CPC(HEP & NP), 2011, **35**(4): 392–396 Chinese Physics C Vol. 35, No. 4, Apr., 2011

Sm_2Co_{17} magnet blocks for the in-vacuum undulators (IVU20) at the SSRF*

HE Yong-Zhou(何永周)[1)] ZHOU Qiao-Gen(周巧根) ZHANG Ji-Dong(张继东)

Shanghai Institute of Applied Physics, CAS, Shanghai 201204, China

Abstract: The design and development status of Sm_2Co_{17} magnet blocks for two in-vacuum undulators (IVU20) at the SSRF with the same hybrid design has been described. By the technological improvement of some processes and comparison with the experimental Sm_2Co_{17} magnet blocks for the IVU25A, magnetic properties such as the intrinsic coercive force H_{ci} and the average magnetic moment M are increased, the bend point magnetic field H_k value and pass rate are significantly increased, and the magnetic field uniformity of the magnet blocks are significantly improved. The basic developmental method of high uniformity Sm_2Co_{17} magnet blocks for IVU20 is presented. The magnetic field qualities of the magnet blocks, including the magnetic property, the magnetic moment distribution, the magnetization deviation angle and the magnetic field uniformity, basically satisfy the specifications of the two IVU20 in-vacuum undulators.

Key words: in-vacuum undulators IVU20, Sm_2Co_{17} magnets blocks, magnetic field

PACS: 41.85.Lc, 75.50.Ww **DOI:** 10.1088/1674-1137/35/4/013

1 Introduction

The first 7 beam line stations were built for the SSRF in April 2009, 2 of which are based on two in-vacuum undulators IVU25B. Its magnet blocks are Japanese Shin-Etsu Sm_2Co_{17} magnets. At the same time, two in-vacuum undulators IVU25A are being developed and the domestic experimental Sm_2Co_{17} magnet blocks will be installed. In March 2009, the development plan for two in-vacuum undulators IVU20 with the same hybrid design and containing 636 Sm_2Co_{17} magnet blocks was started by the SSRF for protein beam line stations. Permanent magnets are key components of the undulator. Sm_2Co_{17} magnets, which were believed to be the most resistant against electron irradiation among rare earth magnets meet the requirements of the IVU20 at the SSRF.

Investigations show that Sm_2Co_{17} magnet blocks for in-vacuum undulators of third-generation synchrotron radiation facilities have their own unique technology requirements. Before the construction of the SSRF, China did not have relevant batch development experience. During the development process of experimental Sm_2Co_{17} magnet blocks for IVU25A, several excellent Chinese companies developed 10 samples (the dimensions are 65 mm × 25 mm × 8.965 mm) respectively. The magnetic properties of these samples was measured at the National Institute of Metrology, P. R. China, and the magnetic field of these samples was measured at the SSRF. The results showed that only the magnetic properties of the samples developed by Chengdu Magnetic Material Science & Technology Co. Ltd satisfied the technological requirements (remanence B_r is 1.135 T and intrinsic coercive force H_{ci} is 1667 kA/m). The magnetic moment M distribution was about 4.0%, the magnetization deviation angle T of 7 samples was less than 1.0° and the overall pass rate was 50.0%, however, the highest B_r of samples developed by other companies was only 1.10 T when H_{ci} was not less than 1600 kA/m and the T of only one of the 10 samples was less than 1°.

About 1500 experimental Sm_2Co_{17} magnet blocks for IVU25A were developed. Tests showed that the appearance and dimension accuracy of 1216 magnet blocks meet the requirements, and the magnetic field quality of 631 magnet blocks qualified, but the bend point magnetic field H_k value of the magnet blocks is

Received 25 June 2010

* Supported by National Important Project on Science of SSRF

1) E-mail: heyongzhou@sinap.ac.cn

©2011 Chinese Physical Society and the Institute of High Energy Physics at the Chinese Academy of Sciences and the Institute of Modern Physics at the Chinese Academy of Sciences and IOP Publishing Ltd

only 828 kA/m and the magnetic field symmetry of most of the magnet blocks is not less than 5.0%. The magnetic field measurement of the magnet blocks for the undulator is a heavy workload and the technology requirement is very high [1]. The lower pass rate of the magnet blocks has greatly increased the measurement workload, increased the developmental cost of undulators and wasted rare Sm and Co resources.

In order to raise the pass rate and improve the quality of Sm_2Co_{17} magnet blocks, a series of technological improvements have been made. This paper will introduce the design and development status of the Sm_2Co_{17} magnet blocks for IVU20 by the SSRF and Chengdu Magnetic Material Science & Technology Co. Ltd.

