Injector Solenoids: next-to-next-to-final-designs
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Abstract

Since 2012 I have been working on magnetic designs of of replacement solenoids for the injector, both keV and MeV regions. These are discussed in TNs 12-062, 14-022, 15-029, 15-036 and 18-004. Alicia Hofler has done extensive GPT modeling of the chopper region and less extensive work on the full injector up to the quarter cryomodule. This has informed the choice of a final magnetic design aka the next-to-next-to-final-designs. The "next-to-final-design" will be a mechanical design by Danny Machie. This will include options for metric vs inch materials. The final design will be that of the magnet manufacturer awarded the contract.

Discussion

The field uniformity within a solenoid is determined by the number of coils, the coil locations and the radius of the steel end plate. Since the injector solenoids are a mix of single-wound and counterwound, two coils are within the package. The physical constraint is the size of the recess in the chopper vacuum vessel: 9" ID by about 4.25" long. Inspection showed the 9" recess is not quite round so an 8.5" OD, 0.25" wall carbon steel mechanical tube was chosen for the outer iron. 2.2 mm copper (64 oz. sheet, BS gauge 11) was chosen to provide an "air gap" between coil and 3.2 mm (1/8") end and middle steel annuli. The radius of the three annuli was then varied. One model, with 45 mm IR of the steel, is shown in figure 1.

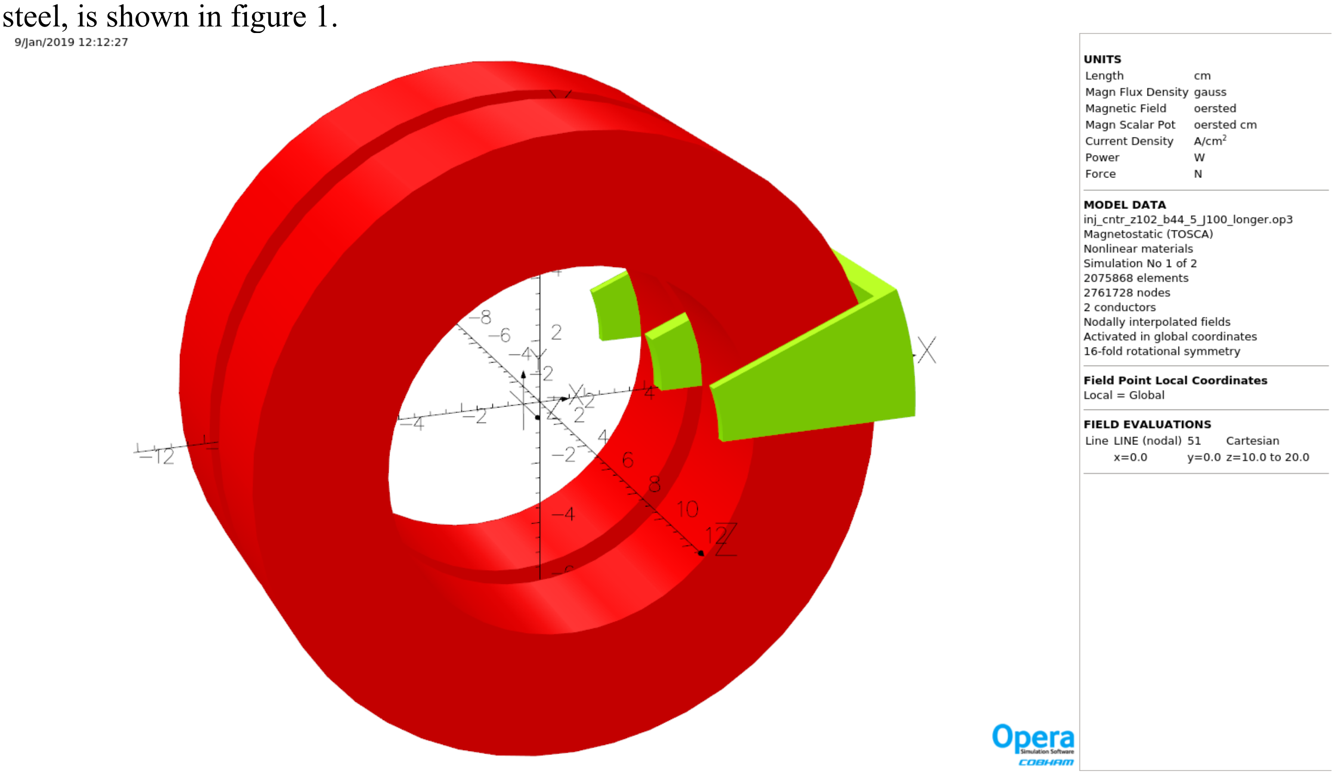


Figure 1. The model with the steel annuli extending in to 45 mm radius. Azimuthal symmetry of n=16 applied to reduce the size of the model. The coils are 57 mm IR. The other model to be discussed in some depth has steel annuli with the same 57 mm IR as the coils. Models with IRs 32, 38, 45, 50, 57, 65, 70, 75, 80, 85, 90 mm were solved during the six years of the effort. See older TNs for discussion.

There is a tradeoff between focusing flatness across the bore of the magnet and field outside the steel. The existing solenoids accept 10-42% variations in focusing across the beam in order to reduce the stray field to negligible values one cm from the end. This seemed to me to be problematic from a halo generation point of view: if the outside of the beam is focused more than the core, the beta functions of the core and halo will be quite different and can persist throughout the accelerator. The 45 mm IR design has 6% span over the chopping slit and the 57 mm 4% vs 40% for the existing solenoids, an improvement of a factor of seven or ten, as shown in the bottom of Figure 2.

1 FD: Magnet setpoints adjusted to produce same focal length at 15 mm

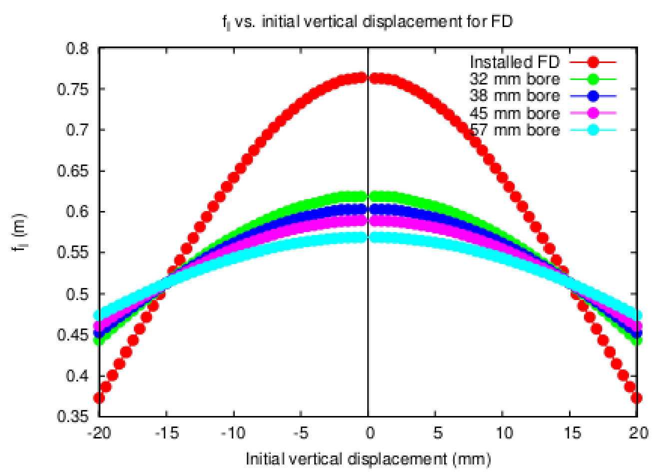


Figure 1: Focal length (f_l) vs. initial vertical displacement

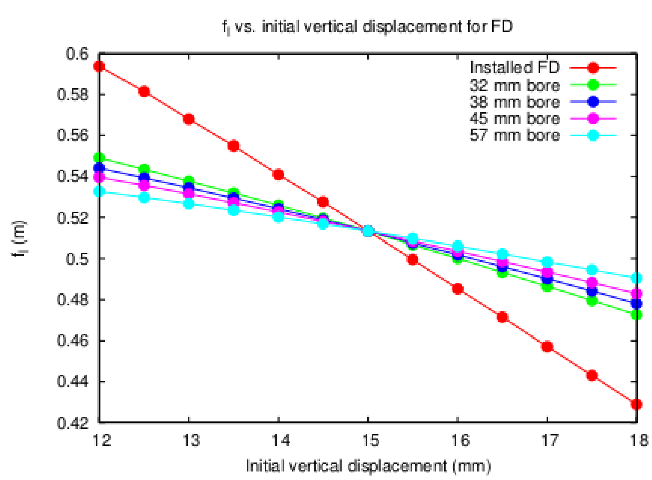


Figure 2: Focal length (f_l) vs. initial vertical displacement around 15 mm

Figure 2. Alicia Hofler's evaluation of the proposed solenoids with varying bores and the existing FD. The chopping circle has 15 mm radius. The slits have +-3mm radial extent about this. Cyan is the model with 57 mm IR and purple the one with 45 mm IR. The models differ only in the inner radius of the three steel annuli.

1 FA: Magnet setpoints adjusted to produce same focal length at 3 mm

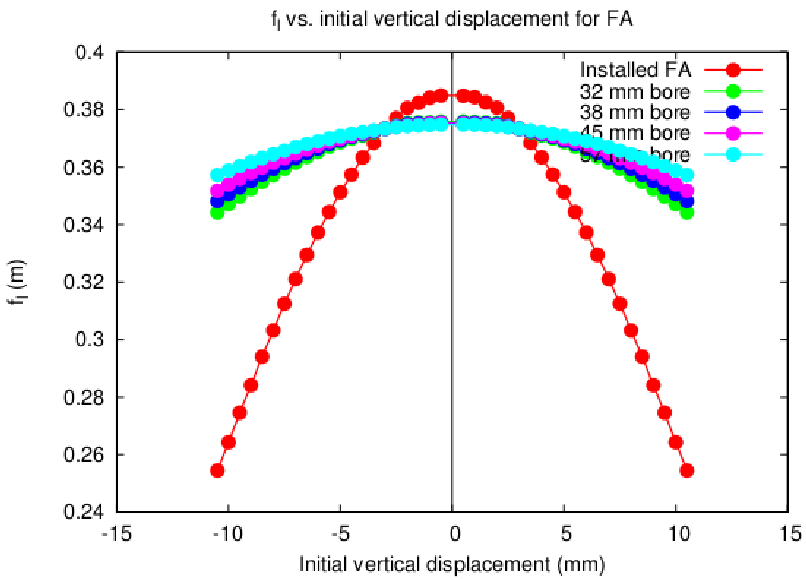


Figure 1: Focal length (f_l) vs. initial vertical displacement

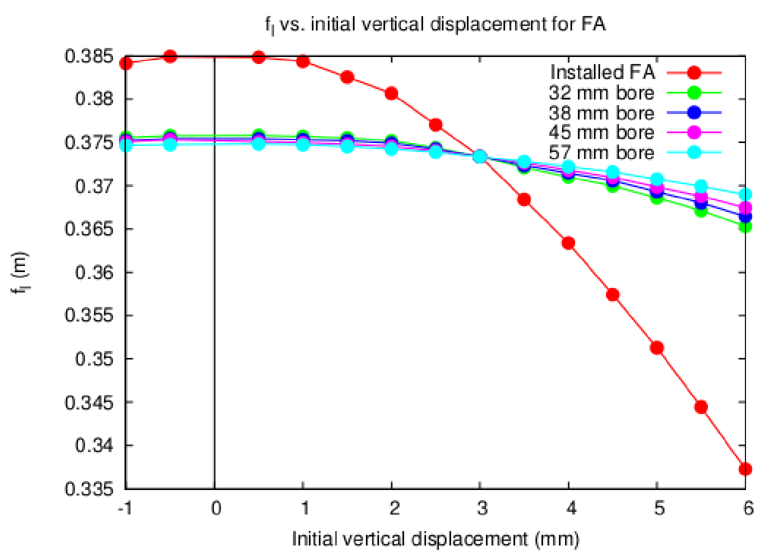


Figure 2: Focal length (f_l) vs. initial vertical displacement around 3 mm

Figure 3. Alicia Hofler's evaluation of a typical solenoid with beam centered and the same four models. The latter hardly differ at small radii. The advantage of a 45 mm IR is that it fits over a 3.375" (85.725mm) CF flange which takes a 2" tube. This flange and the 4.5" (2.5" tube) are most common in the injector. Solenoids which would fit over the 4.5" flange were examined in early years but are very inefficient, low Bz for a given current.

It would seem that the 57 mm IR, which has manufacturing advantages as well as flatter field, is the better choice. Stray field moves the needle. Below one sees how Larmor rotation moves the beam off the center of the B slit as a function of model.

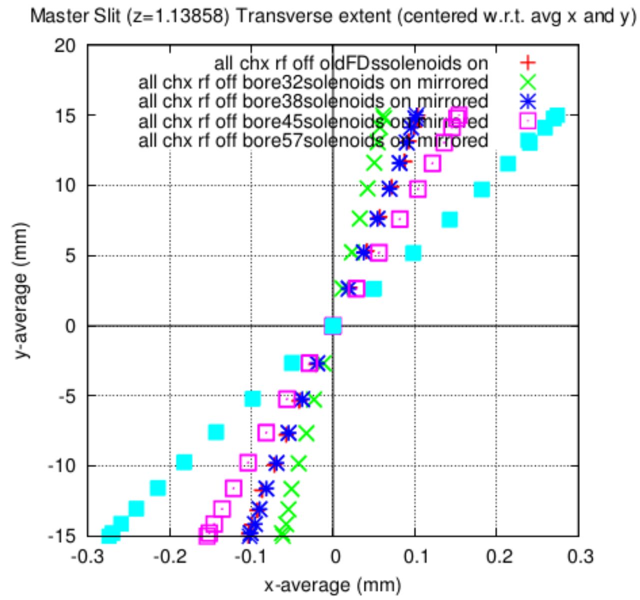


Figure 5: chy rf on mirror transverse at z=1.13858

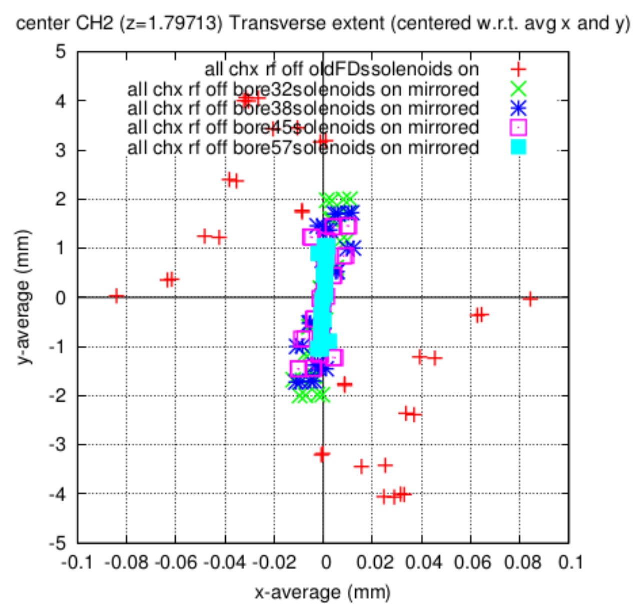


Figure 6: chy rf on mirror transverse at z=1.79713

Figure 4. Top panel, labeled Figure 5 by Alicia, shows a string of 36 bunches at 10 degree intervals at the master slit. The FD model, red crosses, is barely seen under the blue asterisks. The 45 mm IR has about 50% more deflection than the existing FD, to 150 microns, while the 57 mm has 300 microns. The lower pane shows how well the bunches are re-converged at the center of the second chopper cavity. All of my models are a substantial improvement over the existing FD. *Horizontal and vertical scales are very different in both panes of this figure.*

Field for constant amp-turns is another consideration which mitigates towards the 45 mm IR.

