

# Industrial HTS Conductors: Status And Applications

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**Abstract.** First generation (1G) multifilamentary composite wire made from the high temperature superconductor BSCCO-2223, manufactured commercially by American Superconductor (AMSC), is able to carry more than 140-times the electrical current of copper wire of the same cross section, and is robust enough to meet commercial requirements. 1G wire has matured into distinct products which can now be tailored to meet the unique requirements of specific applications.

This paper will report on the performance and reliability testing of these HTS products. Furthermore, we will provide a brief overview of recent results obtained with second generation (2G) coated conductor composite wire, which is in development and has demonstrated uniform and reproducible performance of greater than 100 A/cm at 77 K over 10 meter lengths.

1G HTS wire has already been used in a number of advanced prototype devices in the fields of motors, generators, power cables, and electro-magnets. This paper will report on the most significant uses of HTS technology in motors for ship propulsion, including an update on the 5 MW and 36.5 MW HTS ship propulsion motors that American Superconductor is providing to the U.S. Navy. These contracts are important steps toward the commercialization of HTS rotating machinery.

## 1. Introduction

First generation multi-filamentary HTS wires are composites of silver or silver alloy and  $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$  (BSCCO-2223). The combination of fine filaments (each of order 10  $\mu\text{m}$  in thickness and 200  $\mu\text{m}$  in width) with the metal matrix reduces crack formation and allows critical strains, whether tensile, compressive or bend, in a range of several tenths of a percent,[1] compatible with customer requirements. Critical stresses, determined by the silver alloy sheath, typically range from 50 MPa (for pure silver) up to 130 MPa [2]. These tapes can be further strengthened by lamination with stainless steel, giving stress tolerances up to 265 MPa [1].

2G coated conductor composite wires, which are in development today, typically comprise a nickel-based alloy substrate and one or more micron-thick layers of the HTS material,  $\text{R}_1\text{Ba}_2\text{Cu}_3\text{O}_7$ , where R is yttrium (Y) or a rare earth element. 2G wire can be formed by a variety of processes; however, in all cases, the manufacturing process comprises a series of steps to yield a crystallographically-aligned coating of the HTS

material. The combination of the metal substrate and the thin RBCO layer allows critical strains in the same range as the multifilamentary BSCCO tapes [3].

## 2. Commercial, Multi-Filamentary Composite Products

1G wire is now optimized to meet the specific requirements of each application. American Superconductor (AMSC) currently provides five 1G HTS wire products. The High Current Density wire type is optimized for applications requiring the greatest possible current density, such as specialty magnet applications. The High Strength wire type is optimized for high tensile stresses such as those encountered in high magnetic fields or rotating machinery applications, such as motors and generators. The Compression Tolerant wire type is optimized for applications where longitudinal compressive stresses dominate, including certain rotating machinery applications. The Hermetic wire type is optimized for applications requiring extended immersion in pressurized liquid cryogens, such as power cable applications. Finally, the Low Thermal Conductance wire type (CryoBlock™) uses a specialized matrix that limits heat flow along a temperature gradient, and has been developed for HTS current leads. CryoBlock wire is the building block for AMSC's CryoSaver® current leads. Its matrix combines low thermal conductance, emergency current bypass and stabilizing heat capacity.

