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STATUS OF MAGNETS FOR WALS STORAGE RING

Y. Chen*, P. Xiang, J.M. Zhang, H.J. Wang, G. Wei, J. Li, Y. Zou, H.H. Li, Y.C. Nie, X.R Hao, Y.X. Zhang, Y. Wang, W.W. Zhou, Y.H. Xu, J.K. Wang, J.H. He, IAS, Wuhan University, Wuhan, China

Abstract

Wuhan Advanced Light Source (WALS) accelerators include a 1.5 GeV Linac, 1.5 GeV storage ring (SR) and one beam transport line. Since the longitudinal space is very tight, the lattice of SR employs many combined function magnets to match the beam optics and reduce the emittance. There are horizontal and longitudinal gradient dipoles (LGB), electromagnetic and permanent hybrid dipoles (HYB), anti-bending single sided dipole-quadrupole magnets (ABM). In this paper, the key design methods and issues for these magnets are thoroughly discussed, the field measurement results of the HYD and ABM prototypes are also presented.

INTRODUCTION

Wuhan Advanced Light Source consists of a 1.5 GeV and 250 m Linac, 1.5 GeV storage ring(SR) with 180 m circumference and a 40 m beam transport line, the design emittance is 222.8 pm-rad with 500 mA beam current [1]. WALS/SR is very compact and divided into 8 identical units (Fig. 1), which includes 7 longitudinal gradient dipoles with additional horizontal gradients (LGB), 1 hybrid 3.573 T electromagnetic and permanent combined dipoles (HYB), 4 anti-bending single sided dipole-quadrupole magnets (ABM), 10 quadrupoles and 6 sextupoles. Among these magnets, most of them are highly combined. Also, the large sagitta due to the small radius of SR brings the magnets design and production more difficulties.

In Section II, the detailed considerations, designs, optimizations and measurements are presented. In Section III, a brief summary is concluded.

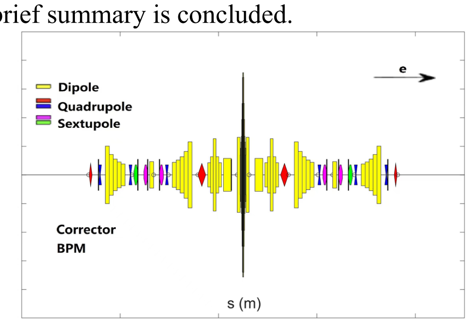

Figure 1: Layout of a WALS/SR unit.

The main parameters of the SR magnets are listed in Table 1. In one unit, 6 sextupoles are categorized into 3 families, and 4 ABMs into 2 families, every family is powered in series. Other magnets are powered individually or permanent types.

Table 1: Main Parameters of the SR Magnets

Name	Number	L (m)	Gap (mm)	B_0 (T)	G (T/m | T/m^2)
HYB	8	0.6	15	3.573	30.825
LGB1		1.2	37	0.2989 - 0.8431	1.925
LGB2	16	1.2	37	0.3405 - 0.9604	2.975
LGB3		0.42	37	0.4510 - 1.3458	20.075
ABM1	16	0.4	35	0.6115	40.3435
ABM2		0.2	45	0.4671	33.0065
Quad1		0.1178	40	-	24.2795
Quad2		0.1127	40	-	12.2995
Quad3	16	0.1127	40	-	7.3000
Quad4		0.1660	40	-	34.7560
Quad5		0.3600	40	-	35.8325
Sext1				-	110.484
Sext2	16	0.2	40	-	87.965
Sext3				-	910.308

PHYSICAL DESIGN OF SR MAGNETS

The typical field quality of the SR combined dipoles and quadrupoles is 5×10^{-4}, 1×10^{-3} for sextupoles, the Good Field Region (GFR) of SR magnets is ±10 mm except HYBs, which is ±6mm. All the magnets are optimized at 1.5 GeV, for electromagnetic parts, the yokes will adopt 0.5 mm laminating structure for the convenience of manufacture. Since the center field reach 3.573 T, the permanent material of HYB is NdFeB, other permanent magnets such as LGBs use SmCo and equipped with FeNi rods to adjust field at a level of 1%.

