Draft
K. Yonehara
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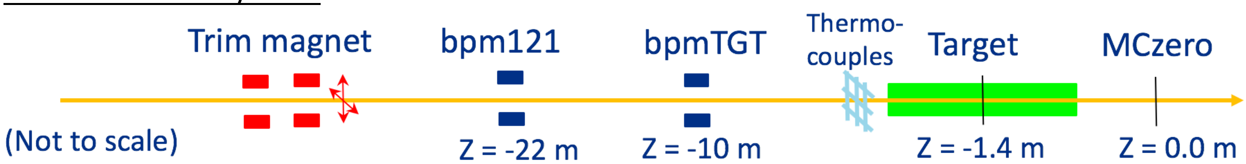
Proposed NuMI beam scan and beam study for FY21

The NuMI beam scan is a proton tomography to find a (x, y) position of a beam element of the NuMI target system including a baffle, target, horn 1 and horn 2, and hadron and muon monitors. A proton beam position is moved by using a trim magnet and the beam position is measured by using a Beam Position Monitor (BPM). Therefore, <u>the observed beam element position is on the BPM coordinate system.</u>



Conceptual drawing for the beam scan. A baffle, horn 1 and 2, BLM, and hadron and muon monitors are not shown in this figure.

There are four types of beam scan. A **hadron monitor scan** is the first scan to find the hadron monitor position on the BPM coordinate system. Note that the hadron monitor position is fixed for several FY operations. Thus, the scan results the relative location of the BPM from the past operations. Once it is done, we run a **X-hair scan** to find a position of the horn 1 and 2 by measuring a hadron monitor and Beam Loss Monitor (BLM) signal which is temporarily installed near Beryllium fins (Appendix A). <u>Note that the hadron monitor scan and X-hair scan run without a target.</u> After the X-hair scan, we may have a special beam study to investigate a residual magnetic field inside the inner horn conductor. The special run is described in later paragraph. After the horn position is recorded on the BPM coordinate system and confirm the position is within the tolerance, the BLM is removed and the target carrier is installed. We run a **target scan** to find the position of the baffle, target, and horn 1 neck. Note that the target pile is not sealed at this moment in order to iterate the target carrier position. <u>Therefore, the beam intensity is very low and the beam repetition rate is very low.</u> When the positions of the target and baffle are found within a tolerance, we seal the target pile and increase a proton beam intensity to start providing a neutrino beam to the NuMI ND/FD (called the HEP run). When the MI runs with a slip stacking mode, we run a **thermocouple calibration** and **horn current scan**. In the calibration run, a signal from a thermocouple in front of the target is calibrated by the BPM. In the horn current scan, the beam monitor signal (muon monitors) is calibrated by the BPM and a horn current. The horn focusing power will be characterized by the beam monitor signal. Note that the present horn current flow is the FHC mode. The polarity of horn power supply will be changed when the neutrino detector group requests. We will repeat those scans with the RHC.

Besides the beam scan, we run the **beam spot size study** and **beam intensity study** when the MI proton beam is stable. In the beam spot size study, the NuMI beam transport lattice is characterized to tune the beam spot size on the target. Especially, a correlation between the spot size and beam intensity is investigated. Once a lattice parameter is handled, we run the beam intensity study. In this study, we fix the beam spot size and measure the beam monitor response by varying the beam intensity and horn current. Especially, a correlation between the beam intensity and horn current is investigated. Usually, the NuMI beam power is gradually increased in the first two months of the HEP operation. The beam study will carry out each time when the beam power is fixed.

Probably, we carry out the **residual magnetic field study** after the X-hair scan (no target in the beam line). A proton beam will be sent near the inner conductor of the neck with and without a horn magnetic field. If the residual field exists inside the inner conductor, the beam will be bent by the field when the horn is turned on. This is an optional test.

Table shows the summary of beam parameter for each beam scan and beam study.

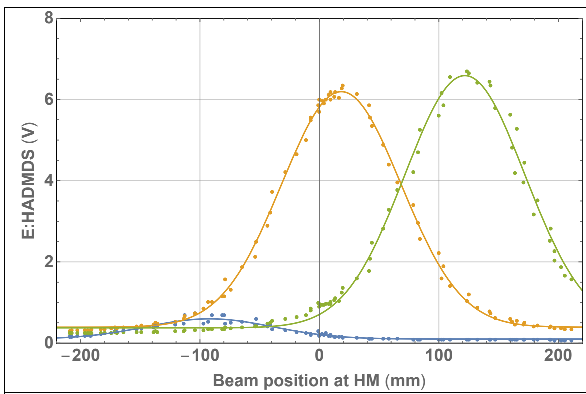
Scan type	**Beam intensity**	**Proton beam position range & horn current**	**Duration**
Hadron monitor scan	< 1e12 protons/pulse. Beam pulse every 10 seconds.	-200 to +200 mm in x and y to cross three or four hadron monitor pixels. 3-5 mm steps. No horn.	20-30 minutes per sweep
X-hair scan	< 1e12 protons/pulse. Beam pulse every 10 seconds.	-10 to +10 mm in x and y until see horn 1 and 2 necks. 1-2 mm steps. No horn.	50-60 minutes per sweep
Target scan	< 1e12 protons on target /pulse. Beam pulse every 10 seconds.	-10 to +10 mm in x and y until see horn 1 and 2 necks. < 1 mm steps.	90-100 minutes per sweep
Thermocouple calibration	~25e12 protons on target/pulse. Beam pulse every 1.33 or 1.2 seconds. No beam sharing with the SY beam line.	-0.8 to +0.8 mm in x and y until see three peaks on the Thermocouple detectors. About 0.1 mm steps.	20-30 minutes per sweep
Horn current scan	< 50e12 protons on target/pulse. Beam pulse every 1.33 or 1.2 seconds. No beam sharing with the SY beam line.	-0.4 to +0.4 mm in x and y until see three peaks on the Thermocouple detectors. 0.02-0.05 mm steps. Vary horn current; 202 (or highest horn current), 201, 199, 198, 195, 190, 180 kA	20-30 minutes per sweep
Beam spot size study	Run when the beam power is fixed. Any beam rep rate.	No beam position change. No horn current change.	60 minutes

Beam intensity study	Run when the beam power is fixed. Beam pulse every 1.33 or 1.2 seconds	-0.8 to +0.8 mm in x and y. Fixed horn current 200 kA. Horn current will be changed by varying beam intensity. Adjust horn current to reach 200 kA.	240 minutes
Residual magnetic field study	< 1e12 protons on target/pulse. Beam pulse every 10 seconds.	Try to close the beam position to the inner conductor at the Horn 1 neck. Turn on and off the horn field.	20 minutes for horn off and 20 minutes with horn field

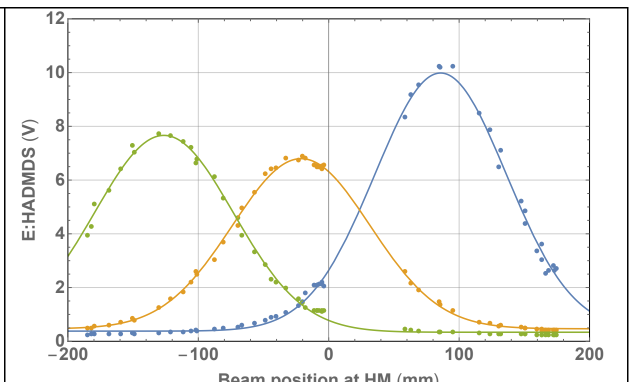
The beam permission switch for a low intensity scan is shown in Appendix B.

