416 mm ID quad for a possible muon beam line
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Abstract

Based on the masters thesis of Antonio Fulci showing muon beam size at the exit of the concrete behind the Hall A dump and some preliminary work with OptimX, I decided to scale the 104 mm ID quadrupole discussed in TN-20-044 by a factor of four transversely and four to six in Z. After much simulation I decided that only a tapered pole, as Tommy Hiatt had used for the QR, would produce enough focusing strength to deal with 6 GeV muons, and only with 200 cm length. This TN shows that quadrupoles with straight sided poles scale only with length for fixed ID, provides a sample OptimX results, and details the performance of the quadrupole with tapered pole.

Beam line

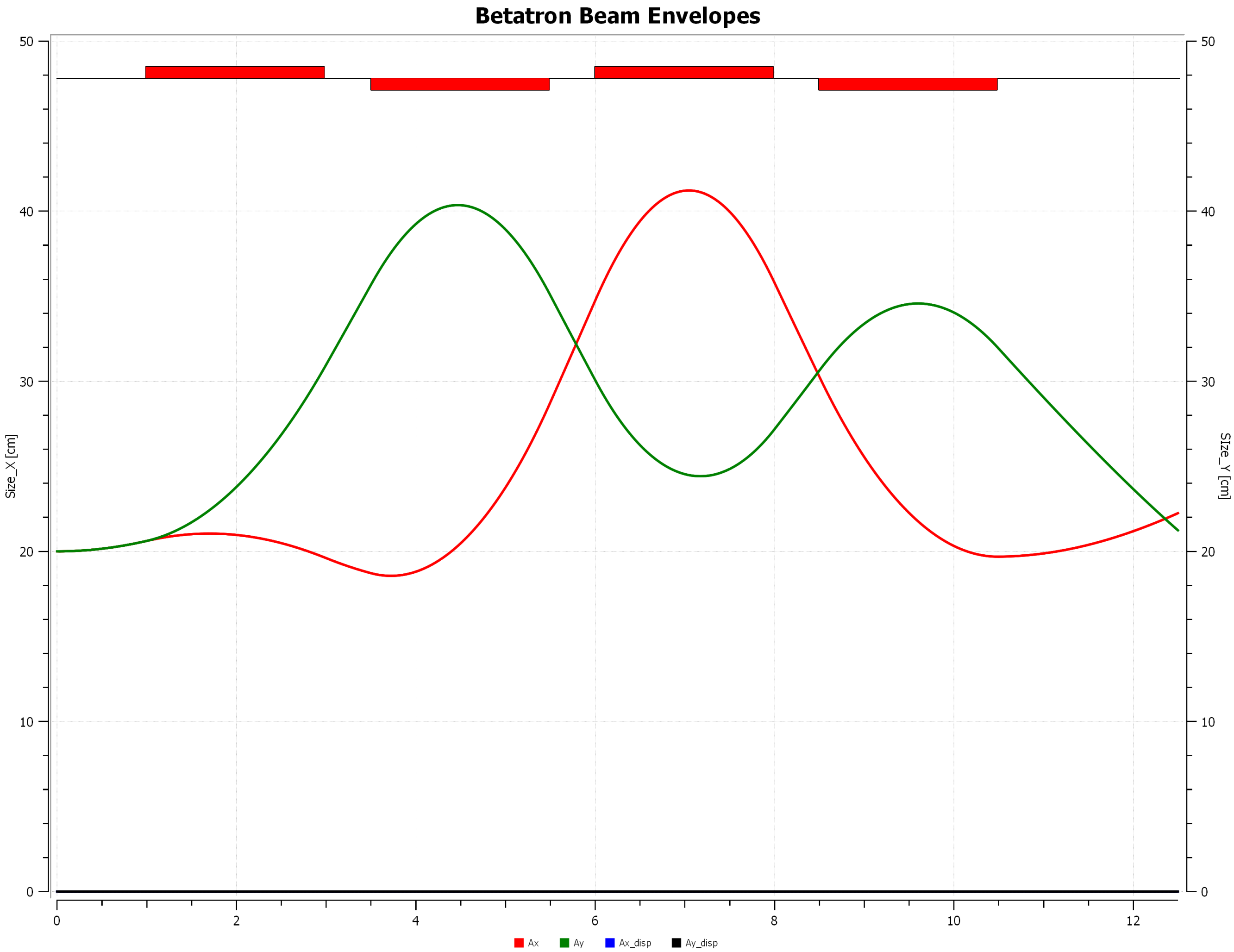

Figure 1. Beam envelopes assuming 20 cm radius exiting the concrete. Fulci's work shows 20 cm sigmas (2 GeV momentum slice) and 10 cm sigmas (6 GeV slice) muon spots. The four red bars are 200 cm quadsrupoles. The first is 100 cm from the concrete at the back of the dump. The spacing between quadrupoles is 50 cm steel to steel or 12 cm coil to coil. If the first quad can be placed closer to the concrete, maximum size would be reduced. 2 GeV muon beam of 20 cm radius assumed.

The FODO lattice of Figure 1 has strengths: Q1 19000 G, Q2 -36000 G, Q3 42000 G, Q4 -28000 G. For muon energies above 2 GeV, scale values. The quadrupole below can deliver ~130000 G so focusing of 6 GeV muons should be possible. OptimX, and any other matrix-based code, is not a good tool for this work but it's what I know so it's the hammer I apply to the screw. Fluka is a better choice. A field map was prepared from an earliersimulation on 22 November and supplied to the proposing group for modeling. A new field map will be supplied for the model discussed here, at 130200 G.

Straight pole quads

The 104 mm quad from which this was scaled started with a model supplied by Sasha Glamazdin. He used what I have known since 2008 (TN-02-060) but have never taken the time to learn: how to apply a mathematical curve to an object in Opera. The pole faces in this model are true hyperboli. For the straight-sided poles of 60 and 80 cm width, I eyeballed the slope of the hyperbola. For the tapered pole, the slope is much steeper and begins at the 20 cm mark of Sasha's pole face. The harmonics are cleaner on the strongly tapered pole. Quadrupole strengths as a function of exciting kAT for five sets of models are shown in Figure 2, normalized to the length of the first set (120 cm). The tapered pole stands out.

