Chapter 6.
Pion/Muon Beam and Monitoring

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6.1. Introduction

In the basic injection scheme used in the CERN experiment, [1] a pion beam was formed and directed parallel to, but just outside of, the muon storage region by means of a pulsed inflector. As the pions executed their first oscillations about their respective closed orbits in the ring, they crossed the storage region and a fraction of them decayed and emitted muons within the transverse and momentum acceptances of the ring. The remaining pions were lost on the focussing electrodes or on the inflector structure after one turn, and produced the "flash" following injection which presented such a challenge to the muon decay electron detectors.

We will use this same method for the initial phases of the experiment, employing a DC superconducting inflector as described in Chapter 10.

An alternative procedure, which we also plan to use, is to allow the pions to decay into muons in a long transport channel which will retain a fraction of the muons. After separating the residual pions by means of a tight momentum selection, the muons will be injected through the inflector into the storage ring and be kicked onto a stable orbit by a fast kicker. This technique of direct muon injection has two benefits:

i) the number of stored muons per fill is increased by an order of magnitude over pion injection

ii) the flash following injection, which is caused by pions which do not produce stored muons, is greatly reduced.

The placement of the storage ring in the former 80″ Bubble Chamber building makes it possible to construct a secondary beam channel which can be utilized for either of these injection methods.

6.2. Proton Extraction and Targeting

During each AGS pulse, it is proposed that 1 to 8 (or 12 depending on the mode of AGS operation) proton bunches be extracted by firing a one-bunch kicker magnet at intervals of about 40 msec. Within the 40 msec intervals, the precession of the muons produced by one proton bunch is measured by the electron counters for a time interval of 10 muon lifetimes, or about 640 μs. In principle, the interval between injections could be much less than 40 ms, but then recharging the kicker's energy storage capacitors becomes more difficult. Hence, a new multi-pulsing kicker power supply has been designed by the AGS Department.

The H10 straight section in the AGS ring has been chosen as the point of ejection of the proton bunches. This is where extraction to the existing Fast External Beam to the neutrino experiment target is accomplished, and where transfer of Heavy Ions to the RHIC will begin. Thus, duplication of much extraction equipment will be avoided. No changes need be made which will compromise normal operation of these other transport lines.

Fig. 6.2.1 illustrates the region of the AGS complex where, after exiting from the AGS at H10, the primary proton beam is carried around the 4 degree bend in the U line to the dipoles VD3,VD4 where it is deflected about 3.0 degrees westward. This allows it to exit into the new targeting area which is under construction. The beam is carried to and then focussed on the "V" target by VQ9- VQ12. This target station will have standard instrumentation for proton beam monitoring, including radiation monitors to monitor beam losses at crucial points in the proton transport line.

The target proper must be designed to withstand high peak and high average beam heating for intensities up to 6×10^{13} protons per AGS pulse. It is not critical that the pion source be sharply defined vertically. Hence, a low density heat sink, such as aluminum or water, could be in direct contact (vertically) with a heavy target such as platinum or copper, letting the incident beam size largely determine the vertical source size. The horizontal target width should be well defined for good momentum resolution.

The list of beamline elements needed for the "V" proton beamline is given in Table 6.2.1.

Figure 6.2.1: Proton Extraction at H10 and Transport to the "V" Target

Table 6.2.1: Equipment required for proton transport from the U-line to the "V" target. The key to the abbreviations is: Q = Quadrupole, D = Dipole, P = Pitching Dipole, hs = Horizontal steering dipole, vs = Vertical steering dipole, SWIC = Segmented Wire Ionization Chamber for beam profile measurement, IONCH = Ionization Chamber for beam pion/muon intensity measurement, SEC = Secondary Emission Chamber for proton intensity measurement.

Magnet	Type	B(kG)/G(kG/in)	$L_{eff}(in)$	I (kA)	R ($m\omega$)	V (V)	P (kW)
VD3	12C100	9.6400	102.00	1.25	21.0	26.	33.
VD4	12C100	9.6400	102.00	1.25	21.0	26.	33.
vs1	4x6d24	1.2000	28.00	-	-	-	-
VQ9	4Q26.5	2.8000	28.5	.310	93.0	28.	9.
hs1	4x6d24	1.2000	28.00	-	-	-	-
VQ10	5Q36	3.1390	37.50	0.7440	97.5	72.5	54.
VQ11	5Q36	3.1390	37.50	0.7440	97.5	72.5	54.
VQ12	N3Q36	7.9130	37.50	1.7820	12.0	21.4	38.
vs2	4x6d24	1.2000	28.00	-	-	-	-
SEC		-	-	-	-	-	-
SWIC	1mm	-	-	-	-	-	-
TARG	Cu	3 mm dia	150 mm				
				Total	"V" Line	Power	221.

