Report of the October 7–8, 2014 Review of Beamline Optics for the Muon g-2 Project

December 1, 2014

A review of the Muon g-2 beamline optics was performed on October 7–8, 2014 by a team consisting of Peter H. Garbincius (Fermilab), Alexander Valishev (Fermilab), Giulio Stancari (Fermilab), and Robert Webber (Fermilab, retired, and MSU).

This review considered the beamlines from the final focus of the primary 8-GeV proton beam on the target at AP0, through the Delivery Ring, up to the interface between the 3.1-GeV muon beamlines and the inflector of the Muon Storage Ring.

The review panel commends and thanks the Muon g-2 Collaboration for the clear presentations and responses to questions, both at the review and in follow-up studies and documentation.

The committee charge, agenda of the review, and written responses to the panel questions are listed in the Appendix and in the References. In this report, we address each charge question individually, and then conclude with overall considerations.

Responses to the charge

- ***1. Does the g-2 beamline design meet the following requirements and specifications?***
  - ***a) proton spot size on target of 0.15 mm RMS with 8-GeV beam***

Short Answer

Yes.

Findings

An optics design was presented that achieves the desired proton spot size on target.

The Muon Department has several years of experience with 8-GeV beam transported to the target for antiproton production.

Comments

In attaining 0.15 mm rms spot size on the target, the primary proton beam has a large size in the final-focus triplet. However, we do not think the spot size on target is a critical parameter. For instance, it was shown that in relaxing the requirement from 0.15 mm to 0.30 mm rms one loses only about 7% in muon yield (document GM2-doc-1789). It may be desirable to increase the spot size on the target and to consequently reduce the maximum amplitude function in the final-focus triplet.

Recommendations

None.

- ***1. Does the g-2 beamline design meet the following requirements and specifications?***
  - ***b) transverse acceptance of 40 π mm mrad and a momentum acceptance of $\pm$2% for 3.1-GeV secondary beam***
  - ***c) beta functions in the pion decay region (after lens-to-beamline matching quads Q801–Q804 to end of M3 line) limited to less than 25 m***
  - ***d) ability to transport 8-GeV primary beam in the g-2 beamlines which are shared with Mu2e***
  - ***e) expected yield at the g-2 storage ring entrance of*** 7×10^5 ***muons per*** 10^{12} ***protons on target (POT) with average polarization >90%.***

As they are closely related, the reviewers chose to address items b), c), d), and e) together.

Short Answer

Yes.

Findings

The current design exceeds 40 π mm mrad except in a few locations. Beam profiles based on lattice functions were shown at each aperture indicating that 40 π mm mrad acceptance is attainable except in a limited number of positions where it was slightly less.

It was demonstrated that the secondary beamline can accept a relative momentum spread of $\pm$2%.

Amplitude lattice functions in the pion decay region are kept below 25 m.

The g-2 beamlines within the scope of this review which are shared with Mu2e can transport 8-GeV primary beams (see also the final overall comments at the end of the report).

The effect of the lithium lens was included in the design by providing the particle fluxes at its downstream end, calculated with the MARS code, as input for the beamline simulations.

A G4beamline simulation was presented which delivered 8×10^5 muons with 1.2% rms momentum spread per 10^{12} POT with 95% polarization to the Muon Storage Ring for a nominal acceptance of 40 π mm mrad. This was based on accepting only very forward muons within 2% of the pion momentum.

Comments

Most beamline designs were based upon the MAD and G4beamline codes. Comparisons and a closer integration between the two approaches may be desirable to further improve the robustness of the design.

For instance, MAD could be used to study the effect of field imperfections and aligment errors on lattice functions and acceptances, whose impact on the muon yield can then be estimated with G4beamline.

The review panel requested a study of the effect of magnetic field errors on muon yield for the Delivery Ring and for the M4/M5 beamline. This could be done with a beta-wave study in MAD to find the maximum expected excursions and their effect on the flux. At this stage of the design, the study was dismissed by the presenters.

From past experience, one may expect amplitude excursions of about 20%, so an alternative study is to see whether reducing the most critical apertures by this amount would significantly reduce the muon yield.

