Commissioning the HMS optics in the 2017-18 run period

Holly Szumila-Vance*

Jefferson Lab
hszumila@jlab.org

Abstract

The purpose of this document is to record the procedures and studies that are established for setting the High Momentum Spectrometer (HMS) in the 12 GeV era. The NMR probe in the HMS magnet was moved and set to a new location since the 6 GeV era during the summer of 2017. Initial measurements were taken to precisely determine the central field values and the external NMR field measurements of the HMS dipole magnet with the corresponding current settings. The field setting programs and initial optimization of the HMS are discussed.

1 Introduction

The HMS in Hall C at Jefferson Lab has an acceptance of 6 mSr and momentum resolution better than 0.1% ($\delta P/P$). The HMS can be set to a central momentum in the range of 0.5–7.5 GeV/c and can rotated to measure particles at angles of 12.5–90 degrees from the beam line. The HMS was studied in great detail during the running of experiments in the 6 GeV era.

The HMS dipole has NMR probes installed close to the central field region of the magnet that are used to lock onto the field for field regulation. The exact field (B) to momentum (P) relationship, B/P, must be known for setting the spectrometer to a central momentum for data-taking. Prior to the first 12 GeV era beam in Hall C, the NMR probe used for field regulation was removed and replaced. Therefore, the exact field settings used previously for NMR field regulation are no longer precisely correct. Additionally, many of the experiments in the 12 GeV physics era in Hall C run at much higher central momenta where saturation effects in the dipole and quadrupole magnets of the HMS are anticipated and not well-studied. With the beam energy upgrade, the Super High Momentum Spectrometer (SHMS) was installed in Hall C, and new drift chambers were installed in the HMS hut. The weight of the SHMS modifies the HMS pointing and is initially measured from survey and verified with data. The installation of the new drift chambers adds an additional variable when understanding the HMS track reconstruction.

To understand the HMS dipole field, measurements were conducted using central probes and the externally-mounted NMR probe (used for locking onto the field) prior to beam during the fall of 2017. These measurements yielded a relatively precise field to current (I) parameterization, B/I. The measurements of the field were compared to previous measurements so that the dipole could be set to the same desired central momentum using a different field setting to lock onto. The quadrupole magnets were not studied further since the the 12 GeV era and rely on the parameterizations used previously (from the latest field03 model).

Special beam runs using hydrogen elastic scattering and carbon data with the sieve installed are helpful for understanding the pointing/angle offsets and central momentum as well as for re-optimization of the matrix elements used in the reconstruction of tracks from the focal plane to their interaction at the target.

*

The focus of this document is to record the central field studies of the HMS dipole and the methods for setting the central field. The parameterizations of the quadrupole magnets with respect to the central momentum are also discussed.

1.1. TOSCA models

The TOSCA models on the HMS dipole are maintained by Steve Lassiter. Here follows a short discussion on the parameterized effective field length (EFL) as it relates to understanding the non-linearity of the field-to-momentum ratio of the dipole when pushed to higher central momenta [5]
.

The EFL is most recently computed as a curved section ranging from ±12.5 degrees from the center of the magnet with an arc radius of 12.05625 m in addition to straight line segments at the ends of the arc, each measuring approximately 2 m in length. This parameterization is used to calculate the full integral field in TOSCA and is divided by the central field to give the EFL in m.