The proton beam position and angle are measured the BPM signal (ACNET parameter: E:HP121, E:VP121, E:HPTGT, E:VPTGT). The beam angle is estimated from two BPM signals. Assume we know z position for each beam element, then (x, y) position for each beam element is estimated from the scan result. The beam intensity is monitored by a current transformer (E:TRTGTD), which normalizes the BLM and beam monitor signals.

Below plots show the result of the hadron monitor scan in Fall 2018. The observed ACNET parameters for the hadron monitor signal are E:HADMDS[173], E:HADMDS[174], E:HADMDS[175], E:HADMDS[176], E:HADMDS[177], E:HADMDS[178], E:HADMDS[179] for horizontal, and E:HADMDS[155], E:HADMDS[162], E:HADMDS[169], E:HADMDS[176], E:HADMDS[183], E:HADMDS[190], E:HADMDS[197] for vertical. The RMS of gaussian-fit curve shows the width of the sense area of a single hadron monitor pixel. The peak position shows the center of each pixel. Thus, the gap between peak positions shows the gap of pixel center.

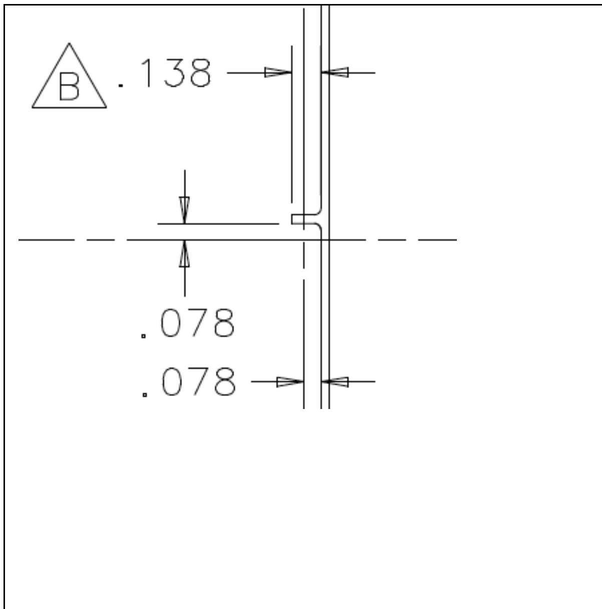


The result of horizontal hadron monitor scan in October 2018. The observed horizontal center of HM is 16.019 +/- 1.112 mm.

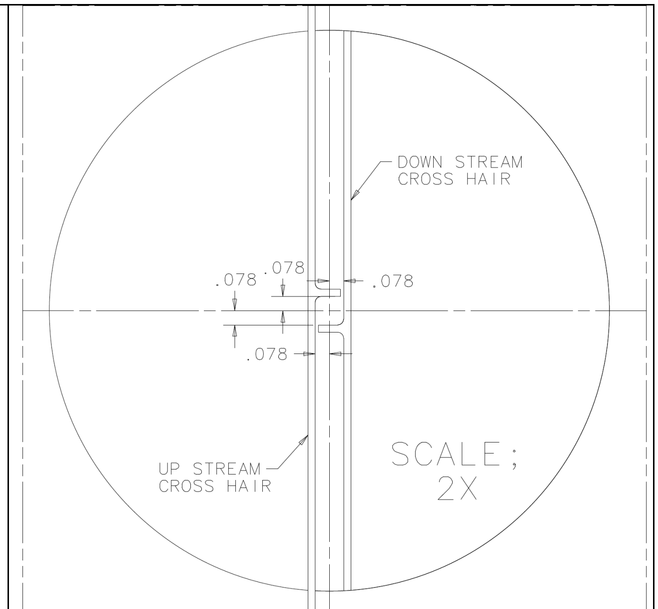


The result of vertical hadron monitor scan in October 2018. The observed vertical center of HM is -20.558 +/- 0.508 mm.

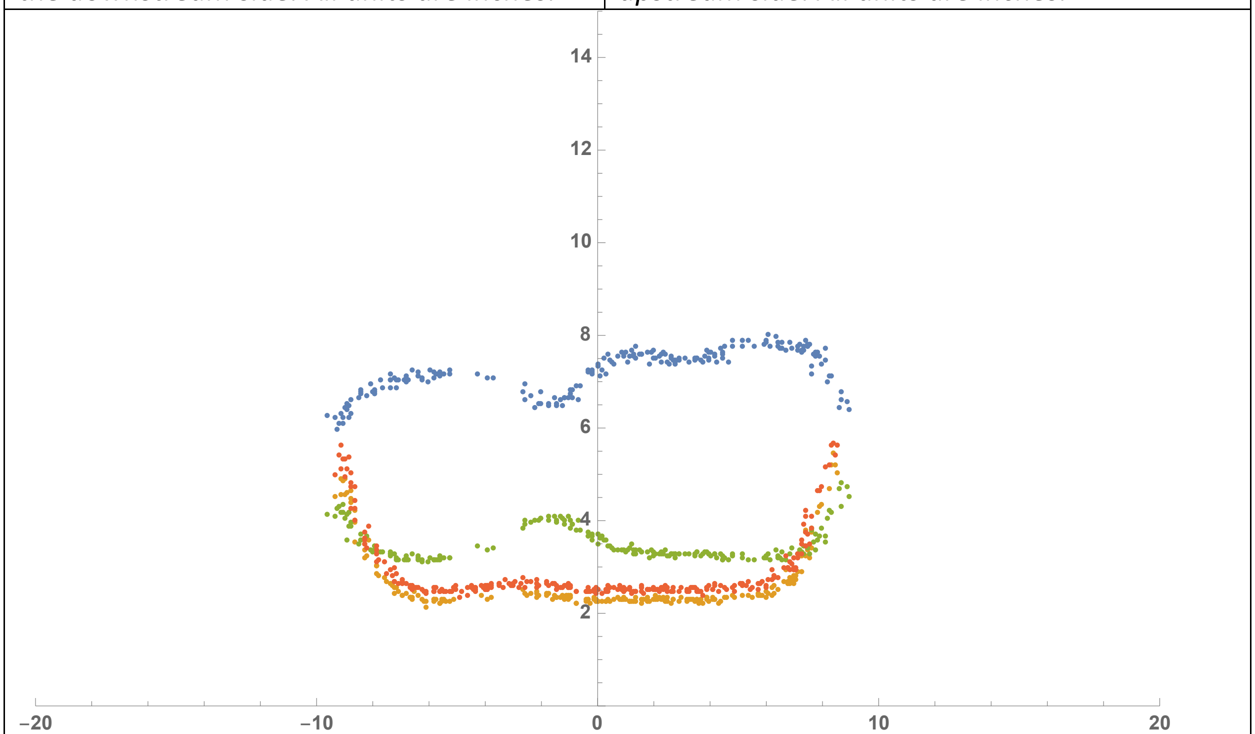
Below plots show the result of the X-hair scan in Fall 2018. The BLM is located near downstream fin of each horn to observe the scattered protons from the Beryllium fin (see Appendix A). The horn 1 has only one vertical X-hair at the downstream end. It locates beam-left by 0.078 inches (-1.98 mm in the BPM x coordinate system). The horn 2 has two vertical X-hairs at upstream and downstream ends. The upstream and downstream X-hairs are located beam-left and beam-right by -0.078 and +0.078 inches, respectively. Each vertical X-hair has a nub which is horizontally extended by 3.5 mm towards the center of the beam and 1 mm height. The ACNET parameter is added E:H1ALM, E:H2ALM and E:HADINT to include the BLM and hadron monitor signals in the analysis.



