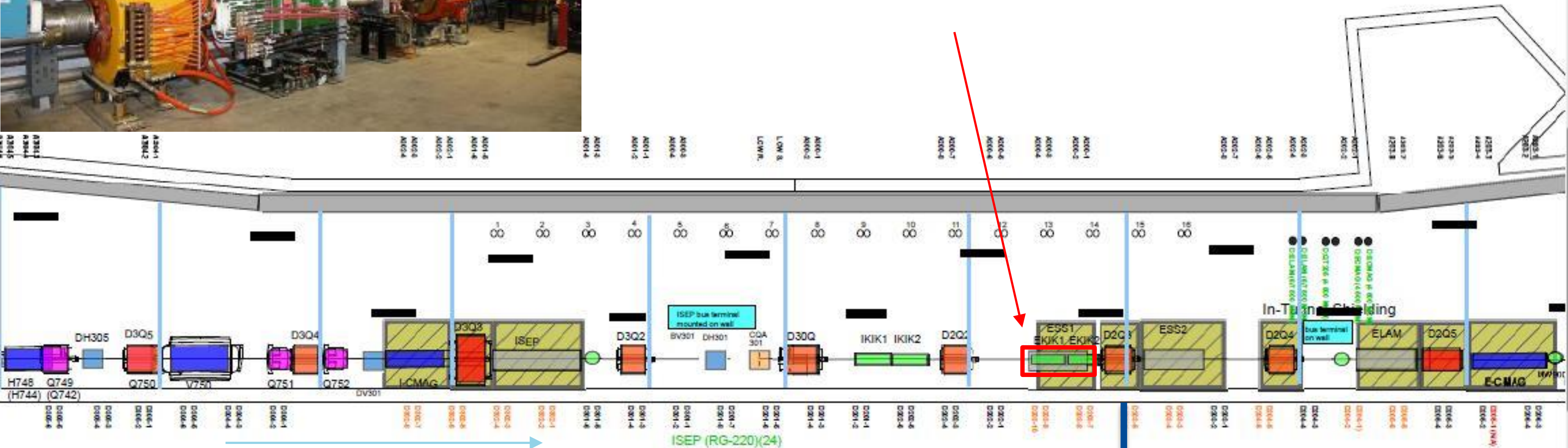
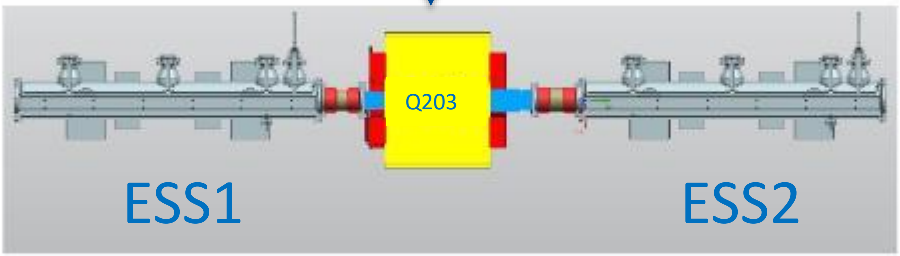
Mode changing – different extraction methods

