# Design of a HTS Magnet for Application to Resonant X-Ray Scattering

S. D. Chen, Y. T. Yu, Z. W. Huang, J. C. Jan, C. S. Hwang, I. G. Chen, C. H. Du, T. M. Uen, D. J. Huang, and C. Y. Chang

***Abstract*—In material research, the characteristics of novel materials vary greatly with the environment. A magnet with a strong field will be developed for an experimental station for resonant X-ray scattering to investigate the magnetic properties of materials. This magnet will be developed with high-temperature superconductor (HTS) bulk $YBa_2Cu_3O_7$ and magnetized with a HTS coil magnet wound with 2G HTS wire. HTS (RE) BCO will be selected to construct the coil of this magnet. Both the bulk and coil magnets will be assembled on the same movable system. The bulk HTS magnet will provide flux density greater than 4 T with a gap 34 mm that can accommodate the sample holder of the experimental station. The bulk magnet will be cooled with cryocoolers to 29 K and the coil magnet to 4.2 K; the coil magnet is separable from the bulk magnet after the field is trapped. We describe the concept of the magnetic-field calculation, the overall design of these magnets, and the cooling algorithm for the bulk HTS magnet system.**

***Index Terms*—Bean model, bulk HTS, cryocooler, HTS wire.**

## I. Introduction

RESEARCH on magnetic materials in basic or applied science continues to be actively pursued. Neutron sources are applied in material research, but massive samples are needed. As a result of both improvements of a synchrotron light source for resolution, spectral range and ease of control of polarization and progress in gauging technology, such sources that require only small samples are already in widespread use for research in atomic structure, electronic and magnetic structure of magnetic materials. For these purposes, research institutes control typically not only the temperature and pressure of the sample environment but also the magnetic environment. For beam line BL07 at NSRRC, we plan to construct a facility to treat the magnetic environment using bulk HTS associated with the magnetization system. This facility, which will be placed on eight-direction diffraction instruments, allows X-ray scattering experiments.

To achieve this goal, one must understand the characteristics of bulk HTS; the density of magnetic flux contributed by the bulk HTS is expected to attain greater than 4 T. The magnetized magnet is a HTS coil that will be fabricated from 2G HTS wire (Superpower Inc.) [1]. The design specifies that the magnetic field at the location of a sample exceed 4 T; according to a simulation of the bulk model, the magnetizing magnet coil applying DC current must contribute a static magnetic field exceeding 13.4 T at 4.2 K.

The method of simulating the magnetic field of bulk HTS has been investigated and described. A modified algorithm with the Bean model [2] was used. The gap between two HTS bulks is designed to be adjustable to decrease the length of the magnetizing solenoid. To facilitate adjustment of the gap, the bulk is divided into two housings. The overall system has cryocoolers in three sets—one to cool the magnetizer, and the other two sets to cool the two HTS bulks.

The expected uniformity of the magnetic field at the sample location, within 1.5 mm in the transverse direction, is about 1%. A characteristic of the incompletely magnetized bulk HTS was used to extend the demanded region of homogeneous field. The uniformity of the field of the magnetizing magnet was also analysed. The $YBa_2Cu_3O_7$ bulk magnet is cooled to 29 K and the 2G wire solenoid magnet to 4.2 K; they will be set up in two accommodating cryogenic vacuum chambers, separable after the bulk HTS has trapped the field. The bulk HTS and its own cooling system can be placed on the load-bearing table of the diffraction instrument. The end-station system for X-ray scattering experiments includes an eight-direction diffraction system, a HTS bulk magnet with a cryogenic system and a magnetization magnet with its cryogenic system. In this paper, we discuss only the latter two items—the calculation of the fields of the bulk HTS magnet and the magnetization magnet.

## II. Calculation of the Field of the Bulk Magnet

To provide a magnetic field for eight-direction diffraction instruments, a pair of HTS bulk disks was designed; see Fig. 1. The magnetic field at the center between two bulk HTS can be equivalent to the contributions of a surface current $(J_s)$ and a volume current $(J_v)$ [3]. Based on this concept, the magnetic field of the double-disk bulk HTS was calculated with Radia simulation code [4]. According to the Bean model, the magnitude of $J_v$ is constant inside the bulk HTS, but some conditions of the design of the magnetic circuit are inconsistent with assumptions of that Bean model. A special $J_v$ distribution will be

Manuscript received August 03, 2010; accepted October 15, 2010. Date of publication November 29, 2010; date of current version May 27, 2011. This work was supported in part by the National Science Council of Taiwan under Contract NSC 99-2221-E-213-004.

