DESIGN AND MANUFACTURING OF THE SNS ACCUMULATOR RING AND TRANSPORT SYSTEM DC MAGNETS*

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Abstract

The Spallation Neutron Source* Accumulator Ring requires large aperture dipole magnets, strong focusing quadrupole and sextupole magnets, and low field corrector dipole, quadrupole, sextupole, and octopole magnets. All of these magnets will provide a fixed magnetic field throughout the accumulator's fill/storage/extraction cycle. Similar fixed field magnets are also being built for the beam transport lines from the linac and to the target. Because of the high intensity in the accumulator, the magnets must be built with tight tolerances for optimum field quality. Because some of the magnets are powered in strings, those magnets must have tight tolerances and consistent material properties to provide the same integral field from magnet to magnet. Radiation resistance, maintainability, and cost were other major factors in determining the magnets' design.[1] The accumulator ring and transport line lattice design required 32 different magnet types out of the 312 magnets to be installed. This resulted in small quantity procurements that affected the cost of fabrication and testing of the magnets.

INTRODUCTION

The SNS physics group defined the detailed performance requirements, apertures, and lengths. High beam intensity and 60 Hz repetition rate[2] necessitated a design that was reliable and easy to maintain. The physics design required large aperture magnets for low loss and over 180 tons of collimation[3] will provide some protection from radiation damage for the magnets. As in any particle accelerator or accumulator there are many different magnets types to provide bending, focusing, steering adjustment, injection and extraction. The most common magnet types are provided in table 1. In addition to the types listed there are another 13 magnet types and a total of 312 magnets required.

MAGNET DESIGN

The 32 magnet types required were the biggest cost driver in the magnet development. Defining the parameters, doing the field analysis, providing a detailed design, and procurement all account for 1 man-year of cost per magnet type, some more. Where possible magnets were used in multiple areas. The ring 21Q40 and 30Q44/58 quadrupoles were used in the high-energy beam transfer line (HEBT) and ring to target beam transfer line (RTBT). This saved design and development effort, provided bulk savings in manufacturing, and reduced the requirements for spares.

Table 1: Magnet types used for the SNS Ring, HEBT, and RTBT lines. 21CS26 nomenclature provides: type - CS Corrector Sextupole, aperture – 21 cm, and core length – 26 cm.

Magnet Types	Aperture and Length in Cm.	Field/Grad T, m	Total Devices
Dipoles	17D120	.92 T	32
	8D533	.24 T	8
Quads	21Q40	5.6 T/m	59
	26Q40	5.3 T/m	8
	30Q44	5.4 T/m	11
	30Q58	5.0 T/m	11
	12Q45	7.2 T/m	32
Sextupoles	21S26	.86 T/m^2	12
	26S26	.86 T/m^2	8
Correctors	21CS26	.73 T/m^2	8
	21CO26	.129 T/m^3	8

An early decision was to manufacture the magnets with solid steel cores. Based on the constant beam energy, high field quality requirements, and cost savings considerations this was a good choice. The various vendors were able to provide high quality machined cores that met all of the dimensional requirements: mating surfaces flat to $\pm$.025mm, pole tip profiles machined to $\pm$.025mm, and apertures to .01mm. Unfortunately for the ring magnets that had to be powered in strings by a common power supply this turned out to be a difficult decision. The requirement for consistency exceeded the consistency of the steel used. Even though the steel was procured in common lots from the same "pour" the magnet to magnet variation was greater than the 1 x 10^{-4} integral transfer function requirement for the magnets powered in strings.[4] Magnets made from steel from different lots were significantly different. An advantage of the solid core design was that it was possible to shim the cores to achieve the required magnet to magnet uniformity. Even with the shimming and the additional magnetic measurement required for small procurements the solid steel cores were cost effective.

A major driver for the cost savings of solid cores was the use of serialized core components. The vendor was required to machine individual parts to $\pm$.15mm tolerances. The final tolerance of the magnet aperture, which determined the field quality, was provided on a core drawing. The vendor could adjust the core component parts as necessary to achieve the final gap

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tolerance by machining or positioning in the case of a quadrupole. The manufacturer then serialized the matched parts of the core so components could not be switched. The components were then pinned after alignment to allow magnet disassembly for vacuum chamber placement, future coil repairs, or as noted above shimming. Another cost savings was the use of 1006 steel for all of the magnet cores. It is cheap, easy to obtain, and easy to machine.

All of the high field magnets used conventional water-cooled copper bus with fiberglass epoxy resin systems applied. To provide an added degree of radiation resistance ½ lapped .005 Kapton was required around the conductor for turn-to-turn insulation. Other than added cost, the Kapton did not add any complications to the ring system magnets. On quadrupoles used for the Linac portion of the SNS project there was a problem. Because the kapton tape glue had been improperly cured by the manufacturer, coils from that particular batch had bubbles in them. The glue would outgas excessively when the coil was as the epoxy curing temperature causing the generation of the bubbles. Changing the tape eliminated the problem.