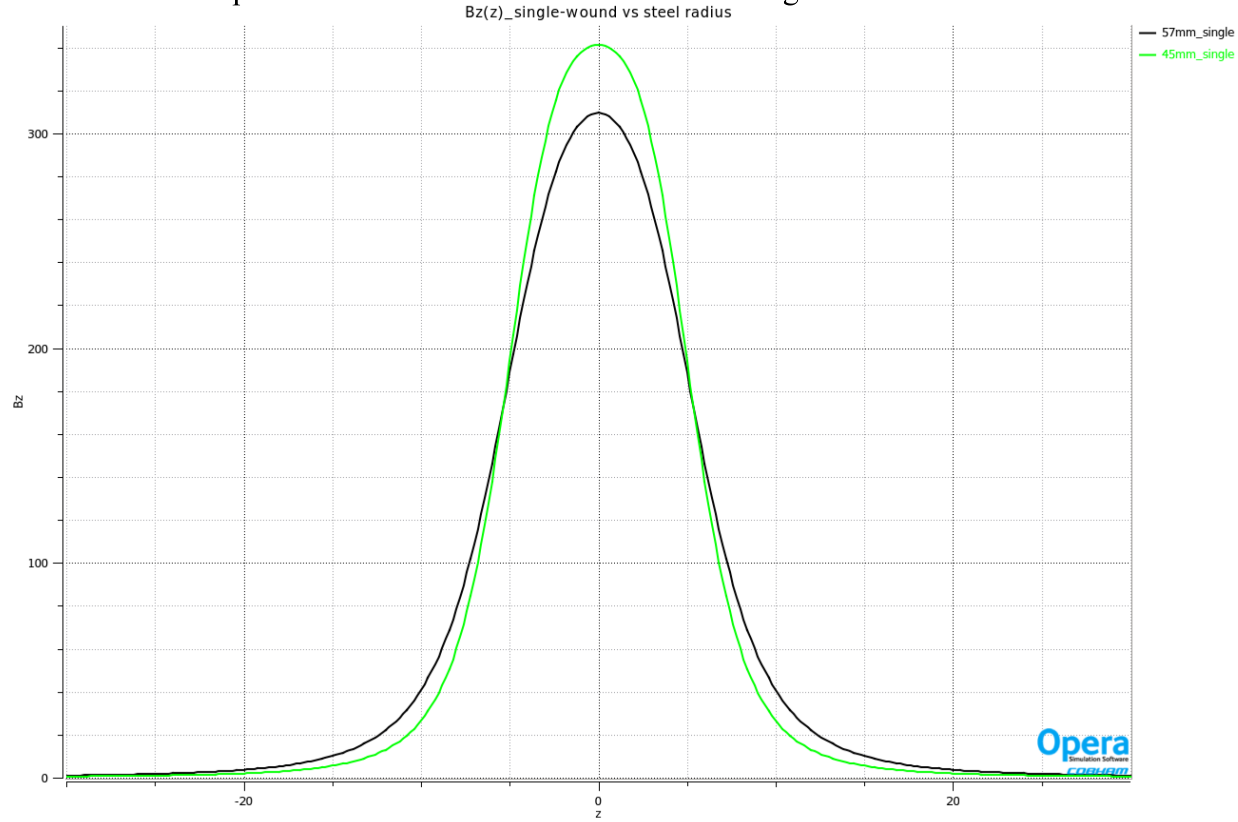


Figure 5. Bz(z) for single-wound units with 57 mm (black) or 45 mm (green) IR annuli, 1600 AT.

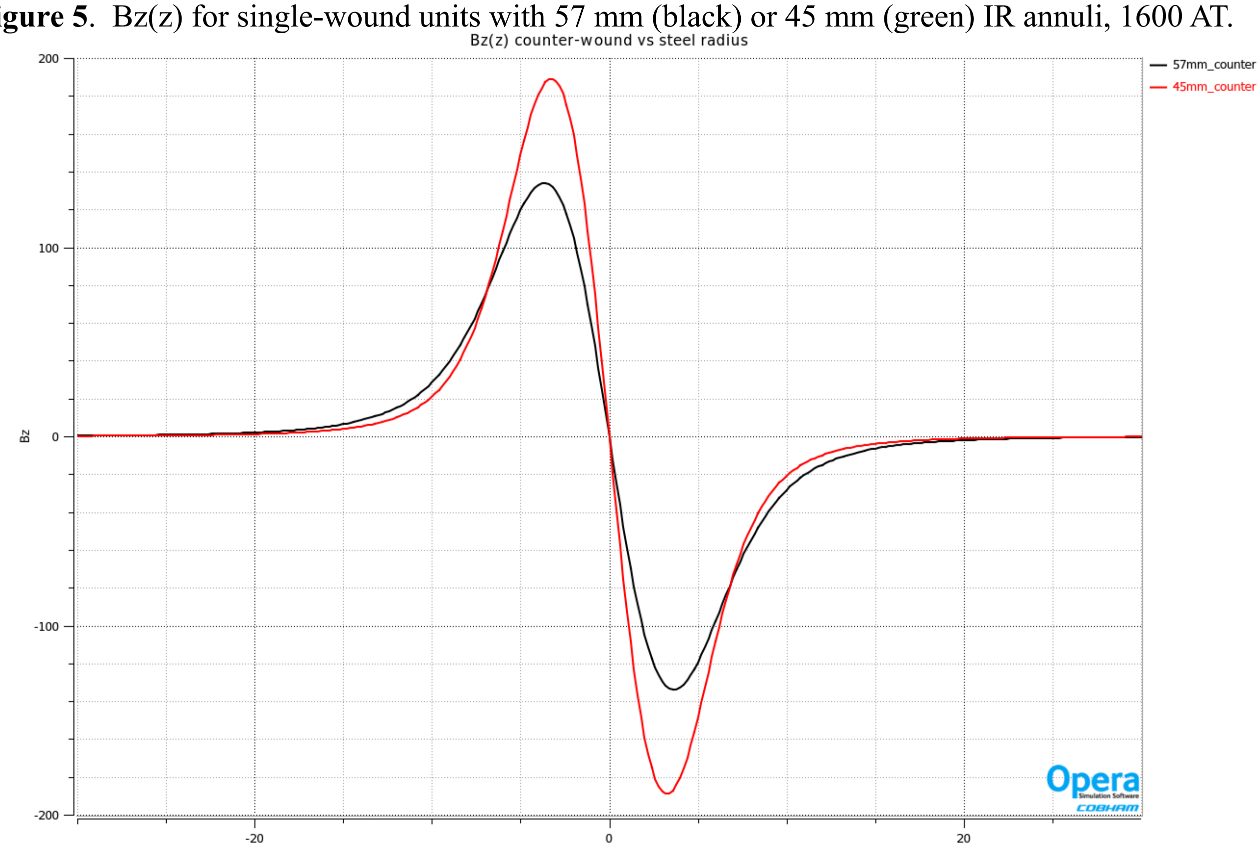


Figure 6. Bz(z) for counter-wound units with 57 mm (black) or 45 mm (red) IR annuli, 1600 AT.

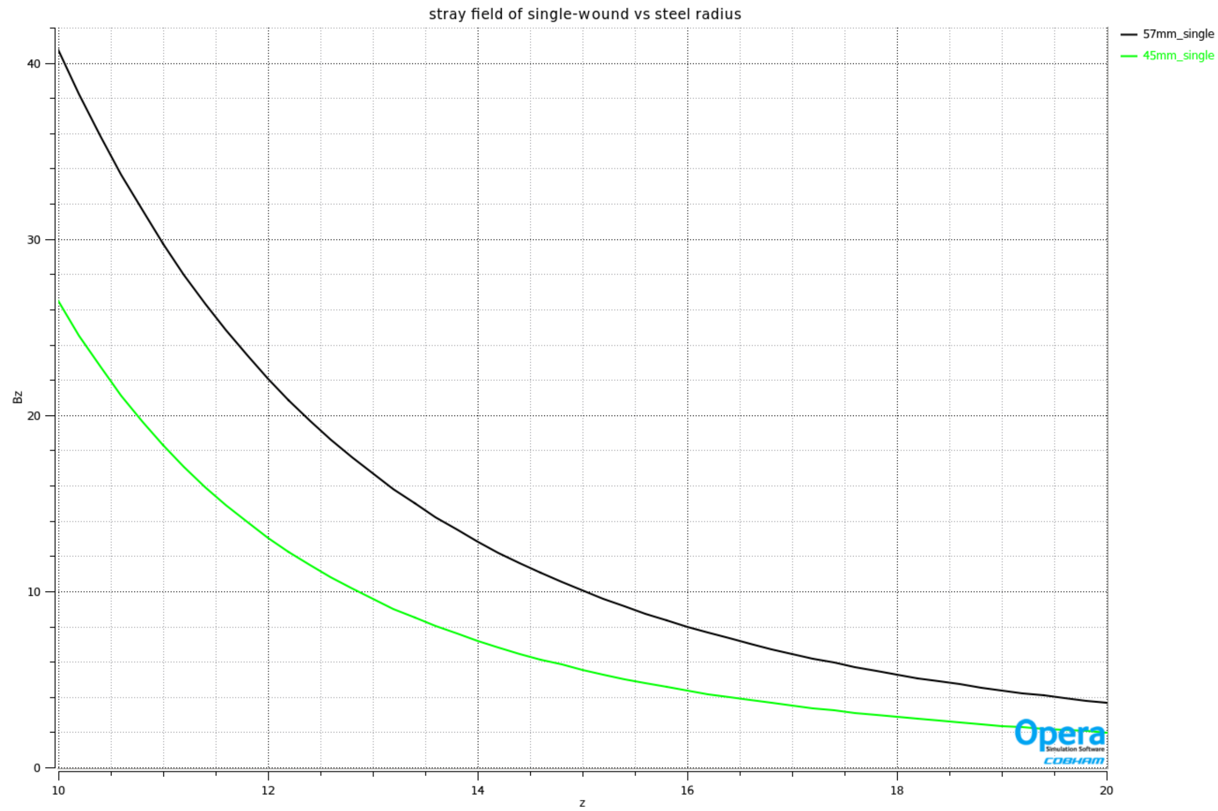


Figure 7. Enlarged section of Figure 5 to better show stray field extent. 45 mm radius has less, as expected.

