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Superconductor Industry in Germany: Status and Perspectives

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Abstract – **This overview of superconductor industry in Germany is based on an introductory talk presented at the First German Symposium on High-temperature Superconductivity for Energy Technology (ZIEHL), held in Bonn on February 20 and 21, 2008. Developed in Germany electric grid subsystems using high-temperature superconductors (HTS), and energy-intensive industrial products involving HTS are used as examples. The need for large-scale investment is accentuated as paramount for the future of this industry.**

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I. INTRODUCTION

This overview of superconductor industry in Germany is based on my introductory talk presented at the First German Symposium on "Future and Innovation in Energy Technology Using High-temperature Superconductors" (ZIEHL). The purpose of the ZIEHL Symposium, organized with encouragement of the German Ministry for Economy (BMWi), was to disseminate information on the German status of high-temperature superconducting (HTS) technology and its applications in energy industry, and to point out their potential for increased energy efficiency. The targeted audience were engineers active in energy technology, potential future investors, and hopefully decision makers in politics, economy, industry and environmental protection. The underlying belief of organizers has been that after nearly twenty years of R&D, at least some HTS applications are becoming ready for implementation in energy industry, and should be tested as real-scale demonstrators also in Germany.

The purpose of this overview is to provide succinct information on German HTS industry and its potential for energy technology and higher energy efficiency. Therefore, I omit the general introduction to superconductors and their applications included in my talk, and concentrate on the overview of German companies active in superconductivity, with strong emphasis on HTS technology. In contrast to the large-scale use of low-temperature superconductors (LTS) in scientific machines for fundamental research, such as accelerators, the efficiency of today's electric energy generation, storage, transmission and distribution systems can benefit only from the implementation of HTS rather than LTS conductors, mainly because of the much lesser cost and higher efficiency of the attending cryogenics (refrigeration), and especially of closed-cycle cryocoolers. Present long-term energy experiments, such as the nuclear fusion project ITER (see review CR-6, this issue) have to rely mostly on LTS conductors and magnets; the refrigeration cost is acceptable at such large scale (see also Forum review CR-4, Issue 2) while HTS conductors are not mature enough for this purpose, except as current leads. However, in the future designs, LTS conductors might be superseded by superior HTS equivalents.

In this article, I include activities of multinational industrial organizations having German subsidiaries, and some foreign companies in near-the-border areas, which are closely associated with a German company and may be even members of "ivSupra". However, I do not discuss the cryogenic industry in any detail.

II. POTENTIAL OF HTS FOR ENERGY TECHNOLOGY

A. General Advantages Offered by High-temperature Superconductivity

The main potential of HTS for energy technology derives mainly, but not exclusively, from the low-loss electric current-carrying capability exceeding that of copper conductors by two orders of magnitude. The effective (engineering) current density of copper conductors is 1 to 5 A/mm^2 compared with well over 100 A/mm^2 for HTS conductors. Consequently, incomparably higher magnetic fields can be generated by superconducting magnets. Together, high current densities and high magnetic fields result in high energy density in electrical machines and cables. That can lead to smaller and lighter grid components and subsystems with simultaneously significantly higher ratings. Negligible or low electric energy losses lead to improved efficiency of these components and subsystems with the attendant reduction in CO_2 generation.

In fields such as grid components and industrial equipment, superconducting technology must be able to compete with the conventional one both technically and economically. In most cases, the direct efficiency increase is not the dominant argument in favor of HTS, but rather the significantly reduced size and weight or much higher rating capability without size and weight increase. This in turn translates into savings of energy resources. With regard to efficiency, I like to note that the lower is the efficiency of conventional apparatus the stronger are arguments favoring the use of HTS. An example is the metal induction heater (Section VIII), which in conventional technology has an efficiency of only about 40 %.

Additional environmental advantage of HTS is the absence of oil cooling of transformers and cables. A further advantage is absence of thermal aging of components. Finally, superconductivity itself leads to novel important grid components, such as the fast, automatically resetting HTS fault current limiters (FCL), which otherwise would not be possible (Section VII).

B. The Cryocooling Issue

The HTS technology has potentially a much broader application range than LTS in addressing the conventional technology fields, because of significantly reduced cryogenic penalty. While the Carnot efficiency is only 1.4% at 4.2 K, it improves to 34.5% at 77K. Cryocoolers attain only a fraction of this ideal efficiency, and that fraction also increases with temperature, albeit slowly. At cooling power ratings required for relatively large grid components, the typical overall efficiency is about 0.38 % (0.27 of Carnot) at 4.2 K (LTS), but already 10% (0.29 of Carnot) at 77 K (HTS), an overall improvement by a factor of 26. Therefore, for HTS the required cooling power can be a negligible fraction of the grid component or industrial machinery power rating, if the latter is very high (>> 100 kW).

Utilities and industrial users might be initially reticent to adopt cryogenic cooling, but even today we are surrounded by large-scale refrigeration, which is proven, highly reliable and generally accepted. For example, the worldwide fleet of tankers transporting liquefied natural gas (LNG) at temperature of 110 K (-163 degrees centigrade) consists of 200 vessels, each transporting between 150 and 250 thousand of cubic meters. In Germany alone, 3 to 4 million tons of nitrogen (LN_2) are liquefied annually for various industrial uses. In the case of superconducting installations on the grid it is not difficult to build in a high degree of cryogenic redundancy. For example, in the superconducting transmission line project for New Orleans to be completed in 2011 (Section V, Table IV,) a 3-fold redundancy is to be build in. In addition to active cooling there is planned a long-term (30 days) and short-term (8 hours) storage of liquid nitrogen.

C. Cost of Superconducting Material (Wire)

The main pre-condition for large-scale harnessing of HTS potential in the energy industry is that the present cost of composite HTS conductors and cables decreases to economically acceptable level. This pre-condition was not met thus far by the BSCCO composites of the 1st generation (1G), but the YBCO or ReBCO coatings (Re = rare earth element) on stainless steel and alloy tapes, *i.e.*, the coated conductors (CC) hold the promise of more significant gradual cost reduction to the desired level, fully competitive with that of copper conductors, especially at currently soaring copper prices. Figure 2 presents the projected evolution of prices in EUR per kiloamperemeter (kAm) from 2006 to year 2020 for copper wires, 1G and 2G conductors. The contribution of silver to the overall price of 1G is also included. The wide bands represent estimated uncertainty ranges. I readily admit this is an optimistic and perhaps even controversial projection, but there is little doubt that if produced commercially at large enough scale, the 2G conductors can become competitive with copper.

The second pre-condition is to fully develop a technology suitable for conductor operation in high ac magnetic fields. Twisting of tapes is not practical, scribing alone, even if possible at large scale, doesn't solve the problem fully. At present, experiments with Roebel transposed conductors indicate a possible way (see Forum papers ST-15 and ST-26, Issue 3), but such a process must also become economically feasible.