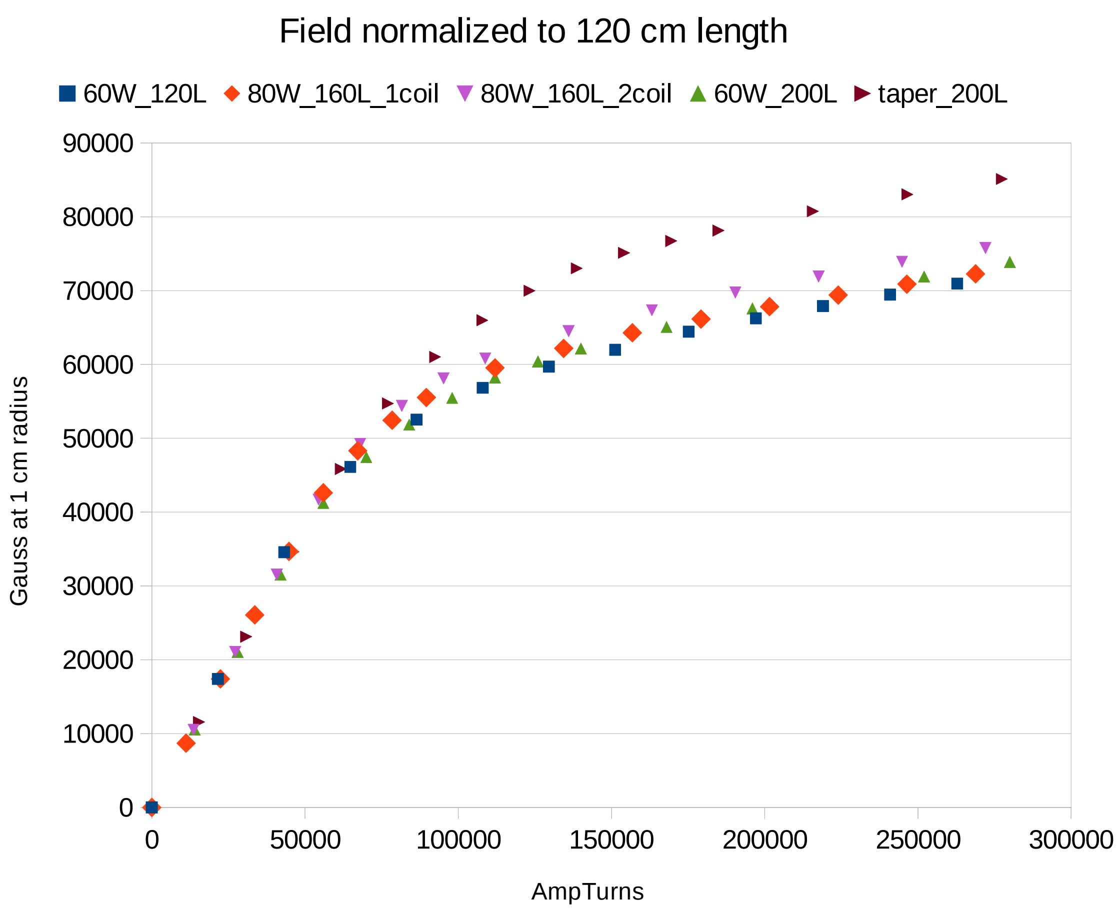

Figure 2. Focusing strength as a function of AmpTurns for five sets of models. The 200 cm tapered pole stands out. Legends for the other four sets are pole width an length. The 80W_160L_2coil set has a small coil very close to the pole tip in addition to the main coil, pushing a bit more flux into the tip. This is nowhere near as effective as the tapered pole.

