Muon g-2 WBS 476.02.02 – Target Station

Muon g-2 DOE CD-2/3 Review
July 29-31, 2014

D. Still
Muon g-2 L3 Manager
Outline

- WBS L3 Organization
- WBS L3 Scope of this system
- Requirements
- Design
- Alternatives Considered and Value Engineering
- Risk Analysis
- ES&H
- Quality Control and Assurance
- Schedule Summary
- Cost Summary
- Summary
Target Station Scope

- A target station that is capable of a suitable pion production rate based on g-2 pulse repetition rate and the re-use of the AP0 target hall including
  - Target
  - Lithium lens and pulsed power supply
  - Momentum selection magnet and pulsed power supply
  - Beam dump for off-momentum secondaries
Target Station Requirements

- Accept 8-GeV protons on target and pulse the lens and momentum-selection magnet at 12 Hz average, with 100 Hz bursts

- Produce and capture 3.1 GeV/c secondary $\pi^+$
  - Approximately $3 \times 10^7 \pi^+$ with $|dp/p|<2\%$ per $10^{12}$ POT required for desired muon yield to storage ring
  - Integrate $4 \times 10^{20}$ protons on target to reach expected experimental performance.
Target Station Design

• The design for the target station is based on reusing and repurposing the antiproton production target station used for the collider program.

• 25+ years of experience and modifications /improvements

• Re-use will include:
  • Target tunnel Vault & Vault components
  • Radioactive remote handling area & 25 years of good practice procedures
  • Lens and PMAG pulse testing area
  • Closed loop radioactive water cooling systems
  • Pulsed power supplies for testing
  • Controls and timing
  • Radioactive storage vault

(AP0 Target Station Building)

(AP0 Target Station Building – Showing Target Vault area and pulse testing area)
Target System Design (cont)

- Re-use target, lithium lens, momentum-selection magnet
- Replace dump with copy of existing
- New pulsed power supplies

8.89 Gev/c primary beam

3.11 Gev/c secondary beam
Yield – Simulations & Measurements

G4Beamline Predicts
After 5 Turns in the DR & before the inflector
1.5 x 10^-7 Muons/POT or 1.5 x 10^5 per fill (1 x 10^{12} POT)
dp/p = ± 0.5%

MARS Predicts
80.0 x 10^-5 Pions/POT in p range 2.7 to 3.5 Gev
for default Target system. Note: All pions excepted even those
not captured by magic momentum.

(16% difference in predicted vs. measured)

• MARS was used to predict yield from the Target.
• MARS yield was placed into G4beamline to predict number of muons at the end of the M5 beamline.
• Predicted pion target yield is on par with number of muons required by the experiment (~6000). Note: There is a 6-10% transmission eff. through the Muon Ring inflector resulting in 9000-15000 muons.

(V. Tishchenko, “MARS & G4beamline Simulations for AP2 Beamline” GM2-doc-1885)

(V. Tishchenko, “MARS & G4beamline Simulations:” GM2-doc-1668)
MARS simulations were used to optimize the target system.

Optimizing parameters for target spot size, target to lens focal length and lens gradient it is estimated that up to a 30% gain in pion production could be achieved.
g-2 Target

- Target is solid Inconel 600 core with 5.715 cm radius. Typical chord length of 8.37 cm.
- Target center is bored out for pressurize air to pass for internal cooling.
- It has a Be outer cover to keep it from sputtering Inconel onto Lens.
- Incorporates target motion control for x-y-z positioning & rotational motion 1 turn/45 sec

- Plan is to use the presently Installed target
### Lithium Lens

<table>
<thead>
<tr>
<th>Lens operation</th>
<th>Pulse width (µsec)</th>
<th>Peak Current (kA)</th>
<th>Gradient (T/m)</th>
<th>Pulses per day</th>
<th>Rep Rate (Hz)</th>
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</thead>
<tbody>
<tr>
<td>Antiproton production</td>
<td>400</td>
<td>450</td>
<td>670</td>
<td>38880</td>
<td>.45</td>
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<tr>
<td>g-2 pion production</td>
<td>400</td>
<td>155</td>
<td>232</td>
<td>1036800</td>
<td>12</td>
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</table>

- The lens is a 1 cm radius x 15 cm long lithium cylinder that carries at large current to provide large focusing effect to divergent particles off target.

- The lens and transformer are water cooled.

- The lens will be re-used as is.