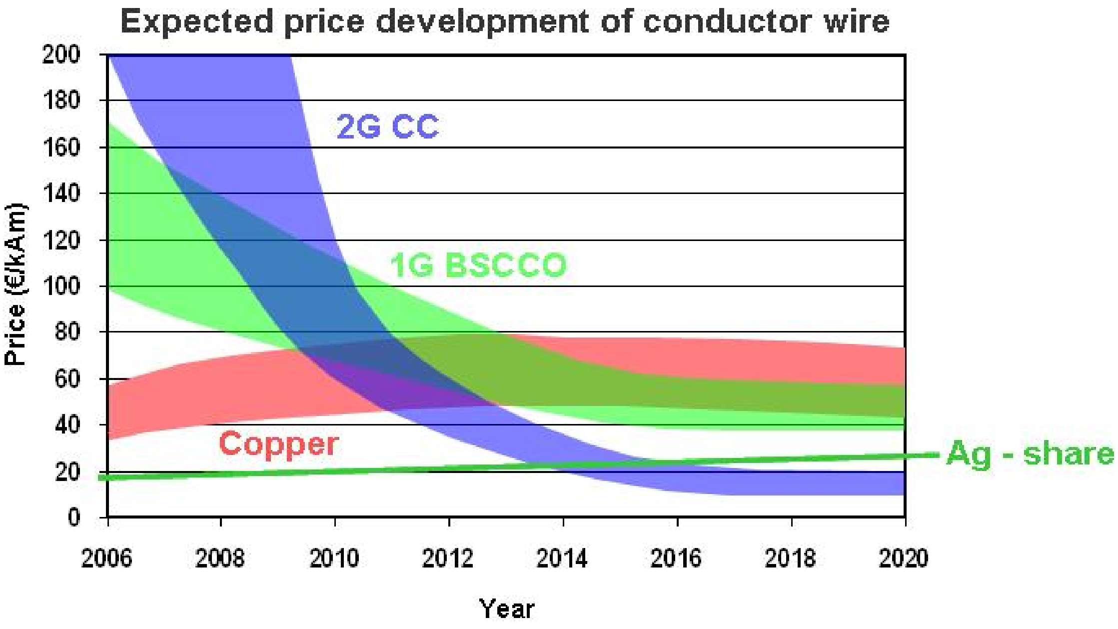


Fig. 2. Price development projections from present to year 2020 for copper and composite HTS conductors of first and second generation (1G and 2G). Wide bands represent the uncertainty ranges.

III. GERMAN INDUSTRIAL LANDSCAPE IN SUPERCONDUCTIVITY

Germany has the worldwide highest density of companies active in superconductivity technology; this is especially true for HTS and related products. Figure 2 shows locations in HTS companies in Germany and indicates their areas of activity (materials and conductors, refrigeration, systems) of consequence to energy technology. Tables I and II present the hopefully complete alphabetic listings of German companies and identify major products classes. Table I lists those active mainly in LTS, while the listing of Table II largely corresponds to Figure 2.

Most of superconductivity companies are small or medium enterprises, a situation typical for innovative technology. In fact, the only very large German company currently active in HTS is Siemens AG. While small size offers the advantage of flexibility and high development dynamics, the usual penalty for being small is the penury of financing and liquidity, aggravated in Germany by limited access to venture capital. Furthermore, execution of large projects is difficult and might be beyond reach for some small entities. What they expect of politics is, first of all, the creation of more favorable boundary conditions for technology R&D at small companies. The present Federal Government rules and bureaucratic practices in Germany clearly favor very large enterprises. Second, especially in energy technology, they need governmental financing of pilot projects permitting to gain operational experience. From German energy utilities, large industry and (venture) capital sources they need cooperation and financial commitment, also to test HTS components in the electric grid with emphasis on longer-term in-field reliability.

In the following sections I highlight only some of the companies accounted for in Figure 2, grouped by product(s) and type of application. Naturally, I begin with materials and conductors, as these leverage all possible system applications. I also mention those LTS companies, which are involved in energy technology. For each class of application, I list companies participating in foreign demonstration projects. Unfortunately, no large-scale demonstration programs are executed in Germany, because of lack of government support. Currently such projects are conducted mainly in USA, Japan and Korea, and represent an absolute necessity for two reasons:

1. By involving the power facilities and energy industry, demonstrators permit them to gain experience with operating superconducting subsystems and systems, and tangibly show the advantages of HTS, as well as problems which still need to be addressed.
2. Demonstrators permit one to assess long-term reliability of HTS components in realistic operating conditions, which is of extreme importance to utilities.

Fig. 2. Contour map of Germany with State (Land) boundaries marked. Companies developing and manufacturing HTS and related products are shown and color-coded in three groups listed above.

Table I. German Companies: LTS Technology & Cryogenics

No.	*Name*	*Address*	*Product(s)*
1	ACCEL Instruments GmbH (2006 acquired by Varian Medical Systems)	Friedrich-Ebert-Straße 1 D-51429 Bergisch Gladbach Phone: +49 2204 8425 00 Fax: +49 2204 8425 01	Accelerator & related technology – development and manufacturing, service. Proton therapy
2	European Advanced Superconductors GmbH & Co. KG (EAS) (Bruker Group, former Vacuumschmelze)	Ehrichstraße 10 D-63450 Hanau Phone: +49 6181 438 441 00 Fax: +49 6181 438 444 00	LTS conductors, magnetic materials, magnetic shielded rooms
3	Babcock-Noell GmbH	Div. Magnet Technology Alfred-Nobel-Straße 20 D-97080 Würzburg Phone.: + 49 931 903 6054 Fax.: + 49 931 903 6010	Design & manufacturing of large LTS magnets for accelerators & fusion
4	BMDSys GmgH	Wildenbruchstr. 15 D-07745 Jena Phone: +49 3641 235 851, Fax: +49 3641 236 155	Magnetic field imaging (MFI, magnetocardiography)
5	Bruker-BioSpin GmbH	Silberstreifen 4 D-76287 Rheinstetten Phone: +49 721 5161 0 Fax: +49 721 5171 01	LTS magnets for medicine (MRI) and analytics
6	Magnicon GbR	Lemsahler Landstrasse 171 D-22397 Hamburg Phone: +49 40 788 922-11 Fax: +49 40 788 922-12	SQUID sensors & electronics (LTS & HTS)
7	Oerlikon Leybold Vacuum Dresden GmbH	Division Cryogenics Zur Wetterwarte 50 Haus 304 D-01109 Dresden Phone.: + 49 351 885 5014 Fax.: +49 351 885 5040	Low temperature refrigerator systems for applications incl. superconductivity. Systems consist of a helium compressor, flexible helium lines (Flexlines) and a cold head
8	Philips Medizin Systeme GmbH	Röntgenstraße 24 D-22335 Hamburg Phone: +49 40 5078 0 Fax: +49 40 5078 2002	MRI systems (magnets manufactured in USA)
9	Siemens AG	Medical Solutions Henkestraße 127 D-91052 Erlangen Phone: +49 9131 84 0 Fax: +49 9131 84 29 24	MRI systems (magnets manufactured in UK)
10	Supracon AG	Wildenbruchstraße 15 D-07745 Jena Phone: +49 3641-675380 Fax: +49 3641-675387	SQUID sensors and SQUID systems; geomagnetic applications., voltage standards
11	TransMIT GmbH	Centre for Adaptive Cryotechnology and Sensors Heinrich-Buff-Ring 16 D-35392 Gießen Phone: +49 641 993 346 0 Fax: +49 641 993 340 9	SQUID sensors, electronics and applications (LTS & HTS): pulse-tube cryocoolers
12	VeriCold Technologies GmbH (now belonging to Oxford Instruments plc.)	Bahnhofstr. 21 D-85737 Ismaning Phone: +49 89 969 985 60 Fax: +49 89 969 985 69	X-ray sensors, pulse tube and dilution refrigerators, cryostats