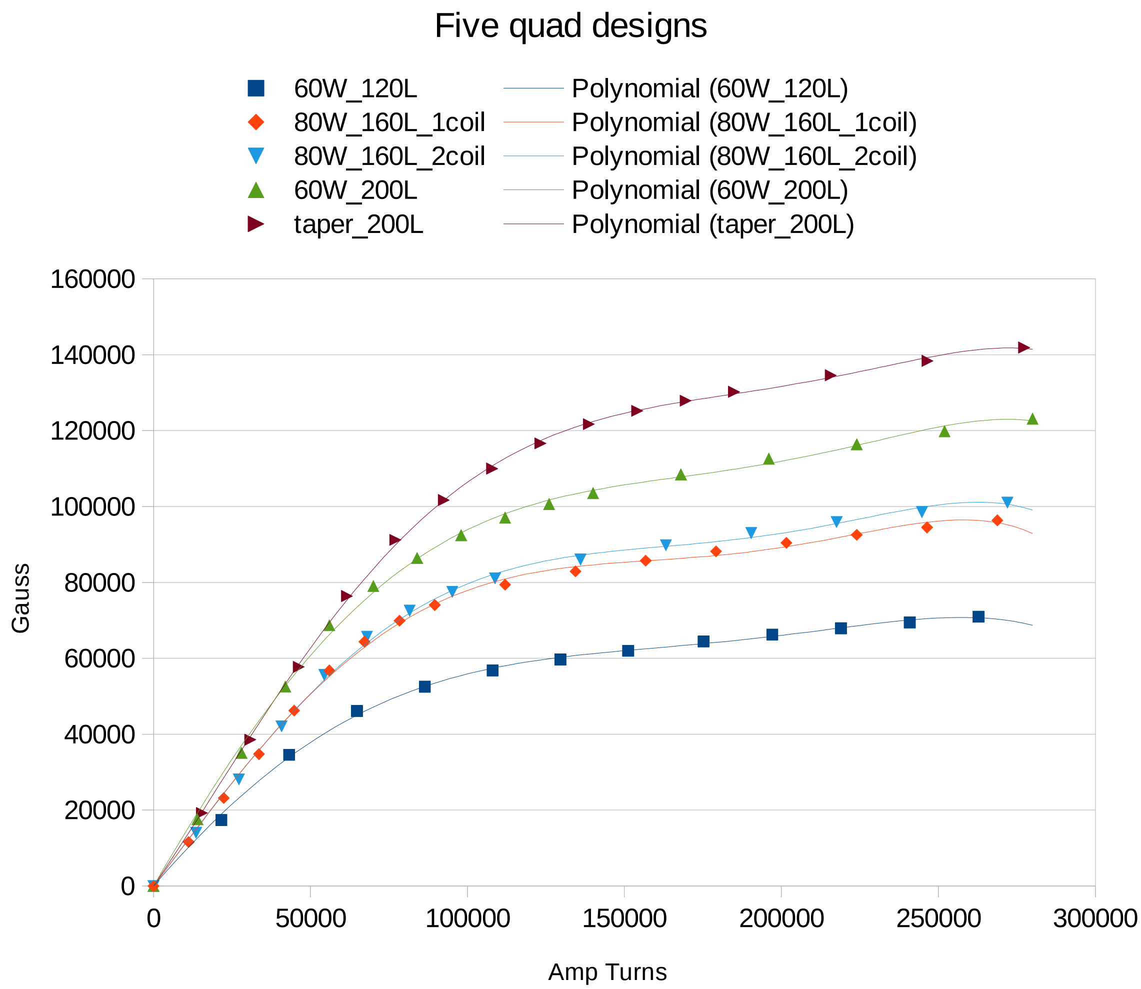

Figure 3. Same five data sets, unnormalized. For the tapered pole, 300 A/cm^2 yields 185 kAT and 130218 G focusing. Fifth order polynomial fits. Odd order is physical as every BH curve is odd.

The choice of conductor is key to heat removal in a conventional magnet. Luvata has a very long standard tool list. https://www.luvata.com/products/hollow-conductors I chose 8549, 11.5 mm square with 8.5 mm hole and 1 mm corner radius after trying a number of options using the pressure drop calculator http://www.pressure-drop.com/Online-Calculator/ to determine whether adequate water flow rates could be achieved in an 122 m straight tube with pressure drop under 15 bar. 150 g/s requires 12.7 bar and would remove 6 kW with 40 C rise and perfect heat transfer. With bends in the double pancake, pressure drop larger. Average temperature will be lower than this delta so resistivity 2E-6 Ω-cm, corresponding to ~60 C copper temperature, was used for the calculations below. The 122 m cited corresponds to the largest double pancake of ten turns/layer, twenty turns total, of Luvata 8549. Six of these make up each of the first three coil layers, for a modeled conductor volume of 12 x 12 cm assuming 0.1 mm of half-lapped glass insulation on the conductor to a total of 12 mm square. More details on the coil packs are given below. For the 300 A/cm^2 of Figure 3 caption, 432 A in the conductor. Each of the largest double pancakes will have a resistance 33.7 mΩ with these assumptions. Power dissipated in each double pancake 6.3 kW so 42 C temperature rise. While one can push the steel harder as shown in Figure 3, the heat removal problem becomes intractable quickly: it's not worth the additional 10000 G focusing above the 130000 chosen.

