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ELECTROMECHANICAL PROPERTIES OF SUPERCONDUCTORS FOR DOE FUSION APPLICATIONS

J.W. Ekin
S.L. Bray
C.L. Lutgen
W.L. Bahn

AI01-84ER52113

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W.L. Bahn

Electromagnetic Technology Division
Electronics and Electrical Engineering Laboratory
National Institute of Standards and Technology
Boulder, Colorado 80303-3328

January 1994

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Electromechanical Properties of Superconductors for DOE Fusion Applications

J. W. Ekin, S. L. Bray, C. L. Lutgen, and W. L. Bahn

*Electromagnetic Technology Division
Electronics and Electrical Engineering Laboratory
National Institute of Standards and Technology
Boulder, Colorado 80303*

The electrical performance of many superconducting materials is strongly dependent on mechanical load. This report presents electromechanical data on a broad range of high-magnetic-field superconductors. The conductors that were studied fall into three general categories: candidate conductors, experimental conductors, and reference conductors. Research on candidate conductors for fusion applications provides screening data for superconductor selection as well as engineering data for magnet design and performance analysis. The effect of axial tensile strain on critical-current density was measured for several Nb₃Sn candidate conductors including the US-DPC (United States Demonstration Poloidal Coil) cable strand and an ITER (International Thermonuclear Experimental Reactor) candidate conductor. Also, data are presented on promising experimental superconductors that have strong potential for fusion applications. Axial strain measurements were made on a V₃Ga tape conductor that has good performance at magnetic fields up to 20 T. Axial strain data are also presented for three experimental Nb₃Sn conductors that contain dispersion hardened copper reinforcement for increased tensile strength. Finally, electromechanical characteristics were measured for three different Nb₃Sn reference conductors from the first and second VAMAS (Versailles Project on Advanced Materials and Standards) international Nb₃Sn critical-current round robins. Published papers containing key results, including the first measurement of the transverse stress effect in Nb₃Sn, the effect of stress concentration at cable-strand crossovers, and electromechanical characteristics of Nb₃Al, are included throughout the report.

Key words: axial stress effect; electromechanical; fusion; Nb₃Al; Nb₃Sn; stress effect; superconductor; transverse stress effect; V₃Ga

Executive Summary

This report presents the results of work done for the U. S. Department of Energy, Office of Fusion Energy, during the period 1986-1993, under interagency agreement No. DE-AI01-84ER52113.

Within the windings of an energized superconducting magnet, the Lorentz force can produce large stresses that increase with magnet size and field. These stresses can significantly degrade the performance of the magnet through a reduction in the superconductor's critical-current density (J_c). There are two dominant stress components, a tensile stress that is aligned with the wire's longitudinal axis (axial stress) and a compressive stress that is perpendicular to its axis (transverse stress).

Presently, the most common conductor material used in high-field (>10 T) superconducting magnet designs is Nb_3Sn . The J_c of Nb_3Sn is highly sensitive to its stress state. Consequently, it is the internal stress state of the magnet windings, rather than the J_c of the unstressed superconductor, that determines the design limits for large high-field magnets. Electromechanical measurements of Nb_3Sn candidate conductors for ITER (International Thermonuclear Experimental Reactor) provide screening data for superconductor selection as well as engineering data for magnet design and performance analysis. Data are presented on several Nb_3Sn candidate conductors.

As new magnet designs call for larger coils and higher fields, stresses must be limited by structural reinforcement of the magnet windings. Control of the stress, which accumulates radially within the windings, requires distributed reinforcement. Aside from complicating the design and increasing the cost of the magnet, additional internal reinforcement limits the superconductor packing fraction and, thus, reduces the magnetic field. At present, the determining factors of the amount of reinforcement are not just structural, but dominated by the stress sensitivity of Nb_3Sn . Consequently, a superconductor less sensitive to stress than the existing high-field conductors, but comparable in J_c , could significantly extend the present magnet design limits. Data are presented on five experimental conductors that have strong potential for fusion applications with lowered stress sensitivity— V_3Ga , Nb_3Al , and Nb_3Sn superconductors with dispersion hardened copper.

The consistency of interlaboratory J_c measurements of Nb_3Sn superconductors is typically much lower than for $NbTi$. This is largely due to stress effects, which are much smaller for $NbTi$. Since measurement inconsistency implies uncertainty in the engineering data for these conductors, it directly impacts DOE magnet designs. In response to this situation, two studies on J_c measurements of Nb_3Sn , the first and second VAMAS (Versailles Project on Advanced Materials and Standards) international Nb_3Sn critical-current round robins, have been conducted. NIST participated in both of these studies, providing electromechanical data on the superconductors. The results of these measurements are presented in the Appendices.

The report has three main sections: Electromechanical Characteristics of Nb_3Sn Superconductors, Electromechanical Characteristics of Experimental High-Field Superconductors, and the Appendices. Within each main section, the data are presented in two formats: published papers, which present comprehensive results, and unpublished data on specific conductors.

The first section contains papers reporting seminal measurements of the transverse stress effect in Nb₃Sn, a comparison of transverse stress effects in bronze-process and internal-tin Nb₃Sn conductors, and the effect of concentrated transverse stress at cable-strand crossover points. Key results from these publications show that the effect of transverse stress on the J_c of Nb₃Sn is much greater than that of axial stress, that anisotropy in stress sensitivity is not a peculiarity associated with a specific Nb₃Sn processing method, and that transverse stress data from measurements of single wires subjected to uniform stress are applicable in modeling the concentrated stress at strand crossover points in superconducting cables. Also, complete sets of axial stress data are presented for the US-DPC (United States Demonstration Poloidal Coil) Nb₃Sn cable strand, the LLNL (Lawrence Livermore National Laboratory) cable-test strand, and an ITER (International Thermonuclear Experimental Reactor) candidate conductor.

