Do CEBAF septa have to be lengthened for 22 GeV FFA?
Jay Benesch
23 March 2022

Abstract

A working group is examining the possibility of doubling CEBAF's energy yet again, to 22 GeV to Halls A, B and C. In TN-21-051 I modeled a dipole which could be used to deliver beam to Halls A and C through the BSY arcs. Here I discuss the need for a new type of septum magnet and models showing that the steel length of the present septa is sufficient if the current density can be doubled by using a conductively cooled HTSC in place of copper. [1,2] Existing septa are summarized in the first section. In the second and third sections my two meter YC and YR models {3] are pushed to BdL values twice that needed in the ZA at 11 GeV per meter. Steel is added to the YR model to better approximate the ZA without creating a new model. I then draw tentative conclusions. Two tables giving Fourier harmonics along five orbits follow. Appendices contains the material send to BNL; EPICs field maps for four existing septa and some useful information for each, including top level assembly drawing number.

Existing current sheet septum magnets

There are five types of septum magnets employed in these regions, four current sheets and one Lambertson-style. The latter may be extended in length and will not be discussed further. Basic parameters of the four current sheets are given in the table below. All four are running at very high current densities in the copper; they can have neither current density nor length increased to deal with the proposed doubling of energy. The guidance my magnet mentor provided five decades ago, which I recently learned is still used at CERN, is that current density in copper of a water cooled conductor should not significantly exceed 10 A/mm^2.

Table 1. Existing CEBAF current sheet septum magnet types

Magnet	Steel length (cm)	Turns	Amps	∫BdL (G-cm)	|B| (G)	J (A/mm2) in copper	Stainless bet. beams (cm)
YA	100	5	70	35050	350	30	0.9
YB	96.1	24	447	515680	5367	27.8	3.28
YR*	194.8	24	688	1535720	7883	42.8	5.06
ZA*	298.2	24	814	2753440	9234	47.7	3.36

At my suggestion BNL may propose a conductively cooled MgB2 or REBCO septum magnet development project in response to an FOA issued by ONP: DE-FOA-0002670. In my submission to BNL I assumed that the ZA steel would have to be extended and the YR steel might have to be at twice the |B| values in the table. This TN results from my decision to verify that assumption. As the next section will show, the YR steel is not far from linear response at twice the ∫BdL in the table and can even be pushed to 4/3 the ∫BdL in the table for the ZA, suggesting that the ZA need not be increased in length either. These conclusions will simplify the design of new spreaders and recombiners in the higher energy lattice. This document will be provided to BNL to supplement the prior one.

A failed but instructive alternative

Three septa are described in [3]: the YR current sheet septum, a Lambertson variation, and a combination I designated YC which has not been built. See TN-17-047 for more information and extensions of the published work. The YC model has been run to provide 2.45E6 G-cm with 5 cm beam separation and results displayed below. While this concept cannot be pushed as hard as the YR, the model does show that a 0.2 cm carbon steel vacuum vessel around the beam which is "unbent" will reduce the stray field by about three orders of magnitude in the case modeled, to under 1 kG-cm. Compare this with the values in the multipole table for YR models in Appendix 2.

