Operational Methods For Delivering Meson Test Beam to Fermi Test Beam Facility

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1 Introduction

The purpose of this document is to describe operational methods used to determine and deliver beam to the Meson Test experiments at Fermi Test Beam Facility. This will include information on: 120 GeV Proton mode, Low Energy Pion Mode and High Energy Pion Mode. This will include Historical and current methods for momentum selection along with planned improvements for the future. Figure 1 is included for reference throughout this document. It is a list of all of the secondary beamline components in order.

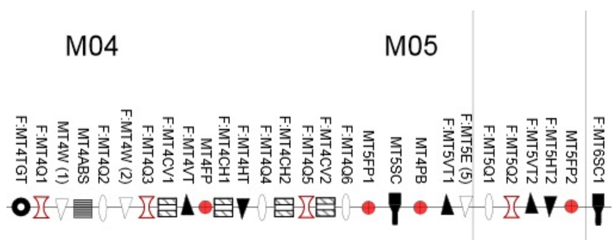

Figure 1: MTest secondary beamline components

2 120 GeV Proton Mode

For 120 GeV Proton mode we deliver protons directly from the Main Injector. To understand this mode, one must first understand the Main Injector Beam. The momentum of beam delivered out of Main Injector, though called 120 GeV is actually 119.7 GeV. Figure 2 shows the program the LLRF system uses to select the momentum and the 119.7 setting. This setting is also an input to the magnet power supplies. Uncertainty in this process requires an understanding of the precision of the RF system, the magnet power supply control system, and the BPM system which is used as a feedback into the RF system. This will be included in an update to this document.

Using the Main Injector BPM system one can measure pulse to pulse variations in momentum delivered to the switchyard and ultimately to Meson Test. This is $\frac{dp}{P}$. It should be clarified that the term $\frac{dp}{P}$ is used in multiple ways in accelerator physics. As illustrated in figure 3, this document will use $\frac{dp}{P}$ to mean the difference between a desired momentum of 119.7 GeV and the measured momentum based on orbit variations in the Main Injector. The variables $\frac{\sigma P}{P}$ will be used for the statistical spread in momentum.

By measuring the average difference in BPM (Beam Position Monitor) measurements through multiple machine orbits at flattop (or the 120 $\frac{GeV}{c}$ portion of the ramp), one can determine variations in momentum of beam delivered to the experiments. Figure 4 shows one sample of a Main Injector orbit profile for beam to switchyard. Using 25 saved orbits between 2013 and 2015 the average $\frac{dp}{P}$ was found to be $-.00012$ with a standard deviation of .0000645. This means an average momentum of 119.6856 $\frac{GeV}{c}$ and the positive and negative standard deviations result in values between 119.6779 $\frac{GeV}{c}$ and 119.6934 $\frac{GeV}{c}$. Hence forward we will refer to the momentum as 120 $\frac{GeV}{c}$.

This describes the beam at flattop in the Main Injector. The process of slow extraction is not a momentum independent process, thus to fully understand variations in momentum throughout the spill, one must understand $\frac{\sigma P}{P}$. For this we will use the resistive wall current in Main Injector. These studies will be done and included in an update of this text.

In order to reduce the intensity of 120 $\frac{GeV}{c}$ beam delivered to the Meson Test experiments the M01 target (F:MW1TGT) is inserted. This target consists of 10 in of aluminum which is only used to attenuate the primary beam [5]. The protons that do not interact in this target are delivered with their full momentum to the Fermi Test Beam Facility.

The 120 $\frac{GeV}{c}$ beam is a primary calibration source for the Test Beam facilities and the external beamlines department. Knowledge of magnet currents needed to deliver 120 $\frac{GeV}{c}$ can be used to properly scale magnet power supply currents to lower momentum values.