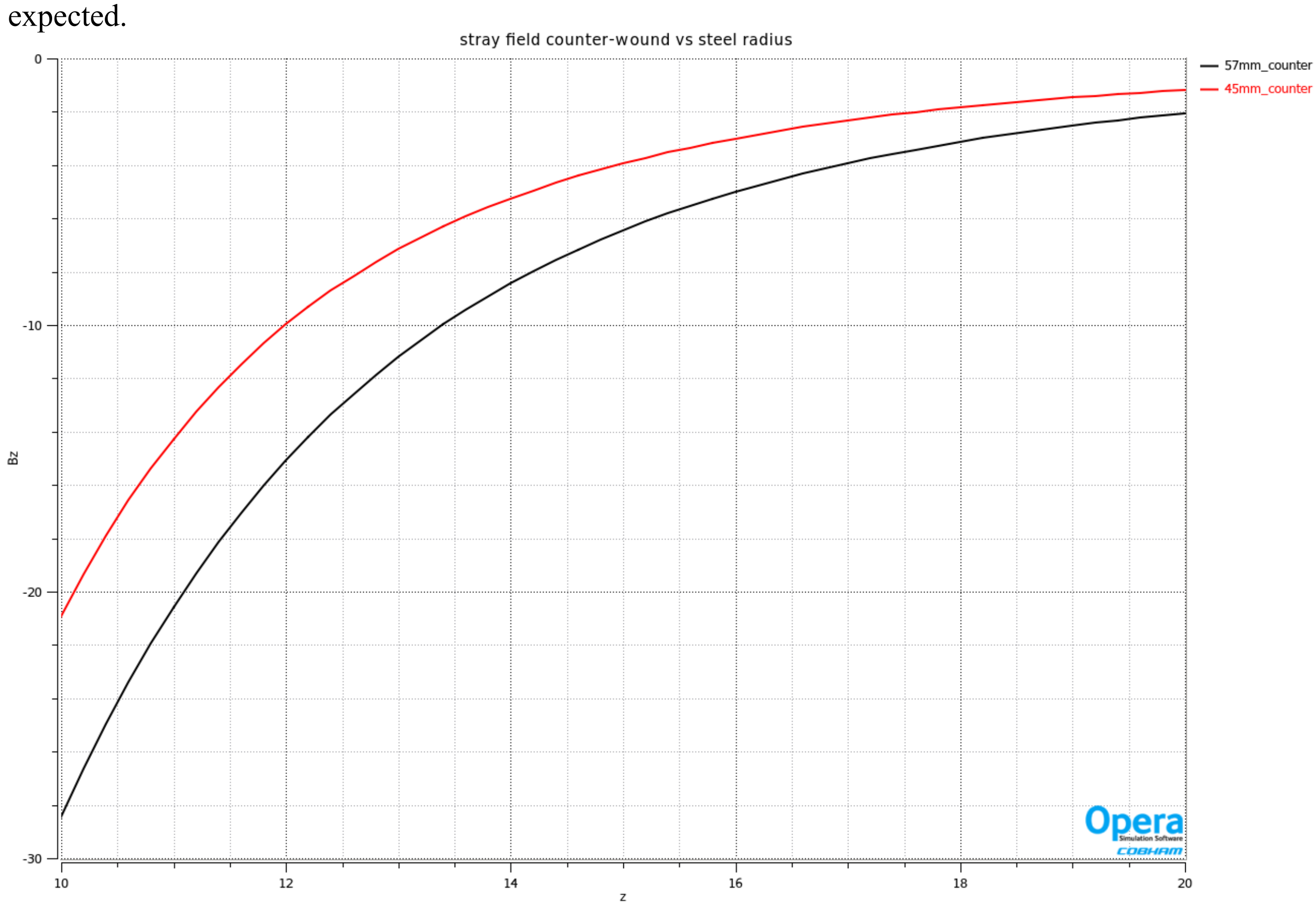


Figure 8. Enlarged section of Figure 6 to better show stray field extent

The lower stray field of the magnets with 45 mm IR annuli produce the lower deflection shown in the top pane of Figure 4. The greater efficiency, i.e. larger B^2 at fixed Amp-Turns (AT), also weights the scale in favor of the 45 mm design. Unfortunately, this complicates the mechanical design. All the parts of the 57 mm IR design could be mounted on a 4” copper water pipe, 4” ID and 4.5” OD, turned down slightly to make the OD a better reference (datum). The 45 mm IRs mean that the system must be mounted on a part with 86 mm ID as sketched below. The middle steel annulus must be made in two parts as it can't slide over the 57 mm OR section.

One assembly concept is crudely sketched below. If Danny Machie can come up with another method to align the inner radii of the steel and coils to within 0.1 mm concentricity, great. The mandrel shown below would be aluminum for assemblies which will not be baked, to reduce machining costs, and austenitic (300 series) stainless for the four that will or might be baked to 200 C. Differential expansion of aluminum vs copper precludes its use in the baked region.

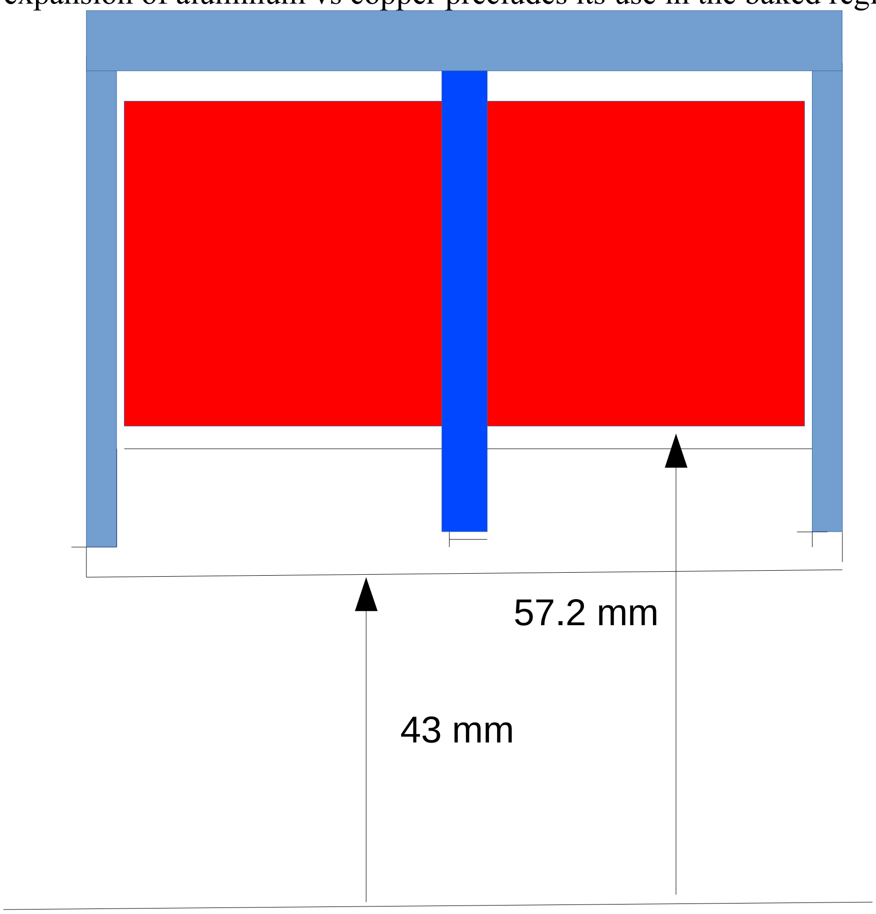


Figure 9. Crude cross-section sketch. Dark blue steel must be in two pieces since it can't slide over the OD of the mandrel at the coil locations.

An alternative would be to mount the coils on ~4 cm segments of 4” copper pipe, 4.5” OD (57.15 mm OR) with 0.25” wall, make the steel pieces full annuli, and drill four precision 3 mm holes through which alignment rods with threaded ends can be slid to align the package. Another variation would be to machine the IDs of the five segments precisely and make a precision tool mandrel on which they would be slid to align. The holes in the five pieces need not be as precise in this case, the IDs are the datums.

In https://jlabdoc.jlab.org/docushare/dsweb/Get/Document-105912/15-029.pdf (appended) I discuss the use of similar solenoids in the 6 MeV region. Two coils with 9-10 mm cooling plates on either side, three total, would be required. These coils would be run in series to form a single-wound assembly so no central steel would be used. A pair of these assemblies separated by 12 cm would make a counter-wound unit. Copying a table and paragraph from page 5 of the TN:

Table 1. Nominal Z spans of materials in the low and high momentum solenoids

Material	Low P (mm)	High P (mm)
Steel annulus	3.2	6.4
Copper*	2.2	10
Coil	43	43
Copper*	2.2	10
Steel annulus	6.4	0
Copper*	2.2	0
Coil	43	43
Copper*	2.2	10
Steel annulus	3.2	6.4
Sum	107.6	128.8

Copper* thicknesses must be adjusted by varying sheet gauge to keep coils symmetric about the center of the assembly and equidistant from the steel annuli, compensating for the fact that the MMC of #14 square wire with heavy film is 7.7% above the LMC. For water cooled units use viton spacers between steel annuli and copper, to help with Z thermal expansion. Paired coils will also have to be matched as well as possible in OD to keep the fields right. At least 30 coils would have to be wound at ~920' each. If one can buy wire in 15,000' spools, 230# copper plus insulation, two would wind 32 coils. If not, it's probably easiest to buy 1000' spools for handling. Wind all the coils, measure width and OD, pair them up, then assemble.

For 24 turns level winding with minimum pitch, it now seems to me that the bobbin needs to be 25 turns wide. This is likely cheaper than a winding with all turns normal to Z as the winding can be automated except for lead placement.

Maximum width for #14 square is 0.0651”. Maximum heavy film build is 0.005”. Total MMC 0.0701”. For 25 turns, 44.5 mm, more than I allocated above. Nominal: 0.0641+0.004 = 0.0681” *25 equals 43.24 mm. So even at nominal copper sheet would have to be thinner. If I allow 0.5 mm/side for glass/epoxy, coil width 44.5-45.5 mm. Drawing 39200-D00061 shows that the slit assembly recess into which the low power solenoids must fit is 5.81-0.25-0.68= 4.88”=124mm. Nuts and wrench clearance (13 mm ?) are required on the back of the flange unless it's replaced with a threaded flange when the original is ground off to replace the FD with the new solenoid. Some mechanism to keep the magnet located in Z and centered in the recess is needed. A portion of the cited drawing is shown on the top of the next page. The full chopper assembly drawing is 39200-D00066. While it would take a lot more care than simply grinding off the existing 4.5” flange, the 2.5” tube could be lengthened during the operation. Weld a short tube into the flange and then weld the two tubes together to increase the 5.81” dimension? Or reduce the turns/layer from 24 to 23, cutting width by 1.8 mm MMC?

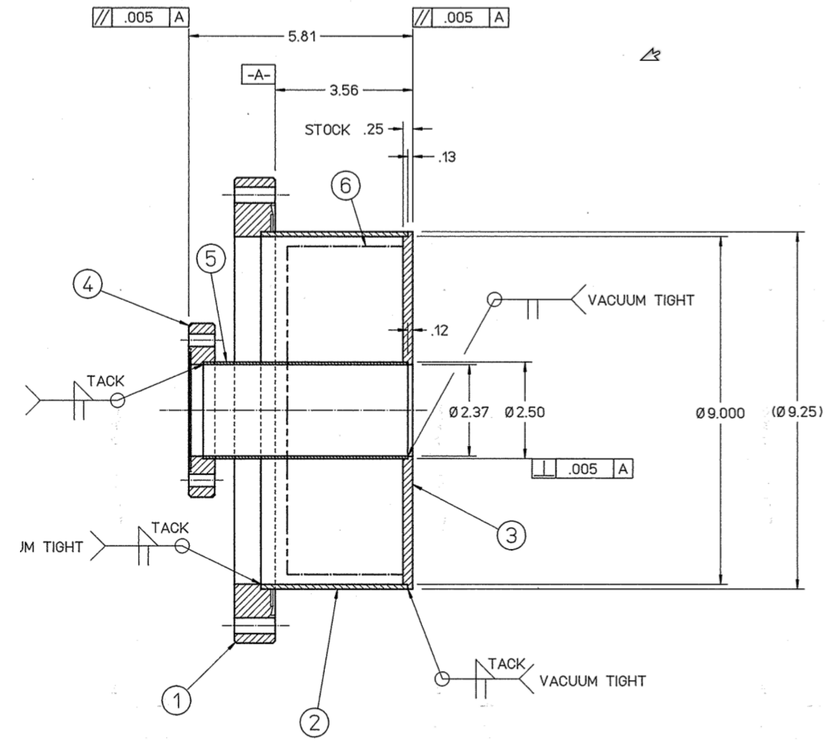


Figure 10. Portion of 39200-D-0061 showing recess which defines maximum size of the solenoids discussed.

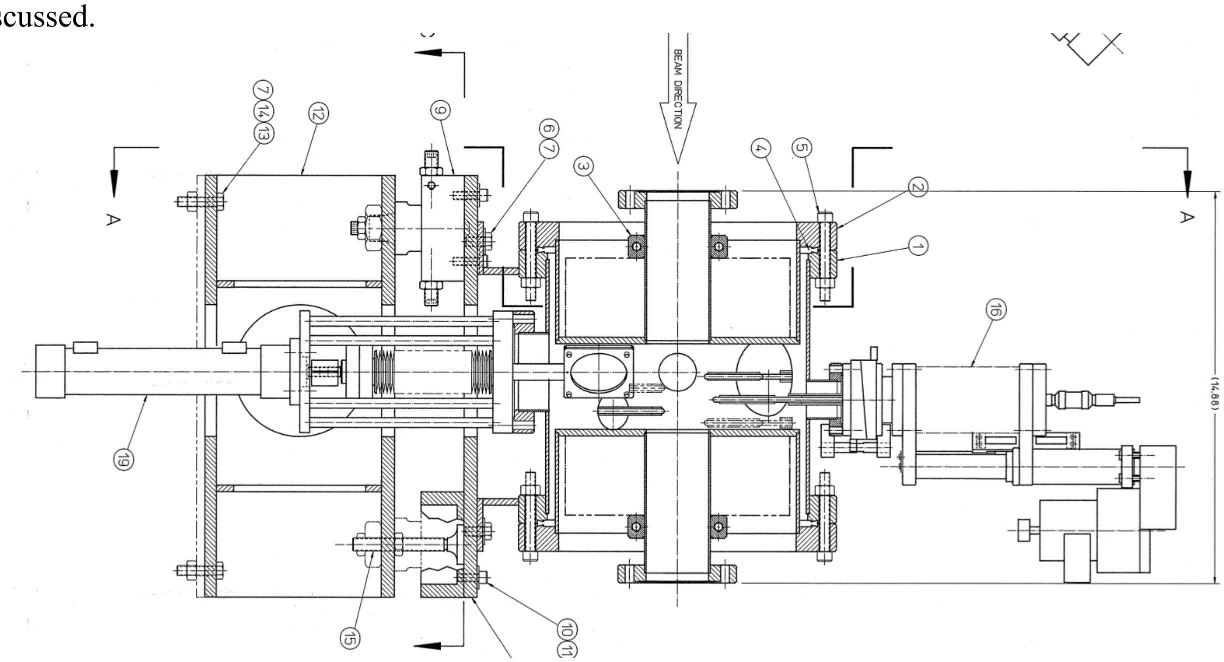


Figure 11. Portion of 39200-D-0066, the full chopper assembly drawing. If one wants to replace the FD or modify the solenoid recess one has to unbolt the 12" CF flanges. One should do this even if one is only grinding off the flange to replace the FD. Note that the slits for the different halls are off the horizontal (in this view) centerline of the space between the solenoids. This is where the top pane of Figure 4 comes into play. One can adjust laser phase to get the core centered but the slope will still be present so lower slope is better.

