Cylindrical correctors for use in injector, linacs and spreaders

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Abstract

This work began in response to a request for alternatives to the “Haimson” correctors used in the injector and UITF as they are proving difficult to procure. They provide about 200 G-cm in each plane, are about 3” long, and there are units which mount on 1.5” and 2.75” (or 3”) diameter tube. The latter can be mounted over the short BPMs used in the injector. Sets which fit over M15 BPMs can be 13 cm long without interfering with the SMA connectors. The DB/DJ correctors now in the linacs provide ~1000 G-cm. Finally, given the NE spreader BLM trips from which we've been suffering, I decided to expand the set to include 30 cm length. The common dipoles are 1.5E6 G-cm, air cooled correctors can provide only about 0.3% of this value. This TN will describe six corrector types of similar design: 7.5, 13 and 30 cm lengths, 1..5” and 3” ID.

Design choices

A rule of thumb I learned 45 years ago is that coils without forced air or water cooling should have less than 500 A/cm^2 current density. In #18 round wire, 4A is 486 A/cm^2 so that is where most of the models were evaluated. Where this would exceed 28V, in the 3” ID by 30 cm unit, voltage-limited currents were also modeled. In calculating resistance I assumed minimum material condition in the wire and 60 C temperature copper. I looked at hexagonal close pack with #16 and #18 wire and chose the latter after considering clearances and stock tubing sizes. Twelve layers at heavy film maximum material condition are 1.17 cm thick. Aluminum tube is available in 0.5” (1.27 cm) wall. One mm will remain under the groove, sufficient. For the short units, 10.5 turns/layer (inner) and 12.5 turns/layer (outer) were chosen for coil width, with half-turn needed for hexagonal pack, again at maximum material thickness. On the 1.5” ID units, these coils subtend just over thirty degrees of the circle. Groove bottoms must machined to radius, not flat. If this provides a winding problem for the vendor, an alternative is ten layers of #18 square, again on radius-bottom groove. Current maximum ~5A in this case given reduced resistance. Groove width may be reduced by vendor to match actual wire size as opposed to maximum material condition. For the 13 cm and 30 cm by 3” ID units, turns count per layer was increased to maintain the thrity degree angle. For the inner layer on these, 18.5 turns/layer groove and outer 24.5 turns/layer groove. Again, maximum material condition.

Wire insulation should be 220 C rated polyimide for radiation resistance. Coils may be wound dry and simply taped in the grooves. Coils may be wound wet with electrical varnish or epoxy with at least 150C rating. Coils may also be vacuum potted with varnish or epoxy of 150 C or better rating.

Coil calculations were made with helical ends (see images) as these are solved more quickly than those with constant perimeter or similar, more complicated ends. Vendor may propose another end treatment to ease winding via contiuous tension.

For 1.5” ID, aluminum tube 2.5” OD by 0.5” wall is assumed for the inner coil and 3.5” OD by 0.5” wall for the outer coil. Steel flux return DOM tube 3.75” OD by 0.125” wall is available from speedymetals.com and other sources.

For 3” ID, aluminum tube 4” OD by 0.5” wall is assumed for the inner coil and 5” OD by 0.5” wall for the outer coil. Steel flux return DOM tube 5.25” OD by 0.125” wall is available from same sources.

Steel tube to be bored out to provide slide fit over outer aluminum tube and coil. Half the tube purchased will be scrap as kerf is not permissable: each coil form and steel piece must be a full semi-circle.

Coils may be wound on the aluminum parts and bonded during/after winding or may be wound on tooling and inserted afterwards. Grooves in aluminum may be tapered to allow insertion of coils wound on tooling, gaps should be filled with something other than neat epoxy or varnish. Filler material non-magnetic and 150+ C compatible.