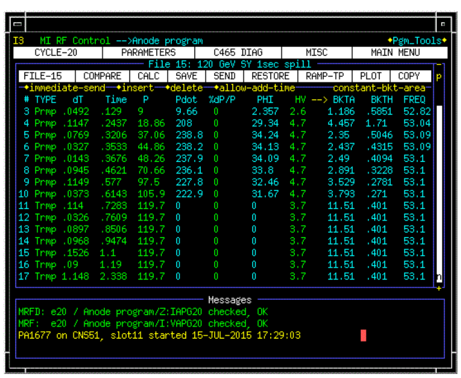

Figure 2: Main Injector Beam

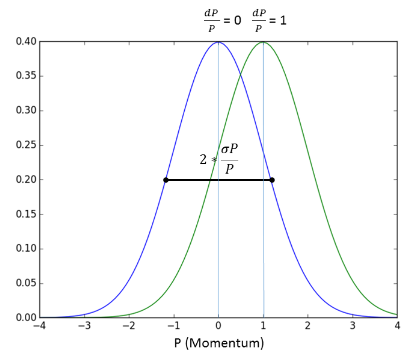

Figure 3: Momentum Spread vs Momentum Variations

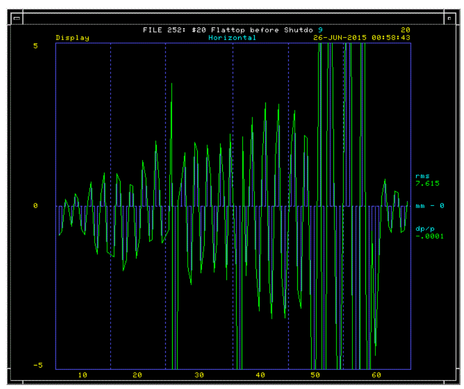

Figure 4: Main Injector Orbit

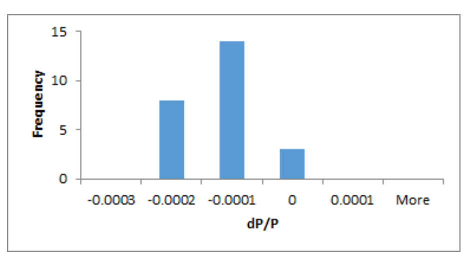

Figure 5: Using 25 orbits between 2013 and 2015 one can get a better understanding of the consistency of momenta delivered by the Main Injector.

3 High Energy Pion Mode

High energy pion mode is obtained by creating a secondary beam off of the aluminum target in M01 (F:MW1TGT). This mode of running is only for pions over 32 GeV. The method is not very efficient and seldom used. Currently in order to use high energy pion mode one must restore a file that has all of the magnet settings saved for that specific momentum. Currently there are 40, 50 and 60 $\frac{GeV}{c}$ files. This mode of running needs study time to improve.

4 Low Energy Pion Mode

Momentum selection in the Meson Test secondary beamline is accomplished with two EPB dipole magnets fed in series by the F:MT4W and F:MT4WL power supplies. The F:MT4W is a high current power supply while F:MT4WL is a smaller power supply which allows regulation at low currents. Fermi Electrical Engineering support reports that F:MT4W currents are read out by a Hitec Topacc T40-8 current measurement system in the tens of ppm. The low momentum supply F:MT4WL is read out by a LEM LT-500-S module at .3 %. For positive beam selection these dipoles provide a downward pointing magnetic field and a Westward bending field. Polarity selection of the power supply allows an upward bending magnetic field, thus bending negative particles Westward into the established beamline path. There are two moveable collimators, F:MT4CH1 and F:MT4CH2. These collimators can be adjusted from 90 mm to about 5 mm. There impact on momentum selection is described in Beams Document #4831 [6]. For momentum selection the next large bend is provided by 5 EPB dipoles powered by power supplies F:MT5E and F:MT5EL, once again a high current and a low current power supply. Electrical engineerig support reports that current measurements for F:MT5E are readout with a Holec system equivalent to the newer Hitek Topacc system used on MT4W. As with F:MT4WL, F:MT5EL is read out by a LEM LT-500-S module at .3 % [13].

Hysteresis effects are problematic at low momentums. Below 16 $\frac{GeV}{c}$ power supply current settings are determined by hall probe readbacks and thus the momentum is selected based on magnetic field vs power supply current. The probes used for momentum selection are Group 3 model MPT-230 read into Group 3 DTM-133 modules [7]. The second dipole magnet of MT4W contains two hall probes in the downstream end. F:MT4WH is positioned in the East Side while F:MT4Q2H (also named F:MT4WHB) rests in the West side. Probes are positioned in an air gap between the beam pipe and the magnet steel. Each are sandwiched between layers of rigid pink foam insulation in order to maintain the correct orientation. There are 3 hall probes in MT5E, F:MT5EH (MT5E-3 West side), F:MT5EHR (MT5E-3 East high range probe), and F:MT4Q6H (MT5E-1 West side) [10]. F:MT5EHR is called the high range probe because it uses a different Group 3 hall probe which can measure greater the 3000 Gauss.