Table 2: Magnet Specifications

Magnet	Current (amps)	Coil Turns per pole	Current Density
17D120	5260	12	452
8D533	650	12	277
21Q40	870	28	558
26Q40	800	44	513
30Q44	1180	41	536
30Q58	1100	41	500
12Q45	520	20	401
21S26	200	21	342
26S26	330	23	564

After the physics group defined the field requirements and length, the mechanical engineer and the magnet design analyst defined the basic core design. 3D field analysis was done using the Opera 3D program. The results were used to define the pole shape (for quadrupoles and multipoles), pole longitudinal shims (for dipoles), and end chamfer (for quadrupoles). At this point there was a negotiation of trade-offs between the mechanical engineers and the electrical engineers (power supplies). The trade-offs were coil turns to achieve the required current density and matching the power supplies into matched groups that could be procured in large numbers.[5] The other trade-off was high current vs. low current for the mechanical engineer. High current magnets required large cross-section bus with a large cooling passage. The advantage was easy and efficient water flow, fewer turns for the coil winder, and more copper per given cross-section. The trade off is a lot of copper is required to get the current from the power supply house to the magnet. Therefore high current magnets were only used for the ring dipoles that were powered in series and the special injection and extraction magnets where the extra copper was needed to power otherwise tight magnet designs.

PROCUREMENT AND SCHEDULE

Multiple methods of magnet fabrication and procurement were employed depending on the magnet type. The majority of the large production magnets were built to specification with an accompanying detailed drawing package that defined in detail how the magnet was to be constructed. Most of the magnets were procured as complete assemblies that were shipped to BNL or ORNL for testing and magnetic measurement. The ring dipole (17D120) core and coils were purchased separately and then assembled and tested at BNL. This was done because core design iteration with steel was still on going while the project schedule was requiring fabrication of the magnet. The coils were sent out to bid while this testing continued. The cores followed four months later. The advantage of this was that the cores were bid to magnet manufacturers and large machine shops that specialized in machining heavy pieces. The large machine shops under bid the magnet manufacturers by 35% and did an excellent job delivering the magnets on time. Other effects on the magnet cost were the quantity purchased and the complexity of the design. Compare the table 3 with the quantities in table 1 and there is a significant effect. Also quadrupoles cost more than equivalent sized dipoles because of the complexity of the pole tip profile and more pieces have to be machined. Sextupoles have a step increase as well.

Table 3: Magnet Cost (This table does not include the first article magnet cost which was typically 50% higher).

Magnet Type	Total Weight	Unit Cost	Core $/lbs	Coil $/lbs
17D120	19500	$ 70,000	$ 1.59	$ 7.66
8D533	30400	$ 74,500	$ 2.33	$ 3.90
8D406	2600	$ 78,000	$ 2.84	$ 5.14
21Q40	4000	$ 29,400	$ 5.48	$ 4.00
26Q40	6000	$ 38,300	$ 7.39	$ 3.56
30Q44	6000	$ 33,000	$ 4.07	$ 7.74
30Q58	7300	$ 35,000	$ 2.97	$ 8.02
21S26	1200	$ 30,100	$ 6.48	$ 6.00
26S26	1400	$ 34,500	$ 8.63	$ 6.00

Each magnet procurement was competitively bid with the winning vendor being chosen based on lowest price without exceptions to the bid package. The bid package included the fabrication drawing package, three specifications (core steel, coil, and overall magnet assembly), and a statement of work (SOW). The SOW provided schedule information and project reporting requirements. After winning the low bid award, the technical team visited the vendor and all of the documentation was reviewed to clarify the requirements. What became clear at this point was that some vendors were not thorough in reading the specifications or the

SOW. They focused on the drawings and missed hardware and schedule requirements in the specifications and SOW. Scheduled weekly phone conferences were held to maintain contact and review progress.

Except for one of the kind magnets, all of the magnet contracts require that the vendor first build a 1st article magnet for inspection and magnetic measurement before proceeding with the rest of the production order. This allowed BNL to do detailed magnetic measurement to verify the field quality of the design and it gave BNL an option point where it could cancel an order if the vendor was not performing to specification. More important it allowed BNL to iterate on the magnetic design by modifying the steel. All of the ring quadrupole magnets required the procurement of additional pole tips so iterations could be done on the pole tip chamfers that added steel. Because the profile of the quadrupole pole tip was so critical to the magnetic performance, vendors also provided 1" thick samples to demonstrate the performance of their CNC machines before machining the full length 1st article pole tips. When tested all three of the ring quadrupoles magnet types that required the highest field quality went through at least two iterations of the pole tip shape or end chamfer before they were approved for production. These iterations required disassembly of the magnets to remove and remachine the pole tips or to remove and replace the pole tips. This required two to three months of testing time before a 1st article magnet could be approved for production.

Table 4: Time is in weeks after receipt of order.

Magnet Type	1st Article	Production Approval	1st Production	Order Complete
SOW	31	32	54	70
17D120	16	18	26	35
8D533	48	52	65	104
21Q40	39	43	56	100
26Q40	48	54	76	89
30Q58	36	53	83	95

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Every production magnet received is high potted, leak checked, and magnetic measured. The magnetic measurement was used to verify the magnet matching and the requirement for shimming as discussed previously. If shimming was required, the magnets were magnetically measured again. Magnetic measurement results also were used to locate the magnets in the lattice.[6] Magnetic measurement was also used to verify the magnetic center of the multipole magnets.

CONCLUSIONS

The magnets for the SNS accumulator are conservatively designed for reliability in a high radiation environment, low cost, and ease of maintenance. Field quality has been a high priority because these magnets are part of a high intensity machine. Multiple steps have been taken to insure field quality and excellent matching from magnet to magnet. At this time of the 312 magnets required for the SNS ring systems, 182 have been delivered by the vendors, and 82 have been shipped to ORNL, tested, and are ready for installation.

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