Table II. German Companies: HTS - Technology & Cryogenics

No.	*Name*	*Address*	*Product(s)*
1	ACCEL Instruments GmbH	Friedrich-Ebert-Straße 1 D-51429 Bergisch Gladbach Phone: +49 2204 842 500 Fax: +49 2204 842 501	Accelerators, magnets
2	Adelwitz Technologiezentrum GmbH	Rittergut Adelwitz D-04886 Arzberg Phone: +49 34222 452 00 Fax: +49 34222 452 02	HTS powders, targets, textured bulk, magnetic bearings and systems, flywheel activities
3	Bruker-BioSpin GmbH	Silberstreifen 4 D-76287 Rheinstetten Phone: +49 721 516 10 Fax: +49 721 517 101	NMR Magnets, NMR sensors
4	Bültmann GmbH	Hönnestr. 31 D-58809 Neuenrade Phone: +49 2394 18 0 Fax: +49 2394 18 171	Industrial systems for metal forming, induction heaters
5	Converteam GmbH	Culemeyerstraße 1 D-12277 Berlin Phone: +49 30 7622 0 Fax: +49 30 7622 2109	Power generators
6	ERT Refrigeration Technology GmbH	Johnsweg 6 D-21077 Hamburg Phone: +49 40 761 048 0 Fax: +49 40 760 541 9	Cryocoolers and refrigerators, gas liquefiers
7	European High Temperature Superconductors (EHTS) GmbH & Co. KG (Bruker group)	Siemensstr. 88 D-63755 Alzenau Phone: +49 6181 4384 4062 Fax: +49 6181 4384 4453	BSCCO and YBCO conductors (1G and 2G)
8	EVICO GmbH	Helmholtzstr. 20 D-11069 Dresden Phone: +49 351 465 9880 Fax: +49 351 465 9320	Textured Ni-W alloy tapes for conductor coating by chemical methods: MOCVD, CSD
9	L3-Communications Magnet-Motor GmbH	Petersbrunner Straße 2 D-82319 Starnberg Phone: +49 8151 262-0 Fax: +49 8151 262-250	Energy storage systems, rotating machines
10	Nexans SuperConductors GmbH	Chemiepark Knapsack D-50351 Hürth Phone: +49 2233 486 658 Fax: +49 2233 486 847	Development and manufacturing of HTS materials (YBCO and BSCCO 2212; powders and bulk parts), HTS coated conductors, HTS components (current leads, FCL elements and systems for medium voltage level; complete systems for magnetic bearings.
11	Nexans Deutschland Industries GmbH & Co. KG	Kabelkamp 20 D-30179 Hannover Phone: +49 511 676 1	Cables
12	nkt cables GmbH	nkt cables GmbH Schanzenstraße 6-20 D-51063 Köln Phone: +49 221 676 0 Fax: +49 221 676 2646	Cables

13	Oswald Elektromotoren GmbH	Benzstraße 12 D- 63897 Miltenberg Phone: +49 9371 9719 0 Fax: +49 9371 9719 50	Electric motors and drives
14	PerCoTech AG	Bienroder Weg 53 D-38108 Braunschweig Phone: +49 531 391 9410 Fax: +49 531 391 9400	MOCVD systems and coatings, CC development
15	Siemens AG Corporate Technology Automation and Drives	Corporate Technology CT PS 3 Günther-Scharowsky-Str. 1 D-91058 Erlangen Phone: +49 9131 7 33083 Fax: +49 9131 7 21339	Fault current limiters, motors and drives, marine systems
16	THEVA Dünnschichttechnik GmbH	Rote-Kreuz-Str. 8 D-85737 Ismaning Phone: +49 89-923 346 0 Fax: +49 89-923 346 10	HTS superconductor material, HTS films and coated conductors, vacuum coating and tape processing technology, quality inspection tools, current leads
17	Zenergy Power GmbH (former Trithor GmbH)	Heisenbergstr. 16 D-53359 Rheinbach Phone: +49 2226 9060 0 Fax: +49 2226 9060 900	Induction heaters, HTS systems for energy technology, CC development

IV. MATERIALS, CONDUCTORS AND CABLES

A. LTS Companies

European Advanced Superconductors, recently acquired by Bruker, is known better as (formerly) Vakuumschmelze, Hanau. It is the largest and most renowned company in Germany having a long tradition in fabricating superconducting materials and wires,. It manufactures currently over 30,000 kilometers of superconducting wire per annum, both NbTi and Nb_3Sn, mostly for LTS superconducting magnets of various uses, which also include magnets for large-scale energy-related experiments such as ITER. Figure 2 shows the overall view of the EAS manufacturing facility in Hanau.

Fig. 2. The EAS manufacturing facility in Hanau, Germany

B. HTS Companies

The HTS materials in the form of typically YBCO powder, bulk elements and textured bulk are manufactured by Adelwitz Technologiezentrum GmbH (ATZ) and by Nexans Superconductors GmbH. The bulk parts include magnetic bearings and components of levitation systems. Nexans (formerly Hoechst) fabricates also BSCCO 2212 powders and tubes for current leads and fault current limiters. Figure 3 shows few examples of manufactured parts.

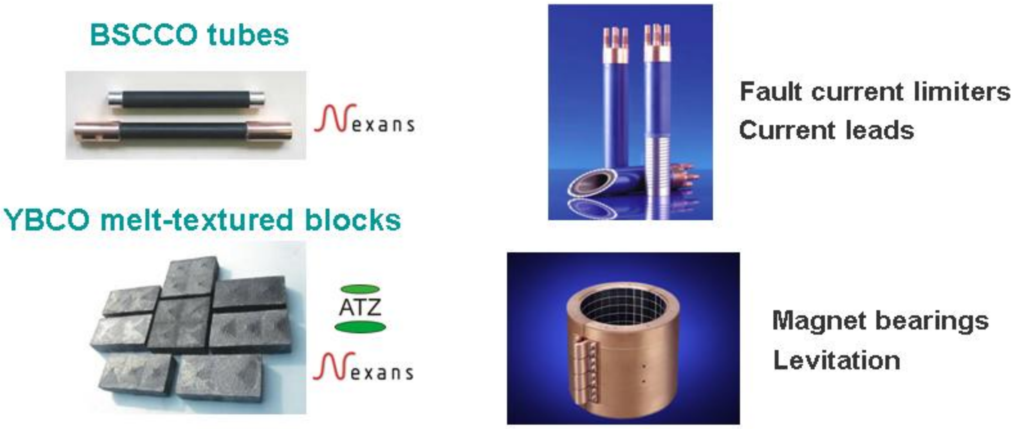


Fig. 3. Examples of manufactured HTS bulk superconductor parts.

Several German companies develop and manufacture or intend to manufacture HTS tape conductors of 2G coated-conductor type. These companies include EHTS, Nexans, PerCoTech, THEVA and Zenergy. Each of these companies pursues a different technological approach, either PVD (physical vapor deposition), MOCVD (metal-organic chemical vapor deposition) or CSD/MOD (coated substrate deposition/metal-organic deposition). The rule of thumb states that low pressure PVD results in highest performance (highest current density and uniformity) conductors, while the coatings sprayed and decomposed at atmospheric pressure have the potential for lowest cost when mass-produced. The EHTS is also manufacturing lengths (sections up to 1.5 km) of 1G conductors by the usual powder-in-tube (PIT) technique. The BSCCO wires (tapes) are fabricated with silver matrix including 37, 55 or 121 filaments. Below, only 2G results are overviewed.