S. D. Chen and T. M. Uen are with the Department of Electrophysics, National Chiao Tung University, Hsinchu, Taiwan.

Y. T. Yu is with the Graduate Program for Science and Technology of Accelerator Light Source, Department of Electronic Engineering, National Chiao Tung University, Hsinchu, Taiwan.

Z. W. Huang is with the Department of Physics, National Tsing Hua University Hsinchu 30043, Taiwan.

J. C. Jan and C. S. Hwang are with the National Synchrotron Radiation Research Center, Hsinchu 30076, Taiwan (e-mail: cshwang@nsrrc.org.tw).

I. G. Chen is with the Department of Materials Science and Engineering, National Cheng Kung University, Tainan, Taiwan.

C. H. Du is with the Department of Physics, Tamkang University, Taiwan.

D. J. Huang is with the National Synchrotron Radiation Research Center, Hsinchu 30076, Taiwan, and also with the Department of Physics, National Tsing Hua University Hsinchu 30043, Taiwan.

C. Y. Chang is with the Department of Electronic Engineering, National Chiao Tung University, Hsinchu, Taiwan

Digital Object Identifier 10.1109/TASC.2010.2089410

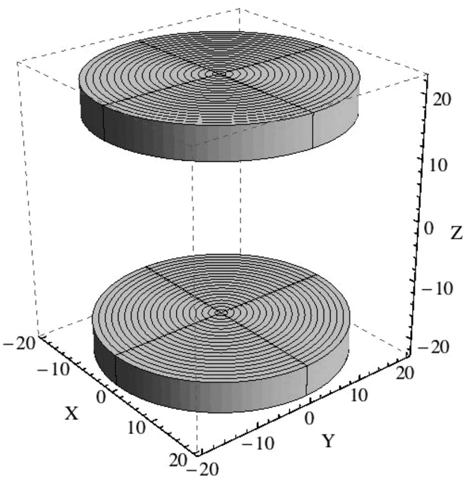


Fig. 1. A pair of HTS bulk disks constructed from two thin cylindrical bulk HTS simulated with Radia code. The concentric circles signify that the cylinder is made with multi-layer current rings; the unit is mm.

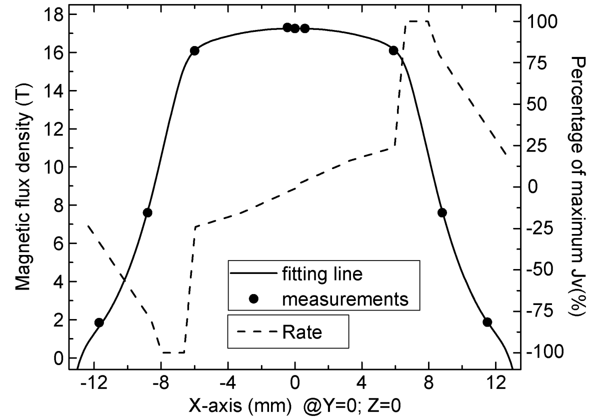


Fig. 2. Measurements (points) and fitted result (solid line) with maximum $J_{\rm v} = 5460\ \mathrm{A/mm^2}$ and $J_{\rm s} = 5700\ \mathrm{A/mm}$. In the concentric circular current loops $J_{\rm v}$ varies from the center to the edge of the bulk, specifying the $J_v$ distribution. The magnitude of $J_{\rm v}$ is such that the fraction of maximum $J_{\rm v}$ multiplies the maximum $J_{\rm v}$, and the sign indicates the direction of the current along the $Y$-axis. $J_{\rm v}$ goes in the $+Y$ direction at $+X$ and goes into $-Y$ at $-X$.

TABLE I
PARAMETERS OF TWO HTS BULK DISKS

| | |
|---|---|
| Center $B$-field/T | 4.04 |
| Maximum $J_{\rm v}$/A mm$^{-2}$ | 5460 |
| $J_{\rm s}$/A mm$^{-1}$ | 5700 |
| Gap between bulks/mm | 34 |
| Bulk diameter/mm | 40 |
| Bulk thickness/mm | 5.1 |

obtained on fitting the simulation result with a chosen measurement result. This special $J_{\rm v}$ distribution is the foundation of the magnetic circuit design, which we describe here.

