Potential Effect of the New High-Temperature Superconductor on SSC Costs

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While very little information is known regarding the ultimate potential of the new materials that exhibit superconducting characteristics at high temperatures, a model is developed to explore the possible cost consequences to the SSC project if such a material were to become available with the performance characteristics required by the SSC magnets.

It might be assumed, if SSC magnet coils were fabricated with the new material, that the higher fields that could be achieved, allowing the SSC ring to be reduced in size, would result in attendant cost reductions. This is not the case under the rather optimistic set of assumptions presented here.

The various components of the SSC construction project cost estimate have been categorized according to whether they are cost dependent or independent of the collider magnetic field. For example, the injector accelerators and the central laboratory facilities do not depend on the maximum magnetic field of the collider. Approximately 40% of the total SSC costs are in this category. For the remaining 60% of the costs, the related systems and components have been analyzed in terms of their specific cost dependence on magnetic field. The results show, assuming a fixed maximum energy of 20 TeV per beam, that the costs of the magnet systems themselves increase faster with peak magnetic field than do the cost savings resulting from the attendant smaller size of the collider ring. The net effect is a cost increase with decreasing circumference of the collider.

A. General Assumptions

1. The new material will achieve the same current density as that of the present SSC magnet models (~2750 A/mm^2 at 5 T).
2. This current density will be constant, independent of field.
3. The material can be formed into relatively "ductile" filaments of 5μ size, allowing usable cables to be fabricated in the same manner as that required by current designs as these designs have the most efficient conductor arrangement known.
4. The above cables can be mass produced as required by the SSC schedule.
5. The unit cost of the new material is the same as the quoted price of NbTi used in the CDR cost estimate.

B. The Dipole Magnet

The philosophy employed in this study is to maintain the basic SSC-CDR dipole design, with appropriate changes in cross section dimensions. It is assumed that a dipole of the same length as that specified in the CDR can be produced. In this model, the dipole current density is held fixed at the CDR value as the coil thickness and resulting field is increased.

The coil is regarded as a thick cylinder with the current density proportional to cosine theta, independent of radius. The yoke is regarded as having infinite permeability. For this model, the aperture field, circumferential stress in the coil, and stored energy match those of real coils within 5 to 10%, provided the field at the iron inner surface does not exceed 3 T, the average field across the yoke on the horizontal axis does not exceed 2 T, and the coil's outside-to-inside diameter ratio does not exceed about 3.

The circumferential prestress in the coil must exceed the total of the circumferential components of the Lorentz body forces in order to prevent the coil from separating from the structure. The prestress is supplied by the "collars." The thickness of the collars of the CDR dipoles has been reduced to the practical minimum. In this study, the thickness of the collars has been scaled from the CDR design in proportion to the total Lorentz force.

In the CDR design, the outside surface of the collars is in contact with the yoke, and the field at the inside surface of the yoke is about 3 T. If contact between the collars and yoke is maintained as the coil thickness is increased, the field at the yoke surface increases. In this analysis, the inside radius of the yoke is that which results in a field of 3 T at the surface. There is, therefore, a space between the collars and the iron radial forces produced by the coil, the cost of which has not been included. In a real design, the yoke might be in contact; there would then be a slight increase in field distortion and a slight increase in the magnitude of the field. In this study, the average field in the yoke on the horizontal axis is maintained at the CDR value of about 2 T.

Table I shows the results for the coil, collar, and yoke dimensions as the field increases from 6.6 to 14.2 teslas.

In order to provide a cost estimate for the designs of Table I, we use the CDR cost estimate data at 6.6 T for the various dipole components, and scale the component costs appropriately with changes in dimensions. Details of these calculations are presented in Table II.

The major cost elements of the SSC dipole are listed. At 6.6 T, the dipole unit cost is 103.59 K$ (in FY88 dollars). The scaling for each