The European High Temperature Superconductors GmbH & Co. KG (EHTS) is another of the Bruker group companies. The 2G coated conductors are manufactured using stainless steel substrates with YSZ (yttria-stabilized zirconia) and CeO_2 buffer layers, and large-scale high-rate pulsed-laser-deposition (HRPLD) of YBCO. This technology is based on the ABAD approach (alternating ion-beam assisted deposition) initially developed at the University of Göttingen. Galvanic plating of CC with Cu allowed EHTS to improve significantly the mechanical and electrical parameters of CCs, reducing, for instance, the critical bending radius to 6 mm. The company is now in the process of scaling up from the present maximum section length manufacturing capability of 100 m per section with engineering current density up to 250 A/cm-width and good I_c uniformity to a couple of kilometers with the goal of 500 A/cm-width. Some details of the 2G process can be found in the Forum paper ST8.

Another company pursuing the PVD approach is THEVA, which used physical e-beam evaporation. Optimized MgO buffer layer and DyBCO superconductor are deposited on Hastelloy C276 substrate. Thus far, tape sections up to 10 m long have been demonstrated with minimum engineering current density of 350 A/cm-width. The I_c uniformity over these lengths has been good, as shown in Figure 4. Scaling up to commercial lengths requires a future investment by external sources of capital. THEVA's other well-established products are various superconducting thin films for various electronic and RF- applications.

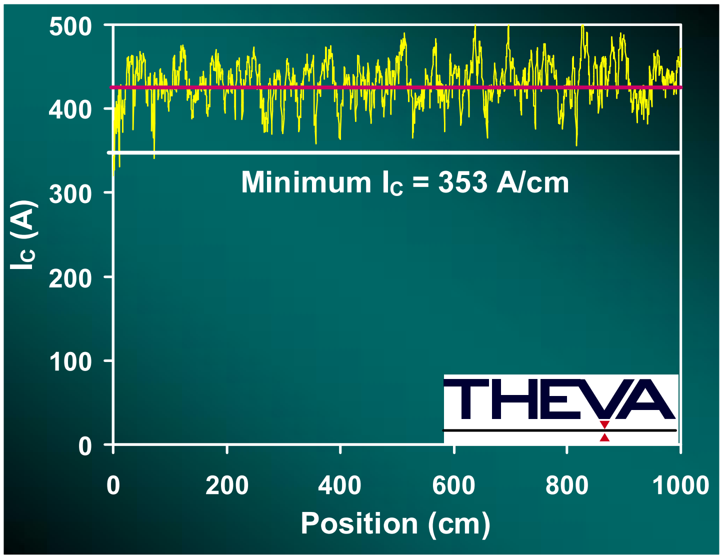


Fig. 4. 10 m long CC with critical current of 353 A/cm (average 433 A/cm).

The fledgling company PerCoTech pursues the medium-pressure MOCVD approach, used for both buffer and YBCO film deposition on textured Ni-W tapes. On short tape sections the superconductor net I_c exceeding 1 MA/cm^2 was attained, with hopes to approximately double this performance. Scaling up to practical length and product sales are still pending. Similar is the situation at Nexans and Zenergy (former Trithor). Each of these companies pursue slightly different approaches to atmospheric pressure deposition on Ni-W alloy tapes, with the view of the future manufacturing of medium-quality, but lowest-price conductors. Only short tape sections (around 10 m) have been demonstrated. The Ni-W tape substrates for all German users are supplied by EVICO of Dresden.

It is instructive to list the companies worldwide currently capable of supplying longer lengths of HTS conductor. Table III summarizes the current situation after AMSC of USA terminated manufacturing of 1G.

Table III. Companies Worldwide Capable of Supplying Engineering Lengths of HTS Conductors

(Courtesy of Dr. M. Becker, Trithor)

Company/Country	*2G Short Sample record*	*Deliverable Performance & Length*
EHTS (1G) / Germany	--	80-120 A/mm^2, 1500 m
Sumitomo (1G) / Japan	--	180-220 A/mm^2, 200 m
AMSC (2G) / USA	400 A/cm-width, 10 m	150-200 A/cm-width, 100 m
EHTS (2G) / Germany	> 500 A/cm-width, 10 m	250 A/cm-width, 100 m
SuperPower (2G) / USA	500 A/cm-width, 10 m	250 A/cm-width, >500 m

One infers from Table III that at this juncture EHTS is quite competitive with world leaders. For all German companies, the biggest impediment against scaling up to practical lengths is lack of sufficient capital investment. For lengths exceeding 2 km this applies even to EHTS. Germany will have the chance to compete in the world market if such investments occur very soon.

V. HTS CABLES FOR ENERGY TRANSMISSION

The application of superconductivity, which was of interest to utilities even in times before the discovery of HTS, is energy transmission *via* superconducting cables. It imposes the lightest burden on the superconductor because such cables operate in low self-field, in contrast to most other grid & energy applications. Therefore some LTS transmission cable demonstrations were funded and performed successfully. However, the economical advantages of the LTS solution could not be convincingly demonstrated due to the cost of liquid helium cryogenics.

With the advent of HTS, interest in this application was promptly reactivated, because its economic viability appeared to be much more realistic and attractive enough. In LTS times the dc transmission was also considered, because it is lossless, except for ac/dc and dc/ac conversion losses and associated cost, but today's HTS projects are practically all ac due to technical compatibility with the grid. The main attractive attributes of HTS superconducting underground cables are: high transmission capacity at low loss, compactness (relatively low trenching cost), electromagnetic shielding and the inherent option of build-in current limitation. Such cables are thus ideal solutions for congested underground urban areas and for retrofits, wherever space is at premium and power rating must be significantly increased to satisfy demand. Both 1G and 2G conductors are readily utilizable, and some ongoing projects already use 2G. By this juncture, quite many pilot projects, listed in Table IV, have been executed worldwide, with some operating on the grid or expected to be on the grid upon completion (red lettering indicates grid operation). The green background part of the table presents projects approved or in progress, yellow background signifies planning stage.

Of international companies and consortia listed, two have activities in Germany: Nexans and nkt Cables (Ultera). They have been involved in several foreign programs, already completed, ongoing and planned. Therefore, they gained already and are continuously gaining more operational experience. Past on-the-grid demonstrators were all medium-voltage installations (13.8 to 35 kV). However, Nexans experimented with a high-voltage alternative (138 kV), demonstrated it at their Hanover laboratory, and is now involved as cable manufacturer in the Long Island Power authority (LIPA, USA) program aiming at a high-rating, over 570 MVA, 3-phase cable section 600 m long.