Upstream Mu2e electrostatic septa will be located where Extraction Kicker is now





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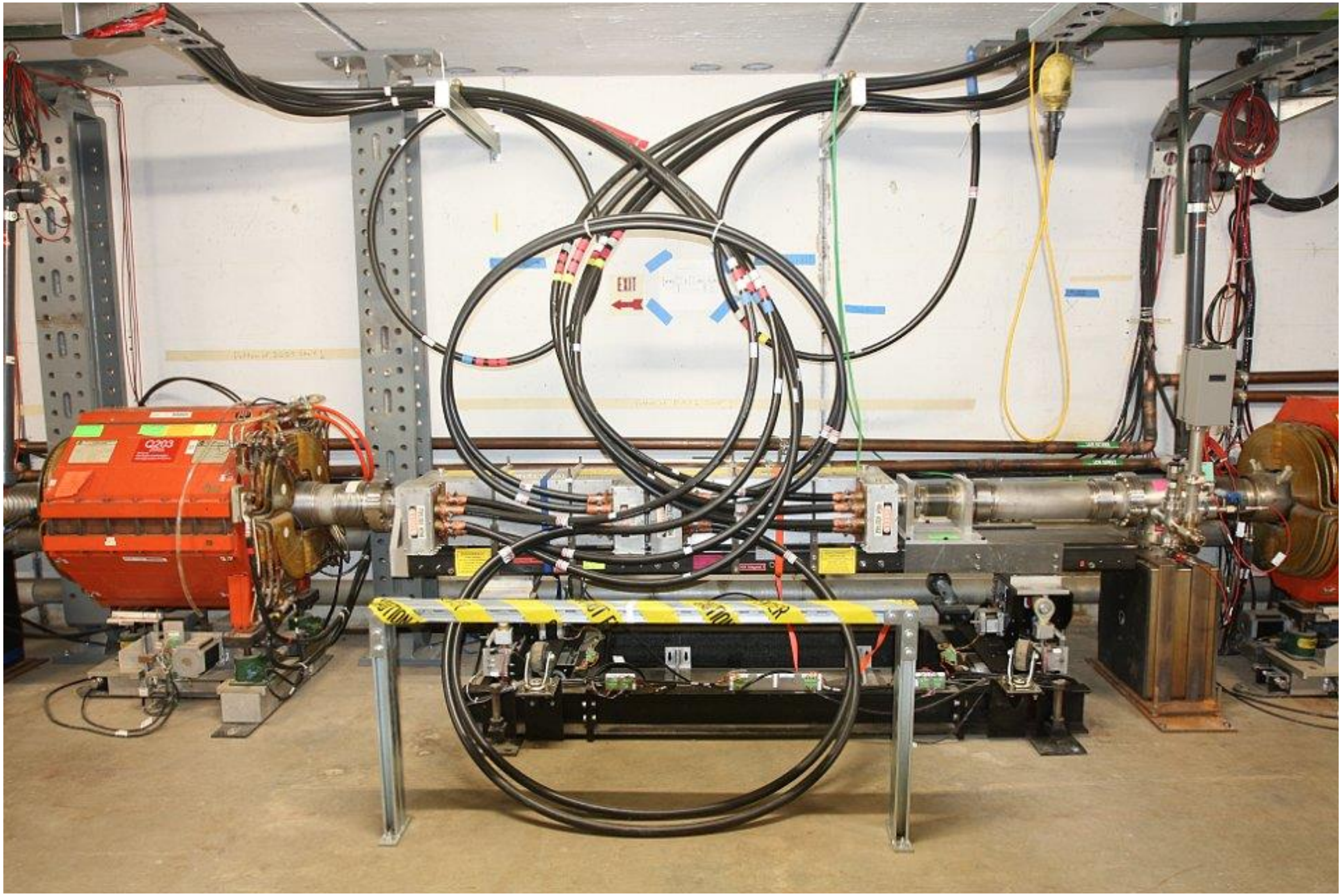