### 2.1 High Current Density Wire

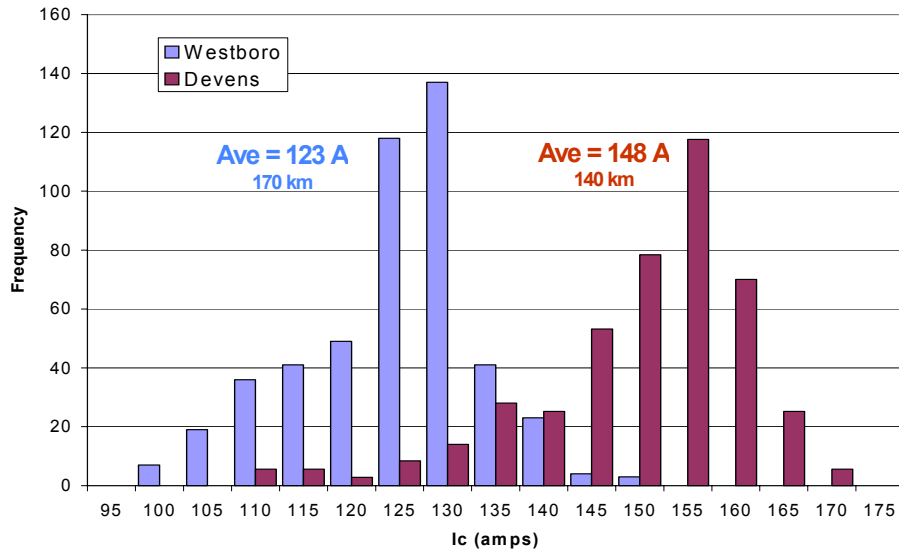
Fig. 1 is a photomicrograph of a cross section of AMSC's standard High Current Density wire. This wire, measuring approximately  $0.21 \times 4.2 \text{ mm}^2$ , comprises 55 filaments of BSCCO-2223 imbedded in a metal matrix of oxide-dispersion strengthened silver alloy. The typical wire performance is illustrated with the critical current histogram shown in Fig. 2. Performance in AMSC's Devens manufacturing plant ranges from 115 A to 170 A, with the average approximately 150 A. By contrast the performance in AMSC's earlier Westborough pilot facility averaged around 125 A. The improvement is related to superior process control at Devens, plus some process improvements. The minimum engineering critical current density of this wire product is  $13.5 \text{ kA/cm}^2$ , while the average is approximately  $17 \text{ kA/cm}^2$ . This wire is the highest performance commercial HTS wire achieved today. A description of the process for this wire can be found in a paper by Huang et al. [4].



**Figure 1:** Cross-section photomicrograph of High Current Density wire.

### 2.2 High Strength Wire

For applications where high tensile stresses are encountered, such as high field magnets or rotating machinery, AMSC reinforces the wire with stainless steel strips as shown in Fig. 3. A description of the process for this wire can be found in a paper by Masur et al. [1]. The High Strength Wire offers the same critical current as the High Current Density Wire, but at the expense of a reduced current density. However, the High Strength Wire offers a much higher level of mechanical tolerance (stress tolerance of greater than 265 MPa and strain tolerance greater than 0.4%). Additional stress and strain tolerance data can be found in a paper by Masur et al. [5].



**Figure 2.**  $I_c$  performance histogram comparing approximately 170 km of production from the Westborough factory to approximately 140 km of production from the Devens factory. An increase of approximately 20% is noted in the two population averages (123 A compared to 148 A).



**Figure 3.** Cross-section photomicrograph of High Strength wire showing 37  $\mu\text{m}$  thin strips of stainless steel on the top and bottom of the tape.

### 2.3 Compression Tolerant Wire

In certain rotating equipment applications, the wire is subjected to not only tensile stresses and strains, but also to significant longitudinal compressive stresses and strains. High Strength Wire has been optimized to withstand very high tensile stresses and strains; however, it does so at the expense of reduced compressive strain tolerance. For example, High Strength Wire has a typical tensile strain tolerance of 0.45%, but a typical compressive strain tolerance of 0.15%. To address the market need for HTS wire with higher compressive strain tolerance, AMSC has developed a new product that provides a balance between tensile and compressive strain tolerance. By adjusting the lamination process parameters, AMSC has substantially improved the compressive tolerance at only a small expense to the tensile tolerance. As a result, Compression Tolerant Wire has a typical tensile strain tolerance of 0.4% and a typical compressive strain tolerance of 0.25%. These properties are illustrated in Fig. 4.