I added four 3 mm holes to the model and ran it with four-fold symmetry. Field on the surface is shown in Figure 12.

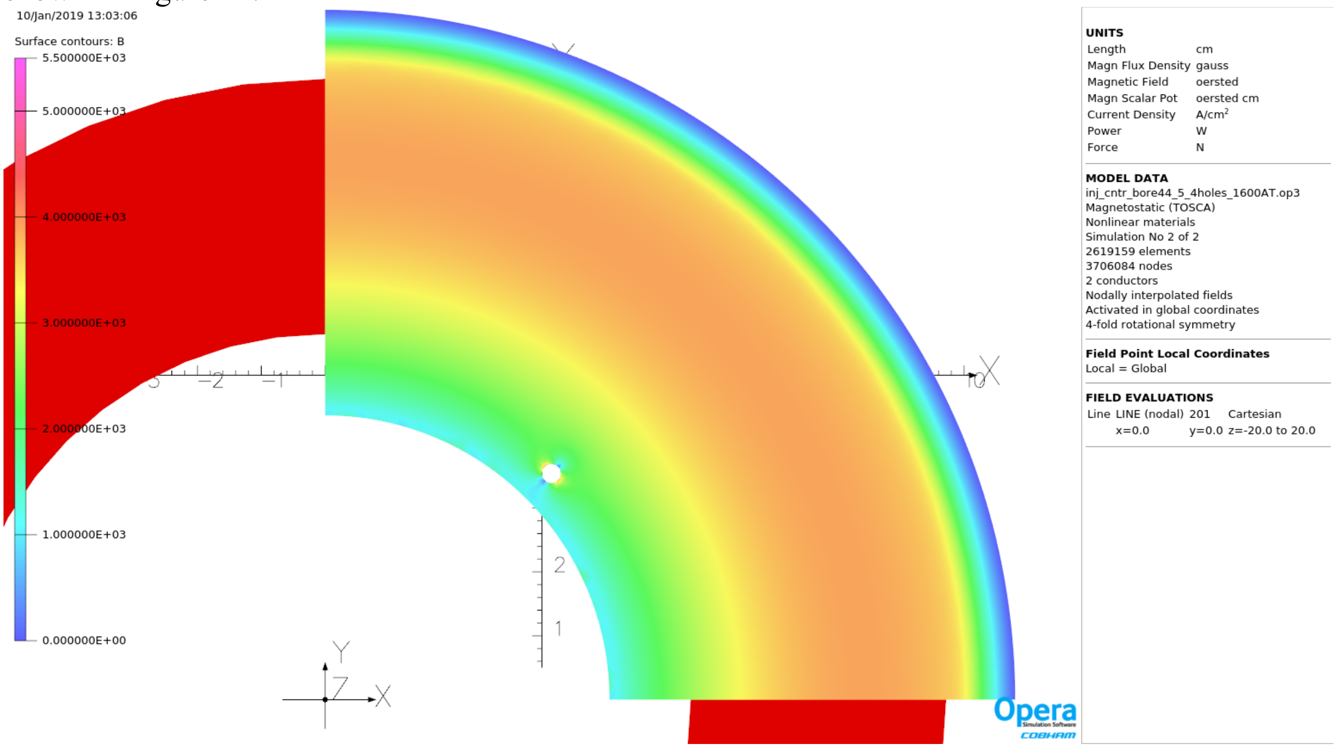


Figure 12. Model with four 3 mm holes equally spaced on 50 mm radius.

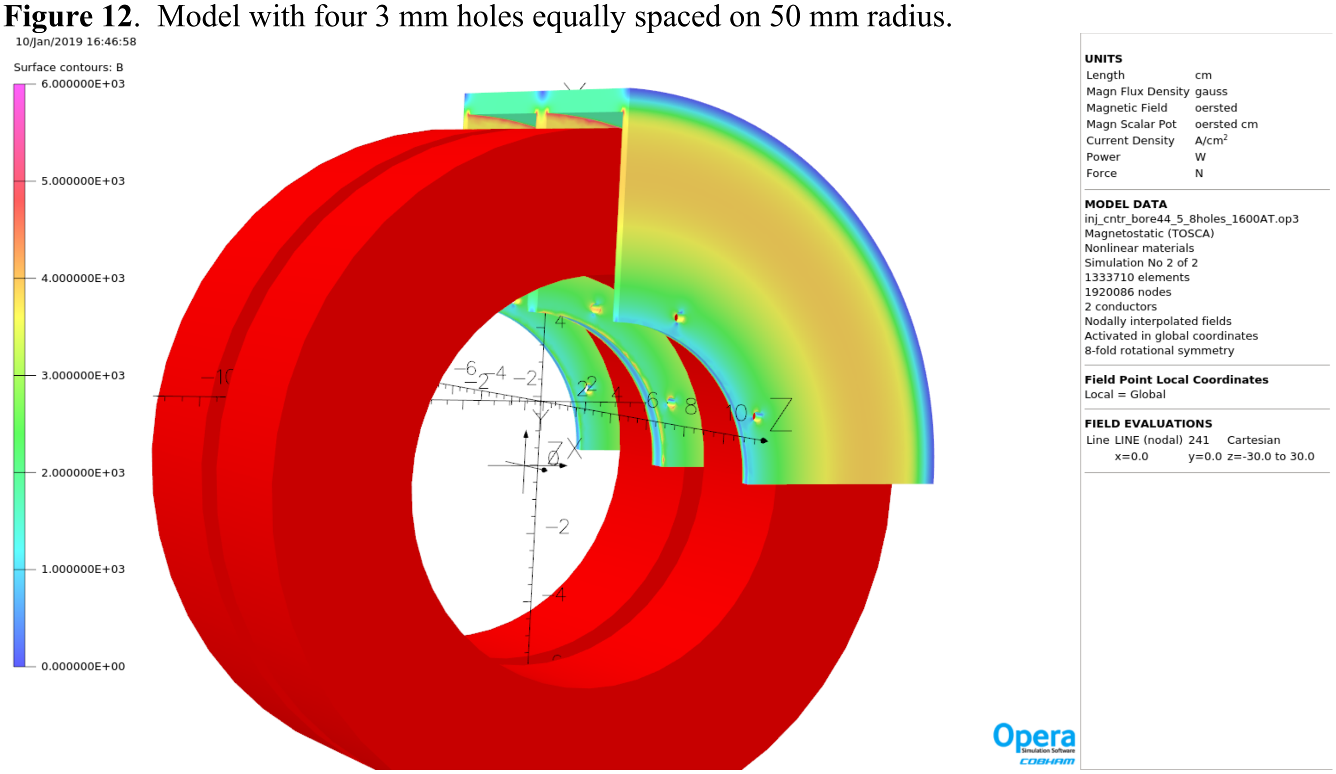


Figure 13. Model with eight 3 mm holes equally spaced on 50 mm radius. Note B scale change as peak is 3% higher in this model. No significant volume at that B.

The fully symmetric model was solved using 16-fold cylindrical symmetry. The model with 4 holes used 4-fold symmetry and the model with 8 holes 8-fold symmetry. There will be mesh-dependent differences in the results. Single particle orbit differences of order ten microns were seen by Alicia

Hofler in GPT simulations using models with 16-fold symmetry vs models which did not apply symmetry. These must have been caused by the mesh because the steel and coils were the same. The field maps being used in the GPT simulations cover x and y=[-2.2,2.2] in 1 mm steps and z=[-45,45] in 0.5 mm steps (gradients are larger in z). To compare the models without holes to the two with holes I generated smaller field maps with the same step size covering only the upper right quadrant and z=[-25,25]. Field at the Z boundary of this map was ~0.5G. These maps have 529529 points. For the counterwound magnets I then subtracted: (no holes - 4 holes) and (no holes - 8 holes). I imported the differences into JMP and made histograms. Referring back to figure 10 one sees that the ID of the tube through which the electrons pass is 2.37" = 6.02 cm. The outer radius of the hall slits in the chopper is 1.8 cm. I made histograms which eliminate points with R>3. The plots are on the next pages. The symmetry imposed and mesh size used have large impact on the results, so the 76 outliers are non-physical and using such holes likely will have less effect than other manufacturing tolerancs.

https://upload.wikimedia.org/wikipedia/commons/2/28/Gauge_Chart.pdf is a wire gauge comparison chart. There appears to be a metric wire size 1.6 mm which is 0.983*#14_AWG. This would be an acceptable replacement from a resistance standpoint and would reduce the coil Z extent slightly as is desirable. Assuming 0.1 mm insulation film build, 25 turns = 42.5 mm.

Looking back again at Figure 10 I assert it's worth making entirely new replacement parts, for schedule float if no other reason. Change the ID of the 9.25" tube to 8.75" or even 8.5" so it can support the weight of the new solenoid and locate it. Change the CF flange to 3.375" (2" OD tube, 47.75 mm ID) so the new magnet may pass over the flange rather than being welded in place. Lengthen the new tube to allow for easier alignment of the solenoid. The drift tubes used fore and aft of the chopper chamber (Figure 11) would have to be shortened/replaced. Again, make new pieces; don't rework.

Table 2. Nominal Z spans of metric materials in the low and high momentum solenoids

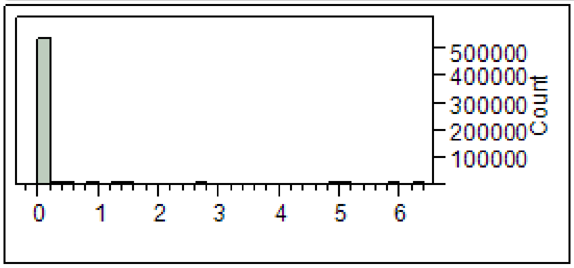
Material	Low P (mm)	High P (mm)
Steel annulus	3	6
Copper*	2	10
Coil+insulation	43.5	43.5
Copper*	2	10
Steel annulus	6	0
Copper*	2	0
Coil+insulation	43.5	43.5
Copper*	2	10
Steel annulus	3	6
Sum	107	129

Summary

The intent of this document is to provide enough information to the designer to create drawings which may be used to procure solenoids for use in low (9) and high momentum (7) regions of the injector. If a mandrel like that sketched in figure 9 is used for low momentum, four should be of stainless and five of aluminum. Since there is no center steel annulus for high momentum, a simple copper cylinder (4" pipe size) would suffice there. Two sets of drawings, perhaps, one with "customary" units (table 1) and one with metric units. Or just the metric.

Distributions

B



Quantiles

100.0%	maximum	6.20946
99.5%		0.0262
97.5%		0.01542
90.0%		0.00809
75.0%	quartile	0.00408
50.0%	median	0.00069
25.0%	quartile	0.00019
10.0%		0.00009
2.5%		4.44e-5
0.5%		2.36e-5
0.0%	minimum	2.16e-6

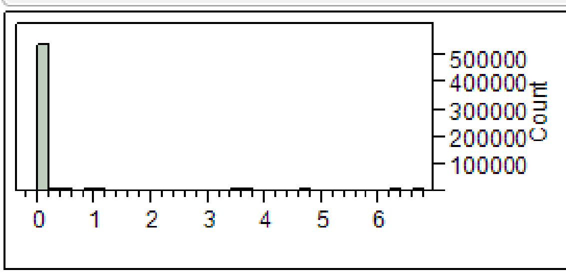
Moments

Mean	0.0029782
Std Dev	0.0170148
Std Err Mean	2.3449e-5
Upper 95% Mean	0.0030241
Lower 95% Mean	0.0029322
N	526526

Figure 14. |B| for (0 holes - 4 holes) with 1mm mesh in 3.2 cm radius beam air. Only 76 of the points have |B|>0.1 and only 25 have |B|>0.2. Those are near the Z axis and must be due to mesh variations between the models.

Distributions

B



Quantiles

100.0%	maximum	6.75406
99.5%		0.03293
97.5%		0.02459
90.0%		0.01573
75.0%	quartile	0.00498
50.0%	median	0.00097
25.0%	quartile	0.00028
10.0%		0.00014
2.5%		7.47e-5
0.5%		4.35e-5
0.0%	minimum	2.06e-6

Moments

Mean	0.0045384
Std Dev	0.0179384
Std Err Mean	2.4721e-5
Upper 95% Mean	0.0045869
Lower 95% Mean	0.00449
N	526526

Figure 15. |B| for (0 holes - 8 holes) with 1mm mesh in 3.2 cm radius beam air. Only 76 of the points have |B|>0.1 and only 27 have |B|>0.2. Their locations are different from the outliers of Figure 14. These outliers are also near the Z axis and must be due to mesh variations between the models.