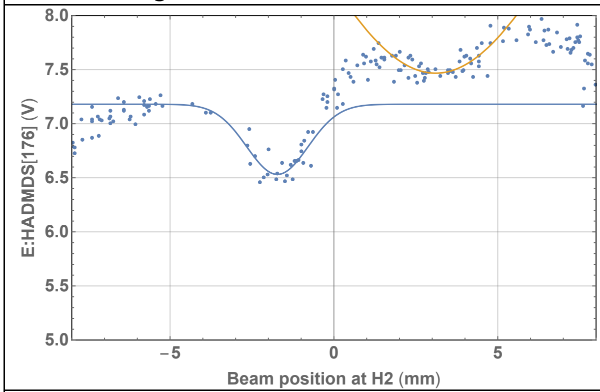
Horn 1 vertical X-hair and nub. View from the downstream side. All units are inches.



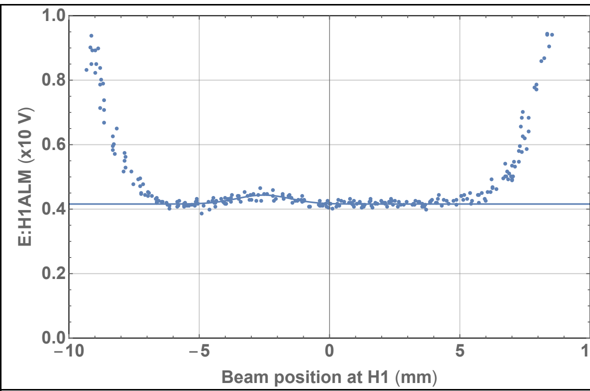
Horn 2 vertical X-hair and nub. View from the upstream side. All units are inches.



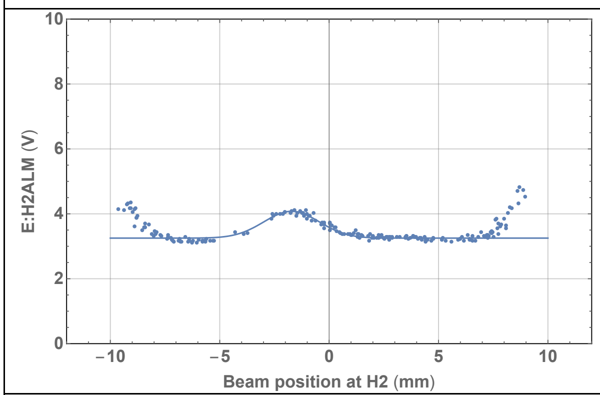
Raw X-hair horizontal scan. Blue is the hadron monitor signal and green, red, and orange are the BLM signal.



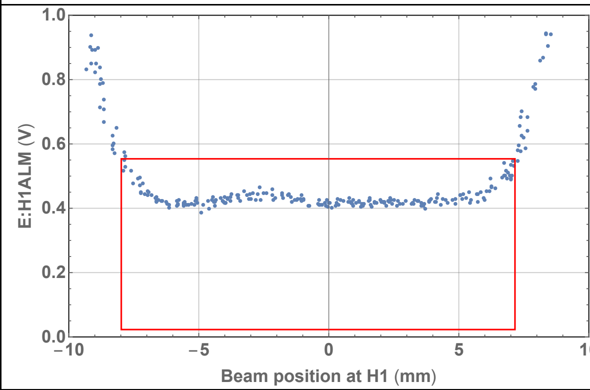
The observed HM signal and analysis curves. The estimated positions of two blips from fitting are -1.725 and 3.103 mm. Former blip can be caused by two X-hairs from the downstream of horn 1 and upstream of horn 2. While the latter blip was made from the X-hair at horn 2.



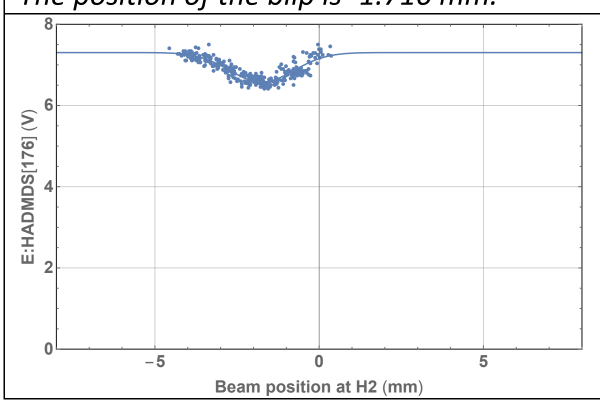
A H1 BLM signal and analysis curve for Horn 1. A blip is caused by the X-hair at horn 1. The position of the blip is -2.530 mm.

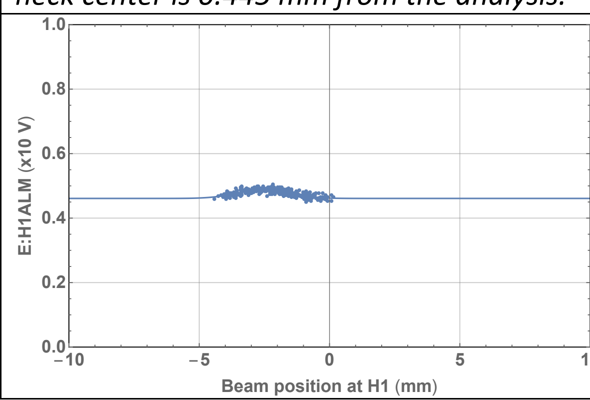


A H2 BLM signal and analysis curve for Horn 2. A blip is caused only by the horn 2 X-hair. The position of the blip is -1.716 mm.