5 Operational Methods For Delivering Beam of the Proper Momentum

Before April 3, 2015 power supply settings and desired hall probe readbacks were maintained in save restore files. Each desired momentum required one save restore file which included both primary and secondary beamline devices. When this system was put into place there were not very many files required, but as time went on, user requests increased. By 2015 there were over 60 files that each had to be maintained. These files were prone to corruption and saved settings often required operator intervention to properly deliver beam to the Fermi Test Beam Facility.

Michael Geelhoed started the process of creating an algorithm that could properly set the MTest beam momentum without the use of save files. George Deinlen of operations and the external beamlines group finished this process and on April 3, 2015 we successfully tested a new sequencer which was able to reduce the number of save restore files down to two files [9]. There is one file for 120 $\frac{GeV}{c}$ proton mode and another file that covers all of the low energy pion modes. High energy pion modes are not included in the sequencer thus anything between 32 $\frac{GeV}{c}$ and 120 $\frac{GeV}{c}$ must be restored using a save file.

This new sequencer uses the settings of the first momentum selection dipoles (MT4W-1 and MT4W-2) to determine the momentum of delivered beam. For momenta less than 16 GeV this is accomplished by changing the power supply F:MT4WL until the desired hall probe readback is achieved on F:MT4WH. The desired field was determined by using the desired field in each of the former save restore files and fitting a linear equation as shown in equations 1 and 2. The algorithm for F:MT5EL was then tuned by adjusting the currents in magnets MT5E-1 through MT5E-5 to center the beam in MT6WC1 and MT6WC2 (proportional wire chambers in enclosure MT6 section 1). The new sequencer was extremely successful and has greatly reduced the time that it takes for an operator to change the desired momentum.

$$MT4WH = 10.96 + 57.92 * P \tag{1}$$

$$P = \frac{(MT4WH - 10.96)}{57.92} \tag{2}$$

This method of fitting showed that earlier models of magnetic field vs momentum had a positive zero offset in the linear equation. Hall probes often have some zero offset, thus this prompted measurements to properly determine the zero offsets which are outlined in the next section. A zero offset in the fitting equation implies that a 0 Gauss magnetic field results in beam with a momentum other than 0. For the fit to properly match reality, a 0 Gauss magnetic field must select a 0 $\frac{GeV}{c}$ beam.

Since the probes are mounted in rigid foam, the first measurement of the zero offset of the hall probe was done without moving the hall probes as described in the next section. This was performed on April 22, 2015 [10] and resulted in a change in the equation used to relate momentum to hall probe readback as listed in equations 3 and 4.

$$MT4WH = -11.75 + 57.92 * P \tag{3}$$

$$P = \frac{(MT4WH + 11.75)}{57.92} \tag{4}$$

On June 17 and 18, 2015 the zero offset measurements were repeated as described in detail in the next section. During this process it was determined that the Group 3 hall probe module used different offsets for different hall probe ranges. The hall probe used the first range for $0 - 300$ Gauss, the second for $300 - 600$ Gauss, the third for $600 - 1200$ Gauss and the fourth for $1200 - 3000$ Gauss. If the field was increasing then the probe switches range at 105 % of the maximum value and if the field is decreasing it switches at 95 % of the maximum value. A notable difference in this measurement and the zero offsets of other ranges prompted experts to use another method of both zeroing the probe and determining the past zero offset. On these days the F:MT4WH probe was removed from its position of rest in the magnet and zeroed in a zero Gauss field outside the magnet. When the probe is zeroed in autorange mode, the zero offset is properly set for all ranges. Operations altered the sequencer equations as shown in equations 5 and 6.

$$MT4WH = 57.92 * P \tag{5}$$

$$P = \frac{(MT4WH)}{57.92} \tag{6}$$

6 Determining the Zero Offset of the F:MT4WH Hall Probe

6.1 First Measurement of Hall Probe Zero Offset on April 22, 2015

The first measurements of hall probe offsets only measure the $0 - 300$ Guass offsets as the impact of autorange mode on zero offsets was not yet understood. These measurements took place on April 22. The goal of these measurements was to determine the zero offset without disturbing the position of the probe which is sandwiched betwen two pieces of rigid foam insulation. The method used was to zero an independant probe within a mu metal shield, then place that probe as close to the location of the permanent probe in order to measure the remnant field in the magnet. This would tell us the actual field B. Knowing the actual field and the acnet readback (MT4WH) one can find the OS as defined in equation 7. Zero offsets were measured and calculated for all of the probes and are document in [10]. For this analysis we will focus on F:MT4WH. At the time of the measurement -2 Gauss remnant field was measured. At the same time the acnet readback F:MT4WH read -13.75. As shown in equation 9, this results in a $+11.75$ Gauss offset as documented in the previous section.