2 Design of the magnet blocks

For the physical design and development of IVU20, a higher magnetic property and field quality (M distribution and smaller T value), better magnetic field uniformity and higher size precision of the Sm_2Co_{17} magnet blocks will be conducive to improving the overall magnetic field performance of IVU20. According to the physical design and work environment of IVU20, the main technology requirements of the Sm_2Co_{17} magnet blocks are as follows:

1) In order to obtain a higher magnetic field peak and good resistance to radiation，at 20°, B_r and H_{ci} shall not be less than 1.12 T and 1600 kA/m, respectively, H_k shall not be less than 1000 kA/m.

2) The M distribution for each IVU20 shall be less than 2.0% (the quantity is 320), the T shall be less than 1.0°, T can be expressed using the following formula [2]:

$$T=\arctan\frac{\sqrt{M_x^2+M_y^2}}{M_z}\ . \tag{1}$$

In the above formula, M_x, M_y, M_z are the magnetic moment of the three directions (M_z means main magnetization moment) and M is the total magnetic moment. The three-dimensional magnetic field (M_x, M_y, M_z) distribution of the magnet blocks is measured with a Helmholtz coil.

3) The maximum relative difference between the magnetic field amplitudes measured at 3 mm from the two opposite faces of each magnet block perpendicular to the main magnetization direction must not exceed 5.0%, the formula is as follows:

$$S=\frac{2(|B_N|-|B_S|)}{|B_N|+|B_S|}(\%)\,. \tag{2}$$

Where $|B_N|$ and $|B_S|$ mean the magnetic field amplitude of each block, the S means the magnet field symmetry of magnet block, it is measured with the Hall-probe measurement system at the SSRF.

4) For vacuum performance of IVU20, the density of the magnet blocks shall not be less than 8.4 g/cm^3 and the thickness of TiN coating about 0.007 mm.

5) The number of defects on the magnet block surface should be less than five and the size for each smaller than 0.5 mm × 0.5 mm × 0.5 mm.

6) The size is 65 mm × 27 mm × 7.165 mm, the chamfers of sites A are 1.2 mm × 1.2 mm for reducing the electron beam loss of the storage ring and the chamfers of sites B are 4.0 mm × 4.0 mm for installation of magnet blocks. The shape and the chamfer of the magnet block are shown in Fig. 1.

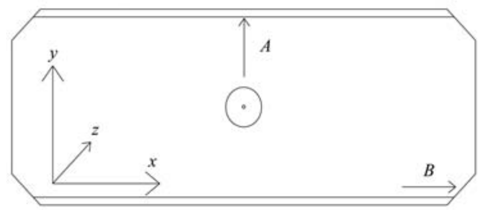

Fig. 1. The Sm_2Co_{17} magnet blocks for IVU20 (the dot means M_z).

3 The development of magnet blocks

3.1 The magnetic property

The Sm_2Co_{17} magnet blocks for IVU20 at the SSRF were developed with powder-metallurgy technology [2], the phase diagram design of IVU20 was based on IVU25A and was improved, and the specifications for processes such as suppression and sintering were optimized. For the Sm_2Co_{17} magnet blocks of IVU20, the B-H curve shows that the B_r is 1.136 T and the H_{ci} is 1755 kA/m and the H_k value is 1140 kA/m. The Helmholtz coil tests show that the averaged M of the magnet blocks is 2.5% higher than that of IVU25A. However, the magnetic property of the magnet blocks for IVU20 are still lower than Japan's Shin-Etsu R32HS magnet blocks for IVU25B at the SSRF (the dimension is also 65 mm × 25 mm × 8.965 mm), see Table 1.

Table 1. The parameters for the domestic and Japan's Shin-Etsu Sm_2Co_{17} magnet blocks.

case	IVU25A (1216 parts)	IVU20 (852 parts)	Shin-Etsu (730 parts)
the material mark	XG30/20	XG30/20	R32HS
B_r/T	1.135	1.136	1.157
H_{ci}/(kA/m)	1668	1755	2075
H_k/(kA/m)	824	1140	1825
$\boldsymbol{M}$/T	0.975	1.00	1.05

3.2 The three-dimensional magnetic field distribution

In order to improve the magnetic field quality of the magnet blocks for IVU20, some factors have been considered, such as the parameters of the orientation electromagnet, the shape features of the magnet blocks and the forming space. The volume of suppression rough of the magnet blocks has been optimized. A suppression rough for IVU20 has 3 magnet blocks, but a suppression rough for IVU25A has 2 magnet blocks. The suppression rough is placed in a good field region of the sinter furnace, the temperature-time curves of the sinter and cooling treatment have been optimally designed according to the magnetic property design requirements. The sinter temperature control accuracy has been improved from 2.0 ℃ of rough for IVU25A magnet blocks to 1 ℃ of rough for IVU20 magnet blocks. Through the technology transformation, the cooling rates of the tubular sinter furnace are basically the same between the two tips and the intermediate.