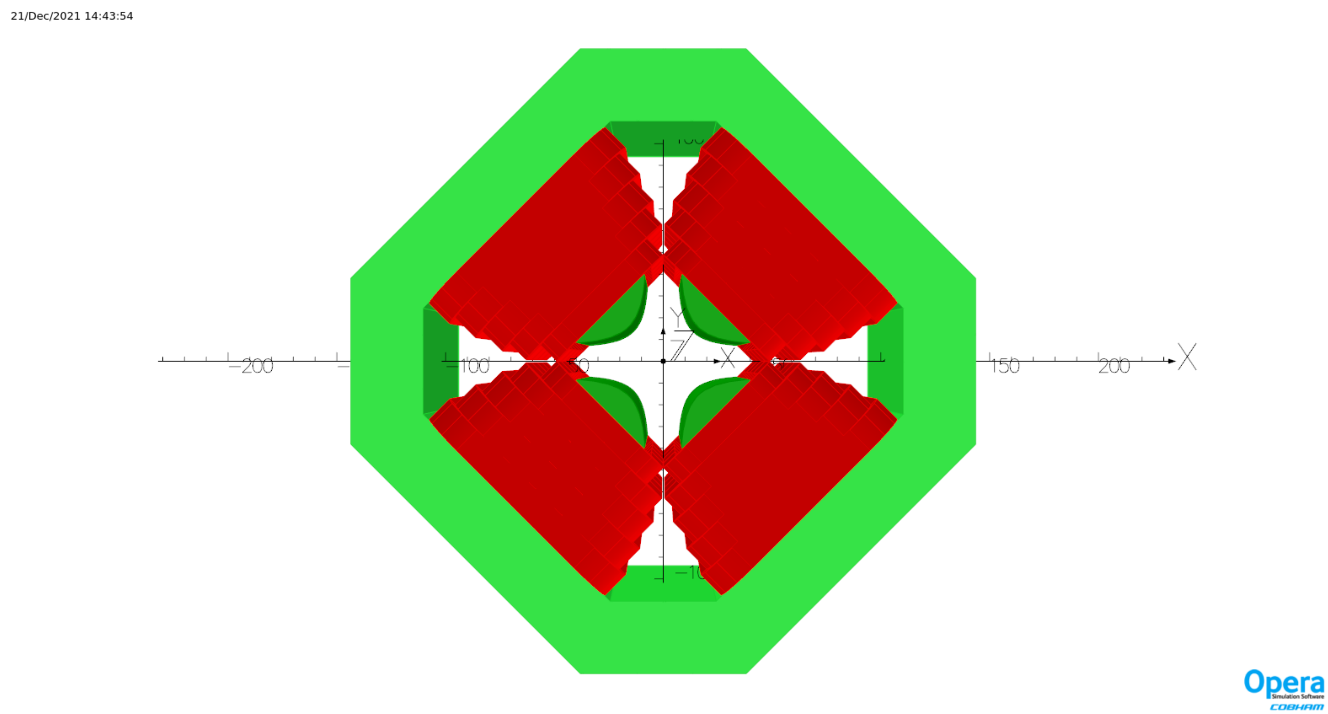

Figure 4. Perspective view of end of the quad with tapered pole and five stepped coils per pole. Except for the top double pancake of the smallest coil, it is assumed that the layer to layer transition within the double pancake takes place in the air between poles. For the smallest double pancake, turns count may have to be reduced by two to make it fit as the corners are almost touching.

