THE DESIGN AND CONSTRUCTION OF NSLS-II MAGNETS*

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Abstract

NSLS-II is a new medium-energy synchrotron light source designed to deliver state-of-the-art emittance with top-off operation for constant output. Design and engineering began in 2005, construction started in 2009, and operations are scheduled to begin in 2014. Machine energy is 3Gev and the circumference 792 m. The magnetic lattice requires elements with optimized field quality. These magnets have been designed using modern 3D modeling tools. This paper describes some unique aspects of the NSLS-II magnets, the magnet development program, and the resulting production specifications.

INTRODUCTION

While the design is relatively robust due to the use of damping wigglers, the introduction of Three-Pole Wigglers adjacent to the main dipoles has pushed the (linear) optics to a level where, e.g., tighter tolerances are required for the magnets in the dispersive sections; as compared to the existing state-of-the-arts [ref: SLS, SOLEIL, DIAMOND]. And, since leeway must be provided to accommodate the nonlinear effects from insertion devices, care is required for the systematic and random multipole errors from all the lattice magnets.

To obtain the required field quality within programmatic constraints, a development program was implemented. Reference designs were developed and optimized while advanced manufacturing methods were demonstrated by industry. The lattice required an unusually large number of variants to be prototyped, and resulted in magnets that incorporate premium design practices while minimizing production costs. The prototype results yielded data that were used in beam orbit studies. This provided existence proofs while allowing additional optimization, further reducing programmatic risks.

PROTOTYPE MAGNET PROGRAM

In 2008 a series of 12 prototype magnets were build to specification by industry. A reference design established the magnets' spatial constraints. The contractors had freedom to improve on the reference design and investigate advanced yet cost-effective manufacturing methods. After contractor design reviews, all prototypes were completed in less than 6 months.

The Dipoles

The 3Gev low emittance beam requires very soft bends design. At 0.4 Tesla, 6-degree bend dipoles take up an inordinate lattice space. To accommodate vacuum chamber and absorber constraints, a curved C-style dipole design as was selected. as selected. To free up over 10m of lattice space, a "nose piece" at either end of the 35mm dipole was adopted [1].

A large aperture dipole is necessary to service the IR community, but cost constraints required that the majority of dipoles have a much smaller aperture. Thus, NSLS-II is unique in having two different aperture dipoles. The noise on the 35 mm dipole provides a means to improve end and integrated field quality, with chamfered sector ends to match the field integrals of the two aperture magnets.

To reduce costs and improve rigidity of the relatively long curved magnet, the laminations are all stacked in parallel and then welded to the curved surface of a three-sided straight steel box section. This produces a very rigid magnet assembly that can be fixtured to allow precision machining of the pole profile to achieve field quality specifications. A prototype of each aperture was built commercially and, when measured, yielded acceptable performance, thus demonstrating the production specifications in Table 1.

Table 1: Sample Production Dipole Parameters

Description		A	B
Quantity required	Each	54	6
Aperture, min.	mm	35	90
Operating DC field	T	0.4	0.4
Magnetic length	mm	2,620	2,620
Radius of beam axis	m	25.02	25.02
Operating current	A	360	360
Operating voltage, max.	V	11	32
Field homogeneity, X=±20mm Y ±10mm, in magnet body	%	<0.015	<0.015
Total integral field homogeneity X=±20mm x Y ±10mm	%	<0.05	<0.05
Turns per pole		16	42
Dipole amp-turns/pole		5,760	15,120
Power	kW	4	11.5
Current density in Cu, max.	A/mm²	3.5	3.5
Yoke length, nominal	mm	2,584	2,528
Lamination thickness, nominal	mm	1	1
Number of water circuits		4	6
Trim coil field, (±) maximum	T	0.012	0.012
Trim coil amp-turns/pole	NI	172	454
Trim operating current, max.	A	3.31	8.10

Typical Aspects of NSLS-II Multipoles

The magnet aperture and yoke design of the multipoles are primarily driven be the geometric constraints imposed by the vacuum system and cost constraints. Accelerator physics studies showing the NSLS-II lattice to be unusually sensitive to higher order allowed harmonic terms such as b10(20pole) and b14(28pole) for the quadrupole and b15(30pole) and b21(42pole) for the sextupole, diminishing the dynamic aperture and beam lifetime. This sensitivity was found only for the few multipoles in the dispersive section at the middle of each cell. Other regions were found to be less sensitive to higher order terms. To optimize the design, pole radii were increased only where needed, from 34 to 38mm for 10% of the sextupoles, and from 33 to 45mm for 20% of the quads, while field quality

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was significantly relaxed in all other areas, thus reducing overall cost and programmatic risk for all the multipoles.