The section on experimental superconductors includes a paper on stress effects in Nb₃Al, where this superconducting compound was shown to be significantly less sensitive to both axial and transverse stress than Nb₃Sn. Like Nb₃Sn, the Nb₃Al conductor was more sensitive to transverse stress than axial stress. This demonstrates that the anisotropy, which was first observed in Nb₃Sn, is not associated with a particular processing method or even a particular material, but is much more general. Axial stress data are also presented for a V₃Ga tape conductor that has good performance at magnetic fields up to 20 T and for three experimental Nb₃Sn conductors that contain dispersion hardened copper reinforcement for increased tensile strength.

In addition to the VAMAS publications and data, the Appendices contain an excerpt from the Concise Encyclopedia of Magnetic & Superconducting Materials entitled "Superconductor Specification" and a paper on the development of an internal-tin Nb₃Sn conductor for fusion applications, which is processed using hot isostatic pressure (HIP) to double its intrinsic irreversible strain limit.

Unless otherwise noted, the critical-current measurement accuracy is $\pm 2\%$. Axial strains were determined within $\pm 0.02\%$, and transverse loads were determined within $\pm 1\%$.

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US-DPC Nb₃Sn Cable Strand

A complete set of axial strain data was obtained for the critical current of the US-DPC cable strand at magnetic fields from 10 T to 24 T. The conductor specifications are shown in Table 1, and the measured data are shown in Table 2. The data are presented graphically in Figs. 1-4. The I_c and J_c values are based on an electric field criterion (E_c) of 2 $\mu\text{V}/\text{cm}$. The results show a zero-strain 12 T value of J_c (referred to the noncopper area) which was 0.54 GA/m^2 and a peak (strain-free) J_c value of 0.62 GA/m^2 . The irreversible strain limit was reasonably high, 0.82%, and the compressive prestrain was 0.38%. The sample did not fracture until 1.31% strain.

Table 1. US-DPC Nb₃Sn conductor specifications.

Wire diameter	0.78 mm
Stabilizing Copper	54 vol.%
Noncopper	46 vol.%
Nb Filament	22.9 vol.%
Copper	48.7 vol.%
Tin	15.8 vol.%
Vanadium	12.6 vol.%
Local Cu:Nb Ratio	1.7:1
Filament Size	3 μm
Filament Composition	Nb-1 wt.% Ti
Subelements	18
Twist Pitch	2 twists per inch

Table 2. High-field critical current of US-DPC Nb₃Sn sample CRE 1087 B4H21 as a function of axial tensile strain applied at 4 K.

E (%)	E ₀ (%)	I _c (Amperes)	Field (Tesla)	J _c (6A/m ²)	J _{cB} (6N/m ³)	I _c /I _{cm}
0.00	-.38	183.460	10.00	0.819	8.190	0.8576
		121.140	12.00	0.541	6.490	
		74.870	14.00	0.334	4.679	
		42.423	16.00	0.189	3.030	
		19.799	18.00	0.088	1.591	
		7.209	20.00	0.032	0.644	
		3.793	21.00	0.017	0.356	
		1.724	22.00	0.008	0.169	
		0.665	23.00	0.003	0.068	
0.18	-.20	197.230	10.00	0.880	8.805	0.9543
		134.810	12.00	0.602	7.222	
0.23	-.16	138.430	12.00	0.618	7.416	0.9800
0.30	-.08	141.260	12.00	0.631	7.568	1.0000
0.41	0.03	140.020	12.00	0.625	7.501	0.9912
		90.757	14.00	0.405	5.672	
		53.369	16.00	0.238	3.812	
		27.644	18.00	0.123	2.221	
		11.528	20.00	0.051	1.029	
		6.746	21.00	0.030	0.632	
		3.503	22.00	0.016	0.344	
		1.581	23.00	0.007	0.162	
		0.538	24.00	0.002	0.058	
0.52	0.14	132.150	12.00	0.590	7.080	0.9355
0.63	0.25	117.940	12.00	0.527	6.318	0.8349
0.72	0.34	103.970	12.00	0.464	5.570	0.7360
0.33	-.05	140.880	12.00	0.629	7.547	0.9973
0.82	0.44	87.687	12.00	0.391	4.698	0.6208
0.40	0.02	135.650	12.00	0.606	7.267	0.9603
0.90	0.52	75.108	12.00	0.335	4.024	0.5317
0.45	0.07	127.270	12.00	0.568	6.818	0.9010
0.96	0.58	60.134	12.00	0.268	3.222	0.4257

Table 2 cont'd

E (%)	E ₀ (%)	I _c (Amperes)	Field (Tesla)	J _c (GA/m ²)	J _{cB} (GN/m ³)	I _c /I _{cm}
0.49	0.11	116.870	12.00	0.522	6.261	0.8273
1.07	0.69	40.730	12.00	0.182	2.182	0.2883
0.53	0.15	94.626	12.00	0.422	5.069	0.6699
1.17	0.79	24.363	12.00	0.109	1.305	0.1725
0.58	0.20	67.861	12.00	0.303	3.635	0.4804
1.27	0.89	11.251	12.00	0.050	0.603	0.0796
0.66	0.28	34.885	12.00	0.156	1.869	0.2470

Figure 1. Effect of axial tensile strain on the critical current of US-DPC Nb₃Sn sample CRE 1087 B4H21 at 4 K and several magnetic fields.

Figure 2. Effect of magnetic field on the critical current density of US-DPC Nb_3Sn sample CRE 1087 B4H21 at 4 K .

Figure 3. $(J_C \times B^{0.5})^{0.5}$ as a function of magnetic field for US-DPC Nb_3Sn sample CRE 1087 B4H21 at 0.01% and 0.23% strain.

Figure 4. Effect of magnetic field on n^{th} power of US-DPC Nb_3Sn sample CRE 1087 B4H21 at 4 K.