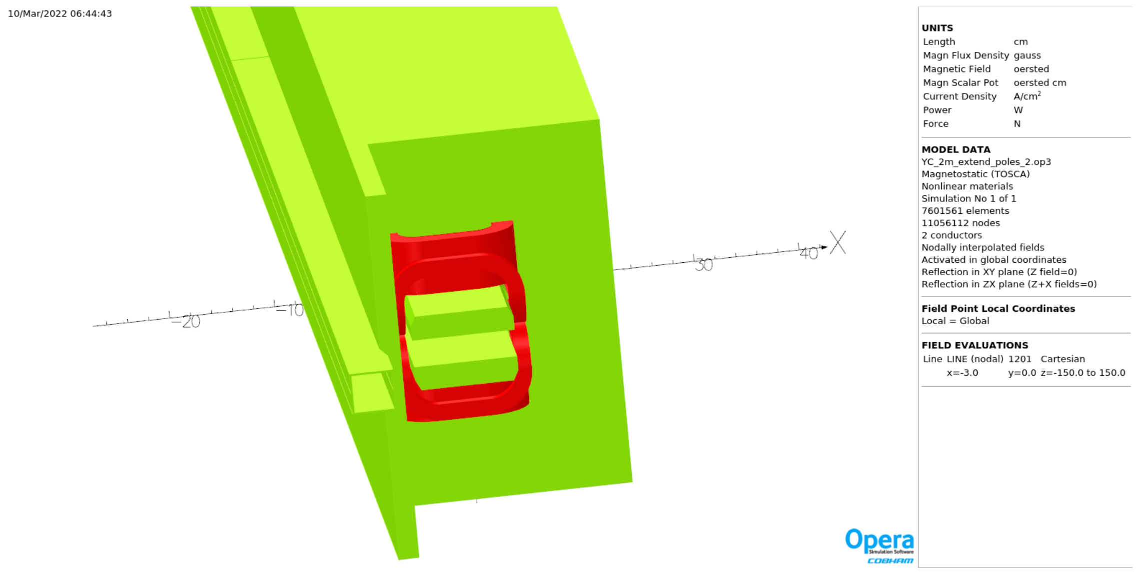

Figure 1. YC model end view

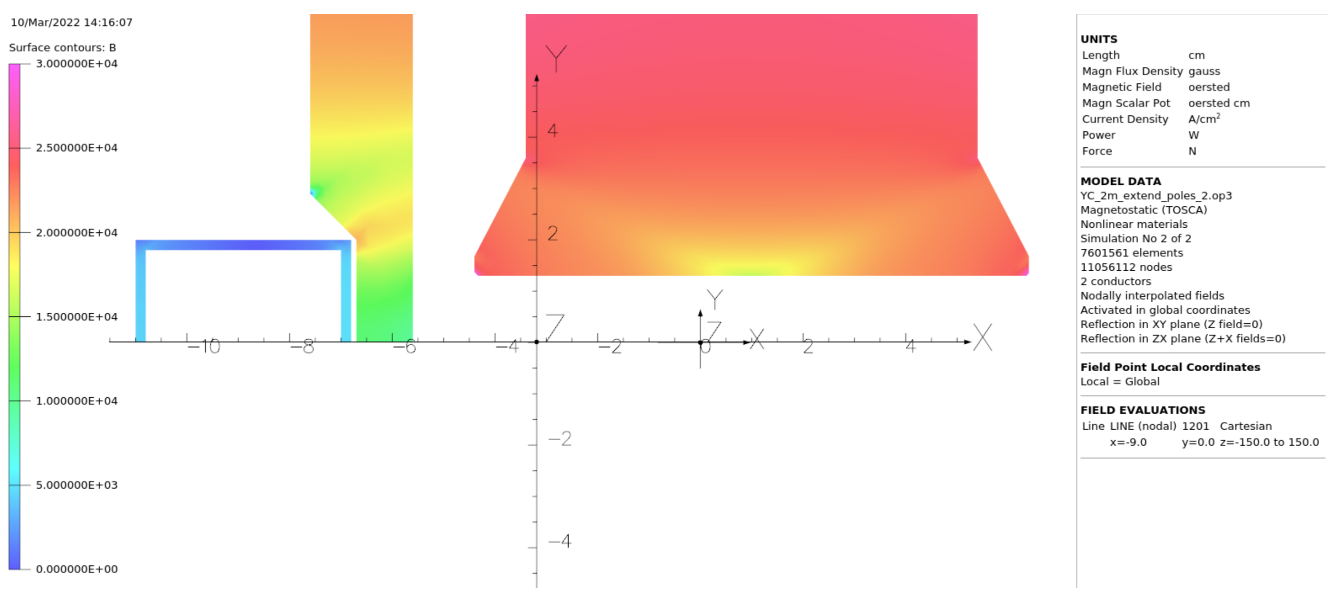

Figure 2. |B| on the surface of the top half of the YC model at 2.45E6 G-cm. Note that the box on the left for the "unbent" beam sees low field, ∫BdL = 801 G-cm over 300 cm. The cm of steel to its right obviously contributes to field diversion but the principle is what matters below.

The YR model

The YR magnet model is discussed in TN-18-037 and [3]. In 2018 cases were run up to an ∫BdL of 1.75E6 G-cm, equivalent to ZA value of 2.625E6 G-cm or roughly the value at which it is run to provide 11 GeV to Halls A, B and C. The ∫BdL ZA value in Table 1, 2.75E6, is the maximum measured value (see Appendix 2). This work extends the YR model to 3.66E6 G-cm, equivalent to 5.5E6 G-cm at the ZA length, twice the measured maximum. The current densities used in the models are not possible in water cooled copper. It is hoped that a conductively cooled MgB2 or REBCO superconductor can be used at ~20 K. There are three commercial suppliers for MgB2 and at least one for REBCO. [1,2]

Unfortunately the YR model does not lend itself to the addition of a straight steel tube outside the current sheet given the way it was constructed and I do not wish to take the time to rebuild it. The peak field in the "unbent" beam path by the YR is 1800 G near the upstream conductor. A 1.25 cm outer radius carbon steel tube with 0.15 cm wall will exclude most of this flux from the beam path.

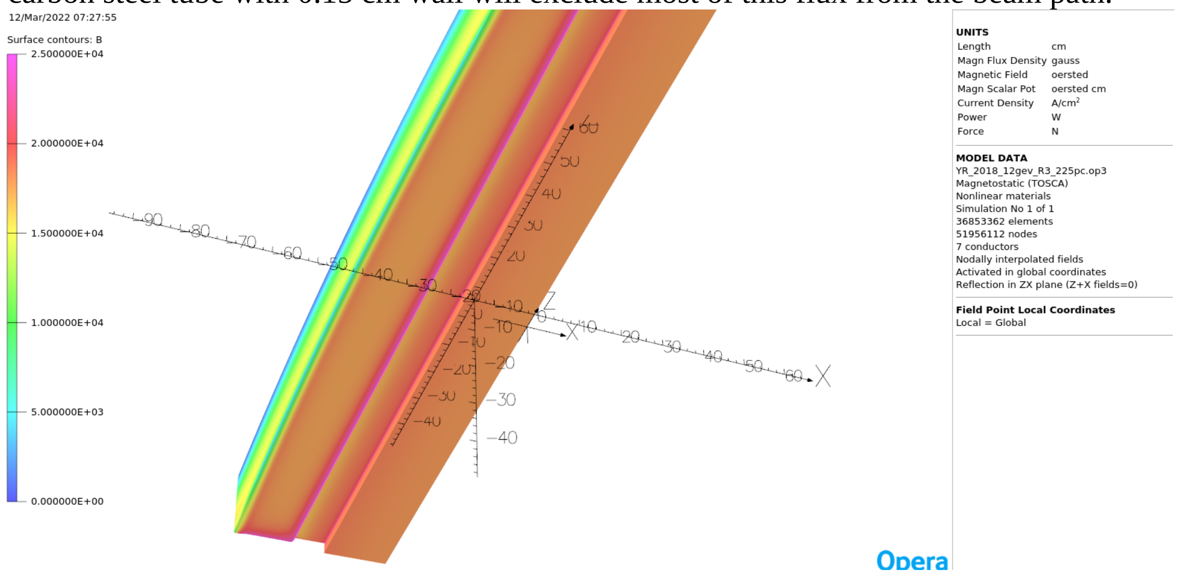

Figure 3. Field on bottom surface of the YR magnet with 41650 AT in 24 turns, 1735 A or 102 A/mm^2, quite impossible for water cooled copper. This model provides 3.5E6 G-cm, not quite ZA equivalent.