6.3. The Secondary Pion and Muon Beam

The secondary beamline is designed with a 72 m straight section so that a substantial fraction of the pions can decay to muons, thus providing either pions or muons to inject into the storage ring.

6.3.1. Pion Collection and Momentum Definition

The secondary beam layout is included in Fig. 6.3.1 and the beam envelopes and momentum dispersion are shown in Fig. 6.3.2. Quadrupoles V1Q1 and V1Q2 collect pions within a solid angle of 1.5 msr (32 mrad horizontal $\times$ 60 mrad vertical) and with accepted emittances of $42 \times 10^{-6}\pi\ m$ and $56 \times 10^{-6}\pi\ m$ respectively. The pions are focused on the momentum defining apertures near V1Q4-V1Q5, where the dispersion due to V1D1 and D2 is $0.42''/percent$. The desired pion momentum band is about 2.0% base width. Dispersion in the selected pion beam is then removed by the action of V1Q3-V1Q6 and V1D3 and D4. Primary protons bend only 2.1 degrees in V1D1, miss D2 and are subsequently absorbed in the beam stop.

Figure 6.3.1: The secondary π/μ Beam to the Muon Storage Ring

Figure 6.3.2: Envelopes and Dispersion of the π/μ Beam

Table 6.3.1: Equipment for the "V1" line. The key to the abbreviations is: Q = Quadrupole, D = Dipole, P = Pitching Dipole, hs = Horizontal steering dipole, vs = Vertical steering dipole, SWIC = Segmented Wire Ionization Chamber for beam profile measurement, IONCH = Ionization Chamber for beam pion/muon intensity measurement, SEC = Secondary Emission Chamber for proton intensity measurement.

Mag	Type	B(kG)/G(kG/in)	$L_{eff}(in)$	I (kA)	R ($m\omega$)	V (V)	P (kW)
V1Q1	8Q48	3.3578	52.00	2.7790	35.0	97.	270.
V1Q2	8Q32	2.6384	36.00	2.1180	25.6	54.	115.
V1D1	6x18D72	14.8940	75.00	0.8500	46.0	72.	114.
V1D2	6x18C72	14.8610	75.00	1.3000	35.0	46.	61.
V1Q3	4Q16	3.1036	18.00	0.2799	183.0	51.	14.
V1Q4	4Q16	3.4065	18.00	0.3072	183.0	56.	17.
V1Q5	4Q16	3.4065	18.00	0.3072	183.0	56.	17.
V1Q6	4Q16	3.1036	18.00	0.2299	183.0	51.	14.
V1D3	3x18D72	14.8610	75.00	0.9120	46.0	33.	24.
V1D4	3x18D72	16.1320	75.00	0.9900	46.0	36.	30.
V1Q7	8Q24	2.0263	28.00	1.5918	21.4	34.	54.
V1Q8	8Q24	2.1306	28.00	1.6759	21.4	35.	60.
vs1	4d16	0.6100	16.00	0.0300	500.	15.	.5
V1Q9	4Q24	1.0288	26.00	0.1306	30.4	4.	.5
V1Q10	4Q24	1.2356	26.00	0.1568	30.4	4.	.7
hs1	4d16	0.6100	16.00	0.0300	500.	15.	.5
IONCH1		-	-	-	-	-	-
SWIC1	3mm	-	-	-	-	-	-
V1Q11	4Q24	0.9658	26.00	0.1226	30.4	3.	.5
V1P1	5D22	4.9859	36.00	0.6760	40.0	27.	18.
SWIC2	3mm	-	-	-	-	-	-
V1Q12	8Q24	0.9658	26.00	0.1226	30.4	3.	.5
hs2	4d16	0.6100	16.00	0.0300	500.	15.	.5
SWIC3	3mm	-	-	-	-	-	-
V1Q13	4Q24	0.9658	26.00	0.1226	30.4	3.	.5
vs2	4d16	0.6100	16.00	0.0300	500.	15.	.5
SWIC4	3mm	-	-	-	-	-	-
V1Q14	4Q24	0.9658	26.00	0.1226	30.4	3.	.5
V1Q15	4Q24	0.9658	26.00	0.1226	30.4	3.	.5
V1Q16	4Q24	0.9658	26.00	0.1226	30.4	3.	.5
V1Q17	4Q24	0.9658	26.00	0.1226	30.4	3.	.5
vs3	4d16	0.6100	16.00	0.0300	500.	15.	.5
V1Q18	4Q24	0.9658	26.00	0.1226	30.4	3.	.5
hs3	4d16	0.6100	16.00	0.0300	500.	15.	.5
V1Q19	4Q24	0.9658	26.00	0.1226	30.4	3.	.5
vs6	4d16	0.6100	16.00	0.0300	500.	15.	.5