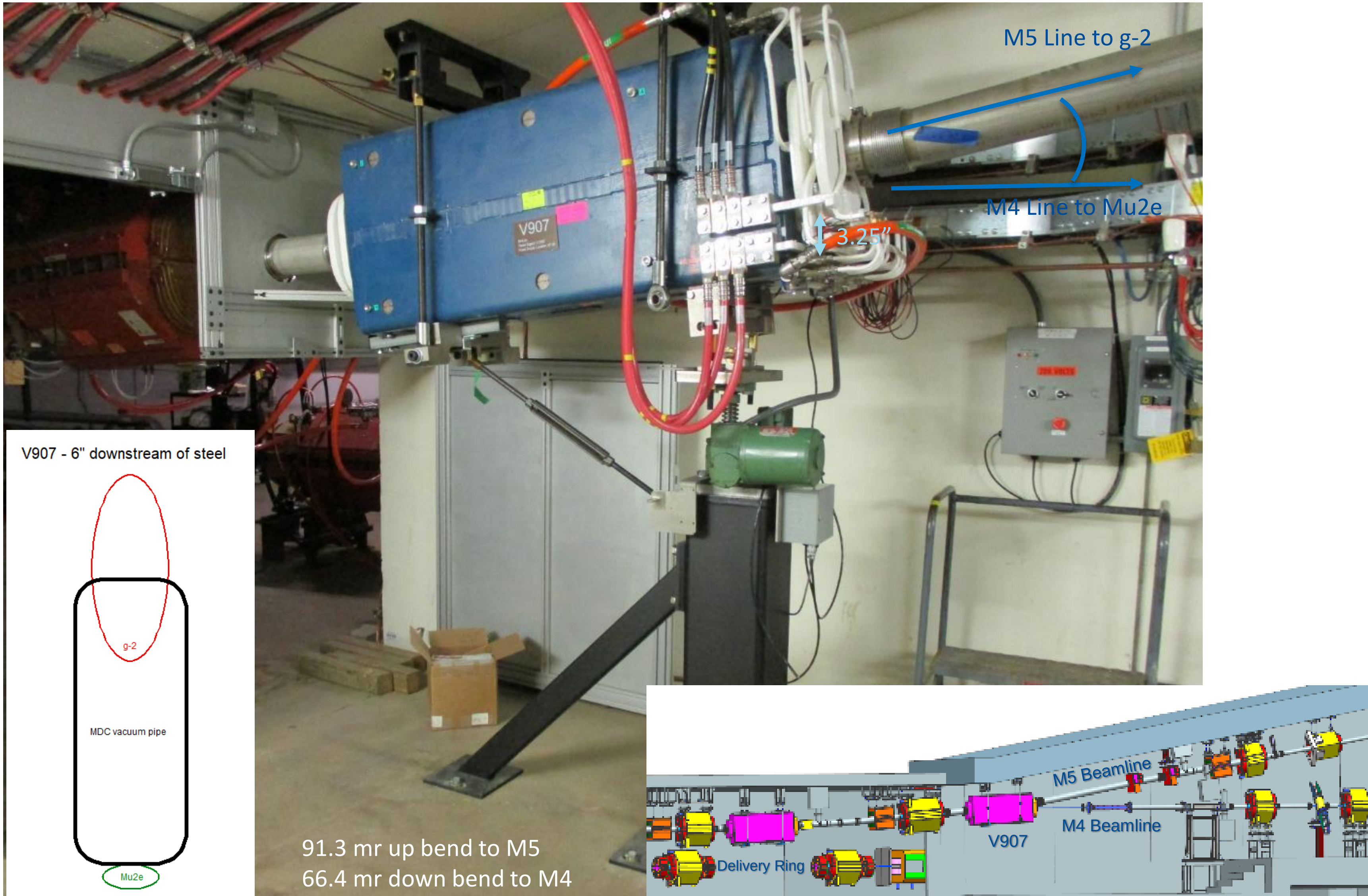
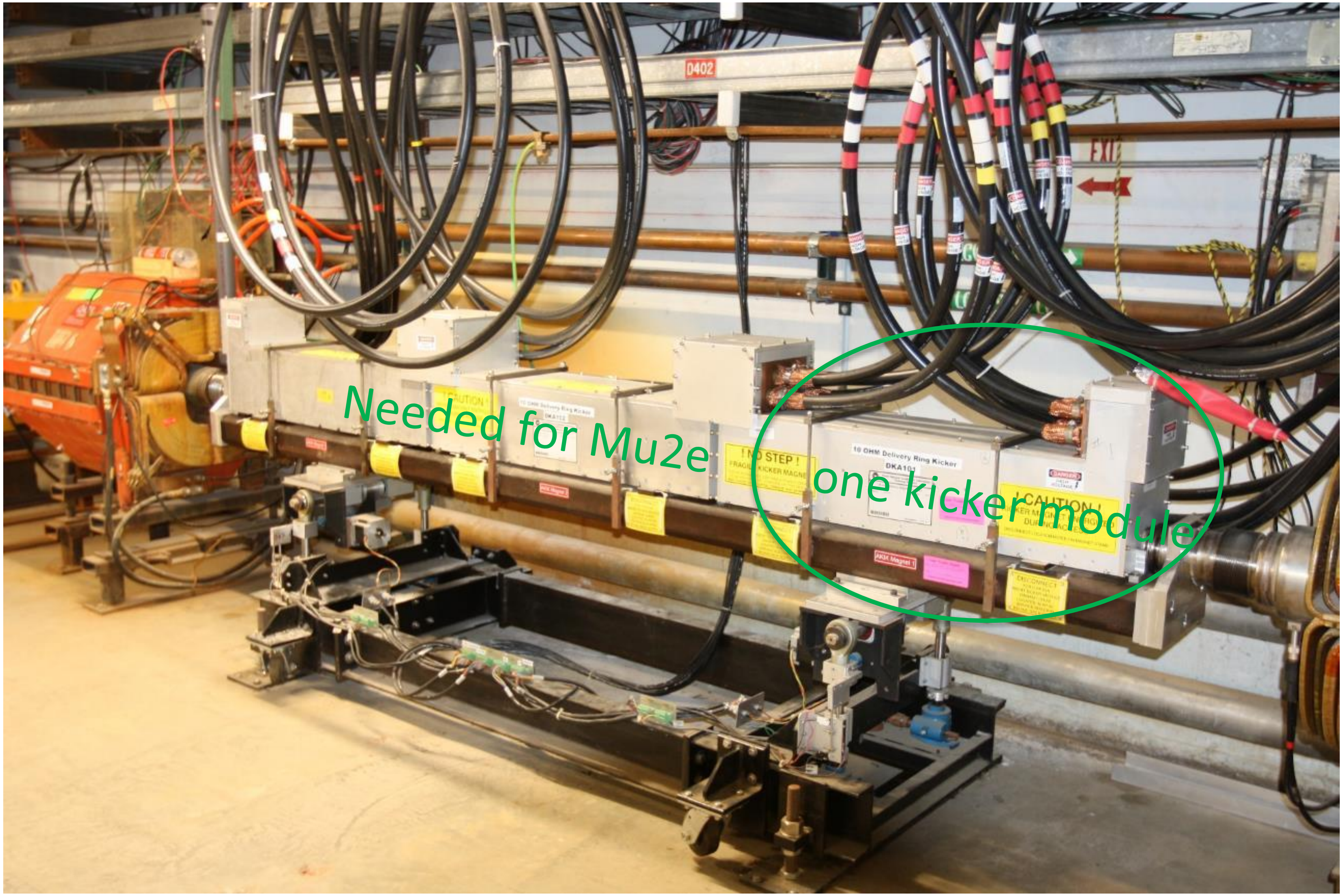
Extraction Kickers (replaced by ESS1 when Mu2e runs)