TABLE I

DIPOLE COMPONENT DIMENSIONS VS FIELD

INDEX	FIELD	COIL		COLLAR	YOKE	
		OUTSIDE RD	CROSS SEC	CROSS SEC	CROSS SEC	OUTSIDE RD
	teslas	m	m^2	m^2	m^2	m
1	6.600000	.040000	.003770	.009850	.052400	.140770
2	7.109000	.042000	.004285	.011110	.061840	.152930
3	7.617000	.044000	.004825	.012460	.072220	.165270
4	8.126000	.046000	.005391	.013920	.083600	.177800
5	8.634000	.048000	.005982	.015470	.096000	.190540
6	9.143000	.050000	.006597	.017120	.109490	.203480
7	9.652000	.052000	.007238	.018880	.124090	.216620
8	10.160000	.054000	.007904	.020760	.139860	.229980
9	10.669000	.056000	.008595	.022750	.156850	.243540
10	11.178000	.058000	.009312	.024850	.175090	.257320
11	11.686000	.060000	.010053	.027080	.194640	.271300
12	12.195000	.062000	.010820	.029430	.215530	.285490
13	12.703000	.064000	.011611	.031910	.237820	.299890
14	13.212000	.066000	.012428	.034560	.261540	.314490
15	13.721000	.068000	.013270	.037280	.286750	.329300
16	14.229000	.070000	.014137	.040170	.313480	.344300

TABLE II

ASSIGNMENT OF UNIT COSTS TO SCALING CATEGORIES

	COST K$	PROPORTIONAL TO	COSTS PROPORTIONAL TO... CONSTANT	COIL C. SEC	COLLAR C. SEC	YOKE C. SEC	YOKE OUTR RAD	TOT OF OTHERS
MAGNET COILS	(50.62)							
COLD BEAM TUBE	6.25	CONSTANT	6.25					
COILS	36.96	COIL C. SEC.		36.96				
COIL COLLARING	7.41	COLLAR C. SEC.			7.41			
YOKE AND HELIUM CONTAINMENT	(15.93)							
YOKE AND COMPONENTS	12.36	YOKE C. SEC.				12.36		
HELIUM CONTAINMENT VESSEL	3.57	YOKE O.D.					3.57	
FINAL ASSEMBLY	(15.86)							
COLD MASS SUB-ASY PREP	.96	CONSTANT	.96					
COLD MASS SUPPORTS	5.17	YOKE C. SEC.				5.17		
20K HEAT SHIELD	1.42	YOKE O.D.					1.42	
80K HEAT SHIELD	2.50	YOKE O.D.					2.50	
VACUUM VESSEL AND COMP	3.62	YOKE O.D.					3.62	
ASSEMBLY LABOR	2.20	YOKE O.D.					2.20	
ELECTRICAL SYSTEM	(3.99)	CONSTANT	3.99					
MAGNET INTERCONNECTIONS	(1.82)	CONSTANT	1.82					
MAGNETIC MEASUREMENTS	(1.11)	CONSTANT	1.11					
MISCELLANEOUS	(14.26)	TOTAL OF OTHERS						14.26
ALLOWANCE FOR REJECTS	1.87							
ALLOWANCE FOR MTLS USAGE	2.03							
FACTORY SUPPORT	3.49							
SHIPPING, STRG, HNDLNG	1.57							
MTLS PROCURMT ALLOWANCE	.99							
INDUSTRIAL FEES	4.30							
TOTALS	103.59		14.13	36.96	7.41	17.53	13.30	14.26

component is specified in Table II. For example, coil costs vary directly as the coil cross section (i.e., the amount of superconductor). The beam tube and magnetic measurements are examples of cost elements that do not change with the magnet size.

In Table III, for each higher-field design the cost elements of Table II are scaled by the new design dimensions that are tabulated in Table I. The unit dipole costs are shown to increase from 103.59 K$ at 6.6 T to 371.53 K$ at 14.23 T.

C. Other Magnet Systems

For convenience, all magnet costs are totaled before scaling (or reducing the number of elements) commensurately with the smaller 20 TeV ring sizes of the higher fields.

In line 1 of Table IV the results of the last section (Table III) for dipole unit costs are scaled by multiplying the unit costs by the total number of SSC dipoles in a collider with a 52 mile circumference (7,680 units).

It is now assumed that standard quadrupoles and IR quadrupoles will also be made from the new superconductor, and that their costs will scale in the same manner as the dipoles. That tabulation is presented in lines 2 and 3 of Table IV.

Magnet tooling (line 5) is projected to increase in cost in proportion to the magnet size or the yoke outer radius. The spool pieces, as well as the costs for installation and survey are assumed to be constant factors independent of the magnetic field increase.

The bottom line of Table IV shows the total costs (FY88 M$) for all magnet systems of the collider with the same number of elements as in the CDR (i.e., for a collider ring of 52 mile circumference).