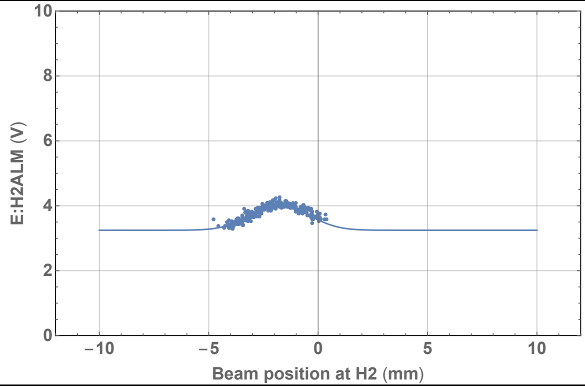
Observed H1 BLM signal. A box is a guide for the eye to find the center of the horn 1 neck. The neck center is 0.445 mm from the analysis.



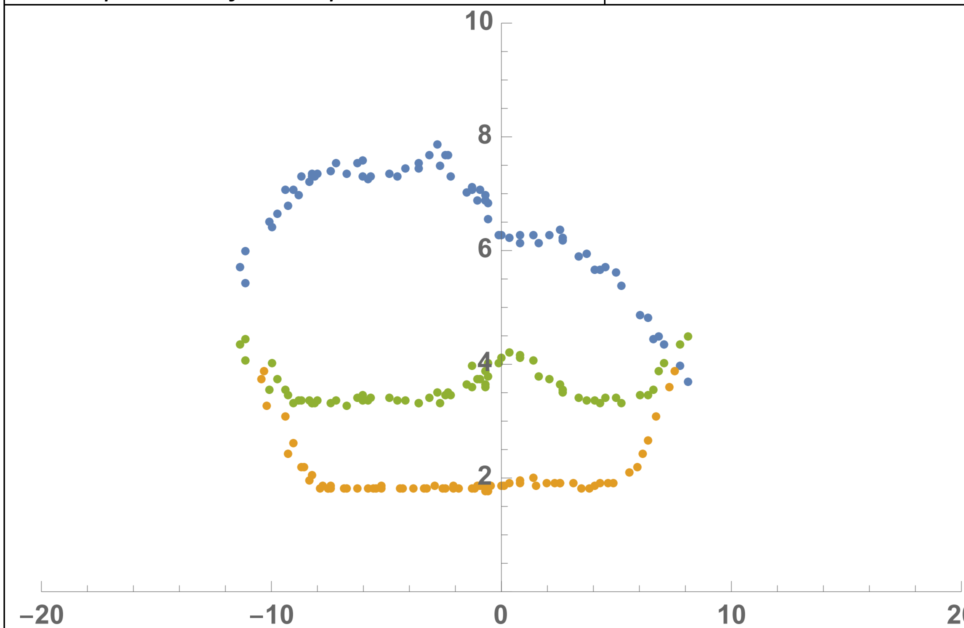


Observed HM signals and analysis curves. The estimated position of a blip from fitting is -1.745 mm.

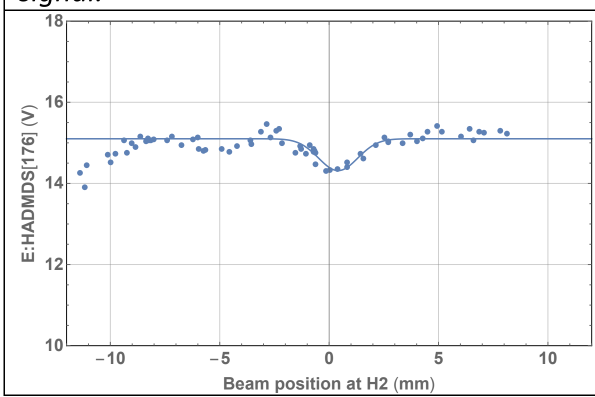
A H1 BLM signal and analysis curve for Horn 1. The position of the blip is -2.532 mm.

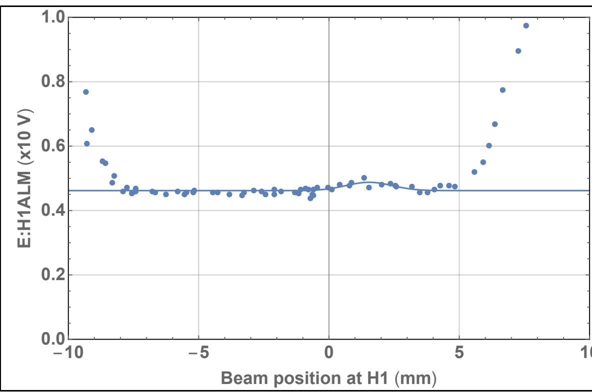


A H2 BLM signal and analysis curve for Horn 2. The position of the blip is -1.742 mm.



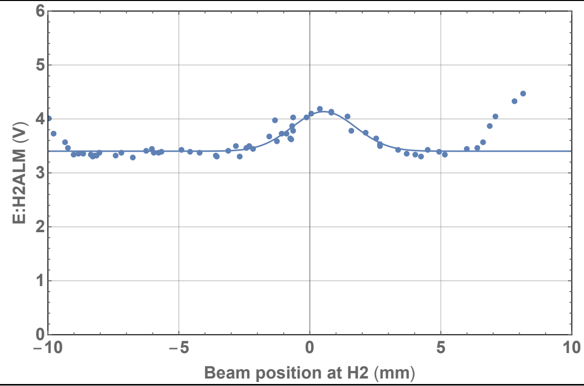
Raw X-hair vertical scan. Blue is the hadron monitor signal, and green and orange are the BLM signal.

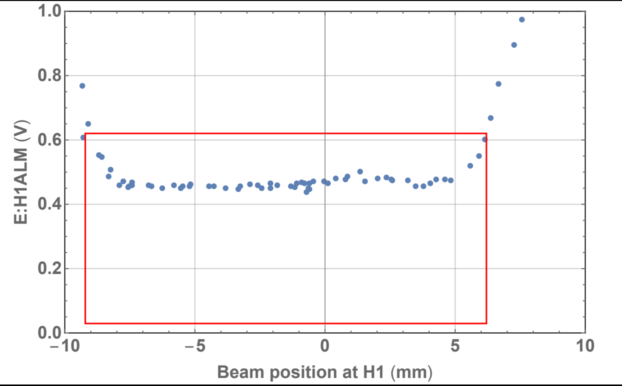




Observed HM signal and analysis curves. The estimated position of the fitted blip is 0.412 mm. We expect that it shows the superposition of two nubs.