$$B = MT4WH + OS \tag{7}$$

$$OS = B - MT4WH \tag{8}$$

$$OS = -2 - (-13.75) = +11.75(Gauss) \tag{9}$$

6.2 Second Measurement of the Hall Probe Zero Offset on June 17 and 18, 2015

Before the second round of hall probe offset measurements it was discovered that the hall probes always return to autorange mode when power cycled. The power had definitely been cycled in the past year! This lead to the fact that all of the hall probes were functioning in autorange mode. The probes have independent zero offsets for each range. If you zero the hall probe in autorange mode, it will properly zero all of the offsets. The purpose of the second round of hall probe measurements was to determine the zero offsets for all of the ranges on F:MT4WH and F:MT4Q2H (which is in the West side of MT4W-2).

When you put positive current on MT4WL you get a positive field on MT4WH this means the field is pointing down. The MT4WH hall probe chip is positioned so down pointing magnetic fields read back positive on the probe. Down pointing field will cause a Westward bending magnet to positively charged beam, Hence the name MT4W or MT4West. The results of the second round of measurements for F:MT4WH are shown in table 1

For this round of measurements we also measured the zero offset of F:MT4Q2H which is displayed in table 2. The chip for F:MT4Q2H is installed in the opposite direction of F:MT4WH thus the field of MT4Q2H has the opposite sign.

These measurements show that there were large differences between the zero offsets at different ranges for F:MT4WH. There were effectively no differences in the zero offsets for different ranges for F:MT4Q2H, and the probes zero offset was measured to be -3 Gauss. This makes F:MT4Q2H a very useful parameter for verifying the momentum of the beam delivered.

Table 1: MT4WH Zero Offsets by Independently Measuring Remnant Field B

Range (G)	F:MT4WH (G)	B (G)	Zero Offset (G)
0-300	+1.8	+7	-5.2
300-600	+23.9	+7	+16.9
600-1200	+32.4	+7	+25.4
1200-3000	+32.5	+7	+25.5

Table 2: MT4Q2H Zero Offsets by Independently Measuring Remnant Field B

Range (G)	F:MT4Q2H (G)	B (G)	Zero Offset (G)
0-300	-10.0	-7	-3
300-600	-10.0	-7	-3
600-1200	-10.2	-7	-3.2
1200-3000	-10.5	-7	-3.5

6.3 Third Method for Determining the Past Zero Offset of MT4WH Hall Probe

As documented in section 4, there are two hall probes in the downstream end of the MT4W-2 magnet. F:MT4WH is in the East gap between the beam pipe and the steel while F:MT4Q2H (now also named F:MT4WHB) rests in the West gap. On June 17, 2015 F:MT4WH was zeroed in autorange mode in a zero gauss field. The zero Gauss field was determined by properly zeroing an FW Bell Model 5080 X hall probe within a Lakeshore Mu Metal shield [8]. With the zero offset of this probe accounted for, it was then used to find a location in space where a zero Gauss field was measured. The F:MT4WH hall probe was then held and observed in this field while zeroing the module in autorange mode, thus establishing a proper zero offset for all of the ranges. This method results in a hall probe whose readback is the actual field within the magnet.

Before zeroing the MT4WH hall probe the actual magnetic field (B) within MT4W-2 is equal to the hall probe readback (MT4WH) plus some offset (OS) as shown in equations 10 and 11.

$$B = MT4WH + OS \tag{10}$$

$$MT4WH = B - OS \tag{11}$$

After zeroing the hall probe the the measurement of MT4WH is the actual field within the magnet as shown in equation 12

$$B = MT4WH \tag{12}$$

The relationship between F:MT4Q2H (F:MT4WB) and F:MT4WH is also known before and after zeroing. This relationship must be evaluated within each of the ranges of the hall probe while not using data between 95 % and 105 % of full scale. The results of this evaluation are shown in figure 6 and reference [11]. One must be cautious of how you define the offset with regards to the plus and minus signs thus the algebra is worked out step by step. The variable Int_{before} is the Y intercept of the relationship between F:MT4Q2H and F:MT4WH found before the probe was zeroed. Int_{after} is this same relationship after the probe was zeroed. The slope for this relationship was always found to be -1.4 thus it is included as a constant.