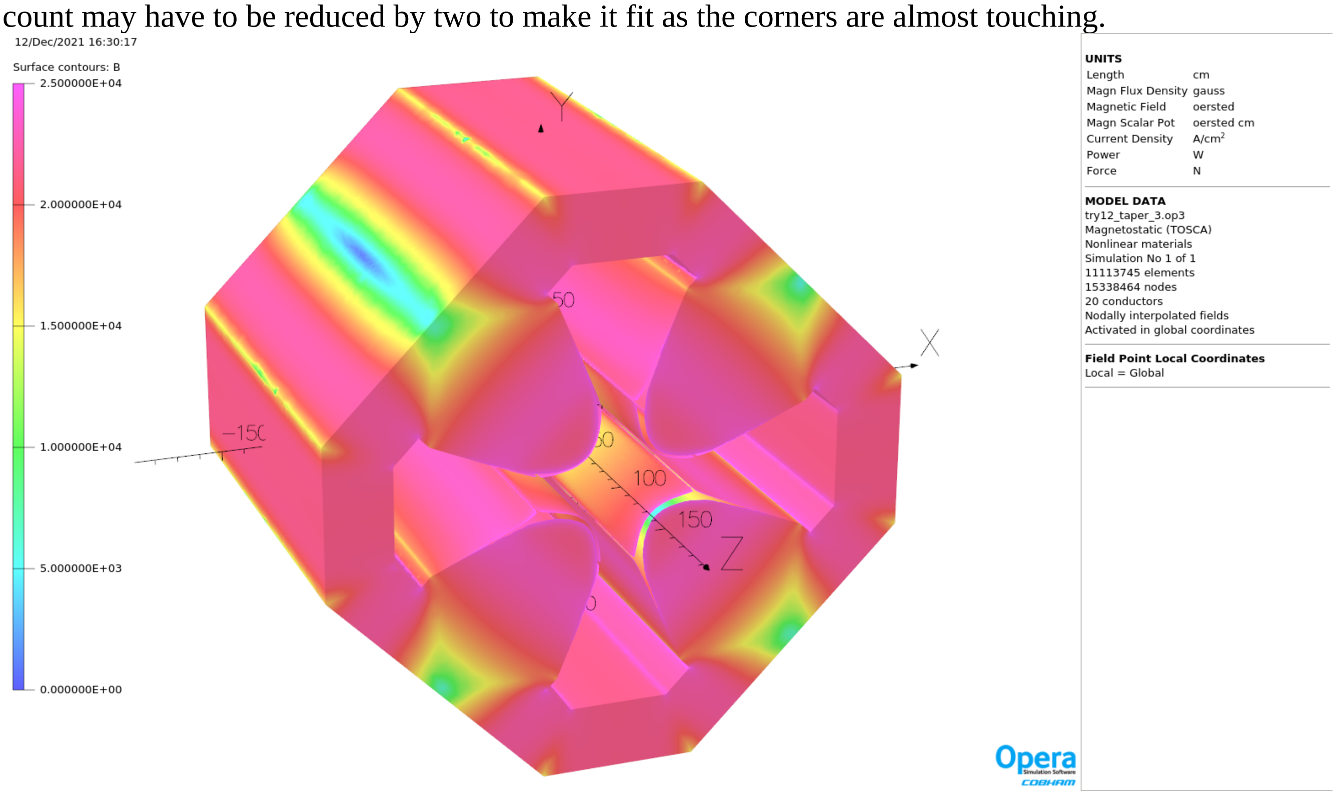

Figure 5. Field on the surface of the steel for 300 A/cm^2 drive. If the yoke thickness is increased from 30.5 to 40 cm the focusing strength available increases by ~3%.