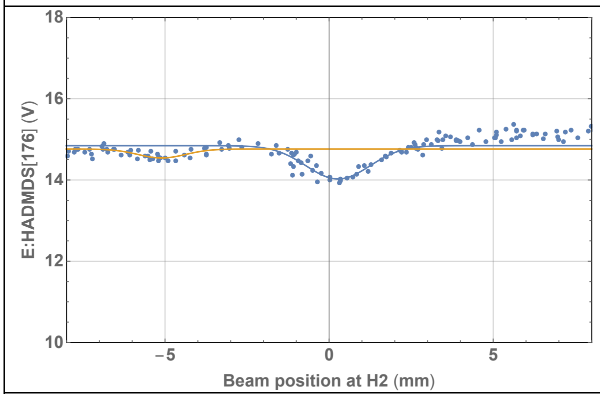
Observed H1 BLM signal and analysis curve for Horn 1. The position of the blip is 1.540 mm.

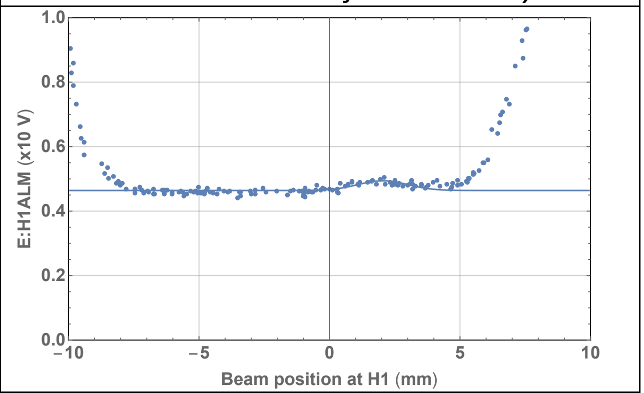




Observed H2 BLM signal and analysis curve for Horn 1. The position of the blip is 0.534 mm.

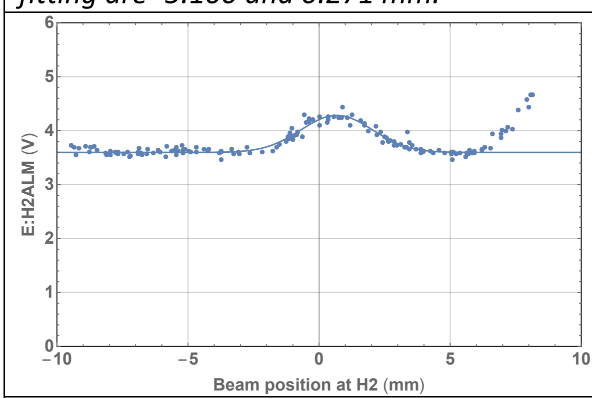
Observed H1 BLM signal. A box is a guide for the eye to find the center of the horn 1 neck. The neck center is -1.535 mm from the analysis.

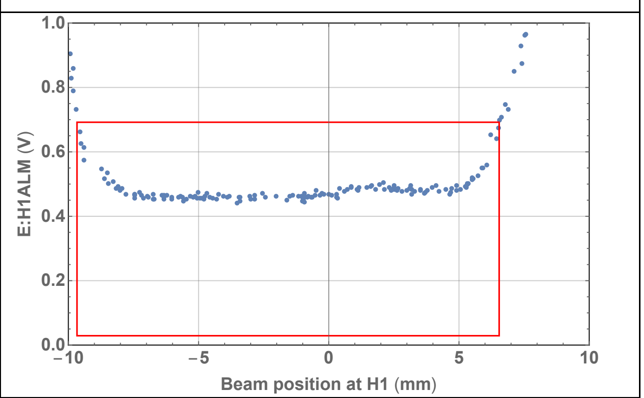




The observed HM signal and analysis curves. The estimated positions of two blips from fitting are -5.100 and 0.271 mm.

Observed H1 BLM signal and analysis curve for Horn 1. The position of the blip is 2.046 mm.

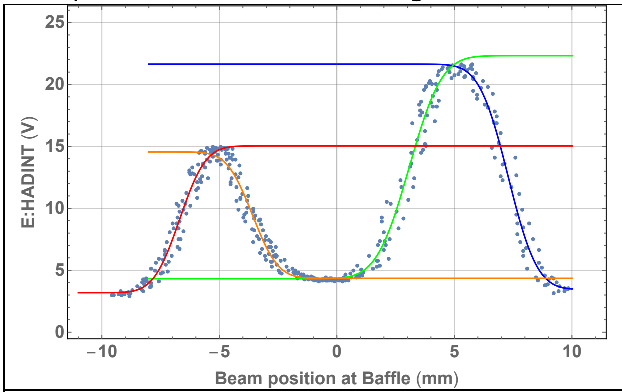
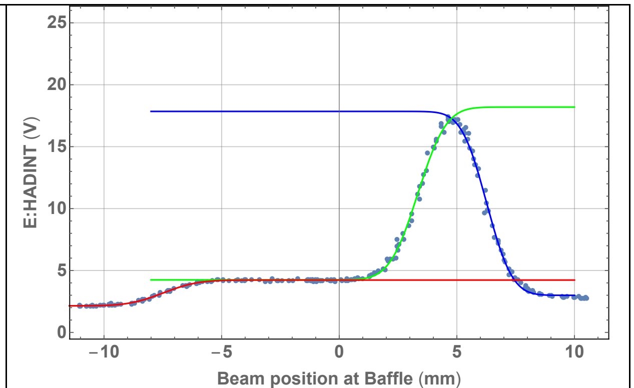




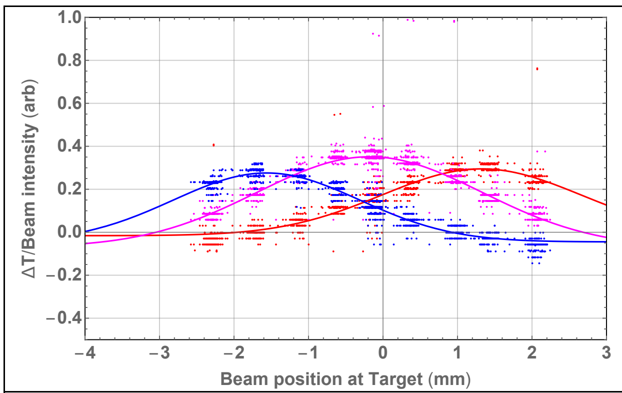
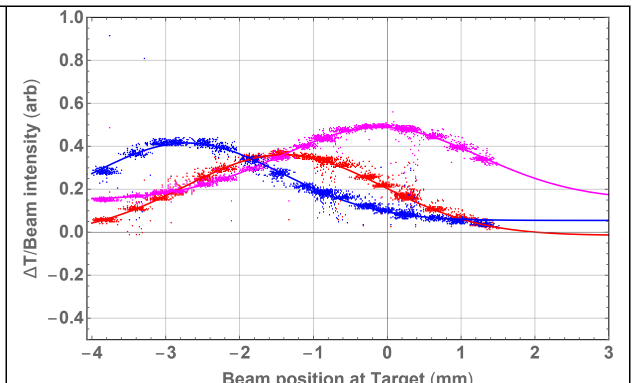
Observed H2 BLM signal and analysis curve for Horn 1. The position of the blip is 0.674 mm.