At the request of the review panel, G4beamline simulations were run with a range of artificially reduced circular apertures placed at three places along the beamline in order to get a feeling for how the muon yield scales as a function of beamline acceptance. This study was presented at positions before the first collection quadrupole downstream of the production target, near the center of the AP30 straight section in the Delivery Ring, and at the interface to the Muon Storage Ring at the downstream end of the M5 beamline. These special cases are representative of where one would expect problems to arise.

In summary, these studies showed that realistic beamline imperfections would cost about 20% to 30% in transmission efficiency. The reviewers feel that this is acceptable, for the following reasons. First, these variations are within the expected uncertainties on experiment run time. Secondly, recent kicker simulations indicate that injection into the ring will be significantly more efficient than what was assumed in the Technical Design Report. Moreover, a previous baseline design specification was 7×10^{-7} muons/POT within a momentum spread of $\pm 2\%$ and within 50 π mm mrad at the downstream end of the beamline, at the entry to the Muon Storage Ring iron yoke. These specifications were to insure an adequate number of muons are accepted into the storage ring. These specifications have been met by the current beamline design (with zero dispersion) at this interface point. Providing this number of muons within 40 π mm mrad or less acceptance, and a momentum spread of less than $\pm 2\%$, which implies a higher density in phase space, can only help to improve the injection efficiency.

Muon yield simulations were not yet done with realistic apertures at all locations. G4beamline has only rectangular and circular apertures, not the 'star' vacuum chambers which follow the quadrupole magnet pole piece shape. The 'star' chambers in the SQ series of quadrupole magnets was modeled by a square aperture rotated by 45° from the horizontal-vertical orientation. According to Figure 8.12 of the Technical Design Report, the side of this square aperture was modeled as 84 mm for the M2/M3 beamline, but as 108 mm for the Delivery Ring. This aperture is overestimated relative to the steel pole pieces of the SQ quadrupole magnets.

During Antiproton Source operations, the measured aperture of the Debuncher Ring with the stochastic cooling tanks installed was in the range of 30–32 π mm mrad. It is expected that the Delivery Ring magnets alone (the Debuncher Ring without the stochastic cooling tanks) will have an aperture of about 50 π mm mrad, with the overall acceptance limited to slightly more than 40 π mm mrad by the kicker magnets.

The review panel asked why it is necessary for the beamline to transmit a momentum spread of $\pm 2\%$ when the Muon Storage Ring can only accept $\pm 0.5\%$: Could an acceptance of more than 40 π mm mrad be attained within the smaller momentum bite, which could result in an increased number of stored muons? It was responded that the Delivery Ring already has a momentum acceptance of $\pm 2\%$, so it is not difficult to preserve that momentum bite down to the hand-off point to the Muon Storage Ring.

It was also mentioned that the G4beamline program can simulate component offsets, random field errors, and responses of instrumentation, which might be a useful tool for design and commissioning studies.

Recommendations

The quadrupole magnet apertures in the Delivery Ring should be modeled using a more conservative rotated 84 mm square, rather than the 108 mm apertures, to ascertain the yield of muons.

We suggest that both lattice and tracking simulations be expanded to include a more complete set of apertures, component offsets, and magnet field errors, in order to check the robustness of the design and flux expectations against these possible problems.

- ***2. Do the final beamlines provide the required flexibility to optimize the injection into the storage ring through the existing E821 inflector, as well as the possibility of injecting through an upgraded inflector with a 36-mm horizontal aperture?***

Short Answer

Yes, the beamline design provides sufficient flexibility to optimize injection into the storage ring through the existing inflector and that flexibility is sufficiently quantified to steer design parameters of an upgraded, but as yet unspecified, inflector with a 36-mm aperture.

Findings

With the current E821 inflector, the requirements on the lattice functions and their tolerances were clearly stated. At a beamline design meeting, these input requirements for the storage ring were shown.

The beamline as designed for zero dispersion into the E831 deflector works. In considering a possible, future larger horizontal aperture inflector, the inflector designers requested a final dispersion of 2 m at the exit of the inflector to optimize the capture of muons into the storage ring. This translates into a required dispersion of 5 m at the hand-off, interface point between beamline and storage ring, located 0.3 m upstream of the storage ring steel. Such a large dispersion leads to concerns regarding large beam size vs. aperture in the focusing quadrupoles just upstream of the Muon Storage Ring. At this time, a solution to transport a $\pm 1\%$ momentum band with this dispersion through the final-focus quads has not been found. However, the reviewers do not consider this a major issue, because it was shown that muon capture efficiency is only negligibly reduced by changing the dispersion from 2 m to zero.