V907 pitching dipole stand, the fork in the road



Mu2e Abort Kicker configured for g-2 proton removal



Mode switching between Mu2e and g-2

- Difficult – Extraction systems are not compatible
  - Single-turn extraction with proton removal for g-2, resonant extraction for Mu2e
  - Mu2e upstream Electrostatic septa will be located where Extraction Kicker is now
  - Removing septum and installing kicker will be challenging due to septum rad levels
    - Roughly 1,000 – 3,000 mr/hr @ 1 ft after 24-hour cooldown during normal Mu2e operation
    - Vacuum connections, high voltage connections, removing anchors and moving etc.
  - Preliminary concepts exist for a relocated and compact extraction kicker
    - Can't go just anywhere, must have proper phase relationship with Lambertson
    - D30 region where injection and extraction regions are located has very little available room
    - May be able to use single kicker instead of two, with modification and proper placement
- Not too difficult – Reconfiguring Mu2e Abort
  - Should take less than a day
- Not too difficult – Change charging supplies in pulsed devices
  - Injection Kicker, Injection septum and Abort septum, should take less than a day
- Not Difficult – Changing magnet currents and reconfiguring beamlines
  - Already have software to do this in 5 - 10 minutes
- Not difficult – Repositioning V907 dipole vertically
  - Special pitching magnet stand and controller installed over summer
  - Vacuum windows used for shorter duration changes, perhaps 3% muon loss
  - Vacuum spool pieces used for longer periods, but switch takes about two days