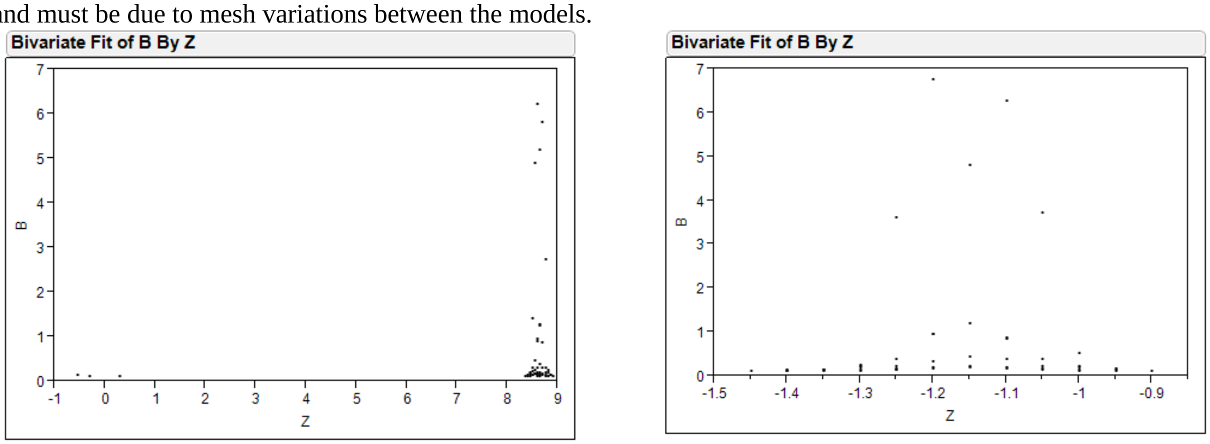


Figure 16. Plots of B vs Z for (0 holes - 4 holes) left and (0 holes - 8 holes) right for the 76 outliers in each set. I have no idea why the mesh fault occurred in such different locations. In all three models I meshed a quarter of the model (symmetry = 4) and had 1 mm mesh in a cylinder 92 cm long with 3.2 cm radius. The only difference was in the number of 3 mm holes in the steel at 5 cm radius: 0, 4 or 8. The outliers are physically irrelevant as they must be incorrect.

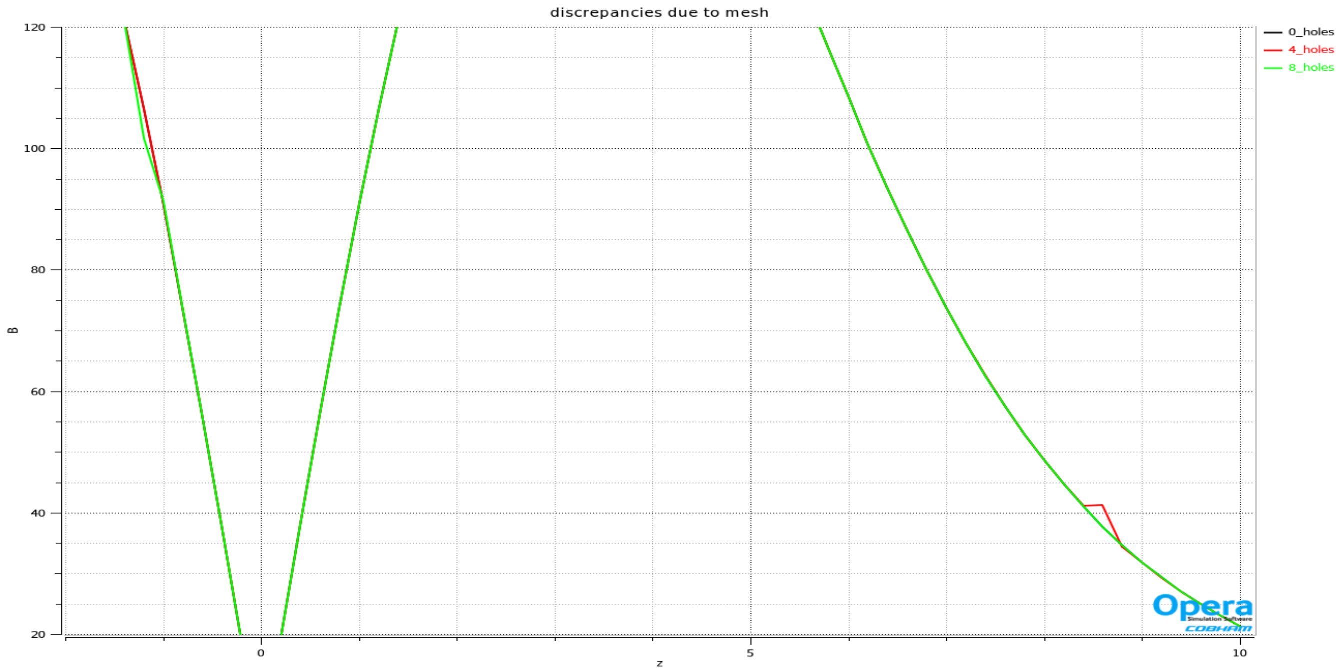


Figure 17. Plot is along the Z axis (x=y=0) Discrepancy at lower right has 4_hole model departing from other two. In upper left the 8_hole model departs from the others. See also Figure 16 left. When providing models to Alicia for comparison with fopt data I found that 16-fold symmetry seemed not to have such trouble. But that isn't possbile here.

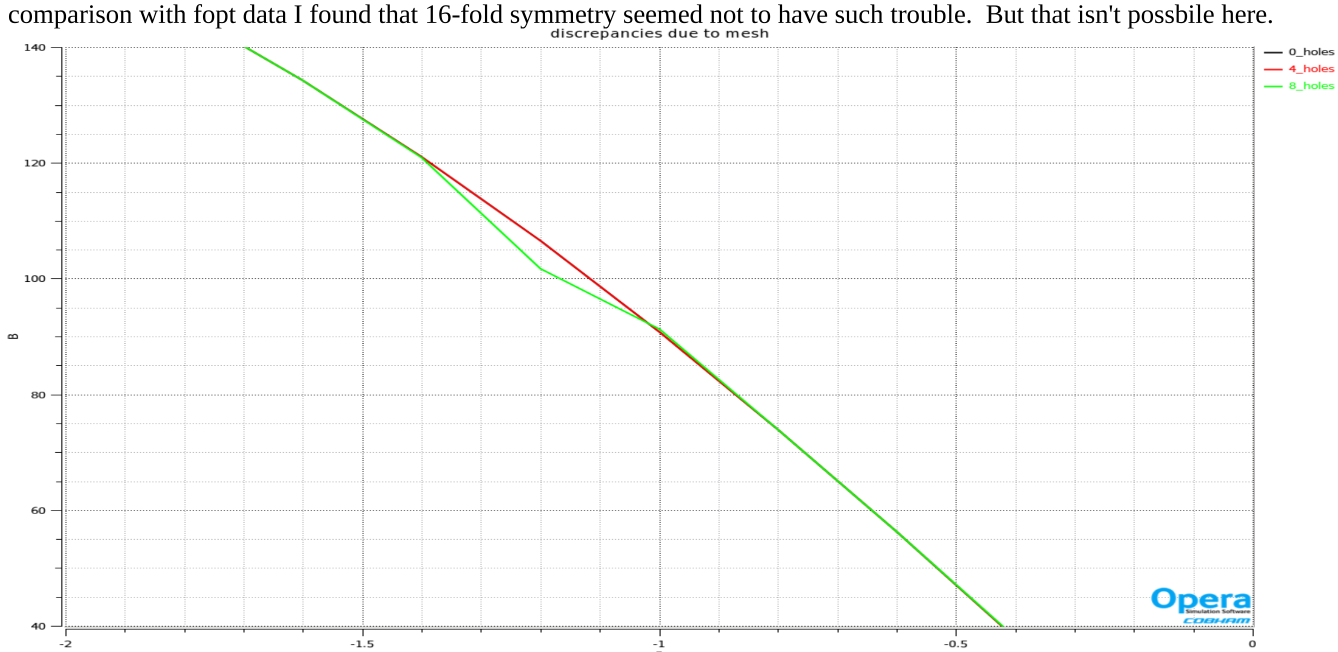
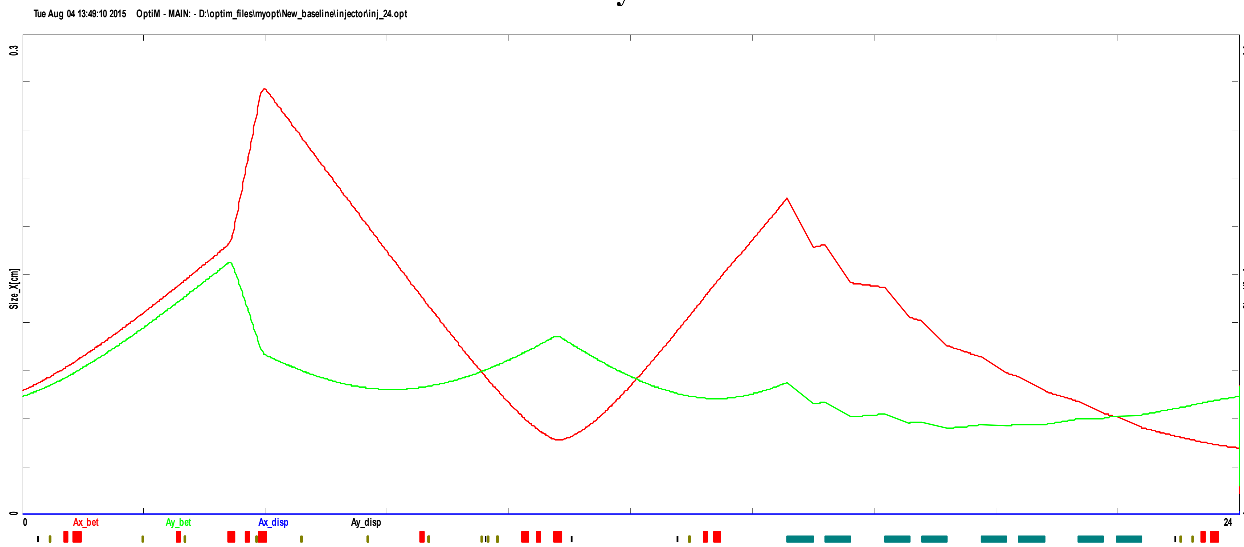


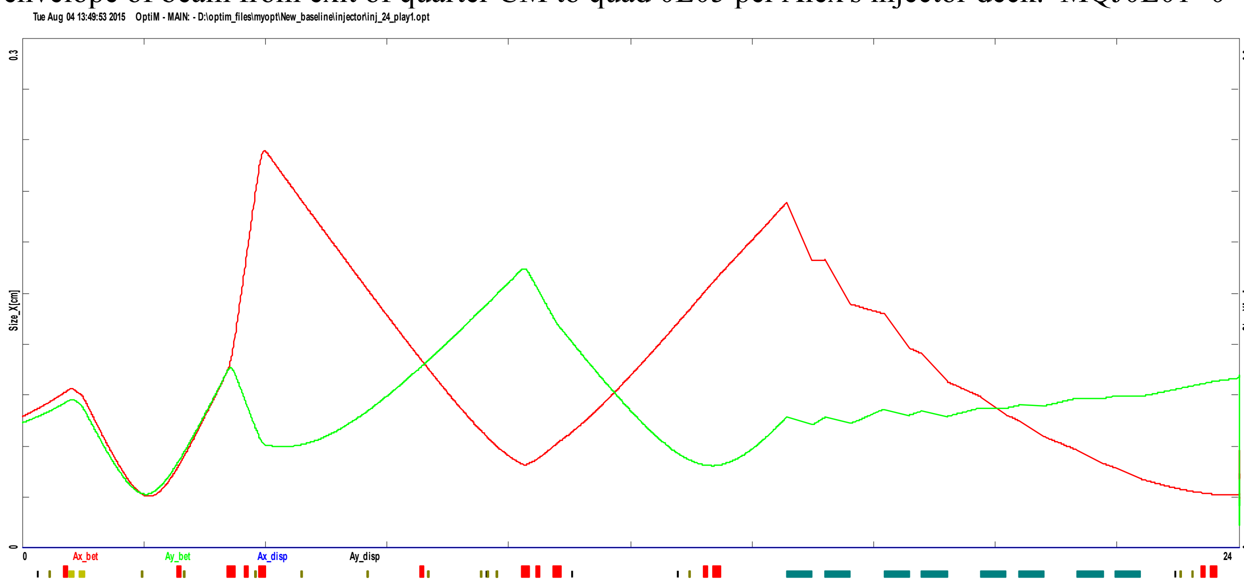
Figure 18. Enlarging the upper left discrepancy above. See also Figure 16 right.

Appendix: Solenoid focusing in "6 MeV" region of injector (TN15-029)

Jay Benesch



envelope of beam from exit of quarter CM to quad 0L05 per Alex's injector deck. MQJ0L01=0



envelope of beam when pair of 10 cm solenoids with 15 cm gap, powered as counter-wound pair, replaces MQJ0L01. Peak size in X 2.32 mm vs 2.65 mm in nominal optics.

Twiss parameters are matched at IPM0L04, in front of quad 0L04, so 0L matching region and 0R chicane don't change. Twleve percent reduction in beam size. Additional reduction is not significant if more 0L quads are invoked.

Solenoid field is 0.8864 kG in a hard-edged 10 cm solenoid. Matching this with the "real" solenoid design summarized in https://jlabdoc.jlab.org/docushare/dsweb/Get/Document-94987/14-022.pdf requires a current ~8.75A into two 1.8 ohm coils per package, too much for a single trim card when wired in series within each package. Either four trim cards or one 20A/75V trim supply would be required to drive the pair of solenoids, each containing two coils. The solenoids weigh about 25 kg each. 4" ID, 8.5" OD, 4" long.