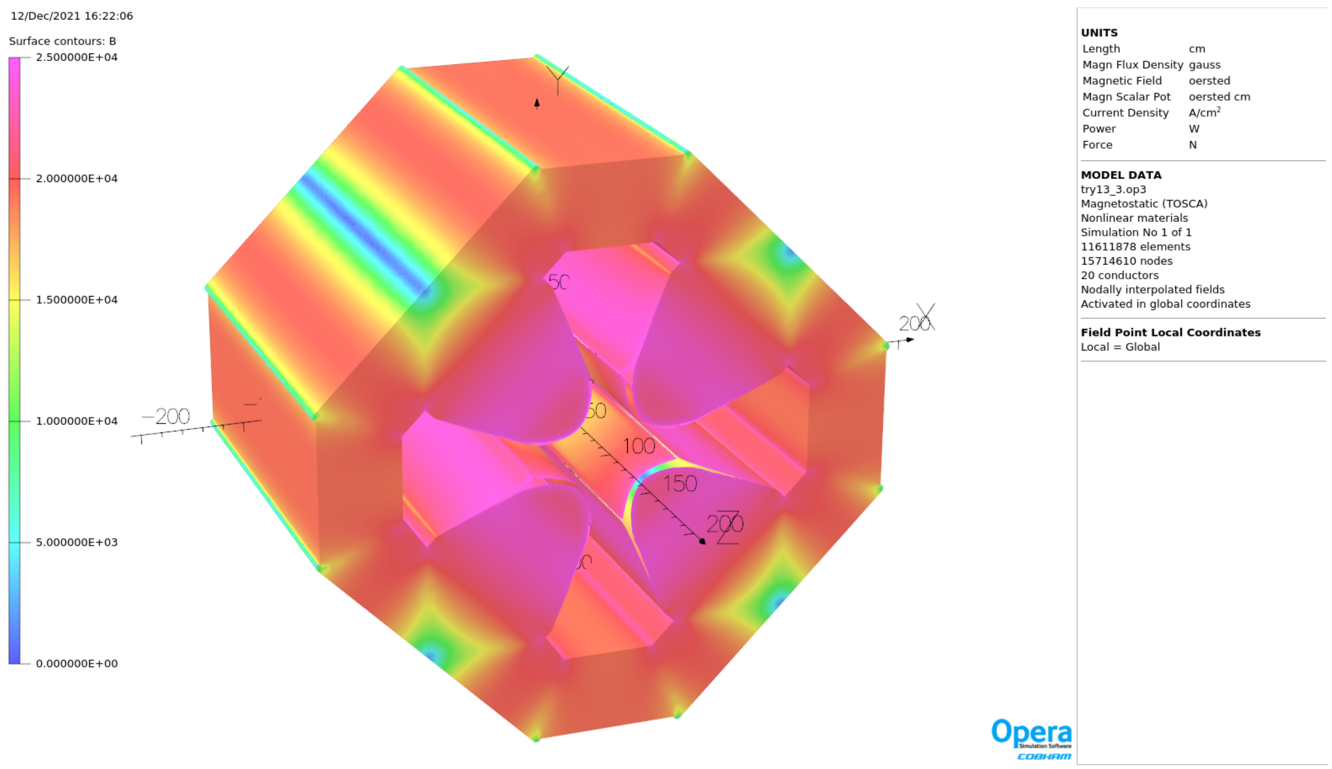

Figure 6. Field on surface of steel with 40 cm thick yoke. Green outside edges are there because I used a quick and dirty method to increase thickness. The additional cost and mass seems to me not worth the 3% benefit cited in Figure 5 caption. YMMV.

NB: *The yoke in figure 5 is 12” thick. Focusing will decrease slightly if it is fabricated from ISO standard 100 mm plate totalling 300 mm. The poles can be fabricated from seven 100 mm plates stacked as one would a cake. A near net trapezoidal forging 80 x 70 x 200 cm would be better.*

It is easier for me to build coils around the Y axis, copy them, and then rotate the ensemble 45°.

Table 1: Coil layout around Y axis. All dimensions cm. Half-length of straight 100 cm. 6 cm radius

layer	width x	height y	x corner	y corner	number of double pancakes	length per double pancake
1	12	12	40.5	-87	5	12200
2	12	12	37.0	-75	5	11920
3	12	12	33	-63	5	11600
4	12	9.6	28.5	-51	4	11240
5	7.2	9.6	24.5	-41.4	4	6432 or 5360

It occurred to me as I was creating the table that the radius of the coil end can be reduced to 4.8, 4.2 or even 3.6 cm without putting too much strain on the inner turn of the coils. This will shorten the assembly. Based on recent work on a dipole, it won't affect the focusing strength significantly. I am not going to re-simulate with the shorter coil. The bottom right box in the table has two options depending on whether or not the cross-over between layers can be accommodated between adjacent coils or the turns count per layer must be reduced to create the needed space.