Observed H1 BLM signal. A box is a guide for the eye to find the center of the horn 1 neck. The neck center is -1.553 mm from the analysis.

Below plots show the result of the target scan. The beam tolerance is evaluated with the target scan result. If we cannot find a beam position within the tolerance, we readjust the target and horn positions and redo the target scan.

	
Observed horizontal target scan. A red and blue curve are the fitting for the left and right sides of baffle, a green and orange curves are the fitting for the left and right sides of target, respectively. The baffle center is 0.300 mm, and the target center is -0.256 mm from the analysis.	*Observed vertical target scan. A red curve is the fitting for the lower side of baffle, a green curve is the fitting for the upper side of target, and a blue curve is the upper side of baffle, respectively. The baffle center is -0.604 mm, and the target center is -0.355 mm from the analysis.*

Below plots show the result of the horn current scan. The first scan is taken with relatively low beam intensity to check the target position. An ACNET parameter is added, E:THPTTW, E:THPTCW, E:THPTBW, and E:THPTHS for horizontal scan, and E:TGTT1, E:TGTT2, E:TGTT3, E:TGTT4 for vertical scan.

	
Observed horizontal scan with the horizontal thermocouple detector. The estimated target center is -0.140 mm.	*Observed vertical scan with the vertical thermocouple detector. The estimated target center is -1.403 mm.*

The beam alignment is evaluated with a tolerance. The estimated beam position and the tolerance of each beam element for the FY19 run are shown in the below spread sheet.

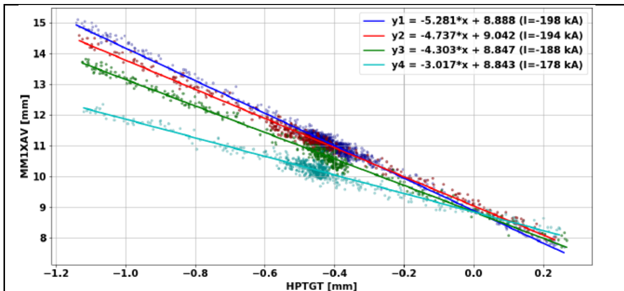
						thpt scar	hpt scan					
				11-Jan-19		med beari	gh beam			Wes		
		(mm)		3nd target scan		(mm)	(mm)	average	residual	est		square of resid
mmin	prev	H bp		station (m)				X (mm)	(mm)	(mm)	esid/est	(R/E)^2
	-0.6	-0.55	set	bpm121	-22							
	-0.5	-0.35	set	bpmtgt	-10							
		-0.223		baffle	-2.4			-0.113	0.11	0.5	0.22	0.04912724
		-0.207		tgt	-1.4	-0.14	-0.295	-0.217	-0.01	0.5	-0.02	0.00046512
		-0.183		MCZERO	0							
		-0.17	extrap	neck	0.82			-0.52	-0.35	0.5	-0.70	0.49092957
		-0.128	extrap	H1 DS fin	3.343			-0.023	0.11	0.7	0.15	0.02250305
		0.146	extrap	H2 US fin	19.76			0.9757	0.83	1	0.83	0.68845519
		0.2127	extrap	H2 DS fin	23.76					1		
		11.633	extrap	HM	709			16.0	4.37	27	0.16	0.02615607
		H										1.27763626
		slope										
		0.2	mm									
		0.0167	mr									

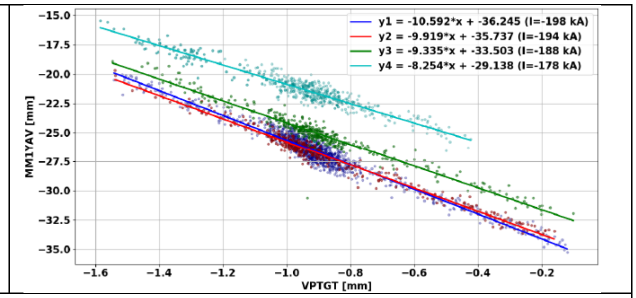
Summary of horizontal beam scan. Top two numbers in the 1st left column (-0.55, -0.35 in the sheet) are the proposed beam position on bpm121 and bpmtgt. Those are used as the AutoTune for the beam operation. The values below are estimated beam position at each beam element from the proposed beam position. The 4th left column (-22, -10 …) are the z location of each element. The 5th and 6th columns are the beam scan result. The 7th column (-0.113, -0.217…) is the average of all beam scan measurement. The 8th column (0.11, -0.01…) is the residual from the estimated beam position and the average element center (ex. -0.113 – (-0.223) = 0.11, (-0.217)-(-0.207) = -0.01 etc). The 9th column is a tolerance of each element. Smaller tolerance means tighter constraint. The 10th and 11th columns are the evaluation of beam alignment. We try to obtain the 10th column value less than 1 and minimize the square of the 10th column value in the 11th column by adjusting the proposed beam position.

						tvpt scar	tvpt scan					
				11-Jan-19		Med beari	gh beam			Wes		
		(mm)		3rd beam scan		(mm)	(mm)	average	residual	est		square of resid
mmin	prev	V bp		station (m)				X (mm)	(mm)	(mm)	esid/est	(R/E)^2
	-0.55	-1.02	set	bpm121	-22							
	-0.65	-1.17	set	bpmtgt	-10							
		-1.265		baffle	-2.4			-1.211	0.05	0.5	0.11	0.01149184
		-1.278		tgt	-1.4	-1.403	-1.624	-1.514	-0.24	0.5	-0.47	0.22321845
		-1.295		MCZERO	0							
		-1.31	extrap	neck	0.82			-1.544	-0.24	0.5	-0.48	0.22762656
		-1.34	extrap	H1 DS fin	3.343			-0.704	0.63	0.7	0.90	0.81795786
		-1.542	extrap	H2 US fin	19.76			-1.942	-0.40	1	-0.40	0.15984004
		-1.592	extrap	H2 DS fin	23.76					1		
		-10.16	extrap	HM	709			-20.6	-10.44	27	-0.39	0.14958272
		V										1.58971747
		slope										
		-0.150	mm									
		-0.013	mr									

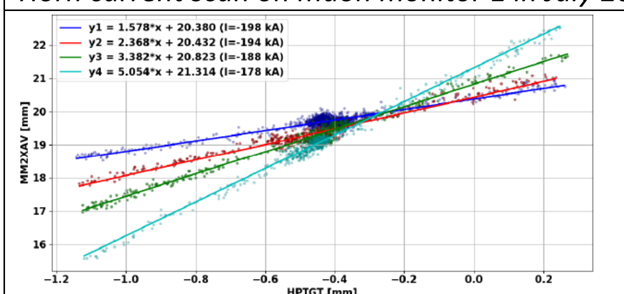
Summary of vertical beam scan. Similar column structure as the horizontal spread sheet.