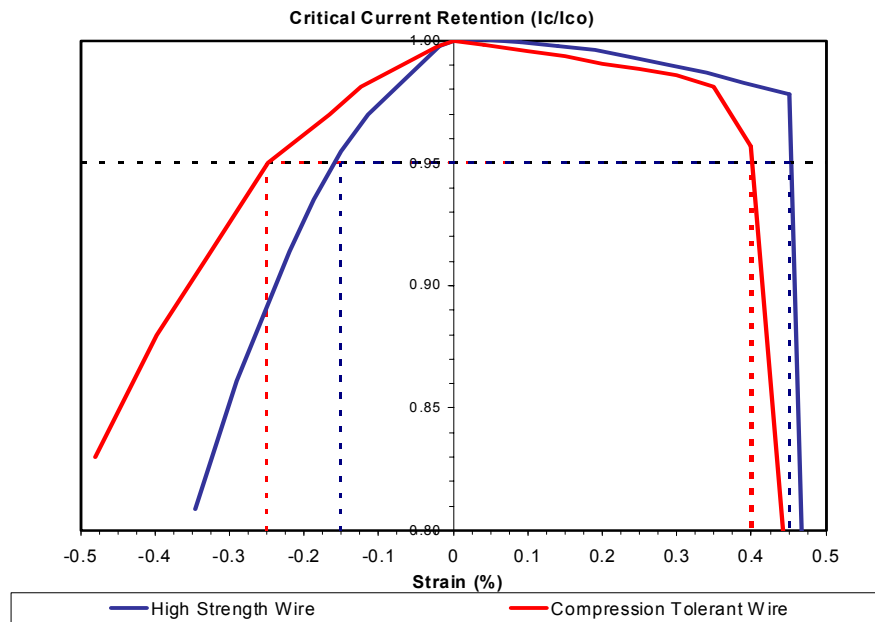
### 2.4 Hermetic Sealed Wire

For applications requiring extended immersion in liquid cryogenics, such as cable applications, high strength and high current density wires do not have sufficient resistance to environmental degradation to perform reliably over extended periods of time. As described in Masur et al. [1], damage can result when high current density wire is immersed in pressurized liquid nitrogen for an extended period of time and then warmed to room temperature.

To protect against the infiltration by liquid cryogenics, AMSC has developed a wire that is completely encased with solder and stainless steel, as illustrated in Fig. 5. The combination of

stainless steel and solder produces a wire that is robust enough to be used with industrial cable stranding equipment, and environmentally resistant enough to withstand extended exposure to 30 bar of liquid nitrogen.

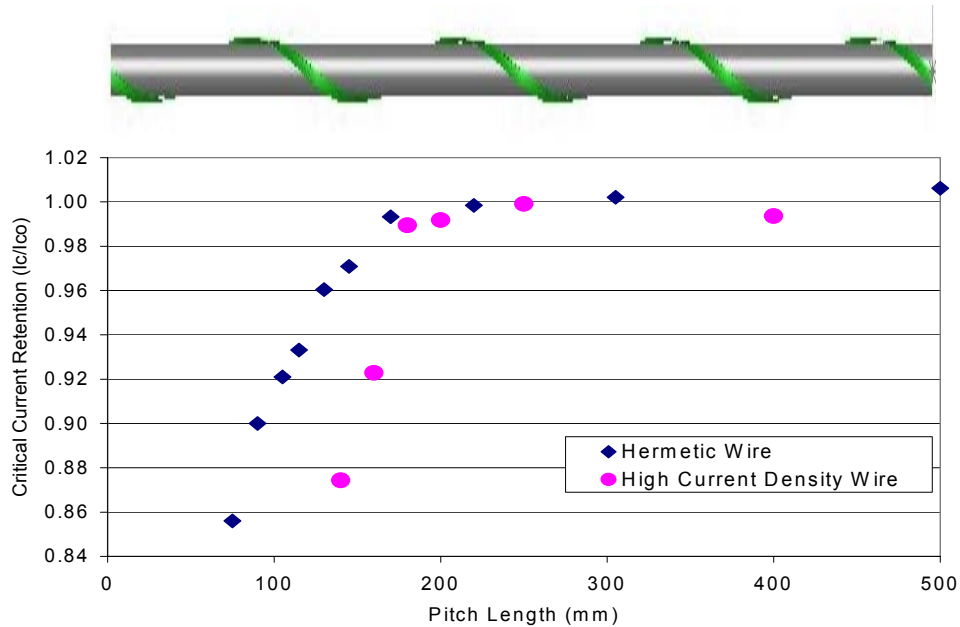
For cable applications, the mechanical performance of the wire is frequently determined by whether the critical current degrades when the wire is spirally wound around a former. Using a 16 mm diameter former, we have measured the retention in  $I_c$  as the wire is spirally wound around the former with ever decreasing pitch length. In Fig. 6, we compare the  $I_c$  retention between our High Current Density and Hermetic wire types, illustrating the large improvement in properties resulting from the lamination process.



**Figure 4.** Comparison plot of normalized critical current retention versus axial tensile and compressive strain for High Strength and Compression Tolerant wires, illustrating the improvement in compressive strain tolerance by adjusting lamination processing conditions.



**Figure 5.** Cross-section photomicrograph of Hermetic Wire showing thin strips of stainless steel on the top and bottom of the tape and solder fillets on the left and right of the tape.