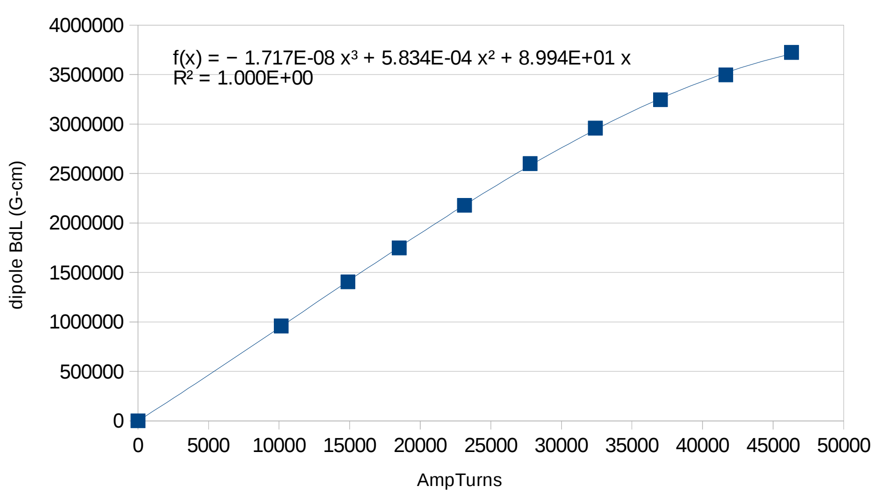

Figure 4. BdL v AmpTurns for YR model. Not that far off a straight line in spite of Figure 3.

Since the ZA steel is 35% wider and 25% higher than that of the YR shown in the figures, I added 10 cm of steel to top and right side of the model as an approximation and started three cases which should encompass the needed ∫BdL. This will reduce the field in the bulk steel. Dipole field on the "unbent" beam side of the current sheet is also reduced but some of the higher Fourier components are not.

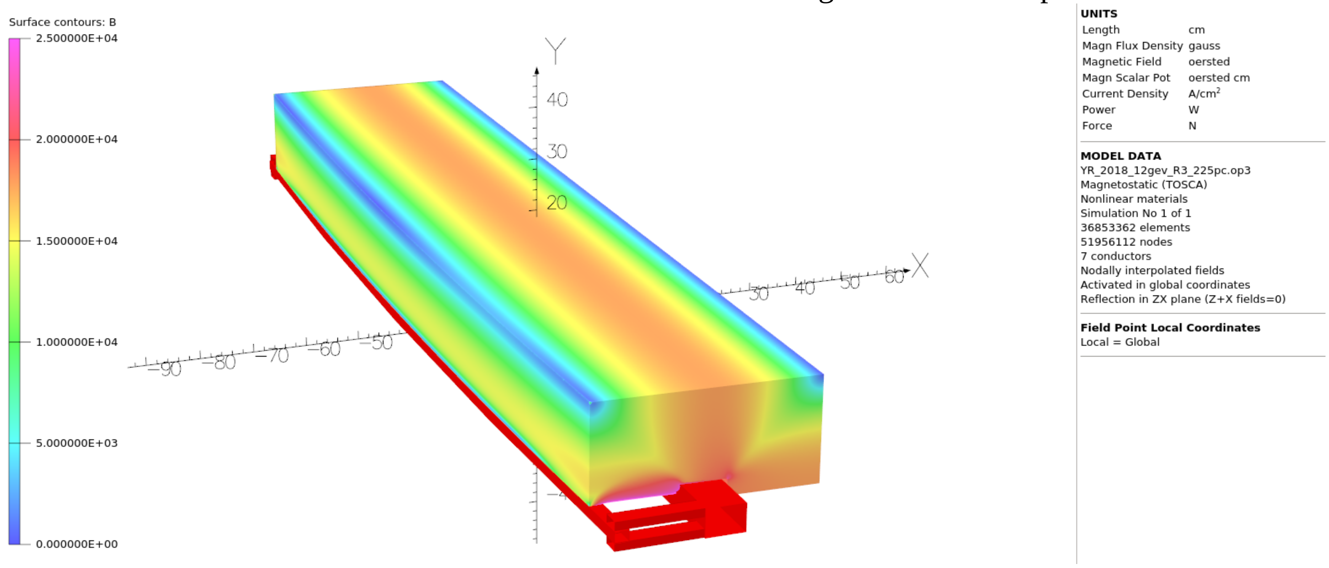

Figure 5. |B| on surface of of the YR magnet with 41650 AT in 24 turns, 102 A/mm^2, same as Fig. 3