### A. Distribution of $J_v$ and $J_s$

The distribution of $J_{\rm v}$ and $J_{\rm s}$ is complicated in a cylindrical bulk. It is generally accepted that $J_{\rm v}$ of a bulk of this kind can be modeled with an assumption of concentric circular current loops with finite current density. To simulate the $B$-field of bulk HTS, three assumptions are made to form a simple model of the current loop. First, a cylindrical bulk of finite thickness can be considered to comprise multi-layer thin disks; $J_{\rm s}$ and $J_{\rm v}$ of these thin disks are assumed to be identical, layer by layer. Second, the magnitude of $J_{\rm s}$ and the maximum value of $J_{\rm v}$ are assumed to take unique values for a given temperature of the YBCO bulk. Third, the $J_{\rm v}$ distribution in the bulk might depend on the geometric characteristics and the dimensions of the bulk, but the details are omitted here. For simplification, an assumption is made that the $J_{\rm v}$ distribution is constant for varied dimensions of the bulk cylinders.

The measurements of a pair of bulk HTS that can trap 17 T under 29 K [5] were fitted to obtain a $J_{\rm v}$ distribution, and the magnitude of $J_{\rm s}$ and $J_{\rm v}$. The parameters are listed in Table I; the fitting results appear in Fig. 2.

The reference case has many properties similar to those of the magnetic circuit in this paper: they both have a double-disk structure, YBCO material, cooling to 29 K, and a field-cooling method to magnetize the bulks. The distribution of $J_{\rm v}$ from the fitted result is used in the code to simulate a magnetic field.

### B. Model and Circuit Design

The HTS magnet model designed for eight-direction diffraction instruments is shown in Fig. 1. To form a non- uniform distribution of $J_{\rm v}$ in the cylinder, it was composed of twenty layers of circular current rings, which can have the given current density; see the circular lines on the bulk in Fig. 1. A cylindrical thin shell attached to the cylinder with a current density serves as $J_{\rm s}$.

For measurements with the eight-direction diffraction instrument near 295 K, a magnetic flux density 4 T at the center point between the double disks was designed. The diameter of the bulk HTS is restricted by the manufacturing technology of the bulk to 40 mm. The gap between two bulk cylinders is limited by the dimension of the cryostat, 24 mm, and the space requirement of the sample holder, 10 mm; in total, 34 mm. The magnitude of $J_{\rm s}$, the maximum $J_{\rm v}$ and the $J_{\rm v}$ distribution are defined by the fitted result in Fig. 2. In the circuit design, the operation current density always keeps smaller than the critical current density. Under this condition, we prefer to use the thin HTS cylindrical bulk. It is due to that the field strength at center is less efficiency to the thick of bulk HTS. With these restrictions, a single HTS cylindrical bulk of thickness 5.1 mm was obtained after the optimization of the magnet circuit. The optimized parameters and results of the field calculation are listed in Table I.

To obtain a uniform field at the sample location, the HTS bulks are designed to be not fully magnetized. According to the description of the Bean model, the distribution of magnetic field will be uniform in the transverse-axis at the nearby center of the bulk if the bulk is not fully magnetized, like the measurement result in Fig. 2. This characteristic was used to design a magnetic field with a uniform field over a wide region. The magnetic profile and the uniformity of the designed double disk are shown in Fig. 3. A wider uniform field can be obtained alternatively with a fully magnetized bulk YBCO or with a hole at the bulk center. The x-ray beam (along the $z$-axis) would pass through that hole and parallel to the longitudinal field for another x-ray experiment, but limitations of performance of the present superconducting wire make it difficult to magnetize fully these YBCO bulk disks. A non-fully magnetized HTS bulk disk was hence used instead.