- Initially reusing the Lithium Lens was one of the biggest concerns. Pulsing at the g-2 rep rate means 1M/day where lifetimes of a lens in collider was on the order of 5-10M pulses.
Concerns with the Lens pulsing with the g-2 repetition rate.

R. Schultz conclude after a full ANSYS thermal & fatigue analysis that the Lens should be able to operate reliably at 12Hz.

ANSYS thermal model – Temperatures for 12Hz well below Li melting point

Lens ANSYS Fatigue analysis. Lens is under fatigue limit at 12Hz
• On Nov 20, 2012 lens running at 12Hz at 19.25kA (g-2 operating current)

• Since then, attempting to accumulate pulses. Want ~ 100 M pulses @ 1M/ day

• Pulses to date = 80M at 19.25kA (155kA secondary peak) at 12Hz for 3 months without a lens problem!
Pulsed Magnet (PMAG)

- PMAG will select 3.11 Gev/c positive particles $\pi^+$
- Bends particles $3^\circ$ into the M2 line
- Operates at 0.53T and is 1.07 m long.
- It is a single turn magnet that has incorporated rad hard hardware (ceramic insulators between magnet steel, single conductor bars, Torlon insulated bolts)
- PMAG is water cooled and has 3 spares.
- A collimator was installed upstream of PMAG to help shield it from radiation to prevent failures. The collimator will be re-used.
- PMAG magnet will be re-used.
### g-2 LENs POWER SUPPLY SPECIFICATION

**MAGNET:**
- Type: Transformer-Lens
- Location: AP0
- Inductance: 2.83 uH, from transformer primary.
- Resistance: 0.0145 ohms

**CURRENT PROGRAM**
- Pulsed – ½ sinewave:
  - Peak Nominal Current: 20 kamp
  - Peak Maximum Current: 25 kamp
  - Pulse base: 400 usec (same as existing lens system)
- Maximum rep rate: 100 Hz
- Maximum average rep rate:
  - nominal 12 Hz,
  - maximum 18 Hz.

**REGULATION:**
- Drift and Stability: +/- 0.1% of maximum

**AC input:** 480 VAC, 3phase
**Cooling:** Air and/or LCW
**Controls:** Accelerator timing system
**POWER SUPPLY LOCATION:** AP0
  - must fit within present PS footprint.

### g-2 PMAG POWER SUPPLY SPECIFICATION

**MAGNET:**
- Type: 1-turn Magnet
- Location: AP0
- Inductance: 2.539 uH
- Resistance: 0.003387 ohms

**CURRENT PROGRAM**
- Pulsed – ½ sinewave:
  - Peak Nominal Current: 15.3 kamp
  - Peak Maximum Current: 18 kamp
  - Pulse base: 355 usec (same as existing mag system)
- Maximum rep rate: 100 Hz
- Maximum average rep rate:
  - nominal 12 Hz,
  - maximum 18 Hz.

**REGULATION:**
- Drift and Stability: +/- 0.1% of maximum

**AC input:** 480 VAC, 3phase
**Cooling:** Air and/or LCW
**Controls:** Accelerator timing system
**POWER SUPPLY LOCATION:** AP0
  - must fit within present PS footprint.
Both the Lens & PMAG power supply will need to change to accomplish 12Hz rate.
Both power supplies will have the same design - Charge transfer method.
Both power supplies will modify the existing power supply.
Power supply controls will be upgraded.
All load cables and load connections will be reused.
The current power enclosures will need to be expanded.
Currently have a fully developed spice model, component designs and layout.
Current Beam Dump

- Target beam dump absorbs particles that are not momentum selected by PMAG.
- Dump consists of a water cooled graphite & Aluminum core.
- It is 16 cm in diameter and 2m in length.
- Dump capacity is 80kW.
- The current dump developed an irreparable water leak at the end of the collider run.
Beam Dump Plans

Table 1: A summary of partial peak radiation dose rates in mrem/hr at contact with various surfaces of the beam dump and beam dump plug are given in the Table. The peak dose rates are taken from the MARS histogram results for each irradiation/cooling period. The upper limit of peak dose rate is indicated in the sum column.