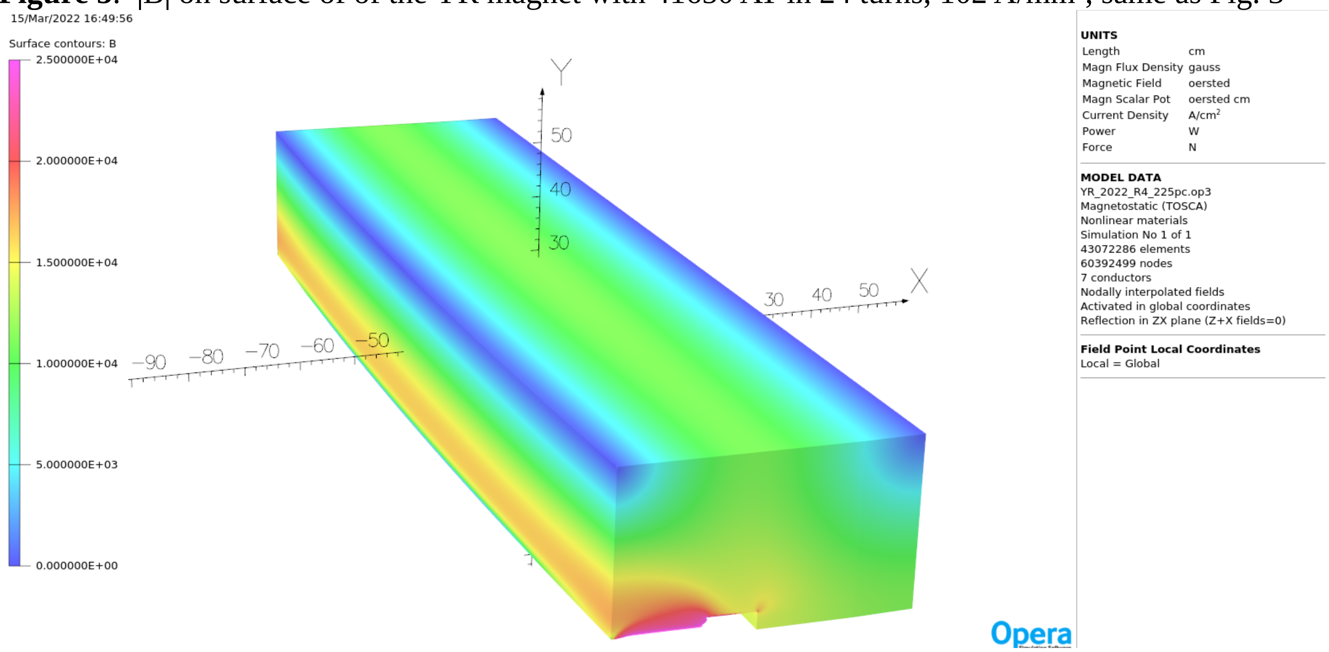

Figure 6. |B| on surface of the model with 10 cm extra steel top and right, 41650 AT in 24 turns. Same conductors as Fig. 5. 108 A/mm^2 in copper. This model provides BdL 3.8E6, more than needed for the ZA equivalent. Since it has steel comparable to the ZA at 3 m length and the field in most of the steel is ~1.2 T, I am going to run models with higher current density to determine if the ZA may be shortened; engineering current density in the superconductor at 20 K can be ~200 A/mm^2, twice that used here. A shorter ZA with smaller beam separation would ease CEBAF separator/recombiner design. Figure 4 suggests the YR can also be shortened somewhat.

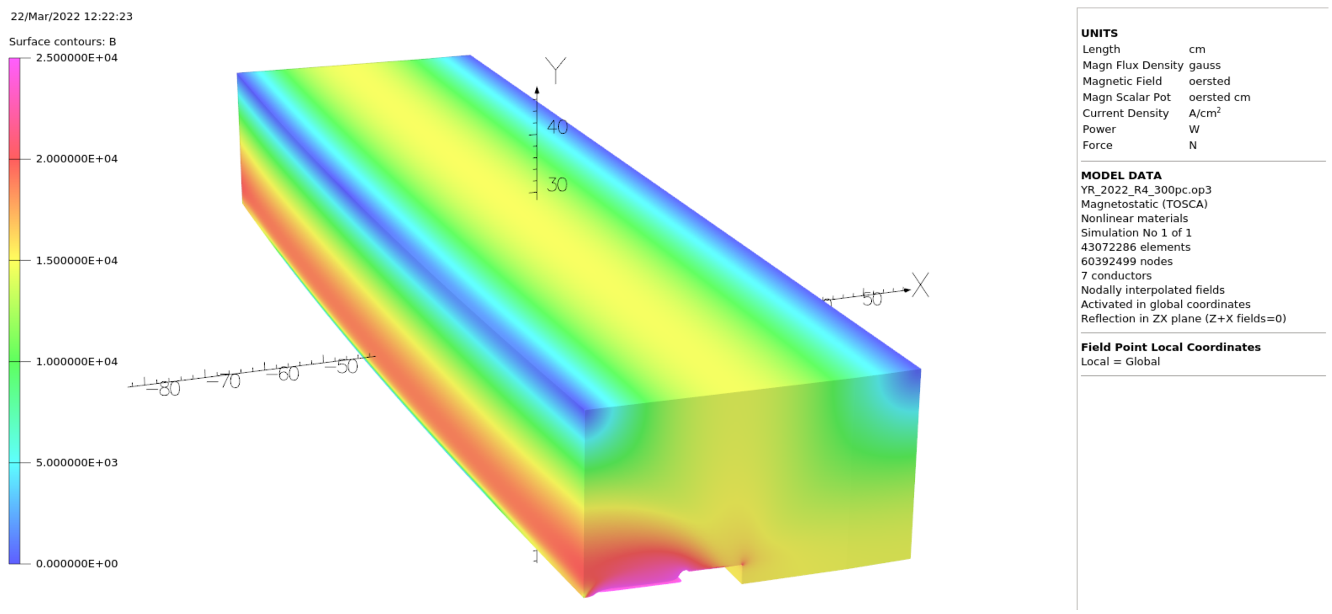

Figure 7. Same steel as Figure 6, 55545 AT aka three times the value needed to get the 11 GeV ZA-representative BdL in the YR steel. Again, this model has 10 cm additional steel top and right. 144 A/mm^2 in copper