TABLE III

UNIT DIPOLE MAGNET COST (K$) VS FIELD (T)

MAGNETIC FIELD tesla	6.60	7.11	7.62	8.13	8.63	9.14	9.65	10.16
CONSTANT COSTS	14.13	14.13	14.13	14.13	14.13	14.13	14.13	14.13
COSTS PROPORTIONAL TO:								
COIL CROSS SEC.	36.96	42.01	47.31	52.86	58.65	64.69	70.97	77.50
COLLAR CROSS SEC.	7.41	8.36	9.38	10.47	11.64	12.88	14.21	15.62
YOKE CROSS SEC.	17.53	20.69	24.16	27.97	32.12	36.63	41.52	46.80
YOKE OUTER RADIUS	13.29	14.44	15.60	16.78	17.99	19.21	20.45	21.71
COSTS PROPORTIONAL TO TOTAL OF ABOVE	14.27	15.92	17.66	19.52	21.49	23.57	25.76	28.08
TOTAL COST	103.59	115.55	128.25	141.74	156.01	171.11	187.03	203.83

MAGNETIC FIELD tesla	10.67	11.18	11.69	12.20	12.70	13.21	13.72	14.23
CONSTANT COSTS	14.13	14.13	14.13	14.13	14.13	14.13	14.13	14.13
COSTS PROPORTIONAL TO:								
COIL CROSS SEC.	84.28	91.30	98.57	106.08	113.85	121.85	130.11	138.61
COLLAR CROSS SEC.	17.12	18.70	20.38	22.15	24.01	26.01	28.05	30.23
YOKE CROSS SEC.	52.48	58.58	65.12	72.11	79.57	87.51	95.94	104.89
YOKE OUTER RADIUS	22.99	24.29	25.61	26.95	28.31	29.69	31.08	32.50
COSTS PROPORTIONAL TO TOTAL OF ABOVE	30.51	33.07	35.75	38.57	41.51	44.60	47.81	51.17
TOTAL COST	221.50	240.07	259.56	279.99	301.38	323.78	347.13	371.53

TABLE IV

TOTAL MAGNET SYSTEMS COSTS (FY88M$) VS FIELD (T) FOR SSC/CDR SIZE RING

	B:	6.600	7.109	7.617	8.126	8.634	9.143	9.652	10.160	10.669	11.178	11.686	12.195	12.703	13.212	13.721
1.Dipole Total Costs	(M/MO)	795.675	887.540	985.088	1088.705	1198.313	1314.296	1436.577	1565.618	1701.341	1843.978	1993.680	2150.603	2314.900	2486.954	2666.152
2.Quad Total Costs	(M/MO)	41.805	46.631	51.756	57.200	62.959	69.053	75.478	82.257	89.388	96.882	104.748	112.992	121.625	130.664	140.079
3.I.R. Mag Costs	(M/MO)	41.805	46.631	51.756	57.200	62.959	69.053	75.478	82.257	89.388	96.882	104.748	112.992	121.625	130.664	140.079
4.Spools	(Mo)	83.289	83.289	83.289	83.289	83.289	83.289	83.289	83.289	83.289	83.289	83.289	83.289	83.289	83.289	83.289
5.Tooling	(K/KO)	59.721	65.266	70.385	75.931	81.476	86.595	92.567	98.113	104.085	109.631	115.603	121.575	127.973	133.946	140.314
6.Install/Survey	(Mo)	45.388	45.388	45.388	45.388	45.388	45.388	45.388	45.388	45.388	45.388	45.388	45.388	45.388	45.388	45.388
Total Collider Magnet Systems: (CDR Ring Size)		1067.682	1174.746	1287.664	1407.714	1534.385	1667.674	1808.777	1956.923	2112.880	2276.050	2447.456	2626.840	2814.799	3010.905	3215.332

D. Final Result -- All Systems

Part I of Table V provides a summary of all field dependent systems. The results of Table IV are scaled inversely as the field in order to correspond to a 20 TeV collider ring of reduced size, commensurate with the higher fields, and are presented as Item A. Similarly, the costs for the collider tunnel (item C) are scaled inversely to the field. The corresponding Engineering, Design and Inspection costs related to the variations in both Items A and C are summarized as Item D.