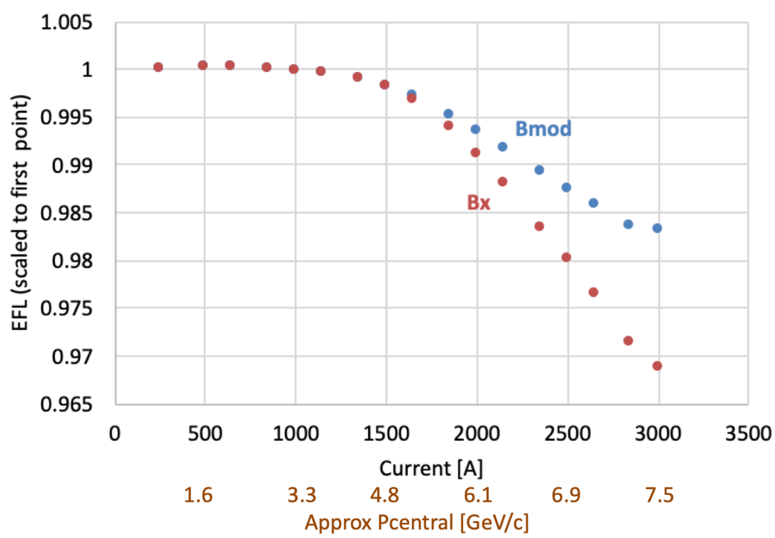

Figure 1: *The EFL is calculated from TOSCA and is re-scaled here such that the first point at 250 A is 1 and all subsequent points are with respect to the point at 250 A. The approximate central momentum (to nearest 100 MeV) corresponding to the set currents is shown below the x-axis[5].*

The exact numbers (not normalized to 1) from the calculation of the EFL are contained in the Appendix.

2 HMS central field measurements

The central field of the HMS was measured during the fall of 2017. A 3-axis hall probe and an NMR probe were placed in the center of the dipole magnet to be compared to measurements from the externally placed NMR probe that is used to set the field of the magnet during run conditions. The 3-axis hall probe covered the full momentum range of the dipole but was measured to have a precision to within approximately 0.4%. The central NMR probe had a measured precision better than 0.01% but only worked over a central working range of 1000 A to 3000 A (excluding momentum settings less than approximately 3.5 GeV/c). The externally-mounted NMR probe used for setting the field during run conditions works over the full range of the magnet. The measurements from all probes are contained in the repository: [10].

The set current and not the read back current was used for all measurements. The read back current is related to the exact constants input at the power supply and can change based on the parameters used. Therefore, the set current is used for parameterizing the currents in all magnets since it is most reliable and will not change.

The ramping measurements of the NMR probe (externally mounted) used for setting the field during run conditions is shown in Fig. 2. The dipole was first ramped from 0 A to 2990 A on positive polarity. After ramping the magnet back to 0 A, a ramp to the maximum current was performed on negative polarity. A second ramp on the positive polarity was performed to check for repeatability on the positive polarity.

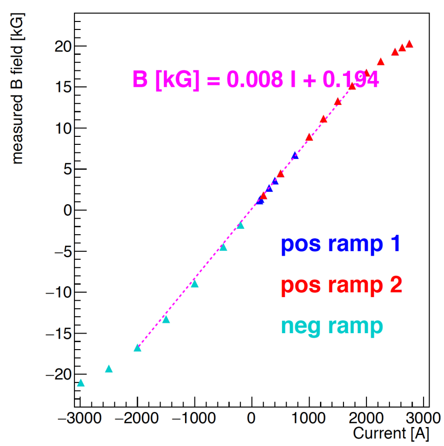

Figure 2: *The HMS dipole was ramped from 0 A to maximum 2990 A on positive polarity. Then the dipole was ramped to 0 A and then to the maximum 2990 A on negative polarity. A second ramp on positive polarity was then measured starting at 0 A again.The linear fit shown here is a fit to the more linear portion of the HMS dipole ramp, less than 2000 A.*

The two ramping measurements on positive polarity agreed to within less than 0.05% for all measurements showing good reproducibility of data. Assuming that the absolute value of the field measurements on positive or negative polarity should be the same, the relative difference can measure the precision of the measurements taken with the NMR probe. The relative difference is shown in Fig. 5.