Before zeroing relationship

$$MT4WH = -1.4(MT4Q2H) + Int_{before} \tag{13}$$

Using equation 11

$$B - OS = -1.4(MT4Q2H) + Int_{before} \tag{14}$$

After zeroing relationship

$$MT4WH = -1.4(MT4Q2H) + Int_{after} \tag{15}$$

And using equation 12

$$B = -1.4(MT4Q2H) + Int_{after} \tag{16}$$

Since B is the actual magnetic field, it exists in both equation 14 and equation 16. By plugging equation 16 into equation 14 one can solve for the offset OS as it existed before zeroing the probe. This is shown in equation 17 and 18. Table 3 shows the data for this method of determining the zero offsets.

$$(-1.4(MT4Q2H) + Int_{after}) - OS = -1.4(MT4Q2H) + Int_{before} \tag{17}$$

$$OS = Int_{after} - Int_{before} \tag{18}$$

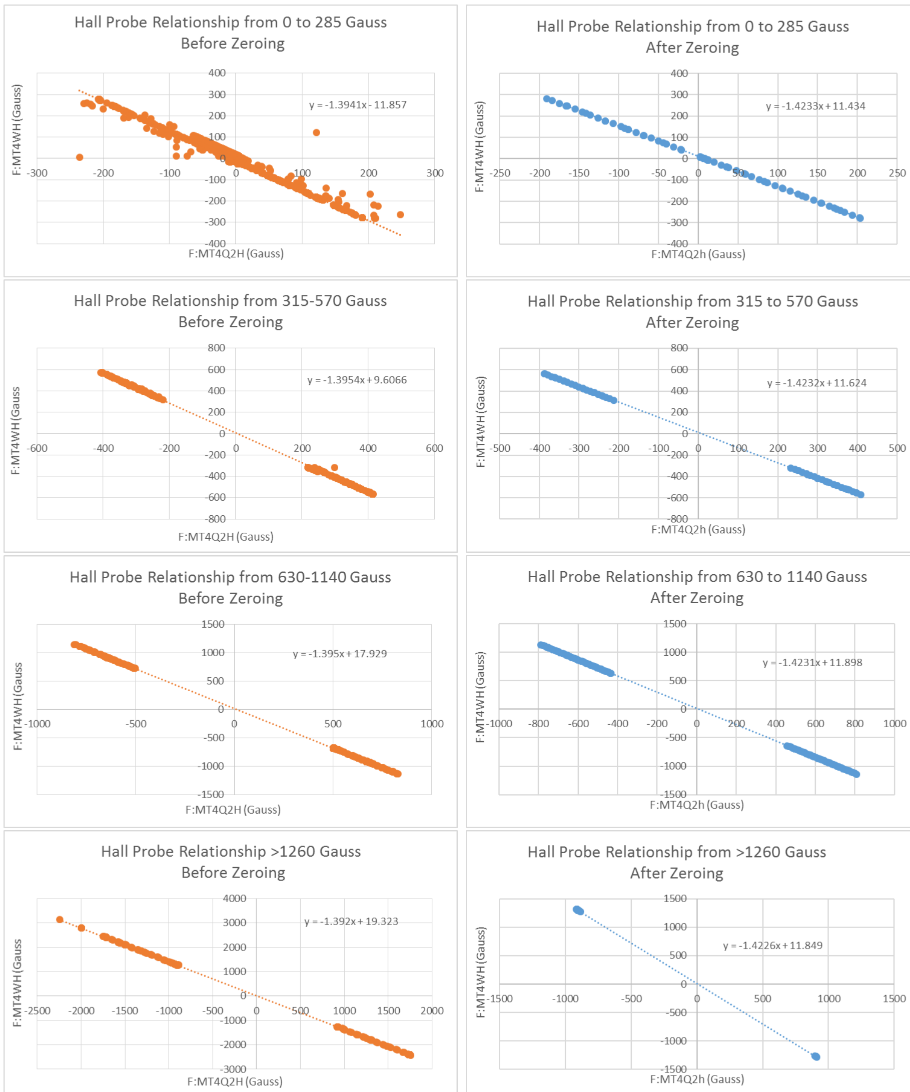

Figure 6: Int_{before} and Int_{after} are the Y intercepts found from the relationship between MT4WH and MT4Q2H. This relationship for each hall probe range is displayed in these figures along with the linear fit which is used to determine Int_{before} and Int_{after}.