Nb₃Sn LLNL Cable Test Strand

Axial strain characterization was completed for a Nb₃Sn conductor from Lawrence Livermore National Lab used in a transverse stress test of a cable-in-conduit conductor. The effect of axial strain on the critical current of the LLNL Nb₃Sn test strand was measured at magnetic fields from 8 T to 22 T. The conductor specifications are shown in Table 3, and the measured data are shown in Table 4. The data are presented graphically in Figs. 5 through 7. The I_c and J_c values are based on an electric field criterion (E_c) of 2 $\mu\text{V}/\text{cm}$. The zero-strain 12 T value of J_c (referred to the noncopper area) was measured to be 0.36 GA/m^2 and the peak (strain-free) J_c at 12 T was 0.39 GA/m^2 . The irreversible strain limit was quite high, 1.0% strain, and the compressive prestrain was relatively low at 0.27%. Fracture strain was 1.10%.

Table 3. LLNL Nb₃Sn cable test strand specifications.

Wire Diameter	0.533 mm
Local Cu:Nb Ratio	1.0:1.0
Copper Stabilizer	50%
7 Subelements	
Filament Composition	1.2 wt.% Ti
Filament Dia.	$\sim 4 \mu\text{m}$
Nb Diffusion Barrier with Cu Interlayers	

Table 4. High-field critical current of LLNL Nb₃Sn cable test strand.

E (%)	E ₀ (%)	I _c (Amperes)	Field (Tesla)	J _c (GA/m ²)	J _{cB} (GN/m ³)	I _c /I _{cm}
0.00	-.27	145.290	8.00	0.650	5.201	
		110.270	10.00	0.493	4.934	
		80.560	12.00	0.360	4.325	0.9400
		53.920	14.00	0.241	3.378	0.8841
		32.595	16.00	0.146	2.333	0.8267
		17.377	18.00	0.078	1.399	0.7837
		7.169	20.00	0.032	0.642	0.6709
		1.738	22.00	0.008	0.171	0.4791
0.11	-.16	117.860	10.00	0.527	5.273	
		83.413	12.00	0.373	4.479	0.9732
		58.083	14.00	0.260	3.638	0.9523
		37.288	16.00	0.167	2.669	0.9457
		20.045	18.00	0.090	1.614	0.9040
		8.838	20.00	0.040	0.791	0.8271
		2.782	22.00	0.012	0.274	0.7669
0.22	-.05	86.088	12.00	0.385	4.622	1.0044
		62.262	14.00	0.279	3.900	1.0208
		39.527	16.00	0.177	2.830	1.0025
		22.082	18.00	0.099	1.778	0.9959
		10.435	20.00	0.047	0.934	0.9765
		3.578	22.00	0.016	0.352	0.9862
0.30	0.03	85.707	12.00	0.383	4.602	1.0000
		60.991	14.00	0.273	3.820	1.0000
		39.428	16.00	0.176	2.823	1.0000
		22.173	18.00	0.099	1.786	1.0000
		10.686	20.00	0.048	0.956	1.0000
		3.628	22.00	0.016	0.357	1.0000
0.14	-.13	84.150	12.00	0.377	4.518	0.9818
0.42	0.15	81.861	12.00	0.366	4.395	0.9551
		56.325	14.00	0.252	3.528	0.9235
		35.765	16.00	0.160	2.560	0.9071
		19.807	18.00	0.089	1.595	0.8933
		8.360	20.00	0.037	0.748	0.7823
		2.605	22.00	0.012	0.256	0.7179
0.21	-.06	86.830	12.00	0.389	4.662	1.0131
0.58	0.31	68.364	12.00	0.306	3.671	0.7977

Table 4 cont'd

E (%)	E ₀ (%)	I _c (Amperes)	Field (Tesla)	J _c (GA/m ²)	J _{cB} (GN/m ³)	I _c /I _{cm}
0.58	0.31	43.135	14.00	0.193	2.702	0.7072
		25.307	16.00	0.113	1.812	0.6419
		11.253	18.00	0.050	0.906	0.5075
		3.882	20.00	0.017	0.347	0.3633
		0.821	22.00	0.004	0.081	0.2264
0.30	0.03	86.684	12.00	0.388	4.654	1.0114
0.72	0.45	54.983	12.00	0.246	2.952	0.6415
		32.503	14.00	0.145	2.036	0.5329
		15.588	16.00	0.070	1.116	0.3954
		5.680	18.00	0.025	0.457	0.2562
		1.214	20.00	0.005	0.109	0.1136
		0.153	22.00	0.001	0.015	0.0422
0.41	0.14	85.143	12.00	0.381	4.571	0.9934
0.82	0.55	48.772	12.00	0.218	2.619	0.5691
		25.524	14.00	0.114	1.599	0.4185
		9.981	16.00	0.045	0.715	0.2532
		2.889	18.00	0.013	0.233	0.1303
		0.395	20.00	0.002	0.035	0.0369
0.50	0.23	80.263	12.00	0.359	4.309	0.9365
0.96	0.69	37.542	12.00	0.168	2.016	0.4380
0.59	0.32	70.639	12.00	0.316	3.793	0.8242
1.03	0.76	25.740	12.00	0.115	1.382	0.3003
0.60	0.33	52.654	12.00	0.236	2.827	0.6144

Figure 5. Effect of axial tensile strain on the critical current of LLNL Nb₃Sn cable test strand at 4 K and several magnetic fields.

Figure 6. Effect of magnetic field on the critical current density of LLNL Nb_3Sn cable test strand at 4 K.

Figure 7. Effect of magnetic field on the n^{th} power of LLNL Nb₃Sn cable test strand at 4 K.

Nb₃Sn ITER Candidate Conductor

An internal-tin-process Nb₃Sn conductor, which is a prototype for the International Thermonuclear Experimental Reactor (ITER), was tested. The axial strain measurements were made over a range of magnetic fields from 15 to 25 T. The conductor specifications are given in Table 5, and the measured data are presented in Table 6 and Figs. 8 through 10. The I_c and J_c values are based on an electric field criterion (E_c) of 2 μ V/cm. The results show a zero-strain 15 T value of J_c (referred to the noncopper area) which was 0.50 GA/m² and a peak (strain-free) J_c value of 0.55 GA/m². The irreversible strain limit was reasonably high, 0.92%, and the compressive prestrain was 0.28%. The sample did not fracture until 1.09% strain.