Table IV. Transmission Line Demonstrator Projects

Consortium	Country / year	Location	Length (m)	Specs		Power (MVA)	Phase	German contractor	Material
				kV	kA				
TEPCO / SEI	Japan / 1997	CRIEPI	30	66	1	66	1-ph.		1G
Southwire / IGC	USA / 2000	Carrollton, GA	3 x 30	12.4	1.25	27	3x1-ph.		1G
nkt Cables / NST	Denmark / 2001	Copenhagen	3 x 30	30	2	104	3x1-ph.	nkt cables	1G
Pirelli / Detroit Edison / AMSC	USA / 2002	Detroit, IL	120	24	2.4	100	3-ph.		1G
TEPCO / SEI	Japan / 2002	CRIEPI	100	66	1	114	3-ph.		1G
SuperAce / Furukawa / CRIEPI	Japan / 2004	CRIEPI	500	77	1	77	1-ph.		1G
KERI / SEI	Korea / 2004	LG Cable	30	22	1.2	47	3-ph.		1G
Innopower / Yunnan EP	China / 2004	Puji	33.5	35	2	121	3-ph.		1G
KEPRI / SEI	Korea / 2005	KEPRI (Gochang)	100	22	1.25	48	3-ph.		1G
Tratos Cavi, AMSC	Italy / 2005	Pieve Santo Stefano	50	45	2	156	3-ph.		1G
CAS / AMSC	China / 2005	Chang Tong Cable	75	15	1.5	39	3-ph.		1G
FGS - UES / VNIIKP	Russia / 2006	Lab Test	5	-	3	-	1-ph.		1G
Ultera / AEP / Oak Ridge	USA / 2006	Columbus, OH	200	13.2	3	69	3-ph.	nkt cables	1G
Superpower / SEI	USA / 2006	Albany, NY	350	34.5	0.8	48	3-ph.		1G
LS Cable	Korea / 2007	KEPRI (Gochang)	100	22	1,25	48	3-ph.		1G
ConduMex / AMSC / CFE	Mexico / 2007	Queretaro	100	23	2	80	3-ph.		1G
LIPA / AMSC / Nexans	USA / 2007	Long Island, NY	660	138	2,4	573	3-ph.	Nexans	1G
Superpower / SEI	USA / 2007	Albany, NY	30	34.5	0.8	48	3-ph.		2G
Nexans / AMSC	Germany / 2007	Hanover: Lab test	30	138	1,8	248	1-ph.	Nexans	2G
Nexans / EHTS	Germany / 2008	Hanover: Lab test	30	10	1	10	1-ph.	Nexans	2G
ConEd / Southwire / AMSC	USA / 2010	New York	240	13.8	4	96	3-ph.	nkt cables	2G & SSB
Southwire / Ultera / Entergy	USA / 2011	New Orleans	1700	13.8	2.5	60	3-ph.	nkt cables	undecided
LIPA / AMSC / Nexans	USA / 2010	Long Island, NY	600	138	2.4	574	1-ph.	Nexans	2G
TEPCO / SEI	Japan / 2011	Tokyo	300	66	3	340	3-ph.		1G
LS Cable	Korea / 2011	KEPRI (Gochang)	100	154	3.75	1000	3-ph.		1G
nkt Cables / NUON	Netherlands / 2012	Amsterdam	6000	50	2.9	250	3-ph.	nkt cables	2G
Stadtwerke Augsburg	Germany / 2009	Augsburg	425	10	0.3	6	3-ph.	Nexans ?	?

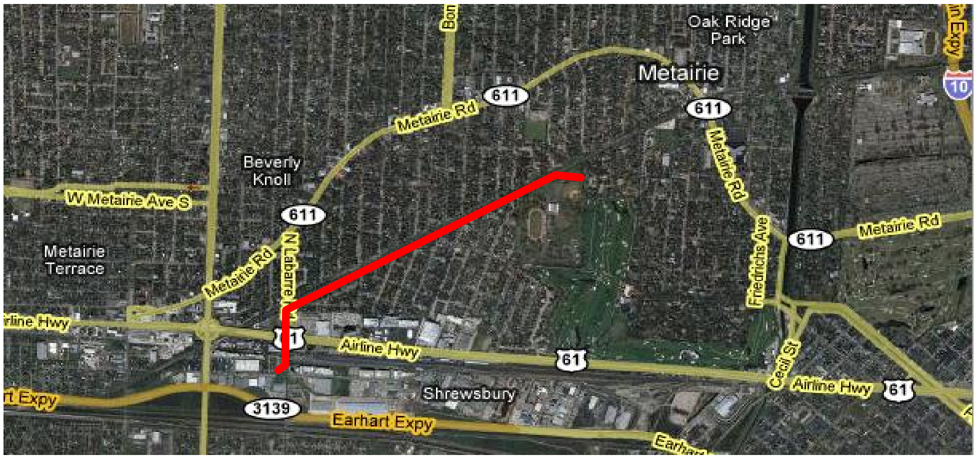


Fig. 4. New Orleans 1700 m cable connecting Metaire and Labarre substations, installation scheduled 2011.

The most ambitious of new HTS cable programs planned, which might become one of the first ever regular large-scale applications if it becomes a reality, is that of nkt Cables with NUON utility, to be completed in year 2012 and installed in Amsterdam, the Netherlands. It is a 6-kilometers-long, medium-voltage (50 kV, 2.9 kA) 3-phase cable rated at 250 MVA. The first grid installation in Germany, a local initiative of the Augsburg University with that city's utility (Stadtwerke Augsburg), is contemplated. This is a much lower scale project (425m long 3-phace cable rated at 6 MVA (10 kV, 300 A) than those mentioned above, justified by increasing power need of the university.

VI. ROTATING MACHINERY

Superconducting rotating machinery, especially power generators, were also investigated and demonstrated before the advent of HTS. Many of the early projects had military motivation (lightweight airborne generators), but synchronous generators for the electric power grid were also investigated in USA, Japan and Europe. None of these early projects resulted in practical use - for the same reason as in the case of transmission lines – the cryogenic burden was excessive and economics rather prohibitive.

The most important advantage of HTS rotating machinery is the significant reduction of size, weight and electric loss. Another is an improvement in efficiency and still another is the improved dynamics and response to overload. There is a wide range of HTS machinery candidates for implementation in practice: from high-torque wind power generators (range of 15 RPM) through gearless ship propulsion motors (range of 150 RPM) to high-power utility generators (1500 RPM) and high-speed machines (both generators and motors, range of 15,000 RPM) for energy storage. At present, all these are in development by German companies, or international consortia with German participation. In all the rotating machinery demonstrated or being constructed thus far, BSCCO 1G conductors have been used, mainly due to availability and cost.

Wind generators in the 8 to 10 MW range for off-shore wind farms are developed by the consortium Converteam/Zenergy under the British leadership (Table II and V). The motivation is higher power rating than conventionally possible with maximum acceptable mechanical support structures and the much improved reliability through elimination of mechanical gear. While the worldwide installed wind power was about 15 GW in 2006, it is expected to exceed 30 GW in 2011, with about 10% of it from large off-shore farms.

Gearless ship propulsion motors are developed by Siemens AG. A 4 MW propulsion system is developed in a program to be completed in 2010. The main motivation is the reduced weight and size with reliability and flexibility of operation improved due by elimination of mechanical gear, and also the possibility of placing the motor in a maneuverable pod. The worldwide largest ship propulsion demonstrator is currently the 36.5 MW, 120 RPM motor completed by AMSC in 2007. The use of HTS resulted in dramatic weight reduction from 280 tons in conventional version to less than 75 tons! Figure 5 compares the sizes of conventional and HTS motor.

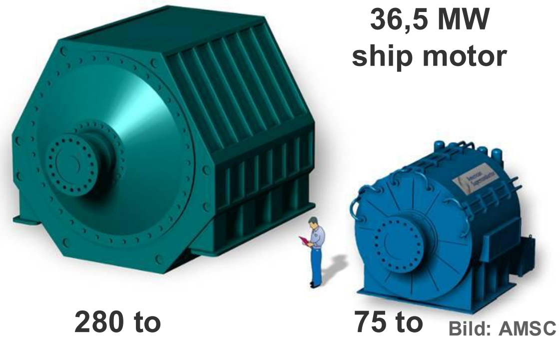


Fig. 5. The comparison to scale of 36.5 MW ship propulsion motors: left – conventional version, right the HTS machine constructed by AMSC (Courtesy of AMSC). The number below each picture indicates the weight in tons.

Generators are also developed by Siemens AG. Thus far, the largest HTS machine completed and successfully tested was a 4 MVA for ship-borne application, but studies for retrofitting dc rotors of large conventional power plant generators are also underway. While this use does not offer all the benefits of reduced size and mass, it represents, according to Siemens, a potentially economic way of increasing the power rating of existing power plants when overhauling turbine generators, with the additional benefit of about 0.5% improvement in efficiency, and improved cooling of the stator. Such retrofits would require only minimal change or upgrade of the peripheral supply aggregates.