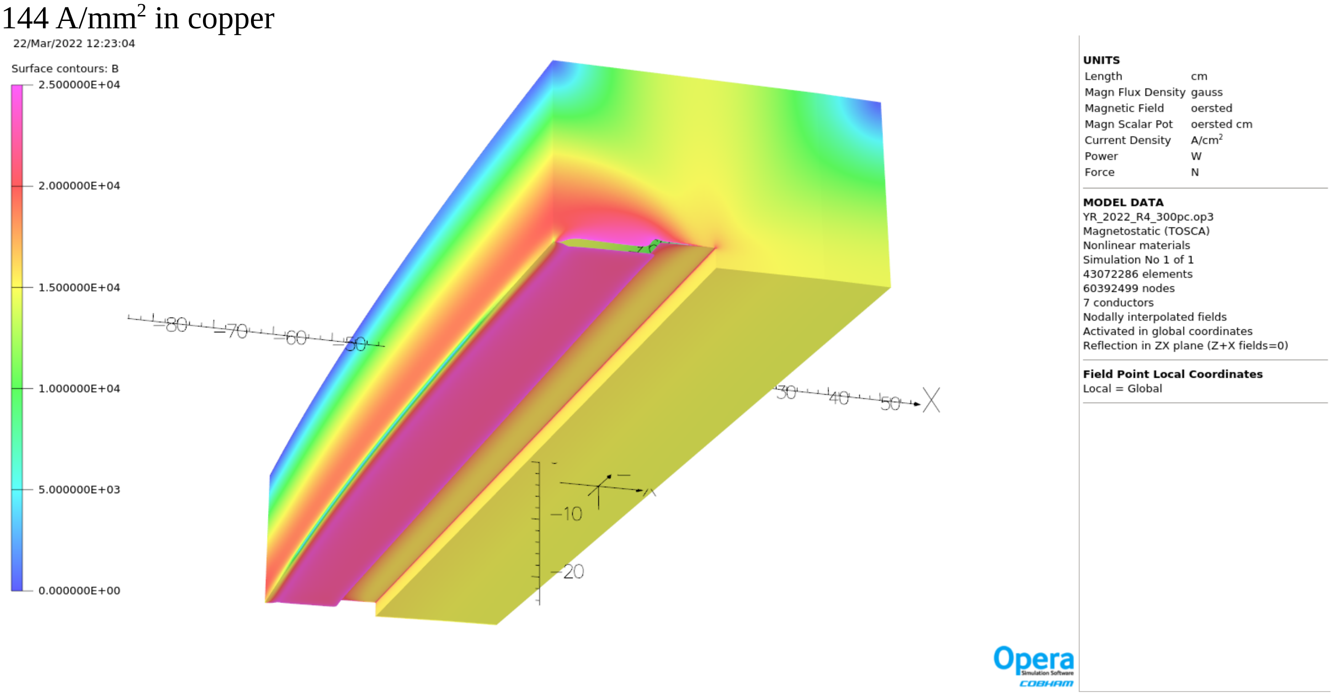

Figure 8. Bottom view of Fig. 7. Note that the pole is clipped by the 25 kG maximum imposed. BdL 4.566E6 G-cm, equivalent to 6.99E6 at ZA length, 27% more than is needed to double the energy to 22 GeV. A ZA-equivalent with MgB2 and ~270 cm length should serve given that the coupling between conductor and steel will be reduced by the intervening cryostat (warm iron assumed).

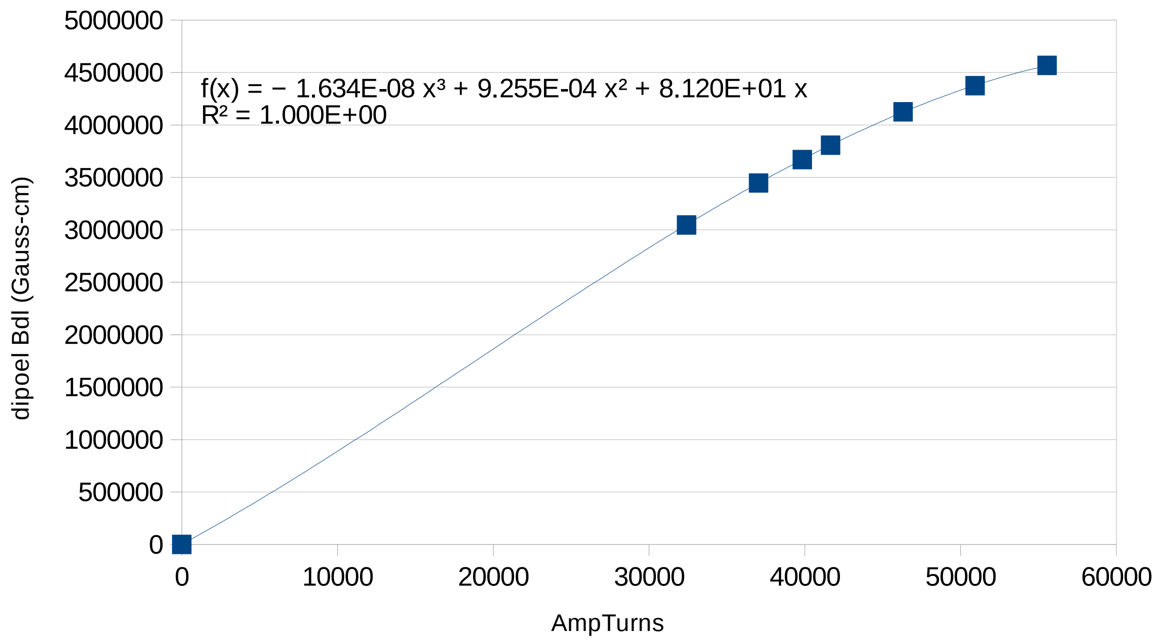

Figure 9. B(AT) for the model in figures 6-8. Last point is that used in figures 7,8.

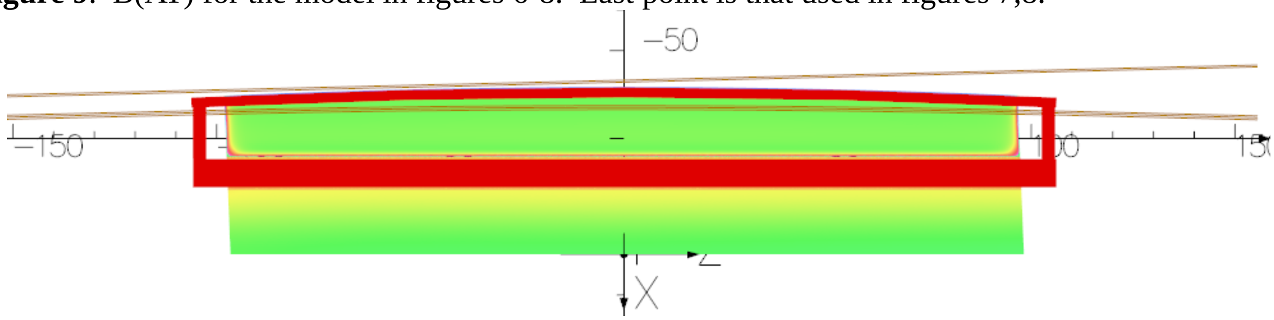

Figure 10. Five trajectories calculated in 2018. The command file generated then was used to calculate Fourier components every 0.25 cm along the orbits, on 1 cm radius circles, for the two models considered in this paper. Figures 4 and 9 show dipole component along the orbit closest to the coil. Note that the steel at the ends of the YR are inclined with respect to the back (bottom here) of the yoke. Harmonic content is given in tables on the next two pages.