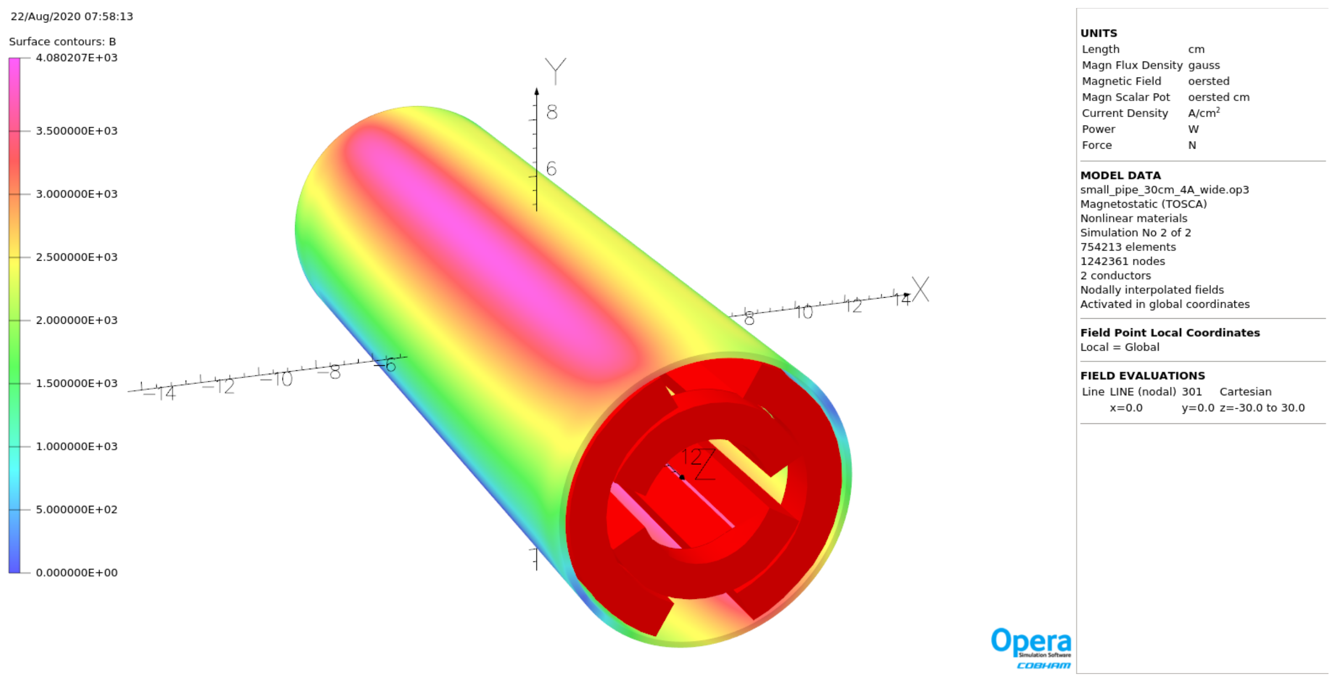

Figure 1. Coils and steel of 1.5" ID by 30 cm long unit. There is a 1 mm gap between inner and outer coils which will be occupied by the aluminum outer form. The IR of the inner coil is 2.005 cm versus 1.905 cm outer radius of 1.5" OD tube. Steel is modeled here as 2 mm thick but should be tangent to the outer aluminum and coil, to 3 mm thick. Inner coil produces By and outer Bx. The unit may be rotated 90° , of course, to change this. Seams in steel should be in low field region. 4A in each coil.