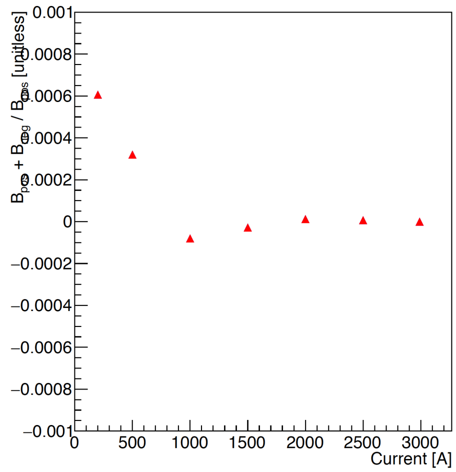

Figure 3: *A general check between the positive and negative polarity data can show if there is a systematic bias in the data taken. Assuming that the absolute value of the field measurement should measure the same for positive and negative polarity, the relative difference can measure the precision of the NMR probe.*

The asymmetry between the measurements taken at positive and negative polarity indicates a precision of less than 0.07% and better than 0.02% for all measurements above 500 A. This satisfies the requirements of the study as simulation of the optics shows sensitivity to offsets at 0.1% level.

2.1. Central field B/I parameterization

The B/I ratio as a function of the set current is shown in Fig. 5. The measurements are fit with an 8^{th} order polynomial described in Eq. 1.

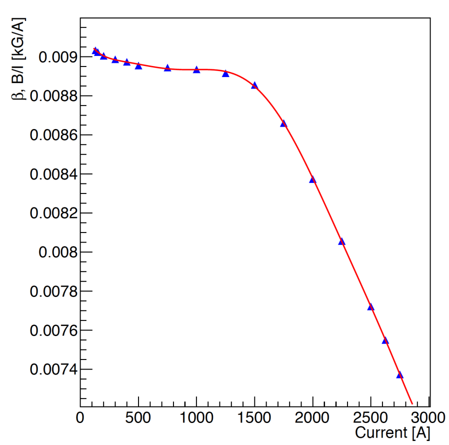

Figure 4: *The B/I measurement ratio is shown as a function of the set current.*

$$\begin{aligned} B/I_{set} = & \; 7.76495 \times 10^{-29} I_{set}^8 - 9.59365 \times 10^{-25} I_{set}^7 + 4.80895 \times 10^{-21} I_{set}^6 \\ & -1.25206 \times 10^{-17} I_{set}^5 + 1.81193 \times 10^{-14} I_{set}^4 - 1.48202 \times 10^{-11} I_{set}^3 \\ & +6.77632 \times 10^{-9} I_{set}^2 - 1.71809 \times 10^{-6} I_{set} + 0.00916971 \end{aligned} \tag{1}$$

The residual of the parameterization is shown in Fig. 5. The largest residual is approximately 0.1% for measurements taken at approximately 1500 A as this region has the largest change in shape of the B/I ratio. This region occurs at approximately 4.8 GeV central momentum and marks the transition from the nearly linear B/I ratios at less than 1000 A and greater than 2000 A.

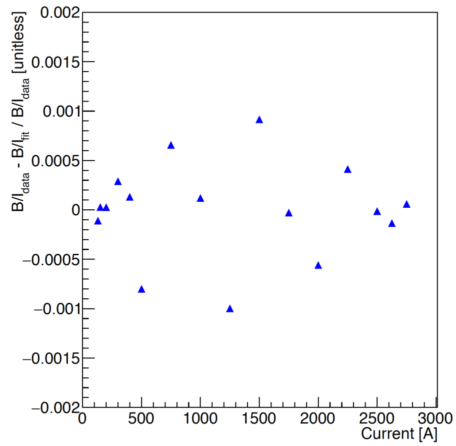

Figure 5: *The relative residual of the fit compared to data for the B/I ratio is shown. The relative residual is largest for the range between 1000 A to 2000 A at 0.1%.*

While the worst residual is approximately 0.1%, this is not a problem for setting the dipole since we set by field. This poorer residual indicates that the associated approximate current for setting the field might have more of a deviation from the nominal value for the field. Additionally, because we set by field, the non-linear behavior of the true saturation model will mostly be the result of not including the effects of the changing EFL.