The high-speed machines for energy storage will be addressed in Section VIII. The demonstrator projects worldwide are listed in Table V. The same color convention is used as in Table IV. One can note that most of European demonstrators in progress or planned are wind energy generators.

Table V. Motor / Generator Demonstrator Projects

Consortium	Country / year	Type	Power (MVA)	Rpm	Weight (to)	Eff. %	Budget	Material
AMSC	USA / 2001	Motor	3.8	1800	6.8			1G
Oswald	Germany / 2002	Torque Motor	0.2					Bulk
Siemens	Germany / 2002	Generator	0.4	1500		96.8		1G
AMSC	USA / 2003	Ship motor	5	230			8 M$	1G
Siemens	Germany / 2005	Generator	4	3600	7	98.7		1G
KERI / Doosan	Korea / 2007	Motor	0.08					1G
SEI	Japan / 2007	Ship motor	0.365	250	4.4			1G
AMSC	USA / 2007	Ship motor	36.5	120	< 75		100 M$	1G
Siemens	Germany / 2008	Ship motor	4	120				1G
KERI / Doosan	Korea / 2011	Motor	5					1G
Converteam / Zenergy / E.ON	Germany / 2009	Generator (Hydro)	1.25	214		>98	3.44 M€	1G
Converteam / Zenergy	UK / 2010	Generator (Wind)	8	12				1G
DTU / Vestas	Denmark / 2010	Generator (Wind)						Design study
AMSC / TECO Westinghouse	USA / 2012	Generator (Wind)	10	11	120		6.8 M$	Design study

VII. FAULT CURRENT LIMITERS

Superconducting fault current limiters (FCL, SFCL) using HTS represent a concept of a device novel to the grid and capable of fast self-triggered limitation of short currents to values exceeding the rated current by only a factor of 2 to 3, combined with self-regeneration to the superconducting state and normal operation. The uniquely advantageous characteristics are both the very fast reaction, on the order of 1 millisecond (giving time the standard interruptors to respond), and the automatic regeneration. In new grid installations it could reduce capital cost by partial elimination of transformers and fast interruptors, and improve the use of existing grids, which presently have insufficient protection. The overall quality and flexibility of the grid could improve through a broad introduction of SFCL. However, such wide introduction will be possible only if the cost of the device will be sufficiently low, *i.e.*, if the cost of the superconductor decreases sufficiently (see Section II.C). Otherwise, the need for continuous cooling and thus the continuous energy consumption is the only minor disadvantage of SFCL. Of course, in new HTS transmission lines it could be easily integrated into without the need for separate refrigeration.

Table VI lists the SFCL demonstrator projects worldwide. The same color code is used as in the preceding tables. Completed projects were limited to rather low power ratings and low to medium voltages. However, the ongoing and planned projects address also much higher ratings on the order of 100 MVA and above, at both medium and high voltage.

Table VI. Fault Current Limiter Demonstrator Projects

Consortium	Country / year	Type	Specs		Power (MVA)	Phases	German contractor	Material
			kV	kA				
ABB	Switzerland / 1997	Inductive	10	0.07	1.2	3-ph.		BSCCO 2212 bulk
ABB	Switzerland / 1997	Resistive	13.8	0.8	6.4	1-ph.		BSCCO 2212 bulk
General Atomics	USA / 2002	Diode bridge	12.5	1.2	9	1-ph.		BSCCO 2223 wire
ACCEL / Nexans (CURL10)	Germany / 2004	Resistive	10	0.6	10,4	3-ph.	Nexans	BSCCO 2212 bulk
Yonsei University	Korea / 2004	Diode bridge	6.6	0.2	2.3	3-ph.		BSCCO 2223 wire
KEPRI	Korea / 2004	Resistive	6.6	0.2	2.3	3-ph.	THEVA	YBCO films
CRIEPI	Japan / 2004	Resistive	1.7	0.04	0.04	1-ph.	THEVA	YBCO films
Mitsubishi	Japan / 2004	Resistive	0.3	1.0	0.2	1-ph.	THEVA	YBCO films
Toshiba	Japan / 2004	Resistive	11	0.38	2.5	1-ph.	THEVA	YBCO films
CAS	China / 2005	Diode bridge	10	1.5	27	3-ph.		BSCCO 2223 wire
Rolls Royce	UK / 2007	Resistive	0.4	1.0	0.22	1-ph.		MgB_2
Innopower	China / 2007	Sat. iron core	35	1.6	96	3-ph		BSCCO 2223 wire
KEPRI	Korea / 2007	Hybrid	23	0.63	25	3-ph.	THEVA	YBCO films
Hyundai / AMSC	Korea / 2007	Resistive	23	0.63	8	1-ph.		YBCO CC
Siemens / AMSC	Germany / 2007	Resistive	13	0.3	2.3	1-ph.	Siemens	YBCO CC
KEPRI	Korea / 2009	Hybrid	23	3.0	119	3-ph.	?	undecided
Toshiba	Japan / 2008	Resistive	11	0.6	4	1-ph.		YBCO CC
Zenergy Power	USA, AU, DE / 2007	Sat. iron core	35	3	180	3-ph	Trithor	BSCCO 2223 wire
Rolls Royce	UK / 2009	Resistive	11	1.0	19.8	3-ph.		MgB_2
Nexans (CULT110)	Germany / 2009	Resistive	110	1.8	114	1-ph.	Nexans	BSCCO 2212 bulk
Nexans, RWE (INES110)	Germany / 2010	Resistive	110	1.8	343	3-ph.	Nexans	BSCCO 2212 bulk
KEPRI	Korea / 2010	Hybrid	154	4.0	1068	3-ph.		YBCO CC
Zenergy Power	USA, AU, DE / 2011	Sat. iron core	138	?	?	3-ph	Trithor	BSCCO 2223 wire
Siemens / AMSC	USA / 2011	Resistive	115	?	> 200	3-ph.	Siemens	YBCO CC
Superpower / SEI	USA / 2011	Resistive	138	?	> 240	3-ph.		YBCO CC

Both resistive and reactive (with saturated iron core) SFCLs are under development worldwide. Both approaches are also pursued in Germany. The saturated iron core type is developed by Zenergy (Trithor), while Nexans and Siemens AG develop resistive devices. The Nexans high-voltage (110 KV) SFCL is based on machined bulk tubes of BSCCO, an ingenious, but possibly costly technology. This work is described in the Forum paper ST24. The Siemens medium and high-voltage devices use series/parallel arrays of bifilar coils. In the developed demonstrators the coils are wound of AMSC's 2G YBCO tape, but for the future there exists the potential for significant cost reduction through the use of mass-produced medium-quality 2G tape. Figure 6 shows photos of the resistive models: (a) the Nexans's 10 VK/10 MVA device completed in 2004 (CURL 10), and (b) the 13 kV, 2.3 MVA (rated current 300 A) test model with 15 bifilar YBCO coils tested in 2007 by Siemens AG.

Nexans

Foto: Nexans

Fig. 6 (a). The Nexans 10 kV/10 MVA current limiter CURL 10 (courtesy Nexans) .