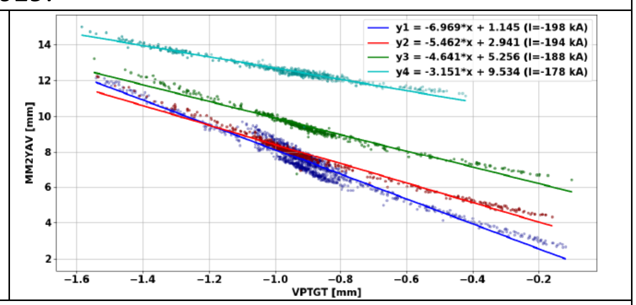
After the target scan is concluded, the target pile is sealed and start the normal beam operation. When the MI run the slip stacking mode, we carry out another horn current scan. Below plots show the result of the horn current scan by using the muon monitor. The observed slope should be unique for each muon monitor while the observed offset is variable since it is caused by misalignment or tilting of the horns. The analysis is still developing. Add ACNET parameter, E:MM1XAV, E:MM2XAV, E:MM3XAV for horizontal scan, and E:MM1YAV, E:MM2YAV, E:MM3YAV for vertical scan.



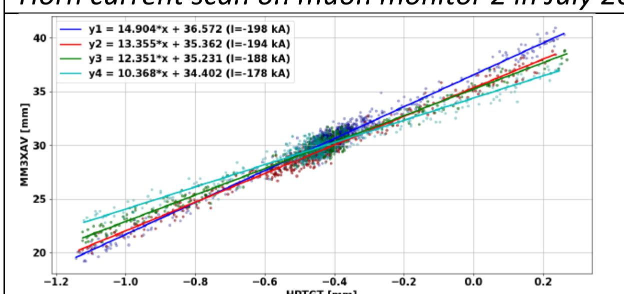


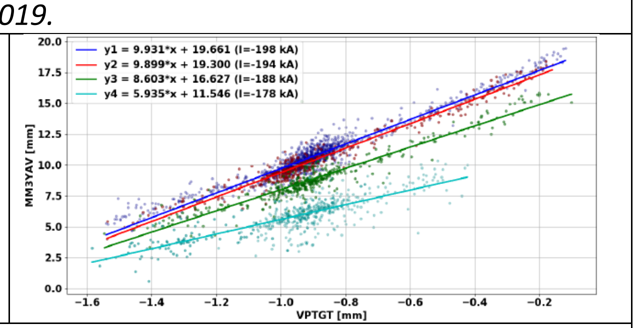
Horn current scan on muon monitor 1 in July 2019.





Horn current scan on muon monitor 2 in July 2019.

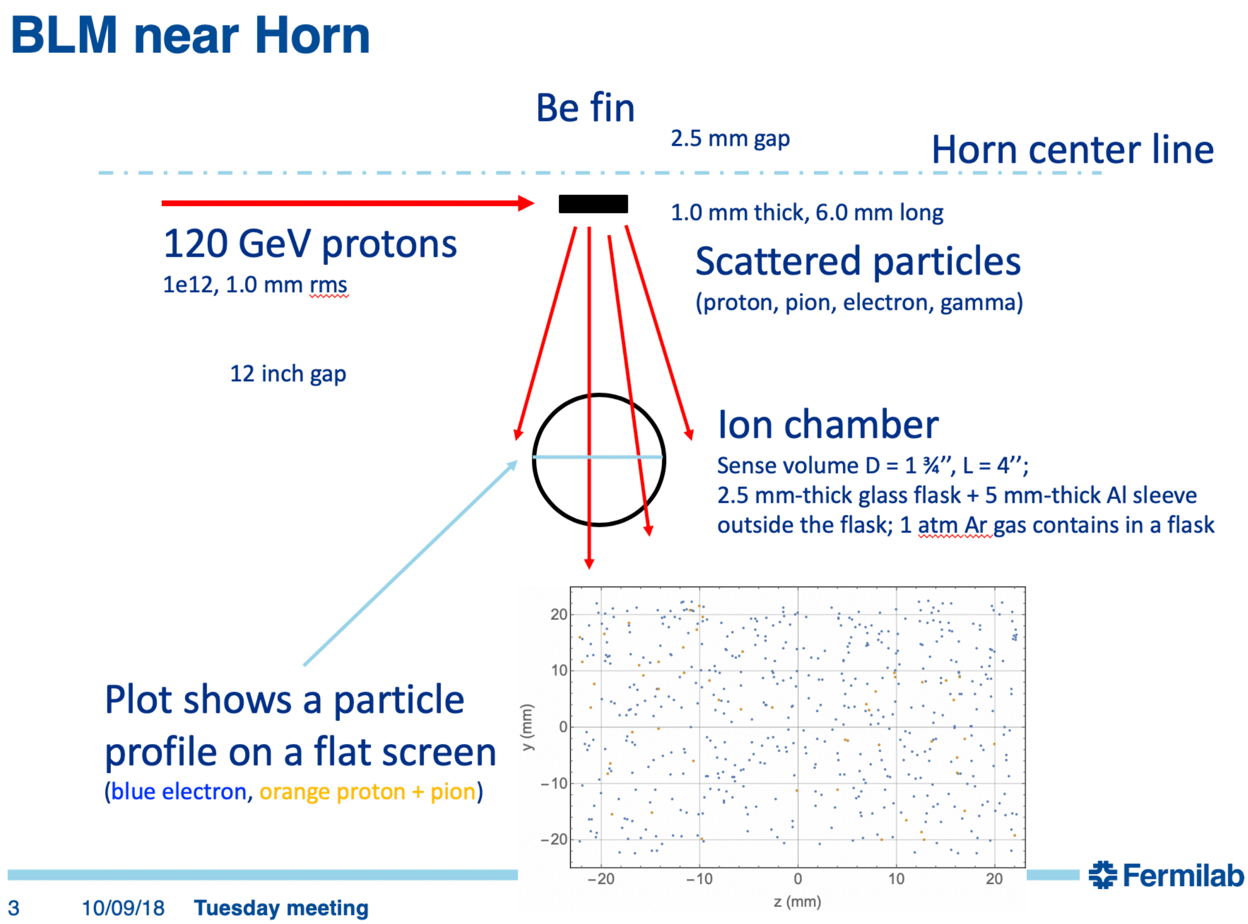




Horn current scan on muon monitor 3 in July 2019.