3 Setting the HMS magnets

The HMS dipole is set by inputting the appropriate field for the desired momentum whereas the quadrupoles are set by current. Experiments during the 6 GeV era used a cycling procedure of going to 200 A above the desired set current before coming back down. For the HMS dipole this included a requirement to cycle to at least 1500 A and have a 300 A buffer above the corresponding current. These cycling procedures have not been studied in further detail and are used for historic reasons.

3.1. Field setting program

The program for setting the dipole is maintained at [1]. The code for setting the quadrupoles is from the field03 fortran code which is now also version-controlled in the same repository. The program takes the desired momentum as input. It uses the B/P ratio to calculate what the field on the NMR probe should read and then uses a bracketing calculation to find the approximate current from the polynomial parameterization of B/I. The nominal B/P ratio is 0.273767660491597 T/GeV. Deviations from this were later added to the code to adjust the optics in regions of measured saturation. The initial deviations were discovered by the growing W offset between data and Monte Carlo in hydrogen scattering data. Optics studies that looked at the correlation and rotation of the $ypTar$ vs $zVertex$ relationship were used to correct for effects in the changing optics.

The HMS quads are set purely by current from the field03 program. Although extensively studied in the 6 GeV era running, it's possible that the saturation models are no longer accurate for the higher central momentum running. The saturation factors as extracted from the field03 program are shown in Fig. 8.

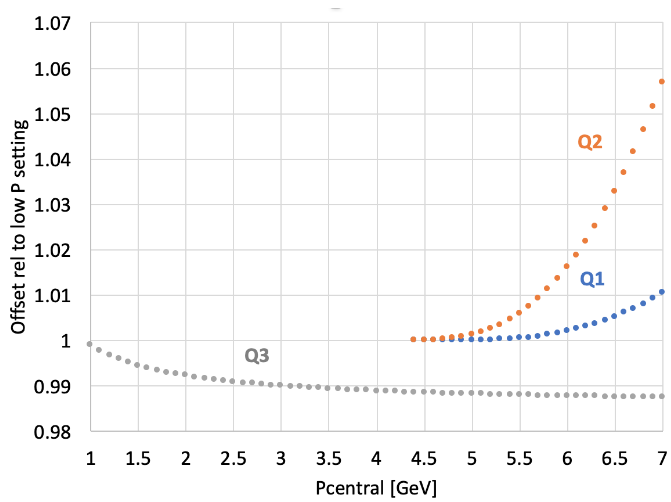

Figure 6: *The HMS quads are set by current using the field03 program. The saturation factors as output from the program are indicated above where only the deviations from the nominal tunes are shown.*

Fig. 8 shows a continuous change in the setting of the Q3 magnet for all momentum (albeit small). The Q3 saturation factor is intended to take into account a zero offset in the Q3 set current.The Q2 and Q1 saturation effects turn on at approximately 4.4 and 4.8 GeV/c, respectively. The effects of these saturation factors are not well understood in the data, but it appears they may have dramatic effects on the optics about 5 GeV/c central momenta where the models have possibly never been precisely studied.

3.2. Relevant changes to setting the dipole field

The initial parameterization with no changes to the B/P ratio is designated Version 0. During the spring 2018 running, it was observed that the $ypTar$ to $zVertex$ relationship becomes correlated above approximately 5 GeV/c central momenta. This prompted the need for Version 1 which included a linear term fit from data to increase the B/P ratio at 5.3 GeV/c and above. During the fall 2018 initial optics studies, this increase was applied to central momentum starting at 5.1 GeV/c and above. The relevant dates of the changes are listed below:

- **Version 1** Applied on April 9, 2018 at 8:42 am starting with coincidence run 3368. The saturation factor applied to the field is $0.01P + 0.948$ at 5.3 GeV/c central momentum and above [9] [6].
- **Version 2** Applied on Sept. 26, 2018 at 7:04 pm starting with coincidence run 4701. The saturation factor applied to the field is $0.01P + 0.949$ at 5.1 GeV/c central momentum and above [7] [8].