**Figure 6.** Comparison of  $I_c$  retention as a function of spiral pitch length for Hermetic and High Current Density wire types, illustrating the improvement in spiral winding performance with lamination. The drawing at the top of the figure is a schematic representation of the spiral winding test.

### 3. Second Generation, Coated Conductor Composites

AMSC is approaching the development of second generation (2G) coated conductor composite wire with an objective to provide the customer with a “form, fit, function” replacement for the company’s 1G HTS wire, but at one-half to one-fifth of the cost. In this way, the customer can migrate from 1G to lower-cost 2G wire with minimal redesign. AMSC has, therefore, pursued 2G with special focus on achieving low-cost, high volume manufacturing in commercial wire geometries.

Up to now, the 2G HTS wire community has focused largely on the development of a single high-performance strand. However, to produce a truly practical commercial wire many other properties must be considered, including mechanical robustness under tensile, compressive, bending and torsional stress; chemical, environmental and electrical stability; and the means to join individual wire lengths (splicing) and to inject current.

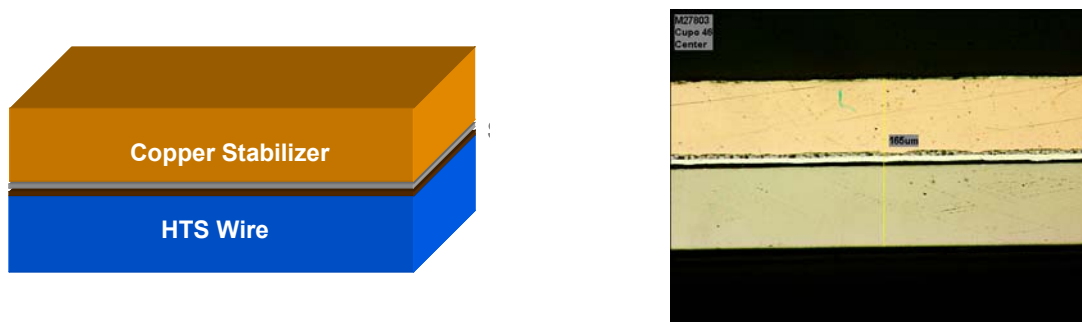
AMSC’s recent progress in fabricating up to 10 m lengths of coated conductor strand by continuous processes [5,6,7] with performance greater than 100 A/cm-width makes it possible to move forward to achieve these critical commercial wire characteristics. A composite structure consisting of a high conductivity layer laminated to the strand can electrically and mechanically stabilize the wire. In this section, we describe the design and fabrication of this composite structure. We call this structure the neutral axis wire, as upon bending the HTS layer is subjected to neither compressive nor tensile strain.

#### 3.1 Fabrication of the Neutral Axis Conductor

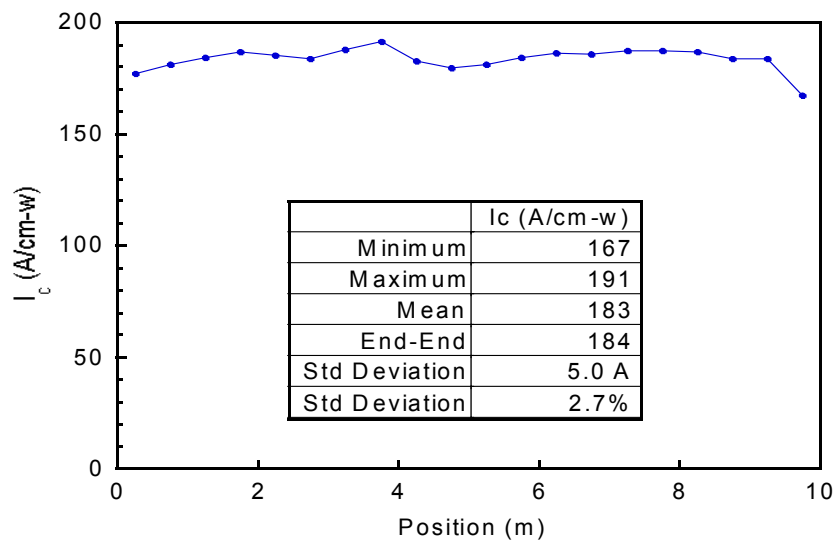
AMSC’s 2G conductor is based on a combination of a solution-based YBCO process, and a biaxially textured RABiTS-type NiW substrate, both low-cost processes which enable high volume manufacturing. The 10mm wide, 75  $\mu\text{m}$  thick Ni-5at%W substrate was coated epitaxially with a 2  $\mu\text{m}$  sputtered Ni layer, a 50 nm E-beam  $\text{Y}_2\text{O}_3$  seed layer, a sputtered

250nm YSZ barrier layer and 30 nm CeO<sub>2</sub> cap layer. The 1 μm thick YBCO layer was deposited using a TFA-based solution process (called metal-organic deposition or MOD) and reacted to form the superconductor [6]. The YBCO layer was subsequently coated with a 3 μm thick Ag layer by sputtering. The conductors in this study were continuously processed in ten meter lengths.

