# Chapter 22.
# Storage Ring Commissioning with Beam

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## 22.1. Introduction

The muon $(g-2)$ storage ring is a unique storage ring which differs from conventional storage rings in several important aspects. There is no RF power, or cooling, so it is essentially a static device. The magnetic field value is fixed by the equilibrium radius and the magic momentum to be $\sim 1.45\ T$. The $n$ value of 0.135 for the ring was chosen both to avoid resonances, and because it could be achieved with reasonable high voltages ($\pm 30\ kV$) and modest coverage of the storage region ($\sim$ 33%) with electrostatic quadrupoles. The quadrupole and vacuum system can be brought into operation before the beam is available, as can the superconducting inflector.

Furthermore, because of the finite muon lifetime (64.4 $\mu s$ at the magic value of $\gamma$), and a cyclotron period of 149 $ns$, one has a maximum of approximately 4000 turns following injection. This means that the usual equilibrium of stable orbits is never reached and there will be particle losses during the entire storage time. These muon losses will be monitored during the storage time, and they have been studied with the tracking code.

The only parameters which can be "tuned" to optimize injection (besides the steering of the incident beam) are the inflector angle, and, in the case of pion injection, the incident beam momentum.

The only other parameter which can be changed is the high voltage on the electrostatic quadrupoles, as discussed in Chapter 5. Initially the quads will be powered asymmetrically, so that the beam is displaced sideways and vertically. After 100 turns, the lower voltage plates are brought up to full voltage over 50 turns, so that they are powered symmetrically, with a quadrupole field centered on the storage aperture. The scraping voltage can be varied, as can the final voltage which will change the average field index of the weak focussing ring.

Muon injection introduces an additional complication, since the fast kicker must be fired such that the full kick is there when the bunch enters, and then gone 149ns later. The beam momentum will be set at the "magic momentum", but there will need to be some optimization of the full aperture kicker, when it is brought on-line.

## 22.2. The Primary Proton Beam and Secondary $\pi/\mu$ Beam

The primary proton beam will be brought to a new target station as described in Chapter 6. The usual beam diagnostics for such a beam will be in place, so that both targeting and losses can be monitored by the AGS Main Control. Responsibility for the primary proton beam will reside with the AGS operators, and in the initial tuning the experimenters, especially H. Brown, will be involved. We are fortunate to have several collaboration members who have extensive experience in both proton and secondary beam tuning at the AGS. Bunce, Miller, Morse and Roberts have all had such responsibility, and H. Brown has been responsible for many of the AGS beams over the years.

### 22.2.1. The Fast Kicker to the V-line

The AGS contains twelve proton bunches which are equally spaced with a peak to peak separation of 217 $ns$, although it is likely that this will be changed to eight bunches. When fully operational, the fast kicker will be able to extract from one to 12 (or 8) bunches per AGS cycle, with a separation of 40 $ms$ between extractions. With full Booster operation each bunch will contain up to $5 \times 10^{12}$ protons and the bunch width is less than 10 $ns$ full width one tenth maximum.

The fast proton kicker to the $U/V$ lines is currently scheduled to be installed in the AGS in the shutdown after the 1994 running. It will have to be commissioned at the turn-on in January 1995. Since we will not run until January 1996, this system should be installed and fully operational before we need it.

### 22.2.2. V1 Line and the $\pi/\mu$ Beam

The beamline and beam monitoring is fully described in Chapter 6.

The V1 line setup is straightforward, since except for the fast extraction feature, it is similar to existing beam lines. C. Pearson has suggested a beam- stop just before the last dipole in the secondary line to the $(g-2)$ ring, which would permit commissioning and tune-up of the primary proton line and the muon/pion line while work is still going on in the $(g-2)$ hall.

The commissioning of the beam line will take several weeks for the necessary fault studies, tuning, etc. Pion injection will be used during the first running period and the rough procedure will be:

a. Set up all magnets to dead reckoned values, say for p=$1.005p_\mu$.
b. Adjust D3,4 and Q3-6 to get an acromatic (dispersion free) beam centered in Q10,Q12.

c. Adjust steering magnets progressively down V1 Line to align beam on SWIC's and QUAD magnetic centers (i.e., no quad steering).
d. Adjust D5,6 and Q21-25 for an achromatic beam into Q26-29.
e. Adjust steering magnets to align beam on SWIC's and QUAD magnetic centers before entry into ring backleg.
f. Adjust final steering and inflector field to get beam to enter ring and make a turn.

## 22.3. The Storage Ring

The storage ring will be operated at first with the quadrupole high voltage turned off. This makes it an extremely high quality spectrometer magnet, coupled to a beamline. The only adjustments which can be made are the beam momentum, and the inflector angle. The scintillating fiber monitors will provide information on the beam at $180^0$ and $270^0$.