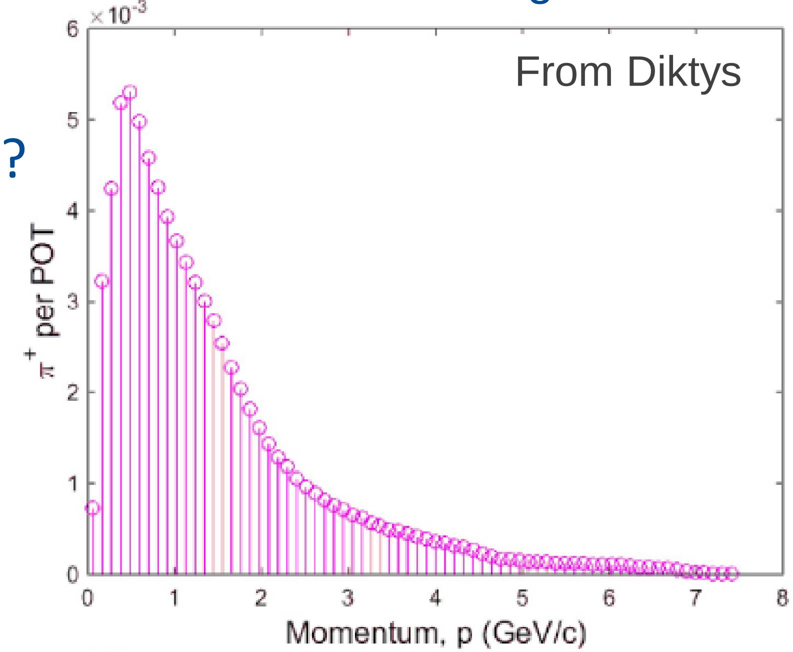
Mode switching Summary

- Present configuration supports mode changing between Mu2e and g-2
  - Operating currents can be changed within a few minutes
  - V907 magnet pitch can be changed in a few minutes
    - Vacuum windows are used during periods of frequent mode changes
  - Reconfiguring Delivery Ring Abort requires a shift or two
  - Charging supplies for kickers and septa should work with both modes
    - If charging supplies need to be changed after all, it would take about a shift
  - Swapping electrostatic ESS1 and Extraction Kicker will take the longest time
    - On the order of days, need to remove Mu2e rad shielding and break vacuum
    - Design is at concept stage, need engineering support to complete
    - Manipulating ESS1 will become more complicated as rad levels increase (1-3 Rem @ 1 ft?)
- What is needed to reduce mode changing to a shift or two
  - Need new extraction kicker scheme that doesn't require ESS1 to be removed
    - Most available space does not have the proper phase advance
  - May have enough room upstream of ESS1 to squeeze in a single kicker
    - Hard to make single kicker strong enough with adequate aperture
    - Concerns that kicker could degrade septa vacuum and cause sparking

Low energy secondary beams

- Power supply regulation should be good to very low energies
  - But impractical to ramp due to high magnet inductance (would take minutes)
- Magnet remnant fields become more of an issue
  - Most magnets in the Muon Campus have small remnant fields
- Increased gas scattering in vacuum chamber
- Some particle lifetimes may be a problem due to the long path length
- The good news is that pion yield is better at lower energies

Good to a few hundred MeV??