The OPERA/TOSCA program [2] is used to perform 3D field calculations of the magnets. For quadrupoles, sextupoles and ABMs, the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) is employed to optimize the pole shapes, which is a nonlinear optimization algorithm and the upgrade of the traditional GA, including non-dominated sorting, crowding distance estimation and elitist strategy[3]. The detailed progress is, firstly, the initial pole is obtained by conformal mapping, which is very helpful for reaching the final optimized pole shape as soon as possible. Secondly, the program completed in MATLAB calls the NSGA-II to adjust the pole shape in some random ways, and sends these new shapes to

* chenyuan79@whu.edu.cn

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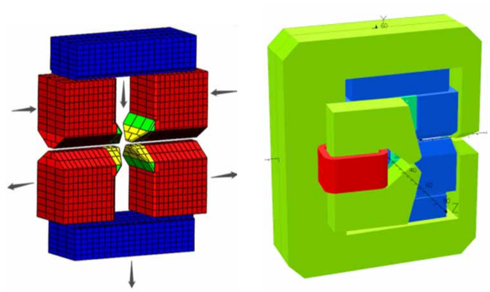
OPERA2D. Then the magnetic field simulations are performed in parallel by OPERA2D. Thirdly, the program runs NSGA-II to choose elitist individuals and iterates this step. The best results are saved when the number of generation is satisfied. With an 8-core processor, the optimizing time of a normal quadrupole or sextupole is about one hour. Generally, the irritation number of 15-20 generations will be enough.

HYBs Designs

HYB magnet consists of one permanent magnet dipole and 2 electromagnetic gradient dipoles on both sides of the center dipole, the angle between them is 4.2 degrees. The center field is designed as 3.57 Tesla to produce the hard-X radiation with a 15 mm pole gap, which takes the superbends used by SIRIUS as a reference[4]. The permanent magnet structure of HYB is shown as Fig.2(a), three kinds of permanent magnet materials NdFeB are used at different places, the blue and red blocks are N48H, which remnant field B_r and coercivity H_{cj} are 1.365 Tesla and 18 kOe respectively. Green and yellow blocks are located nearby the poles, which need higher coercivity, the H_{cj} of the former is 21 kOe, and the other is 35 kOe. Since the field is very high, some regions of magnetic blocks at pole tips will be demagnetized, the shapes of them will be decided after 3D simulations, that mean the regions with a field above H_{cj} will be cut, the material of the two pole tips is FeCoV. The adjacent gradient dipoles are excited by power supplies, the coils are installed on the returning yokes, in order to make space for the flanges because of the compact longitudinal space, each coil pancake is ground insulated with 50% overlapped fiberglass tape and then epoxy impregnated. The 3D simulation model of HYB is shown as Fig.2(b), the measurement results are compared in Section IV, with several iterations, the field integrals arrive at 3×10^{-4} within ±6 mm.

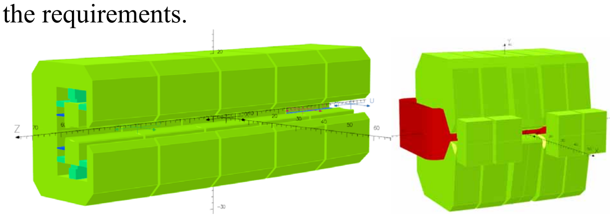


(a) (b)

Figure 2: (a)The permanent magnet blocks structure (b)The 3D HYB model.