4 Optimization of matrix elements

The general procedure for optimizing the HMS matrix elements is documented in detail at [2]. The updated code for optimizing the HMS matrix elements is maintained in gitHub [3]. The initial matrix optimization for commissioning used runs taken with 3-pass beam energy at central momenta between 2 to 4 GeV/c and central angles from 15 to 30 degrees. These runs were taken with a separate DAQ for the HMS with run numbers 1337–1352.

4.1. Mis-pointings from surveys

The mis-pointing surveys are explained in detail here: [11]. Included below are the relevant mis-pointing parameterizations for the HMS data as used in the matrix optimization.

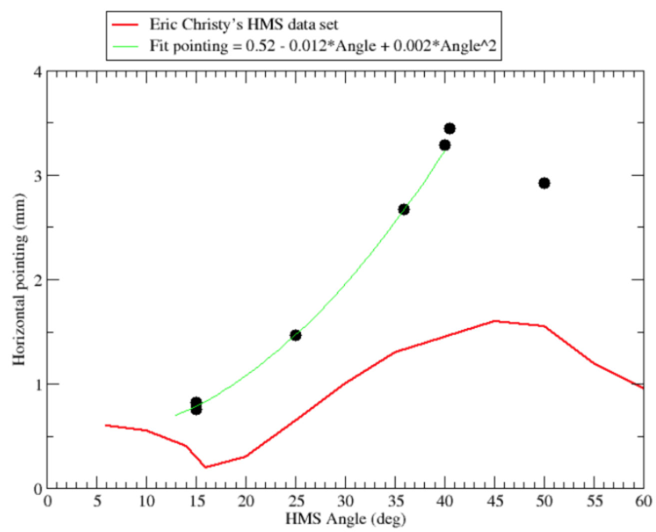

Figure 7: *The horizontal mis-pointing data is shown from survey with a polynomial fit [11].*

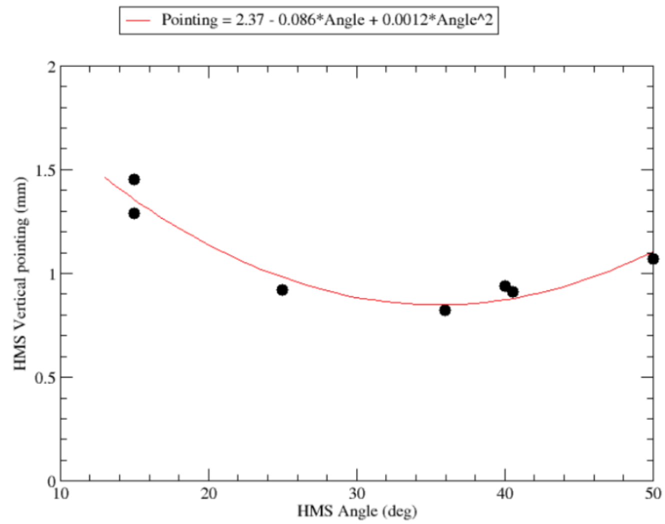

Figure 8: *The vertical mis-pointing data is shown from survey with a polynomial fit [11].*

While the mis-pointing survey data appears to maintain a consistent picture for the matrix optimization data taken at central angles between 15 and 30 degrees, mis-pointings above 40 degrees would benefit from further measurements.

5 Conclusion

This document establishes a record for setting the HMS magnets during experimental running in Hall C. The HMS dipole setting program is the result of measurements taken prior to beam by measuring the field with the NMR probe used for field regulation. Further changes were later applied to the HMS dipole when changes in the optics were observed during beam running. Initial hydrogen data corroborates with the changes seen in the EFL from TOSCA but not precisely enough to implement in the field setting program. Further studies of the effects of the HMS quads and the hysteresis cycling procedure are recommended for future running. Without a thorough understanding of the saturation effects of the HMS quads and dipole at high central momenta, optics data with a sieve is useful for improving the optics at specific settings.