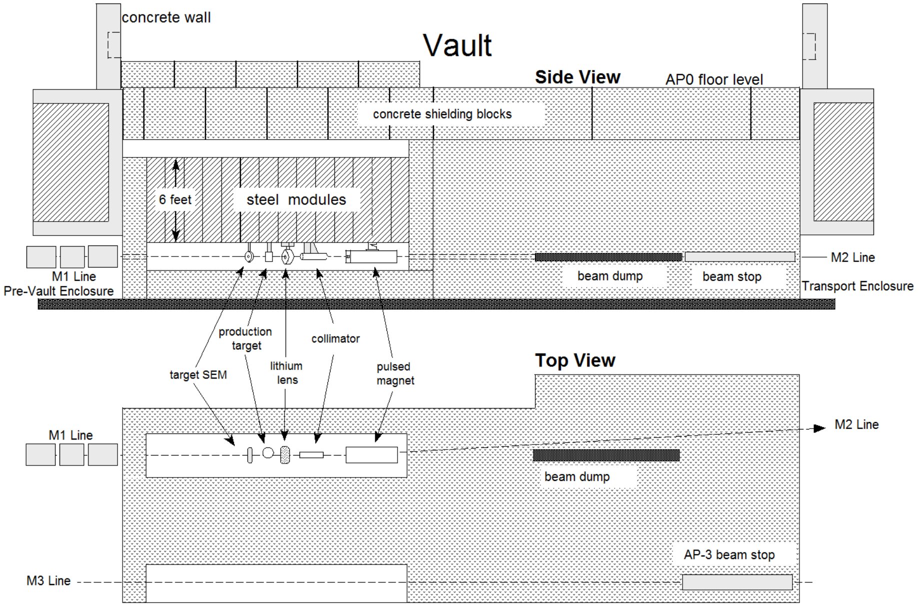


AP-0 Target Station

- Built with the rest of the Antiproton Source in 1984
- Used for antiproton production 1985 – 2011
  - 120 GeV primary beam from Main Injector, 8 GeV secondaries
  - 2.2 second cycle time (0.45 Hz)
- Used largely intact to support the g-2 Experiment
  - 8 GeV primary beam from Recycler, 3.1 GeV secondaries
  - New lithium lens and pulsed magnet power supplies to handle faster cycle time
  - Dump core replaced due to cooling water leaks
  - Existing Pbar spares were considered adequate for entire g-2 run

AP-0 Target Station - layout

- AP-0 is posted as a Radiation Area
- Components hung from six-foot steel modules in "Vault"
  - SEM profile monitor, Target, Lithium Lens, Collimator, Pulsed Magnet
  - Located under concrete shielding blocks, within concrete block enclosure
- Dump located downstream of Vault, designed for 80 kW of beam power
  - Water-cooled dump core made of graphite, aluminum and steel
  - Steel shielding surrounds dump core
- Vault air is forced through tunnel to minimize airborne radiation release
  - Special air-handling system to create positive pressure in building



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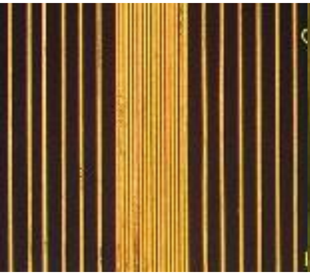
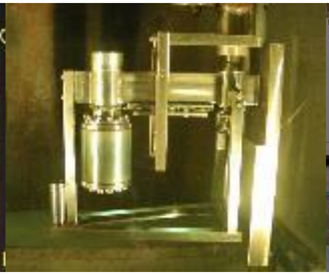
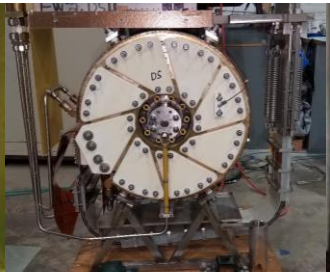
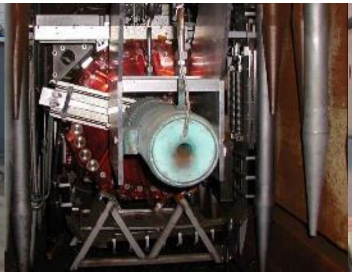
AP-0 Target Station – major components

- Target Secondary Emission Monitor
  - Inner wires have 0.125 mm spacing to resolve small primary beam spot
- Production Target
  - Inconel cylinder contained in beryllium jacket to minimize oxidation
- Lithium Lens
  - High current, strong focusing device contained in 8:1 transformer
- Collimator
  - Water-cooled copper cylinder to help shield Pulsed Magnet from beam spray
- Pulsed magnet
  - Single turn radiation hardened dipole
- Dump core
  - Intercepts primary beam that didn’t interact in target and low-angle secondary beam