A challenging aspect of the NSLS-II multipoles is achieving demanding magnetic alignment tolerances within budgetary constraints. All multipoles on a girder must share a common magnetic axis to within ±30µm. A vibrating wire-based magnet alignment system has been developed to establish multipole magnetic alignment to within ±10µm [2]. Laser tracker targets located on the top and faces record the spatial geometry of each multipole relative to targets mounted to the girder to within ±50µm.

Design innovations are being implemented to enhance magnet reliability and minimize non scheduled down time should an incident occur. NSLS-II multipoles are designed to be assembled around a fixed vacuum chamber. This programmatic decoupling minimizes the impact of multipole incidents on non scheduled machine down time. The multipoles are designed with a novel, all-metal water-cooled power distribution system that utilizes a shielded isolation block. This technique eliminates hoses, resulting in a maintenance-free magnet assembly. The two hose connections and DI water manifold are shielded by the girder and will result is less down time needed for hose maintenance. Based on the APS model, water flow sensors and magnet isolation valves are not used, eliminating the potential of false trips. A system of innovative, low-cost single-wire thermal sensors installed on each magnet coil will be monitored to establish trends and diagnose developing problems. Dual thermal switches will be used on coil output lines, but these switches will have different set points of 40°C and 60°C wired to individual enunciators; thus false trips can be diagnosed externally and addressed during regularly scheduled maintenance periods. Non-oriented, UNS 100600 steel alloy equivalent or better, 1mm thick, is specified for all multipole yoke laminations.

Production specifications have been written for each class of multipole used in the NSLS-II lattice.

- "Standard" small-aperture quadrupoles
- "Standard" small-aperture sextupoles
- Large-aperture multipoles

The Standard Quadrupoles

NSLS-II will require standard quadrupole magnets in a number of variations (Table 2). The term "standard" refers to 240 quadrupoles of identical aperture and field quality specifications. To reduce costs, in four locations of the cell where full-field quads are not required, half-field (A, B) single inner-coil magnets are used. The majority of quads (C, D, E) have both inner and outer coils per pole to produce the maximum operating field gradients. Most of the quadrupoles have symmetric iron yokes, although wide magnets with both single and double coils are designed to allow X-ray extraction through the inside of the yoke. Long quadrupoles (C) come in two minor variants; half are symmetric, while half (C′) are designed to accommodate X-ray extraction on the outside yoke mid-plane, and are named "kinked" quads.

Table 2: Sample Standard Quadrupole Parameters

Description	A sym.	B wide	C, C′ kinked	D sym.	E wide
Quantity	60	30	60	60	30
Magnetic length. mm	250	250	400	250	250
Aperture min, mm	66	66	66	66	66
Max. field grad, T/m	11.0	11.0	22.0	22.0	22.0
Pole tip field , T	0.36	0.36	0.73	0.73	0.73
Allowed b_6(units)*	1.0	1.0	1.0	1.0	1.0
Allowed b_{10} *	3.0	3.0	3.0	3.0	3.0
Allowed b_{14} *	2.0	2.0	2.0	2.0	2.0
Non-allowed b_1*	1.0	1.0	1.0	1.0	1.0
Non-allowed b_3- b_4*	2.0	2.0	2.0	2.0	2.0
Non-allowed b_5 *	1.0	1.0	1.0	1.0	1.0
Non-allowed b_7-b_8 *	0.5	0.5	0.5	0.5	0.5
Non-Allowed b_9-b_{15}*	0.1	0.1	0.1	0.1	0.1
Skew terms a_1*	1.0	1.0	1.0	1.0	1.0
Skew terms a_3*	2.0	2.0	2.0	2.0	2.0
Skew terms a_4-a_5*	1.0	1.0	1.0	1.0	1.0
Skew terms a_6 -a_8*	0.5	0.5	0.5	0.5	0.5
Skew terms a_9 -a_{15} *	0.1	0.1	0.1	0.1	0.1
Max. current , A	125	125	138	138	138
Max. voltage, V	6.6	6.6	21.8	14.5	14.5
Amp - turns per pole	4,864	4,864	9,933	9,933	9,933
Max. field integral, T	2.76	2.76	8.80	5.50	5.50
Max. iron length, cm	21.7	21.7	36.7	21.7	21.7
Power per mag., kW	0.83	0.83	3.00	2.00	2.00
Turns per pole	39	39	72	72	72
Min.# water circuits	2	2	4	4	4
Current density, Cu	3.5	3.5	3.9	3.9	3.9