### 22.3.1. Using the Storage Ring as Spectrometer

One can use the $(g-2)$ storage ring dipole magnetic field as an analyzing magnet/spectrometer system when the electrostatic quadrupoles are turned off. This will permit us to determine a number of properties of the beam, which will help us tune up the ring.

With the electrostatic quadrupoles turned off, $\beta_x = X_p = R_0 = 7.112m$, where $\beta_x$ is the betatron function and $X_p$ is the dispersion function. One can observe the centroid position of the beam using a scintillating fiber profile monitor placed at 180 degrees around the ring from the inflector exit. The transform to there is the negative Unit Matrix. For a single particle in matrix notation we write

$$\begin{pmatrix} X_f - R_0\frac{dp}{p} \\ X_f' \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} X_i - R_0\frac{dp}{p} \\ X_i' \end{pmatrix}$$

One will observe an average central value (denoted by $<>$) given by

$$< X_f > -R_0 < \frac{dp}{p} >= -\left(< X_i > -R_0 < \frac{dp}{p} >\right)$$

independent of $X_i'$, and

$$< \frac{dp}{p} >= 0.5\left(\frac{< X_f > + < X_i >}{R_0}\right)$$

where $< X_i >$ is the mean centroid at the inflector exit and $< X_f >$ is the mean centroid at $180^0$. Some fiddling needs to be done to feel assured that beam is centered in the inflector exit aperture; then, $< X_i >= 76mm$. (The ring field should be adjusted to put the $< X_f >$ near the center for good measurement.) Then,

$$< P >= P_0 \left(1+ < \frac{dp}{p} >\right) \qquad P_0 = eB_0R_0$$

In this way we can calibrate the momentum defining dipoles D1,D2 and then select a desired $< P >$ with some confidence. If the $X$ centroids above are determined to about 5 mm, then the accuracy of the measurement will be about $\sqrt{2} \times 5/7112 = .0010$. ($R_0$ will be known to better than 1 mm and $B_0$ known very well.)

### 22.3.2. Measurement of Mean Angle of the Beam Exiting the Inflector

If we also have a scintillating fiber detector placed well away from the $180^o$ point, we can measure the mean angle of the beam exiting the inflector. Suppose we have a monitor at $270^o$. The transformation (with quads off) is:

$$\begin{pmatrix} X_f - R_0\frac{dp}{p} \\ X_f' \end{pmatrix} = \begin{pmatrix} 0 & -R_0 \\ 1/R_0 & 0 \end{pmatrix} \begin{pmatrix} X_i - R_0\frac{dp}{p} \\ X_i' \end{pmatrix}$$

so

$$< X_f > -R_0 < \frac{dp}{p} >= -R_0 < X_i' >$$

and

$$< X_i' >= -\frac{< X_f >}{R_0} + < \frac{dp}{p} >$$

Thus, having first measured $< \frac{dp}{p} >$, we can measure the mean angle at the inflector exit and set it as desired. The accuracy of measurement will be about 1 *mrad*.

In above procedure, the scattering and interactions caused by the passage of particles through the quadrupole electrodes may cause an offset in the observed beam centroid $< X_f >$, so we'll have to be cautious about the results.

### 22.3.3. Scraping and Loss Studies

Once the beam is injected into the storage ring, we will turn on the quadrupoles to their setpoint voltages and study the unscraped beam. Since the fiber monitors are so thin, they are useful for measuring the beam during several turns, and will be a useful diagnostic tool during the turn on.

The CERN ring [1] had muon losses of 1.0% per lifetime without scraping the beam. Our calculations show that we can do considerably better than CERN, as discussed in Chapter 6.

We will measure the lost muons, as discussed in Chapter 16, so that on-line we will be able to tell the effectiveness of the scraping.

### 22.3.4. Detector and Electronics Set-up

Once the beam is set up, the performance of the electron calorimeters can be optimized. With pion injection the response of the detectors/electronics to the pion flash must be studied. This will be essential, since the muon-decay-electron detectors will provide an essential monitor of the performance of the injection into the storage ring, and will play a key role in the setting-up of muon injection in the following year.

The decay-electron traceback system will provide information on the distribution of muons in the storage ring at all times. Whereas the information from this system may not be as useful as the destructive monitors during the initial set up, they will be an important tool in the continuous monitoring of the performance of the storage ring.

The pickup electrodes will be installed in the ring as well. This device will provide information on the muon distribution in a non-destructive way.

Once the system is optimized with pion injection, the CERN experiment can be repeated, and systematic studies can be performed. We will then have a number of months to correct any problems and to prepare for muon injection into the storage ring.

A full WBS section is under preparation on the commissioning of the experiment and will be included in the final version of this edition.

## 22.4. References

1. J. Bailey et al. Nucl. Phys. B150, 1 (1979).