The 10mm wide Ag-coated conductor was laminated to a 10mm wide 50 or 75 μm thick copper foil using a reel-to-reel lamination process. This process used a conventional solder and was optimized to yield a thin, ~ 5 μm thick solder layer. Various tests have shown no discernable degradation of the lamination process with respect to end-to-end I<sub>c</sub> or I<sub>c</sub> variability. Fig. 7 shows a cross section in which the NiW and Cu layer both have a 75 μm thickness. The solder layer and Ag cap layer have comparable thicknesses of a few microns.



**Figure 7.** Schematic cross section of a laminated YBCO coated conductor with neutral axis geometry (left). Cross section photomicrograph of a laminated YBCO Coated Conductor with neutral axis geometry (right). Top: Cu 110. Bottom: NiW substrate. Black: buffer+HTS, with Ag (white) and solder (gray) layer.



**Figure 8.** Performance of a 10m long laminated Coated Conductor, 184A end-to-end,  $\sigma = 5A$

The geometry as shown in Fig. 7 allows room temperature bending around small diameter mandrels without adversely affecting I<sub>c</sub>, as was reported previously [8]. The geometry also allows the slitting to 4mm width without appreciable losses in I<sub>c</sub>/cm-width. Furthermore, the slit

conductor can also be subjected to the same strain regime as an unslit conductor without showing a significant performance decrease due to this slitting operation.

As an example of process reproducibility, thirty 1.5 m long neutral-axis wires were manufactured for a 1 m long cable which was built by Ultera (a Southwire/nkt cables joint venture). The coated conductor process was run in 10 m lengths and laminated to a 50  $\mu\text{m}$  thick copper foil. The laminated conductors were subsequently measured at 77 K and cut to the required lengths. Fig. 8 shows the  $I_c$  vs. position for a 10 m length of conductor with a 184 A end-to-end performance. The cable, tested at Oak Ridge National Laboratory, achieved commercial level performance with 4200 A of dc and 2000 of ac current at 77 K.

#### **4. High Temperature Superconducting Motors for Ship Propulsion**

HTS wire is finding application in many fields, including power cables, synchronous condensers, utility generators and speciality magnets. Here we give one example, summarizing progress in development of marine propulsion motors. In modern ships, propulsion systems are so large and heavy that in many applications they force the rest of the ship to be constructed around them. HTS alternating current (AC) synchronous motors provide a very attractive alternative, having the following advantages over other ship propulsion technologies [9]

- Up to three times higher torque density than alternative technologies, and thus greatly reduced size and weight compared to other motors;
- Inherently quiet with low weight rotors, no iron teeth, and active field control;
- Greater than 98% efficiency across a wide range of ship operating profiles (~10% to 100% motor output), which can lower fuel consumption and ship operating costs;
- Compatibility with naval and commercial electric ship drives;
- More durable - negligible rotor heating eliminates need for major repair and refurbishing due to thermal cycling;
- Compact and suitable for podded and in-hull propulsion;
- Reduced transport costs, greater flexibility in installation due to lower weight, compact volume;
- Mechanically simple, which minimizes production costs.

The HTS motor weight and volume advantages are very significant over a broad range of ratings [9]. Due to the absence of resistive losses in the rotor and the air core design of HTS motors, the efficiency drop-off associated with conventional propulsion motors operating at reduced loads does not occur. This is important when considering the operational cost of a ship. In normal load profiles, ship motors run partial load most of the time and 12% of the motor power produces 50% of the speed. Furthermore, the cost of a commercial HTS ship propulsion motor is expected to be equivalent to that of a conventional motor of comparable rating.

##### *4.1 5 MW Motor Design and Testing*

In order to validate efficiency and advantages and to demonstrate core technologies for HTS ship propulsion motors, such as the HTS coil design, the rotor integration, the brushless exciter technology, the cryogenic integration and air-core stator, AMSC has developed and built a 5 MW model motor for the U.S. Navy. The motor characteristics are shown in Table 1.