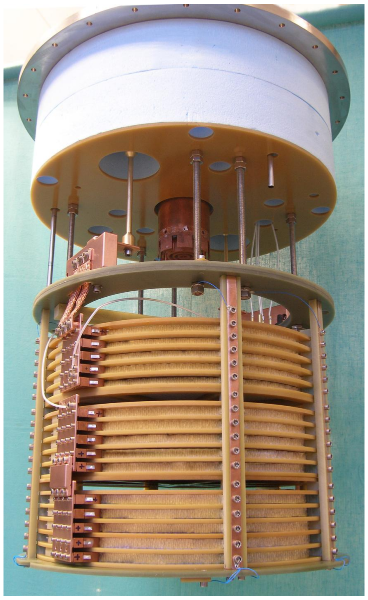


Fig. 6 (b). The 13 kV/2.3 MVA SFCL model with 15 bifilar YBCO coils tested by Siemens AG (courtesy Siemens AG).

Figure 7 shows an example of test results obtained for the Siemens device. The plot shows the recorded voltage (blue) and current (red) trace over the period of 50 milliseconds after a short circuit occurred at $t = 0$ in the load connected to a 7.7 kV_{rms} source. Without the SFCL the prospective short circuit current would have reached 28 kA_{rms}, 100 times the rated current of 0.28 kA_{rms}. With the tested device in series, the highest actual current after about 1 millisecond reached 3.2 kA, and decreased to 1 kA (peak) after about 40 milliseconds. The plot of Figure 7 dramatically illustrates the effectiveness of protection offered by a SFCL.

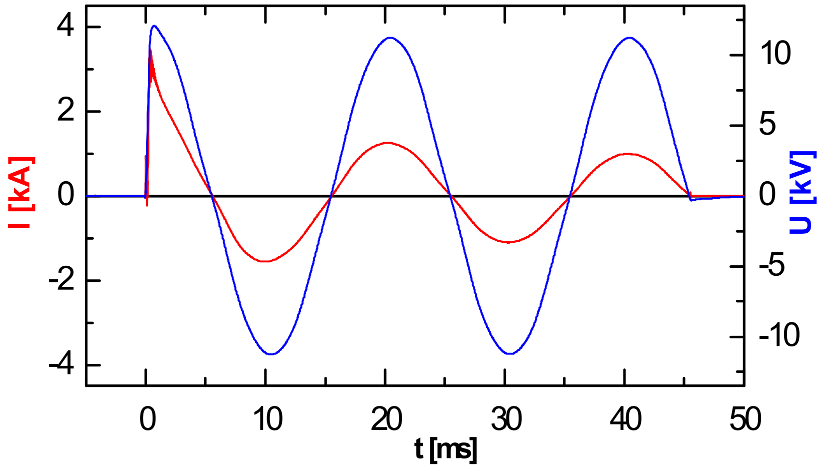


Fig. 7. Voltage (blue) and current (red) traces during the test of the Siemens AG 300 A rated device described in the text (courtesy Siemens AG).

VIII. ENERGY STORAGE AND INDUSTRIAL ENERGY CONVERSION

A. Magnetodynamic Energy Storage

To complete my overview of German HTS industry, in this section I like to mention two examples of HTS energy-related applications, which are not related to the electric power grid performance, but have a good potential for near-to-medium term utilization.

The first example is that of mechanical (magnetodynamic) flywheel energy (momentum) storage (MDS) using cooled HTS magnetic bearings. Each MDS unit contain, in addition to the flywheel, a coupled high-RPM motor/generator unit. In the energy storing mode, the motor accelerates the flywheel to the rated maximum momentum, while in the delivery mode the generator supplies electric energy. The development of MDS is performed in Germany by the company “L-3 Communications Magnet-Motor GmbH” (L-3 MM). The company has experience in manufacturing conventional MDS units, which have been finding application in diverse areas, including communal transportation. In Basel, Switzerland, conventional MDS units rated 200 kW, 2 kWh, have been installed in 12 of the city trolleybuses since 1995 and acquired a very positive performance record with average energy savings of 20% and high reliability. Stationary MDS demonstrators have been also installed in the subway power supply grid of Cologne-Ensen (Germany) as backup units. These units permit to store the vehicle braking energy, reduce injection power and stabilize the voltage of the power supply network.

The advantages of using HTS rather than conventional bearings derive from the absence of wear and nearly loss free operation, reduced noise and vibrations. Control electronics is not needed, so with HTS bearings the MDS units could be virtually maintenance-free, with scheduled maintenance infrequent. Experiments showed that even temporary lack of cooling can be tolerated due to the build-in thermal capacity. However, today only high-rating stationary units can be contemplated as potentially economical.

In collaboration with ATZ (see Table II), the L-3 MM company developed a 5 kWh/250 kW MDS model with HTS upper bearing carrying the full axial and radial load. Radial support at the bottom is provided by a permanent magnet bearing. The model is shown in Figure 8. The stator (beige brown) of the motor/generator unit is mounted at the bottom, with the (red) permanent magnet ring imbedded in the rotor serving as the rotating part of the unit. Both bearings are labeled green. The company is currently completing a 10 kWh/250 kW demonstrator, while a 15 kWh/400 kW unit is on order and is scheduled for delivery by the end of 2008.

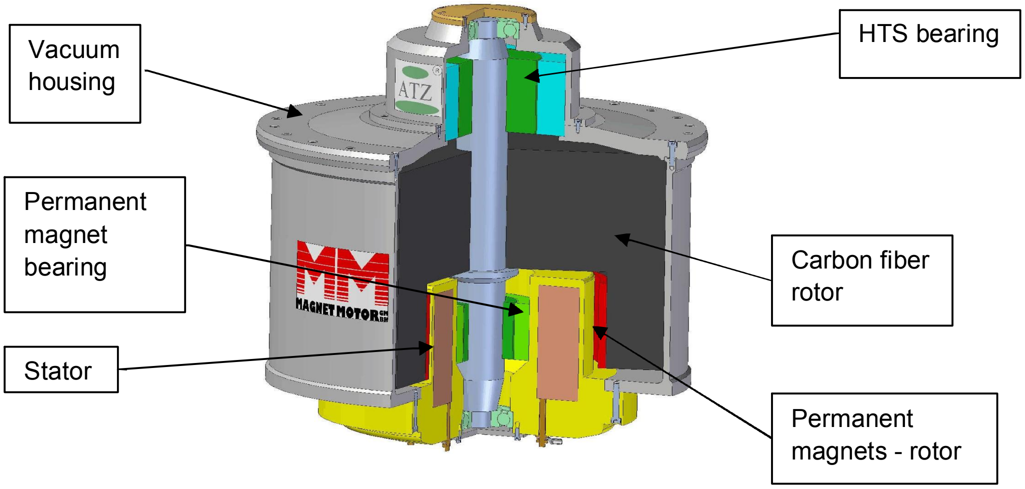


Fig. 8. Compact model of a 5kWh/250 kW MDS unit with HTS bearing from ATZ (courtesy of L-3 MM).

The 10 kWh demonstrator, currently in the process of completion, has a diameter 1030 mm, height of 1100 mm and weights 1200 kg. The magnetic bearing fully supports the 600 kg carbon fiber rotor rated at 10,000 RPM. A 35 W @ 60 K integrated GM (Gifford-McMahon) cryocooler maintains the bearing temperature at 60-65 K. Testing is scheduled for May 2008.

I should note in closing that the L-3 MM development is only one of several which have been or are performed in the US, Japan, Korea and also Germany. The Piller-Nexans consortium in Germany is developing a 11 kWh, 2 MW MDS demonstrator, where a radial (but not axial!) HTS bearing is used. The largest MDS rating attempted thus far is the 50 kWh/1MW unit currently under development in Japan with NEDO support.