Table 6.3.2: Table 6.3.1 continued

Magnet	Type	B(kG)/G(kG/in)	$L_{eff}(in)$	I (kA)	R ($m\omega$)	V (V)	P (kW)
V1P2	5D22	4.9859	36.00	0.6760	40.0	27.	18.
SWIC5	3mm	-	-	-	-	-	-
V1Q20	4Q24	0.4829	26.00	0.0613	30.4	1.	.1
V1D5	3x18D72	20.1635	75.00	1.2000	45.8	55.	66.
V1Q21	4Q24	0.8668	26.00	0.1100	30.4	3.	.4
V1Q22	4Q24	1.2184	26.00	0.1546	30.4	4.	.7
vs4	4d16	0.6100	16.00	0.0300	500.	15.	.5
hs4	4d16	0.6100	16.00	0.0300	500.	15.	.5
IONCH2		-	-	-	-	-	-
V1Q23	4Q24	1.4267	26.00	0.1811	30.4	5.	1.
V1Q24	4Q24	1.2184	26.00	0.1546	30.4	4.	.7
V1Q25	4Q24	0.8668	26.00	0.1100	30.4	3.	.4
V1D6	3x18D72	20.1635	75.00	1.2000	45.8	55.	66.
vs5	4d16	0.6100	16.00	0.0300	500.	15.	.5
SWIC6	3mm	-	-	-	-	-	-
V1Q26	4Q24	0.7105	26.00	0.0902	30.4	2.	.2
V1Q27	4Q24	0.3104	26.00	0.0394	30.4	1.	.1
vs6	4d16	0.6100	16.00	0.0300	500.	15.	.5
V1Q28	8Q24	2.5596	28.00	2.0322	21.4	43.	88.
V1Q29	8Q24	2.8110	28.00	2.2549	21.4	48.	109.
SWIC7	3mm	-	-	-	-	-	-
IONCH3		-	-	-	-	-	-
hs5	4d16	0.6100	16.00	0.0300	500.	15.	.5
				Total	"V1" Line	Power	1170.

A list of the necessary beamline elements for the "V1" beamline is given in Table 6.3.1 and Table 6.3.2.

6.3.2. π/μ Transport Channel

Quadrupoles V1Q7, V1Q8, V1Q9 and V1Q10 then match the pion emittance to a regular FODO transport channel composed of V1Q10 through V1Q20. The phase advance per cell is 90 degrees.

The floor of the 80$''$ Bubble Chamber building is 7 feet below grade, which will put the plane of the muon ring at or about 2 feet below grade. The necessary 6.9 foot drop from the AGS plane can be accomplished by inserting a 2.41 degree downward pitching magnet near V1Q12 and recovering to the horizontal with an upward 2.41 degree pitch near V1Q20. The 360 degree phase shift between these two vertical deflections will act to remove any residual vertical momentum dispersion caused by this translation of level. The peak vertical momentum dispersion between the pitching magnets is only about $0.15''/percent$ and leads to virtually no loss of beam.

The beam transport elements will be housed in a combination of a concrete block house, portable buildings, corrugated steel pipe tunnels, and poured concrete "cellars". The latter two are now completed.

6.3.3. π/μ Momentum Spectrometer

Dipoles V1D5 and V1D6, bending 21 degrees each, and the quadrupoles V1Q21-V1Q25 form an adispersive momentum spectrometer. When the pion injection scheme is used, then V1D1-V1D6 are simply set to pass pions slightly above p_μ (by about 0.5%) through to the ring. For direct muon injection, the residual pions in a 2.0% band centered at 3.152 GeV/c are separated from the useable muon band centered 1.8% lower at the magic momentum p_μ=3.094 GeV/c.

At this momentum, the pion decay length is 174 m. As a pion beam, the effective length is from the target to the tangent point at the storage ring, or 122 meters, so the fraction of pions which survive is 0.496. As a muon forming beam, the effective length is from the pion selecting slit at 8.7 m to the pion rejection slit at 97.5 m. Thus, the fraction of the original pions at the target, which decay within this region, is $[e^{-8.7/174} - e^{-97.5/174}] = 0.380$.

6.4. Matching Through the Inflector to the Ring

Table 6.4.1: Pion and muon fluxes at the inflector exit.