Table 5. ITER conductor specifications.

Wire Diameter	0.817 mm
Copper Stabilizer	46.5%
Nb Diffusion Barrier (of Non-Cu Area)	8.5%
Noncopper	53.5%
Filament No.	4902
Filament Dia.	3.5 μ m
Subelement No.	19
Ti Addition	1.2%

Table 6. High-field critical current of Nb₃Sn ITER candidate conductor as a function of axial tensile strain applied at 4 K.

SP	E (%)	E0 (%)	FIELD (T)	Ic (A)	Jc (MA/m^2)	Ic/Icmax	N
0	0.048	-0.232	15	139.99	499.24	0.91	20.95
			16	109.56	390.73	0.90	17.73
			18	62.83	224.09	0.85	13.40
			20	27.43	97.82	0.74	8.33
			22	7.71	27.51	0.57	4.65
			24	0.47	1.68	0.23	1.78
			25				1.26
1	0.12	-0.16	15	149.89	534.55	0.97	18.47
			16	122.29	436.13	1.00	19.53
			18	72.23	257.60	0.97	15.16
			20	35.98	128.31	0.97	11.10
			22	11.86	42.31	0.88	6.02
			24	1.30	4.65	0.65	2.30
			25	0.11	0.41	0.50	1.48
2	0.232	-0.048	15	153.94	548.99	1.00	19.35
			16	117.86	420.34	0.96	13.27
			18	74.34	265.12	1.00	13.83
			20	37.00	131.94	1.00	9.19
			22	13.51	48.18	1.00	5.80
			24	2.01	7.17	1.00	2.59
			25	0.23	0.82	1.00	1.55
3	0.321	0.041	15	133.33	475.49	0.87	11.17
			16	118.64	423.11	0.97	17.35
			18	68.70	245.02	0.92	11.67
			20	34.23	122.06	0.93	8.53
			22	11.31	40.35	0.84	4.91
			24	1.75	6.24	0.87	2.50
			25	0.21	0.73	0.90	1.55
4	0.439	0.159	15	122.38	436.44	0.79	11.44
			16	97.63	348.18	0.80	11.35
			18	55.95	199.52	0.75	9.19
			20	25.39	90.55	0.69	6.53
			22	7.26	25.90	0.54	3.90
			24	0.71	2.52	0.35	1.92
			25	0.04	0.14	0.18	1.41
4U	0.221	-0.059	15	152.11	542.48	0.99	18.17
5	0.546	0.266	15	107.88	384.73	0.70	12.30

Table 6 cont'd

SP	E (%)	E0 (%)	FIELD (T)	Ic (A)	Jc (MA/m ²)	Ic/Icmax	N
			16	82.70	294.92	0.68	10.89
			18	41.28	147.22	0.56	7.35
			20	14.49	51.69	0.39	4.55
			22	3.23	11.51	0.24	2.83
			24	0.08	0.27	0.04	1.39
			25				1.15
5U	0.286	0.006	15	149.34	532.60	0.97	16.09
6	0.648	0.368	15	86.54	308.63	0.56	9.76
			16	64.56	230.24	0.53	9.20
			18	28.96	103.29	0.39	6.39
			20	8.13	28.98	0.22	3.67
			22	0.92	3.28	0.07	1.89
			24				1.19
6U	0.348	0.068	15	143.07	510.24	0.93	13.45
7	0.745	0.465	15	69.06	246.29	0.45	8.45
			16	50.40	179.73	0.41	8.09
			18	17.86	63.69	0.24	4.96
			20	3.37	12.01	0.09	2.64
			22	0.31	1.12	0.02	1.63
			24				1.07
7U	0.403	0.123	15	149.43	532.90	0.97	20.93
8	0.844	0.564	15	48.58	173.26	0.32	6.73
8U	0.464	0.184	15	116.39	415.08	0.76	9.17
9	0.919	0.639	15	34.64	123.54	0.23	5.40
9U	0.503	0.223	15	109.07	388.96	0.71	9.84
10	0.999	0.719	15	22.79	81.28	0.15	4.62
10U	0.55	0.27	15	74.68	266.35	0.49	6.05
11	1.088	0.808	15	13.20	47.09	0.09	3.52
11U	0.619	0.339	15	32.03	114.23	0.21	3.00

Figure 8. Effect of axial tensile strain on the critical current of the ITER Nb₃Sn candidate conductor at 4 K and several magnetic fields.

Figure 9. Effect of magnetic field on the critical current density of the ITER candidate conductor at 4 K.

Figure 10. Effect of magnetic field on the n^{th} power of the ITER candidate conductor at 4 K.

Nb₃Sn Conductors Reinforced with Dispersion-Hardened Copper (DHC) Alloy

The axial strain characteristics of a group of three similar experimental Nb₃Sn superconductors were measured over a broad range of magnetic fields. All three conductors were manufactured using the internal-tin process, and a dispersion-hardened-copper (DHC) reinforcement was used in each conductor for increased tensile strength. The first conductor has two concentric rings of stabilizing copper surrounding the noncopper core, which contains the internal tin. The inner ring is pure copper and the outer ring is DHC. The copper stabilizer makes up 72% of the conductor's total volume. Both of the other conductors have an internal-tin ring surrounding their cores and 56% external copper stabilizer. One of the conductors uses pure copper for the stabilizer and DHC for the core's matrix; the other conductor has the opposite configuration, a pure-copper matrix and DHC stabilizer. All three conductors have tantalum diffusion barriers between core and stabilizer. The conductor specifications are given in Tables 7 through 9. The I_c and J_c values are based on an electric field criterion (E_c) of 2 μ V/cm.

The measured data for the tin-core conductor are presented in Table 10 and in Figs. 11 through 13. The large prestrain ($\epsilon_m=0.55\%$) for this conductor is caused by the high copper fraction, 72%. The I_c doubles at 12 T between $\epsilon=0$ and $\epsilon=\epsilon_m$ because of the large value of ϵ_m . The noncopper peak J_c ($\epsilon=\epsilon_m$) at 12 T is 850 A/mm².