The HTS field winding, its cooling system and brushless exciter were built by AMSC. The stator was built by ALSTOM, Nancy, France, and the motor was assembled and tested in Rugby, England, and delivered to the US Navy in July 2003 for further testing. The stator winding employed copper coils using a liquid cooling approach. The stator is designed for 4.2

kV (line-to-line) for operation with a standard ALSTOM commercial marine electric variable speed drive. The completed motor is shown in Figure 9 on the ALSTOM factory test stand.



**Figure 9:** 5 MW HTS Motor (left) connected to a 2.5 MW conventional generator on a factory test stand.

Factory testing has been conducted to IEEE Std. 115 [10] with an ALSTOM variable speed drive and a conventional 2.5 MW load motor running as a generator. The motor met or exceeded all its design requirements and verified the design approaches for an HTS field winding, its cooling system, brushless exciter and stator. No-load tests were conducted to validate machine steady-state and transient electrical parameters and losses (efficiency was shown to be 96.1%). The motor was also successfully tested to full torque at half-speed to validate rotor and stator mechanical design. The motor was delivered to the U.S. Navy in July 2003, and will undergo further testing beginning in the fall of 2003.

List of parameters	Value
Weight	26 t
Number of Poles	6
Motor Outside Diameter	1.6 m
Motor length over end turns	1.6 m
Number of Phases	3
<b>Full Load</b>	
Power	5 MW
Speed	230 RPM

**Table 1.** Selected 5 MW Motor Characteristics.

#### 4.2 36.5 MW, 120-RPM Motor Concept

AMSC is now working on a second contract from the US Navy, for developing and delivering a 36.5 MW, 120-RPM motor intended for a military application but also of potential use in new commercial ships. For the same torque, the HTS motor will weigh < 75 tons (t), as compared to 280 t for an advanced induction motor and 400 t for the synchronous motor of the type used by the Queen Elizabeth 2.

The 36.5 MW motor is the largest HTS ship propulsion motor under development today. It is being designed and built under an Office of Naval Research (ONR) contract and will be a candidate for use in the next generation of all-electric U.S. Navy warships. AMSC SuperMachines business unit will deliver this motor, integrated with a commercial Variable Frequency Drive, in early 2006.

## 5. Conclusions

1G HTS wire is now available commercially in different product forms and with proven high performance. Key initial applications for this wire are ship propulsion motors, electrical generators and power transmission cables. To reduce cost of this HTS wire and to advance commercialization of HTS applications, American Superconductor has a new manufacturing facility dedicated to the manufacturing of 1G wire with an initial gross capacity of 900 km per year.

AMSC's 2G HTS wire, which is in development, is designed to be a form, fit, function replacement for the company's first generation wire, but at two to five times lower cost. AMSC's 2G wire process will enable low-cost high-volume manufacturing and has been validated with the first delivery of 45 m of wire for a cable prototype with commercial current performance.

As one example of applications progress with HTS wire, HTS ship propulsion motor have attractive attributes of compact size, light weight, low noise, greater durability and high efficiency, and major progress has been made in the demonstration and testing of a 5 MW prototype. This progress is expected to encourage commercial as well as naval applications in the near future.

## References

- [1] Masur L J et al. IEEE Trans. on Applied Superconductivity 11 (2001) 3256.
- [2] Fischer K et al. IEEE Trans. on Applied Superconductivity 9 (1999) 2625.
- [3] Thieme C et al. IEEE Trans. on Applied Superconductivity 9 (1999) 1494.
- [4] Huang Y B et al. Advances in Cryogenic Engineering (Materials), Vol. 48b (AIP, Melville NY, 2002), pp. 717-723.
- [5] Masur L J et al. Accepted for ISS2002 conference proceedings, Yokohama, Japan, Nov. 11-14, 2002
- [6] Rupich M W et al. 2002 Appl. Super. Conf. Proc. Accepted for Publication
- [7] Verebelyi D T et al. 2003 Supercond. Sci. and Technol. 16 L1
- [8] Verebelyi D et al. 2003 Supercond. Sci. and Technol. 16 L1
- [9] Kalsi et al. Status of Superconducting Motors for Ship Propulsion, International Cooperation on Marine Engineering Systems (ICMES), 19-21 May 2003
- [10] IEEE Std. 115-1995, IEEE Test Guide: Test Procedures for Synchronous Machines