Figure 2 shows the M distribution of 1216 magnet blocks for two IVU25A and 852 magnet blocks for one IVU20. It can be seen that the M distribution of most of the magnet blocks for IVU25A is about 5.0%, however, the M distribution of almost all of the magnet blocks for IVU20 is about 2.5%, through technology improvements, the M distribution of Sm_2Co_{17} magnet blocks for IVU20 has a larger improvement.

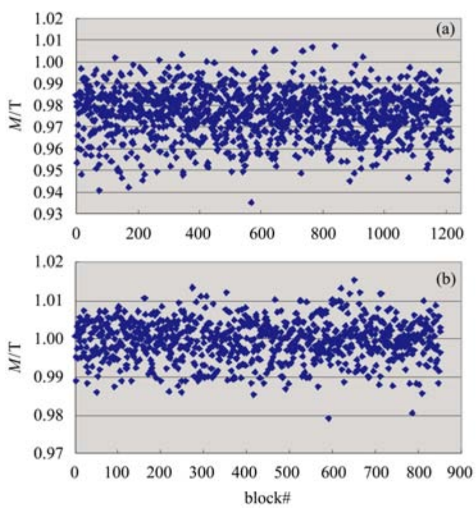

Fig. 2. The magnetic moment M distribution of Sm_2Co_{17} magnet blocks for IVU25s (a) and IVU20s (b).

In the grinding-slicing process of sintered rough Sm_2Co_{17}, it was necessary to make the surface along the magnetic field orientation strictly parallel to the magnetic field orientation. In the development of the Sm_2Co_{17} magnet block for IVU20, the a [2] was adjusted to be less than 1.0°. The magnetic field treatment of materials associated with the micro-effect is widespread, the material that has magnetic or magnetic components is dealt with by magnetic field, which affects the system's energy. So if the anisotropy micro-structural features of ferromagnetic material are dealt with by magnetic field, then an orientation effect will appear [3]. After heat treatment that is magnetically annealed, the instability organization or domain structure of the magnetized Sm_2Co_{17} magnet blocks can be eliminated. A further enhanced orientation of magnet blocks was found at 150 ℃/120 min aging annealing, the T of most magnet blocks have a certain decrease.

Figure 3 shows the T distribution of 1216 magnet blocks for two IVU25A and 852 magnet blocks for one IVU20, we can see that through technological improvements of orientation forming and grinding-slicing and annealing, the pass rate of T has increased from 46.8% of IVU25A to 72.2% of IVU20.

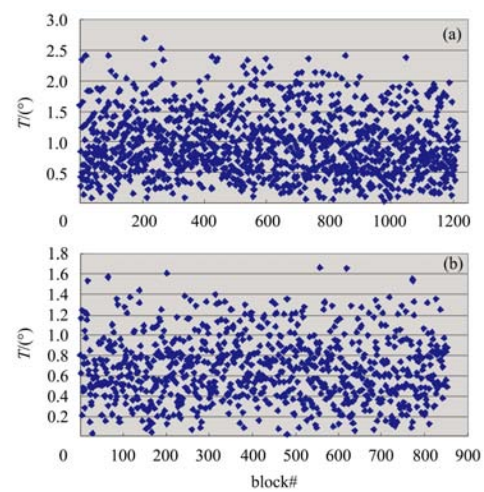

Fig. 3. The magnetization deviation angle T distribution of Sm_2Co_{17} magnet blocks for IVU25 (a) and IVU20 (b).

3.3 The magnetic field uniformity

The magnetic field uniformity of magnet blocks is very important to the development of high-quality vacuum undulators, particularly to short period undulators.

Symmetry is an important indicator of magnetic field uniformity. Before the mass production of suppression-sinter rough on magnet blocks, Programs A, B and C were designed. Programs A, B and C represent a suppression-sinter rough with two magnet blocks (A-1, A-2), three magnet blocks (B-1, B-2, B-3) and four magnet blocks (C-1, C-2, C-3, C-4), respectively, after sintering, the round part of the suppression-sinter rough will be cut off, see Fig. 4. The two surfaces along the orientation direction of B-2 magnet blocks have basically the same microstructure, but for the other magnet blocks, the microstructure of two surfaces along the orientation direction is different. Test results show that Program A and Program C received bad results. The magnetic field symmetry of almost all of the sample magnet blocks is not less than 5.0%, but for Program B, measurements show that the central magnet block (B-2) of the suppression-sinter rough has better magnetic field symmetry, the magnet field symmetry of 10 samples of B-2 is less than 4.3%. 7 of these are less than 2.0%, however, the magnetic field symmetry of only 1 sample each of the 10 B-1 and B-3 is less than 5.0%.