<table>
<thead>
<tr>
<th>Histogram number</th>
<th>Histogram name</th>
<th>2001</th>
<th>2004</th>
<th>2007</th>
<th>2011</th>
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<td>701</td>
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<td>230</td>
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<td>23,000</td>
<td>24</td>
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<td>180</td>
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<td>18,000</td>
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<td>200</td>
<td>1,200</td>
<td>20,000</td>
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<td>13</td>
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<td>705</td>
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<td>15,000</td>
<td>61,000</td>
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<td>downstream_core</td>
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<td>200</td>
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<td>4.6</td>
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<td>560</td>
<td>0.61</td>
<td>590</td>
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<tr>
<td>710</td>
<td>DS_lower_plug_face</td>
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<td>33</td>
<td>240</td>
<td>5,200</td>
<td>5.9</td>
<td>5,485</td>
</tr>
</tbody>
</table>

Fig 1.17: (left) Front face of the beam dump as taken in 2003. (Right) Looking down on the top of the dump plug below the surface of the shielding blocks.

- Plan is to build an upgraded copy of the current 80kW dump for replacement.

- MARS simulations have been completed to determine radioactive dose rates for planning replacement to mitigate radioactive contamination and worker exposure.

- Plan is to build a coffin and place the current beam dump in for transportation and storage onsite at TSB.
Target Station Risks

Registry contains 1 risk:
• Removal of the dump takes longer than estimated
  – Small impact on project

Registry contains 3 risks removed where a Threat is Avoided or the Opportunity Realized:
• Lens is not able to pulse at g-2 rep rate
  – ANSYS analysis has determined that the lens should be able to handle the fatigue at the g-2 rep rate
  – Pulse testing (80M pulses over 3 months) has confirmed that the lens can operate at 12Hz at full gradient
  – At this point the risk is low
• Default target found to not produce the desired pion yield
  – Run longer or build alternate target (~10% gain)
• Opportunity that yard transformer to support lens power supply is not needed ($100k)
  – Transformer no longer part of the design after Preliminary Design phase.
• Replacing the dump has never been performed. There will need to be careful planning with attention to radiological concerns. GM2-doc-1691 outline MARS estimates from dose rates on dump. Preliminary detailed beam dump removal procedure can be found in GM2-doc-2025.

• Detailed procedures exist for handling components in the radioactive target vault, and the activation will be lower after years of not running beam than it was during antiproton production.
Quality Control and Assurance

• The building of the pulsed power supplies and the beam dump have high engineering oversight in order to ensure quality to design.

• They utilize standard adherence to the Fermilab Engineering Manual.

• There is a good history of operating experience with similar of repurposed devices of purchasing quality components to ensure quality and predetermined performance. There is QA summary document of practices, policy and procedures in GM2-doc-2021.

• There is a month of power supply conditioning and testing and beam dump testing at the end of the implementation phase in order to assure working order and g-2 performance.
## Schedule

<table>
<thead>
<tr>
<th></th>
<th>FY14</th>
<th>FY15</th>
<th>FY16</th>
<th>FY17</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target Station:</strong></td>
<td>Prototype ctrl</td>
<td>Lens, PMAG power supply</td>
<td>Dump</td>
<td>Target station ready for operations</td>
</tr>
<tr>
<td></td>
<td>Final drawings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Beamlines:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Final Focus</td>
<td>Final drawings</td>
<td>Magnet power supplies</td>
<td></td>
<td></td>
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<tr>
<td>- M2/M3</td>
<td>Final design</td>
<td>Magnet supports, vacuum materials</td>
<td>AP2/AP3 disassembly</td>
<td>Installation</td>
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<tr>
<td>- D30 Straight</td>
<td>Cable trays, relocate bus</td>
<td>LCW</td>
<td>Installation</td>
<td></td>
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<tr>
<td>- DR extraction</td>
<td>Decommissioning</td>
<td>Magnets from TD</td>
<td>Installation</td>
<td></td>
</tr>
<tr>
<td>- M4/M5</td>
<td>Final design</td>
<td>Beamline enclosure beneficial occupancy</td>
<td>Magnet supports, vacuum materials</td>
<td>Installation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LCW</td>
<td>Magnets from TD</td>
<td></td>
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<tr>
<td><strong>Controls and Instrumentation:</strong></td>
<td>Final design</td>
<td>Controls MC-1 ODH, interlocks</td>
<td>SEMs</td>
<td>DR interlocks</td>
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<td></td>
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<td>Final design</td>
<td>Cerenkov</td>
<td>Installation</td>
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<td></td>
<td></td>
<td>Final design</td>
<td>PWCs</td>
<td>BLMs</td>
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<tr>
<td></td>
<td></td>
<td>Final design</td>
<td>Ion chambers</td>
<td></td>
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</table>