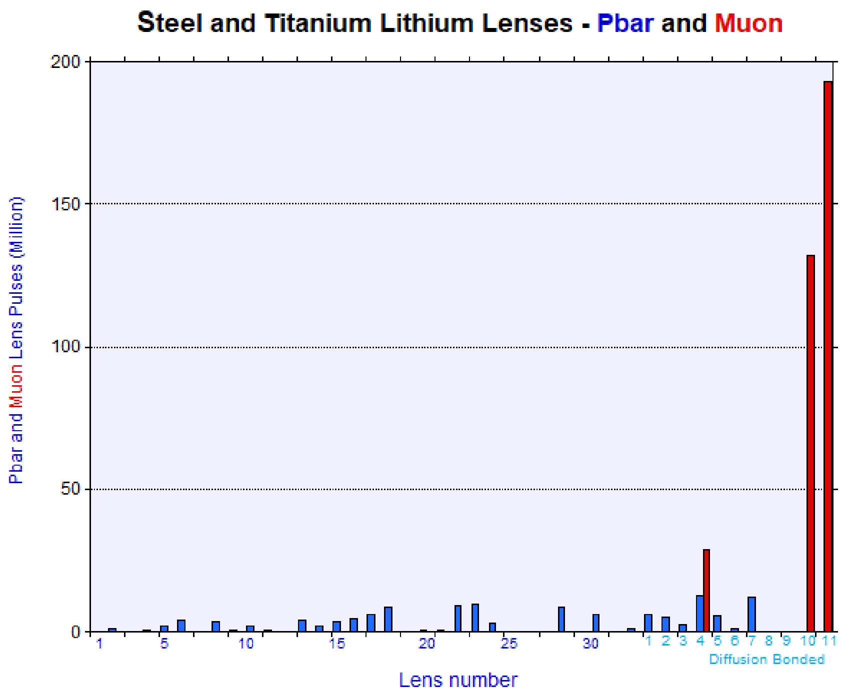





AP-0 Target Station – spare situation

- Target Secondary Emission Monitor
  - None
  - Only two Target SEMs ever built, the first removed due to broken wires and a vacuum leak
- Production Target
  - One assembled, one awaiting assembly
  - Present target began operation January 2019
- Lithium Lens
  - Three or four (more details to follow)
  - Present lens began operation March 2019
- Collimator
  - None
  - Not in original design, added to address premature Pulsed Magnet failures
- Pulsed magnet
  - Two
  - Magnet presently in use began operation November 2010
- Dump core
  - None
  - Original removed due to large cooling water leaks on both sets of coils

AP-0 Target Station – Lithium Lens history

- Lens failures generally related to heating from current pulse and beam
- Lenses operated at higher current for Pbar production, but low cycle time
- Lens operating current for g-2 based on estimates of lens heating
  - Extensive testing at 12 Hz, but did not account for "burst" of cycles for g-2 operation
  - Premature failures of first two lenses prompted running at lower current and lower yield (15%)
- Present lens has exceeded our expectations for longevity
- It will be very difficult and expensive to restart lens construction



Lens	Muon g-2 Pulses	Comment
10mm-4	29 Million	+12.4 Million Pbar pulses (record)
10mm-10	51 Million	+80 Million test Muon pulses
10mm-11	192 Million+	In operation (reduced gradient)

Table 1: Lithium Lenses used for Muon Operation

AP-0 Target Station – Lithium Lens spares

Lithium Lens spare and potential spare status

J. Morgan – May 19, 2019

Modern lenses are titanium and Diffusion-bonded, old style lenses have a welded titanium septum with a steel body
Modern transformers are internally cooled, old style transformers are externally cooled