Table 3: Zero Offsets For Different Ranges of the MT4WH Hall Probe

Range (G)	$Yint_{before}$	$Yint_{after}$	Zero Offset (G)
0-300	-11.857	$+11.434$	$+23.29$
300-600	$+9.607$	$+11.624$	$+2.017$
600-1200	$+17.929$	$+11.898$	-6.031
1200-3000	$+19.323$	$+11.849$	-7.474

This information will not only be used to better deliver beams of proper momentum to the Fermi Test Beam Facility, but will also be used to characterize actual momentum delivered to past experiments. We are only focusing on data from the last year. Using the method outlined in this section we can determine a relationship between the data logged reading from F:MT4WH (MT4WH) and the actual momentum of beam delivered. Equation 19 shows that there should be a linear relationship between the actual magnetic field (B) and the momentum (P) characterized only by the slope (m). In reality the actual field (B) is equal to the readback of F:MT4WH (MT4WH) plus an offset (OS) as shown in equation 20. This leads to equations 21 and 22.

$$B = m * P \tag{19}$$

$$MT4WH + OS = m * P \tag{20}$$

$$MT4WH = m * P - OS \tag{21}$$

$$P = \frac{MT4WH + OS}{m} \tag{22}$$

7 Future Improvements

7.1 Improved Hall Probe Mounting Hardware

The hall probes are currently held in place by rigid foam insulation. This means the process of removing and replacing the hall probe for zeroing can change the orientation of the hall probe. While caution can be taken to manipulate this mechanism, a new system is currently under construction to improve stability. Chris Olsen of Accelerator Division Operations has built multiple PVC blocks which have been milled to accept a rectangular shaped PVC guide system. The hall probe chips will be protected and positioned in this internal piece. This will provide a consistent mounting system for all of the probes. It will also allow one to remove the hall probe and insert it into a mu metal shield for proper zeroing. The probe can then be repositioned in the same orientation with no fear of changing the original orientation.

7.2 Using the 120 $\frac{GeV}{c}$ Ramp Reset to Monitor the Zero Offset

Once the probes are properly zeroed, a method is needed to determine if and when enough drift has occurred to warrant re-zeroing the probes. During 120 $\frac{GeV}{c}$ operations both MT5E and MT4W are ramped to the desired current during the spill and set to 0 Amps for the remainder of the supercycle. It was noted that the remnant field is consistent during the 0 Amp portions of the supercycle. Dataloggers were recently established to monitor the hall probe readbacks 10 seconds after the end of spill. After the 2015 shutdown, this system of monitoring the hall probe offsets will be rigorously tested. If it is found that the remnant field between the 120 $\frac{GeV}{c}$ ramp is always the same, then once a week the magnets can be ramped in 120 $\frac{GeV}{c}$ for 10 minutes as a test to ensure proper hall probe offsets.

7.3 Adding More Hall Probes to Both MT4W and MT5E

Currently MT4W-2 has 2 hall probes while MT4W-1 has none. MT5E-1 and MT5E-3 both have hall probes while MT5E-2, 4 and 5 have none. There are currently hall probes installed in the fringe fields of quadrupole magnets in the Meson Test Secondary beamline. Before the end of the shutdown we will use these extra hall probes to better instrument the momentum selection dipoles. This will serve the purposes of: providing more statistics in field measurements, providing redundancy should an individual probe fail, and provide information regarding the consistency of field quality in other momentum selection dipoles.

7.4 Reference Magnets

Investigation is underway with regards to the idea of using a reference magnet for each of the momentum selecting dipole strings. This would mean a reference magnet for MT4W and one for MT5E. This would allow hall probes to be positioned in the center of the dipoles therefore measuring the actual field that the beam sees. This would either be done with a 120 in (full size) EPB dipoles, or with a shorter version of the magnet that has the same field. The goal is to find a way to place these reference magnets in the service buildings upstairs which will allow installation and work during times of beam operations.

7.5 Beam Profile Monitors Before and After MT5E bend String

Knowledge of the position of the beam entering and exiting MT5E1-5, along with verified knowledge of the dipole field could allow us to use MT5E as not only a momentum selection device but also a momentum monitoring device. Investigation is underway to determine what system of profile monitors would be best for this purpose.

8 Conclusion

An improved understanding of both momentum and momentum spread delivered to the Fermi Test Beam Facility will greatly benefit both the Fermi Test Beam Facility and their users. The Minerva Test Beam group has found discrepancies in selected momentum which have partially been resolved by an understanding of the zero offsets of the hall probes. More work is underway to make this system of momentum selection both robust in instrumentation and documentation. This work will factor greatly into both future experiments and those analyzing past data.

References

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