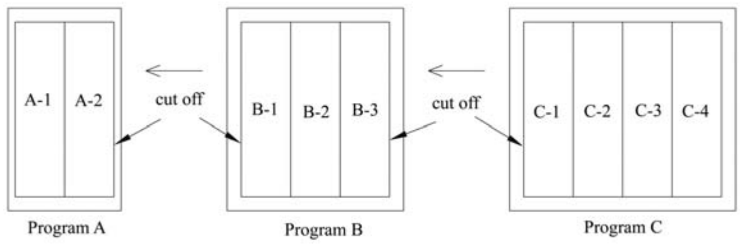

Fig. 4. Three kinds of programs of suppression rough for magnet blocks of IVU20 (A, B and C), the level arrow indicates the orientation direction.

Therefore, Program B was selected for the mass production of Sm_2Co_{17} magnet blocks, all the central B-2 magnet blocks and some of the magnet blocks from B-1 and B-3 were adopted for IVU20. The magnet field symmetry of about 570 of 852 magnet blocks for IVU20 is less than 5.0%. The magnetic field symmetry of the magnet blocks which were installed in IVU20 is almost less than 6.0%. The test result shows that the magnetic field symmetry of most of the Japanese Shin-Etsu Sm_2Co_{17} magnet blocks is less than 2.0%.

The skew quadrupole of the magnet blocks is also one important indicator of magnetic field uniformity. Fig. 5 indicates skew quadrupole B_x and B_y of the two side faces along the x direction of one magnet block. We can find that there are magnetic field micro-fluctuations in B_x and B_y. The measurement results show that almost all of the magnet blocks have certain skew quadrupole components. In order to reduce or eliminate this component, the skew quadrupole of the two side faces along the x direction of all of the magnet blocks should be measured before installation. Each two-magnets with a opposite direction tilt of B_x and B_y should be arranged in pairs when all of the magnets are installed. In addition, the magnetic field shimming of IVU20 can also eliminate skew quadrupole components. We also found that Japan's Shin-Etsu Sm_2Co_{17} magnet blocks also have quadrupole, but its value is smaller and has no magnetic field micro-fluctuations along the x direction of the magnet blocks.

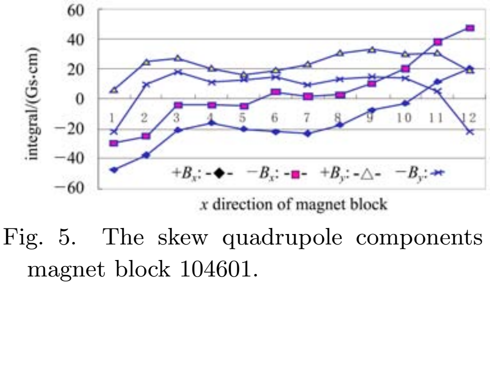

Fig. 5. The skew quadrupole components of magnet block 104601.

3.4 The re-magnetization

At re-magnetization, for the smaller value of L/D (L means the orientation length of 7.165 mm, D means the x length of 65.00 mm), in order to achieve saturation magnetization, 3 magnet blocks were stuck together and then put in the center of the magnetic coil, see Fig. 6. In the suppression-orientation phase, some of the magnet blocks may have a slight bell shape orientation. If all magnet blocks are re-magnetized along a direction, then the magnetic induction B amplitudes from the two opposite faces perpendicular to the orientation direction of each magnet block is different. For eliminating the systematic errors of magnet blocks, there are two magnetization methods, see Fig. 6. (a) The magnetic field of the coil is parallel to the forming orientation of the half magnet blocks. (b) The magnetic field of the coil is anti-parallel to the forming orientation of the remaining half magnet blocks.