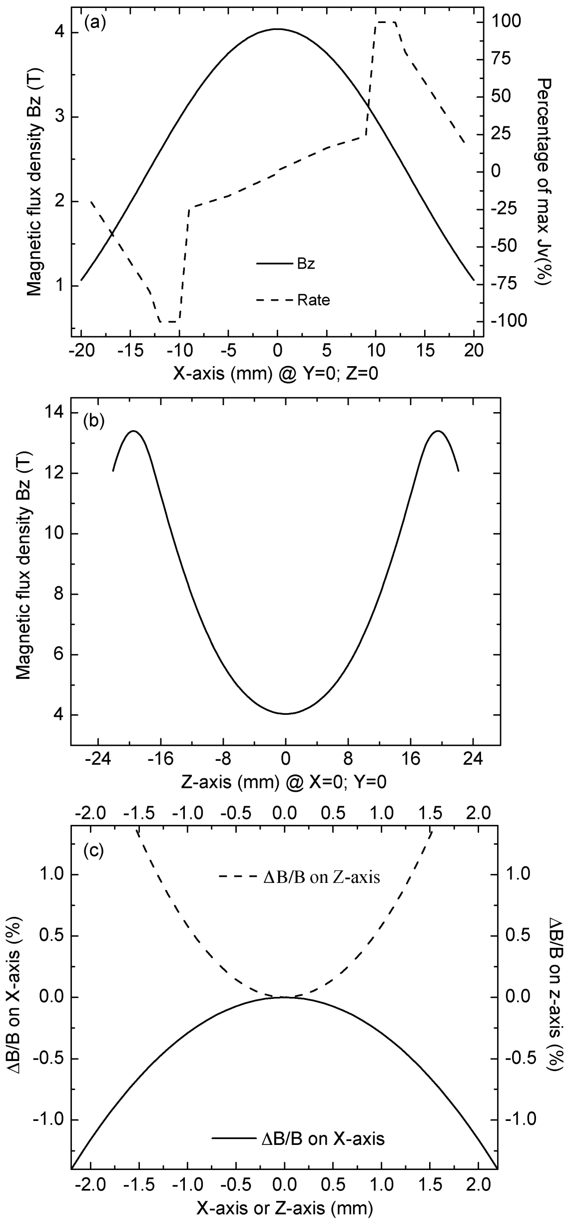


Fig. 3. Magnetic profile of the designed double bulk HTS disks. (a) $B$-field in the transverse direction and the distribution of applied percentage of $J_v$. (b) $B$-field on the transverse axis in the central plane of two bulks; two maxima of field strength at $\pm$19.5 mm. (c) Distribution of the region of uniformity field.

## III. HTS Bulk Magnet With Cooling Method

The bulk HTS was designed to operate at 29 K. Fig. 4 reveals a diagram of the bulk HTS and a design concept of thermal insulation. The bulk HTS is installed inside the vacuum housing with two layers at 70 and 29 K, with three layers of super- insulation to decrease the heat load from thermal radiation. The pressure in the evacuated region is less than $10^{-5}$ Tor. The wall of the vacuum housing, which is manufactured of stainless steel and three layers of super-insulation, serves to decrease the heat load from thermal radiation.

The cylindrical FRP with cross section 3 $\mathrm{mm}^2$ and 1 $\mathrm{mm}^2$ at each end serve to decrease the conducted heat load between the HTS bulk and the vacuum housing. The space in the bulk HTS cryostat including the double-layer heat insulation is 24 mm (see Fig. 4), which is the minimum gap of the two HTS bulk disks.

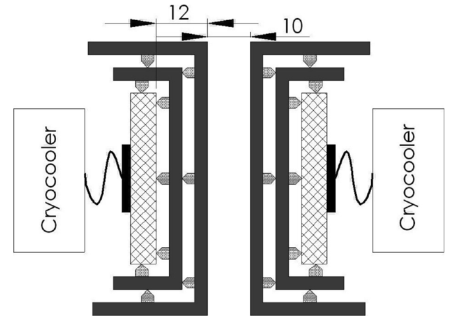


Fig. 4. Schematic concept of the pair of HTS bulk disks and the cooling method; the unit is mm.