- Installation
- Reinstall M3 side
- Reinstall M4 side
- DR interlocks
- Controls and Instrumentation ready for operations
# Milestones

## 476-BaselineDOE-1.02.02 Target Station

<table>
<thead>
<tr>
<th>Name</th>
<th>Start</th>
<th>Finish</th>
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<tbody>
<tr>
<td>L4 Dump Operational</td>
<td>25-Mar-16</td>
<td></td>
</tr>
<tr>
<td>L4 - Lens PS Operational</td>
<td>30-Mar-16</td>
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<tr>
<td>L4 - PMAG PS Operational</td>
<td>07-Jun-16</td>
<td></td>
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<tr>
<td>L5 - Lens testing complete</td>
<td>19-Jun-14</td>
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<tr>
<td>L5 - Pulsed-magnet testing complete</td>
<td>02-Mar-15</td>
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- L4 Dump Operational
- L4 - Lens PS Operational
- L4 - PMAG PS Operational
- L5 - Lens testing complete
- L5 - Pulsed-magnet testing complete
### Cost Distribution

<table>
<thead>
<tr>
<th>DOE</th>
<th>Fermilab Labor</th>
<th>M&amp;S</th>
<th>Non-FNAL Labor</th>
<th>Total</th>
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<td>Base ($K)</td>
<td>Base ($K)</td>
<td>Base ($K)</td>
<td>Base ($K)</td>
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<td>2.2 Target Station</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>2.2.1 Conceptual Design</td>
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<td>312</td>
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<td>21</td>
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<td>2.2.3 Focus</td>
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<td>164</td>
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<td>484</td>
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<td>2.2.4 Momentum Selection</td>
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<td>150</td>
<td>0</td>
<td>514</td>
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<td>2.2.5 Dump</td>
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<td>142</td>
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<td><strong>Grand Total</strong></td>
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<td><strong>475</strong></td>
<td><strong>0</strong></td>
<td><strong>1,585</strong></td>
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</table>
Cost Distribution

2.2.1 Conceptual Design
$312 K
19.7%

2.2.3 Focus
$484 K
30.5%

2.2.5 Dump
$254 K
16.0%

2.2.4 Momentum Selection
$514 K
32.4%

2.2.2 Target
$21 K
1.4%

Cost Driver: Assemble new dump

Cost Driver: Assemble and test power supply

Cost Driver: Assemble and test power supply
Resource Type

- Fermilab Labor: $1,110 K (70%)
- M&S: $475 K (30%)
Costed FTEs by FY

D. Still     Muon g-2 DOE CD-2/3 Review    July 29-31, 2014
Labor Resources by Type

- **Elec Eng**: 1.61 FTE (33.9%)
- **Elec Tech**: 1.31 FTE (27.6%)
- **Mech Tech**: 0.88 FTE (18.6%)
- **Other Tech**: 0.43 FTE (9.0%)
- **Mech Eng**: 0.22 FTE (4.7%)
- **Costed Sci**: 0.20 FTE (4.2%)
- **Design**: 0.10 FTE (2.0%)
Cost Profile by FY

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<tr>
<th>Fiscal Year</th>
<th>M&amp;S</th>
<th>Non-FNAL Labor</th>
<th>Fermilab Labor</th>
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<td>$242 K</td>
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<td>FY17</td>
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## Estimate Uncertainty

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<th>Performed</th>
<th>ETC (Scheduled - Performed)</th>
<th>Est. Uncertainty</th>
<th>% EU on ETC</th>
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<tr>
<td>2.2 Target Station</td>
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<tr>
<td>2.2.1 Conceptual Design</td>
<td>311,660</td>
<td>(0)</td>
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<td>0%</td>
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<td>2.2.2 Target</td>
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<td><strong>341,566</strong></td>
<td><strong>30%</strong></td>
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EVMS Since January – Target Station

This is L3 EVMS for the Target Station. Practicing since January 2014

- Using practice baseline from Dec 2013
- Target station work is under budget and slightly behind schedule as of May
Summary

• This system accepts 8-GeV protons on target at the g-2 beam repetition rate and produces 3.1 GeV $\pi^+$

• The $\pi^+$ yield is expected to satisfy requirements for the number of $\mu^+$ transported to the muon storage ring.

• The cost is $1.6M

• Cost drivers are the construction of 2 pulsed power supplies and the construction of a 80kW beam dump.