3.5 Thermal stability

For in-vacuum undulator NdFeB magnets, prior to the vacuum commissioning at 120 ℃, the magnetic stabilization of the undulator magnets was made at 145 ℃ in order to prevent high-temperature deterioration of the field quality during vacuum commission-

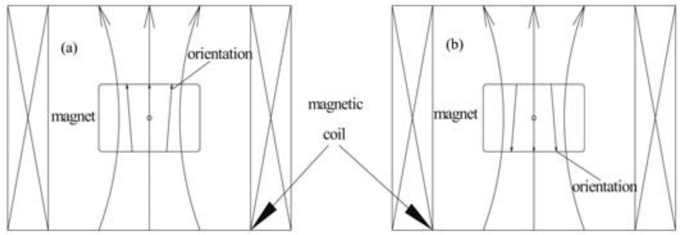

Fig. 6. The two magnetization modes of magnet blocks for IVU20 (a) and (b) ('magnet' including 3 magnet blocks).

ing [4, 5]. The Sm_2Co_{17} magnets have better thermal stability than the NdFeB magnet. The IVU20 at the SSRF does not do this work. The vacuum commissioning time at 120 ℃ of IVU20 is about 96 h. The selected 10 sample magnet blocks were made at 120 ℃/156 h, Fig. 7(a) shows that the T of the sample magnet blocks have no significant changes, however, a different degree of magnetic field loss of the magnet blocks were found (from 0.5% to 2.3%), see (b). So, the vacuum commissioning may have some influence on the magnetic fields quality of in-vacuum undulators IVU20.

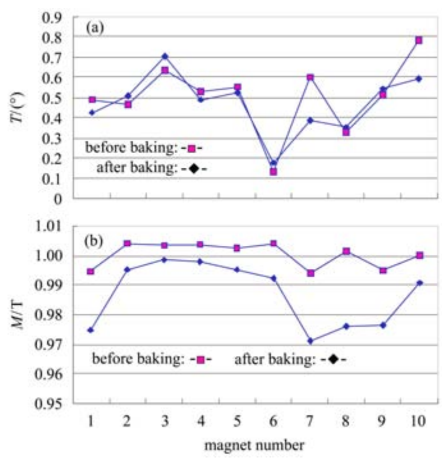

Fig. 7. The magnetic field changes of 10 sample magnet blocks which were made at 120 ℃/156 h.

4 Summary

A total of about 2000 Sm_2Co_{17} magnet blocks for two in-vacuum undulators IVU20 were developed with the overall pass rate being 57.0%, the surfaces of the magnet blocks were coated with TiN of about 0.0072 mm by the Shanghai Tools Factory. The following results were obtained by the development of magnet blocks for IVU20:

1) Through technological improvement and compared with the experimental magnet blocks for IVU25A at the SSRF, the magnetic property (H_{ci} and M) of Sm_2Co_{17} magnet blocks for IVU20 have been increased, the H_k value, the magnetic field uniformity and the pass rate have been increased significantly.

2) The basic development method of high uniformity Sm_2Co_{17} magnet blocks for IVU20 was presented and it was also found that the central part of suppression-sinter rough for Sm_2Co_{17} magnet blocks has better magnetic field uniformity. The specifications of magnet blocks basically satisfy the requirements of two IVU20s.

3) Compared with Japan's Shin-Etsu R32HS magnet blocks, the magnetic property and magnetic field uniformity, etc. the domestic Sm_2Co_{17} magnet blocks for in-vacuum undulator need to be further improved. A series of advanced technologies, such as the oxidation-reduction proliferation process, hypoxia technology and improvement of ingredient, accurate temperature control sintering technology were used to develop Japan's Shin-Etsu Sm_2Co_{17} magnet blocks [6].

The demagnetization heterogeneity after vacuum commissioning and the magnetic field uniformity, including magnetic field micro-fluctuations of Sm_2Co_{17} magnet blocks, may limit the magnetic field quality of the in-vacuum undulator, So further research of the magnetic principles and technology innovations of Sm_2Co_{17} magnet blocks for in-vacuum undulators is very important.

References

1 JIA Qi-Ka. High Power Laser and Particle Beams, 2003, **15**(6): 5 (in Chinese)

2 HE Yong-Zhou, ZHANG Ji-Dong, ZHOU Qiao-Gen et al. High Power Laser and Particle Beams, 2010, **22**(7): 1629 (in Chinese)

3 Rober C.O'handley. Modern Magnetic Materials Principles and Applications. Beijing: Chemical Industry Press, 2002. 506–507

4 Yamamoto S et al. Rev. Sci. Instrum., 1992, **63**(1): 400-4-3

5 Yamamoto S et al. AIP Conf. Proc., 2004, **705**: 211–214

6 HE Shui-Jiao. The Latest Developments of High-Performance SmCo Rare Earth Permanent Magnet. In: HE Shui-Jiao. China Magnetic Industry- Strategies Seminar for Sustainable Development by Leaps and Bounds. Mianyang: Southwest Institute of Applied Magnetic of China (SIAM), 2003. 66 (in Chinese)