LGBs Designs

The LGBs employed by WALS have longitudinal and horizontal gradients at mean time, which are all assembled by 5 magnetic units. Among them, LGB1 and LGB2 adopt permanent magnet scheme. LGB3 is chosen as an electromagnetic magnet because the center unit needs to reach 1.35 Tesla, if permanent scheme is adopted, adjacent units will bypass the magnetic flux, which reduces the center field. For permanent magnet LGB1s and LGB2s, they all need to take the temperature coefficient of permanent magnet material in account. Compared with NdFeB, the SmCo alloy with a temperature coefficient 3×10^{-4} /°C is chosen. Additionally, unlike HYBs, LGB1s and LGB2s cannot change the fields via exciting currents, some FeNi alloy sheets are inserted to connect returning yokes and poles, the tendencies of permeability of FeNi and SmCo alloy are same when temperature changes, the FeNi sheets will bypass a part of magnetic flux from poles at the same ratio, that maintains the center field almost unchanged, less than 50PPM/°C. Lastly, remnant field differences of all the blocks are about ±1.5%, so in the stage of designing, the gradient of each unit has an increase of 1.5% to avoid the gradients reductions. In order to adjust the center fields, all the units need to be movable transversely within ±2mm. The 3D models of LGB1 and LGB3 are shown in Fig. 3, four iron blocks located on the outsides are used to modify the homogeneity of the field integrals. After optimizing, the homogeneities of all the LGBs are lower than 5.0×10^{-4}, which meet the requirements.



(a) (b)

Figure 3: (a)The model of LGB1, (b) The model of LGB3.

ABMs Designs

ABMs have two type choices usually, one is the large aperture quadrupole type, to accommodate the center shift. According to WALS beam optics requirements, the shifts for the two ABMs reach about 15 mm, adding the apertures of them, the pole tip fields beyond 1 Tesla, so this type is given up. The other type is employed by ESRF[5], which is a type of single sided dipole-quadrupole magnet, Fig. 4 (a) shows the AB1 of WALS. The right massive poles can be seen as a half of a normal quadrupole, the left slim poles are auxiliary, to correct the gradient produced by right two poles, until arrive at a required homogeneity. In optimizing process, the NSGA-II is used to find proper shapes of the left and right poles. Of course, there are many shapes of all the poles can satisfy the specifications. For simplicity, there are 3 groups of variables are built to optimize the pole shapes. 2 groups are added on the right poles, which means they are designed as asymmetry ones with respect to the pole vertexes. The third group is used to modify the left auxiliary poles. The whole process consumes about 1.5 hour and the irritation number is 12 generations. Figure 4 (b) plots the harmonics components of ABM2 normalized by dipole field, the harmonic orders larger than 11 are ignored. In practice, there is a correcting coil on each auxiliary pole to adjust

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the gradient and harmonic components slightly, other coils are connected in series.

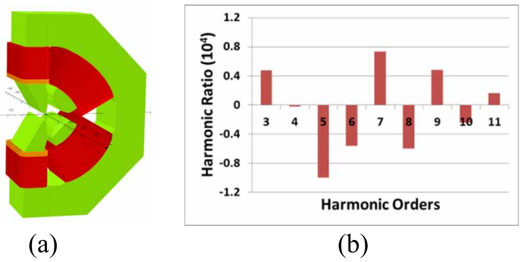

Figure 4: (a)The 3D ABM2 model, (b) The harmonic errors of ABM2 within Φ 32 mm.

Quadrupoles and Sextupoles Designs

Since the longitudinal space is highly squeezed, all the quadrupoles and sextupoles have large aspect factors, which result in stronger fringe effects and increase the difficulty of pole shape optimization, the NSGA-II algorithm is also adopted to obtain pole shapes. Unlike ABMs, there is only one group of variables to modify the half of pole shape because of the hyperbola pole symmetry. For the same reason, all the sextupoles are equipped with the horizontal and vertical dipole corrections coils and a skew quadrupole correction coil. The 3D sextupole model is shown in Fig. 5(a).