The measured data for the tin-ring conductors are presented in Tables 11 and 12 and in Figs. 14 through 19. The lower copper-stabilizer fraction (56%) results in a smaller prestrain for both conductors ($\epsilon_m=0.3\%$). The noncopper peak J_c ($\epsilon=\epsilon_m$) at 12 T is 1120 A/mm² for the pure-copper stabilized conductor and 1030 A/mm² for the DHC stabilized conductor. The low-field n-value for the pure-copper stabilized wire is ~ 30 and ~ 20 for the other wire. This difference is probably associated with the smaller filament diameter for the DHC stabilized conductor (1.7 μ m compared to 3 μ m).

Table 7. DHC reinforced tin-core Nb₃Sn conductor specifications.

Wire Diameter	0.389 mm
DHC (outside)	33%
Copper Stabilizer	39%
Noncopper Core	28%
Nb in Core	$\sim 31\%$
Ta Barrier	3.8%
Filament No.	37 x 894 = 33078
Filament Dia.	0.6 μ m @ 0.389 mm dia.
Local Cu:Nb Ratio	0.8:1

Table 8. Conductor specifications for DHC reinforced tin-ring Nb₃Sn wire with pure-copper stabilizer.

Wire Diameter	0.267 mm
Noncopper Core	44%
DHC Core	
Pure Copper Stabilizer	56%
Ta Barrier	8%
Nb-1.3 wt. % Ti	~8%
Filament No.	624
Filament Dia.	~3 μ m
Local Cu:Nb Ratio	1:1

Table 9. Conductor specifications for DHC reinforced tin-ring Nb₃Sn with DHC stabilizer.

Wire Diameter	0.267 mm
Local Cu:Nb Ratio	0.8:1
Noncopper Core	44%
DHC Stabilizer (outside)	56%
Ta Barrier	8%
Nb-1.3 wt. % Ti	13.5%
Filament No.	2796
Filament Dia.	~1.7 μ m

Table 10. High-field critical current of copper-alloy reinforced tin-core Nb₃Sn as a function of axial tensile strain applied at 4 K.

E (%)	E ₀ (%)	I _c (Amperes)	Field (Tesla)	J _c (6A/m ²)	J _{cB} (6N/m ³)	I _c /I _{cm}
0.00	-.55	74.630	8.00	2.241	17.929	0.7957
		36.650	10.00	1.101	11.006	
		14.918	12.00	0.448	5.376	
		4.284	14.00	0.129	1.801	
		0.747	16.00	0.022	0.359	
0.08	-.47	78.200	8.00	2.348	18.786	0.8338
0.23	-.32	87.400	8.00	2.625	20.997	0.9319
0.35	-.20	93.790	8.00	2.817	22.532	1.0000
0.51	-.04	54.605	10.00	1.640	16.398	
		28.265	12.00	0.849	10.186	
		12.293	14.00	0.369	5.168	
		3.971	16.00	0.119	1.908	
		0.765	18.00	0.023	0.414	
0.59	0.04	54.270	10.00	1.630	16.297	
0.71	0.16	43.855	10.00	1.317	13.170	
0.80	0.25	29.455	10.00	0.885	8.845	
0.41	-.14	31.195	10.00	0.937	9.368	
0.88	0.33	15.580	10.00	0.468	4.679	
0.47	-.08	18.260	10.00	0.548	5.484	
0.97	0.42	5.410	10.00	0.162	1.625	
0.53	-.02	3.450	10.00	0.104	1.036

Figure 11. Effect of axial tensile strain on the critical current of DHC reinforced Nb₃Sn conductor at 4 K and several magnetic fields.

Figure 12. Effect of magnetic field on the critical current density of DHC reinforced Nb₃Sn conductor at 4 K.

Figure 13. Effect of magnetic field on the n^{th} power of DHC reinforced Nb₃Sn conductor at 4 K.

Table 11. High-field critical current of DHC reinforced tin-ring Nb₃Sn with pure copper stabilizer as a function of axial tensile strain applied at 4 K.

E (%)	E ₀ (%)	Field (T)	I _c (A)	J _c (MA/m ²)	I _c /I _{cm}	n value
0.00	-.30	10.00	36.49	1484.72	0.958	30.0
		12.00	26.30	1070.00	0.957	30.3
		14.00	18.49	752.13	0.945	29.8
		16.00	12.28	499.54	0.926	28.5
		18.00	7.63	310.58	0.907	23.7
		20.00	4.08	165.99	0.866	17.8
		22.00	1.66	67.45	0.777	11.7
		24.00	0.37	15.09	0.640	6.3
		25.00	0.10	4.27	0.529	3.6
0.09	-.21	10.00	36.68	1492.41	0.962	32.4
		12.00	26.30	1070.08	0.957	31.8
		14.00	18.45	750.44	0.943	30.7
		16.00	12.28	499.66	0.926	28.8
		18.00	7.52	305.80	0.893	23.1
		20.00	3.96	161.18	0.841	17.5
		22.00	1.58	64.10	0.738	11.1
		24.00	0.36	14.57	0.618	7.3
0.16	-.14	10.00	37.48	1524.77	0.983	32.1
		12.00	27.12	1103.40	0.987	34.6
		14.00	19.24	782.63	0.983	34.0
		16.00	13.06	531.45	0.985	33.3
		18.00	8.19	333.19	0.973	28.8
		20.00	4.45	180.85	0.943	19.8
		22.00	1.92	78.06	0.899	13.3
		24.00	0.46	18.89	0.801	6.5
		25.00	0.15	6.25	0.774	4.4
0.33	0.03	10.00	38.11	1550.59	1.000	35.8
		12.00	27.48	1117.80	1.000	33.3
		14.00	19.56	795.77	1.000	31.2
		16.00	13.26	539.65	1.000	29.5
		18.00	8.42	342.39	1.000	23.7
		20.00	4.71	191.69	1.000	18.1
		22.00	2.13	86.80	1.000	13.8
		24.00	0.58	23.58	1.000	7.4
		25.00	0.20	8.07	1.000	4.8
0.48	0.18	10.00	34.19	1391.03	0.897	27.4
		12.00	24.28	987.95	0.884	25.8
		14.00	16.68	678.64	0.853	25.1
		16.00	10.83	440.43	0.816	21.9
		18.00	6.26	254.68	0.744	14.5
		20.00	2.98	121.16	0.632	10.1