(Failed) 10mm-4 Diffusion-bonded lens with ext. cooler Xformer had 12.4 M Pbar and 28.9 M Muon pulses (08/21/10-04/06/09)
(Failed) 10mm-10 Diffusion-bonded lens with int. cooled Xformer had 80 M Muon test pulses and 51.8 M Muon pulses (04/06/18-03/12/19)

	Lens	Pulses	Description
	10mm-11	0.2 Million Pbar 192.8 Million Muon	Diffusion-bonded lens with internally cooled transformer. Operational - installed 3/12/19 As of May 19, 2021
	Viable Spares		
	32	1.0 Million Pbar	Old style lens with externally cooled transformer, was working when replaced with diffusion-bonded lens
	10mm-1	6.2 Million Pbar	Diffusion-bonded lens with externally cooled transformer, moved to different transformer as hot job after original transformer failed in service. Should be hanging from module in hot storage.
Built 2009	10mm-8	0.3 Million Pbar	Diffusion-bonded lens with externally cooled transformer. Lens was tested in multiple transformers.
	10mm-3	1.8 Million Pbar	Diffusion-bonded lens with internally cooled transformer, failed stripline was replaced as hot Job in 2008 after original failed in service. Should be in hot storage, has small VCR seal leak, missing Clamp ring bolts and a soft ground fault that may not clear.
	Possible Spares requiring repair		
	10mm-2	5.2 Million Pbar	Diffusion-bonded lens with externally cooled transformer, moved to a different transformer as hot Job after original transformer failed in service, also removed another time to repair loose tie rod.
	23	9.4 Million Pbar	Old style lens with externally cooled transformer, transformer repaired after it failed in service
	30	6.1 Million Pbar	Old style lens with externally cooled transformer, has sputtered target material on beryllium end cap, elogs suggest that the transformer leaked and it was run without transformer cooling water
	4	0.6 Million Pbar	Early old style lens with no transformer cooling

AP-0 Target Station – Pulses needed to finish g-2 Runs

- Predicted pulses needed to complete g-2 runs is about 195M
- Future lithium lens longevity presents greatest uncertainty and risk
  - History of highly variable lens service life
  - If present lens is representative of expected life, we're in good shape
  - Most difficult, expensive and lengthy component to build
- Targets and Pulsed Magnets should last through g-2 and beyond
  - Targets relatively easy to build
  - Have several sets of Pulsed Magnet cores remaining from Pbar operation

	Start-up	Run 1	Run 2	Run 3	Run 4
Protons on Target (E20)	0.09	0.54	0.39	0.63	0.78
Data collected (BNL)	0	1.94	2.21	3.22	4.37
Target Station pulses (Million)	20.7	57.8	40.3	68.4	86.4
Data collected per proton (BNL/E20 POT)	0	3.59	5.67	5.11	5.62
Data collected per pulse (BNL/Mpulses)	0	.0336	.0548	.0471	.0506

Data collection required (TDR) / still needed	21.0 BNL / 9.26 BNL
Protons needed for g-2 (TDR)	2.30 E20
Protons needed for g-2 (scaled from Runs 2 - 4)	4.13 E20
Pulses needed for g-2 (TDR)	150 Million
Pulses needed for g-2 (scaled from Runs 2 - 4)	469 Million
Remaining POT and pulses*	**1.70E20 / 195 Million**

*As of May 19, 2021, 11.74 BNL, 2.43E20 POT & 273.6 Million pulses

Table 6: Predicted protons and pulses needed for g-2

AP-0 Target Station operation beyond g-2

- Spare situation is tenuous, especially for lithium lenses
  - Hard to predict future lens longevity, history of infant mortality
- Projected spare count at the end of g-2 running will be low
  - Some used lithium lenses may be salvageable, but complicated due to rad levels
- Support for AP-0 operation was much higher during Pbar
  - Approximately 8 to 10 full time Engineers, Engineering Physicists and Technicians
  - Support for g-2 operation at least x4 less
  - Very few newly built components, no new lenses
- Increased support needed for reliable future running
  - Both an increase in personnel and M&S budget
  - Best to attempt repairing used lenses instead of restarting production
  - Recommend two Pulsed Magnet and one target spare to begin new program