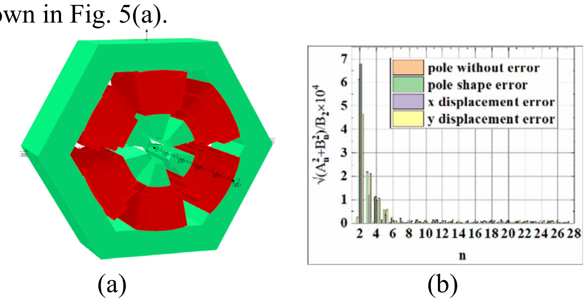

Figure 5: (a)The 3D sextupole model, (b) The error analysis for the sextupole.

In order to install coils, the sextupole yoke is made of two segments respect to the middle plane, four poles are removable except 6 and 12 o'clock poles. The random multipole errors caused by the rotational, shear and vertical displacements of the core sections will be corrected by chamfering the ends, after 3D simulating and end chamfering, the multipole errors of all quadrupoles and sextupoles are all lower than 5×10^{-4}, the homogeneities of dipole and skew quadrupole are around 1×10^{-2}. The effect of a variation of permeability is minimized by shuffling the laminations. The ears in the laminations are non-symmetrical and are alternately stacked in packs to allow space for the bolts. The magnet core is fabricated from J23 steel laminations 0.5 mm thick. After precisely stacking, aligning and gluing the laminations, they are compressed and bolted with tie rods. A machining tolerance is obtained by adding the coordinated errors on ideal pole tip, with many error analysis, the tolerance should be less than ±0.02 mm. Fig. 5(b) gives the multipole variations with pole tip errors and assembly errors for the sextupole, only the dipole component is higher than 5×10^{-4}, which can be eliminated by alignment.

Measurements

By the end of March, 2023, the prototypes of HYB and ABM1 for the WALS/SR were completed. Hall measurement shows the field arrives at 3.67 Tesla, which is higher than the specification 3.5 Tesla. The total field integral on the beam orbit can be adjusted by translating the adjacent electromagnets transversely in order to obtain the required bending angle. The homogeneity of the field integrals reaches about 4×10^{-4} within ±6 mm, the prototype and the distribution is shown in Fig.6. AB1 prototype is also measured by Hall probe and rotating coils, the center gradient reaches 37.7 T/m, the multipole errors of sextupole and octupole are 1.02×10^{-3} and 6.1×10^{-4} respectively, which exceed the requirements. One reason is the ABM is cantilever structure, when excited the relative positions of two auxiliary poles have a 0.04mm shifting, which makes multipoles worse. The prototype of AB1 under measuring is shown as Fig. 6(b).

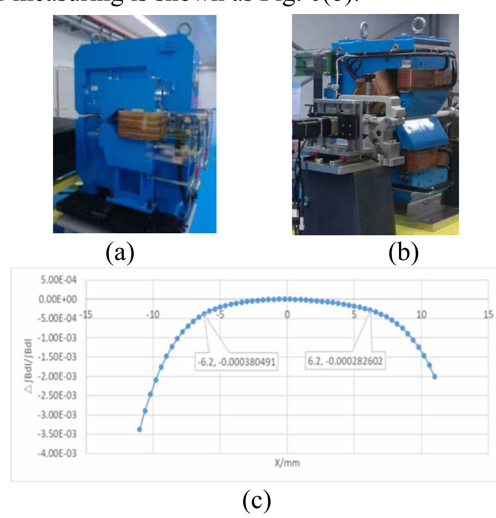

Figure 6: (a) HYB prototype, (b) AB1 prototype and measuring, (c) The field integrals homogeneity of HYB prototype.

CONCLUSION

The work presented is in the first time to design, produce and measure particle accelerator magnets in Wuhan University, In order to optimize the pole tips shapes, the NSGA-II algorithm and many times iterations are employed. Until now, the prototypes of HYB and ABM1 are completed, but some field specifications still not good enough, this motivates us to update the corresponding designs according to the first prototypes. Additionally, since the lattice is very compact, the next ongoing task is to analyze magnet assemblies used in WALS/SR, their real magnetic fields descriptions due to fringe field interference will be investigated.

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