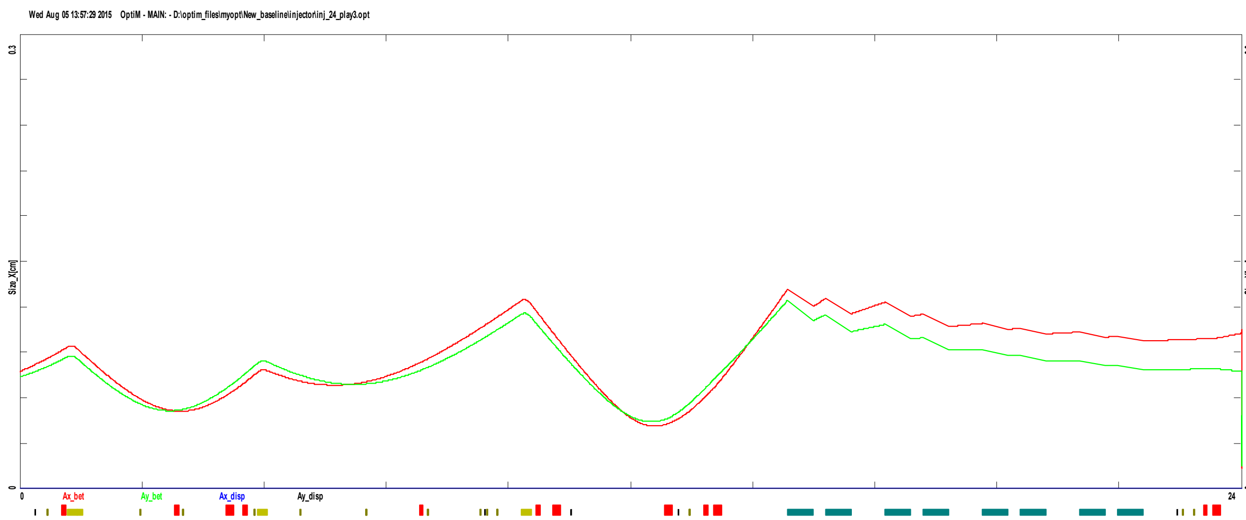
Reza stopped by. I showed him the page above. He asked first about steering. We examined this and found that the solenoid will steer offset beams towards zero: good. He then asked whether the beam parameters could be measured with harp 0L03 by turning the quads off and using just the solenoid. At the harp with quads off, the beam radius is about 5 mm at nominal solenoid setting, 0.8864 kG, declines to 2 mm at 0.53 kG, and then begins to increase again as solenoid is lowered further. These seem to me too large to get a good measurement, but I don't know what the normal range is at IHA0L03; the standard optics suggests the size could go as high as 3 mm during the quad sweep.

The key table of TN14-022 is reproduced below with minor modifications:

Integral Bz*Bz over positive half of model						
radial location	FA	FD	FG	FL	4" cntrwnd	4" wired single
0	52411.5		884901	320649	84559.9	430885
0.3	54326.2		885951	334976	84939.4	431290
0.5	57944.8		887815	362373	85614	432010
1.2		62593.5			90905.6	
1.5		73733.9			94771.4	
1.8		90989.3			99808.8	
1.7		*84367.9*			*97987*	
2		*107682*			*103939*	
2.3		*145283*			*111454*	
fractional variation in focusing strength from working location (0, 1.5 or 2)						
radial location	FA (typ cntr)	FD (chopper)	FG (wien flip)	FL (500 keV)	4" cntrwnd	4" wired single
0	1		1	1	1	1
0.3	1.0365		1.0012	1.0447	1.0045	1.0009
0.5	1.1056		1.0033	1.1301	1.0125	1.0026
1.2		0.8489			0.9592	
1.5		1			1	
1.8		1.2340			1.0532	
1.7		*0.7835*			*0.9427*	
2		*1*			*1*	
2.3		*1.3492*			*1.0723*	

One sees in the bottom half of the table that the spherical aberration is 3.7% for the FA solenoids and 4.5% for the FL across the 6 mm apertures which define the beam. Across the chopper slits the aberration is -15% to +23%, far larger, on existing 3 cm diameter circle. The new design cuts the on-axis aberration a factor of ten and the chopper aberration a factor of four.

Reza also asked whether replacing the two quad doublets with counter-wound solenoids would provide a greater benefit. It does. As shown below, it reduces the peak beam size in the 0L region from 2.65 mm in the original optics to 1.31 mm in the new case. A 0L04 doublet is required; the field of the new quad is small enough (15G), that an air core quad would suffice. (See page 8. In fact, it's best to turn off the 0L04 and 0L05 quads and rely only on the three counter-wound solenoids.) The skew quads can do 60 G. This is inserted between the Faraday cup and the differential pumping station. There is a an electrostatic precipitator in this location which would have to be replaced with standard beam pipe. Twiss parameters are the same at the drift after MQB0L10 as they are in the standard optics, so match into the 0R chicane should be fine. Solenoid fields here are 80% of those needed when only one unit is placed at 0L01 so two standard trim cards each would work for 0L01 and 0L02. 7A, 3.8 ohms per package, ~190W. 0L03 needs more during Twiss measurement as discussed below.



Three counter-wound solenoids where 0L01, 0L02/2A and 0L03A/3 now live, plus a small quad between Faraday cup and DP station. Scale is the same as in the first two figures. Beam envelope is much more uniform and half the nominal value.

The 0L03 counter-wound solenoid would have to be water-cooled to sweep through the fields necessary to measure Twiss parameters at IHA0L3. Each of the packages would need its own 20A/75V power supply (~13A/52V needed to get well past waist.)

If one wants to retain the capability of running beams up to 15 MeV KE, all three counter-wound solenoid sets after the quarter would have to be water cooled and have twice the original end plate thickness, 1/4" instead of 1/8". The water cooling concept in the original design is cooling only the 0.25" wall 4.5" OD copper tube on which the coils are mounted. There are 64 oz (0.0863") copper spacers between coil and steel end plates of 1.75" radial extent to conduct some heat down to the copper tube, thermal grease interface. This should suffice for the 6.8A at ~4 ohms needed for the focusing shown in the figure above (assumes 50C copper wire). It might even suffice for the Twiss measurement if done quickly, relying on heat capacity.

I talked to Ernie Ihloff (MIT) at the MOLLER collaboration meeting 8/12. He reminded me of a design I learned 40 years ago and forgot 30 years ago. The pair of 1/8" steel annuli at the center of the package provide only magnetic continuity at the OD. If the four copper and steel annuli at the center are replaced with one 10.8 mm copper annulus, this could be water cooled via a tube pressed into a machined groove and might suffice, with ID cooling, to keep the coil at an acceptable temperature. FEA still needed, but this would preserve the 8.5" OD envelope. One of the two steel tubes in the package would have to be extended by 0.25", but that shouldn't increase cost too much. Worst case replace end copper annuli with the thicker one.

The homogeneity of these models is the same as the last column of the table on the previous page, 1.0009 at 0.3 cm radius and 1.0025 at 0.5 cm radius, referenced to center of solenoid, for all currents up to 11200 AT, much more than can easily have heat removed.

A simple-minded thermal analysis:

heat flow aka power = (thermal conductivity coeff) * (Area/length)*(temperture delta)

Assume thermal conductivity coefficient of Kapton, 0.5 W/m-K, because I can't find a value at room temperature for ML or any other film insulation. All films are going to be within a factor of two of Kapton.

Area of the side of the coil 195 cm^2 or 0.0195 m^2.

Heavy film build is 0.005" max per wire. Twelve turns per half-coil, assuming coiling plates on both sides, yields ~1.5 mm or 0.0015 m length. Since copper thermal conductivity 1000*insulation, assume it's a thermal short.

Then

W= 0.5 W/m-K * (0.0195/0.0015)* (delta T)
W= 6.5 *(delta T)
200 W cooling one side so length doubles: 62C delta T
200 W cooling both sides 31C
600 W cooling both sides 92C delta (~130C abs) vs 220 C limit for ML
200 W cooling just ID, (area 0.032 / length 0.003) so 38C delta T

This assumes all the heat is deposited on the Z midplane of the coil (side cooling) or on OD, rather than distributed through the coil, so real temperature will be lower. Except thermal conductivity of insulation could be lower than Kapton, so this may not be too far off.

It follows that if one wants 15 MeV/c capability the 1 cm thick copper cooling plates described on the bottom of the last page will have to be included on both sides of the coils, three total, not just in the center where space is available in the present magnet model. Only the coils will remain common to low P and medium P designs, but that will still lower costs.

Magnet model update

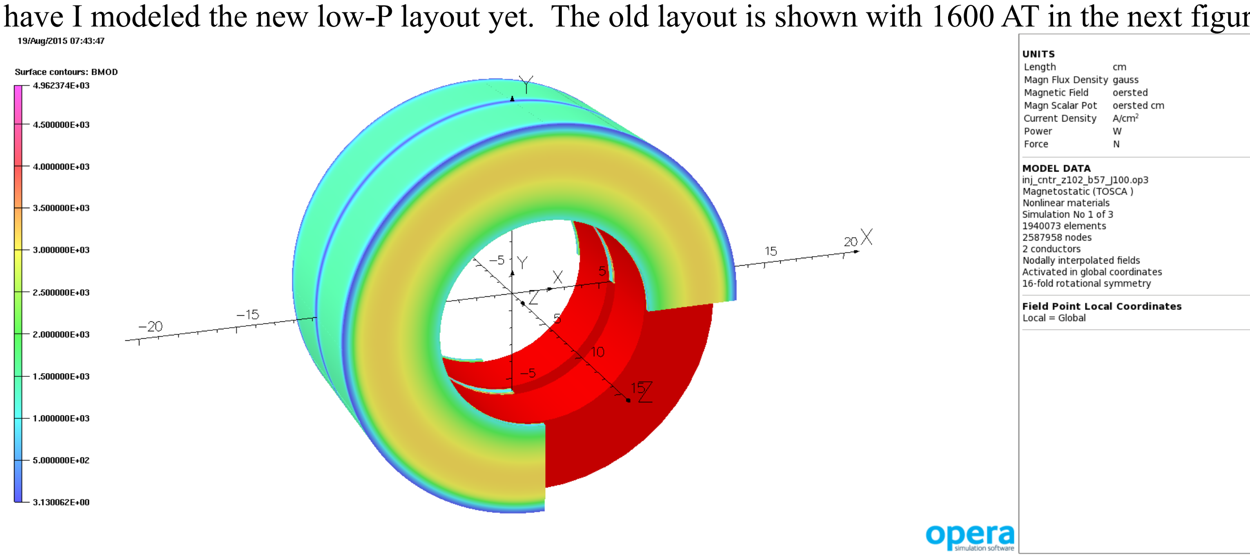
It is clear from the simple heat transfer model above that chill plates would be required on both sides of each coil in the units for use at 6-14 MeV/c. I decided to increase the number of turns in the coils to 24, increasing R and lowering I^2 to get power down a bit. The 20A/75V power supplies will run out of voltage somewhere between 8000 AT and 9600 AT depending on wire temperature and therefore resistance. At 6400 AT the new design focuses a 13 MeV KE beam around 300 cm from center of array, so that's OK. That would be 250-300W per coil, two per package, depending on cooling. I have not yet reworked the low momentum design with the slightly larger coil; I checked the chopper and determined that 115 mm is available.

The layouts in Z for the low P and high P units are given in the following table. Copper pipe for ID and steel tube for OD are the same stock for both, but lengths will differ. Coils and therefore winding tooling are kept common. Coil width is now taken at 24 turns times maximum material condition for #14 square wire with heavy film insulation.

Material	Low P (mm)	High P (mm)
Steel annulus	3.2	6.4
Copper*	2.2	10
Coil	43	43
Copper*	2.2	10
Steel annulus	6.4	0
Copper*	2.2	0
Coil	43	43
Copper*	2.2	10
Steel annulus	3.2	6.4
Sum	107.6	128.8

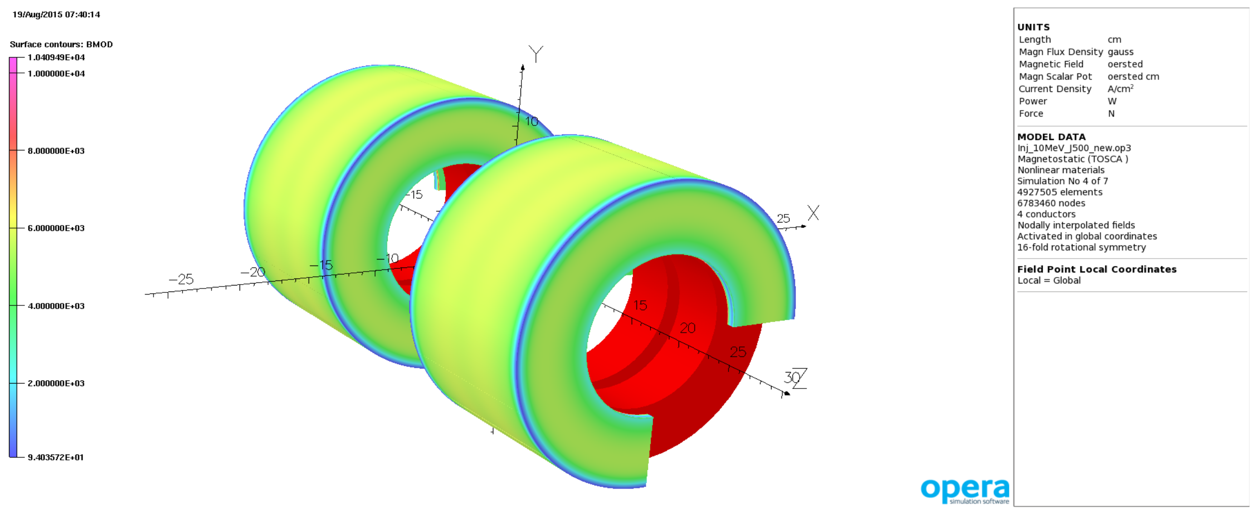
Copper* thicknesses must be adjusted by varying sheet gauge to keep coils symmetric about the center of the assembly and equidistant from the steel annuli, compensating for the fact that the MMC of #14 square wire with heavy film is 7.7% above the LMC. For water cooled units use viton spacers between steel annuli and copper, to help with Z thermal expansion. Paired coils will also have to be matched as well as possible in OD to keep the fields right. At least 30 coils would have to be wound at ~920' each. If one can buy wire in 15,000' spools, 230# copper plus insulation, two would wind 32 coils. If not, it's probably easiest to buy 1000' spools for handling. Wind all the coils, measure width and OD, pair them up, then assemble.