Table 11 cont'd

E (%)	E ₀ (%)	Field (T)	I _c (A)	J _c (MA/m ²)	I _c /I _{cm}	n value
		22.00	0.94	38.27	0.441	5.1
		24.00	0.15	5.91	0.251	3.2
		25.00	0.03	1.31	0.162	2.0
0.64	0.34	10.00	29.33	1193.16	0.769	24.7
		12.00	19.91	810.06	0.725	24.2
		14.00	12.74	518.15	0.651	21.1
		16.00	7.30	296.80	0.550	14.1
		18.00	3.40	138.16	0.404	10.4
		20.00	1.08	43.77	0.228	6.0
		22.00	0.18	7.30	0.084	3.9
0.33	0.03	10.00	36.53	1486.03	1.000	28.8
0.77	0.47	10.00	23.21	944.15	0.609	20.0
0.39	0.09	10.00	33.67	1369.79	0.922	23.4
0.87	0.57	10.00	18.68	760.07	0.490	21.5
0.44	0.14	10.00	28.84	1173.51	0.790	15.6
0.97	0.67	10.00	12.38	503.63	0.325	10.8
0.49	0.19	10.00	22.79	927.05	0.624	12.3

Figure 14. Effect of axial tensile strain on the critical current of DHC reinforced Nb_3Sn conductor at 4 K and several magnetic fields.

Figure 15. Effect of magnetic field on the critical current density of DHC reinforced Nb₃Sn conductor at 4 K.

Figure 16. Effect of magnetic field on the n^{th} power of DHC reinforced Nb₃Sn conductor at 4 K.

Table 12. High-field critical current of DHC reinforced tin-ring Nb₃Sn with DHC stabilizer as a function of axial tensile strain applied at 4 K.

SP	E (%)	E0 (%)	FIELD (T)	Ic (A)	Jc (MA/m^2)	Ic/Icmax	N
0	0.205	-0.095	10	33.85	1376.20	1.00	19.14
			12	24.62	1000.80	0.97	20.80
			14	17.09	694.69	0.96	19.93
			15	14.03	570.16	0.97	17.81
			16	11.25	457.51	0.97	17.76
			18	6.75	274.49	0.94	16.26
			20	3.39	137.68	0.90	14.26
			22	1.25	50.82	0.86	9.32
			24	0.22	8.94	0.78	4.77
			25	0.05	2.04	0.75	2.64
1	0.286	-0.014	12	25.45	1034.44	1.00	29.26
			14	17.73	720.73	1.00	25.60
			15	14.52	590.43	1.00	22.01
			16	11.65	473.74	1.00	18.06
			18	7.21	293.00	1.00	20.94
			20	3.75	152.55	1.00	15.15
			22	1.45	59.01	1.00	11.66
			24	0.28	11.41	1.00	5.40
2	0.387	0.087	25	0.07	2.71	1.00	3.46
			12	24.14	981.39	0.95	15.33
			14	17.06	693.31	0.96	18.67
			15	14.14	574.85	0.97	21.45
			16	11.34	461.04	0.97	17.70
			18	6.88	279.64	0.95	16.03
			20	3.49	141.97	0.93	14.06
			22	1.28	52.10	0.88	9.86
			24	0.20	8.20	0.72	4.69
			25	0.04	1.60	0.59	2.42
3	0.515	0.215	14	15.45	628.01	0.87	19.06
			15	12.15	493.83	0.84	16.12
			16	9.69	393.80	0.83	17.93
			18	5.40	219.53	0.75	13.89
			20	2.33	94.67	0.62	8.97
			22	0.62	25.09	0.43	5.25
			24	0.06	2.37	0.21	2.38
3U	0.298	-0.002	12	24.80	1008.03	0.97	15.24
4	0.643	0.343	14	12.25	497.83	0.69	16.40
			15	9.47	384.76	0.65	16.37

Table 12 cont'd

SP	E (%)	E0 (%)	FIELD (T)	Ic (A)	Jc (MA/m^2)	Ic/Icmax	N
			16	6.96	282.84	0.60	12.69
			18	3.30	133.96	0.46	10.44
			20	0.96	39.05	0.26	5.42
			22	0.13	5.11	0.09	2.79
			24	0.01	0.51	0.04	1.38
4U	0.341	0.041	12	24.90	1012.01	0.98	21.63
5	0.755	0.455	12	15.70	638.11	0.62	14.49
5U	0.41	0.11	12	24.01	976.14	0.94	19.69
6	0.863	0.563	12	13.00	528.55	0.51	17.10
6U	0.48	0.18	12	22.83	928.24	0.90	20.82
7	0.972	0.672	12	10.15	412.76	0.40	13.83
7U	0.526	0.226	12	20.55	835.30	0.81	11.90
8	1.08	0.78	12	7.65	310.97	0.30	9.85
8U	0.581	0.281	12	17.88	726.83	0.70	10.38
9	1.188	0.888	12	6.37	259.12	0.28	7.07
9U	0.681	0.381	12	11.00	447.07	0.68	9.02

Figure 17. Effect of axial tensile strain on the critical current of DHC reinforced Nb₃Sn conductor at 4 K and several magnetic fields.

Figure 18. Effect of magnetic field on the critical current density of DHC reinforced Nb₃Sn conductor at 4 K.

Figure 19. Effect of magnetic field on the n^{th} power of DHC reinforced Nb₃Sn conductor at 4 K.