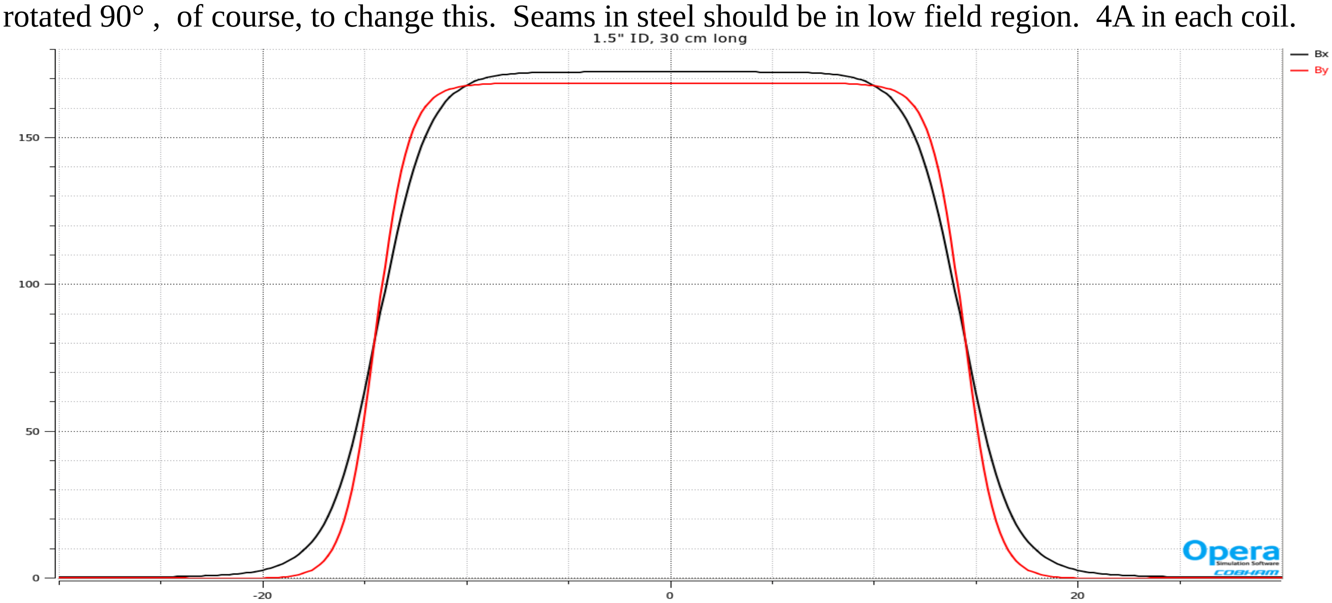

Figure 2. Fields of the coils shown in figure 1 along the Z axis.

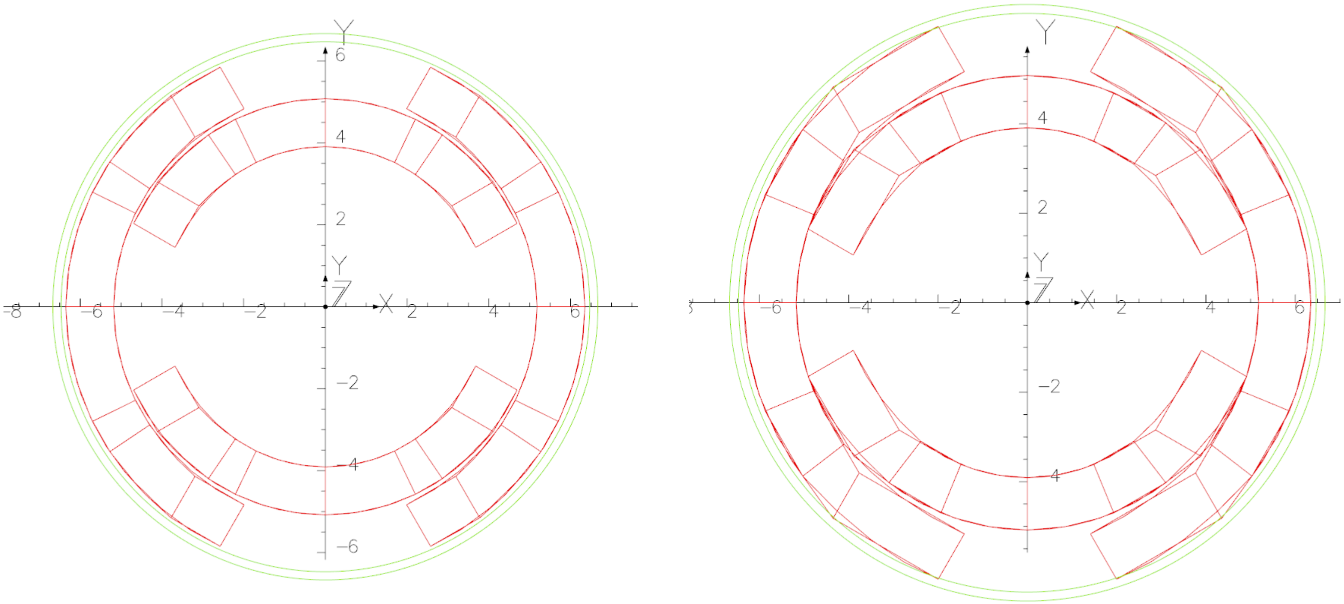

Figure 3. (poor) Prismatic representations of the coils in the 3 inch models. Left has azimuth 1.17 cm on inner coil and 1.388 cm on outer. One can sort of see the difference between the width of the rectangles on the ends of the inner and outer arcs. This is used only for the 7.5 cm length in 3" ID so straight legs are longer. The azimuthal extents cited are used in all the 1.5" ID models as they subtend very roughly 30° there. On the right one sees the coils used in the 13 cm and 30 cm by 3" ID models. Azimuthal extent for inner coil 2.054 cm and for outer 2.730 cm. The difference in rectangle width is more obvious here. Again, subtended angle is about 30°. All coils are 12 layers hexagonal close pack, 1.17 cm thick. Only the turns/layer change.