Comments

A new 36-mm horizontal aperture inflector would increase the number of stored muons by more than a factor 2, therefore improving the statistical significance of the Muon g-2 experiment for a given running time. A detailed cost-benefit analysis would help in making decisions on this expensive upgrade.

Recommendations

From the designs and simulations presented at the review, it appears that no significant gain in muon capture efficiency would be attained by designing for dispersions of 2 m at the output of the inflector, which corresponds to a dispersion of about 5 m at the hand-off point. The recommendation is to design for zero dispersion and avoid the complications and cost of larger final-focus quadrupole magnets.

- ***3. Are the types and locations of instrumentation sufficient to commission and monitor beam from the target to the g-2 storage ring?***

Short Answer

Yes, but there is still room for optimization of the diagnostic locations.

Findings

One of the challenges of the Muon g-2 experiment beamlines is to accurately monitor low average beam currents with high instantaneous particle fluxes. The M2/M3 beamlines and the Delivery Ring will normally transport a mixture of protons, pions, and muons. In M4/M5, one will have a pure muon beam with less than 10^6 particles per bunch in a 120-ns pulse. It is possible to transport secondary protons through the whole beamline for commissioning purposes.

The Muon Department is planning to refurbish and reuse equipment from the Antiproton Source. They performed beam tests showing that some of the instrumentation (secondary-emission profile monitors and ion-chamber intensity monitors) will work with approximately the expected pulse lengths and intensities. The proportional wire chambers are sensitive to low particle counts, but so far they could only be tested with low instantaneous fluxes.

Simulated beam profiles were shown at a few places along the beamline, with resolutions comparable to the available instrumentation. Upstream of the Delivery Ring, the proton and pion beam intensities will be much larger than those of muons. However, the simulations showed that the muon profile and momentum distributions are sufficiently close to those of protons and pions. Therefore, tuning on total intensities should allow one to achieve high muon transport efficiencies. The ultimate criterion for beamline optimization will be maximization of the number of muons in the Muon Storage Ring.

Comments

If the proportional wire chambers exhibit unacceptable saturation effects at the required instantaneous fluxes, a backup solution could be profile monitors based on scintillating fibers. The performance of either ionization or scintillation-based profile monitors for short beam pulses might be studied using short batch single-turn extracted beam from the Fermilab Booster. Other options include the Fermilab ASTA facility or the Beam Test Facility at Frascati.

The team has not yet identified locations of instruments to provide specific beam parameter measurements. It may be possible to optimize the locations of the instrumentation for beam commissioning and tuning.

Recommendations

None.

- ***4. Is there a credible plan for commissioning the beamlines?***

Short Answer

Yes.

Findings

A comprehensive, detailed, and well thought-out plan for commissioning was presented. The plan takes advantage of using the well understood 8-GeV primary beam to commission up to the M4/M5 split. Only after magnet polarities, beamline optics, and instrumentation are verified with the 8-GeV primary beam are the secondary beamline magnets scaled down to transport a 3.1-GeV beam.

Comments

The Muon Department members have years of experience operating the Antiproton Source beamlines and rings. The commissioning plan is based on that experience for both the beamlines and the Delivery Ring.

As noted in the diagnostics section, similar profiles are expected for the 3.1-GeV muons and the secondary protons and pions. This bodes well for using the higher intensity combined beams of protons, pions, and muons for preliminary tuning and commissioning.

The committee suggests that it may be beneficial to simulate commissioning procedures, to develop automated tuning programs, and to upgrade hardware in order to optimize the commissioning phase, therefore extending the experiment's available running time. This work may be done with the help of a post-doc supported by Fermilab or by one of the other collaborating institutions.

Recommendations

None.

Overall Considerations

Findings

After reviewing the beamline optics designs for the Muon g-2 Project, the committee finds that the designs presented substantially meet the stated requirements and specifications.