Table 2: Allowed harmonics and saturation. Two values are given for each harmonic, at r=20 cm where evaluated and at r=1 cm, the CEBAF convention. The “fraction” column shows the fraction of the focusing strength calculated divided by that which would have been the case if the steel were linear and did not saturate. For the last “taper_200L” value in Figures 2 and 3 the fraction is 0.409. Units Gauss for harmonics, A/cm^2 for J/1000. AT AmpTurns

J/1000	AT	radius (cm)	Cos1	Cos5	cos5/cos1	Cos9	cos9/cos1	fraction
0.025	15408	20	-385408	19406	-0.050	-3034	0.008	
	0	1	-19270	0		0		
0.05	30816	20	-770727	38817	-0.050	-6071	0.008	
	0	1	-38536	0		0		1.000
0.075	46224	20	-1154394	58219	-0.050	-9128	0.008	
	0	1	-57720	0		0		0.998
0.1	61632	20	-1528117	77135	-0.050	-12087	0.008	
	0	1	-76406	0		0		0.991
0.125	77040	20	-1823989	92083	-0.050	-14397	0.008	
	0	1	-91199	0		0		0.947
0.15	92448	20	-2033873	102553	-0.050	-16002	0.008	
	0	1	-101694	0		0		0.880
0.175	107856	20	-2199569	110725	-0.050	-17253	0.008	
	0	1	-109978	0		0		0.815
0.2	123264	20	-2332657	117204	-0.050	-18241	0.008	
	0	1	-116633	0		0		0.757
0.225	138672	20	-2433762	122039	-0.050	-18979	0.008	
	0	1	-121688	0		0		0.702
0.25	154080	20	-2504118	125342	-0.050	-19484	0.008	
	0	1	-125206	0		0		0.650
0.275	169488	20	-2557447	127812	-0.050	-19864	0.008	
		1	-127872	0		0		0.603
0.3	184896	20	-2604368	129965	-0.050	-20195	0.008	
	0	1	-130218	0		0		0.563

All normal and skew harmonics through 20-pole for all of the models with tapered poles are provided in the accompanying spreadsheet. For J=275 A/cm^2 the current is 396 A and the power 5.3 kW per double pancake. Given the small increase in focusing from that line to the next, it might be sensible to stop at 400 A. The sum of the resistance of all four coils is ~2.75 Ω so 1100 V would be required to drive 400 A. To be prudent given the approximations used, 1250 V or a 500 kW power supply. One needed for each quad. Given muon beam quality, regulation needn't be stringent. The quads and the power supplies (PS) will still be expensive. Guesstimate $1M per quad/PS pair.

Alternative to FODO

Siemens sells a 7T whole-body MRI scanner. If they will sell just the magnet to an EU lab, it can be used to transport the muon beam without change in properties (**x,p**) . Multiple magnets would make a tranport channel to the new experimental hall if they can be placed in close enough proximity to each other. Cost may be excessive if Siemens will not sell just the magnet as everything else in the MRI system will have to be donated to other Siemens customers as spare parts. Muon heating of the superconductor will have to be estimated - field may have to be reduced to keep it from quenching. https://www.siemens-healthineers.com/en-us/magnetic-resonance-imaging/7t-mri-scanner/magnetom-terra

Conclusion

A resistive quadrupole with adequate strength for focusing a 6 MeV muon beam has been designed and the basic engineering evalution done. A simple beam line which may be translated to Fluka for detailed simulation has been devised.

Personal Note

This material may be referenced in a proposal to the JLab PAC. There is no need to include me in the collaboration. I learned something about quad design by doing this. That suffices.