Based on past experience, I'd like to have the centers of each current bolus symmetric and located with respect to the iron at the 100 micron level. I haven't done error studies yet, so this is a gut call. Nor have I modeled the new low-P layout yet. The old layout is shown with 1600 AT in the next figure.

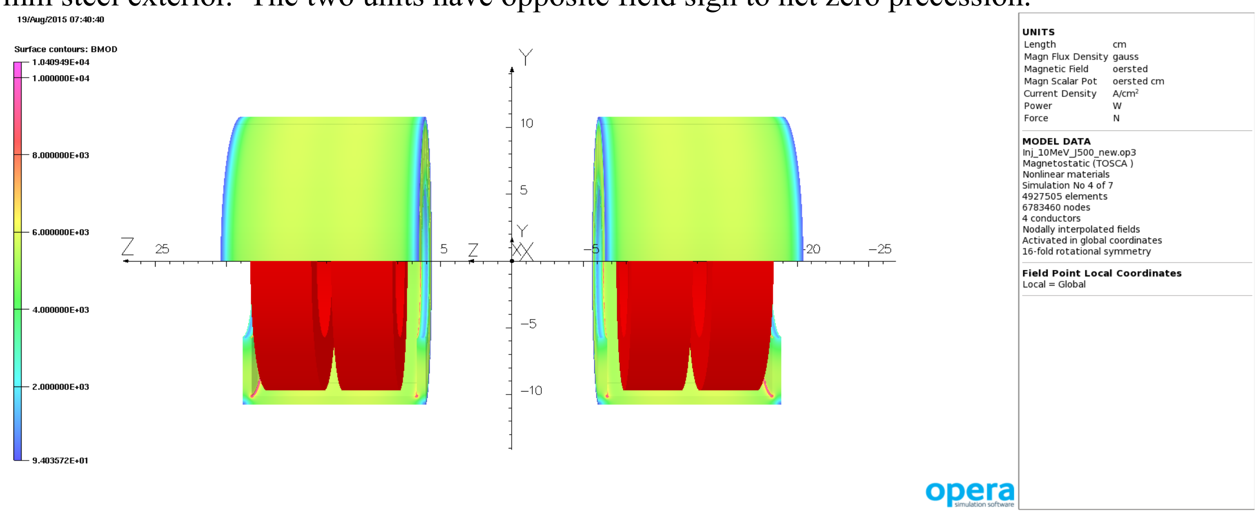


Low-P magnet system with steel between coils, used to 0.5 MeV KE.

The new high-P system is shown in the next two figures from different viewpoints. 6400 AT, likely the maximum which will be used. This would be 250W per coil at 20 C and perhaps as much as 300W per coil (70C wire). The heat removal plan outlined above should be fine for this. Even 8000 AT would be possible with one of the 20A/75V supplies, drawing ~900W total which should again be removable with three chill plates. 8000 AT corresponds to ~16 MeV KE, more than is needed in region in question.



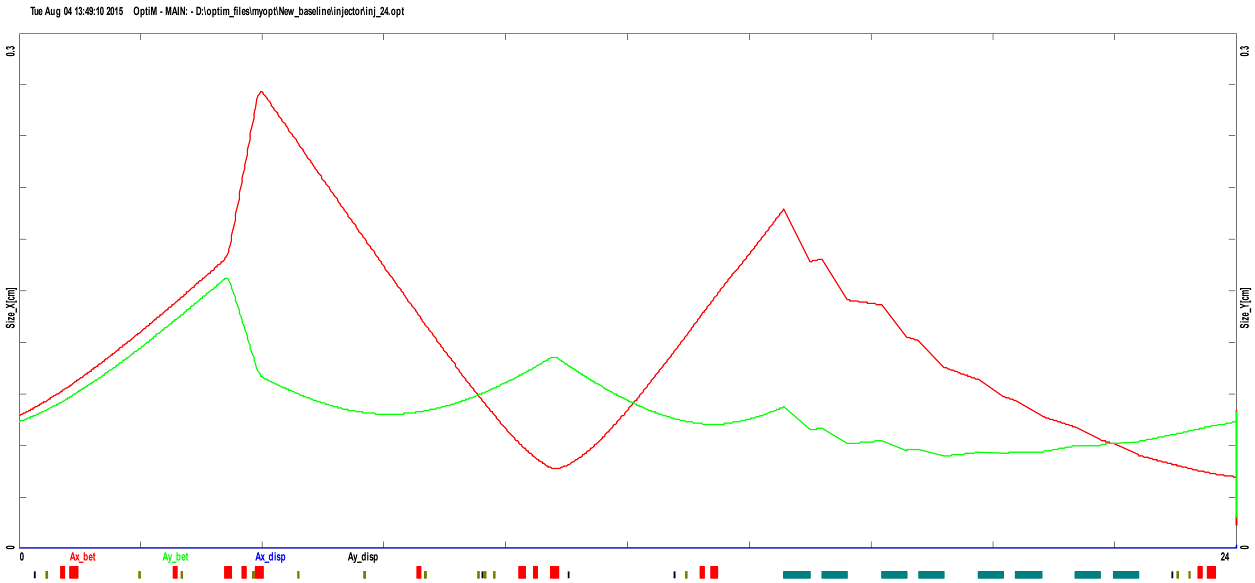
Perspective view of two units, each with two coils 24x24 as in previous figure, no center steel and 6.4 mm steel exterior. The two units have opposite field sign to net zero precession.



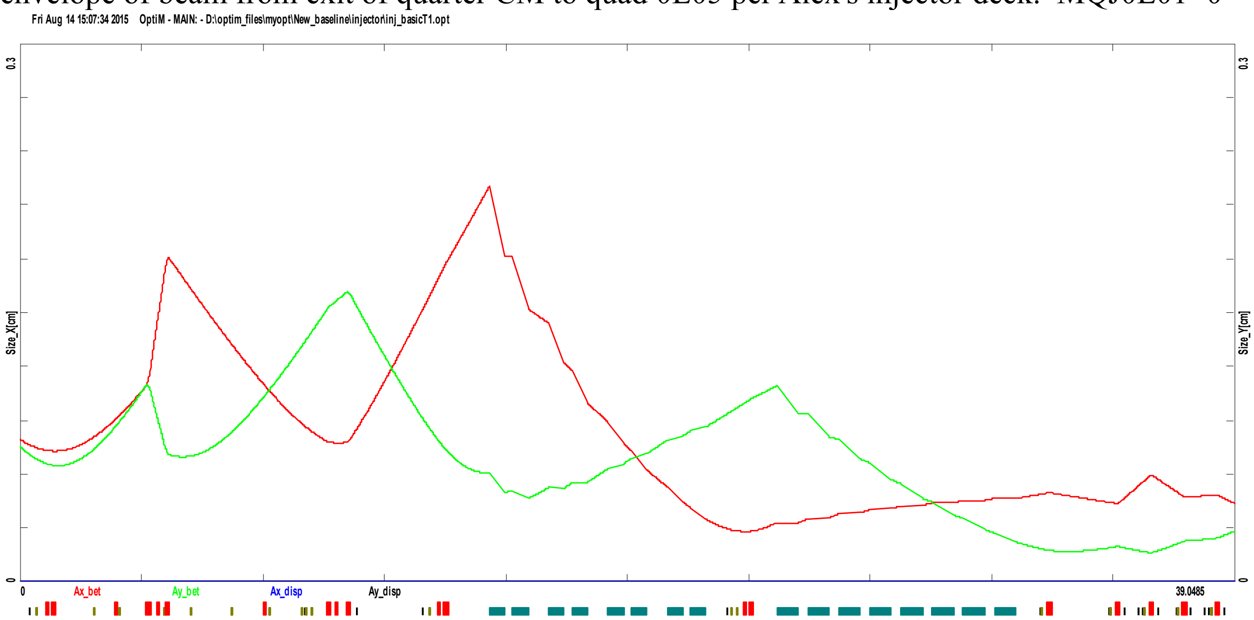
One sees in this side view that the peak field (pink) is an artifact of the sharp inner corners in the model; most of the steel is under 6 kG at 6400 AT.

For 24 turns level winding with minimum pitch, it now seems to me that the bobbin needs to be 25 turns wide. This is likely cheaper than a winding with all turns normal to Z as the winding can be automated except for lead placement. There's just enough room in the chopper recesses for this. To secure the end plates to the cylinders I'm now thinking about stainless clips bridging ID to OD rather than just holes in the OD steel cylinders, letting the carbon steel annuli flap until magnetic forces pull them in or epoxy. Six to eight such clips circumferentially, 12.5 cm radial extent, 1? cm width and 4 mm thick. Torque spec on threaded rod to minimize bowing.

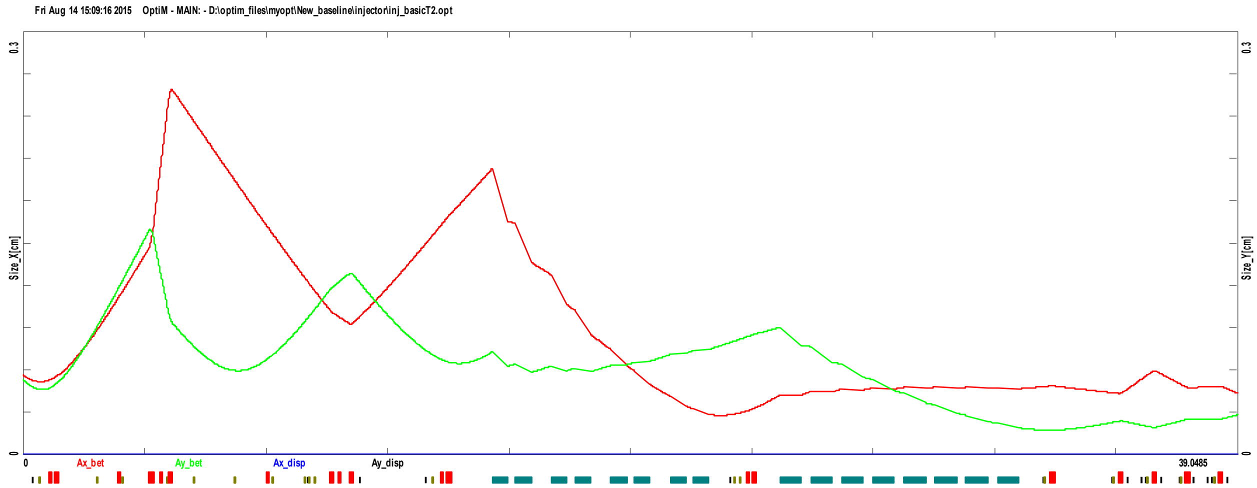
At the beam transport team meeting 8/11/15 where this idea was discussed, Geoff Krafft asked about the effect of different incoming Twiss parameters, recalling that Nick Serreno had converging beam coming out of the quarter. I played with this in Optim with the following results.