V₃Ga Tape

We also tested an experimental high-field V₃Ga tape conductor manufactured in Japan, which is not available from US manufacturers. The conductor specifications are shown in Table 13. The complete set of J_c vs. strain data at magnetic fields from 10 T to 19.65 T is given in Table 14, and the data are presented graphically in Figs. 20 through 22. The I_c and J_c values are based on an electric field criterion (E_c) of 2 μ V/cm. This material has good J_c properties out to 20 T and is a viable candidate material for extending superconducting magnets to this field range. The results show a peak (strain-free) J_c that is high and nearly constant out to 20 T. The initial prestrain, however, is very low, only about 0.05%, and the irreversible strain limit is only 0.2%.

Table 13. V₃Ga tape specifications.

In-Situ Process	
Cross-Sectional Dimensions	4 mm x 150 μ m
Noncopper Area	0.440 mm ²
Superconductor Area	0.1016 mm ²
Core Composition	Cu-35at.%V

Table 14. High-field critical current of V₃Ga tape.

E (%)	E ₀ (%)	I _c (Amperes)	Field (Tesla)	J _c (GA/m ²)	J _c B (GN/m ³)	I _c /I _{cm}
0.00	-0.05	154.700	10.00	0.103	1.031	0.9937
		143.530	12.00	0.096	1.148	1.0527
		126.130	14.00	0.084	1.177	0.9953
		117.850	16.00	0.079	1.257	0.9940
		103.680	18.00	0.069	1.244	1.0026
		87.320	19.00	0.058	1.106	1.0029
		69.980	19.65	0.047	0.917	0.9779
0.05	0.00	155.680	10.00	0.104	1.038	1.0000
		136.350	12.00	0.091	1.091	1.0000
		126.730	14.00	0.084	1.183	1.0000
		118.560	16.00	0.079	1.265	1.0000
		103.410	18.00	0.069	1.241	1.0000
		87.070	19.00	0.058	1.103	1.0000
		71.560	19.65	0.048	0.937	1.0000
0.16	0.11	152.730	10.00	0.102	1.018	0.9811
		132.000	12.00	0.088	1.056	0.9681
		118.300	14.00	0.079	1.104	0.9335
		102.970	16.00	0.069	1.098	0.8685
		83.980	18.00	0.056	1.008	0.8121
		69.720	19.00	0.046	0.883	0.8007
		58.090	19.65	0.039	0.761	0.8118
0.19	0.14	137.900	10.00	0.092	0.919	0.8858
		118.600	12.00	0.079	0.949	0.8698
		106.980	14.00	0.071	0.998	0.8442
		94.270	16.00	0.063	1.006	0.7951
		75.810	18.00	0.051	0.910	0.7331
		63.610	19.00	0.042	0.806	0.7306
		52.190	19.65	0.035	0.684	0.7293
0.07	0.02	136.500	10.00	0.091	0.910	0.8768
0.26	0.21	125.430	10.00	0.084	0.836	0.8057
		104.400	12.00	0.070	0.835	0.7657
		94.280	14.00	0.063	0.880	0.7439
		81.630	16.00	0.054	0.871	0.6885
		66.490	18.00	0.044	0.798	0.6430
		54.710	19.00	0.036	0.693	0.6284
		44.870	19.65	0.030	0.588	0.6270
0.09	0.04	117.050	10.00	0.078	0.780	0.7519

Table 14 cont'd

E (%)	E ₀ (%)	I _c (Amperes)	Field (Tesla)	J _c (GA/m ²)	J _{cB} (GN/m ³)	I _c /I _{cm}
0.33	0.28	61.570	10.00	0.041	0.410	0.3955
		51.000	12.00	0.034	0.408	0.3740
		45.520	14.00	0.030	0.425	0.3592
		37.630	16.00	0.025	0.401	0.3174
		26.880	18.00	0.018	0.323	0.2599
		19.020	19.00	0.013	0.241	0.2184
		14.320	19.65	0.010	0.188	0.2001
0.11	0.06	60.430	10.00	0.040	0.403	0.3882
0.38	0.33	40.050	10.00	0.027	0.267	0.2573
		26.090	12.00	0.017	0.209	0.1914
		20.130	14.00	0.013	0.188	0.1588
		14.565	16.00	0.010	0.155	0.1229
		8.505	18.00	0.006	0.102	0.0822
		5.378	19.00	0.004	0.068	0.0618
		3.460	19.65	0.002	0.045	0.0484
0.13	0.08	47.850	10.00	0.032	0.319	0.3074

Figure 20. Effect of axial tensile strain on the critical current of V_3Ga tape at 4 K and several magnetic fields.

Figure 21. Effect of magnetic field on the critical current density of V₃Ga tape at 4 K.

Figure 22. Effect of magnetic field on the n^{th} power of V_3Ga tape at 4 K.

VAMAS Nb₃Sn Test Conductor

A bronze-process Nb₃Sn conductor was measured as part of the second VAMAS (Versailles Project on Advanced Materials and Standards) international critical-current round robin. The conductor specifications are given in Table 15. The critical current was measured as a function of magnetic field and axial tensile strain. The measured data are presented in Table 16 and in Figs. 23 and 24. The I_c and J_c values are based on an electric field criterion (E_c) of 1 μ V/cm. In the first VAMAS round robin tests, differences in the test specimens' axial strain, caused by variations in the thermal contraction of different test fixtures, was a major source of interlaboratory variation in the critical-current data. Consequently, *electromechanical* characterization of the test specimen is important for data interpretation and error analysis. In the second round robin, the test apparatus and procedure were more rigidly specified. This increased experimental control reduced the critical-current variation by a factor of 3.5. The results of our measurements will be published in the final VAMAS report.

Table 15. VAMAS Nb₃Sn test conductor specifications.

Wire Diameter	1.0 mm
Cu:Non-Cu Ratio	1.68:1
Bronze:Core Ratio	2.5:1
Filament Dia.	4.5 μ m
Filament No.	5047

Table 16. High-field critical current of VAMAS Nb₃Sn test conductor as a function of axial tensile strain applied at 4 K.