6 Appendix

HMS Dipole EFL Bx
Tosca Model HMS-Dipole-cases 2017

Current	Central Field	Integral Arc	Integral Straight	EFL
A	T	T.m	T.m	m
250	0.2224115	0.56564	0.022241	5.2864
500	0.445455	1.13299	0.044645	5.2873
650	0.578962	1.47253	0.058002	5.2872
850	0.756324	1.9235	0.075639	5.2865
1000	0.888596	2.25972	0.088666	5.2856
1150	1.01961	2.59254	0.101354	5.2842
1350	1.19104	3.02753	0.117405	5.2810
1500	1.314402	3.33974	0.128045	5.2766
1650	1.429012	3.62852	0.136331	5.2692
1850	1.564026	3.9661	0.142629	5.2540
2000	1.65293	4.18613	0.144144	5.2395
2150	1.733145	4.38243	0.143556	5.2229
2350	1.827965	4.61133	0.140322	5.1988
2500	1.890419	4.76072	0.136295	5.1809
2650	1.946016	4.89163	0.130824	5.1618
2850	2.010685	5.0408500	0.122338	5.1357
3000	2.050703	5.13607	0.115574	5.1218

EFL = 2 x (arc + straight) / Central field

Figure 9: *The EFL from TOSCA calculation using the $x-$component of the magnetic field [5].*

HMS Dipole EFL Bmod
Tosca Model HMS-Dipole-cases 2017

Current	Central Field	Integral Arc	Integral Straight	EFL
A	T	T.m	T.m	m
250	0.2224115	0.56564	0.022241	5.2864
500	0.445455	1.13299	0.044645	5.2873
650	0.578962	1.47253	0.058002	5.2872
850	0.756324	1.9235	0.075639	5.2865
1000	0.888596	2.25972	0.088666	5.2856
1150	1.01961	2.59254	0.101367	5.2842
1350	1.19104	3.02753	0.117544	5.2812
1500	1.314402	3.33974	0.12857	5.2774
1650	1.429012	3.62852	0.137982	5.2715
1850	1.564026	3.9661	0.148055	5.2610
2000	1.65293	4.18613	0.15449	5.2520
2150	1.733145	4.38243	0.160472	5.2424
2350	1.827965	4.61133	0.168087	5.2292
2500	1.890419	4.76072	0.173597	5.2203
2650	1.946016	4.89163	0.179113	5.2114
2850	2.010685	5.04085	0.186773	5.1998
3000	2.050703	5.13607	0.192811	5.1971

EFL = 2 x (arc + straight) / Central field

Figure 10: *The EFL from TOSCA calculation using all three components (modulus) of the magnetic field [5].*

References

[1] field17 gitHub repository, https://github.com/hszumila/field17

[2] Bericic, J., Notes on the HMS Optics, https://hallcweb.jlab.org/DocDB/0008/000849/001/HMS_optics_notes.pdf

[3] HMS optics matrix optimization gitHub repository, https://github.com/hszumila/HMS_optics

[4] Magnetic field studies of the SHMS magnets and HMS dipole, https://github.com/hszumila/magnets

[5] Private e-mail with Steve Lassiter on Nov. 1, 2018.

[6] https://logbooks.jlab.org/entry/3557352

[7] https://logbooks.jlab.org/entry/3598407

[8] https://logbooks.jlab.org/entry/3598356

[9] https://logbooks.jlab.org/entry/3554200

[10] magnet testing gitHub repo, https://github.com/hszumila/magnets

[11] Mis-pointing survey summary, https://github.com/MarkKJones/fall2017-plans/blob/master/Surveys/survey-summary.pdf