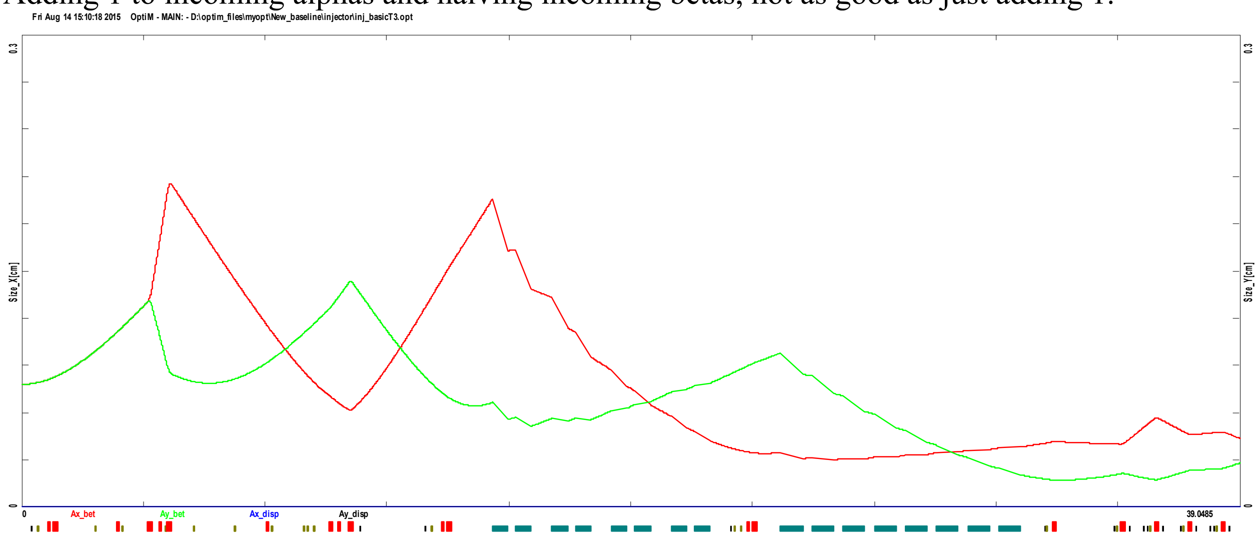
envelope of beam from exit of quarter CM to quad 0L05 per Alex's injector deck. MQJ0L01=0



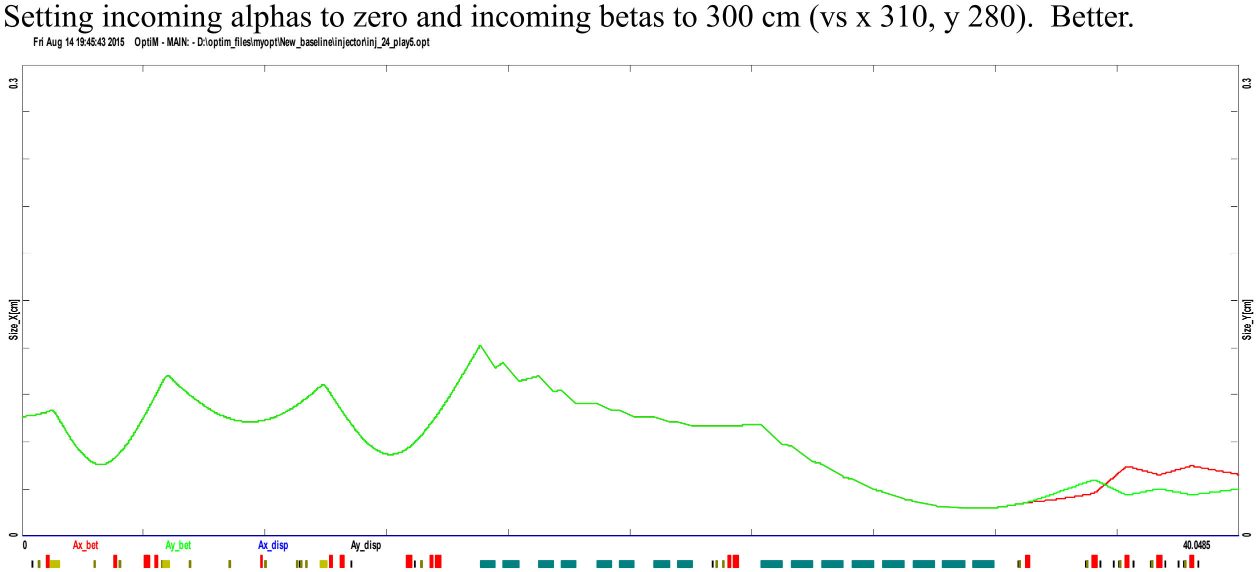
Adding 1 to incoming alphas to get converging beam and matching to entrance of MBL0R01 improves things a bit



Adding 1 to incoming alphas and halving incoming betas, not as good as just adding 1.



Setting incoming alphas to zero and incoming betas to 300 cm (vs x 310, y 280). Better.



Three counter-wound solenoids. All quads before 0L06 set to zero, relying only on the solenoids and RF focusing in modules. The smallest envelope yet. Still matched at MBL0R01 entrance. Alphas set to zero and betas to 300 cm at start.

Conclusions

Putting the waist due to MFL0I07 and RF focusing at the end of the quarter cryomodule is likely better than alternatives.

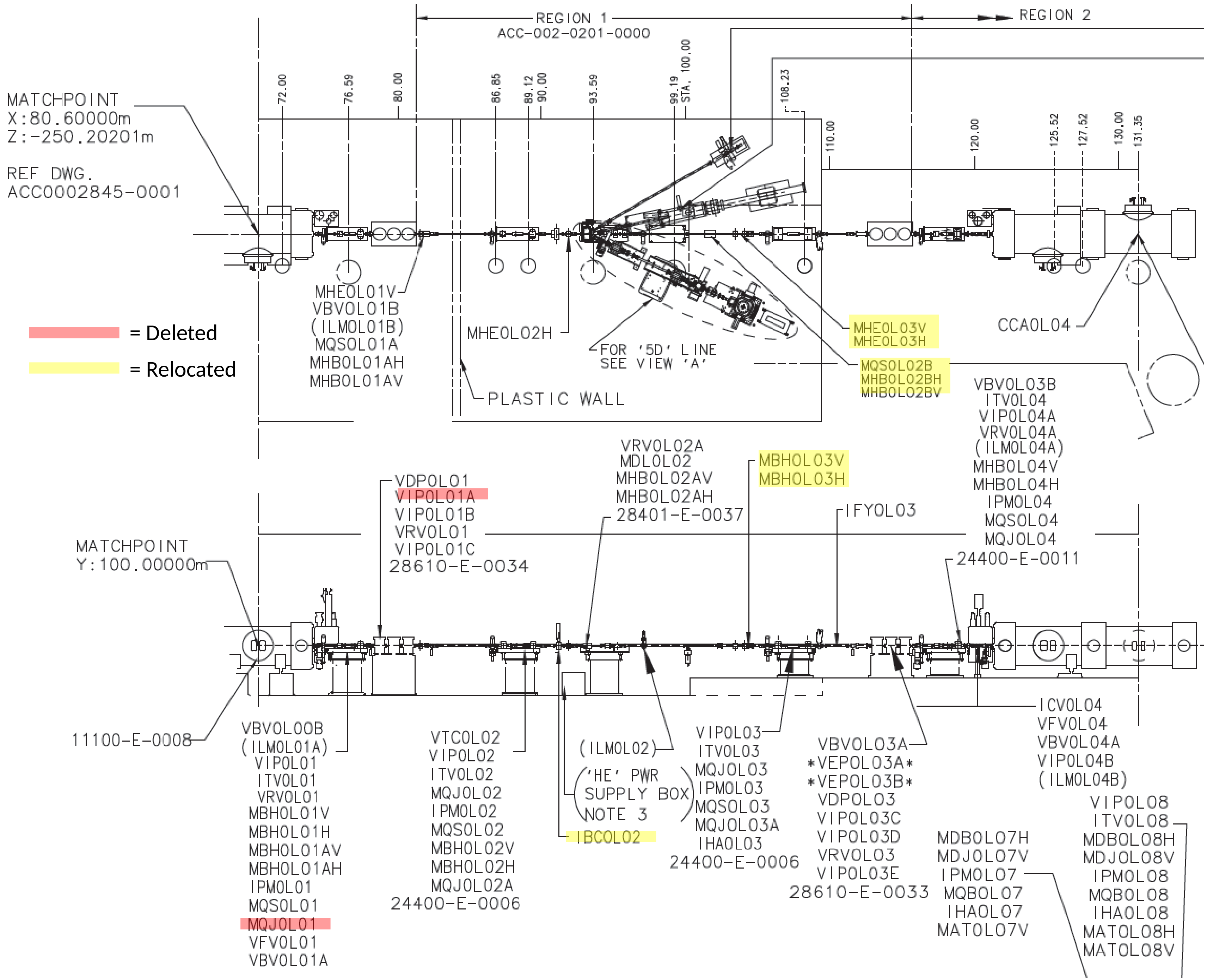
Solenoid focusing is better yet.

A solution for the solenoid thermal problem in the high momentum region has likely been found.

Postscript

The design discussed above is built on 4" ID copper pipe with 0.25" wall; it will clear a 3.375" CF (2" tube) flange without difficulty. If one wants to clear 3" tube and 4.625" CF flange in the chopper so it doesn't have to be welded in place like the present solenoids, one would have to change to 5" type K copper water tubing, 5.125" OD with 0.160" wall, hence 4.805" ID. The recess into which the chopper solenoids fits appears to be 9" ID. If one starts with a 9" OD steel tube and turns it down OD by 1.35 mm and ID by 1 mm (net 4mm left), one can fit 24 layers of #14 square maximum material condition between copper and steel. The coil ID area increases by 30% so the maximum focusing attainable will be much smaller. This isn't a problem at low momentum but is a problem at high. The units would also weigh a lot more. It seems best to retain the "weld in place" installation in the chopper and use the 4" ID unit throughout. One could make a pair of larger units just for the chopper, since the homogeneity would increase roughly linearly with the radius increase.

The next two pages were provided by Chase Dubbe. They show the current 6 MeV song sheet with indications of what needs to be deleted or moved and the proposed new song sheet with three counterwound solenoid units. The deleted quad, MQJ0L01, is not in use. The two remaining segments of the differential pumping station suffice.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STA. 100.00
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110.00
120.00
125.52
127.52
130.00
131.35
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= Relocated
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VBVOL01B
(ILMOL01B)
MQSOL01A
MHBOL01AH
MHBOL01AV
MHEOL02H
FOR '5D' LINE
SEE VIEW 'A'
PLASTIC WALL
MHEOL03V
MHEOL03H
MQSOL02B
MHBOL02BH
MHBOL02BV
CCAOL04
VBVOL03B
ITVOL04
VIPOL04A
VRVOL04A
(ILMOL04A)
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IPMOL04
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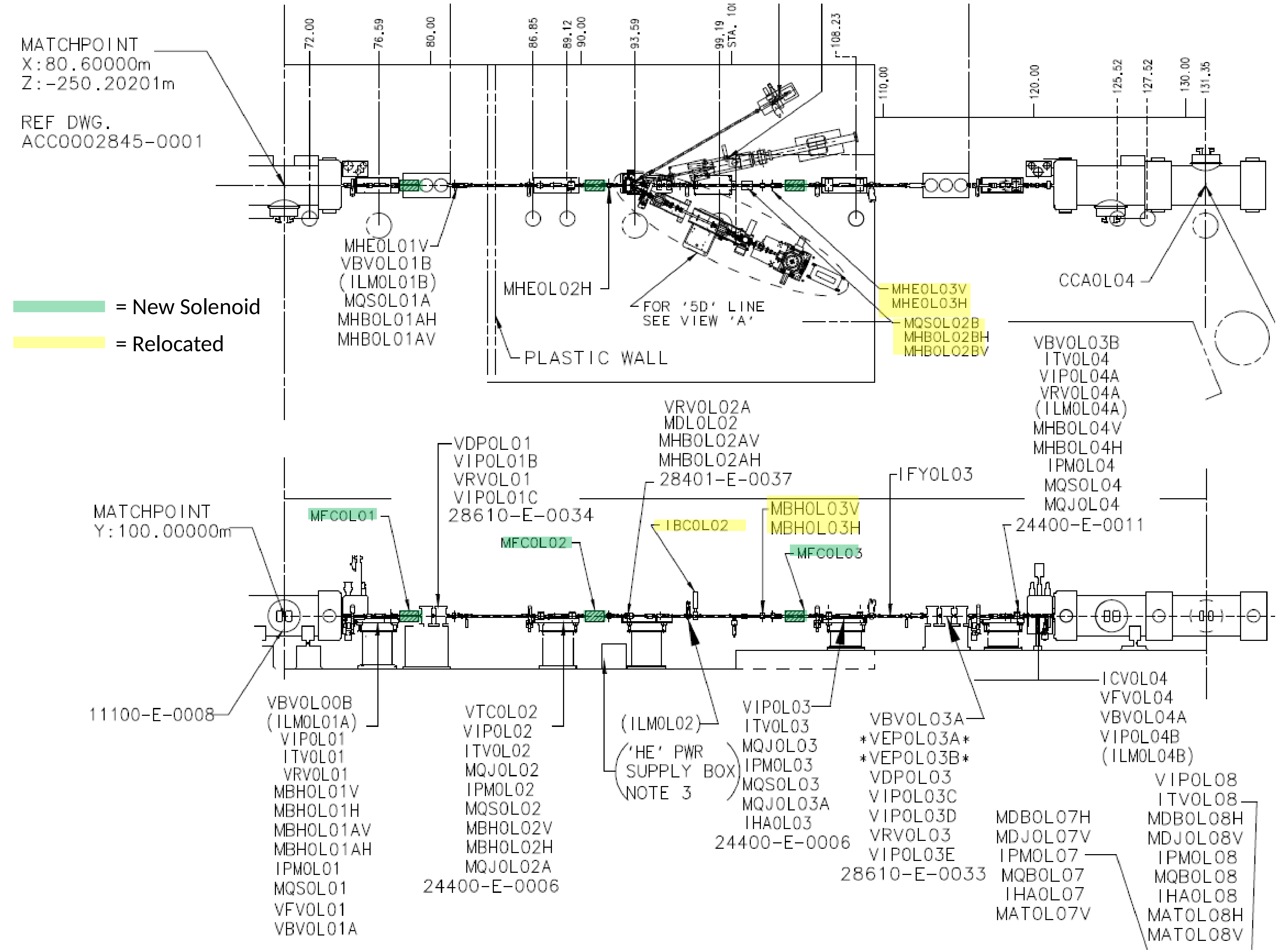
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130.00
131.35
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VBV0L01B
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MHB0L01AV
MHE0L02H
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SEE VIEW 'A'
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