*Field specifications are defined as harmonic terms integrated and normalized to the quadrupole evaluated at a 25mm radius x 10^4

The quad lamination has been specified to have two poles with a common back leg. This two-lamination design improves field quality by reducing non-allowed harmonic terms caused by assembly errors [3]. The glued laminated yoke blocks are identical for either symmetric or wide quads. The yokes are bolted and pinned to solid iron mid-plane spacer blocks. Variant spacer blocks are used to define a magnet as symmetric, wide, or kinked. The magnet assembly is bolted to a steel base plate, which in turn is stud-and-nut mounted to the girder. The magnet could be supported equally well from the mid plane spacer block. Prototype results were used to develop production specifications. Detailed quadrupole design and data can be found in Reference No.4.

The Standard Sextupoles

NSLS-II will require standard sextupole magnets in two variations (Table 3). Here the term "standard" refers to 270 sextupoles of identical aperture and field quality specifications. Most of the sextupoles (A) will have symmetric iron yokes. Wide sextupoles (B) will accommodate X-ray extraction. All of these magnets will have a single coil per pole. The sextupole lamination has been specified to have two poles on either side of a removable center pole with a common back leg. The keyed center pole is used to allow coil assembly. Like that for the quadrupole , this two-lamination magnet design improves field quality

Table 3: Sextupole Parameters

Description	A	B
Quantity required	195	75
Magnetic length, mm	200	200
Aperture, min, mm	68	68
Max. field 2^{nd} dirv. T/m^2	400	400
Pole tip field , T	0.23	0.23
Allowed b_9 (units)*	1.0	1.0
Allowed b_{15} *	0.4	0.4
Non-allowed b_1*	15.0	15.0
Non-allowed b_3*	5.0	5.0
Non-allowed b_4*	2.5	2.5
Non-allowed b_5 & b_7 *	1.0	1.0
Non-allowed b_6 & b_8*	0.5	0.5
Non-allowed b_{10}-b_{11}*	0.2	0.2
Non-allowed b_{12}-b_{14}*	0.1	0.1
Skew terms a_1*	5.0	5.0
Skew terms a_4-a_5*	1.0	1.0
Skew terms a_6 –a_7*	0.2	0.2
Skew terms a_8 -a_{15}*	0.1	0.1
Max. current , A	96	96
Max. voltage, V	4.0	4.0
Amp - turns per pole	2195	2195
Max. field integral, T	80	80
Max. iron length, cm	17.8	17.8
Power per mag., kW	0.38	0.38
Turns per pole	23	23
Current density, Cu	2.7	2.7

by reducing non-allowed terms caused by assembly errors [3]. Pinned end plates help register the center pole precisely between the two adjacent poles. All laminated yoke blocks are identical for either symmetric or wide sextupoles. Different solid spacer blocks are used in order to produce a symmetric or wide magnet. To provide good field quality and maximize good field region steering coils are not used on the NSLS II Sextupoles. Detailed sextupole design and prototype field measurement results can be found in Reference No.5.