Comments

Although it is outside the scope of the present review, we note that the g-2 primary proton beam configuration for the M3 target bypass is not well matched for the high-intensity running of the Mu2e experiment, but it will function adequately through Mu2e commissioning and tune-up. Implementing a solution for the high-intensity data running of Mu2e could be deferred until required, but it might be more optimal in the long run to install an integrated beamline that meets both g-2 and Mu2e needs from the start. As part of the Muon Campus AIP projects, one may consider implementing the full intensity target bypass beamline for Mu2e at the time of the g-2 beamline installation.

Recommendations

The committee recommends that

- studies on the optimization of acceptances and muon fluxes be continued and documented;
- construction of the beamline and necessary components commence as soon as possible;
- the project pursue all available avenues to obtain advanced funding, particularly to accelerate construction of long-lead items and to take fullest advantage of available accelerator complex shutdowns.

A Charge to the review committee

Review of Beamline Optics for the Muon g-2 Project

October 7, 2014

The Committee is to conduct a review of the beamline optics for the Muon g-2 Project to determine construction readiness. This review is a project-commissioned review in response to reviewer recommendation from the DOE CD-2/3 Review held in July 2014. The intent of the review is to confirm with independent experts that the current design will meet the experimental requirements so construction in FY15 can commence.

The review committee is asked to address the following questions:

- 1. Does the g-2 beamline design meet the following requirements and specifications:
  - a. proton spot size on target of 0.15 mm RMS with 8 GeV beam
  - b. transverse acceptance of 40 π mm mrad and a momentum acceptance of $\pm 2\%$ for 3.1-GeV secondary beam
  - c. beta functions in the pion decay region (after lens-to-beamline matching quads Q801–Q804 to end of M3 line) limited to less than 25 m
  - d. ability to transport 8 GeV primary beam in the g-2 beamlines which are shared with Mu2e
  - e. expected yield at the g-2 storage ring entrance of 10^5 muons per 10^{12} protons on target (POT)[1] with average polarization $>90\%$?
- 2. Do the final beamlines provide the required flexibility to optimize the injection into the storage ring through the existing E821 inflector, as well as the possibility of injecting through an upgraded inflector with a 36-mm horizontal aperture?
- 3. Are the types and locations of instrumentation sufficient to commission and monitor beam from the target to the g-2 storage ring?
- 4. Is there a credible plan for commissioning the beamlines?

The committee should present findings, comments, recommendations, and answers to the above questions in a draft written report to the Muon g-2 Project Manager within one week after the review and a final report to be submitted within two weeks.

[1] At the review, the charge was corrected to read '7×10^5 muons per 10^{12} protons on target.'

B Agenda of the review

Time	Speaker	Title
		Oct. 7, 2014
9:00	Chris Polly	Introduction and requirements
9:15	Dave Rubin	Injection into the Muon Ring
9:55	Carol Johnstone	M4/M5 lattice design
10:35		break
10:50	Carol Johnstone	M5 external beamline preliminary error analysis
11:10	Jim Morgan	Delivery ring
11:50		lunch
13:00	John Johnstone	M1 final focus
13:20	John Johnstone	M2/M3 lattice design
14:00	John Johnstone	M2/M3 error analysis
14:20		break
14:35	Hisham K. Sayed	Beam simulations
15:05	Jim Morgan	Beamline apertures
		Oct. 8, 2014
9:00	Brian Drendel	Instrumentation
10:00	Jim Morgan	Beamline commissioning plan

References

[Note: Access to documents in the g-2 database is password protected.]

[1] E989 Collaboration, Muon g-2 Technical Design Report, GM2-doc-2055 (July 2014). In particular, Chapter 7: Accelerator and Muon Delivery, and Chapter 8: Beam Rate Simulations.

[2] Agenda of the g-2 Beam Review of Oct. 7–8, 2014, with links to presentations and backup materials: <http://gm2-docdb.fnal.gov:8080/cgi-bin/DisplayMeeting?conferenceid=551>.

[3] J. Morgan, D. Rubin, and H. K. Sayed, Beamline review simulations, GM2-doc-2268 (November 2014).

[4] V. Tishchenko et al., Update on Li-lens optimization, GM2-doc-1789 (April 2014).