The costs for collider cryogenics (Item B) are projected to increase. The model in this analysis assumes that the bore tubes are still maintained at liquid helium temperature to maintain the required vacuum. Even at 6.6 T, the synchrotron light power is a major fraction of the refrigeration heat load. This load will increase in proportion to the field and will require additional refrigeration capacity with the increased costs shown in Table V. Other pumping schemes have been investigated; however, preliminary results indicate that an increased aperture diameter of ~1 cm is required. Such an aperture increase would increase magnet costs by an amount in excess of $100 M (i.e., comparable with the cost associated with operation at liquid helium temperature).

Part II of Table V provides a summary of the other systems of the SSC whose costs are independent of the collider field. The sum of the variable (field dependent) and fixed costs is given at the bottom of Table V. The results are plotted in Fig. 1.

It is concluded for the model investigated here (i.e., J is independent of magnetic field) that the total SSC costs will increase with the increasing magnetic fields even if this material achieves the characteristic properties which were assumed in Section A. If its unit cost should be substantially less than that of NbTi, then the conclusion may be modified slightly.

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TABLE V

SUMMARY OF TOTAL SSC COSTS (FY88M$) VS FIELD (T)

I. SYSTEMS WITH MAGNET DEPENDENT COSTS

	B:	6.600	7.109	7.617	8.126	8.634	9.143	9.652	10.160	10.669	11.178	11.686	12.195	12.703	13.212	13.721
A. Collider-Mag Systems	(1/B)	1067.682	1090.635	1115.739	1143.356	1172.914	1203.834	1236.835	1271.230	1307.059	1343.884	1382.270	1421.660	1462.464	1504.085	1546.621
B. Collider-Cryogenics	(B^0.7)	129.189	136.085	142.822	149.437	155.917	162.296	168.569	174.731	180.814	186.810	192.713	198.551	204.305	210.002	215.633
C. Conv Systems-Tunnel	(1/B)	353.399	328.095	306.214	287.033	270.145	255.106	241.653	229.570	218.618	208.663	199.592	191.261	183.613	176.539	169.990
D. Engineering & Design	(1/B)	74.971	69.603	64.961	60.892	57.309	54.119	51.265	48.702	46.378	44.266	42.342	40.575	38.952	37.452	36.062
E. Contingency		349.445	347.832	347.658	348.787	350.977	353.981	357.867	362.428	367.606	373.270	379.500	386.145	393.266	400.715	408.496
Total Variable Cost:		1974.686	1972.250	1977.393	1989.506	2007.262	2029.335	2056.188	2086.660	2120.474	2156.892	2196.417	2238.192	2282.599	2328.793	2376.802

II. SYSTEMS WITH FIXED COSTS

	B:	6.600	7.109	7.617	8.126	8.634	9.143	9.652	10.160	10.669	11.178	11.686	12.195	12.703	13.212	13.721
A. Injector		201.825	201.825	201.825	201.825	201.825	201.825	201.825	201.825	201.825	201.825	201.825	201.825	201.825	201.825	201.825
B. Collider-Other Tech Sys		119.996	119.996	119.996	119.996	119.996	119.996	119.996	119.996	119.996	119.996	119.996	119.996	119.996	119.996	119.996
C. Conv Systems-Other		261.152	261.152	261.152	261.152	261.152	261.152	261.152	261.152	261.152	261.152	261.152	261.152	261.152	261.152	261.152
D. Engineering & Design		231.739	231.739	231.739	231.739	231.739	231.739	231.739	231.739	231.739	231.739	231.739	231.739	231.739	231.739	231.739
E. Contingency		215.422	215.422	215.422	215.422	215.422	215.422	215.422	215.422	215.422	215.422	215.422	215.422	215.422	215.422	215.422
F. Project Management		205.109	205.109	205.109	205.109	205.109	205.109	205.109	205.109	205.109	205.109	205.109	205.109	205.109	205.109	205.109
Total Fixed Costs:		1235.243	1235.243	1235.243	1235.243	1235.243	1235.243	1235.243	1235.243	1235.243	1235.243	1235.243	1235.243	1235.243	1235.243	1235.243
Total Fixed and Variable Costs:		3209.929	3207.494	3212.637	3224.749	3242.505	3264.578	3291.431	3321.904	3355.717	3392.136	3431.660	3473.435	3517.843	3564.036	3612.045

FIGURE 1

Total SSC Costs

(Fixed and Variable Costs)