TABLE II
CONE-LIKE FRP USED BETWEEN TWO LAYERS OF VACUUM HOUSING. THE NUMBERS OF FRP ARE LISTED. $Q_{\mathrm{G}}$ IS THE CONDUCTIVE HEAT LOAD, $Q_{\mathrm{R}}$ IS THE IRRADIATED HEAT LOAD

| | @ 70 K | @ 29 K |
|---|---|---|
| No. of FRP | 16 | 13 |
| $Q_{\mathrm{G}}$ / W | 2.31 | 0.16 |
| $Q_{\mathrm{R}}$ / W | 0.41 | 0.024 |
| $Q_{\mathrm{total}}$ / W | 2.72 | 0.184 |

TABLE III
SPECIFICATIONS OF THE 2G WIRE OF SCS4050

| | |
|---|---|
| $I_c$ at 77 K (self field) /A | 80 |
| cross section (SCS4050) / mm$^2$ | 0.1*4 |
| Length* $I_c$ at 77 K /A m | 1065*112.8 |
| $I_c$ (4.2 K, 17 T parallel to tape) / $I_c$ (77 K, self field) | 6.48 |
| $I_c$ (4.2 K, 17 T perpendicular to tape) / $I_c$ (77 K, self field) | 1.05 |

The magnet gap between the two cryostats of these disks will be increased from 24 mm to 34 mm (see Fig. 4) to accept the inserted sample holder after the field becomes trapped.

Two cryocoolers will be used on each HTS bulk disk. The thin slices of OFHC copper, serving as thermal conductors, connect the cryocooler and the bulk. S-shaped copper was designed to suppress vibration from the cryocooler to the bulk [6]. Analysis of the head load reveals that the load from 295 K to the insulator at 70 K is 2.72 W and from 70 K to the insulator at 29 K is 0.184 W; detailed data are listed in Table II. The chosen cryocooler (Gifford-McMahon SRDK-205D) [7] provides cooling power 4 W at 50 K and 0.5 W at 4.2 K at each stage.

## IV. Magnetization of the Magnetic Field

A solenoid magnet was designed to magnetize the pair of HTS bulk disks. According to the simulation result in Fig. 3, the bulk HTS disks should be magnetized to 13.4 T. The solenoid magnet for magnetization was designed to provide 14 T, about 4.3% greater than the required field strength. The inner radius of the solenoid is set to match a space that is used for the magnetic field in the eight-direction diffraction instrument, and the space of the cryostat of the solenoid, thickness 18 mm, is also considered. The inner radius of solenoid is thus 152 mm. Fig. 5 specifies the dimensions of the solenoid coil. The 2G wire (SCS4050, Superpower Inc.) was considered to construct the solenoid coil; see Table III.

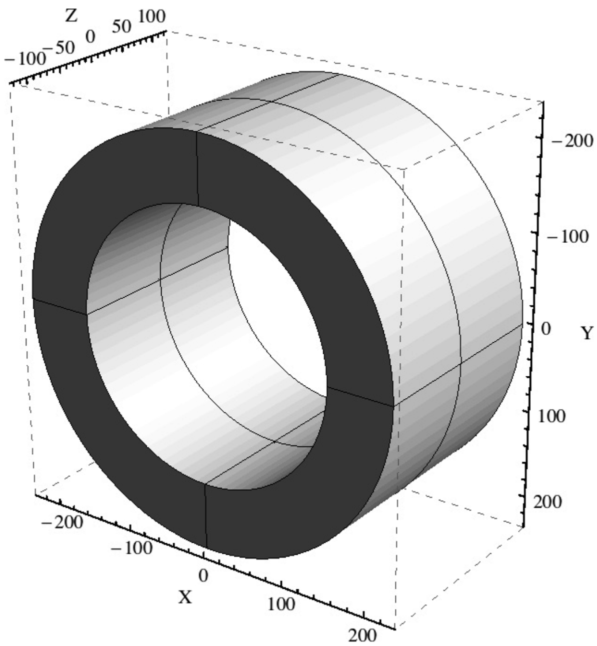


Fig. 5. The diagram and dimension of the solenoid coil of magnetization magnet system. The unit is mm.

TABLE IV
DESIGN PARAMETERS OF MAGNETIZING SOLENOID

| | |
|---|---|
| Operating current /A | 110 |
| Current density /A mm$^{-2}$ | 275 |
| Inner (outer) radius / mm | 152 (227.5) |
| Length / mm | 240 |
| Number of total coil turns | 60x755 |
| Total length of wire / m | 5.4*10$^4$ |
| *B*-field at the center / T | 14.02 |
| *B*-field at the bulk / T | 13.96 |
| Field homogeneity at the bulk area of 5.1 mm / % | ~0.4 |
| Field homogeneity at the bulk radius of 20 mm / % | ~0.4 |
| Maximum field strength *B* (parallel to tape) / T | 22.4 |
| Maximum field strength *B* (perpendicular to tape) / T | 12.0 |