One sees in the tables that follow that the harmonic content seen by the "passing" beam is very large. One must make this beam pipe of carbon steel rather than stainless to avoid the steering and higher order effects of these fields. The values are sums (Gauss) divided by 4 as step size along each orbit was 0.25 cm.

Conclusion

The real estate available in the spreaders and recombiners may suffice if BNL can develop a conductively cooled magnet using MgB2 or REBCO at ~20 K, 2.5 T with warm iron. Warm iron because the time required to cool 5-7 tonnes of return steel with a GM unit approximates forever.

References: see Appendix 1

Table 2. Harmonic content of models with original YR steel along five orbits of Fig. 10

Values evaluated on 1 cm radius circles so units are Gauss for all columns.

AmpTurns	start X cm	Cos0	Cos1	Cos2	Cos3	Cos4	Cos5	Cos6	Cos7	Cos8	Cos9
10150	-33.52	958730	-5279	3036	-1585	722	-267	70	-5	-2	3
	-38.52	-2909	3815	3216	3347	3139	2065	583	-492	-768	-428
	-39	-7204	-5499	-3884	-2373	-1173	-413	-54	57	52	23
	-34	961551	-8507	5598	-2836	882	88	-331	252	-105	2
	-33	956642	-3105	1440	-641	270	-104	39	-11	1	1
14875	-33.52	1404337	-7753	4456	-2327	1057	-389	104	-8	-4	5
	-38.52	-4550	5474	4692	4915	4608	3027	851	-723	-1125	-626
	-39	-10794	-8152	-5718	-3479	-1715	-603	-78	83	75	34
	-34	1408480	-12491	8214	-4156	1290	128	-486	370	-153	2
	-33	1401268	-4563	2114	-941	396	-153	57	-15	2	1
18515	-33.52	1746655	-9680	5553	-2899	1314	-483	131	-11	-6	6
	-38.52	-6211	6589	5802	6139	5752	3768	1054	-902	-1400	-778
	-39	-13888	-10326	-7166	-4333	-2127	-746	-97	102	93	42
	-34	1751828	-15585	10232	-5174	1606	159	-606	461	-189	2
	-33	1742821	-5706	2633	-1173	495	-190	69	-19	4	1
23135	-33.52	2177892	-12209	6959	-3624	1640	-603	165	-13	-9	8
	-38.52	-9670	7453	7113	7742	7243	4710	1300	-1135	-1747	-968
	-39	-18929	-13527	-9128	-5424	-2634	-917	-117	126	114	52
	-34	2184415	-19605	12805	-6467	2007	199	-759	575	-235	3
	-33	2173049	-7226	3305	-1469	617	-236	87	-25	4	1
27790	-33.52	2599427	-14969	8410	-4363	1970	-723	197	-15	-12	9
	-38.52	-18748	6041	8036	9567	8908	5662	1498	-1394	-2089	-1148
	-39	-28626	-18580	-11613	-6549	-3075	-1045	-129	145	130	59
	-34	2607420	-23908	15441	-7772	2406	242	-912	690	-282	3
	-33	2593467	-8937	4005	-1774	743	-284	105	-29	4	1
32410	-33.52	2958356	-18320	9926	-5116	2300	-841	227	-18	-13	11
	-38.52	-54073	-6024	7091	12355	11321	6626	1459	-1761	-2394	-1270
	-39	-60009	-32135	-16449	-7790	-3183	-966	-95	140	119	56
	-34	2968114	-28877	18164	-9088	2801	288	-1066	805	-329	4
	-33	2950989	-11182	4753	-2089	870	-332	122	-33	5	0
37030	-33.52	3245977	-22877	11651	-5914	2638	-959	258	-20	-15	13
	-38.52	-119321	-30217	4024	16247	14595	7610	1154	-2253	-2661	-1330
	-39	-116132	-55400	-23982	-9176	-2920	-654	-9	107	78	41
	-34	3258120	-35281	21169	-10461	3199	338	-1222	921	-375	4
	-33	3236632	-14451	5650	-2434	1004	-381	138	-37	6	0
41650	-33.52	3496108	-28483	13601	-6756	2985	-1078	288	-22	-17	15
	-38.52	-198253	-60012	-32	20636	18258	8602	728	-2803	-2911	-1361
	-39	-183548	-83147	-32759	-10630	-2488	-236	98	60	23	20
	-34	3511188	-42981	24473	-11896	3604	391	-1380	1038	-422	4
	-33	3484300	-18569	6716	-2809	1144	-431	155	-42	7	0
46305	-33.52	3724243	-34981	15753	-7651	3344	-1198	317	-24	-20	16
	-38.52	-285477	-93229	-4695	25324	22159	9604	231	-3391	-3156	-1375
	-39	-257805	-113661	-42314	-12137	-1960	243	218	7	-40	-4
	-34	3742729	-51800	28071	-13406	4019	448	-1543	1156	-468	4
	-33	3709560	-23404	7921	-3215	1292	-483	171	-45	8	0

Table 3. Harmonic content with 10 cm added top and right to YR steel along five orbits of Fig. 10

Values evaluated on 1 cm radius circles so units are Gauss for all columns.