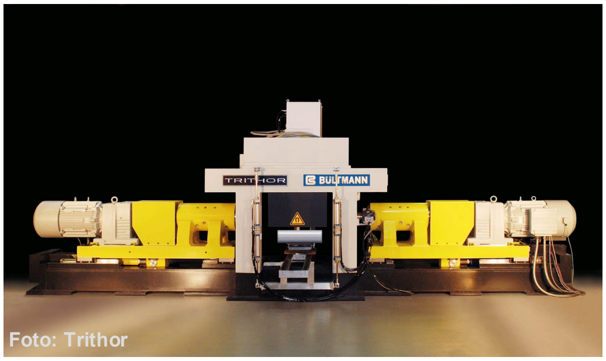
B. Induction Heater

The second example is an energy-related industrial application: the HTS induction metal heater developed by the company Bültmann GmbH in cooperation with Zenergy (Trithor). While I'm not aware of technical details, the general idea implemented in a demonstrator is the use of HTS induction coils rather than conventional coils for energy-efficient industrial preheating of non-ferrous metal blocks under processing. Conventional eddy-current heating of such blocks by a coil system surrounding the whole block results in nonuniform radial distribution of temperature. Furthermore, the efficiency of the conventional heating process is only about 40%, as over half of the supplied electrical energy is dissipated in the normal induction coils and the rest in the control electronics. For example, an Al cylinder 178 mm in diameter inductively heated by 6 kA current at the power line frequency of 50 Hz reaches after 4.5 min of heating an external temperature of 463 C, while the temperature at the axis of this cylinder is only 437 C.

In the demonstrator, HTS coils of a patented design are used for high-power heating of a short section of the block. The local temperature rise is now practically instantaneous, the surface overheating doesn't occur and the energy efficiency approaches 90%, with the rest being dissipated in the control electronics, cryocoolers, and the mechanical drive necessary for displacing the block linearly between the coils. For example, an Al cylinder (comparable to that of the example above) nearly instantly reaches the surface temperature of 500 C, while the temperature at the axis is 501 C. After 30 sec, the surface temperature decreases to 480 C due to heat radiation losses, while the axial temperature is still 500 C. The system is suitable for processing of diverse metals, such as copper and copper alloys, up to (settable) temperatures approaching1100 C. Also difficult materials such as spray-compacted metals can be processed with the danger of cracking minimized. One set of HTS coils is suitable for heating of blocks having a wide range of dimensions. The expected life time of the coils should be long. Figure 9 shows the photo of the induction heating system. The two heating coils are positioned sidewise of the channel (the dark square orifice) through which the (light colored) metal block is transported. The coils are cooled by integrated cryocoolers.

This new development, now crowned by the already available commercial product, dramatically illustrates the potential of HTS for improvement of energy efficiency in industrial processing. I believe that many other such applications may evolve in the future, when the engineering community becomes more aware of HTS use benefits.

Note added after the presentation: at the Hannover Industrial Fair the ingenious concept of the HTS induction heater was honored with the prestigious "Hermes Award" (value 100.000 EUR) – one of the biggest industrial awards worldwide.



TRITHOR BÜLTMANN

Fig. 9. The metal induction heater with HTS coils positioned on two sides of the metal block transport channel (courtesy Thithor).

IX. POLITICAL LANDSCAPE AND SUPPORT FOR HTS

The strategic importance of high-temperature superconductor technology for national power supply and its reliability was first recognized in the US. The "Energy Policy Act" of 2005, Section 925 states: *The Secretary (of Energy) shall establish a comprehensive research, development, and demonstration program to ensure the reliability, efficiency, and environmental integrity of electrical transmission and distribution systems, which shall include …. .. the development and use of high-temperature superconductors…*

In the G8 declaration for global energy safety (St. Petersburg, July 2006), section on "Innovative Energy Technologies", one can read: *We will take measures to further develop other promising technologies, among them modern grids, superconductivity…*

In the document on high technology strategy for Germany issued by German Ministry of Education and Research (BMBF) issued in Berlin in September 2006, measures are discussed to strengthen the efficient use of energy: *The R&D project funding will emphasize …. Efficient use of electrical power, e.g., by applying superconducting materials without losses in generators and in the electrical power grid.*

Political declarations of intent are thus quite supportive of HTS for energy efficiency, both worldwide and in Germany. However, it is essential to implement policies converting the political intent into reality to result in both, financial project support and a favorable climate for investments in HTS for energy. To illustrate the present situation in technologically leading countries worldwide, I collected in Table VII the official estimates of the current public funding for superconductivity energy-related programs - in millions of US dollars. In addition to these, the new „Power Delivery Research Initiative", planned in the US, may soon inject additional US$ 300 millions for the US industry. In Japan, the new HTS program for 2008 – 2012 is expected to provide 150 to 200 millions in addition to the existing funding. One look on the Table VII suffices to realize that the current support in Germany is by an order of magnitude below that of other countries listed, and this in spite of the fact that the German industry has been demonstrating its competence and leadership, by necessity often beyond the borders of the country. Let us hope that the recent interest of BMWi can improve the chances of the German HTS companies become competitive in the global market.

Table VII. Estimated Current Funding of HTS for Energy

Country	*Ministry*	*Program*	*Term*	*Total amount M$*	*Annual M$*
US	DOE	HTS grid components	07 – 12	> 52	> 10
US	DOD	HTS Ship motor (Navy)	05 – 07	100	33
Japan	METI	Coated conductor program (CC) (ISTEC)	03 – 08	145	29
Korea	MOST	DAPAS	01 – 10	103	10
China	?	Energy technol. (cable, trafo, SFCL)	04 – 08	> 50	> 10
Germany	BMBF	CC, motor, energy technology	05 - 08	12	3

What the German HTS industry badly needs is support for realistic full-scale demonstrator projects, and economic incentives which could convince private investors that investment in large-scale HTS manufacturing, especially of HTS conductors, but also of components for the power grid, is sound and should be economically highly profitable in the longer term. The issue of financing is really a crucial one, because necessary investment volume by far exceeds what small and medium enterprises involved in HTS can bring alone.

In addition to the issue of financing, there is that of public awareness and education, where the HTS community needs to be more active and persuasive. To begin with the education of engineers, university programs and courses in energy-related disciplines and design should include superconductivity for energy applications and cryogenics integrated together. Furthermore, we should be able to better inform the public and demonstrate that superconductivity technology is not at the fringes of exotics, but represents a realistic trend for the future of the society by addressing issues of:

- Secure energy supply,
- Energy efficiency,
- Climate change (reduction of CO_2 emisions)
- Protection of the environment and, last but not least,
- Global competitiveness.

The German HTS industry is today well-positioned to participate in the development of the global market, especially in the US and Asia, where engineering "made in Germany" has an established reputation. However, it can miss the window of opportunity if unable to compete by lack of adequate investments on the national and European level. Traditionally, high-end technology products have been strengthening German and European competitiveness. The trend of cooperation with other technologically advanced EU partners (UK, France, Italy, *etc.*) via international consortia has been already pioneered in HTS industry and is one of the approaches to improve the investment climate. There is an important role to play here for incentives by European Commission, which thus far have been missing.

X. CONCLUDING REMARKS

In this overview, I provided an outline of the German industrial companies involved in R&D into the use of high-temperature superconductors (HTS) in the electric power grid and other energy applications. Grid subsystems such as transmission lines, power generators and motors incorporating HTS, as well as novel devices such as current fault limiters can save energy in a multitude of ways and simultaneously improve the grid performance - as demonstrated already in recent projects and demonstrators, most of these outside of Germany. Also in energy-intensive industrial products there is a high opportunity for improving energy efficiency, as illustrated by the dramatic example of the award-winning metal induction heater.

I highly acknowledge the technical information received from companies mentioned in the text.