The Large Aperture Multipoles

NSLS-II will require two types of large-aperture multipole magnets (Table 4). The term "large-aperture magnet" (LAM) refers to quadrupole and sextupole magnets with field quality specifications requiring normalized integrated field errors of 5x 10^{-5} or less for the first three allowed harmonic terms evaluated at a 25mm radius, and a precipitous fall-off in the value of all error terms thereafter. Although larger apertures make achieving precision field tolerances possible, the pole profile must still be precisely manufactured to a dimensional tolerance of about 10 µm. These tolerances were verified by prototype profile measurements as well as magnets with comparable field quality at SOLEIL [6]. Coil and yoke design and assembly methods will be similar to those of the standard quads and sextupoles. Advanced manufacturing methods such as electric discharge machining and precision milling of the pole profiles for the large-aperture quadrupole and sextupole prototypes have yielded acceptable field performance. These test results have been used to optimize production specifications.

The Correctors

NSLS-II requires four variants of DC corrector magnets (Table 5). All of these correctors are combined-function magnets that can produce vertical, horizontal, and skew quadrupole fields. The design of the correctors was driven by their location on either side of the dipole magnet around the inter-girder vacuum bellows, and by the necessity to accommodate the X-ray extraction bellows. This required an open C-style yoke design with a good field region of X, ±15mm&Y±10mm. Detailed Corrector design and data can be found in Reference No. 7.

Table 4: Sample Large Aperture Multipole Parameters

Description	F Quad	Description	C Sext.
Quantity	60	Quantity	30
Magnetic length, mm	271± 2.0	Magnetic length, mm	250±2.0
Aperture =2r_p, mm	90	Aperture =2r_p, mm	76
*Max. quadrupole gradient, T/m	14.0	*Max. sextupole 2nd Derivative, T/m^2	400
Pole tip field, T	0.63	Pole tip field, T	0.29
Allowed b_6	0.5	Allowed b_9	0.5
Allowed b_{10}	0.5	Allowed b_{15}	0.5
Allowed b_{14}	0.5	Allowed b_{21}	0.5
Allowed b_{18}	0.1	Non-allowed b_1	15.0
Non-allowed b_1	1.0	Non-allowed b_3	5.0
Non-allowed b_2	2.0	Non-allowed b_4	3.0
Non-allowed b_3	3.0	Non-allowed b_5,b_7,b_8	0.5
Non-allowed b_4	2.0	Non-allowed b_6	1.0
Non-allowed b_5, b_7–b_9	0.1	Non-allowed b_{10}–b_{14}	0.2
Non-allowed b_{11}–b_{13}	0.1	Non-allowed b_{16}–b_{20}	<0.1
Non-allowed b_{15}–b_{20}	<0.1	Skew terms a_1	10.0
Skew terms a_3	1.5	Skew terms a_4	3.0
Skew terms a_4	0.5	Skew terms a_5–a_8	0.5
Skew terms a_5–a_{10}	0.1	Skew terms a_9–a_{10}	0.2
Skew terms a_{11}–up	<0.1	Skew terms a_{11}–up	<0.1
Max. current, A	170	Max. current, A	133.2
Max. voltage, V	19.8	Max. voltage, V	6.3
Ampere – turns/pole	12,240	Ampere – turns/pole	3,064
Iron length, mm	233	Iron length, mm	225
Magnet power, kW	3.36	Magnet power , kW	0.84
Turns per pole	72	Turns per pole	23
Current ρ,Cu., A/mm^2	4.8	Current ρ, Cu, A/mm^2	3.7

Table 5: Sample Corrector Magnet Parameters

Description	A	B	C	D
	156mm	156mm SkQuad	100mm	100mm SkQuad
Quantity	45	15	105	15
Aperture, physical, mm	156	90	100	65
Max. DC field , Gauss	294	294	400	400
Magnetic length, mm	300	300	200	200
Max. SkQuad T/m	-	0.46	-	0.46
Field homogeneity ,%	1	1	1	1
Max. DC current, A	18	18	18	18
Max. DC voltage, V	8	8	6	6
Vt. field amp turns/pole	2,429	2,429	2,292	2,292
Hz.field amp-turns/pole	4,194	4,194	3,360	3,360
SkQuad amp-turns/pole	-	3,000	-	1,200
Iron yoke length, mm	150	150	100	100

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