AmpTurns	start X cm	Cos0	Cos1	Cos2	Cos3	Cos4	Cos5	Cos6	Cos7	Cos8	Cos9
	-33.52	3046791	-18771	9974	-5129	2307	-840	224	-18	-14	9
32410	-38.52	-11665	11005	10046	10774	10094	6587	1818	-1606	-2469	-1373
	-39	-24875	-18477	-12656	-7593	-3712	-1299	-168	177	160	71
	-34	3056785	-29408	18257	-9114	2801	290	-1072	816	-339	6
	-33	3039205	-11592	4784	-2091	882	-339	113	-29	14	-2
	-33.52	3446583	-24991	11990	-5986	2652	-958	254	-19	-16	11
37030	-38.52	-19205	9798	10969	12528	11707	7526	2019	-1863	-2814	-1555
	-39	-33113	-23326	-15077	-8712	-4165	-1436	-182	197	176	79
	-34	3459820	-37795	21648	-10559	3200	348	-1232	935	-387	6
	-33	3436232	-16266	5894	-2478	1024	-389	129	-33	15	-2
	-33.52	3669774	-29676	13413	-6545	2870	-1030	271	-20	-18	12
39830	-38.52	-28624	6731	11113	13783	12832	8095	2091	-2041	-3016	-1655
	-39	-41957	-28136	-17058	-9417	-4373	-1479	-182	203	181	81
	-34	3685458	-44014	23972	-11490	3448	385	-1332	1007	-416	7
	-33	3657325	-19834	6719	-2740	1114	-420	138	-36	16	-2
	-33.52	3806527	-33051	14419	-6932	3016	-1076	282	-20	-19	12
41650	-38.52	-37077	3628	11010	14690	13633	8464	2115	-2168	-3144	-1714
	-39	-49562	-32152	-18590	-9887	-4477	-1487	-178	205	181	82
	-34	3823978	-48480	25603	-12127	3612	412	-1398	1054	-435	7
	-33	3792564	-22417	7305	-2923	1177	-441	145	-37	17	-2
	-33.52	4124236	-43454	17537	-8137	3441	-1197	304	-17	-23	14
46305	-38.52	-65570	-7530	10159	17264	15881	9403	2107	-2523	-3461	-1848
	-39	-74513	-44995	-23224	-11132	-4653	-1453	-157	202	175	81
	-34	4147188	-62354	30689	-14051	4051	514	-1585	1178	-482	6
	-33	4105604	-30376	9098	-3516	1373	-501	161	-40	17	-2
	-33.52	4373306	-60867	23209	-9979	3934	-1297	310	-10	-29	17
50925	-38.52	-98433	-20689	8877	19933	18213	10323	2052	-2895	-3769	-1971
	-39	-102979	-59378	-28299	-12411	-4779	-1388	-130	194	164	78
	-34	4405709	-86100	39293	-16663	4449	699	-1806	1309	-530	6
	-33	4346994	-43178	12584	-4578	1652	-566	173	-41	16	-2
	-33.52	4566338	-83309	29923	-11938	4491	-1427	326	-4	-35	19
55545	-38.52	-133948	-35035	7260	22585	20557	11219	1969	-3277	-4072	-2090
	-39	-133609	-74648	-33661	-13740	-4895	-1313	-102	184	150	74
	-34	4610813	-115974	49231	-19603	5015	826	-2021	1446	-582	7
	-33	4530020	-60003	17001	-5683	1948	-640	190	-44	15	-2

Appendix 1: Magnet suggestion sent to Ramesh Gupta, BNL, as a possible NP FOA response.

An effort is underway to determine if a Fixed Feld Alternating gradient permanent magnet array may be used to increase the energy of the CEBAF electron beam to ~22 GeV, delivered to the three original halls. The civil construction was designed to accommodate 16 GeV maximum. While there is room in the arcs to deal with the needed permanent magnet length, yielding 86% fill factor, the spreaders, recombiners and extraction regions are much more limited. There are five types of septum magnets employed in these regions, four current sheets and one Lambertson-style. The latter may be extended in length and will not be discussed further. Basic parameters of the four current sheets are given in the table below. All four are running at very high current densities in the copper; they can have neither current density nor length increased to deal with the proposed doubling of energy.

Inspired by two recent arxiv postings [1.2], Jay Benesch (JLab) realized that conductively cooled MgB2 or REBCO SC magnets would allow for thinner septa at more than double the present current density and double the BdL. JLab has no superconducting magnet fabrication experience. It is proposed that BNL design and prototype such a magnet with JLab providing interface details if needed. If a prototype is completed by BNL during the project which can substitute for one of the magnets below, installation and testing will be discussed outside the scope of the project. Four BNL personnel are part of the FFA working group: J.S. Berg, S.J. Brooks, F. Meot and D. Trbojevic. They may be consulted for further details.

Magnet	**Steel length (cm)**	**Turns**	**Amps**	**∫BdL (G-cm)**	**|B| (G)**	**J (A/mm2) in copper**	**Stainless bet. beams (cm)**
YA	100	5	70	35050	350	30	0.9
YB	96.1	24	447	515680	5367	27.8	3.28
YR*	194.8	24	688	1535720	7883	42.8	5.06
ZA*	298.2	24	814	2753440	9234	47.7	3.36

*The YR and ZA have curved septum coils and steel, back legs straight. Straight steel length given.

The ZA likely must have increased length as well as larger amp-turns as the steel will soon begin to saturate. It may be possible to push the YR steel to 1.6 T, maintaining length, but a 20% increase in length would be prudent. The fields in the steel of the YA and YB are low enough that doubling the field is not an issue. A magnetic model of the YR is presented in [3].

[1] Akira Yamamoto and Amalia Ballarino, Advances in MgB2 Superconductor Applications for Particle Accelerators, https://arxiv.org/abs/2201.09501
[2] European Strategy for Particle Physics Accelerator R&D Roadmap, Section 2 High-field magnets https://arxiv.org/abs/2201.07895
[3] J. Benesch, FEM models and Fourier decomposition of three thick septa *JINST* **13** T11001 https://iopscience.iop.org/article/10.1088/1748-0221/13/11/T11001/meta

Appendix 2: Field maps and other information about existing current sheet septum magnets

Magnet ID : YAAT01 assembly 22421-0001
Vacuum vessel length 54.84 inches 139.3 cm Moly 2.44 mm (0.096") max. min beam sep ~10 mm
WR3 WG used as conductor. Hole size: inches(mm)
0.034 [0.8636] 0.017 [0.4318]
Scaling the drawing, since I can't find a WG vendor with outside dimensions, I deduce 0.020" wall thickness and 0.002" corner radius. 0.001" corner radius inside hole. Overall area 4.2054E-3 sq in. Hole area 0.5749E-3 sq in Copper area 3.6306E-3 sq in 2.3423 mm^2.
At 70 A, **J = 30 A/mm^2**. Need double that to double energy.
Insulated 5 turn coil pack: 0.07" by 0.47"

Core length 100 cm
Insulated coil pack sticks out 0.5" on either side of core before individual pieces of WG are separated for water circuits and connection to big conductor on back leg.