The magnetization system was designed in a conservative manner, but it is expected to be extensible to a greater field in the future. To optimize the dimensions of the solenoids, a current slightly less than the magnitude of the world-record current under a self field at 77 K is used; as the working temperature of the solenoid is set at 4.2 K, the solenoid has adequate tolerance to increase the field in the future. The length and outer diameter of solenoid coil were optimized to minimize the total coil length of the magnetization system. This design concept can provide a minimum welding joint of the 2G wire and decrease the cost of the system. The gap between two HTS bulk disks is variable from 24 mm to 34 mm. The bulk HTS can be magnetized with a smaller gap, which can shorten the magnetization system. The design parameters of the solenoid magnet for magnetization appear in Table IV. The maximum field parallel to the tape surface of the 2G wire, 22.4 T, occurs at the center $(z = 0)$ of the innermost layer of coil, but the maximum field perpendicular to the tape, 12.0 T, occurs at both edges $(z = \pm 120\ \mathrm{mm})$ of the middle layer of the coil. The distribution of the calculated magnetic field is shown in Fig. 6. The homogeneity of the field in the bulk 3D dimension space is 0.4%.

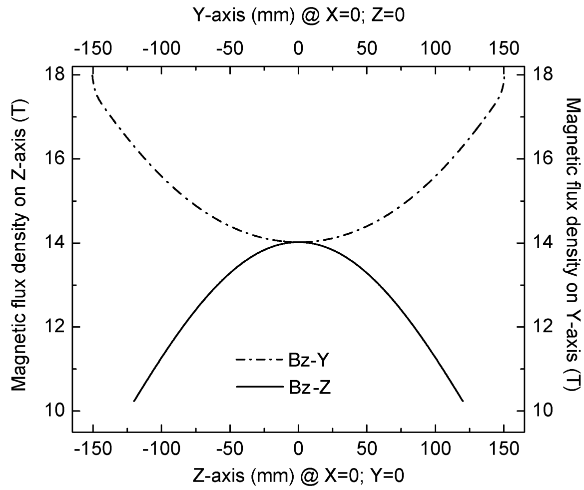


Fig. 6. Profile of the distribution of the magnetic field on the axis of the solenoid of the magnetization system.

## V. CONCLUSION

The dimension of a bulk HTS magnet is limited at present by the fabrication technology of the bulk. We thus depend on the limiting dimension to design the magnetic circuit for the magnet system. For an effective design, the gap between the two HTS bulks must not be larger than their diameter. A region of magnetic field was designed for the sample holder working near 295 K. A large magnetic field will be designed for the sample holder by increasing the bulk diameter.

To enable a precise simulation of the magnetic field of the bulk HTS, we obtained the $J_v$ distribution from fitted data; the behavior of the $J_v$ distribution with varied magnetizing field and dimensions of the bulk HTS is worthy of investigation. The detailed design of the cryogenic system for the magnetization magnet and the HTS bulk magnet are necessary in the future.

## REFERENCES

[1] [Online]. Available: http://www.superpower-inc.com/system/files/SP_Coil+Application_0809.pdf
[2] C. Bean, "Magnetization of high-field superconductors," *Rev. Mod. Phys.*, vol. 36, pp. 31–39, 1964.
[3] I. G. Chen, J. Liu, R. Weinstein, and K. Lau, "Characterization of YBaCuO, including critical current density J, by trapped magnetic field," *J. Appl. Phys.*, vol. 72, pp. 1013–1019, 1992.
[4] P. Elleaume, O. Chubar, and J. Chavanne, "Computing 3D magnetic field from insertion devices," in *Proceedings of the Particle Accelerator Conference PAC1997*, 2007, pp. 3509–3511.
[5] M. Tomita and M. Murakami, "High-temperature superconductor bulk magnets that can trap magnetic fields of over 17 tesla at 29 K," *Nature*, vol. 421, pp. 517–520, 2003.
[6] C. S. Hwang *et al.*, "Design and construction performance of a compact cryogen-free superconducting wavelength shifter," *IEEE Trans. Appl. Supercond.*, vol. 12, no. 1, pp. 686–690, 2002.
[7] [Online]. Available: http://www.shicryogenics.com/index.php?option=com_content&task=view&id=96&Itemid=248