Table 1: coil azimuthal dimensions at inner radius

For coils, subtend about 30 degrees.	cm	30 deg	turns/layer	coil azimuth cm
forming cylinder radius	2.005	1.050	10	1.166
forming cylinder radius	3.275	1.715	12	1.388
forming cylinder radius	3.91	2.047	18	2.054
forming cylinder radius	5.18	2.712	24	2.720

Table 2 ∫BdL(z) results for the models. Last column shows value when steel is removed.

model	comp	turns	AT	Amps	steel G-cm	air G-cm
1.5" by 7.5 cm	Bx	144	575.86	3.999	1083	644
	By	120	-481.72	-4.014	1061	833
3" by 7.5 cm	Bx	144	575.86	3.999	766	433
	By	120	-481.72	-4.014	675	478
1.5" by 13 cm	Bx	144	575.86	3.999	1990	
	By	120	-481.72	-4.014	1983	
3" by 13 cm	Bx	288	1145.66	3.978	2480	
	By	216	-865.14	-4.005	2092	
1.5" by 30 cm	Bx	144	576.34	4.002	4953	
	By	120	-481.72	-4.014	4845	
3" by 30 cm	Bx	288	1145.66	3.978	6508	
	By	216	-865.14	-4.005	5370	
3" by 30 cm trim card limit	Bx	288	716.04	2.486	4067	
	By	216	-757.00	-3.505	4699	

The last two rows may be over-estimates by 8% as I assumed I could get 28V at the magnet from a standard trim card and Sarin Philip advises me that 25V is a more prudent assumption. As mentioned a few lines below the top of this Design Choices section, I used minimum material condition for the wire and 60C copper in calculating resistance. At 28V I get 2.58 A and 3.63A with these assumptions. As-built will be different and must be measured.

In all but the 3" ID by 30 cm case the increased turns count for the outer Bx coils provides more BdL and therefore more vertical steering than the inner coil. In the 3" ID by 30 cm case the voltage limit constrains the current in the outer coil much more than the inner. The unit should be rotated 90° to increase Bx capability, using the inner coil in this case.

One sees in table 2 that the 3" ID by 7.5 cm "air" model has twice the BdL of the comparable Haimson when operated at 4A. Similarly, the 3" ID by 13 cm with steel has twice the BdL of the DB/DJ printed circuit correctors used with the C100s in a shorter assembly which is much more radiation resistant. Finally, the 1.5" and 3" ID by 30 cm units have about 0.3% of the common dipole fields. Recently about 0.5% of NorthEast BCOM2 BdLwas removed to get it closer to design. The 30 cm unit does not match this but would have provided an indication that such a reduction was desirable and made the decistion to resteer the corner via dipoles easier to make if such correctors placed on the 3S and 5S tubes were both railed negative to reduce BLM trips. Having pass-specific steering knobs local to the spreader rather than 300 m upstream in the recombiner should allow exploration and mitigation of BLM trips much more easily.

Table 3: Power in each coil at 4A and 3A. Surface area of end annuli and outer cylinder provided

	power assuming 4 amps			power assuming 3 amps		
	7.5cm_pair_W	13cm_pair_W	30cm_pair_W	7.5cm_pair_W	13cm_pair_W	30cm_pair_W
1.5" ID inner coil	20	30	63	11	17	35
1.5" ID outer coil	30	42	81	17	24	45
surface area cm^2		*868*	*1377*		*868*	*1377*
3" ID inner coil	28	65	124	16	37	70
3" ID outer coil	39	96	174	22	54	98
surface area cm^2		*1297*	*2009*		*1297*	*2009*

The worst case scenario, 4A in the largest unit, is about 150 mW/cm^2. This does not seem excessive. Since the coils can't reach these currents in any event with standard trim cards, 100 mW/cm^2 is closer to real maximum. Maximum usable current will have to be determined in magnet test with first unit. Limiting temperature of 100 C seems reasonable with "HOT do not touch" label given wire insulation and adhesive specifications. Aluminum will expand more than the copper and steel, but not enough to put undue stress on either with this temperature limit, 0.9 ppt increase in aluminum vs steel for 80C increase; 0.6 ppt increase in aluminum vs copper. Maybe 70 C max would be better for the 30 cm units given the differential length expansion and stress on the wire at the corners where it moves from straight to helical end. Perhaps 1 cm radius there so nominal bending stress is less than 5% before expansion stress. For 7.5 cm and 13 cm lenght, 0.5 cm radius should suffice, 10% bending strain plus thermal expansion. Constant perimeter ends would reduce both winding and thermal expansion stresss, allowing larger temperature excursion.