Backleg coil has five turns of 0.188" square with 0.125" diameter hole, except each end has a 0.125" OD 0.020" wall tube brazed in for water connection. Assume just the square section: 23.07E-3 sq in or 14.885 mm^2. Only 4.7 A/mm^2 here. Water cooling still needed, barely. Doubling this J not a problem with our LCW.

Meas. Date : 07/28/13
Coil used : Stretched Wire

Current (amps)	INT(Bdl) (Gauss-cm)	
0.00	0	
4.01	-2381	
24.03	-12178	
28.03	-14152	
33.04	-16628	
37.04	-18599	
42.05	-21099	
47.05	-23585	
51.06	-25575	
56.07	-28071	
61.07	-30573	
65.07	-32559	
70.08	**-35052**	/100 = 350 G
65.07	-32559	
61.07	-30573	
56.07	-28071	
51.06	-25575	
47.05	-23585	
42.05	-21099	
37.04	-18599	
33.04	-16628	
28.03	-14152	
24.03	-12178	
4.01	-2381	

Magnet ID : YBBS06 assembly 22431-0001

vacuum vessel 49.81" with one flange at 1° angle. SS between beams 3.28 cm max, 3.12 mm nom
YB steel core 37.83" (96.09 cm)

back leg conductor 0.438" sq, 0.25 dia hole, corner radius ~0.04" aka 1 mm
four packages of six turns each, insulated dimension 0.53" x 3.02" so 24 turns total
Copper 0.89 cm^2, J 5.025 A/mm^2 at 447 A

Septum conductor: four packages 0.245" x 0.996" consisting of six conductors 0.240" x 0.160", with 0.125" diameter hole. Sharp corners drawn, assume 0.02" radius. Copper 0.1607 cm^2,
J 27.8 A/mm^2 at 447 A.

Meas. # : GENERIC
Meas. Date : 04/30/14
Coil used : Stretched Wire
Current (amps) INT(Bdl) (Gauss-cm)
0 0
3.99 -6239
202.96 -234888
226.96 -262569
251.95 -291311
275.95 -318949
300.95 -347724
324.93 -375345
348.93 -403015
373.93 -431776
397.92 -459323
422.92 -488158
446.91 -515682 /96.09 = 5367 G
422.92 -488158
397.92 -459323
373.93 -431776
348.93 -403015
324.93 -375345
300.95 -347724
275.95 -318949
251.95 -291311
226.96 -262569
202.96 -234888
3.99 -6239
0.00 0

Magnet ID : YRAT02 assembly 22441-0029

vacuum vessel 89.06” long. Stainless between beams: 5.04 cm nominal, 5.06 cm max.
core 76.70” long, not rectangular (194.8 cm)

back coil same conductor as YB so area 0.89 cm^2 and J = 7.73 A/mm^2 at 688 A

front coil same conductor as YB so area 0.1607 cm^2, **J = 42.8 A/mm^2** at 688 A

Meas. # : GENERIC
Meas. Date : 07/28/13
Coil used : Stretched Wire

Current (amps)	INT(Bdl) (Gauss-cm)	
0.00	0	
3.94	-12784	
317.94	-712982	
354.95	-795359	
391.94	-877692	
428.95	-960198	
465.94	-1042389	
502.94	-1124898	
539.95	-1207301	
576.95	-1289490	
613.95	-1371719	
650.95	-1453604	
687.95	**-1535720**	/194.8 = 7883 G
650.95	-1453604	
613.95	-1371719	
576.95	-1289490	
539.95	-1207301	
502.94	-1124898	
465.94	-1042389	
428.95	-960198	
391.94	-877692	
354.95	-795359	
317.94	-712982	
3.94	-12784	
0.00	0	

YR steel is 65.33% of the length of the ZA steel. A YR model 3.6E6 G-cm should show similar steel response to a ZA model at 5.5E6, twice the maximum below. This is 2.05* the BdL of the highest AT YR magnet model I ran in 2018. I am running models at 1.25*, 1.5*, 1.75* and 2* that 2018 model. I have 2018 results at 0.55*, 0.8* and 1.0* the 2018 max drive. It will be interesting to see what the BdL vs AT curve looks like.

Magnet ID : ZA8T04 assembly MAG-003-0011-0001

core length 117.40” (298.2 cm)
vacuum chamber 131.85” (334.9 cm) flanges canted, nom stainless between beams 3.36 cm

back leg coil: Luvata 8327 brazed into 0.531” (13.49 mm) by 0.489” (12.42mm)copper bar so 160.63 mm^2 Cu. J= 5.07 A/mm^2

front leg: Luvata 8327 alone 4 mm by 6 mm with 0.8 mm corner radius, 2.5 mm hole, 17.08 mm^2 Cu J= **47.7 A/mm^2** at 814 A

Meas. # : GENERIC
Meas. Date : 07/28/13
Coil used : Stretched Wire

Current (amps)	INT(Bdl) (Gauss-cm)	
0.00	0	
3.94	-25470	
384.95	-1314267	
426.96	-1456990	
469.96	-1602770	
512.97	-1748283	
555.96	-1893249	
598.96	-2037957	
641.99	-2182132	
684.98	-2325844	
727.99	-2469098	
771.00	-2611365	
814.01	**-2753439**	/298.2=9234 G
771.00	-2611365	
727.99	-2469098	
684.98	-2325844	
641.99	-2182132	
598.96	-2037957	
555.96	-1893249	
512.97	-1748283	
469.96	-1602770	
426.96	-1456990	
384.95	-1314267	
3.94	-25470	
0.00	0	