SP	E (%)	E0 (%)	FIELD (T)	Ic (A)	Jc (MA/m ²)	Ic/Icmax	N
0	0.045	-0.205	12	187.95	641.46	1.00	25.70
			14	134.76	459.92	0.94	34.54
			15	110.99	378.80	1.00	29.12
			16	91.18	311.20	0.92	30.22
			18	56.12	191.54	0.88	23.73
			20	28.81	98.32	0.81	16.17
			22	10.15	34.64	0.68	8.91
			24	1.36	4.63	0.48	3.57
			25	0.24	0.81	0.44	1.98
1	0.119	-0.131	14	140.08	478.10	0.97	34.39
			16	95.41	325.64	0.96	27.37
			18	59.61	203.45	0.94	22.22
			20	32.30	110.25	0.91	17.34
			22	12.73	43.45	0.85	11.62
			24	2.08	7.11	0.74	4.55
			25	0.35	1.18	0.65	2.08
2	0.219	-0.031	14	143.23	488.86	0.99	29.24
			16	99.27	338.82	1.00	30.59
			18	63.18	215.62	0.99	24.14
			20	35.39	120.78	1.00	19.49
			22	14.63	49.92	0.98	12.23
			24	2.81	9.59	1.00	5.42
			25	0.54	1.83	1.00	2.48
3	0.297	0.047	14	144.00	491.46	1.00	31.24
			16	98.91	337.58	1.00	27.22
			18	63.64	217.20	1.00	25.95
			20	35.52	121.24	1.00	18.68
			22	14.91	50.88	1.00	12.63
			24	2.63	8.97	0.94	4.91
			25	0.47	1.60	0.88	2.38
4	0.374	0.124	14	142.34	485.81	0.99	32.41
			16	97.83	333.88	0.99	32.09
			18	61.74	210.71	0.97	24.57
			20	33.42	114.06	0.94	15.96
			22	12.51	42.70	0.84	9.05
			24	1.91	6.53	0.68	3.89
			25	0.33	1.14	0.62	2.05
5	0.448	0.198	14	136.55	466.04	0.95	30.07

Table 16 cont'd

SP	E (%)	E0 (%)	FIELD (T)	Ic (A)	Jc (MA/m ²)	Ic/Icmax	N
			16	91.86	313.50	0.93	25.92
			18	56.54	192.98	0.89	20.93
			20	27.98	95.50	0.79	11.10
			22	17.72	60.47	1.19	5.62
			24	1.01	3.45	0.36	2.53
			25	0.15	0.51	0.28	1.49
6	0.521	0.271	14	127.88	436.46	0.89	24.21
			16	83.90	286.34	0.85	19.46
			18	49.14	167.71	0.77	14.87
			20	22.04	75.24	0.62	8.75
			22	5.79	19.76	0.39	4.65
			24	0.58	1.99	0.21	2.32
			25	0.07	0.23	0.13	1.28
6u	0.355	0.105	14	145.46	496.45	1.01	34.64
7	0.61	0.36	14	116.40	397.27	0.81	21.64
			16	74.10	252.91	0.75	16.18
			18	38.95	132.92	0.61	9.69
			20	15.99	54.56	0.45	7.32
			22	3.20	10.93	0.21	3.52
			24	0.20	0.67	0.07	1.46
			25	0.04	0.13	0.07	1.21
7u	0.401	0.151	14	142.41	486.05	0.99	31.80
8	0.688	0.438	14	107.25	366.04	0.74	23.17
			16	63.97	218.32	0.64	15.03
			18	31.35	106.98	0.49	8.88
			20	10.20	34.80	0.29	5.19
			22	1.63	5.56	0.11	2.72
			24	0.11	0.39	0.04	1.44
			25	0.03	0.09	0.05	1.18
8u	0.463	0.213	14	138.38	472.30	0.96	28.24
9	0.78	0.53	14	89.30	304.76	0.62	13.75
			16	52.00	151.47	0.45	7.80
			18	21.61	73.74	0.34	7.25
			20	5.39	18.40	0.15	3.92
			22	0.62	2.11	0.04	1.97
			24	0.04	0.15	0.02	1.28

Table 16 cont'd

SP	E (%)	E0 (%)	FIELD (T)	Ic (A)	Jc (MA/m^2)	Ic/Icmax	N
9u	0.513	0.263	14	131.75	449.65	0.91	22.67
10	0.869	0.619	14	77.02	262.87	0.53	15.96
			16	39.59	135.13	0.40	10.60
			18	13.73	46.85	0.22	5.87
			20	2.54	8.66	0.07	3.12
			22	0.24	0.83	0.02	1.62
			24	0.03	0.11	0.01	1.19
10u	0.564	0.314	14	119.60	408.18	0.83	16.46
11	0.935	0.685	14	63.83	217.84	0.44	11.97
11u	0.602	0.352	14	104.09	355.24	0.72	10.79
12	1.001	0.751	14	48.52	165.60	0.34	8.19
12u	0.653	0.403	14	82.18	280.47	0.57	7.09
13	1.059	0.809	14	34.15	116.55	0.24	5.52
13u	0.688	0.438	14	56.92	194.25	0.40	4.42
14	1.113	0.863	14	21.26	72.56	0.15	3.81
14u	0.715	0.465	14	34.26	116.94	0.24	3.04
15	1.16	0.91	14	13.72	46.84	0.10	3.02
15u	0.742	0.492	14	21.71	74.09	0.15	2.48
16	1.21	0.96	14	8.25	28.15	0.06	2.37
16u	0.78	0.53	14	14.96	51.06	0.10	2.55
17	1.264	1.014	14	5.31	18.13	0.04	2.34
17u	0.819	0.569	14	10.57	36.08	0.07	2.58

Figure 23. Effect of axial tensile strain on the critical current of the VAMAS Nb₃Sn test conductor at 4 k and several magnetic fields.

Figure 24. Effect of magnetic field on the critical current density of the VAMAS test conductor at 4 K.