Magnet placement in spreaders

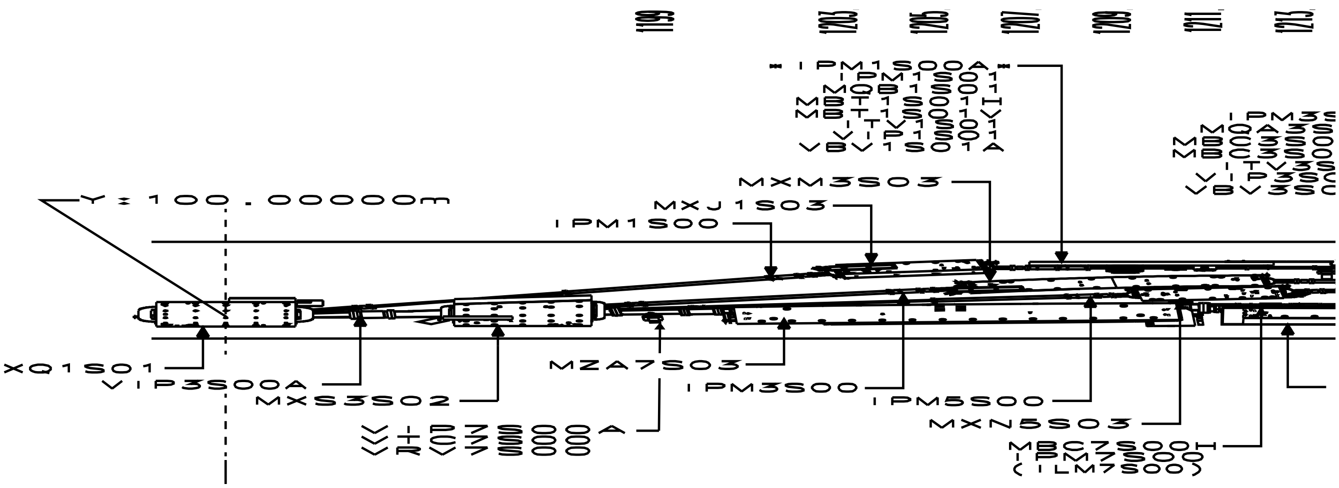

Figure 4 NE spreader

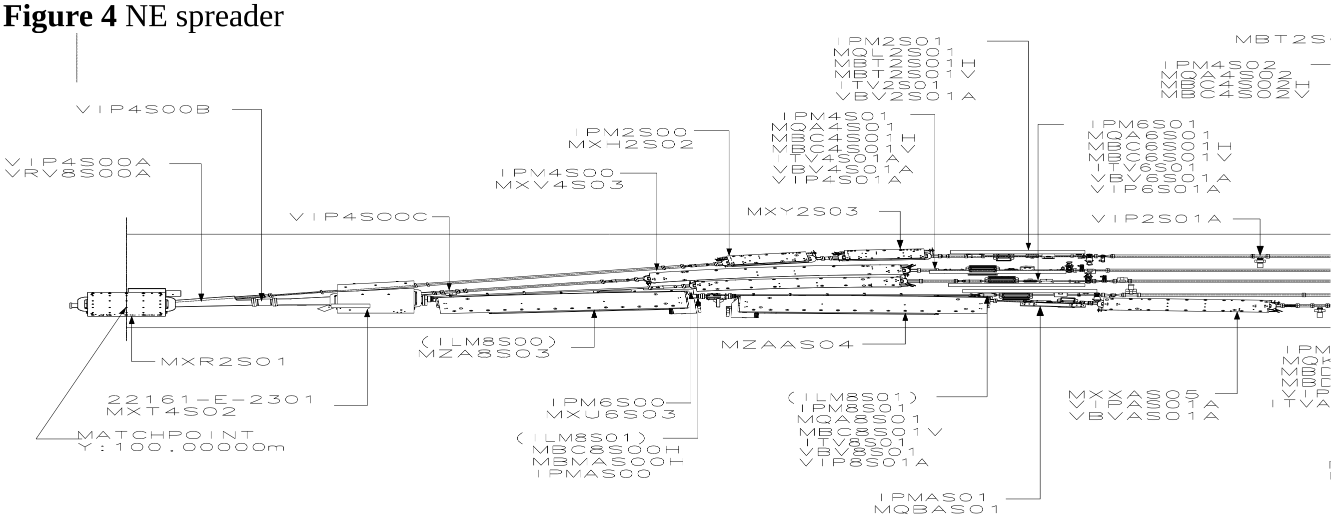

Figure 5 SW spreader

The intent is to identify locations on either 1.5” or 3” beam pipe soas close to the BCOMs as possible in the 1C/3C/5S and 2S/4S/6S lines and install either 1.5” or 3” by 30 cm correctors.