Since we never carry out the beam spot size study and the beam intensity study, we do not have any plot for them. Those studies are very important to find out the systematics in the muon monitor signal. Therefore, we will run the beam study a couple of times.

Appendix A. BLM



Appendix B. Beam permission

8/2/13		Jim Hylen		
11/4/13	rev	Checklist for NuMI special runs beam permit changes	I:VI607N max 23000 becomes 30000	6/20/17
6/3/14	rev	more to mask for tgt scans	E:TOR101 max 40 becomes 54	6/20/17
10/16/15	rev	add E:NHSASF mask for horn slow start reference	add -E:BPBBAM	6/20/17
10/16/15	rev	add note on BLM supplies	I:VI607N scan max 700 becomes 800	Nov-17
10/28/16	rev	no shield wall for horn scan; BLM voltage adjust	Also note 10 sec repetition rate	7/2/18
	rev	BAMs 62 instead of 14 for normal ops	add changing lower limit on I:VI607N	7/3/18
	rev	MINOS no longer a NuMI experiment		

Target scan at LOW INTENSITY

Done	Undone	Action	Notes
		Talk to MCR **crew chief** at start of study	remind about dangers of changes in timeline
		Ask for 2 or 3 turn 1 batch (**8 to 12e11 proton/spill**)	MCR operators
		repetition rate: 10 sec between spills	MCR operators
		Inform **Experiments**	**x2482** common for Minerva NOVA
		E38 BPMS page 2 -E:BPS**BAM** 62 --> 0	Switch from batch averaging (batches 2,3,4,5,6)
		E38 BPMS page 2 -E:BPN**BAM** 62 --> 0	to single batch (1st batch) for BPM readback
		E38 BPMS page 2 -E:BP5**BAM** 62 --> 0	otherwise autotune doesn't work
		E38 BPMS page 2 -E:BPB**BAM** 62 --> 0	
		E40 60A channel 60 **I:VI607N** MAX 30000 -> 700	Abort if too much intensity in Main Injector
		E40 60A channel 60 **I:VI607N** MIN 2000 -> 50	lower the lower intensity limit
		E40 60A channel 47 **E:TOR101** MAX 54 -> 1.2	Trip if too much beam comes down NUMI line
		IF target pile fan speed slow:	*(because R-blocks not caulked yet)*
		mask E40 THA channel 45 E:TPCFDP	Target pile fan differential pressure
		Change spot size (quad currents) IF DESIRED	*See separate instructions in memo pad*
		let Autotune get beam aligned	
		turn off Autotune	
		mask E40 65A channel 52 **E:HP121P**	Otherwise BPM will trip when scan
		mask E40 65A channel 53 **E:VP121P**	outside normal limits
		mask E40 65A channel 54 **E:HPTGTP**	ditto
		mask E40 65A channel 55 **E:VPTGTP**	ditto
		mask E40 65B channel 20 **E:VT118F**	mask trim magnet current reference
		mask E40 65B channel 21 **E:VT118**	mask trim magnet current readback
		mask E40 65B channel 24 **E:HT119F**	ditto
		mask E40 65B channel 25 **E:HT119**	ditto
		mask E40 65B channel 28 **E:HT121F**	ditto
		mask E40 65B channel 29 **E:HT121**	ditto
		mask E40 65B channel 32 **E:VT121F**	ditto
		mask E40 65B channel 33 **E:VT121**	ditto
		Use **E38 TRMS page 9** XSCAN and YSCAN	for scans parallel to beamline (target scan)
		~1/4 mm steps = ~1/2 amp on HT119 or VT118	F5: vert more pos or horz more neg (F4 opposite)
		*Use **E38 TRMS page 8** XPRSCAN and YPRSCAN*	*if angling beam (hadron monitor scan)*
			F5: vert ang more neg or horz ang more pos
		REVERSE ABOVE STEPS AT END OF SCAN	**MAKE SURE SPOT SIZE is 1.1 or 1.3 mm after scan**

IF Target/baffle module is removed — ***as for horn scans***

Done	Undone	Action	Notes
		mask E39 THB permit input 2	Target and Baffle RAW skid OK
		mask E39 THB permit input 7	Target and Baffle RAW flow OK
		mask E40 THA channel 34 E:BAFT1	baffle temperature
		mask E40 THA channel 35 E:BAFT2	baffle temperature

IF Horn off (E38 Horn page 2) — ***as for horn beam scans***

Done	Undone	Action	Notes
		mask E39 THA permit input 3, E:NHSA	Horn PS Rectifiers On
		mask E40 THA channel 0 E:HSLI	horn current limits
		mask E40 THA channel 1 E:NHSAF	horn supply voltage
		mask E40 THA channel 3 E:NHSASF	horn current slow start
		mask E40 THA channel 5 E:HSLIP	horn current
		For horn current scans, leave E39 THA chan 3 on	***but mask others***

For scan using horn cross-hair BLMs — E:H1ALM, E:H2ALM are the signal channels

Done	Undone	Action	Notes
		manually turn on BLM HV in power supply room	HV should be off at all other times
		2 supplies nominally 200 V marked H1ALM H2ALM	HV should be off at all other times

some notes on conditions:

- Now have movable shielding to be in place during survey of target, need shield wall open to remove it.
- Hence will not close shield wall for horn scan; will remove portable shielding and close shield wall during target install.
- To compensate for lack of shield wall, will not have access underground during horn scan beam.
- Although Trarget module will not be in chase, all the T-blocks and the upstream blue blocks are in.
- Put crane at downstream end of target hall especially during horn scan without target module in.
- Fan is at reduced speed.
- horn scan is done with horn off (ESH asked about horn focus on beam during scan)

Appendix C. ACNET parameter

Hadron monitor scan
E:HP121, E:VP121, E:HPTGT, E:VPTGT, E:TRTGTD
E:HADMDS[173], E:HADMDS[174], E:HADMDS[175], E:HADMDS[176], E:HADMDS[177], E:HADMDS[178], E:HADMDS[179] for horizontal, and
E:HADMDS[155], E:HADMDS[162], E:HADMDS[169], E:HADMDS[176], E:HADMDS[183], E:HADMDS[190], E:HADMDS[197] for vertical

X-hair scan
E:HP121, E:VP121, E:HPTGT, E:VPTGT, E:TRTGTD
E:H1ALM, E:H2ALM, E:HADINT, E:HADMDS[176]

Target scan
E:HP121, E:VP121, E:HPTGT, E:VPTGT, E:TRTGTD
E:HADINT, E:HADMDS[176]

Horn current scan
E:HP121, E:VP121, E:HPTGT, E:VPTGT, E:TRTGTD
E:THPTTW, E:THPTCW, E:THPTBW, and E:THPTHS for horizontal scan, and
E:TGTT1, E:TGTT2, E:TGTT3, E:TGTT4 for vertical scan
E:NSLINA, E:NSLINB, E:NSLINC, E:NSLIND