Particle	# per TP on Target	Mean Momentum	Mean Polarization
π^+	1.8×10^7	$3.11 \pm 0.32\%$	–
μ^+	7.1×10^4	$3.0944 \pm 0.43\%$	0.918 ± 0.026

Quadrupoles V1Q26-V1Q29 match the transverse beam emittances to those which will allow passage through the hole in the back leg of the ring magnet, through the strong vertically focusing storage ring fringing field, the inflector, and into the storage volume. The requirements for pion and muon injection are very similar, and so these four quadrupoles will provide enough flexibility. Note that, because the inflector aperture is immersed in the storage ring but is necessarily substantially smaller than the storage aperture, one cannot match the incoming beam to the ring's Twiss parameters without sacrificing intensity.

Figure 6.4.1: The geometry of the inflector exit and the muon storage region. The storage volume is the 90 mm diameter circle, and the muon beam enters through the "D" shaped beam channel to the left (larger radius side) of the storage region. The vacuum chamber and cryostat all have to fit within the pole piece profile.

This situation is quite different from the conventional storage ring where great care is taken to match the beamline, which feeds the ring, to the acceptance of the ring. In the conventional storage ring the beam is kept on orbit by a number of discrete elements with drift spaces in between. In a drift space it is quite simple to introduce an external beamline of the same aperture as the storage ring. However, this technique is counter to the demands of this experiment, *viz.* that the storage ring field be as uniform a dipole field as it is possible to produce.

We have gone to great trouble and expense to design and construct a monolithic "C" magnet, with no gaps in the yoke or pole pieces. The geometry of the inflector exit is shown in Fig. 6.4.1. A break in the storage ring magnet at the injection point would destroy the ability to perform the precision measurement for which this ring is designed. Thus, the conventional approach of phase space matching is not an acceptable solution for this experiment. Instead, we must take the design as shown in Fig. 6.4.1 and make the best of it.

As was discussed in Chapter 4, the instantaneous detector counting rates following muon injection push the limits of detector technology, so the lost beam could not be used anyway. While it is true that the intensity of stored muons from pion injection is an order of magnitude lower than with muon injection, because of the pion induced flash it is not clear that the backgrounds which would be associated with an increase of pion flux would be manageable, even if more flux were available.

Particle fluxes have been calculated by a Monte Carlo beam tracing program which uses the empirical Sanford-Wang formula [2] for pion production at the target. The fluxes obtained at the inflector exit are given in Table 6.4.1, assuming that the beam travels through vacuum from the production target through the inflector, except for scattering in 6 SWIC/Ion-Chamber units spaced along the pion decay channel and in the superconducting coil material at each end of the inflector.

6.5. Vernier Steering and Diagnostic Instrumentation

The customary primary proton beam control and monitoring will be required in the "V" Line and at the "V" target, including the usual radiation monitors in the proton beam tunnel.

A total of about 11 small (5 mrad) vernier steering magnets will be needed along the pion/muon line in order to ensure good beam alignment. Three of them will be wanted in the final matching section, two vertical pitch verniers and one horizontal yaw vernier (in addition to V1D6), for accurate steering through the inflector and onto the ring tangent.

About 6 SWICs (Segmented Wire Ionization Chambers) will be provided to check beam profiles and centroids for proper channel matching and for injection matching just before entry into the ring's back-leg. Three ionization chambers will be needed for monitoring the beam intensity, one at V1Q9 just outside the primary shielding, one preceding the final momentum analyzing slit, and one just before entry into the storage ring. In addition, two scintillating fiber hodoscopes will be available between V1D6 and the ring to continuously monitor the low intensity muon beam not detectable by the SWICs.

6.6. Summary

Table 6.6.1: Summary of Beamline Elements in "V" and "V1" Lines

Element	"V" Total	"V1" Total
Quadrupoles	4	29
Dipoles	2	6
Horizontal Steering	1	5
Vertical Steering	2	6
Pitching Dipole		2
SWIC	1	7
SEC	1	3
Ion Chambers		3

The fast proton bunch extraction, the production target, and the secondary beam transport line is fairly standard for the AGS. The H10 extraction point will be able to serve *(g-2)*, RHIC or a neutrino experiment without conflicts. A summary of the beamline elements needed is given in Table 6.6.1.

6.7. References

1. J. Bailey et al., *Final Report on the CERN Muon Storage Ring Including the Anomalous Magnetic Moment and the Electric Dipole Moment of the Muon, and a Direct Test of Relativistic Time Dilation*, Nuclear Physics B150 (1979) pp 1-75.

2. J.R. Sanford and C.L. Wang, *Empirical Formulas for Particle Production in P-Be Collisions Between 10 and 35 GeV/c*, AGS Internal Report JRS/CLW-1 March 1967.